CMB Polarization, Past, Present & Future

Dick Bond   Canadian Institute for Theoretical Astrophysics, University of Toronto

theory of CMB polarization

E/B modes

detection history

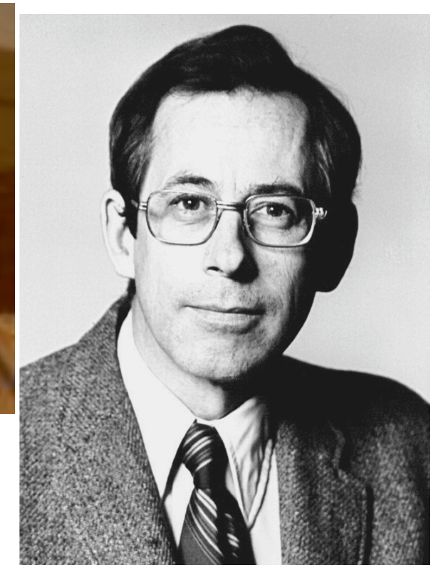
future CMB polarization experiments

reionization ‘trajectories’

inflation & forecasts of the gravity wave level: is the energy scale of inflation high (80s/90s) or low (00s)?

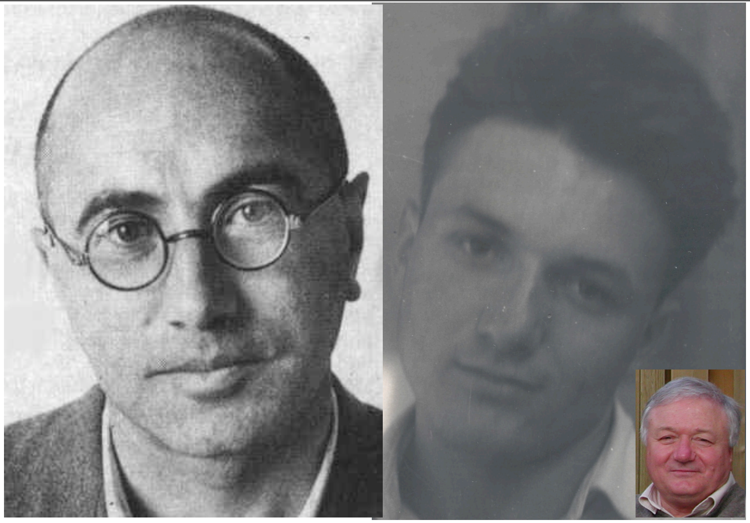
the quest for gravity wave induced B-modes



Peebles, Page, Partridge, *Finding the Big Bang,* ***Feb09 CUP***

Rees 1968: CMB should be polarized; detection 2002 DASI



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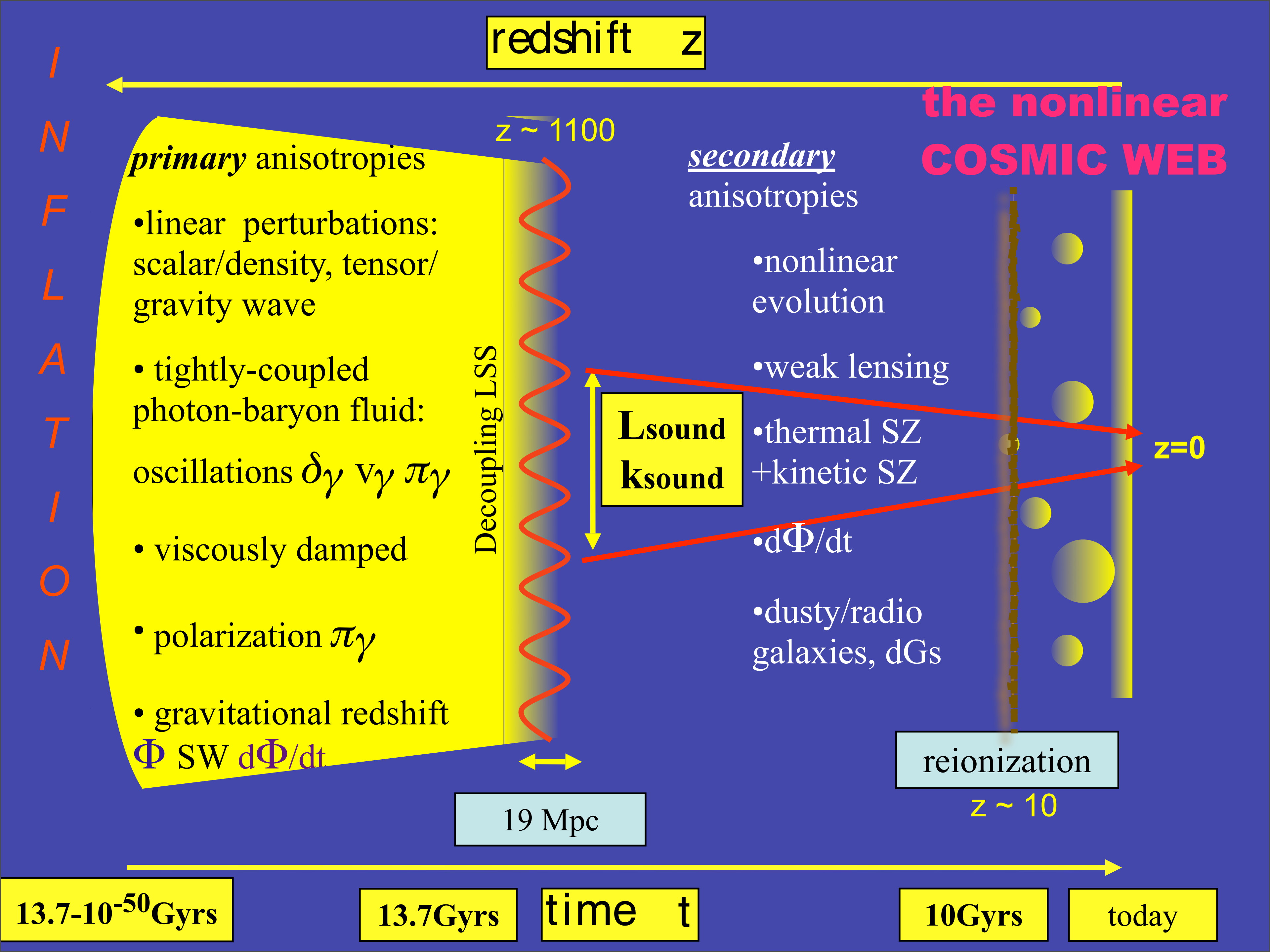

redshift z
INFLATION
z ~ 1100
the nonlinear
COSMIC WEB
primary anisotropies
•linear perturbations: scalar/density, tensor/ gravity wave
• tightly-coupled photon-baryon fluid:
oscillations $\delta\gamma$ $v\gamma$ $\pi\gamma$
• viscously damped
• polarization $\pi\gamma$
• gravitational redshift
Φ SW $d\Phi/dt$
Decoupling LSS
Lsound
ksound
secondary
anisotropies
•nonlinear evolution
•weak lensing
•thermal SZ
+kinetic SZ
•$d\Phi/dt$
•dusty/radio galaxies, dGs
z=0
reionization
z ~ 10
19 Mpc
13.7-10^{-50}Gyrs
13.7Gyrs
time t
10Gyrs
today

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Kaiser83, pol via line-of-sight integration
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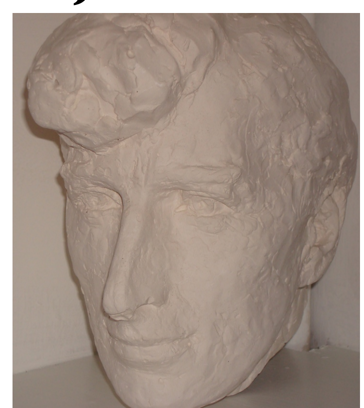
effect on shear viscosity, damping tail, “E” mode
BE87: low to high L full CLpol, maps



First E detection DASI 2002;
CBI04/05, Boom05, WMAP06,
Capmap08, QuAD08; BICEP09?

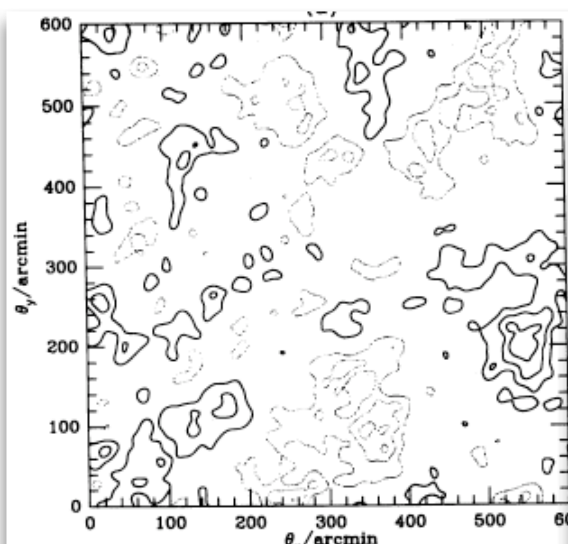
Delta T over Tea Toronto May 1987: first dedicated CMB conference, exptalists+theorists, primary+secondary ΔT/T

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

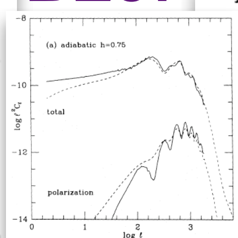
• very small angle anisotropies - VLA results, secondary fluctuations via the Sunyaev-Zeldovich effect, primeval dust emission, and radio sources

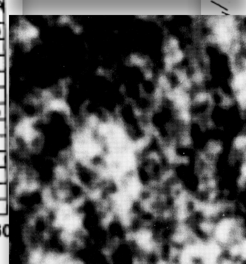
• small angle anisotropies - current results, optimal measuring strategies, statistical methods for small signals in larger noise, which universes can we rule out, the reheating issue, future detectors and techniques, CMB map statistics, polarization

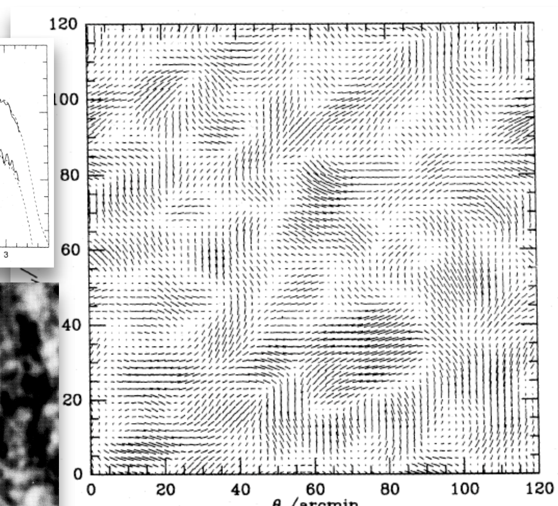
• intermediate and large angle anisotropies - $5^o - 10^o$ results, future experiments at $\sim 1^o$, COBE and other large angle analyses, theoretical $C(\theta)'s$ and their angular power spectra, Sachs-Wolfe effect in open Universes, the isocurvature CDM and baryon stories, $\Delta T/T$ from gravitational waves, the cosmic string story.



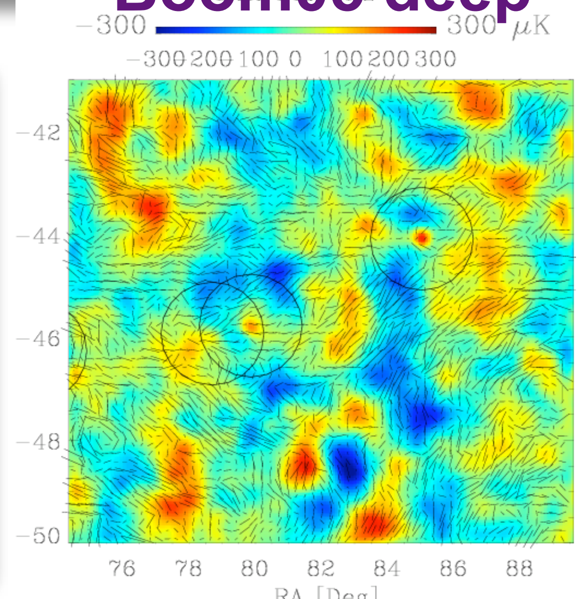
BE87







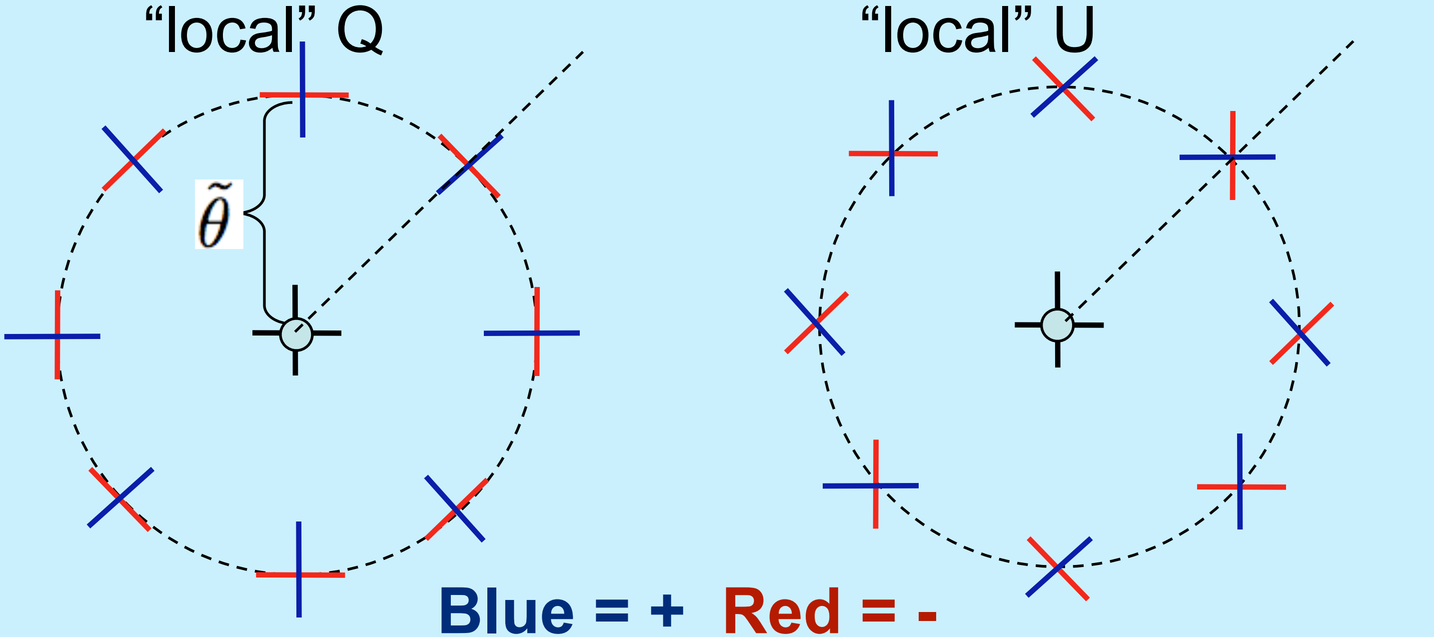
Boom05 deep



E and B modes: f(ss',xpt) Stokes parameters I,Q,U,V with Q-only for Thompson scattering in a plane parallel atmosphere Chandrasekhar...BE84...

scalar polarization basis in Fourier space E=Q(**q**), B=U(**q**), q=L+1/2

large sky patches: $Q+iU(\hat{\mathbf{n}}) = \sum_{lm} {}_2a_{lm}\ {}_2Y_{lm} \quad Q-iU(\hat{\mathbf{n}}) = \sum_{lm} {}_{-2}a_{lm}\ {}_{-2}Y_{lm}$



Tensor perturbations, transverse-traceless metric h_+, h_x **& neutrino+photon anisotropic stress:** U & Q in **q**-space, i.e., **B & E**

"fgnd" lensing by the cosmic web shifts scalar E pattern inducing B & E

"fgnd" Galactic & extragalactic sources give **B &E** separate by frequency, spatial pattern

E and B modes: f(ss',xpt) Stokes parameters I,Q,U,V with Q-only for Thompson scattering in a plane parallel atmosphere Chandrasekhar...BE84...

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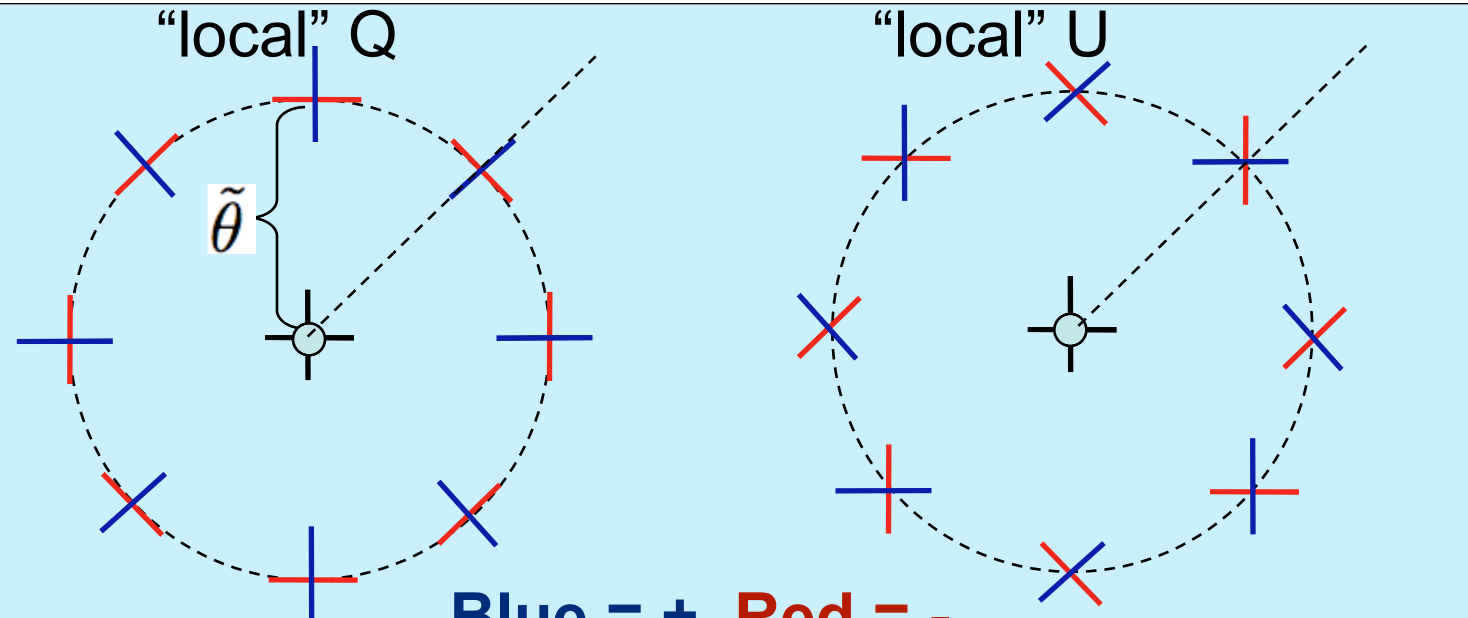

Blue = + Red = -

$$a^E_{lm} = -(\ {}_2a_{lm} + \ {}_{-2}a_{lm})/2 \qquad a^B_{lm} = i(\ {}_2a_{lm} - \ {}_{-2}a_{lm})/2$$

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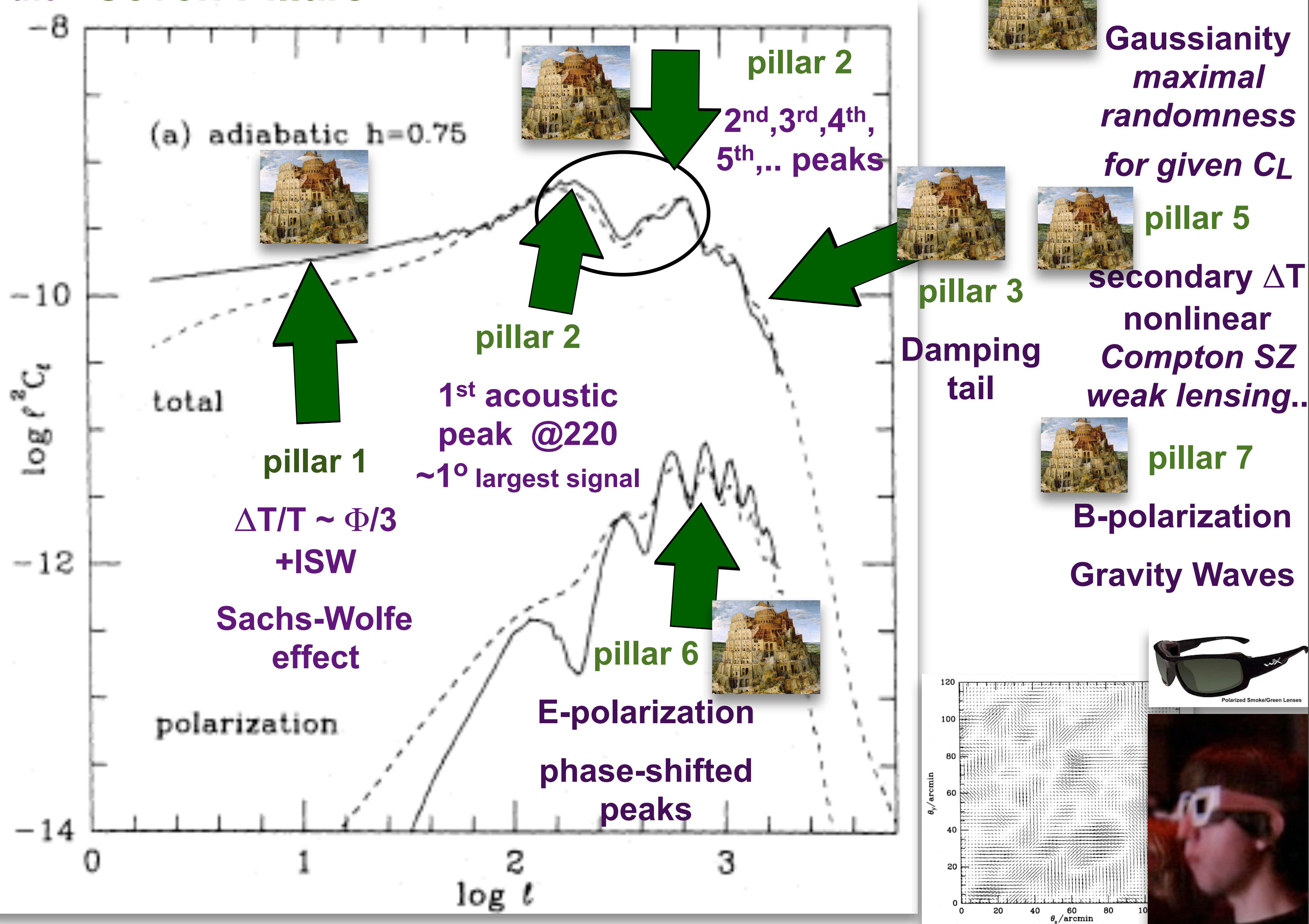
BE87: low to high L full CLpol, maps
Crittenden & Turok 96: TE correlation **DASI02,WMAP03**
Kaiser95, Stebbins96: rotate lensing E to B, a null test
Kamionkowski, Kosowsky & Stebbins97 & Seljak & Zaldarriaga97: apply to CMB E/B modes. emphasize as gravity wave discriminator
Zaldarriaga & Seljak98 lensing distorts E into B

First E detection DASI 2002; CBI04/05, Boom05, WMAP06, Capmap08, QuAD08; BICEP09?

the “Seven Pillars”



CBI pol to Apr'05 @Chile

CBI2

Boom03@LDB

WMAP @L2 to 2009-2013?

DASI @SP

CAPMAP

QUaD @SP

Bicep @SP

Planck09.3

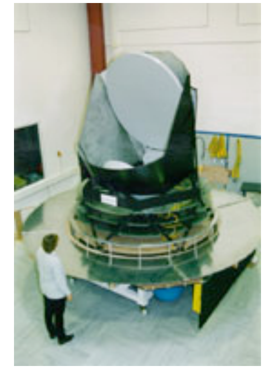
(52 bolometers)
+ HEMTs @L2
9 frequencies

Herschel

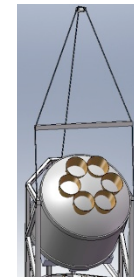
BLAST

Quiet1
@Chile

Bicep2



EBEX
@LDB



Quiet2
1000 HEMTs

Keck/Spud

Spider
2312 bolos
@LDB

CHIP

2004 2006 2008 LHC 2011

2005 2007 2009

Bpol
@L2

Acbar to Jan'06, 08f @SP

SZA
@Cal

AMI

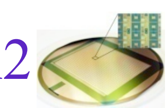
GBT

APEX
~400 bolos
@Chile

SPT
1000 bolos
@SPole

ACT
3000 bolos
3 freqs @Chile

SCUBA2



12000 bolos
JCMT @Hawaii

BLASTpol

Clover
@Chile

Polarbear
300 bolos
@Cal/Chile

SPTpol

ALMA
@Chile

LMT@Mexico

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

QUaD @SP

Quiet1 @Chile

Quiet2 1000 HEMTs

Boom03@LDB

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Planck09.3

(52 bolometers)
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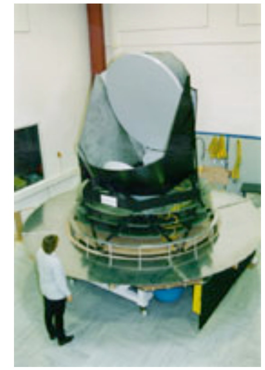
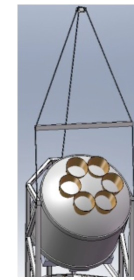


EBEX @LDB

Spider 2312 bolos @LDB



DASI @SP

CAPMAP

Herschel

BLAST

CHIP

2004 — 2005 — 2006 — 2007 — 2008 — 2009 — LHC — 2011

Bpol @L2

Acbar to Jan'06, 08f @SP

SPT 1000 bolos @SPole

BLASTpol

Clover @Chile

SZA @Cal

ACT 3000 bolos 3 freqs @Chile

Polarbear 300 bolos @Cal/Chile

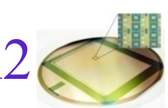
SPTpol

AMI

GBT

APEX ~400 bolos @Chile

SCUBA2



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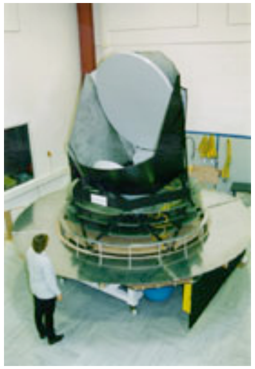

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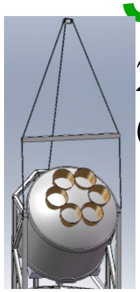

Spider
2312 bolos
@LDB

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CAPMAP

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2004 2005 2006 2007 2008 2009 2011

LHC

Bpol @L2

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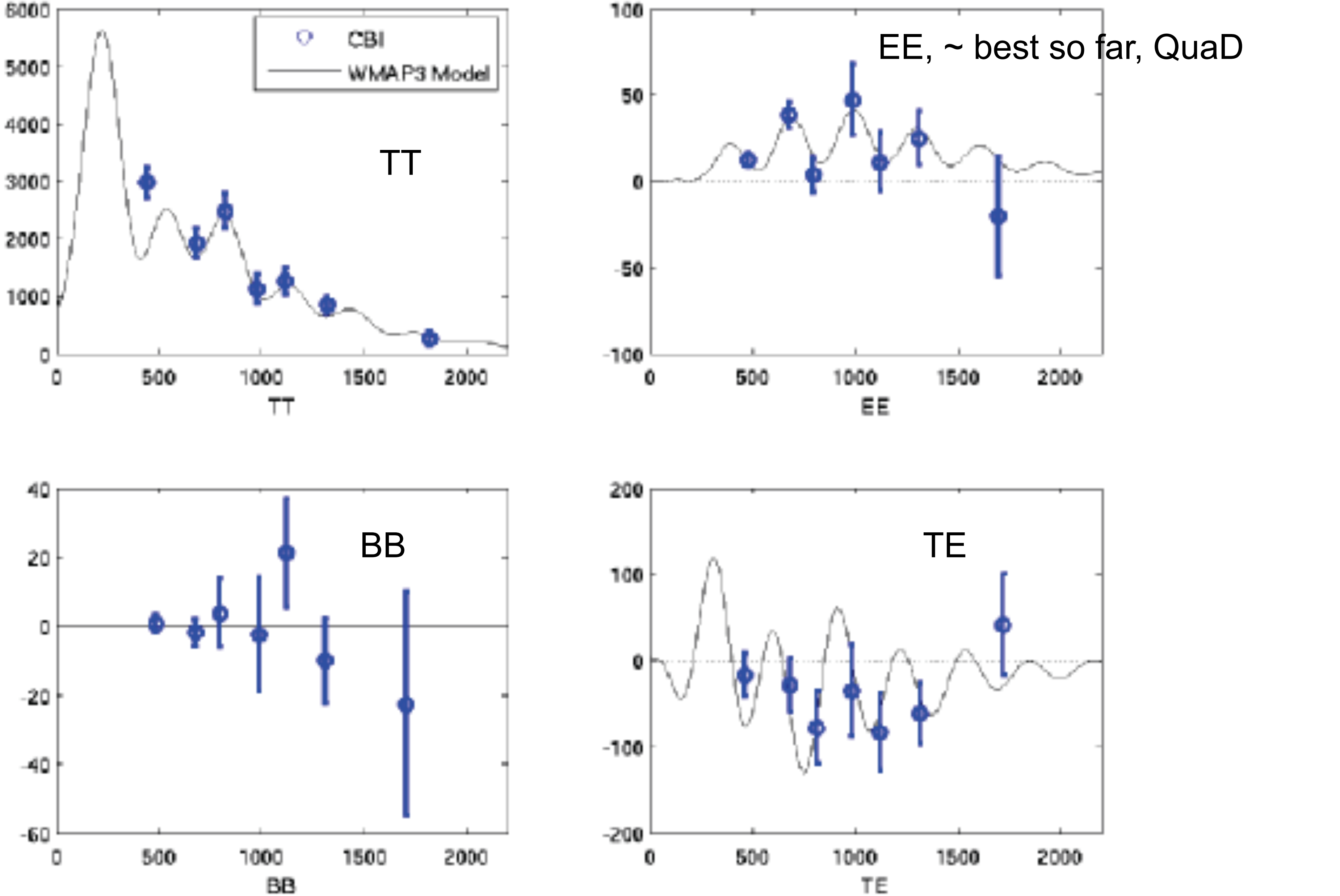
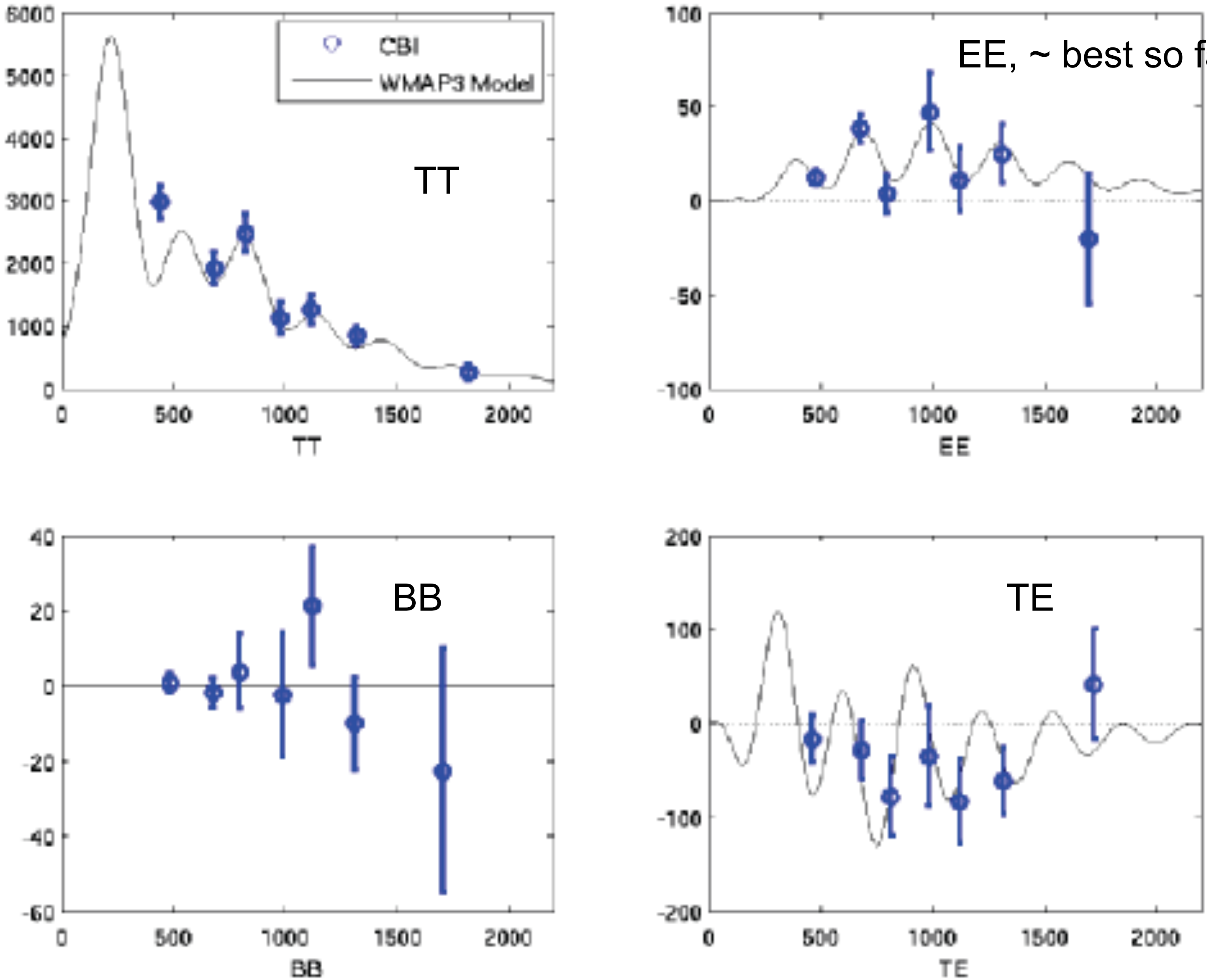
CBIpol 2.5yrs **Sievers etal 05/06, Readhead etal 04**



CBIpol 2.5yrs Sievers etal 05/06, Readhead etal 04



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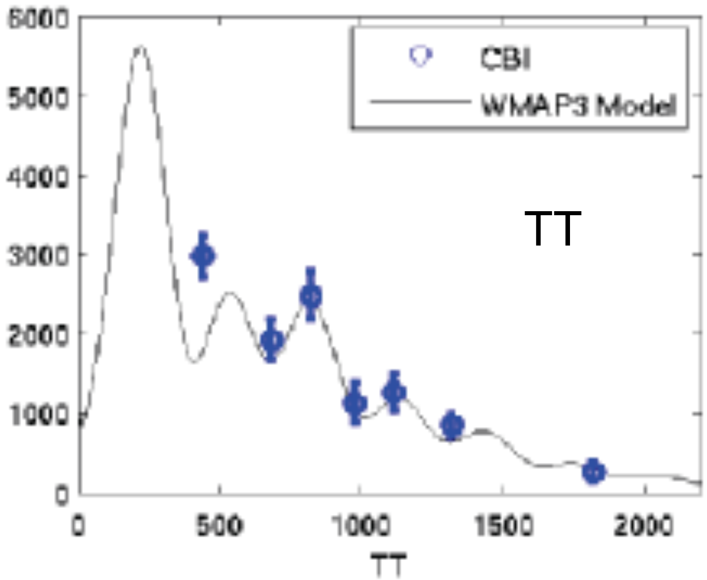
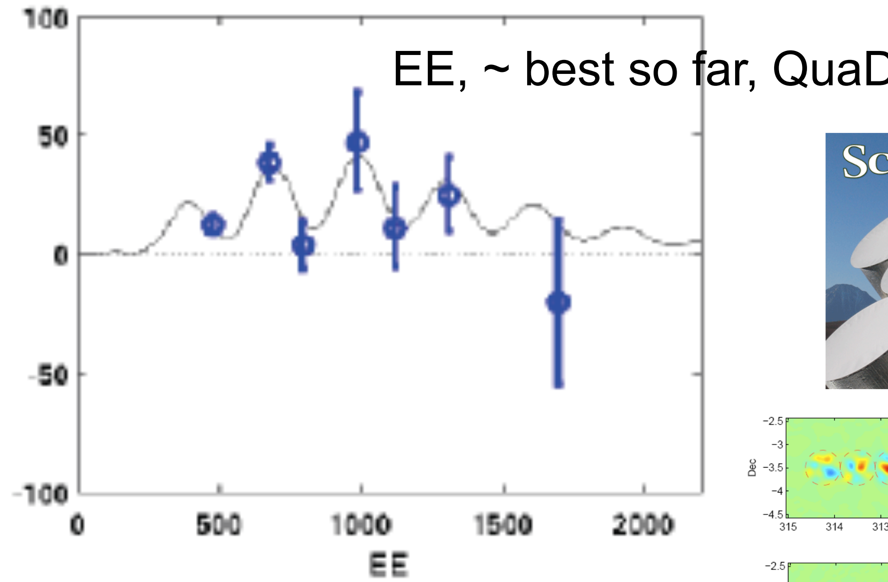
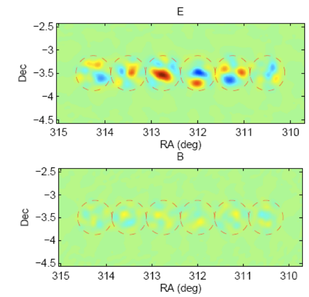
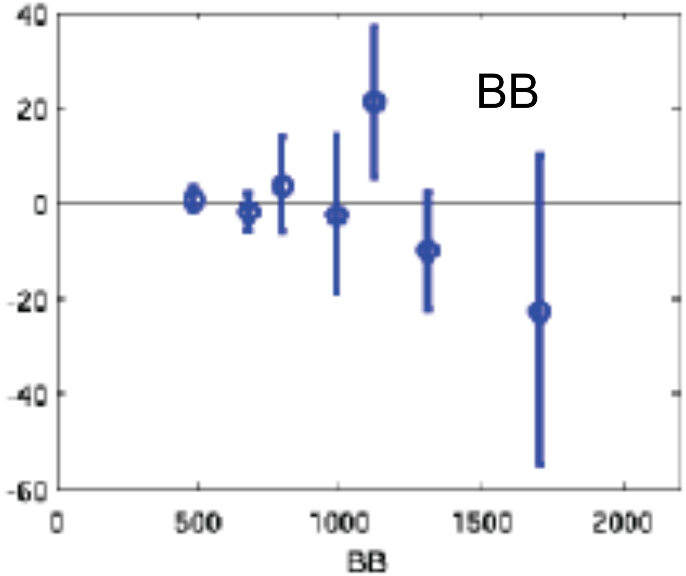
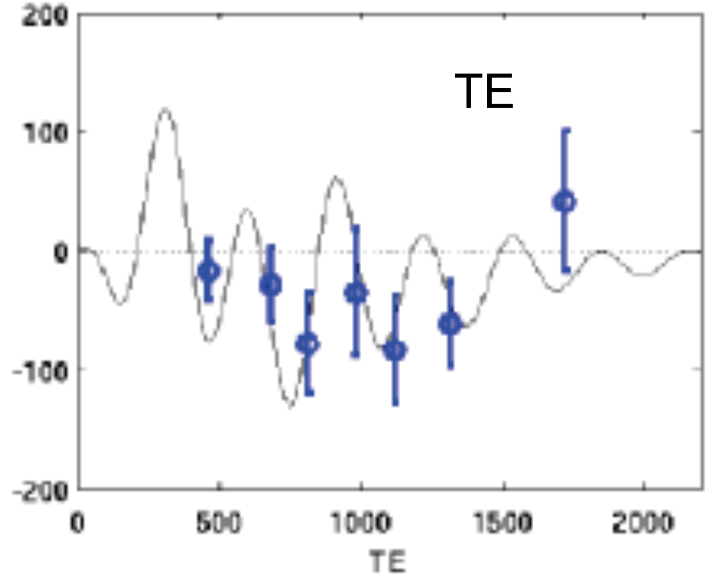




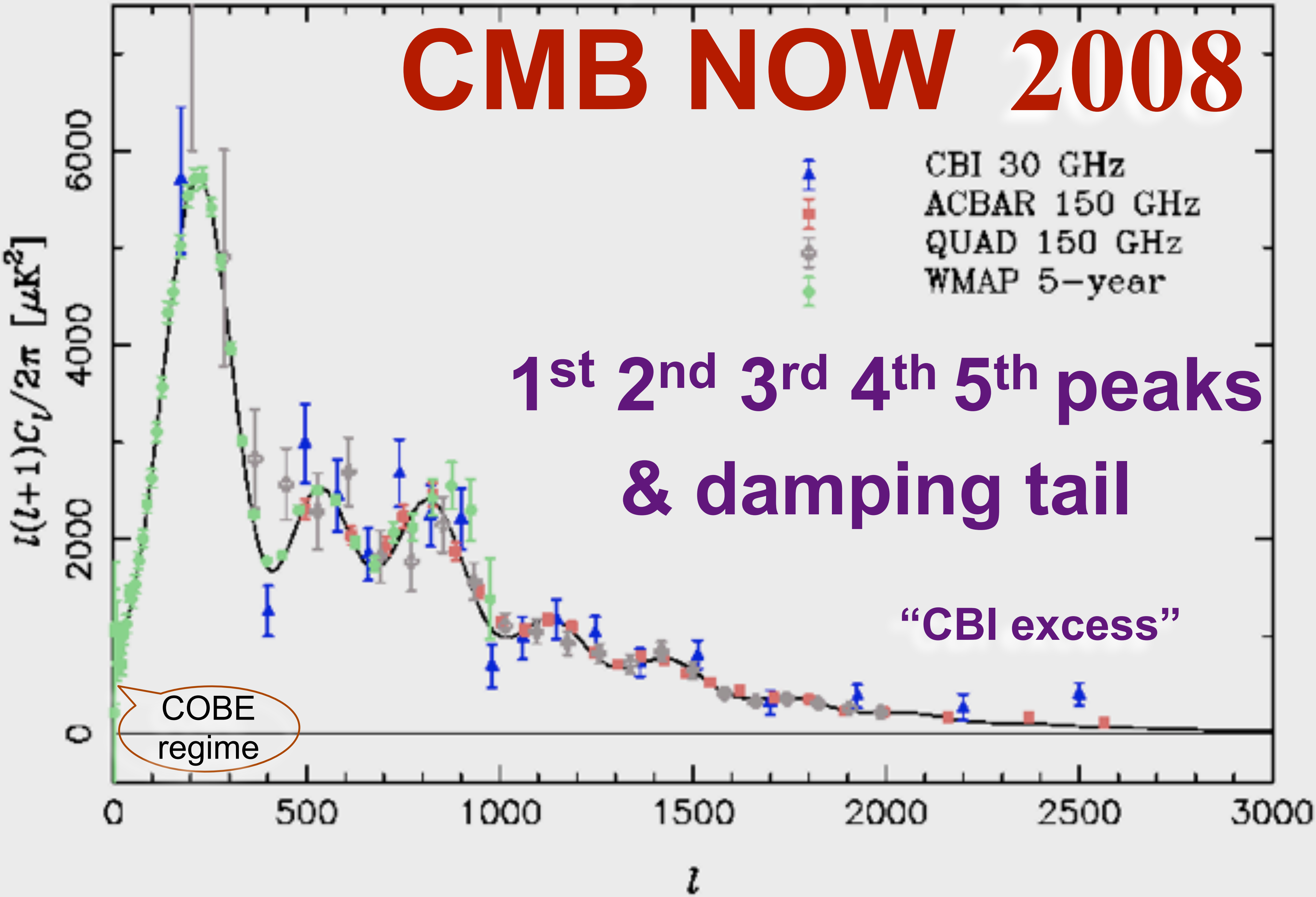






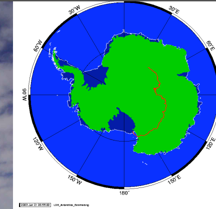
Sievers etal 2008 Dec astroph CBI5yrs, still 2.5yrs pol, so slight effect on TE

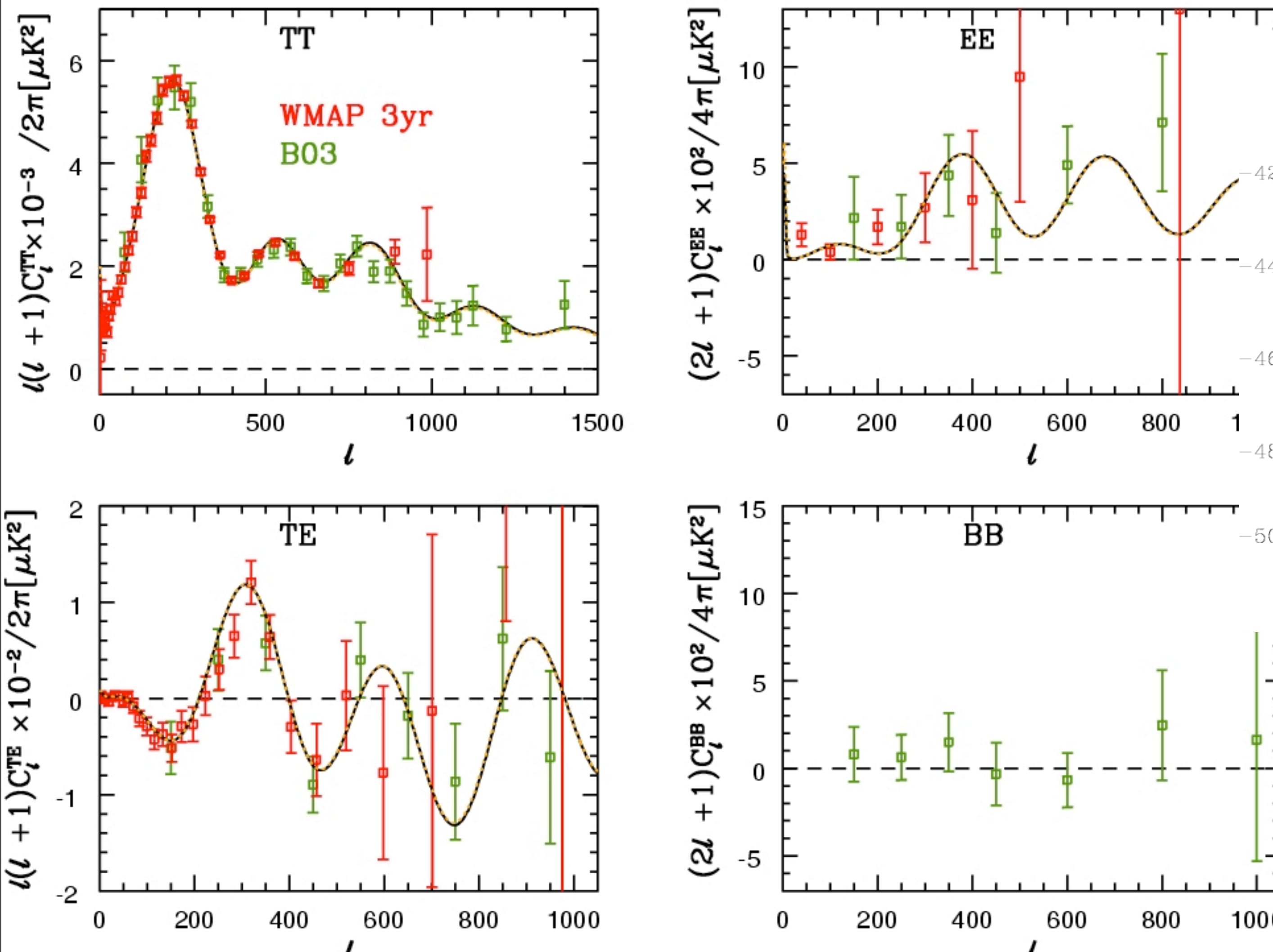
CMB NOW 2008

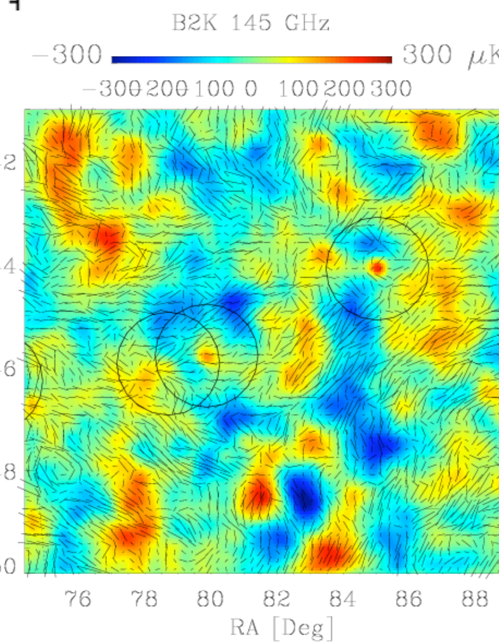


B03 pol TE, EE 2005 1st bolo detection

- ‘Shallow’ scan, 75 hours, f_{sky}=3.0%, large scale TT
- ‘deep’ scan, 125 hours, fsky=0.28% 115sq deg, ~ 2 X Planck2yr







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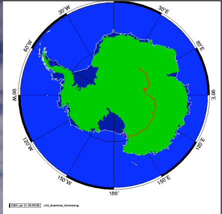

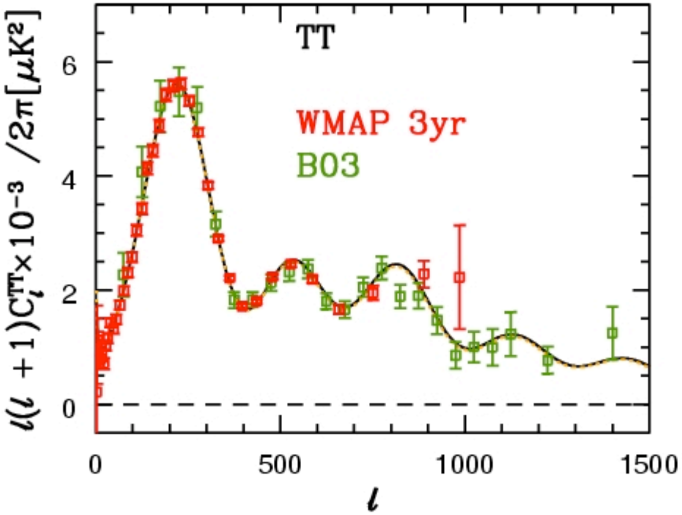

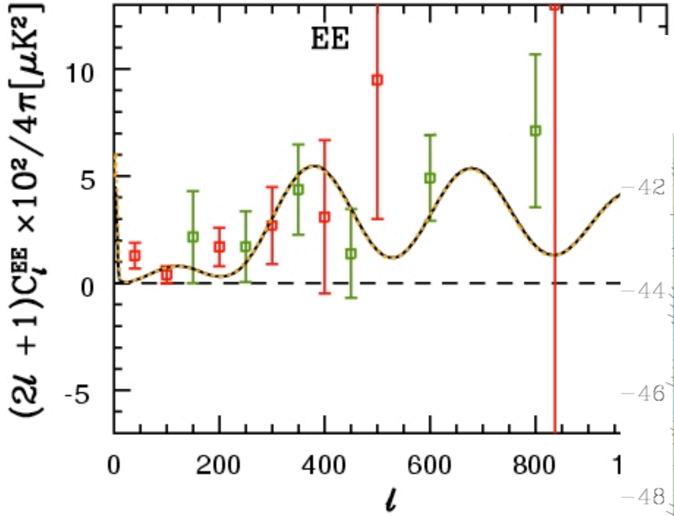

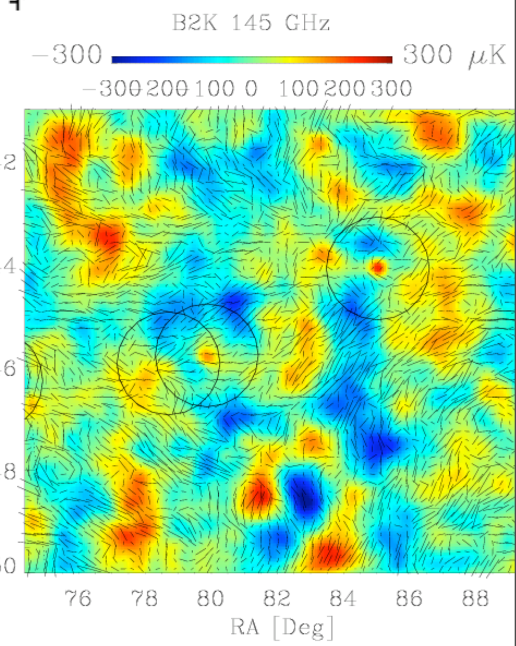

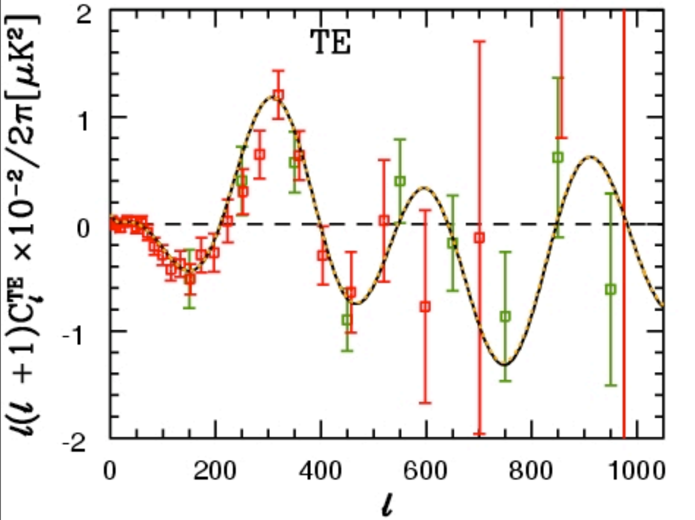

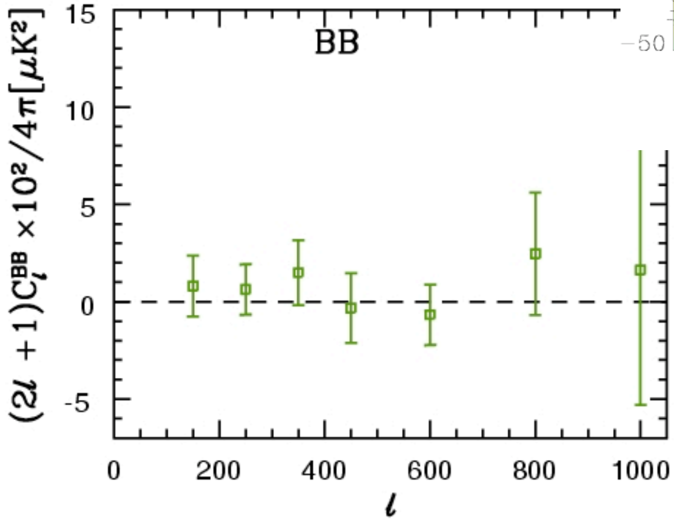

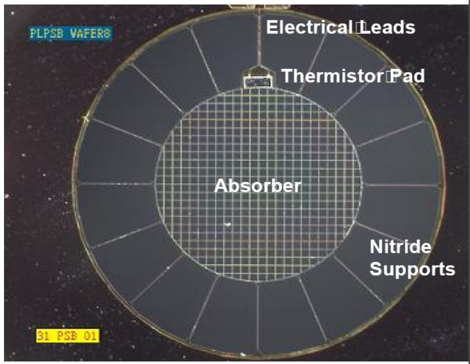

B03+B98 *Contaldi etal 01..09!* **xfaster!** *Boom/Planck/Spider workhorse*

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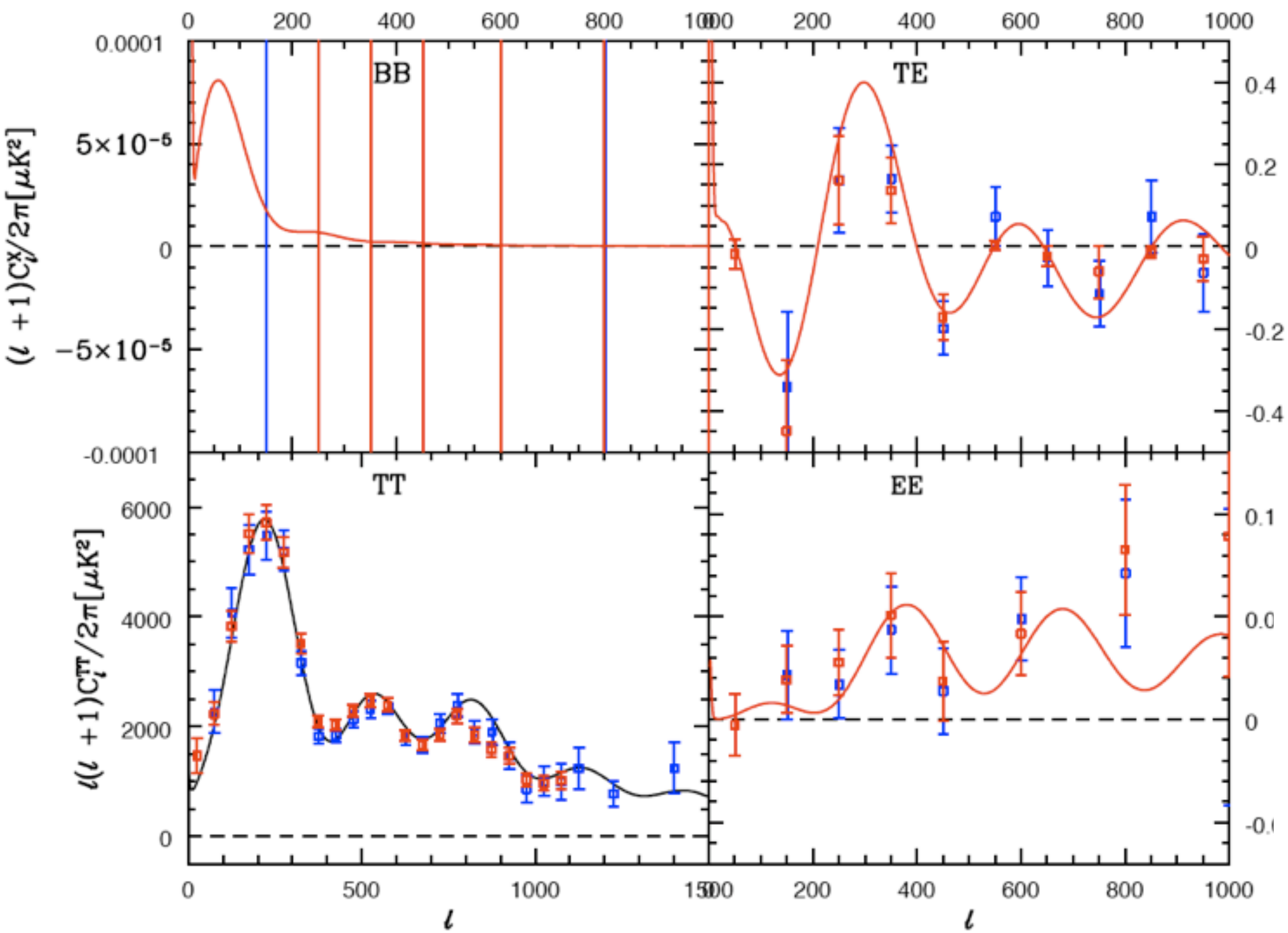
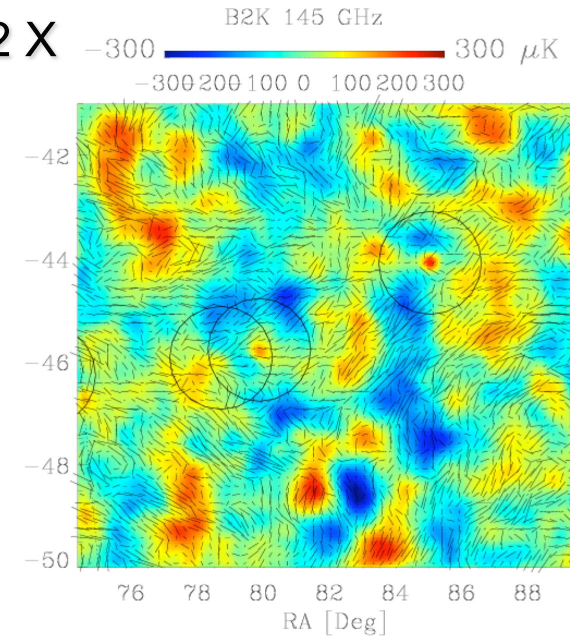
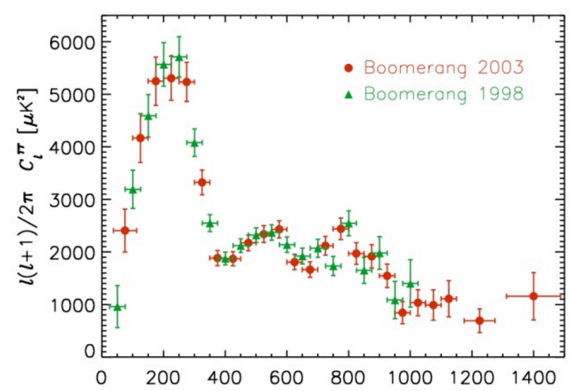


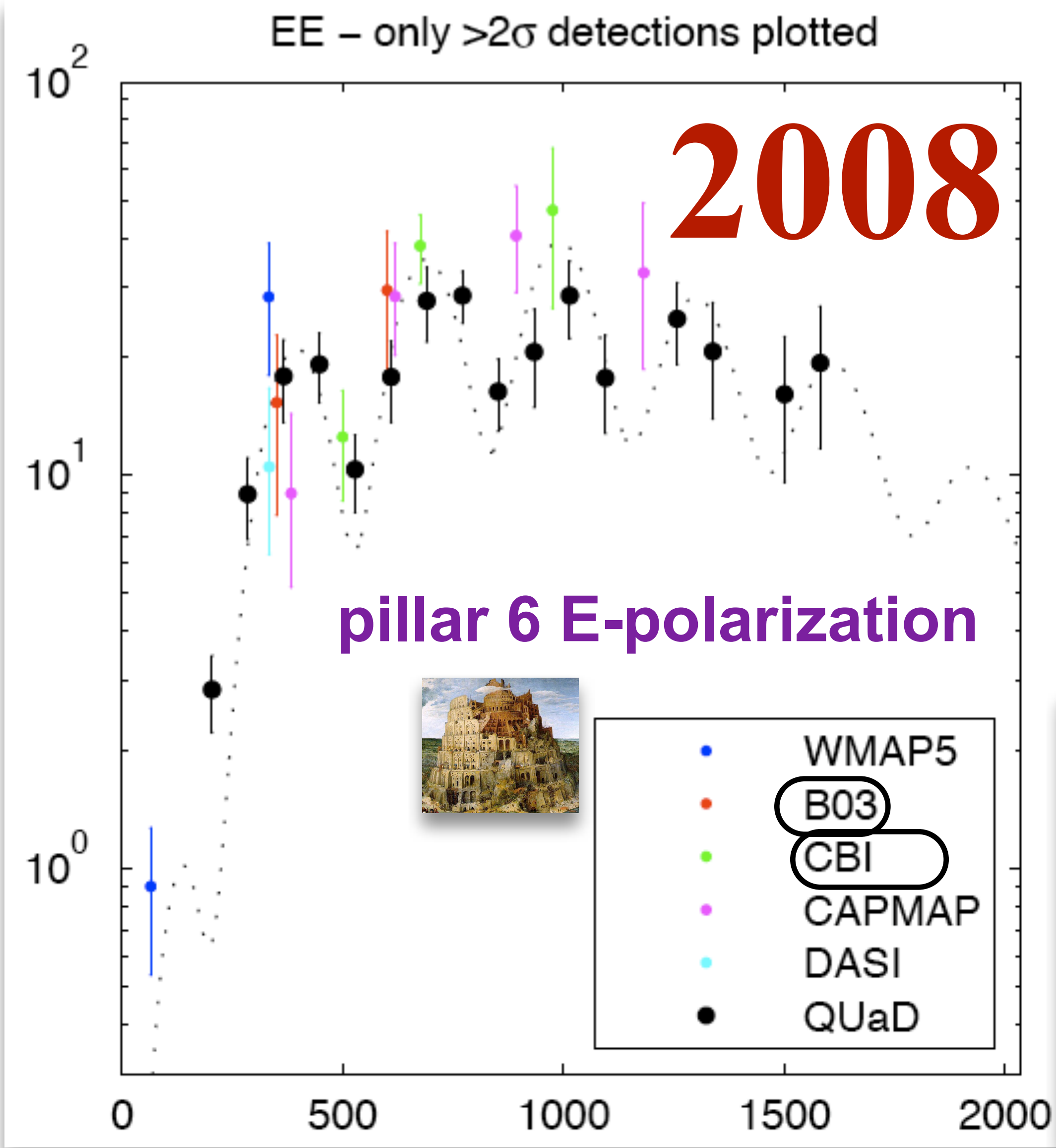


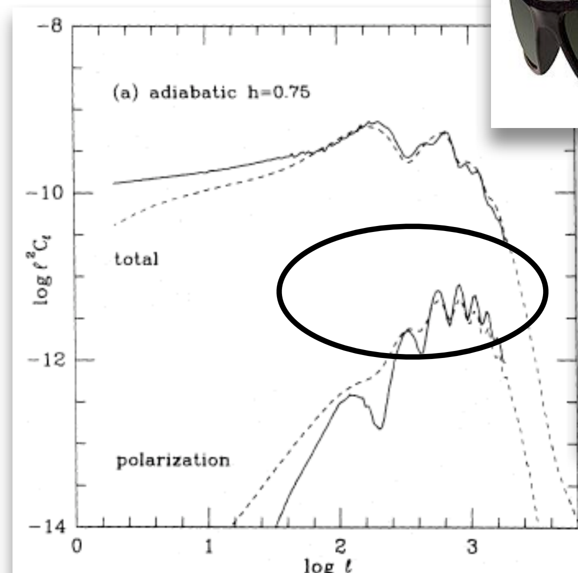


B03+B98 final soon

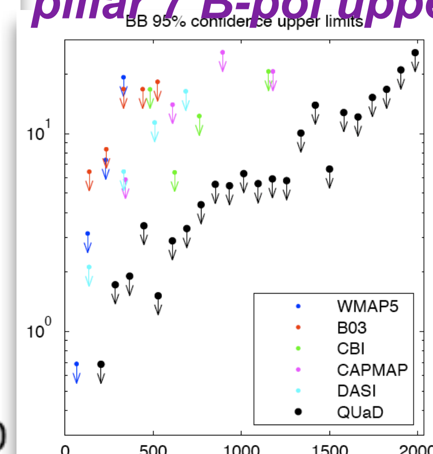
emergence of CMB polarization *power*

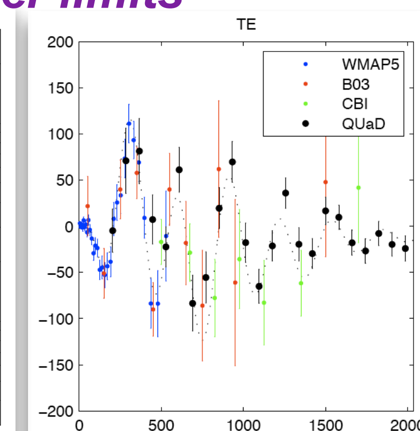
DASI02,04 CBI04 Boom05 CBI05 WMAP3,5 Capmap07 QUaD07,08





pillar 7 B-pol upper limits





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 $r = A_t/A_s$

$1+w_0$, w_a $n_e(a)$ $dn_s/d\ln k$ 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 ...

What do we learn from E polarization?

0 - EE/TE agree with TT forecasts! *pillar6: out-of-phase pks/valleys*

1 - constrain radically broken scale invariance *out-of-phase pks*

2 - constrain subdominant isocurvature modes CBI

3 - constrain anomalies *e.g., WMAP haze, COBE/WMAP "hole" TBD*

4 - aid in lensing reconstruction of lensed CMB *TBD*

5 - aid in separation of components, dust & synchrotron; *SZ*

WMAP1 .166+-.08 TE, WMAP3 .089+-.03 EE fgnd-clean,
WMAP5 .086+-.016, WMAP5 .090+-.019 GibbsMCMC; Planck1yr 09.3+1.5yr +-.005;
Spider test flight 2-6d, 2010.3, Alice Springs, +-.007

6- reionization epoch

τ_C = l.o.s.-int $n_e \sigma_T$ cdt

$\sim .1\ ((1+z_{reh})/15)^{3/2}$

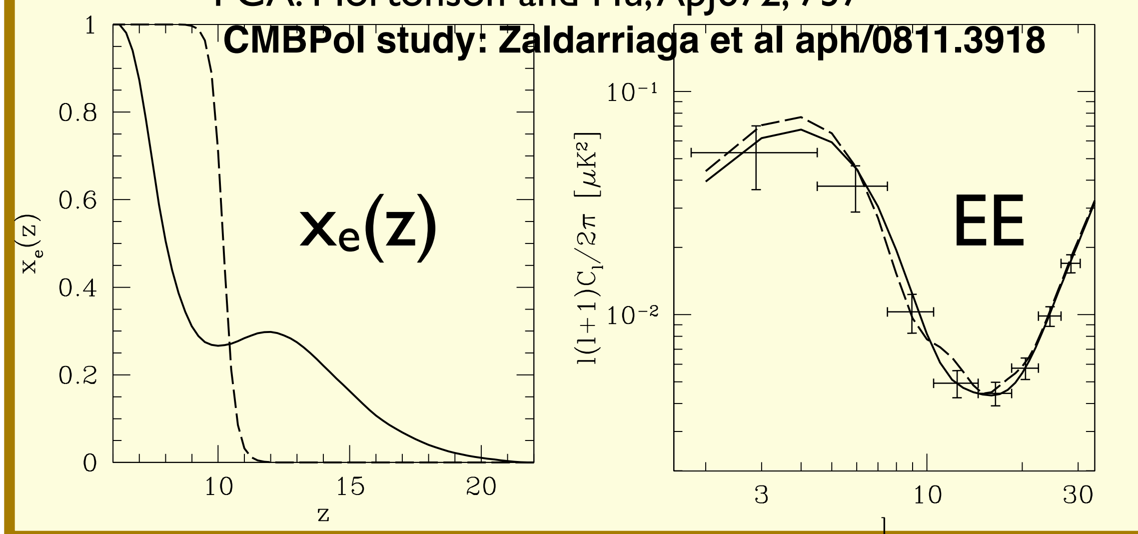
$(\Omega_b h^2/.02)(\Omega_m h^2/.15)^{-1/2}$

0.085+- .017 CMBall$_{cbi10}$

z_{reh} **=0.8 +- 1.5**

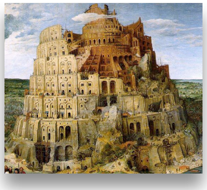
PCA: Mortonson and Hu, ApJ672, 737

CMBPol study: Zaldarriaga et al aph/0811.3918



INFLATION THEN

PROBES NOW



the quest for Pillar 7, B-modes from primordial zero-point gravity waves

"standard inflation space": $\mathbf{n_s}$ $\mathbf{dn_s/dlnk}$ $\mathbf{r}$ **@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

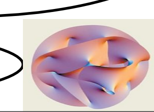
$D3-D7$ inflation

Warped Brane inflation

Tachyon inflation

Racetrack inflation

Roulette inflation **Kahler moduli/axion**



INFLATION THEN

WHAT IS ALLOWED?

radically broken scale invariance by variable braking as acceleration approaches deceleration, preheating & the end of inflation

$\varepsilon(k) = (1+q)(a) = -d\,\ln H / d\,\ln a \;\; = r(k)/16$

Blind power spectrum analysis cf. data, then & now

expand $\varepsilon(k)$ in localized mode functions e.g. Chebyshev/B-spline coefficients ε_b

the measures on ε_b matter - choice for "theory prior" = informed priors?

INFLATION THEN

WHAT IS ALLOWED?

radically broken scale invariance by variable braking as acceleration approaches deceleration, preheating & the end of inflation

$\varepsilon(k)=(1+q)(a)=-d\,ln H/d\,ln a \;\; =r(k)/16$

Blind power spectrum analysis cf. data, then & now

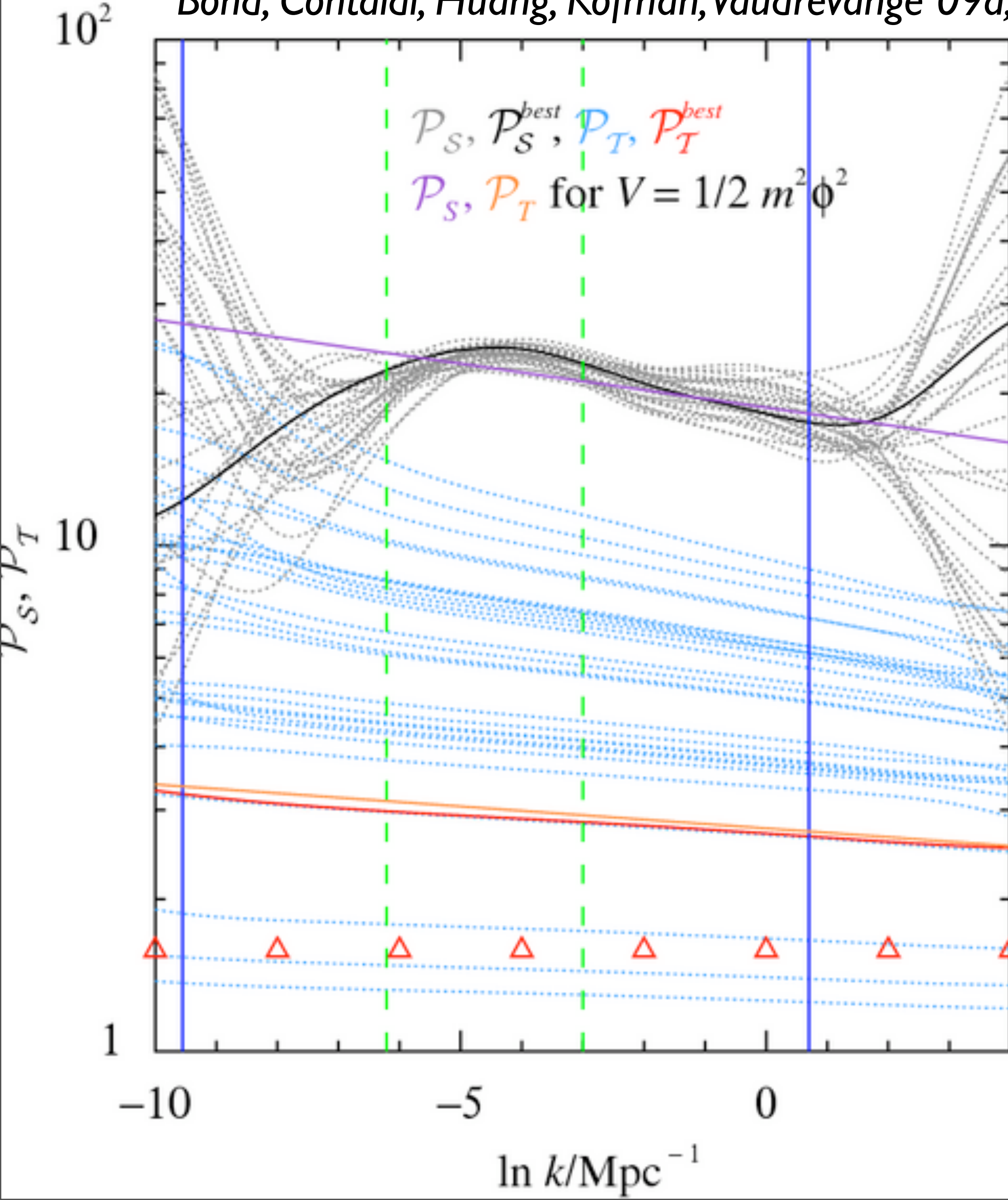
expand $\varepsilon(k)$ in localized mode functions e.g. Chebyshev/B-spline coefficients ε_b

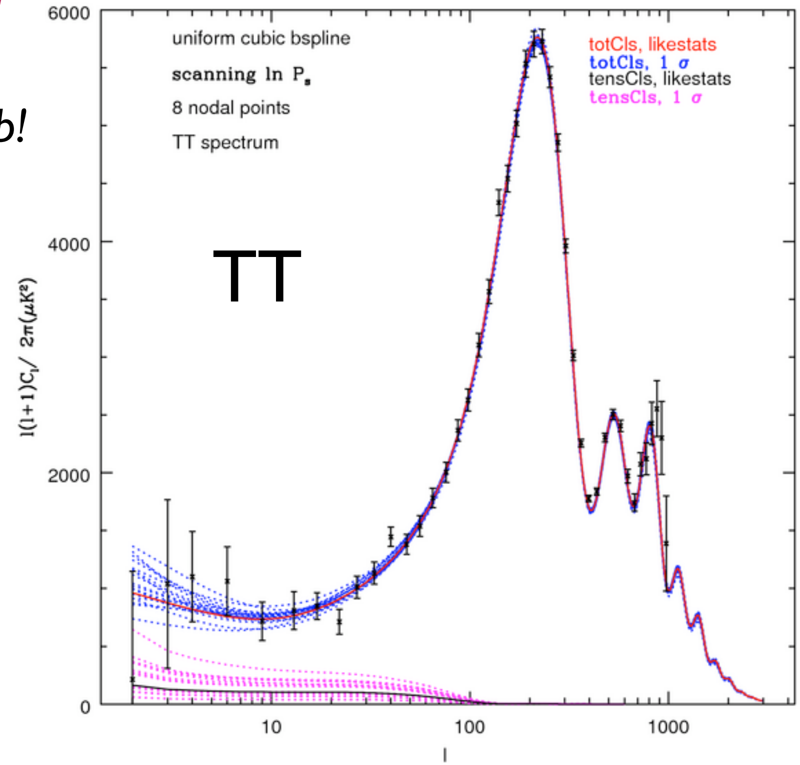
or dual $\ln P_s(k); P_t(k)$

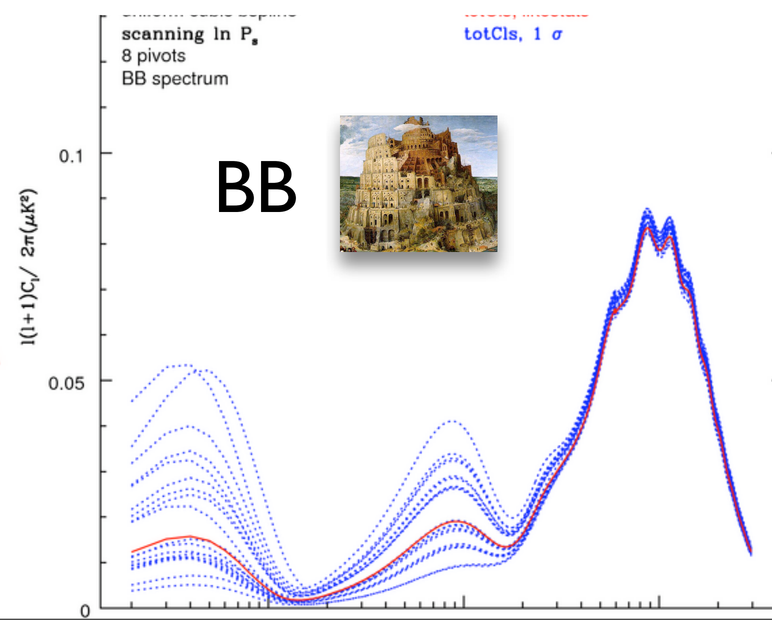
the measures on ε_b matter - choice for “theory prior” = informed priors?

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

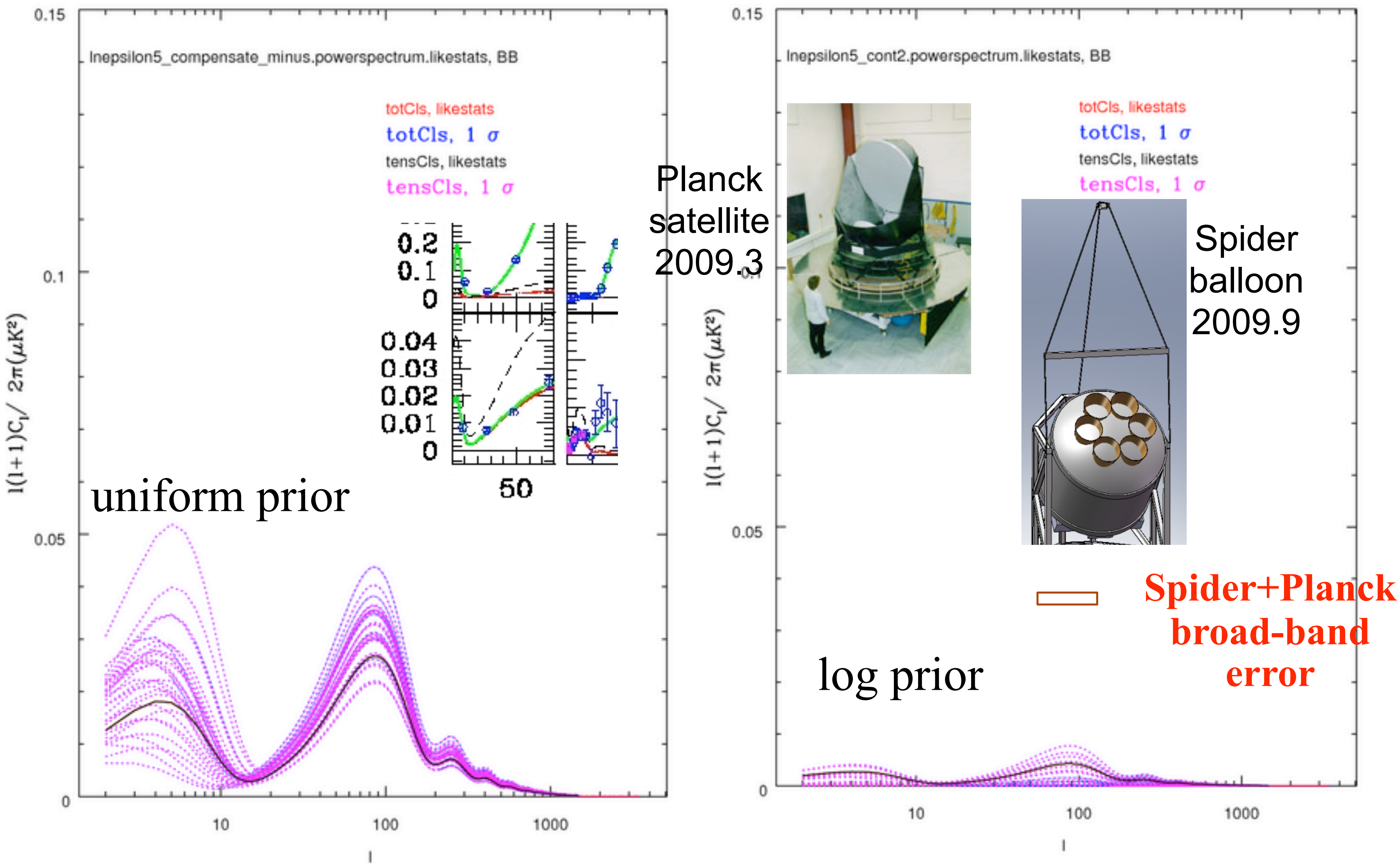
Bond, Contaldi, Huang, Kofman,Vaudrevange 09a,b!







C_L BB for $ln\mathcal{E}_s$ (nodal 5) + 4 params inflation trajectories reconstructed from CMB +LSS data using Chebyshev nodal point expansion & MCMC



INFLATION
THEN

PROBES
THEN

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

QUaD @SP

Quiet1 @Chile

Quiet2 1000 HEMTs

Boom03@LDB

Bicep @SP

Bicep2

Keck/Spud

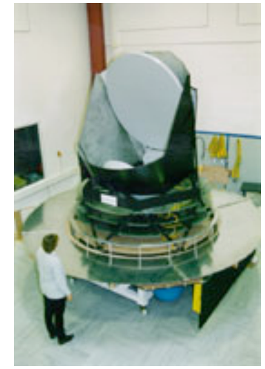
EBEX @LDB

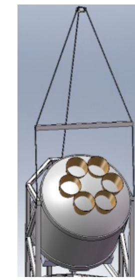
WMAP @L2 **to 2009-2013?**

Planck09.3

(52 bolometers) + HEMTs @L2

9 frequencies





Spider 2312 bolos @LDB

DASI @SP

CAPMAP

CHIP

2004 2005 2006 2007 2008 2009 **LHC** 2011

Bpol @L2

BLASTpol

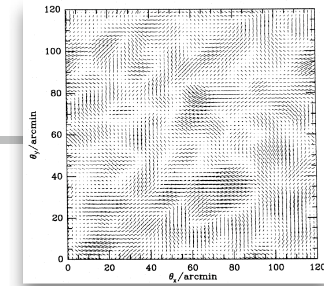
Clover @Chile

Polarbear 300 bolos @Cal/Chile

SPTpol

SPIDER Tensor Signal

Pillar 7
Gravity Waves from **Inflation**

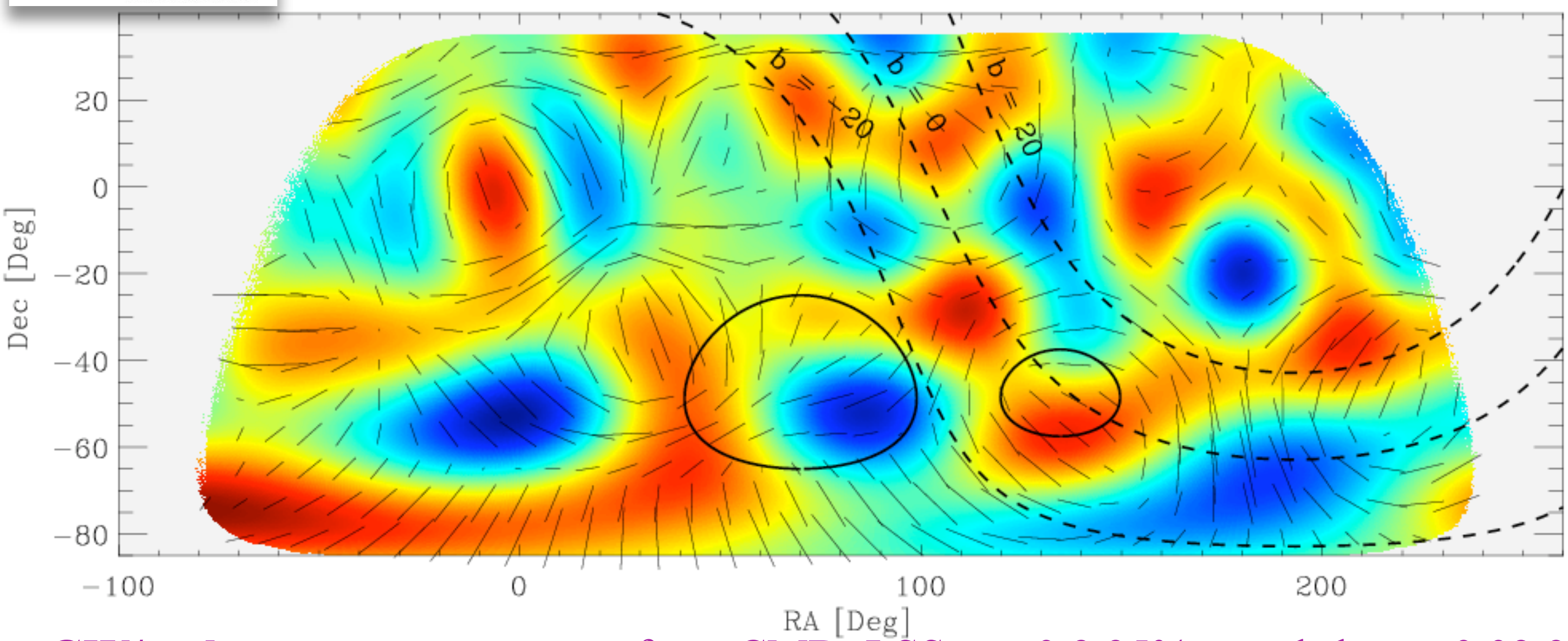


- **Simulation of large scale polarization signal**

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

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

Tensor

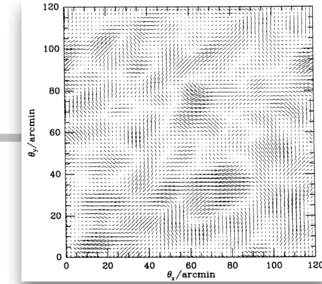


GW/scalar curvature: current from CMB+LSS: r < **0.3** 95%; good shot at **0.02** 95% CL with **BB polarization** **(+- .02 PL2.5+Spider), .01 target; Bpol .001** BUT foregrounds/systematics? But **r(k), low Energy inflation**

SPIDER Tensor Signal

Pillar 7

Gravity Waves from **Inflation**



- **Simulation of large scale polarization signal**

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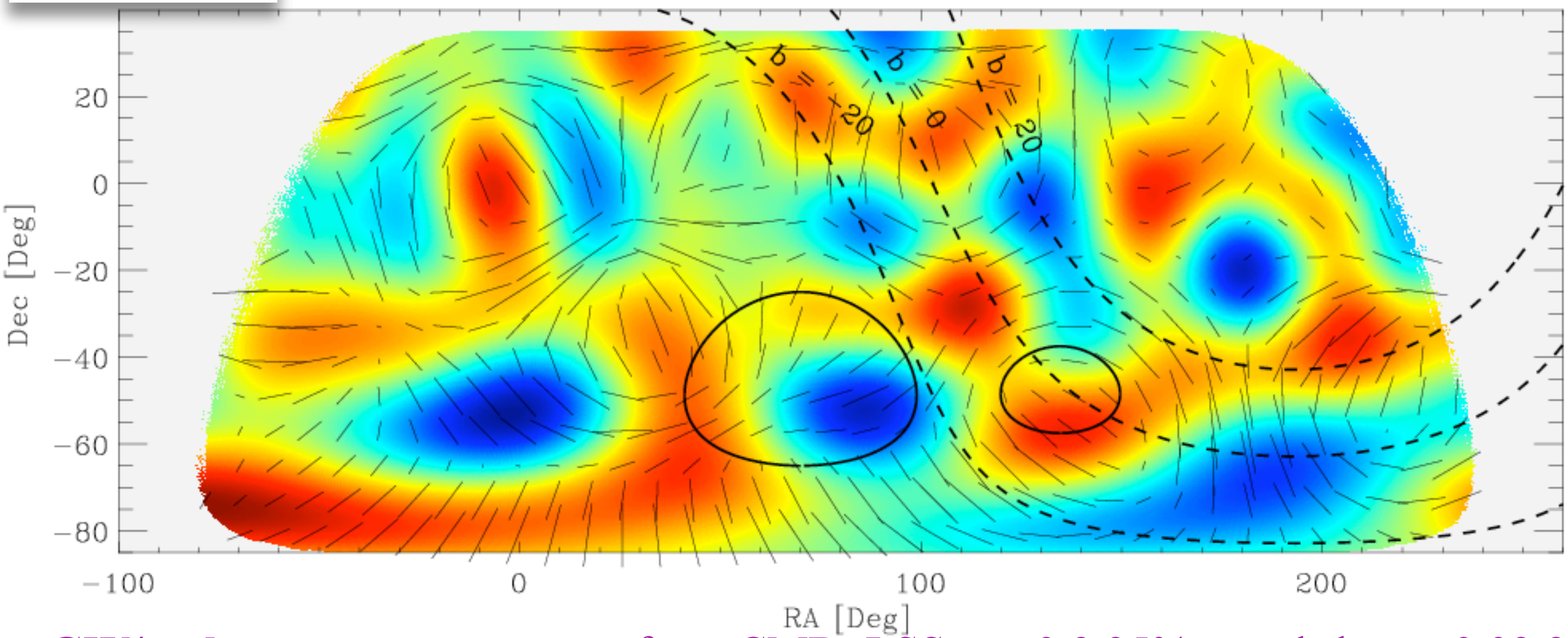
$$\frac{A_T}{A_S} = 0.1$$

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**

tensor-mode parameters: direct *map-based* MLE cf. (partial) E/B separation?

automatically takes care of the E/B problem; used for CBI & feasible for Spider analysis

map

max-likelihood
quadratic "filters"

parameters
r(k) ...

Marzieh Fahrang, Bond, Dore, Netterfield 09

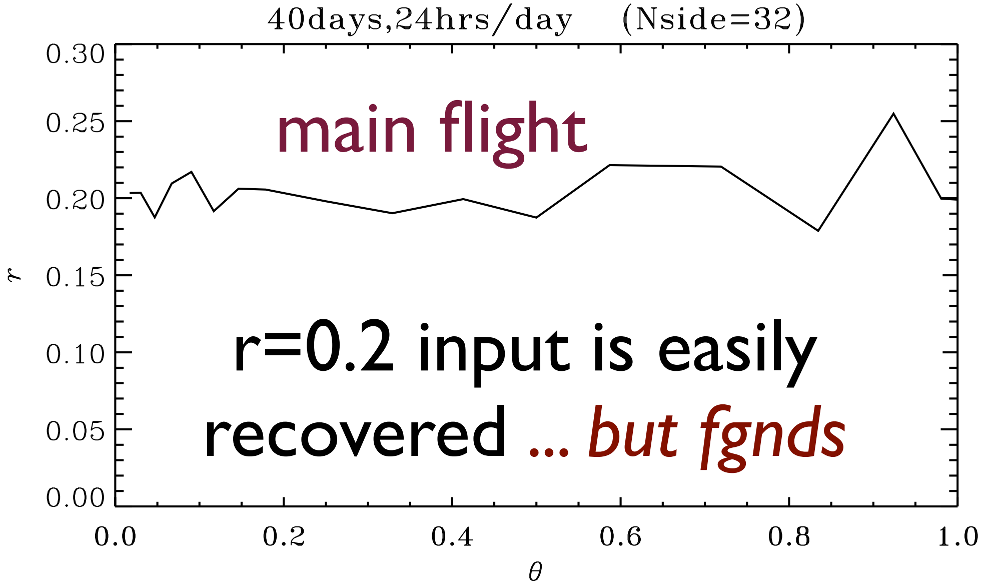
E-B space

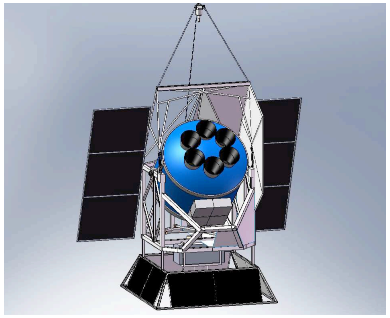
finite sky patch ➡ E/B mixing

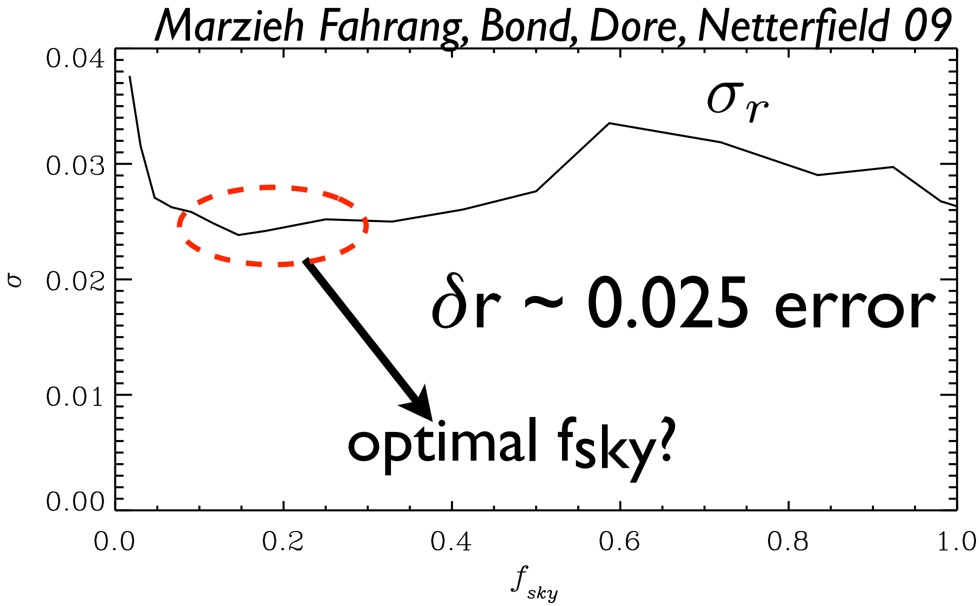
Bunn 02, 08, Bunn etal 03, Lewis etal 06, Smith & Zaldarriaga 07

Spider/Keck: best f_{sky} for E/B-demixing via direct max-L filters for **r** τ

- test LDB flight: 2-6 days, 10.3 Alice Springs
- **main LDB flight: 20-40 days, 11.9 Antarctica**
  N_t~2.5 Tbytes, N_p~10 Mb







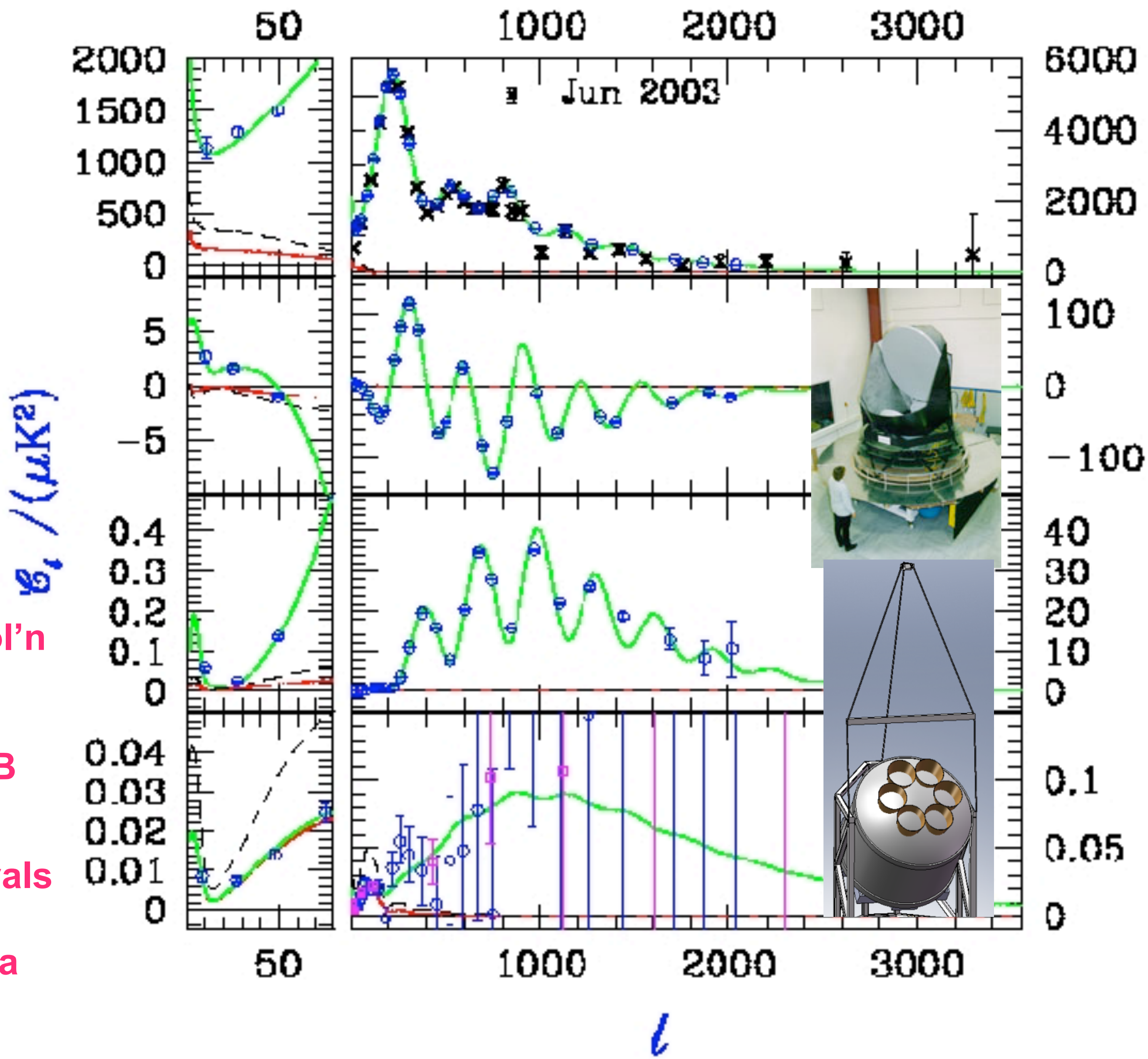
forecast

Planck2.5

100&143

Spider10d

95&150



Synchrotron pol'n

Dust pol'n

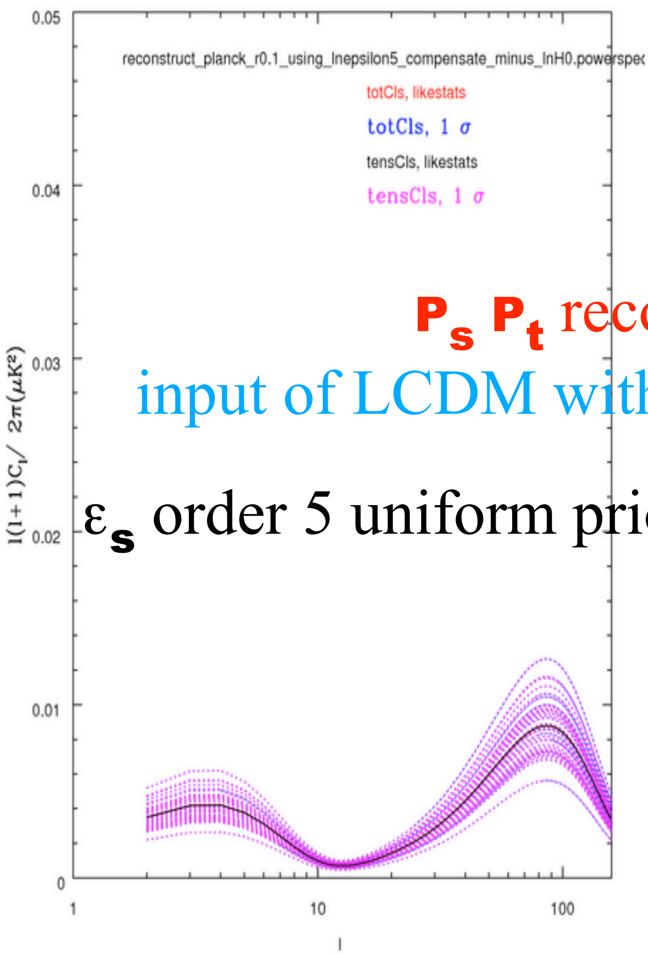
are higher in B

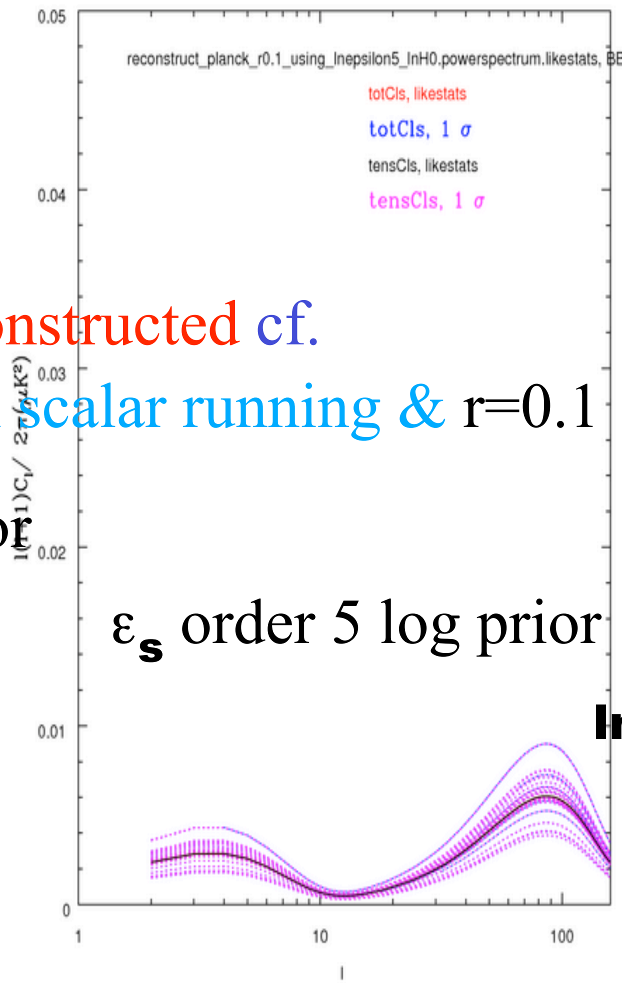
Foreground Template removals from multi-frequency data

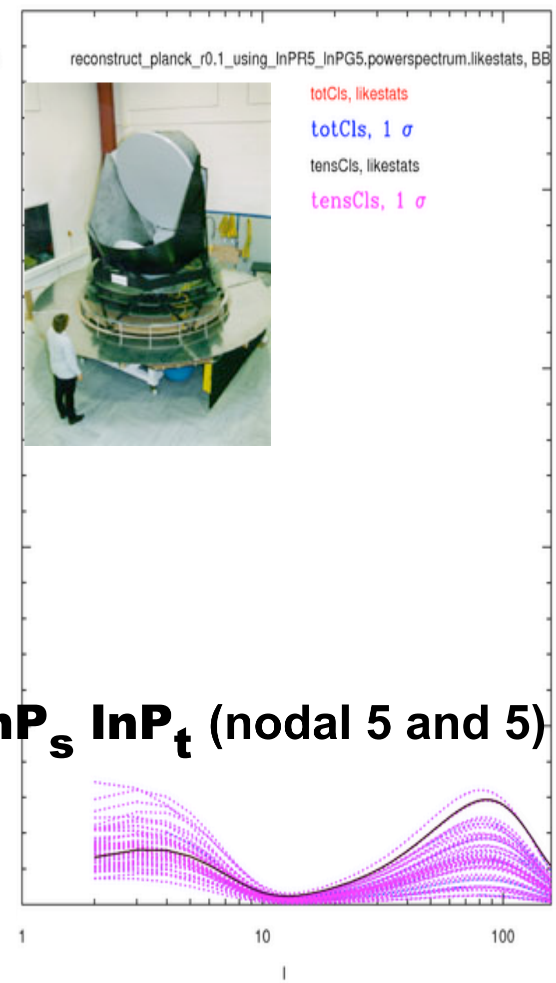
is crucial

Planck1 simulation: input LCDM (Acbar)+run+uniform tensor

r (.002 /Mpc) reconstructed cf. r_{in} to <~ 0.05 prior-independent







P_s P_t reconstructed cf.

input of LCDM with scalar running & r=0.1

ε_s order 5 uniform prior

ε_s order 5 log prior

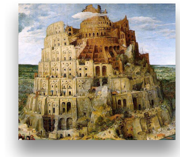
$\ln P_s$ $\ln P_t$ (nodal 5 and 5)

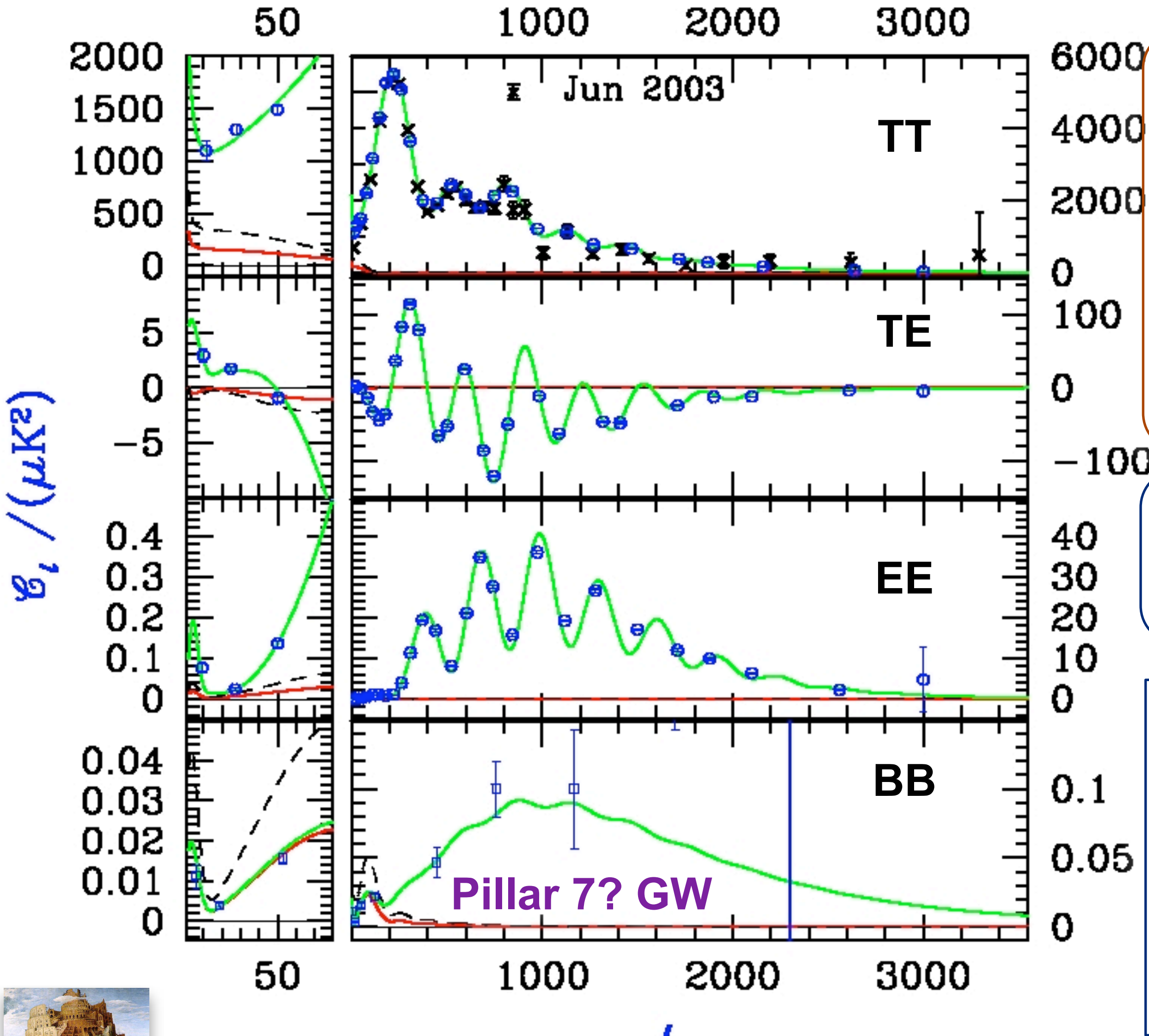
B-pol simulation: ~10K detectors > 100x Planck r_{in} **to <~ 0.001 prior-independent**

a very stringent test of the ε-trajectory methods: A+

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!*

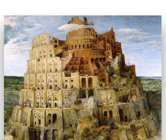
(‘theorem’: $\Delta\psi < 1$ -> **$r<.007$**)

nearly uniform acceleration

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

$r\sim.03$-$.3$! is $\Delta\psi\sim10$ 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

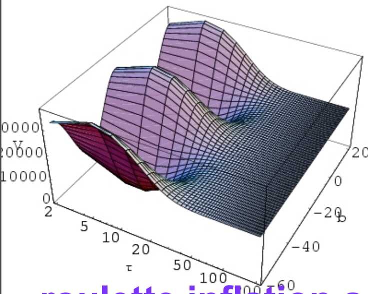


+ Pillar 4: primordial non-Gaussianity **$-9< f_{NL} <111$ (+- 5-10 Planck1)**

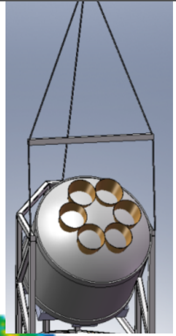
end1

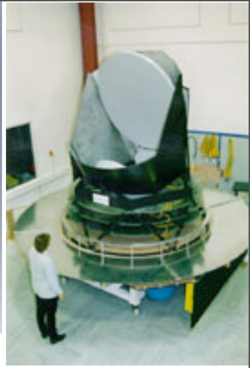
CMBology

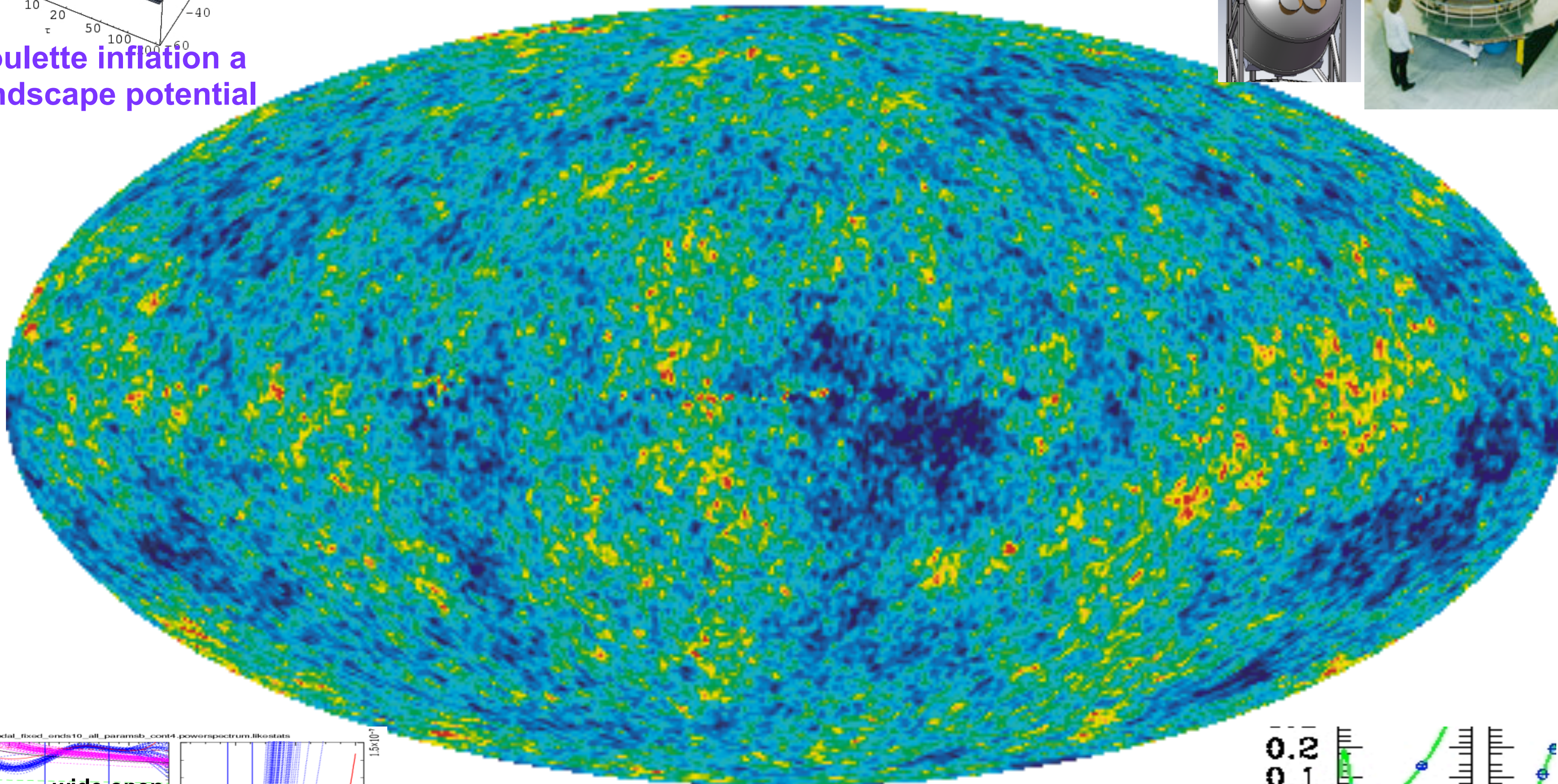
Probing the linear & nonlinear cosmic web

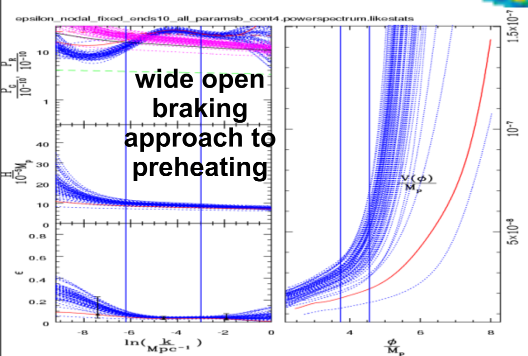


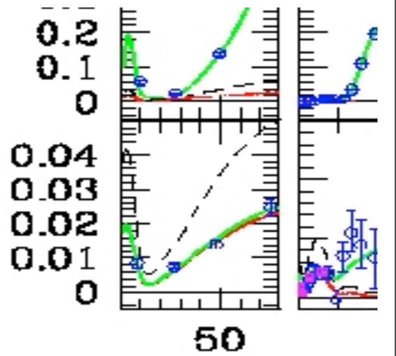
roulette inflation a landscape potential





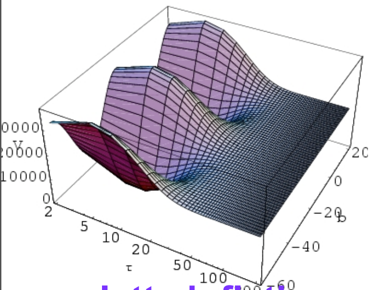




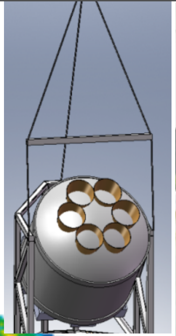


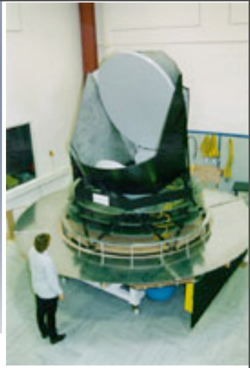
CMBology

Probing the linear & nonlinear cosmic web



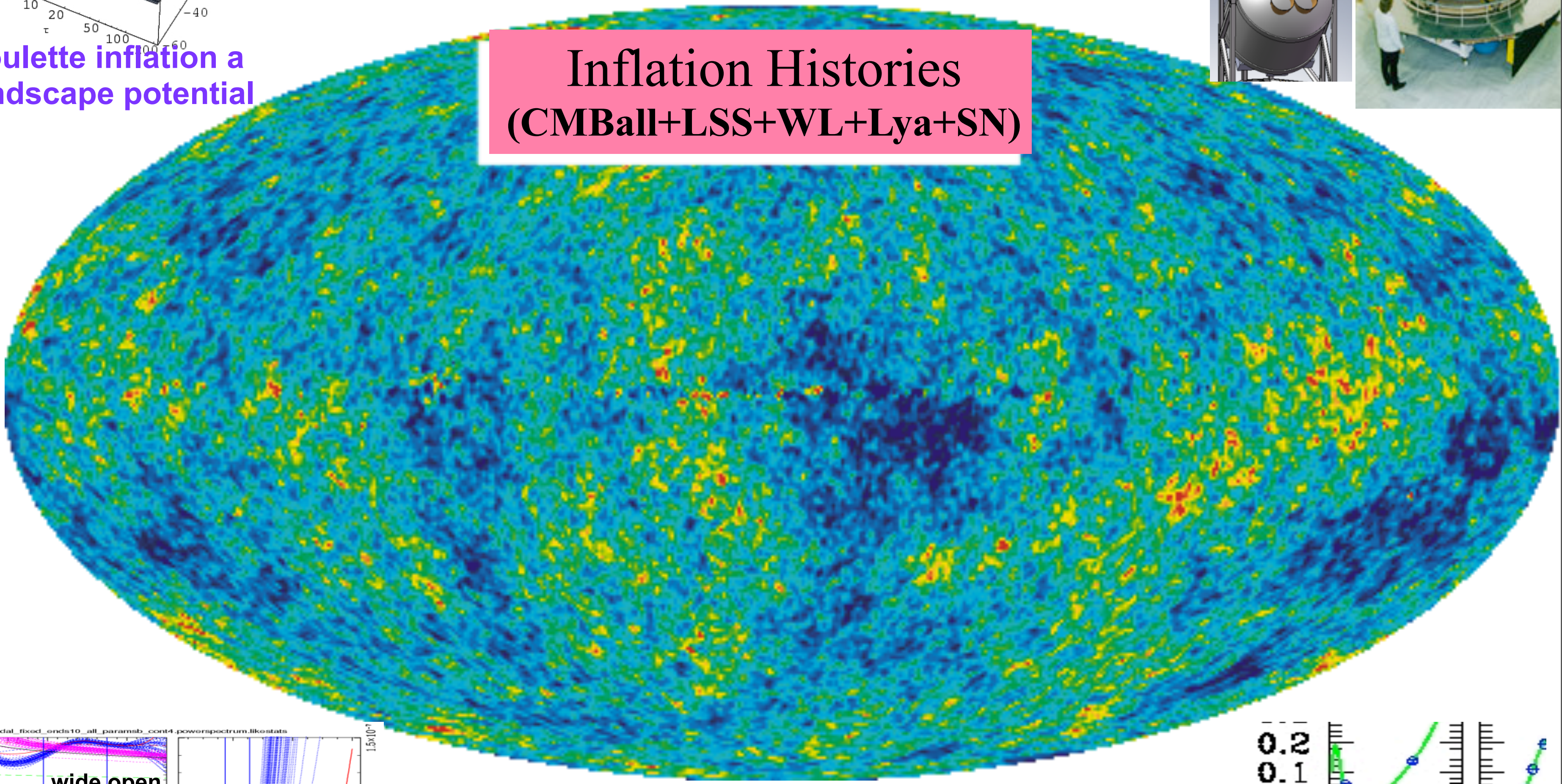
roulette inflation a landscape potential

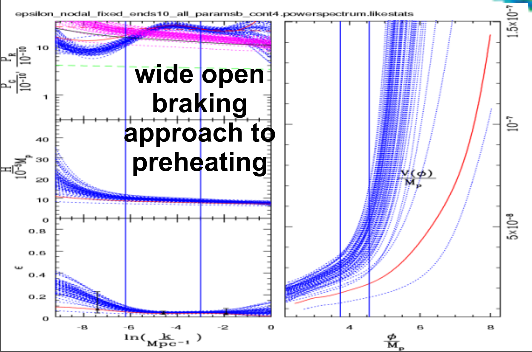


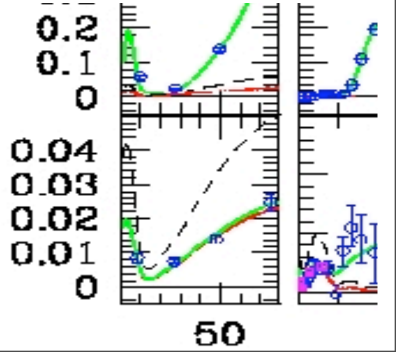


Inflation Histories

(CMBall+LSS+WL+Lya+SN)

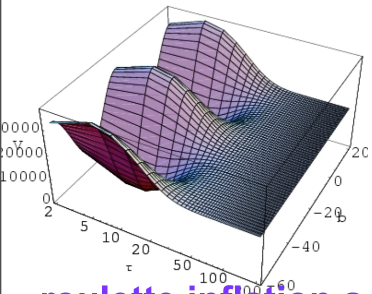




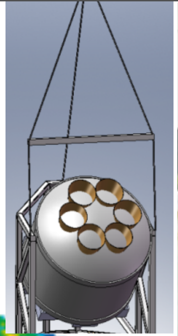


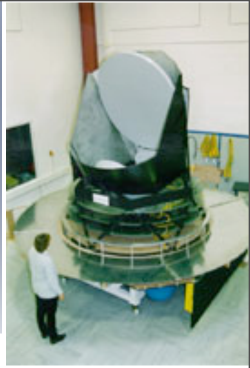
CMBology

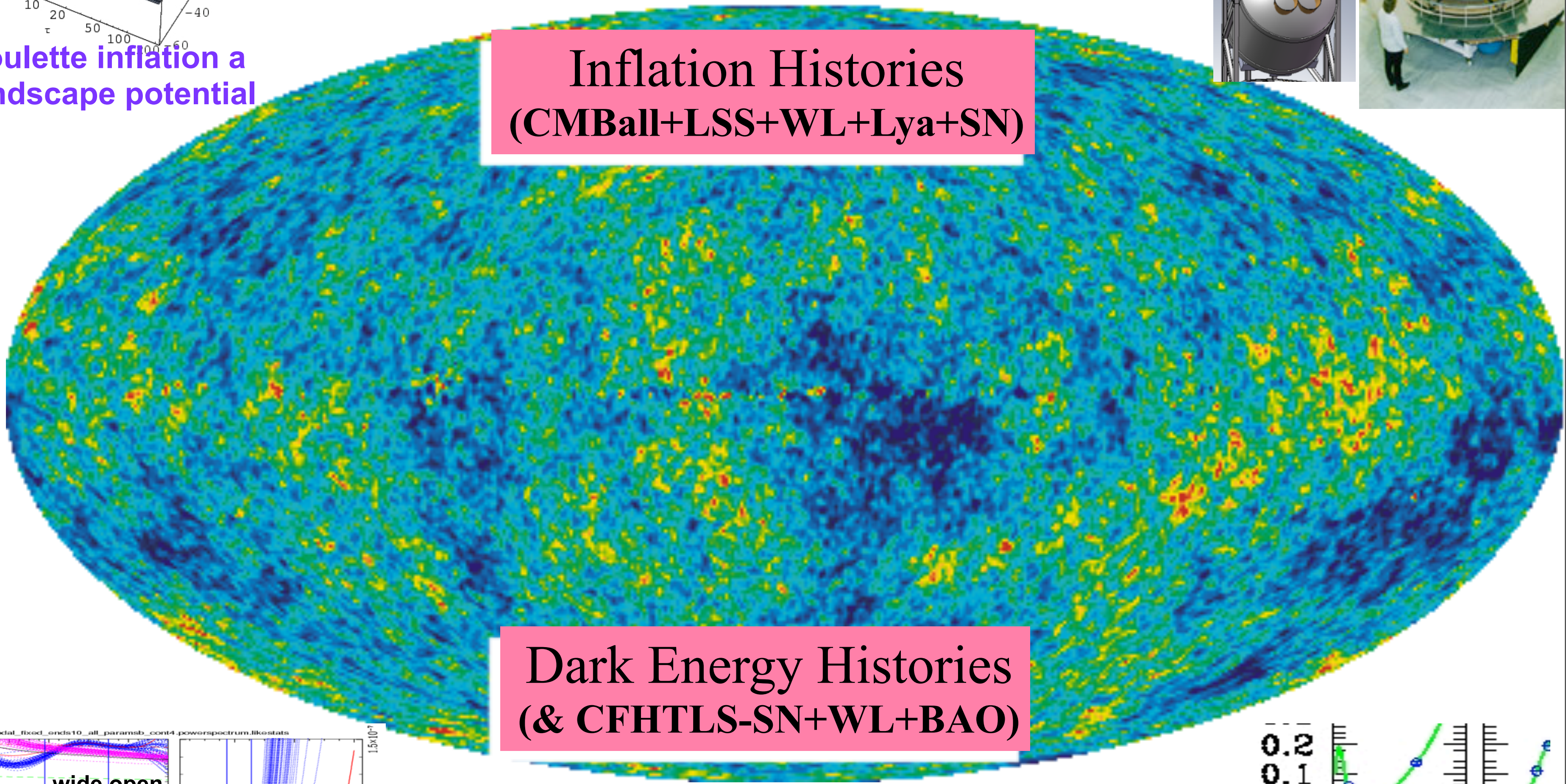
Probing the linear & nonlinear cosmic web



roulette inflation a landscape potential





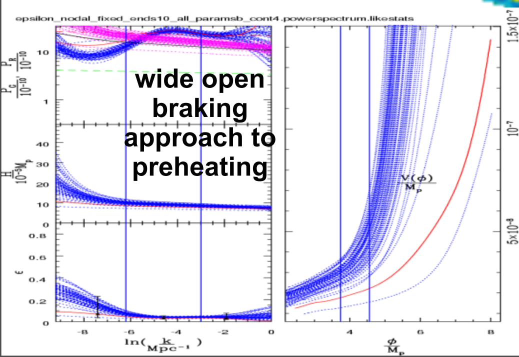


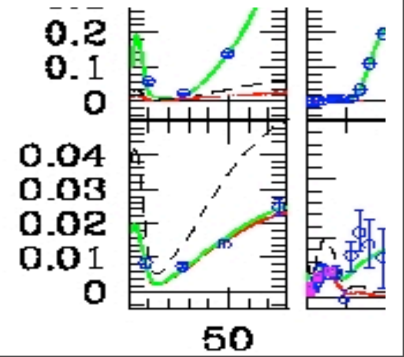
Inflation Histories

(CMBall+LSS+WL+Lya+SN)

Dark Energy Histories

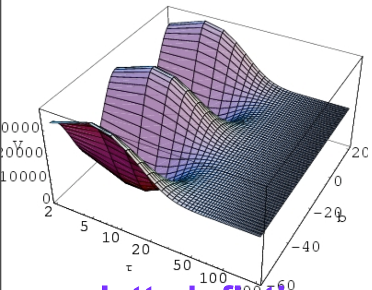
(& CFHTLS-SN+WL+BAO)



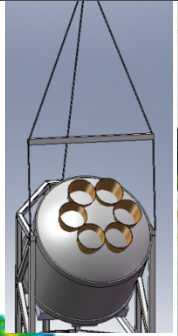


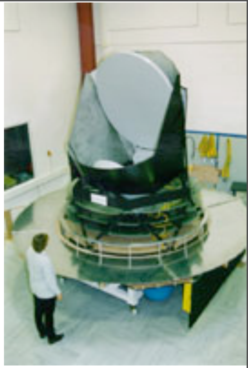
CMBology

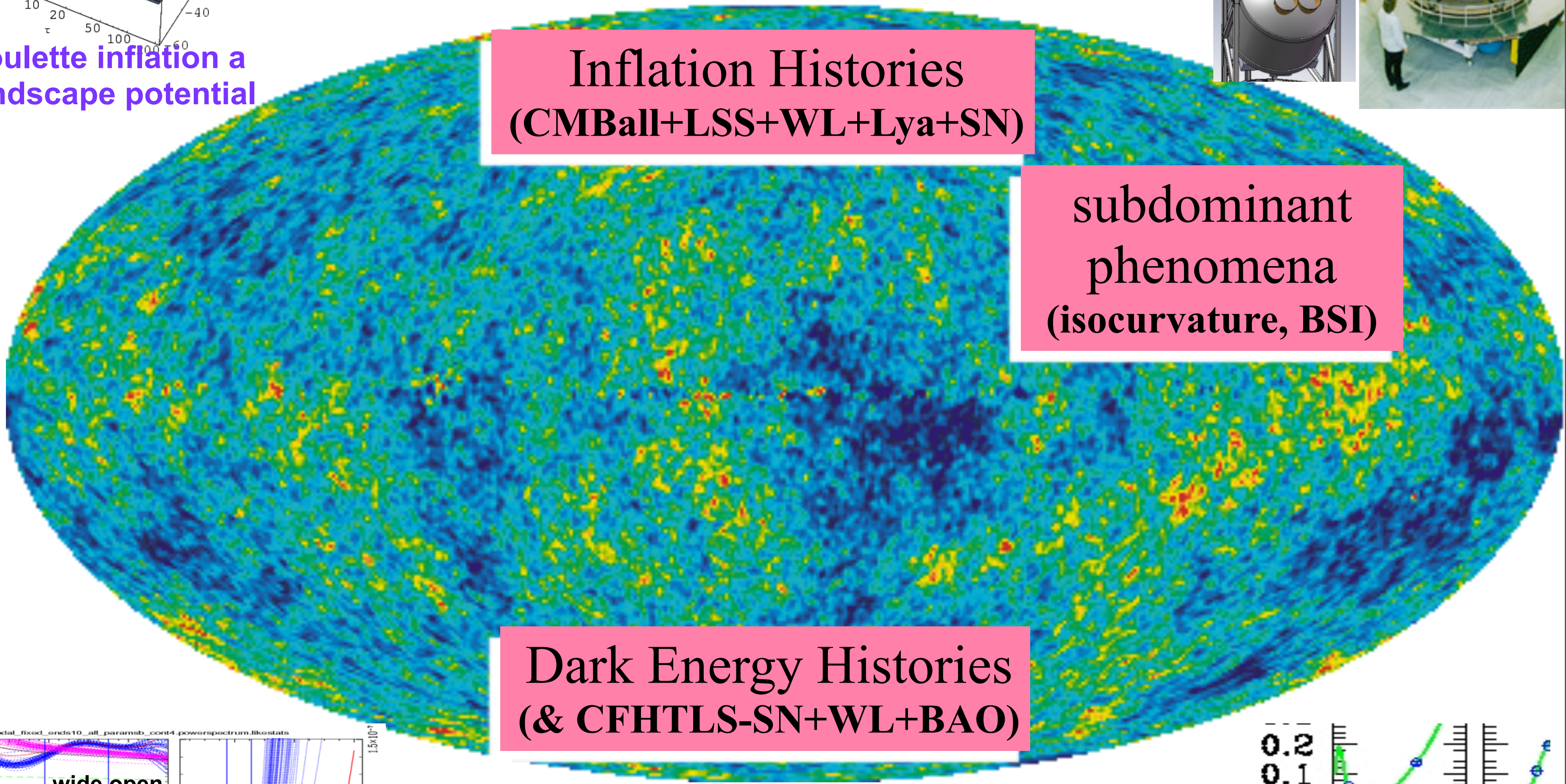
Probing the linear & nonlinear cosmic web



roulette inflation a landscape potential



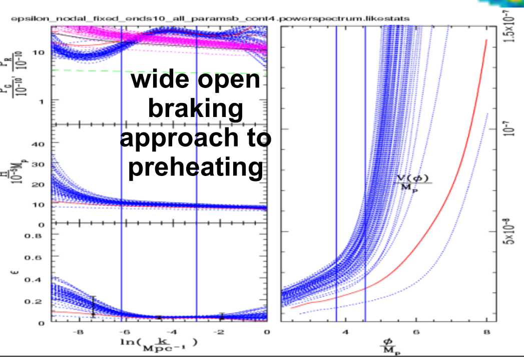


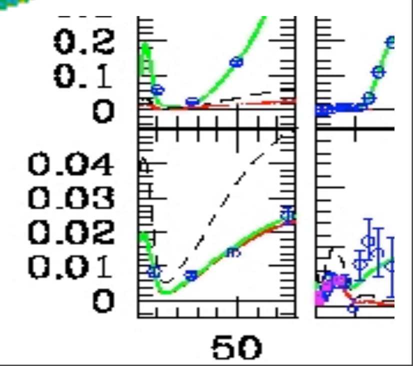


Inflation Histories
(CMBall+LSS+WL+Lya+SN)

subdominant phenomena
(isocurvature, BSI)

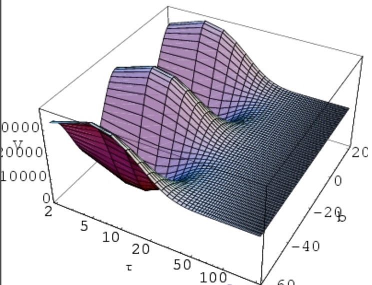
Dark Energy Histories
(& CFHTLS-SN+WL+BAO)



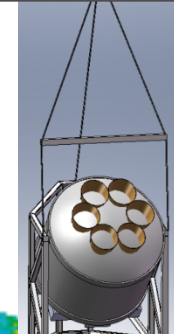


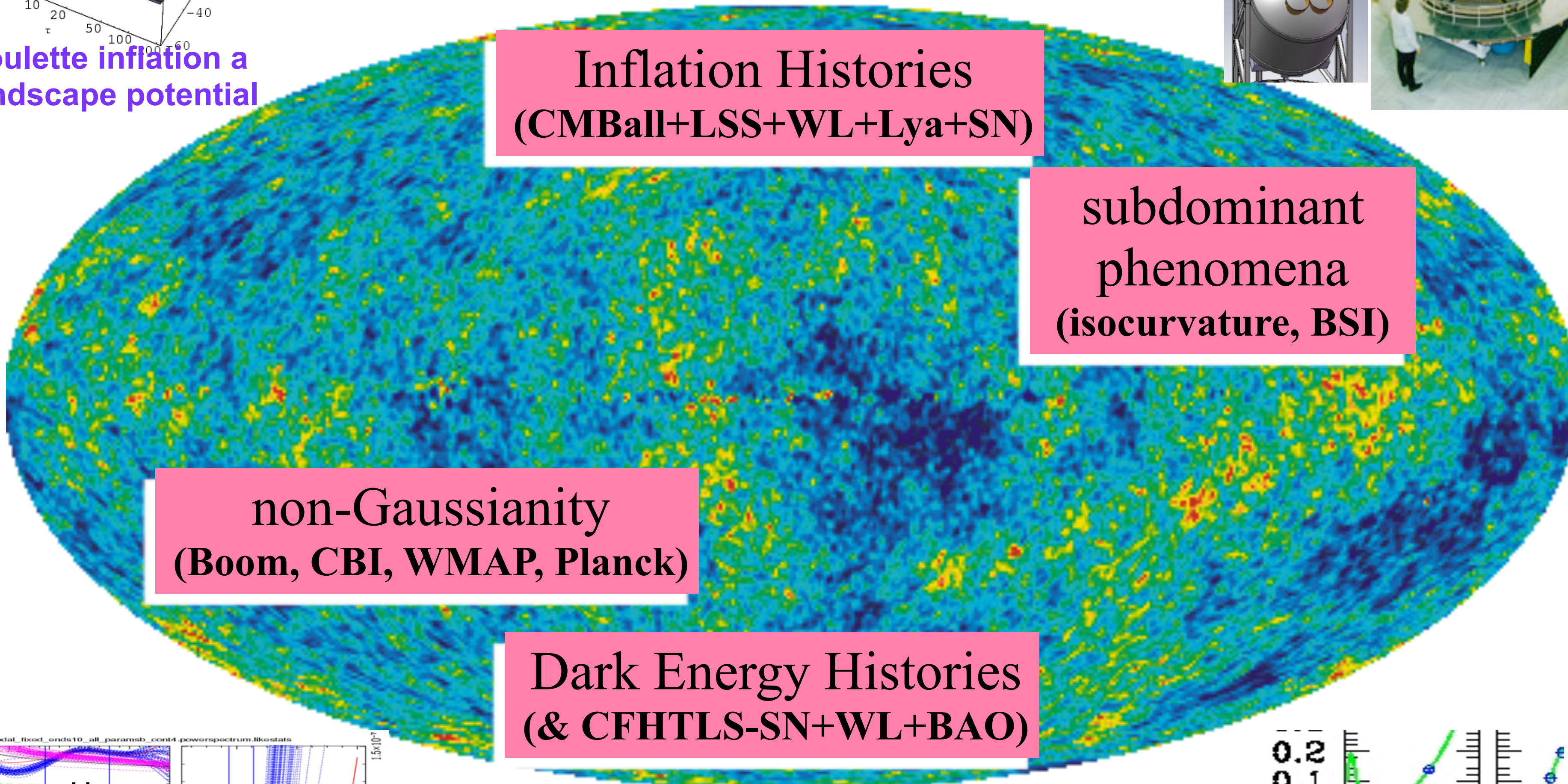
CMBology

Probing the linear & nonlinear cosmic web



roulette inflation a landscape potential





Inflation Histories

(CMBall+LSS+WL+Lya+SN)

subdominant phenomena

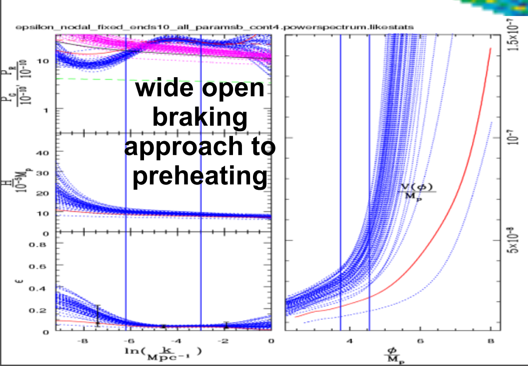
(isocurvature, BSI)

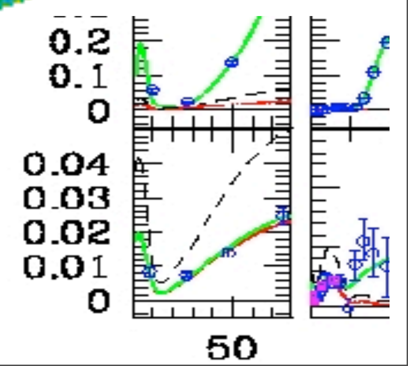
non-Gaussianity

(Boom, CBI, WMAP, Planck)

Dark Energy Histories

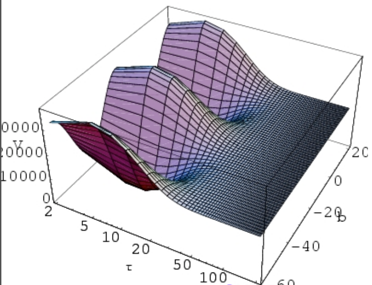
(& CFHTLS-SN+WL+BAO)



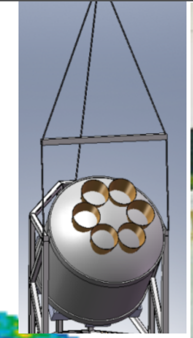


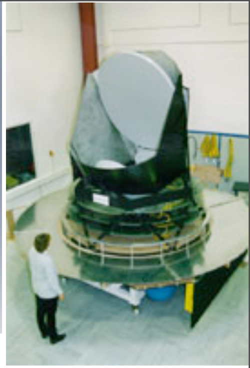
CMBology

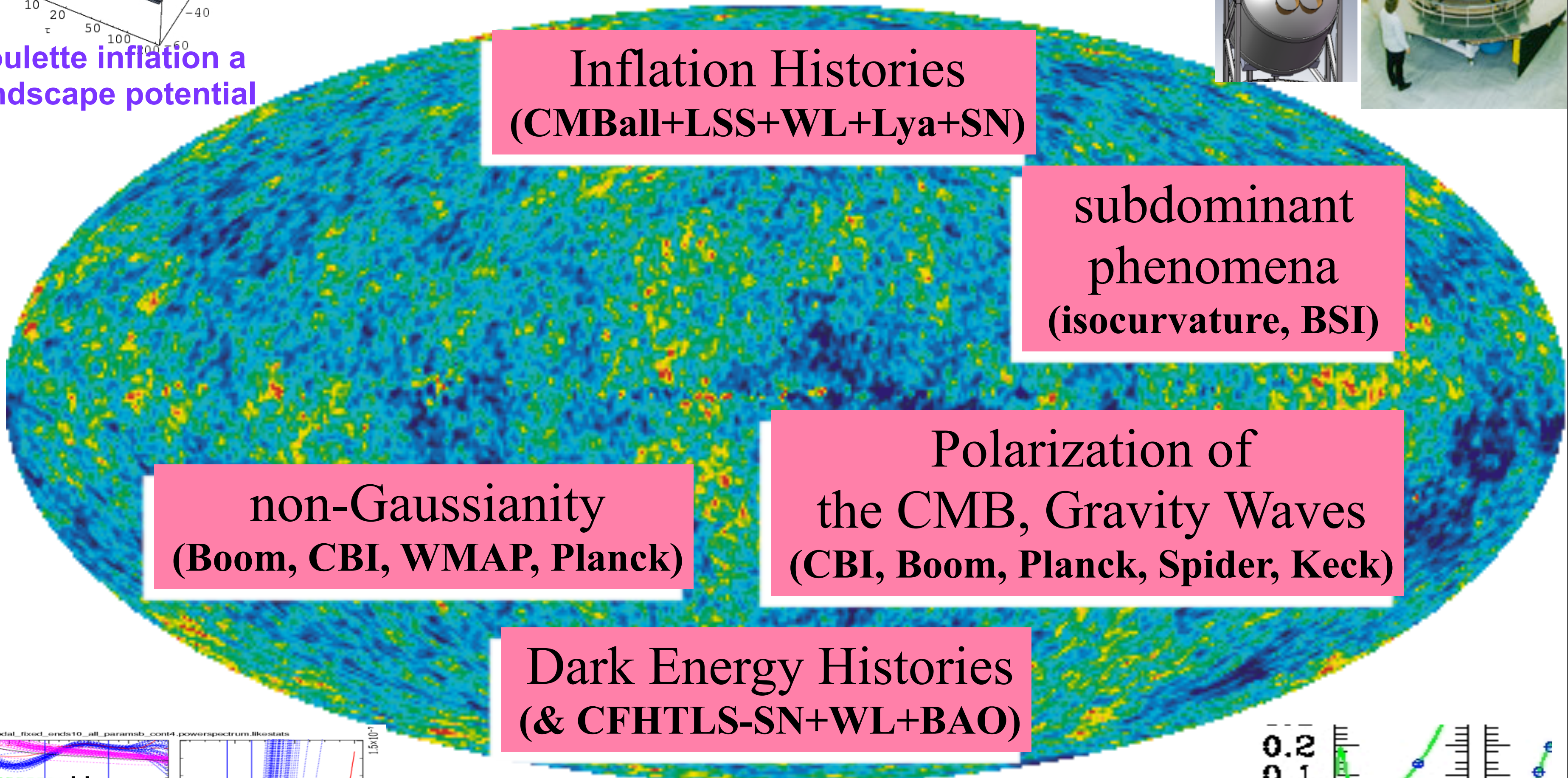
Probing the linear & nonlinear cosmic web



roulette inflation a landscape potential







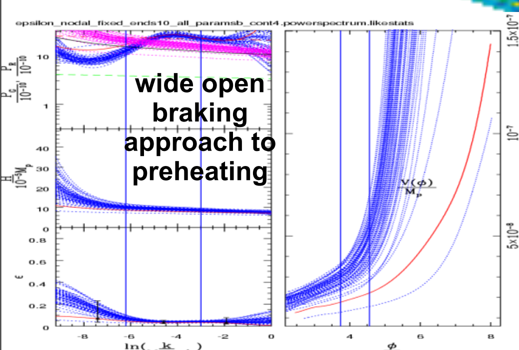
Inflation Histories
(CMBall+LSS+WL+Lya+SN)

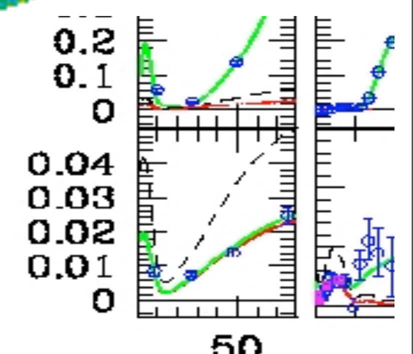
subdominant phenomena
(isocurvature, BSI)

non-Gaussianity
(Boom, CBI, WMAP, Planck)

Polarization of the CMB, Gravity Waves
(CBI, Boom, Planck, Spider, Keck)

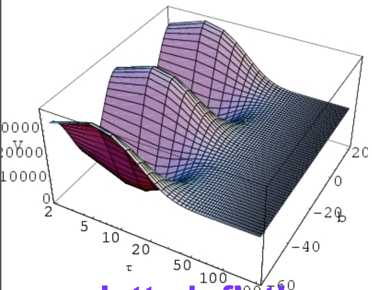
Dark Energy Histories
(& CFHTLS-SN+WL+BAO)



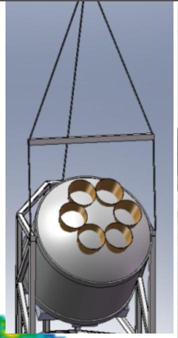


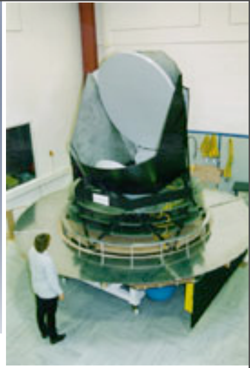
CMBology

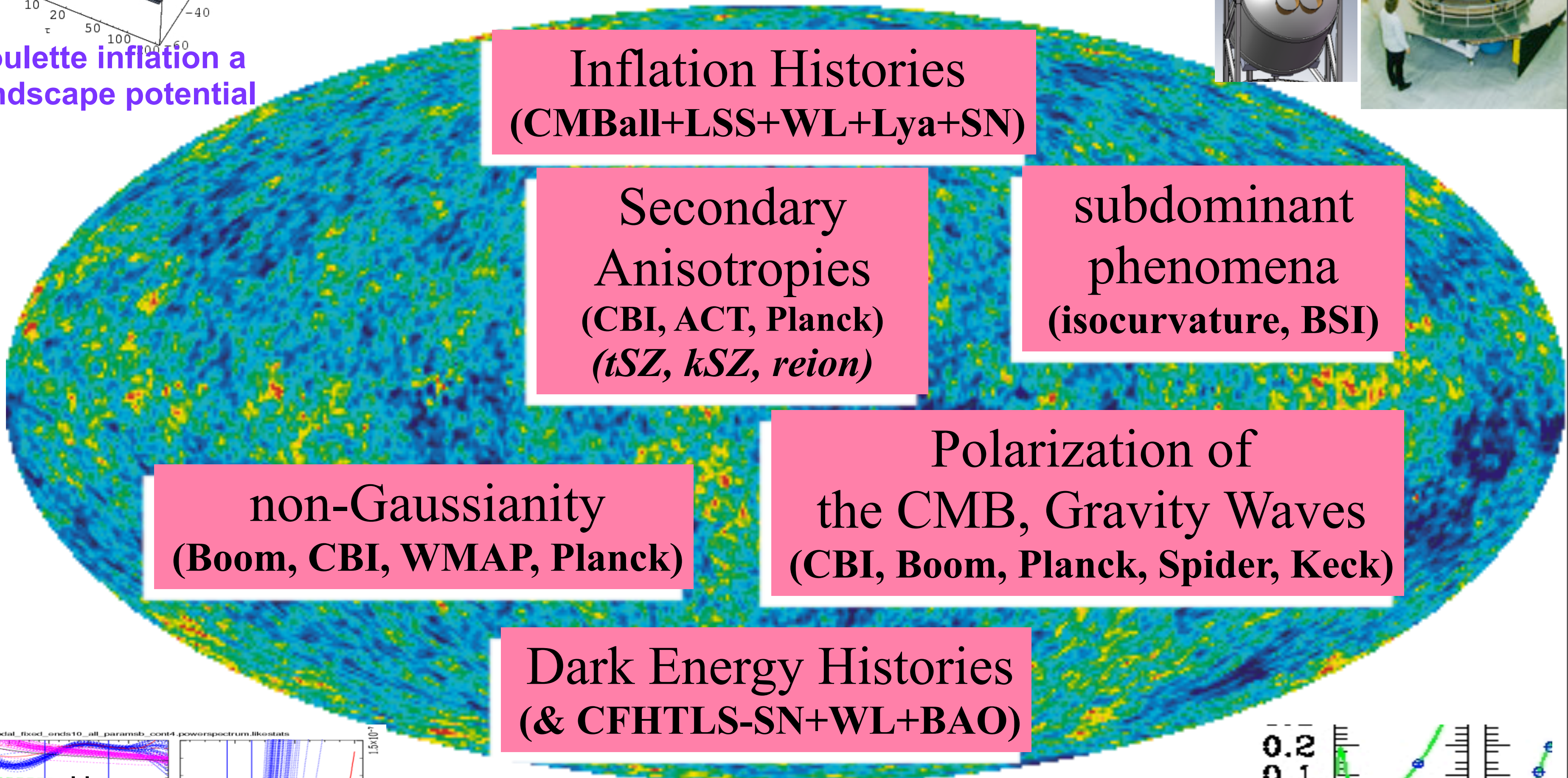
Probing the linear & nonlinear cosmic web



roulette inflation a landscape potential







Inflation Histories
(CMBall+LSS+WL+Lya+SN)

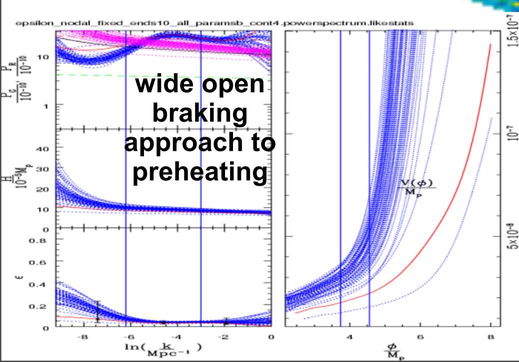
Secondary Anisotropies
(CBI, ACT, Planck)
(tSZ, kSZ, reion)

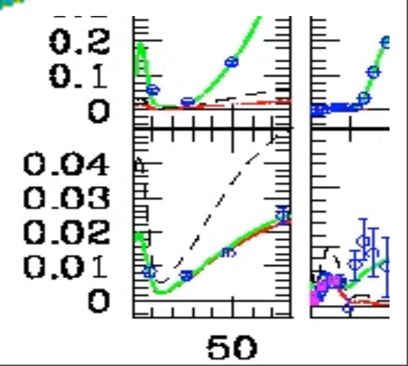
subdominant phenomena
(isocurvature, BSI)

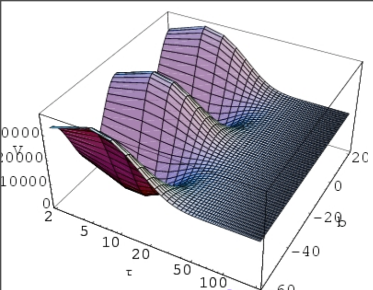
non-Gaussianity
(Boom, CBI, WMAP, Planck)

Polarization of the CMB, Gravity Waves
(CBI, Boom, Planck, Spider, Keck)

Dark Energy Histories
(& CFHTLS-SN+WL+BAO)

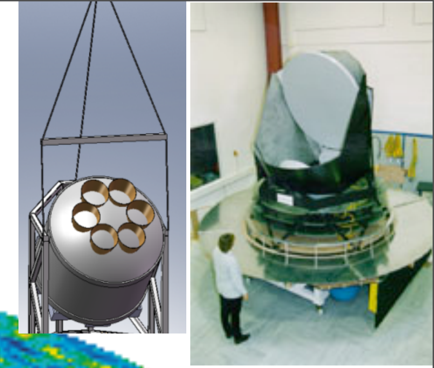






CMBology

Probing the linear & nonlinear cosmic web



Inflation Histories
(CMBall+LSS+WL+Lya+SN)

Secondary Anisotropies
(CBI, ACT, Planck)
(tSZ, kSZ, reion)

subdominant phenomena
(isocurvature, BSI)

Foregrounds
CBI, WMA,Planck

non-Gaussianity
(Boom, CBI, WMAP, Planck)

Polarization of the CMB, Gravity Waves
(CBI, Boom, Planck, Spider, Keck)

Dark Energy Histories
(& CFHTLS-SN+WL+BAO)