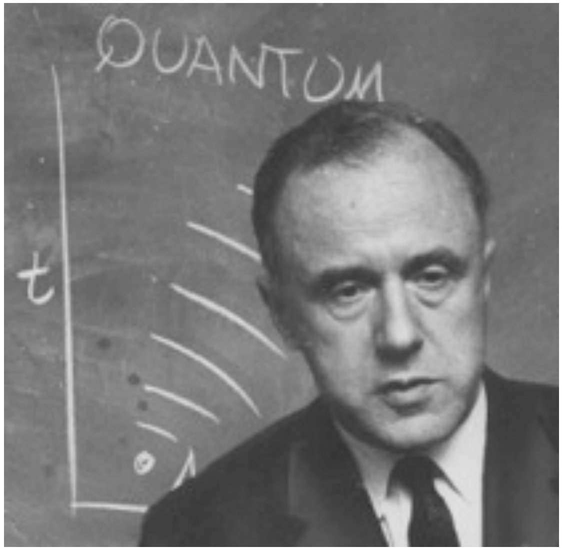
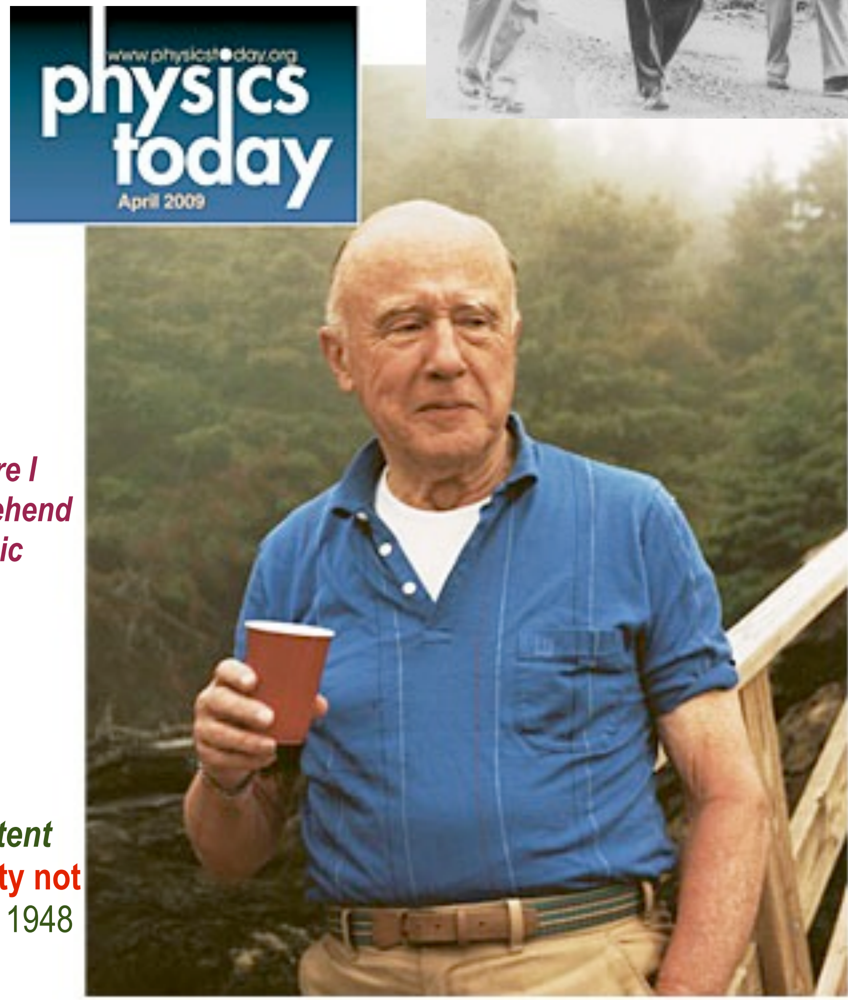
CITA = Cosmic Information Theory & Analysis: *IT from BIT, from BITs in IT*

"black hole" =”gravitationally completely collapsed object"

measurement problem—the role of the observer in defining what "is."





"Now I am in the grip of a new vision, that **Everything Is Information.** *The more I have pondered the mystery of the quantum and our strange ability to comprehend this world in which we live, the more I see possible fundamental roles for logic and information as the bedrock of physical theory. ... I continue to search."*

"What do we mean by 'reality' except the results of observations?"

the observer confers "reality" on the past by observing it, and offered the Big Bang as an example

our Cosmoticians’ Agenda:
Statistical Paths in Cosmic Theory & Data via the Bayesian chain drawing what we know of **It from Its Bits**

information-content =entropy Quantity not Quality Shannon 1948

the medium is the message McLuhan 1964 UofT

Special issue: John Archibald Wheeler

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

25 years cifar

CITA = Cosmic Information Theory & Analysis:
IT from BIT, from BITs in IT, *Studying the Cosmic Tango*

Dick Bond CIAR

en-TANGO-ment the dance of Universe =System(s)+Reservoir
=Signal(s)+Residual *noise* =Effective Theory+*Hidden variables,*
=*Data*+*Theory,* observer(s)+observed
ruled by (information) entropy in bits, entangled. *the fine grains in the coarse grains*

$S_{U,m+r} \sim 10^{88.6}$
in our
Hubble$_\Lambda$Volume
compressed onto

$T_\gamma \approx 2.725$K &

$1/H_0 \approx 14$ Gyr

5.2 bits/Υ

$S_G \sim 10^{121.9}$

$s_m \sim 1$ bits/baryon
atmosphere

~190 in clusters

WMAP9 $10^{12.1}$
Planck $10^{13.6}$
ACT $10^{14.5}$
Compress ~7 parameters

“IT from BIT”

FATE U inflate (again)

a cold death? reheat/rebirth?

Planck era 10^{-43} sec 10^{55+}

NOW 14 Gyr 1

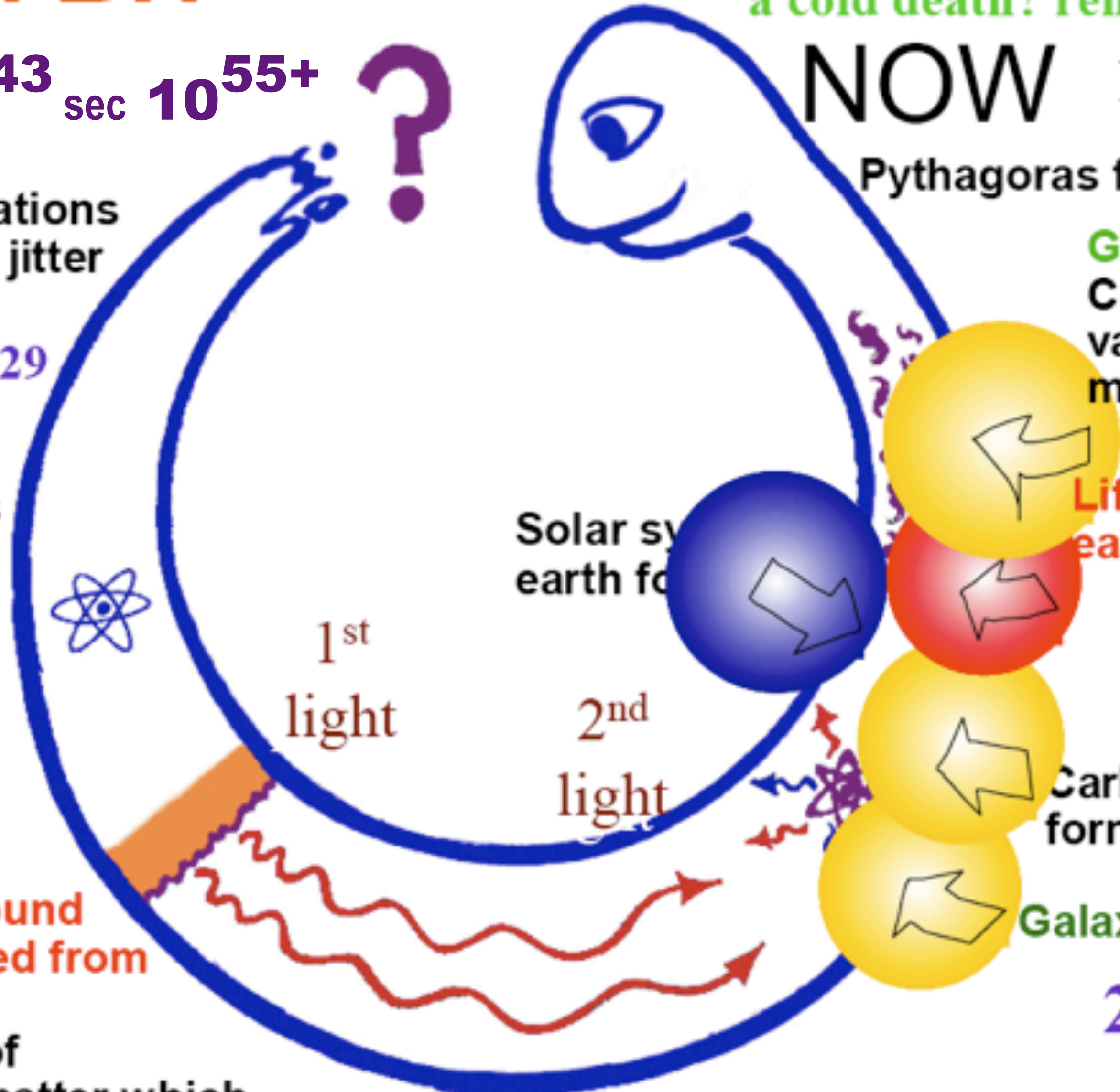
Pythagoras formed

Inflation fluctuations form: quantum jitter

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

Galaxies Cluster

Cosmic “web” of vast filaments + membranes



Protons/Neutrons form

Life forms on earth

9 Gyr 1.4

Helium forms

100 sec 10^{9}

Carbon/oxygen/etc form

Galaxies form

2 Gyr 4

Cosmic background radiation released from matter

carries imprint of fluctuations in matter which grow to generate galaxies etc.

0.4 Myr 1100

The ‘Meaning’ may change
But the facts will remain

PYTHAGORAS 550 BCE ***THEORIST***

Cosmos$\supseteq$ math, harmonic ν/λ, digital

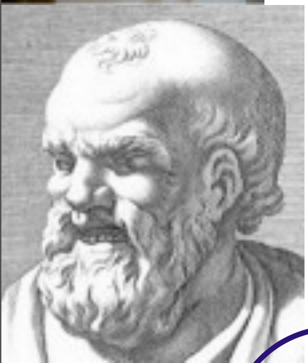
a very brief human history

of how

Cosmic Information

was generated by Us:

highly filtered, compressed,reduced



G

ϱ_{vac}

Milky Way 1953-55

Λ

Λ

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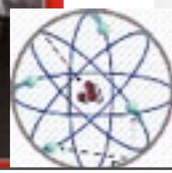

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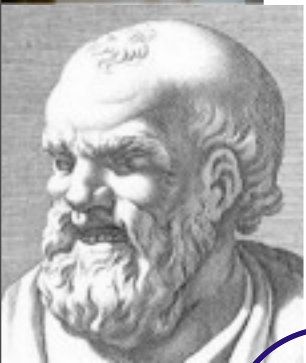

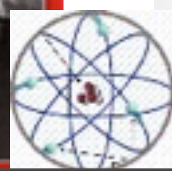

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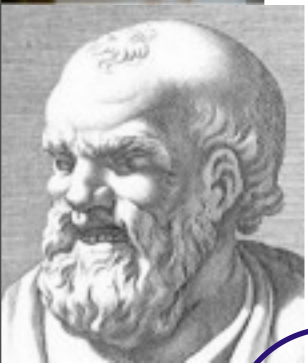

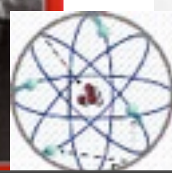

4

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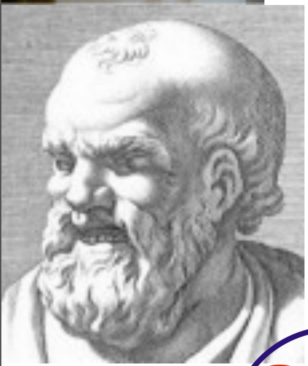

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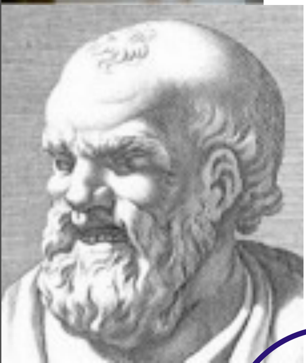


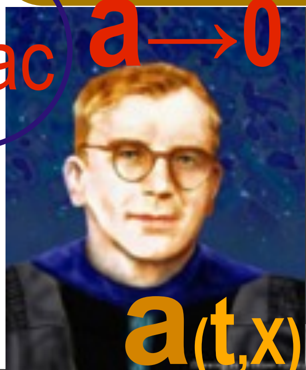





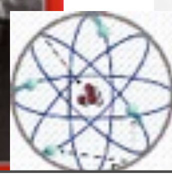

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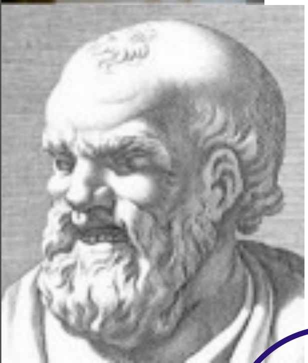
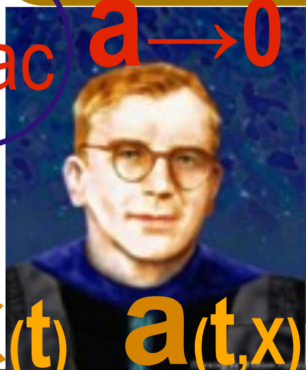


G

ρ_{vac}



$a \to 0$

$\varepsilon(t)$ $a(t,x)$

H

Milky Way 1953-55

Λ

Λ

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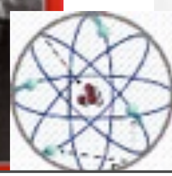

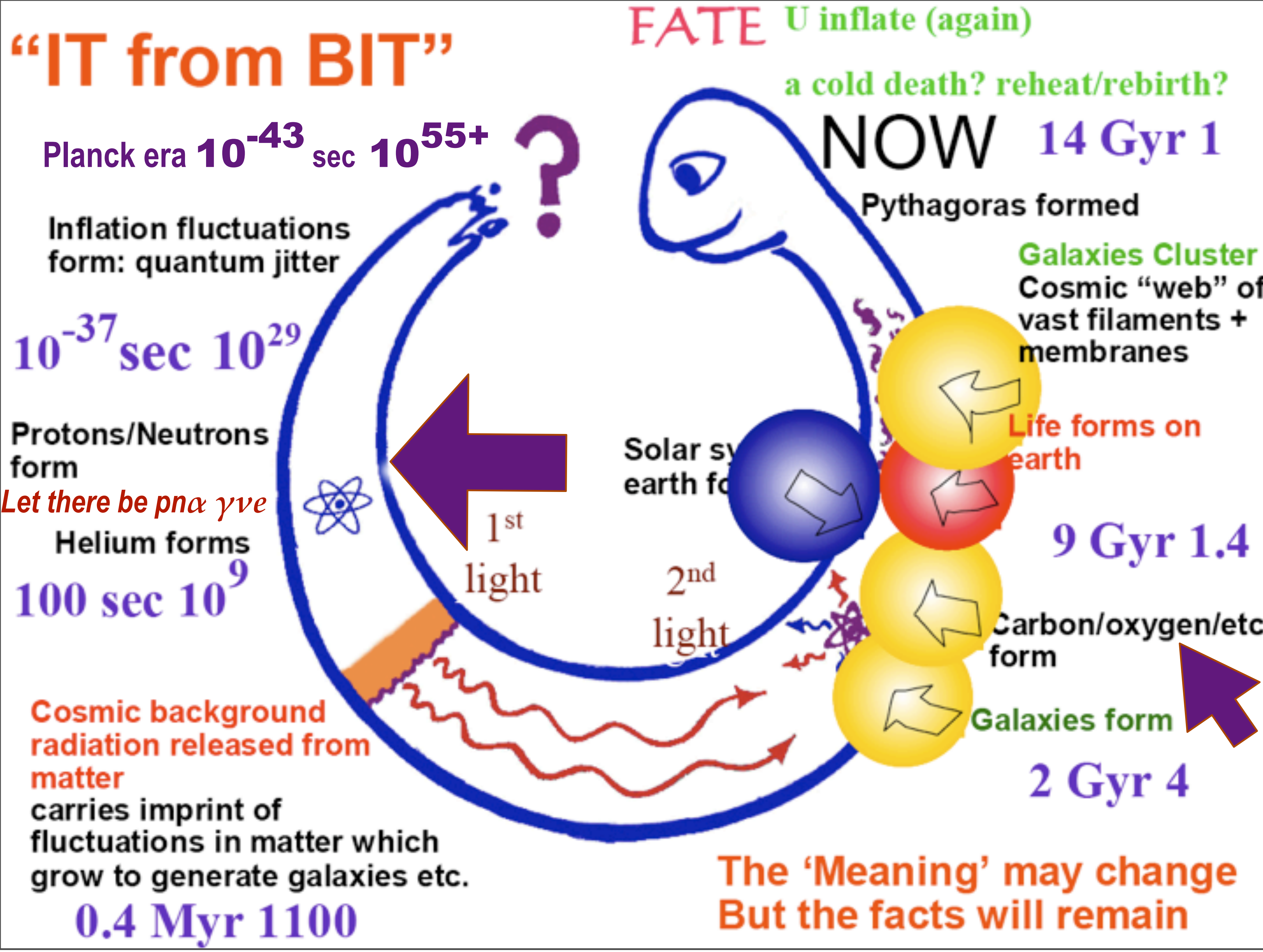
"IT from BIT"
Planck era 10^{-43} sec 10^{55+}
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Galaxies Cluster
Cosmic "web" of
vast filaments +
membranes
Life forms on
earth
Protons/Neutrons
form
Let there be pnα γνe
Helium forms
100 sec 10^{9}
1st
light
Solar sy
earth fo
2nd
light
9 Gyr 1.4
Carbon/oxygen/etc
form
Galaxies form
2 Gyr 4
Cosmic background
radiation released from
matter
carries imprint of
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grow to generate galaxies etc.
0.4 Myr 1100
The 'Meaning' may change
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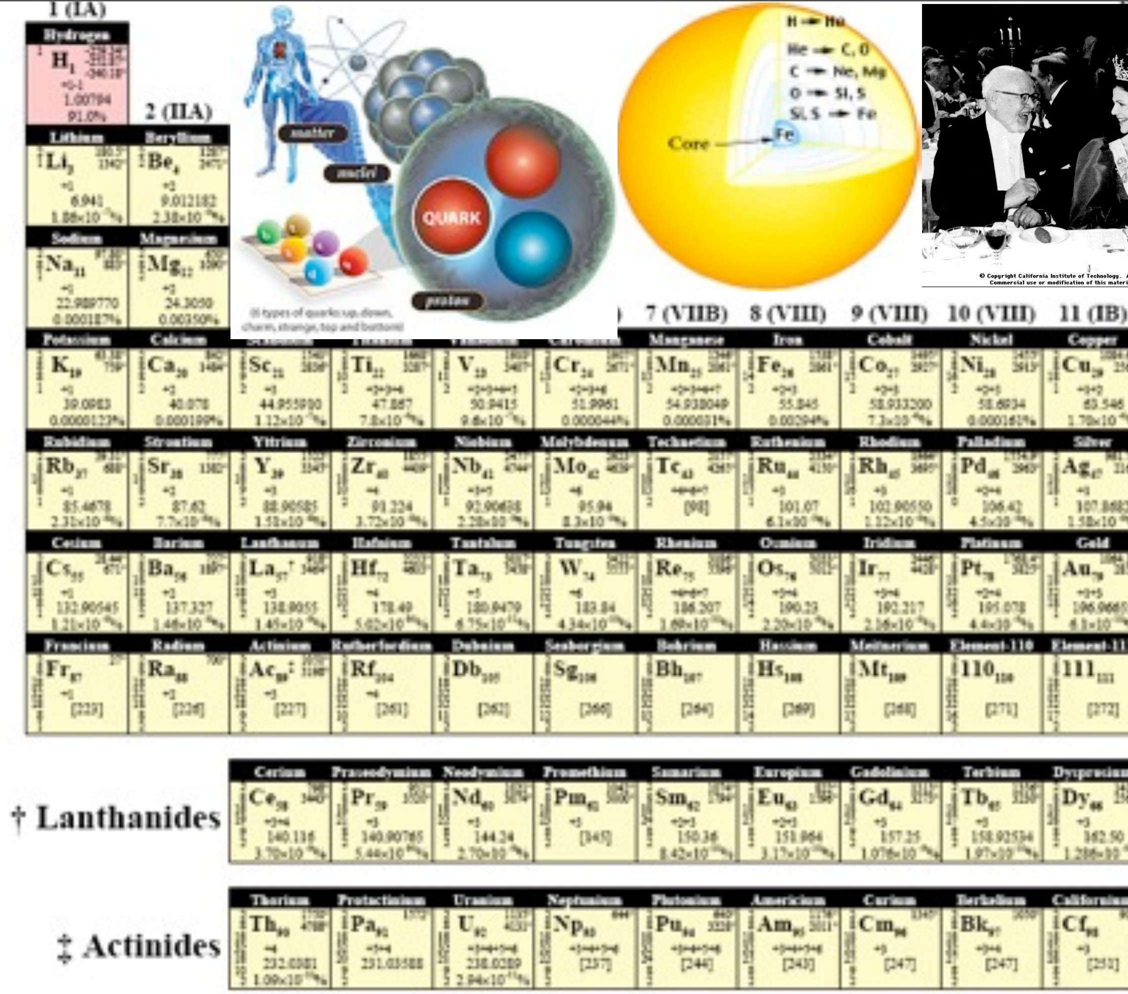
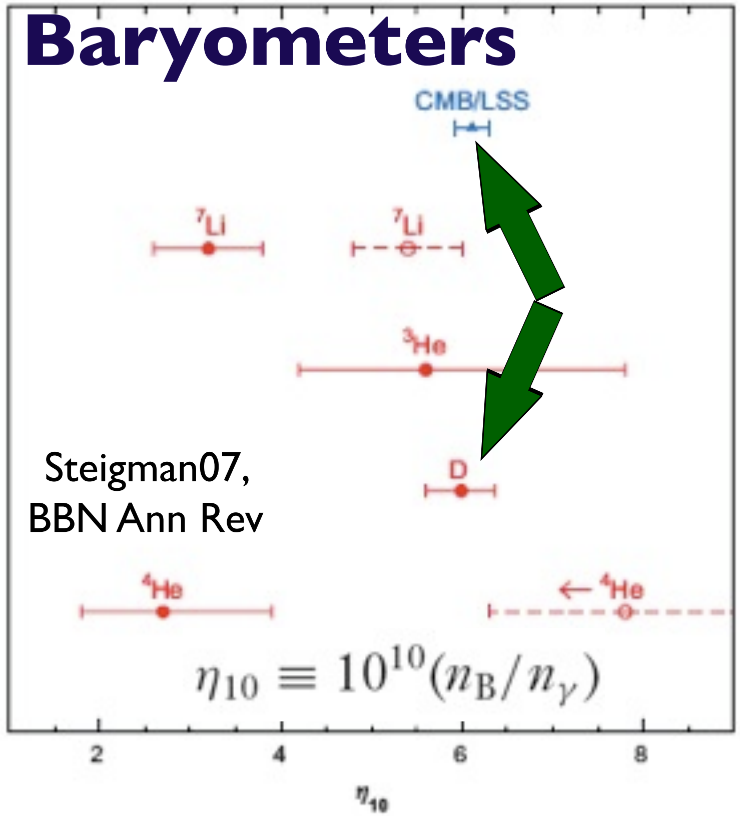


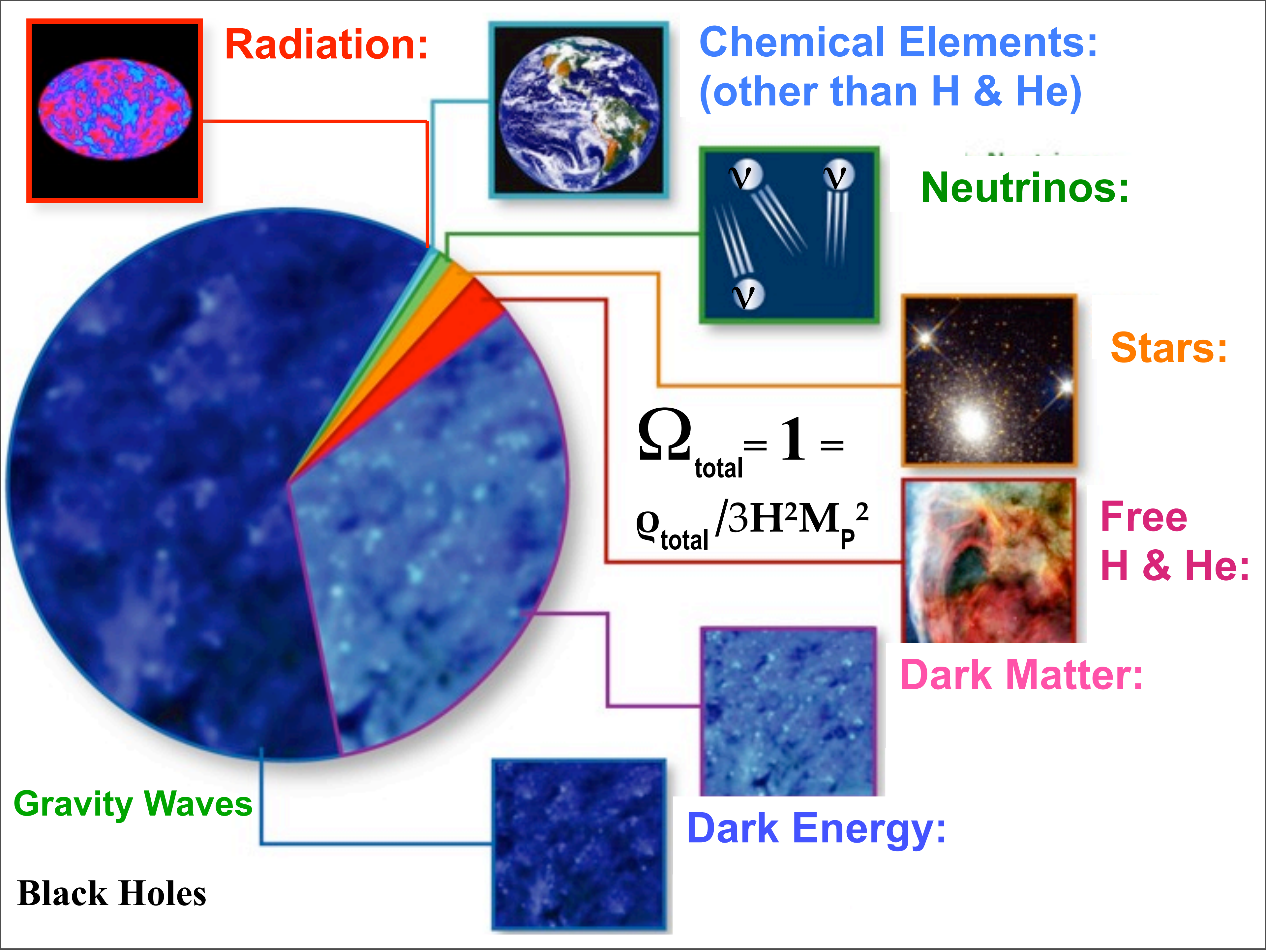
periodic table of the isotopes

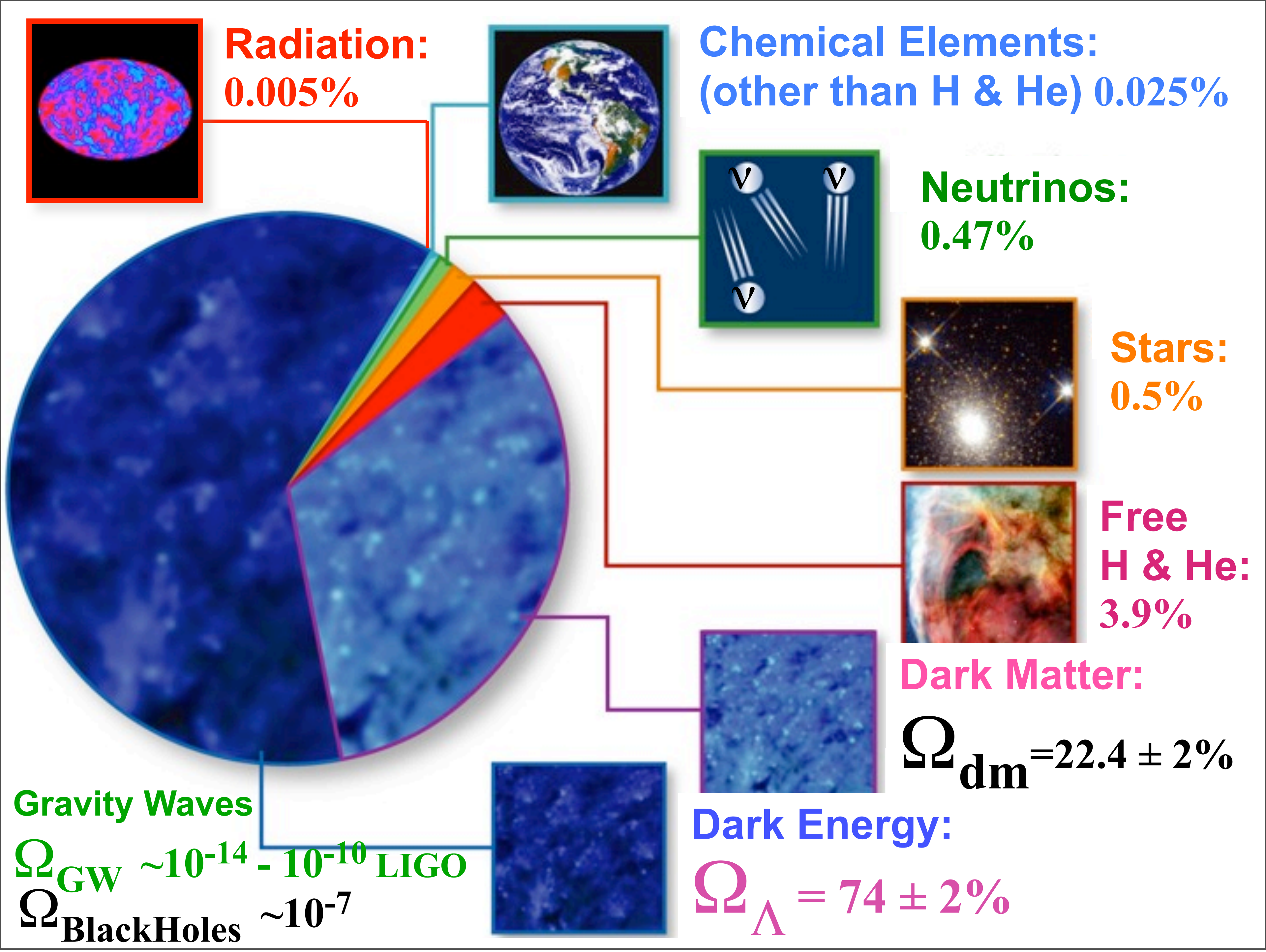


Steigman07,
BBN Ann Rev

cosmic baryon number
$\mathbf{n_b}$=0.254 +-.005 /m^3

from the latest data: wmap7+acbar+cbi+b03+ACT+WL+LSS+SN1+Lya


Radiation:
Chemical Elements:
(other than H & He)
Neutrinos:
ν
ν
ν
Stars:
$\Omega_{total} = 1 = \varrho_{total}/3H^2M_P^{\,2}$
Free
H & He:
Dark Matter:
Gravity Waves
Dark Energy:
Black Holes



Radiation:
0.005%
Chemical Elements:
(other than H & He) 0.025%
ν
ν
ν
Neutrinos:
0.47%
Stars:
0.5%
Free
H & He:
3.9%
Dark Matter:
Ω_{dm}=22.4 ± 2%
Dark Energy:
Ω_{Λ} = 74 ± 2%
Gravity Waves
Ω_{GW} ~10^{-14} - 10^{-10} LIGO
$\Omega_{BlackHoles}$ ~10^{-7}

"IT from BIT"

FATE U inflate (again)

a cold death? reheat/rebirth?

NOW 14 Gyr 1

Planck era 10^{-43} sec 10^{55+}

Pythagoras formed

Inflation fluctuations form: quantum jitter

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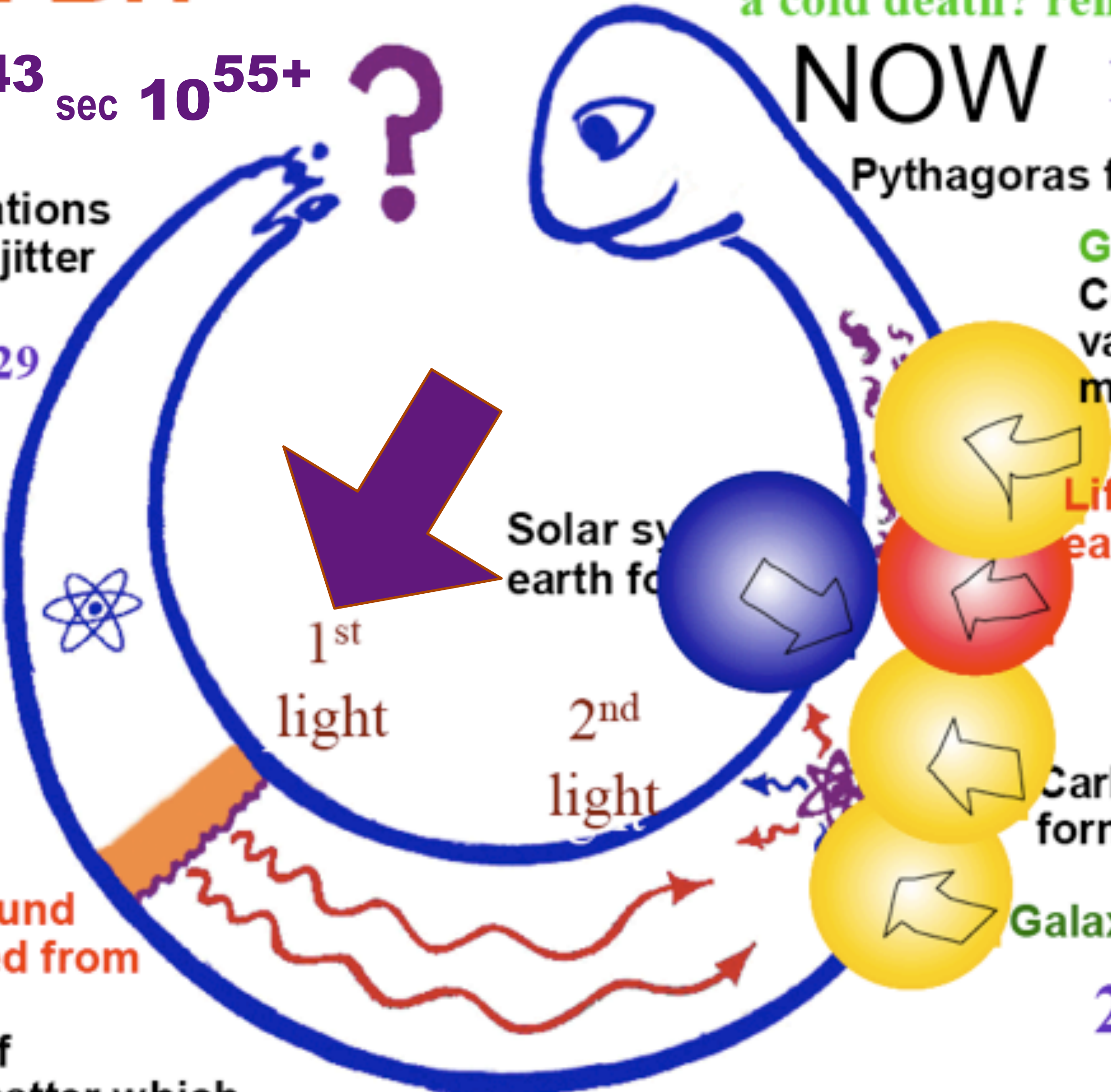


Protons/Neutrons form

Life forms on earth

Helium forms

9 Gyr 1.4

100 sec 10^{9}

Carbon/oxygen/etc form

Let there be Light

Galaxies form

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

2 Gyr 4

0.4 Myr 1100

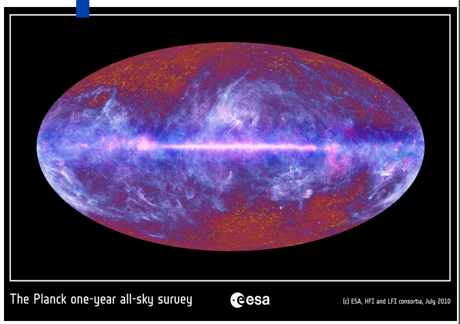
The 'Meaning' may change
But the facts will remain

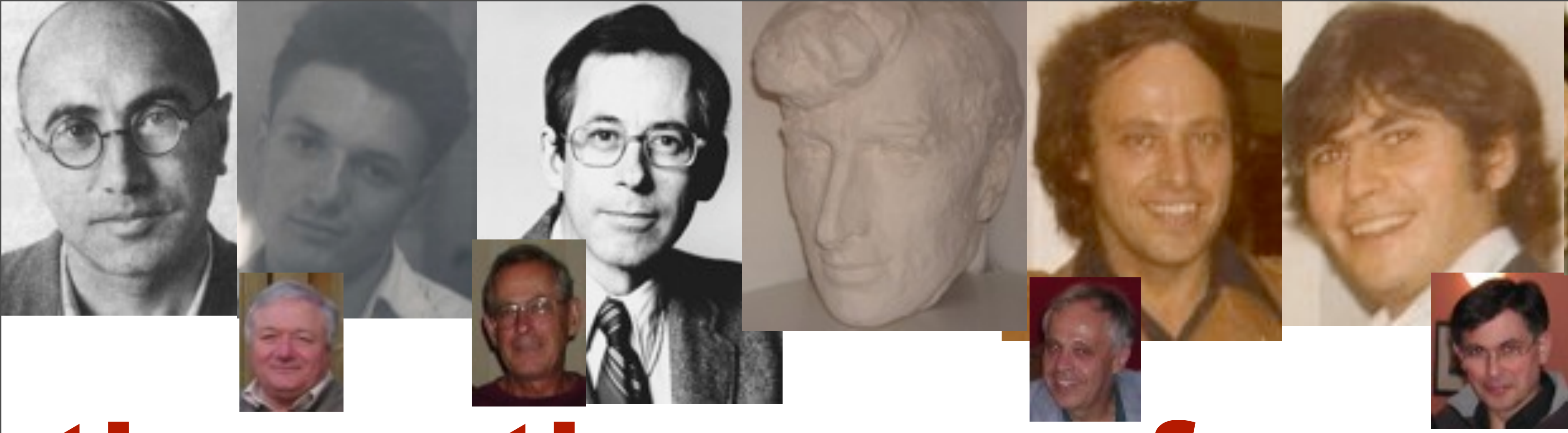
the gatherers of cosmic information

Cosmic Microwave Background+

Large Scale Structure experimental probes

then & now & then





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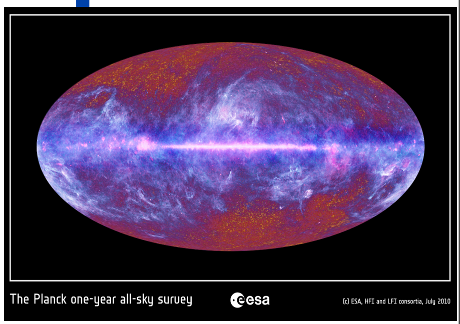
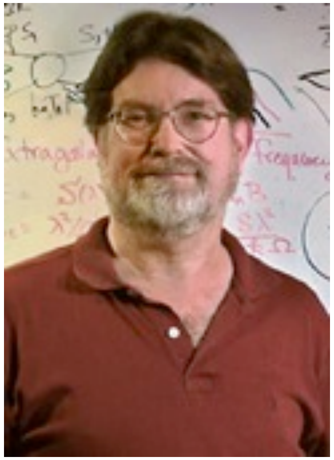


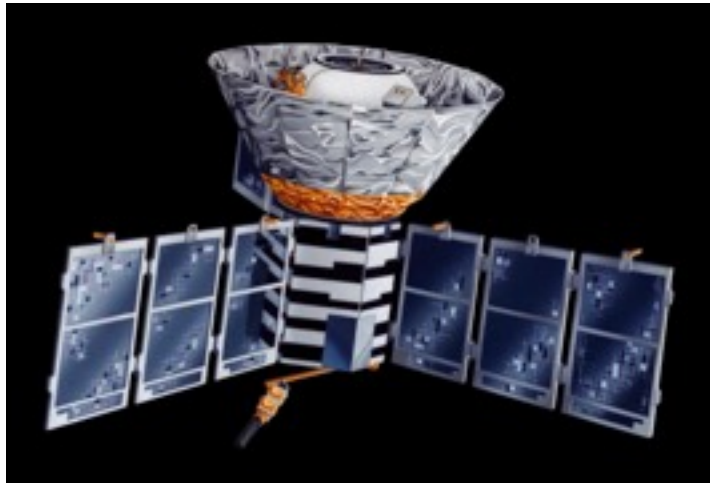
The Nobel Prize in Physics 2006
(also Gruber Prize in Cosmology 2006 for Mather + the COBE team)

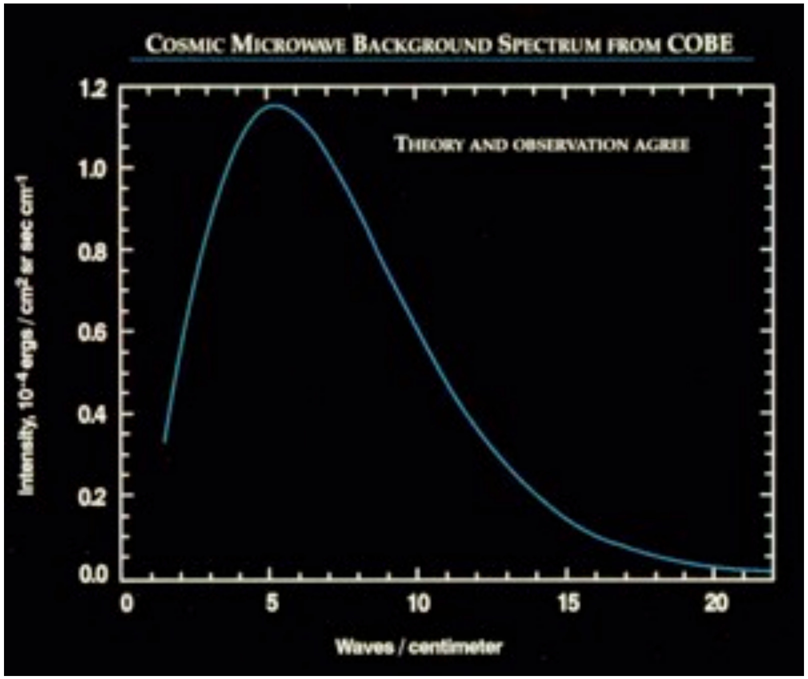
"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"

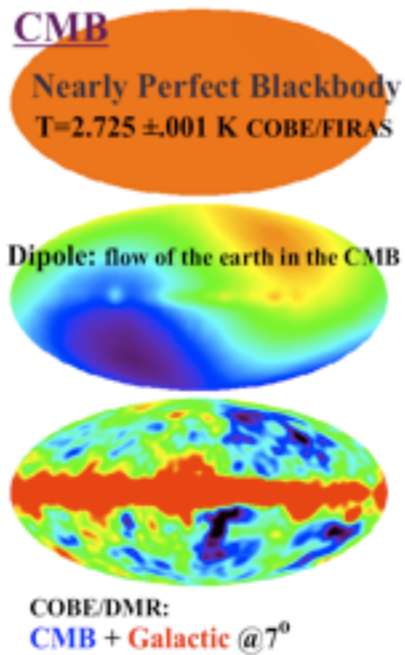
John C. Mather 1946-

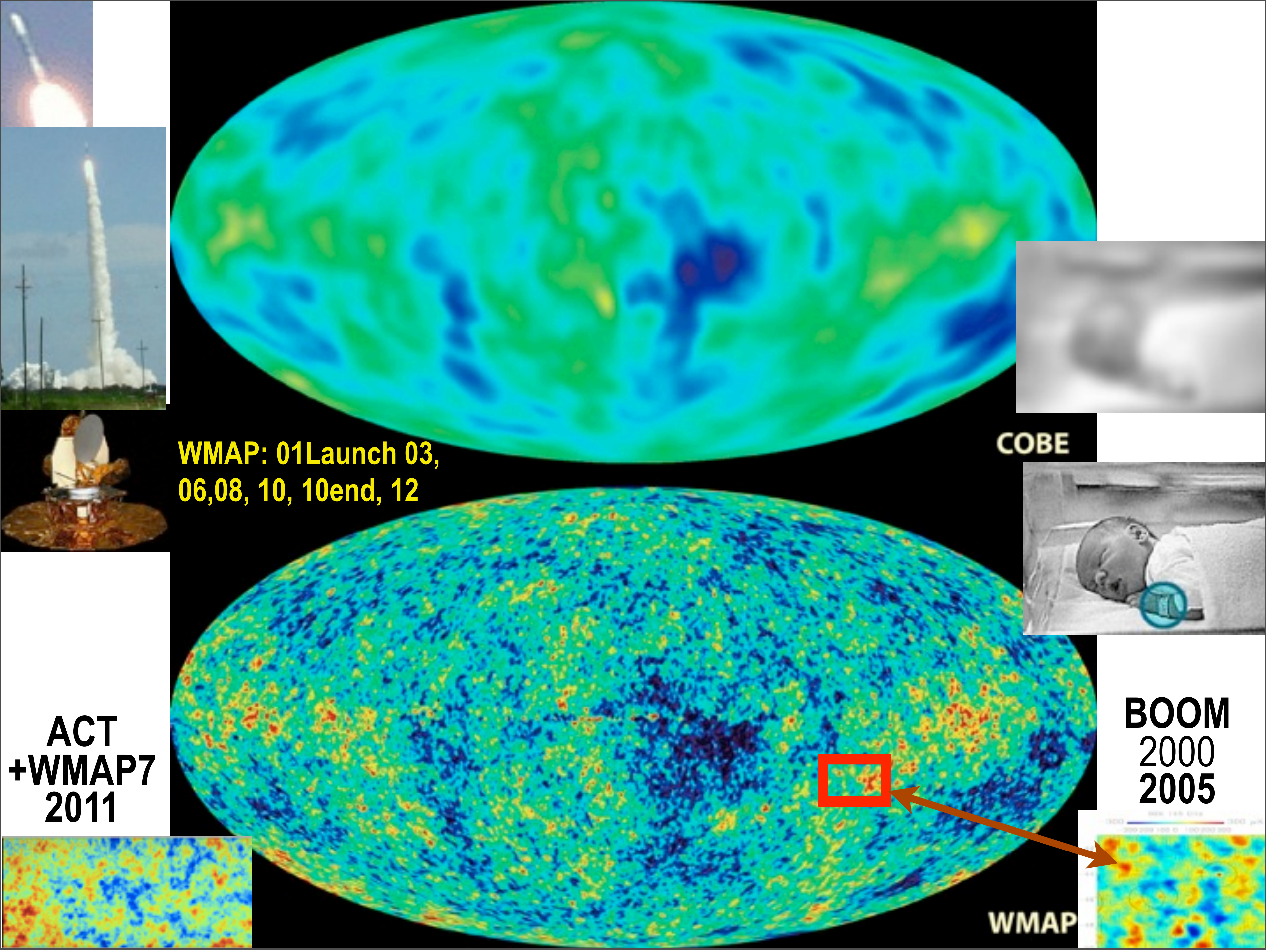


George F. Smoot 1945-







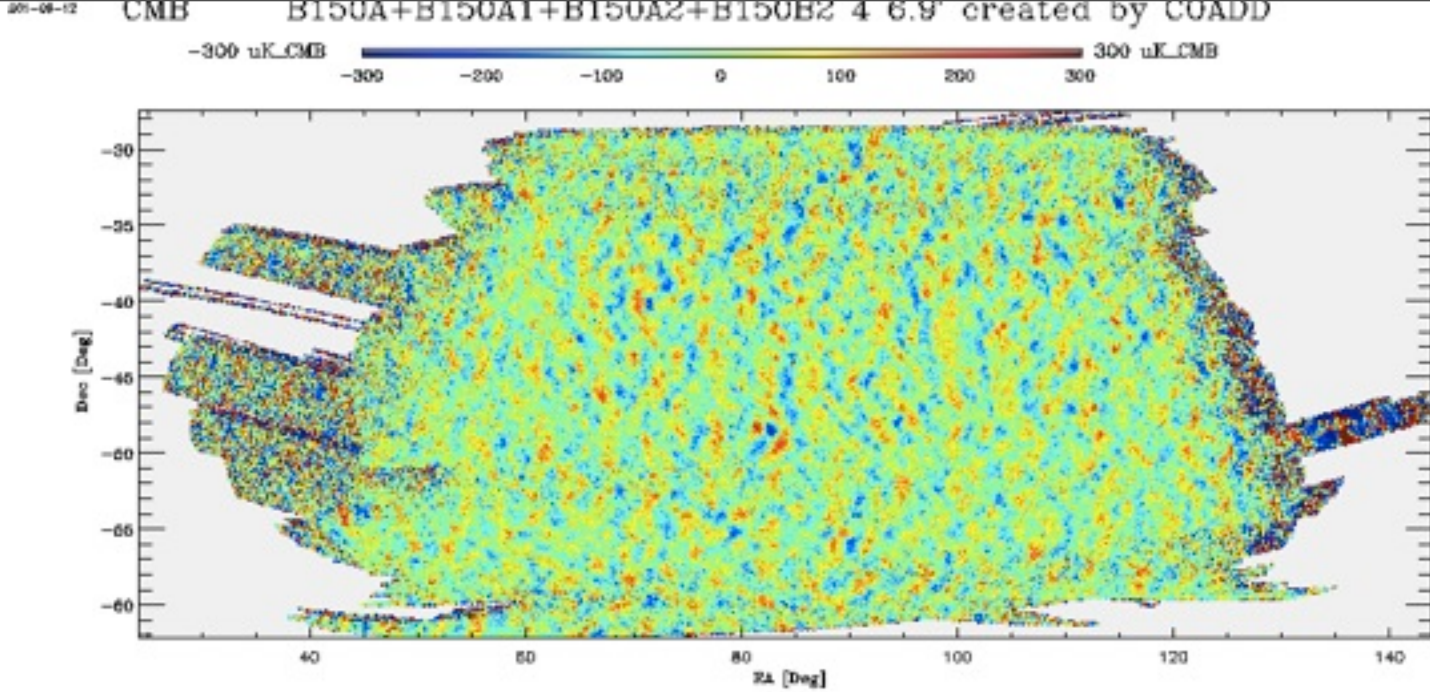

WMAP: 01Launch 03,
06,08, 10, 10end, 12
COBE
ACT
+WMAP7
2011
BOOM
2000
2005
WMAP

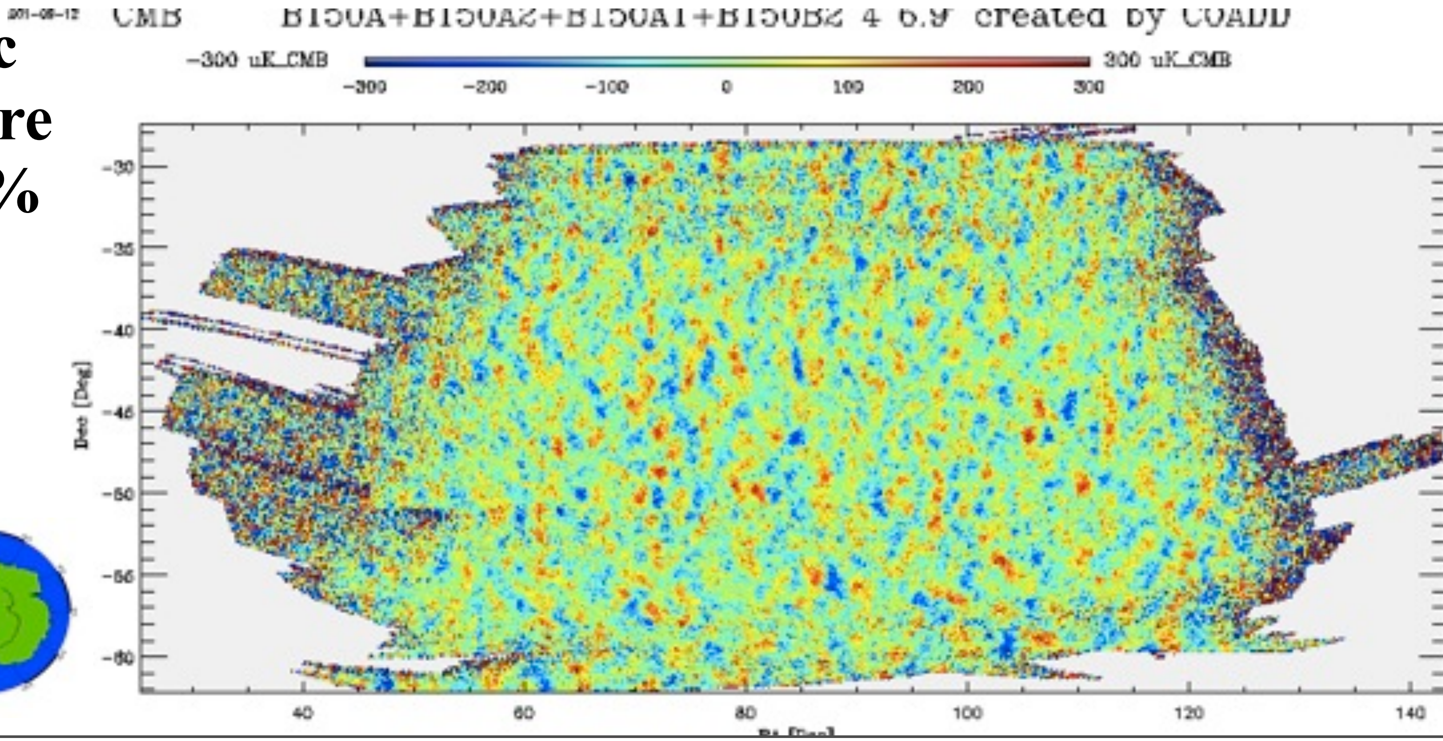
Boomerang98 @150GHz is (nearly) Gaussian:

Simulated vs Real

looks the same

pre-WMAP





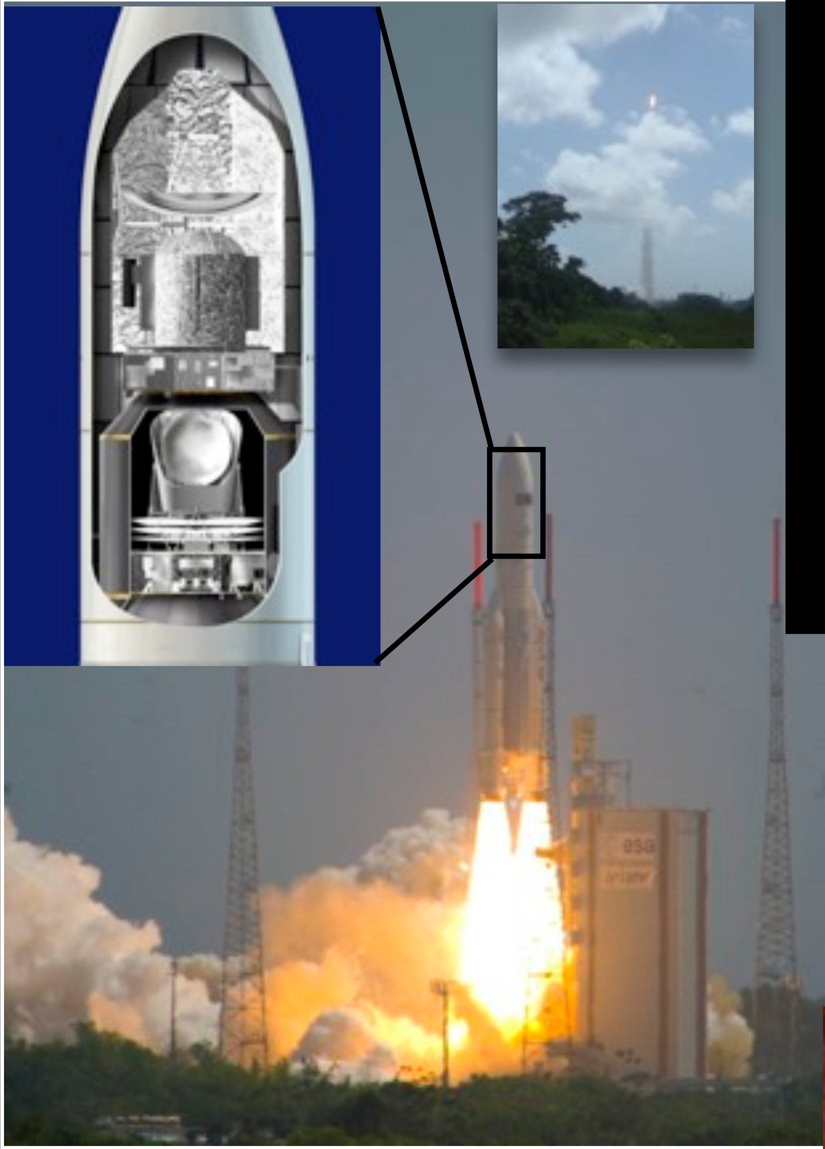
thermodynamic CMB temperature fluctuations 2.9% of sky DT~30

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 50 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency -- ESA -- with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

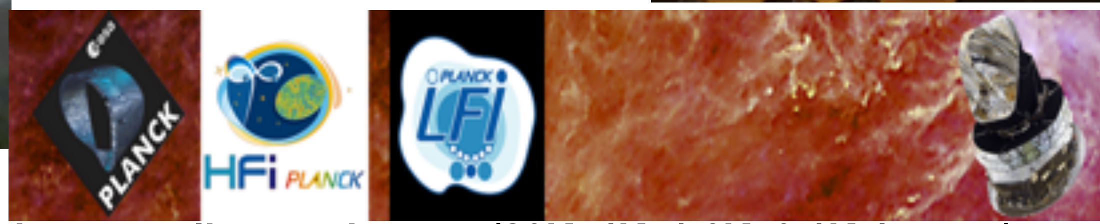
Bond since 1993, Canada since 2001, 1st CSA pre-launch contract 2002-09, post-launch 2010-11, 2011-13

Planck+Herschel Launch May14 09 Fr. Guiana



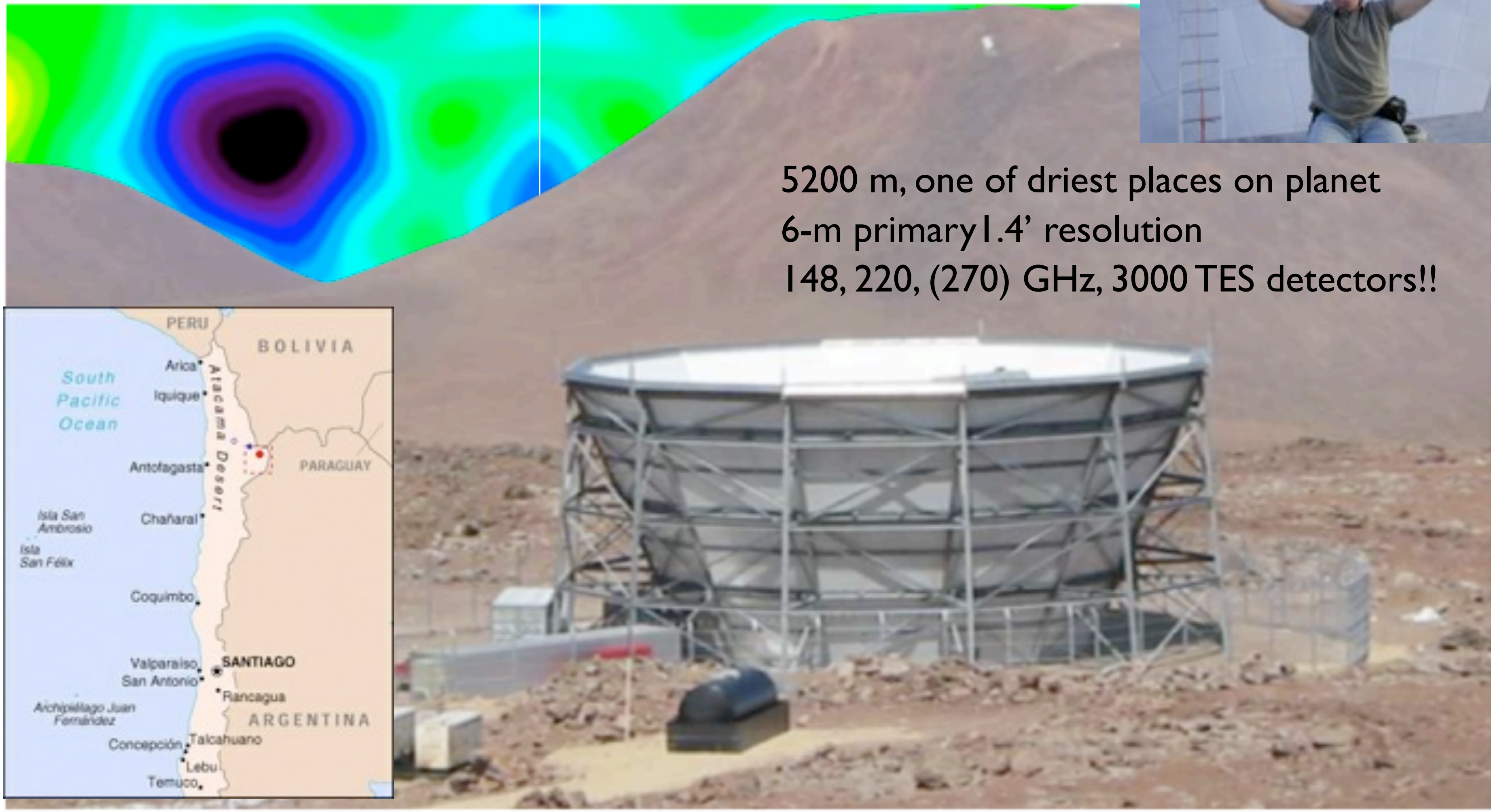
1.5m telescope, HFI bolometers @6freq <100mK, LFI HEMTs@3freq, some bolometers & all HEMTS are polarization sensitive

HFI+LFI **performance** to **spec** or better



Left earth at ~10 km/s, 1.5 million km in 45 days, cooling on the way (20K, 4K, 1.6K, 0.1K 4 stage). @L2 on July 2 09 -almost no trajectory correction @operational temp; Survey started on Aug 13 09 spin@1 rpm, 40-50 minutes on the same circle, covers all-sky in ~6 month, ~4 surveys Aug11, ~5 total

Cosmology From 5200 metres:
the Atacama Cosmology Telescope



5200 m, one of driest places on planet
6-m primary1.4’ resolution
148, 220, (270) GHz, 3000 TES detectors!!

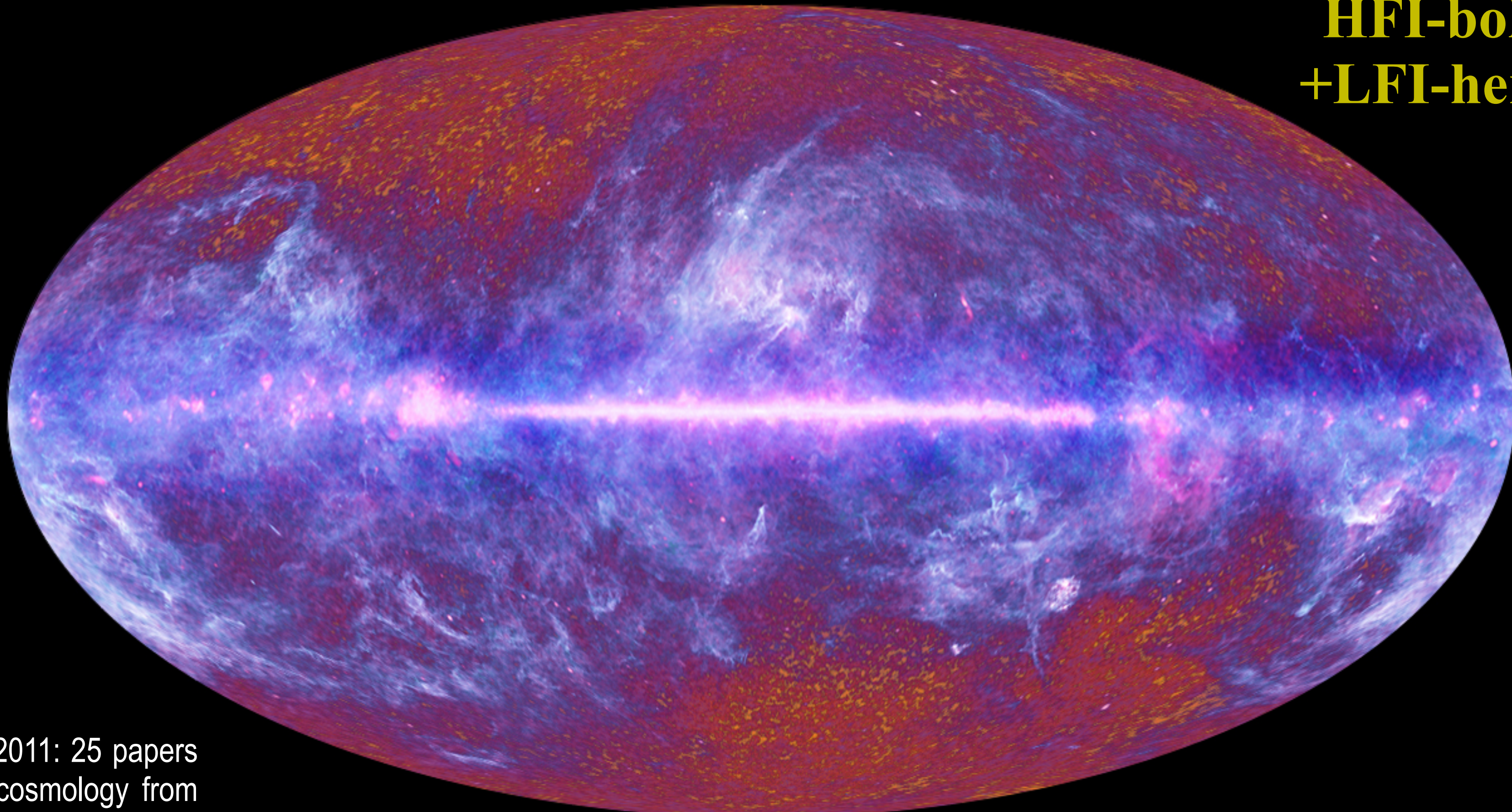
CMB@CITA: Boomerang, Acbar, CBI1,2, Planck, ACT, Spider, Blast, & ACTpol, ABS, QUIET90-2;
GBT-Mustang2, CARMA/SZA, SCUBA2, ALMA

Planck & ACT

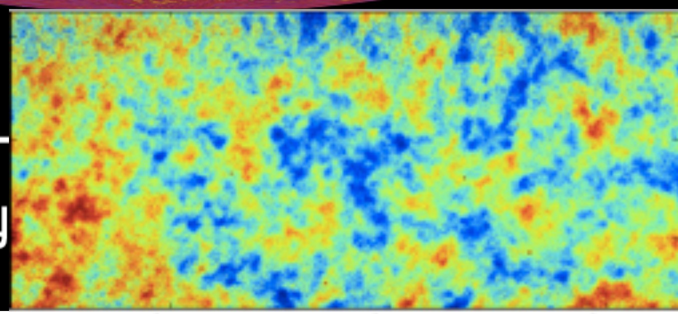
Dick Bond

7 veils(ν)+CMB

9 ν, pol,
HFI-bolos
+LFI-hemts



Jan 2011: 25 papers first cosmology from Planck early 2013, major pol early 2014



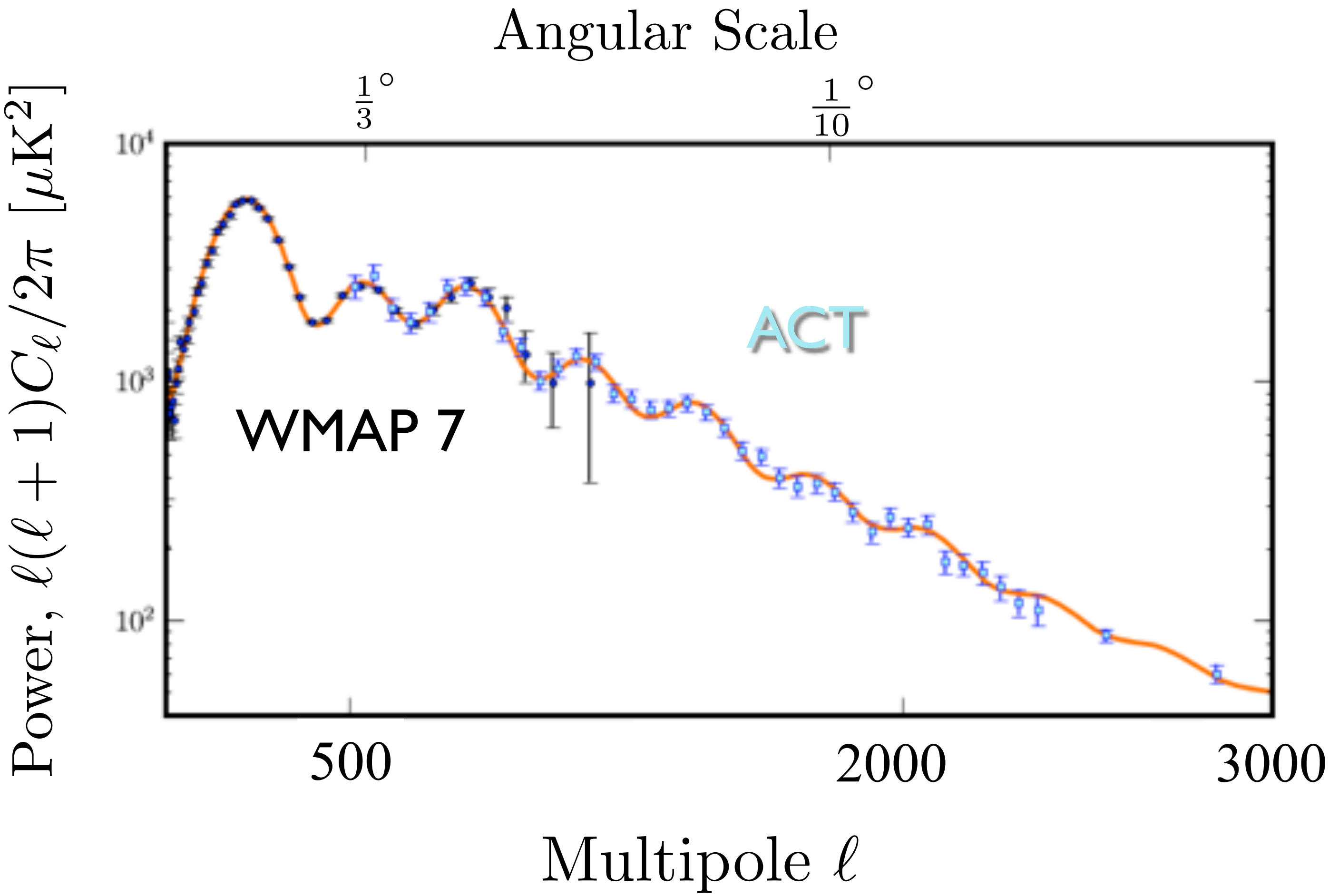
ACT+WMAP7 hajian+10

The Planck one-year all-sky survey

ESA, HFI and LFI consortia, July 2010

(radically) compress: ~0.3 PetaBits of the ~3000 detector timestreams from 3 years => 3 frequency maps, with noise variance, => isotropic Fourier/Y_{LM} -transformed temperature power spectra, ~8000 numbers + variances, => further bandpower compressed at high L

HIGH RESOLUTION POWER SPECTRUM from ACT: OLD



Das+ 2011, ApJ, 729:62, Hajian_2011, **Dunkley+.2011**, Hlozek+ 2011, Das+2011, Sherwin+2011, ..., **Sievers+2012**

tilted ΛCDM a very good fit (n_s constant); data are good enough to search for subdominant cosmic parameters N_ν, X_{He}, r, $dn_s/d\ln k$, $n_s(k)$ in bands, CMB lensing, .. & we have (strings, isocurvature,..)

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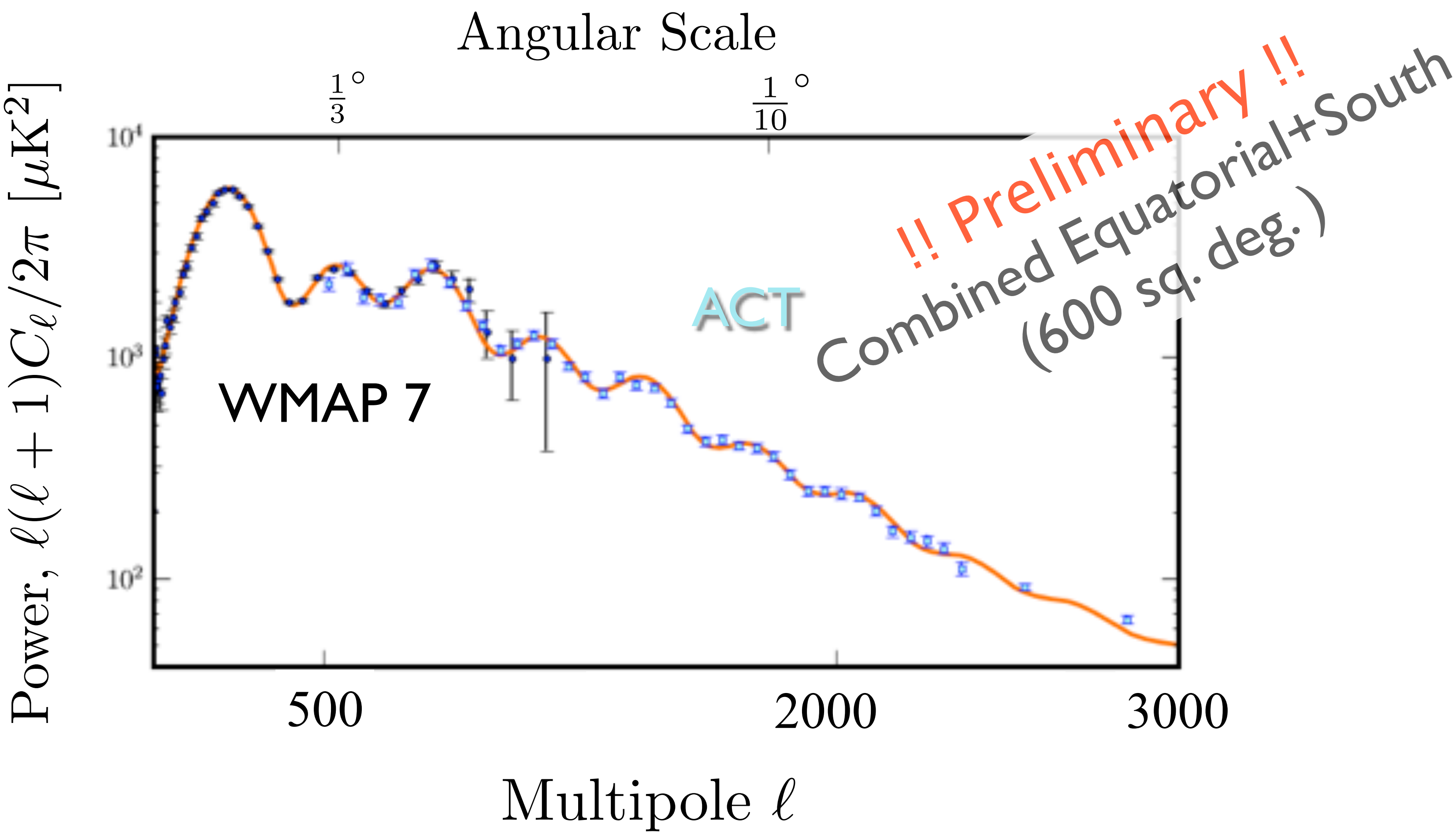
HIGH RESOLUTION POWER SPECTRUM from ACT: NEW



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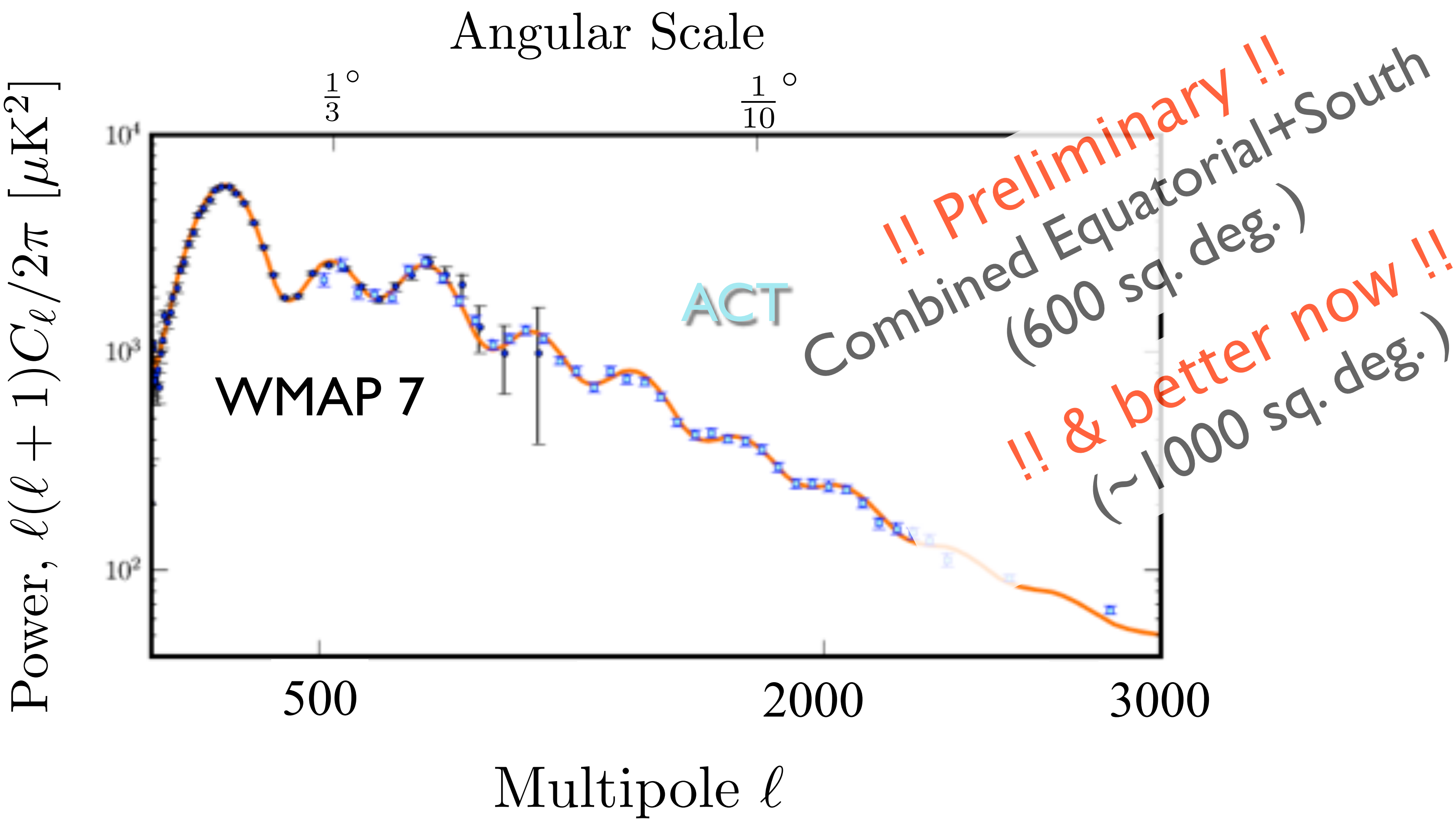

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CBI pol to Apr'05 @Chile CBI2

Quiet1 @Chile

Quiet2 1000 HEMTs

QUaD @SP

Boom03@LDB

Bicep @SP

Bicep2

Keck@SP

ABS@ Chile

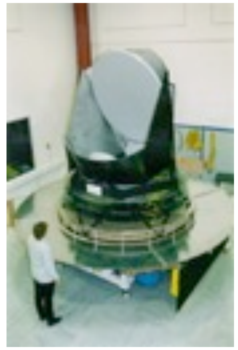
EBEX @LDB

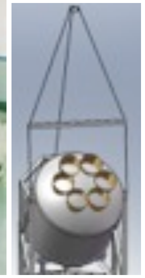
WMAP @L2 to 2010

Planck09.4

52 bolometers + HEMTs @L2

9 frequencies





Spider

2312 bolos @LDB

DASI @SP

CAPMAP

Herschel

2013

BLAST

Pixie/ COrE/ LiteBird @space

2004 2006 2008 LHC 2011

2005 2007 2009

SPT

1000 bolos @SPole

BLASTpol

Piper

Acbar to Jan'06, 08f @SP

SZA @Cal

Polarbear @Chile

ACT

3000 bolos

3 freqs @Chile

SPTpol

AMI

APEX

~400 bolos @Chile

ACTpol

SCUBA2

12000 bolos

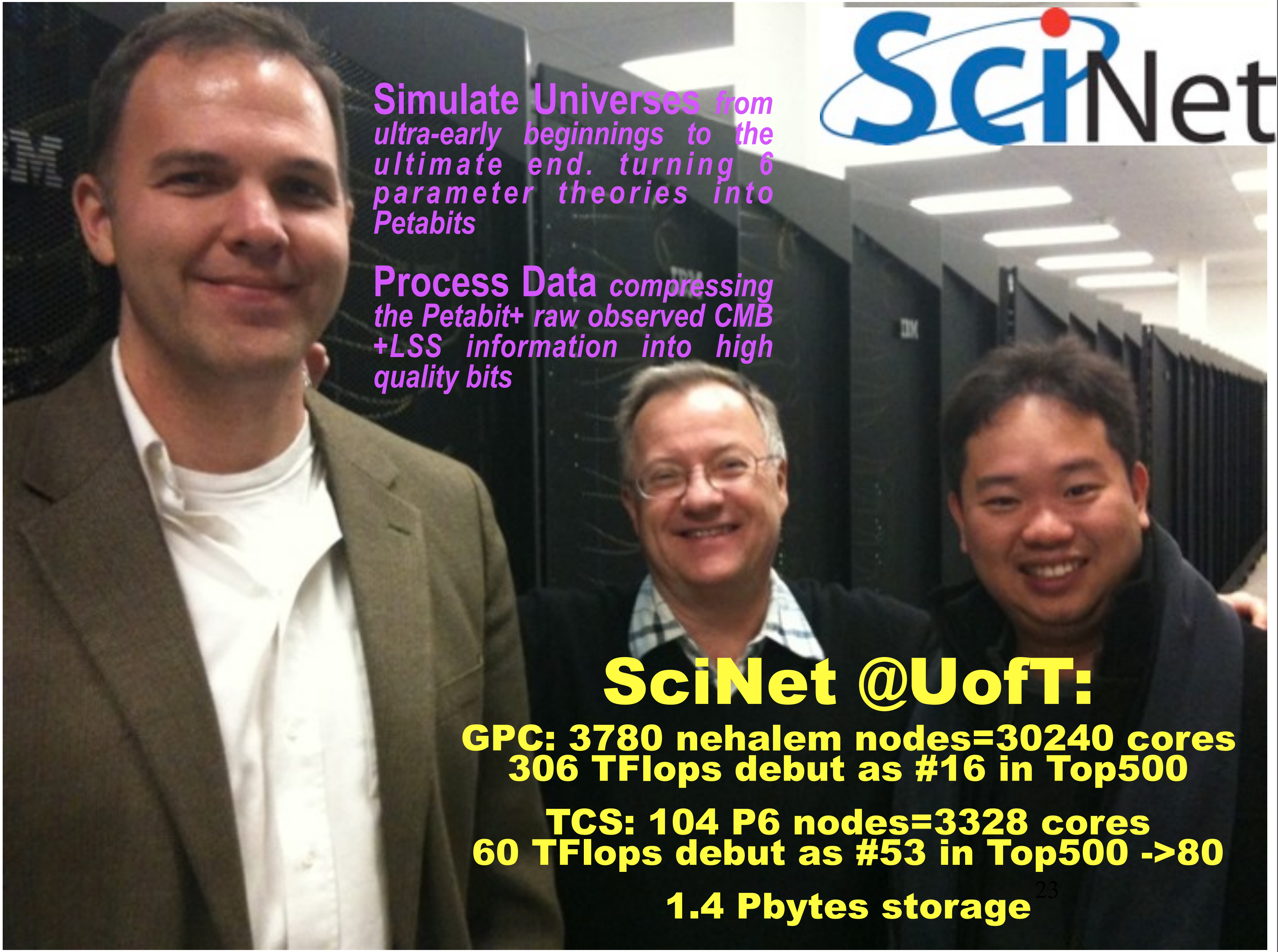
JCMT @Hawaii

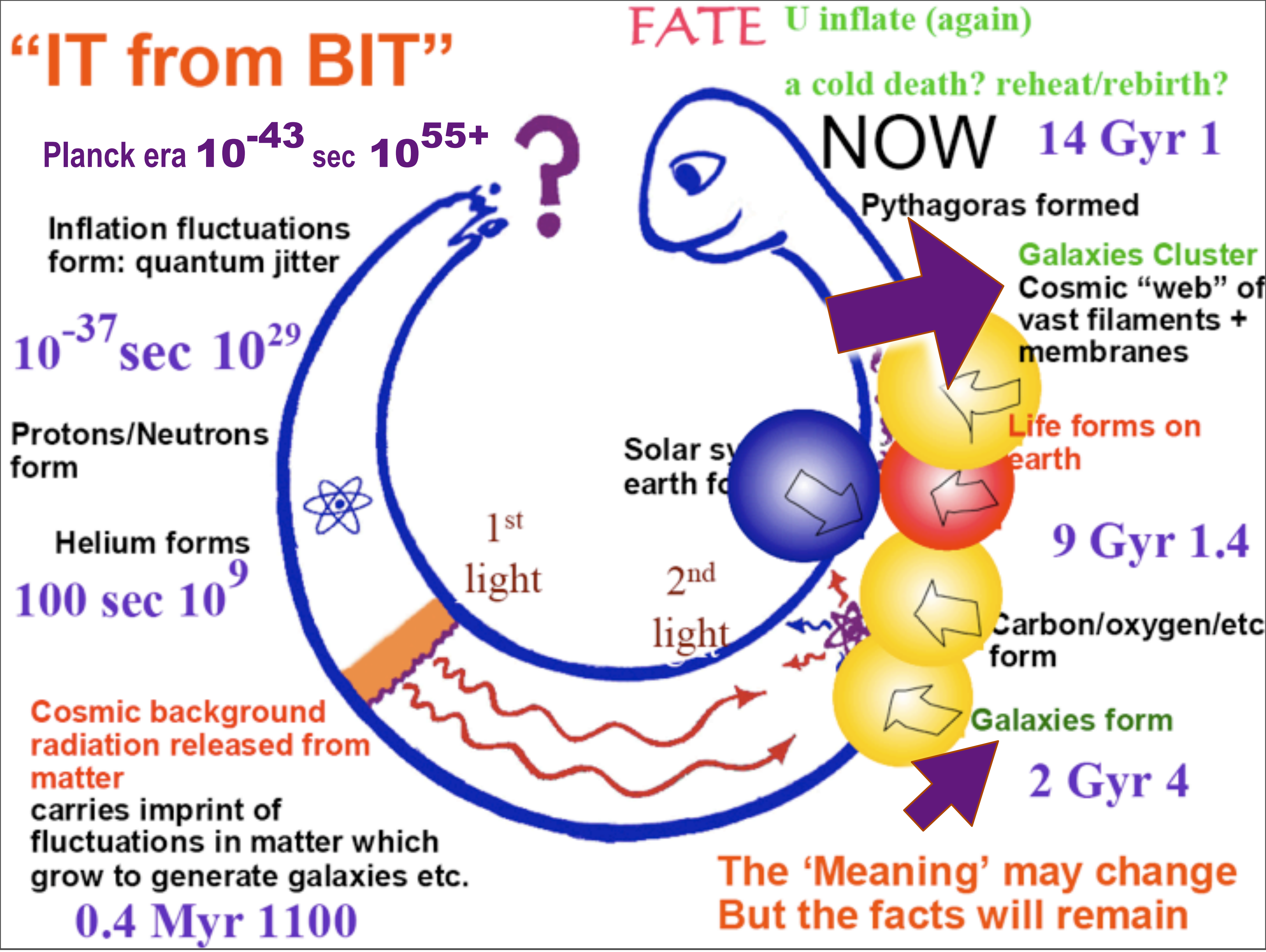
ALMA

GBT

CCAT@Chile

LMT@Mexico


SciNet
Simulate Universes from ultra-early beginnings to the ultimate end. turning 6 parameter theories into Petabits
Process Data compressing the Petabit+ raw observed CMB +LSS information into high quality bits
SciNet @UofT:
GPC: 3780 nehalem nodes=30240 cores
306 TFlops debut as #16 in Top500
TCS: 104 P6 nodes=3328 cores
60 TFlops debut as #53 in Top500 ->80
1.4 Pbytes storage
23


"IT from BIT"
FATE
U inflate (again)
a cold death? reheat/rebirth?
Planck era 10^{-43} sec 10^{55+}
?
NOW
14 Gyr 1
Pythagoras formed
Inflation fluctuations form: quantum jitter
Galaxies Cluster
Cosmic "web" of vast filaments + membranes
10^{-37} sec 10^{29}
Life forms on earth
Protons/Neutrons form
Solar sy earth fo
9 Gyr 1.4
1^{st} light
Helium forms
100 sec 10^{9}
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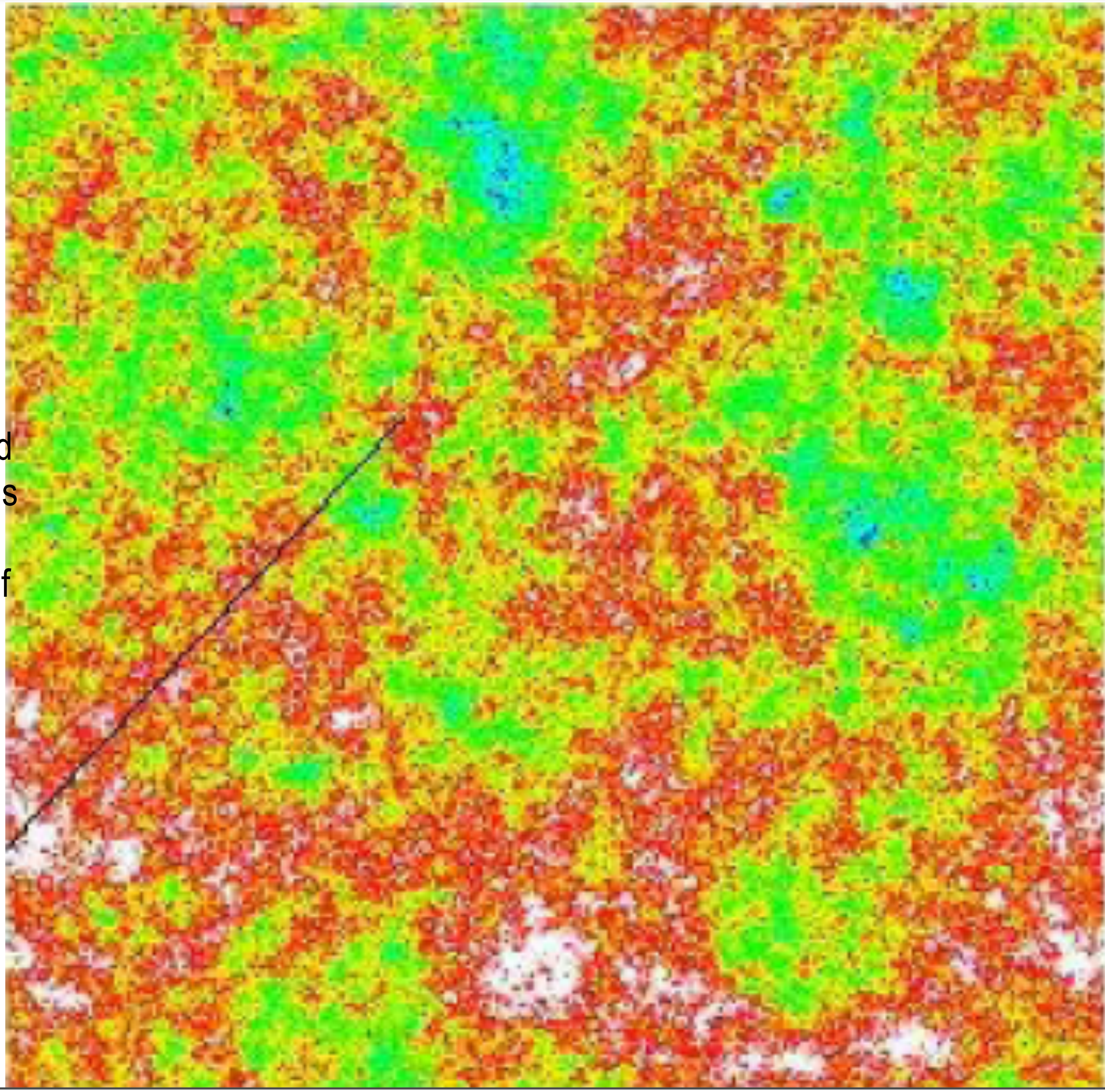
Galaxies form
Cosmic background radiation released from matter carries imprint of fluctuations in matter which grow to generate galaxies etc.
2 Gyr 4
The 'Meaning' may change But the facts will remain
0.4 Myr 1100

fluctuations in the **early universe “vacuum” grow** to *all* **structure**

χ

scalar field fluctuations in the vacuum of the ultra-early Universe

pre-heating patch (~1cm)



10 Gpc

$\chi(\mathbf{x}, \ln \mathbf{a})$

$\ln \mathbf{a}(\mathbf{x}, \ln \mathbf{H})$

evolve from early U vacuum potential and vacuum noise

fluctuations in the **early universe "vacuum" grow** to *all* **structure**

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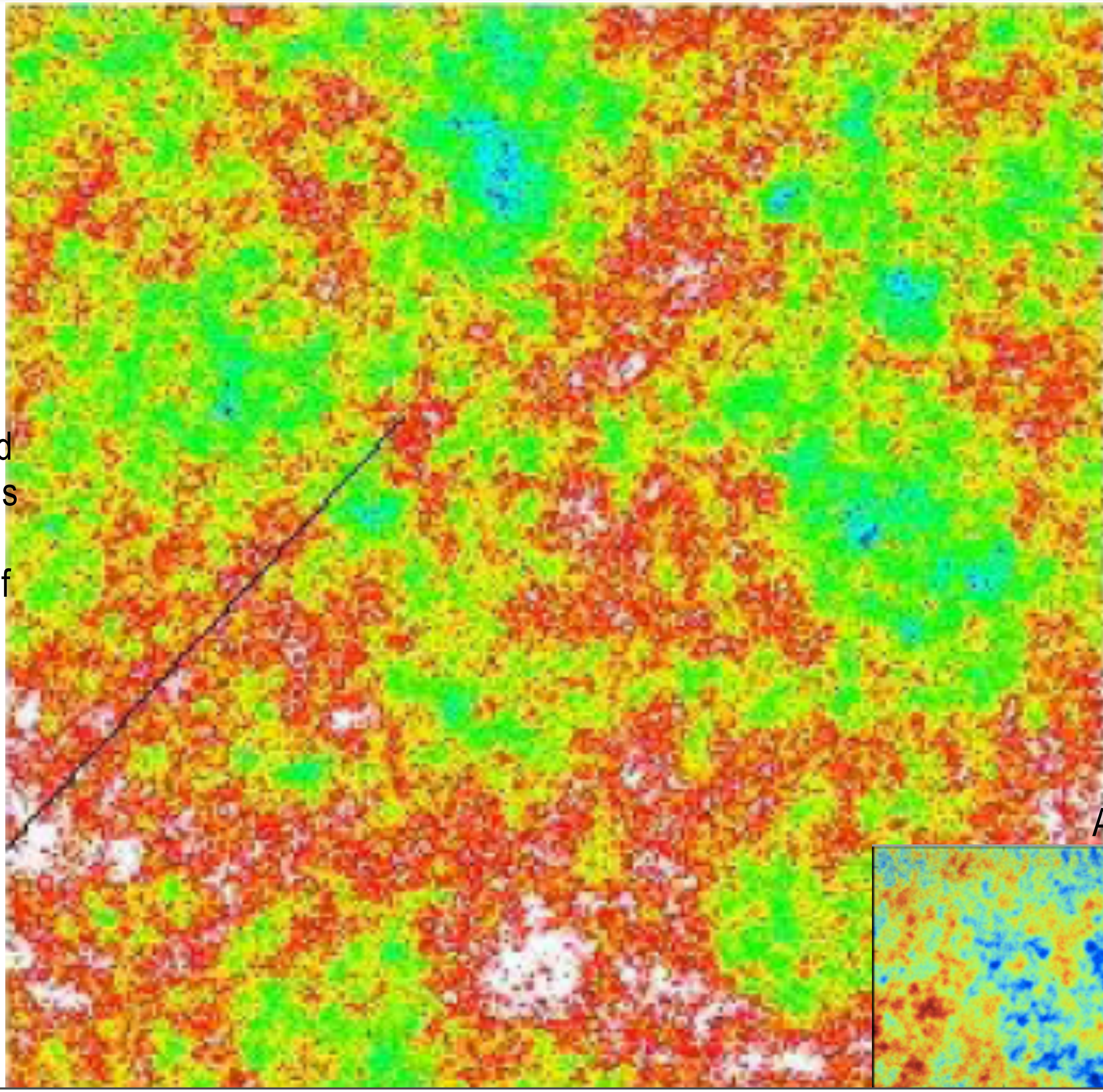
$\ln a(x, \ln H)$



scalar field fluctuations in the vacuum of the ultra-early Universe

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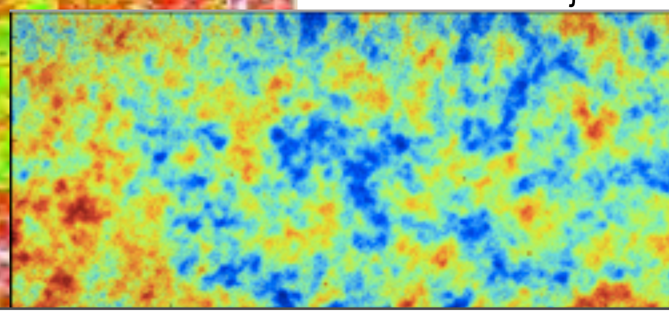
evolve from early U vacuum potential and vacuum noise

aetherial!

ACT+WMAP7 hajian+10



fluctuations in the **early universe "vacuum" grow** to *all* **structure**

400 Mpc

ΛCDM

WMAP5

gas density

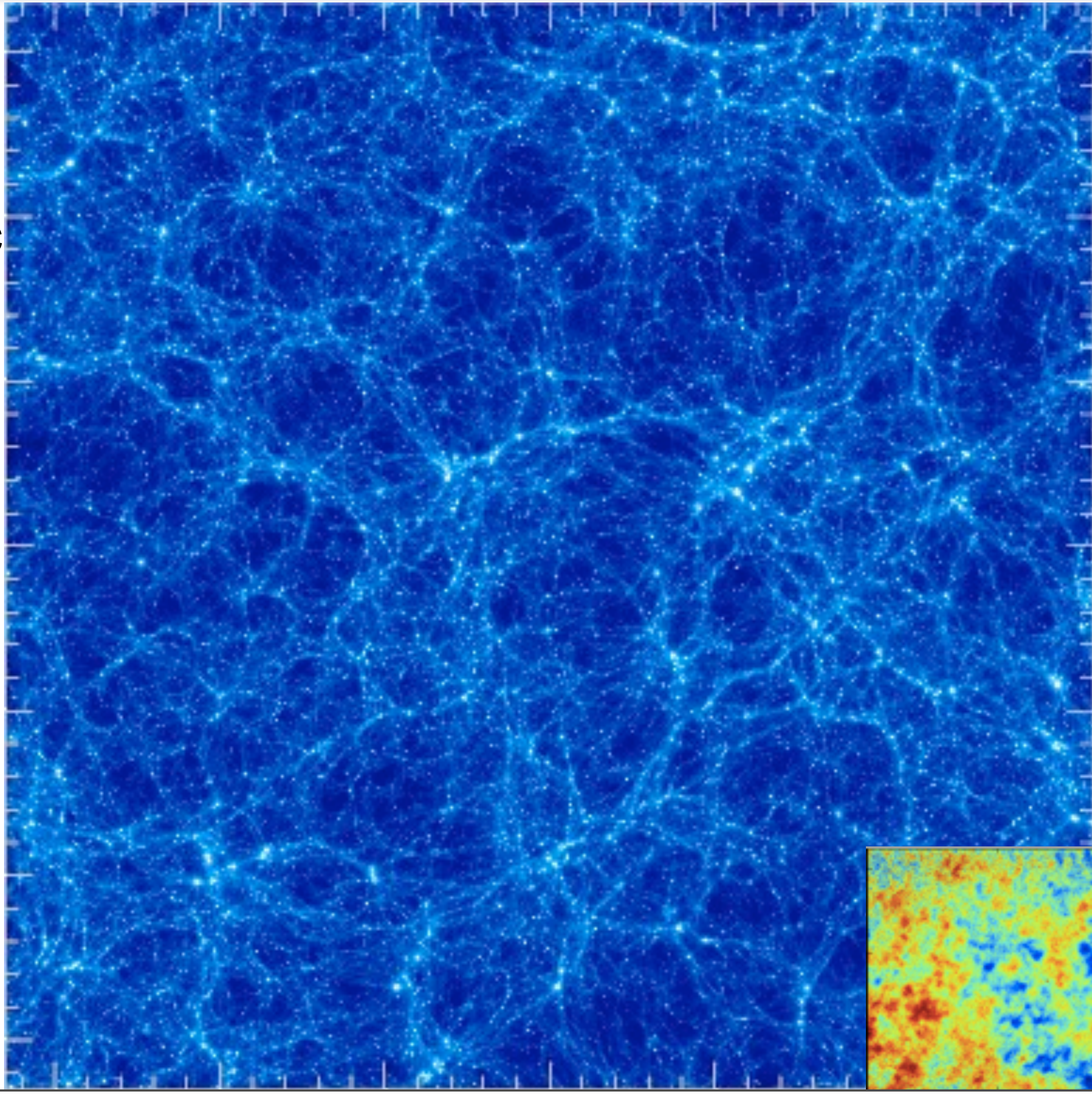
Gadget-3

SF+ SN E+ winds +CRs

512^3

BBPSS10

BBPS1,2,3,4

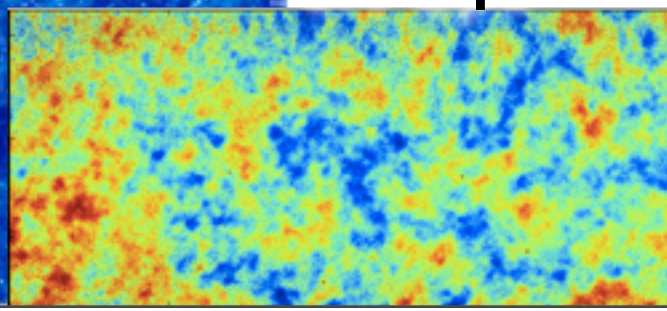


$\rho_g(x,t)$

evolve from early U vacuum potential and vacuum noise

in the presence of late U vacuum potential aka dark energy

0.4 Gpc



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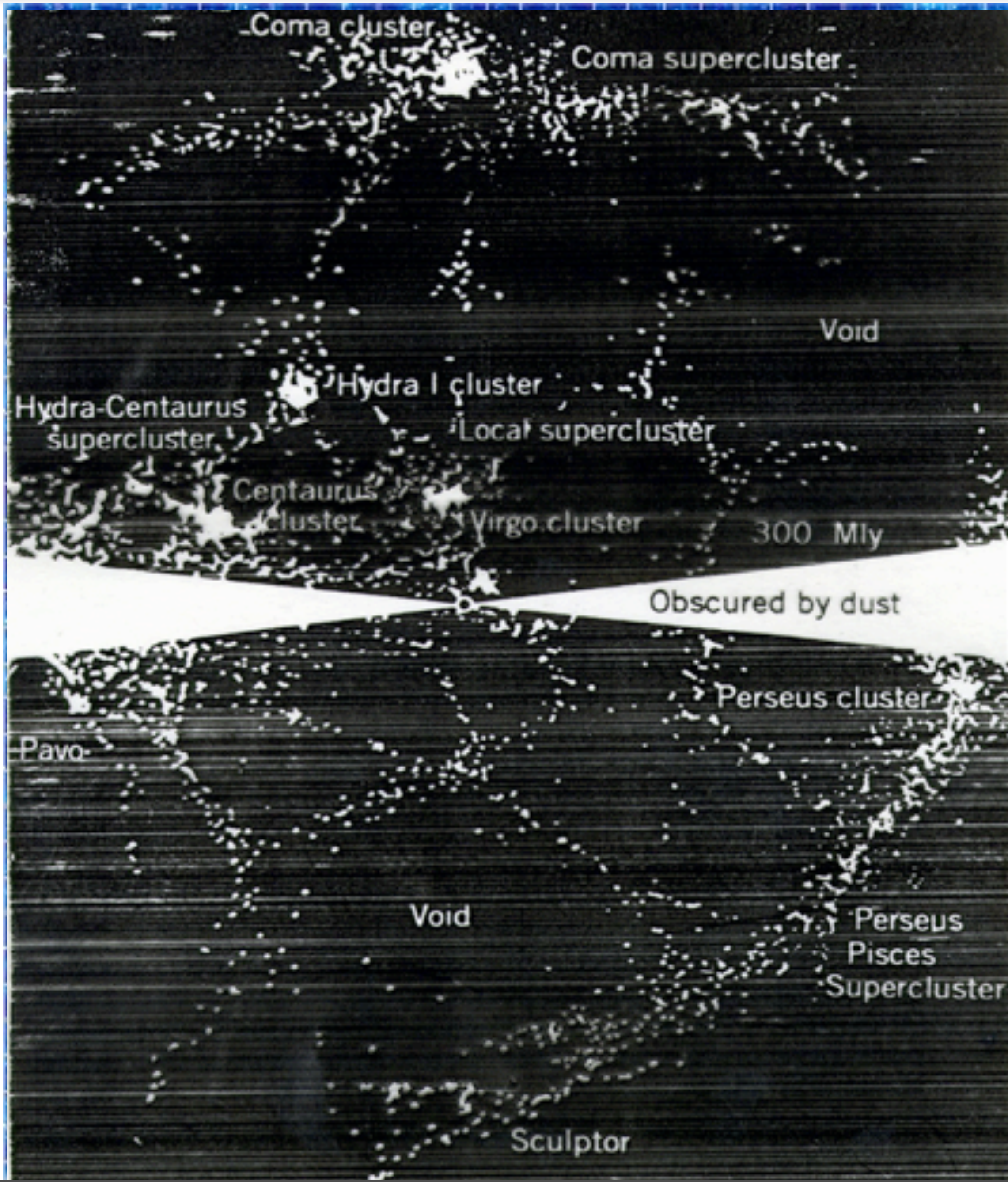

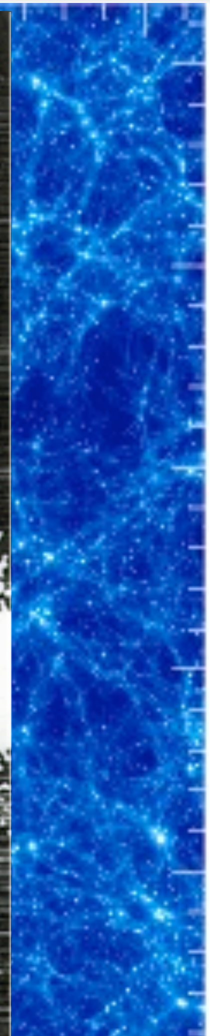

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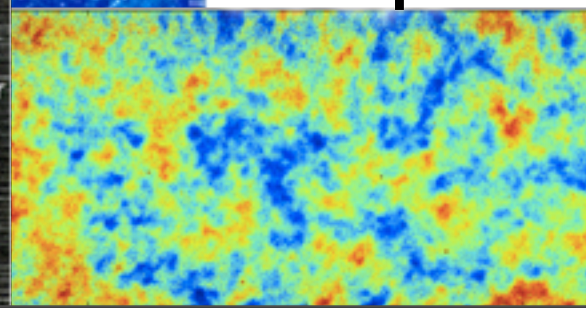


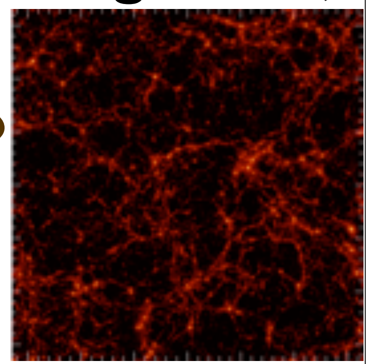
dS/dt 2

how most of the entropy in baryons & dark matter was generated

strain waves break => clusters/groups (galaxies/dwarfs) in the cosmic web collapse => shocked gas & extreme nonlinear phase space entanglement of dark matter / stars

then the baryons feed back entropy: exploding stars, accreting black holes, dusty radiation,

... who, what, where,when, why?



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

morphs *into the nonlinear* ***Cosmic Web: clusters, filaments, voids; galaxies*** (SZ)

gastrophysical simulations with feedback from AGN / starbursts / SN .. confront CMB+LSS data

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

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

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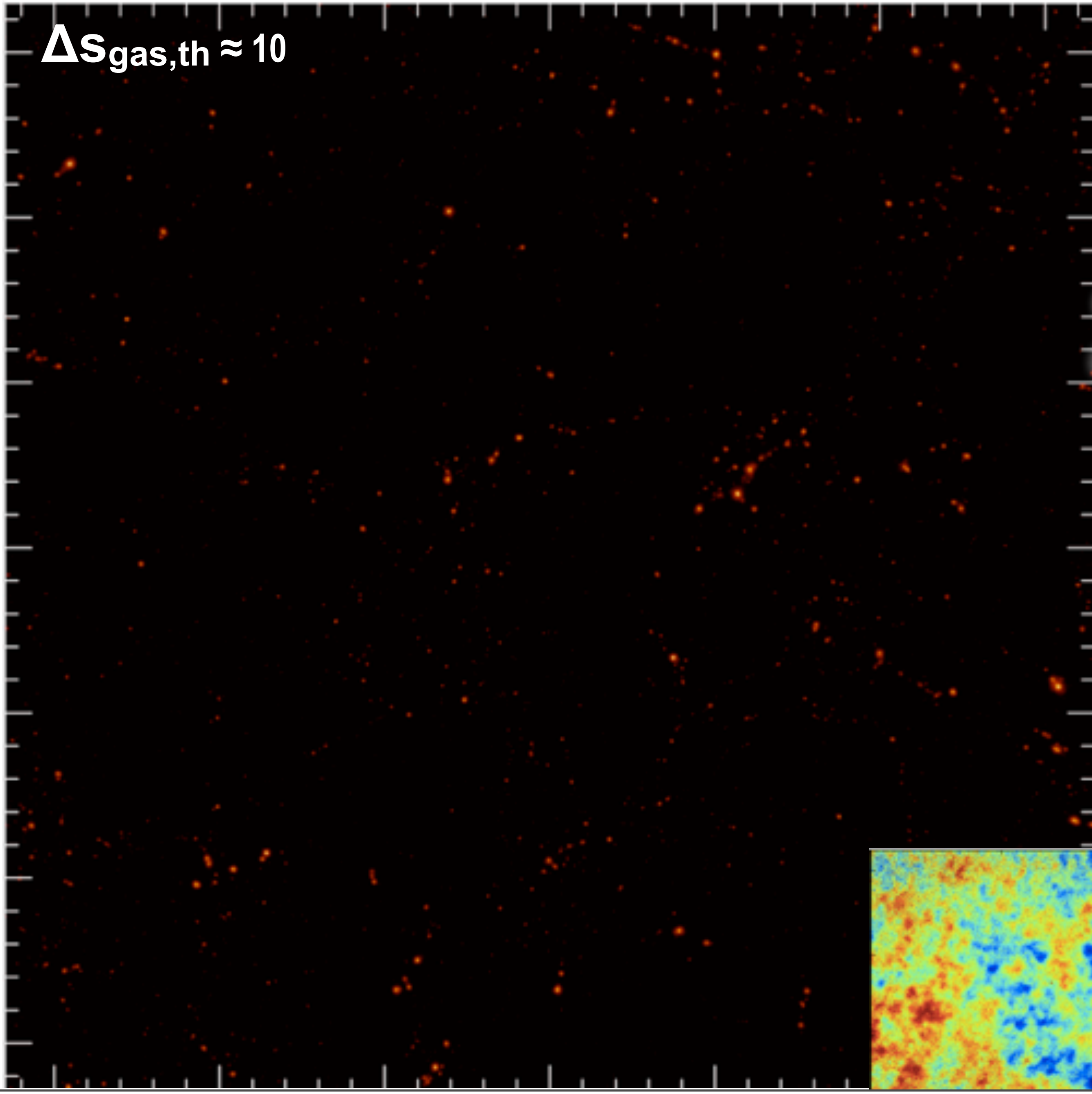


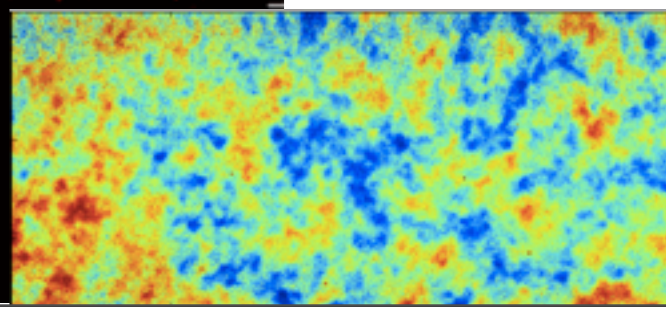
$s_{b,th}(x,t)$

CMB gets entangled in the cosmic web

descending into the real gastrophysics of cosmic weather

the energetic, turbulent, dissipative, compressive

life of the IGM/ICM/ISM



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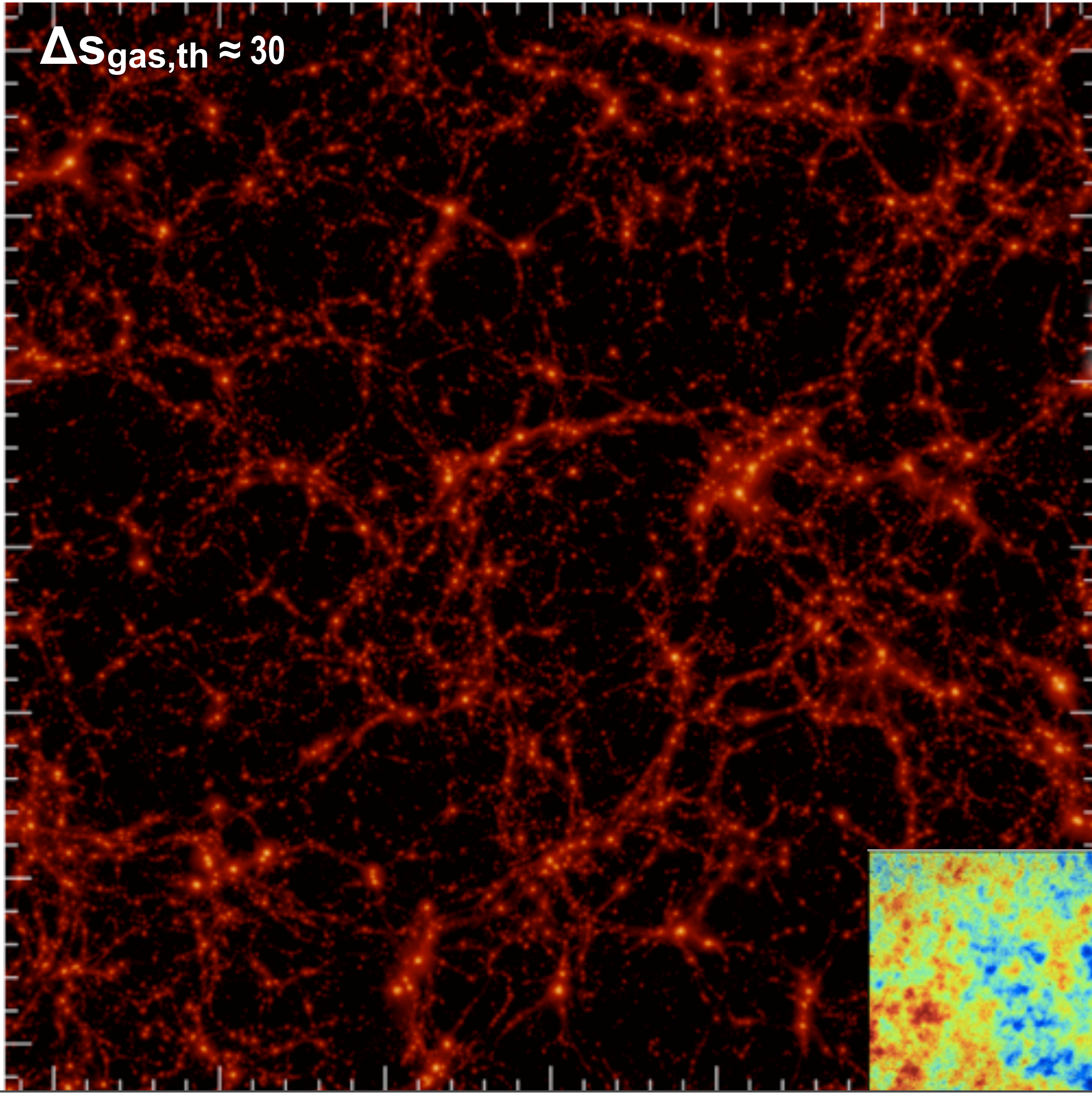

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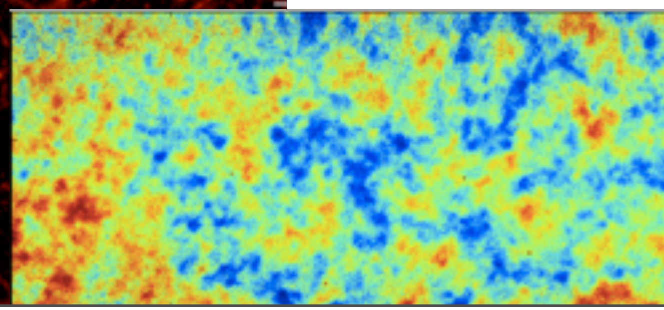

pressure intermittency *in the cosmic web, in cluster-group concentrations probed by* **tSZ**

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

400
Mpc

ΛCDM

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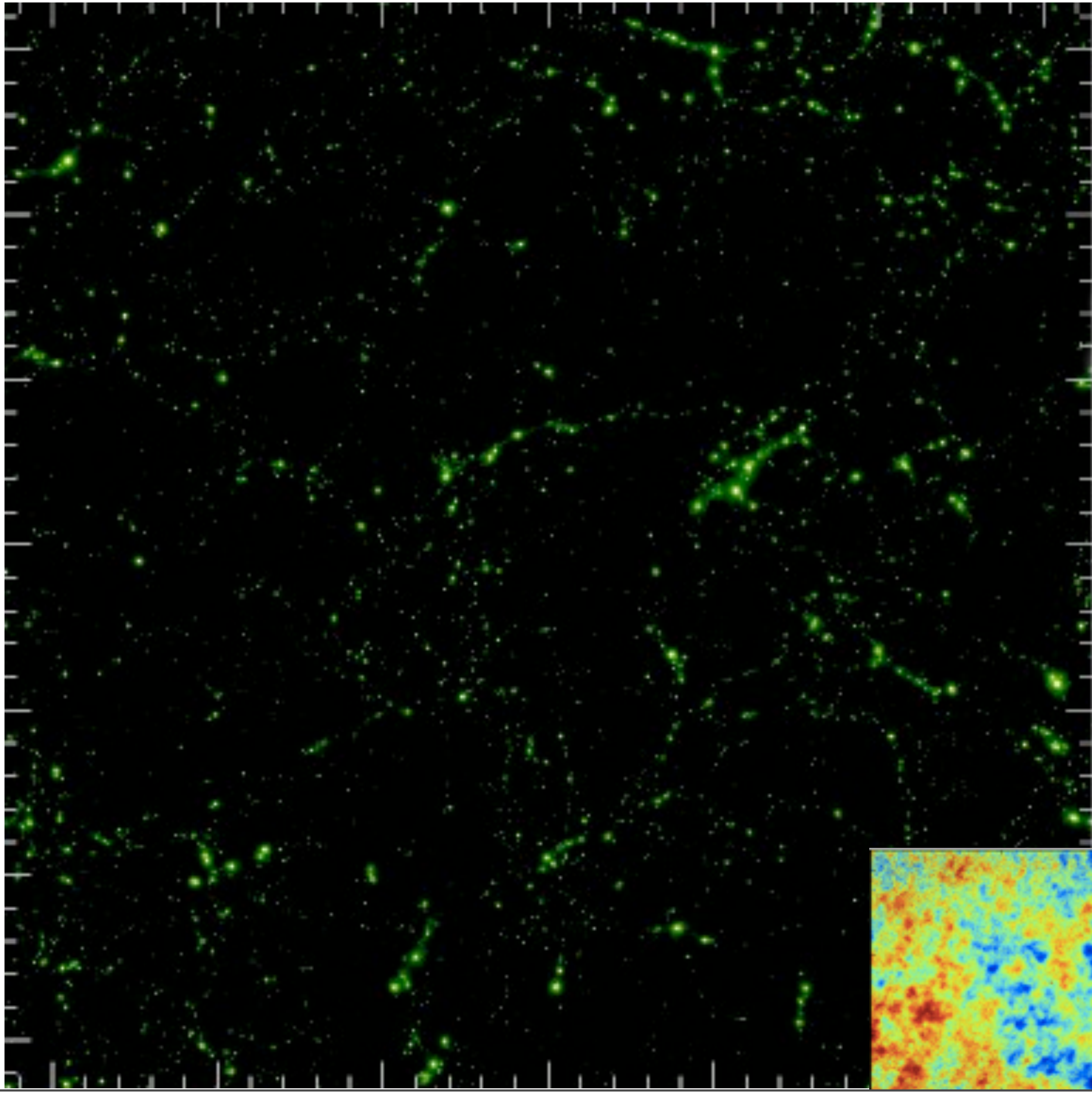

$p_e(x,t)$

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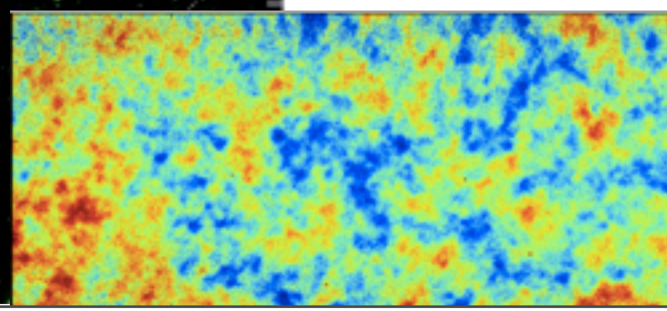
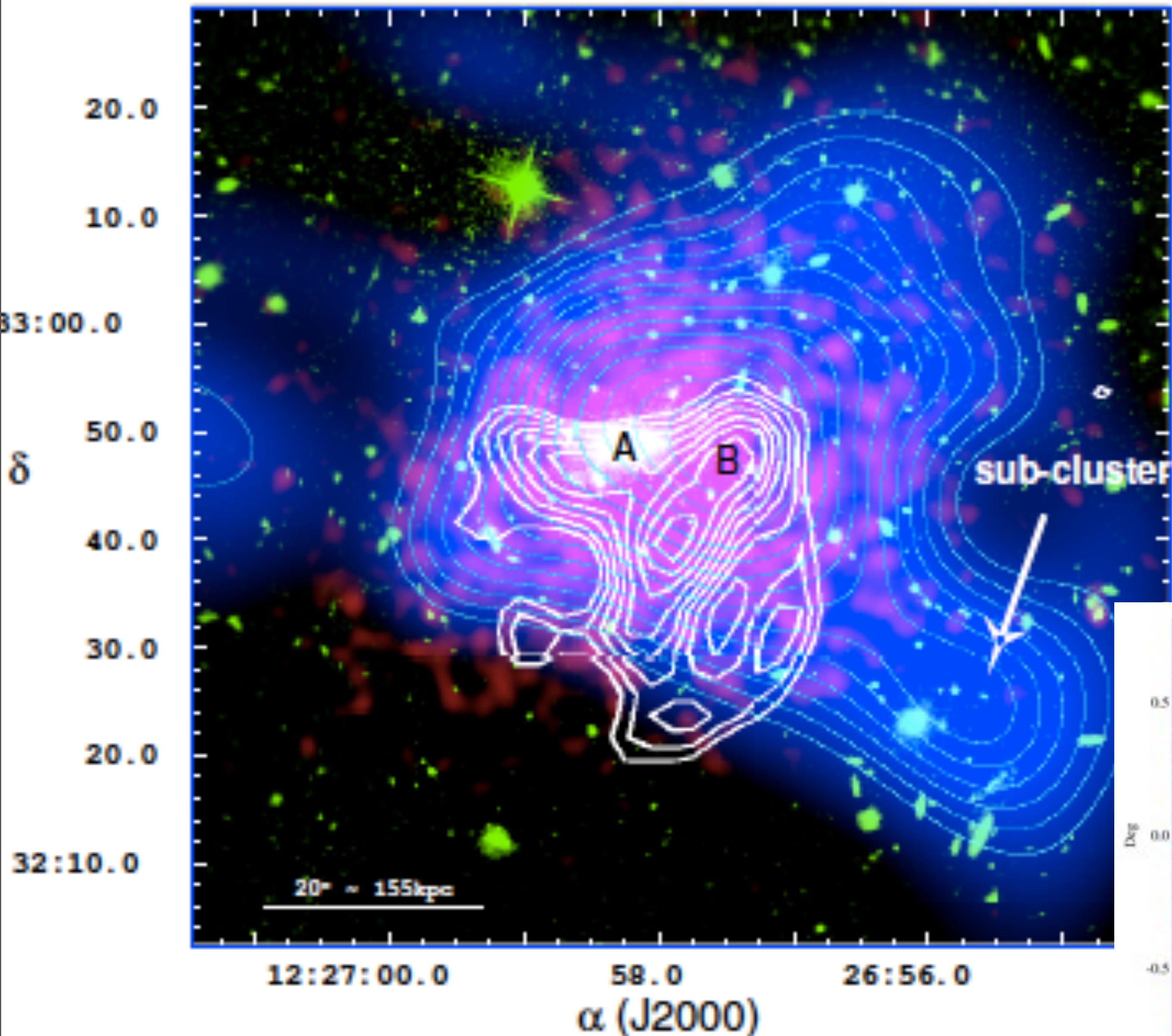


Mustang on GBT 90 GHz 64 bolometer array Imaging SZ @~10" res 4 cls 2010, ~25 Hubble CLASH cls to come Devlin, Mason, ...



real

CL1226 z=0.89

Red Chandra

Blue/cyan weak lens Σ

Green optical

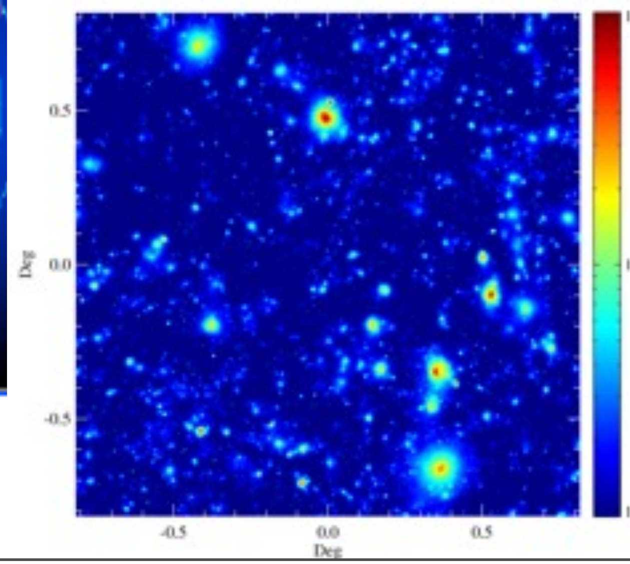
White MUSTANG SZ >3σ

A BCG ~ X-ray peak

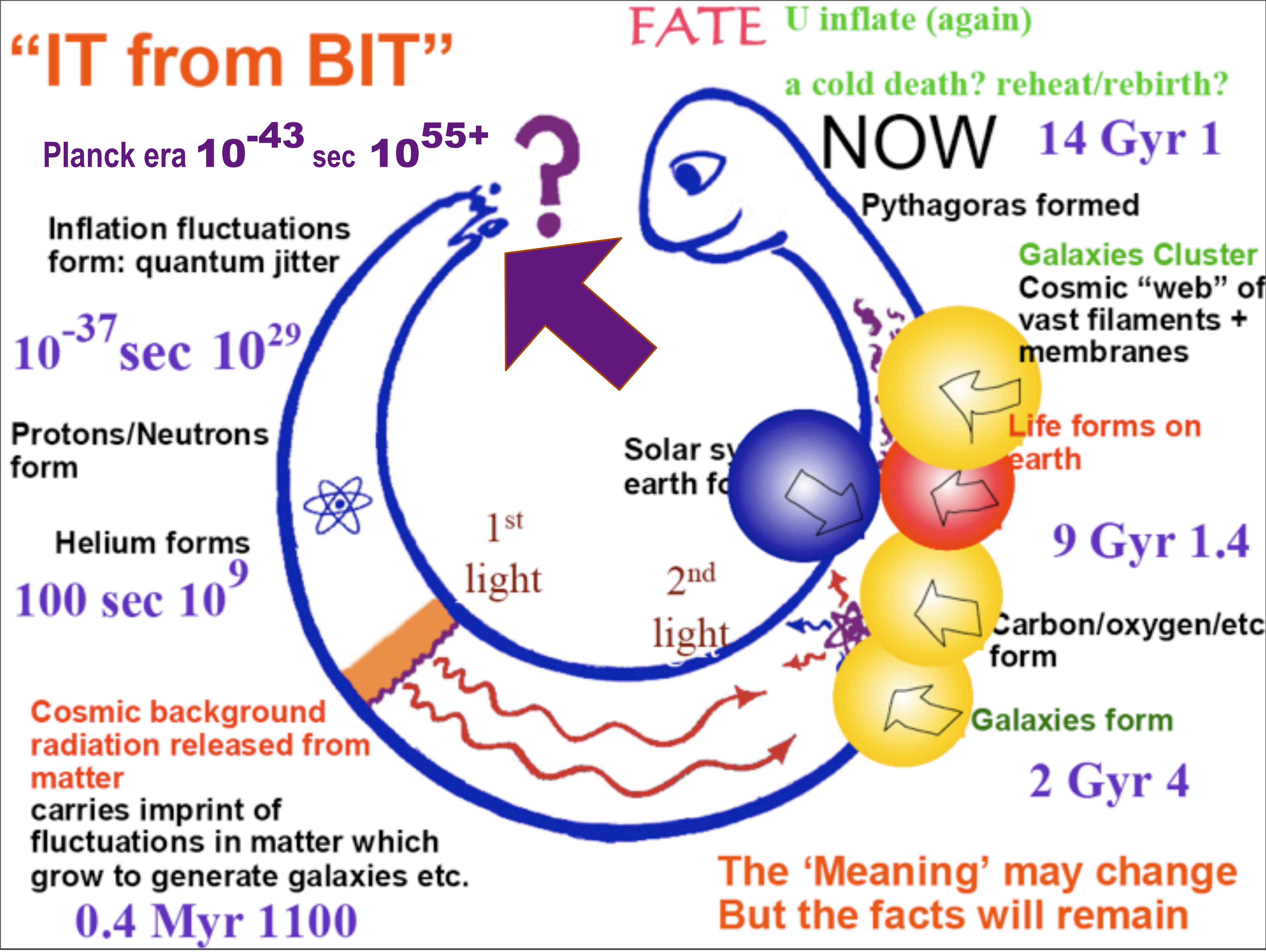
B Dark Matter peak

~ lobe of SZ ridge

simulation



2011 Planck ~200 clusters, SPT ~50 cls, ACT ~50 cls; 2013 1000's



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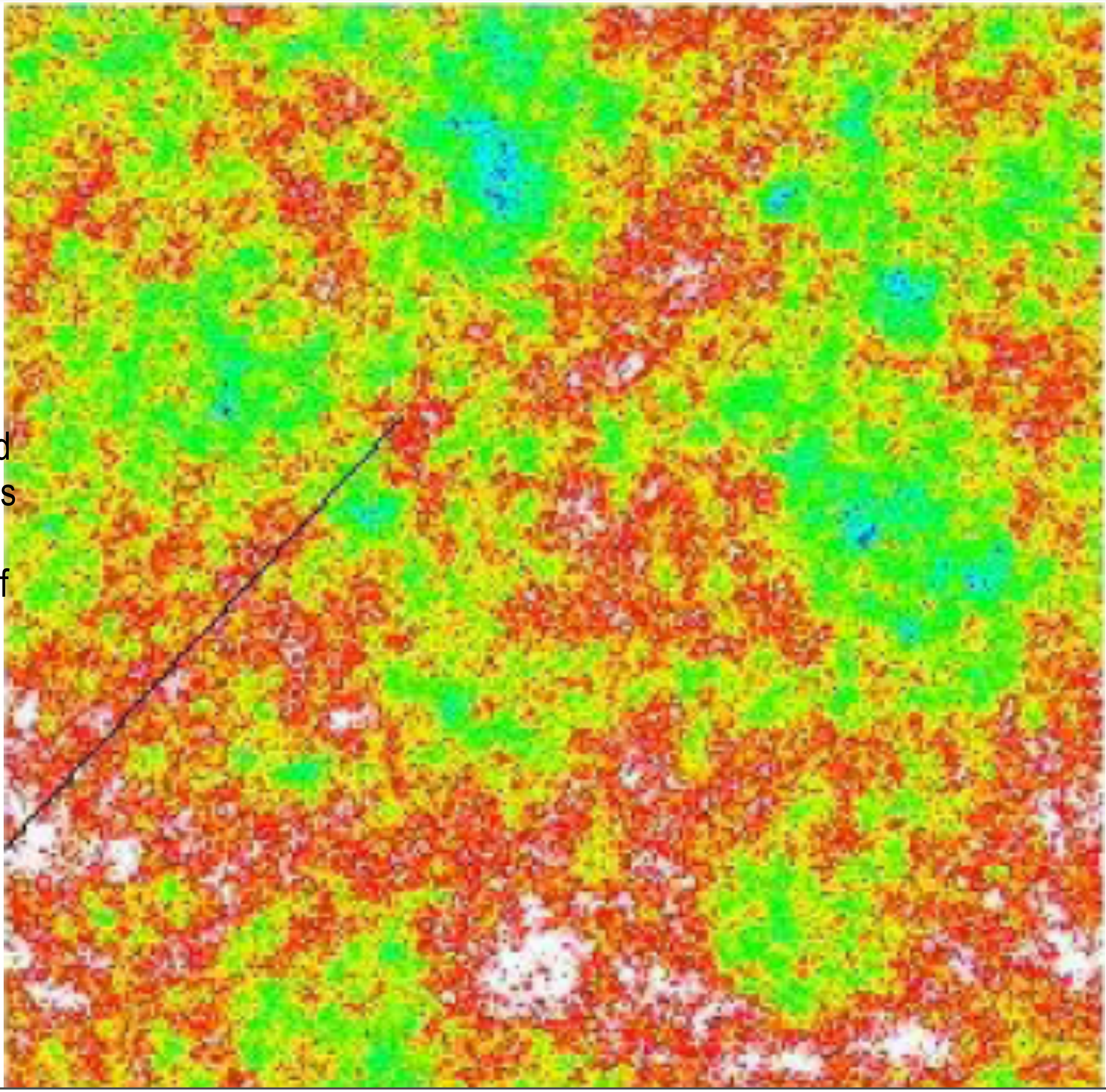


pre-heating patch (~1cm)

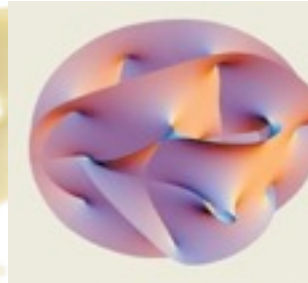
10 Gpc

$\chi(\mathbf{x},\ln a)$

$\ln a(\mathbf{x},\ln H)$

evolve from early U vacuum potential and vacuum noise

Roulette Inflation: *a statistical mini - landscape (one of very many) of the early U origins of observed cosmic structure:*



holey U: sizes/shapes of geometrical structures such as holes in a dynamical extra-dimensional (6-7D) space settling into a stable bit of extra-dim at each point in our 3D space;

braney U: *motions of lower-dimension subspaces*

pre-heating patch (**<1cm**-now, **<10^{-30} cm**-then)

semi ETERNAL INFLATION

quantum diffusion

spatial jitter

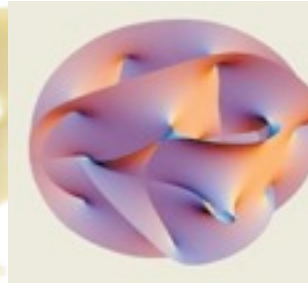
drift

let there be

heat

www.youtube.com/watch?v=FW__su-W-ck&NR=1

Roulette Inflation: ***a statistical mini - landscape (one of very many) of the early U origins of observed cosmic structure:***



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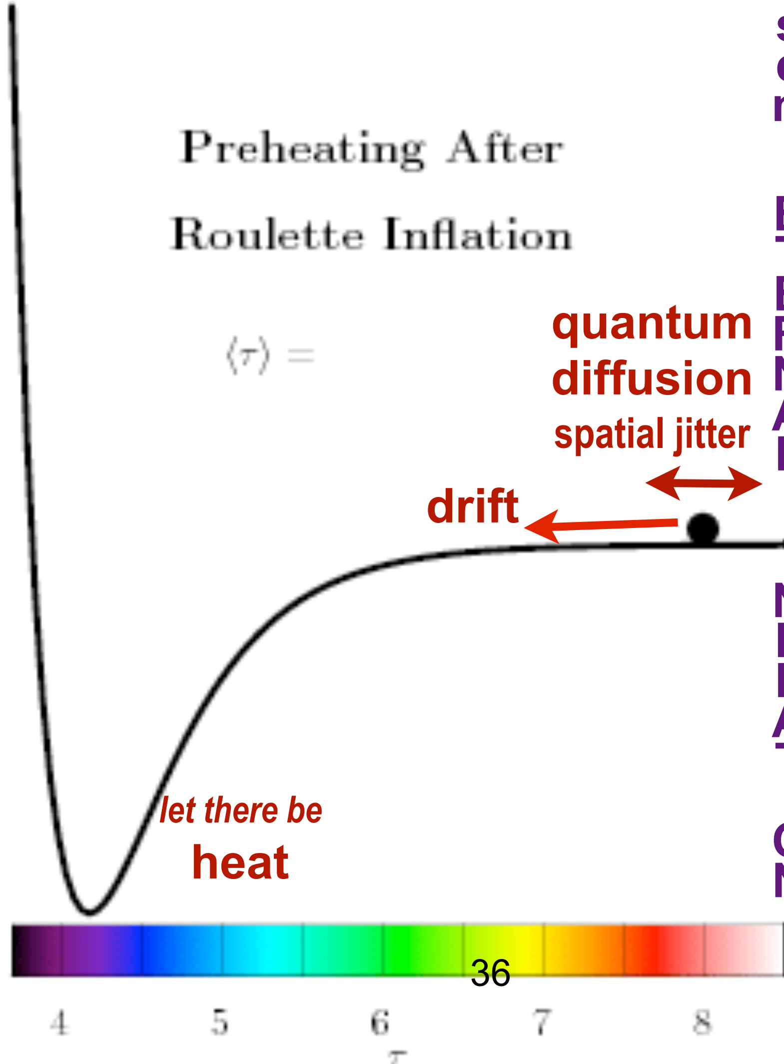
Preheating After

Roulette Inflation

A visualized 2D slice

in lattice simulation



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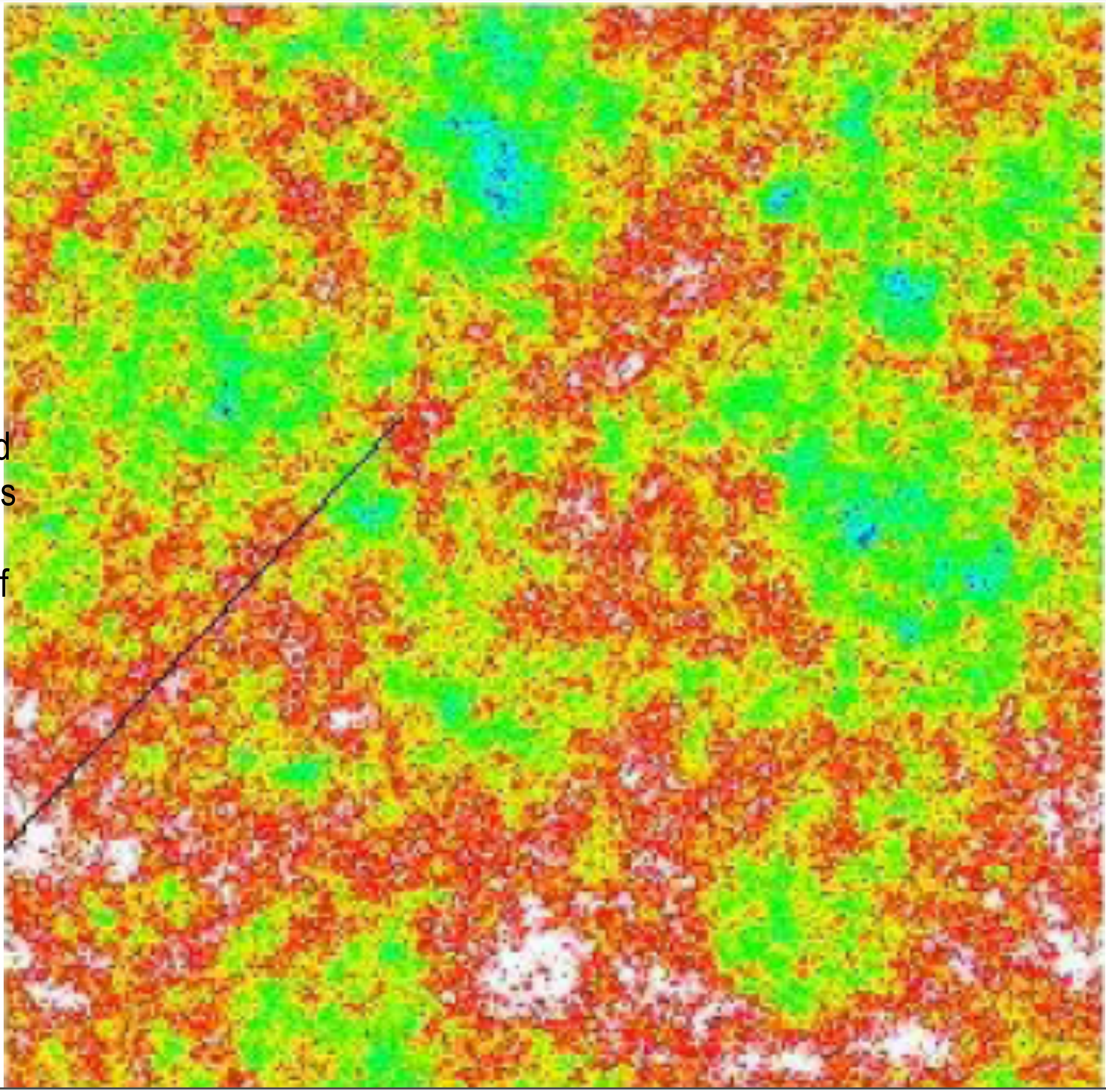

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$\ln \mathbf{a}(\mathbf{x}, \ln \mathbf{H})$

evolve from early U vacuum potential and vacuum noise

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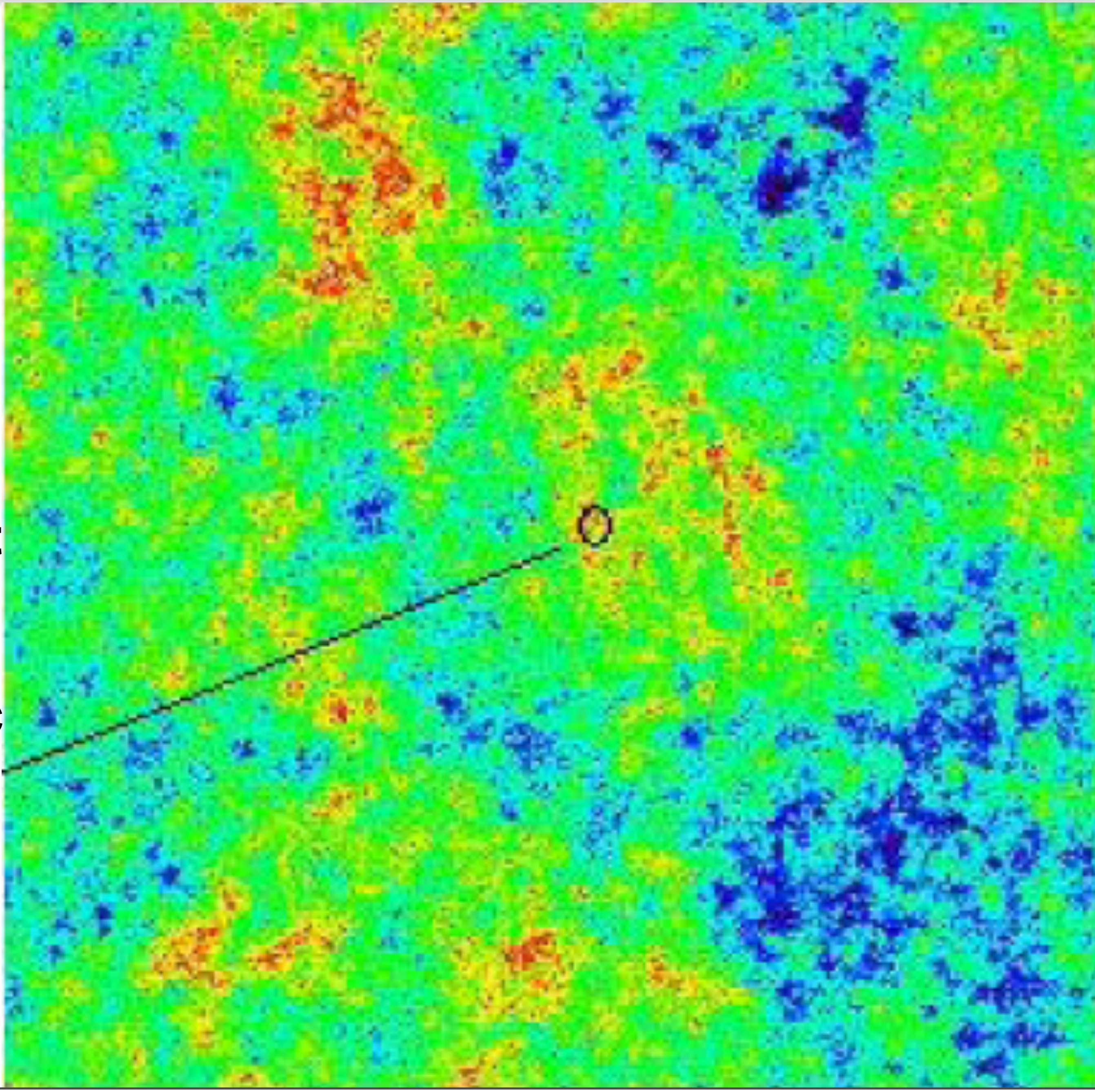
current Hubble patch ~10 Gpc

speed limit horizon



$\ln a(x, \ln H)$

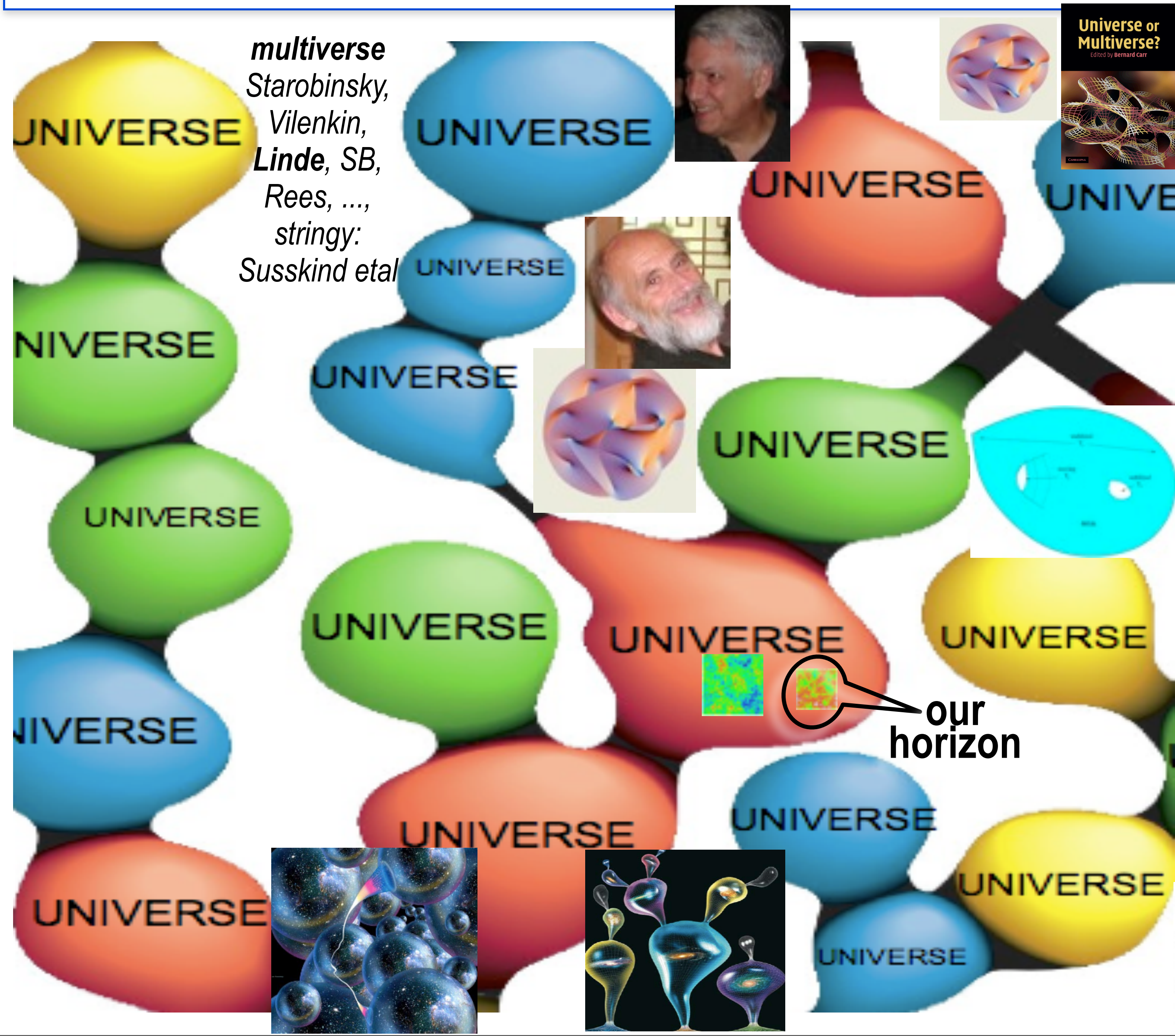
patterns in the quantum jitter evolve under gravity

(& gas dynamics)

1000 Gpc

quantum stochastic *non-Gaussian* **time landscape** cf. **stringy landscape**

multiverse
Starobinsky,
Vilenkin,
***Linde**, SB,*
Rees, ...,
stringy:
Susskind etal



lna(x,lnH)

a "natural" consequence of quantum mechanics of the U's uuUULSS on

lna(x, lnHa)

if quantum diffusion > 'classical' drift

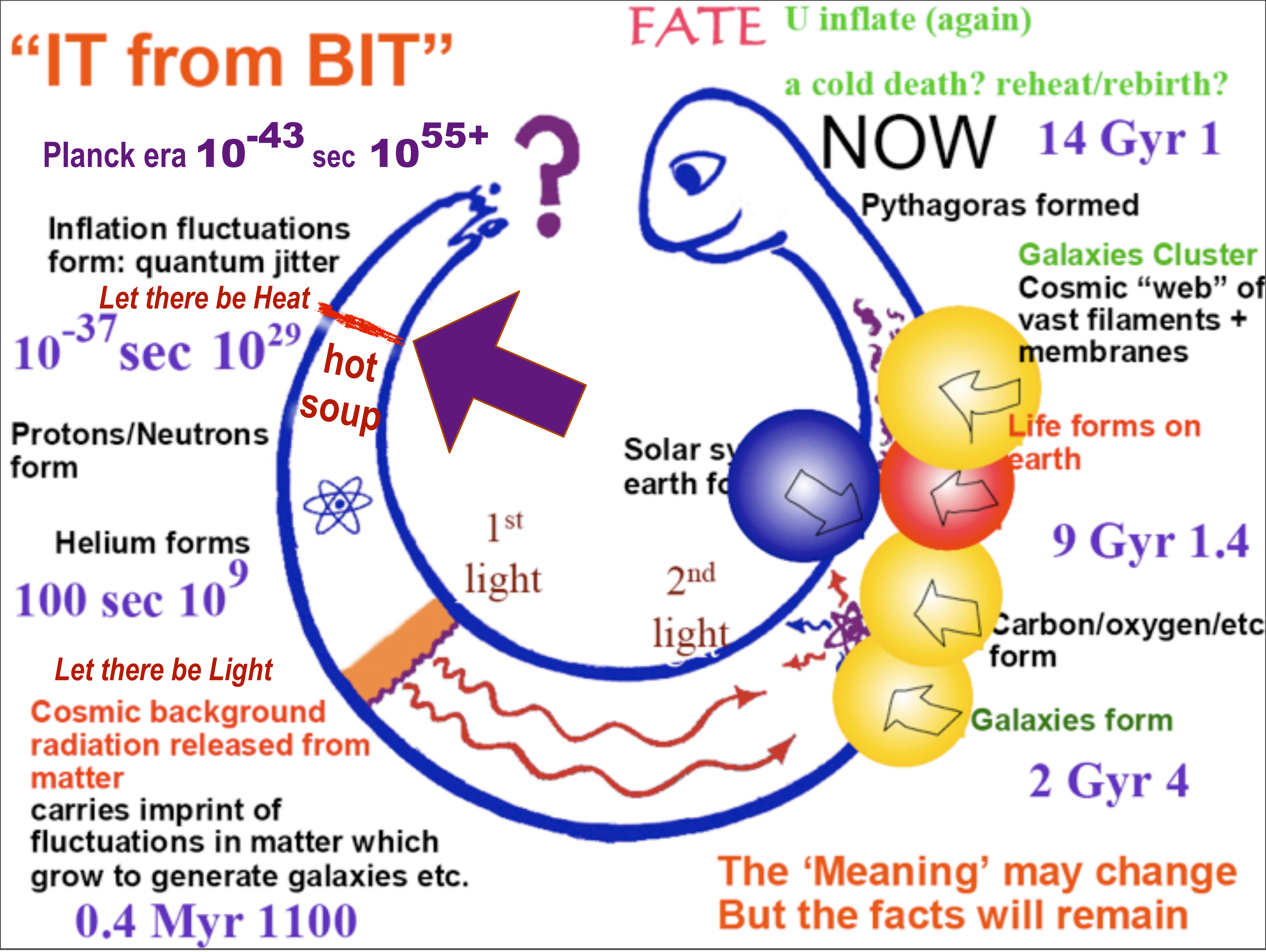
***at* high H**

*cf. our **observable horizon (patch)***

***at* low H**

this eternal inflation can happen even at low H

Salopek & Bond 1991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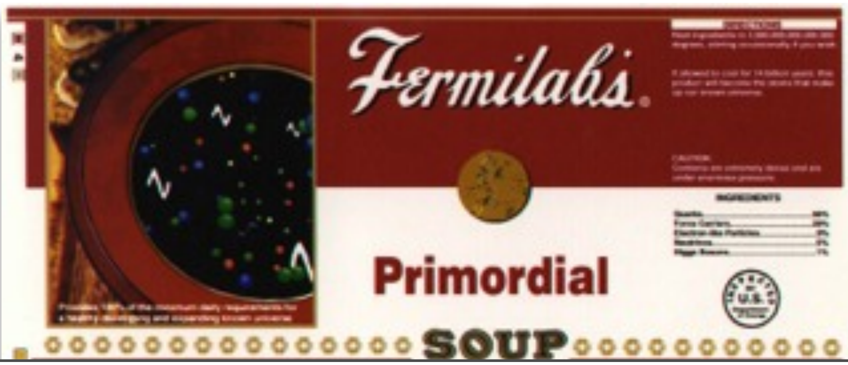
Coherent Inflation *with* Quantum Jitter to Hot Big Bang, an Incoherent Particle Soup

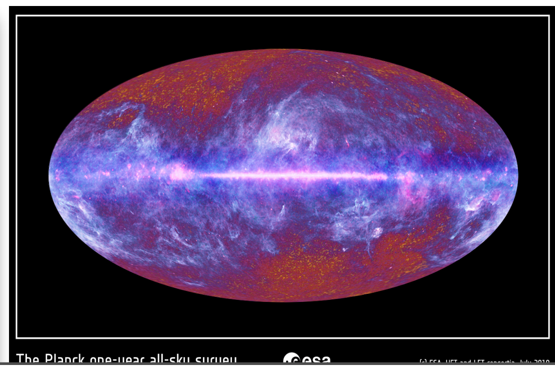
how (most of) the entropy in matter *(GUT plasma/quark soup)* was generated *(a shock-in-time)*

via nonlinear coupling of the inflaton to new interaction channels ... ultimately to standard model degrees of freedom

.. a role for *decaying particles, 1st order phase transitions?*

exactly who, what, where, when, why?

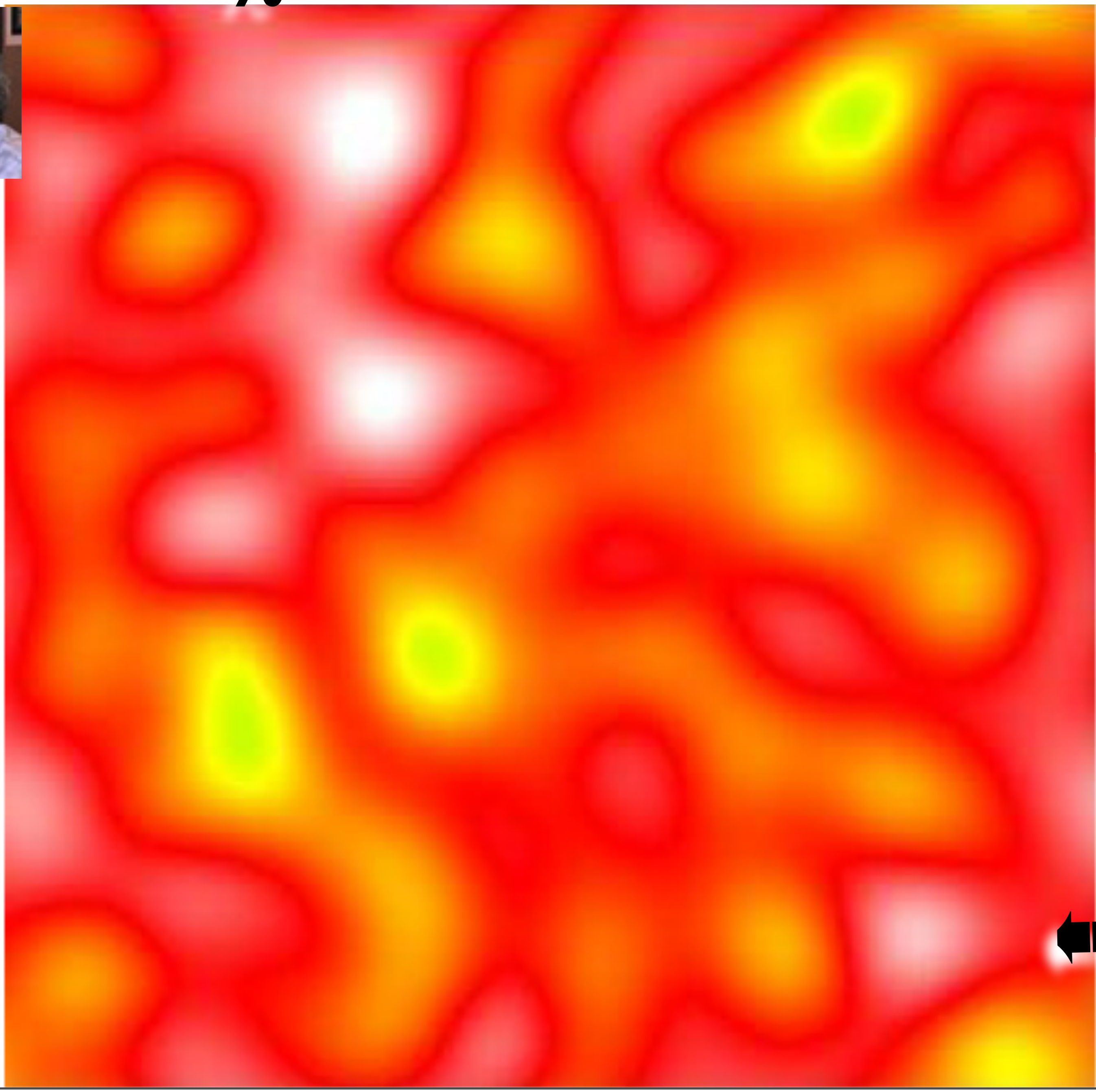




we search for fossil structure from this period with Planck

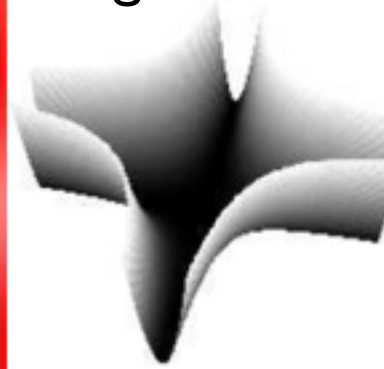
non-Gaussianity
(WMAP, **Planck**, LSS)
spiky nG preheating

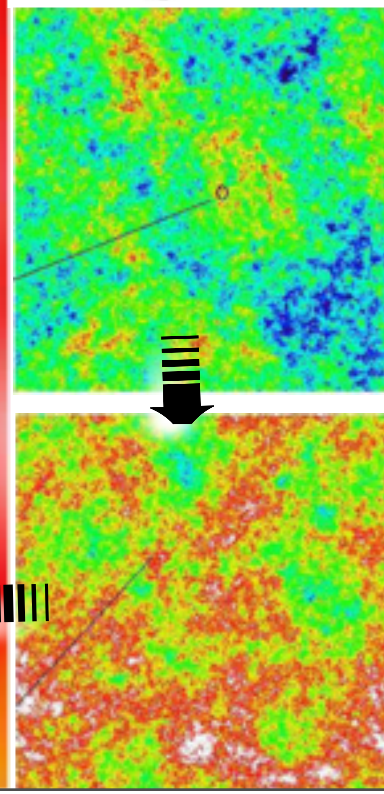
ϕ inflaton χ isocon $V(\phi,\chi) = 1/4\ \lambda\ \phi^4 + 1/2\ g^2\ \phi^2\ \chi^2$



Parametric Resonance

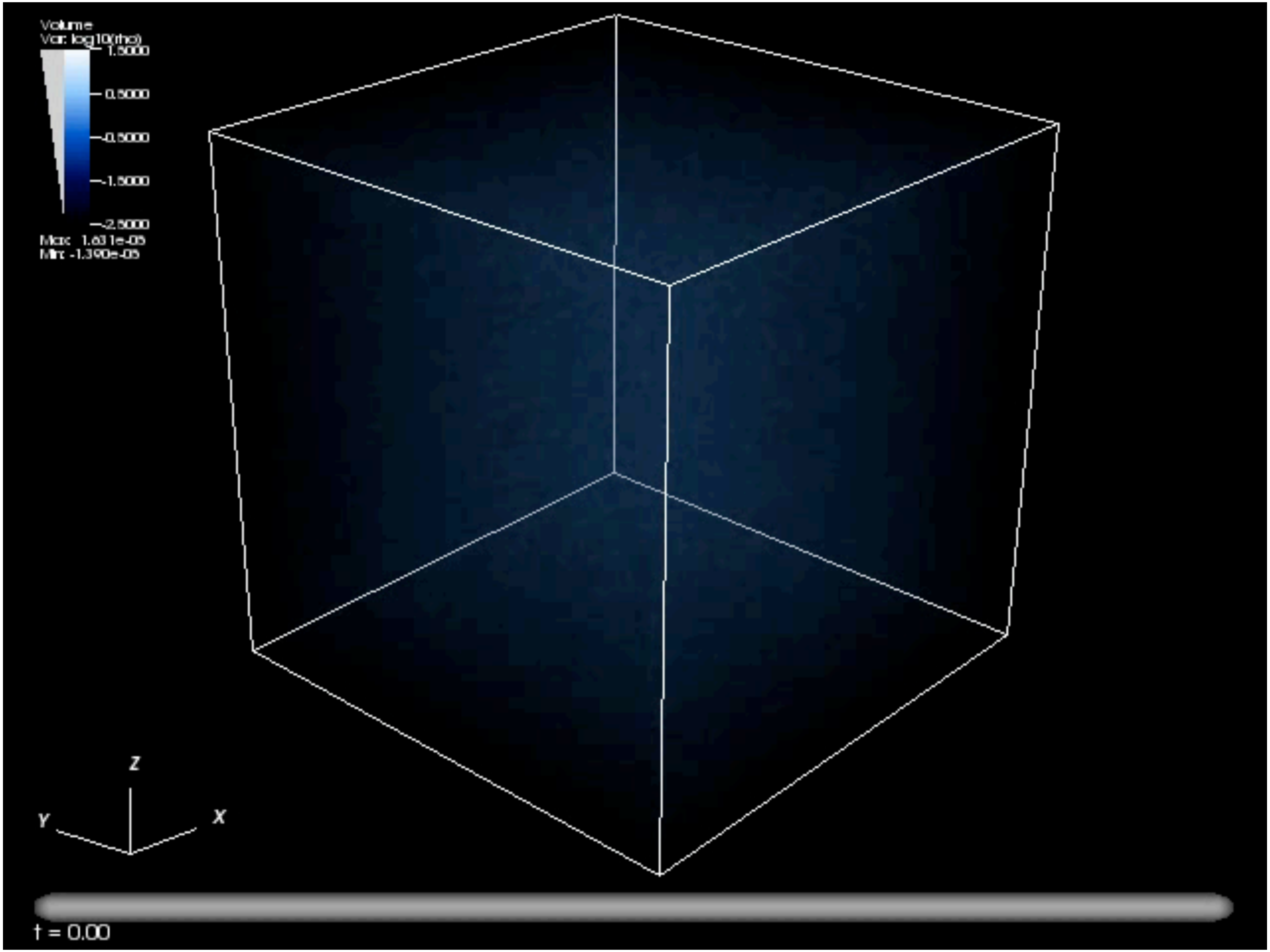
$g^2/\lambda \sim 1$

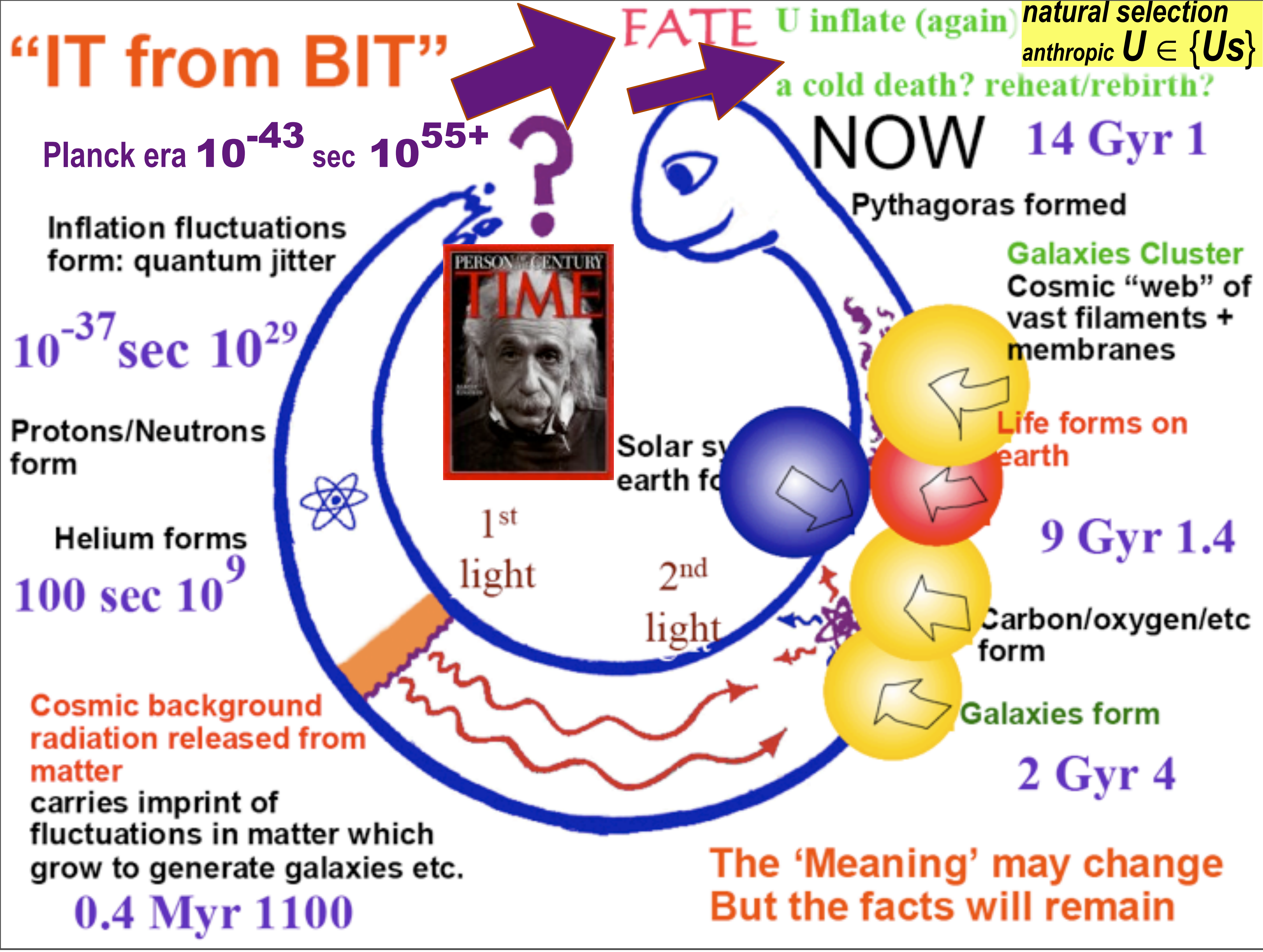




pre-heating patch (~1cm)

Andrei Frolov, Defrost code $V(\phi,\chi) = 1/4\ \lambda\ \phi^4 + 1/2\ g^2\ \phi^2\ \chi^2$

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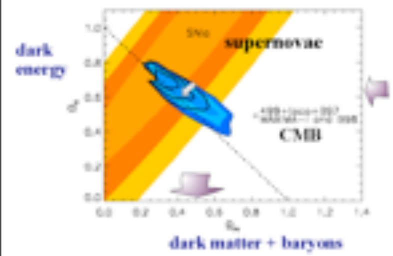


Dark Energy Histories
(SN+WL+BAO+CMB+cls)

future fate?

the cold-death of the Universe (cf. 1800s heat-death)

coherence (dark energy $\rho_{de}(t,x) \Rightarrow V_{de} \sim \Lambda$)

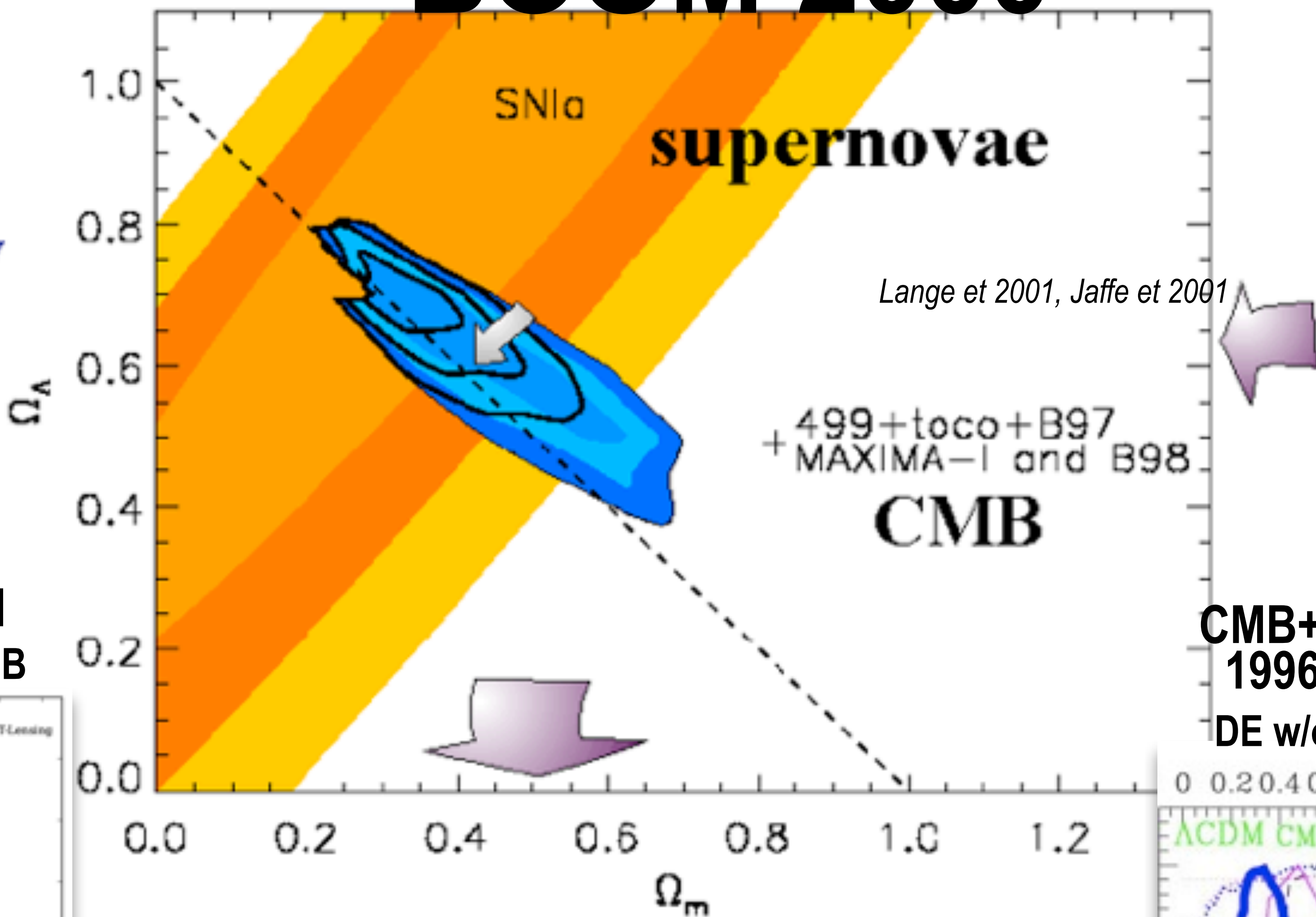
beats incoherence $(\Upsilon, \nu, h_{+x},..p,n,e)$

but entropy/particle remains *(for those particles that survive)*

⇒evidence for "**dark energy**" aka **the cosmological constant**

dark energy

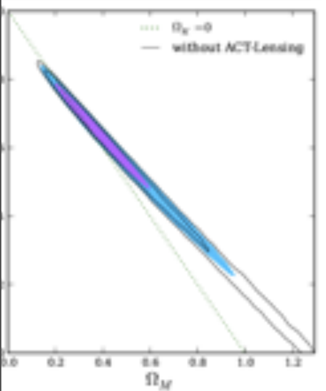
BOOM 2000



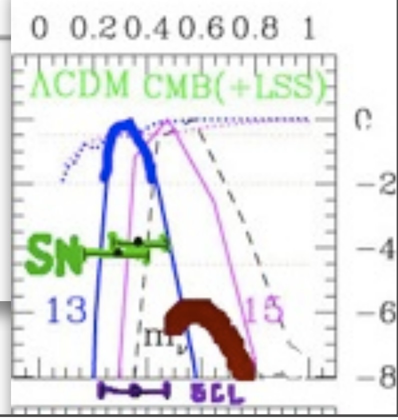
Lange et 2001, Jaffe et 2001

dark matter + baryons

ACT 2011
DE from CMB



CMB+LSS 1996/98
DE w/o SN



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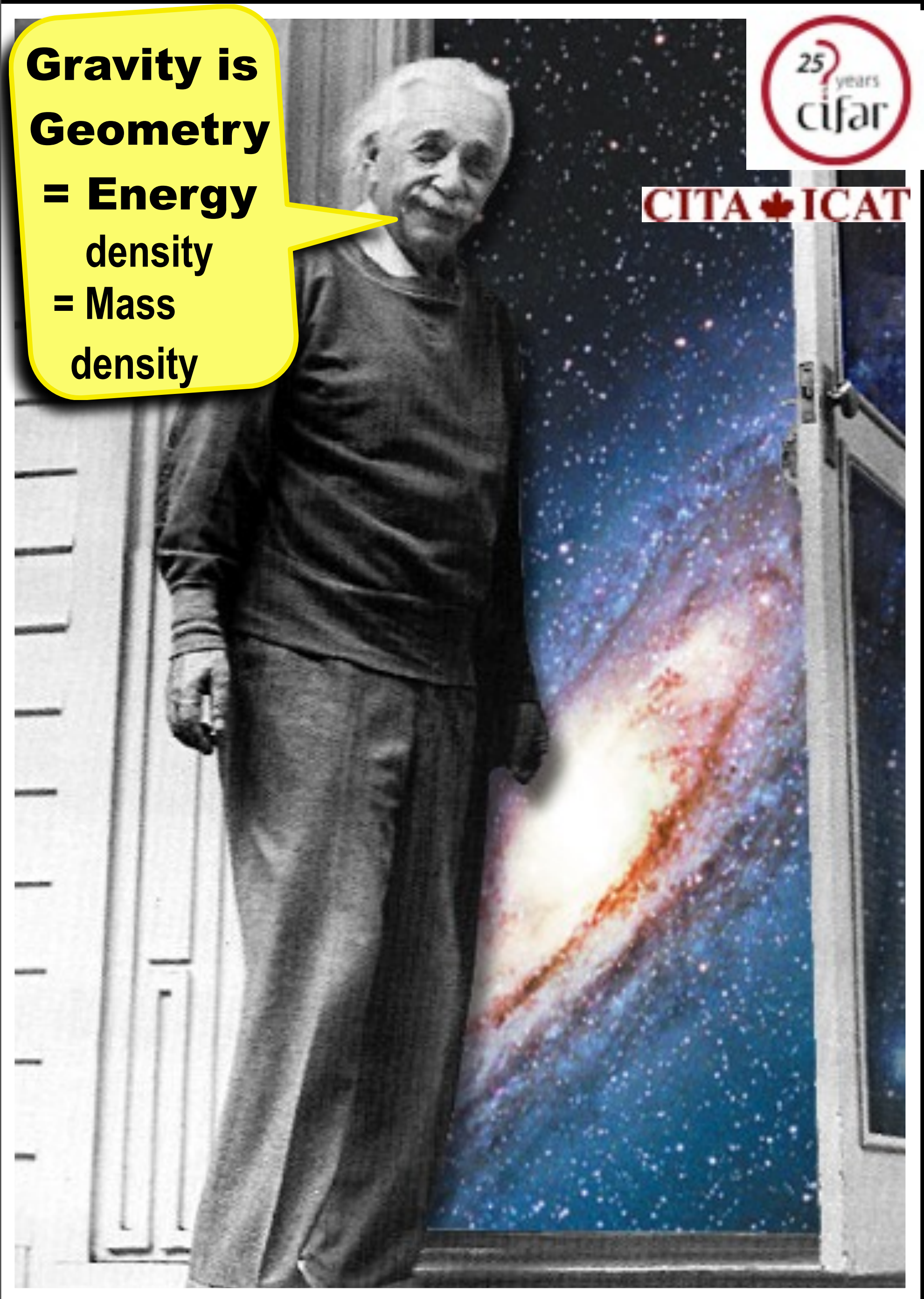
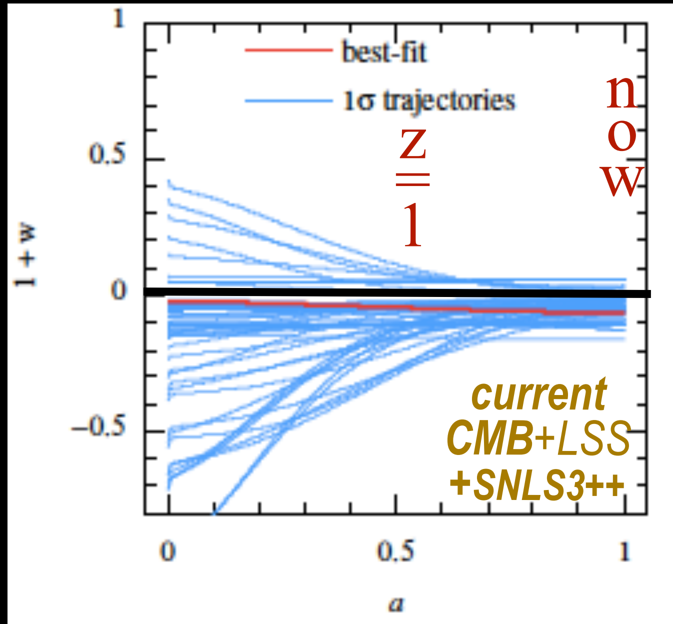
Beyond Einstein

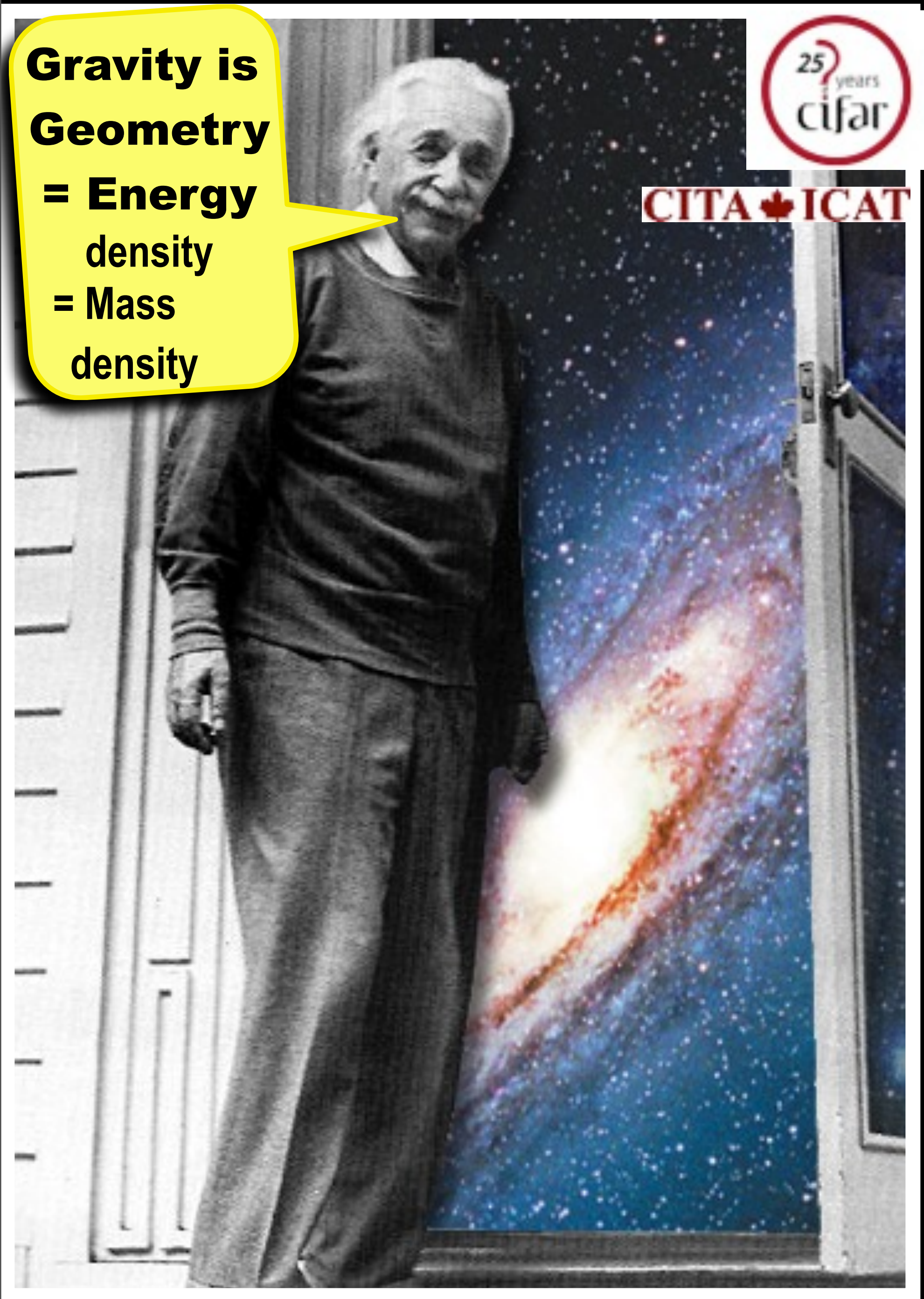




acceleration < 1

$$1+w_{de} = - d\ln\rho_{de} / d\ln a^3$$

$$= 2/3 \;\; \varepsilon_{de}(t)$$



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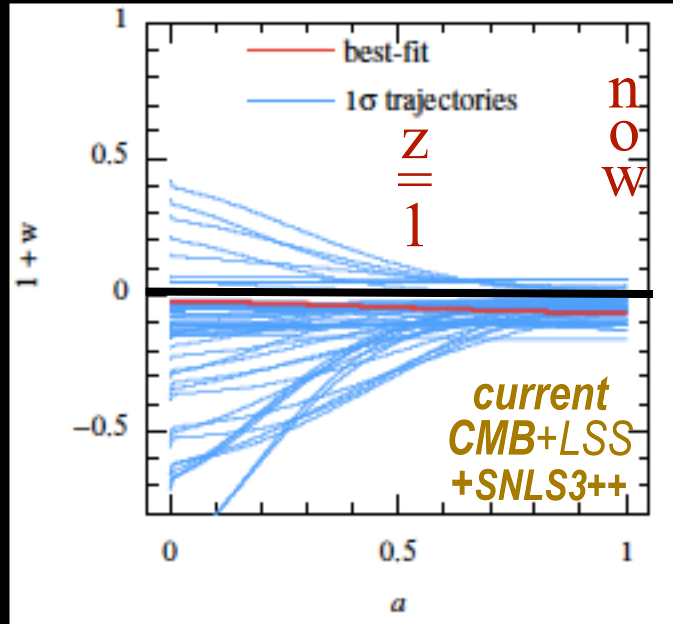

$\varepsilon\,(t,x)$

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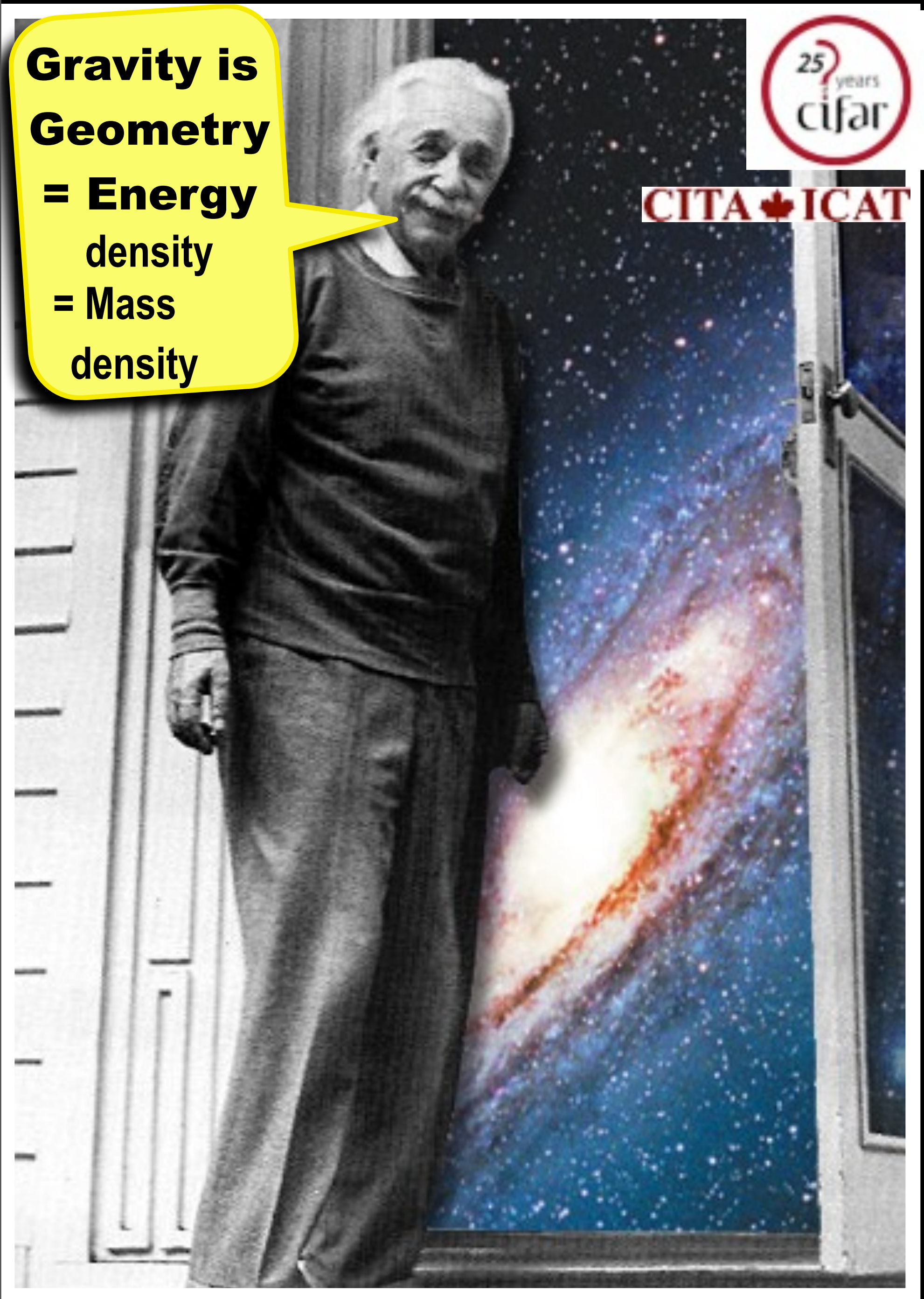
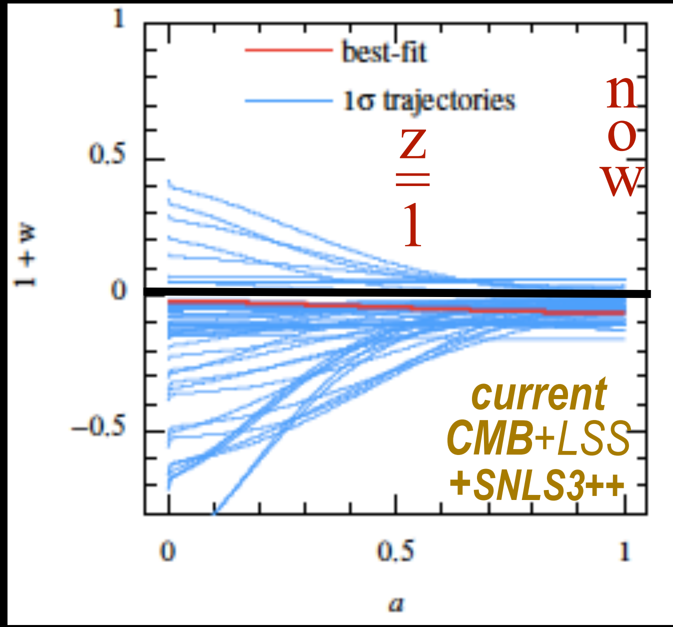
$$1+W_{de} = -\,d\,ln\,\rho_{de} \,/\, d\,ln\,a^3$$

$$=2/3 \quad \varepsilon_{de}(t)$$



Beyond Einstein

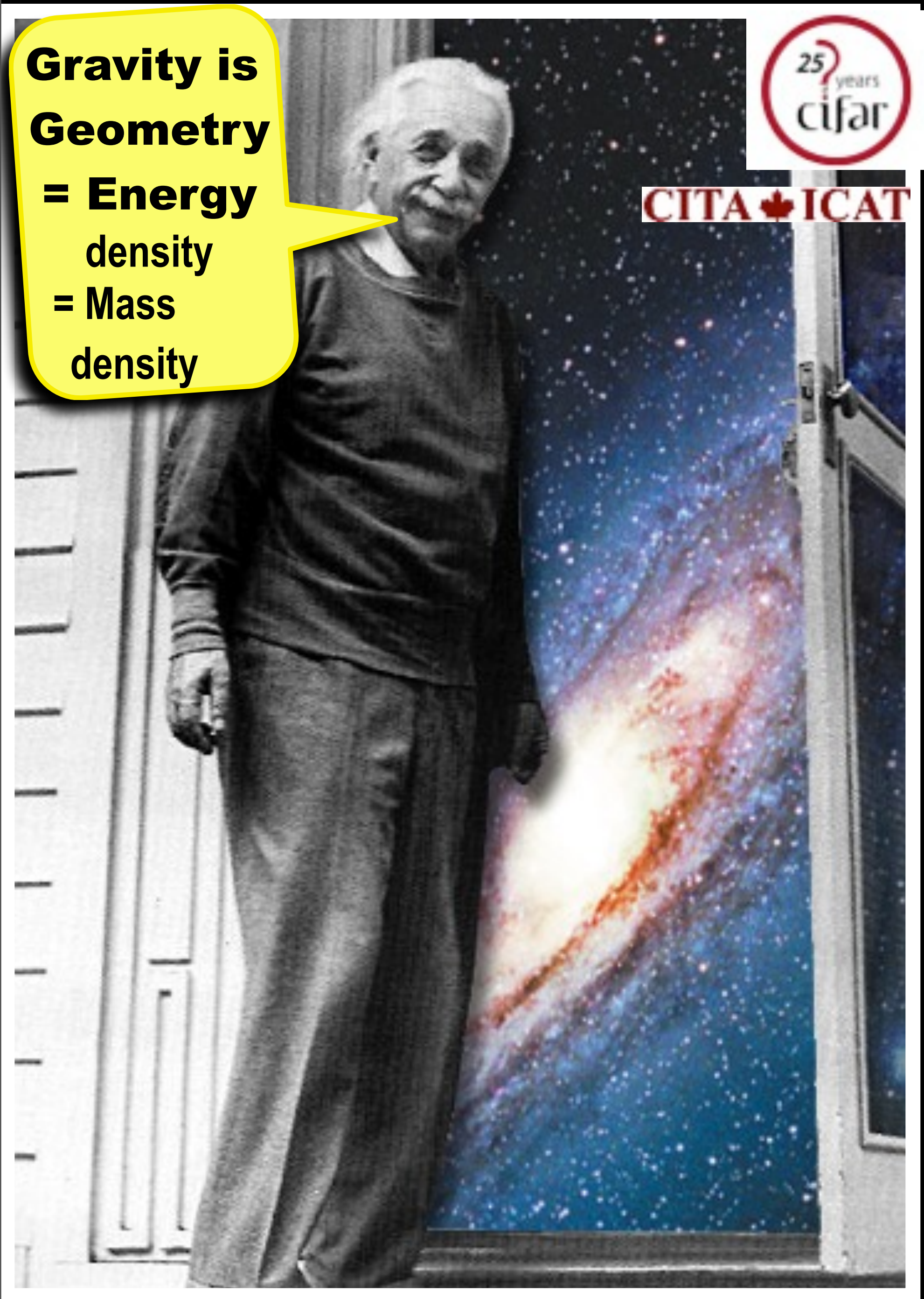


$a(t,x)$ $\varepsilon(t,x)$

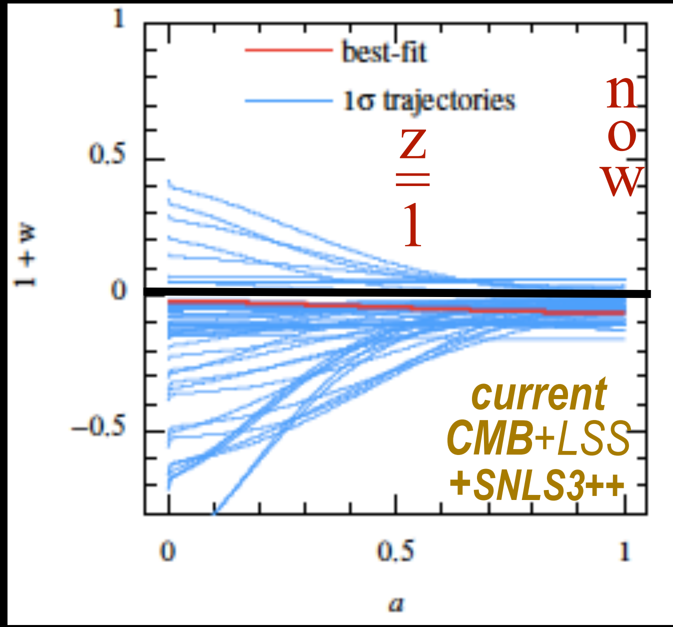
acceleration < 1

$$1+W_{de} = -\, d\,ln\rho_{de} / d\,ln a^3$$

$$= 2/3 \;\; \varepsilon_{de}(t)$$



Beyond Einstein



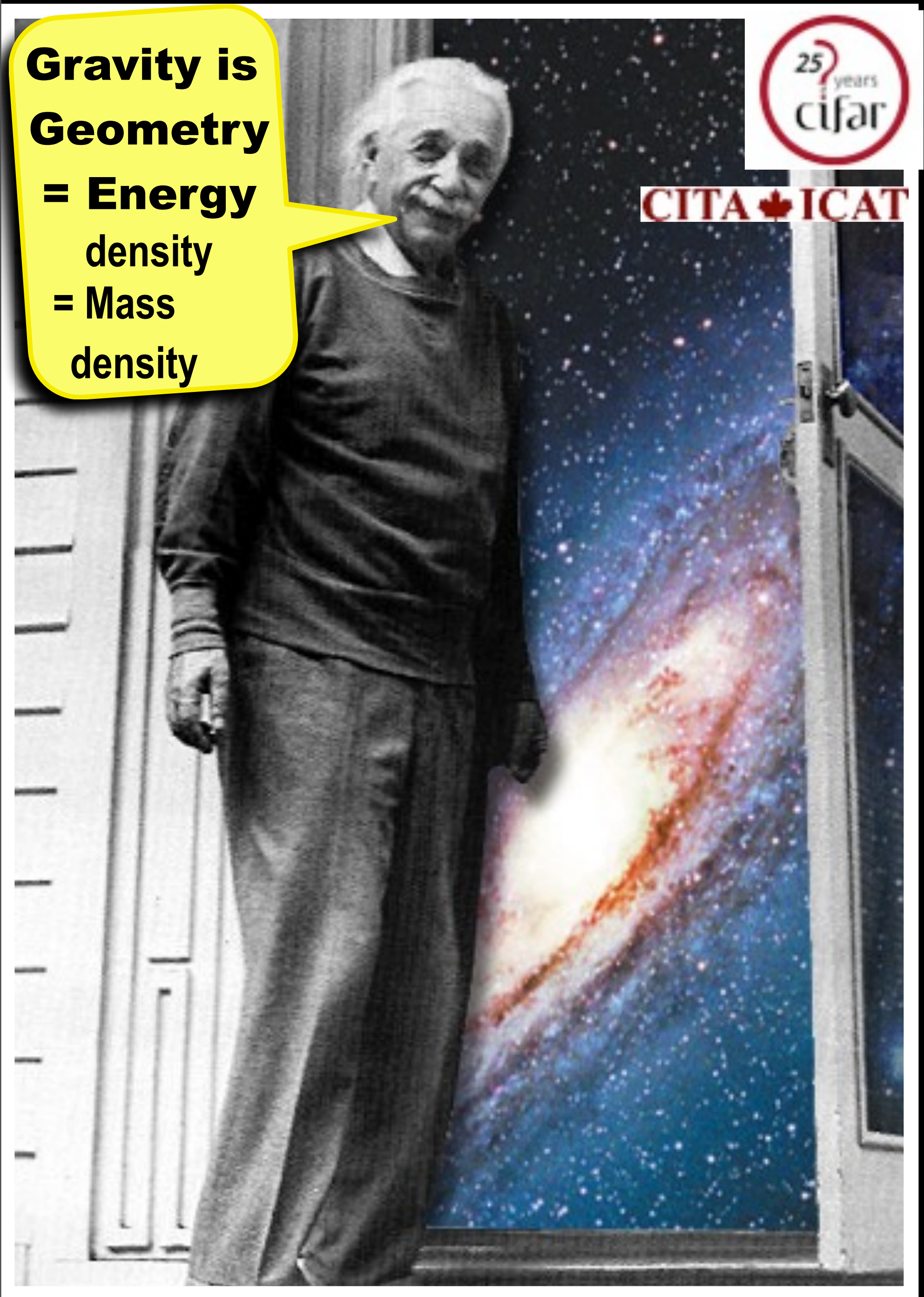
$a(t,x)$ $H(t,x)$ $\varepsilon(t,x)$

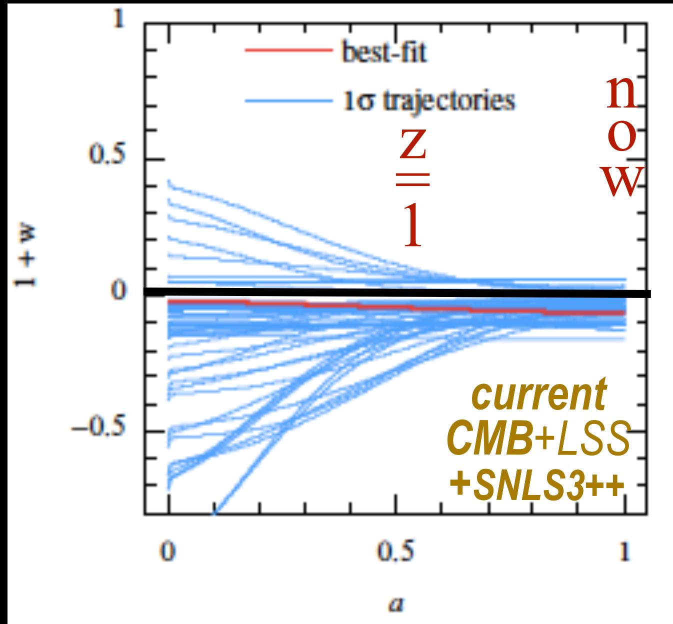
acceleration < 1

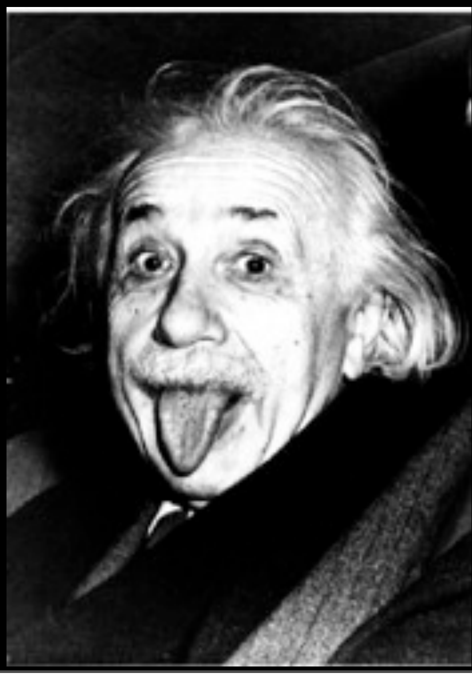
$1+W_{de} = - d\,ln\rho_{de} / d\,ln a^3$

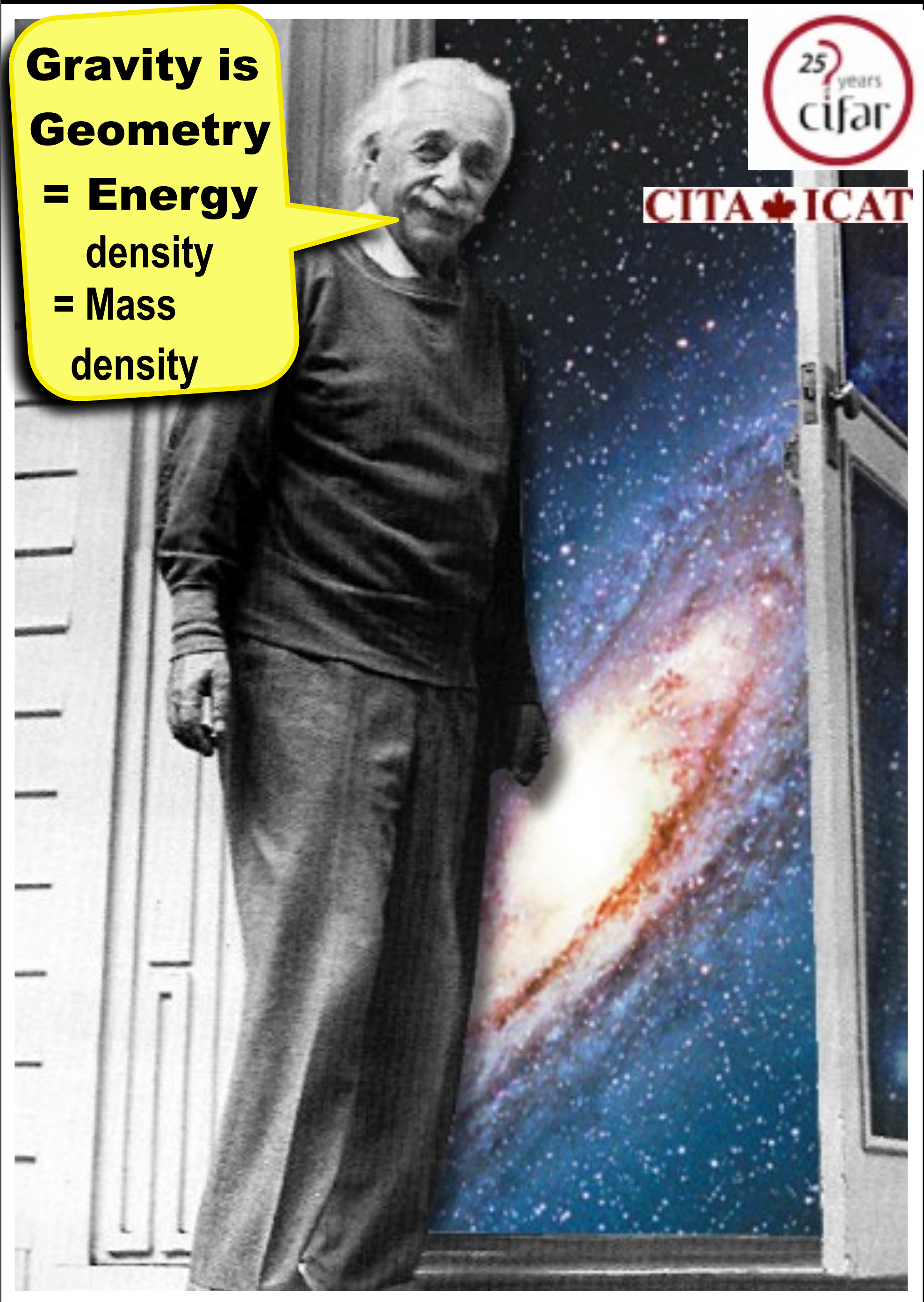
$=2/3\ \varepsilon_{de}(t)$

Beyond Einstein

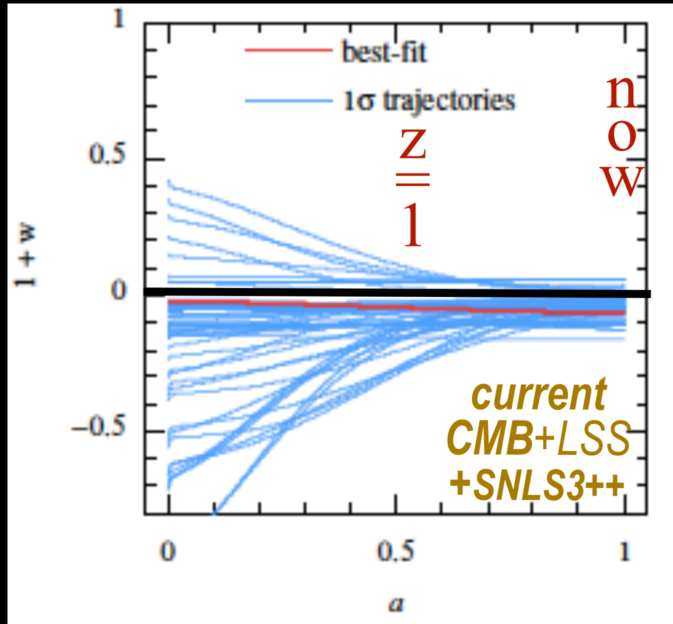




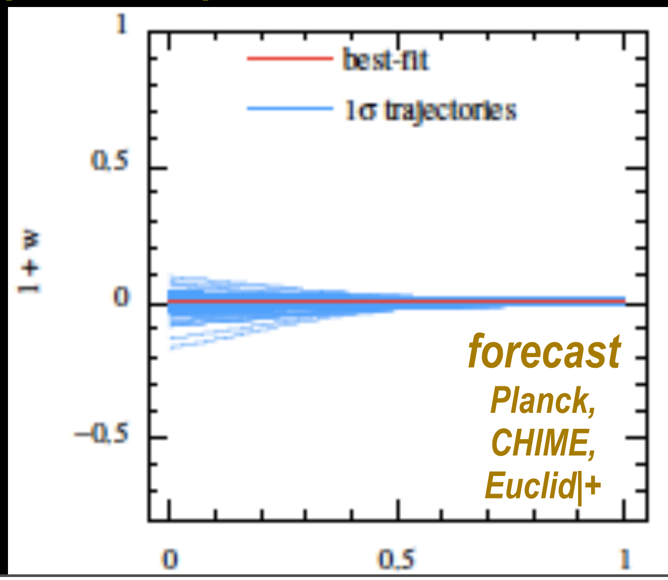


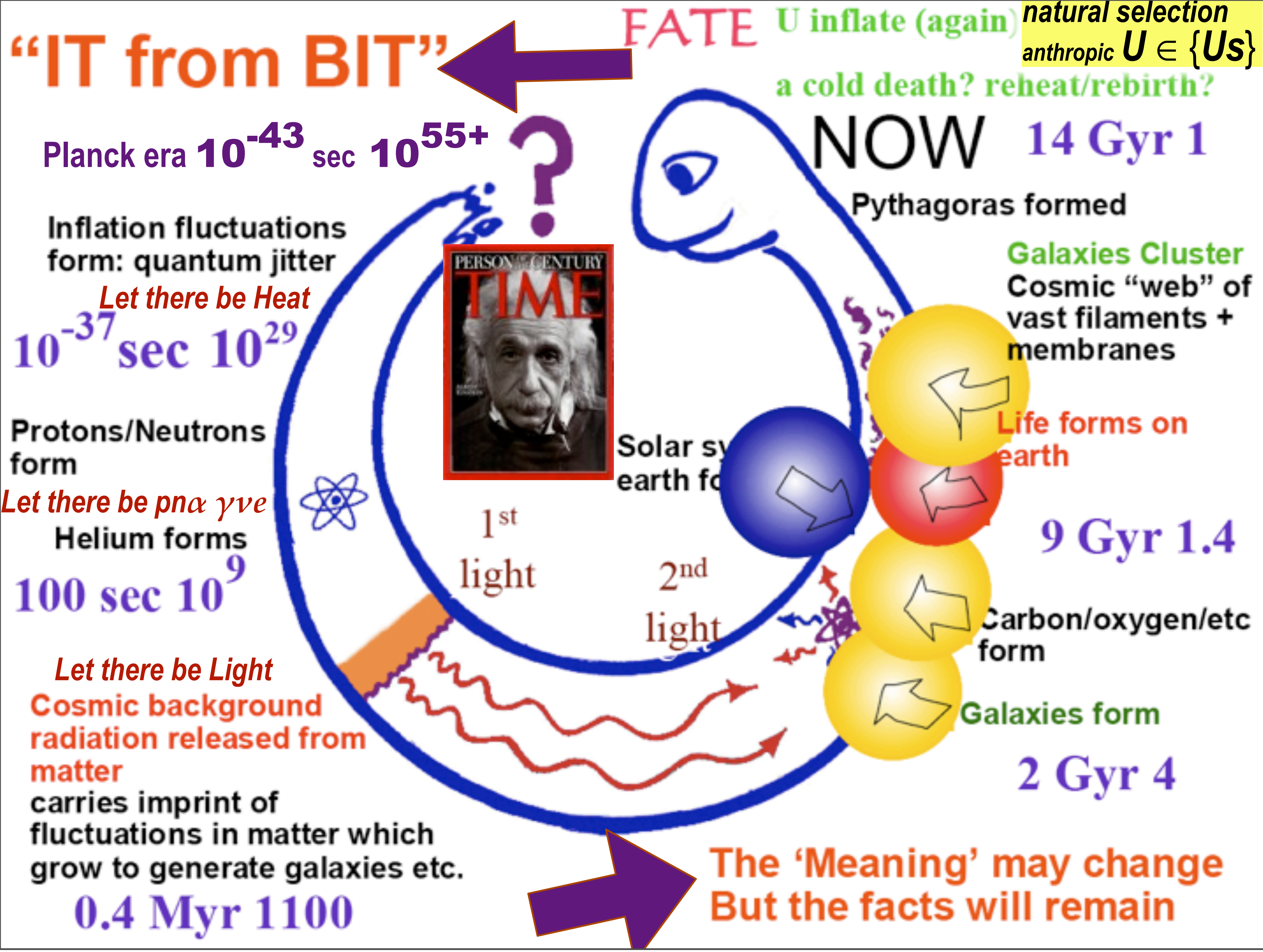


Beyond Einstein



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




"IT from BIT"
FATE
U inflate (again)
natural selection
anthropic U ∈ {Us}
a cold death? reheat/rebirth?
Planck era 10^-43 sec 10^55+
?
NOW
14 Gyr 1
Pythagoras formed
Inflation fluctuations
form: quantum jitter
Let there be Heat
10^-37 sec 10^29
PERSON OF THE CENTURY
TIME
Galaxies Cluster
Cosmic "web" of
vast filaments +
membranes
Life forms on
earth
Protons/Neutrons
form
Solar sy
earth fo
Let there be pnα γνe
Helium forms
1st
light
9 Gyr 1.4
100 sec 10^9
2nd
light
Carbon/oxygen/etc
form
Let there be Light
Cosmic background
radiation released from
matter
carries imprint of
fluctuations in matter which
grow to generate galaxies etc.
Galaxies form
2 Gyr 4
0.4 Myr 1100
The 'Meaning' may change
But the facts will remain

end

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

Dick Bond CIAR

CITA = Cosmic Information Theory & Analysis: *IT from BIT, from BITs in IT,* *Studying the Cosmic Tango*

Universe=System+Res =Data+Theory *en-TANGO-ment*

Cosmic Information Theory and Analysis: IT from BIT, from BITs in IT

John Wheeler's famous mantra, IT from BIT, envisaged the Universe as an information structure of BITs. And, of course, so IT is, fundamentally quantum and statistical, the many-paths/many-worlds information-theoretic story. This lecture uses Cosmic Information Theory and Analysis, CITA, as a unifying theme to explore the vast sweep of our current ideas of the Universe and the experiments we use to probe them, ranging from the ultra-early beginnings to our far-future fate. I describe the intimate entanglement of theory with precision "first-light" and other cosmic data, in particular from the cosmic microwave background satellite Planck and the Andes-based Atacama Cosmology Telescope. Such data are the BITs in IT informing us of the physics that defines the BIT of the Universe accessible to us from which we hope to learn of that vast IT which encodes all Cosmic Information.