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

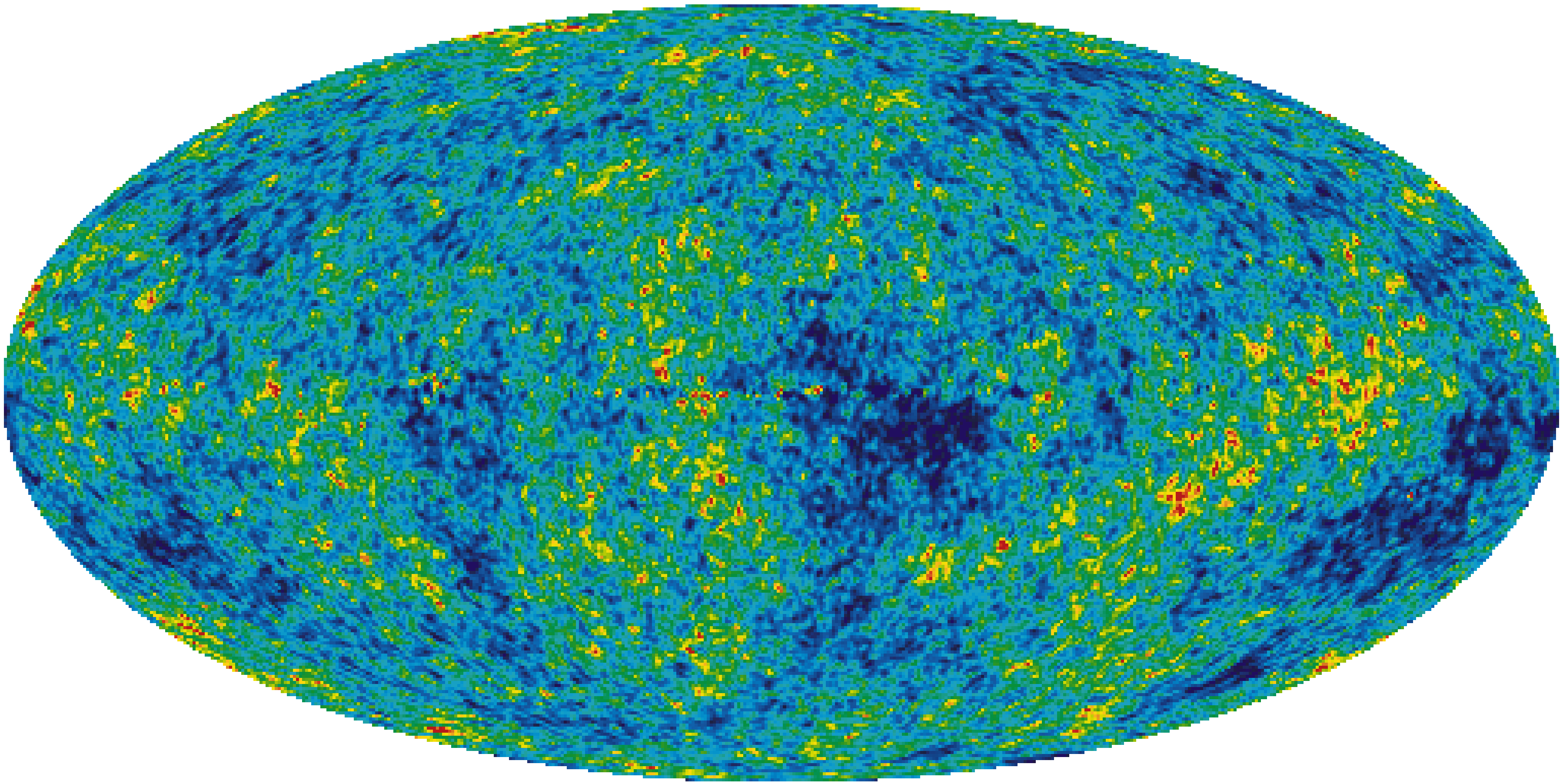
Dick Bond

CIAR

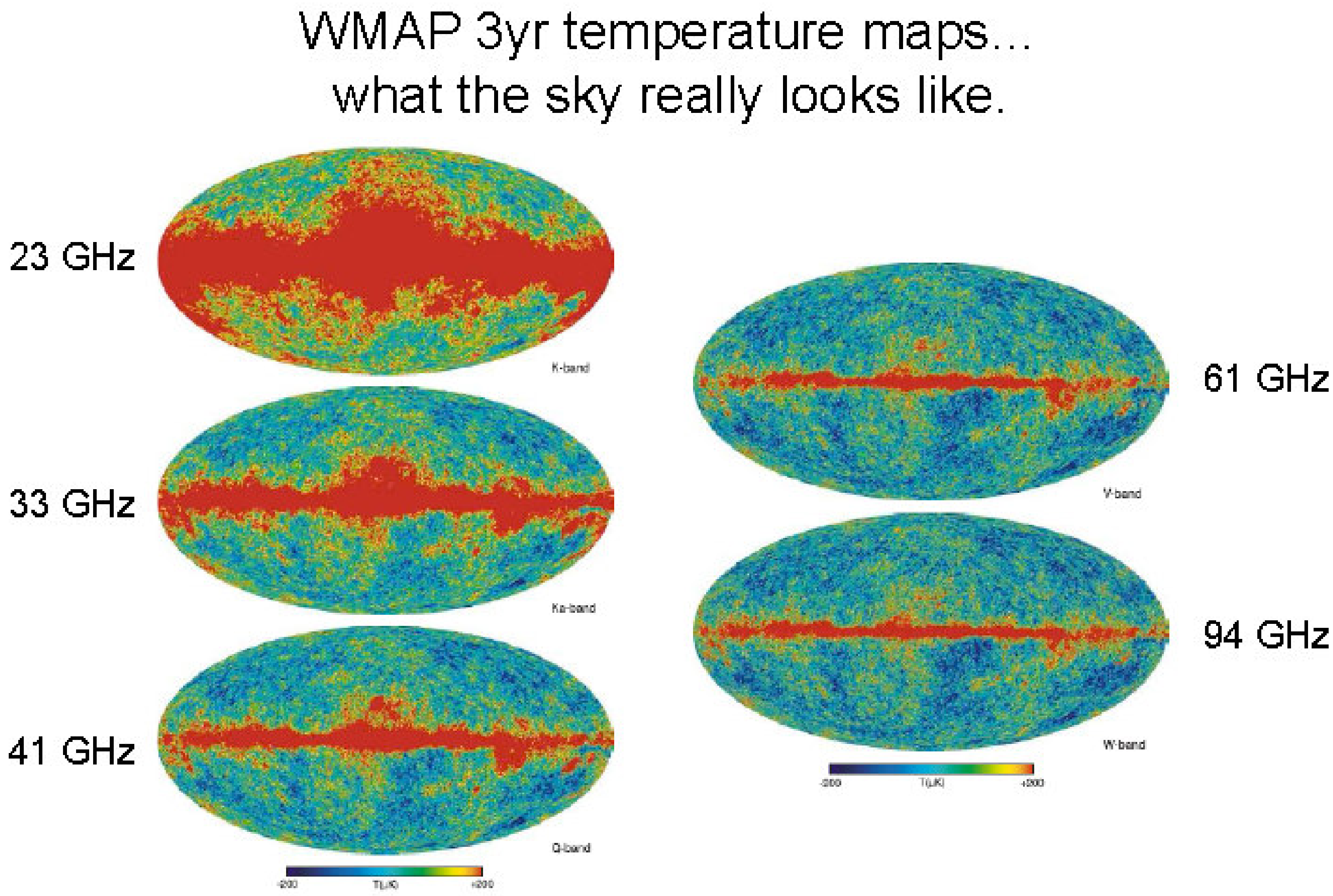
L3a: Measuring Cosmic Parameters

L3b: Cosmic Microwave Background Frontiers: Secondary Anisotropies & Polarization & Gravity Waves

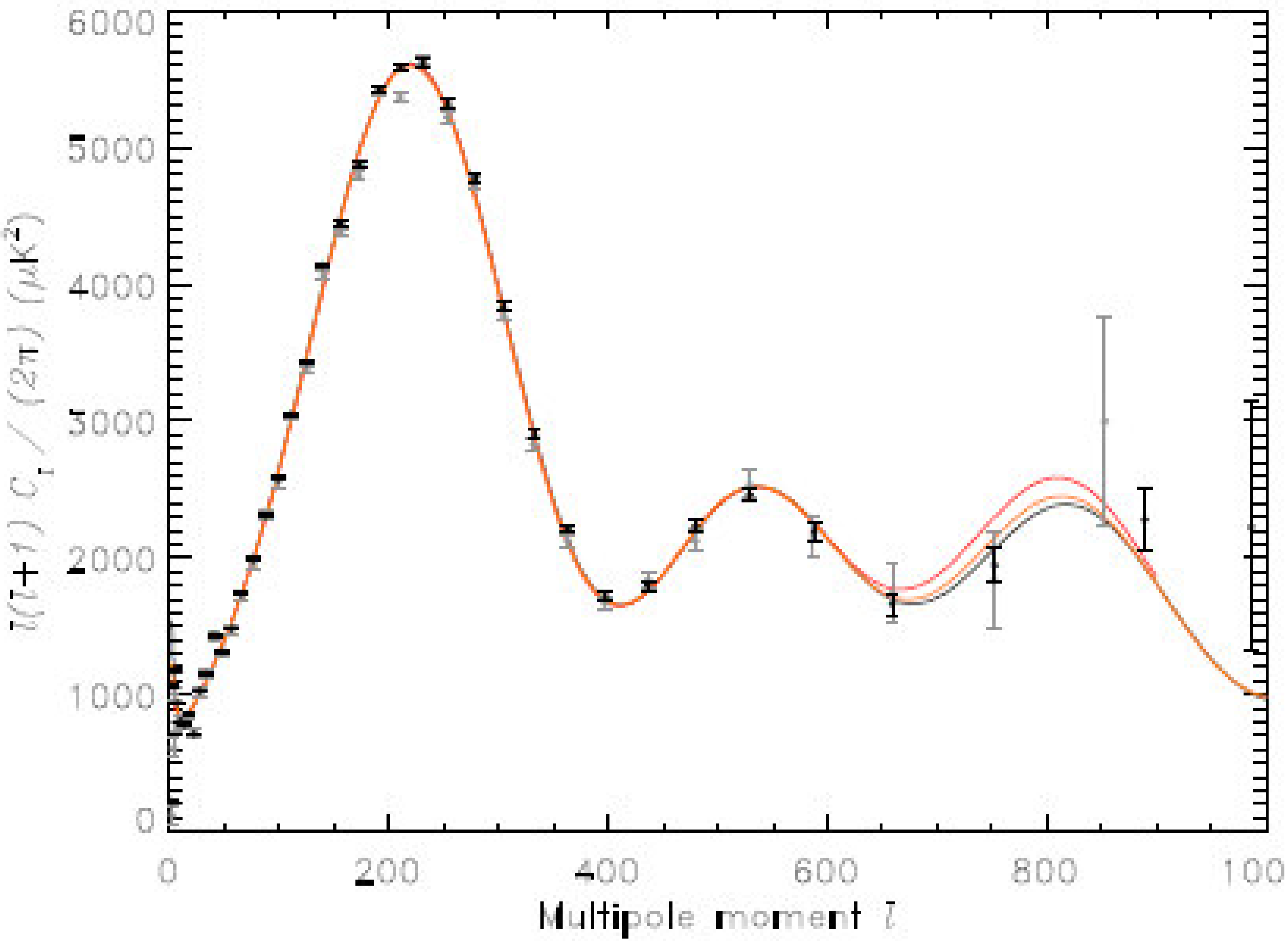
WMAP3 thermodynamic CMB temperature fluctuations



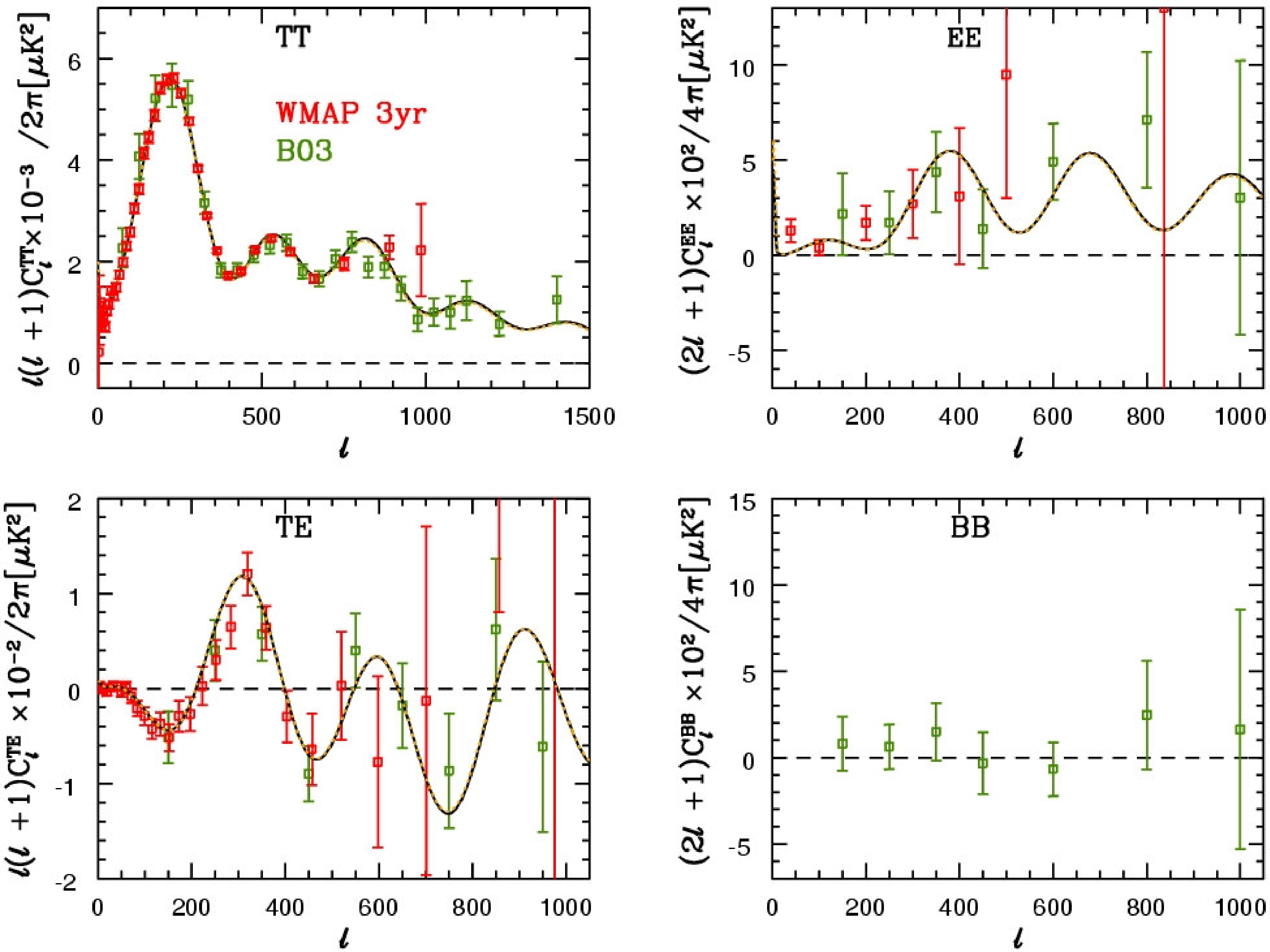
WMAP3 5 channel CMB temperature fluctuations



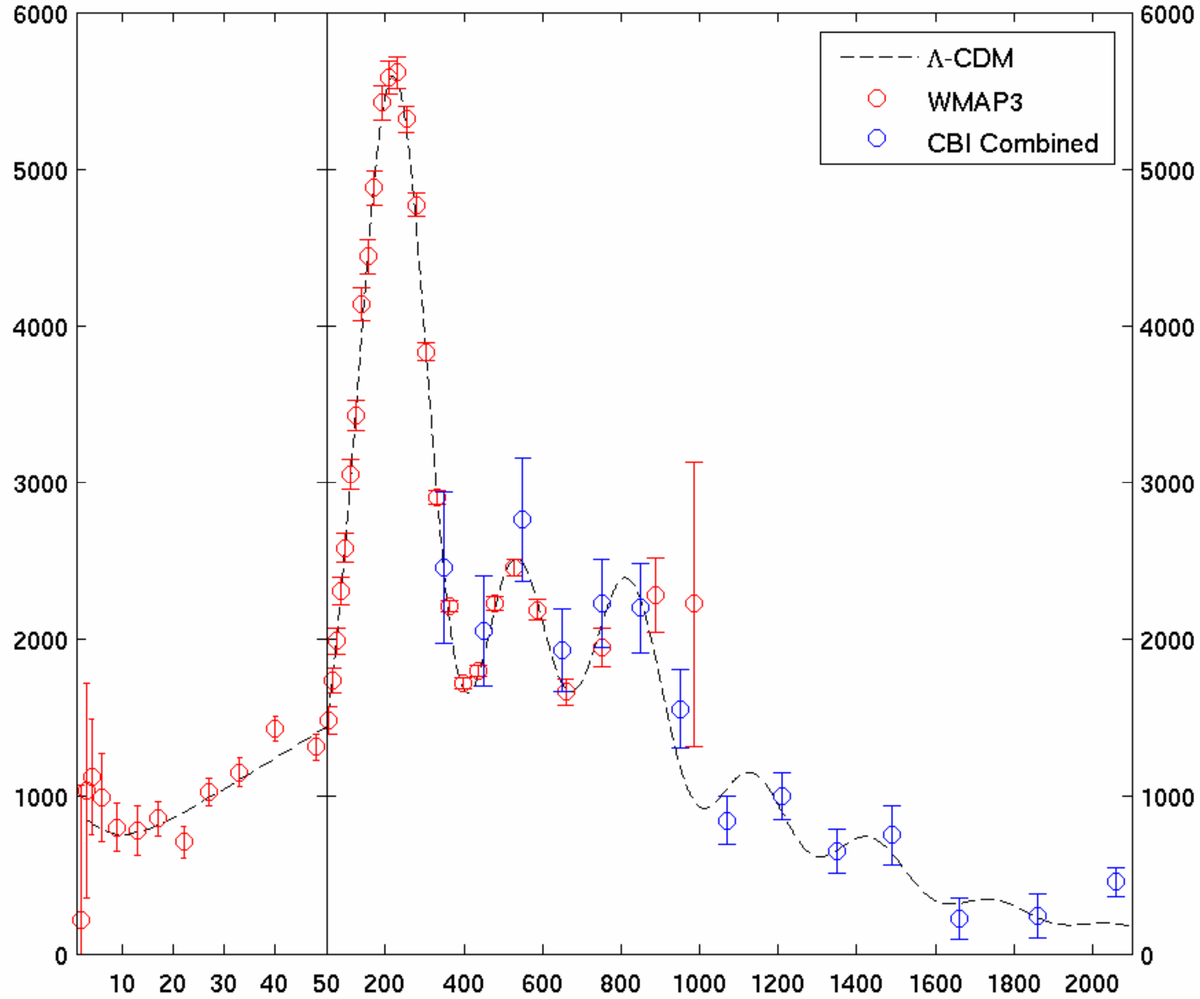
WMAP3 cf. WMAP1



WMAP3 sees 3^{rd} pk, B03 sees 4^{th}



CBI combined TT sees 5th pk



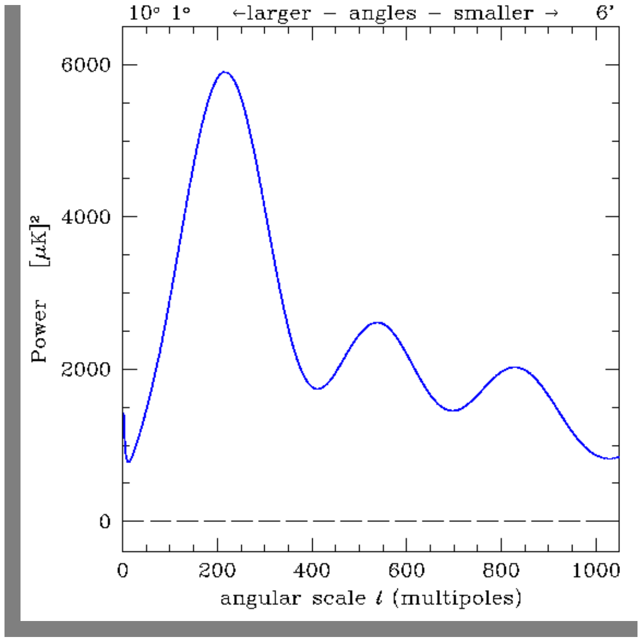
Theory ⇔ Observables

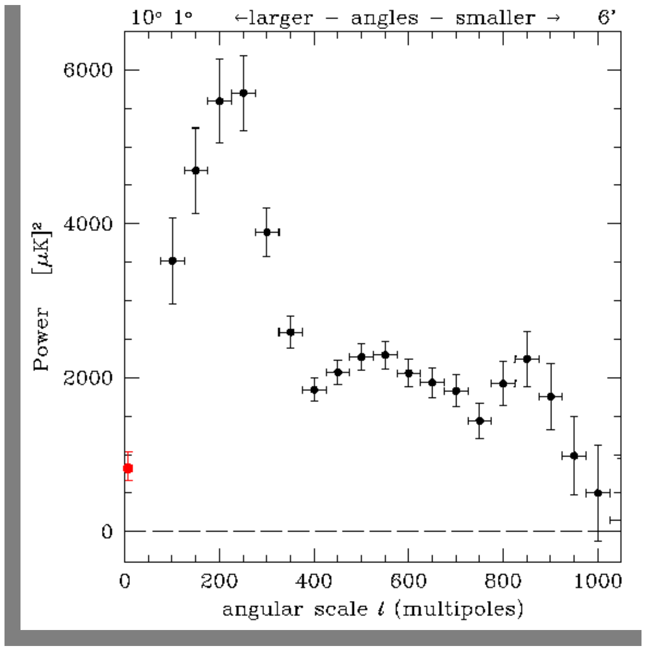
Parameters
H_0, T_0, n, Ω_k
$\Omega_b, \Omega_{CDM}, \Omega_\Lambda$

Cosmic Microwave Background

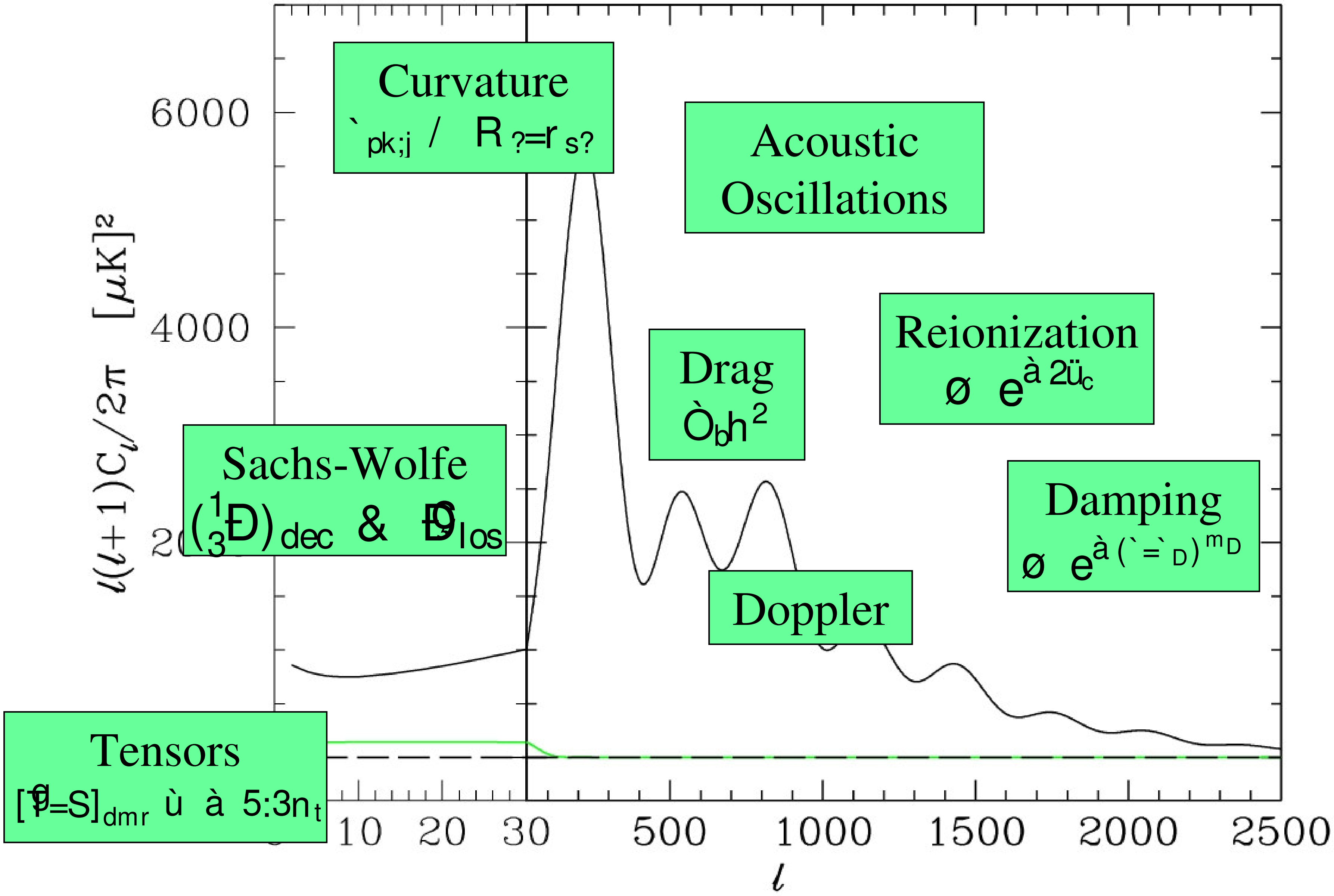
Spectrum Computation

Data Reduction & Noise Separation





Sound & Light in the Early Universe



Parameters of Cosmic Structure Formation

Period of inflationary expansion, quantum noise → metric perturb.

Òk Òbh2 Òdmh2 ÒË üc ns nt As ø û8 At

•Inflation → predicts nearly scale i... ions and background of gravitational wa...

•Passive/adiabatic/coherent/gaussia...

•Nice linear regime

•Boltzman equation + Einstein equ... S

Wha... F... curvatu...

Òk > (

Òk = 0 flat

Òk < 0 open

Densi... interac... M...

Sp... pr... (c... F

Optical Depth to Last Scattering Surface

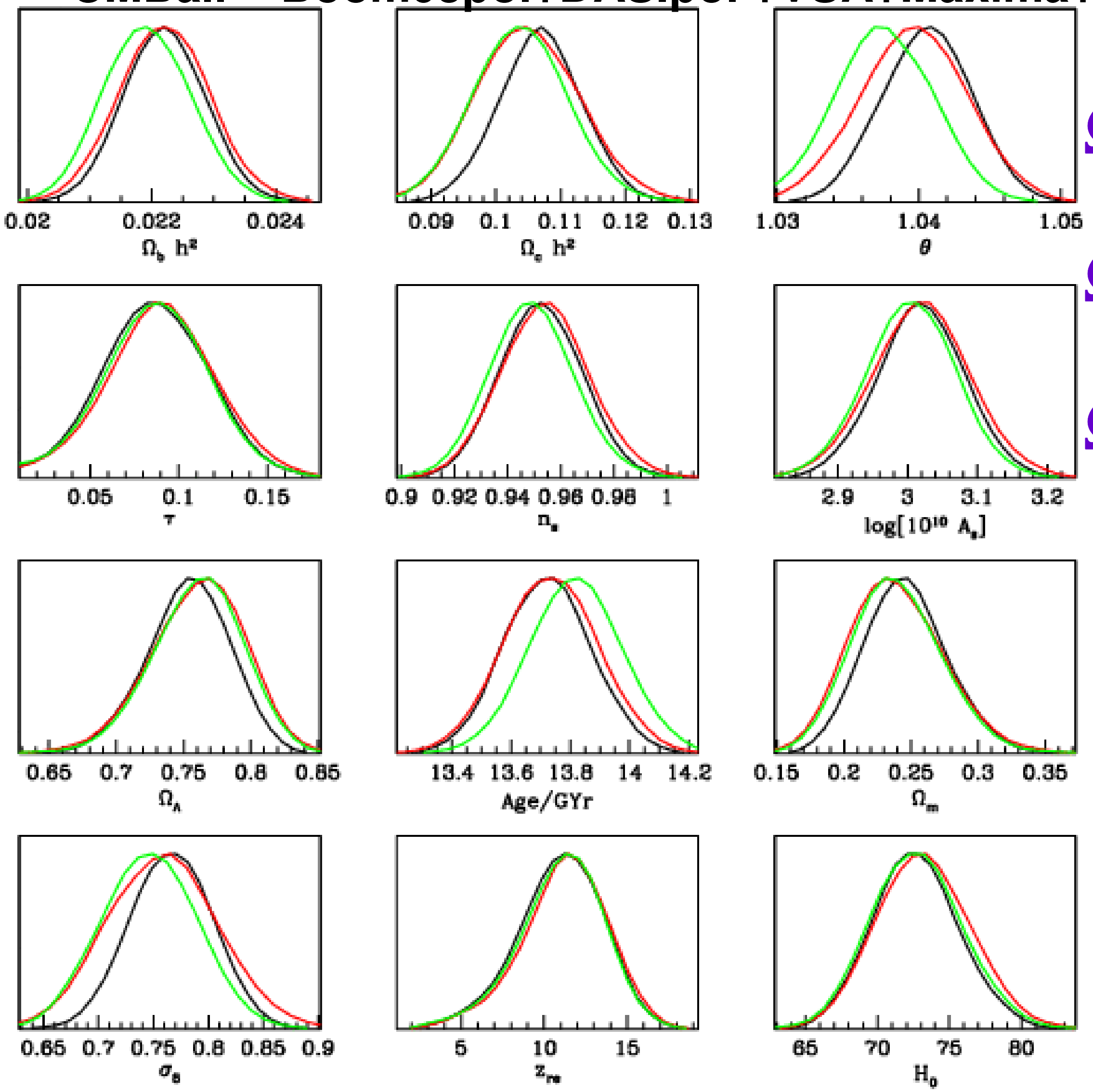
When did stars reionize the universe?

litude sor es) s nt

The Parameters of Cosmic Structure Formation

WMAP3 WMAP3+CBIcombinedTT+CBIpol

CMBall = Boom03pol+DASIpol +VSA+Maxima+WMAP3+CBIcombinedTT+CBIpol



$\Omega_b h^2$ = .0222 +- .0007

$\Omega_c h^2$ = .107 +- .007

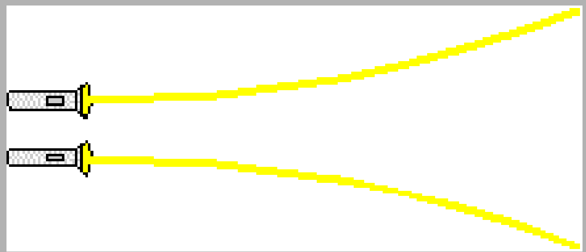
Ω_Λ = .75 +- .03

τ_C = .087 +- .03

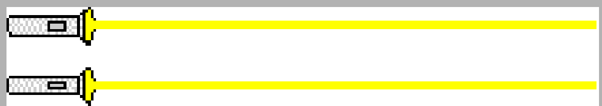
(.005 PL1)

Some Parameters: Total Density

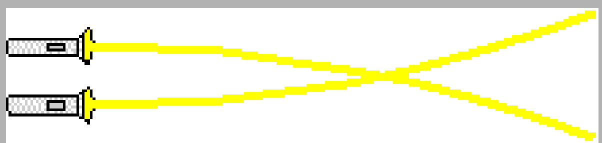
Matter curves space. The *physical* size of the waves is fixed. The *apparent* size is set by size of universe and curvature of space.



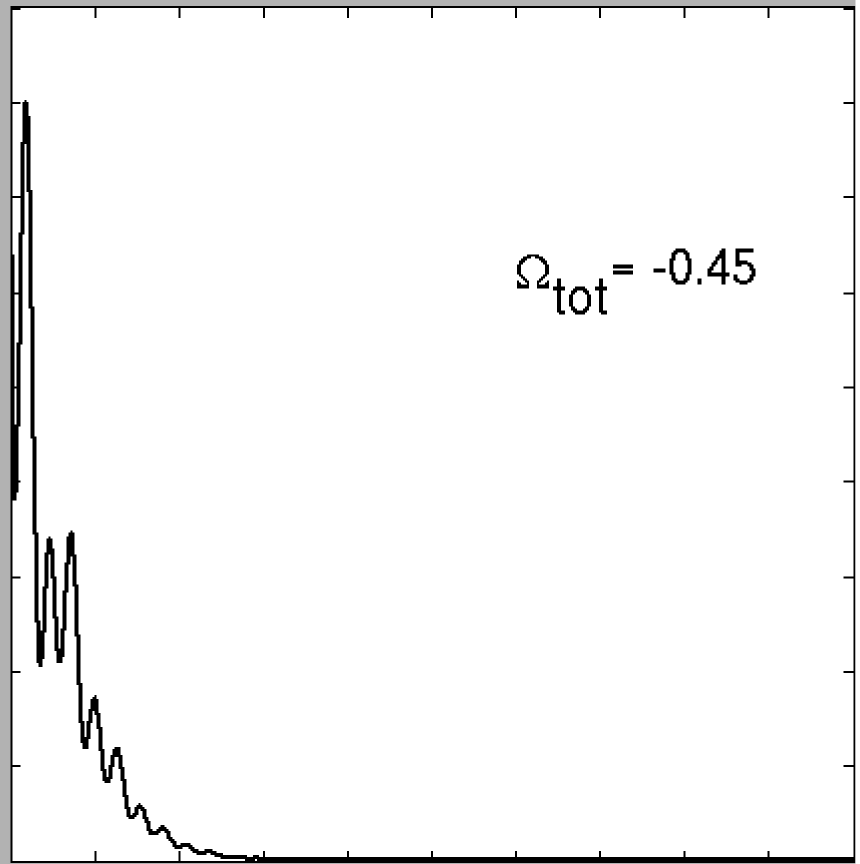
Open – things look small.



Flat – things are medium.

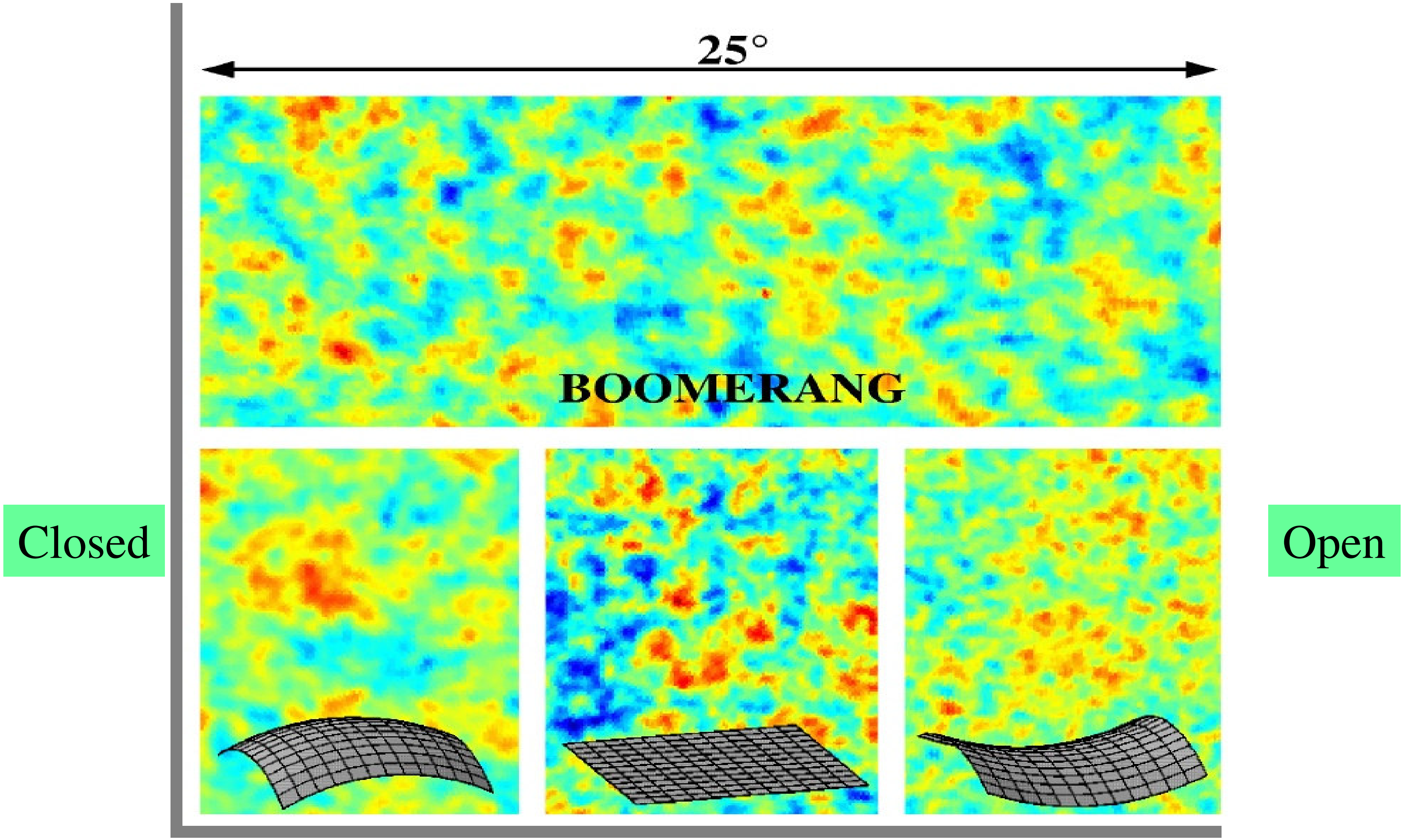


Closed – things are big.

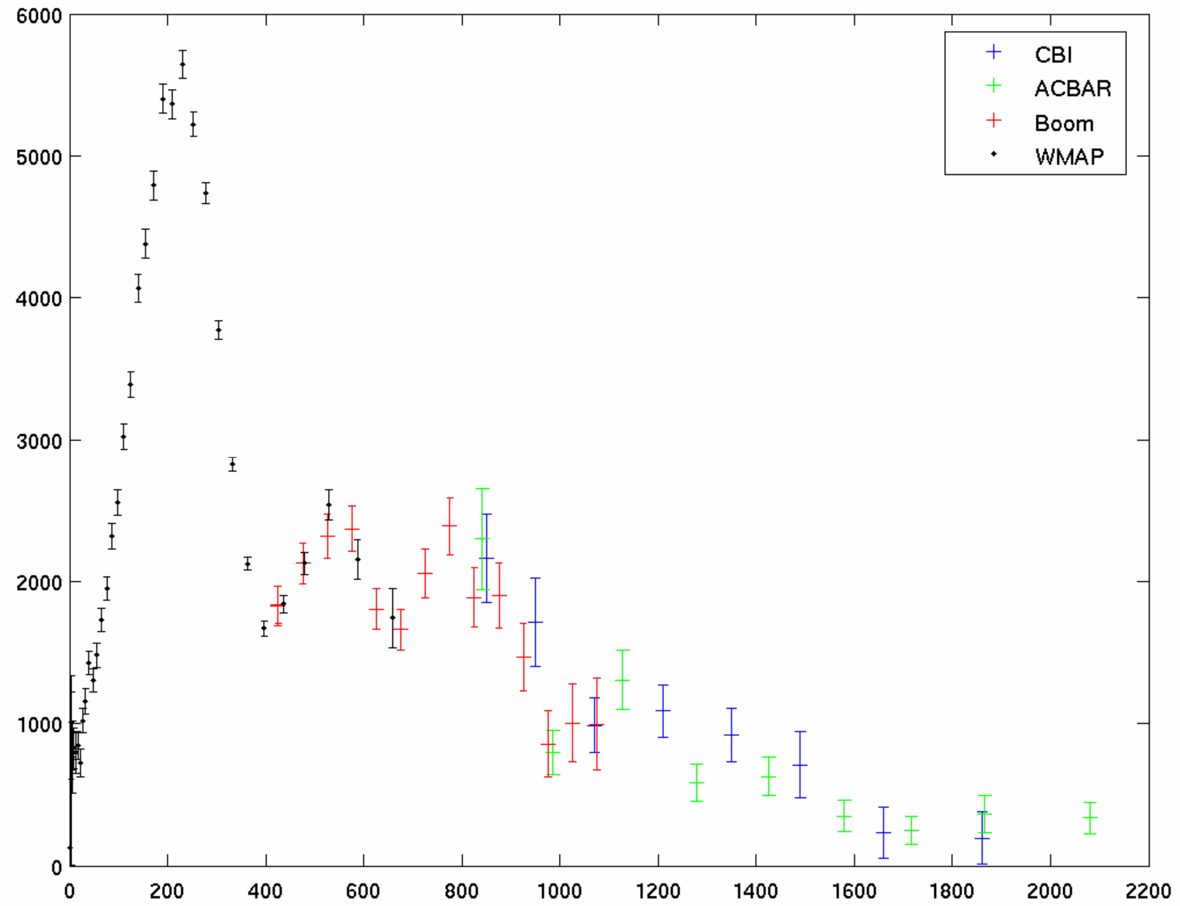


If universe becomes less dense, pattern of peaks shifts to the right (smaller size on the sky).

Curvature of the Universe

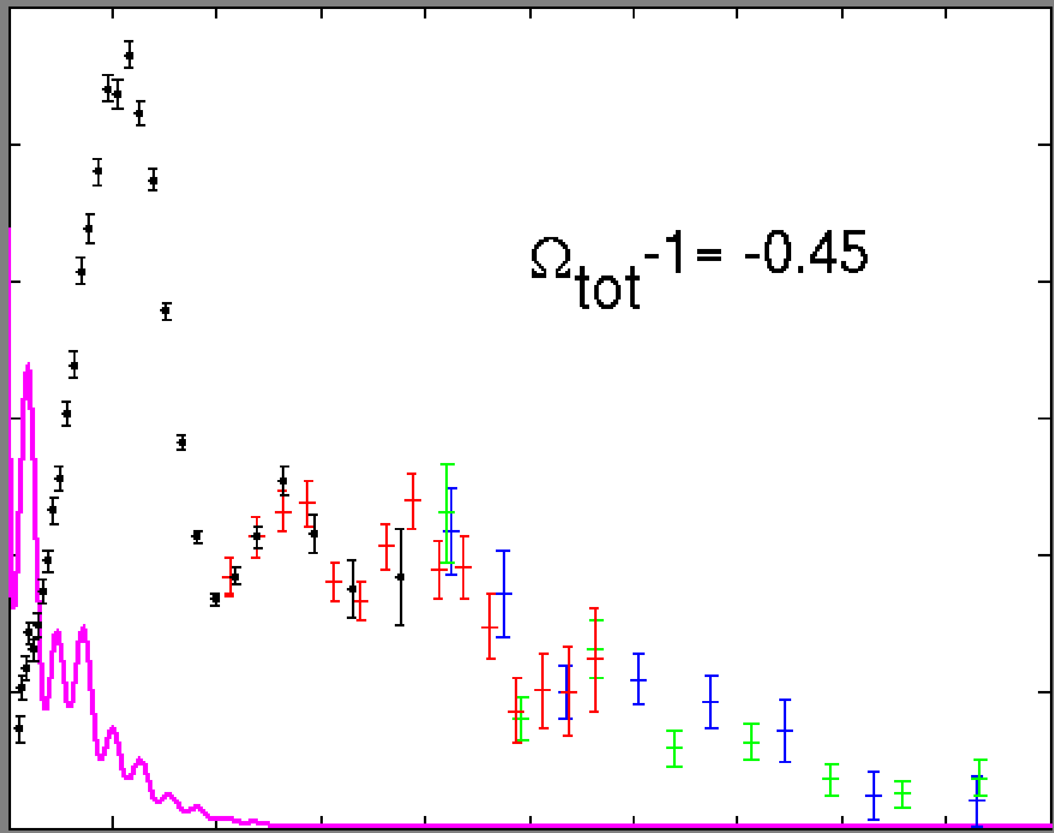


CMB Data pre-WMAP3



How Constrained are Things?

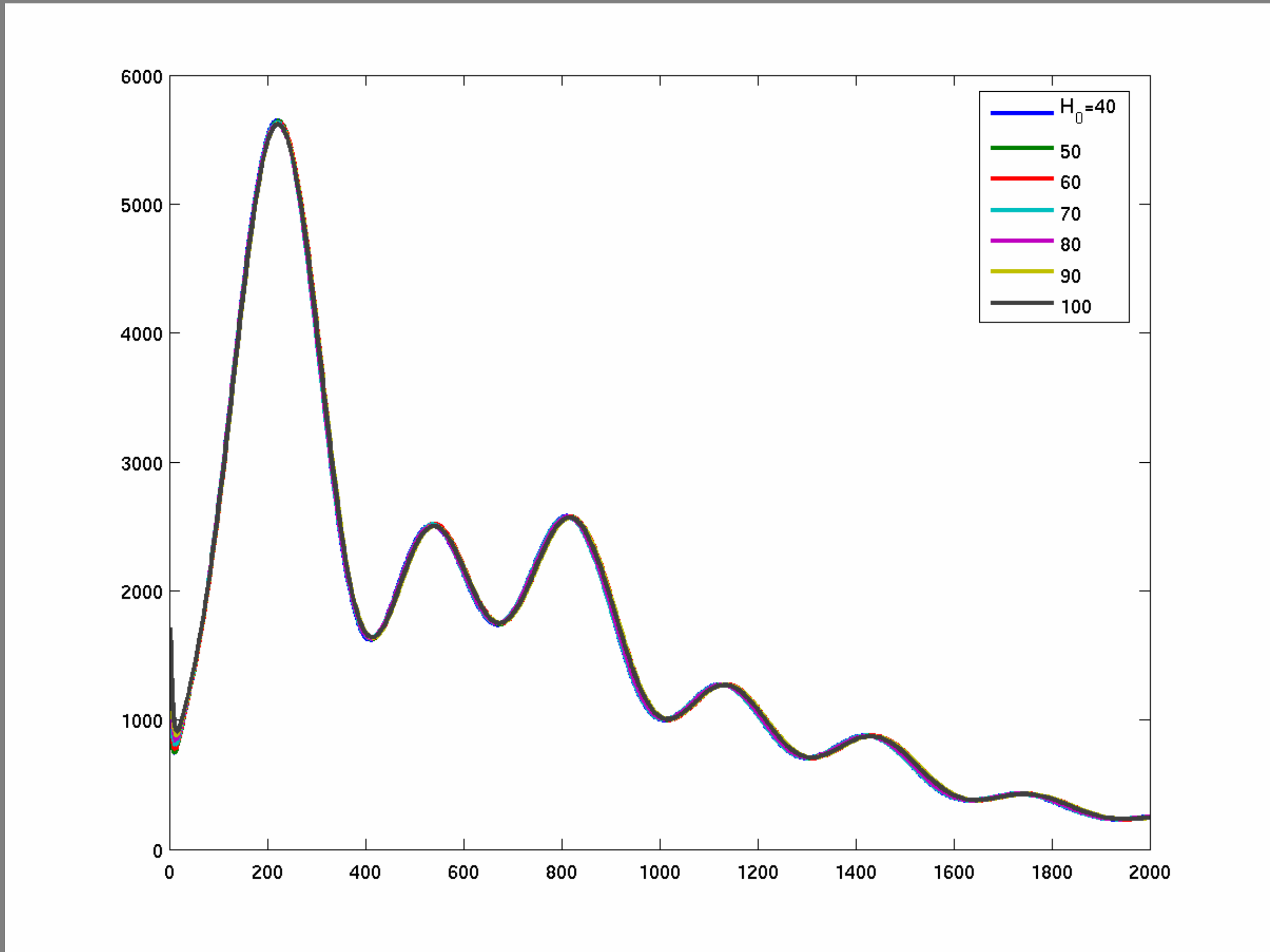
Curvature of the universe: (including other astronomical data)



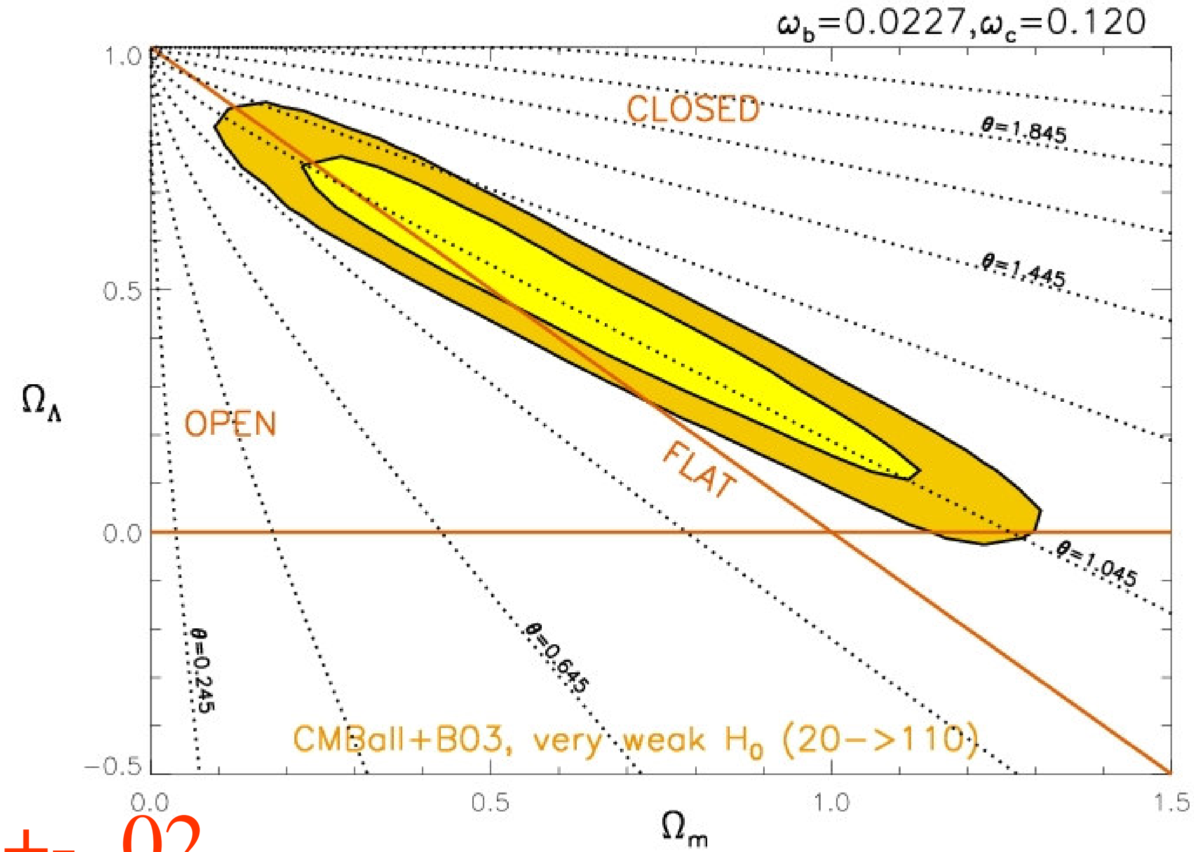
Universe is flat to an accuracy of 2%

Parameter degeneracies

Combinations of Hubble Constant and total curvature leave CMB spectrum virtually unchanged.



Angular Diameter distance degeneracy breaking

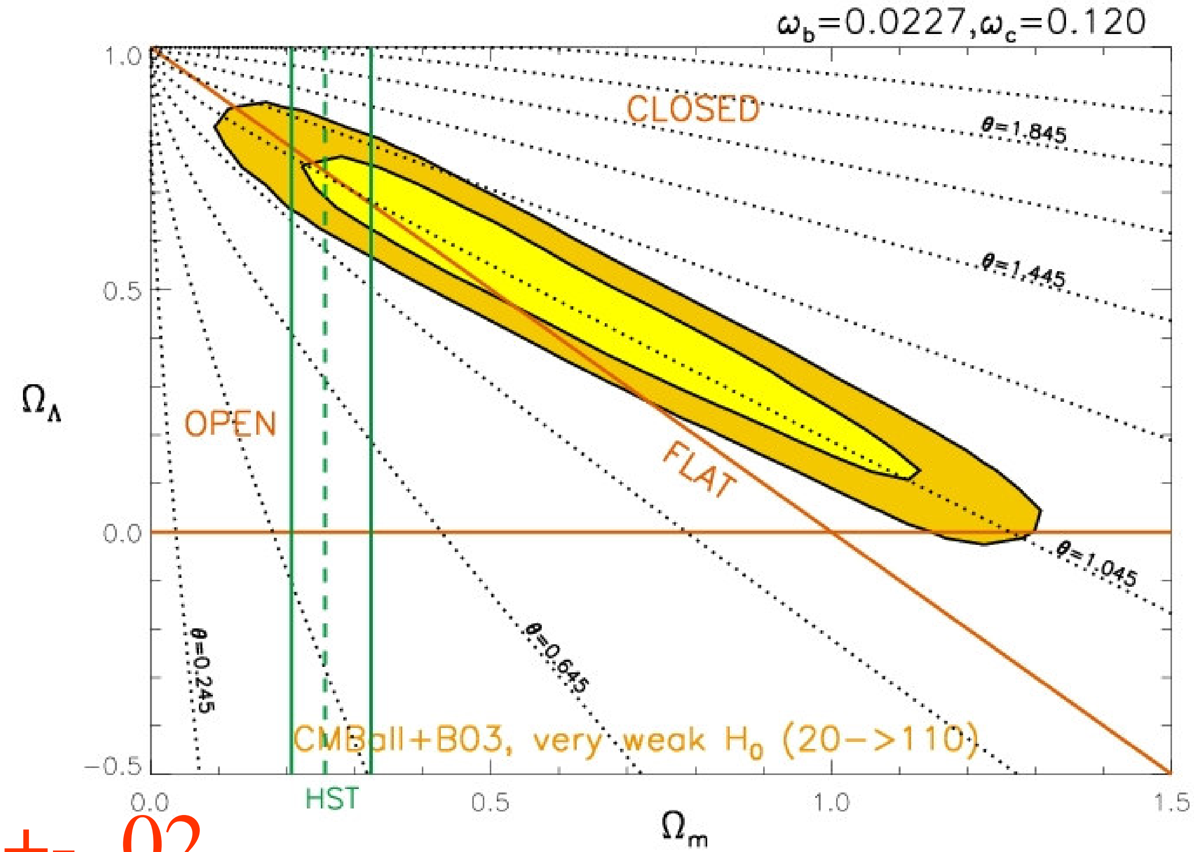


Ω_k = -.02 +- .02 (+HST)

h = .73 +- .03

Ω_Λ = .75 +- .03

Ω_m = .25 +- .03



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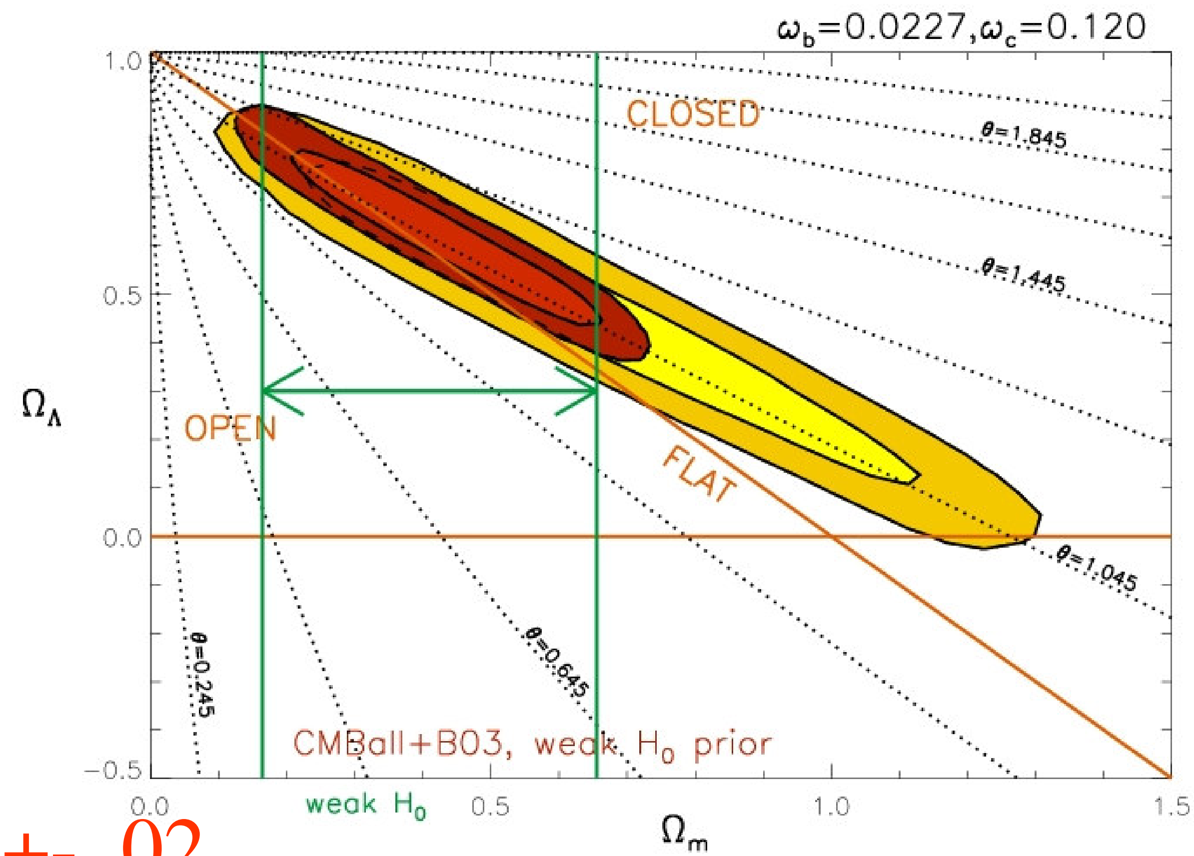
Ω_m = .25 +- .03

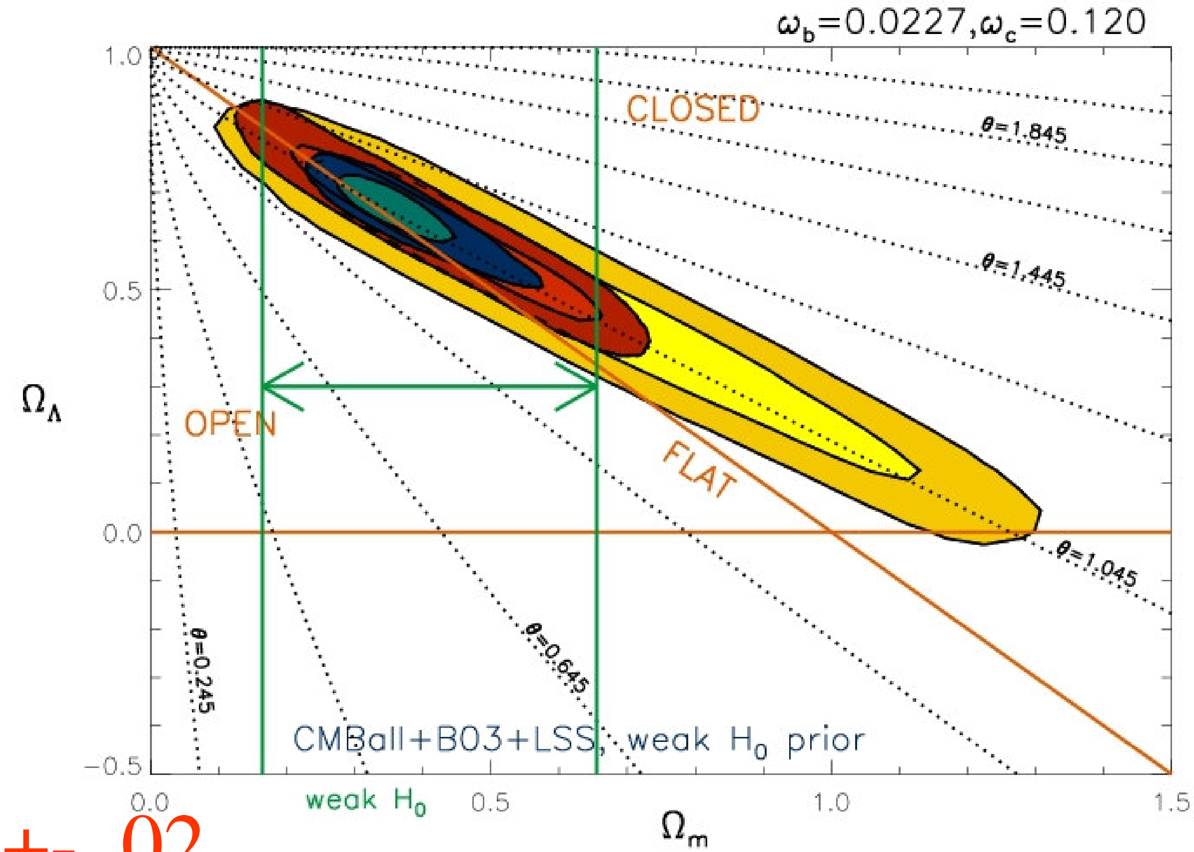


Ω_k = -.02 +- .02
(+HST)

h = .73 +- .03

Ω_Λ = .75 +- .03

Ω_m = .25 +- .03



Ω_k = -.02 +- .02
(+HST)

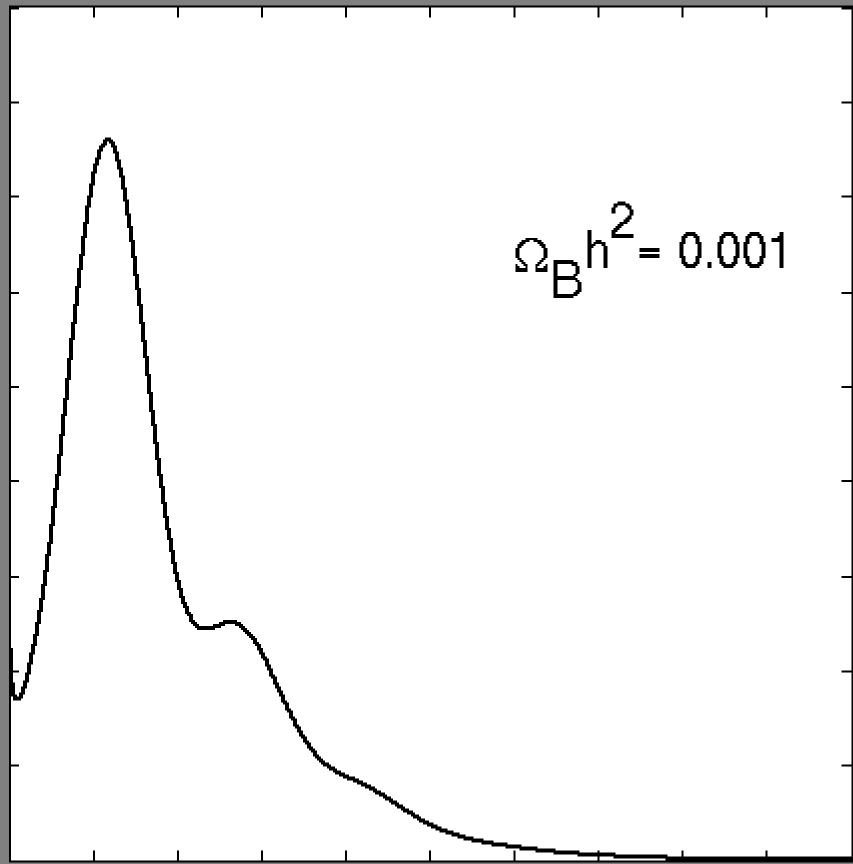
h = .73 +- .03

Ω_Λ = .75 +- .03

Ω_m = .25 +- .03

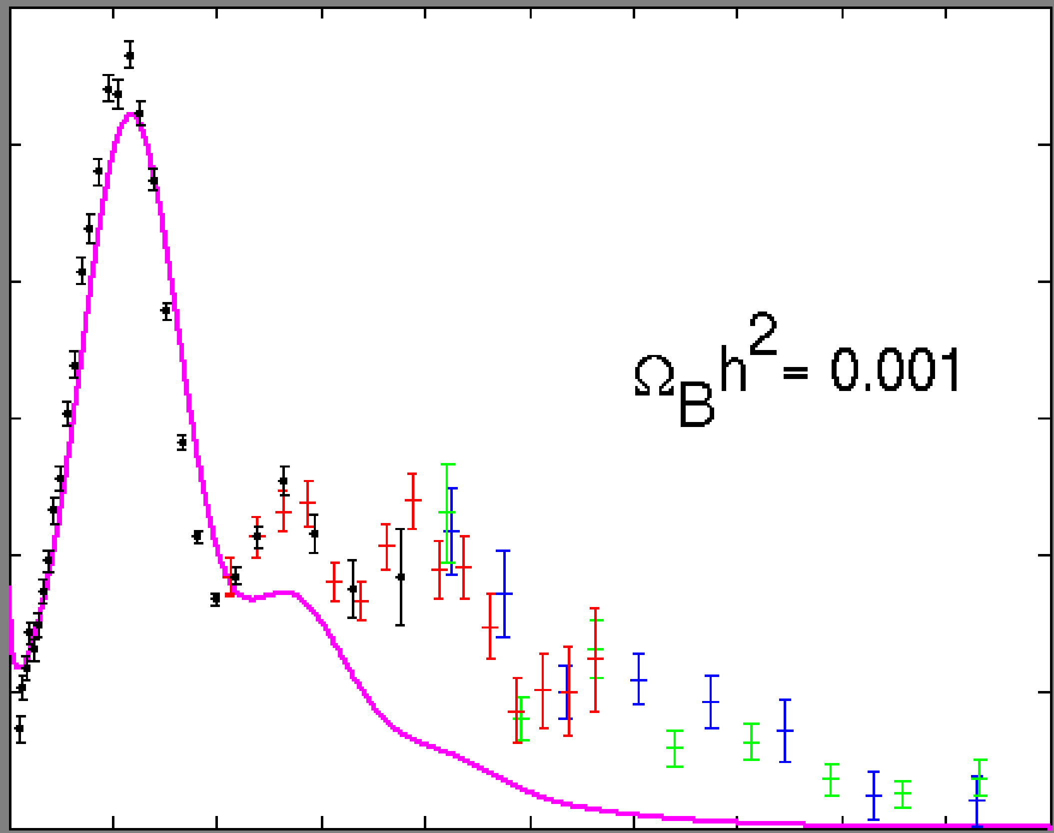
Some Parameters: Baryon Density

Matter wants to fall down. It drags light with it, but the light doesn't want to be squeezed. The more matter there is, the harder the light has to push to turn things around. So, more regular matter (called baryons) means brighter patches.



How Constrained are Things?

Normal Matter (baryon) density of the universe: 4.4%±0.4% of total (in good agreement with helium, lithium abundances).



Normal matter a tiny fraction of the universe

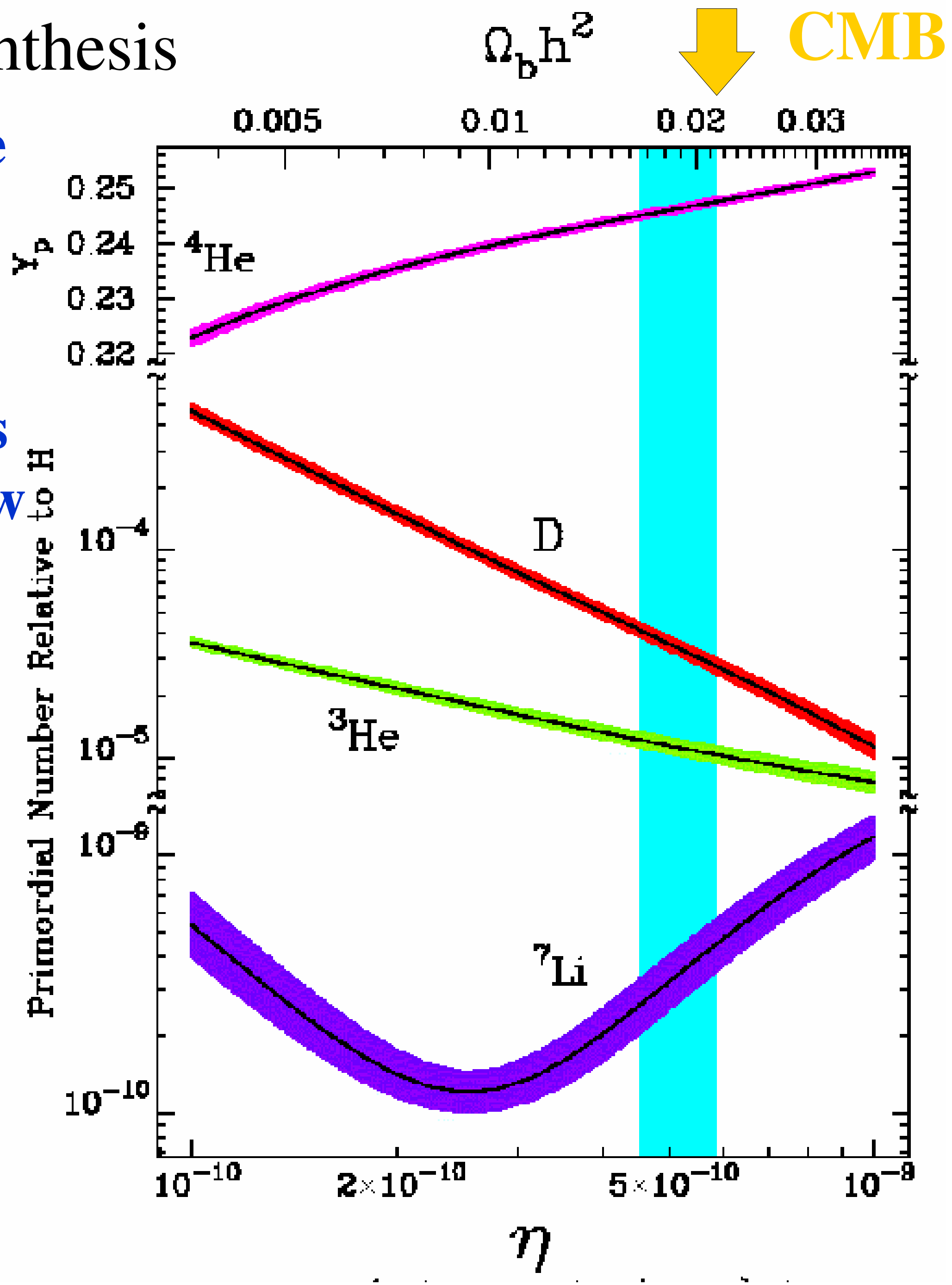
Big Bang Nucleosynthesis

Light Element Abundances are cooked in the

"first 3 minutes"

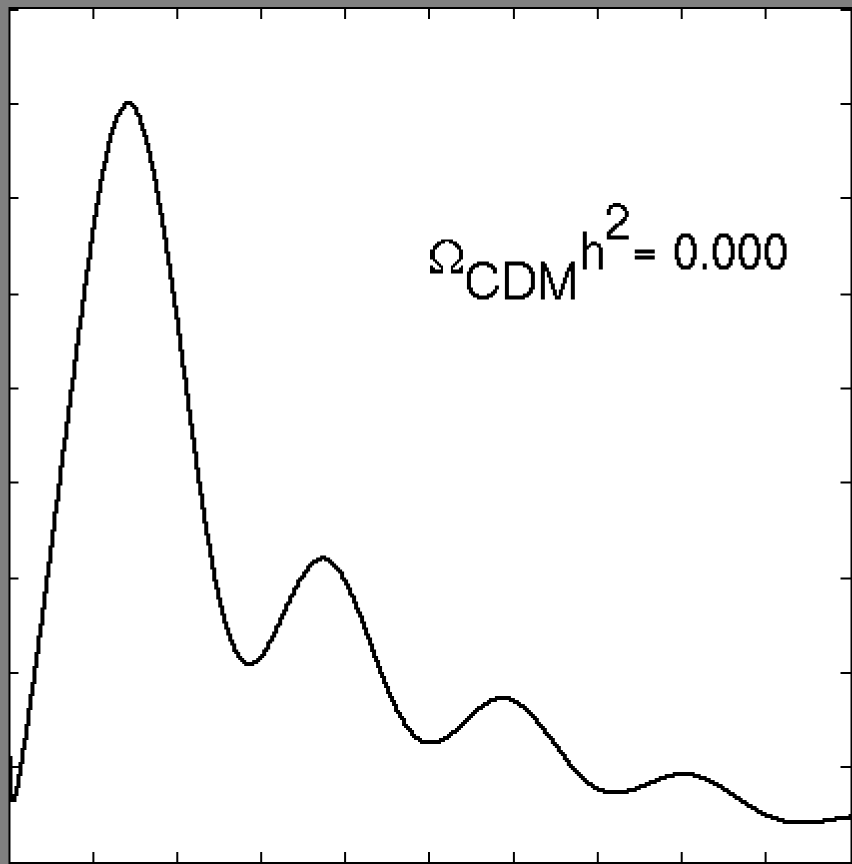
observations of deuterium lines in QSO absorption spectra allow D abundances to be estimated, hence the baryon abundance

$$\Omega_b h^2 = .0222 \pm .0007$$



Some Parameters: Dark Matter Density

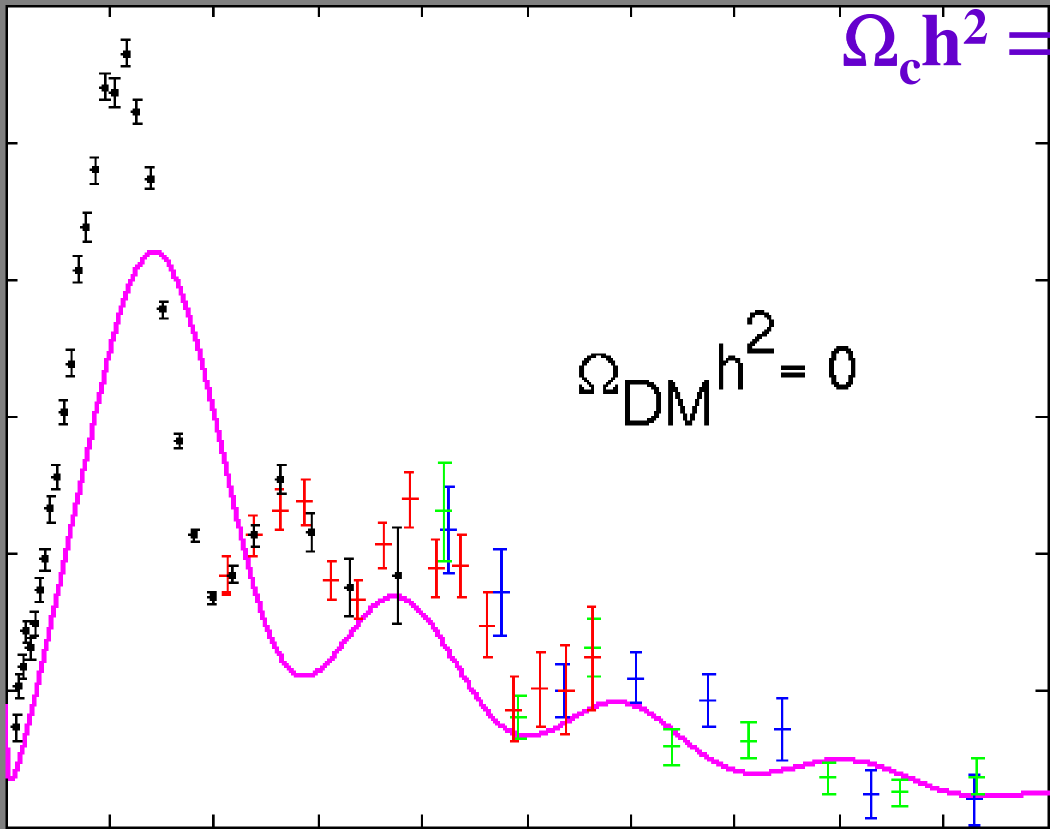
Dark matter doesn't scatter light, so it falls right through the photons. So, no pressure means the dark matter just collapses. Dark matter tries to pull baryons with it through gravity, so 1st, 3rd etc. peaks, DM works with baryons, 2nd, 4th etc. peaks, DM works against baryons. Lots of DM + lots of baryons = big 1st, 3rd peak.



How Constrained are Things?

Dark Matter density of the universe: 23%±4% of total.

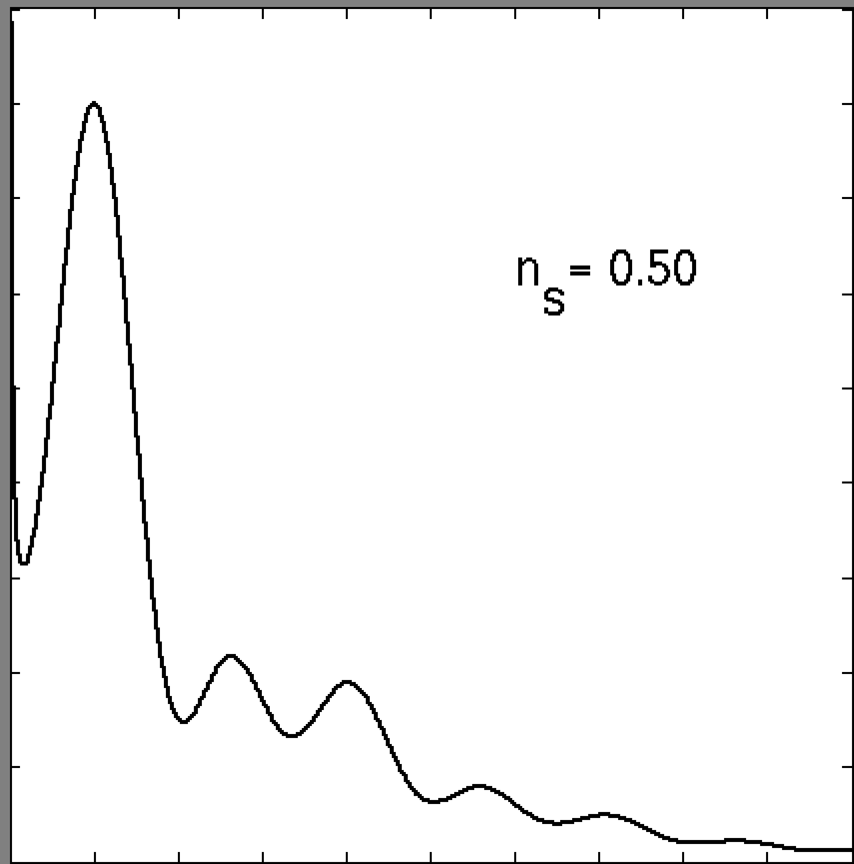
$\Omega_c h^2 = .107 \text{ +- } .007$



Total matter: 27% of universe. What is the rest? A fundamental question for the 21st century, both for theoretical physicists and astronomers.

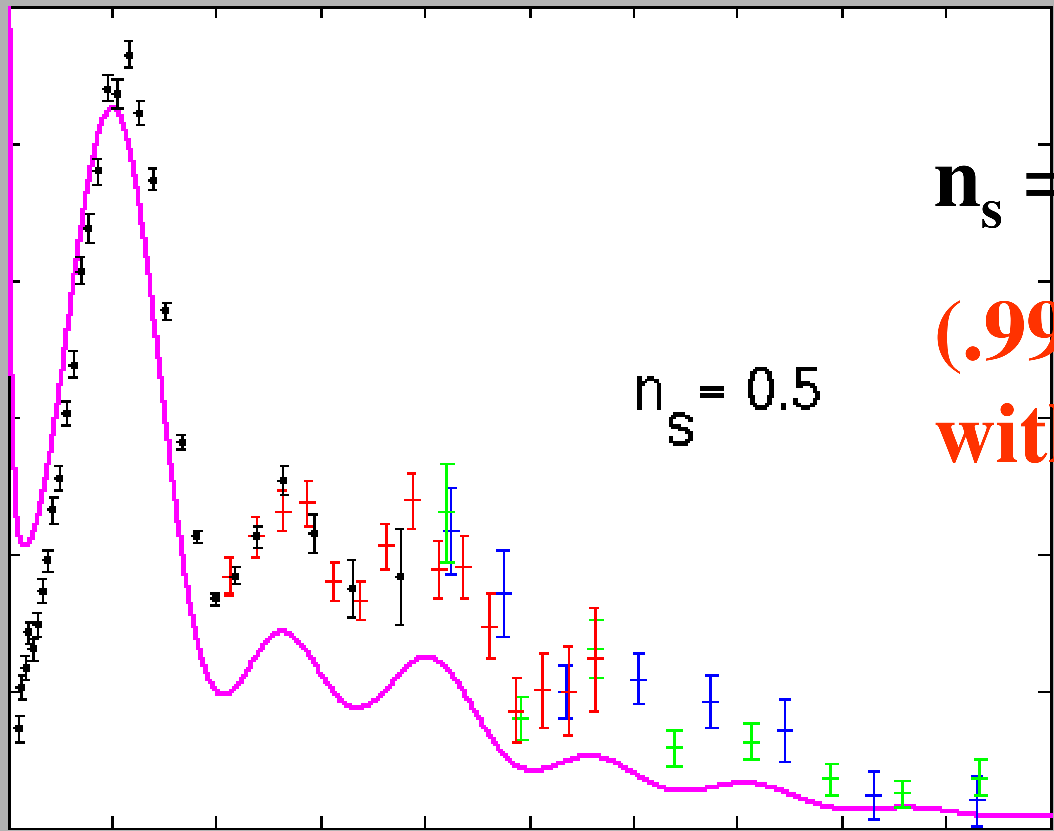
Some Parameters: Initial Fluctuation Shape

What did things look like in the beginning? Inflation predicts that amplitude at the start looks like λ^4. We call a remapping of this parameter n_s, and expect it to be 1 if inflation happened.



How Constrained are Things?

Initial spectrum (from inflation?): 0.95±0.02, just like inflation predicts. Stephen Hawking: "the discovery of the century, if not of all time."

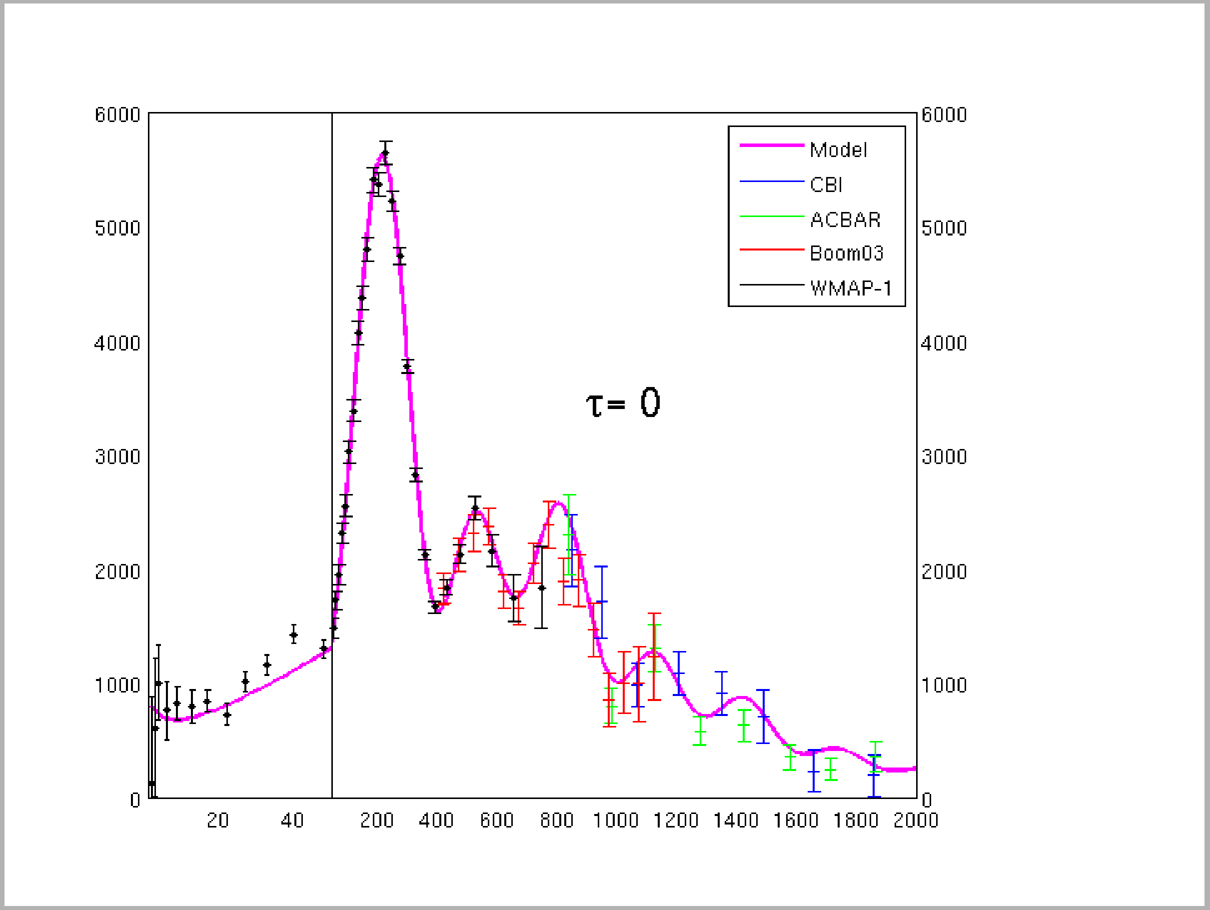


n_s = .95 +- .015

(.99 +.02 -.04 with tensor)

Inflation story looks good. But we still don't know when it happened (or at what energy). Our best hope is through measurements of the polarized CMB. Very difficult – signal is (maybe) few hundred nK.

Compton depth of universe due to re-ionization of hydrogen after stars/quasars turn on.



τ_C = **.087 +- .03**

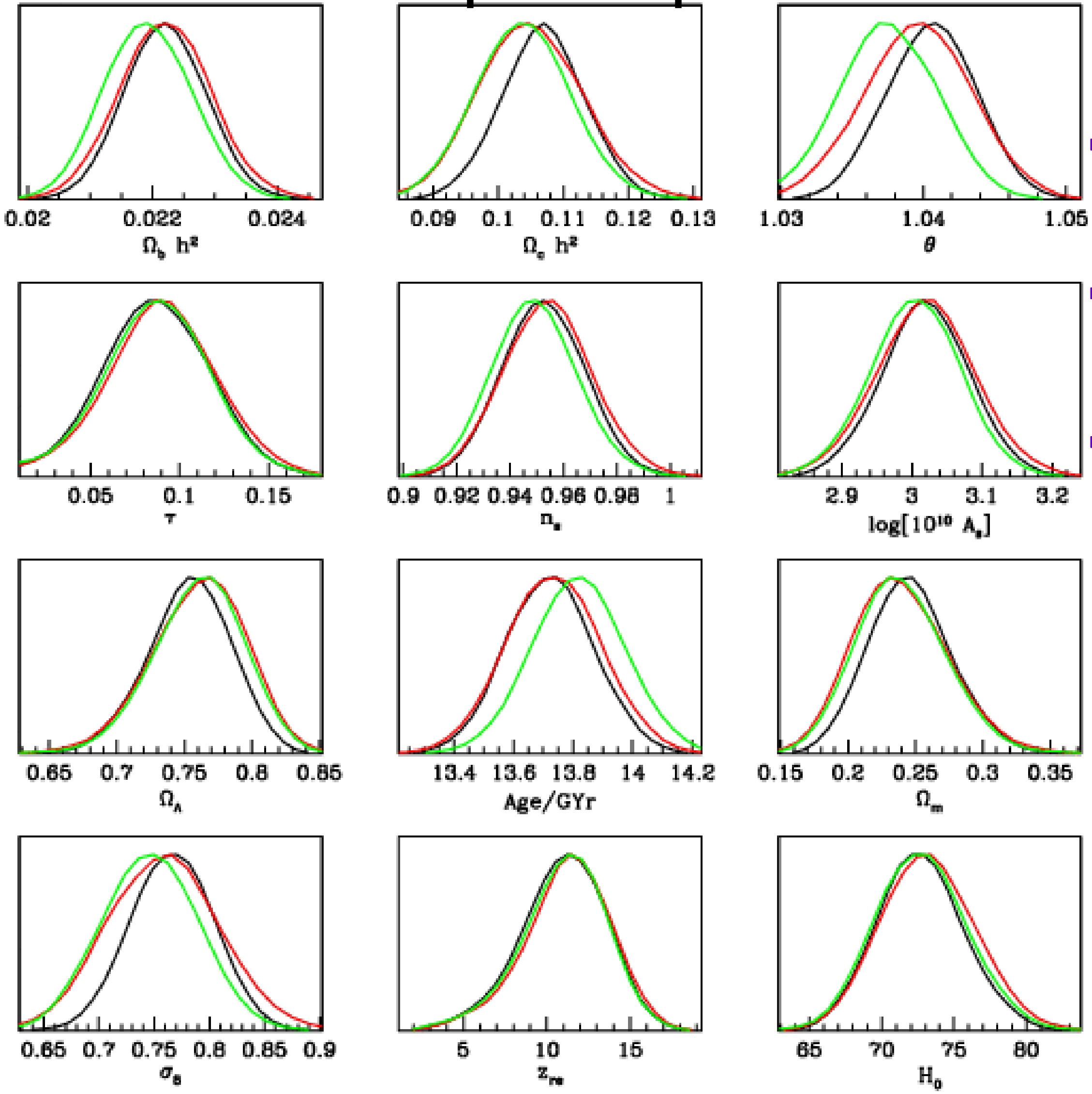
(.005 PL1)

z_{reh} = **11 +- 3**

The Parameters of Cosmic Structure Formation

WMAP3 WMAP3+CBIcombinedTT+CBIpol

CMBall = Boom03pol+DASIpol +VSA+Maxima+WMAP3+CBIcombinedTT+CBIpol



$\Omega_b h^2$ = .0222 +- .0007

$\Omega_c h^2$ = .107 +- .007

Ω_Λ = .75 +- .03

τ_C = .087 +- .03

z_{reh} = 11 +- 3

Ω_k = -.02 +- .02 +HST

The Parameters of Cosmic Structure Formation pre-WMAP3

$\Omega_b h^2 = .0227$ +- .0008 (.0002 PL1)

$\Omega_c h^2 = .126$ +- .007 (.0015 PL1)

$\Omega_\nu h^2 = \Sigma m/94$ ev < .1 if equal mass

(m < 0.4 ev, + bias info < 0.16 ev
Boom03, + Lya < 0.18 ev

cf. 3 ev H^3 $\Delta m^2 \sim 8\times10^{-5}, \sim 2.5\times10^{-3}$)

$\Omega_k = -.03$ +- .02

$\Omega_\Lambda = .70$ +- .03

($w_Q < -0.75$ 95%; .94 +- .10 incl SN)

$\Omega_{er} h^2 = 1.68\ \Omega_\gamma h^2$
+ =4.1x 10^{-5}

$\tau_C = .11$ +- .05
(.005 PL1)

derived

$\sigma_8 = .85$ +- .05

h = .70 +- .03

$\Omega_m = .30$ +- .03

$\Omega_b = .045$ +-

$z_{reh} = 13$ +- 4

The Parameters of Cosmic Structure Formation post-WMAP3

$\Omega_b h^2$ = .0222 +- .0007

$\Omega_c h^2$ = .107 +- .007

$\Omega_\nu h^2 = \Sigma m/94$ ev < .1 if equal mass

(m < + bias info < 0.23 ev

cf. 3 ev H^3 $\Delta m^2 \sim 8\times10^{-5}$,$\sim 2.5\times10^{-3}$)

Ω_k = -.02 +- .02 (+HST)

Ω_Λ = .75 +- .03

(w_Q < -0.83 95%; .97 +- .09 incl SN)

$\Omega_{er} h^2 = 1.68\ \Omega_\gamma h^2$
+ =4.1x 10^{-5}

τ_C = .087 +- .03
(.005 PL1)

derived

σ_8 = .77 +- .04

h = .73 +- .03

Ω_m = .25 +- .03

Ω_b = .045 +-

z_{reh} = 11 +- 3

The Parameters of Cosmic Structure Formation pre-WMAP3

Cosmic Numerology pre-WMAP3: **CMBall + LSS**, stable & consistent pre-WMAP1 & post-WMAP1 (BCP03), Jun03 data (BCLP04), CMBall+CBIpol04, **CMBall+Boom03+LSS Jul'21 05**, CMBall+Acbar Jul05

LSS=2dF, SDSS (weak lensing, cluster abundances); also HST, SN1a

$\mathbf{A_s}$ = 22 +- 3 x 10^{-10}

$\mathbf{n_s}$ = .95 +- .02 (.97 +- .02 with tensor) (+- .004 PL1)

r=A_t / A_s < 0.36 95% CL **(+- .02 PL2.5+Spider)**

$\mathbf{n_t}$ consistency relation

$\mathbf{dn_s}$ /dln k = -.07 +- .04 to -.05 +- .03 (+- .005 P1)

-.002 +- .01 (+Lya McDonald etal 04)

(A_{iso} / A_s < 0.3 large scale, < 3 small scale n_{iso} = 1.1+-.6)

The Parameters of Cosmic Structure Formation post-WMAP3

Cosmic Numerology: WMAP3+CMBallpol (incl CBITT+pol)

WMAP3 + x

A_s = 22 +- 2 x 10^{-10}

n_s = **.95 +- .015 (.99 +.02 -.04 with tensor)**

$r = A_t / A_s$ < 0.28 95% CL <.55 wmap3, **<1.5 +run**

n_t consistency relation

dn_s /dln k = **-.055 +- .025** to -.06 +- .03

-.10 +- .05 (wmap3+tensors)

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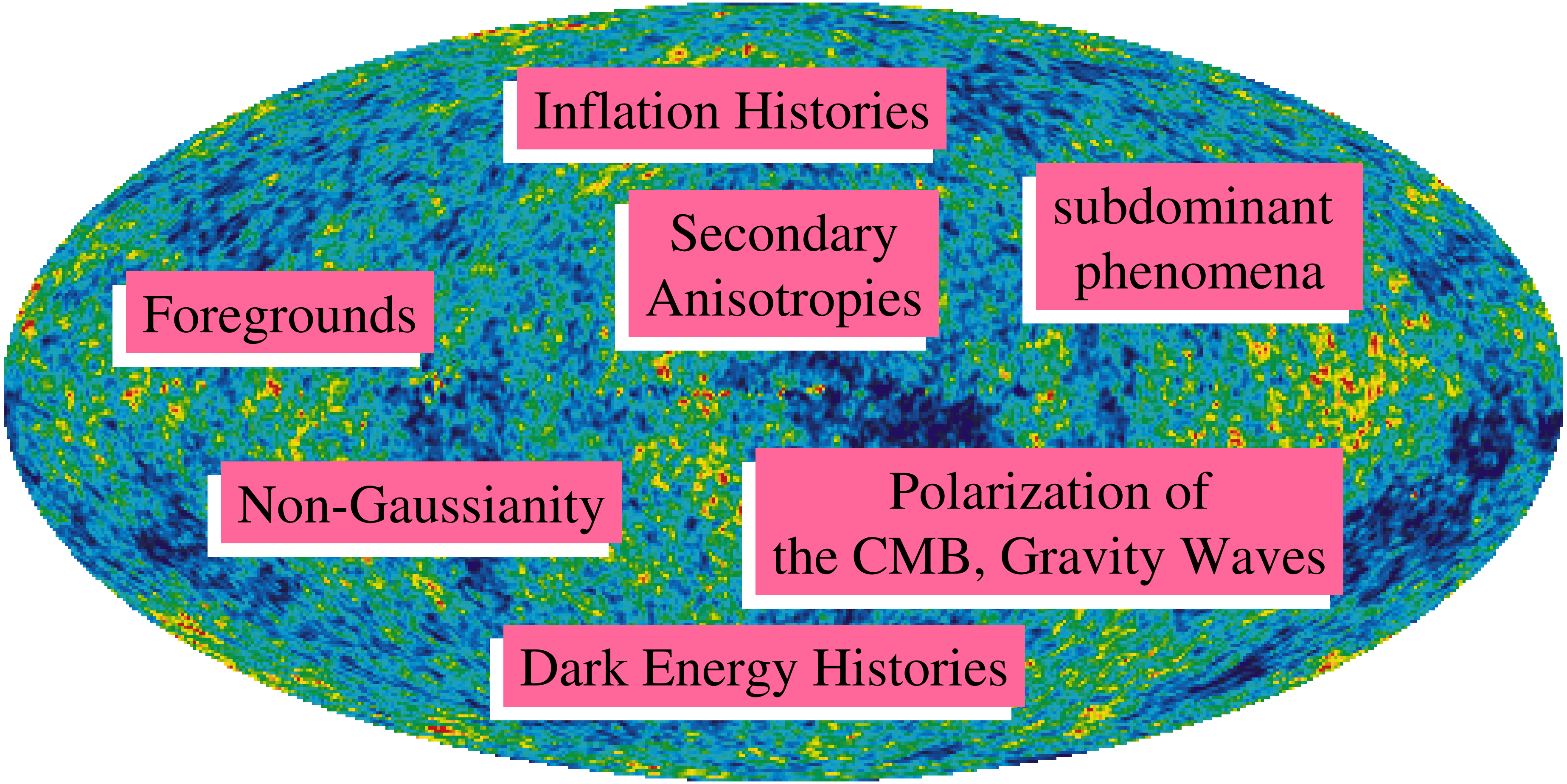
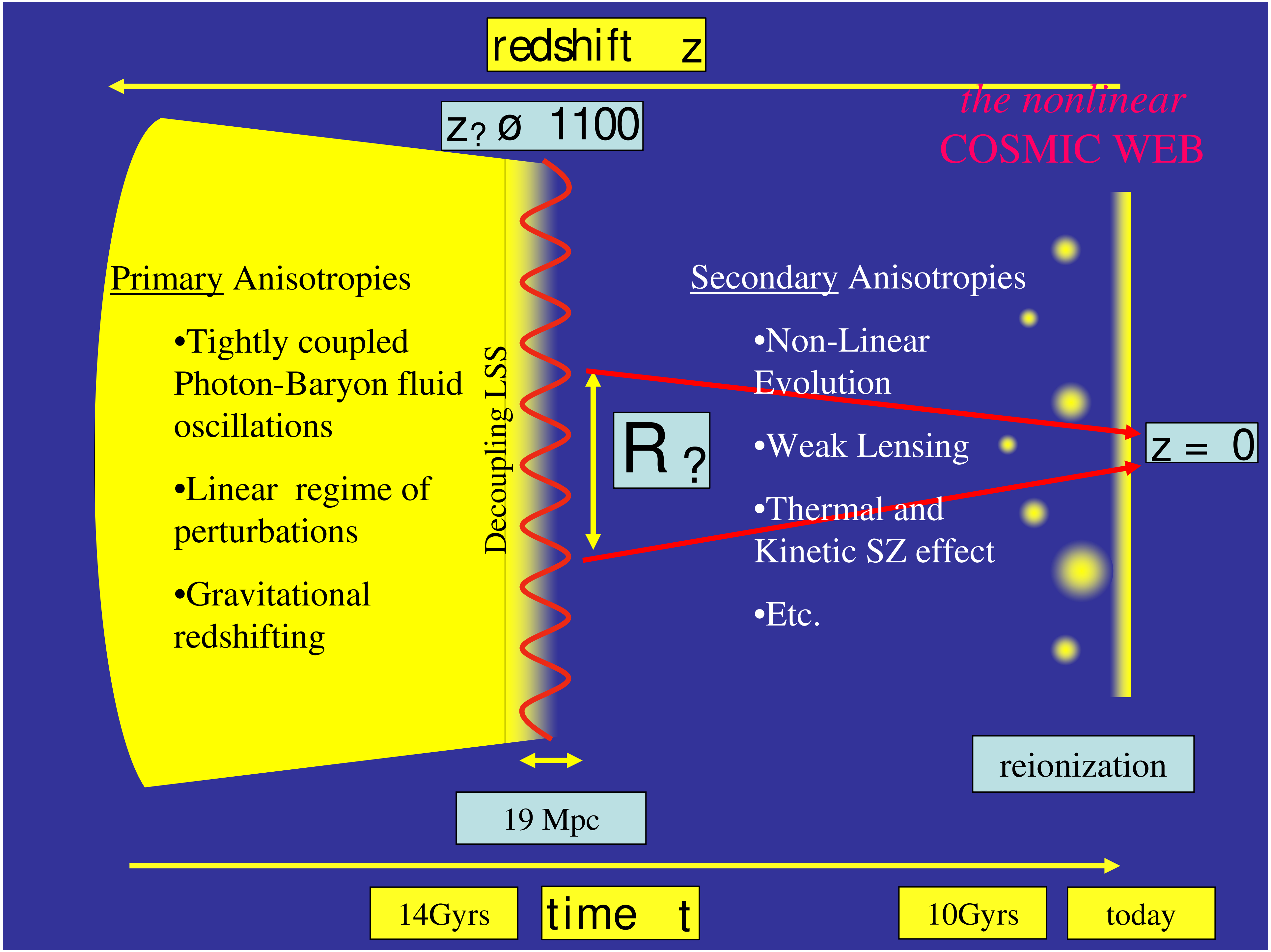
L3b: Cosmic Microwave Background Frontiers: Secondary Anisotropies & Polarization & Gravity Waves

Topics


Inflation Histories
Secondary Anisotropies
subdominant phenomena
Foregrounds
Non-Gaussianity
Polarization of the CMB, Gravity Waves
Dark Energy Histories



redshift z
z ? ø 1100
the nonlinear
COSMIC WEB
Primary Anisotropies
•Tightly coupled Photon-Baryon fluid oscillations
•Linear regime of perturbations
•Gravitational redshifting
Decoupling LSS
R ?
Secondary Anisotropies
•Non-Linear Evolution
•Weak Lensing
•Thermal and Kinetic SZ effect
•Etc.
z = 0
reionization
19 Mpc
14Gyrs
time t
10Gyrs
today

CBI pol to Apr'05

Bicep

Quiet2

CBI2 to Apr'07

(1000 HEMTs)

Chile

Acbar to ~Jan'06

QUaD

Quiet1

SCUBA2

(12000 bolometers)

APEX

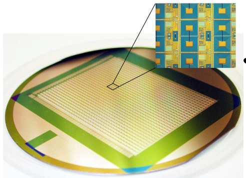
(~400 bolometers)

Chile

SZA

(Interferometer)

California



JCMT, Hawaii

Spider

(1856 bolometer LDB)

ACT

(3000 bolometers)

Chile

Clover

2017

CMBpol

Boom03

2003 2004 2005 2006 2007 2008

WMAP ongoing to 2009

SPT

(1000 bolometers)

South Pole

ALMA

(Interferometer)

Chile

Polarbear

(300 bolometers)

California

DASI

CAPMAP

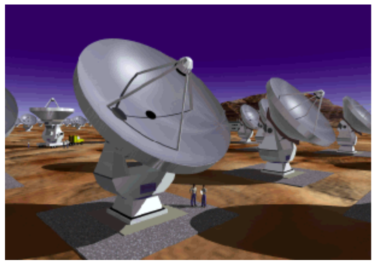
Planck

AMI

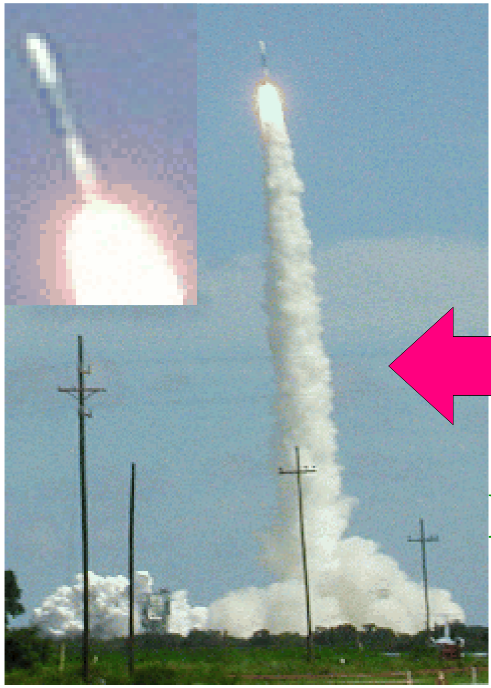
GBT

(84 bolometers)

HEMTs L2



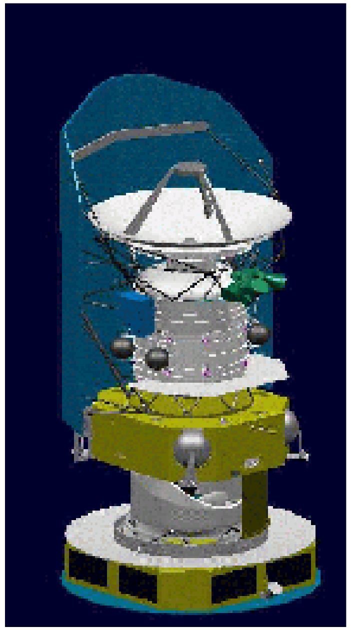
Forecasts of precision on 9 "standard model" parameters

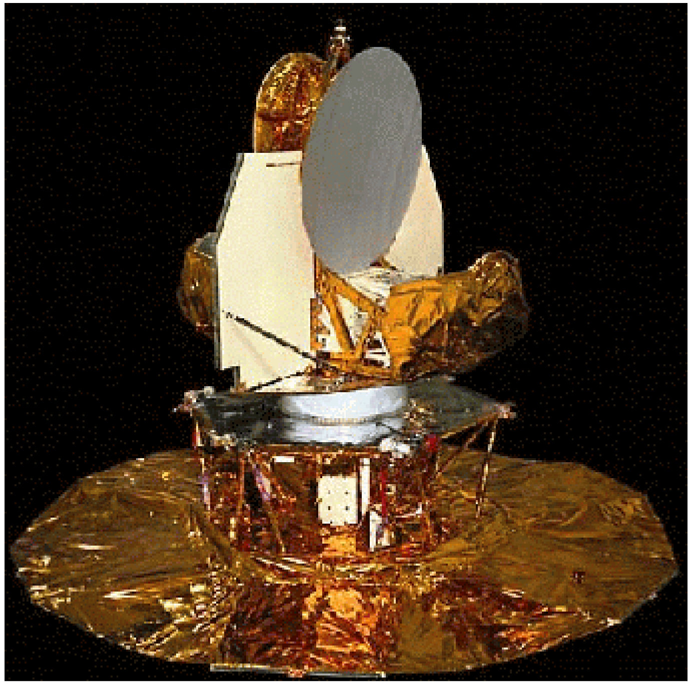


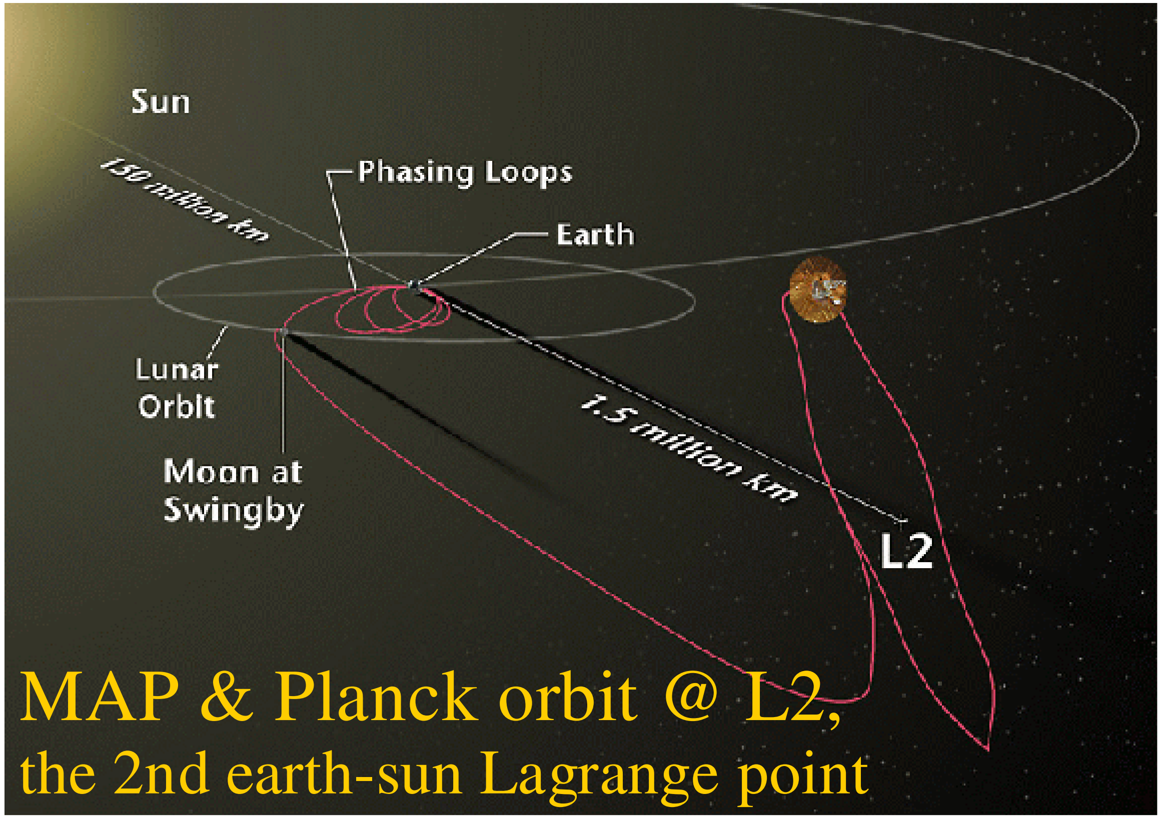
WMAP4 3/9 to ±0.01, 7/9 to ±0. 1

WMAP4+gnd 4/9 to ±0.01, 8/9±0. 1

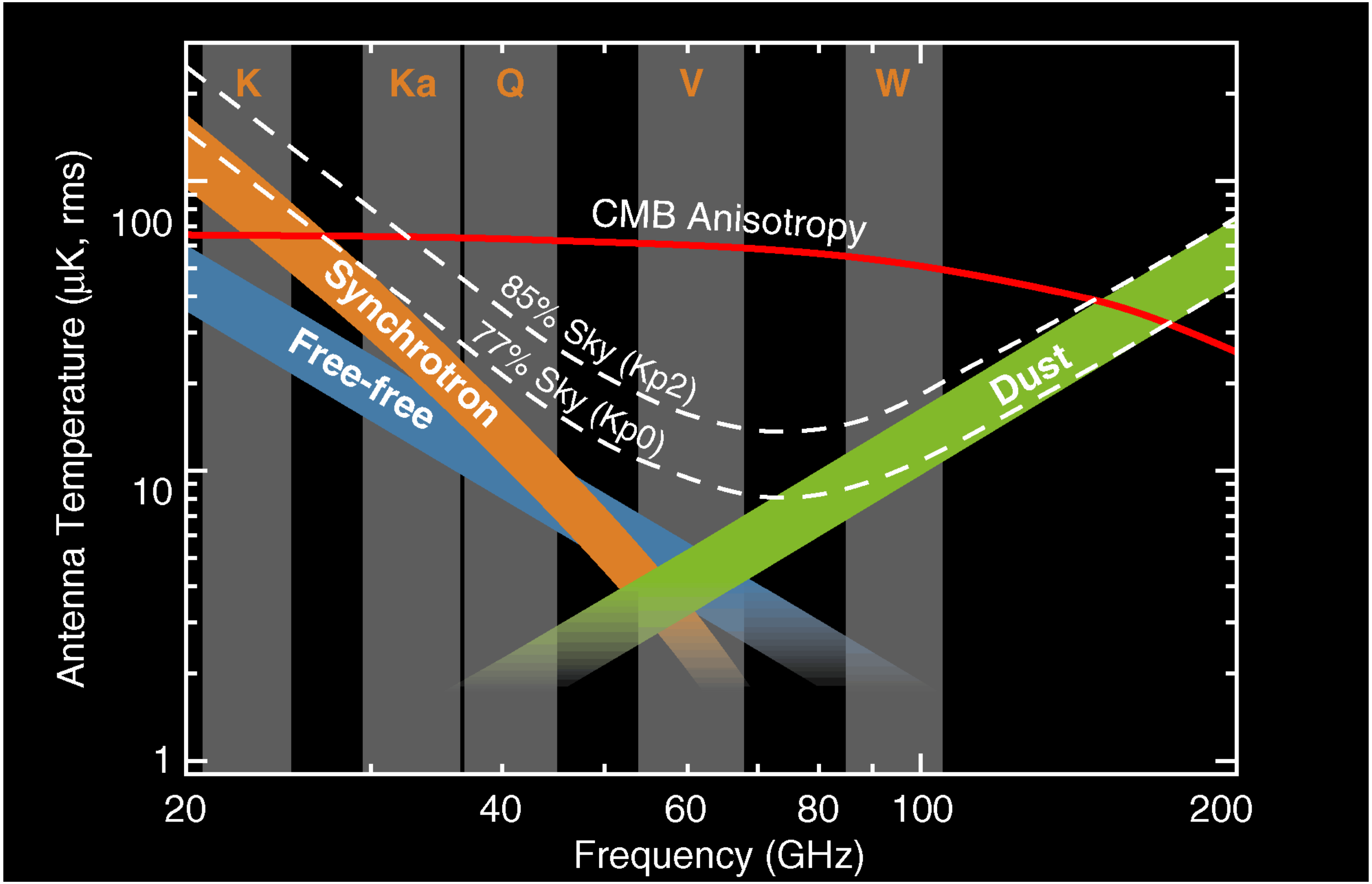
Planck1 2007+ 6/9 to ±0.01, 8/9





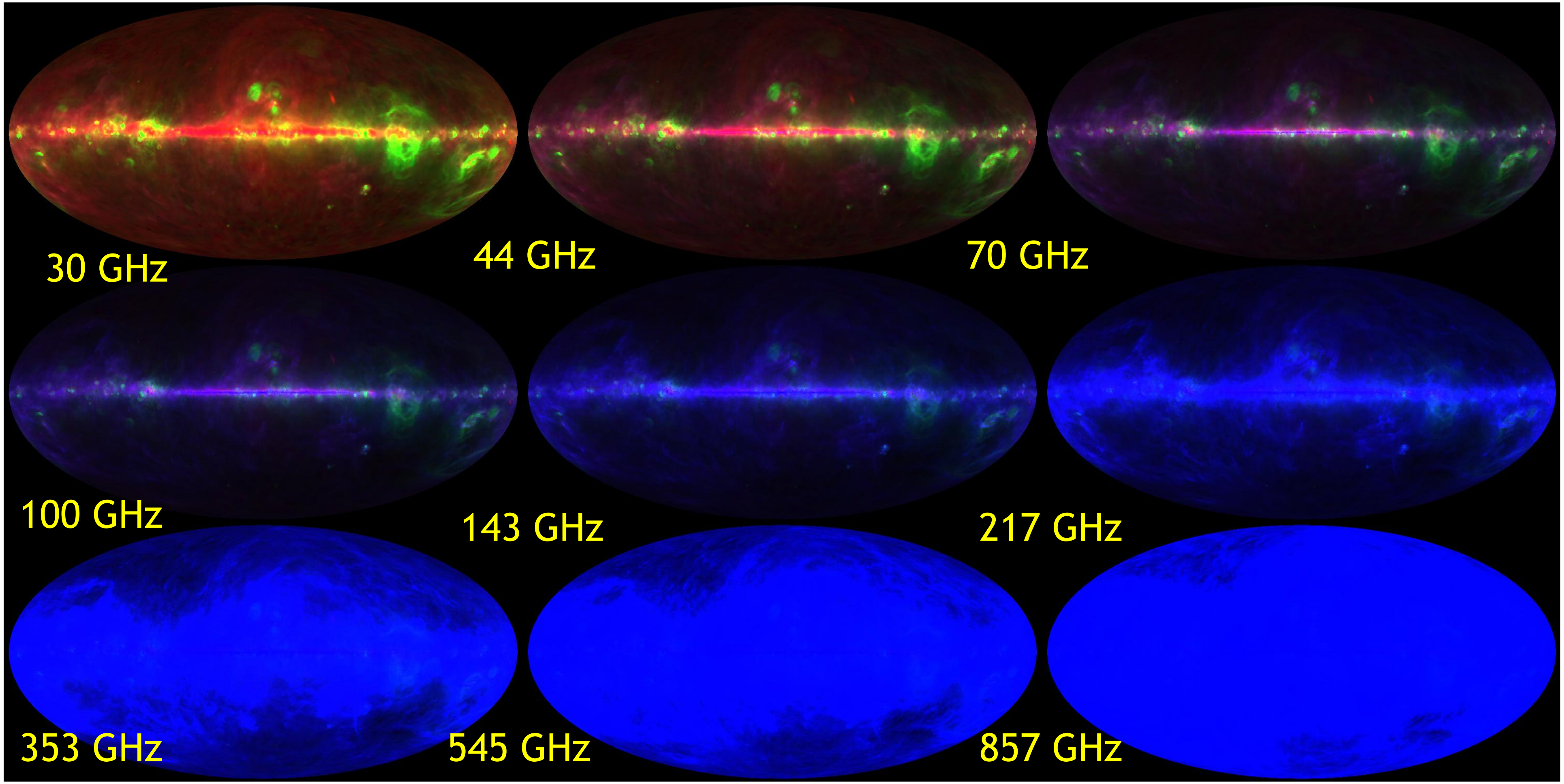


Foreground Spectra



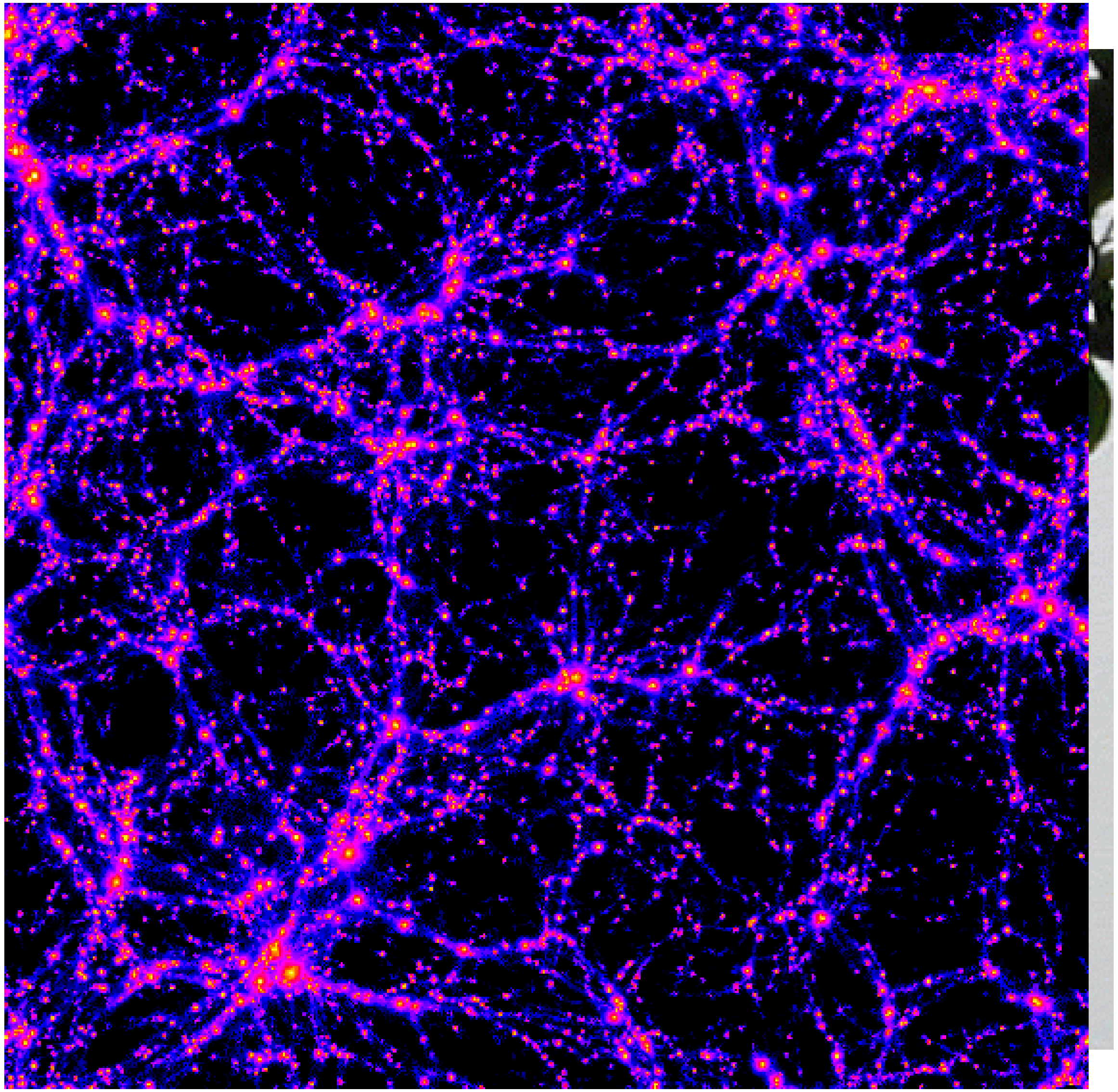
3-Colour Foregrounds

Synchrotron
Bremsstrahlung (Free-Free)
Thermal Dust

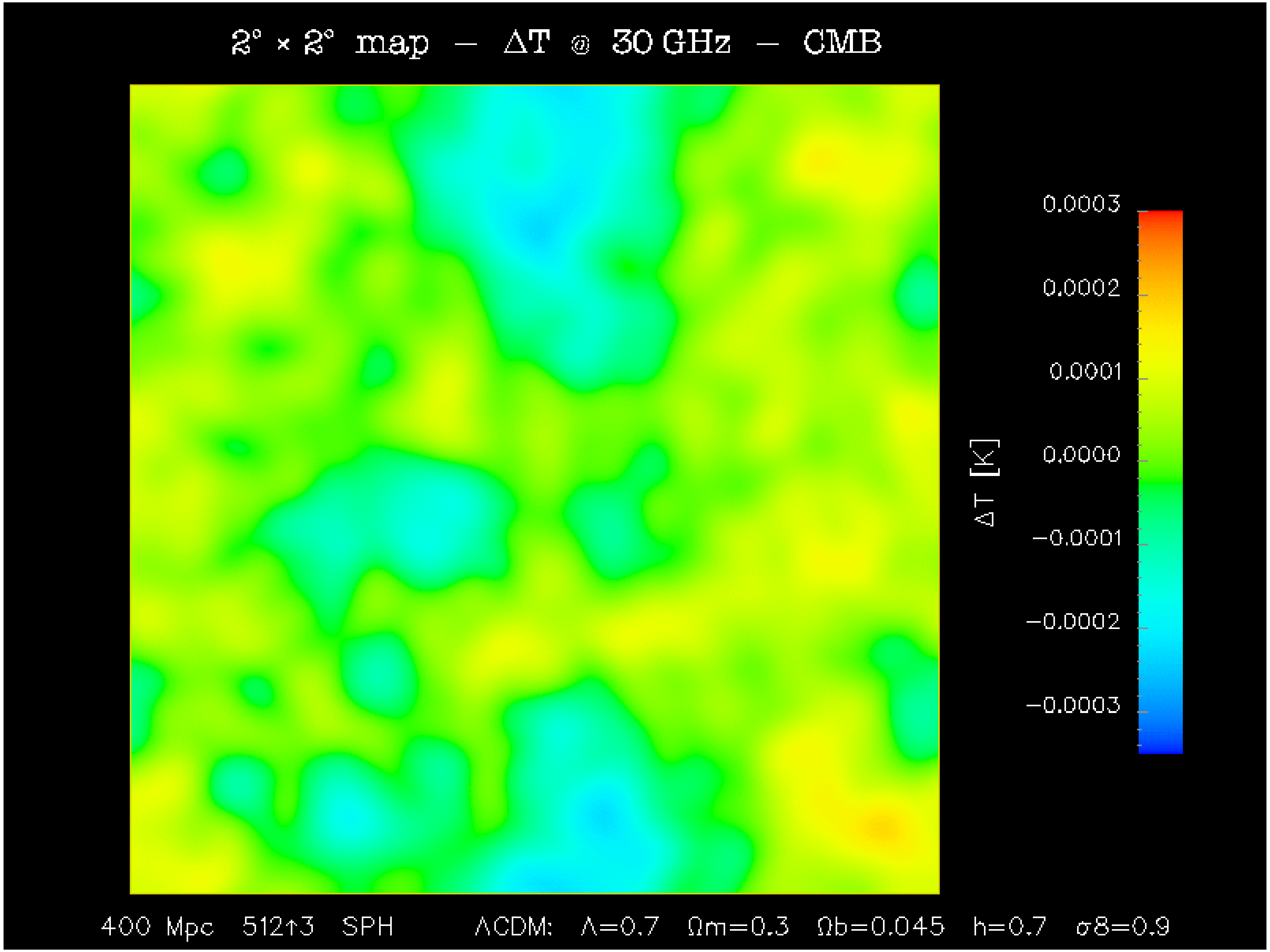


$\Delta T = \delta f / df_{cmb}/dT$ in deg K, linear in sqrt(ΔT), 1K threshold

Cosmic Web & Superclustering: a natural consequence of the gravitational instability of a hierarchical Gaussian random density field



clusters, filaments, membranes & voids



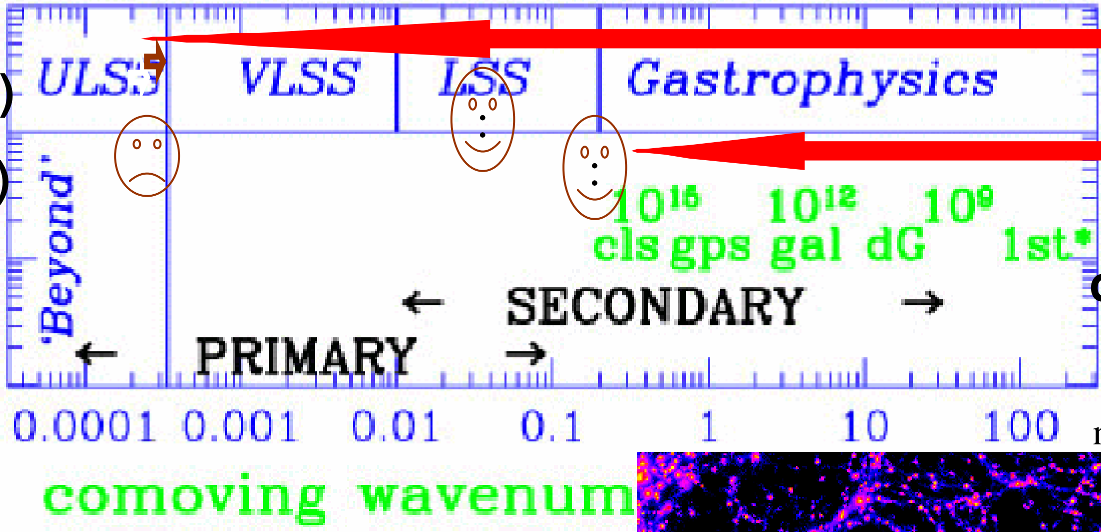
pass the CMB thru the cosmic web; CBI extra power??

resolution P(ln k)

dynamics H(ln a)

are related in inflation (HJ)

~10+ e-folds



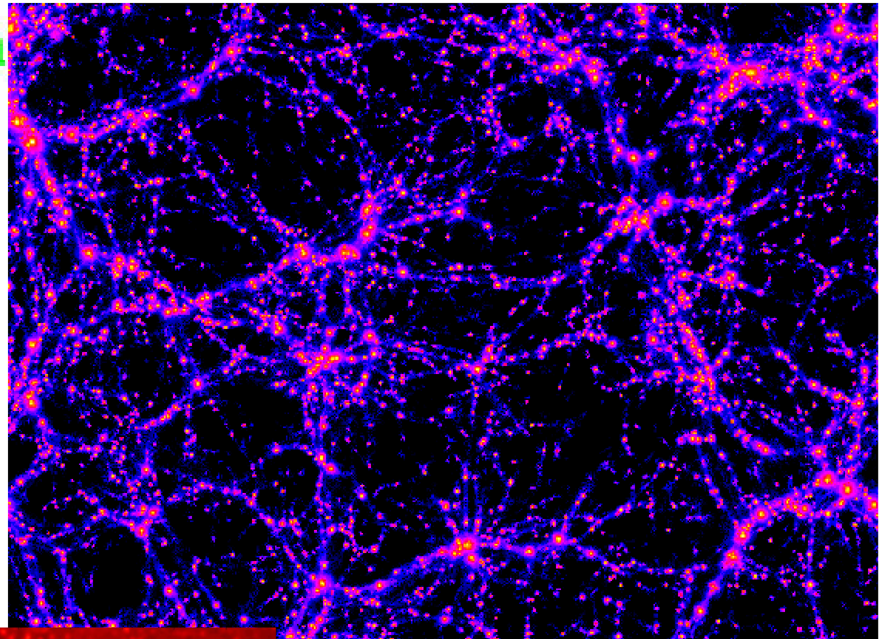
$K_{hor}(t)$=Ha

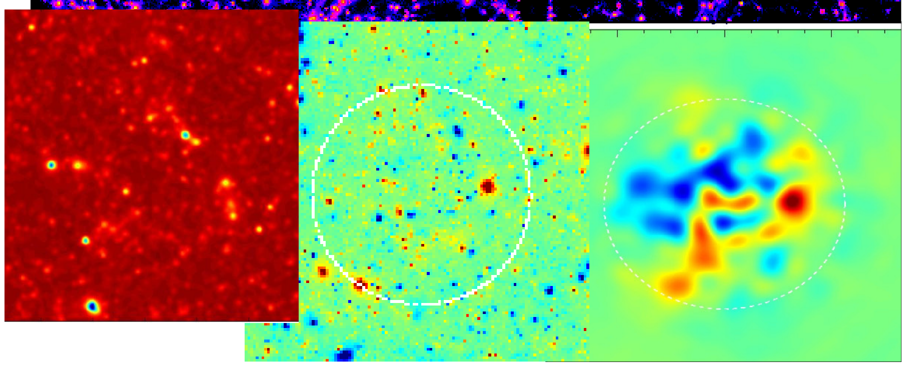
$K_{NL}(t)$

dynamics w(ln a)

~1+ e-folds

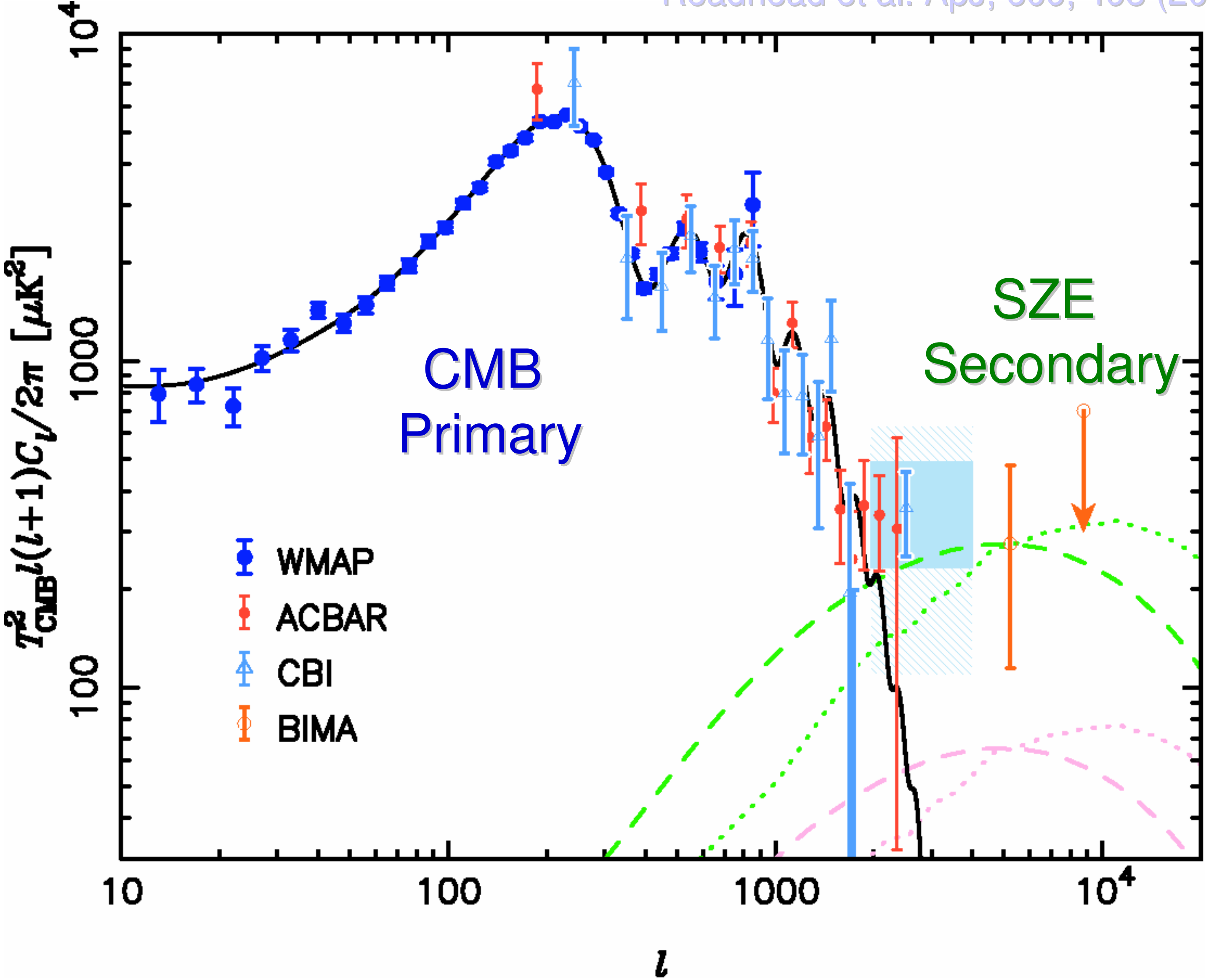
nonlinear Cosmic Web





CBI 2000+2001, WMAP, ACBAR, BIMA

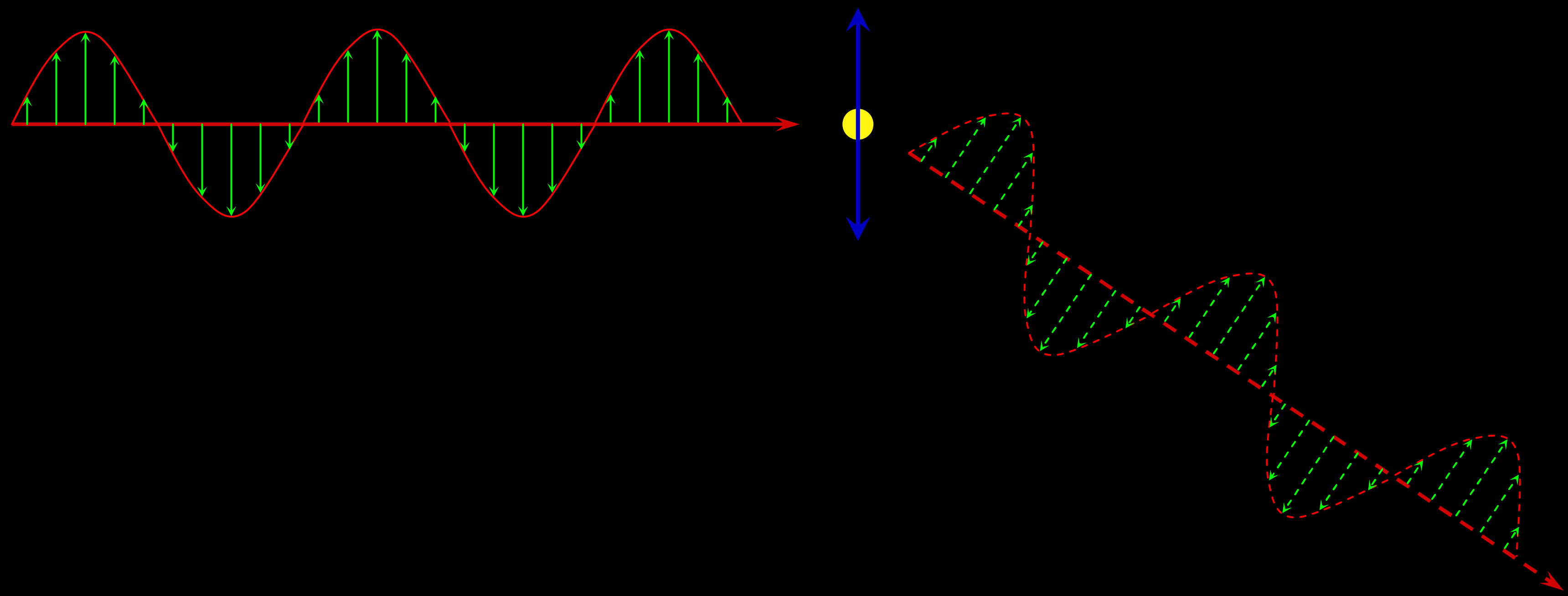
Readhead et al. ApJ, 609, 498 (2004)



+Boom03; Acbar05: very nice TT, Oct05. parameters & new excess analysis as SZ

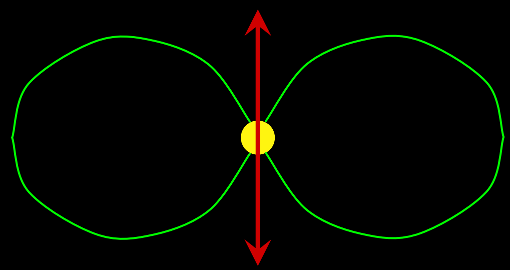
Scattering of light by electrons

1. The electric field of a light wave shakes an electron along the direction of polarization.

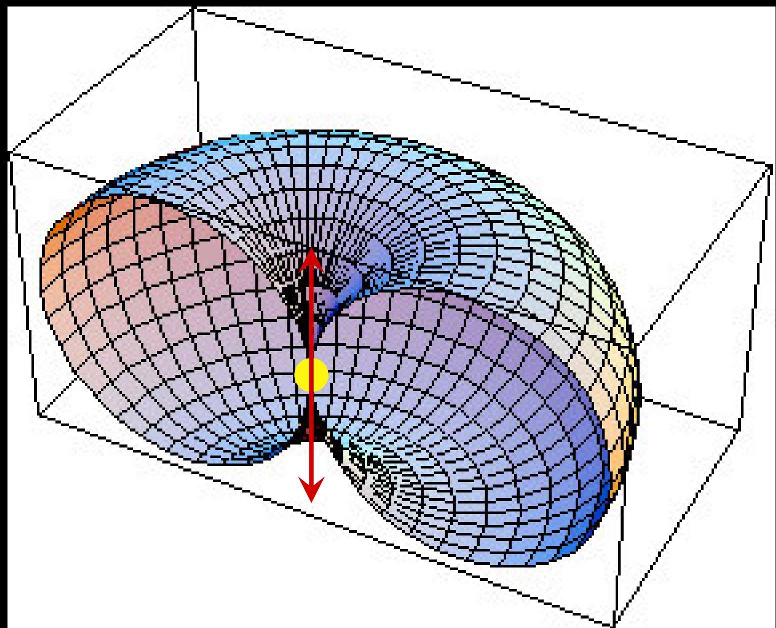


Scattering of light by electrons

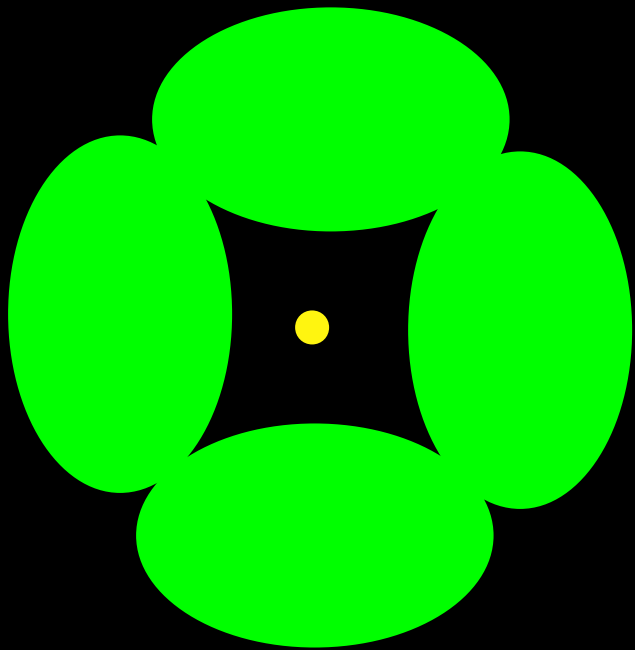
2. Light is not emitted in the direction of shaking!



Green = probability of emitting in that direction…

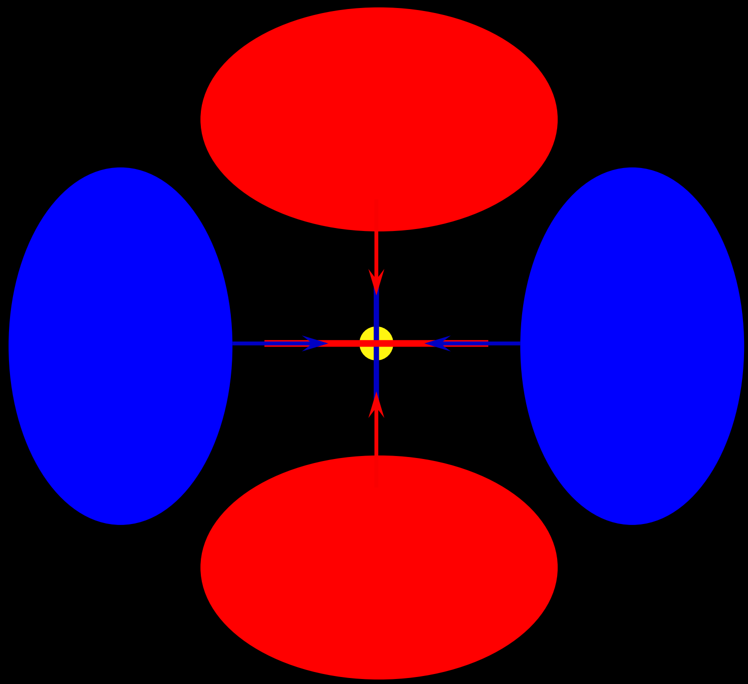


Environment around electrons at t=380,000 years leads to polarization



Uniform "glow" around electron $\Rightarrow$
"shaking" in all directions $\Rightarrow$
all polarizations emitted equally.

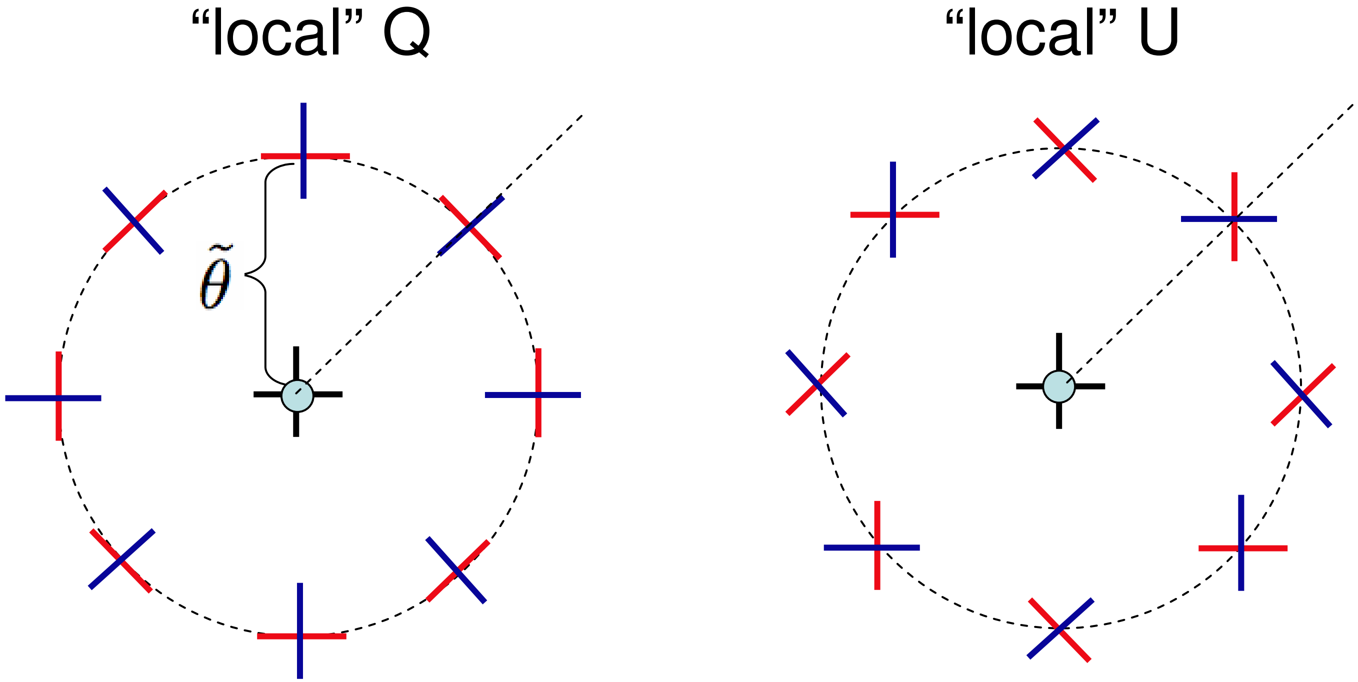
Environment around electrons at t=380,000 years leads to polarization



Non-uniform “glow” around electron ⇒
preferential “shaking” ⇒
polarized emission.

E and B mode patterns

Blue = + Red = -



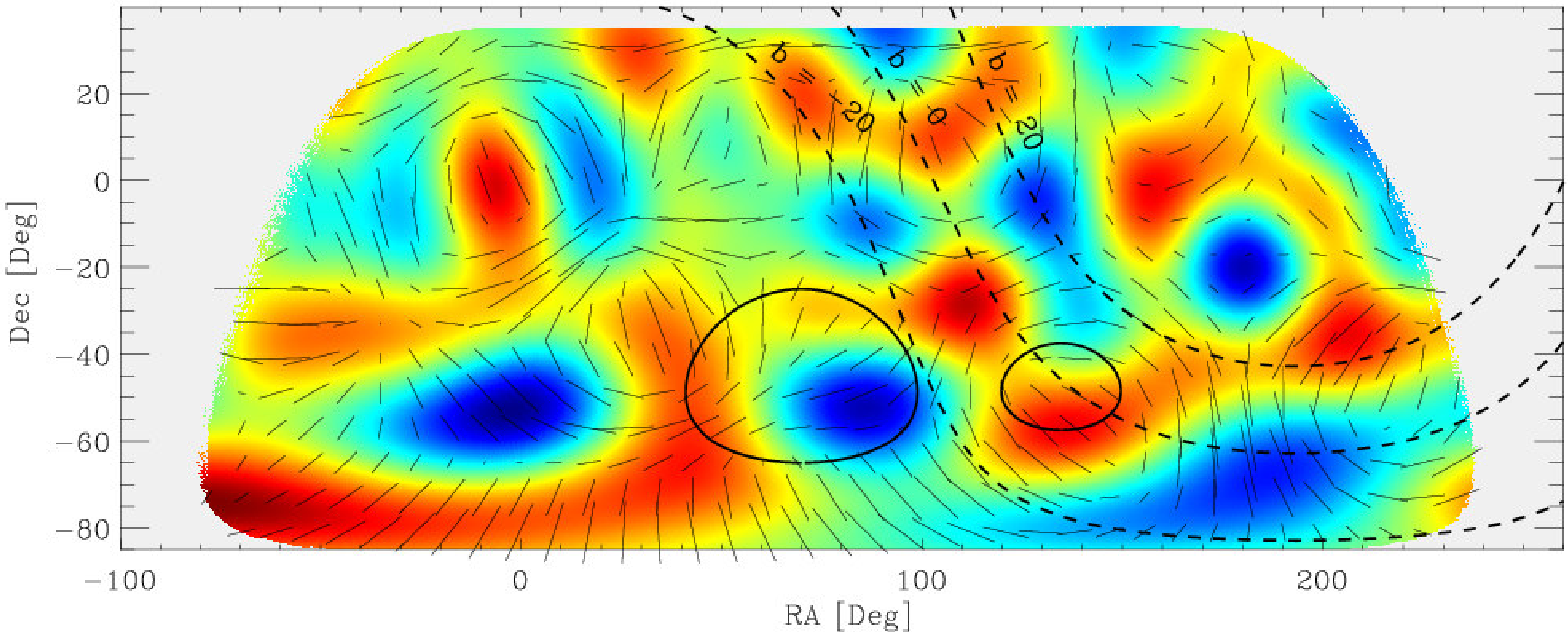
For a given circle ($\tilde{\theta}$), circumference goes as $\tilde{\theta}$, while $\omega(\tilde{\theta}) = 1/\pi\theta^2$, so the contribution of that circle goes as 1/$\tilde{\theta}$.

SPIDER Tensor Signal

- Simulation of large scale polarization signal
- This is what we are after!!

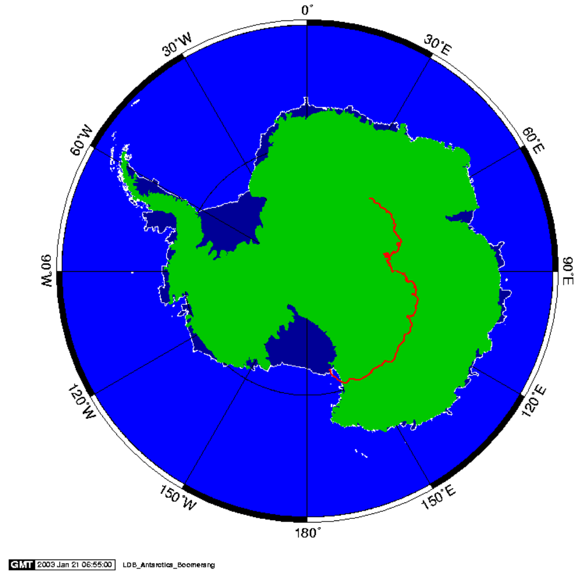
$$\frac{A_T}{A_S} = 0.1$$

Tensor



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

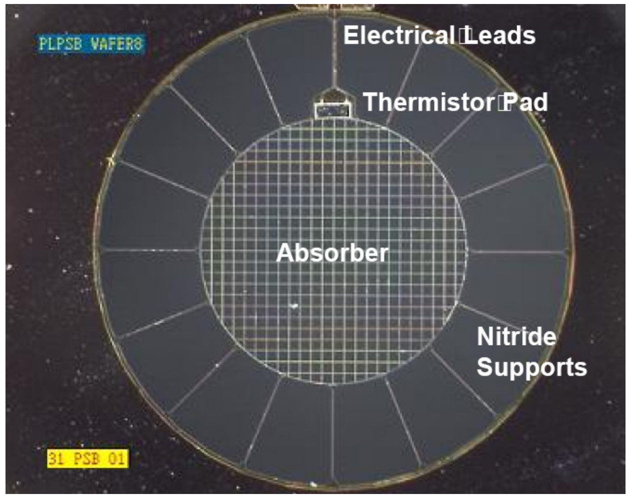
BOOMERanG '03 Flight



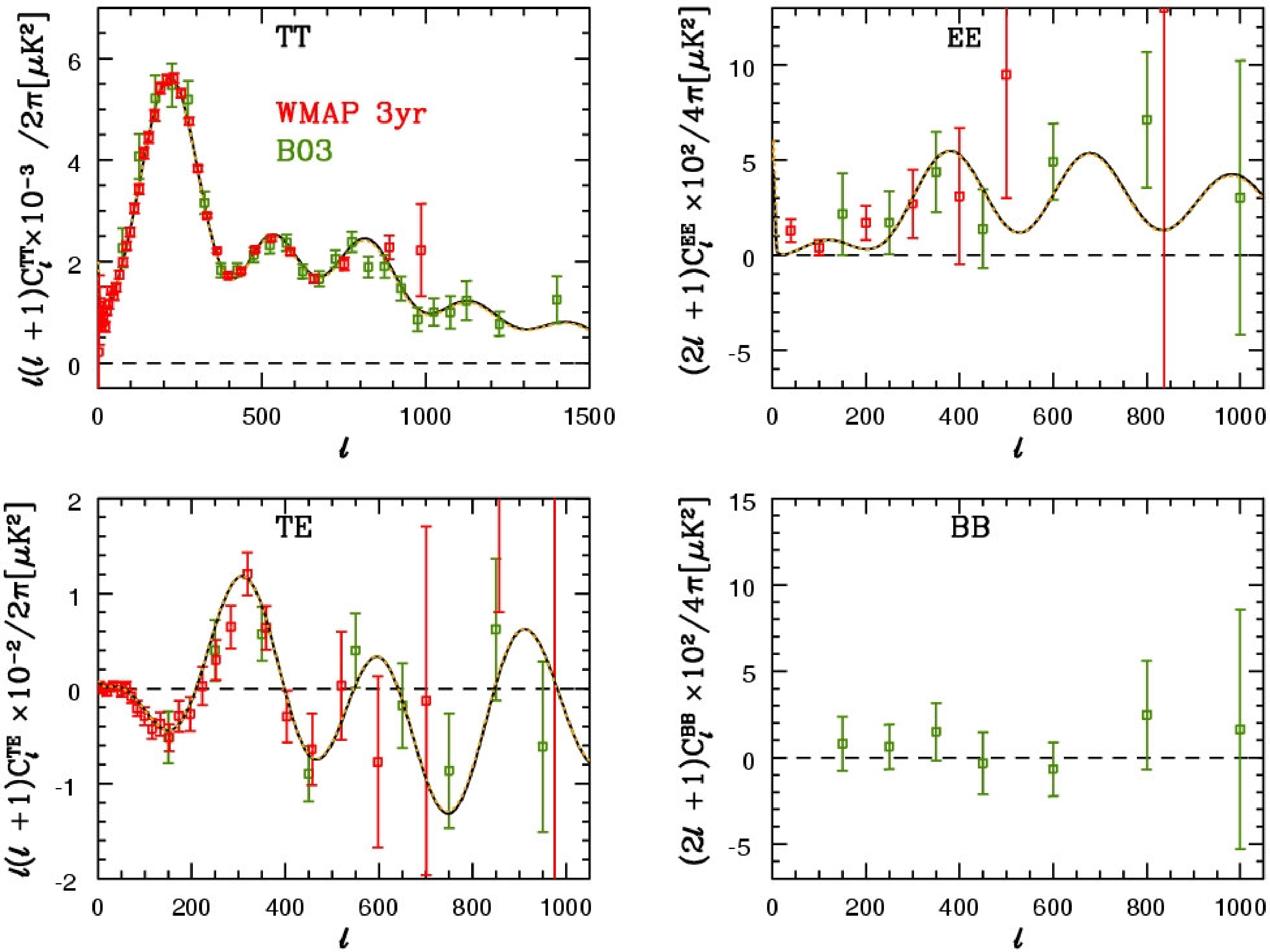
- Polarization sensitive receivers 145/245/345 GHz (PSBs - same as PLANCK detectors)

Flight January 2003

- 195 hours of science data f_{sky}= 1.8%
- First results published in July 2005
  - Masi et al. astro-ph/0507509
  - Jones et al. astro-ph/0507494
  - Piacentini et al. astro-ph/0507507
  - Montroy et al. astro-ph/0507514
  - MacTavish et al. astro-ph/0507503

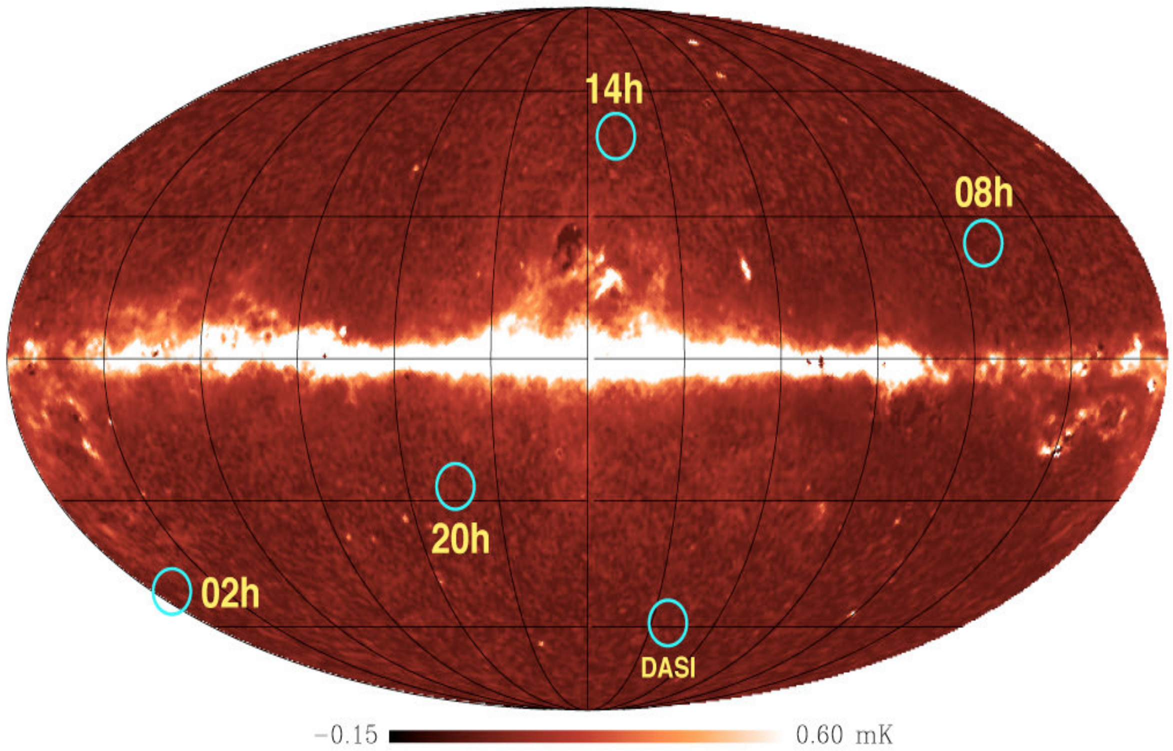


WMAP3 sees 3rd pk, B03 sees 4th

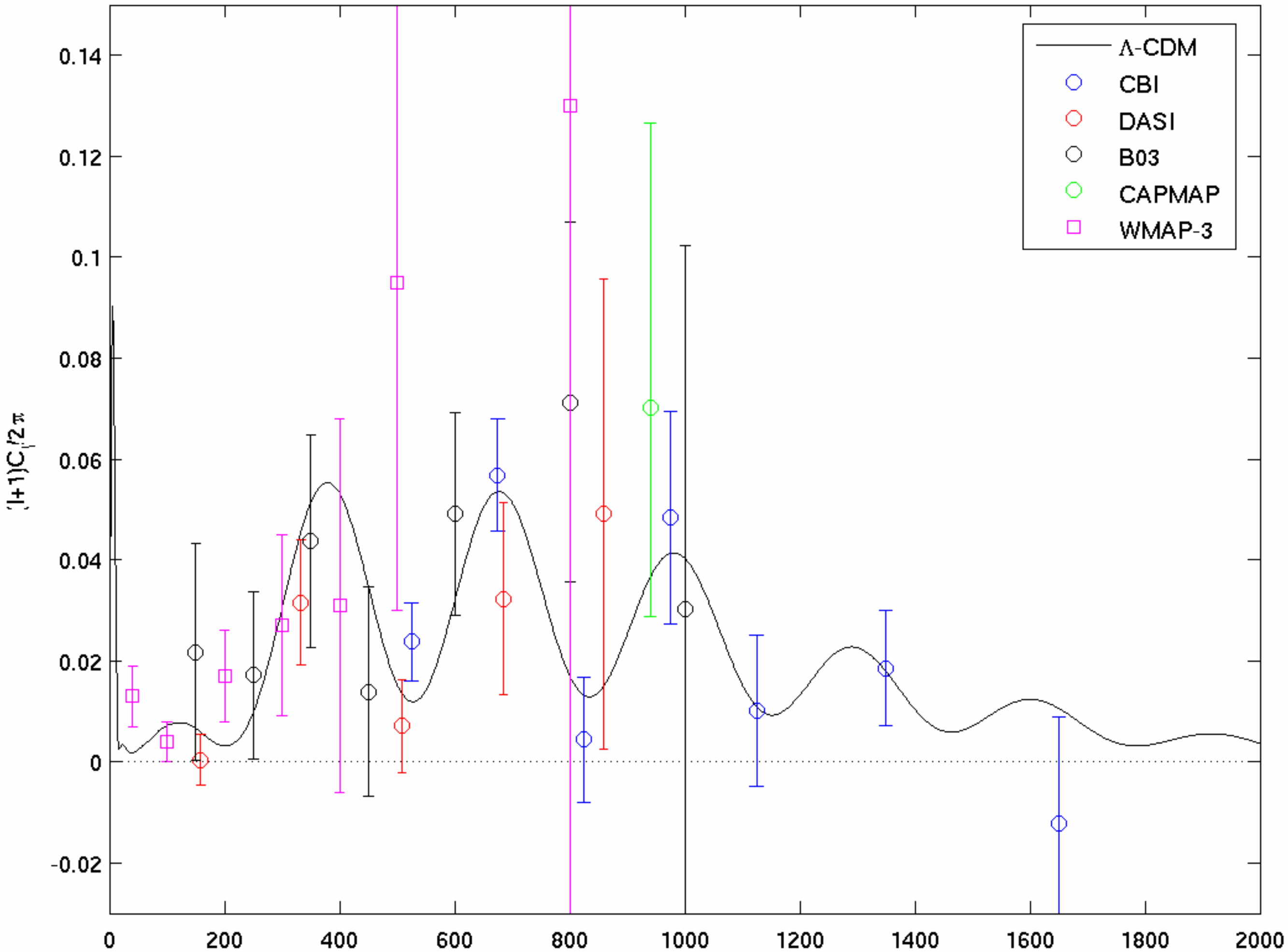


CBI Dataset

- CBI observes 4 patches of sky – 3 mosaics & 1 deep strip
- Pointings in each area separated by 45'. Mosaic 6x6 pointings, for 4.5^{o2}, deep strip 6x1.
- Lose 1 mode per strip to ground.
- 2.5 years of data, Aug 02 – Apr 05.



Polarization EE: WMAP3 sees 1st pk, part of 2nd, DASI sees 2nd pk, B03 sees 2nd and 3rd , CBI sees 3rd, 4th, 5th

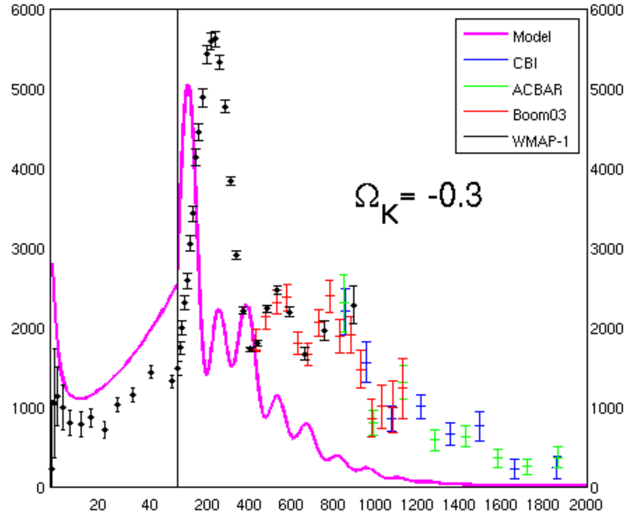


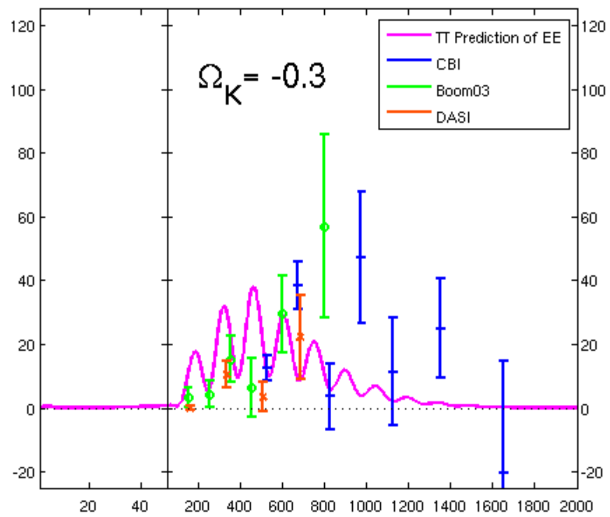
[Sievers et al. astro-ph/0509203]

[Montroy et al. astro-ph/0509203]

[Readhead et al. astro-ph/0409569]

Does TT Predict EE? (incl wmap3 TT data) YES





Take the same TT curvature plot and then show its EE spectrum against the data. There are 0 free parameters in the EE model yet it agrees extremely well with the data. EE-only measures the angular scale of the CMB to 3%, and gets the same answer as TT. Other parameters (dark matter, baryons...) from EE agree as well, but precision isn't great yet (~30-40% accuracies, typically).

CBI ongoing to Sept'05+

Bicep

QUaD

Quiet1

Quiet2

(1000 HEMTs)

Chile

Spider

(1856 bolometer LDB)

EBEX

ACT+

(3000 bolometers)

Chile

Clover

2017

CMBpol

Boom03

2003

2004

2005

2006

2007

2008

WMAP ongoing to 2009

DASI

CAPMAP

Polarbear

(300 bolometers)

California

SPT+

(1000 bolometers)

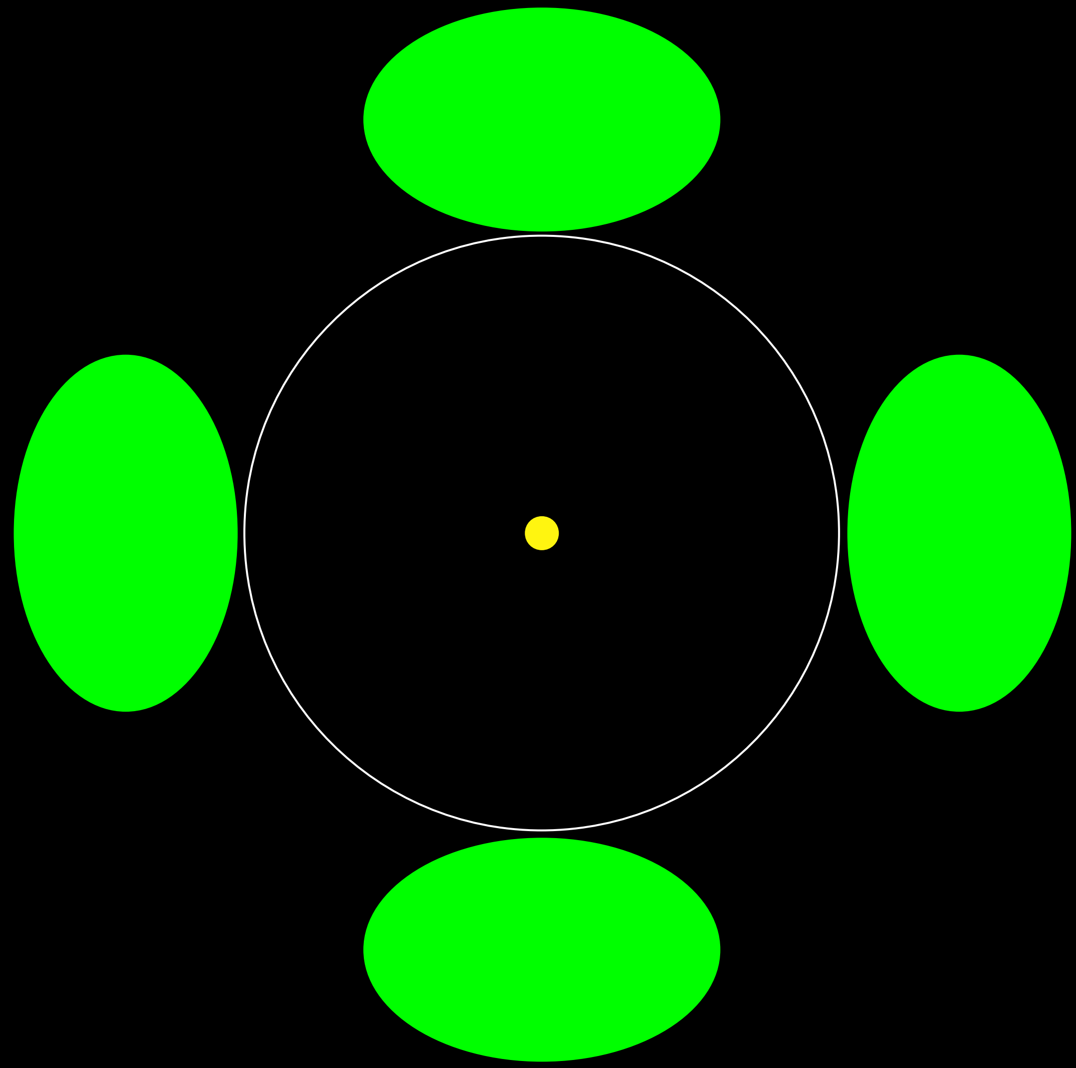
South Pole

Planck

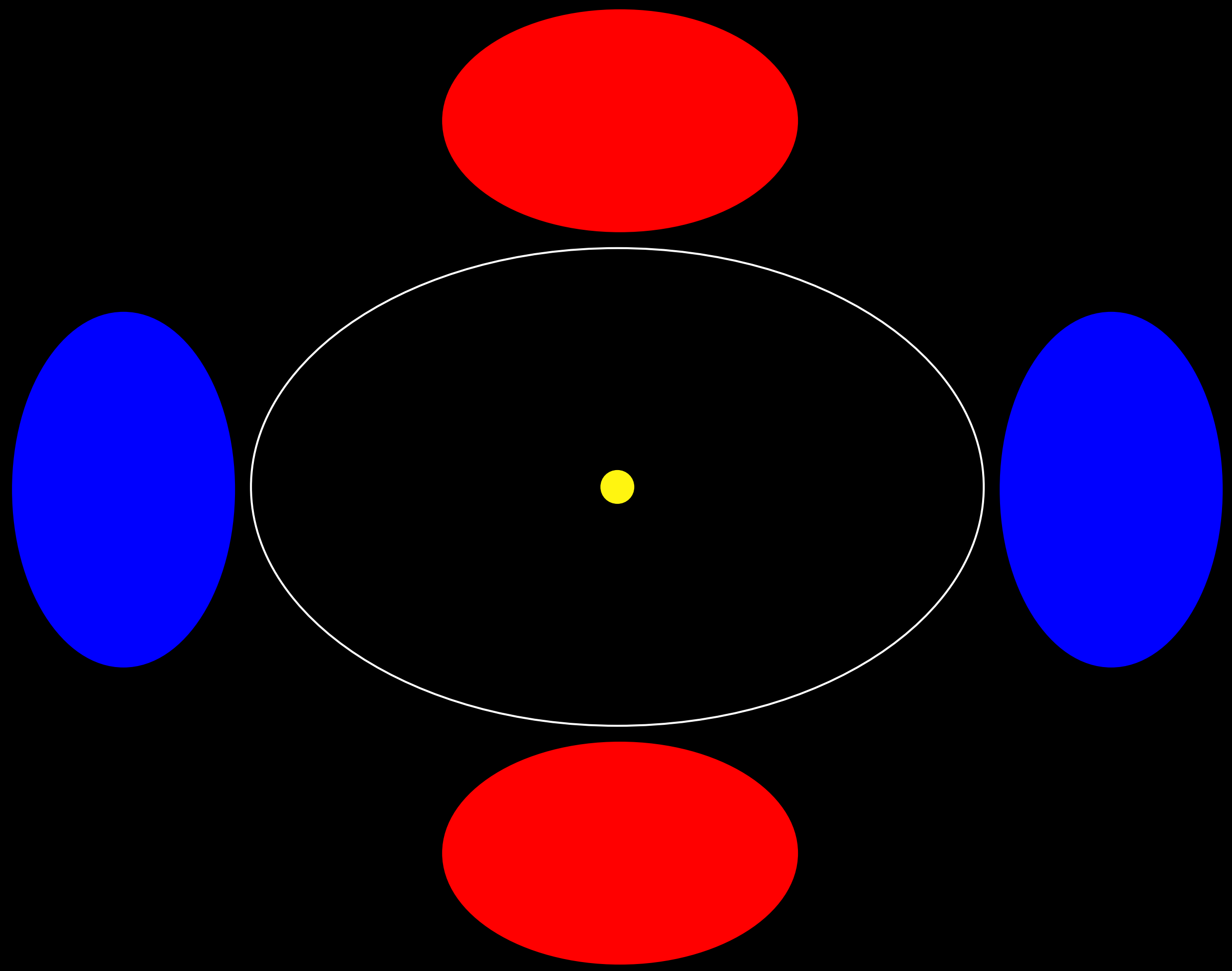
(84 bolometers)

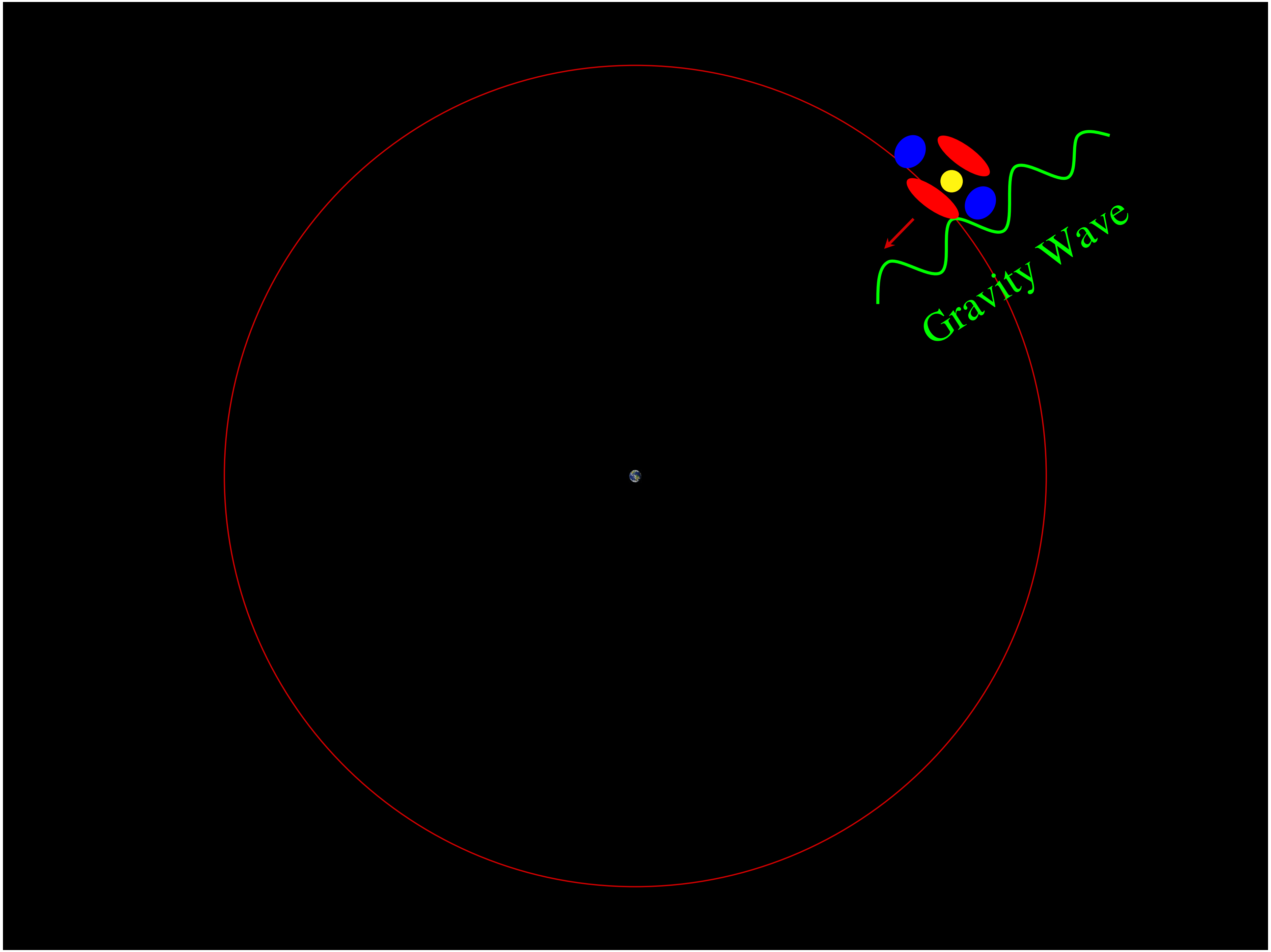
HEMTs L2

Gravity waves stretch space…



… and create variations



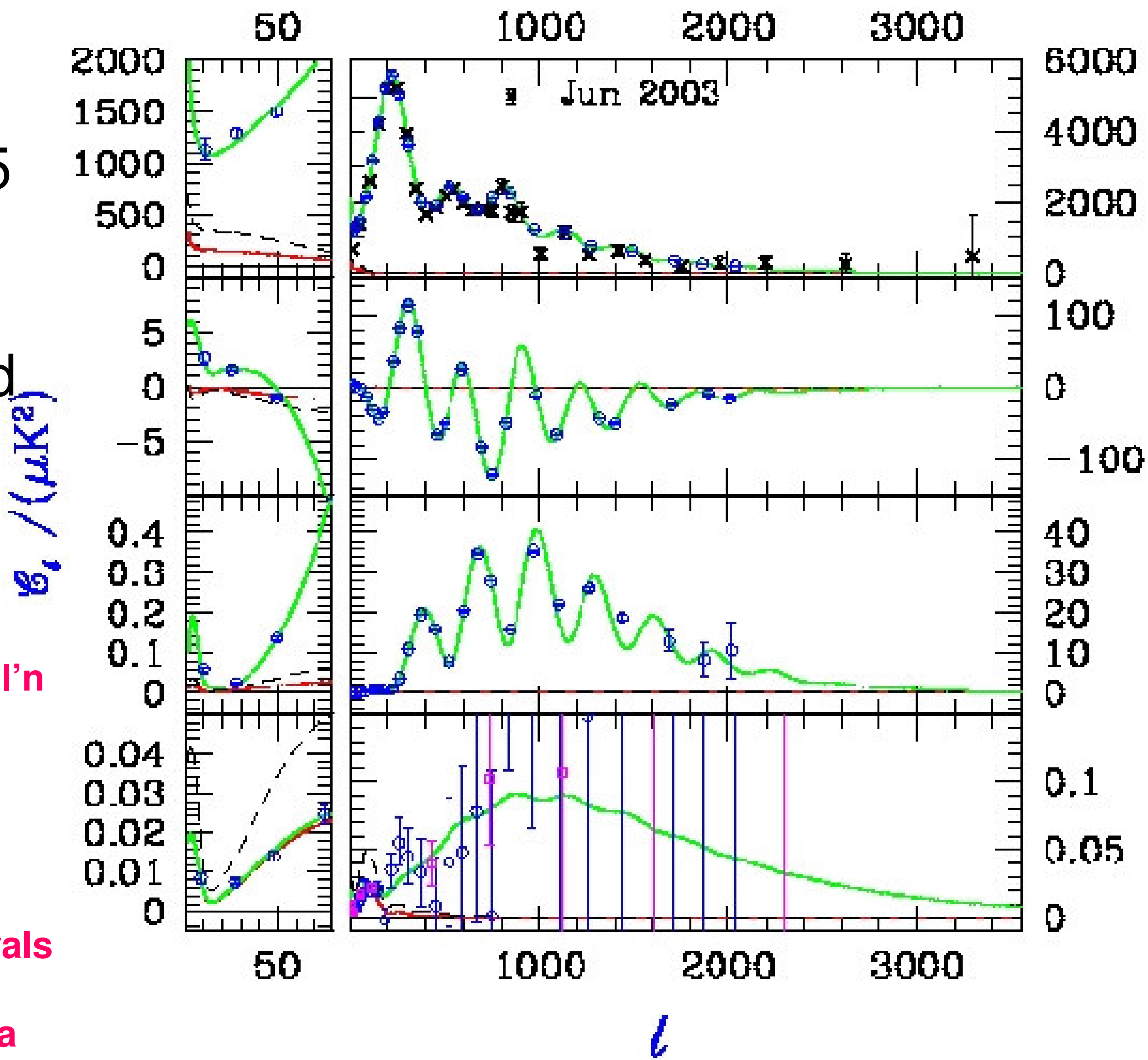

Gravity Wave

forecast Planck2.5

100&143

Spider10d

95&150



Synchrotron pol'n

< .004 ??

Dust pol'n

< 0.1 ??

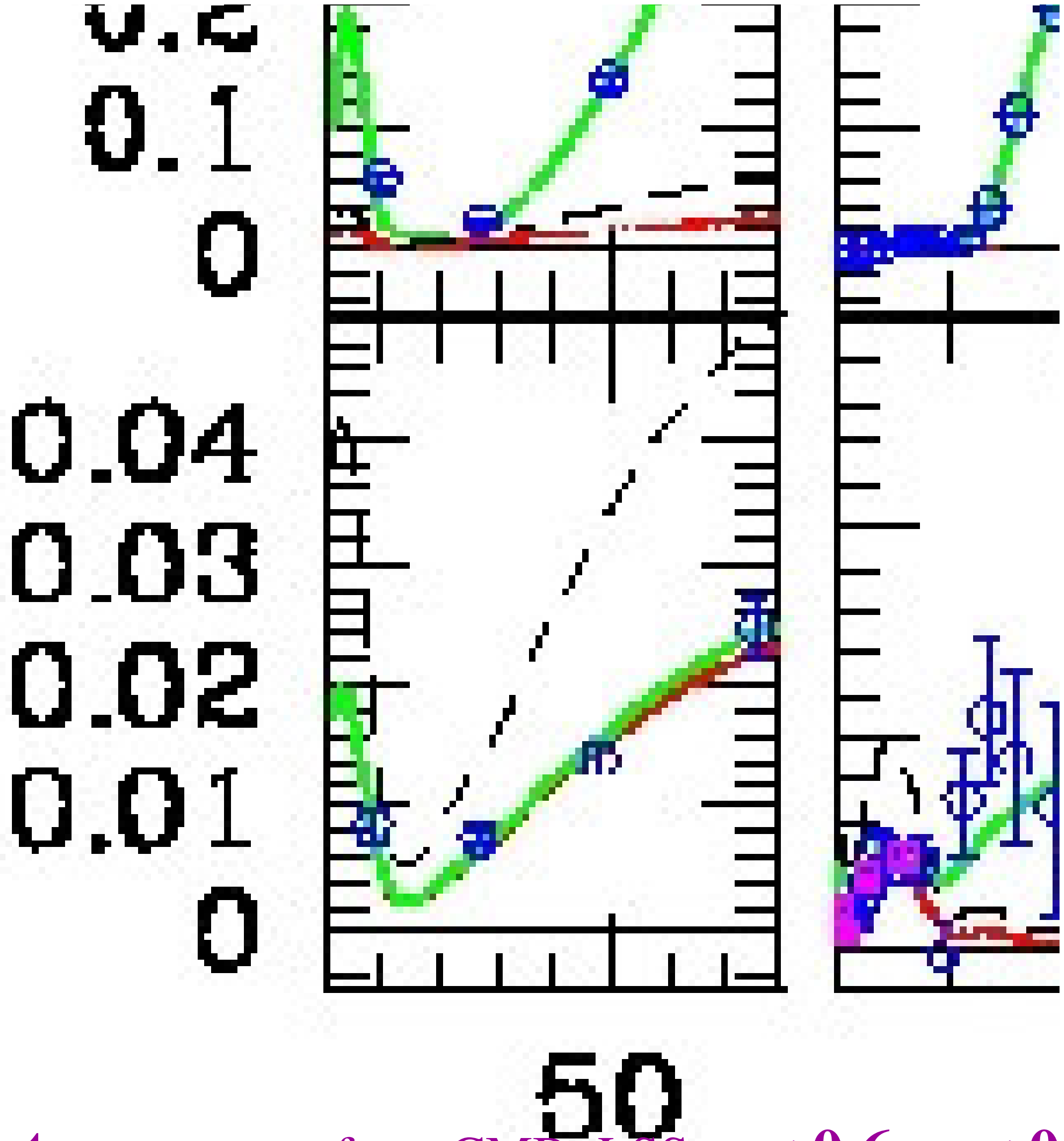
Template removals from multi-frequency data

forecast
Planck2.5

100&143

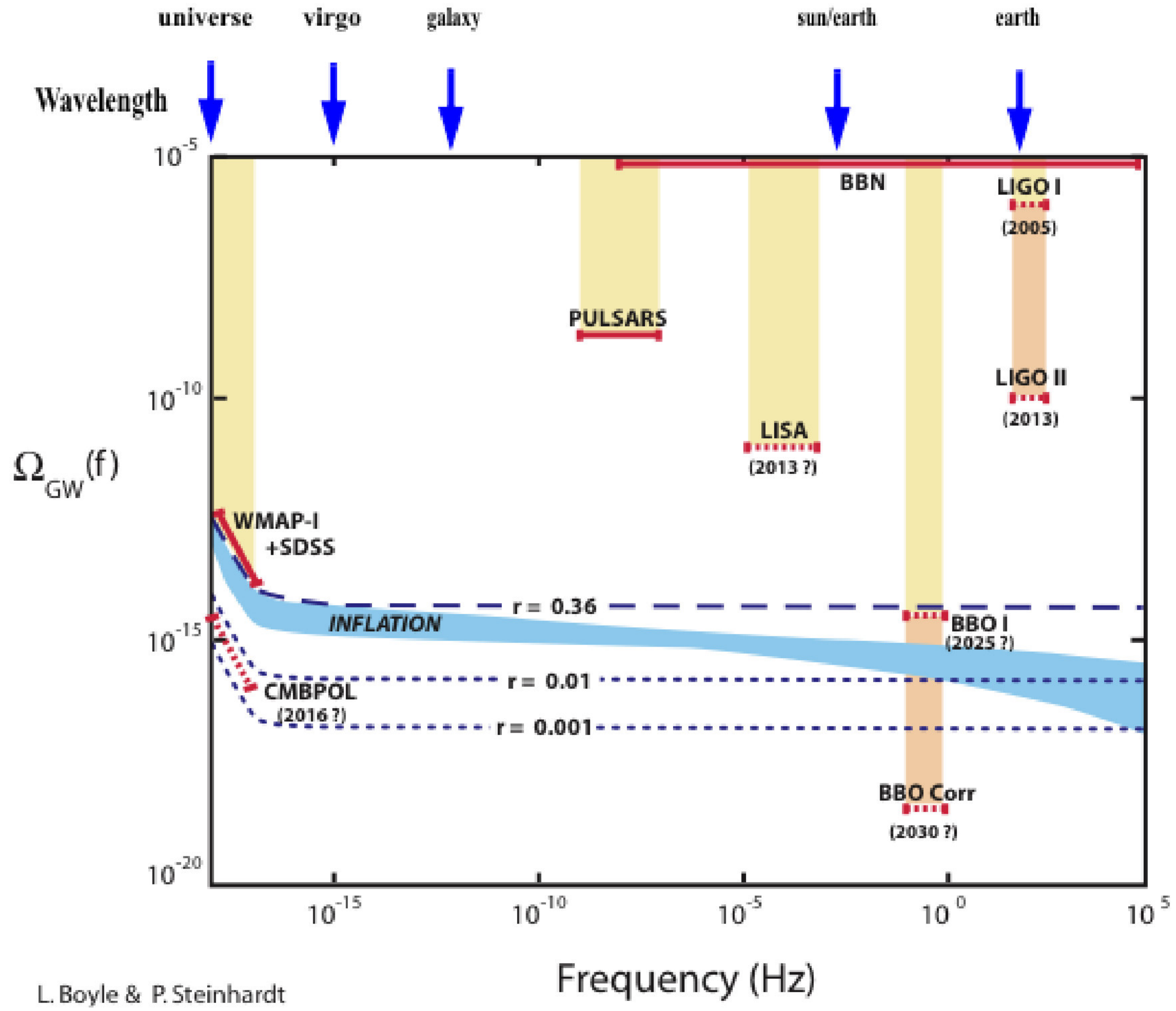
Spider10d

95&150



GW/scalar curvature: current from CMB+LSS: r **< 0.6** or **< 0.3** 95% CL;
good shot at **0.02** 95% CL with **BB polarization** (+- **.02 PL2.5+Spider**)

BUT fgnds/systematics??


Wavelength
universe
virgo
galaxy
sun/earth
earth
BBN
LIGO I
(2005)
PULSARS
LIGO II
(2013)
LISA
(2013 ?)
WMAP-I
+SDSS
r = 0.36
INFLATION
BBO I
(2025 ?)
r = 0.01
CMBPOL
(2016 ?)
r = 0.001
BBO Corr
(2030 ?)
$\Omega_{GW}(f)$
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
10^{0}
10^{5}
Frequency (Hz)
L. Boyle & P. Steinhardt

tensor (gravity wave) power to curvature power, a direct measure of ϵ = (q+1), q=deceleration parameter during inflation

q may be highly complex (scanning inflation trajectories)

many inflaton potentials give the same curvature power spectrum, but the degeneracy is broken if gravity waves are measured

(**q+1**) =~ 0 is possible - low scale inflation – upper limit only

Very very difficult to get at this with direct gravity wave detectors – even in our dreams

Response of the CMB photons to the gravitational wave background leads to a unique signature within the CMB at large angular scales of these GW and at a detectable level. Detecting these B-modes is the new "holy grail" of CMB science.