

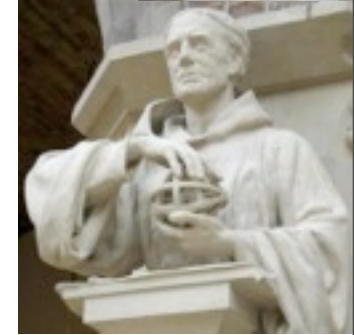
PYTHAGORAS ~ 550 BCE

The THEORIST

- ✓ Cosmos - The Universe as a Mathematical Entity
- ✓ Music of the Heavens – Frequency/Wavelength
- Counting ‘theory’ & whole numbers - Digital



ROGER BACON ~ 1260 AD MARRIAGE: of Experiment to Theory
COPERNICUS/KEPLER/GALILEO et al. ~1600 AD



NEWTON ~ 1660 - 1690 AD

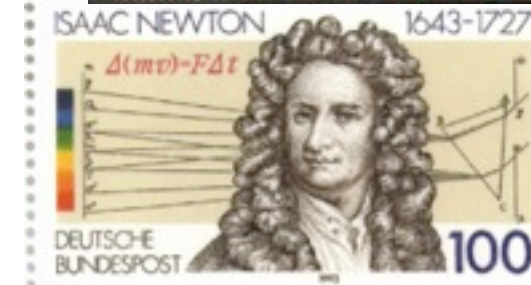
The PHYSICIST

- ✓ LAW OF GRAVITATION - Mass Attraction
- ✓ Heavenly Objects Arise via Clumping .. **Gravitational Instability**
- ✓ Thus: the Universe is Infinite

KANT ~ 1755 AD Galaxies - ‘Island Universes’ YES! (Early 20s)



Milky Way 1953-55



Newton's Death Mask @ROE

Crawford collection



EINSTEIN: SCIENTIFIC COSMOLOGY(1917)

✓ Finite universe without a boundary

✓ “Cosmological Constant” (~ 1895) Λ

Make the Universe Finite via A Repulsive Force

“My greatest blunder”

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FRIEDMANN (1922) Evolving (Expanding) Universe

- ✓ YES! Hubble (late 20s) rate
- ✓ the SINGULARITY (30s,60s),
infinite density (!!!???)

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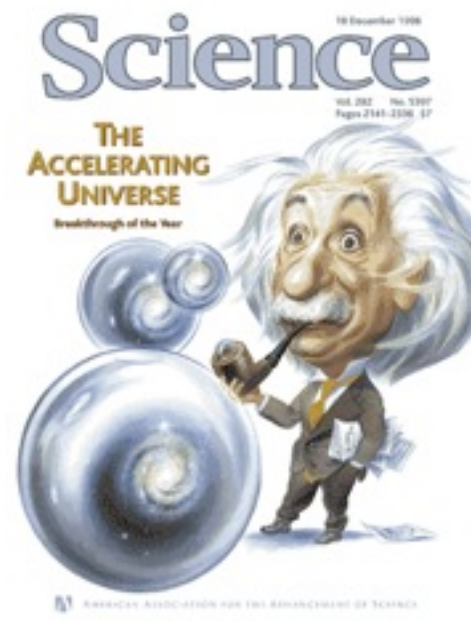
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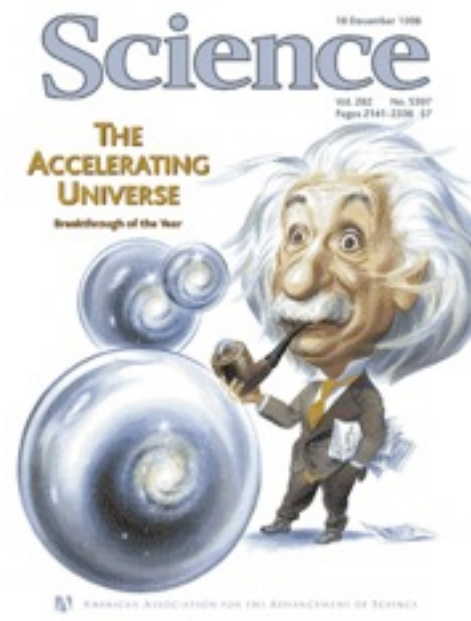
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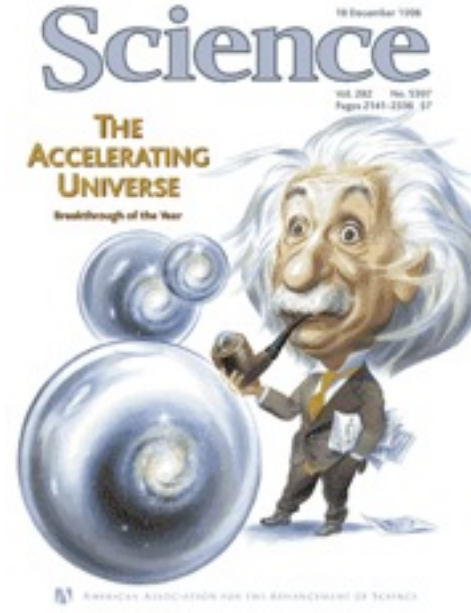
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ρ_{Λ} = vacuum energy density

Sakharov~67



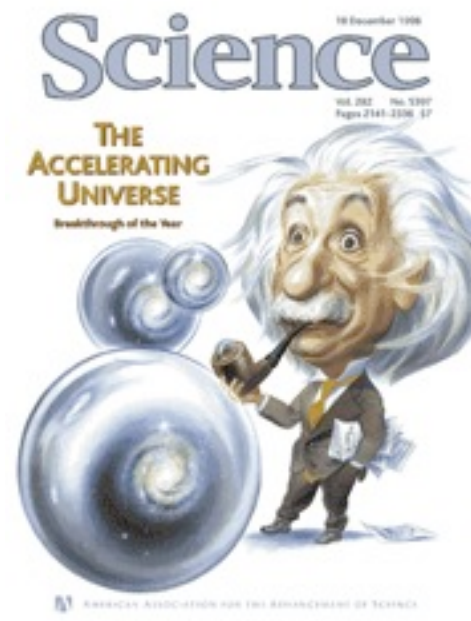
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$V = \Lambda / 8\pi G$ Newton vacuum potential



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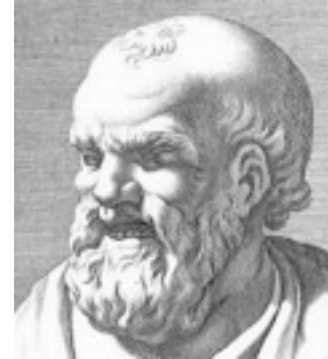
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the Weighty Matter of the Cosmos: what is the Universe made of?

4 elements/ 4 qualities
+ 5th element: **quintessence** aether

Leucippus, Big Cosmology
& **Democritus, Little Cosmology**
460-370BC 2 elements: **atoms** &
the **void**; eternal U, matter conserved



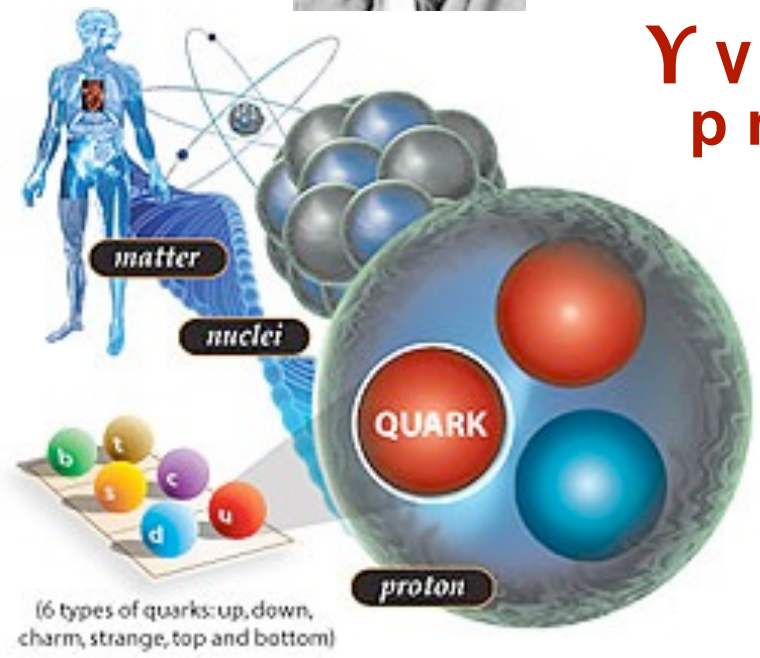
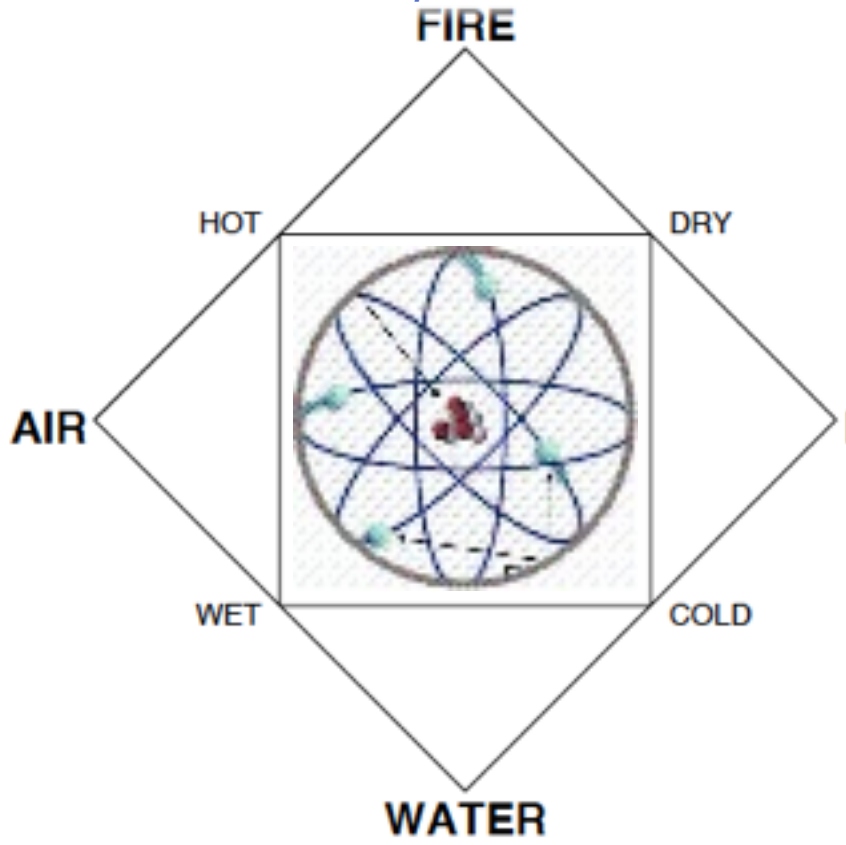
Rutherford
1911 nucleus
+electrons



Dalton
1766
-1844

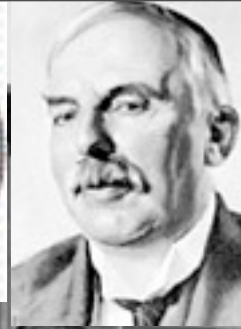


γ ν h_{ν} x
 p n e



(6 types of quarks: up, down, charm, strange, top and bottom)

water (Thales), air (Anaximenes), earth (Xenophanes), and fire (Heraclitus). Empedocles unified theory of all 4. Plato 4 of 5 geometrical crystal-like solids as atoms. Aristotle prevailed: elements as combinations of qualities

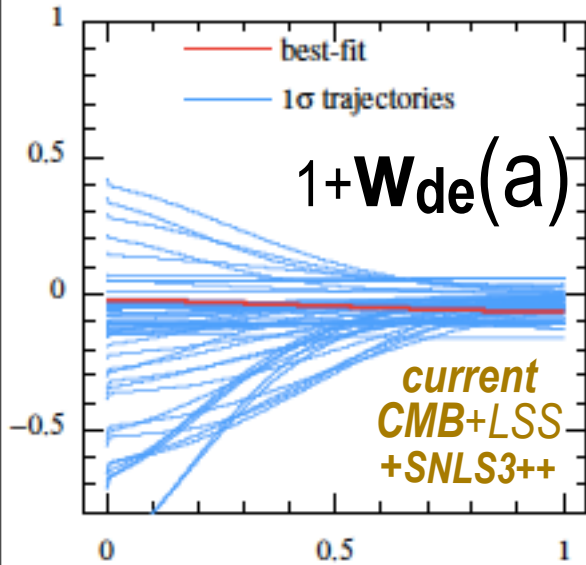


IOTA 1967, Cambridge **B²FH 57, WFH 67, sn**

Beyond Einstein



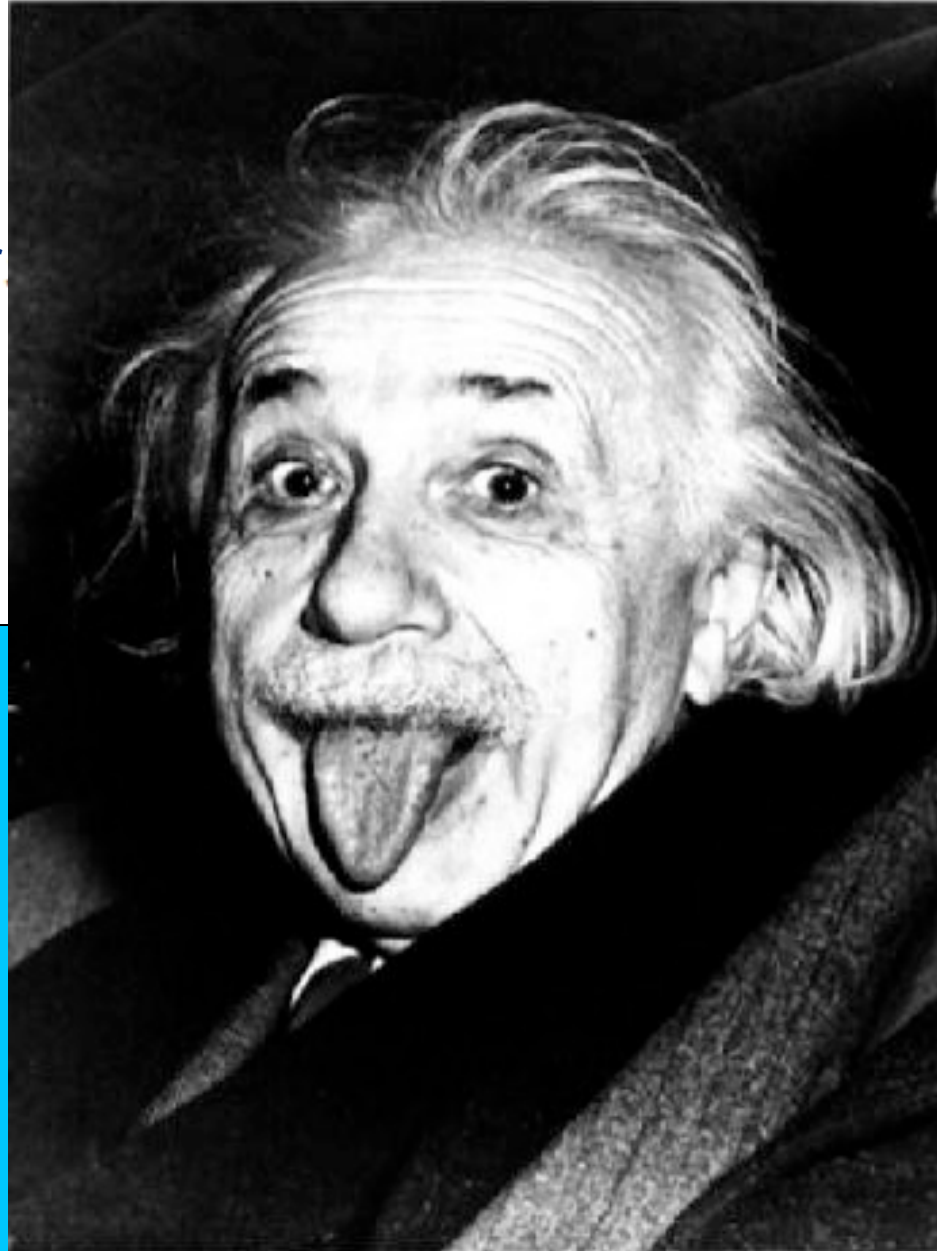
NOW & future DE equation of state trajectories



Current Data
CMB: ACT+WMAP7,
 Acbar (2009), QUAD (2009),
 BICEP (2009), CBI (2008),
 Boomerang-pol, VSA, MAXIMA
Type Ia Supernova 472:
 123 low-z+ 242 SNLS3yr
 +93 SDSS1yr + 14 HST
HST constraint H0 =
73.8 +-2.4 km/s/Mpc
 Weak Lensing: COSMOS +
 CFHTLS-wide + RCS +VIRMOS
 +GaBoDS
 LSS: SDSS-DR7 LRG (2009)
 Ly-alpha Forest: SDSS

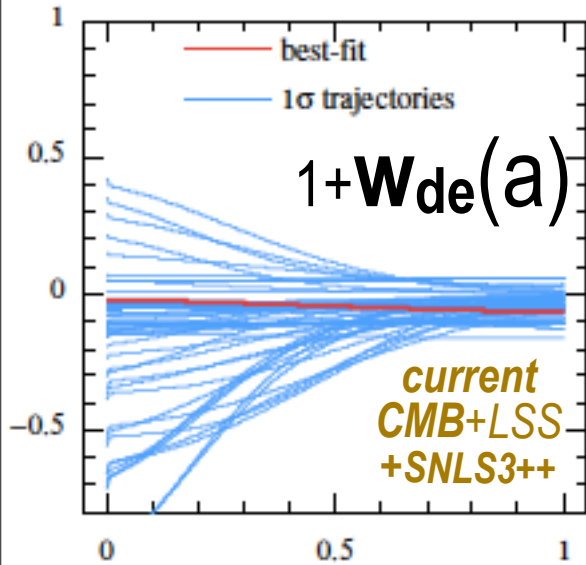
Huang, Bond, Kofman 2010; Bond, Huang 2011

$$(1+W_{de}) = - d \ln p_{de} / d \ln a^3$$

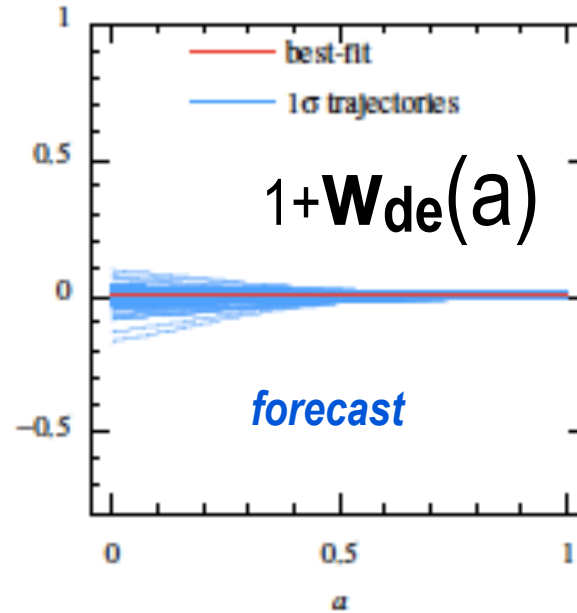


3parameter form paves even wild late-inflaton trajectories

NOW & future DE equation of state trajectories



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Forecast Data
 CMB: Planck2.5yr,
 LSS:
 EUCLID
 spectroscopic redshift
 survey;
 21-cm CHIME BAO
 survey;
 EUCLID weak lensing
 survey

Huang, Bond, Kofman 2010; Bond, Huang 2011

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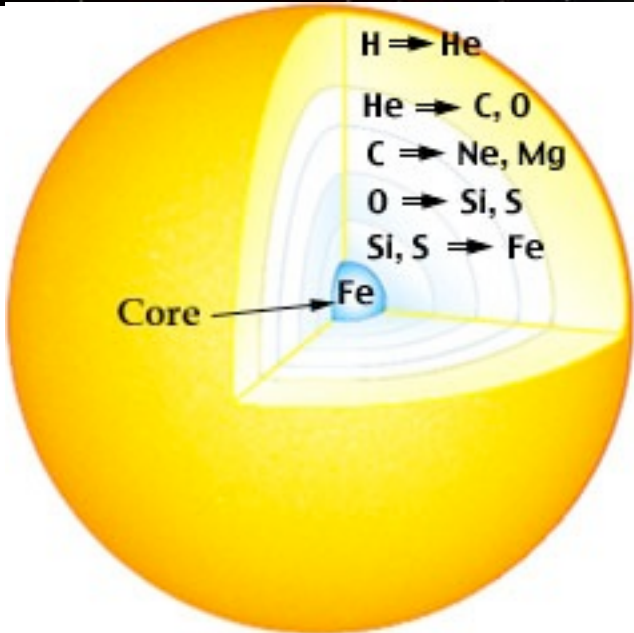
3parameter form paves even wild late-inflaton trajectories

Crab 1054 AD SN + pulsar
i.e. neutron star remnant



SN1987a @LMC

collapse neutrinos,
no neutron star yet



**Nobel
Prize 84
Willy
Fowler +
Chandra
-sekhar**

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extra-“ordinary” matter

Fermilab's

vacuum potential

Primordial SOUP

DIRECTIONS
Heat ingredients to 3,000,000,000,000,000 degrees, stirring occasionally if you wish.

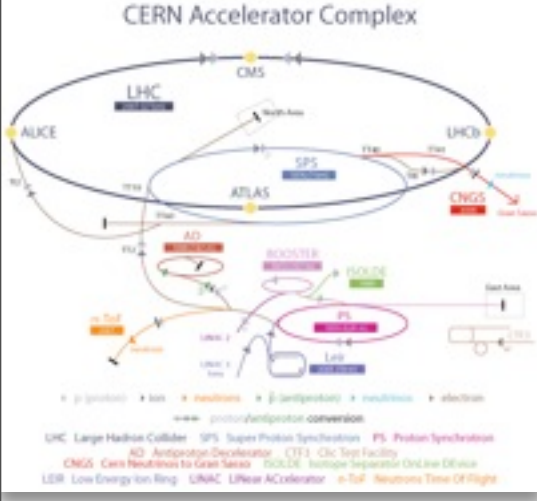
If allowed to cool for 14 billion years, this product will become the atoms that make up our known universe.

CAUTION:
Contents are extremely dense and are under enormous pressure.

INGREDIENTS

Quarks	56%
Force Carriers	29%
Electron-like Particles	9%
Neutrinos	5%
Higgs Bosons	1%

INSPECTED BY U.S. Department of Energy



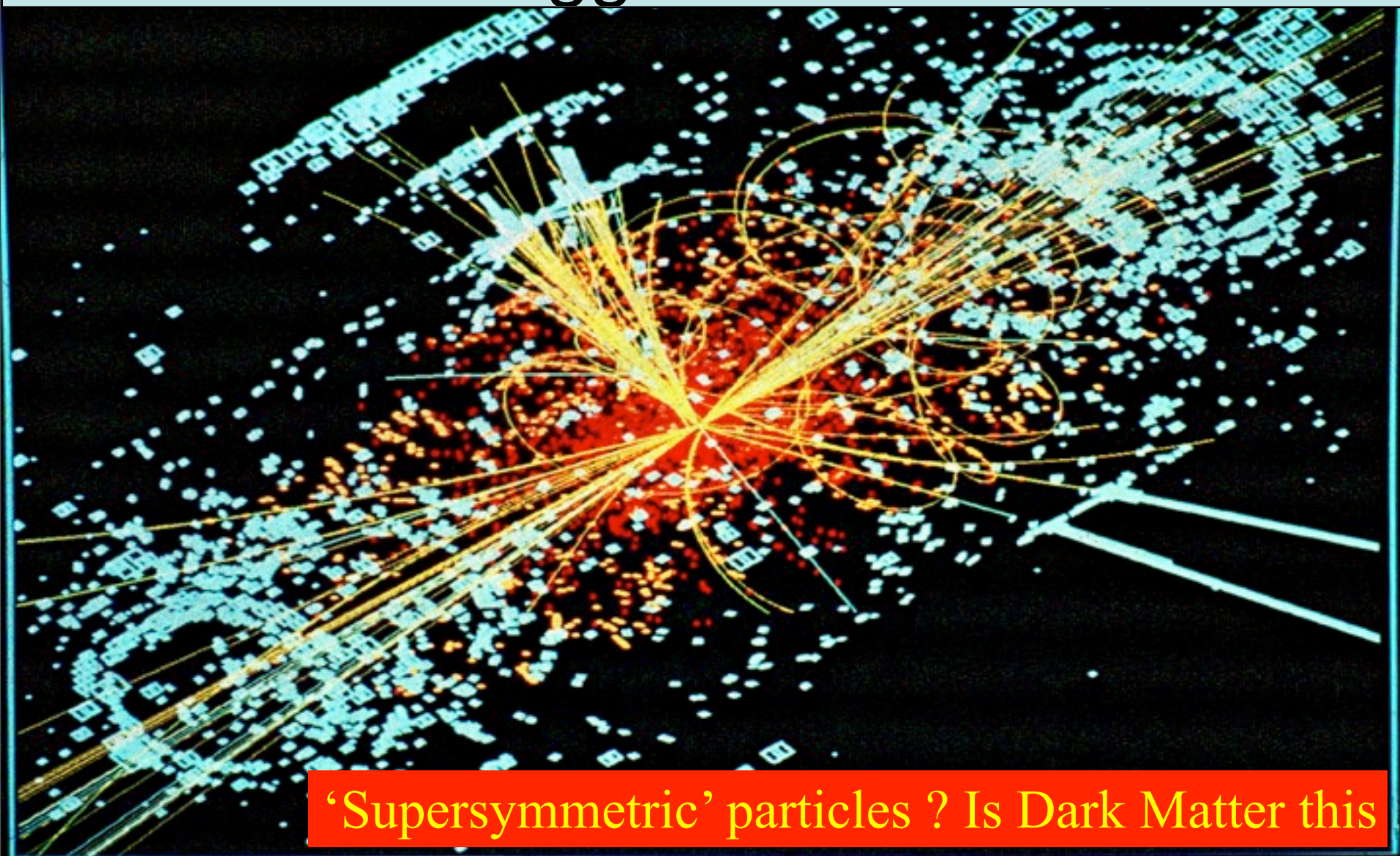
Galileo's Accelerator

LHC “new first light” Dec09
 @CERN “cosmic” accelerator



- what is mass?
- vacuum potential
- dark matter
- antimatter
- asymmetry
- extra dimensions

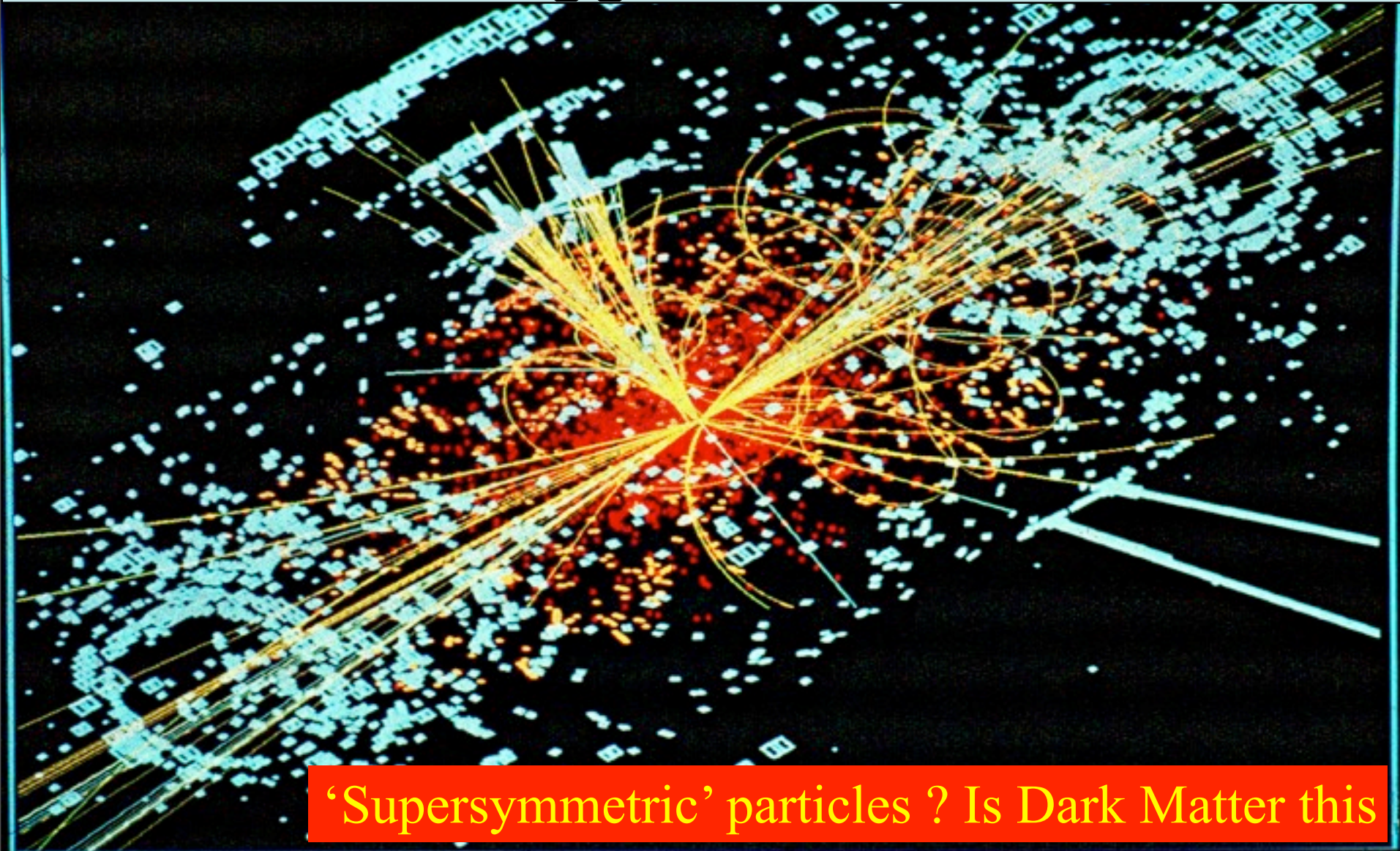
A Simulated Higgs Event in CMS: LHC



‘Supersymmetric’ particles ? Is Dark Matter this

If Dark Matter interacts with ordinary matter by more than gravity, we may “see” it at the Large Hadronic Collider 2009+ or at SNOlab 2010+ in Sudbury

A Simulated Higgs Event in CMS: LHC



‘Supersymmetric’ particles ? Is Dark Matter this

“IT from BIT”

FATE U inflate (again)

a cold death? reheat/rebirth?

NOW 14 Gyr 1

Pythagoras formed

Galaxies Cluster
Cosmic “web” of
vast filaments +
membranes

Life forms on
earth

9 Gyr 1.4

Carbon/oxygen/etc
form

Galaxies form

2 Gyr 4

The ‘Meaning’ may change
But the facts will remain

10^{55}

Inflation fluctuations
form: quantum jitter

10^{-37} sec 10^{29}

Protons/Neutrons
form

Helium forms
 100 sec 10^9

Cosmic background
radiation released from
matter
carries imprint of
fluctuations in matter which
grow to generate galaxies etc.

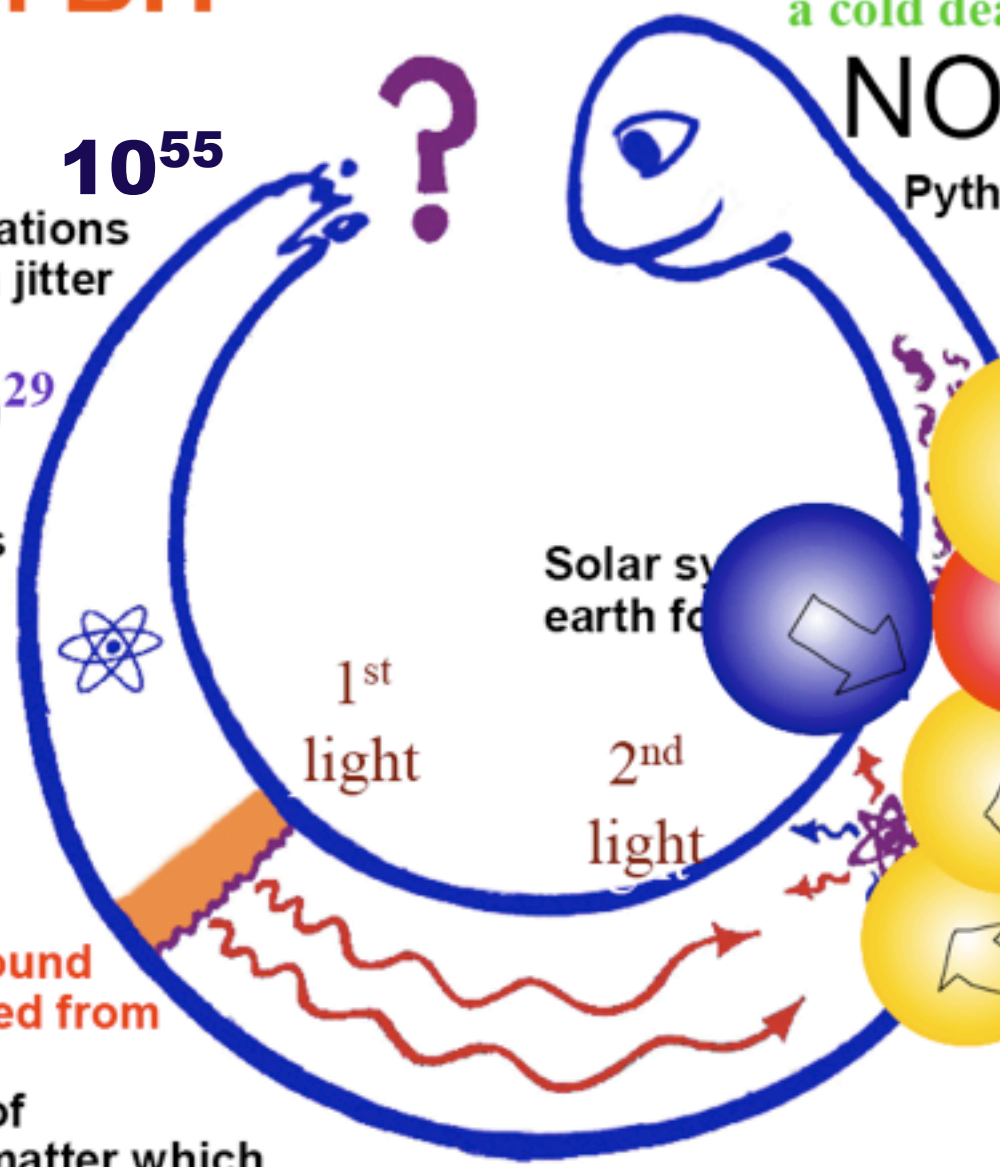
0.4 Myr 1100



1st
light

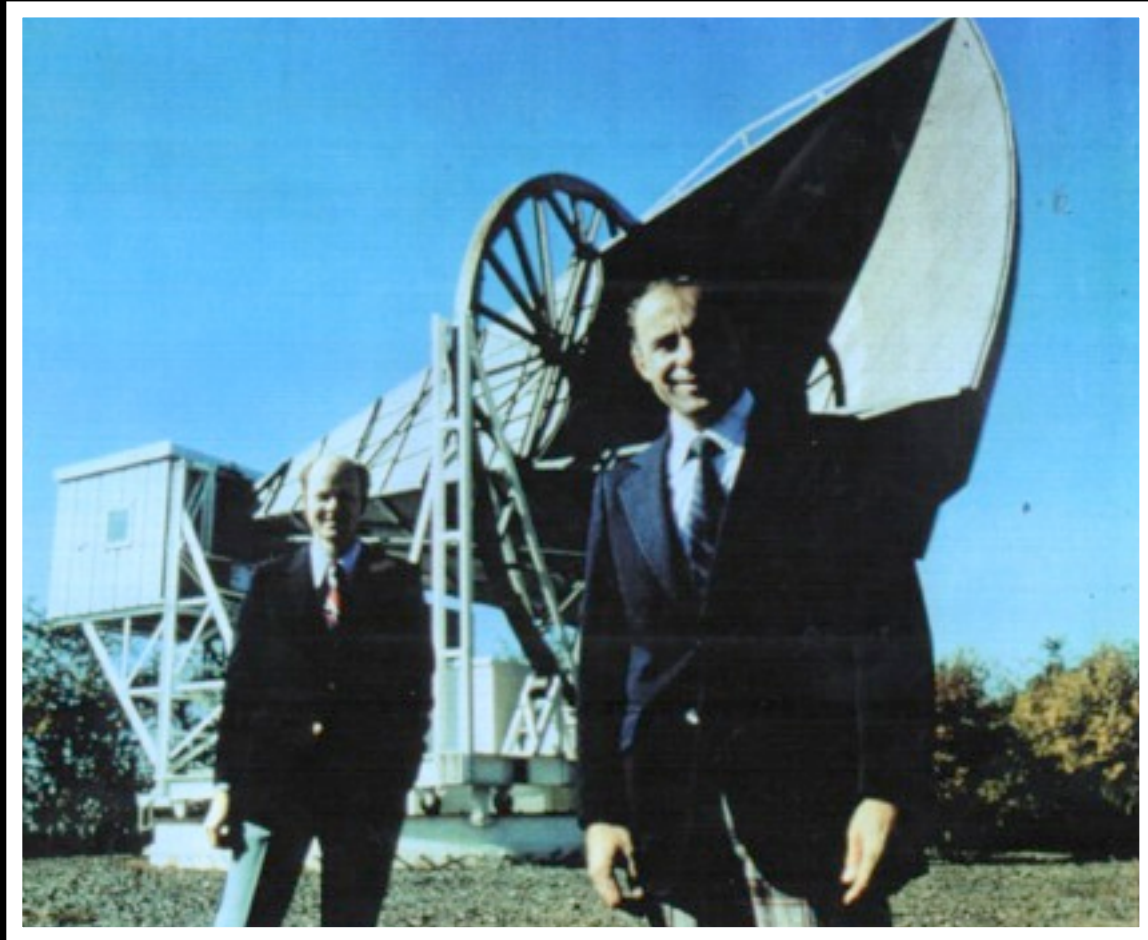
2nd
light

Solar system
earth form



The Universe Is Radiant

**Arno Penzias
Robert Wilson
1965**



“IT from BIT”

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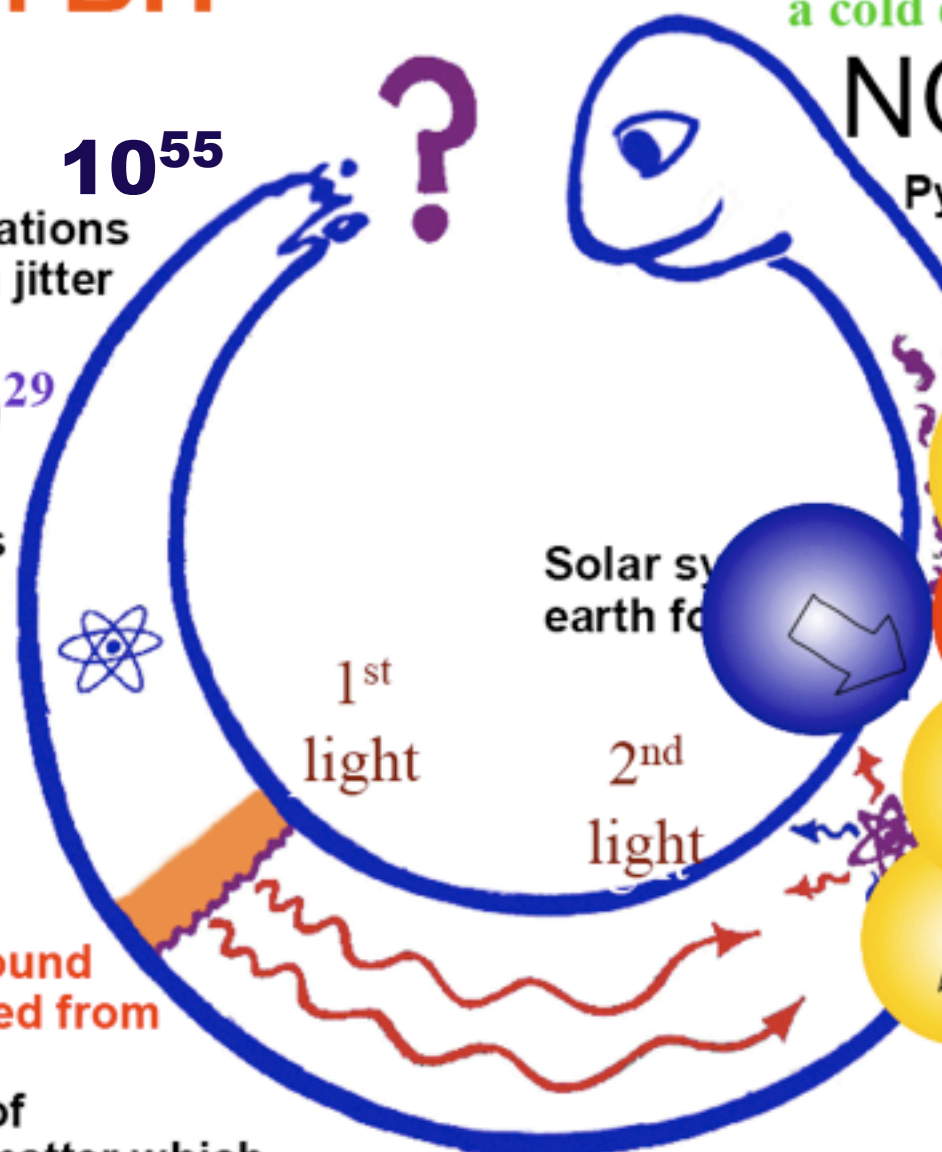
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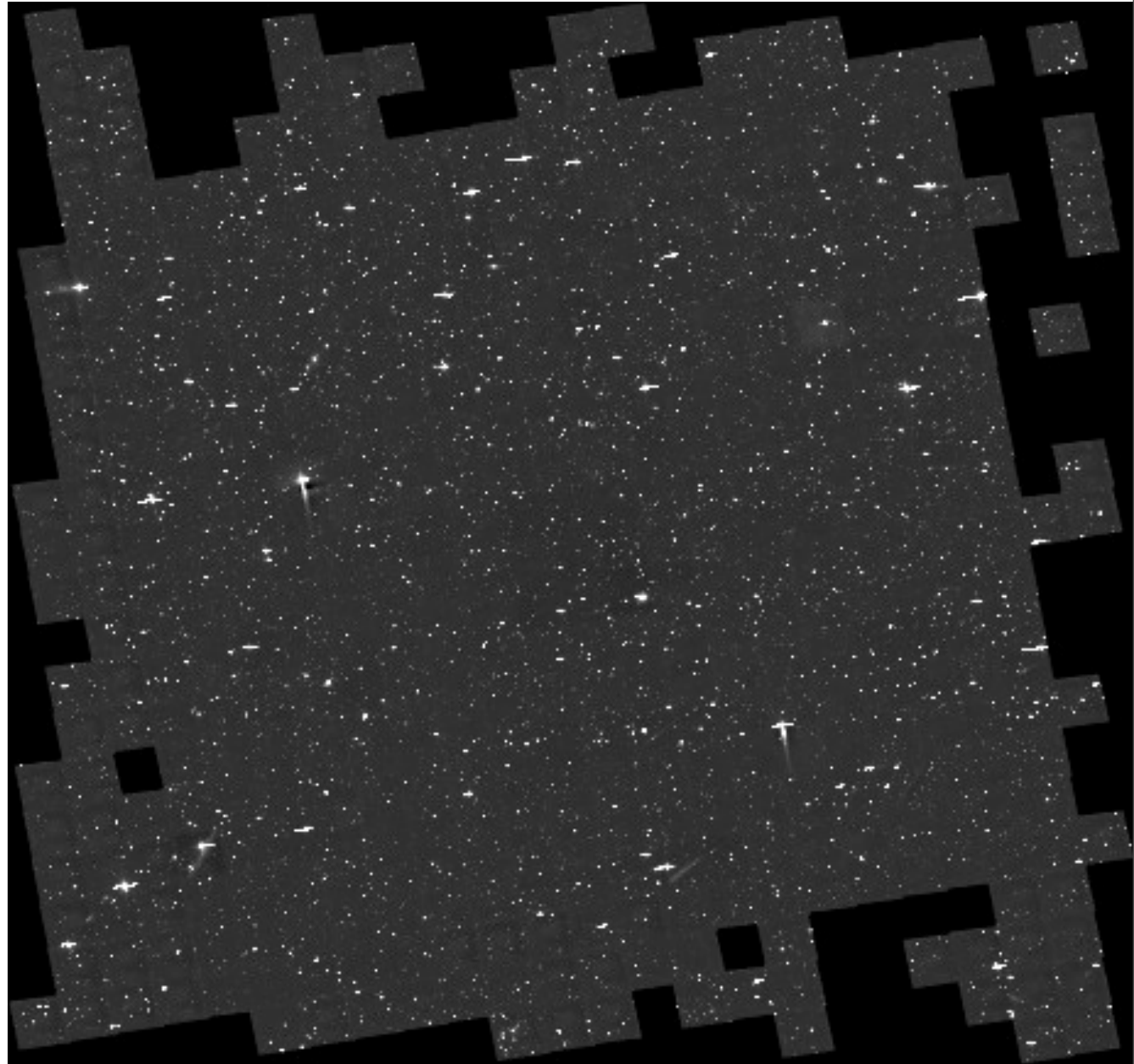


Hubble “Cosmic Evolution Survey”

- 2 deg² Hubble Space Telescope data (largest ever Hubble program)
- > 2 million faint galaxies with measurable shapes



**& Beyond
Hubble: JWST
(+TMT+)**



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**& Beyond
Hubble: JWST
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a **starless**
“dark age”
before the
most
distant
galaxies

dwarflets &
the 1st stars

form at
compression 13

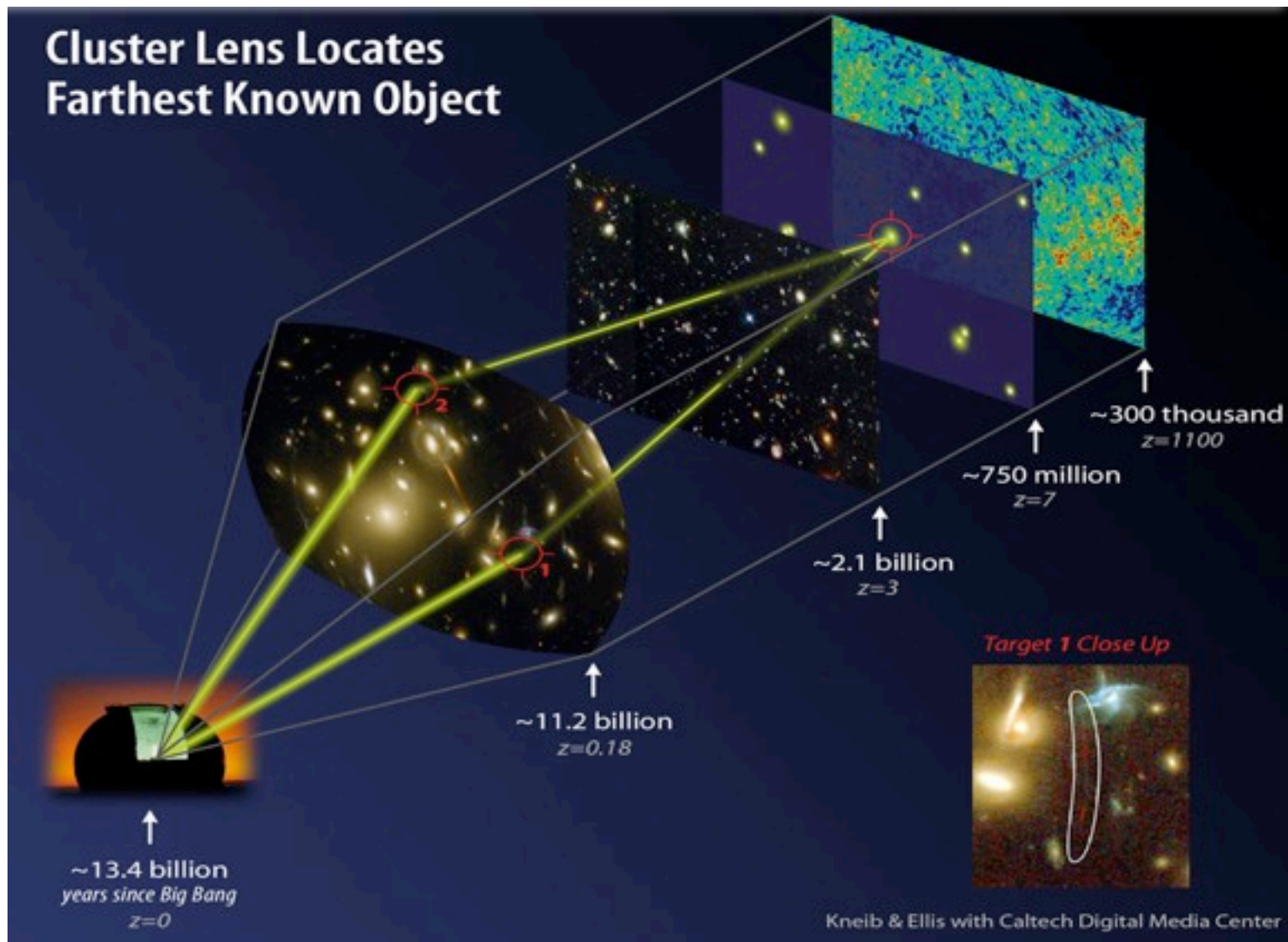
1st light:
Cosmic
Microwave
Background

released at
compression
1100; formed
at $\sim 10^{30}$

EINSTEIN ... 1905 *international year of physics* 2005

international year of astronomy 2009

NEW LAW OF GRAVITATION (1916); speed of light is the ultimate speed **HORIZONS**;
Space is curved by mass; **Light bends, wavelengths change, under gravity**



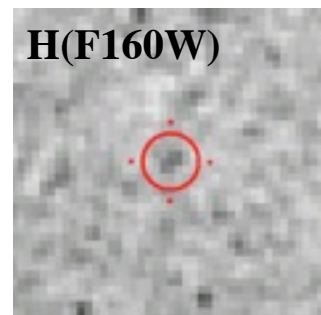
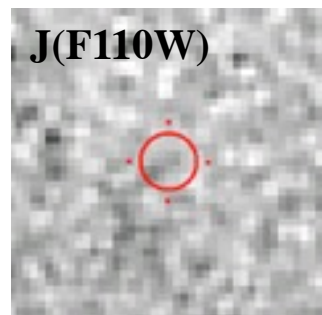
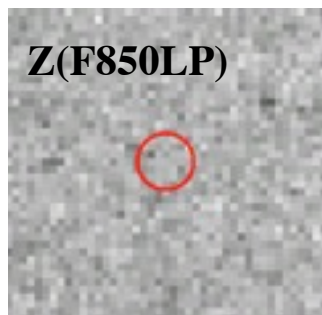
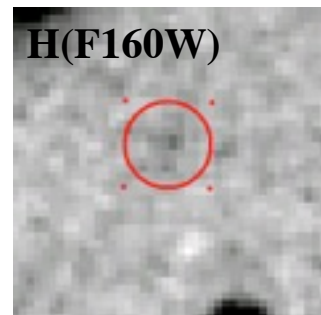
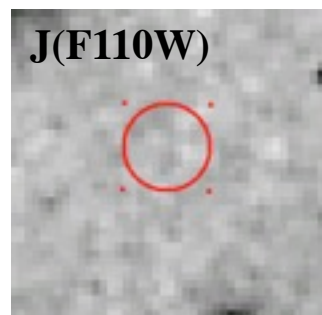
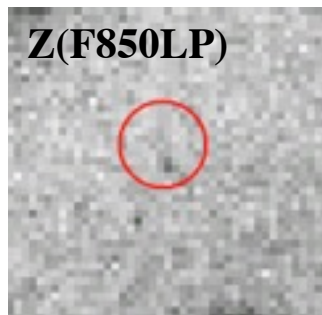


DAVE BARRY

Over the years I have been harshly critical of the scientific community for wasting time researching things nobody cares about, such as the universe. I don't know about you, but I'm tired of reading newspaper stories like this:

“Using a giant telescope, astronomers at the prestigious Crudwinkle Observatory have observed a teensy light smudge that they say is a humongous galaxy cluster 17 jillion light years away, which would make it the farthest-away thing that astronomers have discovered this week. However, astronomers at the rival Fendleman Observatory charged that what the Crudwinkle scientists discovered is actually mayonnaise on the lens. Both groups of astronomers say they plan to use these new findings to obtain even larger telescopes.”

Galaxies at compression 10



“UltraDeep” work of Richard Ellis et al. CifAR Associate

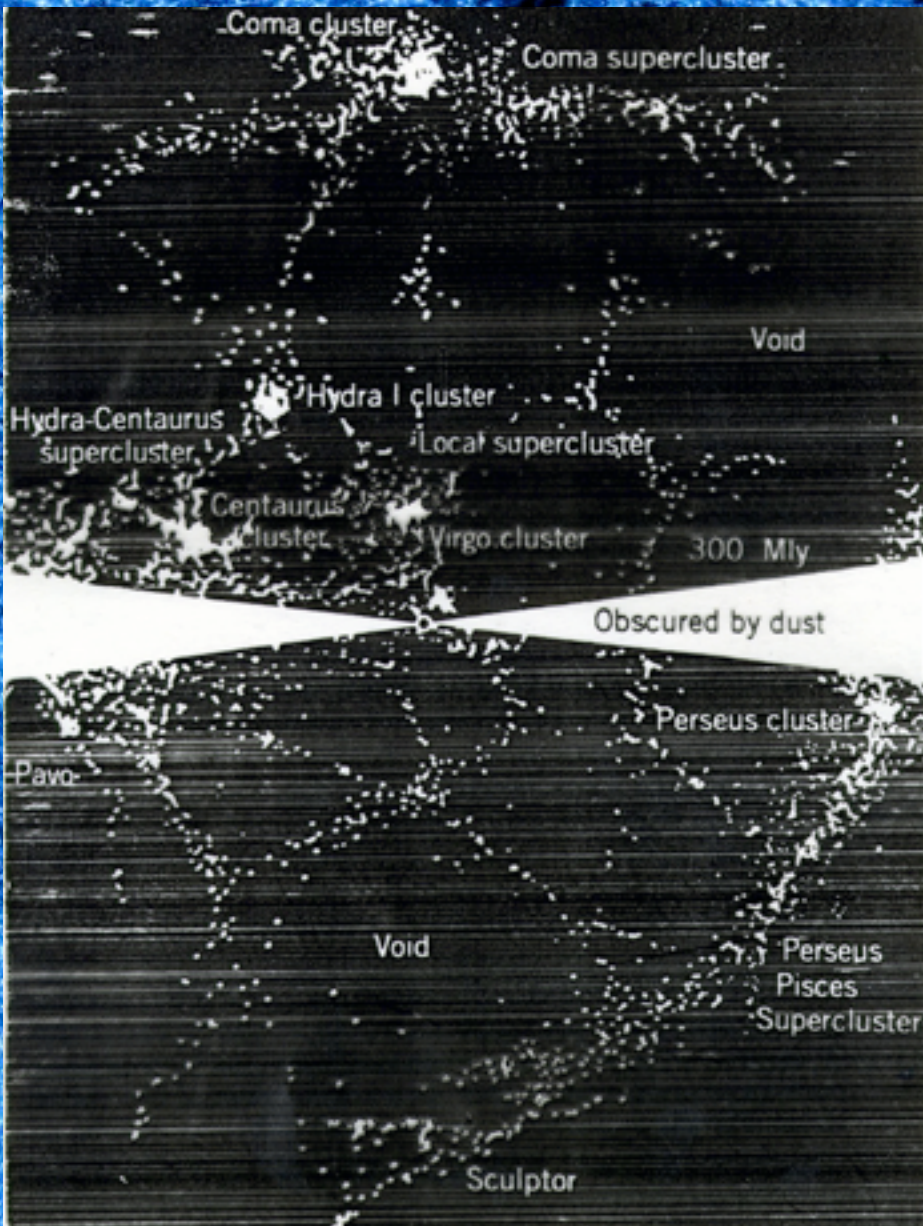
TMT: Thirty Metre Telescope

JWST: James Webb Space Telescope

SKA: Square Kilometre Array



nonlinear Gas & Dark Matter Structure in the Cosmic Web the cluster/gp web “now”, the galaxy/dwarf system “then”



*all this
can
evolve
from
early U
vacuum
potential
and
vacuum
noise

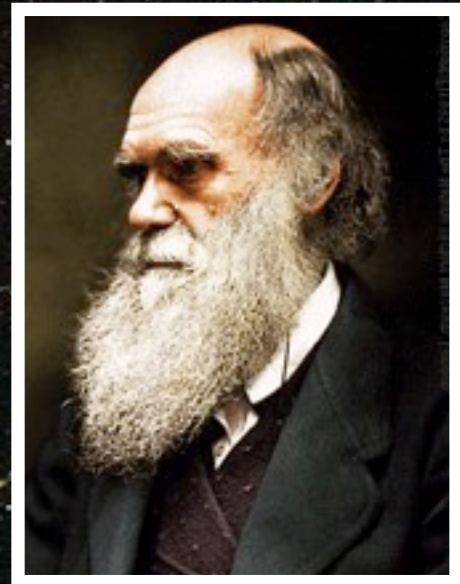
in the
presence
of late U
vacuum
potential
aetherial!*

Cosmology today

- 1) Space and time: geometry shaped by mass-energy
- 2) Origin: “big bang” 13.7 aeons ago
- 3) Evolution: expanding, cooling, **accelerating**
- 4) Arrangement: galaxies in the cosmic web
- 5) Composition: **dark matter** and **dark energy** & **us**

There is grandeur in this view ... from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved.

Charles Darwin
The Origin of Species





Beyond Einstein

the universe is comprehensible!!!

Gravity=Geometry=Mass-Energy

cosmological constant 1917 Λ

1998/2009+: dark energy

Ω_{Λ} (space,time)? $\Omega = \rho / 3M_P^2 H^2$

Ω_{dm} = dark matter (in labs?)

Ω_b = ordinary matter (known)

Gravitational waves – 1917

ripples in spacetime moving at the speed of

light c to be “observed”: from black holes

Ω_{BH} & neutron stars ~2012, from the

quantum early Universe ~2011? Ω_{GW}

detect Ω_{dm} in lab; annihilation in space; early U Ω_{GW} via CMB

ρ_{Λ} (time,space) vacuum E

Then (10^{-37} s) inflation

Now (13.7×10^9 yr)

=dark energy mysteries

in a landscape of

different vacuua

our CfAR future: to the
early & late Universe thru

Theory+Experiment (CMB+Lens+SN+clusters

+ LIGO,LISA,BBO for gravity waves +

SNOlab,CERN,...,Planck,Fermi,.. for dark matter)

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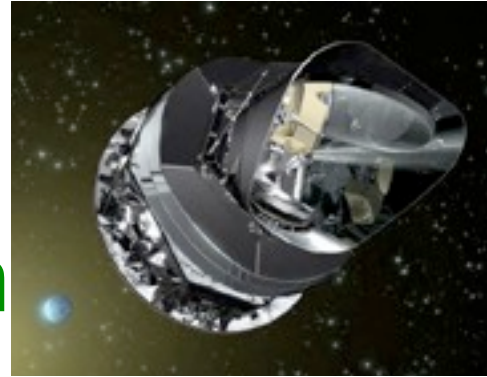
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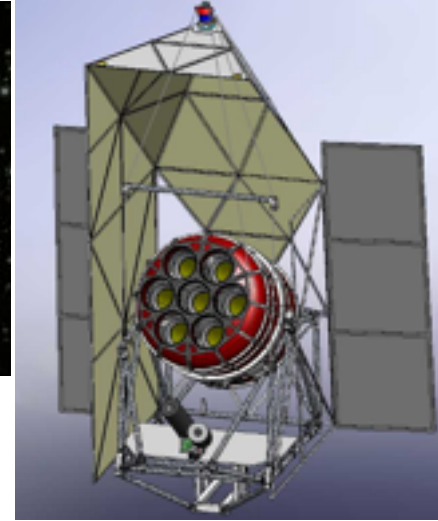
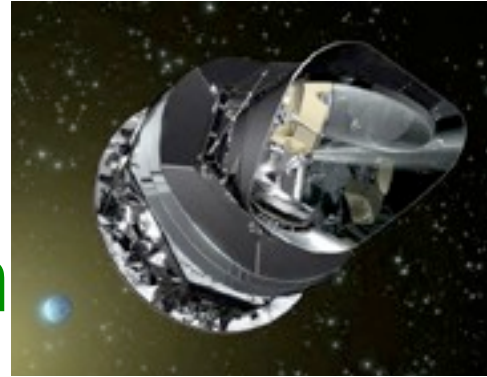
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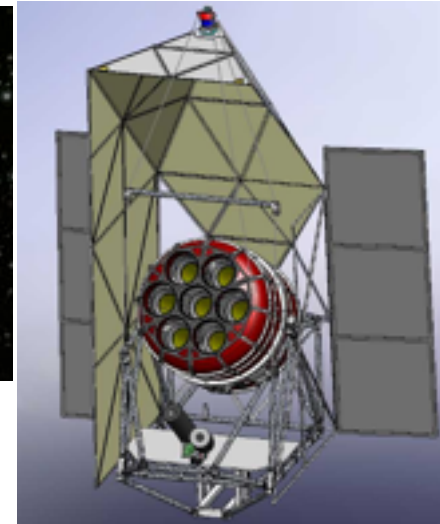
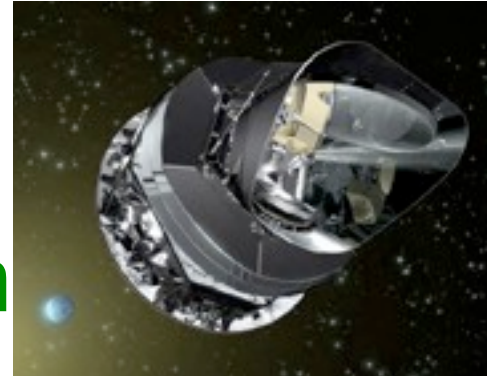
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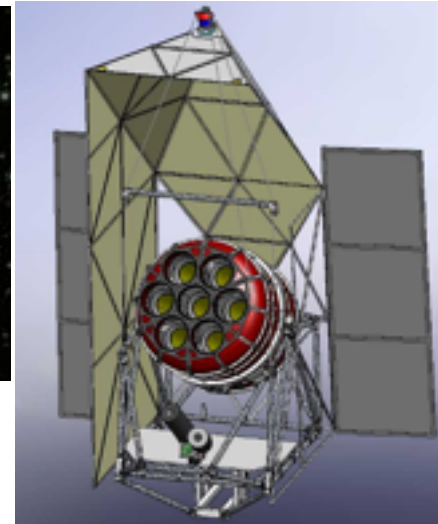
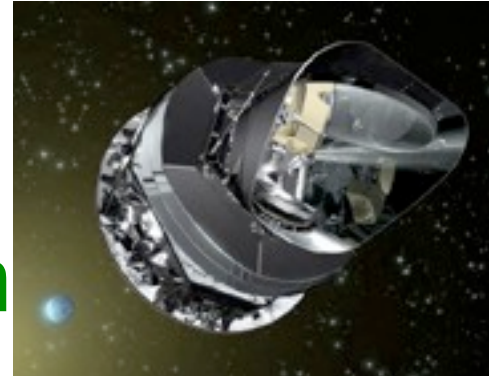
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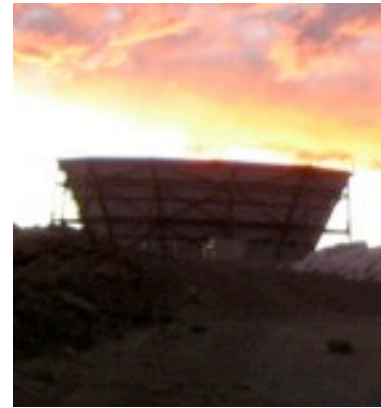
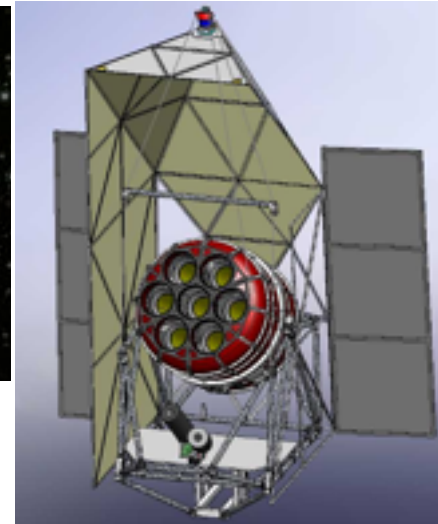
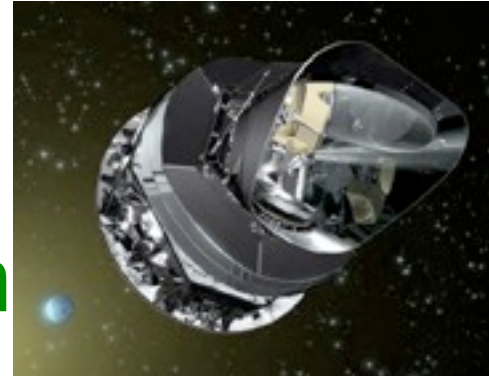
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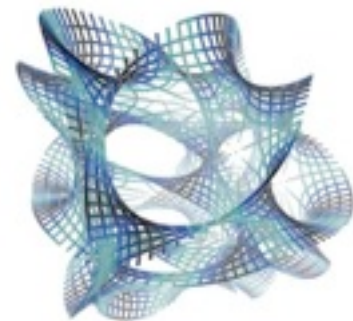
Theory+Experiment (CMB+Lens+SN+clusters
+ LIGO,LISA,BBO for gravity waves +
SNOlab,CERN,...,Planck,Fermi,.. for dark matter)

detect Ω_{dm} in lab; annihilation in space; early U Ω_{GW} via CMB

ρ_{Λ} (time,space) vacuum E
Then (10^{-37} s) inflation
Now (13.7×10^9 yr)
=dark energy mysteries
in a landscape of
different vacuua
our CfAR future: to the
early & late Universe thru

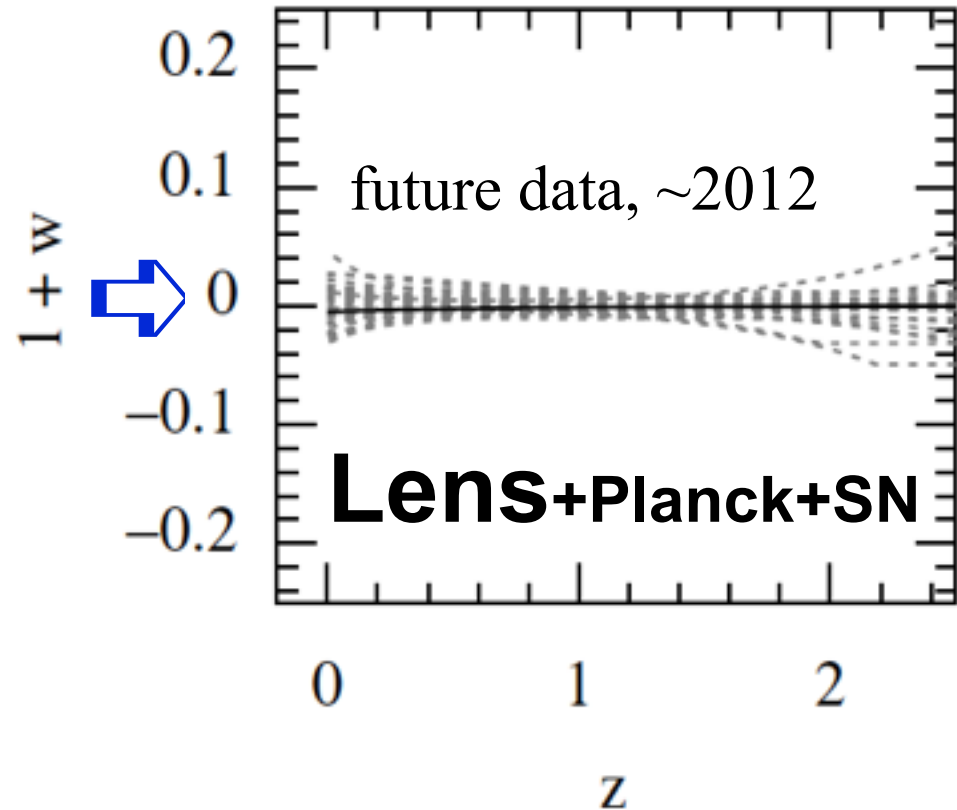
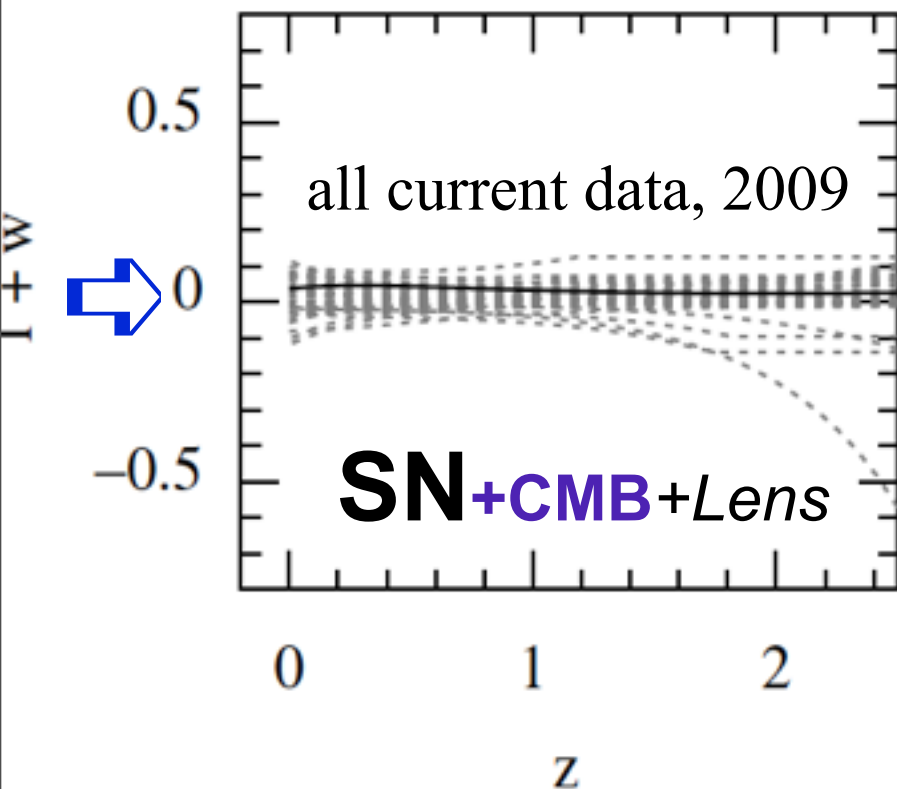


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ρ_{Λ} (time, space) ?

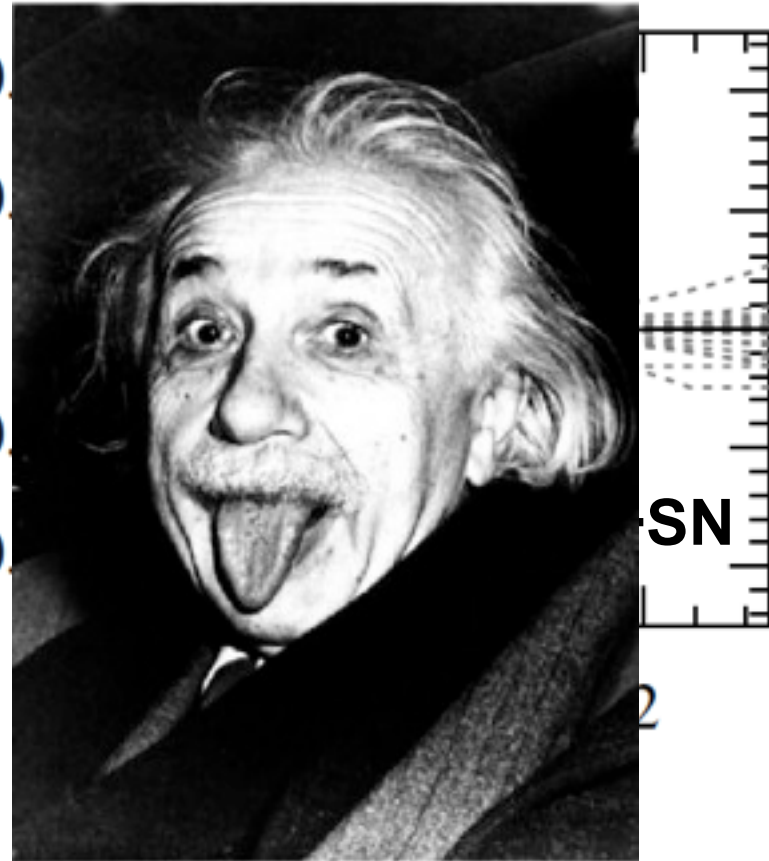
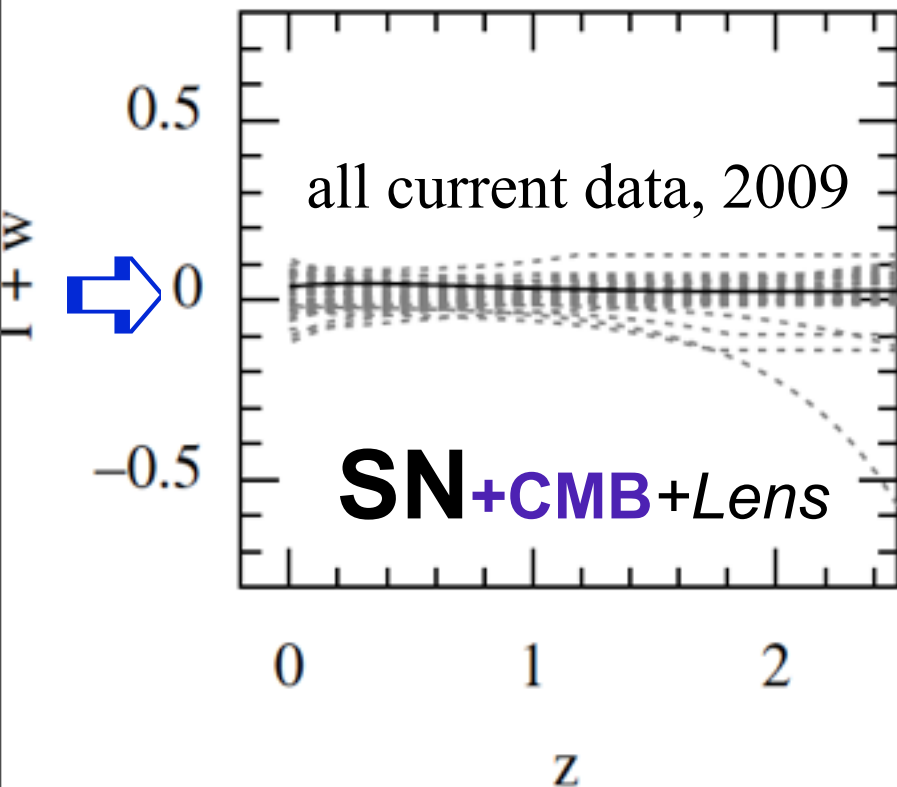
is the **dark energy** “vacuum potential energy” ?



TEST: within errors, energy-density does not change with expansion \Rightarrow Einstein's cosmological constant is best fit so far

ρ_{Λ} (time, space) ?

is the **dark energy** “vacuum potential energy” ?



TEST: within errors, energy-density does not change with expansion \Rightarrow Einstein's cosmological constant is best fit so far

**“To me every hour of the light
and dark is a miracle. Every
cubic inch of space is a miracle.”**

– Walt Whitman

In every cubic centimetre

- **cosmic radiation** 412 cm^{-3}

- **dark matter** $\sim \text{amu m}^{-3} \sim$

**compressed in MW to $\sim 0.1 \text{ amu CM}^{-3}$ for
LHC-type DM, ~ 1 every 10 cm**

- **dark energy** $\sim 4 \text{ keV cm}^{-3}$
 $\sim (\text{milli-eV})^4$

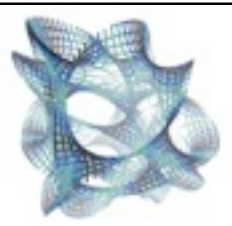
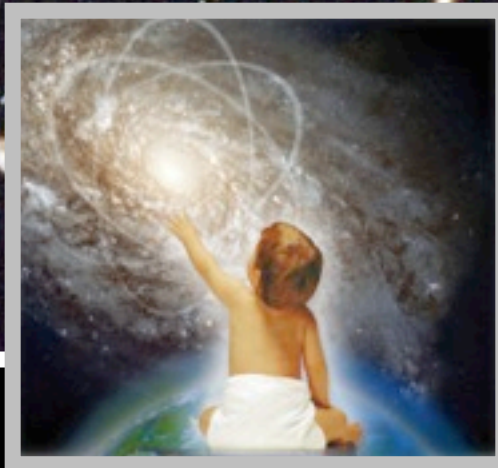
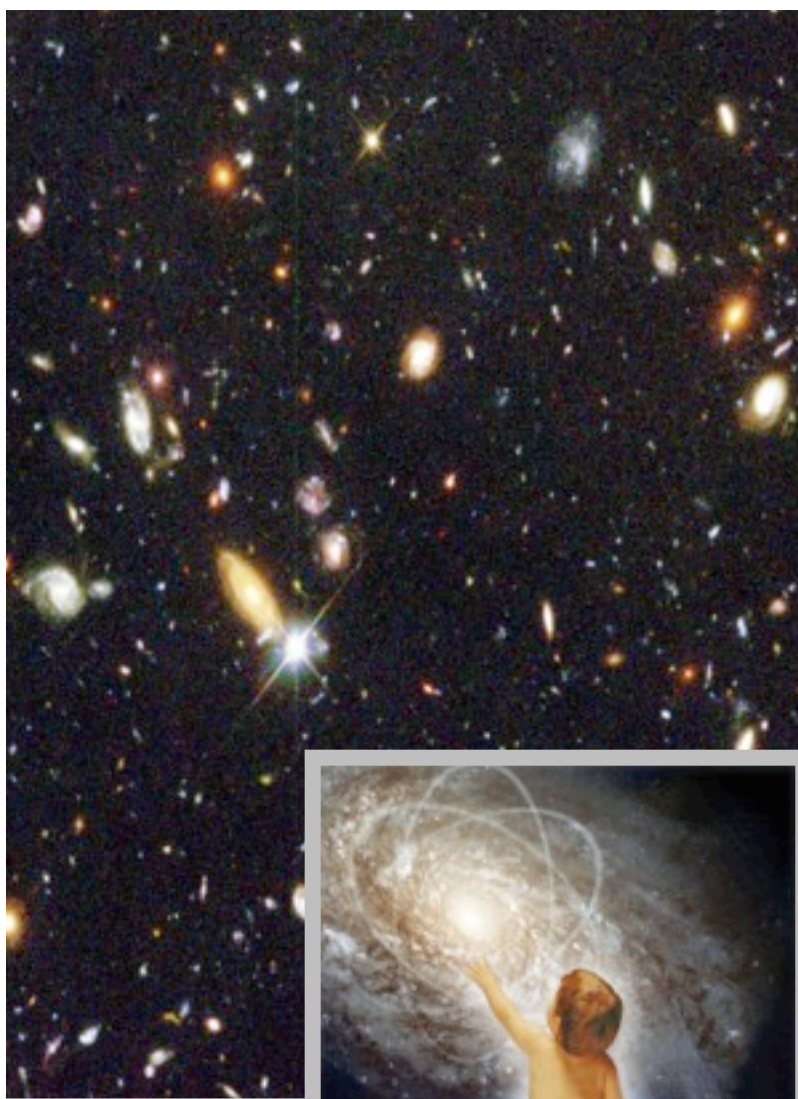
- **neutrinos** \sim CMB photons

- **gravity waves**

- virtual particles - vacuum fluctuations

- Higgs potential - origin of mass

- **extra dimensions here, now?**



PERSON OF THE CENTURY

TIME

ALBERT
EINSTEIN

“The most beautiful thing we can experience is the mysterious. It is the source of all true art and all science. Those to whom this emotion is a stranger, who can no longer pause to wonder and stand rapt in awe, are as good as dead: their eyes are closed.”

Albert Einstein

www.cita.utoronto.ca/~bond/traj/talks/bond_rci_public_09_11_01.pdf



**CITA
ICAT**

Canadian Institute for
Theoretical Astrophysics
L'institut canadien
d'astrophysique theorique

**Cosmic
Times & U**

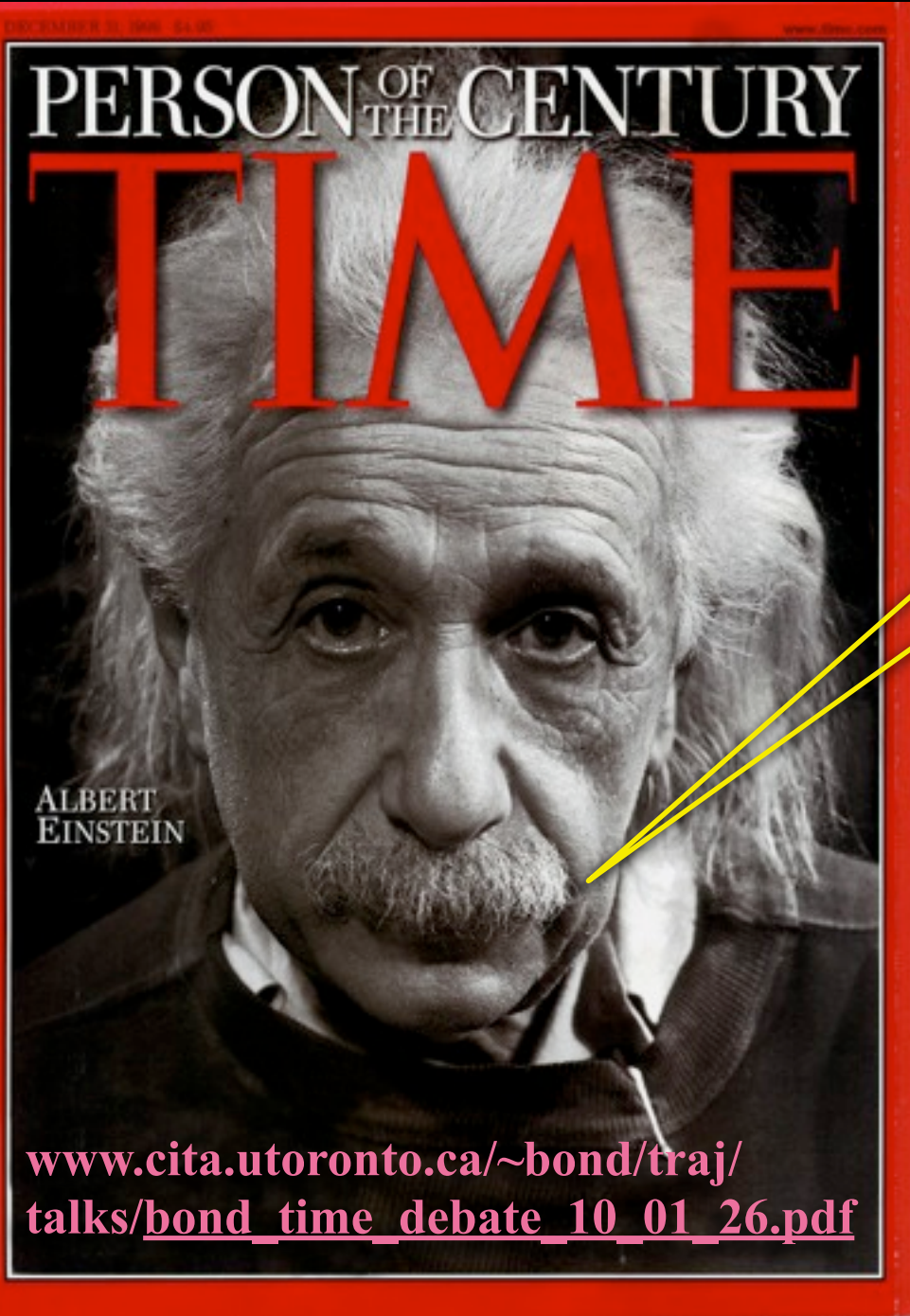


Dick Bond *Canadian Institute for Theoretical Astrophysics, University of Toronto*

THE GREAT TIME DEBATE

Tuesday, January 26, 2010

26



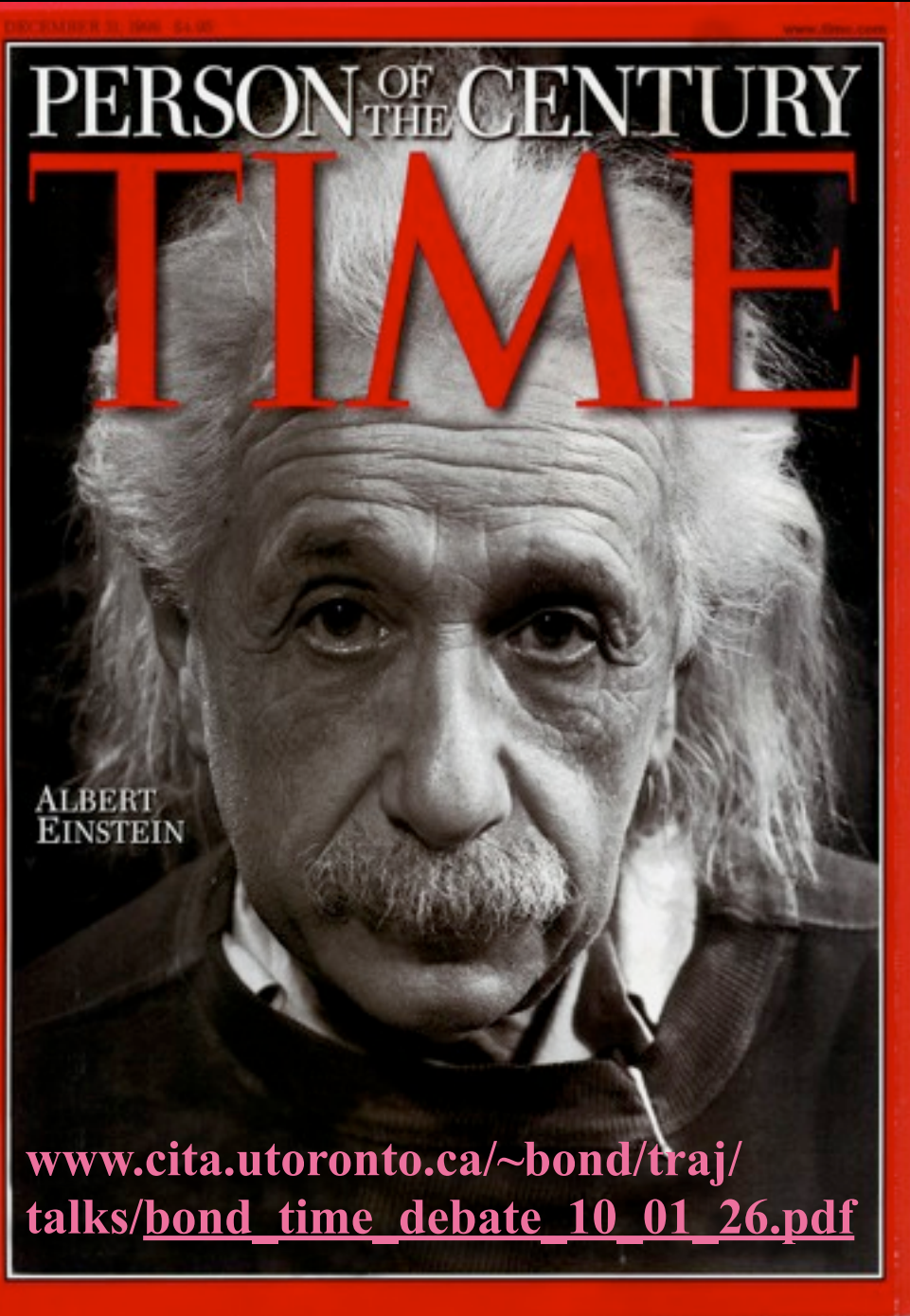
MY TIME $I(t)$, me (t), you (t), $U(t)$

ASTRONOMICAL TIME

PHYSICS TIME

precision

COSMIC TIME!

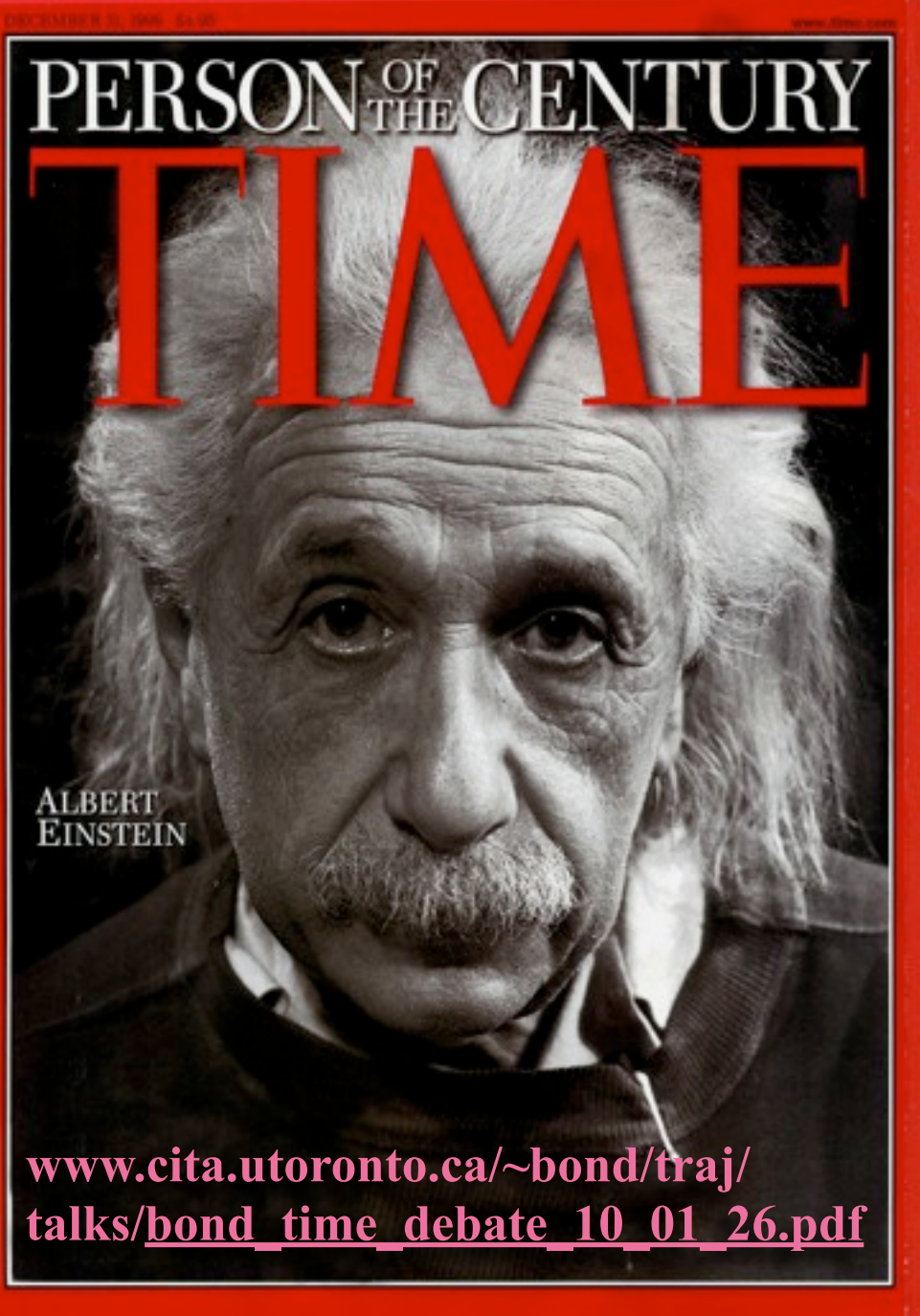


MY TIME **I**(t), **me**(t), **you**(t),
U(t) coherence of being; in the
NOW (\exists no NOW?); **past** &
future, history & forecasting ... **U**
 $\in \{Us\}$

ASTRONOMICAL TIME

PHYSICS TIME

COSMIC TIME



MY TIME $I(t)$, $me(t)$, $you(t)$, $U(t)$ coherence of being; NOW; past & future, history & forecasting

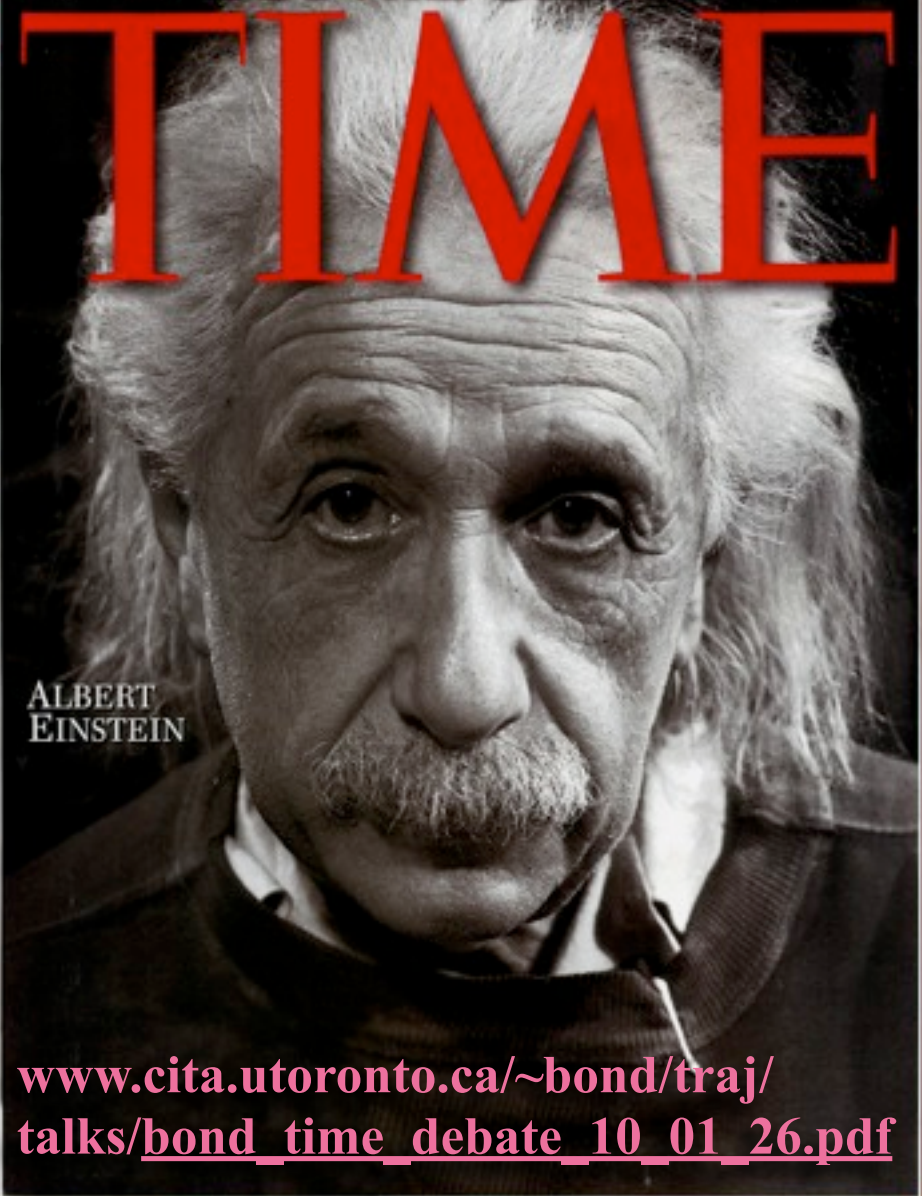
ASTRONOMICAL TIME counting cycles = clock: years (seasons & agriculture), moons (wax & wane), days & nights, hours (medieval); sundials, water clocks & calendars

PHYSICS TIME

COSMIC TIME

PERSON OF THE CENTURY

TIME



ALBERT
EINSTEIN

www.cita.utoronto.ca/~bond/traj/talks/bond_time_debate_10_01_26.pdf

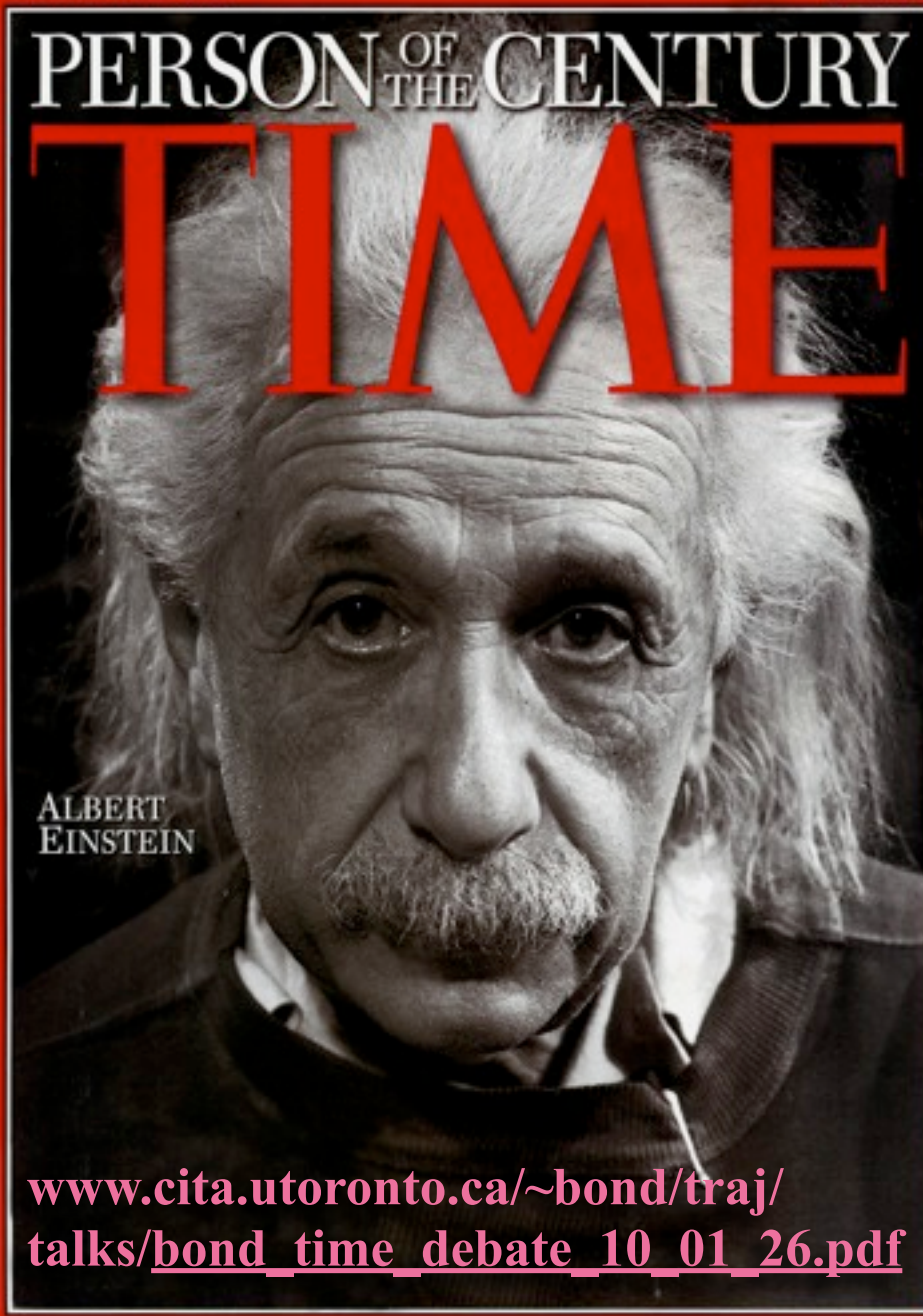
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PHYSICS TIME pythagoras
frequency ν harmonics in music
cycles per minute, second; to millisecc, microsec, nanosec, pico, femto; attosec;
pendulum, spring & crystal clocks, cesium atom standard to ± 30 nanosec 1955-67 0.11 nsec

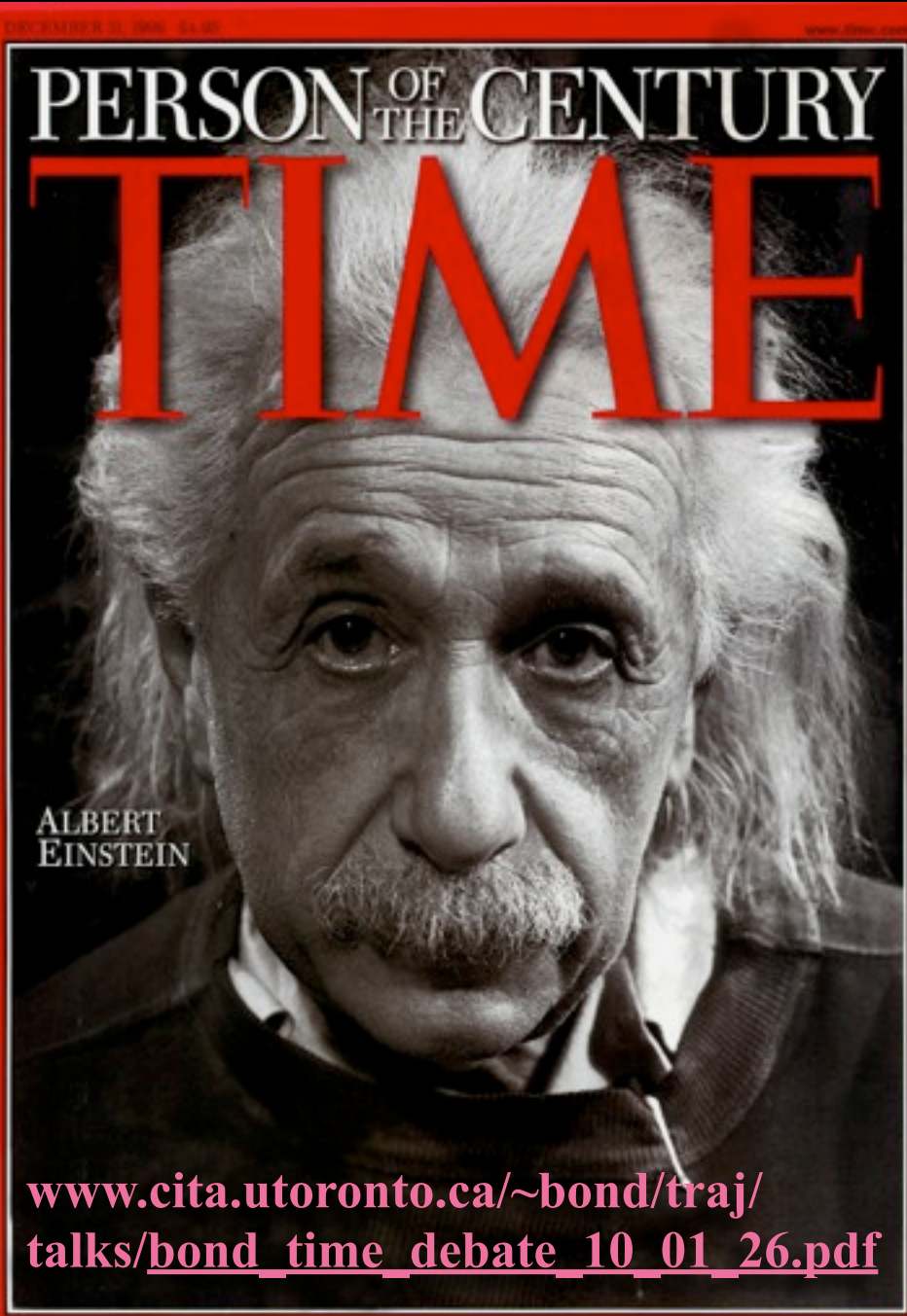
from string oscillations to the cosmic music of the spheres
frequency = conjugate to time
the quantum:
energy $E=h\nu$ conjugate to time

(wavelength)⁻¹ & momentum conjugate of space, light & structure;
phase-space, spacetime & action

physics time \Rightarrow all of physics \Rightarrow COSMIC TIME



MY TIME I(t), me(t), you(t), U(t) coherence of being; NOW; past & future, history & forecasting
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PHYSICS TIME pythagoras frequency ν harmonics in music cycles per minute, second; to **milli, micro, nano, pico, femtosec**; spring clocks, digital clocks, cesium standard from string oscillations to the cosmic music of the spheres frequency = conjugate to time the quantum: energy $E=h\nu$ conjugate to time (wavelength)⁻¹ & momentum conjugate of space, of light and structure; phase-space, phase & action
shortest usable times: ultrafast lasers pulses femtosec \Rightarrow attosec (10^{-18})
CERN quark-gluon plasma light pulses **yoctosec (10^{-24}); LHC collisions (10^{-28})**
COSMIC AGE of U = 13.7 ± 0.1 Gyr AB ($10^{17.6}$) + the time before matter/radiation creation, **pre-BigBang ... pre-spacetime?**



PHYSICS TIME:

points move thru *phase-space* as time progresses **worldline: $x(t), p(t)$**

Special Relativity 1905

spacetime $(x,t: p,E)$

*The views of space and time which I wish to lay before you have sprung from the soil of experimental physics, and therein lies their strength. They are **radical**. Henceforth **space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.*** Minkowski 1908 after Einstein 1905

the relativity of time and space $t(x) \Rightarrow$ so many times

*BUT **time IS fundamentally different** from space. 1 time dimension, 3 ($\Rightarrow 10$) space dimensions, related by:*

the ultimate speed limit: of light & other signals

way back is far out: *only events in our past light cone influence us, we can only influence our future light cone*

we cannot “see” beyond our past horizon

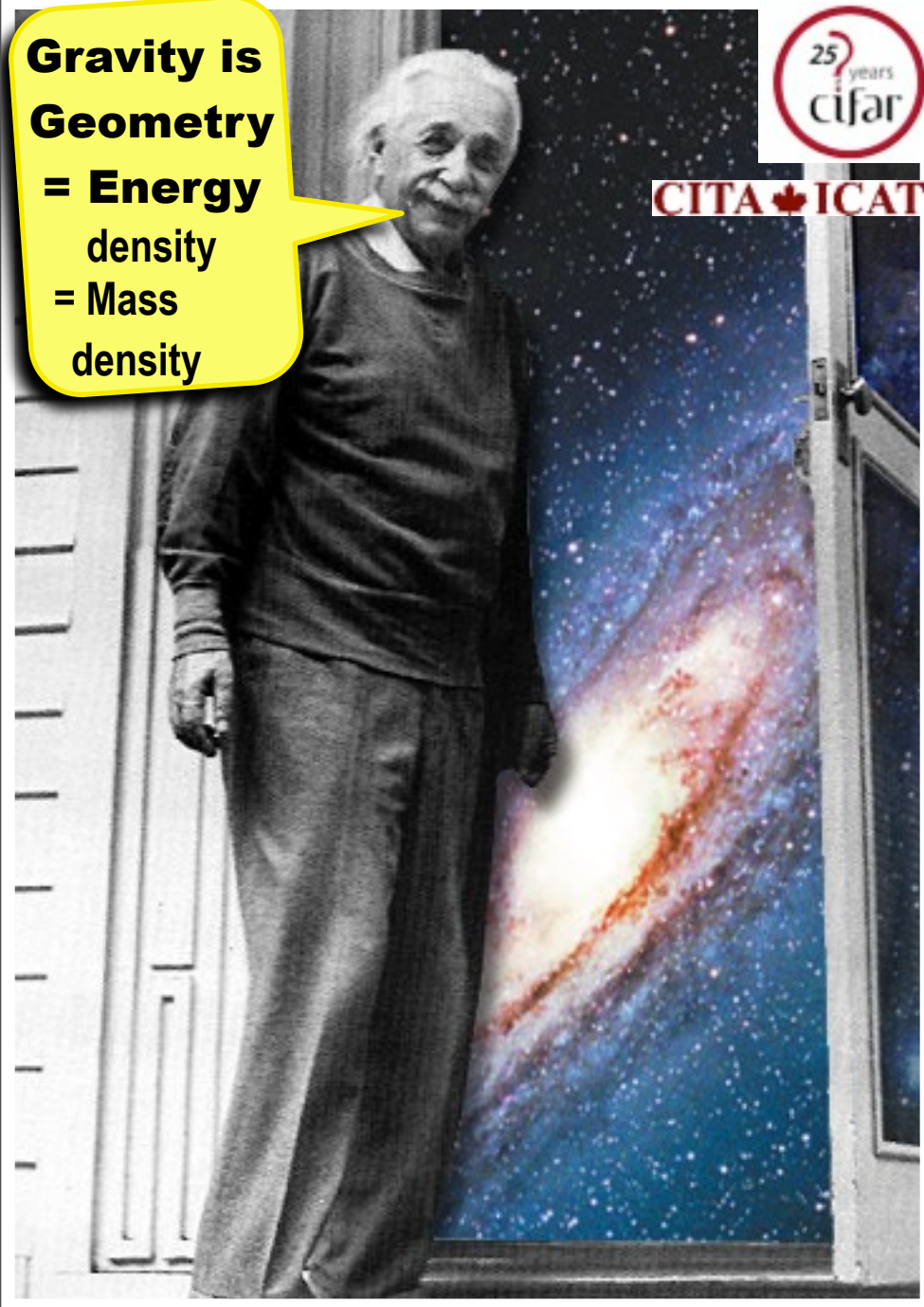
General Relativity 1916-17 cosmology
gravity warps time, time is curved

\Rightarrow COSMIC TIME

**Gravity is
Geometry
= Energy
density
= Mass
density**



CITA ICAT



**ASTRONOMICAL TIME
+ PHYSICS TIME =**

COSMIC TIMEs (x,t) Gigayear = aeon AB

Hubble expansion rate **H** = velocity/distance
 $1/H$ 13.5 ± 0.7 Gyr HST \Rightarrow 13.7 ± 0.5 Gyr CMB

many **TIMES(SPACE,t)**. dynamical cosmic clocks
 expansion factor **a** = $1/\text{compression}$ = $1/(1+\text{redshift})$
 $\ln(a)$ (e-foldings) is better, >130 ABang, 67 AMatter

early Universe physical clocks $\ln a$, $\ln H$, $\ln H a$
 but they fluctuate by **QUANTUM vacuum effects - this is the origin of all cosmic structure!!!!**; quantum breakdown in the ultra-early Universe *Time emerges?*

later Universe, no expansion in earth, star & galaxy gravity wells \Rightarrow *bad clocks even reversing in collapse*

atomic, nuclear clocks OK but ticks vary with gravity: clocks speed up climbing out of gravity wells (redshift), slow down dropping into gravity wells (blueshift)

cosmic veil: the *first light* is released $13.7-.00038$ Gyr
CMB an effective *horizon*, but \exists *beyond* our horizon

cosmic ages **Gigayear = aeon**

Galactic year earth orbital period around the Milky Way centre **0.22 Gyr**; *centre 25000 lyrs*
nuclear chronometers, radioactive elements

Uranium-lead for **earth** (hence sun) **4.54 ± 0.02 Gyr** (created **9.15 Gyr AB** After the Big Bang)

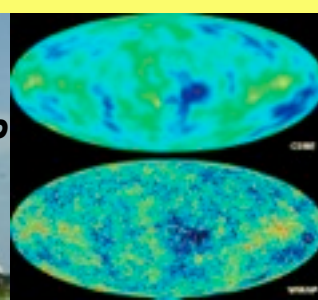
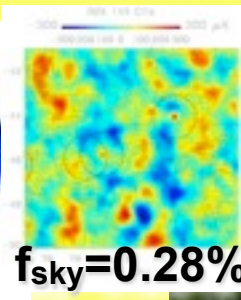
Uranium dating in old stars **12.5 ± 3 Gyr** 2001

Uranium/Thorium dating of old stars **11.8 ± 3.7, 10.9 ± 2.9 and 13.5 ± 2.9 Gyr** 2009

ages of oldest Milky Way (evolution of **globular cluster stars**) ~ **13.4 ± 0.9 Gyr** 2001

expansion of the universe, from stars 1/Hubble = **13.5 ± 0.7 Gyr** HST 2001, 09

CMB+ 13.7 ± 1.9 1999 ⇒ **13.8 ± 0.3** 2002 ⇒ **13.6 ± 0.2** 2005 ⇒ **13.7 ± 0.1 AB** 2010



~350 boom-deeps

age when the "first stars" were created: **0.68 Gyr AB**

age when the **first light (CMB)** was released: **380081 (± 1.5%) years AB**

Big Bang Nucleosynthesis age when hydrogen and helium were created ~**1 minute AB**

Dark Matter synthesis age if dark matter are WIMPS ~ **nanosecond ?** - microsecond

radiation/matter genesis, entropy genesis, baryogenesis: ~ **10⁻³⁷ seconds???**

quantum gravity epoch: **2.8 x 10⁻⁴³ seconds** Planck time (quantum+gravity+light-speed)

LHC@CERN proton collisions will soon probe ~**10⁻²⁸ sec** physics

$$t_P = (\hbar G_{\text{Newton}} c^{-5})^{1/2}_2$$

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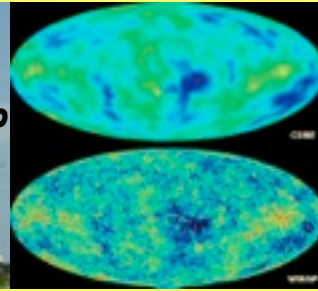
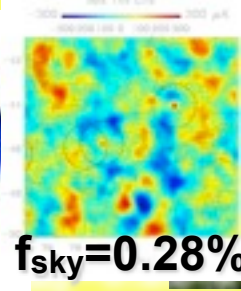
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$$t_P = (h G_{\text{Newton}} c^{-5})^{1/2} 2^{37}$$

a **starless**
“**dark age**”
before the
most
distant
galaxies

dwarf galaxies
& the 1st stars

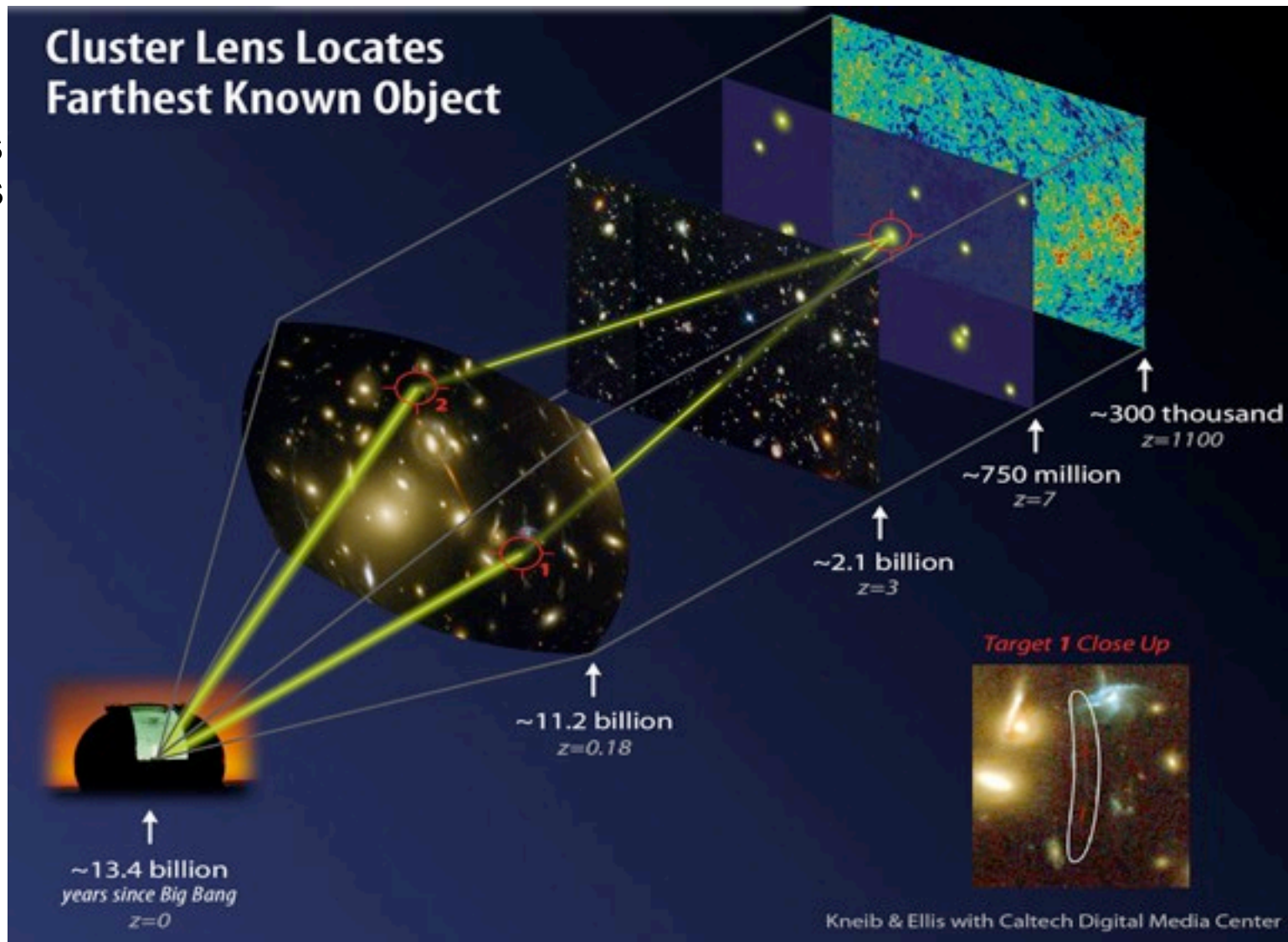
form ~13
compression
0.37 Gyr AB

1st light:
Cosmic
Microwave
Background

released 1100
compression
38000 yr AB;
~10³⁰ formed
~10⁻³⁷ sec AB

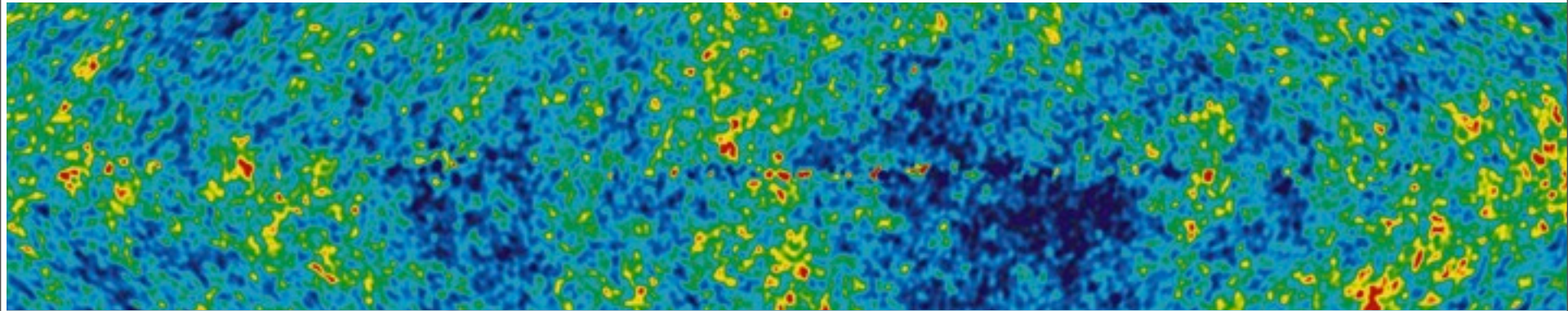


most distant explosion
(gamma ray burst) known,
0.63 Gyr After Bang, 13.1 Gyr
ago, @compression 9.2 2009



end of Bond's TIME

Mapping the Birth of the Universe with ACT and SciNet



ACT@5170m



why Atacama? driest desert in the world. thus: cbi, toco, apex, asti, act, alma, quiet, clover

CBI2@5040m



**We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.**

– T. S. Eliot

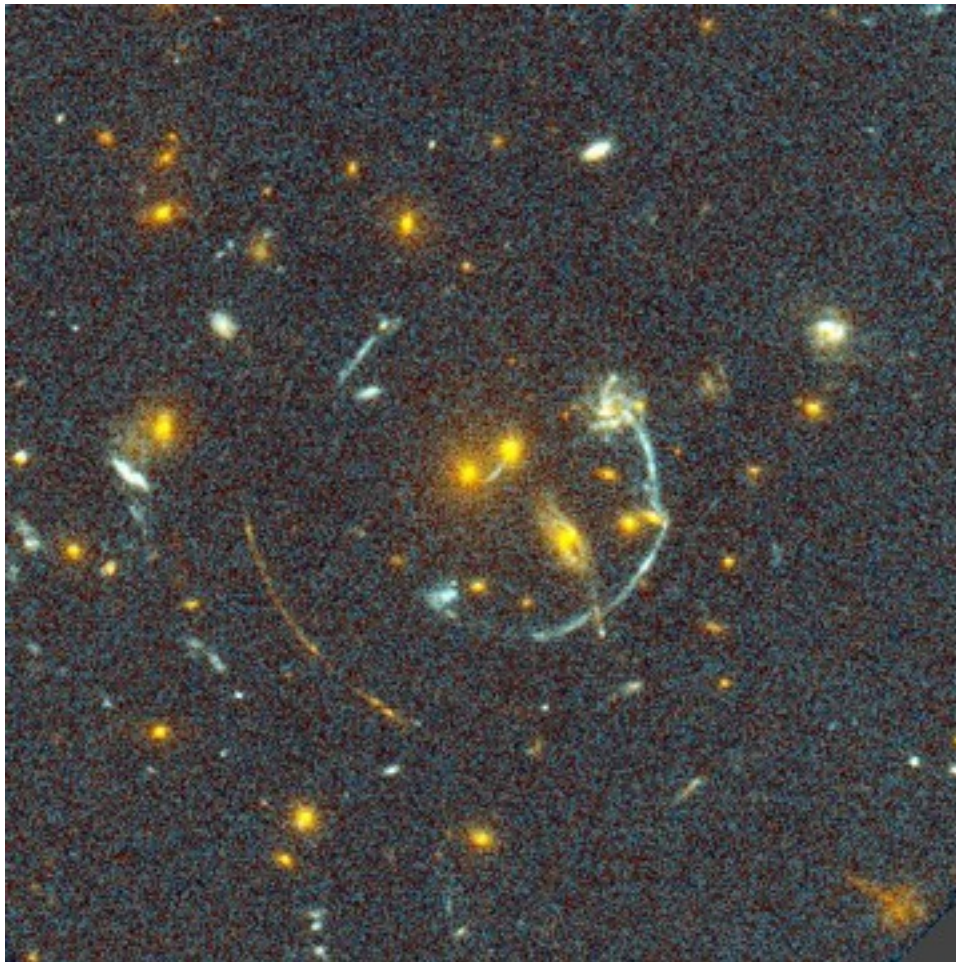
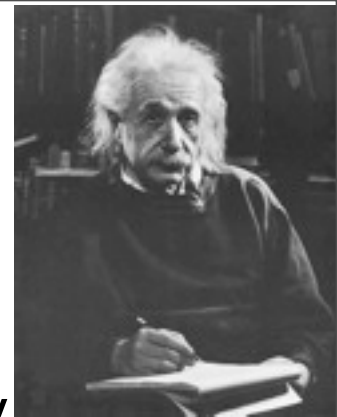


**it is primarily for
this knowing & its
inspiration to young
minds that the world
is spending tens of
billions of dollars on
the cosmic quest for
fundamental physics**

**The world wide web,
technological space
spinoffs, amazing detector
& computational advances,
are (important) asides**

EINSTEIN ... 1905 international year of physics 2005

- ✓ NEW LAW OF GRAVITATION (1916)
- ✓ speed of light is the ultimate speed (**HORIZONS**)
- ✓ Space is curved by mass
- ✓ Lightwaves bend, wavelengths change, under gravity



**Gravitational lensing of
deep galaxies by clusters**

Toronto RCS 2001; RCS2

 **Hoekstra, Gladders, Yee**

**Weak lensing via Canada
France Hawaii Telescope
Legacy Survey 2002-08**



**Hoekstra, van
Waerbeke**





CFHT

SN

Survey

Carlberg,
Pritchett,

et al.



3yr now
300 SN1a

5yr

500





CFHT

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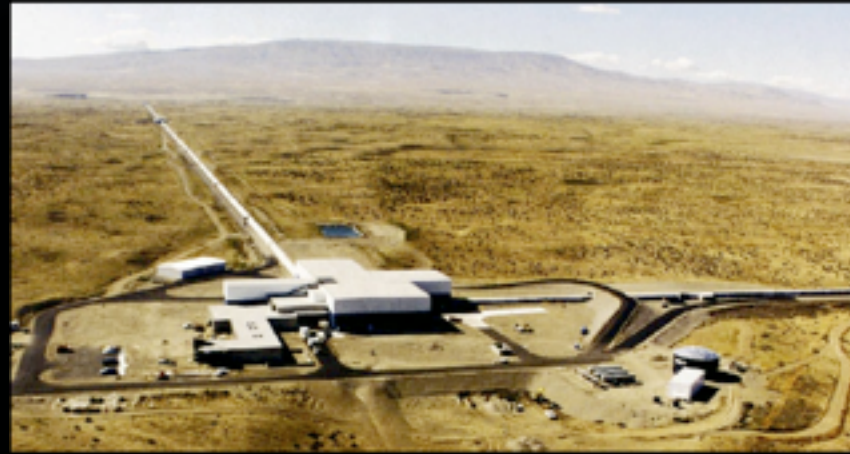
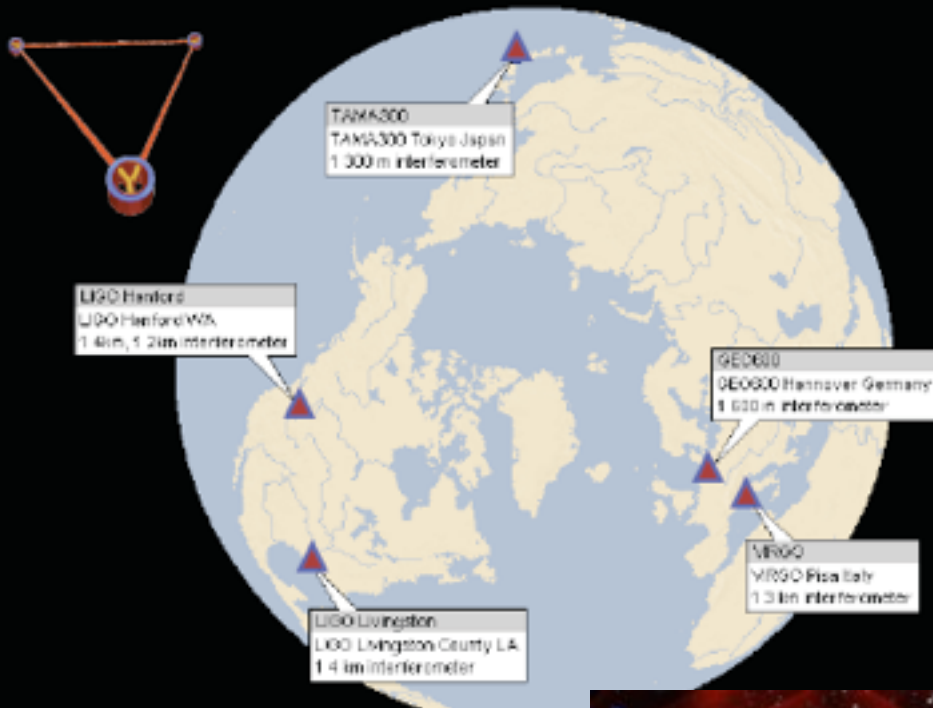
3yr now
300 SN1a

5yr

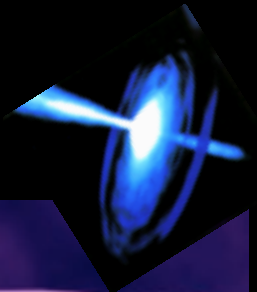
500



Worldwide Interferometer Network



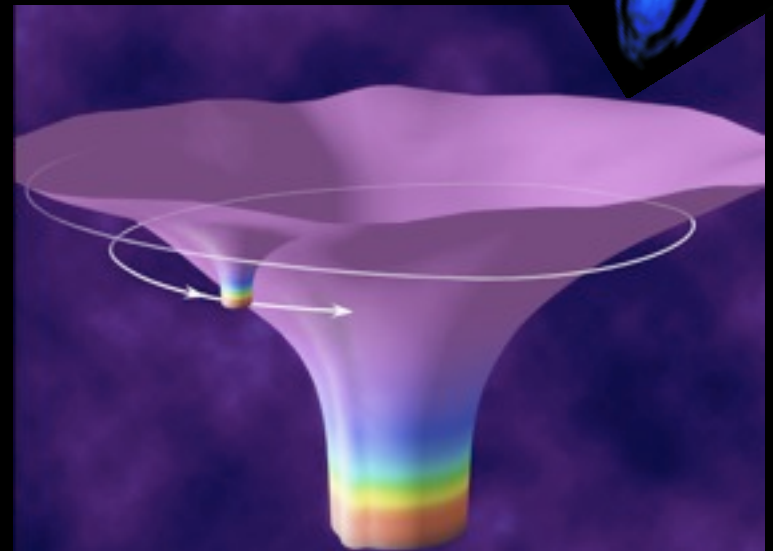
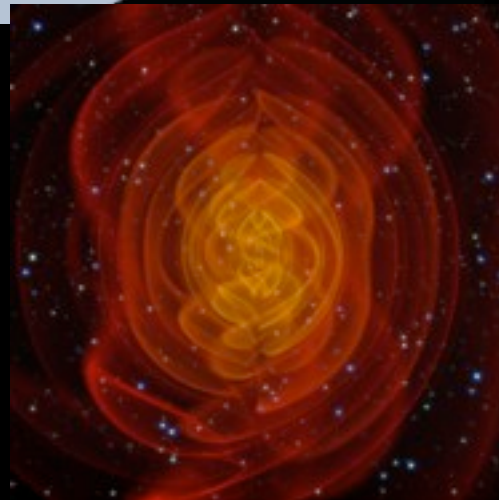
DANGER:
BLACK HOLES
MERGING



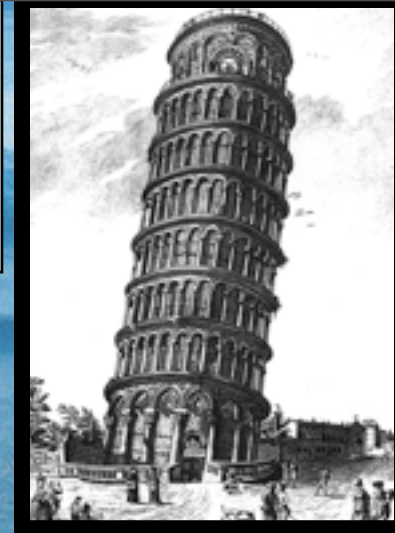
Now-2013+

~km scale

**detect .001 nuclear
radius**



How will Accelerators cast Light on the Dark Side of the Universe?



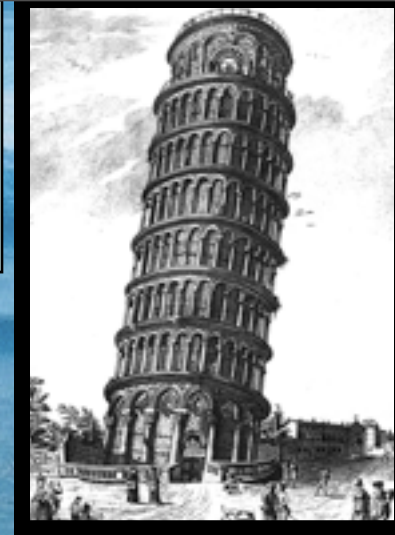
Cern's Accelerator

2008

Galileo's Accelerator



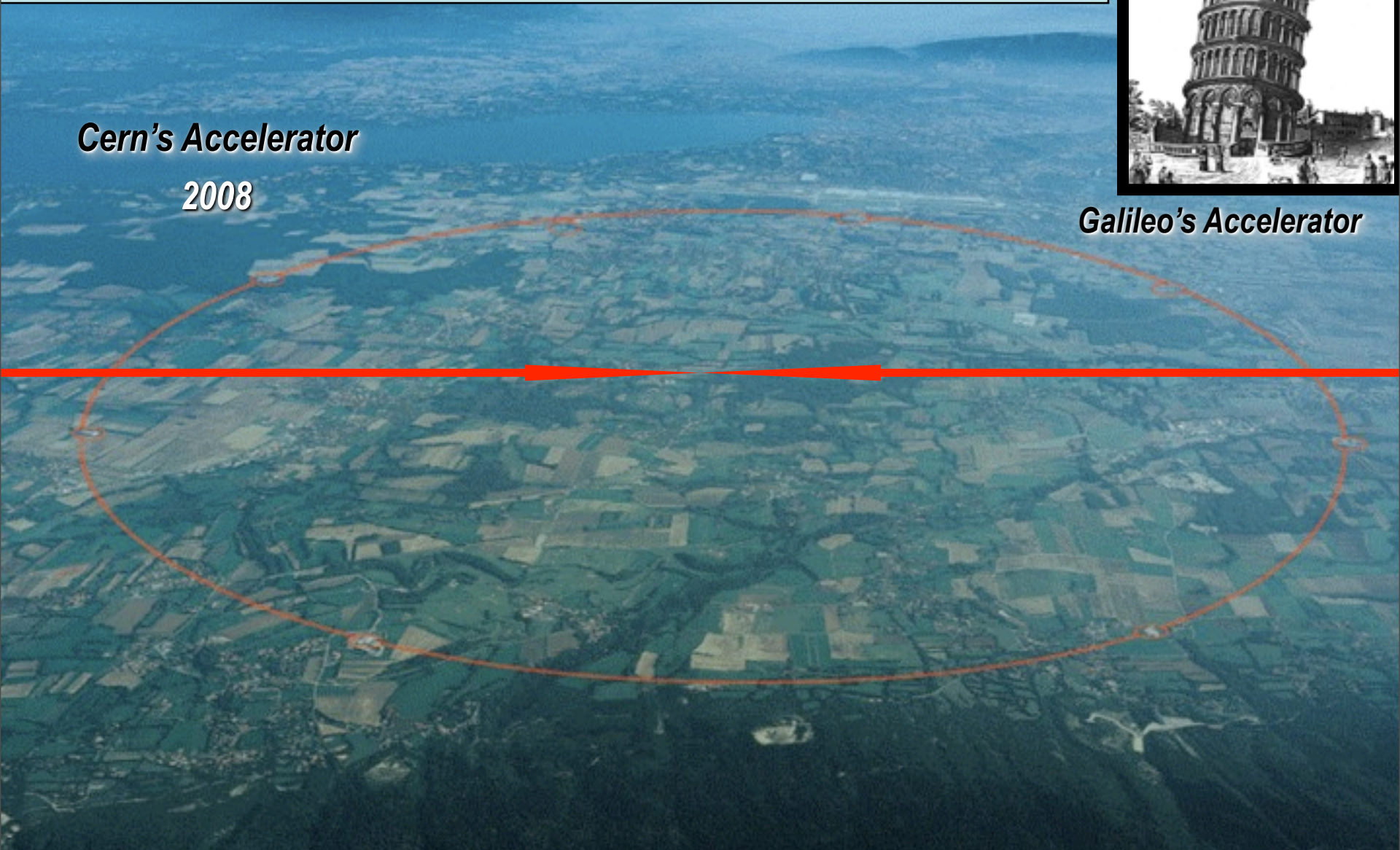
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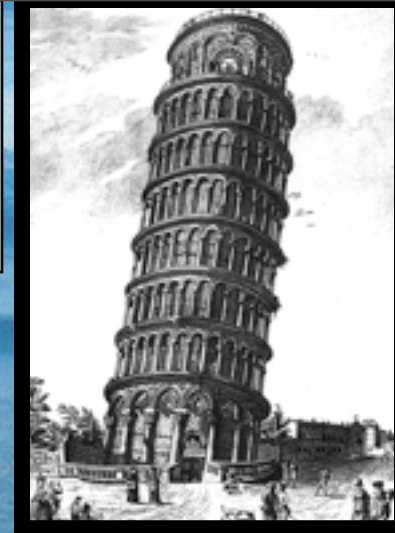
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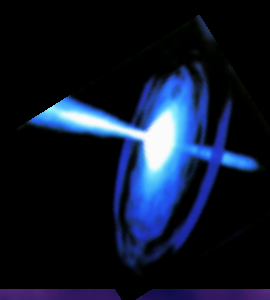
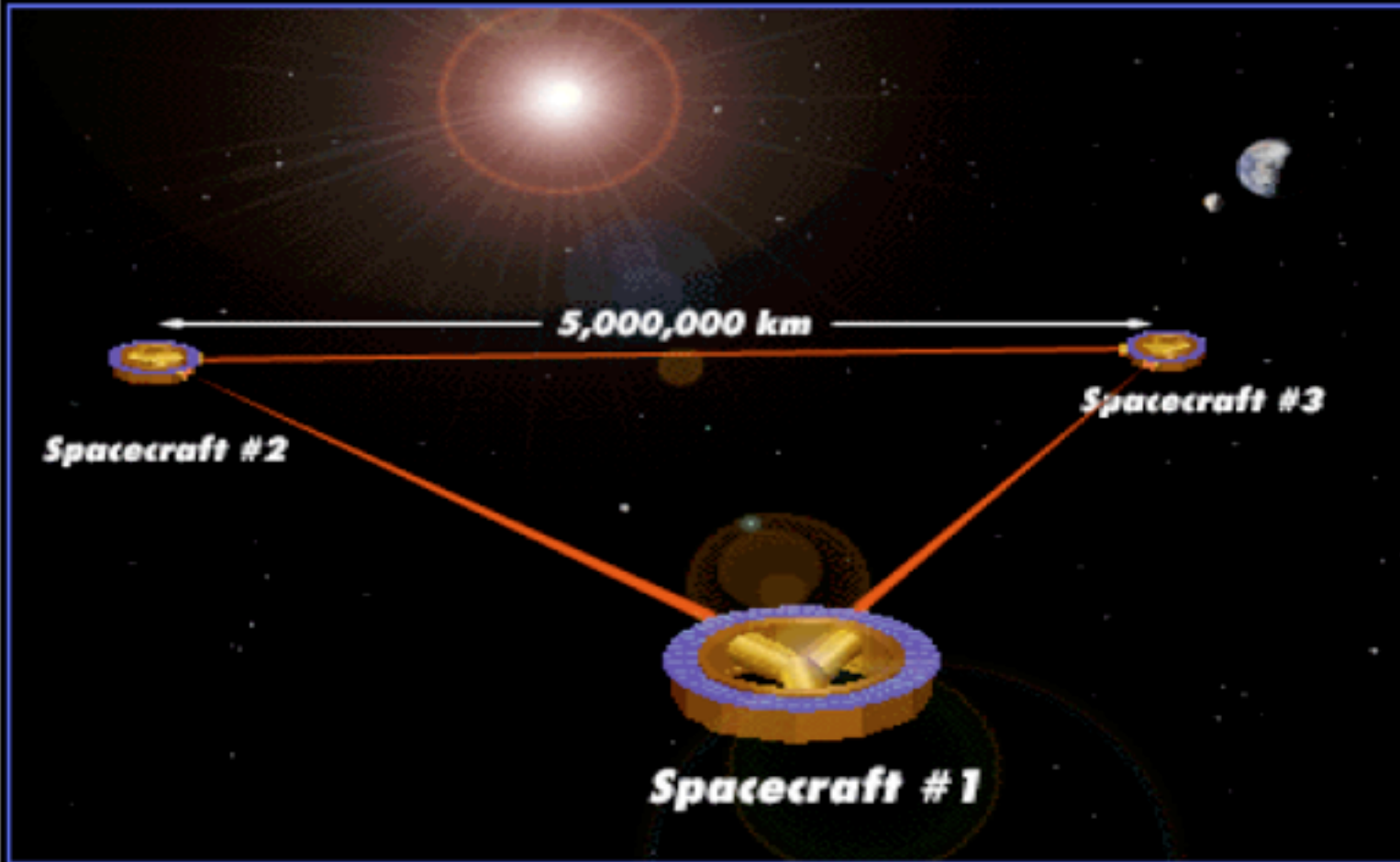
Cern's Accelerator

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If Dark Matter interacts with ordinary matter by more than gravity, we may "see" it at the Large Hadronic Collider 2008+ or at SNOlab 2008+ in Sudbury

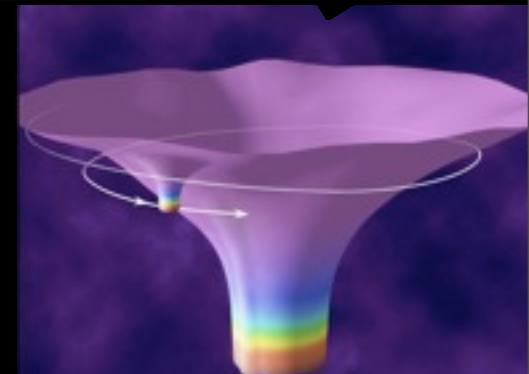
LISA



2017??

**~5 million km scale
detect .001 atomic radius**

**DANGER:
SuperMassive
BLACK HOLES
MERGING**



PYTHAGORAS ~ 550 BCE

The THEORIST

- ✓ Cosmos - The Universe as a Mathematical Entity
- ✓ Music of the Heavens – Frequency/Wavelength

ROGER BACON ~ 1260 AD

MARRIAGE: of Experiment to Theory

COPERNICUS/KEPLER/GALILEO et al. ~1600 AD

NEWTON ~ 1660 - 1690 AD

The PHYSICIST

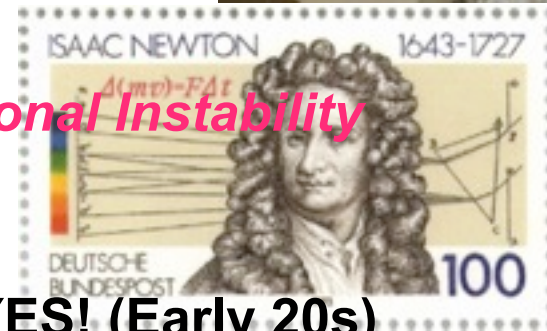
- ✓ LAW OF GRAVITATION - Mass Attraction
- ✓ Heavenly Objects Arise via Clumping .. *Gravitational Instability*
- ✓ Thus: the Universe is Infinite

KANT ~ 1755 AD Galaxies - 'Island Universes'

YES! (Early 20s)



Milky Way 1953-55



*large halo of dark matter
70s/80s relics
or remnants?*

EINSTEIN: SCIENTIFIC COSMOLOGY(1917)

- ✓ Finite universe without a boundary
- ✓ “Cosmological Constant” (~ 1895) Λ

Make the Universe Finite via A Repulsive Force
“My greatest blunder”



$\Lambda / 8\pi G_{\text{Newton}}$

FRIEDMANN (1922) Evolving (Expanding) Universe

- ✓ YES! Hubble (late 20s) rate **H**
- ✓ the SINGULARITY (30s,60s),
infinite density (!!!???)

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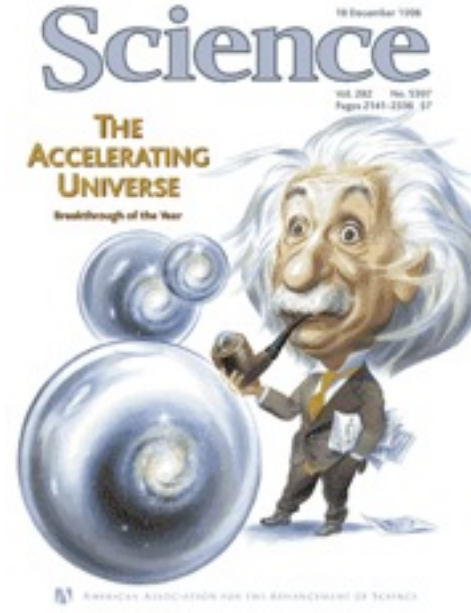
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how the *first cosmic light* illuminates the *Dark Universe*

Dick Bond Canadian Institute for Theoretical Astrophysics, University of Toronto

emergence of the *cosmic standard model* from **CMB (+LSS+SN**
+..) \Rightarrow **x CDM**, **$x = \Lambda$ + tilt**, **status@Jun10** is there a **y** to **x**? @~Dec12

$\Lambda(t, x)$?

how the *first cosmic light* illuminates the *Dark Universe*

Dick Bond Canadian Institute for Theoretical Astrophysics, University of Toronto

What is the Universe made of?

*NOW: baryons + (cold-ish) dark matter + dark energy/inflaton + tiny curvature energy (+light neutrinos+photons+GW) BHs ?strings/textures/?
cosmic web of galaxies/clusters*

THEN: coherent inflaton /“vacuum” energy plus zero-point fluctuations in all fields (\approx *Gaussian RF*) & then preheat via mode coupling via incoherent cascade to thermal equilibrium aka **quark-gluon plasma**



*how was it (\approx *GRF*), is it (*cosmic web*) & will it be (isolating decay?) **distributed?***

how the *first cosmic light* illuminates the *Dark Universe*

Dick Bond Canadian Institute for Theoretical Astrophysics, University of Toronto

very early U early to middle to now U **very late U**
cosmic mysteries
 n_b/n_g ρ_{dm}/ρ_b z_{eq}/z_{rec} ρ_{curv} ρ_{de}/ρ_{dm} $\rho_{de} \sim H^2 M_{Planck}^2$ ρ_{mv}/ρ_{stars}

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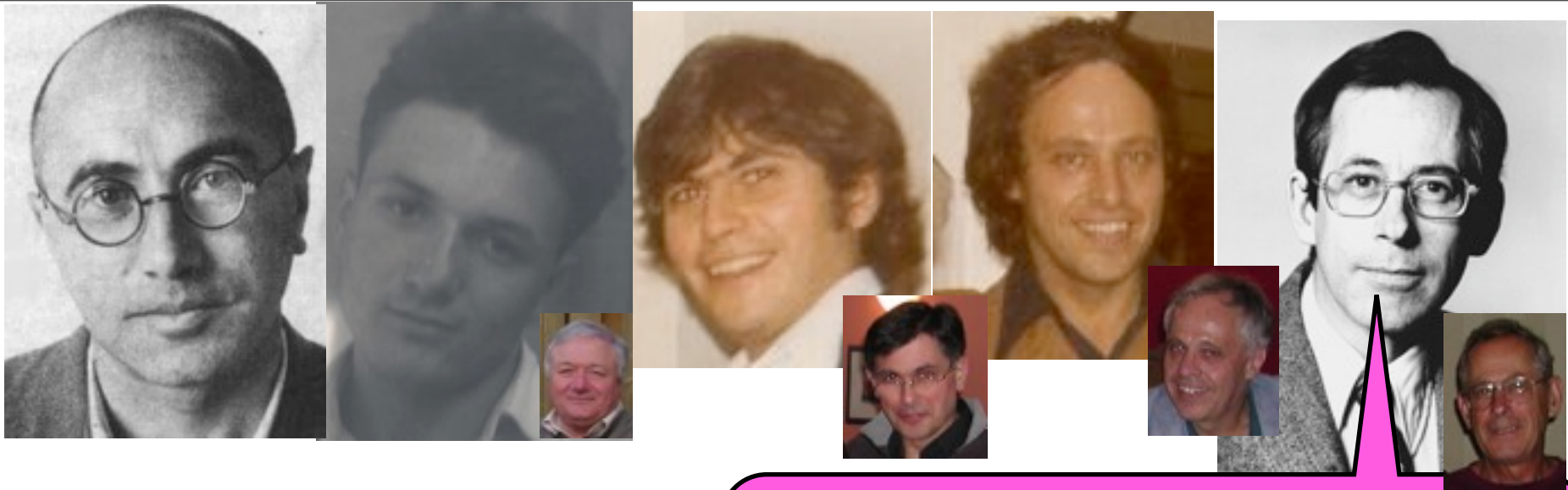


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emergence of the cosmic standard model from CMB (+LSS+SN +..) \Rightarrow Λ CDM, $x = \Lambda$ + tilt, status@Jun10 is there a y to x? @~Dec12

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test with CMB+LSS

~85-87 reconsider Λ , quintessence
“what you see is what you get”

~80-84: Hot (light ν), Warm, Cold DM
hot Big Bang collisionless relics
or
black holes from Very Massive Stars,
Jupiters, primordial black holes



anthropic matters with BJ Carr

vary x in x CDM: find x by the tests

COSMIC PARAMETERS THEN



e.g., BBE1987 **vary x in xCDM**

for xCDM, predict CMB (6deg, 5min); LSS cluster-cluster, cluster-galaxy, bulk flows,

14 Gyr, $W_L=0.8$, $H_0=75$, $b \sim c$,
50mK cf 30mK coBE,

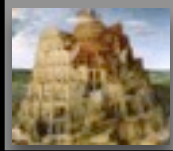
S_8 : redshift of "galaxy formation"

$S_8 \sim 0.72$

X = s / H0 / Λ / Open / is / is+ad / h-c / h+ / b / b / **$\Lambda+b$** / Op+b / t / BSI / BSI2

PREDICTIONS FOR MODELS

Parameter	OBS	CDM	C40	VAC/C	OP/C	ISO/C	ISO/AD	HOT	HC	C+B	B+C	BCV	BCO	CDM + dec	(CDM + X) ₁ ($k_*^{-1} = 300$)	(CDM + X) ₂ ($k_*^{-1} = 200$)
Ω, Ω_b, H_0 .....	...											1, 0.1, 75				
$\Omega_x(\Omega_x), \Omega_{vac}$ .....	...											0.1, 0.8				
b .....	...											1				
t_0 (by)	GC: 14-22 NC: 13-26											14				
$\sigma_0(R_p = 0.35)$ ...	...											2.4				
z_p .....	...											1.3				
$\sigma_0(R_{cl} = 5)$ .....	...											0.72				
$\langle v \rangle_c$ .....	...											2.8				
$\xi_{cc}(20)$	1.5											2.2				
$\xi_{cc}(25)$	1.0											1.7				
$\xi_{cc}(30)$	0.72											1.4				
$\xi_{cc}(50)$	0.29											0.59				
$\xi_{cc}(100)$	0.08											0.36				
$\xi_{cg}(20)$	0.49											0.76				
$\xi_{cg}(25)$	0.33											0.54				
$\xi_{cg}(30)$	0.24											0.41				
$\xi_{cg}(40)$	0.14											0.26				
$\tau(R_f = 3.2)$	610 ± 50											232-1120				
$\tau(R_f = 15)$	599 ± 104											206-987				
$\tau(R_f = 25)$												186-894				
$\tau(R_f = 40)$	970 ± 300											160-771				
$\Delta T/T$ (4:5)	< 25											10				
$\times 10^6$ (6')	< 48											25				



Delta T over Tea Toronto May 1987: first dedicated CMB conference, exptalists+theorists, primary+secondary DT/T

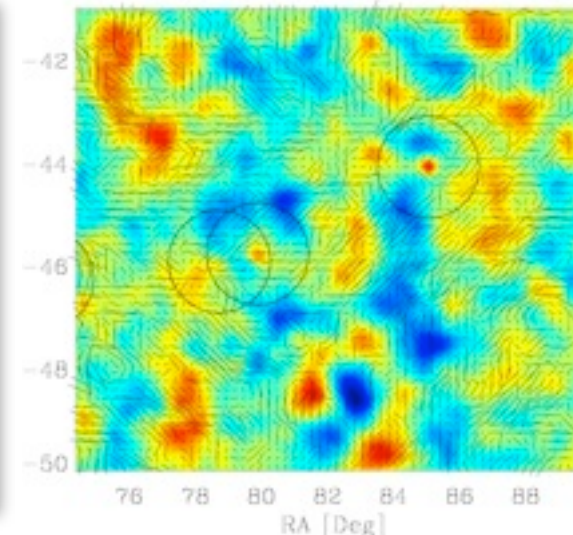
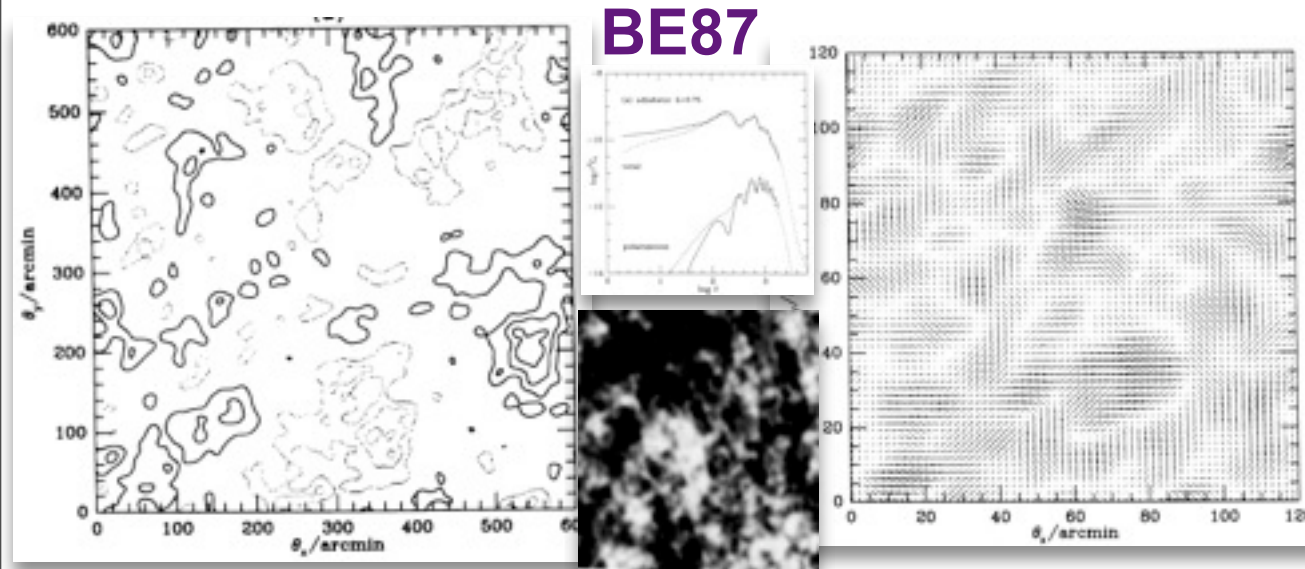
Primary Cosmic Microwave Background Radiation ~ a statistically isotropic all-sky GRF on the 2-sphere $C_L = \langle |DT(LM)|^2 \rangle$ with target C_L shapes

A tentative list of topics organized according to angular scale, with theory and observation intertwined, is:

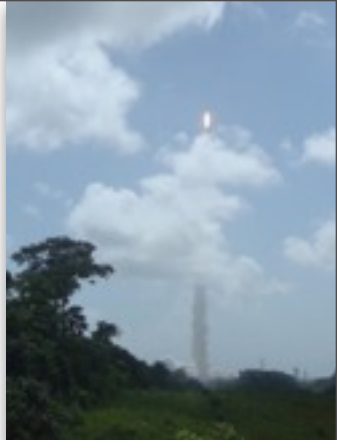
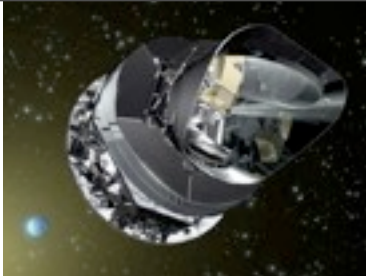
- very small angle anisotropies - VLA results, secondary fluctuations via the Sunyaev-Zeldovich effect, primeval dust emission, and radio sources
- small angle anisotropies - current results, optimal measuring strategies, statistical methods for small signals in larger noise, which universes can we rule out, the reheating issue future detectors and techniques, CMB map statistics, polarization
- intermediate and large angle anisotropies - $5^\circ - 10^\circ$ results, future experiments at $\sim 1^\circ$, COBE and other large angle analyses, theoretical $C(\theta)$'s and their angular power spectra, Sachs-Wolfe effect in open Universes, the isocurvature CDM and baryon stories, $\Delta T/T$ from gravitational waves, the cosmic string story.

Boom05 deep

-300 200 100 0 100 200 300 μK



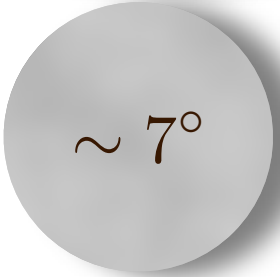
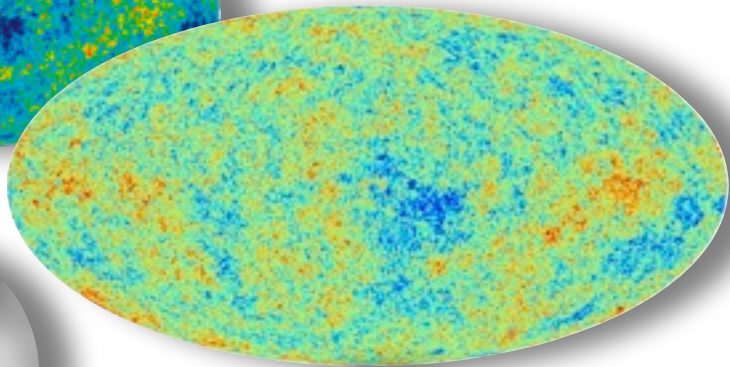
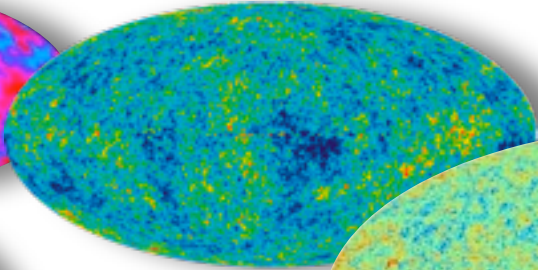
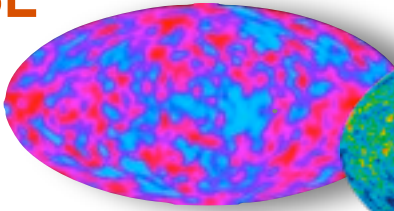
CMB SCIENCE FRONTIERS: Polarization & High Resolution



COBE 89.9; 92.3

WMAP 01.5; 03.2

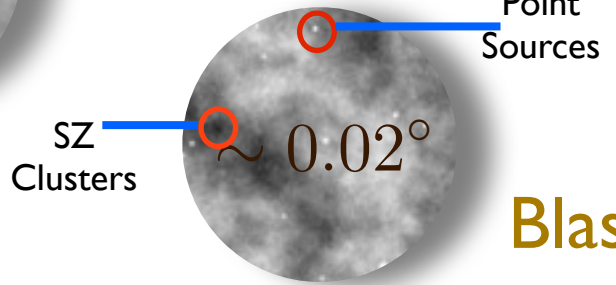
PLANCK (sim) 09.4; 12.9



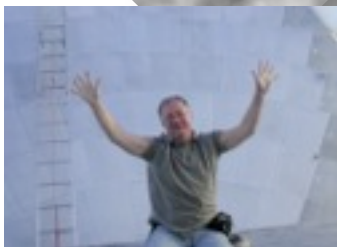
1 degree



ACT/SPT 07.8; 09.1



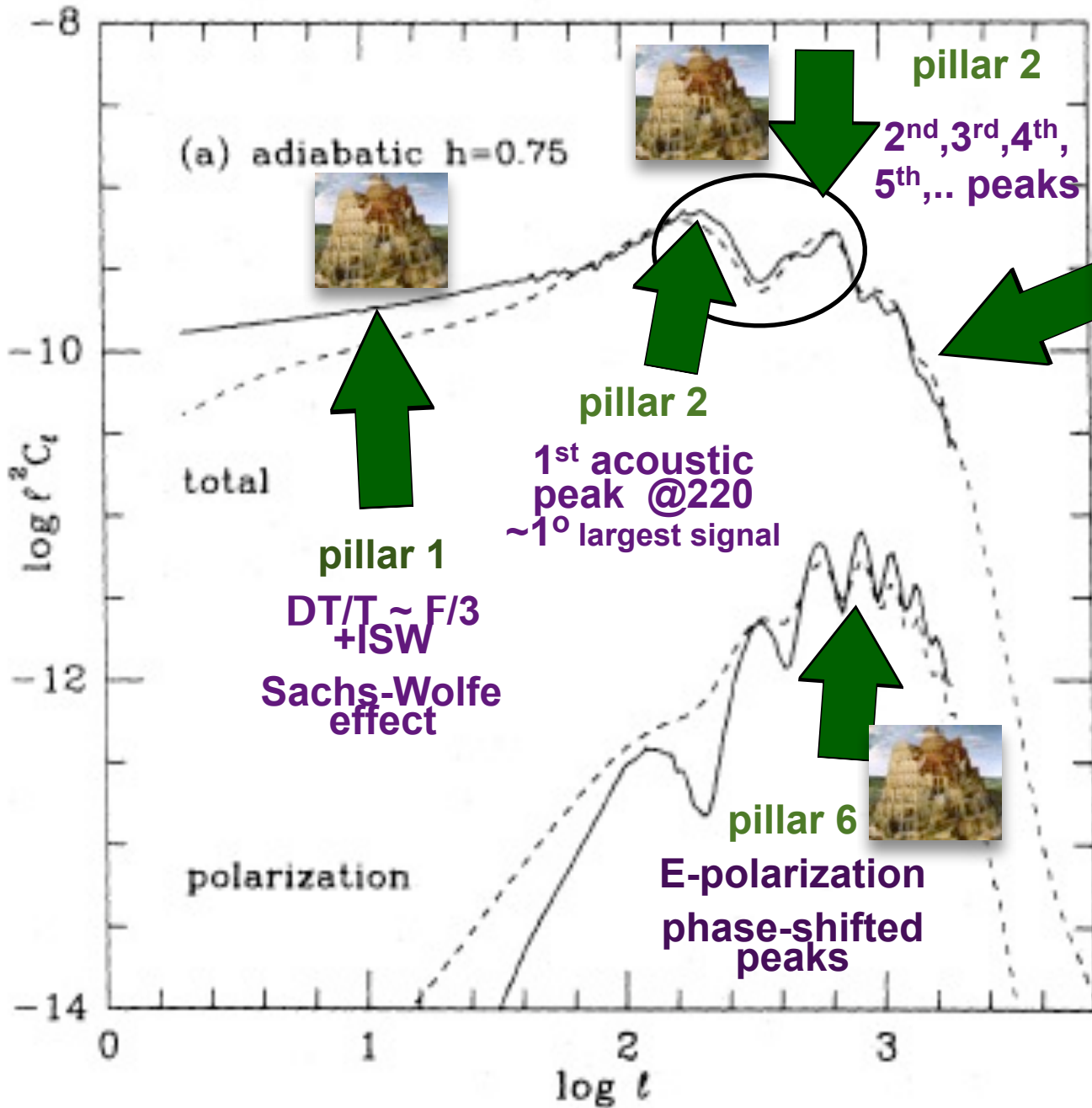
Blast



CMB in Canada: many successes

ΔT over Tea 1987, **COBE, SP, SK, ..., Boomerang, CBI, Acbar, WMAP, DASI, QuAD, APEX, ACT, SPT, Planck, EBEX, Spider, Keck, ACTpol, SPTpol, Bicep, Quiet, ABS,...** acceleration paths for B-modes, dark energy probes, neutrino masses, non-Gaussianity **if there will be a CMBpol from space, Canada should be in it with the US & Europe**

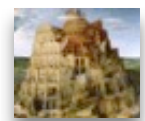
the "Seven Pillars"



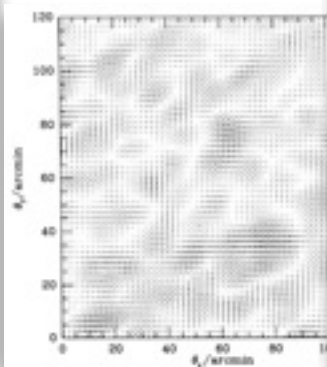
pillar 4
Gaussianity
maximal
randomness
for given CL



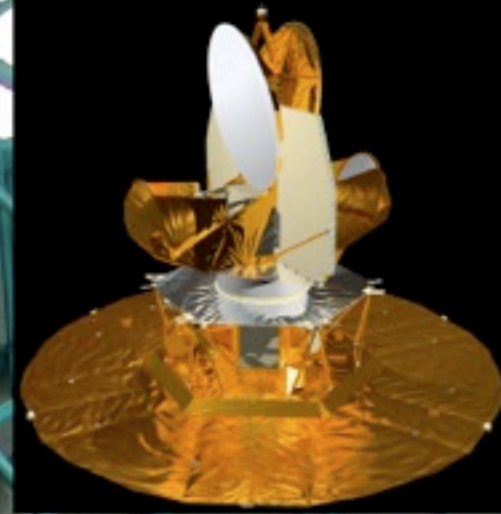
pillar 5
secondary DT
nonlinear
Compton SZ
weak lensing..



pillar 7
B-polarization
Gravity Waves



WMAP launch 2001.5



Dave Wilkinson



Text



Rashid Sunyaev

CMB 2010

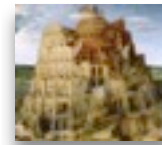
$$\langle |DT_{(LM)}|^2 \rangle_{L(L+1)/2p}$$

pillar 1



COBE
regime

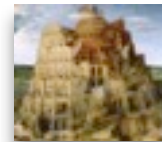
pillars 2,3



1st 2nd 3rd 4th 5th
6th 7th peaks
& damping tail



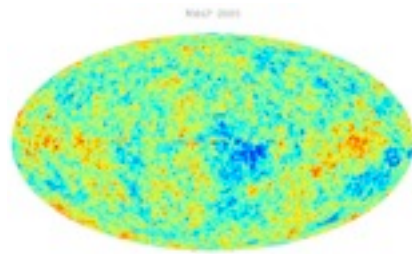
pillar 5
SZ power



pillar 4: *as random as can be given this spectrum*

CMB 2010

$$\langle |DT_{(LM)}|^2 \rangle = L(L+1)/2p$$

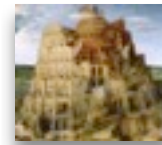


pillar 1



COBE regime

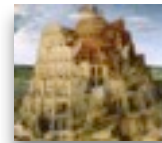
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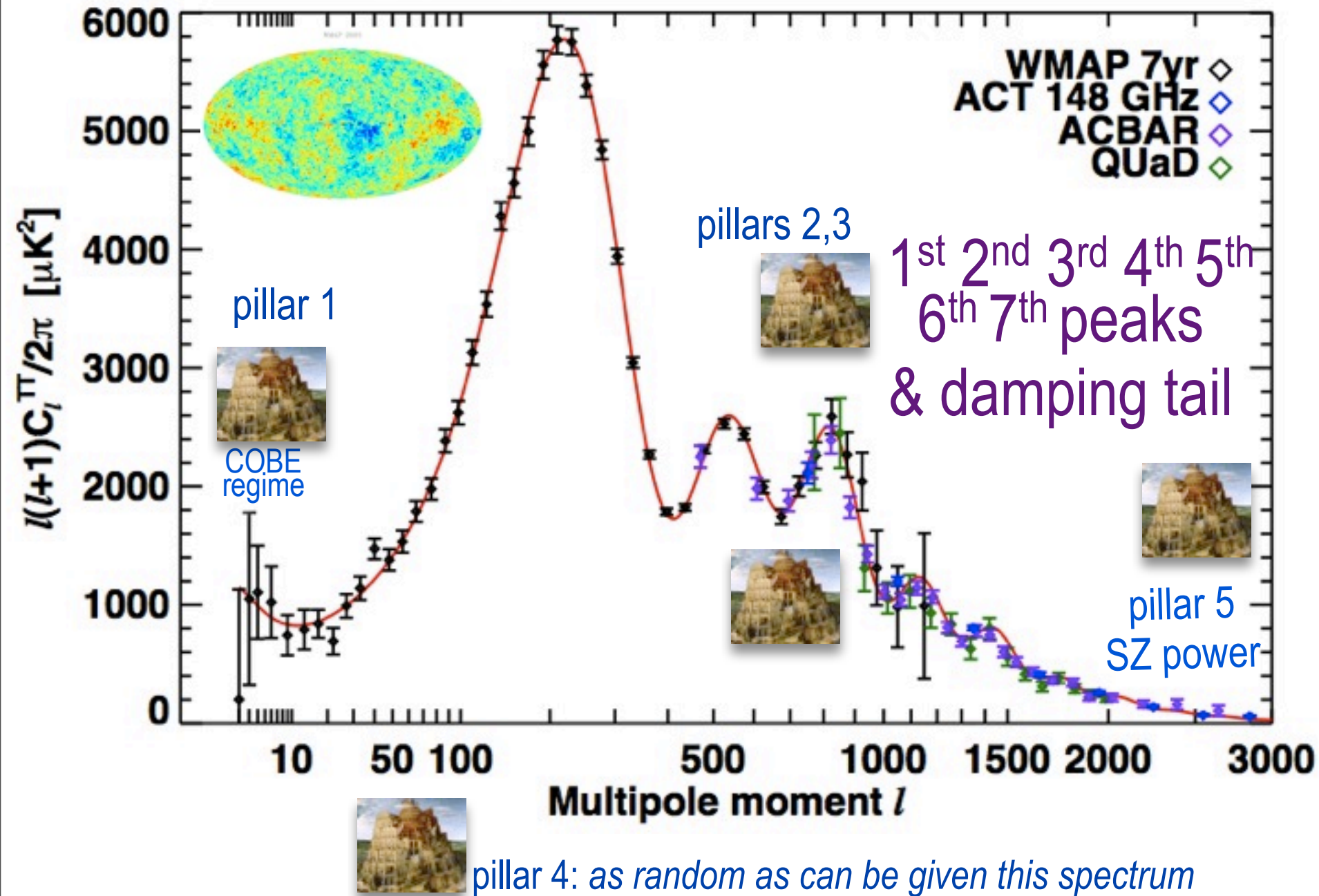
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SZ power



pillar 4: *as random as can be given this spectrum*

CMB 2010

$$\langle |DT_{(LM)}|^2 \rangle = L(L+1)/2p$$



What is the Universe made of?

NOW: baryons + (cold-ish) dark matter + dark energy/inflaton + tiny curvature energy (+light neutrinos+photons). ??a bit of strings/textures/PBHs?? web of galaxies/clusters

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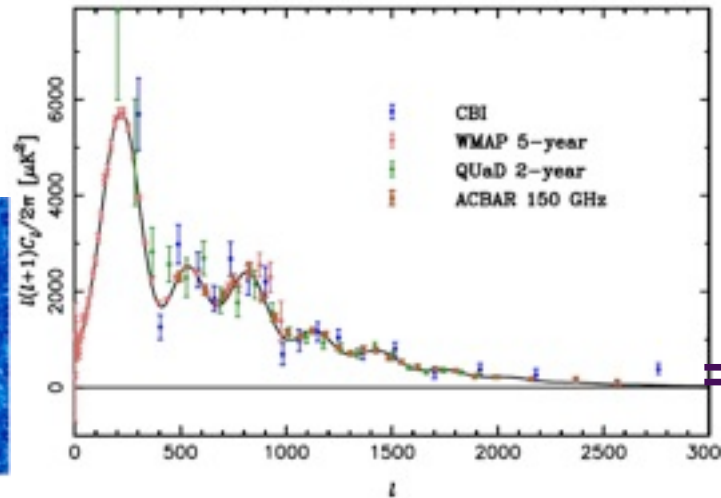
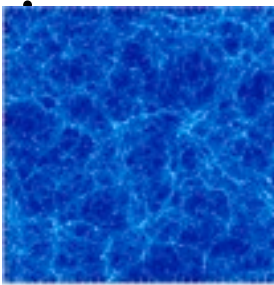
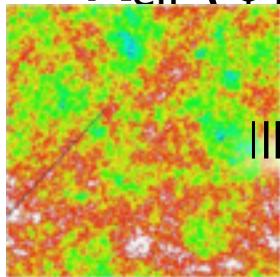
very early U early to middle to now U **very late U**

string theory/landscape/higher dimensions

inflation cyclic baryogenesis dark matter BBN gdec **dark**

$V_{\text{eff}}(\psi_{\text{inf}}) ?$

$K_{\text{eff}}(\psi_{\text{inf}}) ?$



$V_{\text{eff}}(\psi_{\text{inf}}) ?$

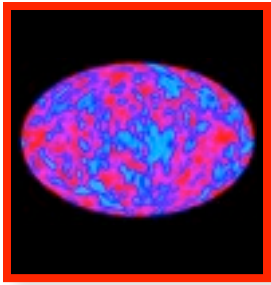
$K_{\text{eff}}(\psi_{\text{inf}}) ?$

$\Rightarrow \rho_{\text{dm}}/\rho_{\text{b}} = 5.2$

$\Rightarrow \rho_{\text{de}}/\rho_{\text{dm}} = 2.9$

cosmic mysteries

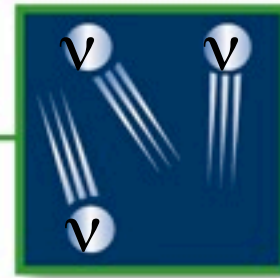
$n_{\text{b}}/n_{\text{g}}$ $\rho_{\text{dm}}/\rho_{\text{b}}$ $z_{\text{eq}}/z_{\text{rec}}$ ρ_{curv} $\rho_{\text{de}}/\rho_{\text{dm}}$ $\rho_{\text{de}} \sim H^2 M_{\text{Planck}}^2$ $\rho_{\text{mv}}/\rho_{\text{stars}}$



Radiation:
0.005%



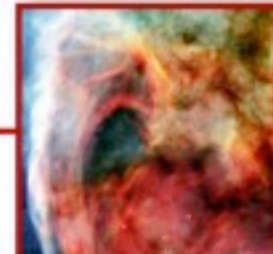
Chemical Elements:
(other than H & He) 0.025%



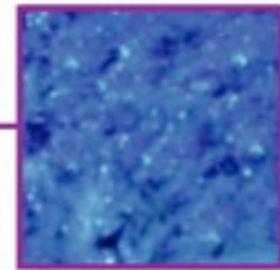
Neutrinos:
0.47%



Stars:
0.5%

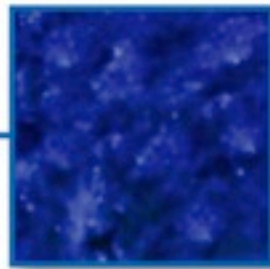


Free H & He:
4.7%



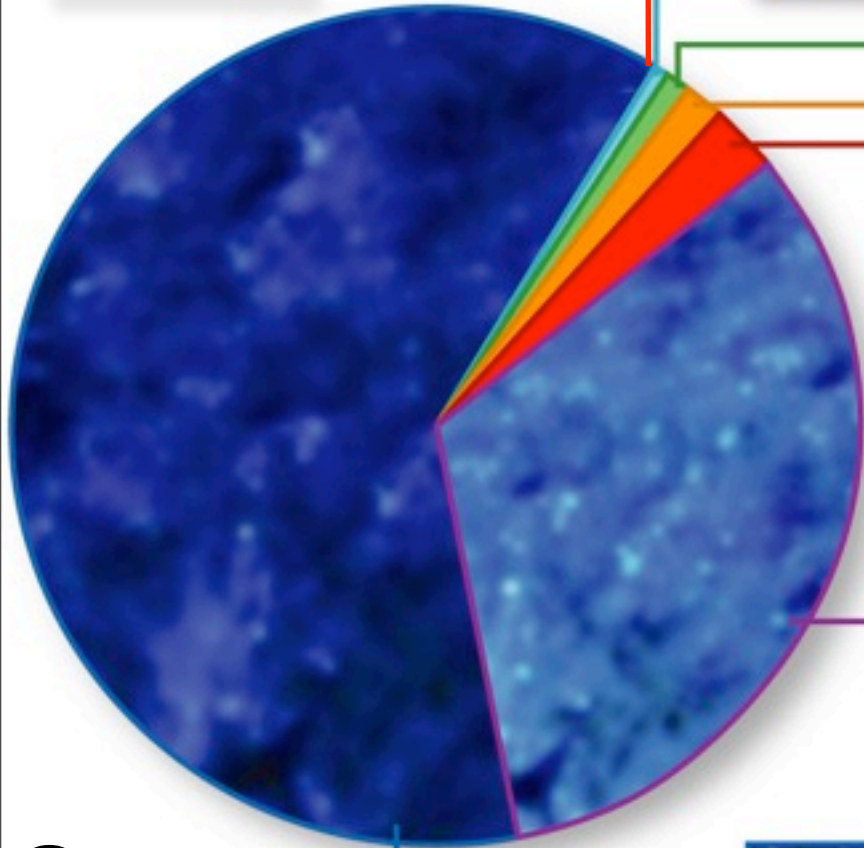
Dark Matter:

$$\Omega_{dm} = 24.5\% \pm 4\%$$



Dark Energy:

$$\Omega_{\Lambda} = 71\% \pm 2\%$$

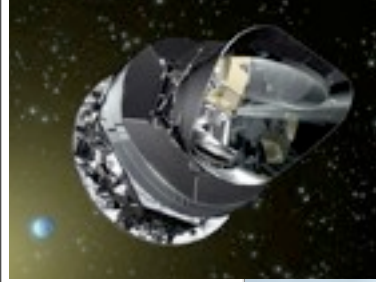


$$\Omega_{curv} = -0.6\% \pm 0.6\%$$

$$\Omega_{GW} \sim 10^{-14} - 10^{-10} \text{ LIGO}$$

$$\Omega_{BlackHoles} \sim 10^{-7}$$

Planck Launch
May 14, 2009
in 2nd sky survey
expect/hope for 5



52 bolometers
+ HEMTs @L2
9 frequencies

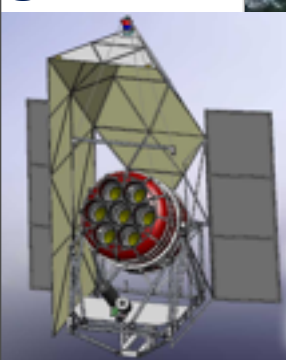
ACTpol

3000 bolos
3 freqs @Chile



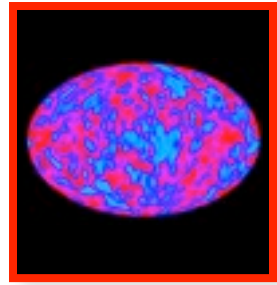
Spider

2312 bolos
@LDB 2011.9



$n_s(k)$, m_v , GW $r(k)$, nonG f_{NL++} ,
 $\rho_{de}(t)$, strings, isocurvature, ...

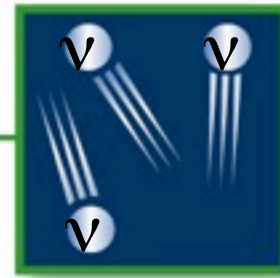




Radiation:
0.005%



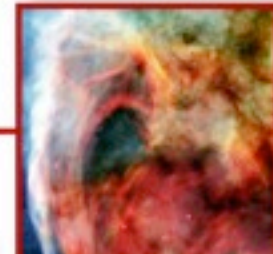
Chemical Elements:
(other than H & He) 0.025%



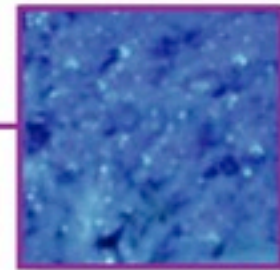
Neutrinos:
0.47%



Stars:
0.5%



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4.7%



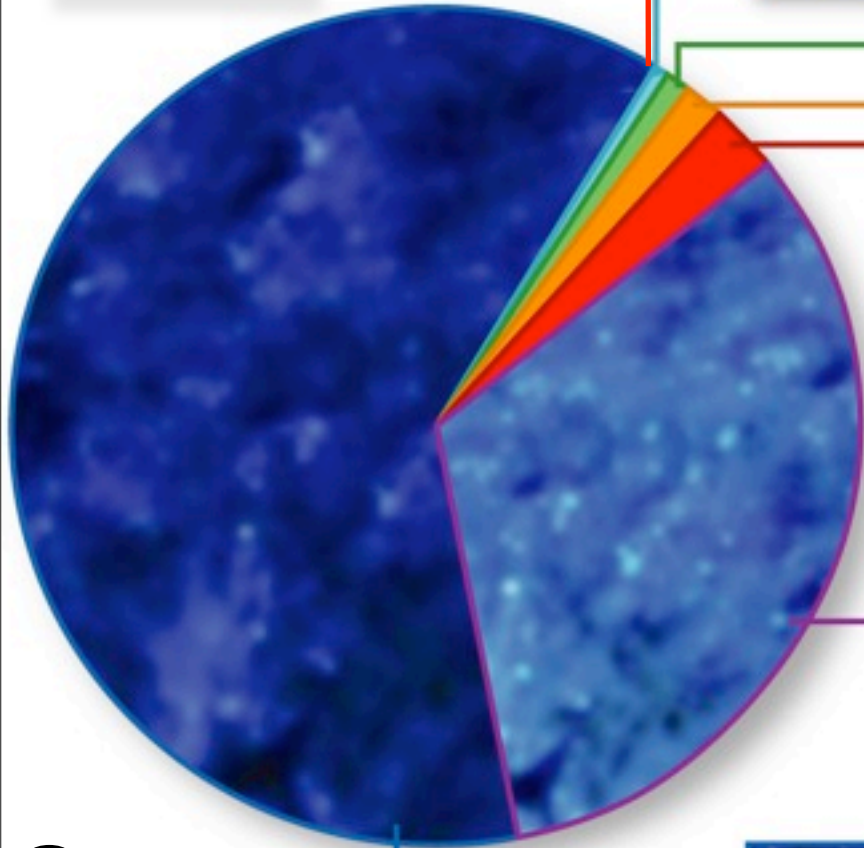
Dark Matter:

$$\Omega_{dm} = 24.5\% \pm 4\% \Rightarrow \mathbf{0.4\%}$$



Dark Energy:

$$\Omega_{\Lambda} = 71\% \pm 2\% \Rightarrow \mathbf{0.2\%}$$



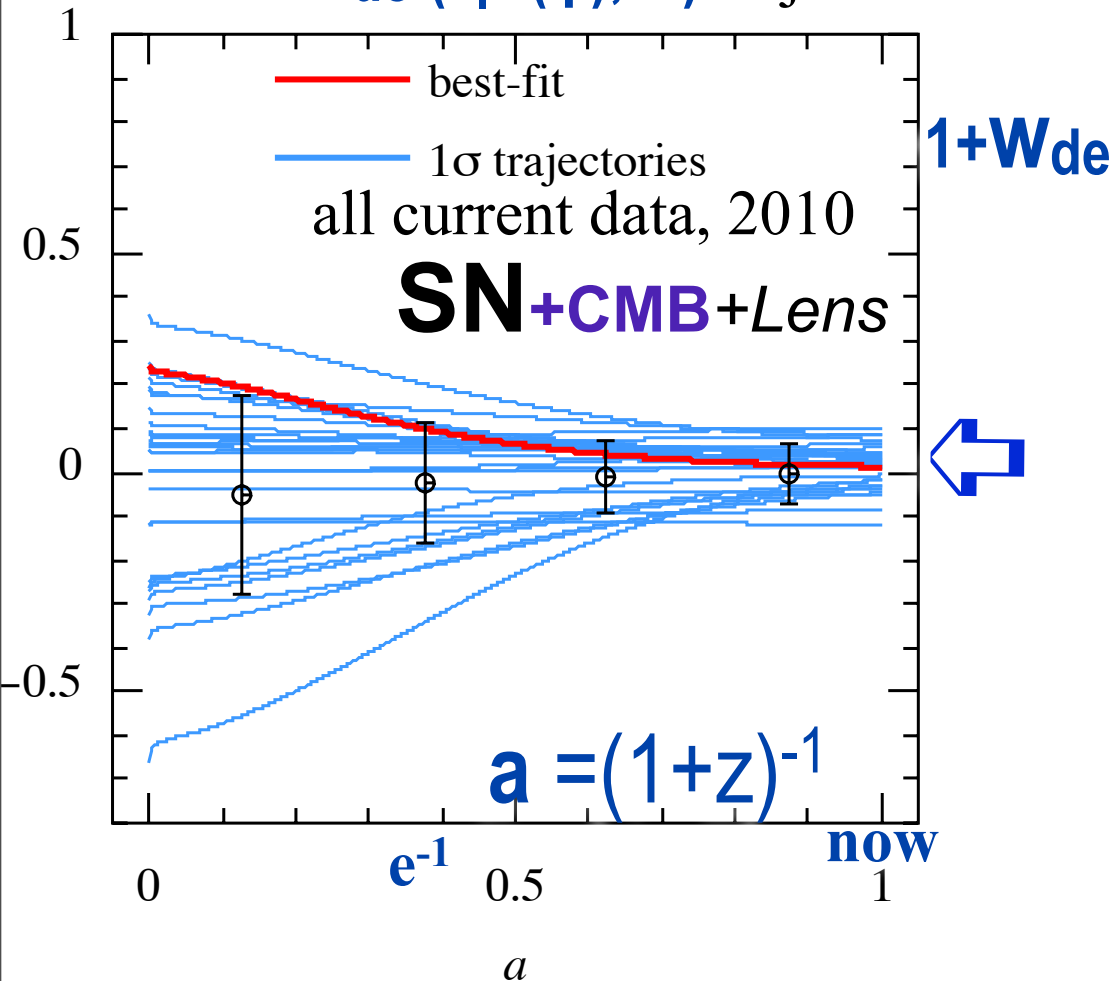
$$\Omega_{curv} = -0.6\% \pm 0.6\%$$

$$\Omega_{GW} \sim 10^{-14} - 10^{-10} \text{ LIGO}$$

$$\Omega_{BlackHoles} \sim 10^{-7}$$

is the dark energy “vacuum potential energy” ?

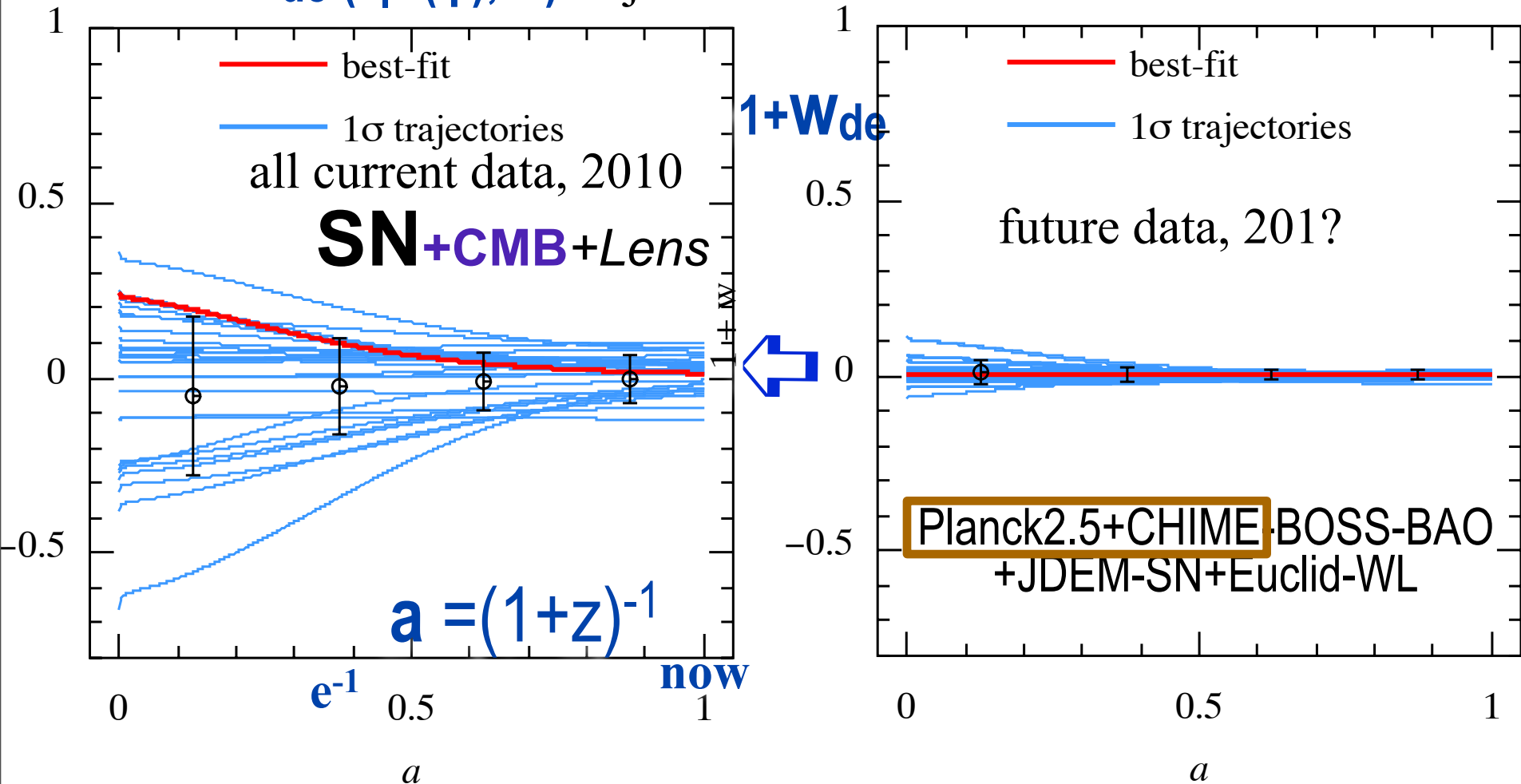
3-parameter paves even wild late-inflaton $w_{de}(z|V(\psi), IC)$ trajectories



TEST: within errors, energy-density does not change with expansion \Rightarrow Einstein's cosmological constant is best fit so far

is the dark energy “vacuum potential energy” ?

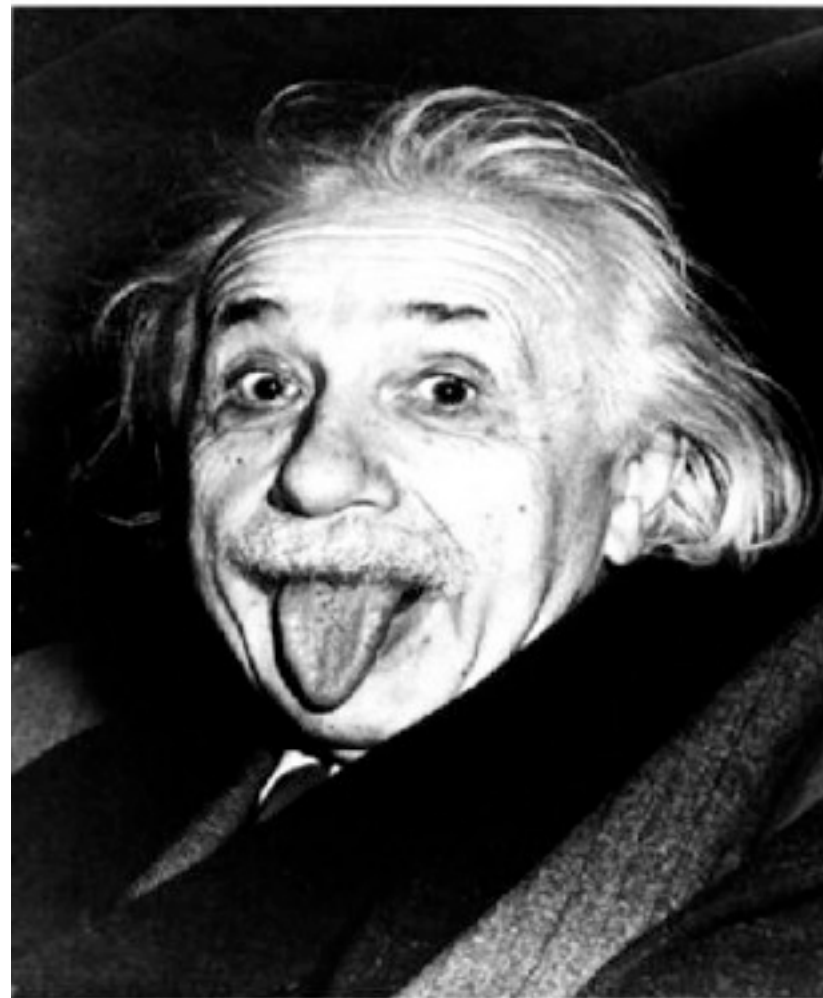
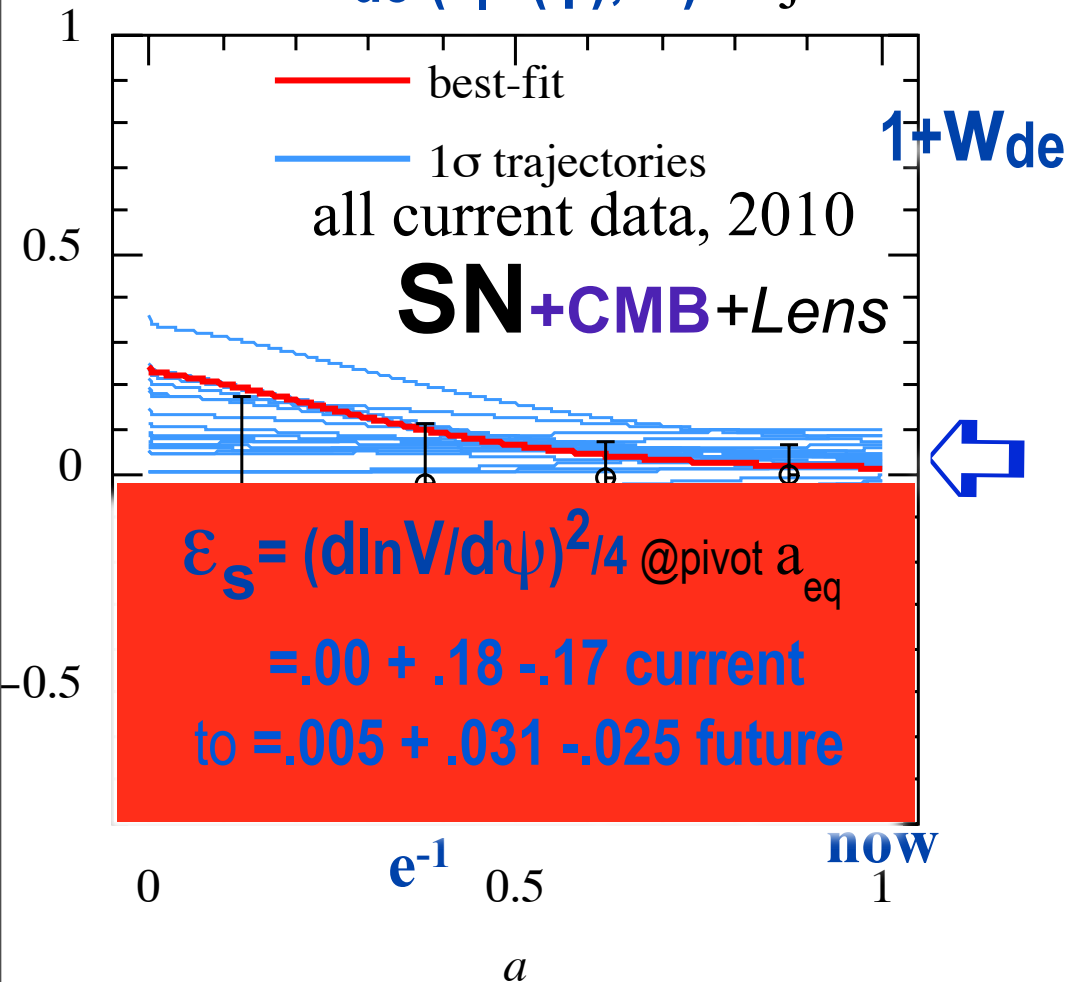
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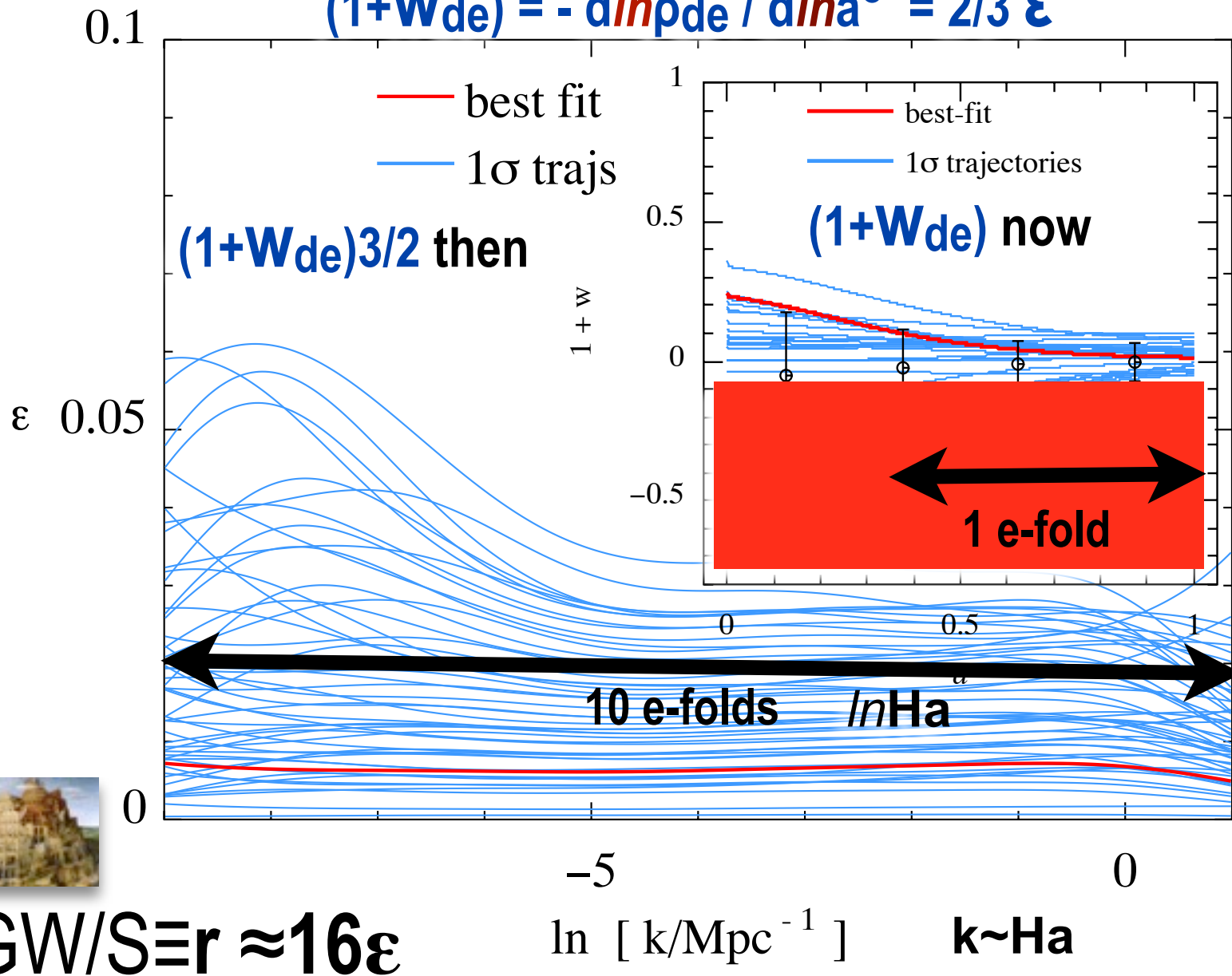
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TEST: within errors, energy-density does not change with expansion \Rightarrow Einstein's cosmological constant is best fit so far

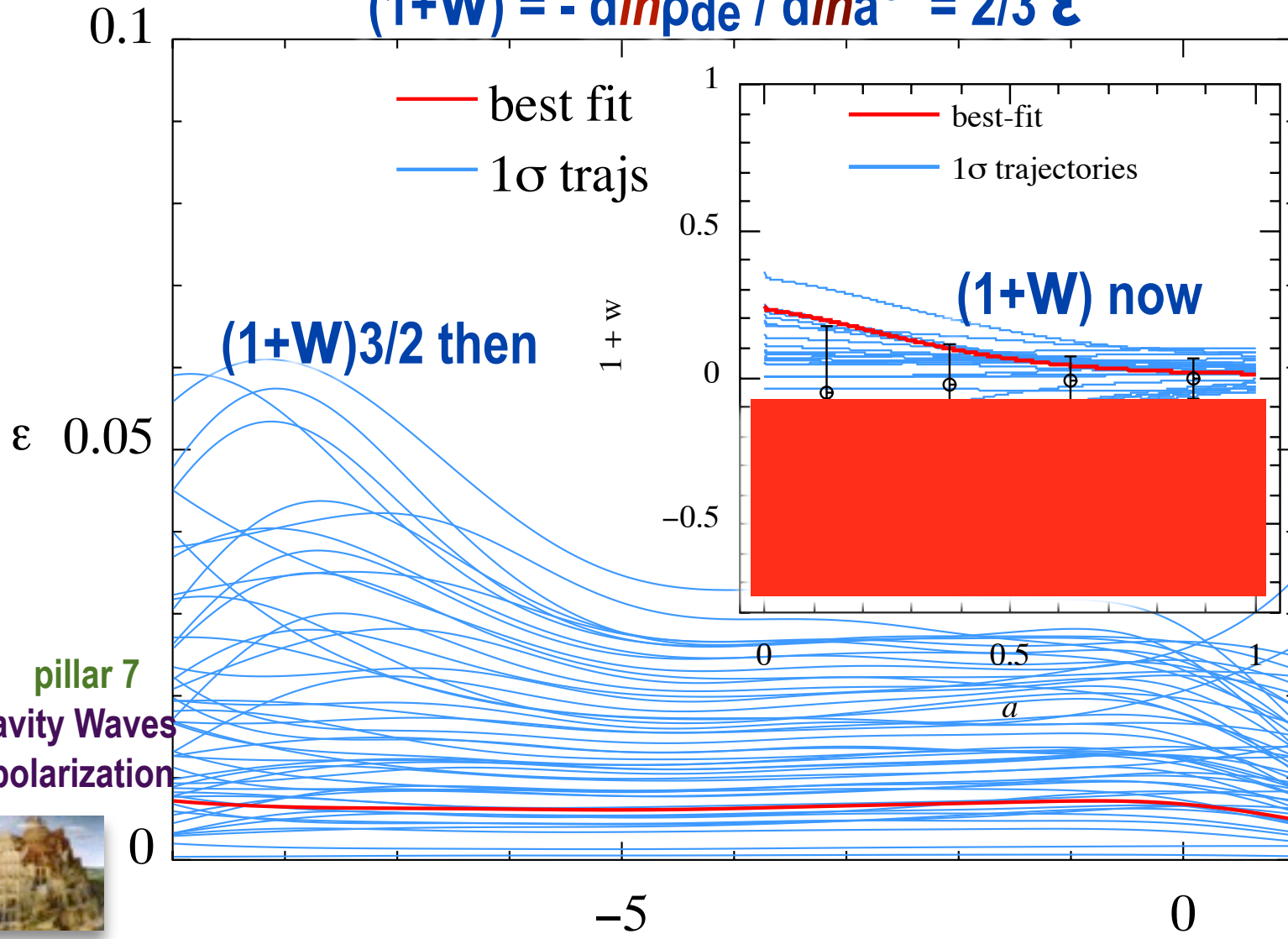
acceleration trajectories then & now

$$(1+W_{de}) = -d \ln p_{de} / d \ln a^3 = 2/3 \epsilon$$



acceleration trajectories then & now

$$(1+W) = -d \ln \rho_{de} / d \ln a^3 = 2/3 \epsilon$$



pillar 7
 Gravity Waves
 B-polarization



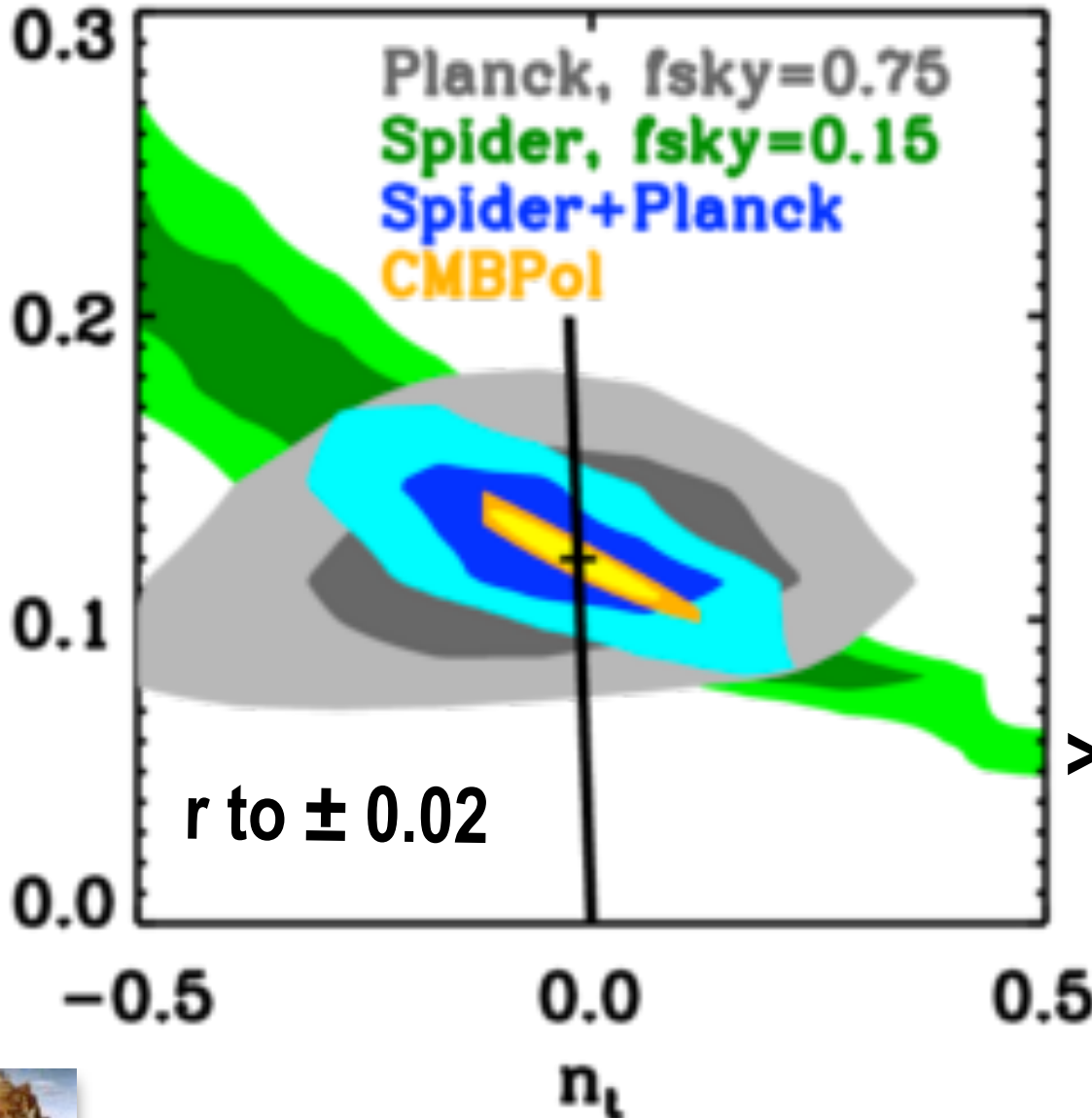
$$r \approx 16 \epsilon \approx -8 n_t$$

$$r \approx 0.008 V / (10^{16} \text{Gev})^4$$

PRIMARY @ 2012?



CMB ~2012: Planck2.5+WMAP9+SPT/ACT/Quiet+Bicep/QuAD/Keck/ABS +Ebex/Spider



Pillar 7? Gravity Waves

nearly uniform acceleration

80s-90s-03 $r \sim 0.03-0.3$

$$r \approx 0.13 \frac{d \ln V}{d \ln \psi^2}$$

e.g. $r = 0.12 \pm 0.02$

string-based modular inflation:
*many-roulette hole sizes in 6D,
brane separations, .. cyclic*

>2003 $r < 10^{-10}$ to $\sim 0.04?$

e.g. $r < 0.02$ 95% CL

+ Pillar 4: primordial non-Gaussianity

$-9 < f_{NL} < 111$ (+- 5-10 Planck1)





Beyond Einstein

the universe is comprehensible!!!

Gravity as Geometry=Mass-Energy



Beyond Einstein

the universe is comprehensible!!!

Gravity as Geometry=Mass-Energy

cosmological constant 1917 Λ



Beyond Einstein

the universe is comprehensible!!!

Gravity as Geometry=Mass-Energy

cosmological constant 1917 Λ

$G - \Lambda g = \text{Energy-density} \times 8\pi G_{\text{Newton}}$



Beyond Einstein

the universe is comprehensible!!!

Gravity as Geometry=Mass-Energy

cosmological constant 1917 Λ

$G - \Lambda g = \text{Energy-density} \times 8\pi G_{\text{Newton}}$

Gravitational waves – 1917



Beyond Einstein

the universe is comprehensible!!!

Gravity as Geometry=Mass-Energy

cosmological constant 1917 Λ

$G - \Lambda g = \text{Energy-density} \times 8\pi G_{\text{Newton}}$

Gravitational waves – 1917

ripples in spacetime moving at the speed of light



Beyond Einstein

the universe is comprehensible!!!

Gravity as Geometry=Mass-Energy

cosmological constant 1917 Λ

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Gravitational waves – 1917

ripples in spacetime moving at the speed of light c



Beyond Einstein

the universe is comprehensible!!!

Gravity as Geometry=Mass-Energy

cosmological constant 1917 Λ

$G-\Lambda g = \text{Energy-density} \times 8\pi G_{\text{Newton}}$

Einstein: Mass = Energy / c^2

Planck's Quantum:

Energy = $h \times \text{frequency}$

Quantum + Gravity \Rightarrow Planck Mass

Gravitational waves – 1917

ripples in spacetime moving at the speed of light c



Beyond Einstein

the universe is comprehensible!!!

Gravity as Geometry=Mass-Energy

cosmological constant 1917 Λ

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Einstein: Mass = Energy / c^2

Planck's Quantum:

Energy = $h \times \text{frequency}$

Quantum + Gravity \Rightarrow Planck Mass

$$M_P = \left(\frac{ch}{G_{\text{Newton}}} \right)^{1/2} / 4\pi$$

Gravitational waves – 1917

ripples in spacetime moving at the speed of light C

KANT ~ 1755 AD Galaxies - 'Island Universes'

YES! (Early 20s)



large *halo* of **dark matter**
70s/80s around galaxies;
30s around clusters.
relics or *remnants*?



Milky Way 1953-55





Beyond Einstein

the universe is comprehensible!!!

Gravity=Geometry=Mass-Energy

cosmological constant 1917 Λ

Gravitational waves – 1917
ripples in spacetime moving at the speed of
light **C**



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1998/2009+: dark energy

ρ_{Λ} (space,time)?

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ρ_{dm} = dark matter (in labs?)

ρ_{b} = ordinary matter (known)

Gravitational waves – 1917

ripples in spacetime moving at the speed of

light c to be “observed”: from black holes

ρ_{BH} & neutron stars ~2012, from the

quantum early Universe ~2011? ρ_{GW}

Periodic Table for the *Table of Isotopes** (2001)

1 (IA)																18 (VIIIA)							
Hydrogen																Helium							
H ₁																He ₂							
1.00794 91.0%																4.002602 99.9%							
2 (IIA)		Group										13 (IIIA)		14 (IVA)		15 (VA)		16 (VIA)		17 (VIIA)			
Lithium		Element										Boron		Carbon		Nitrogen		Oxygen		Fluorine			
Li ₃		E _Z										B ₅		C ₆		N ₇		O ₈		F ₉			
6.941 9.012182 6.88×10 ⁻⁴ %		Atomic Weight Abundance ^a										10.811 12.0107 0.0374		14.00674 0.0374		15.9994 0.0374		18.9984032 2.7×10 ⁻⁵ %		18.9984032 0.0112%			
3 (IIIB)		4 (IVB)		5 (VB)		6 (VIB)		7 (VIIB)		8 (VIII)		9 (VIII)		10 (VIII)		11 (IB)		12 (IIB)					
Sodium		Magnesium		Aluminum		Silicon		Phosphorus		Sulfur		Chlorine		Argon									
Na ₁₁		Mg ₁₂		Al ₁₃		Si ₁₄		P ₁₅		S ₁₆		Cl ₁₇		Ar ₁₈									
22.989770 0.0001127%		24.3050 0.000189%		26.981538 0.000277%		28.0855 0.00036%		30.973762 0.00054%		32.066 0.00082%		35.4527 0.00017%		39.948 0.00032%									
Potassium		Calcium		Scandium		Titanium		Vanadium		Chromium		Manganese		Iron		Cobalt		Nickel		Copper		Zinc	
K ₁₉		Ca ₂₀		Sc ₂₁		Ti ₂₂		V ₂₃		Cr ₂₄		Mn ₂₅		Fe ₂₆		Co ₂₇		Ni ₂₈		Cu ₂₉		Zn ₃₀	
39.0983 0.0001127%		40.078 0.000189%		44.955910 1.12×10 ⁻⁴ %		47.887 7.8×10 ⁻⁵ %		50.9415 9.8×10 ⁻⁵ %		51.9961 0.000044%		54.938044 0.000044%		55.845 0.000044%		58.933200 7.3×10 ⁻⁵ %		58.933200 0.000044%		63.546 1.79×10 ⁻⁴ %		65.38 4.1×10 ⁻⁴ %	
Rubidium		Strontium		Yttrium		Zirconium		Niobium		Molybdenum		Technetium		Ruthenium		Rhodium		Palladium		Silver		Cadmium	
Rb ₃₇		Sr ₃₈		Y ₃₉		Zr ₄₀		Nb ₄₁		Mo ₄₂		Tc ₄₃		Ru ₄₄		Rh ₄₅		Pd ₄₆		Ag ₄₇		Cd ₄₈	
85.4678 2.32×10 ⁻⁴ %		87.62 7.7×10 ⁻⁵ %		88.90585 1.53×10 ⁻⁴ %		91.224 3.72×10 ⁻⁵ %		92.90638 2.28×10 ⁻⁵ %		95.94 3.3×10 ⁻⁵ %		[98]		101.07 6.3×10 ⁻⁵ %		101.9050 1.22×10 ⁻⁴ %		106.42 4.5×10 ⁻⁵ %		107.8682 1.52×10 ⁻⁴ %		112.411 1.1×10 ⁻⁴ %	
Cesium		Barium		Lanthanum		Hafnium		Tantalum		Tungsten		Rhenium		Osmium		Iridium		Platinum		Gold		Mercury	
Cs ₅₅		Ba ₅₆		La ₅₇		Hf ₇₂		Ta ₇₃		W ₇₄		Re ₇₅		Os ₇₆		Ir ₇₇		Pt ₇₈		Au ₇₉		Hg ₈₀	
132.90545 8.2×10 ⁻⁵ %		137.327 1.46×10 ⁻⁴ %		138.9055 1.45×10 ⁻⁴ %		178.49 5.62×10 ⁻⁴ %		180.9479 4.34×10 ⁻⁴ %		183.84 1.29×10 ⁻⁴ %		186.207 2.29×10 ⁻⁴ %		190.23 2.29×10 ⁻⁴ %		192.223 2.28×10 ⁻⁴ %		195.078 4.4×10 ⁻⁵ %		196.96655 6.3×10 ⁻⁵ %		200.59 1.1×10 ⁻⁴ %	
Francium		Radium		Actinium		Rutherfordium		Dubnium		Seaborgium		Bohrium		Hassium		Meitnerium		Element-110		Element-111		Element-112	
Fr ₈₇		Ra ₈₈		Ac ₈₉		Rf ₁₀₄		Db ₁₀₅		Sg ₁₀₆		Bh ₁₀₇		Hs ₁₀₈		Mt ₁₀₉		110 ₁₁₀		111 ₁₁₁		112 ₁₁₂	
[223]		[226]		[227]		[261]		[262]		[266]		[264]		[269]		[268]		[271]		[272]		[277]	

† Lanthanides

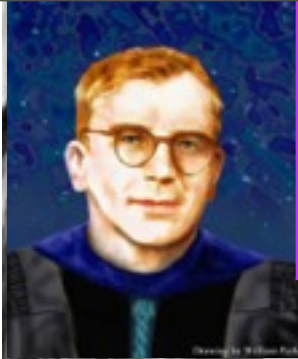
Cerium	Praseodymium	Neodymium	Promethium	Samarium	Europium	Gadolinium	Terbium	Dysprosium	Holmium	Erbium	Thulium	Ytterbium	Lutetium
Ce ₅₈	Pr ₅₉	Nd ₆₀	Pm ₆₁	Sm ₆₂	Eu ₆₃	Gd ₆₄	Tb ₆₅	Dy ₆₆	Ho ₆₇	Er ₆₈	Tm ₆₉	Yb ₇₀	Lu ₇₁
140.116 3.72×10 ⁻⁴ %	140.90765 5.44×10 ⁻⁴ %	144.24 2.70×10 ⁻⁴ %	[145]	150.36 8.42×10 ⁻⁴ %	151.964 3.17×10 ⁻⁴ %	157.25 1.076×10 ⁻³ %	158.92534 1.97×10 ⁻³ %	162.50 1.286×10 ⁻³ %	164.93032 2.09×10 ⁻³ %	167.26 8.18×10 ⁻³ %	168.93421 1.23×10 ⁻² %	173.04 8.98×10 ⁻² %	174.967 1.197×10 ⁻² %

‡ Actinides

Thorium	Protactinium	Uranium	Neptunium	Plutonium	Americium	Curium	Berkelium	Californium	Einsteinium	Fermium	Mendelevium	Nobelium	Lawrencium
Th ₉₀	Pa ₉₁	U ₉₂	Np ₉₃	Pu ₉₄	Am ₉₅	Cm ₉₆	Bk ₉₇	Cf ₉₈	Es ₉₉	Fm ₁₀₀	Md ₁₀₁	No ₁₀₂	Lr ₁₀₃
232.0371 1.09×10 ⁻⁴ %	[231]	238.02891 2.84×10 ⁻⁵ %	[237]	[244]	[243]	[247]	[247]	[251]	[252]	[257]	[258]	[259]	[262]

cosmic baryon number $n_b = 0.261 \pm 0.005 / m^3$

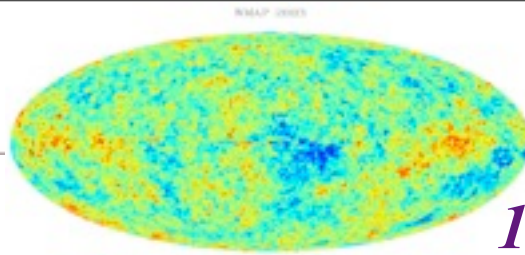
from the latest data: wmap5+acbar+cbi+b03+WL+LSS+SNI+Lya



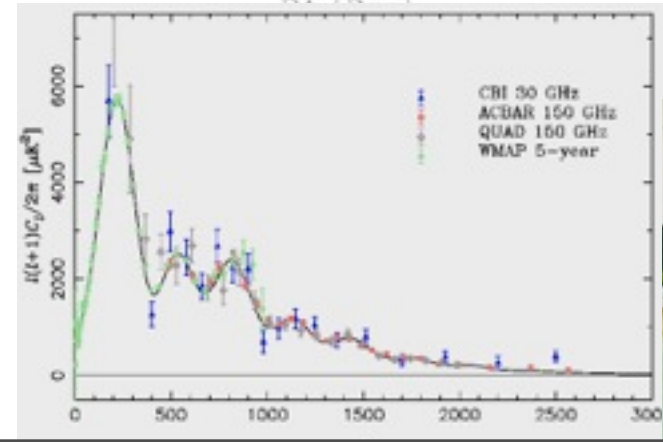
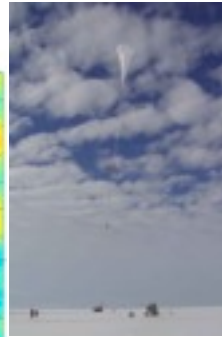
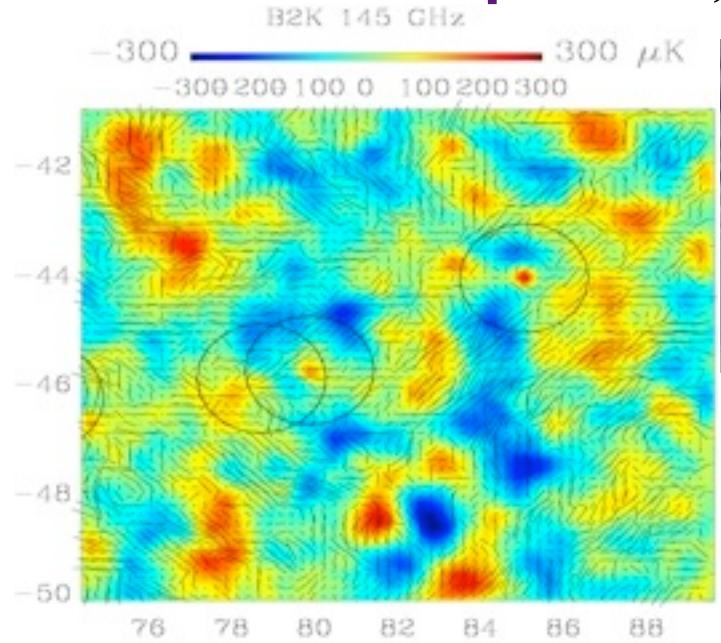
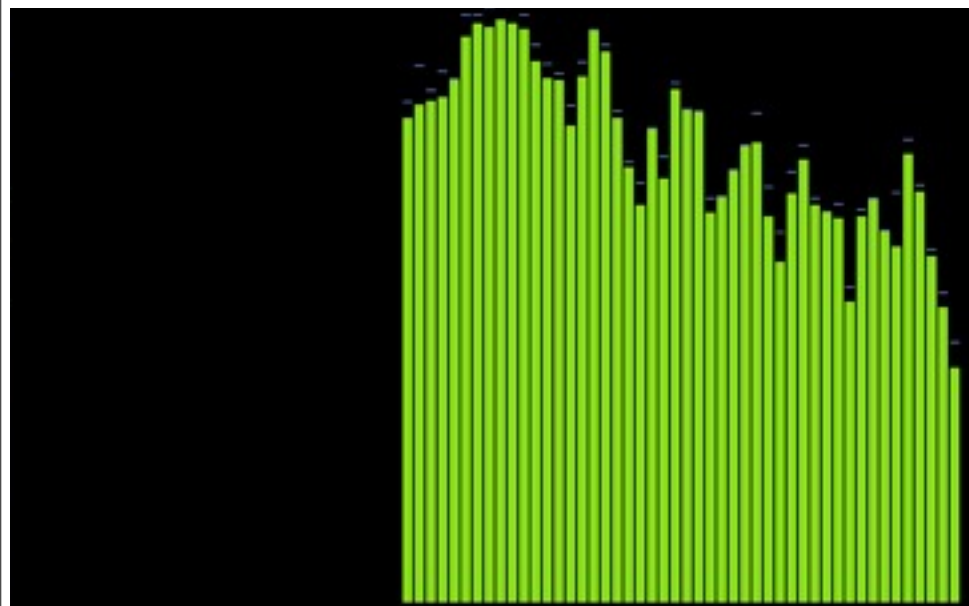
✓ **GAMOW (40s, early 50s) HOT BIG BANG**
Hydrogen (75%) & Helium (25%) Deuterium/Lithium
from the first minutes ; Carbon, Oxygen, Iron,..from
exploding stars 40s-80s



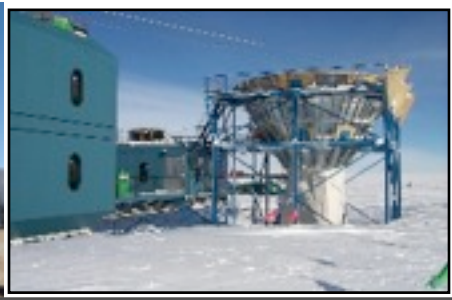
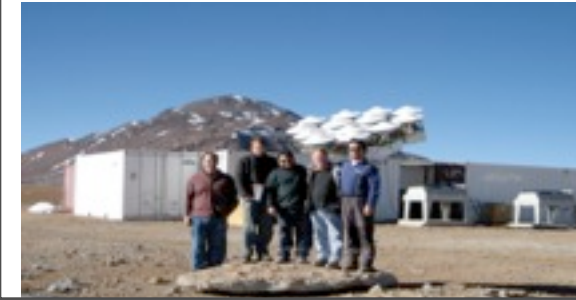
IOTA 1967, Cambridge **B²FH 57, WFH 67, sn**

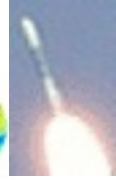
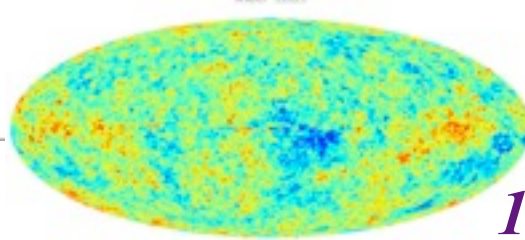


13.65 - 0.00038 billion years ago
Boom05 deep Jul05, Sept08



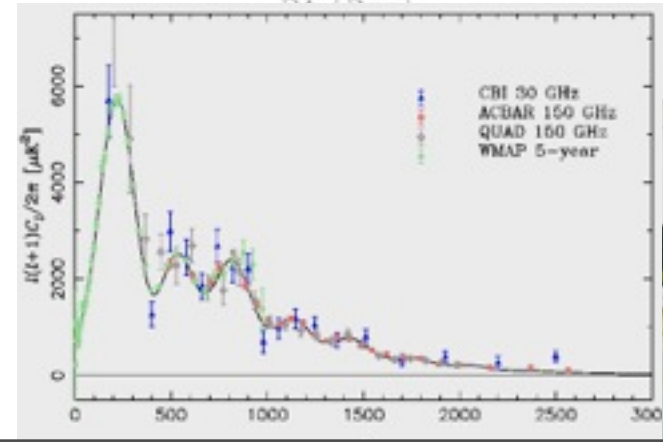
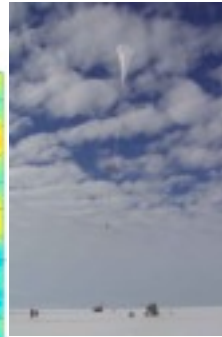
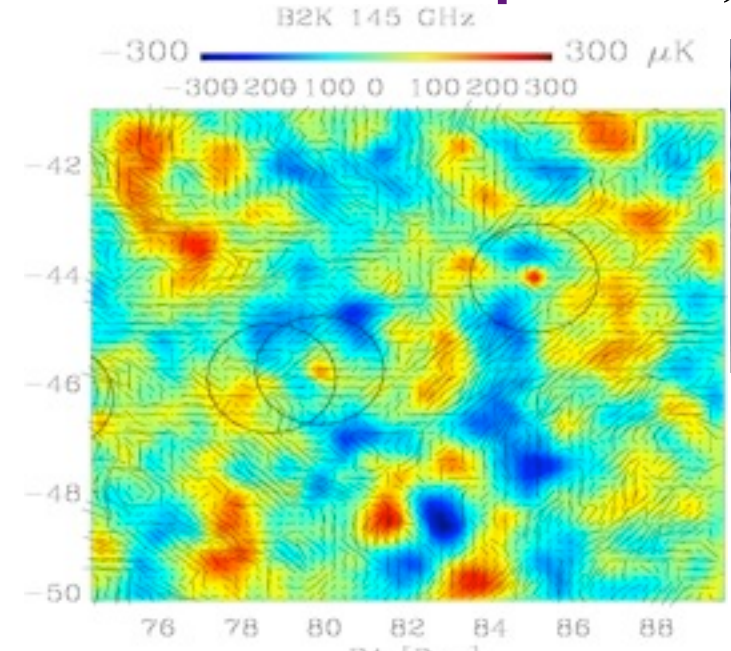
Planck09 as deep





13.65 - 0.00038 billion years ago

Boom05 deep Jul05, Sept08



**Planck09
as deep**



entropy intermittency in the cosmic web, via gravitation-induced shocks (then E/S-feedback)

Secondary Anisotropies
(tSZ, kSZ, WL, reion, CIB; hydro)

$S_{b,th}(x,t)$

CMB gets entangled in the cosmic web
descending into the real gas physics of cosmic weather

the energetic, turbulent, dissipative, compressive

life of the IGM/ICM/ISM

$\Delta S_{gas,th} \approx 30$

400 Mpc

Λ CDM

WMAP5

gas pressure

Gadget-3

SF+

SN E+

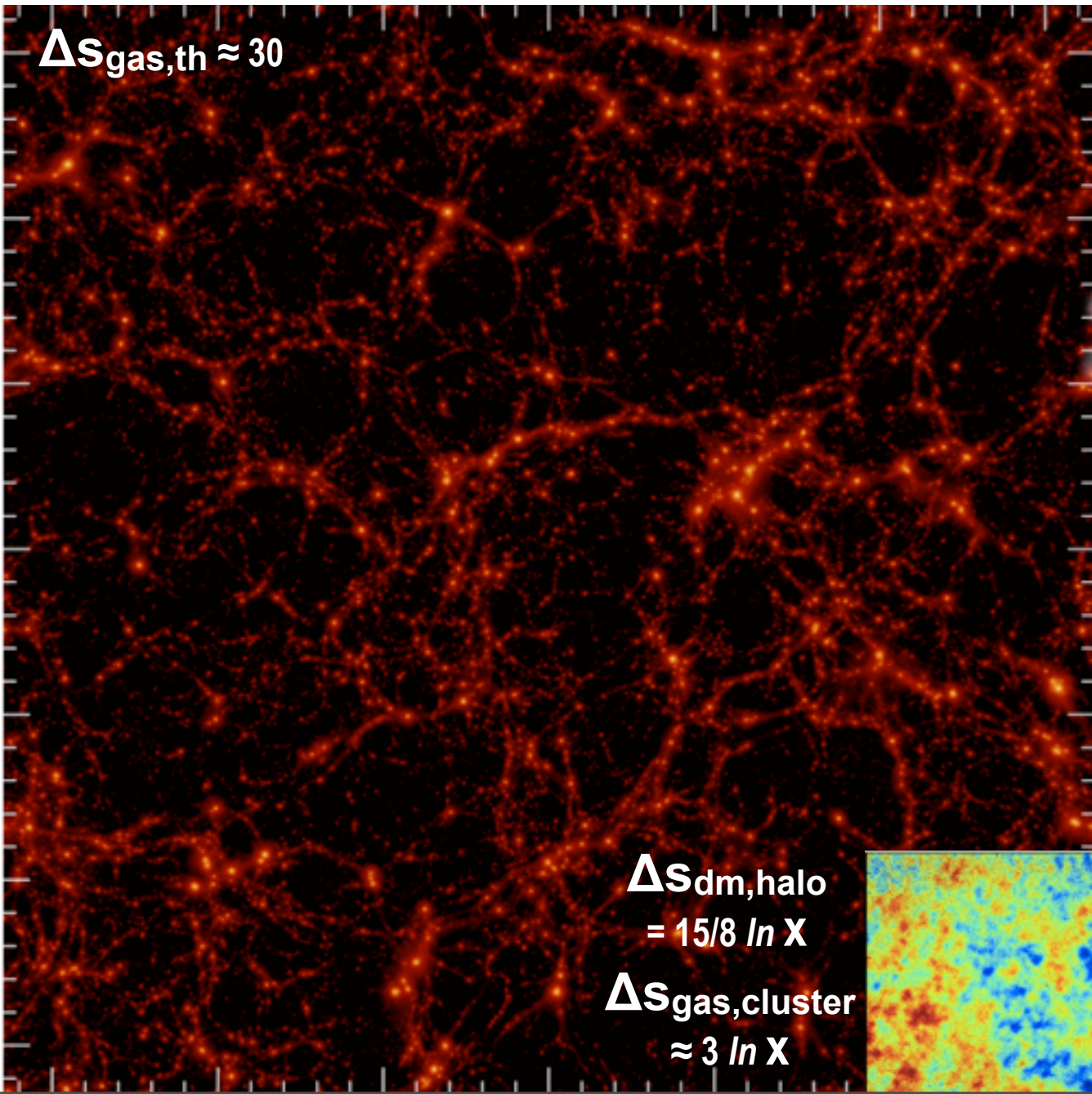
winds

+CRs

512^3

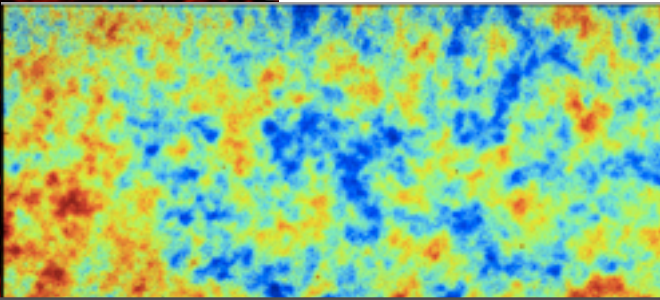
BBPSS10

BBPS1,2,3,4



$\Delta S_{dm,halo} = 15/8 \ln X$

$\Delta S_{gas,cluster} \approx 3 \ln X$



Dark Energy Histories
(SN+WL+BAO+CMB+cls)



Photo: Ariel Zambelich, Copyright © Nobel Media AB

Saul Perlmutter



Photo: Belinda Pratten, Australian National University

Brian P. Schmidt



Photo: Homewood Photography

Adam G. Riess

Λ CDM was the standard “concordance” model since ~1995; much invoked since Peebles 1985 a neo-Lemaitrian WYSIWYG BBE87, PR88, Weinberg87, ...

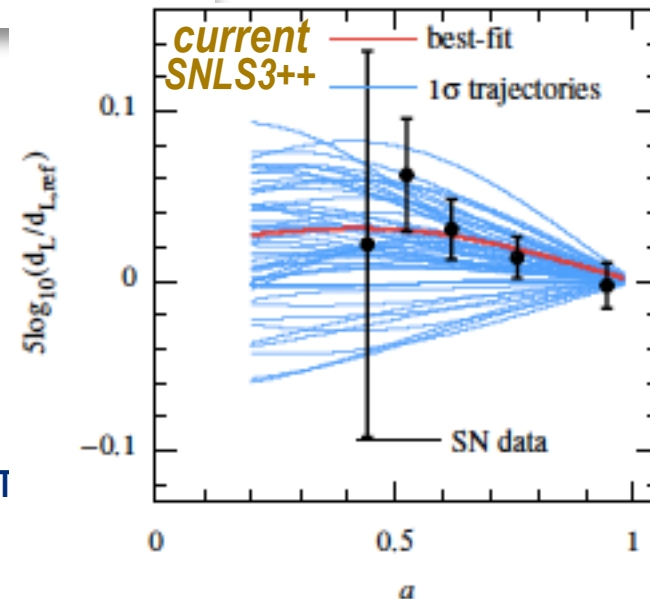
The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *“for the discovery of the accelerating expansion of the Universe through observations of distant supernovae”*.

Bond, Huang 2011



Physics Nobel Prize 2011

current Type Ia Supernova data Apr 2011
472: 123 low-z+ 242 SNLS3yr +93 SDSS1yr + 14 HST
HubbleST constraint $H_0 = 73.8 \pm 2.4$ km/s/Mpc



CMB ↓ CMB ⊕ LSS ↓

$$n_s \approx 1 \pm .05$$

nearly SCALE INVARIANT FLUCTUATIONS

vintage 1998 conclusions

CMB ⊕ LSS SNIa high z CLUSTERS

↓ $\omega_{CDM} \ll \Lambda_{CDM}$ ↓ ↓

$\Omega_{cdm} \sim 0.3$
 $\Omega_b \sim 0.04$
 $H_0 \sim 65-70$
 $t_0 \sim 12-14 \text{ Gyr}$

$$\Omega(x, t) \approx \frac{2}{3}$$

vac
 PLATE TIME

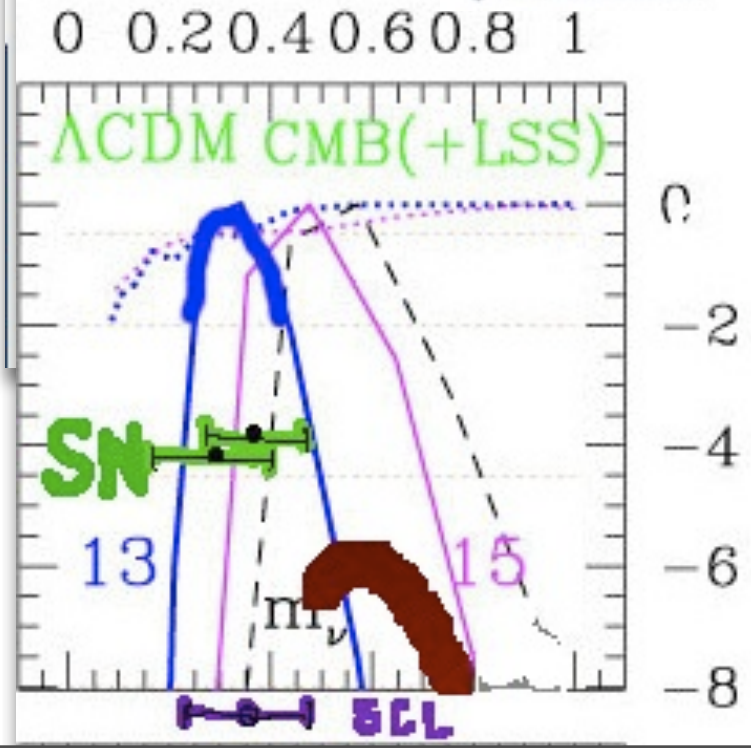
$\Omega_{\nu} \sim .0014$
 $\left(\frac{m_{\nu}}{0.1 \text{ eV}}\right)^2 \sim \frac{1}{2}$ INFLATION is NOW
 $\rho_{\nu} \sim \text{milli eV}$

B+Jaffe '96, '98 (13 Gyr/ t_0)

$$\Omega_{\Lambda} \approx 2/3 \pm .07 \quad +LSS$$

$$n_s = .98 \pm .07$$

$$.96 \pm .06$$

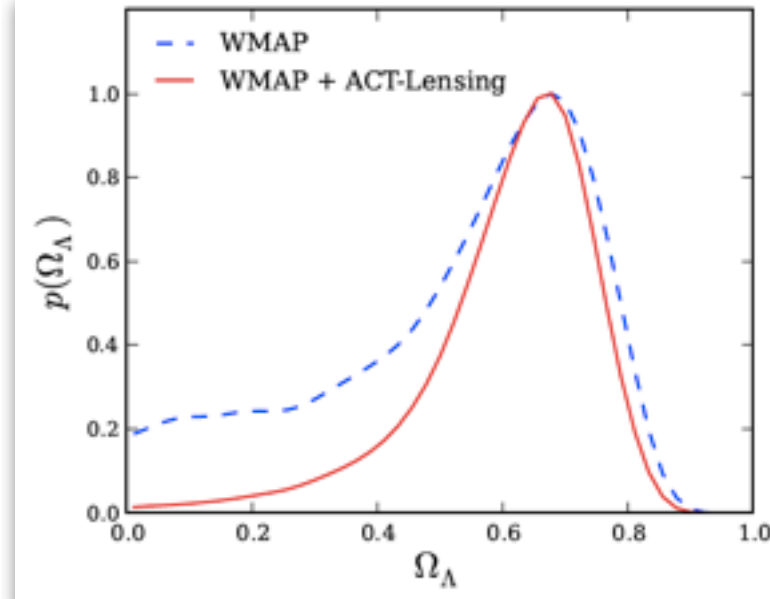
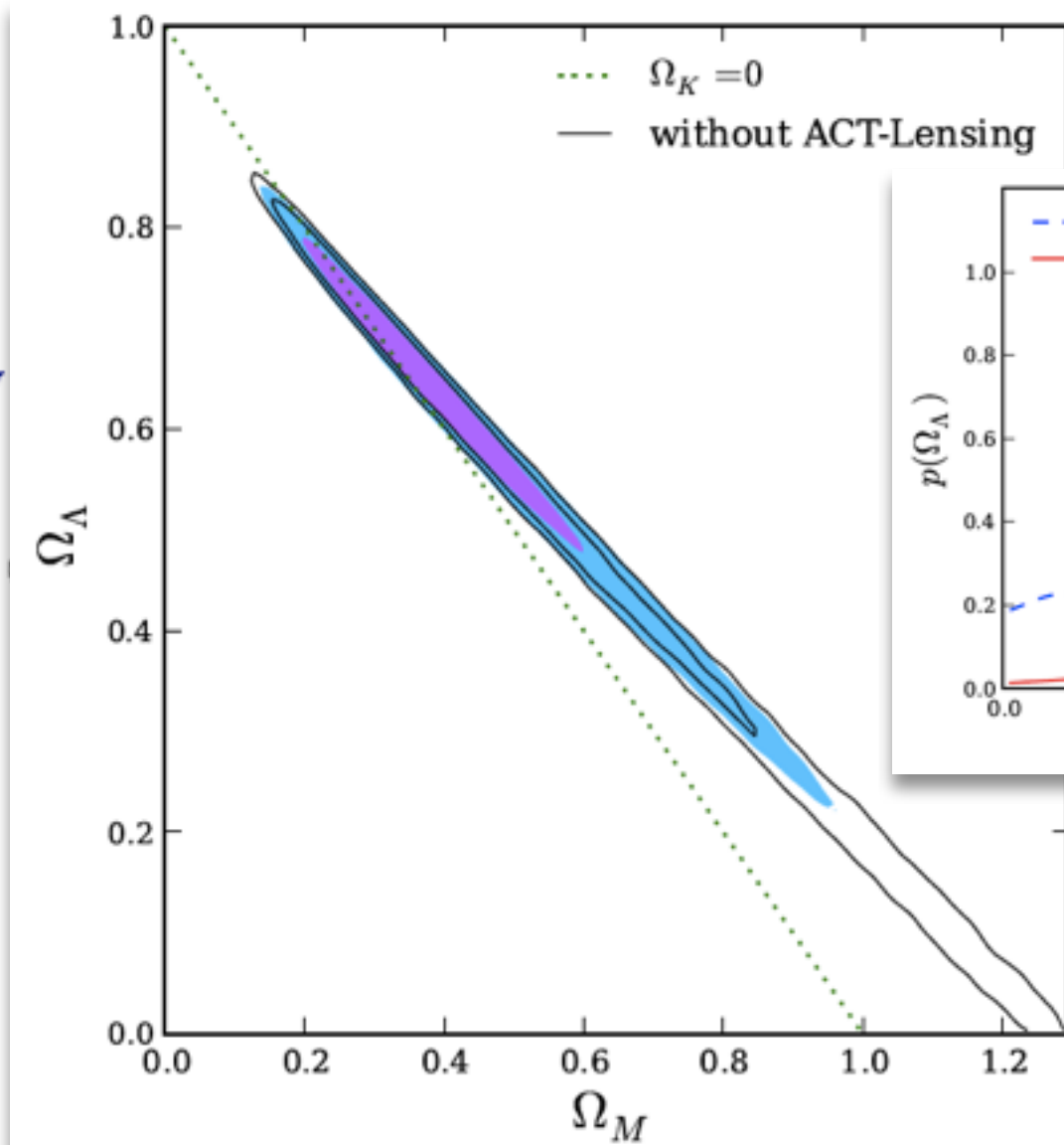


→evidence for “dark energy” aka the cosmological constant

ACT 2011

Sherwin et 2011: Λ from CMB alone

dark energy



Dunkley et 2011 cosmic parameters

$$\Omega_\Lambda = 0.736 \pm 0.012$$

2011: WMAP7+ACT+BAO+H0

=> ± 0.001 (Pext) B+Huang 2011

dark matter + baryons

Dark Energy Histories
(SN+WL+BAO+CMB+cls)

CBI pol to Apr'05 @Chile **CBI2**

QUaD @SP

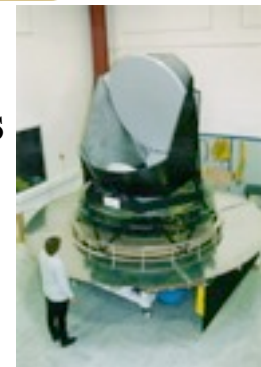
53+35 cls (≥ 40)

189 +10 cls (≥ 1000)



Planck09.4

52+ bolometers
+ HEMTs @L2
9 frequencies



WMAP @L2 to 2010



>96
OVRO
/BIMA
array
38 cls

2005
Acbar@SP
~1 blind

SZA@Cal
3 cls ($z > 1$), x?

2007
AMIBA
6 cls



2008
21+26~50 (≥ 750)

SPT
1000 bolos
@SPole

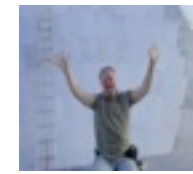


ACT **23+27~50 cls**
3000 bolos
3 freqs @Chile

AMI
7+1 cls $\geq 50+25$



APEX
~400 bolos @Chile
~25 cls



SCUBA2
12000 bolos
JCMT @Hawaii

GBT
4 cls (~25 CLASH)

SPTpol
ACTpol
ALMA

CCAT@Chile
LMT@Mexico