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

CIAR 25 years cifar

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+..)
⇒ *x*CDM, *x*=Λ+*tilt*, status@Jun10 is there a y to x? @~Dec12 Λ(t,x)?

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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 (≈*Gaussian RF)* & then preheat via mode coupling via incoherent cascade to thermal equilibrium aka **quark-gluon plasma**

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

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

cosmic mysteries

n_b/n_γ ρ_{dm}/ρ_b z_{eq}/z_{rec} ρ_{curv} ρ_{de}/ρ_{dm} $\rho_{de}\sim H^2M^2_{Planck}$ $\rho_{m\nu}/\rho_{stars}$

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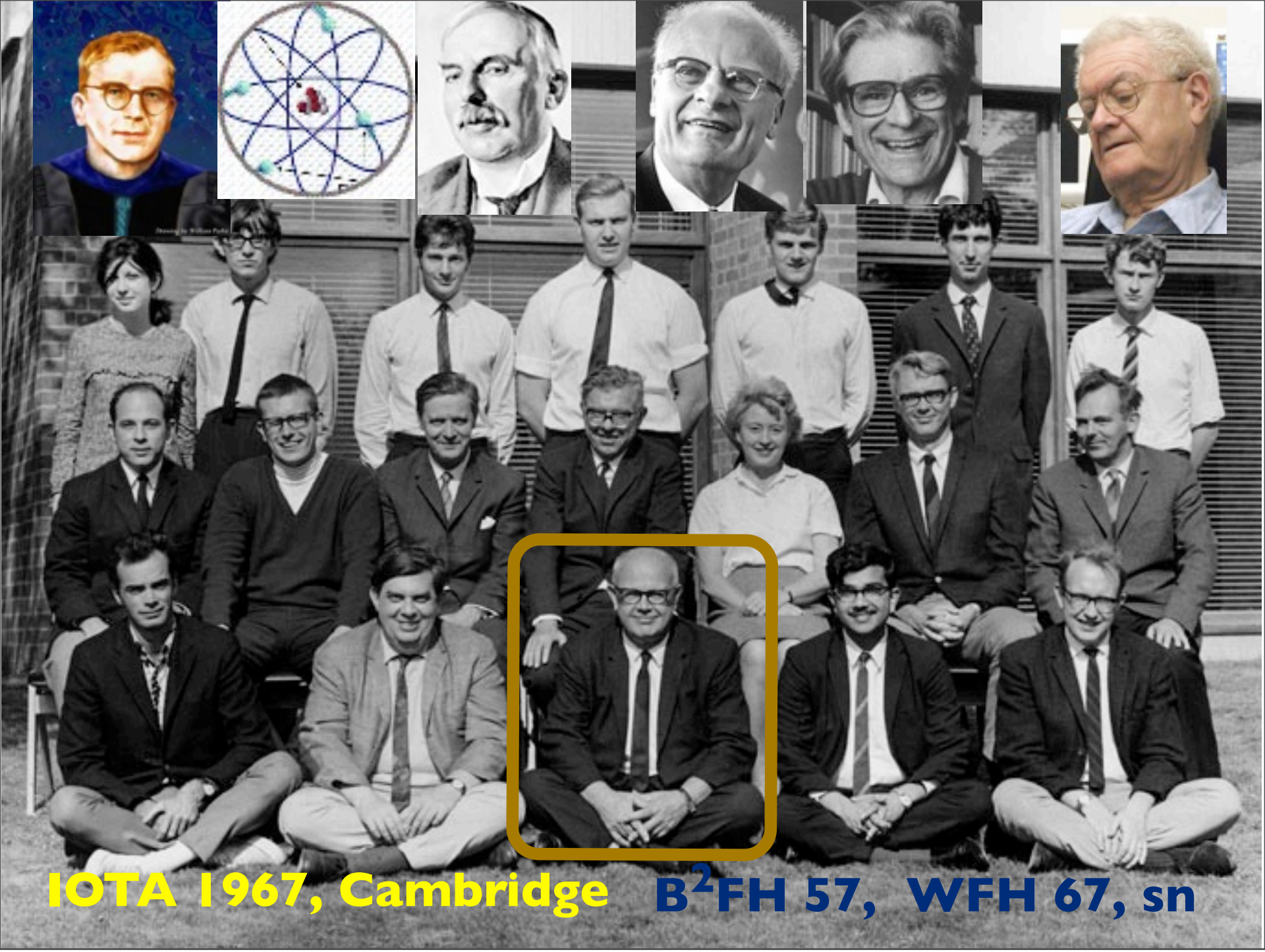
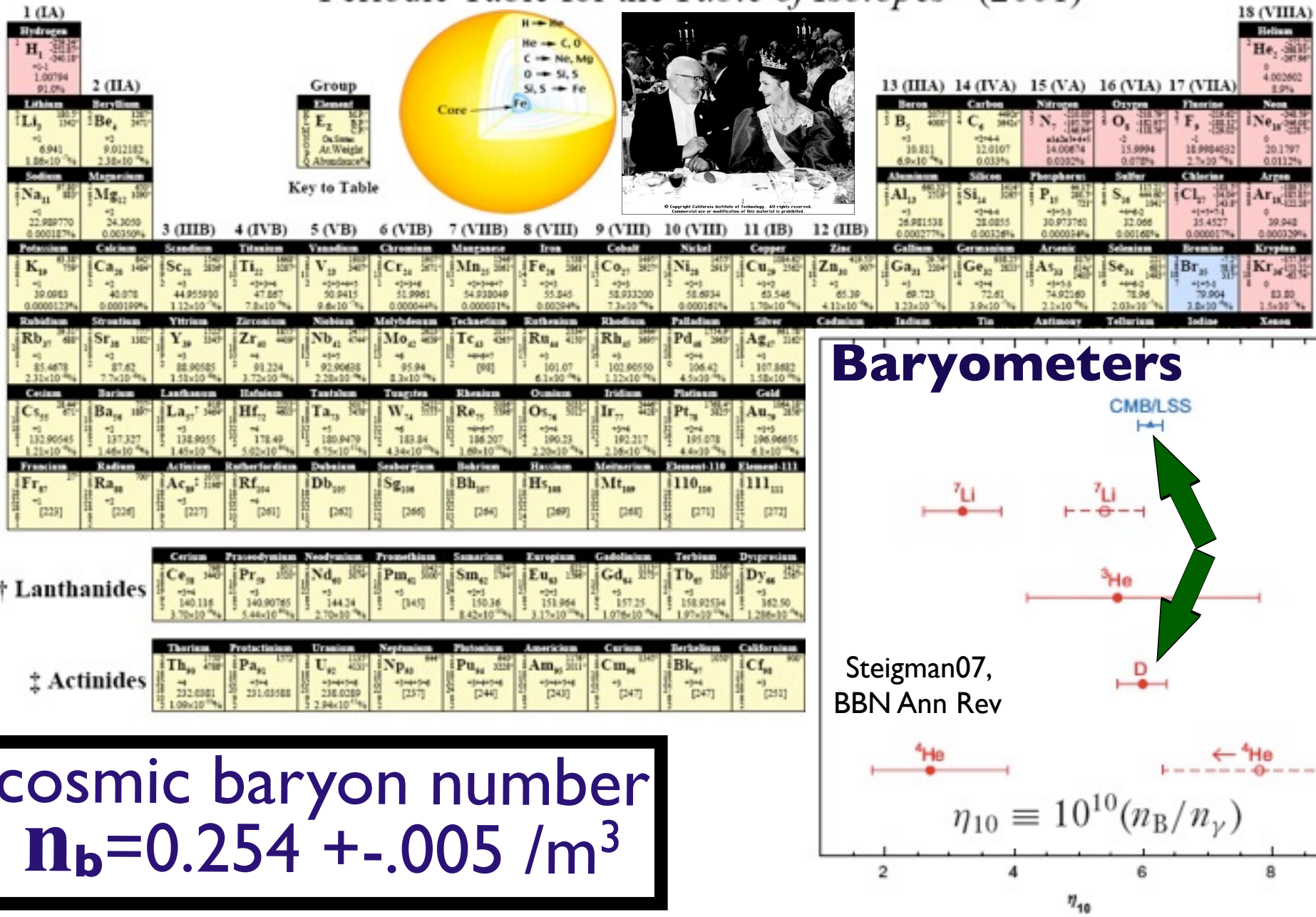

IOTA 1967, Cambridge
B²FH 57, WFH 67, sn



cosmic baryon number

n_b=0.254 +-.005 /m^3

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


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 *x*CDM

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

σ_8: redshift of "galaxy formation"

14 Gyr, Ω_Λ=0.8, H0=75, b~c,

50μK cf 30μK cobe, σ_8~0.72

***X*= s /H0 / Λ / Open/ is /is+ad/ h-c/ h+/ b/ b / Λ+b / Op+b /τ /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)$_3$ (k_*^{-1} = 300)	(CDM + X)$_2$ (k_*^{-1} = 200)
Ω, Ω_B, H_0	...											1, 0.1, 75				
$\Omega_\nu(\Omega_\Lambda)$, Ω_{rel}	...											0.1, 0.8				
b	...											1				
t_0 (by)	GC: 14–22 NC: 13–26											14				
$\sigma_8(R_g = 0.35)$	...											2.4				
z_g	...											1.3				
$\sigma_8(R_{cl} = 5)$	...											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											036				
$\xi_{cg}(20)$	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				
$v(R_f = 3.2)$	610 ± 50											232–1120				
$v(R_f = 15)$	599 ± 104											206–987				
$v(R_f = 25)$												186–894				
$v(R_f = 40)$	970 ± 300											160–771				
$\Delta T/T$ (4.5)	< 25											10				
$\times 10^6$ (6°)	< 48											25				

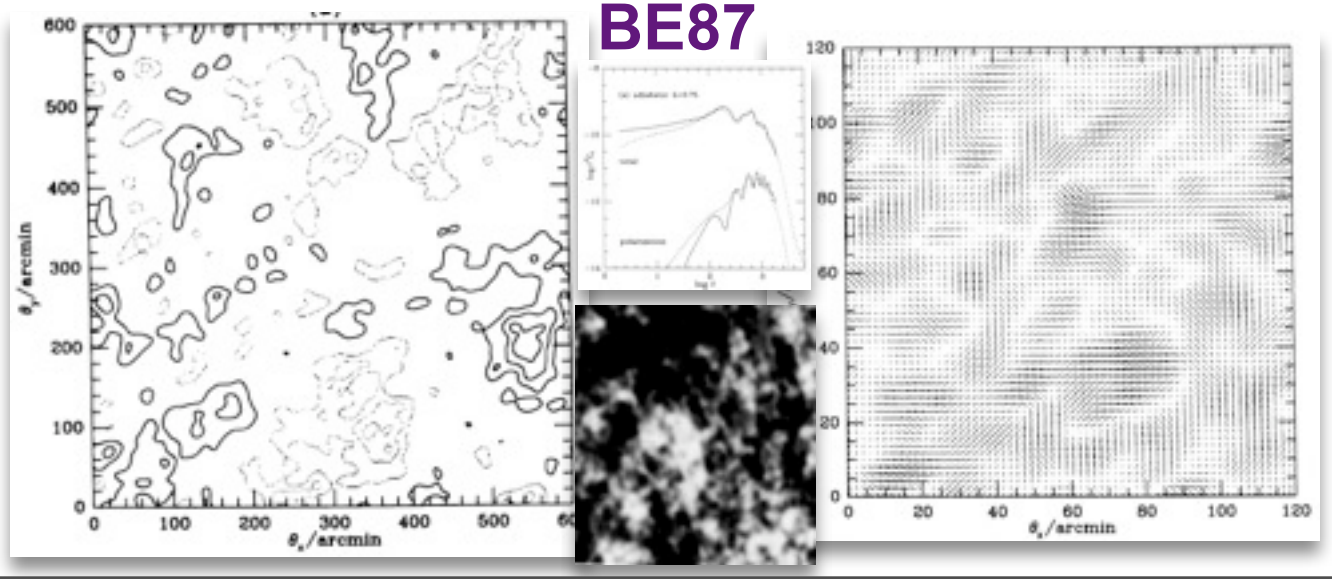
Delta T over Tea Toronto May 1987: first dedicated CMB conference, exptalists+theorists, primary+secondary ΔT/T

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

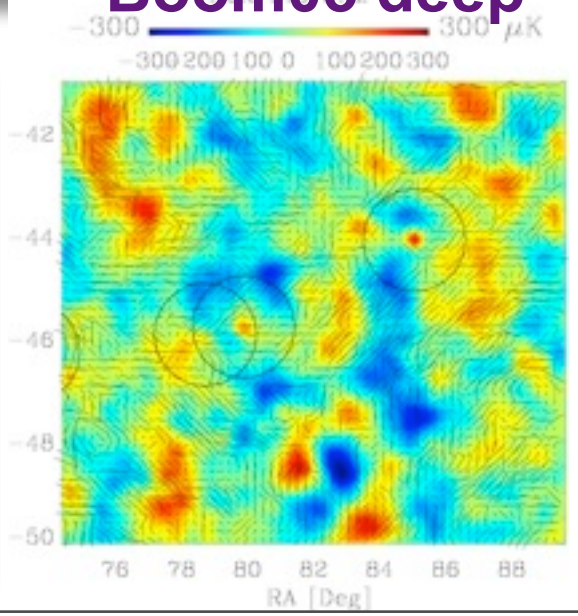
A tentative list of topics organized according to angular scale, with theory and observation intertwined, is:

- 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 - $5^o - 10^o$ results, future experiments at $\sim 1^o$, 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.

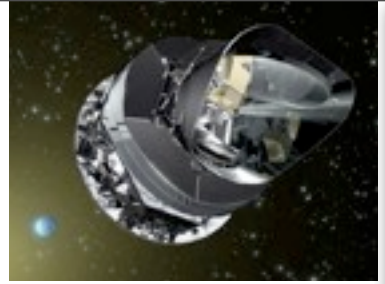
BE87

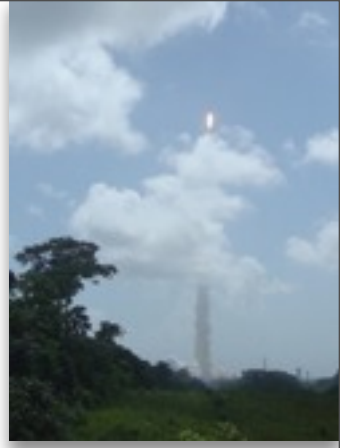


Boom05 deep

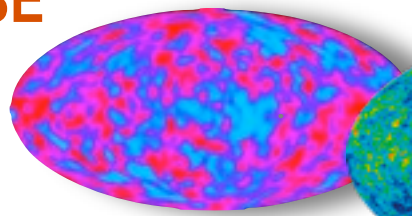


CMB SCIENCE FRONTIERS: Polarization & High Resolution

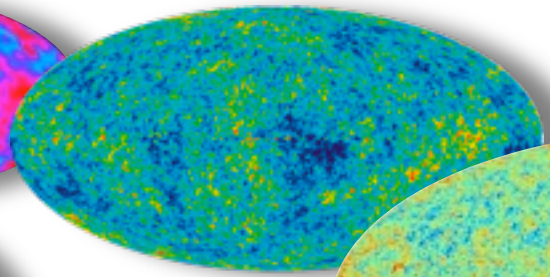




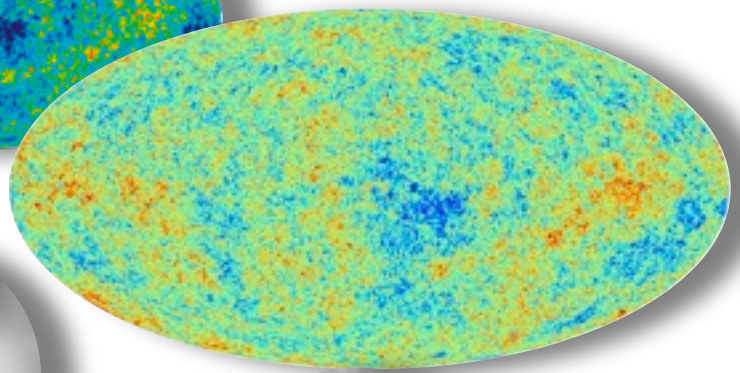
COBE 89.9; 92.3

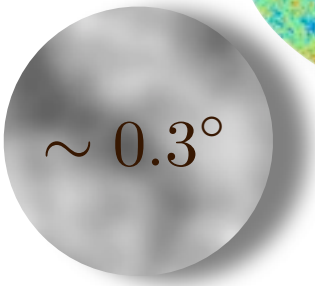


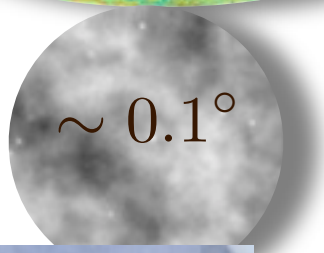
WMAP 01.5; 03.2



PLANCK (sim) 09.4; 12.9

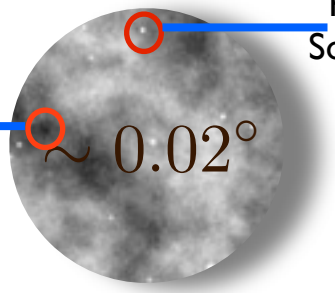




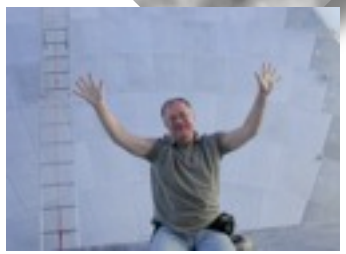


1 degree

ACT/SPT 07.8; 09.1



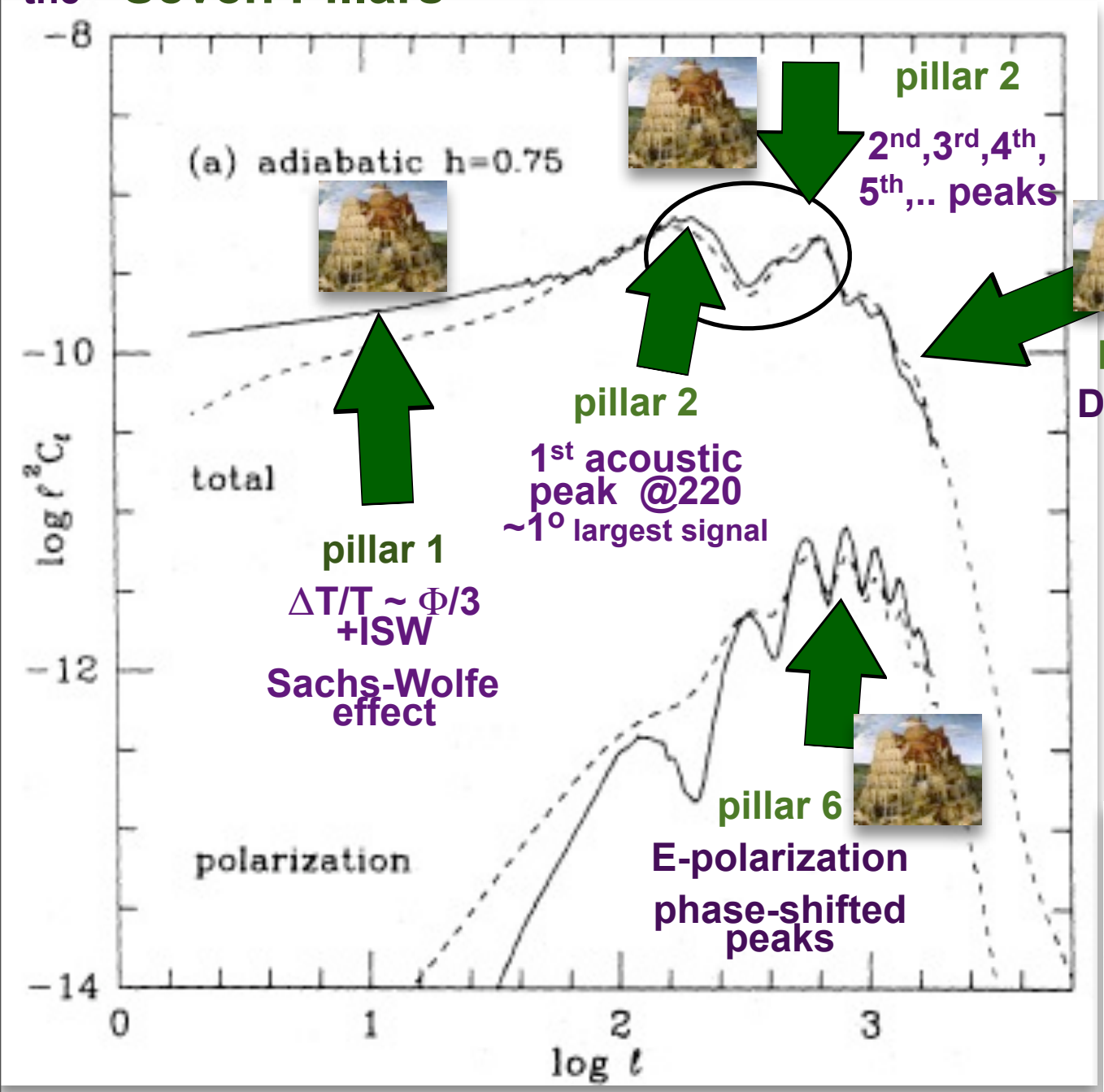
Blast



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 2

2^{nd},3^{rd},4^{th}, 5^{th},.. peaks

pillar 2

1^{st} acoustic peak @220 ~1^o largest signal

pillar 1

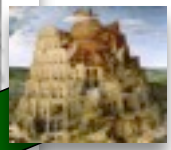
$\Delta T/T \sim \Phi/3$ +ISW

Sachs-Wolfe effect

pillar 6

E-polarization

phase-shifted peaks



pillar 3

Damping tail

pillar 5

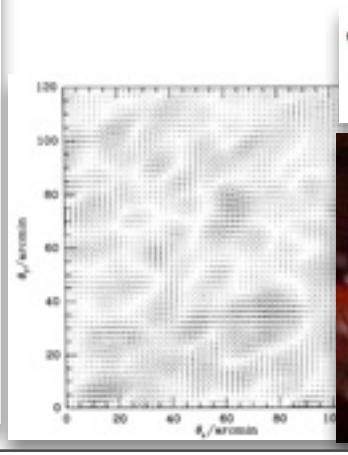
secondary ΔT nonlinear *Compton SZ weak lensing*..

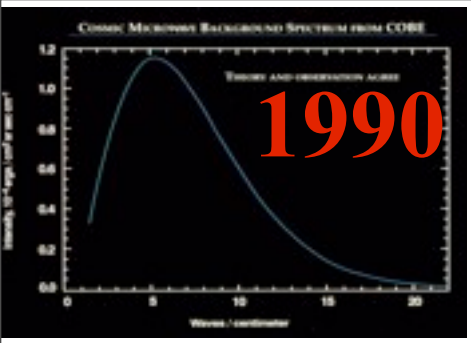
pillar 4

Gaussianity *maximal randomness for given* C_L

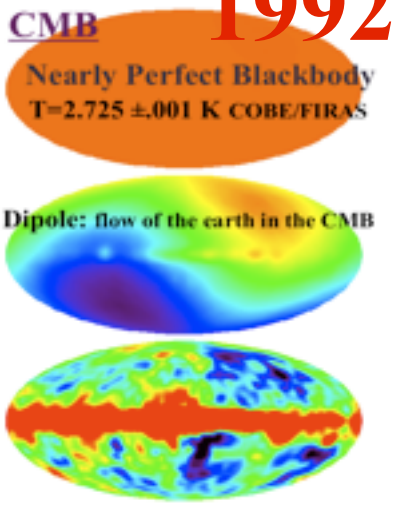
pillar 7

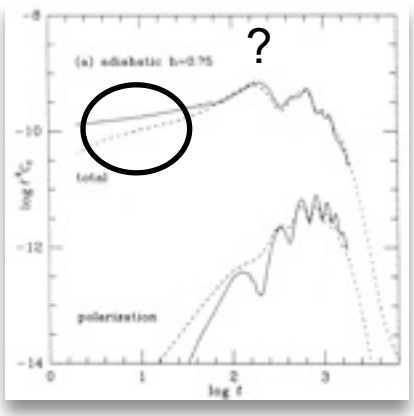
B-polarization Gravity Waves

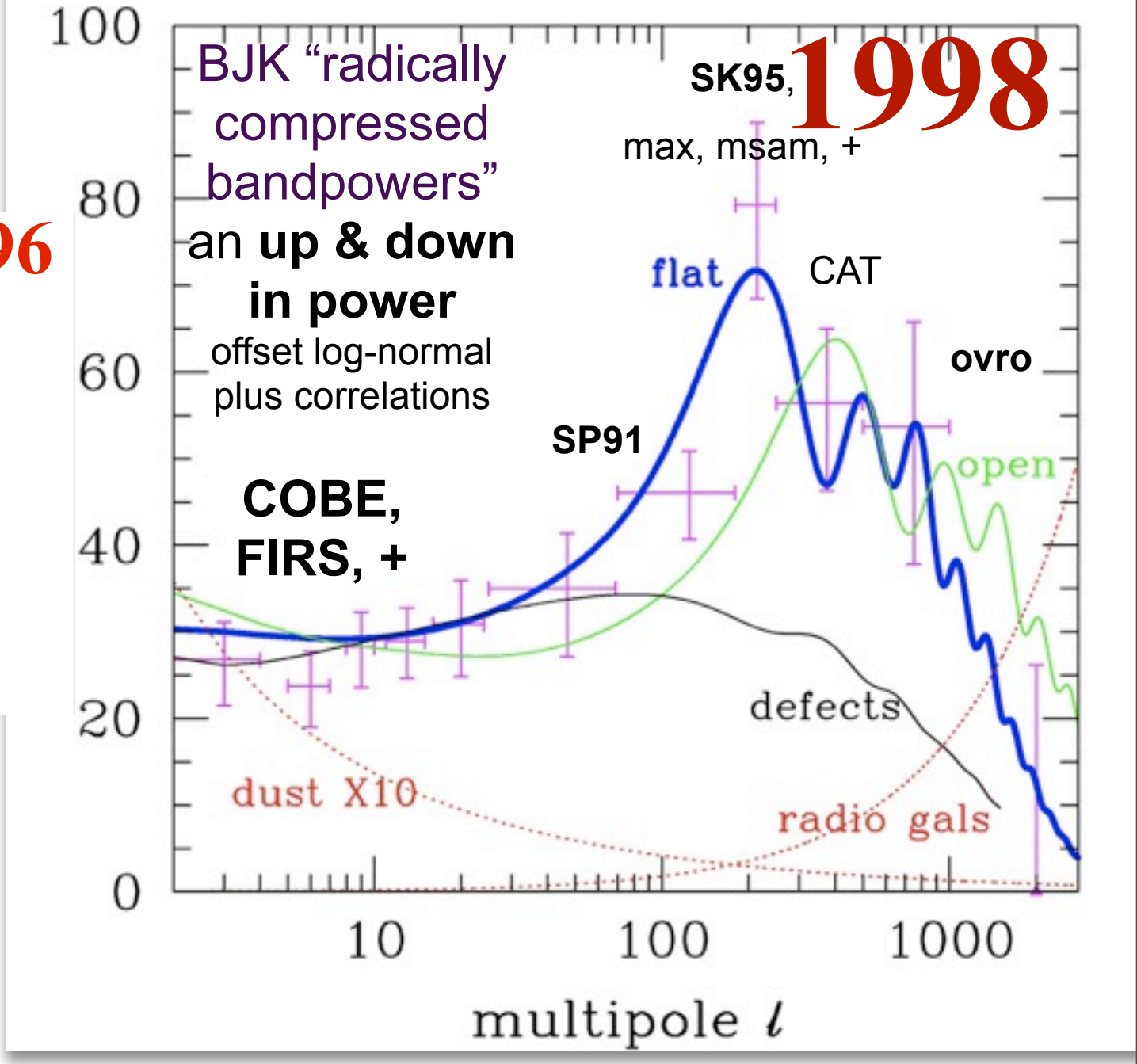



1990

1992/96


CMB
Nearly Perfect Blackbody
T=2.725 ±.001 K COBE/FIRAS
Dipole: flow of the earth in the CMB
COBE/DMR:
CMB + Galactic @7°


?
(a) adiabatic h=0.75
total
polarization
log ℓ


BJK "radically compressed bandpowers"
an up & down in power
offset log-normal plus correlations
COBE, FIRS, +
SK95, 1998
max, msam, +
flat
CAT
ovro
SP91
open
defects
dust X10
radio gals
100
80
60
40
20
0
10
100
1000
multipole ℓ

CMB ⊕ LSS

$n_s \simeq 1 \pm .05$

nearly SCALE INVARIANT FLUCTUAT^{N}S

CMB ⊕ LSS ⇓ ΩCDM << ΛCDM

SNIa ⇓

high z CLUSTERS ⇓

$\Omega_{cdm} \sim .3$

$\Omega_B \sim .04$

$H_0 \sim 65\text{-}70$

$t_0 \simeq 12\text{-}14\,Gyr$

$\Omega_\nu \sim .0014 \left(\frac{m_\nu}{.07\,eV}\right)^2 \frac{2\nu}{2}$

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

Λ vac ⇒ LATE TIME

INFLATION is NOW

$\rho_\Lambda^{1/4} \sim$ milli eV

vintage 98 conclusions

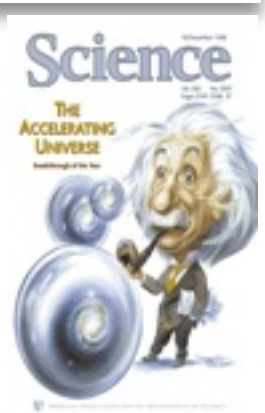
B+Jaffe'96,'98 $(13\,Gyr/t_0)$

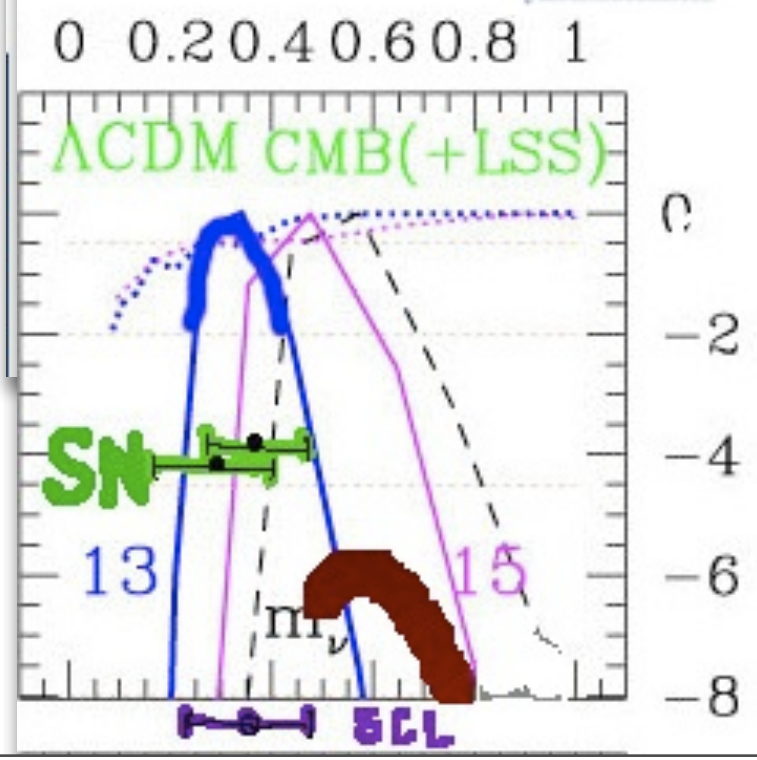
$\Omega_\Lambda \approx 2/3 \pm .07$ +LSS

$n_s =$

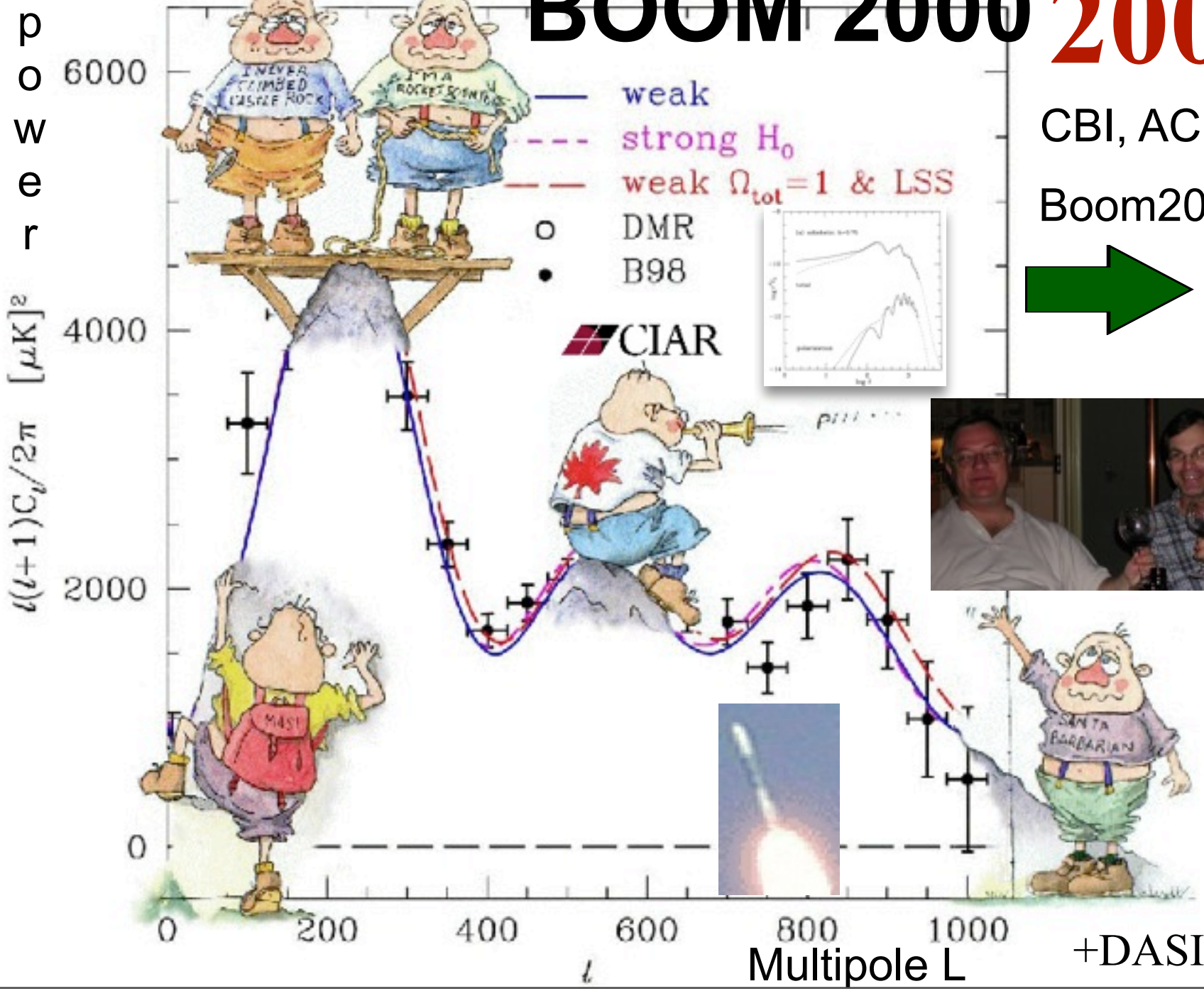
$.98 \pm .07$

$.96 \pm .06$





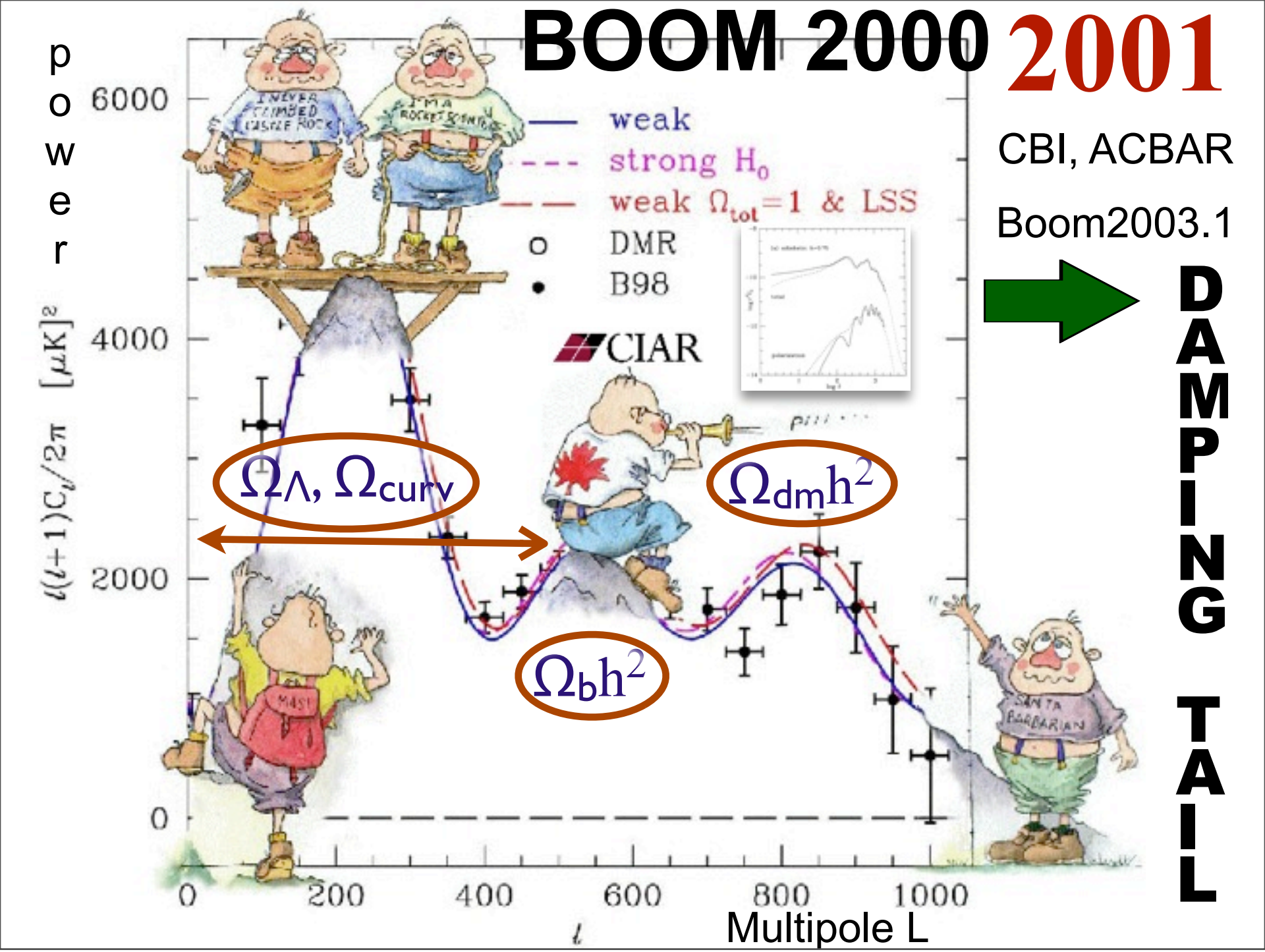
BOOM 2000 2001



CBI, ACBAR

Boom2003.1

+DASI 2001


BOOM 2000
2001
CBI, ACBAR
Boom2003.1
DAMPING TAIL
power
$\ell(\ell+1)C_\ell/2\pi$ [μK]^2
6000
4000
2000
0
weak
strong H_0
weak $\Omega_{tot}=1$ & LSS
DMR
B98
CIAR
$\Omega\Lambda, \Omega_{curv}$
$\Omega_{dm}h^2$
$\Omega_b h^2$
0
200
400
600
800
1000
ℓ
Multipole L


WMAP
launch
2001.5
Text
Dave Wilkinson
Rashid Sunyaev

CMB 2010

$\langle|\Delta T_{(LM)}|^2\rangle L(L+1)/2\pi$

pillars 2,3

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

pillar 1

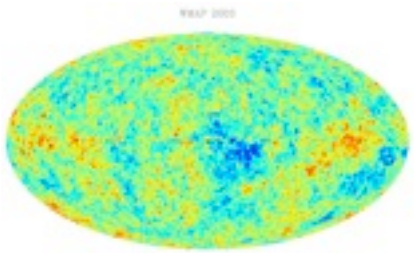
COBE
regime

pillar 5
SZ power

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

CMB 2010

$$\langle|\Delta T_{(LM)}|^2\rangle L(L+1)/2\pi$$



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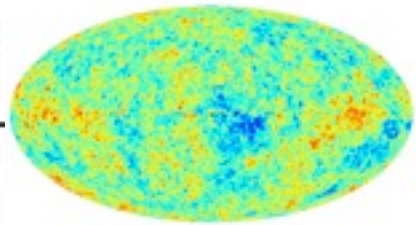


WMAP 7yr
ACT 148 GHz
ACBAR
QUaD

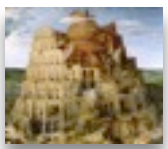
$l(l+1)C_l^{TT}/2\pi$ [μK^2]

6000
5000
4000
3000
2000
1000
0

10 50 100 500 1000 1500 2000 3000

Multipole moment l

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*

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***

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

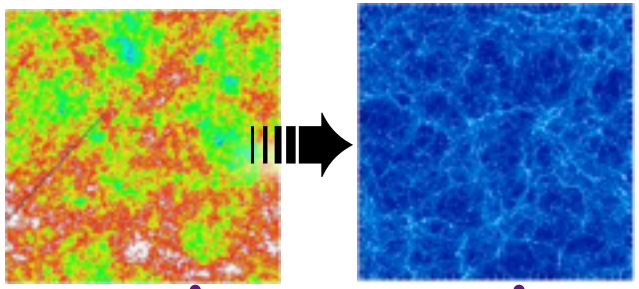
& how was it, is it & will it be distributed?

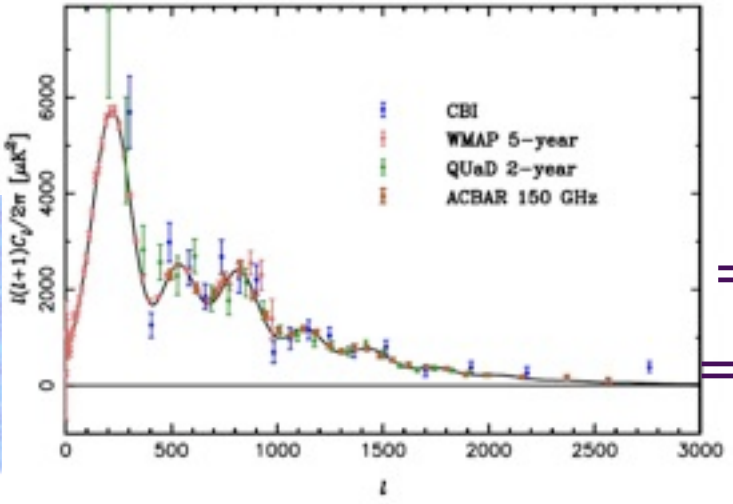
very early U early to middle to now U **very late U**

string theory/landscape/higher dimensions

inflation cyclic baryogenesis dark matter BBN γdec **dark energy**

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





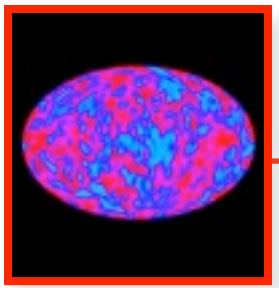
$V_{eff}(\psi_{inf})$?
$K_{eff}(\psi_{inf})$?

$\Rightarrow \rho_{dm}/\rho_b = 5.2$

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

cosmic mysteries

n_b/n_γ ρ_{dm}/ρ_b z_{eq}/z_{rec} ρ_{curv} ρ_{de}/ρ_{dm} $\rho_{de} \sim H^2M^2_{Planck}$ $\rho_{m\nu}/\rho_{stars}$

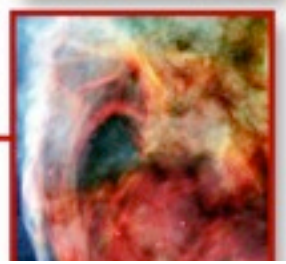


Radiation:
0.005%

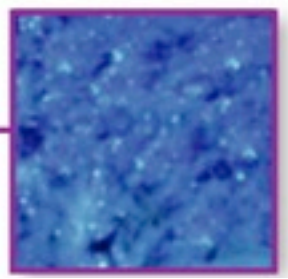
Chemical Elements:
(other than H & He) 0.025%

Neutrinos:
0.47%

Stars:
0.5%

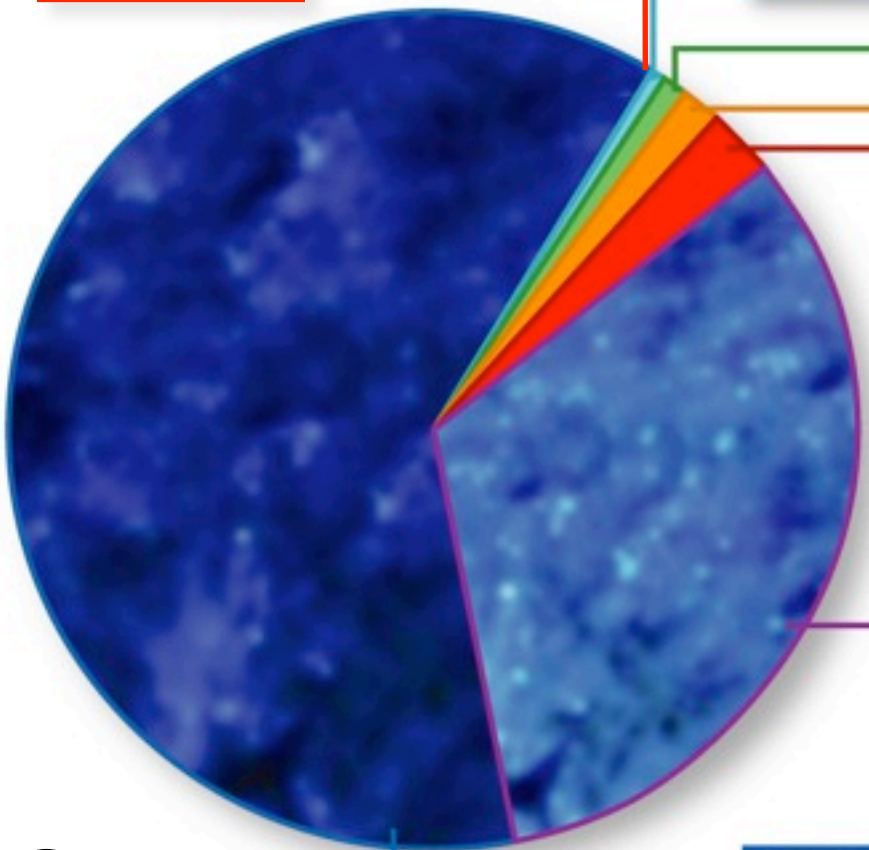


Free
H & He:
4.7%



Dark Matter:

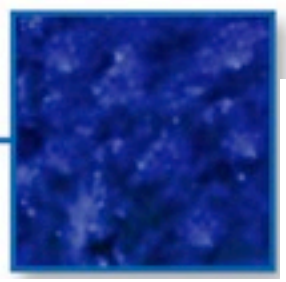
Ω_{dm}=24.5% ±4%



Ω_{curv} -0.6% ±0.6%

Ω_{GW} ~10^{-14} - 10^{-10} LIGO

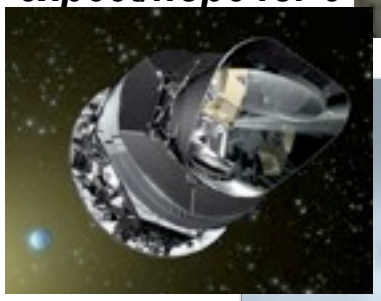
$\Omega_{BlackHoles}$ ~10^{-7}



Dark Energy:

Ω_{Λ} = 71% ± 2%

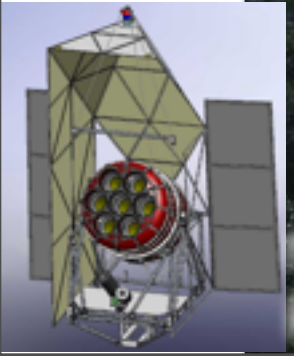
Planck Launch
May 14, 2009
in 2nd sky survey
expect/hope for 5



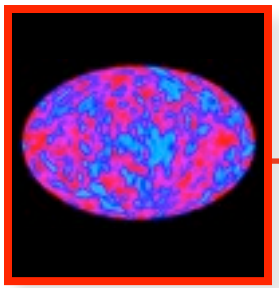
52 bolometers
+ HEMTs @L2
9 frequencies

ACTpol
3000 bolos
3 freqs @Chile

Spider
2312 bolos
@LDB 2011.9



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

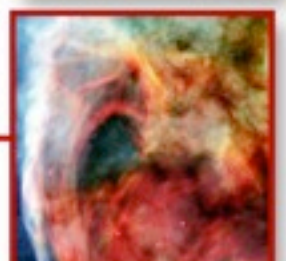


Radiation:
0.005%

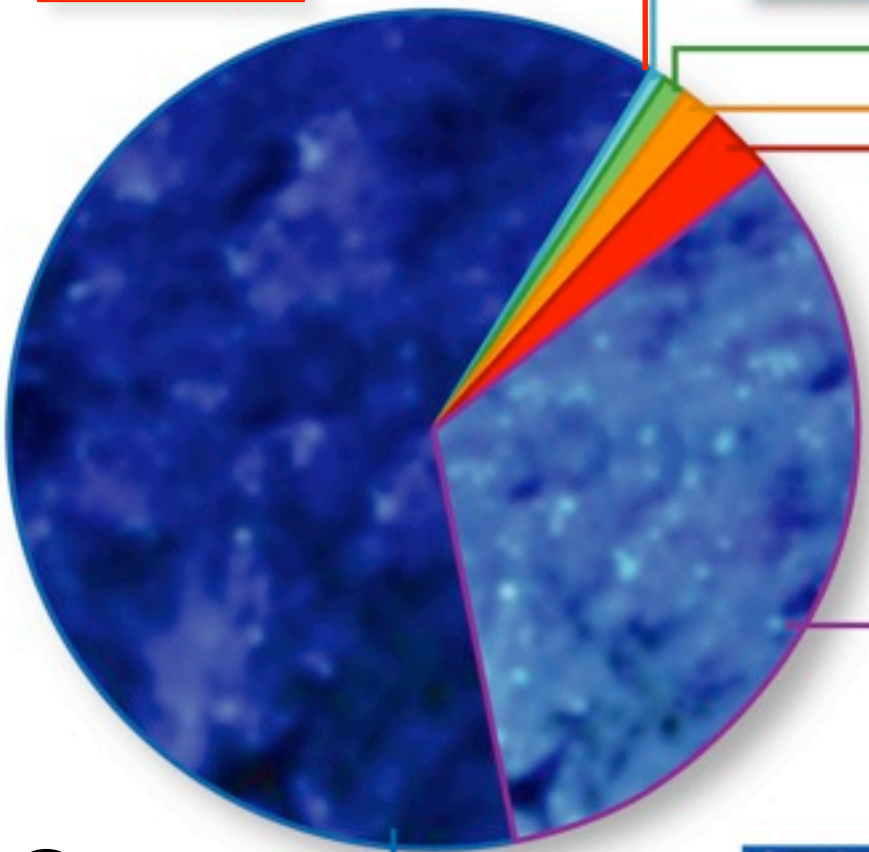
Chemical Elements:
(other than H & He) 0.025%

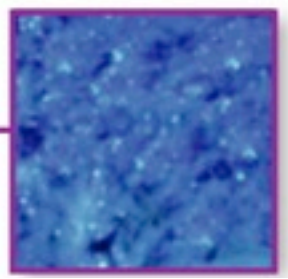
Neutrinos:
0.47%

Stars:
0.5%



Free
H & He:
4.7%





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⇒0.4%

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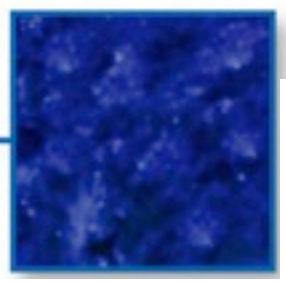
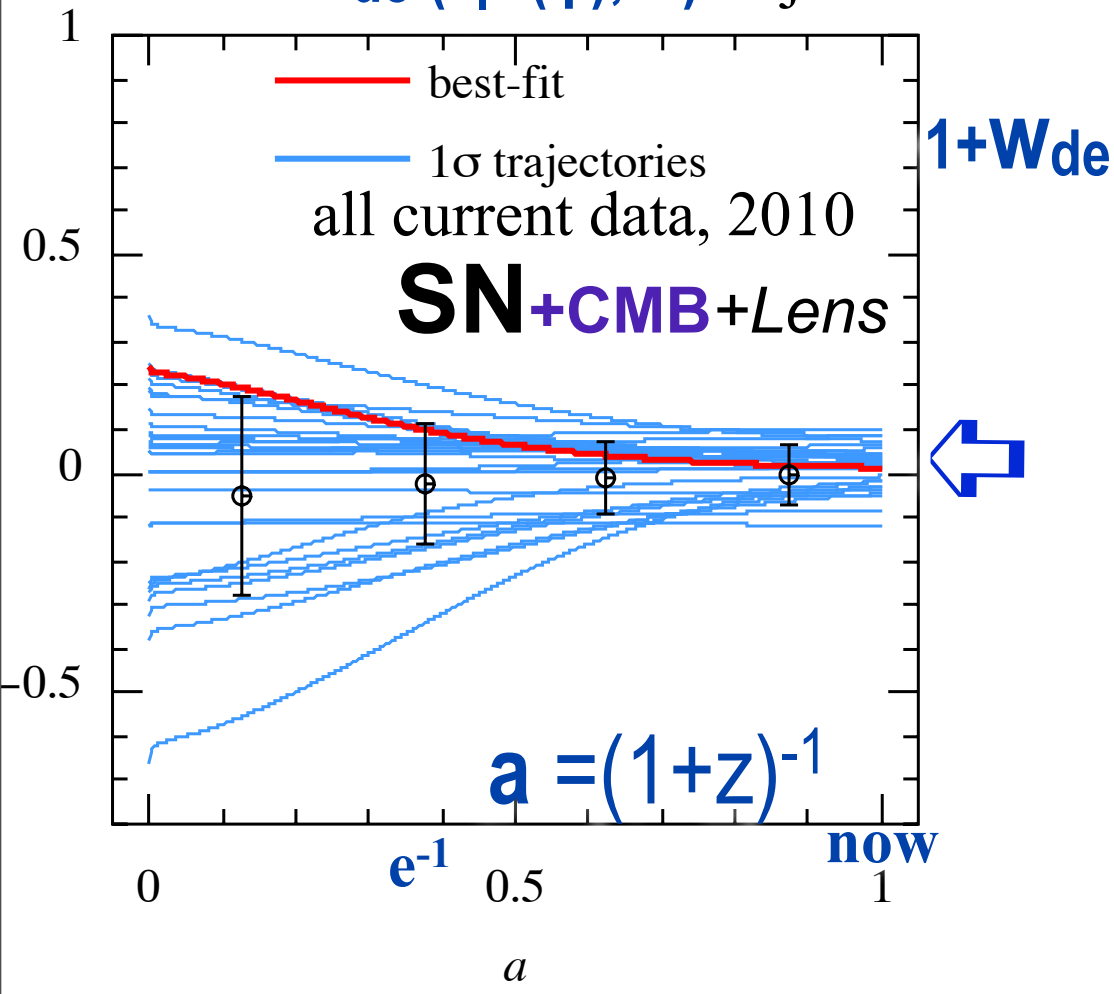


Dark Energy:

Ω_{Λ} = 71% ± 2% ⇒0.2%

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 ⇨Einstein's cosmological constant is best fit so far

is the dark energy "vacuum potential energy" ?

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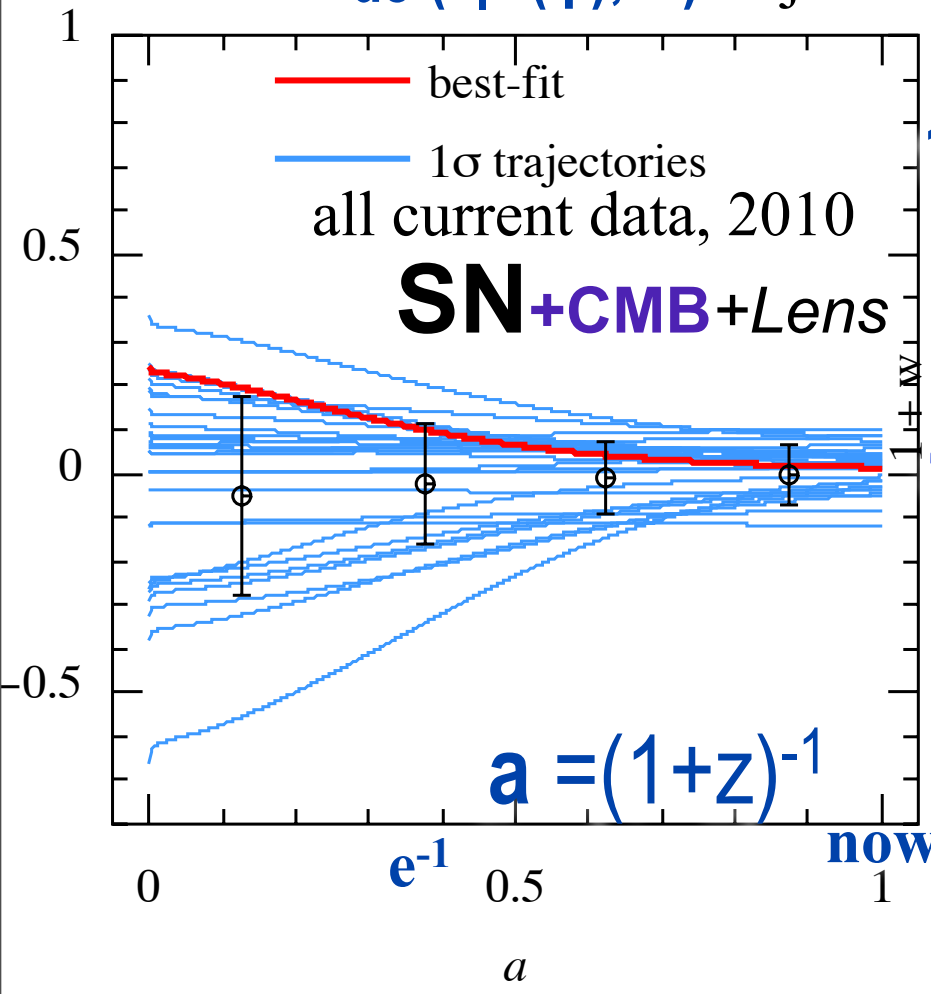
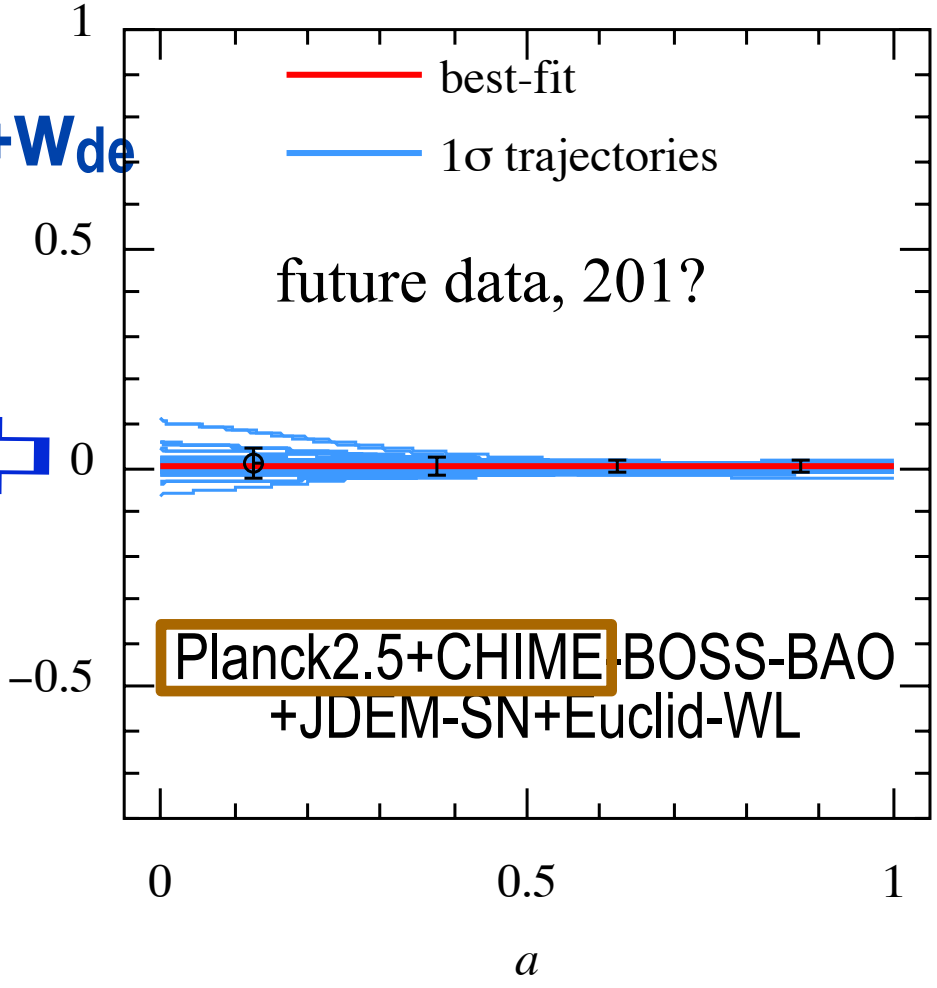


1+Wde



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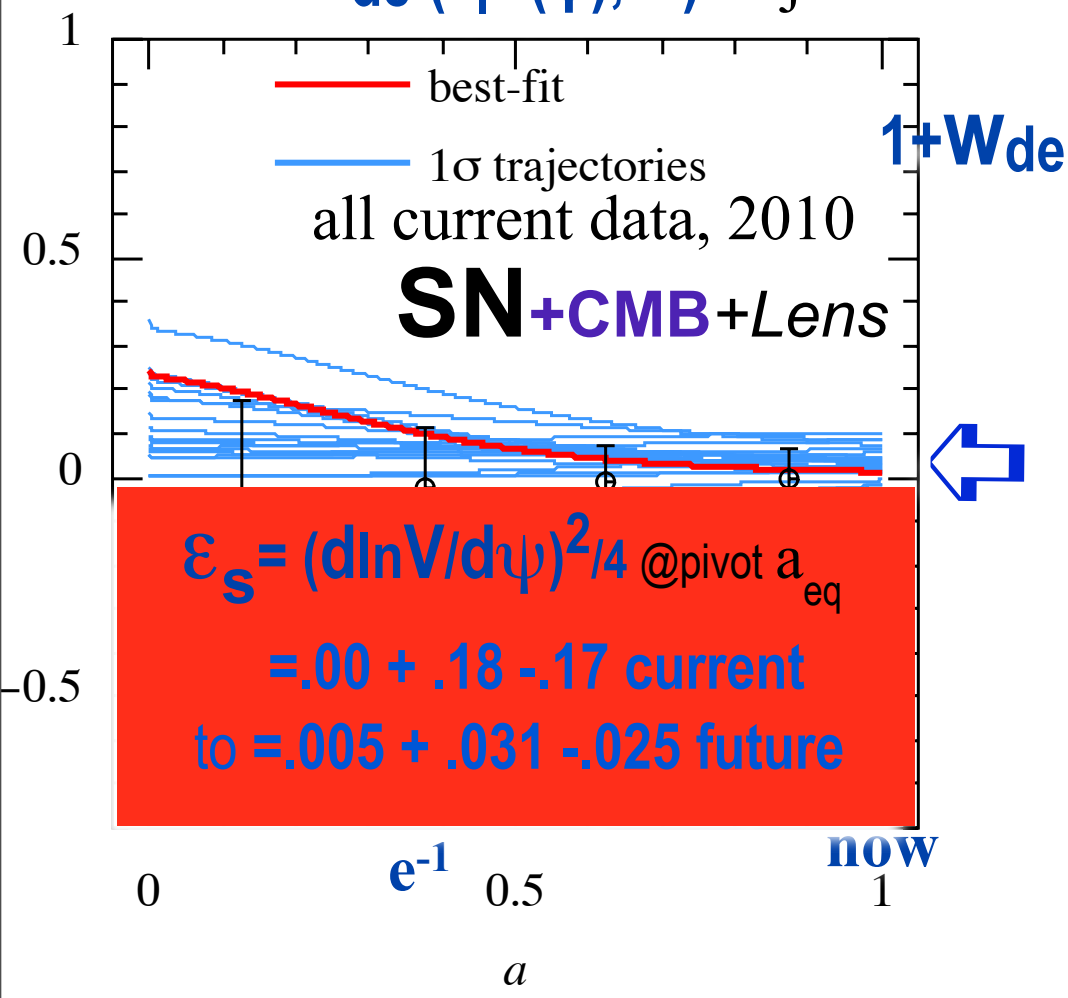

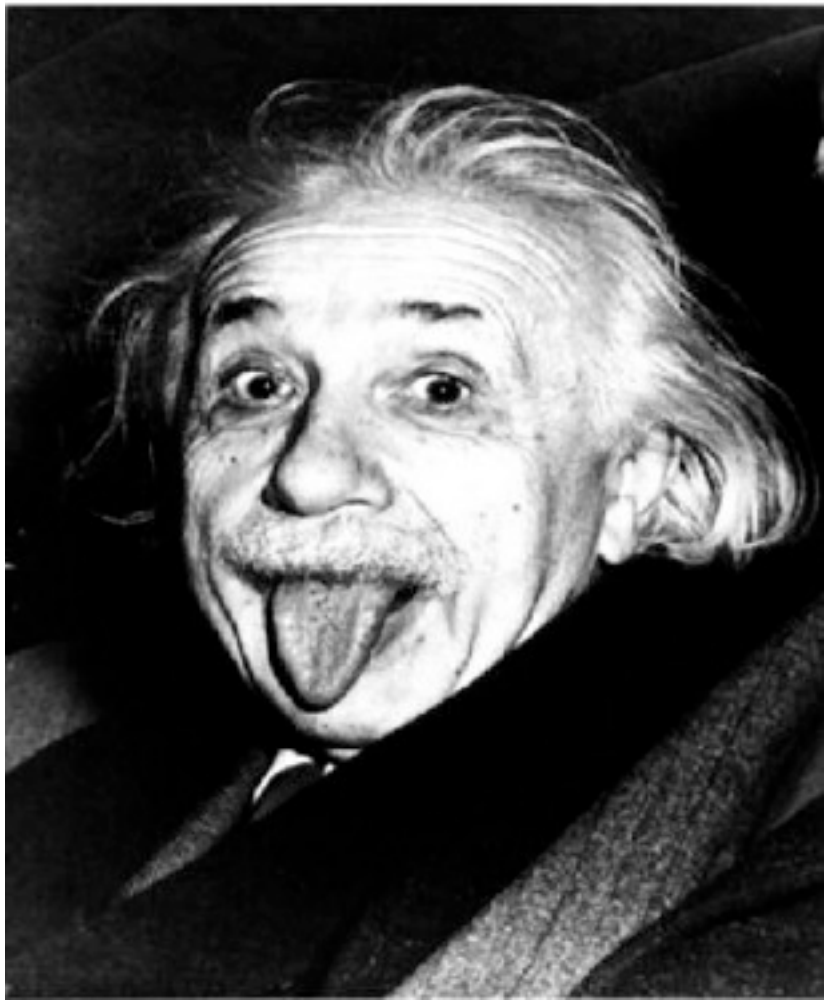

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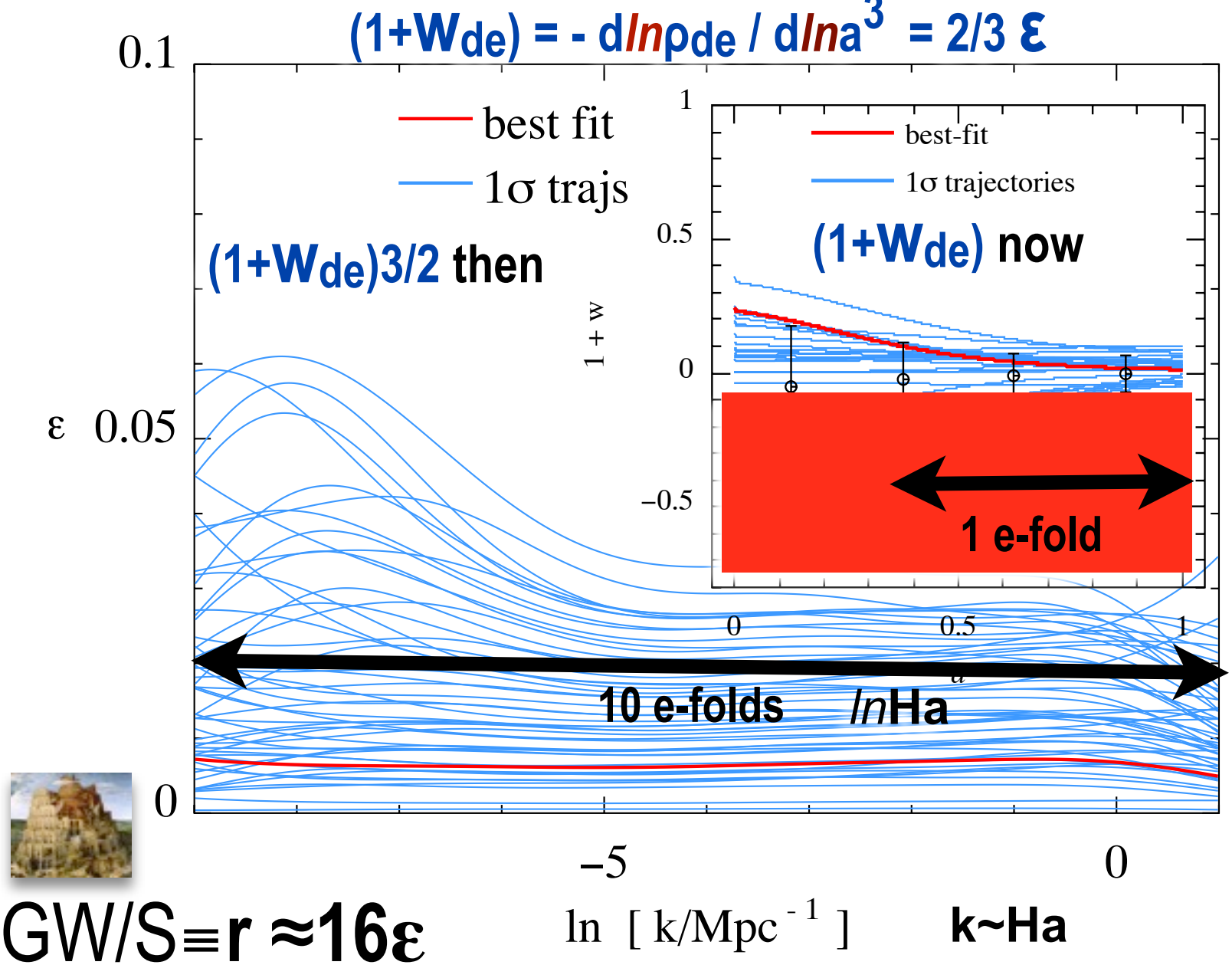
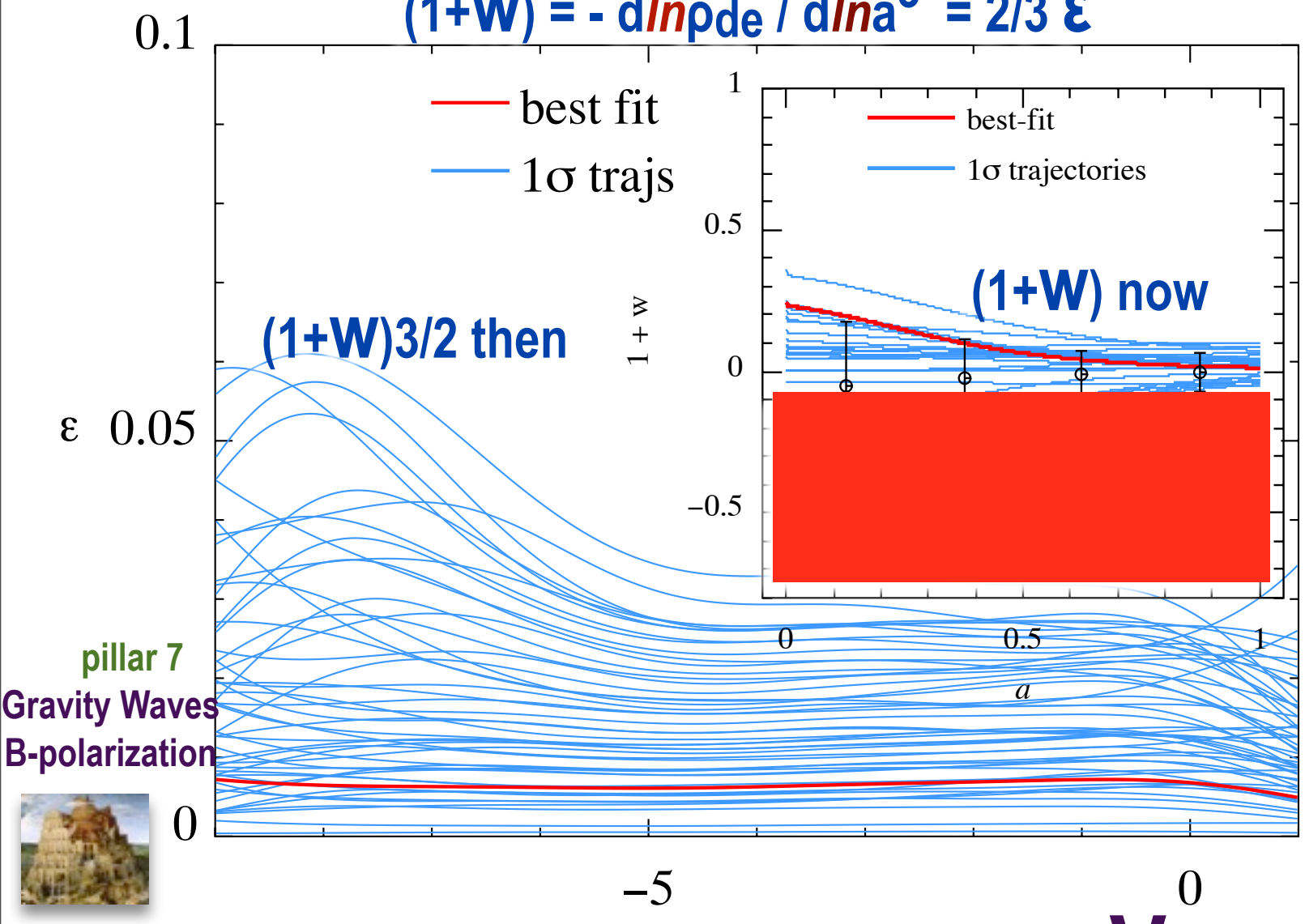
acceleration trajectories then & now



GW/S≡r ≈16ε

acceleration trajectories then & now



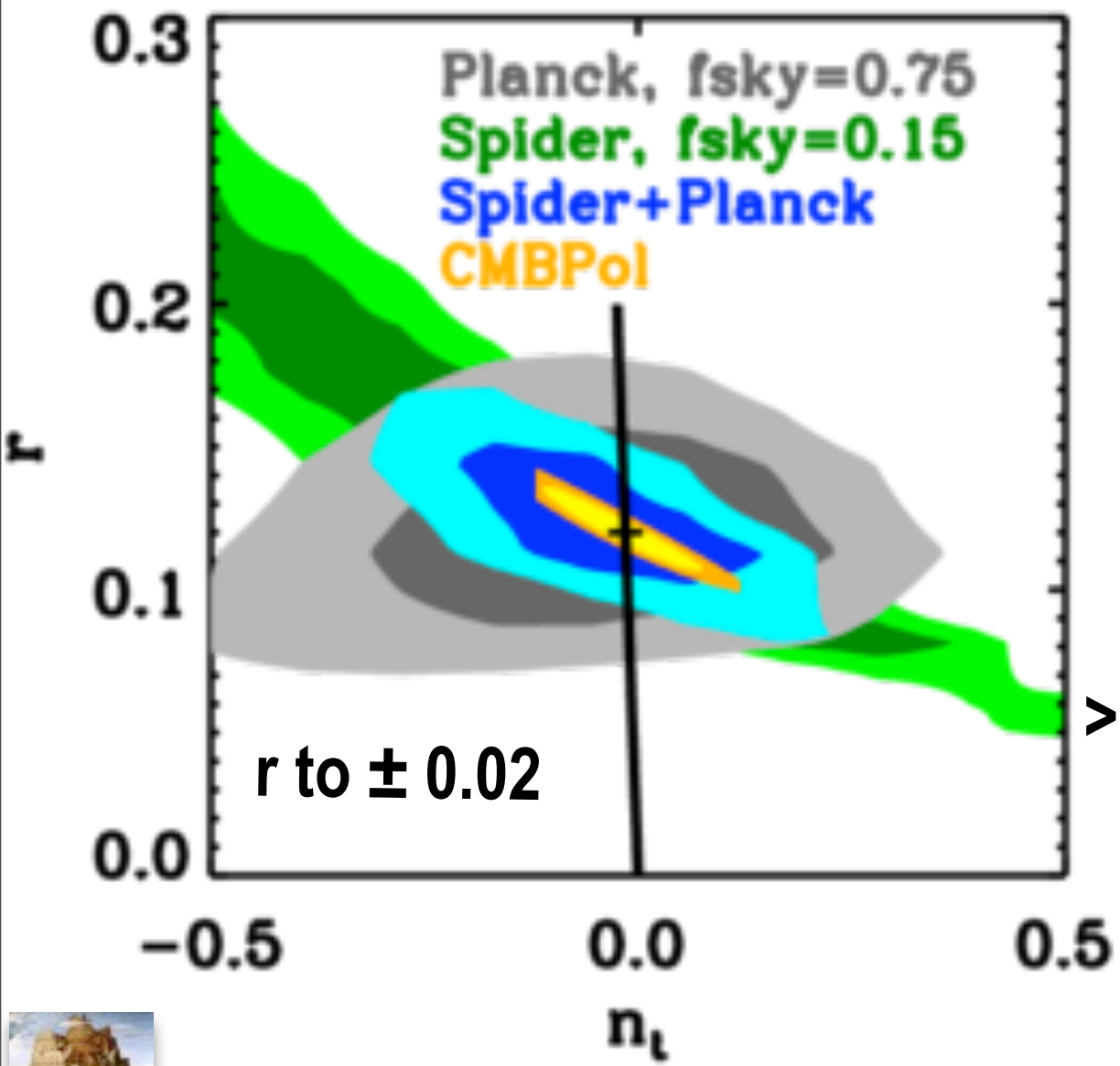
pillar 7
Gravity Waves
B-polarization

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

$r \approx 0.1 V / (10^{16} \text{Gev})^4$

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~0.03-0.3

$r \approx 0.13\ d\ln V/d\ln\psi^2$

e.g. r = 0.12 ± 0.02

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

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

e.g. r<0.02 95% CL

+ Pillar 4: primordial non-Gaussianity $-9 < f_{NL} < 111$ (+- 5-10 Planck1)

end