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

CIAR 25 years cifar

the Cosmology of now & then through first light

Dick Bond Canadian Institute for Theoretical Astrophysics, University of Toronto

Cosmic history: what is U made of?

How Structure in the Universe Arose:

Inflation & the Cosmic Web

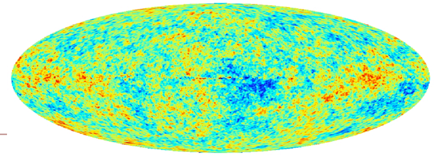
CMB & *x*CDM, *x*=Λ+*tilt*,

status@Sept08

is there a y to x?@Sept11

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

WMAP 2003



WMAP03,06,08

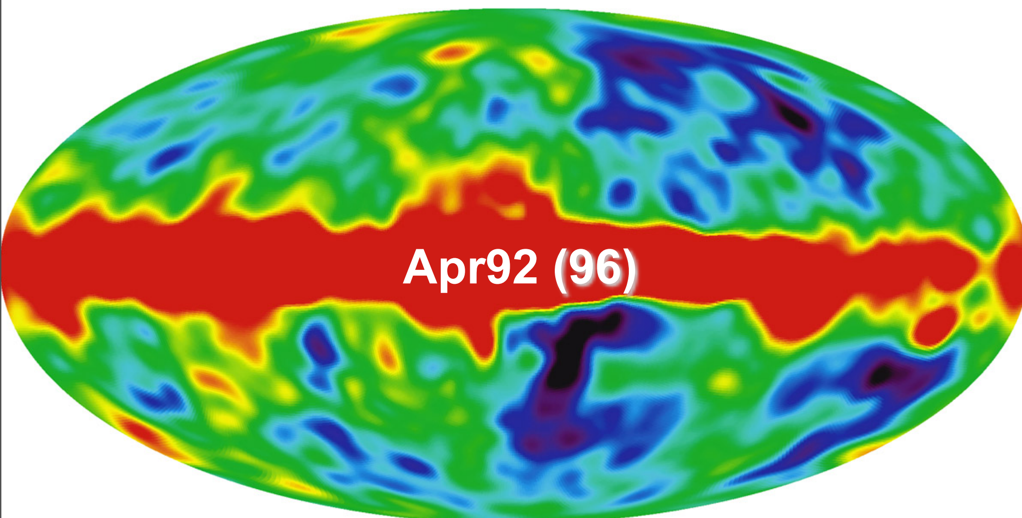
CIAR 25 years cifar

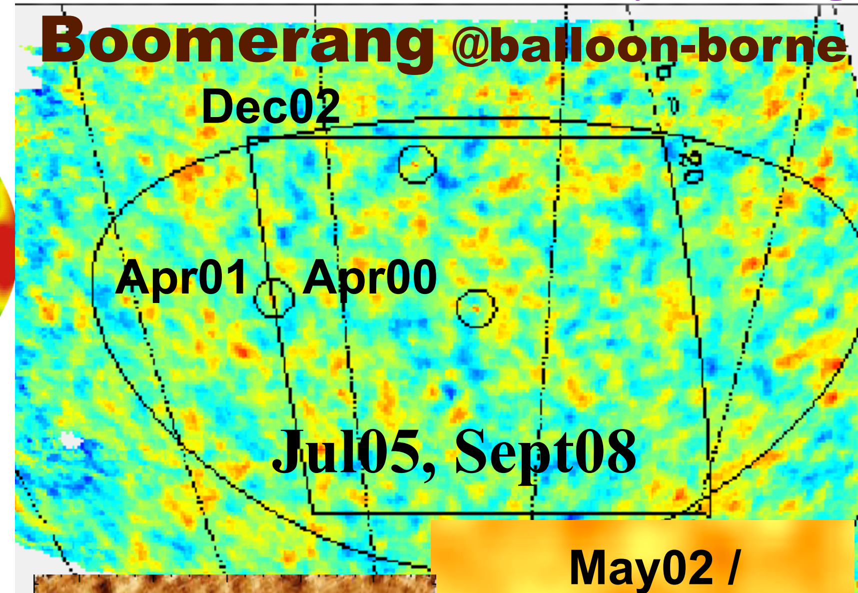
the Cosmology of now & then through first light

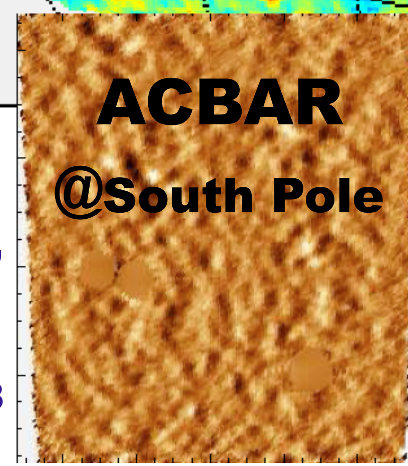
Dick Bond Canadian Institute for Theoretical Astrophysics, University of Toronto

COBE Nobel+Gruber 2006

13.65 -0.00038 billion years ago







Cosmic history: what is U made of?

How Structure in the Universe Arose:

Inflation & the Cosmic Web

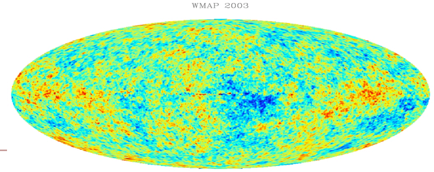
CMB & *x*CDM, *x*=Λ+*tilt*,

status@Sept08

is there a y to x?@Sept11

Dec02, Oct06, Jan08, Sept08

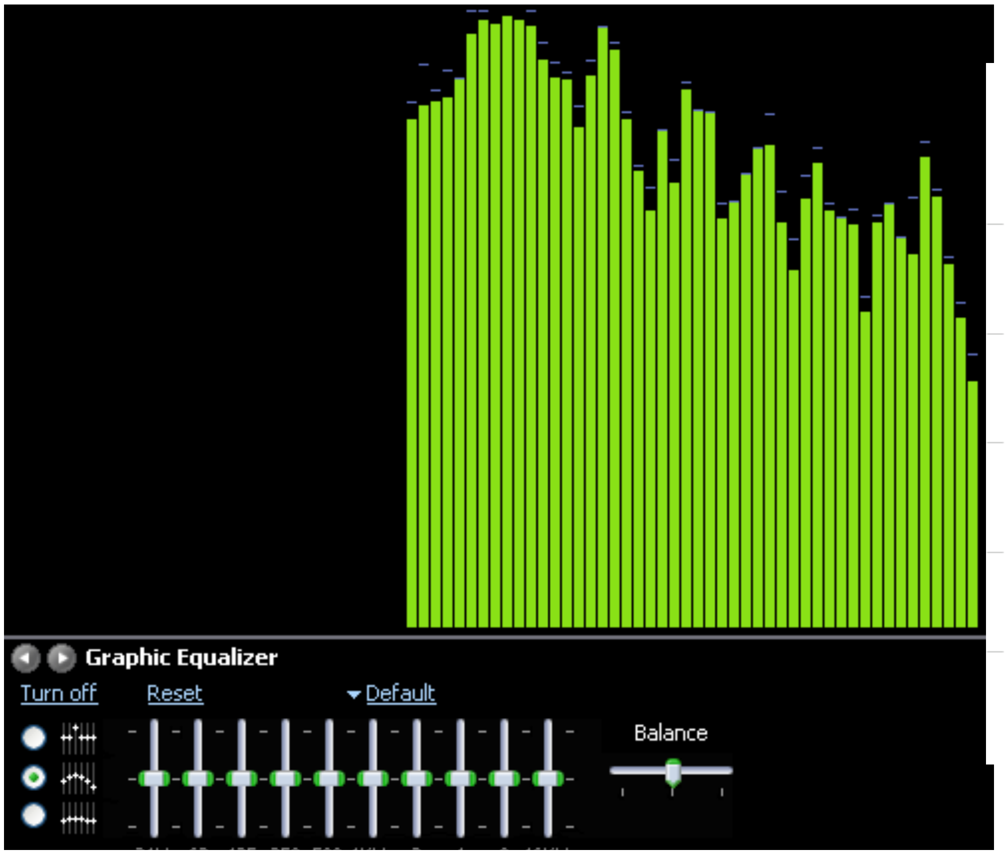
CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique theorique

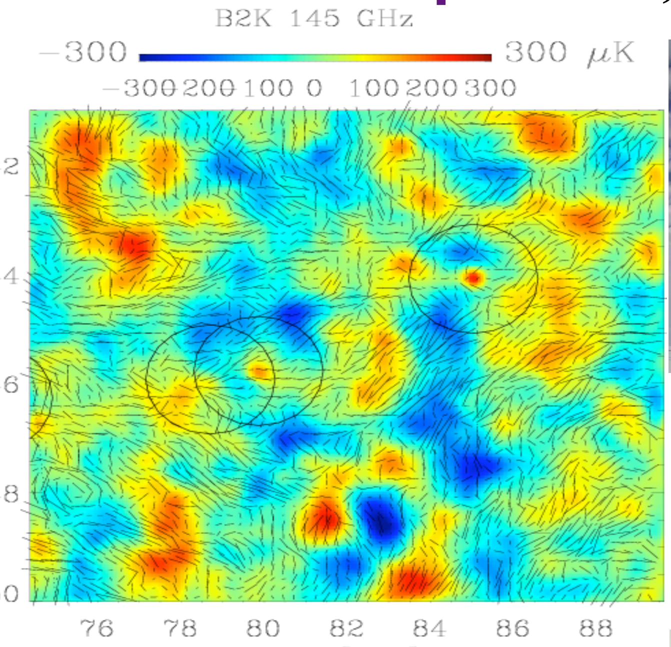


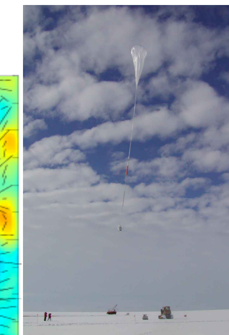
CIAR 25 years cifar

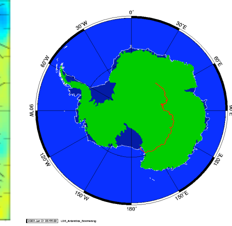
13.65 -0.00038 billion years ago

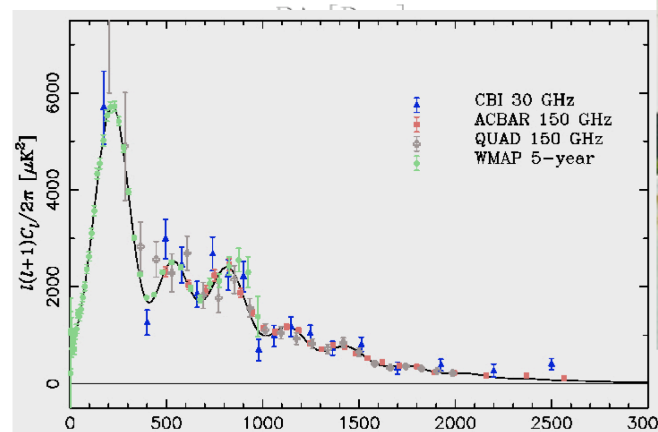
Boom05 deep **Jul05, Sept08**

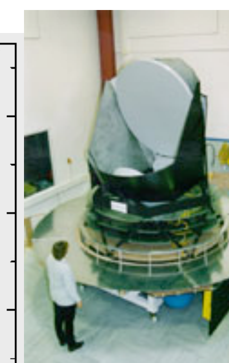




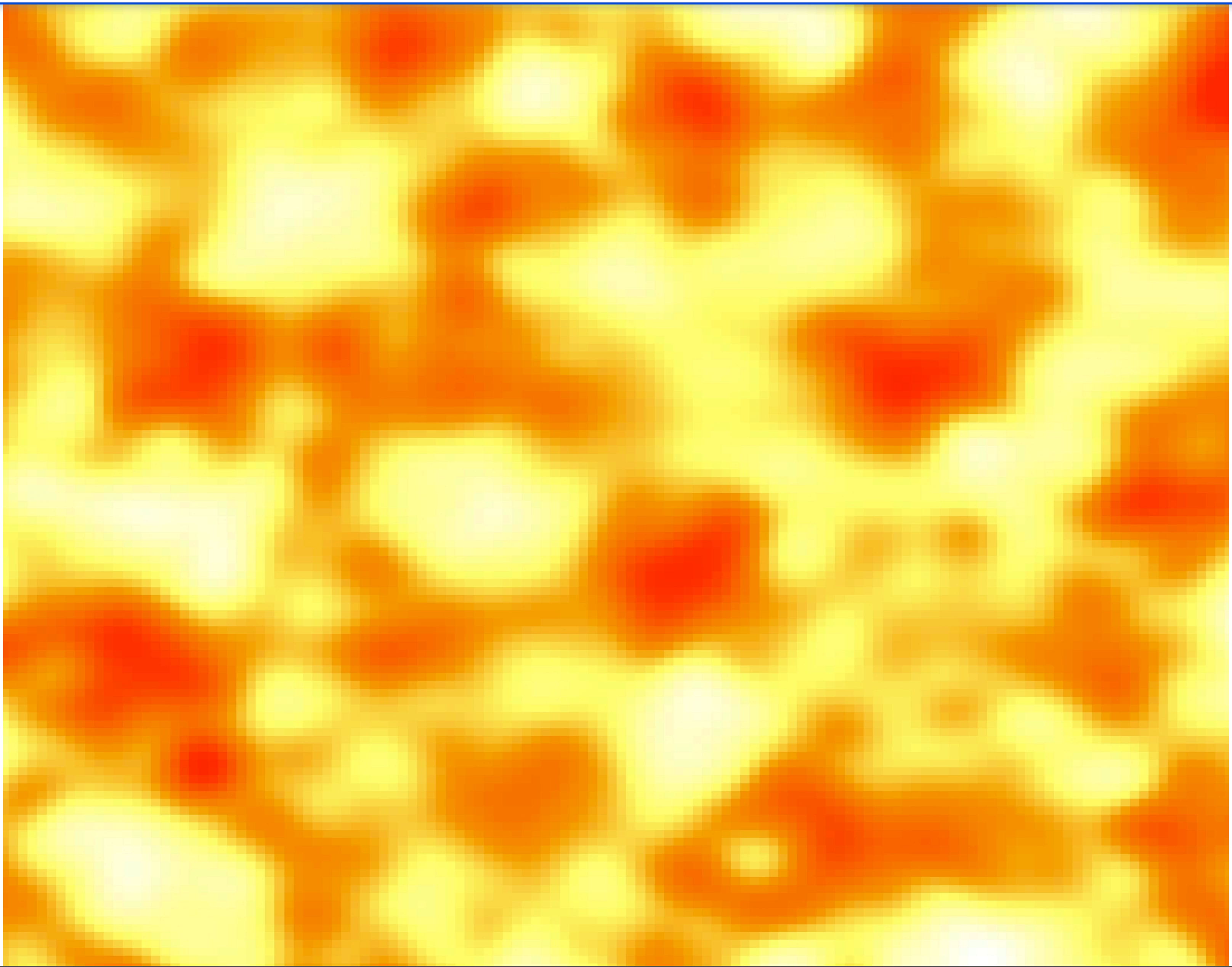




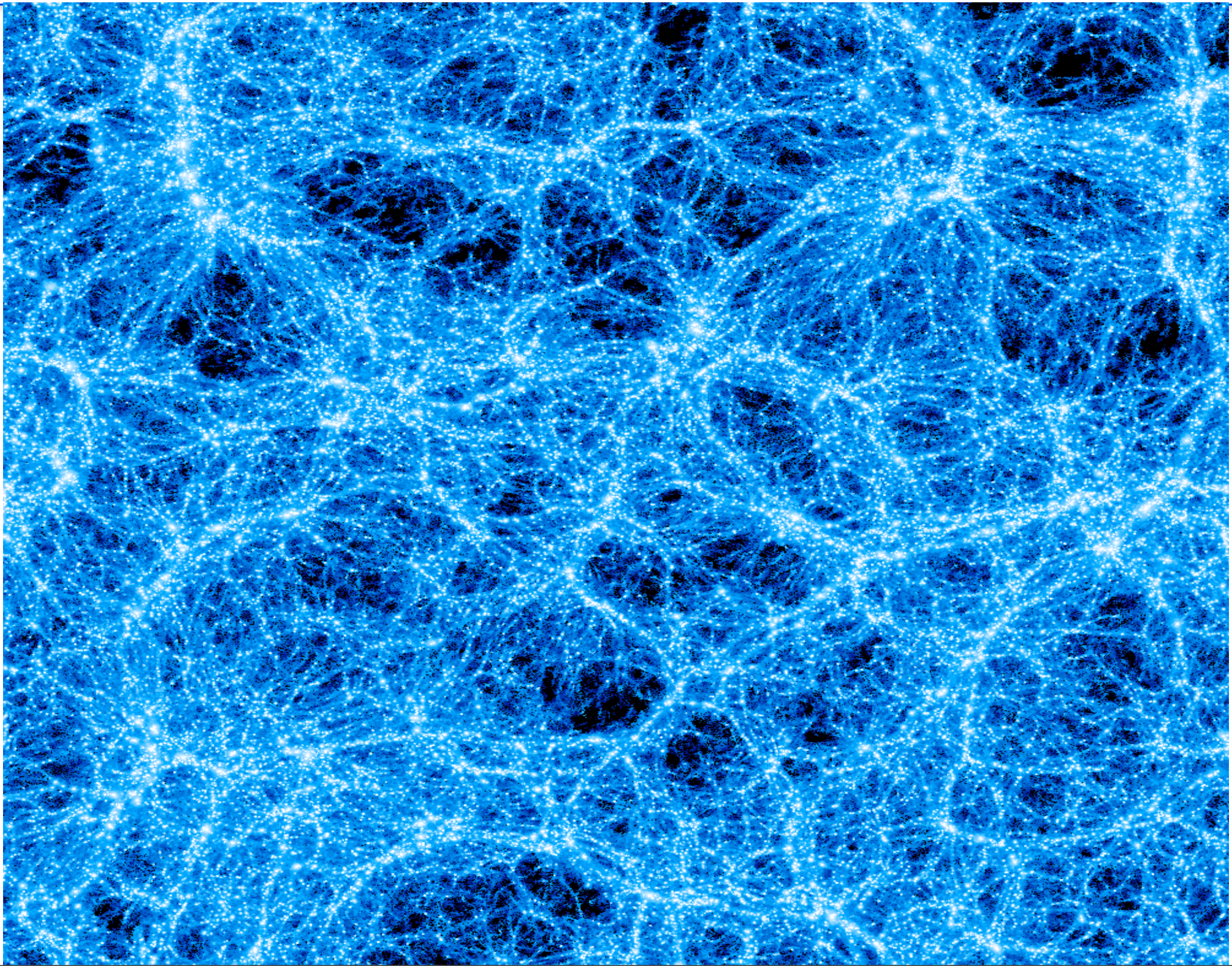




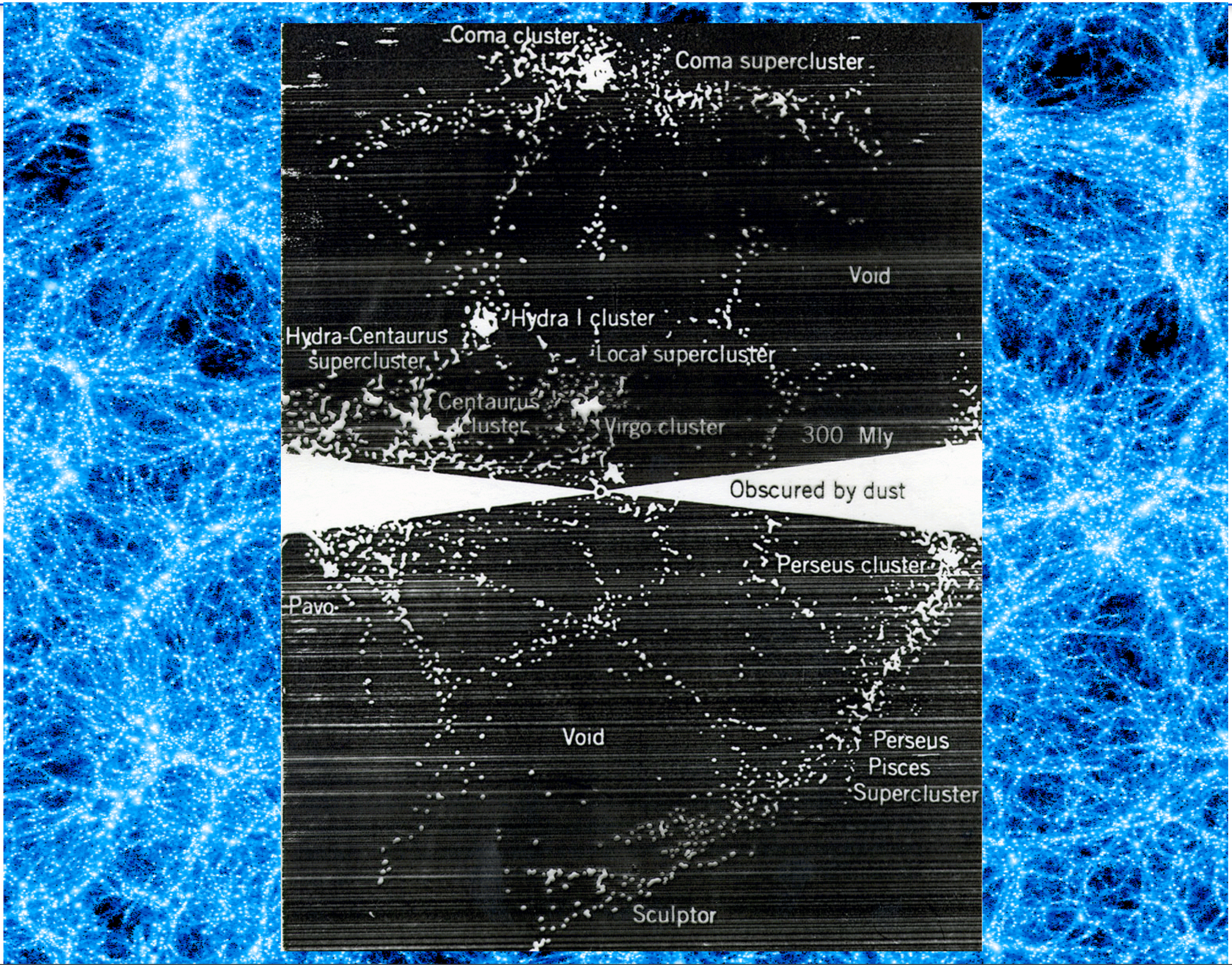
nonlinear Gas & Dark Matter Structure in the Cosmic Web the cluster/gp web "now", the galaxy/dwarf system "then"

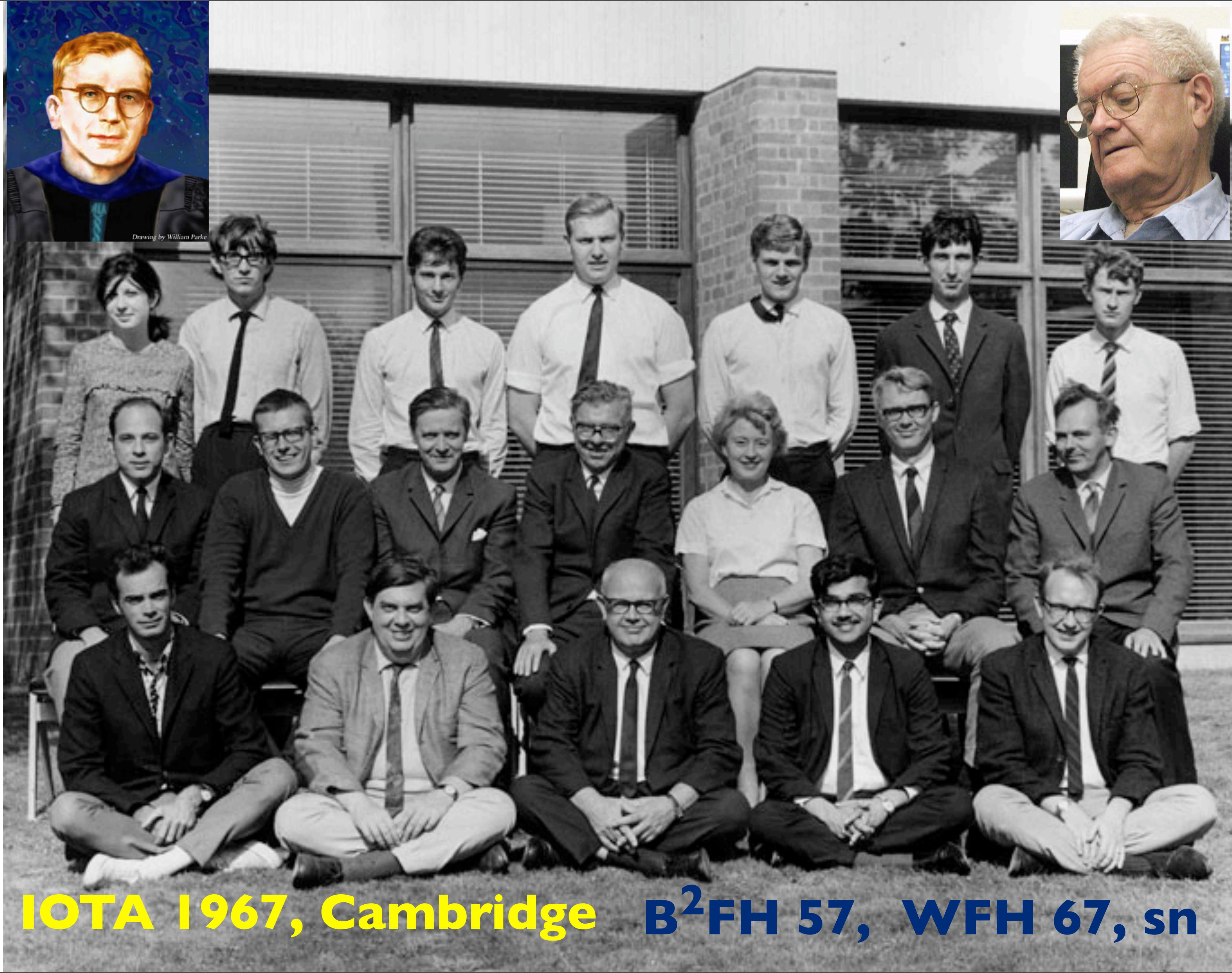


nonlinear Gas & Dark Matter Structure in the Cosmic Web the cluster/gp web "now", the galaxy/dwarf system "then"



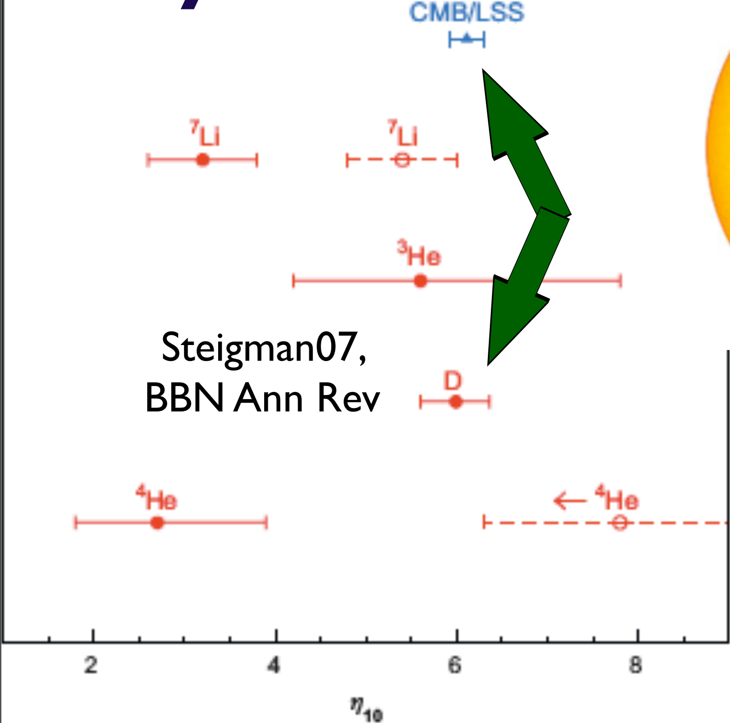
nonlinear Gas & Dark Matter Structure in the Cosmic Web the cluster/gp web "now", the galaxy/dwarf system "then"



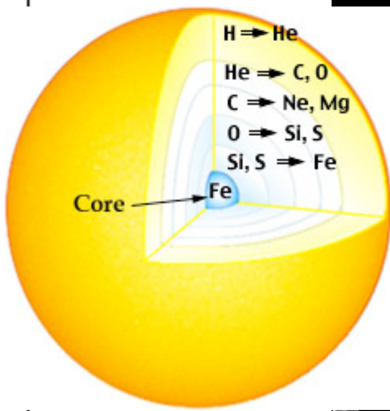


IOTA 1967, Cambridge **B^{2}FH 57, WFH 67, sn**

Baryometers



Steigman07,
BBN Ann Rev



Nobel Prize 84 Willy Fowler + Chandra -sekhar

$$\eta_{10} \equiv 10^{10}(n_B/n_\gamma) \equiv 274\ \Omega_B h^2$$

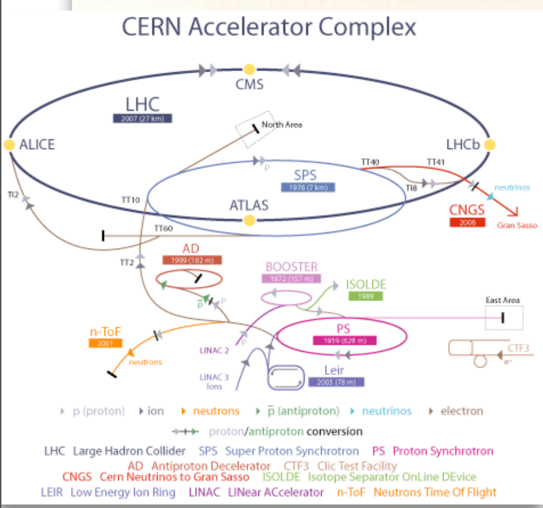
	January 2000	January 2002	June 2002	January 2003	March 2003
$\Omega_b h^2$	$0.0339^{+0.0443}_{-0.0246}$	$0.0222^{+0.0025}_{-0.0021}$	$0.0221^{+0.0024}_{-0.0020}$	$0.0221^{+0.0023}_{-0.0018}$	$0.0233^{+0.0013}_{-0.0013}$

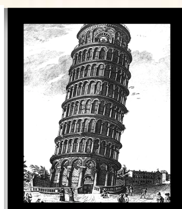
0.0223 ± 0.0007

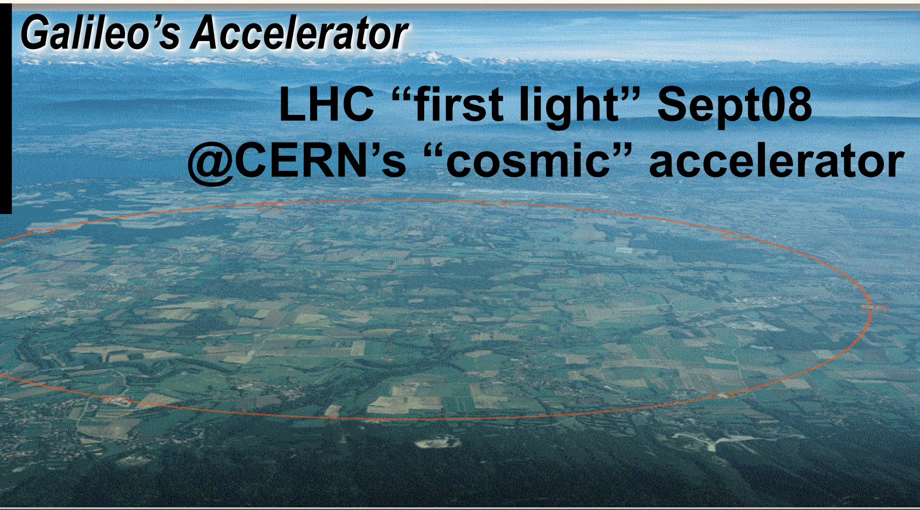
0.0226 +- 0.0006 wmap3+acbar+cbi+... LSS

0.0233 +- 0.0005 wmap5+acbar+cbi+b03+.+WL+LSS+SN1+Lya

extra-“ordinary” matter





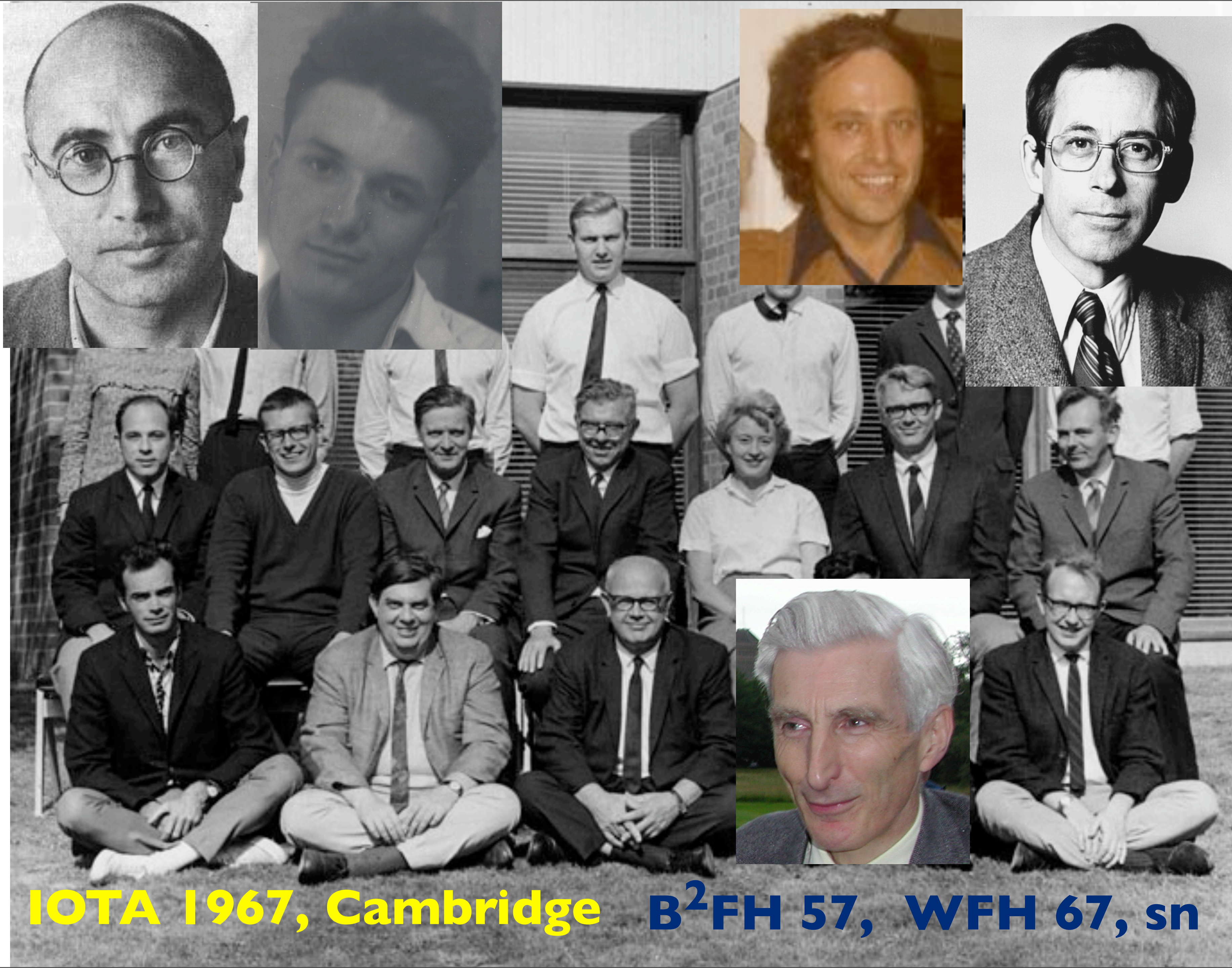


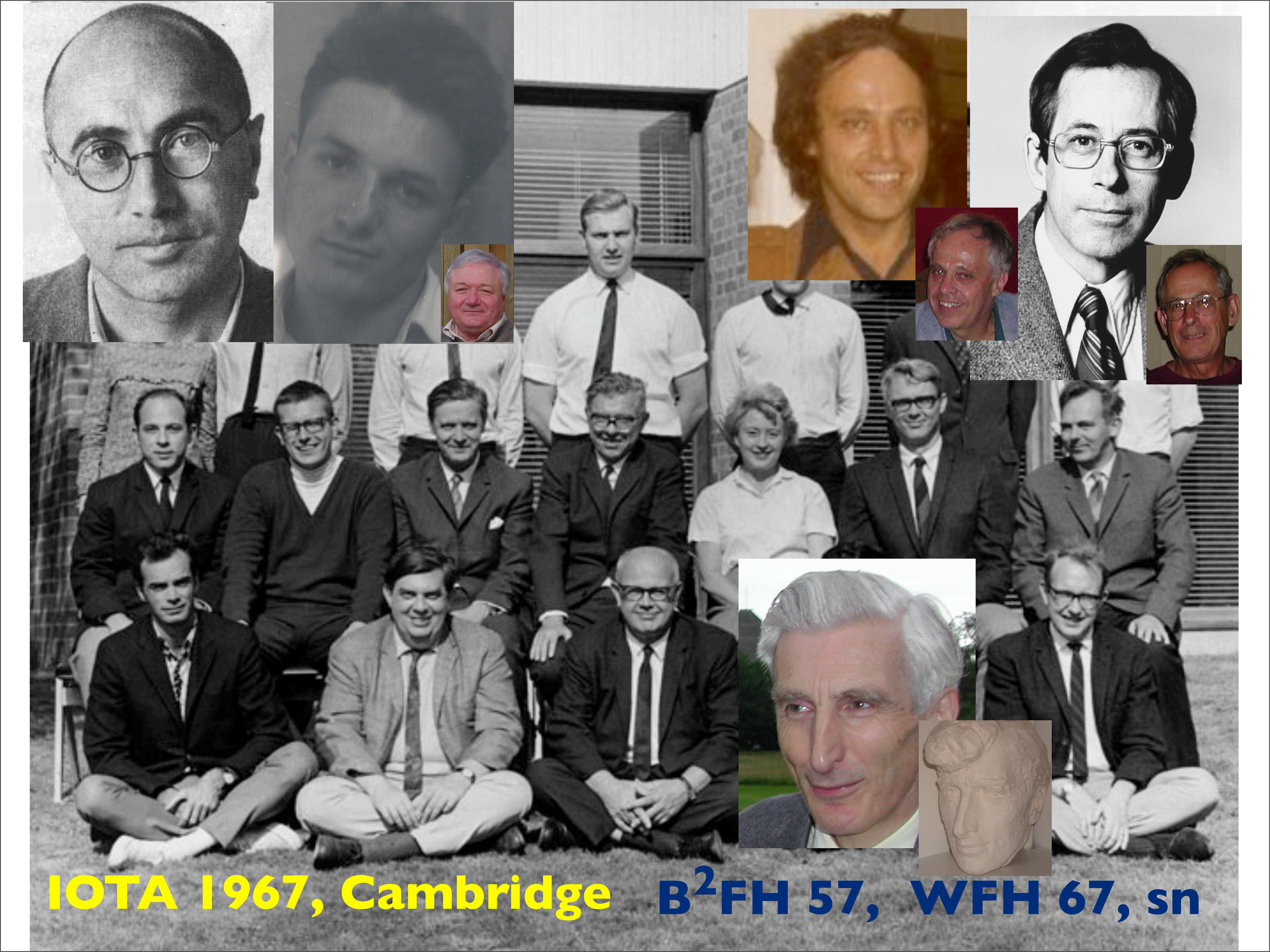
what is mass?

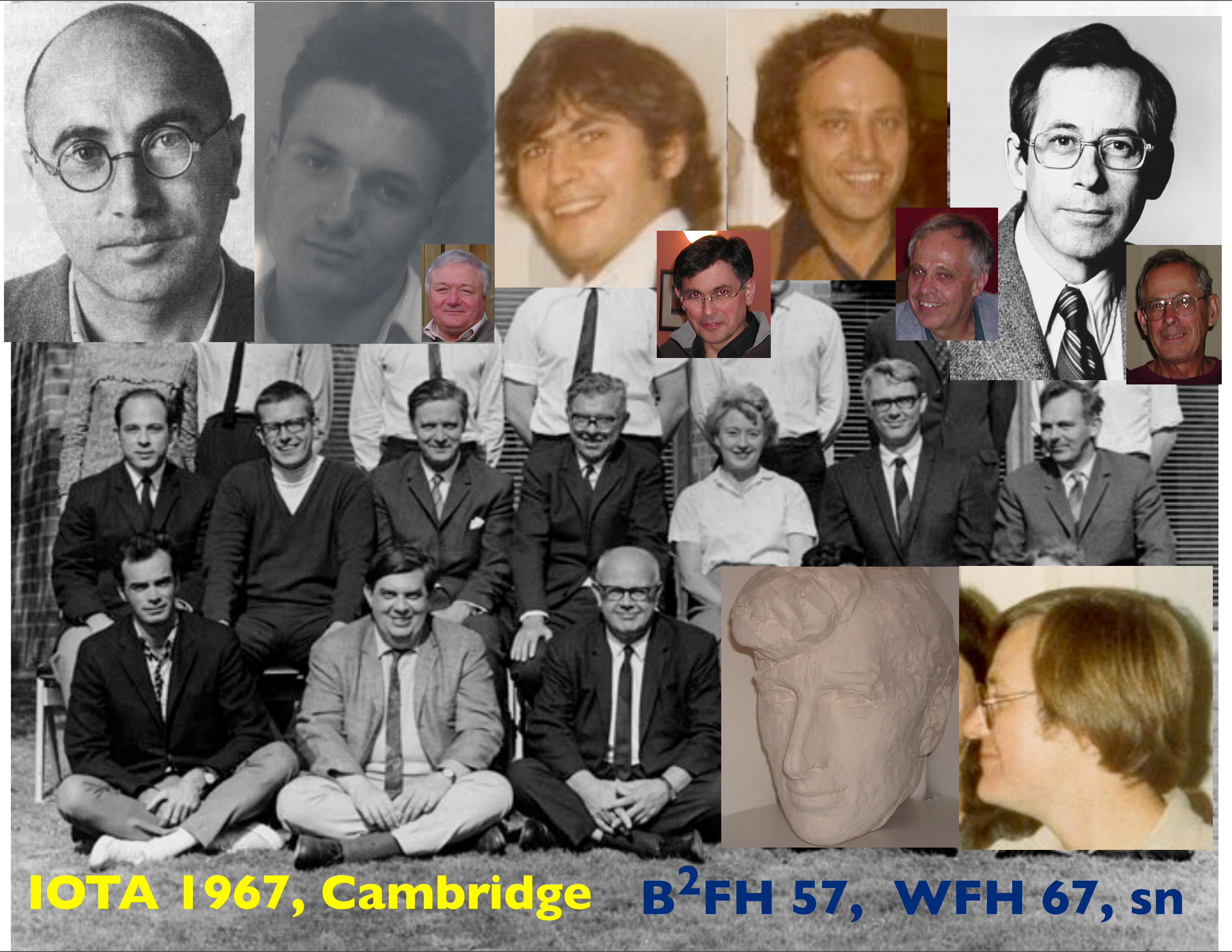
dark matter

antimatter asymmetry

extra dimensions


IOTA 1967, Cambridge
B2FH 57, WFH 67, sn


IOTA 1967, Cambridge
B^{2}FH 57, WFH 67, sn


IOTA 1967, Cambridge
B²FH 57, WFH 67, sn

DELTA T OVER TEA WORKSHOP

1-2 May, 1987
Toronto, Canada

Sponsored by
The Canadian Institute for Theoretical Astrophysics and
The Canadian Institute for Advanced Research

Topics

Present and Future Experiments of Cosmic Microwave Background Anisotropies and Their Theoretical Interpretation on very small ($< 1'$), *small* ($1' - 1^o$), *intermediate* ($1^o - 10^o$) *and large* ($> 10^o +$ *multipole*) *angular scales*

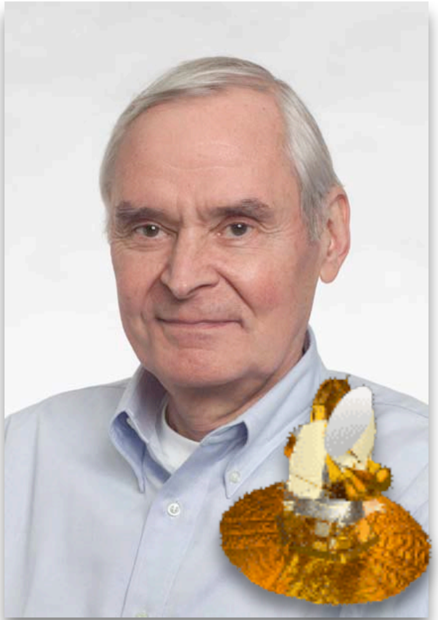
Contact: Dick Bond
CITA, McLennan Labs, University of Toronto
60 St George St., Toronto, Ontario, Canada, M5S 1A1
Phone (416) 978 6879 or 6874
Bitnet BOND@UTORPHYS

Organizers: J.R. Bond (CITA), D.T. Wilkinson (Princeton)

Delta T over Tea Workshop Participants

Bennett, Chuck, Goddard
Birkinshaw, Marc, Harvard *
Bond, Dick, CITA
Boughn, Steve, Haverford
Boynton, Paul, University of Washington
Cannizzo, John, McMaster
Carlberg, Ray, York
Cheng, Ed, MIT
Couchman, Hugh, CITA
Cottingham, David, Princeton
Daly, Ruth, Boston U
Davies, Rod, Jodrell Bank
Davis, Marc, Berkeley
Dragovan, Marc, Bell Labs
Dyer, Charles, U of Toronto
Efstathiou, George, Cambridge
Fitchett, Mike, CITA
Fomalent, Ed, NRAO
Gorski, Chris, Berkeley
Gulkis, Sam, Caltech
Gush, Herb, UBC
Halpern, Marc, UBC
Ip, Peter, U of Toronto
Juszkiewics, Roman, Berkeley
Henriksen, Dick, Queens
Kaiser, Nick, Cambridge
Kellerman, K, NRAO
Kronberg, Phil, Toronto
Lang, Andrew, Berkeley
Lasenby, Anthony, Cambridge
Lawrence, Charles, Caltech
Lee, Hyung-Mok, CITA
Legg, Tom, Herzberg Institute, Ottawa
Little, Blaine, Toronto
Lubin, Phil, Santa Barbara
Matarrese, Sabino, Padova
Mather, John, Goddard
Meyer, Steve, MIT
Meyers, Steve, Caltech
Moseley, Harvey, Goddard
Nelson, Lorne, CITA
Noriega-Crespo, Alberto, CITA
Occhionero, F., Rome *
Ostriker, Jerry, Princeton
Page, Lyman, MIT
Partridge, Bruce, Haverford
Peterson, J.B., Princeton
Radford, Simon, IRAM, France
Readhead, Tony, Caltech
Richards, Paul, Berkeley
Salopek, Dave, Toronto
Sargent, Wal, Caltech *
Schaeffer, Bob, Goddard
Silk, Joe, Berkeley
Silverberg, Bob, Goddard
Stebbins, Albert, Fermilab
Suto, Yasushi, Berkeley
Timby, Peter, Princeton
Tremaine, Scott, CITA
Timusk, Tom, McMaster
Unruh, Bill, UBC
Vishniac, Ethan, U. Texas Austin
Vittorio, Niccolo, Rome
Wilkinson, Dave, Princeton
Webster, Rachel, Toronto

Dave Wilkinson



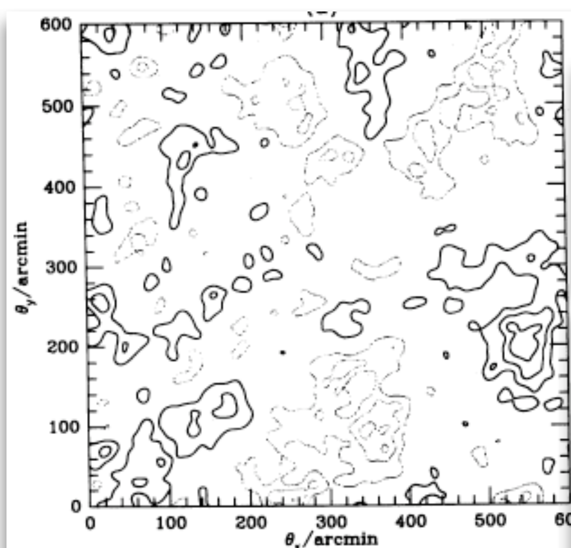
Wilkinson Microwave Anisotropy Probe

first dedicated CMB conference, exptalists+theorists, primary+secondary $\Delta T/T$

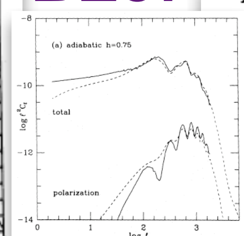
The focus of the meeting will be how best to mesh theory with results from current and future experiments to constrain models of the Universe. This is to be an experts' meeting so we can immediately get down to business. We believe that there are not enough opportunities for the experimentalists and theorists in this field to work together intensively on analysis procedures for the experiments which are approaching discovery level sensitivity for a large class of cosmological models. This workshop is meant to partially satisfy that

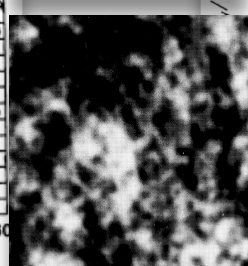
A tentative list of topics organized according to angular scale, with theory and observation intertwined, is:

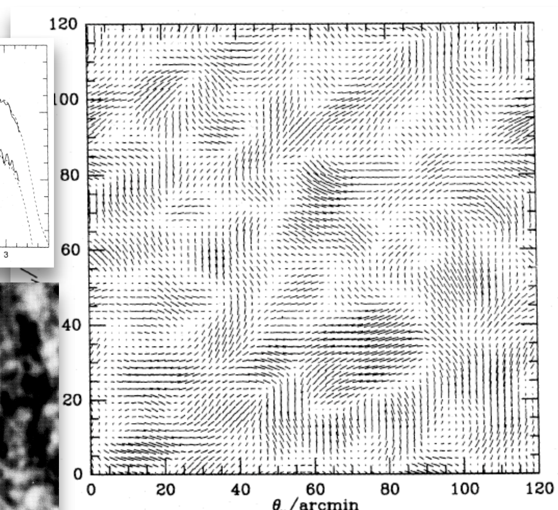
- very small angle anisotropies - VLA results, secondary fluctuations via the Sunyaev-Zeldovich effect, primeval dust emission, and radio sources
- small angle anisotropies - current results, optimal measuring strategies, statistical methods for small signals in larger noise, which universes can we rule 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.



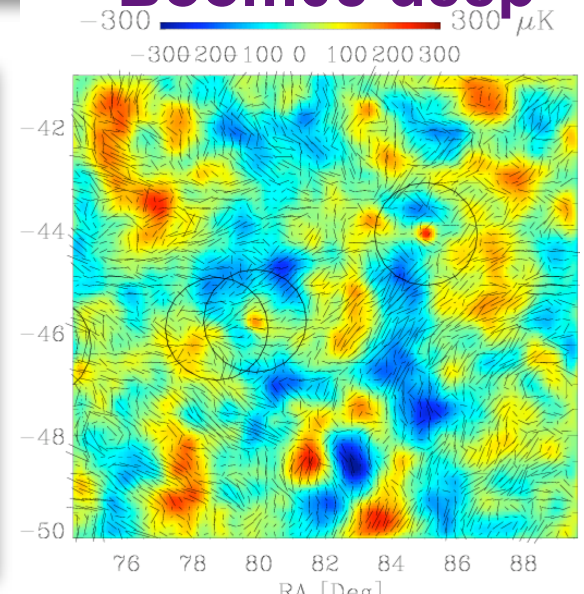
BE87



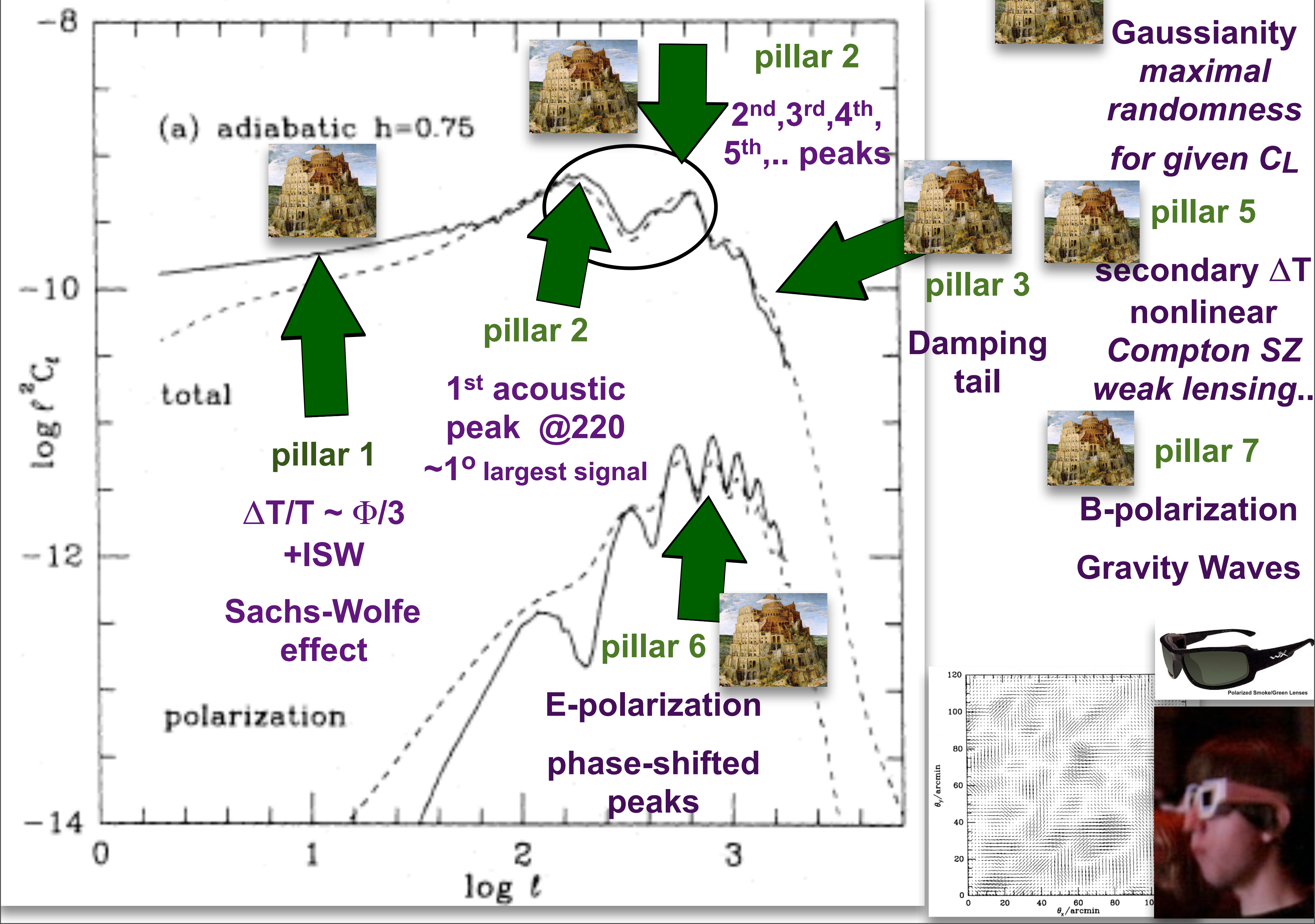




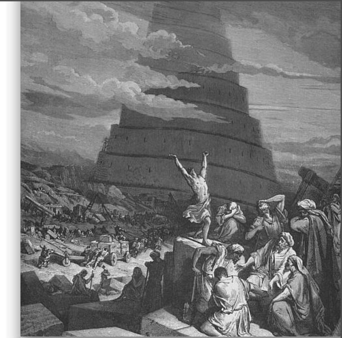
Boom05 deep



the “Seven Pillars”



COSMIC PARAMETERS THEN



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

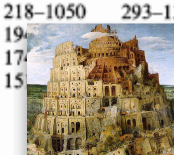
for *x*CDM, predict CMB (6deg, 5min); LSS cluster-cluster, cluster-galaxy, bulk flows,
σ_8: redshift of "galaxy formation"

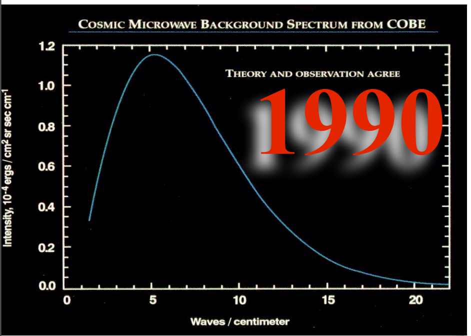
14 Gyr, Ω_Λ=0.8, H0=75, b~c,
50μK cf 30μK cobe, σ_8~0.72

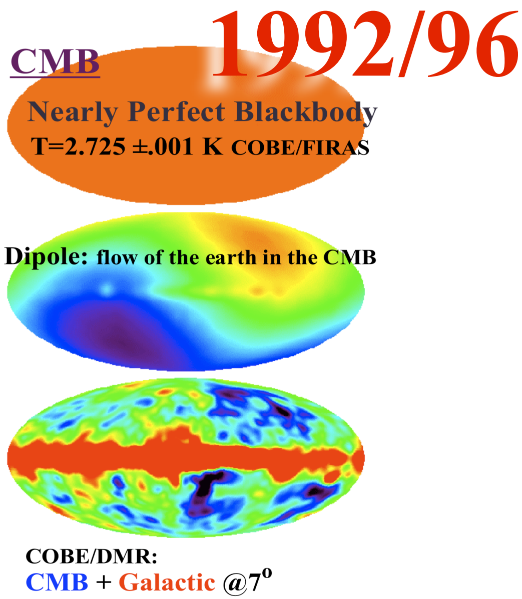
x= s /H0 / Λ / Open/ is /is+ad/ h-c/ h+/ b/ b / Λ+b / Op+b /τ /BSI /BSI2

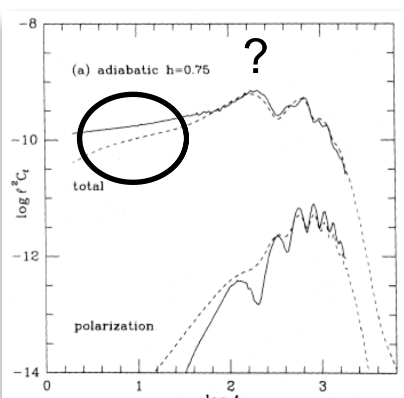
Predictions for Models

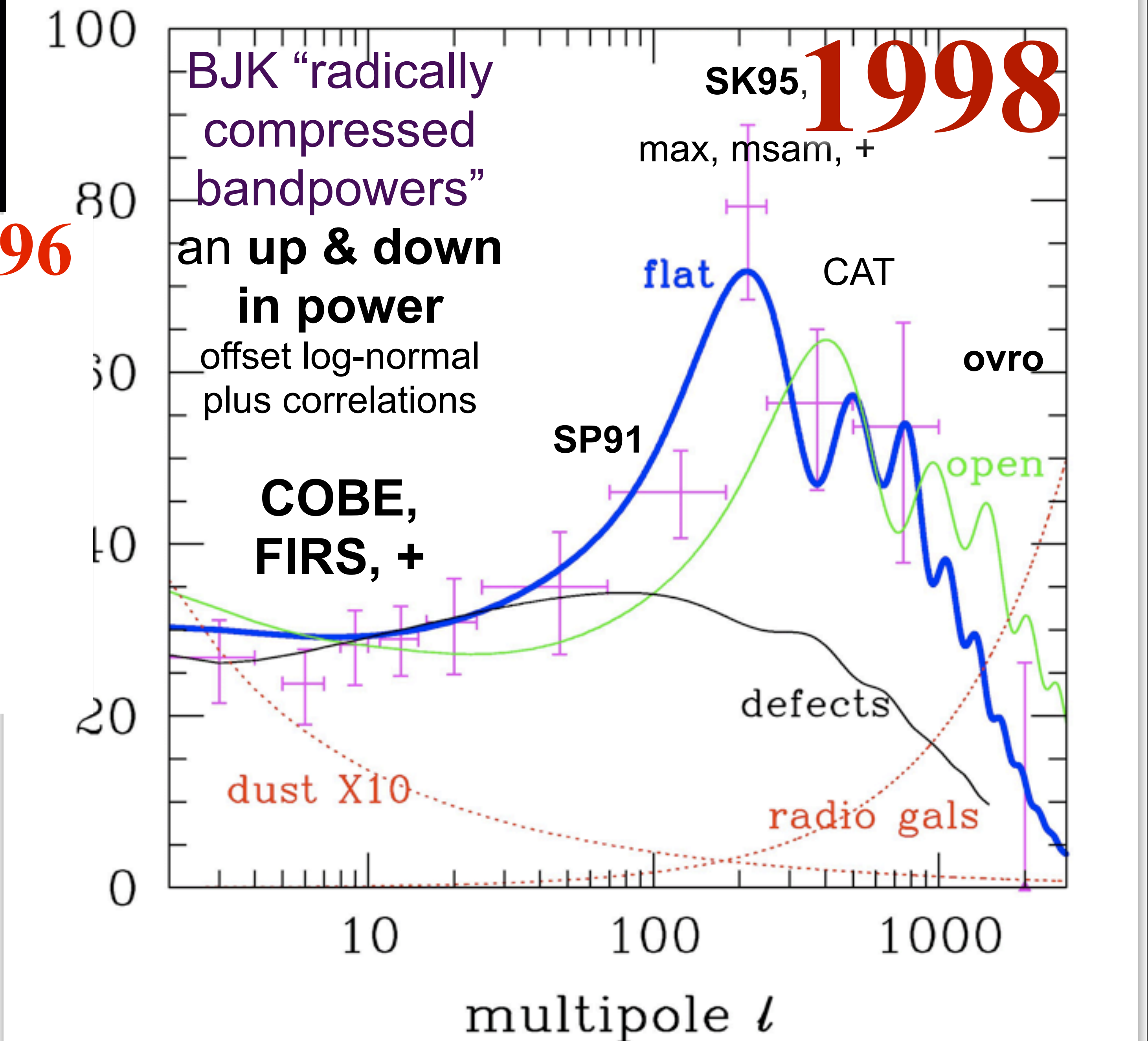
Parameter	OBS	CDM	C40	VAC/C	OP/C	ISO/C	ISO/AD	HOT	HC	C + B	B + C	BCV	BCO	CDM + dec	(CDM + X)$_3$ (k_u^{-1} = 300)	(CDM + X)$_2$ (k_u^{-1} = 200)
Ω, Ω_B, H_0	...	1, 0.1, 50	1, 0.1, 40	1, 0.03, 50	0.2, 0.03, 50	1, 0.1, 50	1, 0.1, 50	1, 0.1, 50	1, 0.1, 50	1, 0.2, 40	1, 0.5, 50	1, 0.1, 75	0.2, 0.1, 75	1, 1, 50	1, 0.1, 40	1, 0.1, 50
$\Omega_X(\Omega_\nu)$, Ω_{vac}	...	0.9, 0	0.9, 0	0.17, 0.8	0.17, 0	0.9, 0	0.9, 0	(0.9), 0	0.5 (0.4), 0	0.8, 0	0.5, 0	0.1, 0.8	0.1, 0	1, 0	0.9, 0	0.9, 0
b	...	1.7	1.8	1	1	1.7	1.7	0.53	1.7	1.8	1.7	1	1	1.7	1.8	1.7
t_0 (by)	GC: 14–22 NC: 13–26	13	17	22	17	13	13	13	13	17	13	14	11	13	17	13
$\sigma_0(R_g = 0.35)$ ...	...	2.9	2.4	2.7	2.7	1.6	2.5	2.0	1.3	2.2	1.9	2.4	2.4	6.8	2.2	2.7
z_g	...	3.7	2.9	2.3	4.0	1.3	3.1	1	1.1	2.5	2.0	1.3	2.0	13	2.6	3.4
$\sigma_0(R_{cl} = 5)$	...	0.42	0.39	0.75	0.75	0.43	0.42	1.4	0.44	0.40	0.44	0.72	0.72	0.47	0.41	0.43
$\langle v \rangle_c$	...	3.2	3.1	3.1	3.1	3.0	3.2	3.1	2.9	3.1	3.0	2.8	2.8	2.7	3.1	3.1
$\xi_{cc}(20)$	1.5	0.15	0.26	1.7	1.7	0.70	0.35	1.1	1.0	0.49	1.3	2.2	2.2	1.8	1.0	0.85
$\xi_{cc}(25)$	1.0	0.08	0.15	1.2	1.2	0.42	0.21	0.45	0.51	031	0.93	1.7	1.7	0.92	0.83	0.68
$\xi_{cc}(30)$	0.72	0.03	0.07	0.85	0.85	0.25	0.11	0.20	0.24	0.20	0.61	1.4	1.4	0.49	0.64	0.51
$\xi_{cc}(50)$	0.29	−0.01*	−0.006*	0.24	0.24	0.02	−0.01*	−0.009*	−0.02*	0.04	0.23	0.59	0.59	0.16	0.28	0.21
$\xi_{cc}(100$	0.08	−0.002*	−0.003*	0.02	0.02	−0.003*	−0.003*	−0.003*	−0.009*	−0.007*	−0.01*	036	0.36	0.02	0.08	0.06
$\xi_{cg}(20)$	0.49	0.13	0.17	0.57	0.57	0.32	0.19	0.96	0.44	0.23	0.50	0.76	0.76	0.70	0.39	0.32
$\xi_{cg}(25)$	0.33	0.04	0.06	0.37	0.37	0.16	0.08	0.35	0.23	0.11	0.32	0.54	0.54	0.42	0.26	0.20
$\xi_{cg}(30)$	0.24	0.01	0.02	0.25	0.25	0.09	0.03	0.12	0.11	0.06	0.22	0.41	0.41	0.24	0.19	0.15
$\xi_{cg}(40)$	0.14	−0.003	0.002	0.13	0.13	0.03	0.006	−0.001	0.02	0.03	0.13	0.26	0.26	0.09	0.12	0.10
$v(R_f = 3.2)$	610 ± 50	136–654	134–650	166–797	157–752	172–824	148–709	594–2850	185–889	149–714	208–1000	232–1120	218–1050	293–1399	280–1331	241–1151
$v(R_f = 15)$	599 ± 104	71–340	76–365	134–639	126–601	114–544	86–409	387–1850	124–587	95–450	154–735	206–987	[illegible]	[illegible]	250–1190	202–970
$v(R_f = 25)$		53–250	56–269	115–550	108–516	89–421	64–309	419–1350	91–435	71–342	119–573	186–894	[illegible]	[illegible]	233–1106	185–882
$v(R_f = 40)$	970 ± 300	35–180	40–192	95–456	90–430	66–315	47–221	200–958	65–311	52–251	87–419	160–771	[illegible]	[illegible]	214–1016	165–787
$\Delta T/T$ (4:5)	< 25	5	6	20	70	...	...	20	...	6	8	10	[illegible]	[illegible]	...	...
$\times 10^6$ (6°)	< 48	7	8	20	40	60	30	20	8	8	15	25	[illegible]	[illegible]	72 (98)	40 (64)



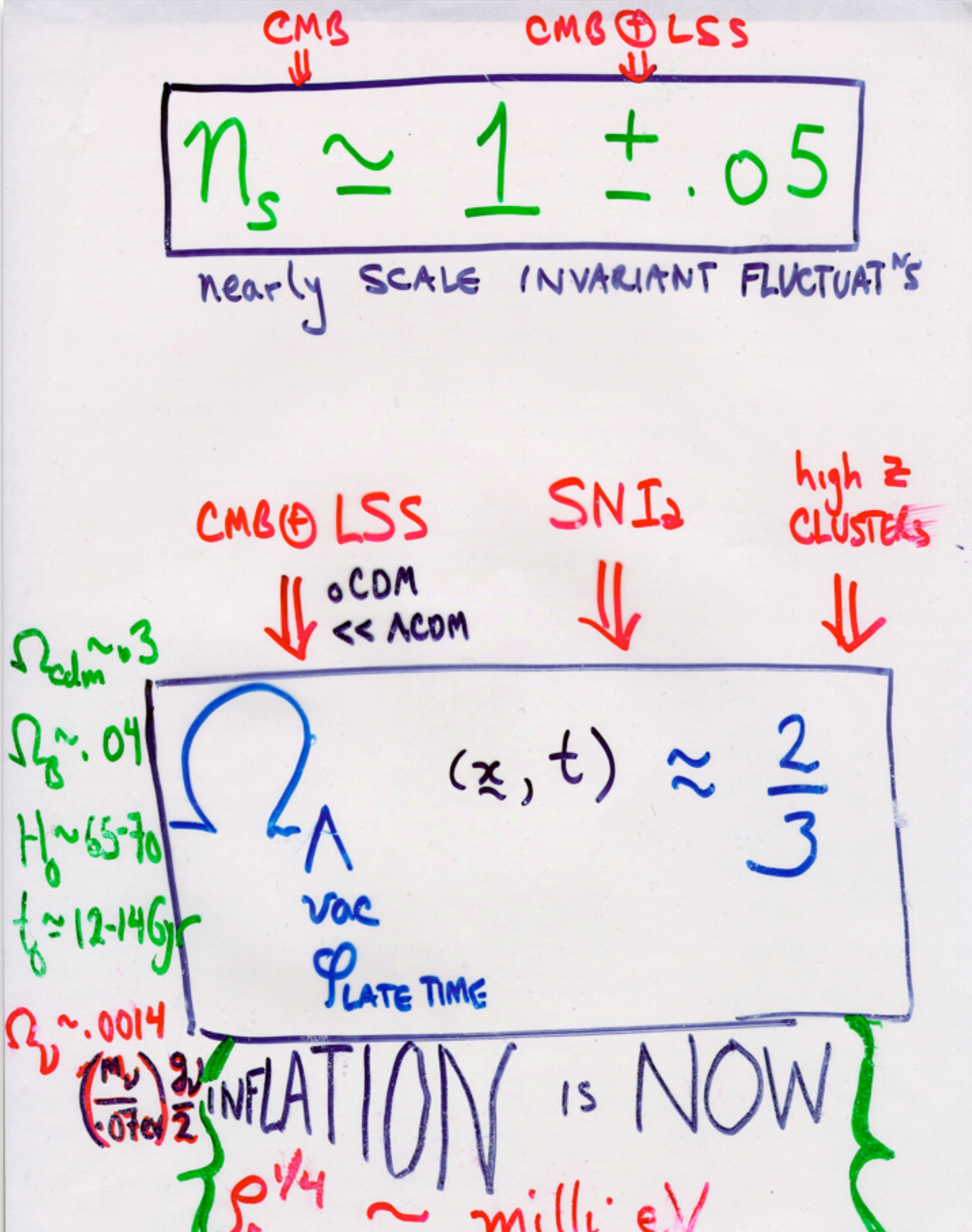

Cosmic Microwave Background Spectrum from COBE
Theory and observation agree
1990
Intensity, 10^-4 ergs / cm^2 sr sec cm^-1
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
Waves / centimeter


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 ℓ²C_ℓ
-8
-10
-12
-14
0
1
2
3
log ℓ


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

vintage 98 conclusions



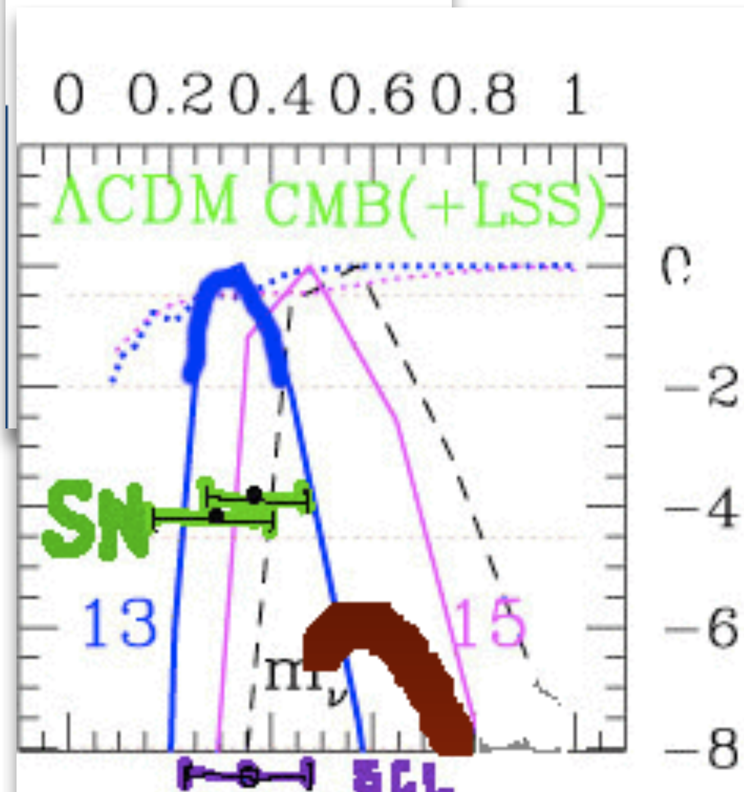
B+Jaffe'96,'98 (13Gyr/t_0)

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

$n_s =$

$.98 \pm .07$

$.96 \pm .06$

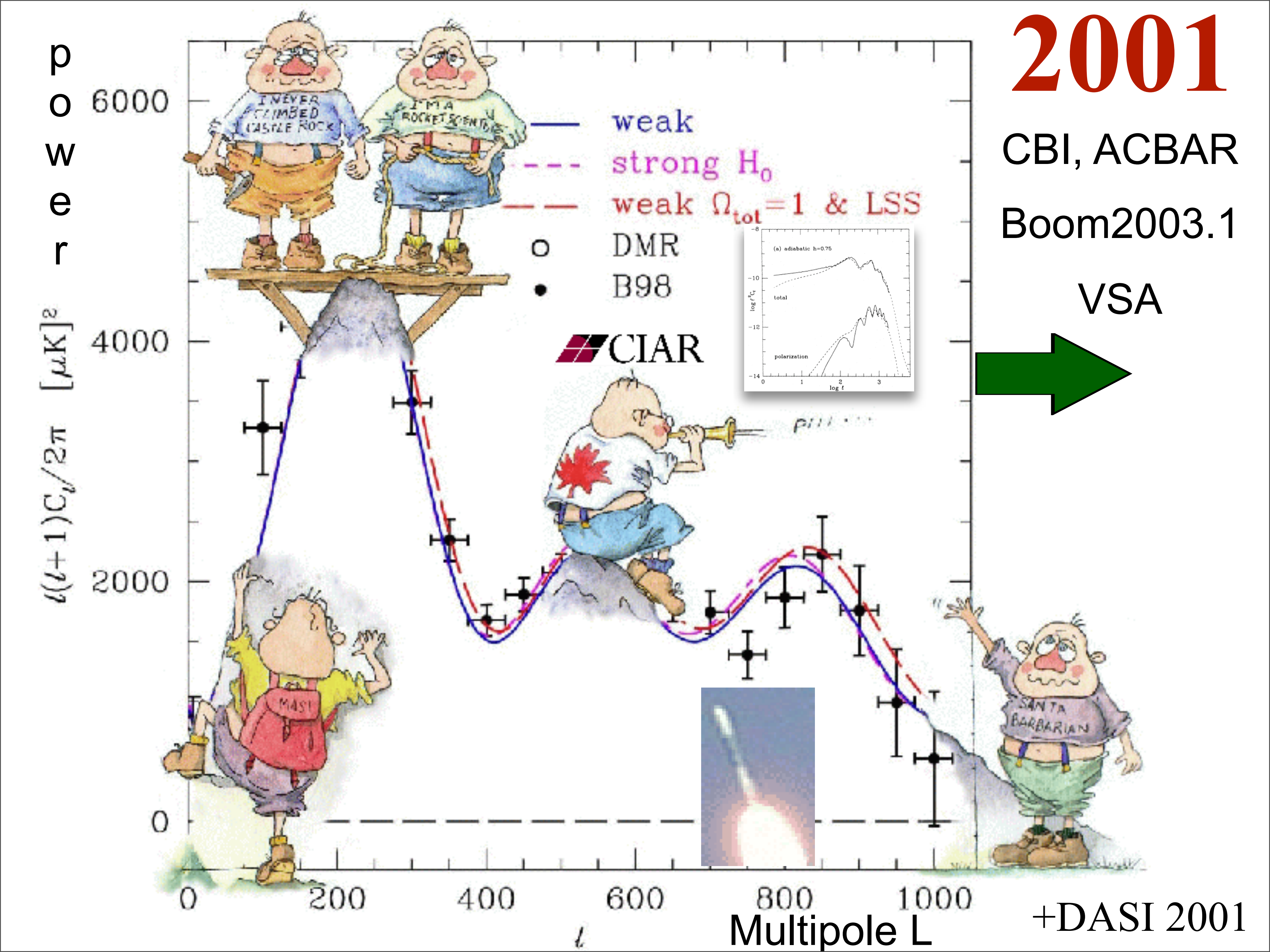


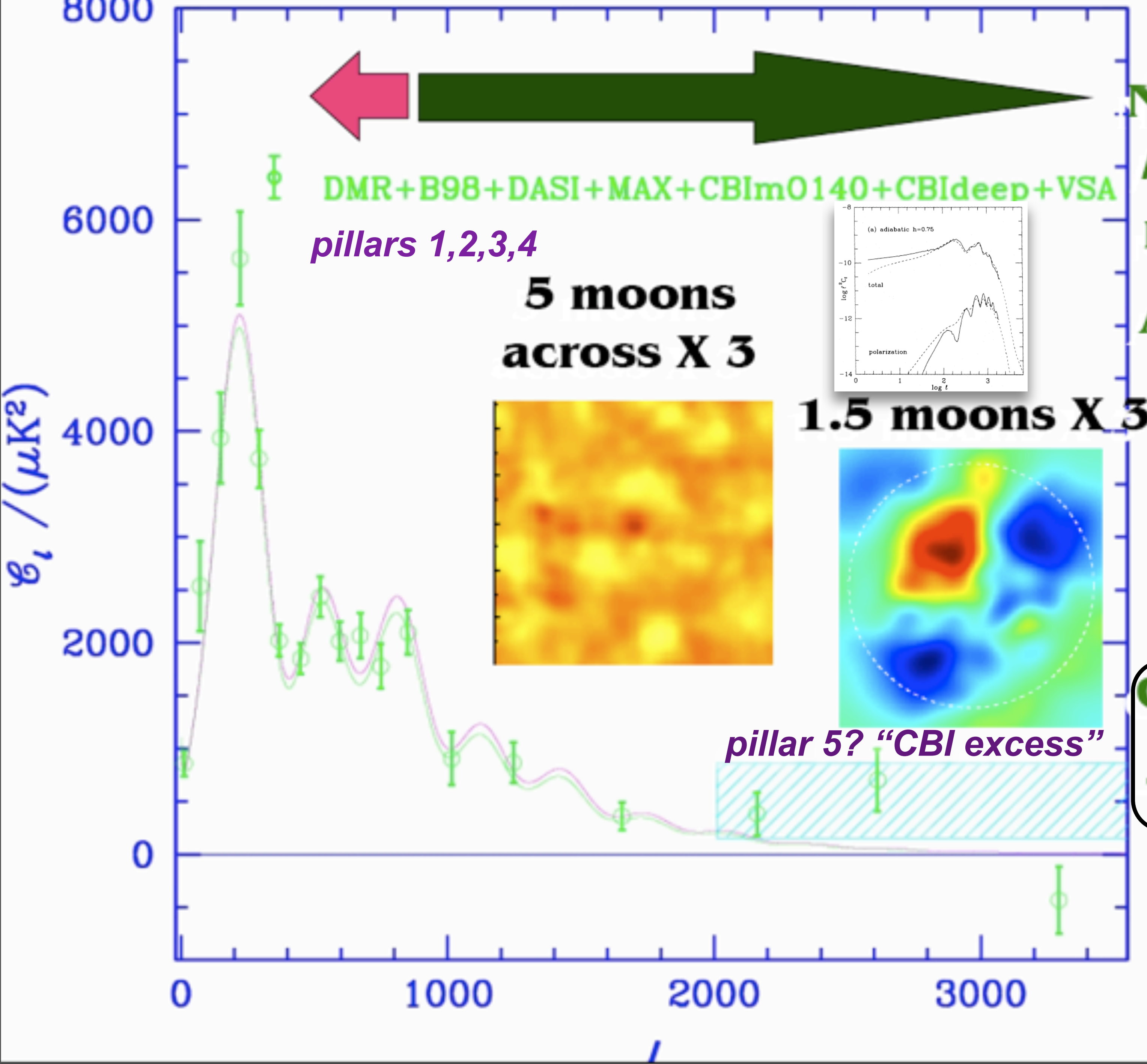
BOOM

2000

TOCO, Boom test 1999

Maxima 2000


2001
CBI, ACBAR
Boom2003.1
VSA
+DASI 2001
power
$\ell(\ell+1)C_\ell/2\pi \quad [\mu K]^2$
6000
4000
2000
0
0
200
400
600
800
1000
ℓ
Multipole L
weak
strong H_0
weak $\Omega_{tot}=1$ & LSS
DMR
B98
CIAR
I NEVER CLIMBED CASTLE ROCK
SANTA BARBARIAN
(a) adiabatic h=0.75
total
polarization
log ℓ



2002

NSF/Caltech /CITA/CIAR

May 23,2002

AAS Jun02

Grand unified spectrum

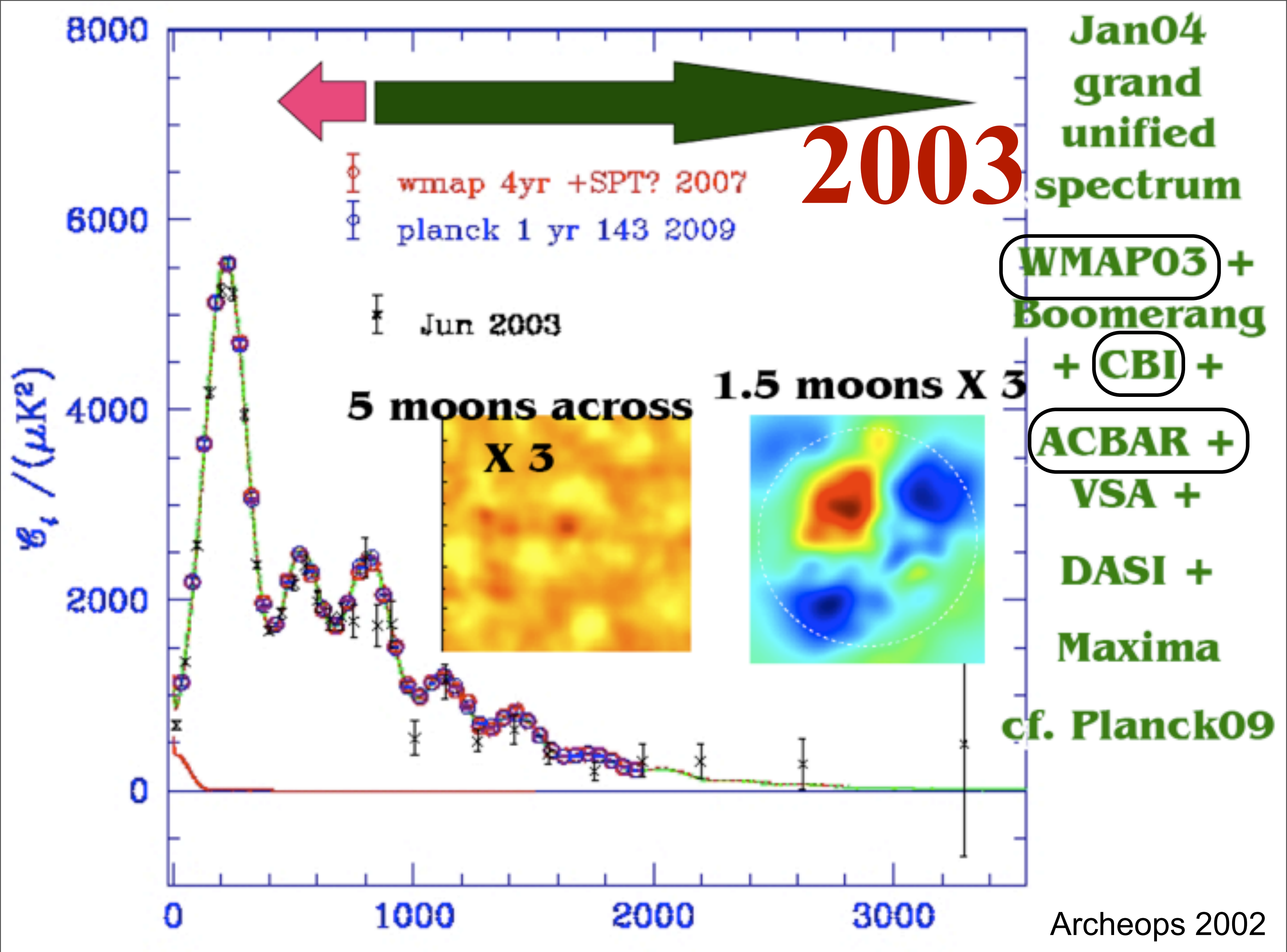
Adds

CBI mosaic

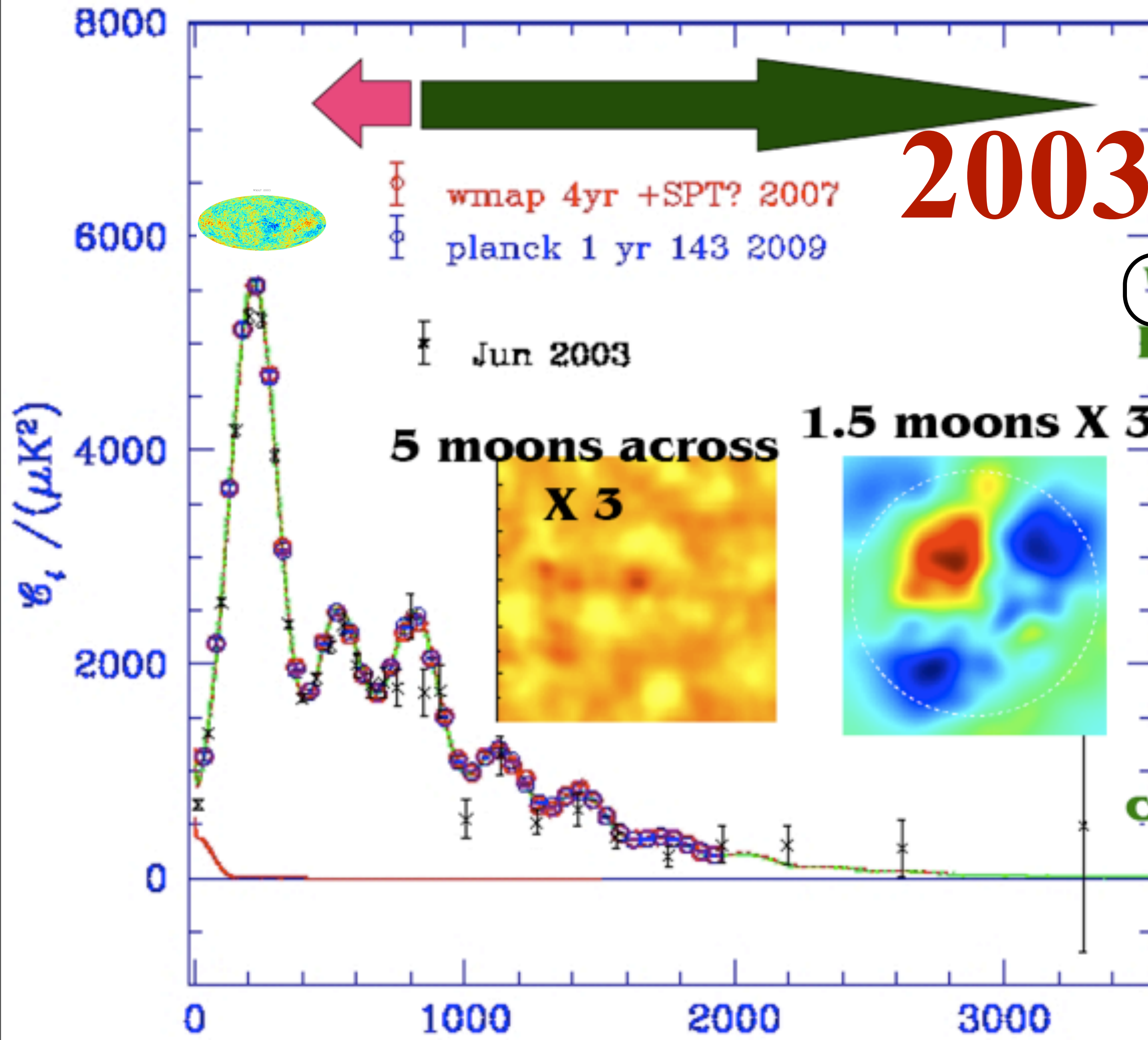
+CBI deep

+VSA


WMAP
launch
2001.6
Text
Dave Wilkinson
Rashid Sunyaev



2003
wmap 4yr +SPT? 2007
planck 1 yr 143 2009
Jun 2003
5 moons across
X 3
1.5 moons X 3
Jan04
grand
unified
spectrum
WMAP03 +
Boomerang
+ CBI +
ACBAR +
VSA +
DASI +
Maxima
cf. Planck09
Archeops 2002
$\mathcal{C}_\ell$ /(μK²)
8000
6000
4000
2000
0
0
1000
2000
3000

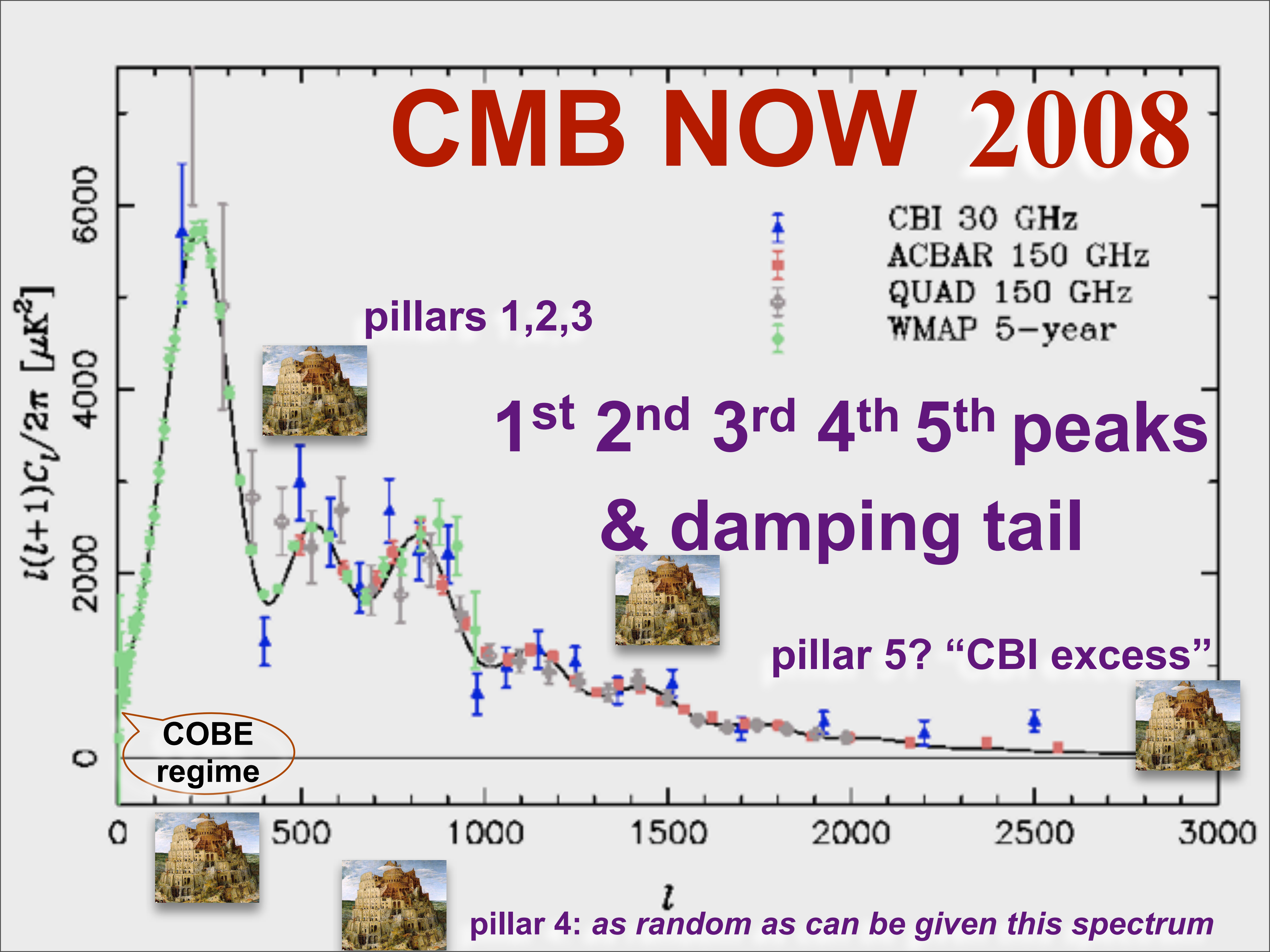


Jan04 grand unified spectrum

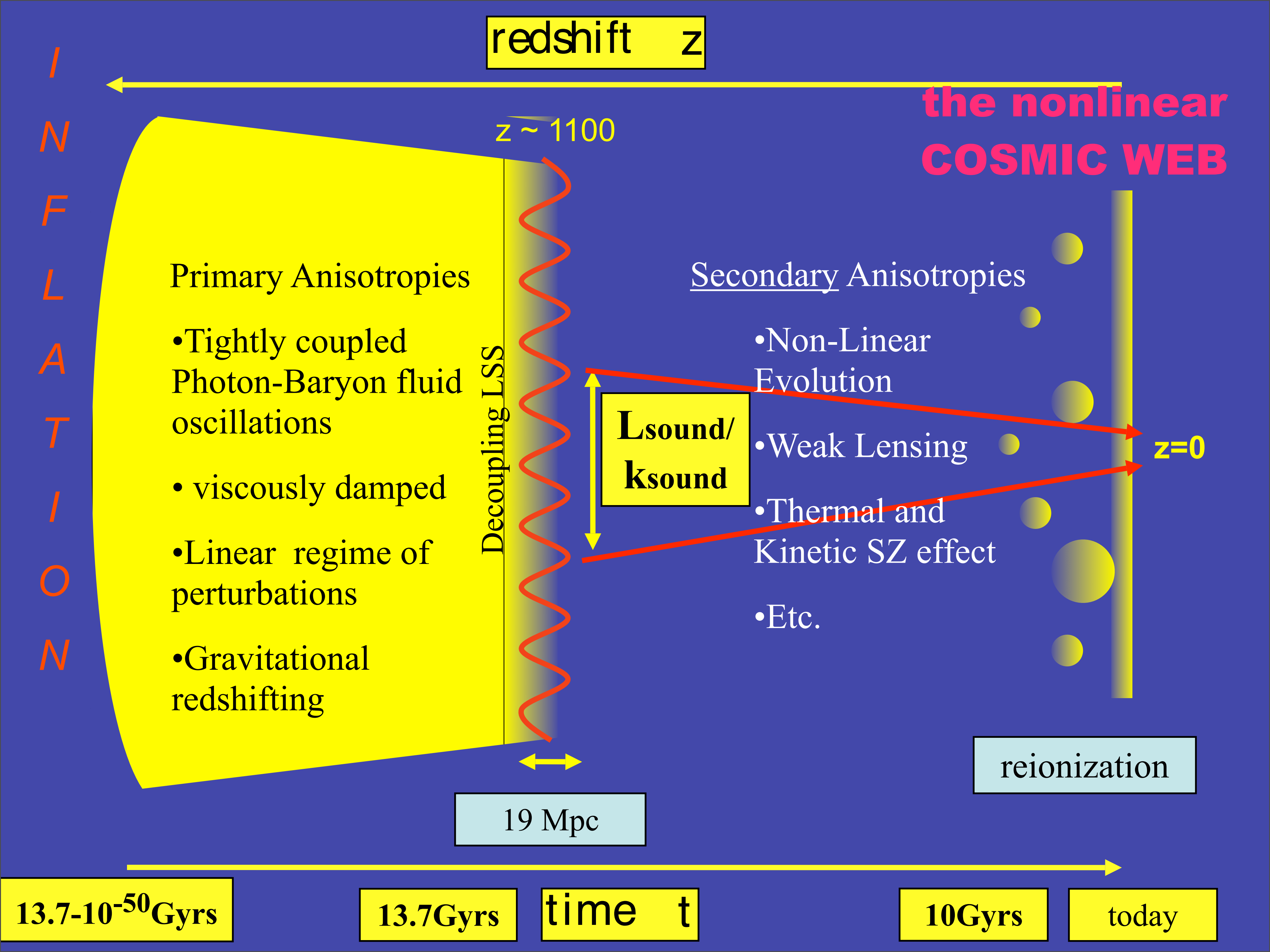
WMAP03 + Boomerang + CBI + ACBAR + VSA + DASI + Maxima

cf. Planck09

Archeops 2002



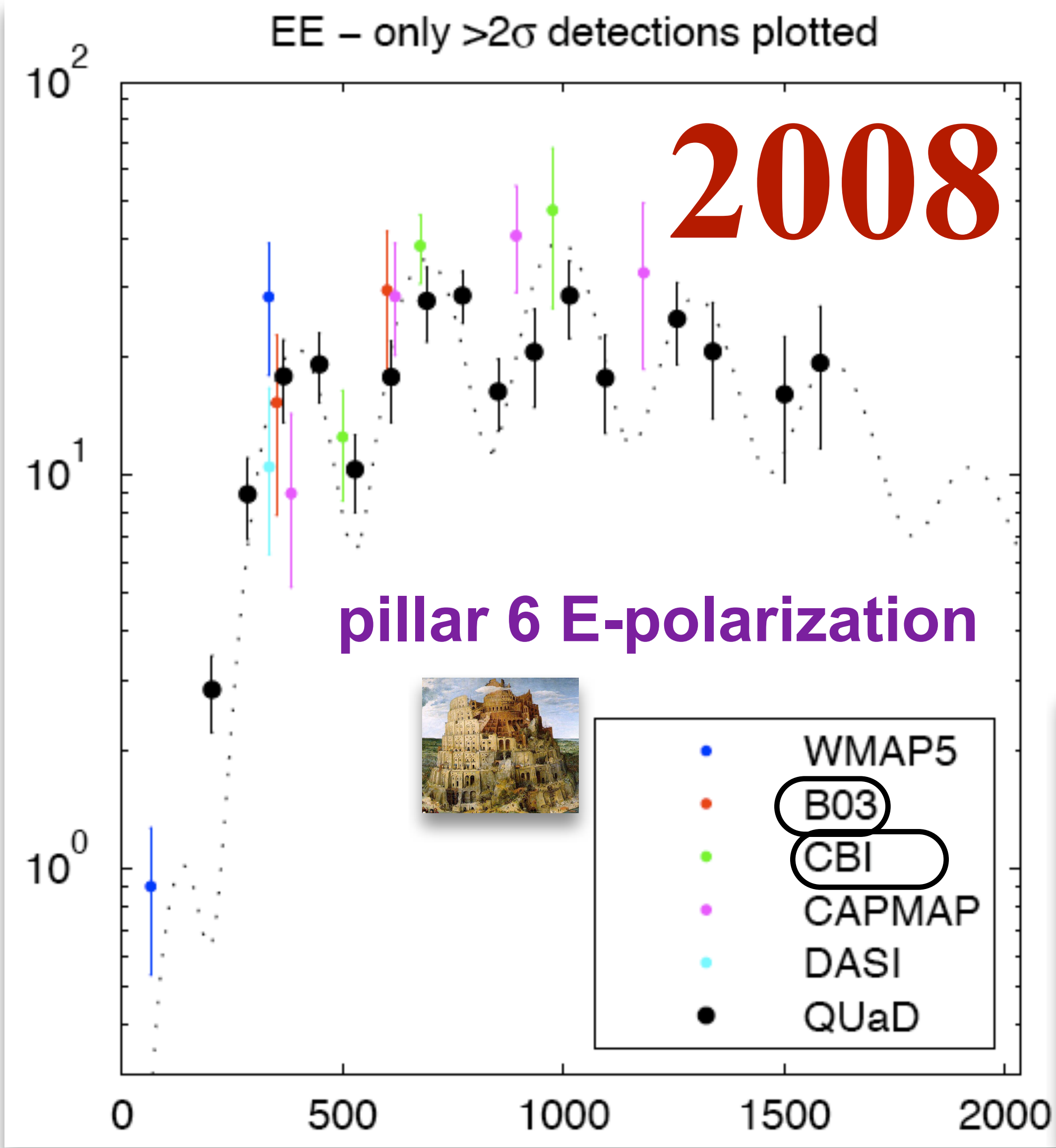
CMB NOW 2008
pillars 1,2,3
1st 2nd 3rd 4th 5th peaks
& damping tail
pillar 5? "CBI excess"
COBE regime
pillar 4: as random as can be given this spectrum
CBI 30 GHz
ACBAR 150 GHz
QUAD 150 GHz
WMAP 5-year
l(l+1)C_l/2π [μK²]
6000
4000
2000
0
0
500
1000
1500
2000
2500
3000
l



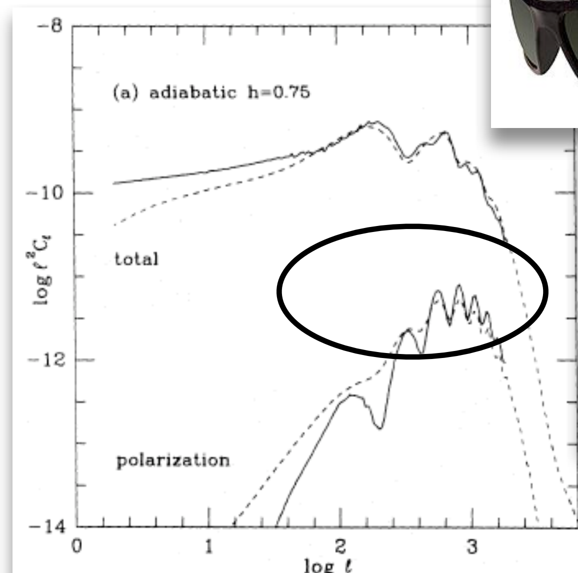
redshift z
INFLATION
the nonlinear
COSMIC WEB
z ~ 1100
Primary Anisotropies
•Tightly coupled Photon-Baryon fluid oscillations
• viscously damped
•Linear regime of perturbations
•Gravitational redshifting
Decoupling LSS
Lsound/ ksound
Secondary Anisotropies
•Non-Linear Evolution
•Weak Lensing
•Thermal and Kinetic SZ effect
•Etc.
z=0
reionization
19 Mpc
13.7-10^-50Gyrs
13.7Gyrs
time t
10Gyrs
today

emergence of **CMB polarization** *power*

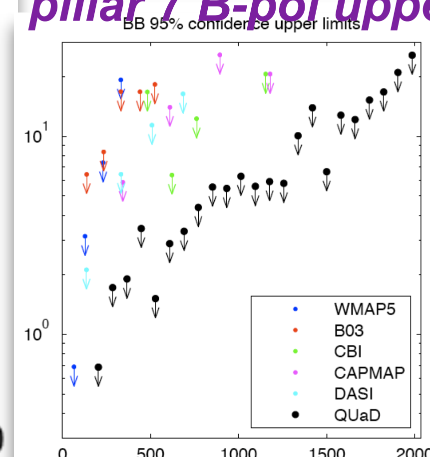
DASI02,04 CBI04 Boom05 CBI05 WMAP3,5 QUaD07,08

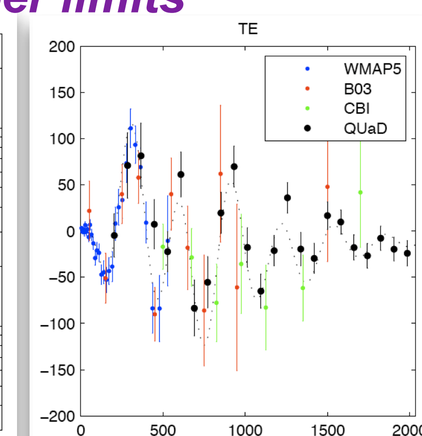


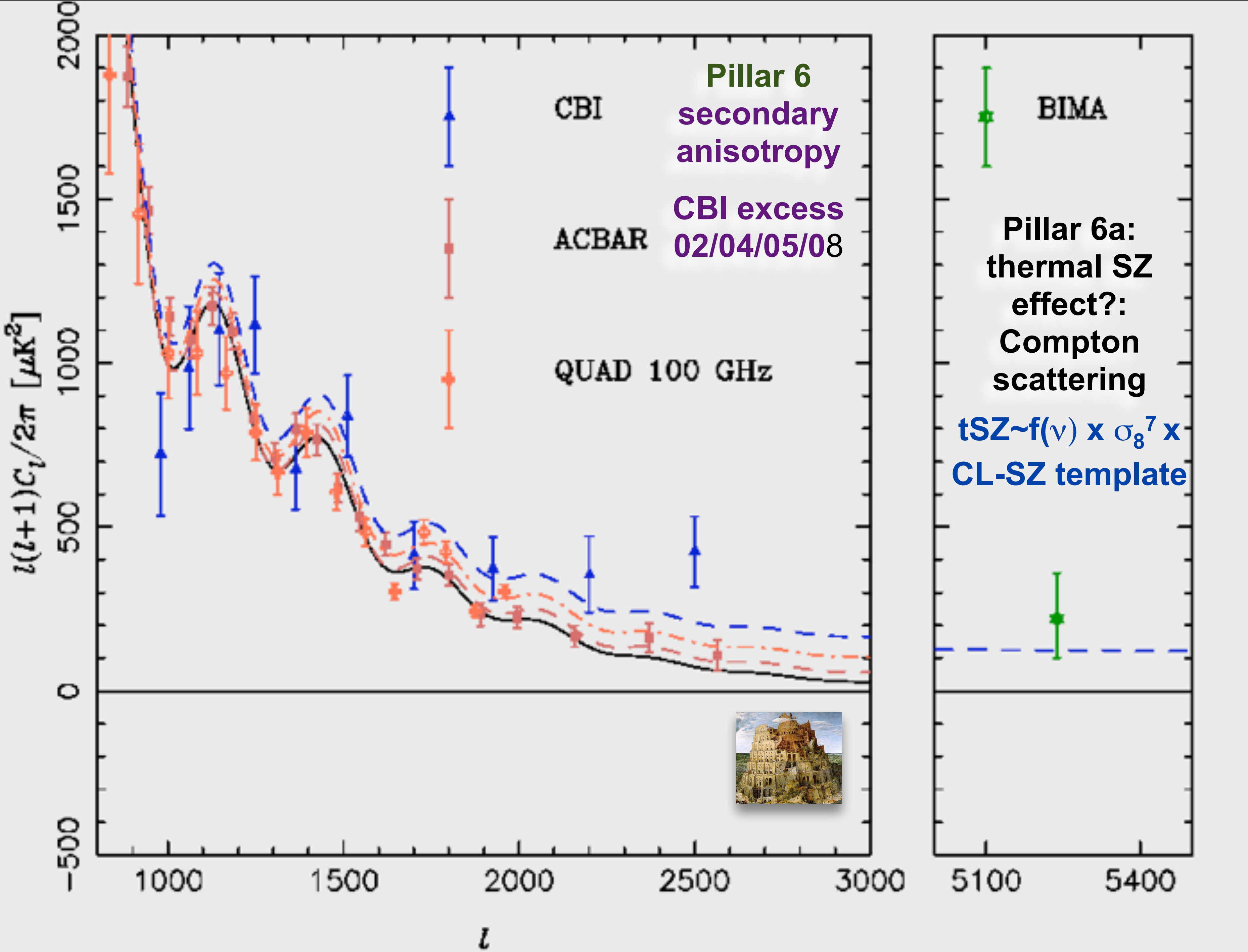
pillar 6 E-polarization



pillar 7 B-pol upper limits





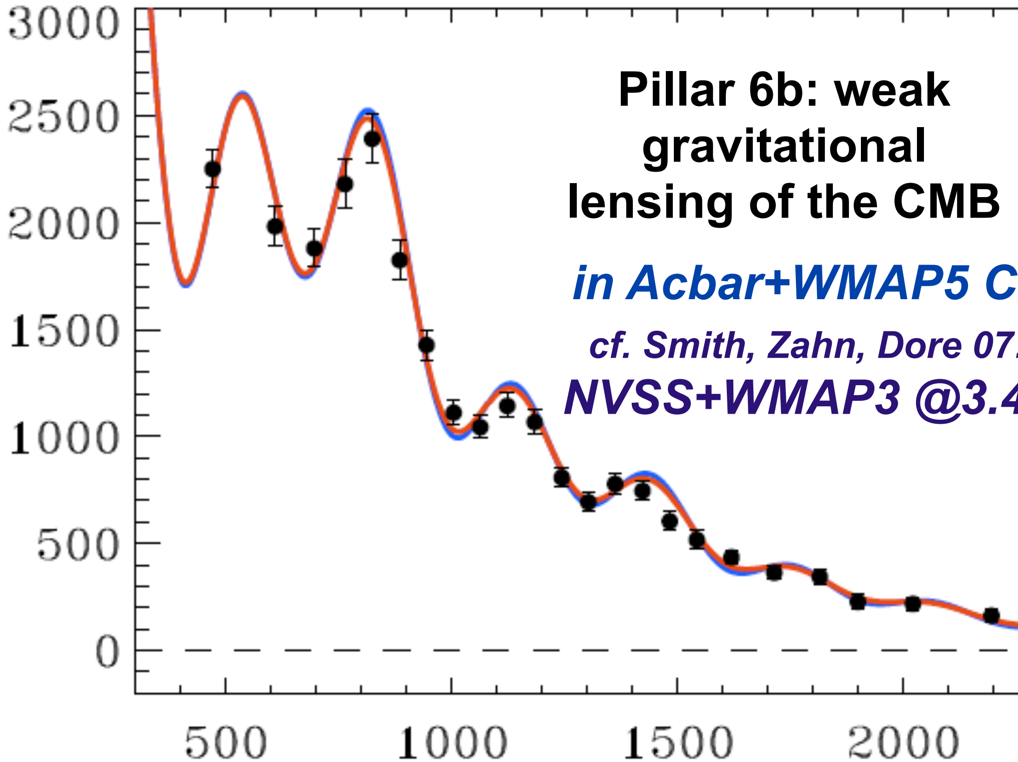


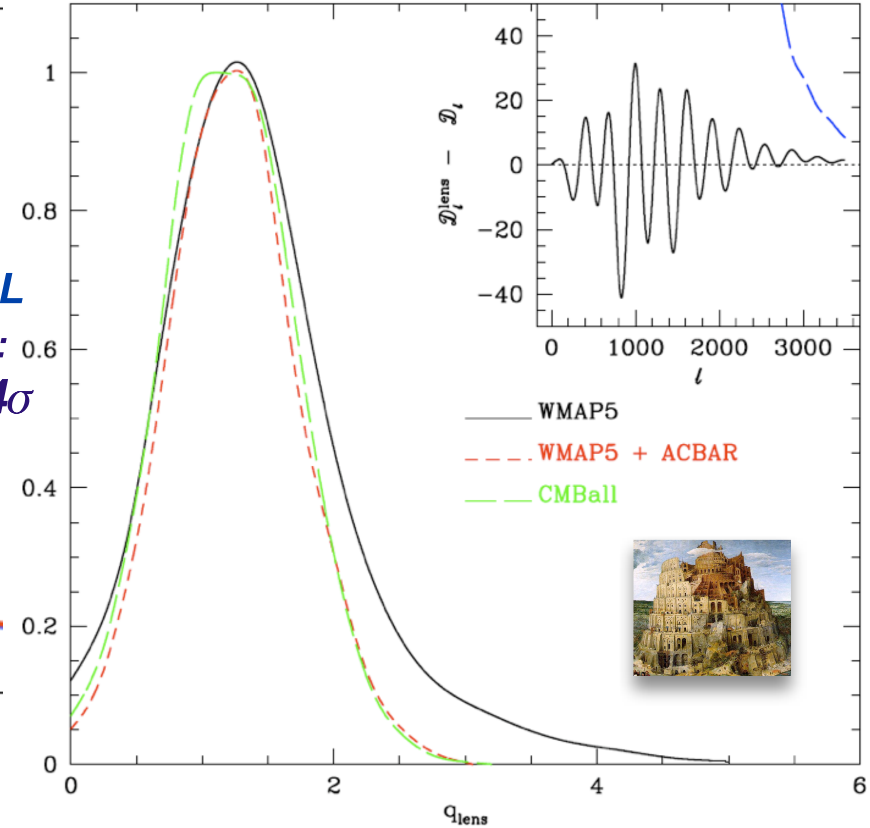
Pillar 6
secondary
anisotropy
CBI excess
02/04/05/08
Pillar 6a:
thermal SZ
effect?:
Compton
scattering
tSZ~f(ν) x σ8^7 x
CL-SZ template
CBI
ACBAR
QUAD 100 GHz
BIMA
l(l+1)C_l/2π [μK^2]
l
2000
1500
1000
500
0
−500
1000
1500
2000
2500
3000
5100
5400

Pillar 6b: weak gravitational lensing of the CMB

in Acbar+WMAP5 C_L

cf. Smith, Zahn, Dore 07: NVSS+WMAP3 @3.4σ





$$C_\ell^{lens} = C_\ell^{no-lens} + q_{lens}\Delta C_\ell^{lens}$$

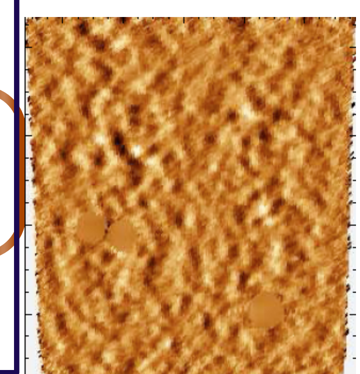
$$\Delta \ln \mathcal{E} = \ln[P(\text{lens}|data, theory)/P(\text{no}-\text{lens}|data, theory)]$$

Bayesian evidence

wmap5 $q_{lens} = 1.34^{+0.27(+1.51)}_{-0.26(-0.85)}$ $\Delta \ln \mathcal{E} = 2.04$

wmap5+acbar $q_{lens} = 1.23^{+0.21(+0.83)}_{-0.23(-0.76)}$ $\Delta \ln \mathcal{E} = 2.89$

CMBall $q_{lens} = 1.21^{+0.24(+0.82)}_{-0.24(-0.76)}$ $\Delta \ln \mathcal{E} = 2.63$



CBI pol to Apr’05 @Chile

Bicep @SP

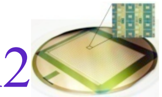
Quiet2 (1000 HEMTs)

Acbar to Jan’06, 07f @SP

QUaD @SP

CBI2 to early’08

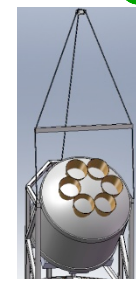
Quiet1 @Chile

SCUBA2 

(12000 bolometers)

JCMT @Hawaii

Spider



2312 bolometer @LDB

SZA (Interferometer) @Cal

APEX (~400 bolometers) @Chile

ACT (3000 bolometers) 3 frequencies @Chile

Clover @Chile

Boom03@LDB

EBEX@LDB

2004 — 2005 — 2006 — 2007 — 2008 — 2009 — 2017

LMT@Mexico

SPT (1000 bolometers) @South Pole

LHC

Bpol@L2

WMAP @L2 to 2009-2013?

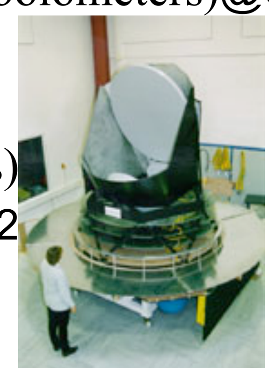
DASI @SP

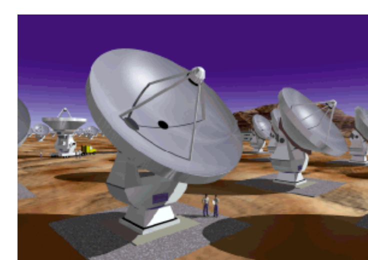
ALMA (Interferometer) @Chile

Polarbear (300 bolometers)@Cal

CAPMAP

Planck09.2





AMI

(52 bolometers) + HEMTs @L2 9 frequencies

GBT

CBI pol to Apr'05 @Chile

Bicep @SP

Acbar to Jan'06, 07f @SP

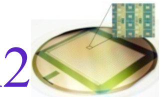
QUaD @SP

CBI2 to early'08

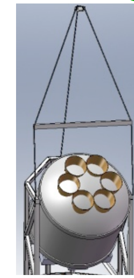
Quiet2 (1000 HEMTs) @Chile

Quiet1 @Chile

SCUBA2 (12000 bolometers) JCMT @Hawaii



Spider 2312 bolometer @LDB



SZA (Interferometer) @Cal

APEX (~400 bolometers) @Chile

ACT (3000 bolometers) 3 frequencies @Chile

Clover @Chile

EBEX@LDB

Boom03@LDB

2004 — 2005 — 2006 — 2007 — 2008 — 2009 — 2017

LMT@Mexico

SPT (1000 bolometers) @South Pole

LHC

Bpol@L2

WMAP @L2 to 2009-2013?

DASI @SP

ALMA (Interferometer) @Chile

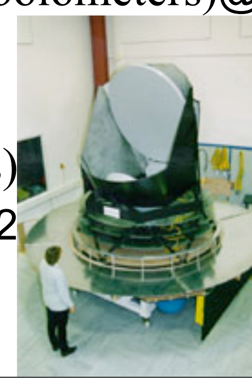
Polarbear (300 bolometers)@Cal

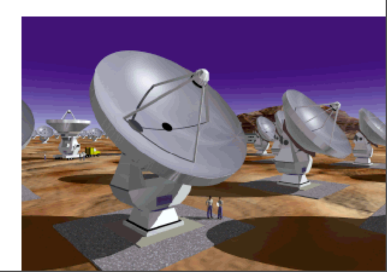
CAPMAP

Planck09.2 (52 bolometers) + HEMTs @L2 9 frequencies

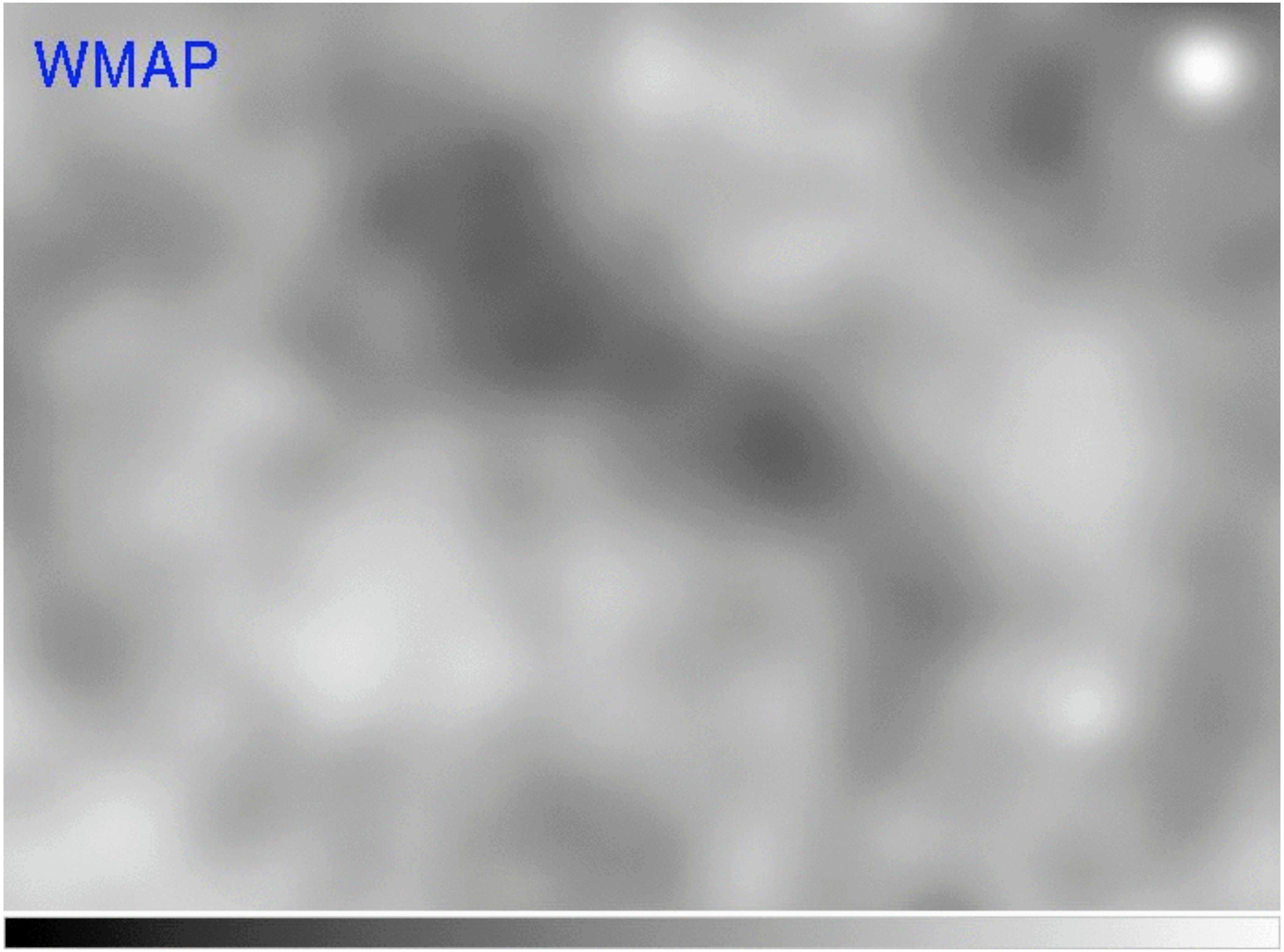
AMI

GBT





WMAP-BOOM-ACBAR-ACT: the high resolution frontier



Toby Marriage 01.08 for the ACT collaboration

ACT@5170m

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

CBI2@5040m

dark matter abundance Ω_m=0.268 +.012 -.012

	January 2000	January 2002	June 2002	January 2003	March 2003
$\Omega_{cdm}h^2$	$0.198^{+0.088}_{-0.080}$	$0.130^{+0.031}_{-0.028}$	$0.124^{+0.026}_{-0.025}$	$0.125^{+0.021}_{-0.022}$	$0.111^{+0.010}_{-0.010}$

CMB-only history (weak-h prior). LSS-then drove to near current

0.1145 +-0.0023 **CMBall+WL+LSS+SN+Lya**

$\rho_{dm}/\rho_b = 5.1$

Ω_Λ	$0.34^{+0.28}_{-0.24}$	$0.52^{+0.17}_{-0.20}$	$0.53^{+0.17}_{-0.19}$	$0.57^{+0.14}_{-0.19}$	$0.73^{+0.06}_{-0.10}$

CMB-only history (weak-h prior). LSS-then drove to near current value

dark energy abundance Ω_Λ=0.736 +.012 -.012

& H_0 = 72 +-1 CMBall+WL+LSS+SN+Lya

$\rho_m/\rho_{de} = .30$

ε=-dlnH/dlna=1+q: now =3/2[Ω_{m0} +(1+w)(1-Ω_{m0})] **~0.40?, to 0?**

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??

THEN: coherent inflaton /**"vacuum" energy plus zero-point fluctuations** in all fields. & then preheat through mode coupling to incoherent cascade to thermal equilibrium aka **quark-gluon plasma**

---

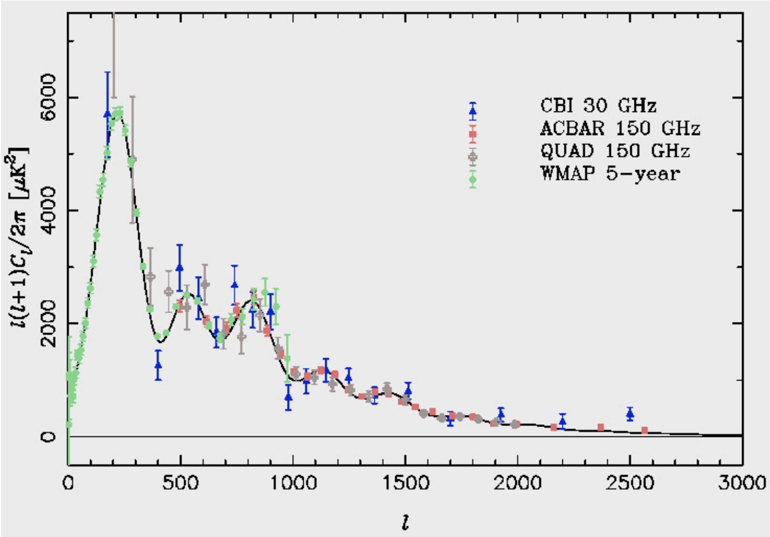
very early U early to middle to now U **very late U**

string theory/landscape/higher dimensions

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

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

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



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

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

cosmic mysteries

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

INFLATION THEN

PROBES NOW

"standard inflation space": n_s $dn_s/d\ln k$ r @k-pivots

n_s(kp)=.962 +-.013 (+-.005 Planck1) .959 +- .011 all data

$r=P_t/P_s$(kp') < 0.40cmb 95% CL (+-.03 P1, +- .01 Spider+P2.5)

dn_s /dln k (kp) =-.016 +- .019 (+-.005 Planck1)

(*partially*) ***blind trajectories*** e.g., n_s(k) and r(kp), ***are better***

INFLATION THEN

WHAT IS PREDICTED?

Smoothly broken scale invariance by nearly uniform braking (standard of 80s/90s/00s) $r \sim 0.03-0.5$

or highly variable braking r tiny

(stringy cosmology) $r < 10^{-10}$

Old view: Theory prior = delta function of THE correct one and only theory

New: Theory prior = probability distribution of late-flows on an energy LANDSCAPE

6/7 tiny extra dimensions

1980

R^2-inflation

Old Inflation

Chaotic inflation

New Inflation

Double Inflation

Power-law inflation

SUGRA inflation

Radical BSI inflation

variable M_P inflation

Extended inflation

1990

Natural pNGB inflation

Hybrid inflation

Assisted inflation

SUSY F-term inflation

SUSY D-term inflation

Brane inflation

2000

SUSY P-term inflation

Super-natural Inflation

K-flation

2003 KKLT

N-flation

ekpyrotic/ cyclic

DBI inflation

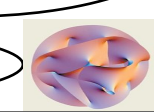
$D3 - D7$ inflation

Tachyon inflation

Warped Brane inflation

Racetrack inflation

Roulette inflation Kahler moduli/axion



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

inflation *string theory/landscape/higher dimensions* **dark energy**

$V_{eff}(\psi_{inf})$? partial shape reconstruction reconstruct gradient $V_{eff}(\psi_{inf})$?

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

trajectory probability

$-d\ln\rho_{tot}/d\ln a\,/2$ => $\mathbb{P}_s, \mathbb{P}_t, V_{eff}(k), \psi_{inf}(k)$

$= \epsilon(k) = 1+q$, $k \sim Ha$

trajectory probability

$-d\ln\rho_\phi/d\ln a\,/2$

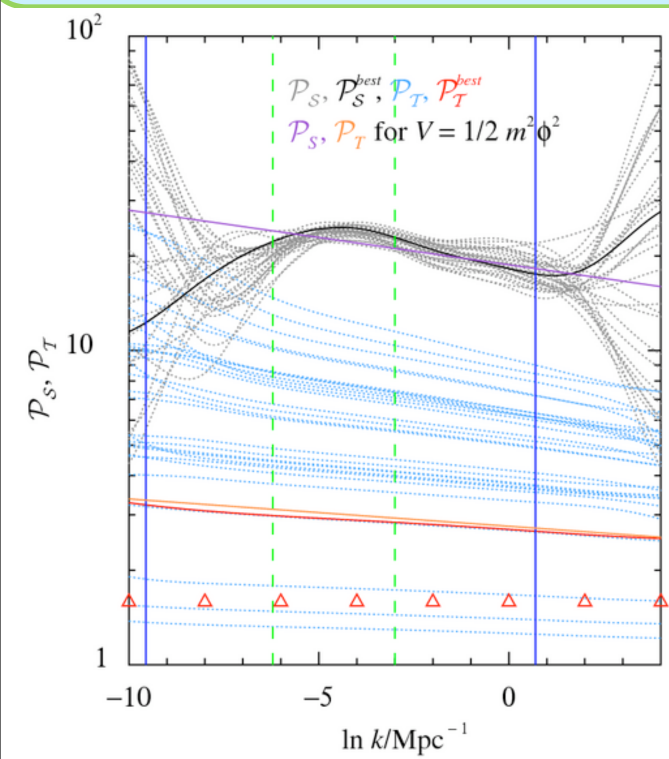
$= \epsilon_\phi(a) = (1+w)2/3$

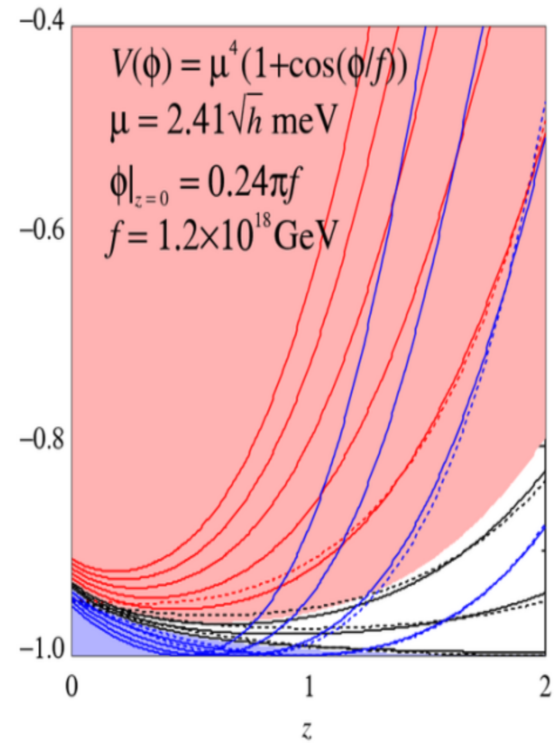
$\epsilon_s = (d\ln V/d\psi)^2/4$

@pivot a_{eq} **yes**

$d^2\ln V/d\psi^2/4$

@pivot a_{eq} **no**



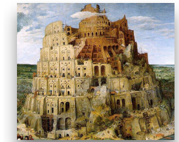


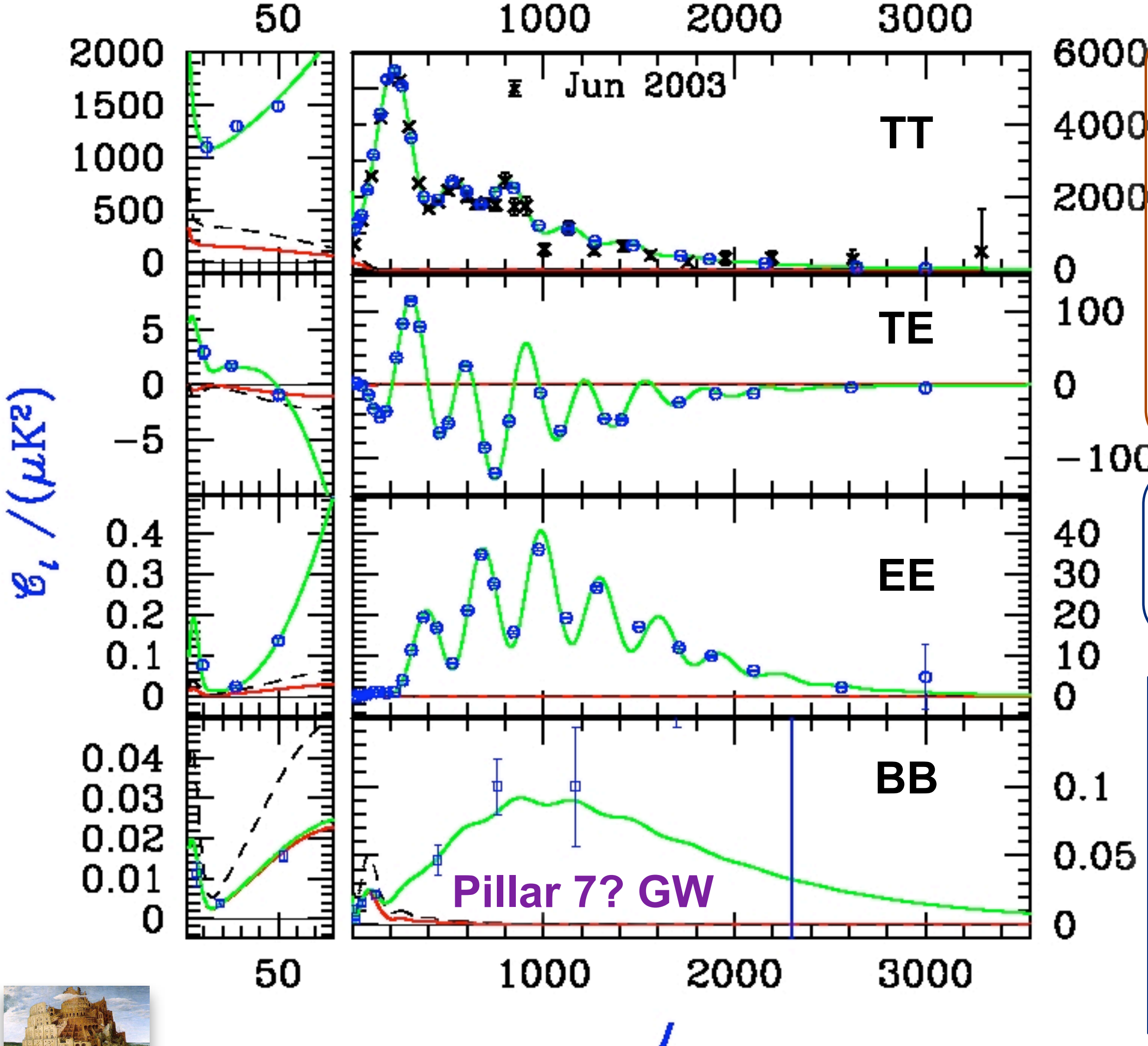
INFLATION
THEN

PROBES
THEN

PRIMARY END @ 2012?

CMB ~2009+ Planck1+WMAP8+SPT/ACT/Quiet+Bicep/QuAD/Quiet +Spider+Clover





Pillar 7? Gravity Waves

An ensemble of trajectories arises in many-moduli string models, whether braney or holey. **Roulette inflation:** ***complex hole sizes in 6D*** TINY **$r<10^{-10}$** ***& n_s from data-selected braking!***

('theorem': $\Delta\psi$< 1 -> **r<.007**)

nearly uniform acceleration

(power law, exp, PNGB, ..potentials)

r~.03-.3! is $\Delta\psi$~10 deadly?

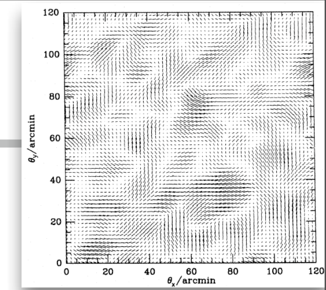
Even with low energy inflation, the prospects are good with Spider plus Planck to either detect the GW-induced B-polarization or set a strong blind upper limit r<0.02 indicating stringy or other exotic models. Both experiments have strong Cdn roles. Bpol 2020?, to r~0.002

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

SPIDER Tensor Signal

Pillar 7

Gravity Waves from **Inflation**

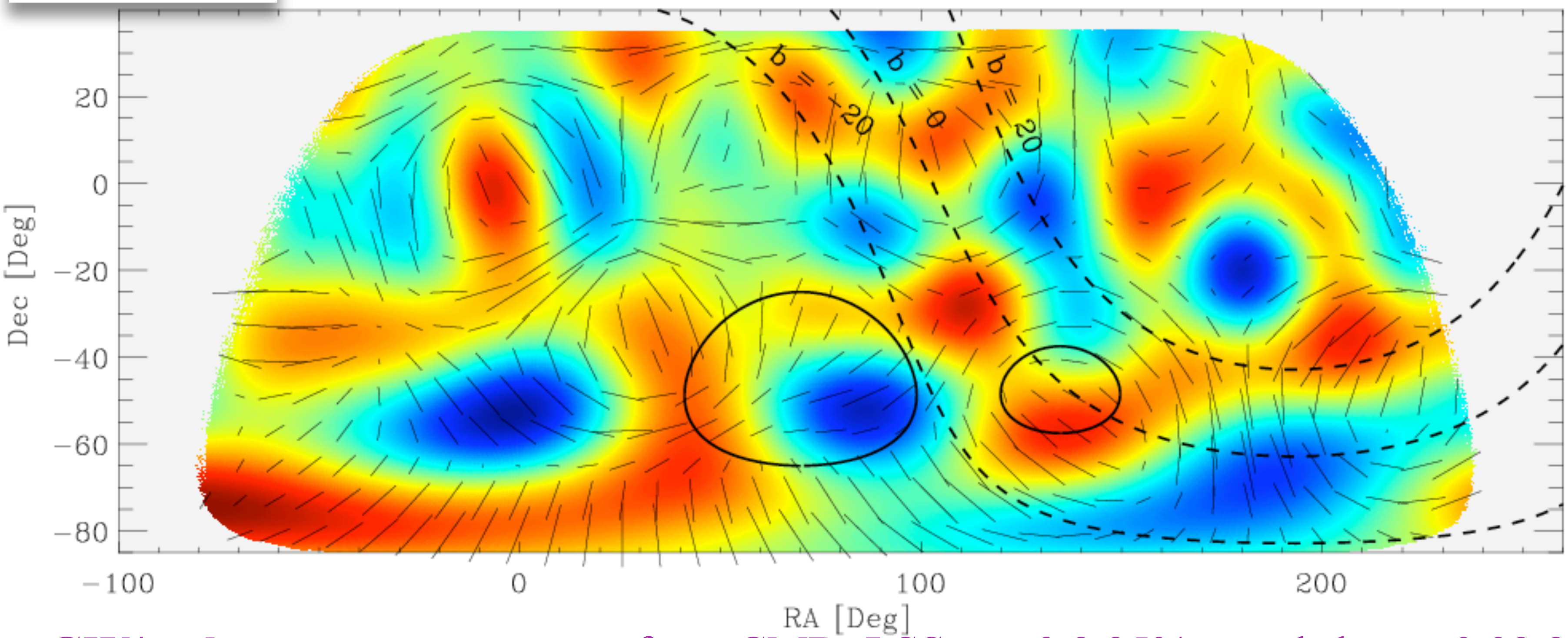


- **Simulation of large scale polarization signal**

http://www.astro.caltech.edu/~lgg/spider_front.htm

$$\frac{A_T}{A_S} = 0.1$$

No Tensor

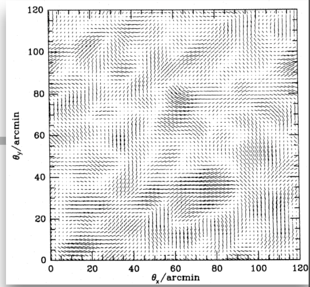


GW/scalar curvature: current from CMB+LSS: r < **0.3** 95%; good shot at **0.02** 95% CL with **BB polarization** (+- .02 PL2.5+Spider), .01 target; Bpol .001 BUT foregrounds/systematics? But **r(k), low Energy inflation**

SPIDER Tensor Signal

Pillar 7

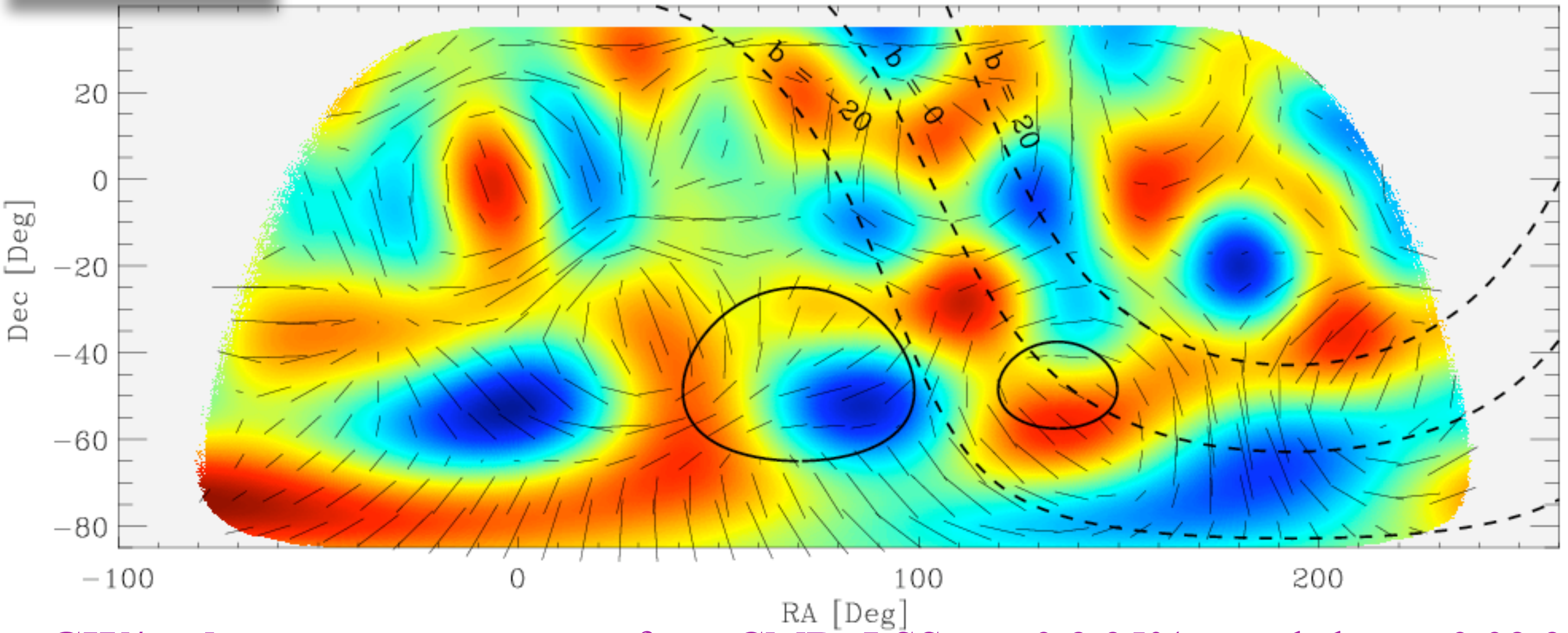
Gravity Waves from **Inflation**



- Simulation of large scale polarization signal

http://www.astro.caltech.edu/~lgg/spider_front.htm

$$\frac{A_T}{A_S} = 0.1$$



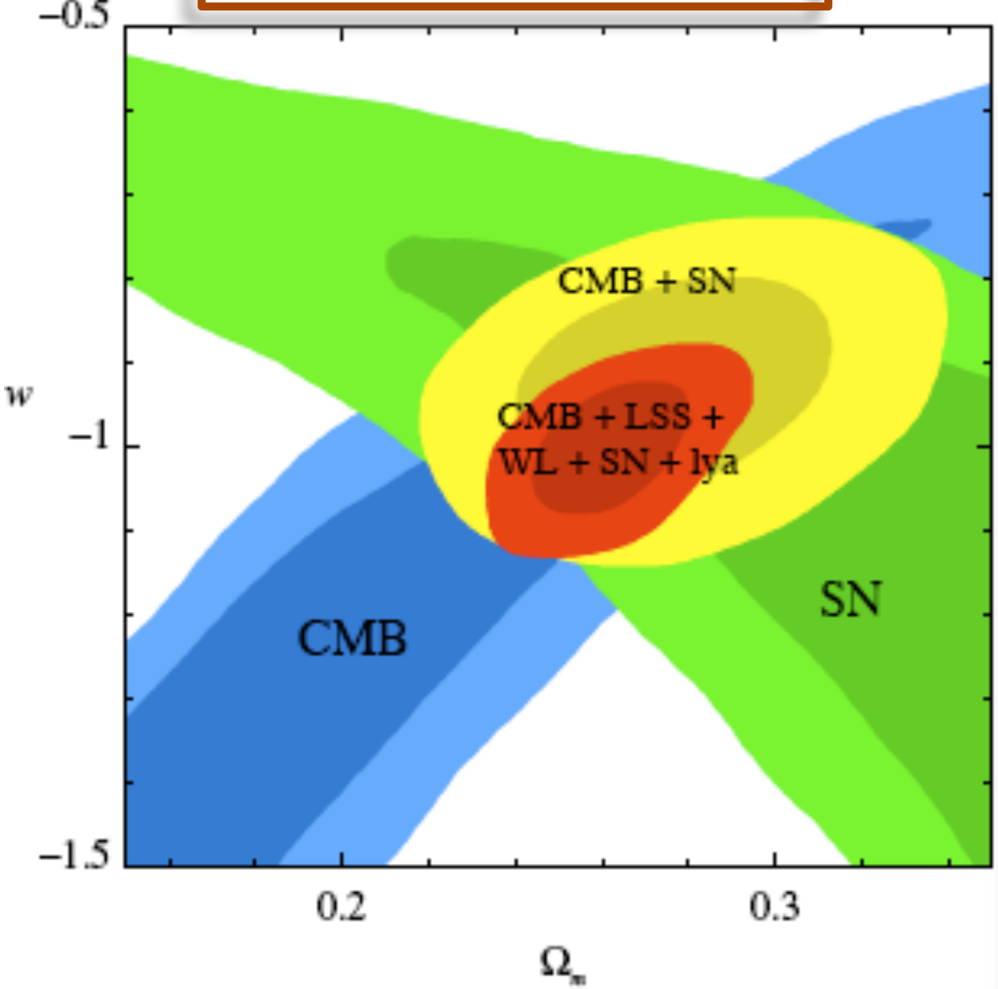
GW/scalar curvature: current from CMB+LSS: r < **0.3** 95%; good shot at **0.02** 95% CL with **BB polarization** (+- .02 PL2.5+Spider), .01 target; Bpol .001 BUT foregrounds/systematics? But **r(k), low Energy inflation**

end1

INFLATION NOW   PROBES NOW

$$w(a) \equiv \frac{p(a)}{\rho(a)}$$

$1+\mathbf{w_0} = -0.0 +/- 0.06$



$\mathbf{w(a)=w_0+w_a(1-a)}$

$1+\mathbf{w_0} = -0.01 +/- 0.19$

$\mathbf{w_a} = 0.0 +0.6-0.8$

piecewise parameterization

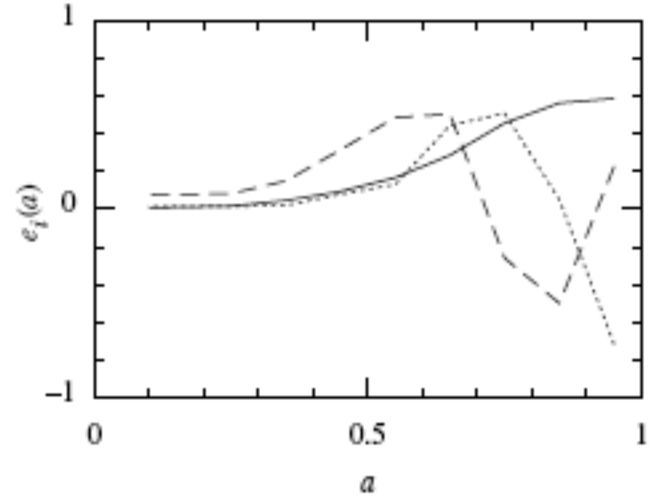
4,9,40 modes in redshift

9 & 40 into Parameter eigenmodes

data cannot determine >2 EOS parameters

DETF Albrecht etal06, Crittenden etal06, hbk08

σ_1**=0.13** σ_2**=0.33** σ_3**=0.58**



. $\varepsilon_{\phi 0}$ **= 0.0 +/- 0.09 if constant,** $\varepsilon_{\phi 0}$ **= -0.015 +/- 0.3 if a-linear model**

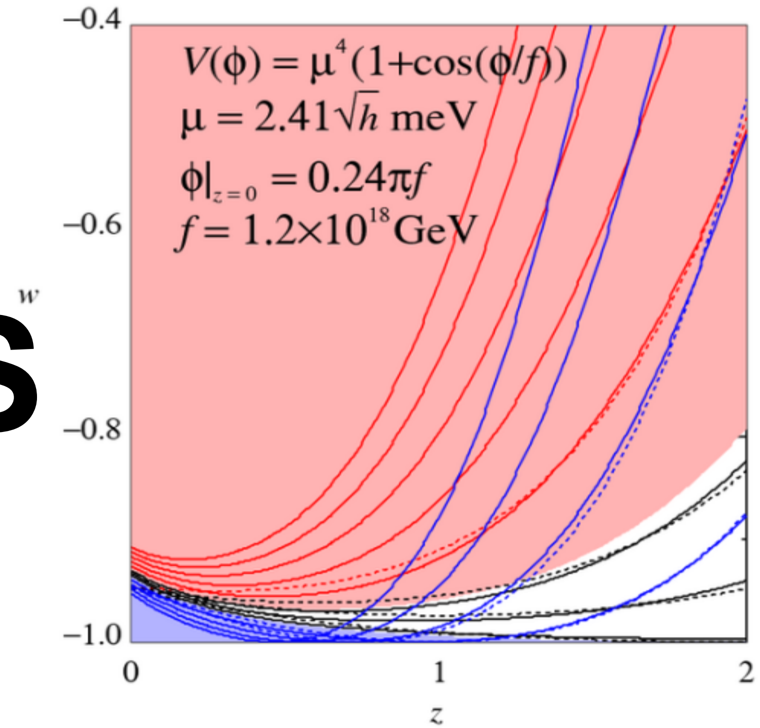
INFLATION NOW PROBES NOW

- **Cosmological Constant (w=-1)**
- **Quintessence**

($-1 \le w \le 1$)

- **Phantom field ($w \le -1$)**
- **Tachyon fields ($-1 \le w \le 0$)**
- **K-essence**

(no prior on w)



trajectory probability: ~1 e-fold => blind is bad => slow-to-moderate roll ++

$-d\ln\rho_\phi / d\ln a \, /2$

$= \varepsilon_\phi(a) \quad = (1+w)2/3$

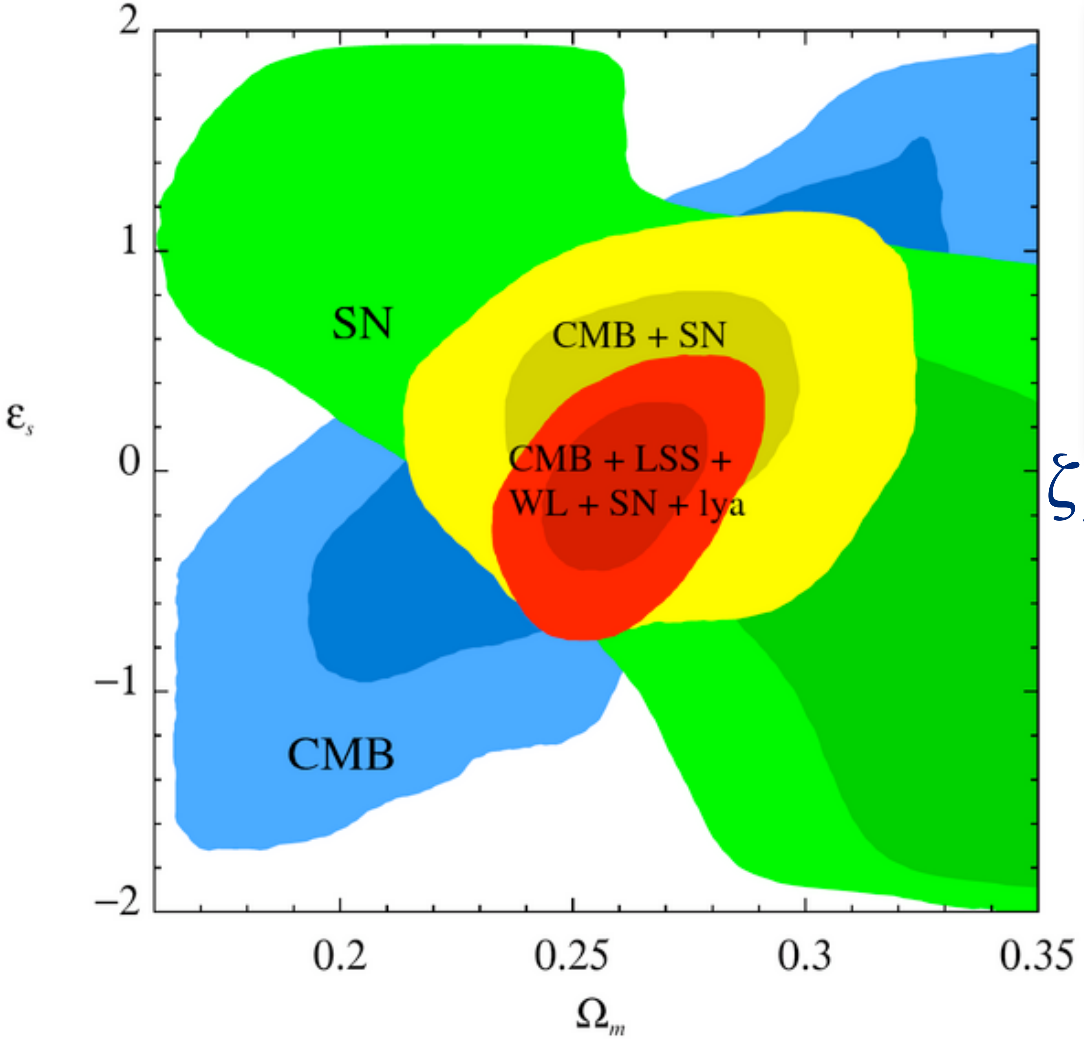
$= \varepsilon_s f(a/a_{\Lambda eq}; a_s/a_{\Lambda eq}; \zeta_s)$

$\varepsilon_s = (d\ln V/d\psi)^2/4$ @pivot a_{eq}

$\zeta_s = +-1.001 d^2\ln V/d\psi^2 /4$ @pivot a_{eq}

$\zeta_s = d\ln\varepsilon_s / d\ln a \times 1/2$ @pivot a_{eq}

measuring ε_s ζ_s a_s=0 tracking (SNe$_{union}$+CMB$_{wmap5+acbar+cbi5yr+b03+}$+WL$_{cfhtls+cosmos}$+LSS$_{sdssRG+2dF}$+Lya)



ε_s= $(d\ln V/d\psi)^2/4$ @pivot a_{eq}

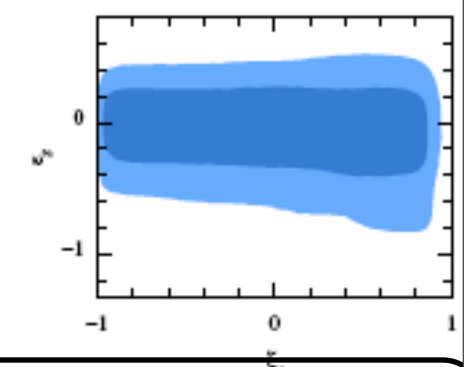
ε_s	.01 + .25 -.28	1
	-.03 + .21 -.25	3
	-.03 + .26 -.30	**2**

ζ_s= +-1.001$d^2\ln V/d\psi^2$ /4 @pivot a_{eq}

ζ_s =dlnε_s /dlna x1/2 @pivot a_{eq}

ill-determined now

$0.1^{+0.6}_{-0.7}$



cannot reconstruct the quintessence potential, just the slope ε_s & ~hubble drag

Beyond Einstein panel: LISA+JDEM

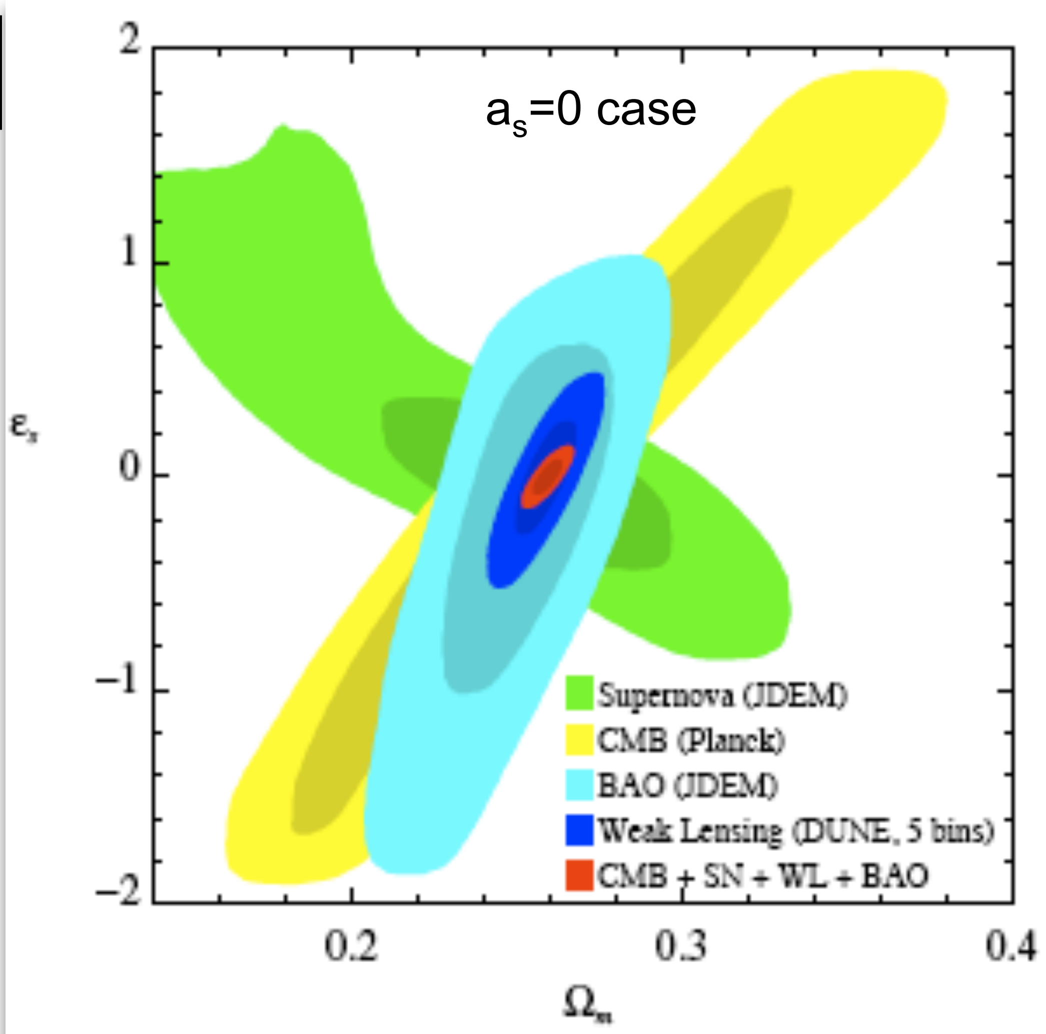
Forecast: **JDEM-SN** (2500 hi-z + 500 low-z)

+ **DUNE-WL** (50% sky, gals @z = 0.1-1.1, 35/min^2) + **Planck1yr**

now ESA /Eucid — ESA (+NASA/CSA)

INFLATION NOW

PROBES THEN

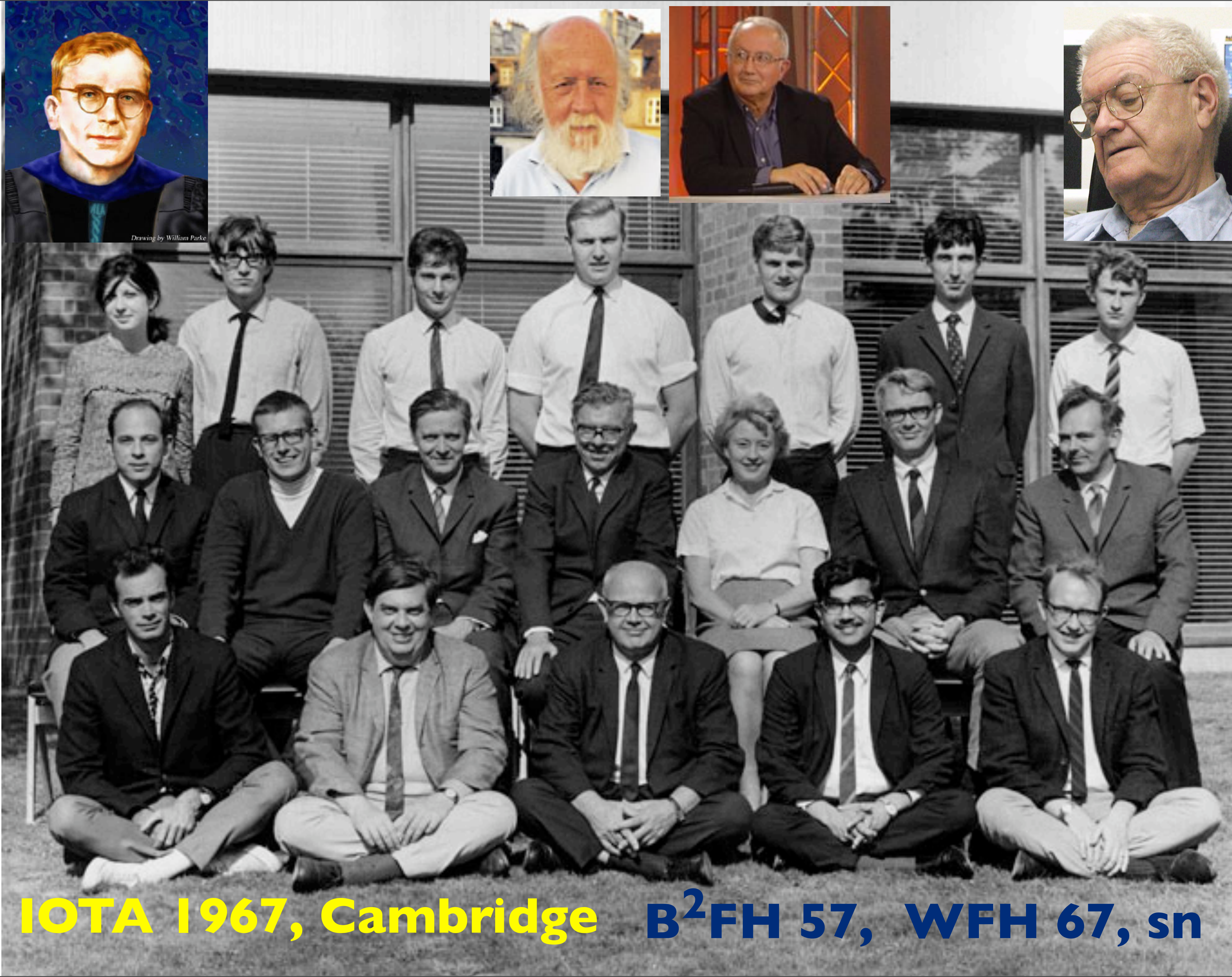


$\varepsilon_s = 0.00^{+0.07}_{-0.06}$

$\zeta_s \sim d\ln\varepsilon_s / d\ln a /2$ $\quad 0.1^{+0.6}_{-0.7}$

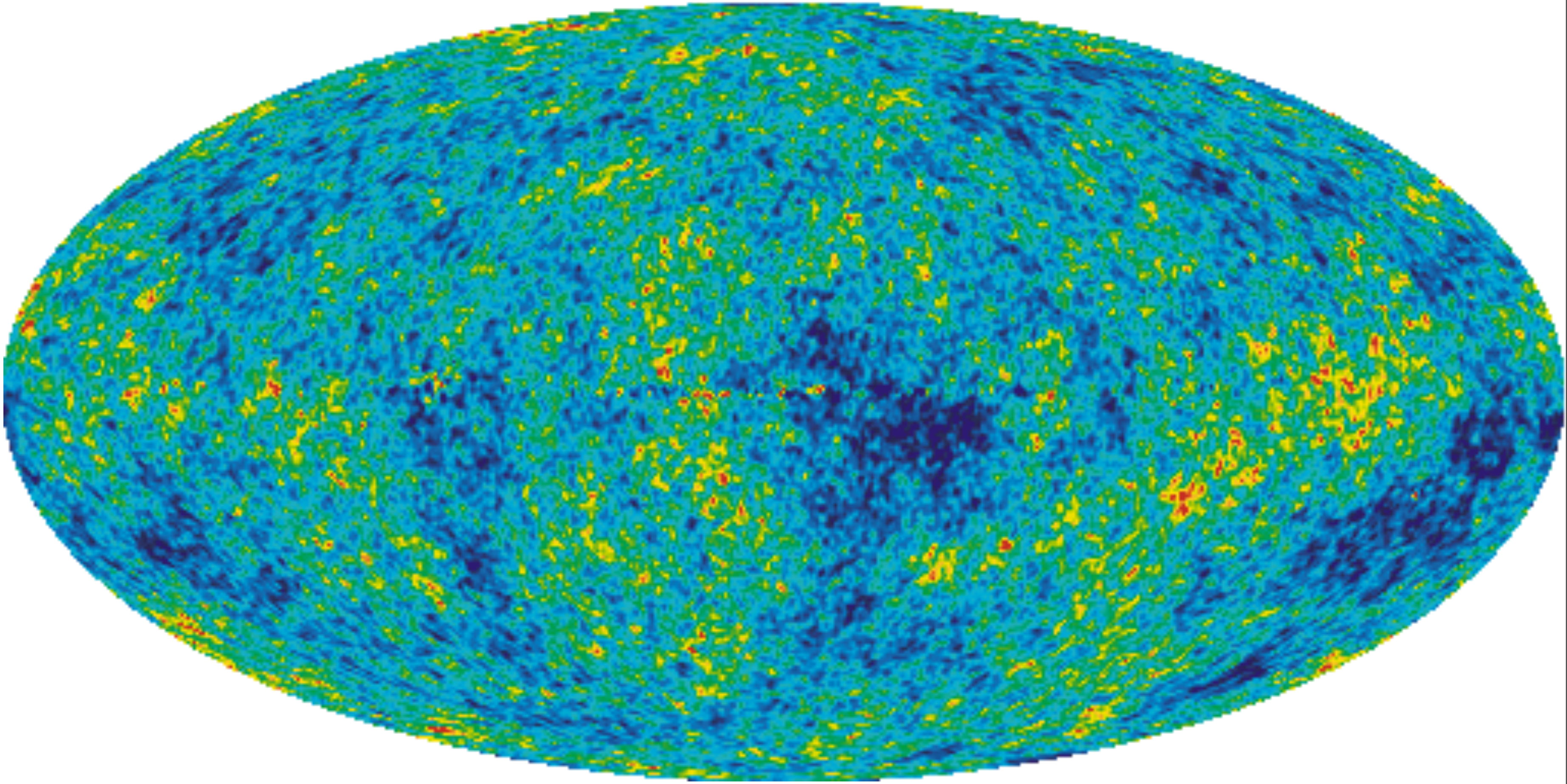
cannot reconstruct the quintessence potential, just the slope ε_s & ~hubble drag

end2


Drawing by William Parke
IOTA 1967, Cambridge
B^2FH 57, WFH 67, sn

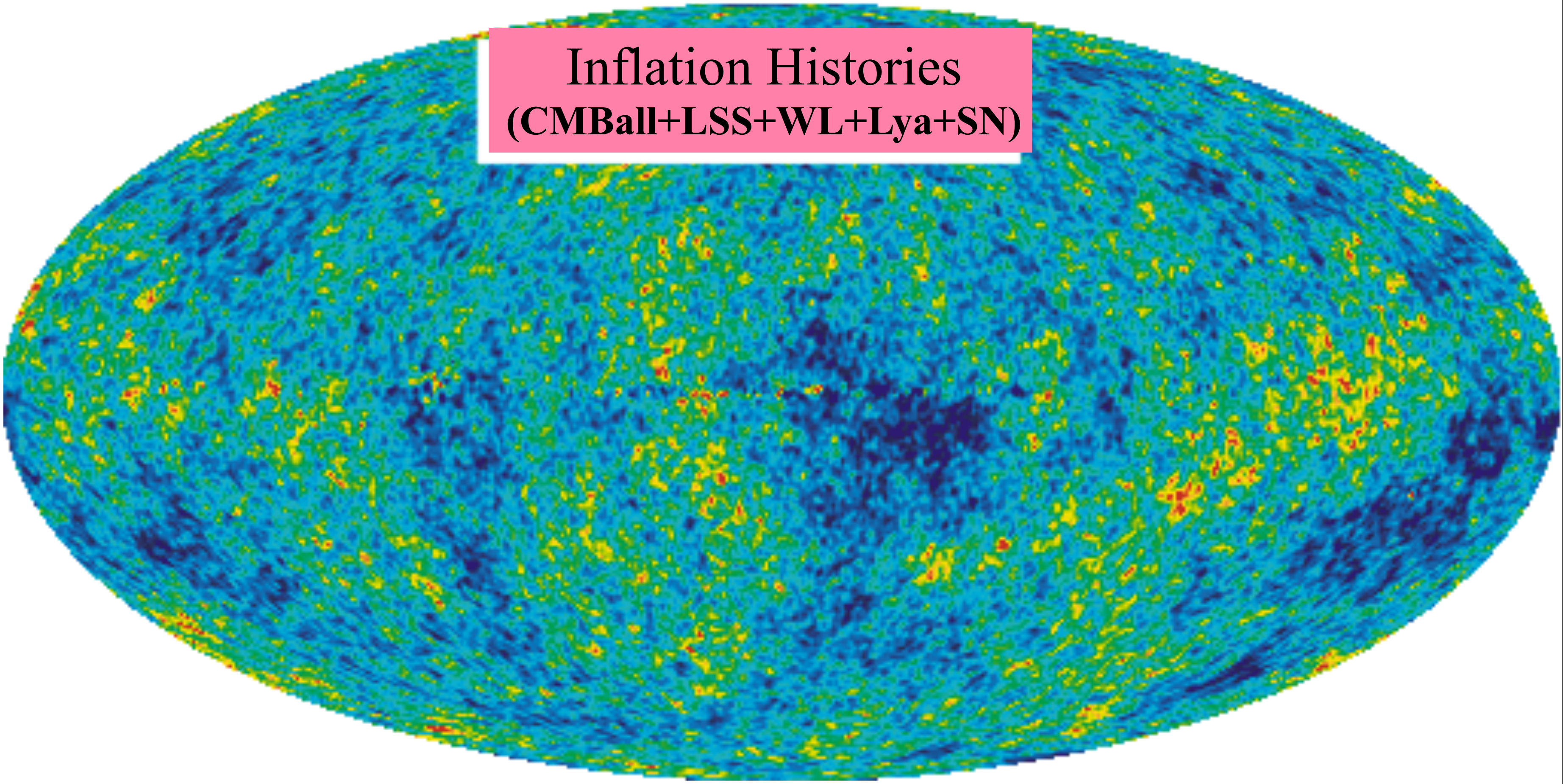
CMBology

Probing the linear & nonlinear cosmic web



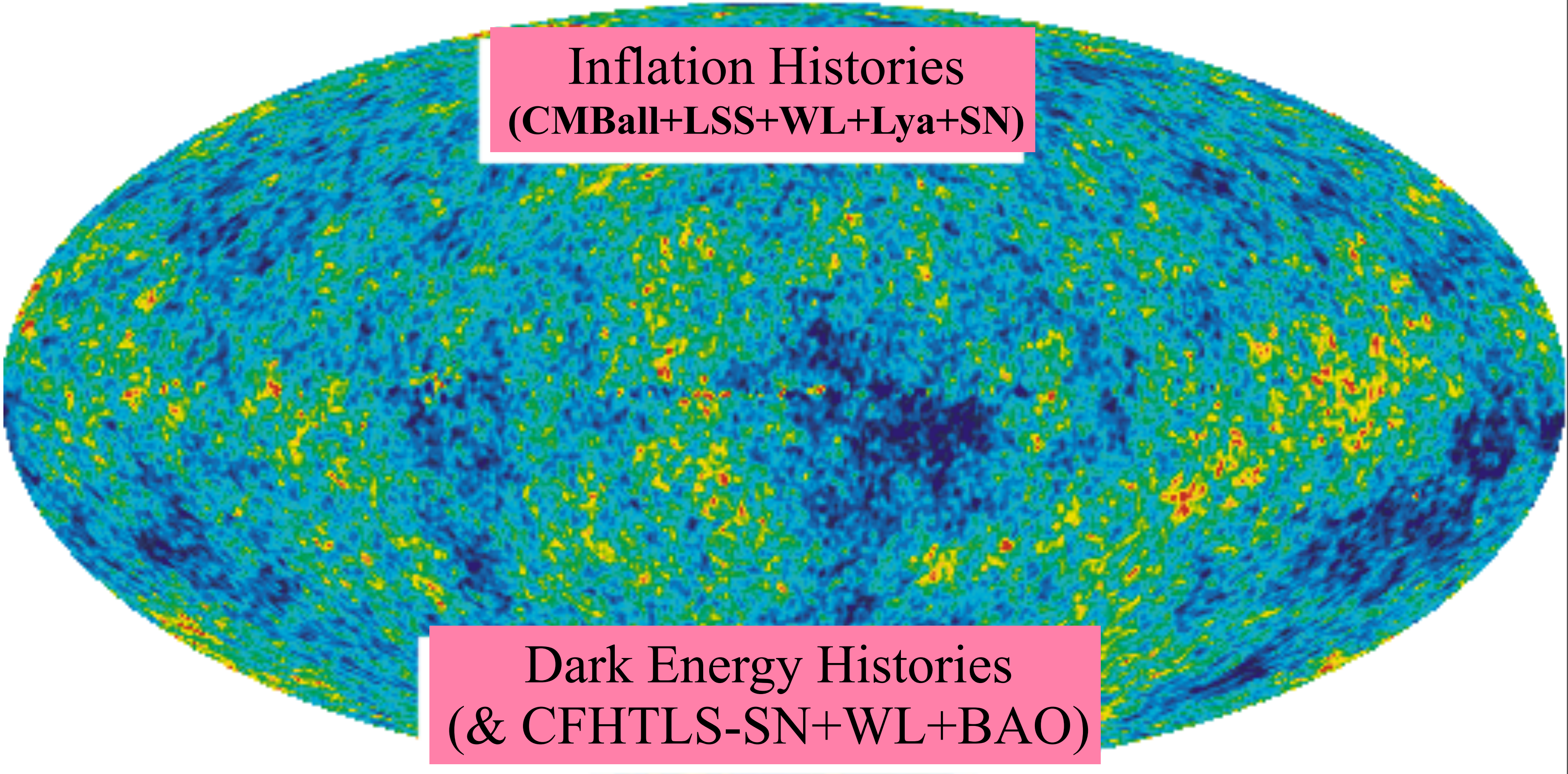
CMBology

Probing the linear & nonlinear cosmic web



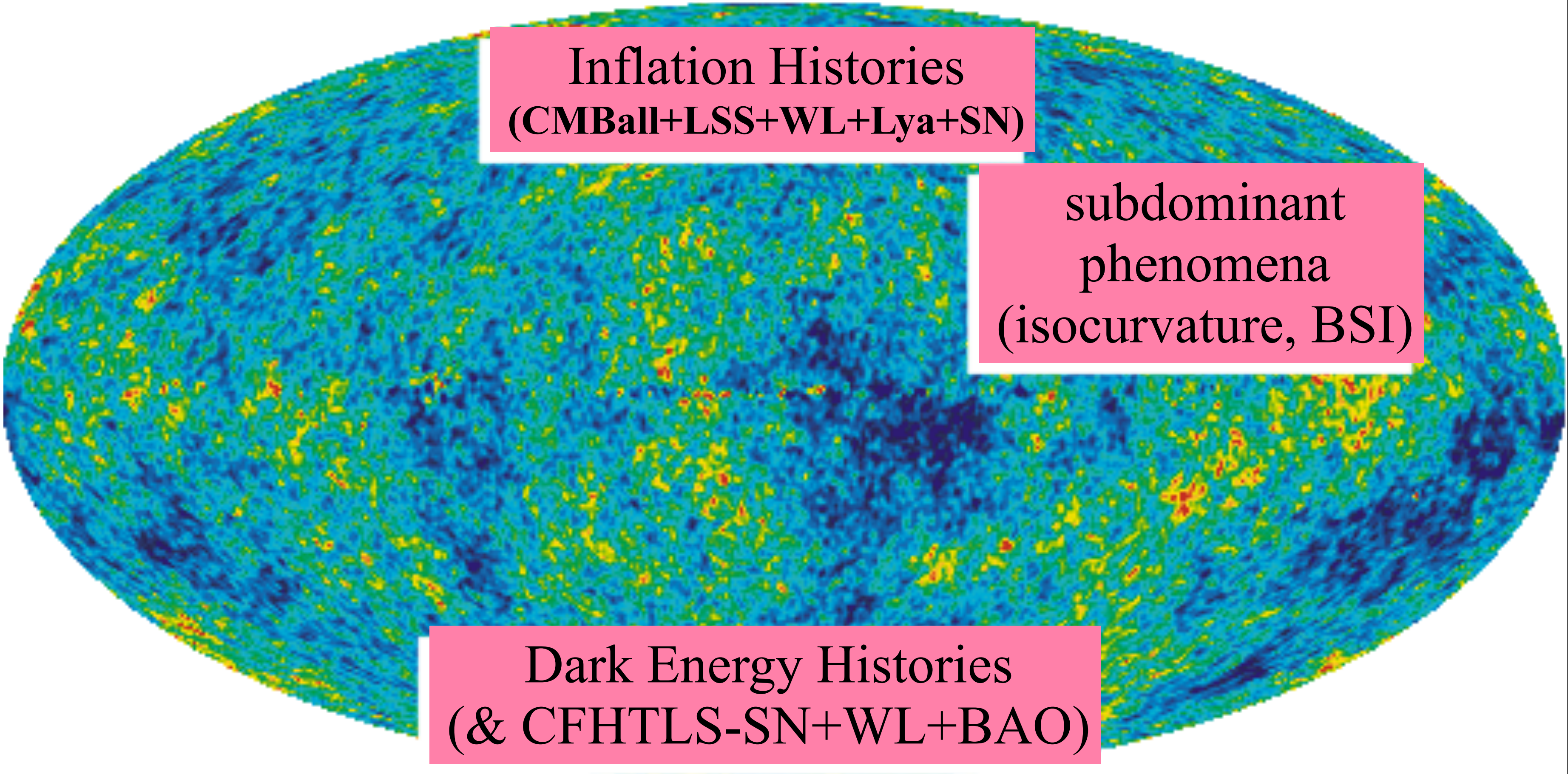
CMBology

Probing the linear & nonlinear cosmic web



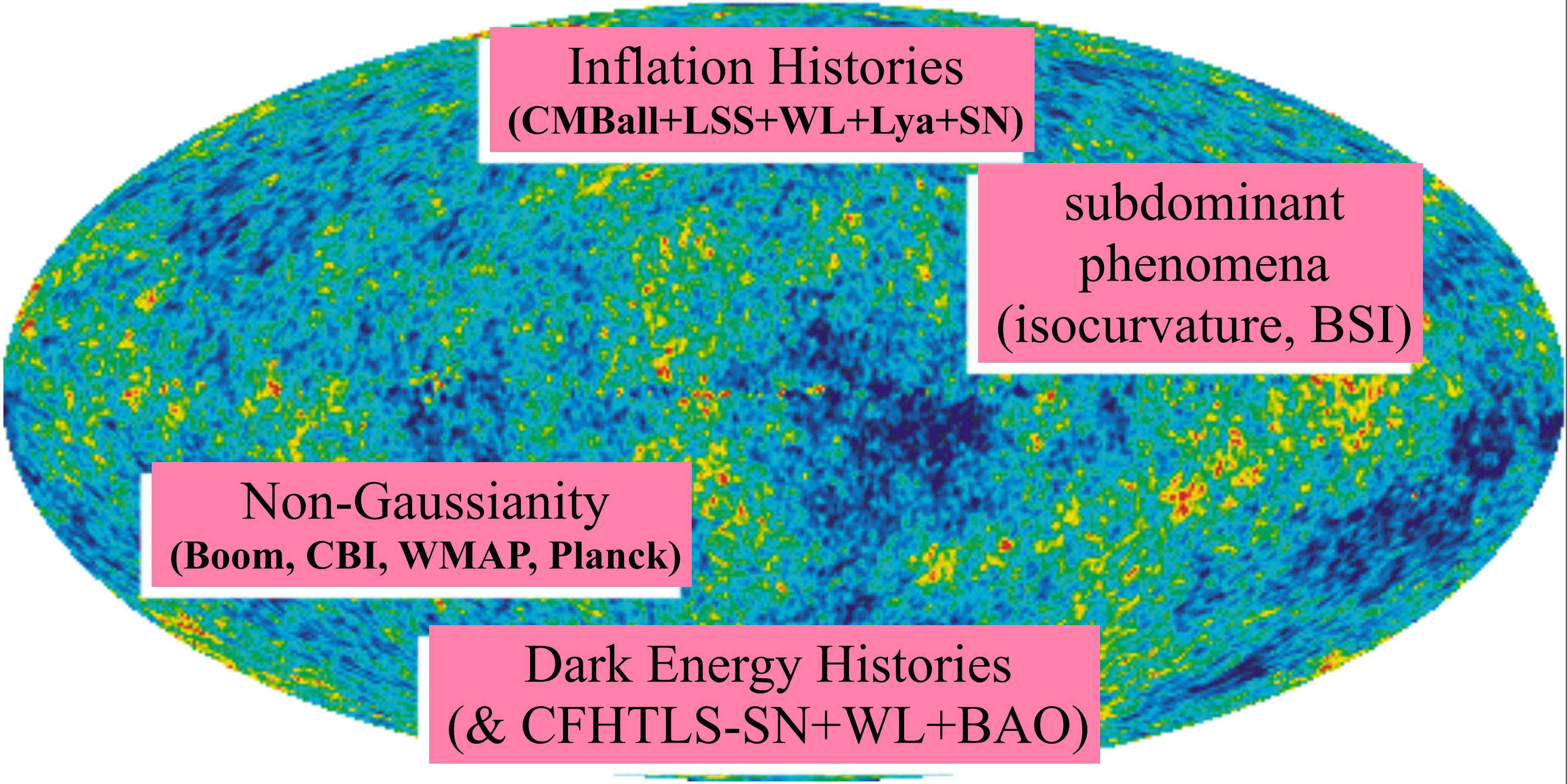
CMBology

Probing the linear & nonlinear cosmic web



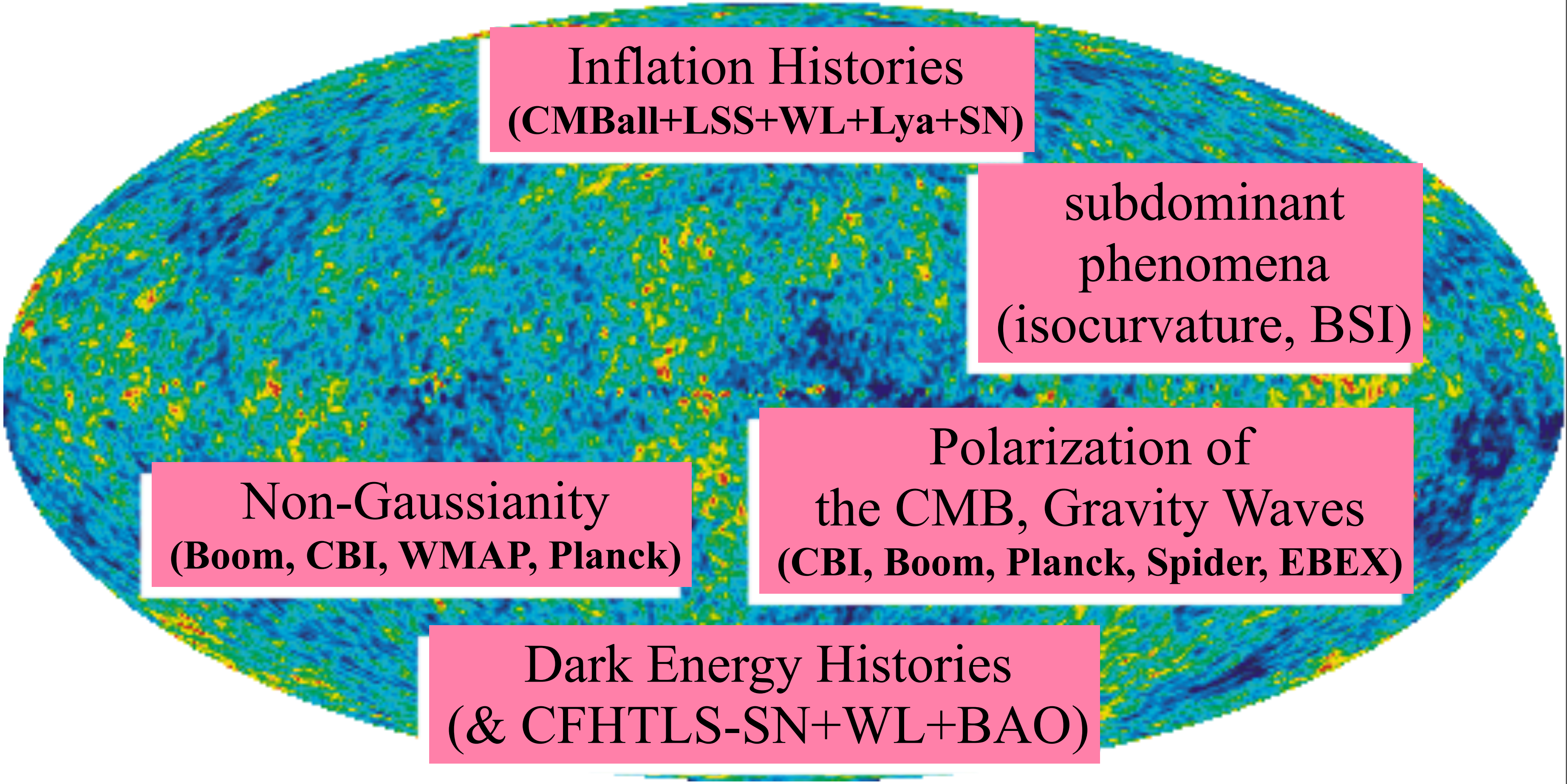
CMBology

Probing the linear & nonlinear cosmic web



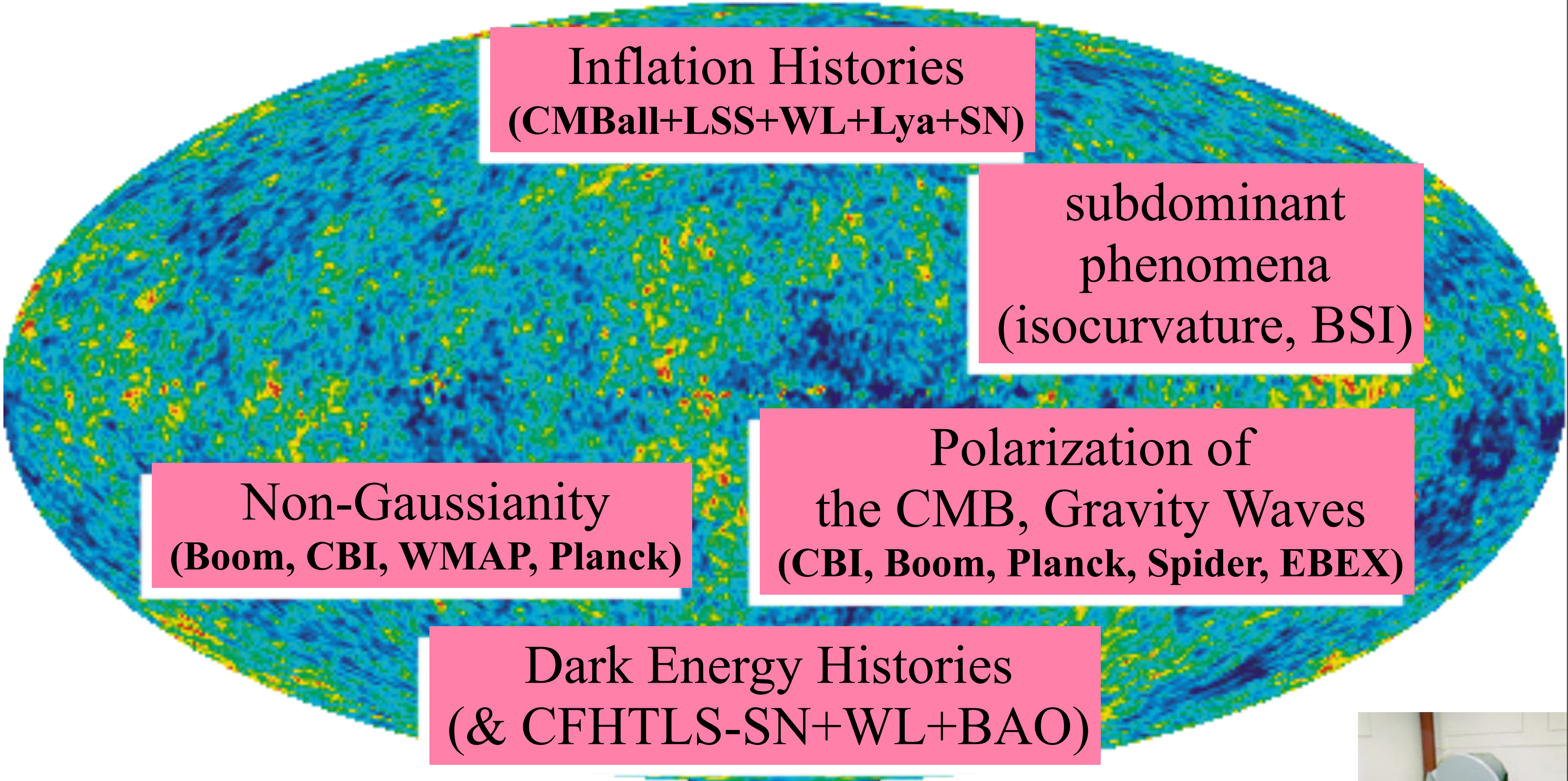
CMBology

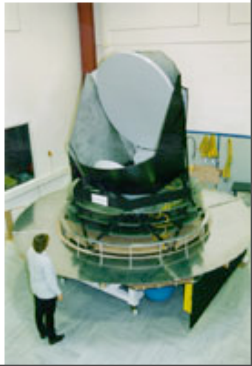
Probing the linear & nonlinear cosmic web



CMBology

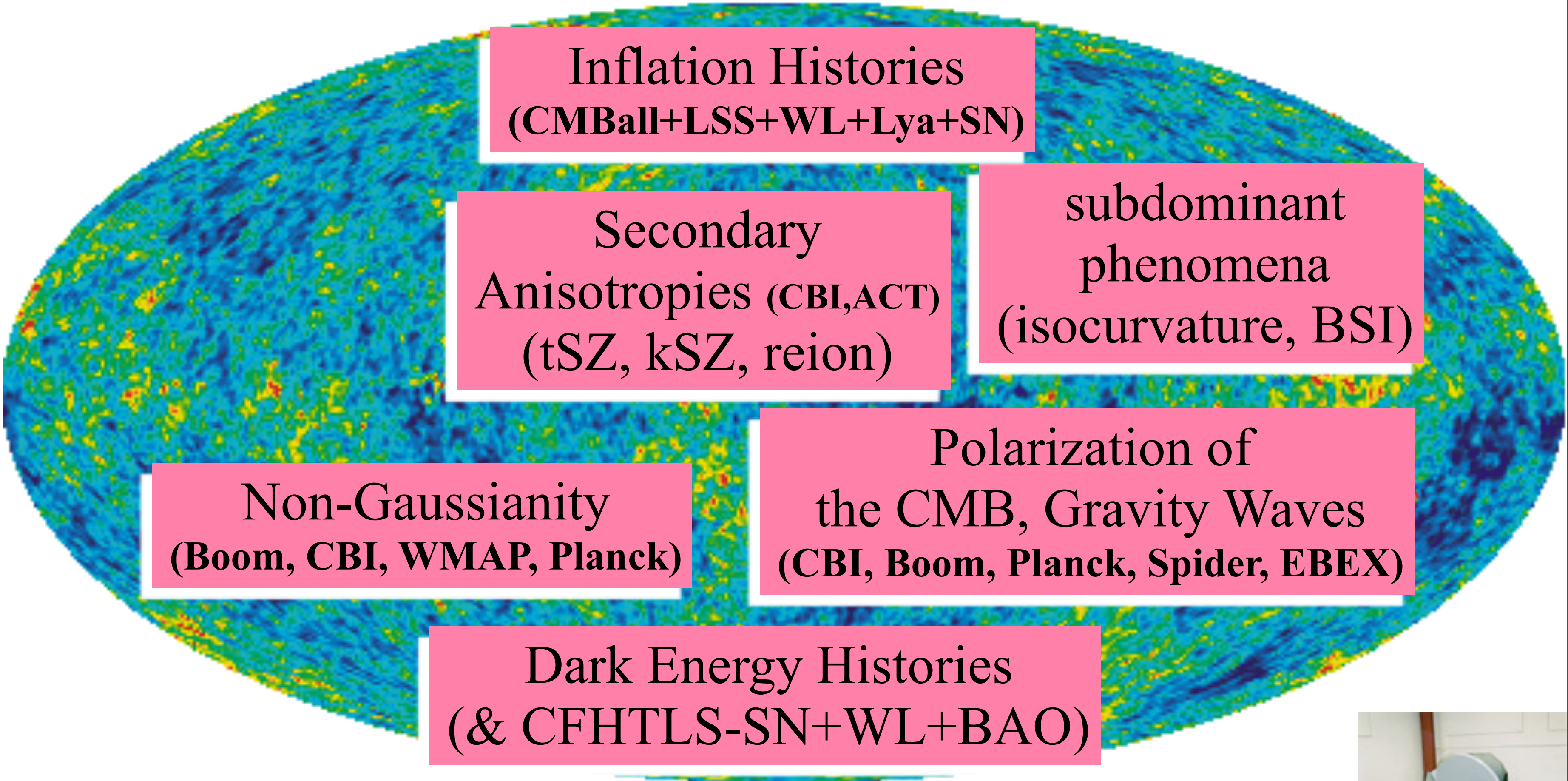
Probing the linear & nonlinear cosmic web

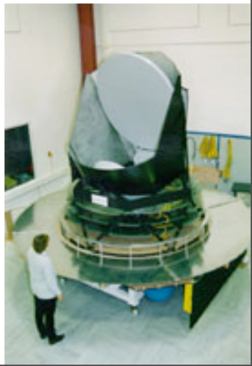




CMBology

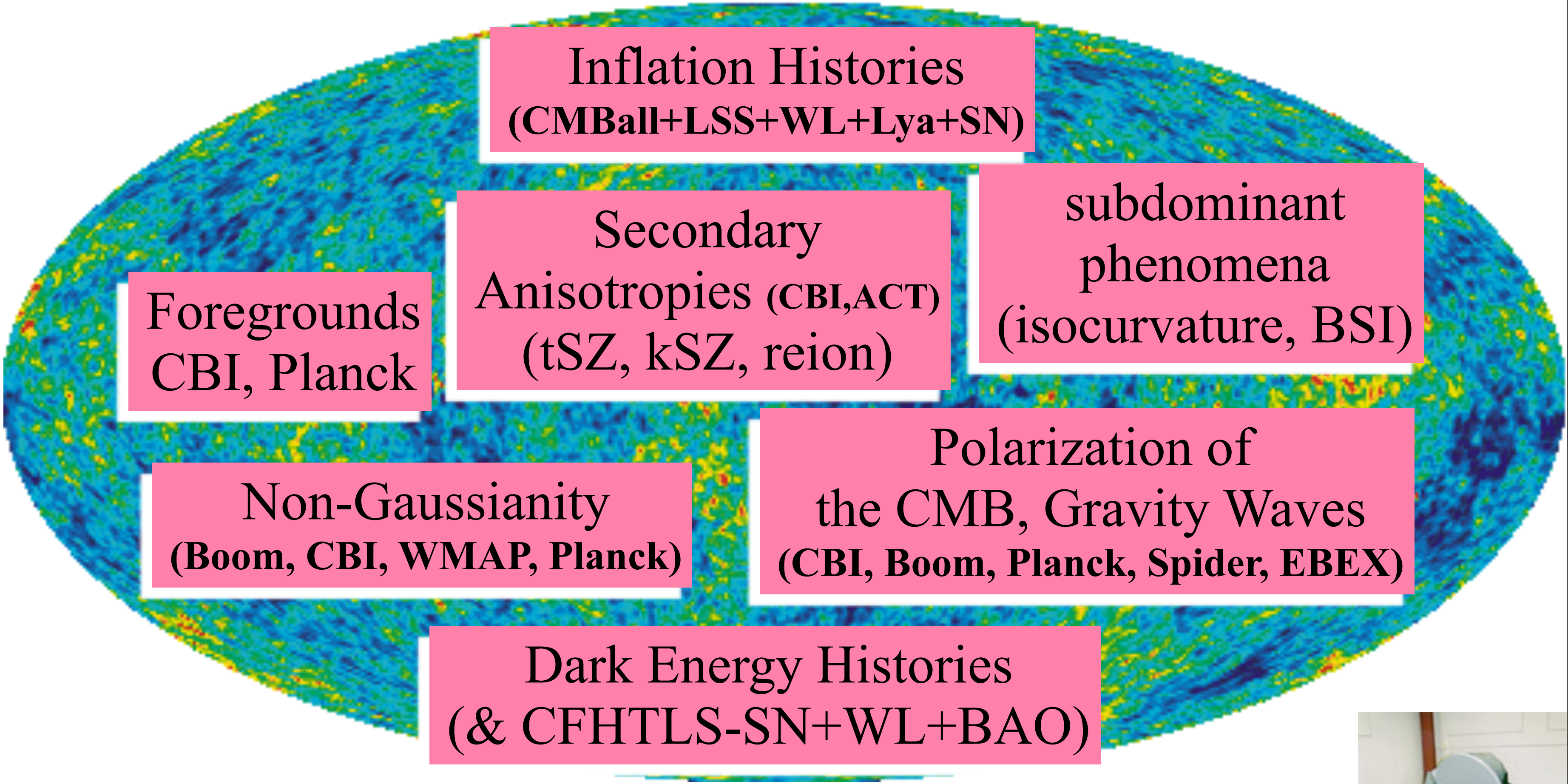
Probing the linear & nonlinear cosmic web

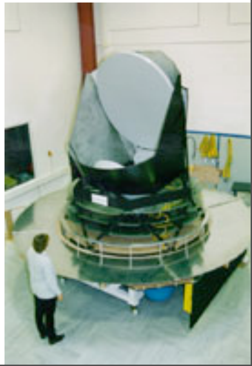




CMBology

Probing the linear & nonlinear cosmic web





Standard Parameters of Cosmic Structure Formation

$\theta \sim \ell_s^{-1}$ $\sim \ln \sigma_8^2$

Ω_k $\Omega_b h^2$ $\Omega_{dm} h^2$ Ω_Λ τ_c $\ln A_s$ n_s $r = A_t / A_s$

1+w0, wa $dn_s / d\ln k$ n_t

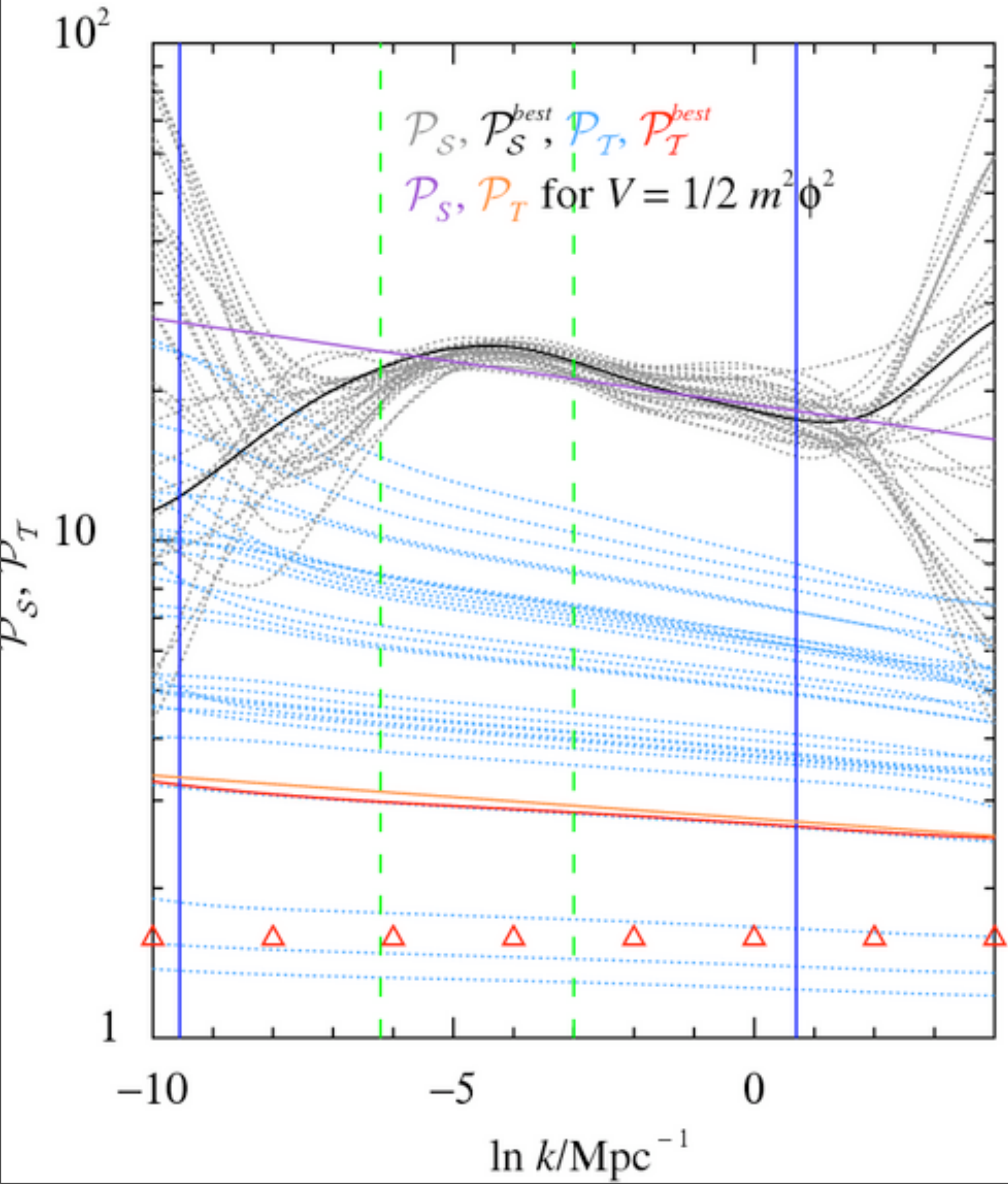
New Parameters of Cosmic Structure Formation: early-inflaton & late-inflaton trajectories

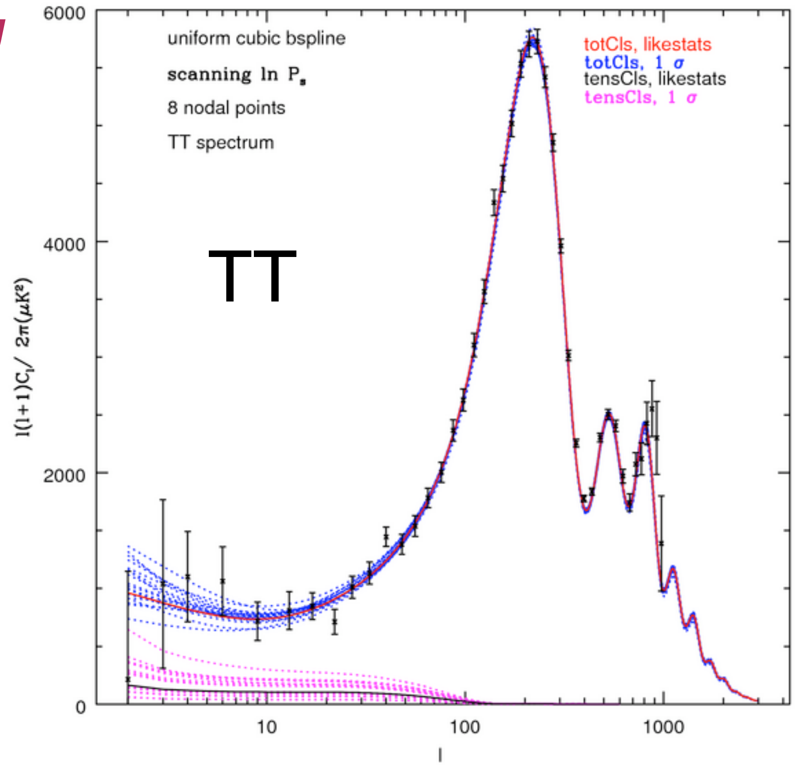
$\varepsilon_\phi = (1+w(a))\times 3/2$ $\epsilon(k), \quad k \approx Ha$ $\ln H(k_p)$

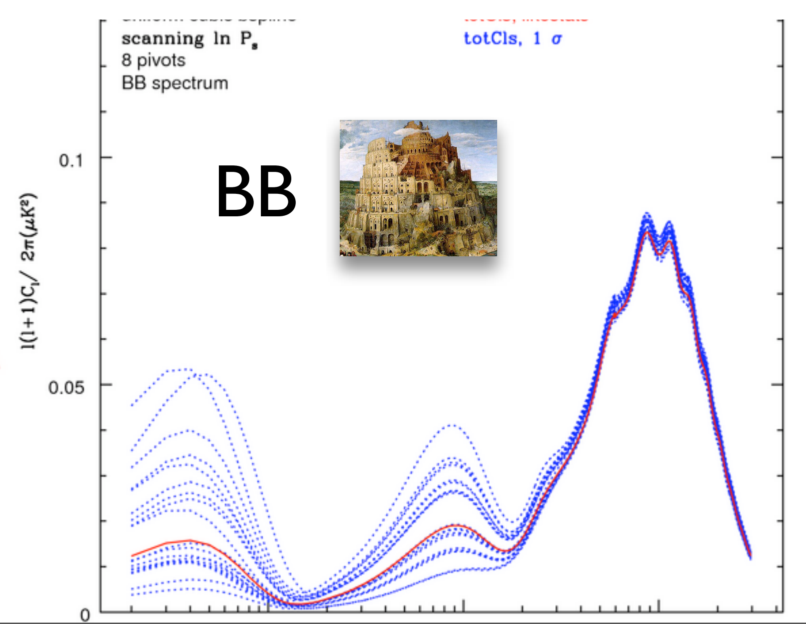
$\varepsilon_s f(a/a_{\Lambda eq}; a_s/a_{\Lambda eq}; \zeta_s)$ $\ln P_s(k)$ $\ln P_t(k)$

+ subdominant isocurvature/cosmic string/ tSZ ...

partially-blind acceleration trajecteries obeying tensor/scalar consistency relation. May08 data







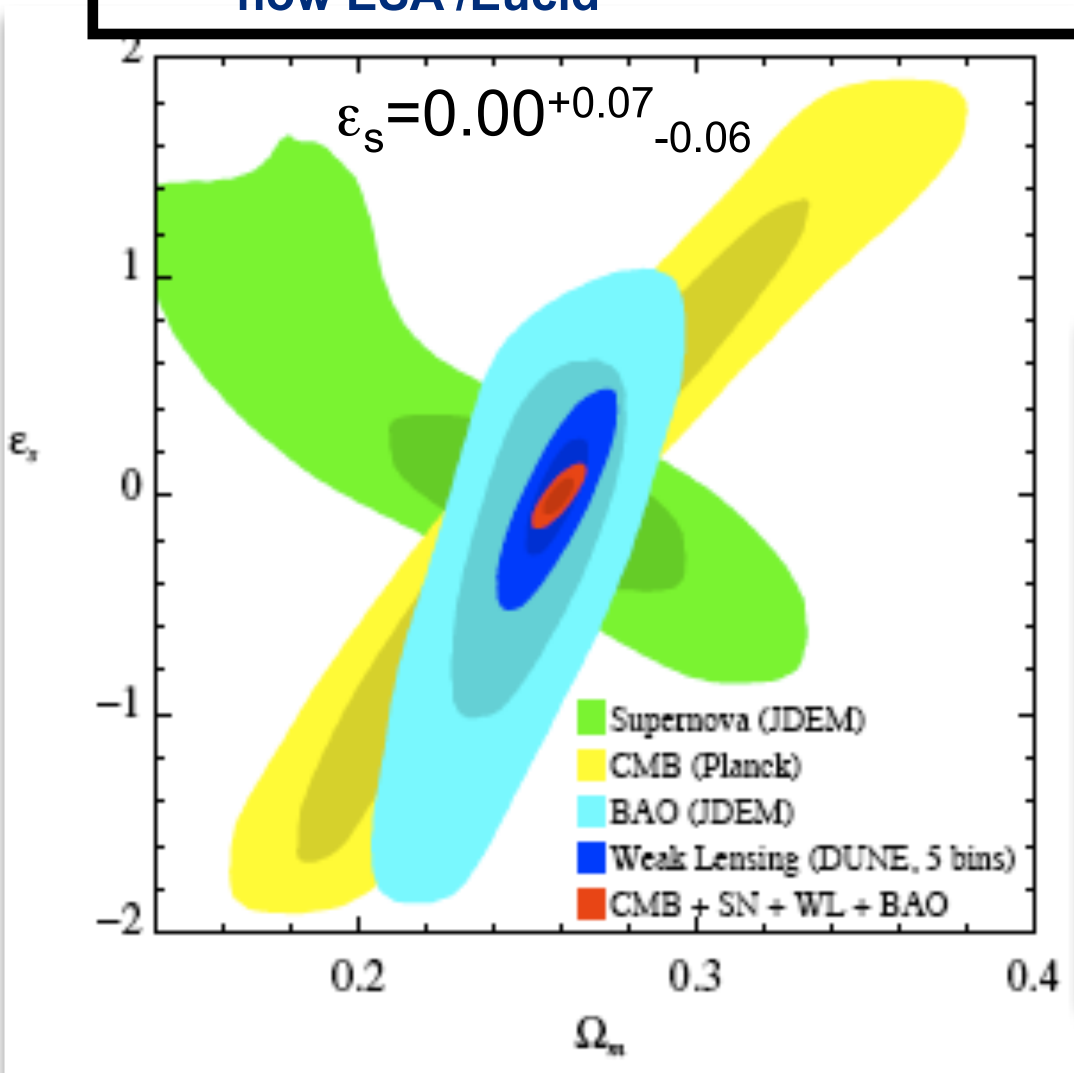
Beyond Einstein panel: LISA+JDEM

Forecast: **JDEM-SN** (2500 hi-z + 500 low-z)

+ **DUNE-WL** (50% sky, gals @z = 0.1-1.1, 35/min^2) + **Planck1yr**

now ESA /Eucid

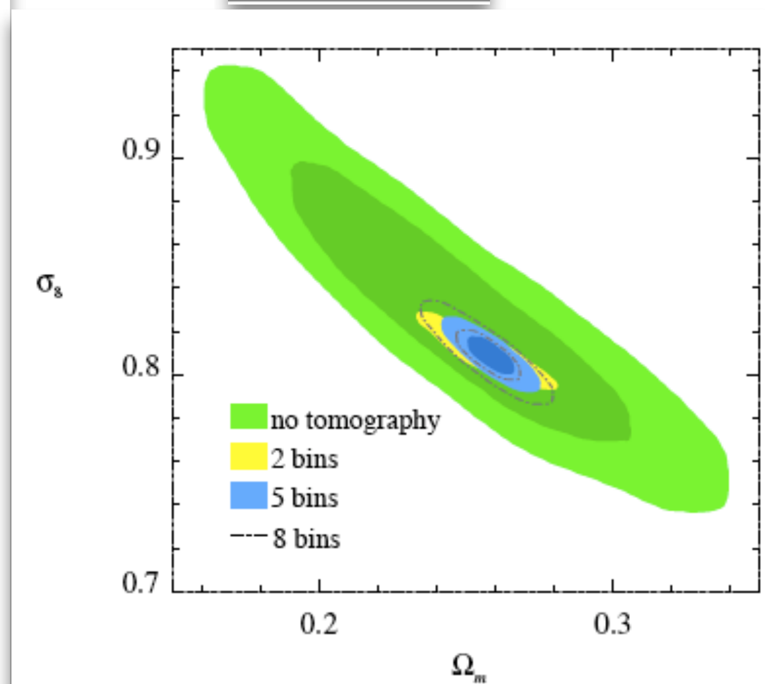
ESA (+NASA/CSA)



a_s=0 case

ζ_s ~dlnε_s /dlna /2 ill-determined

$0.1^{+0.6}_{-0.7}$



cannot reconstruct the quintessence potential, just the slope ε_s & ~hubble drag