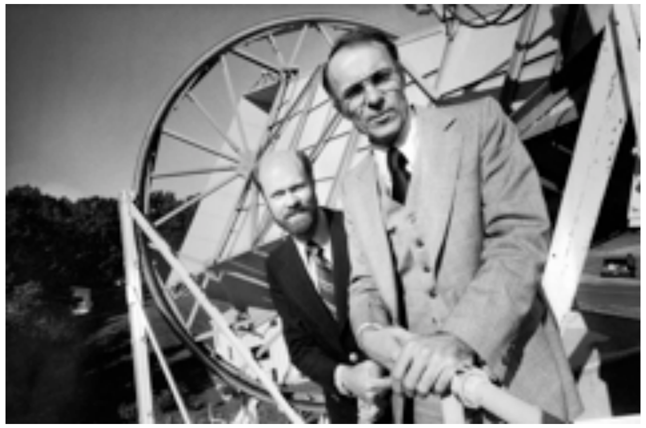
The Universe after Planck and Bicep2

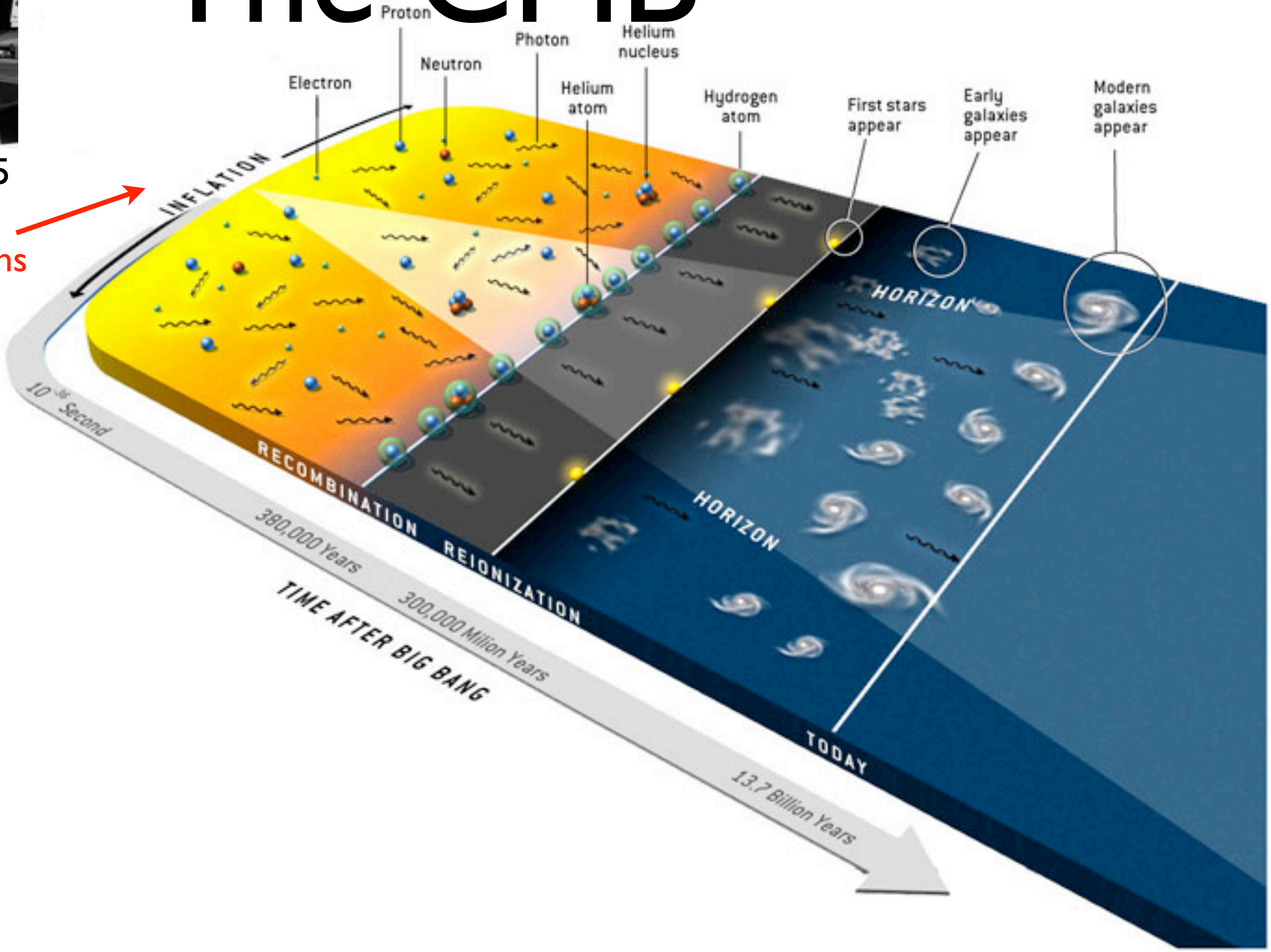
- CMB: what, when/where, who, why
- Planck's (and other's) mission(s)
- Impact on fundamental physics (neutrinos, dark matter, inflation,...)
- Primordial gravitational waves? (Bicep2)
- Conclusions

The CMB



Penzias and Wilson 1965

accelerated expansion
generation of fluctuations



credits: W. Hu

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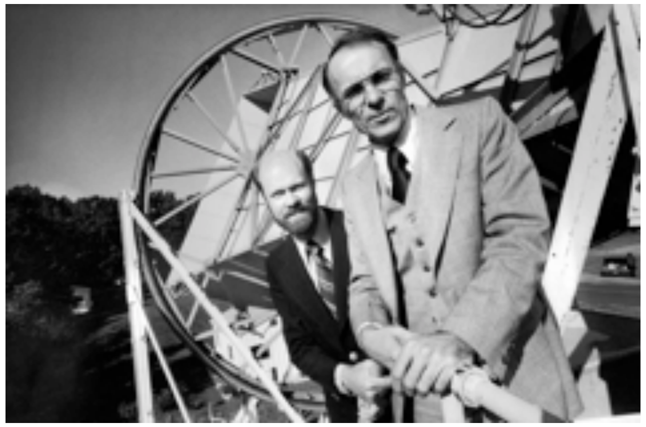

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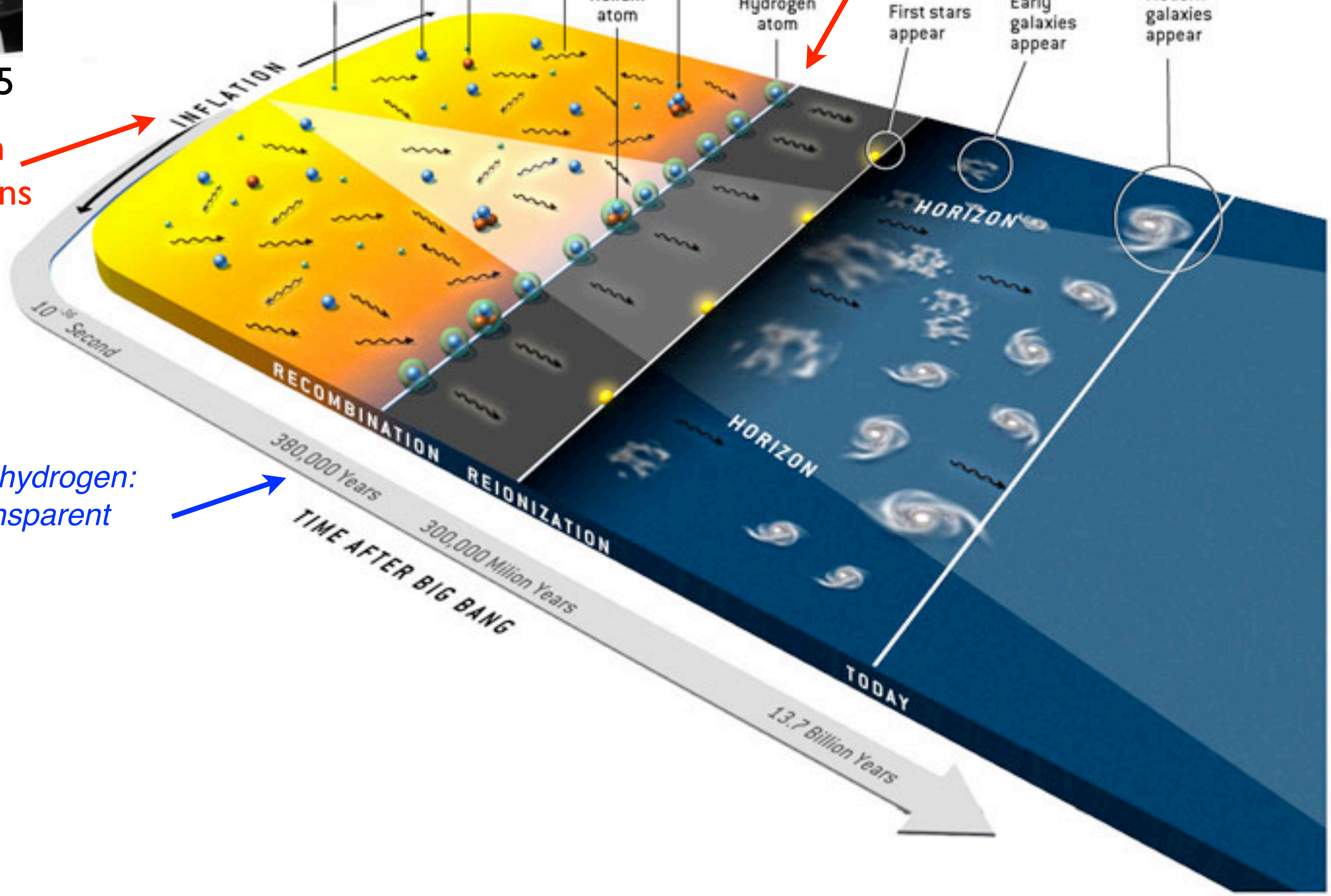
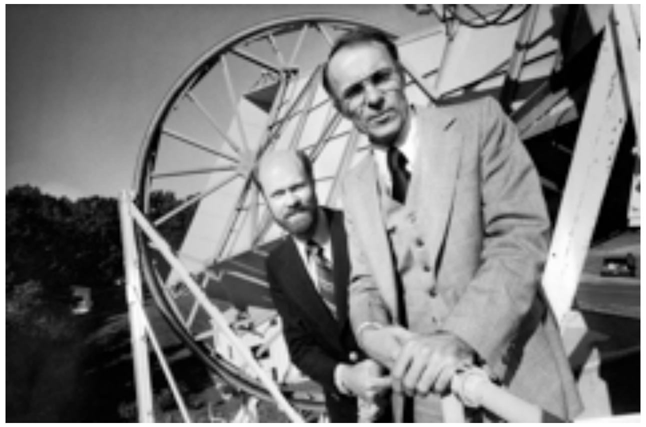
last scattering surface
(380000 yrs after the Bang,
13.7 billion yrs ago)



"recombination" of neutral hydrogen:
the Universe becomes transparent
(T ~ 0.25 eV ~ 3000 K)

credits: W. Hu

The CMB



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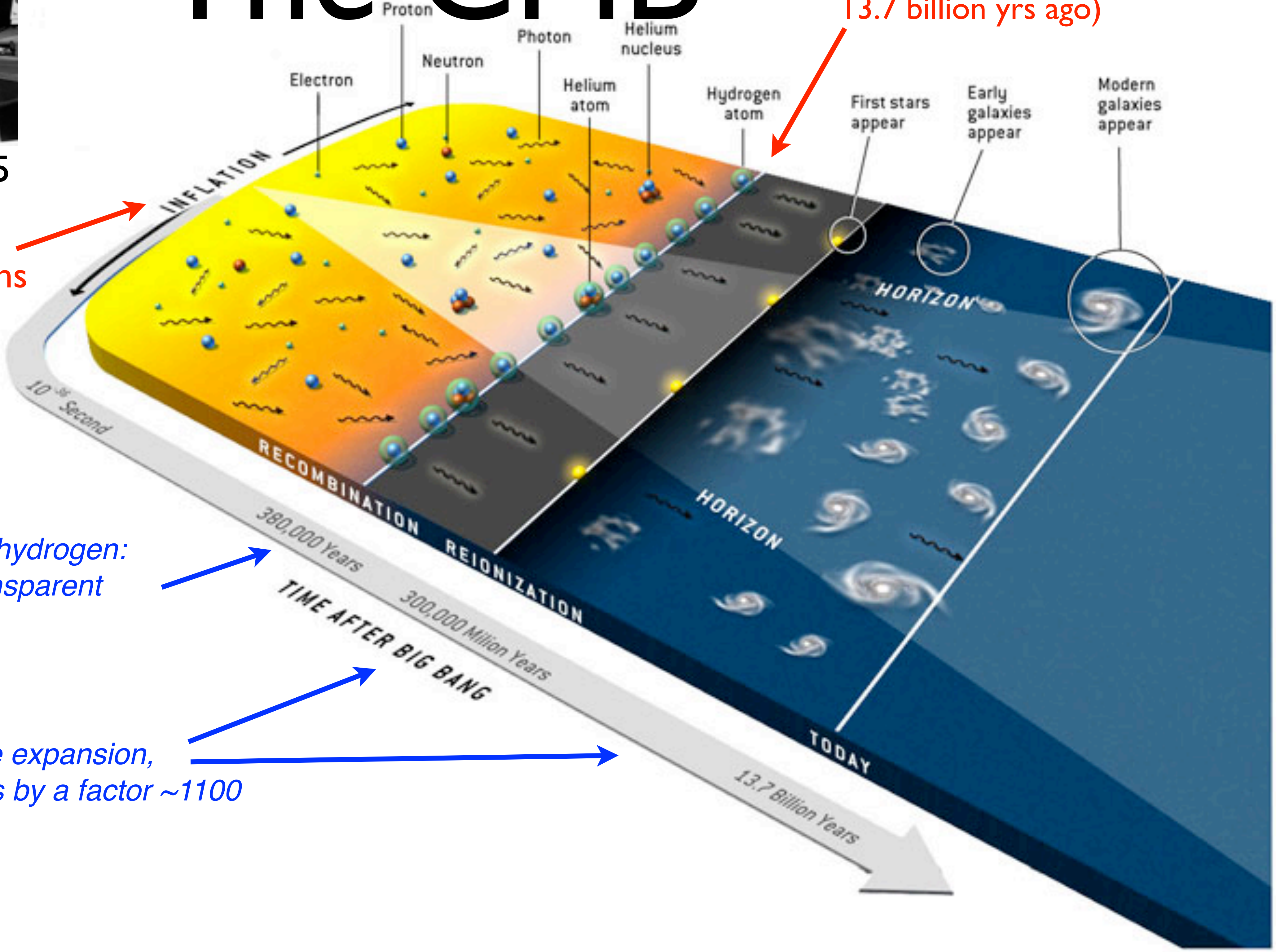

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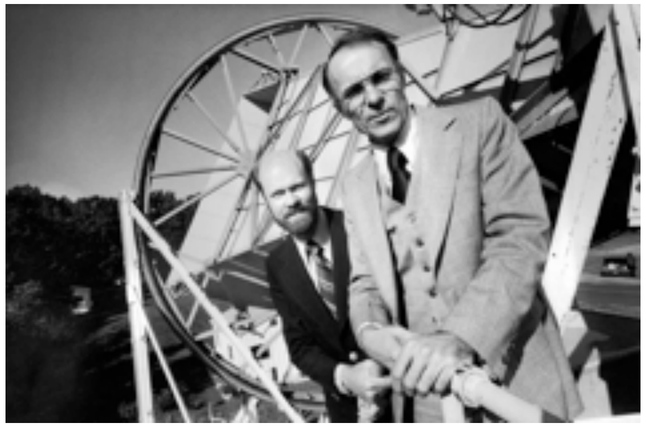

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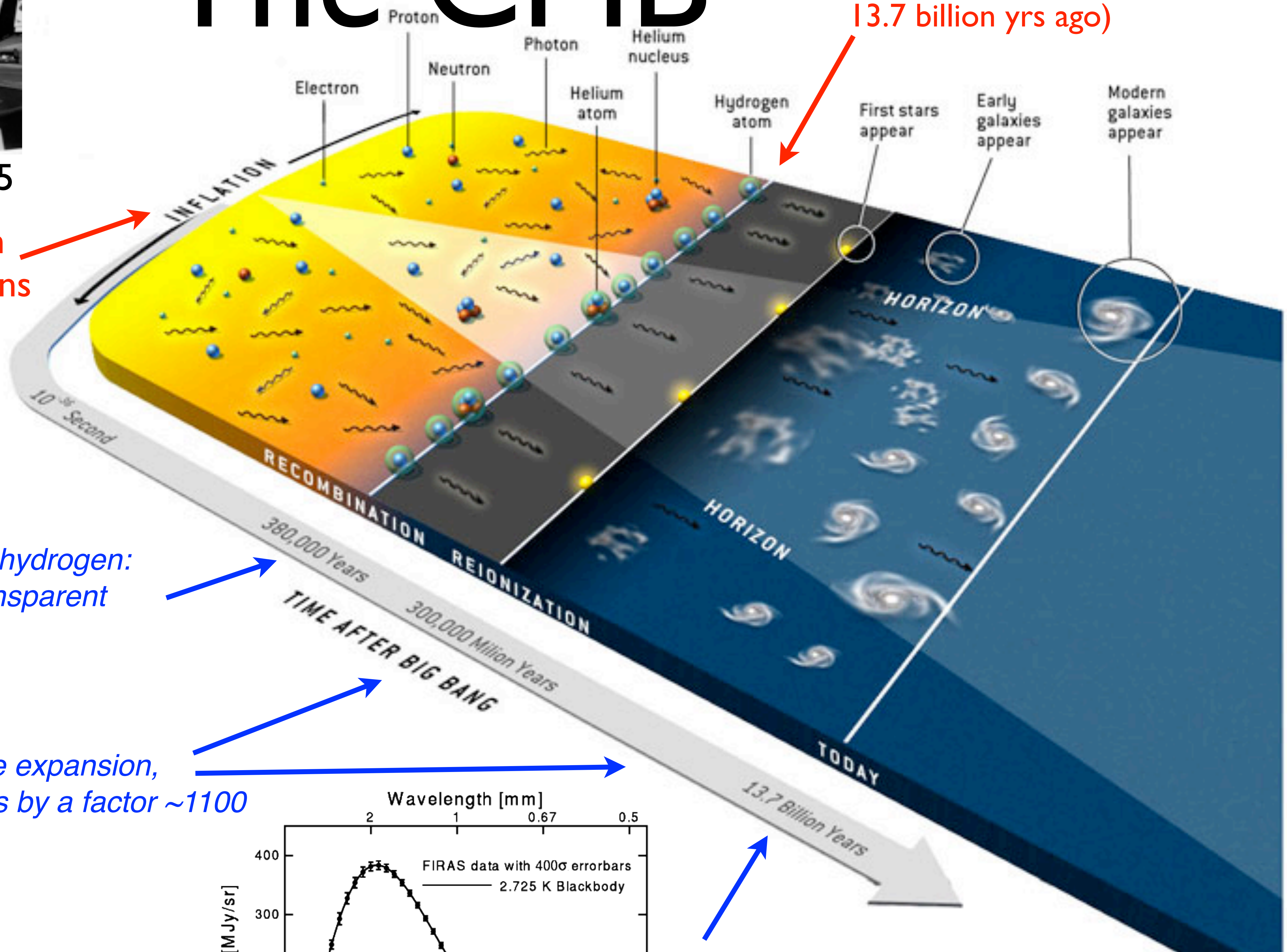

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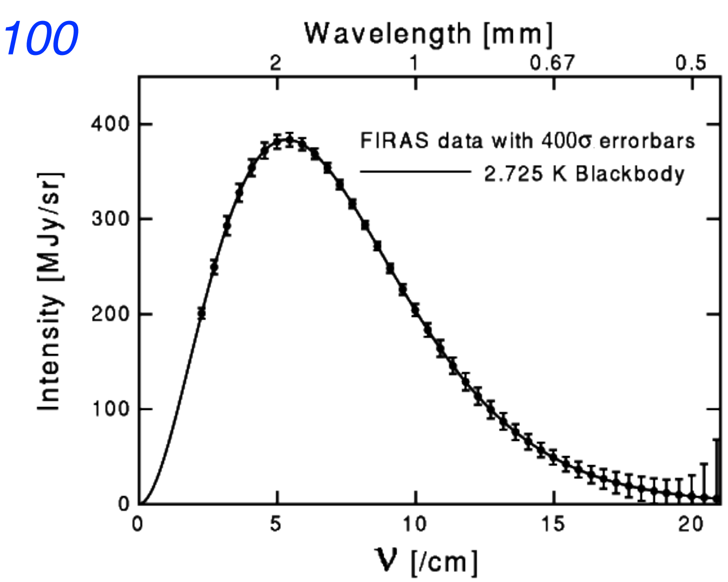


Today the CMB is a perfect blackbody with mean temperature (Fixsen 2009)

T = 2.7255 0.006 K

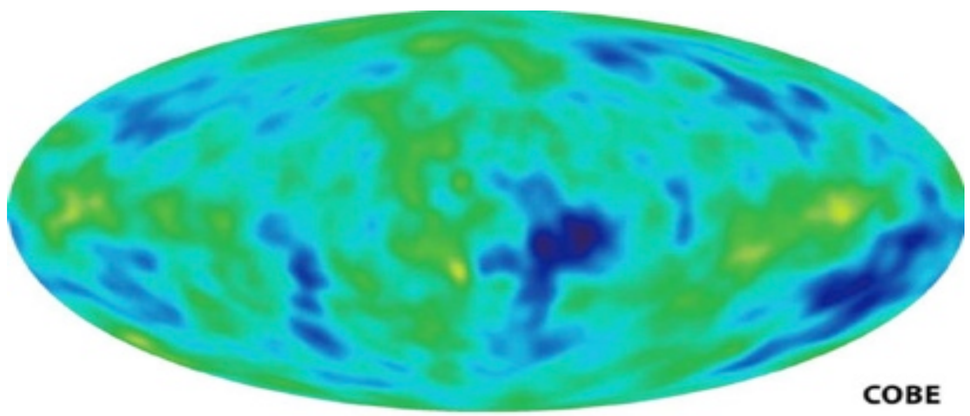
credits: W. Hu

Temperature fluctuations

1994
$N_{pix} \sim 10^4$

ang.res. $\sim 7^o$

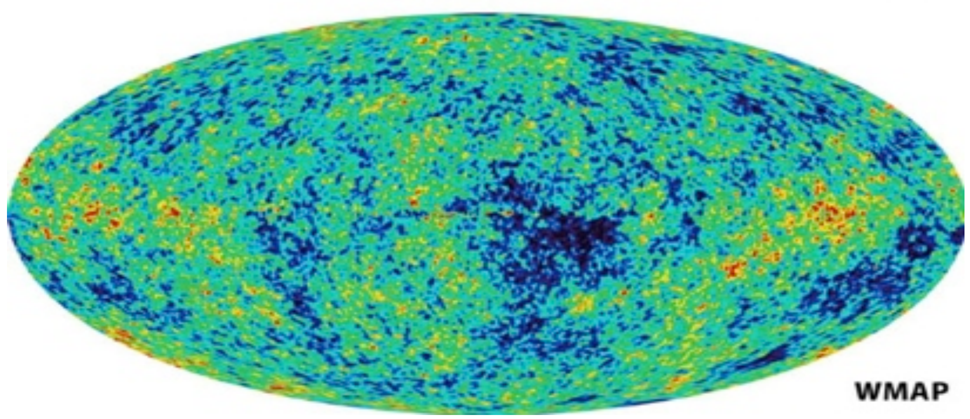
$l_{max} \sim 30$



2003
$N_{pix} \sim 3\ 10^6$

ang.res $\sim 12'$

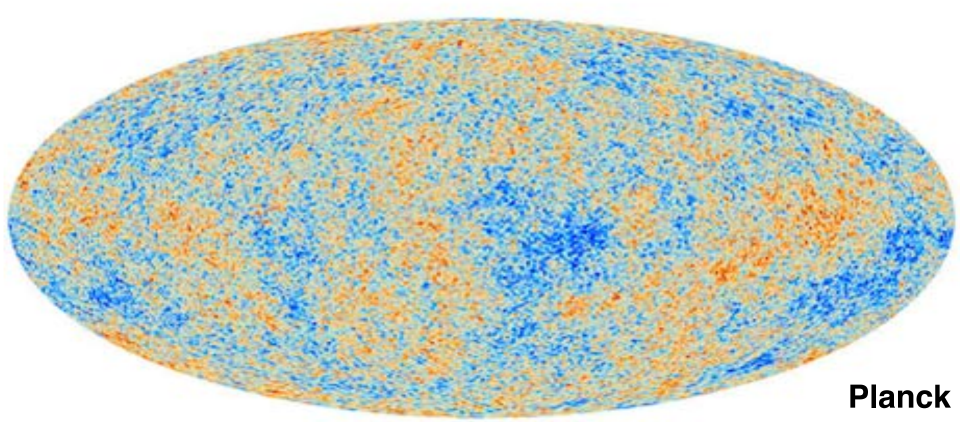
$l_{max} \sim 1000$



2013
$N_{pix} \sim 5\ 10^7$

ang.res $\sim 5'$

$l_{max} \sim 3000$



T=2.7 K

$\Delta T/T \sim 10^{-5}$

... seeds of all the structures (galaxies, clusters, ...) we see today

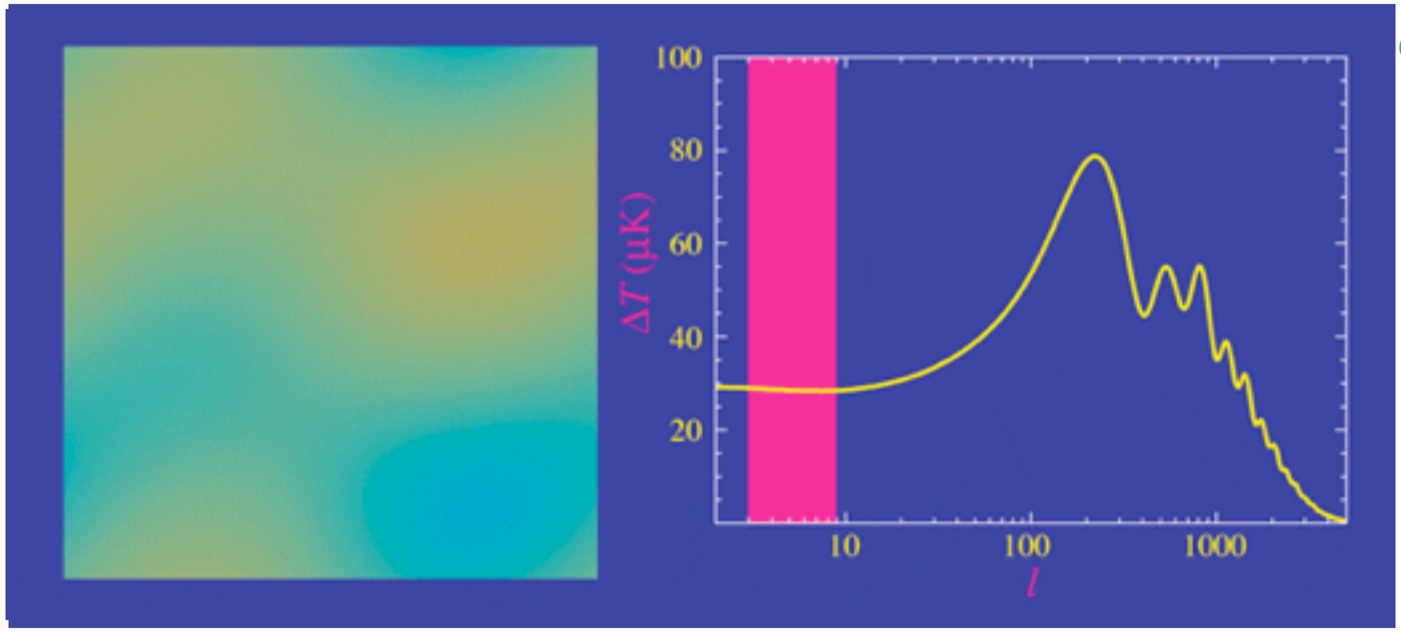
Angular Power Spectrum

$$\Delta T = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

$$C_\ell^T = \langle |a_{\ell m}|^2 \rangle$$

$\ell \sim 200^o / \theta$

$\theta = D/d_a$



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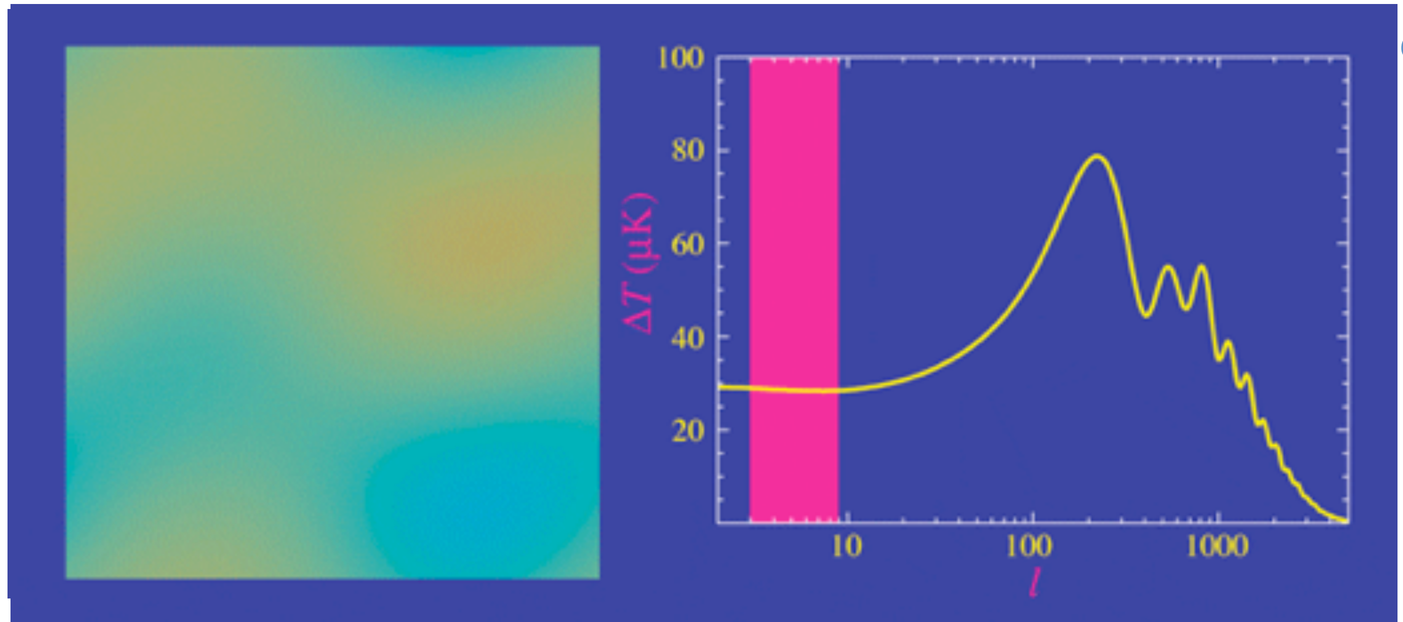
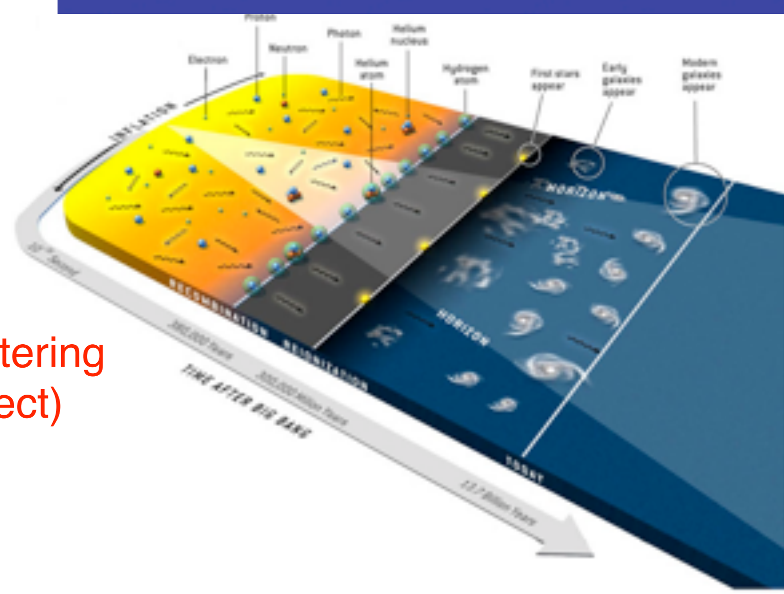


credits: W. Hu

On small scales:

dissipation (photon free streaming)

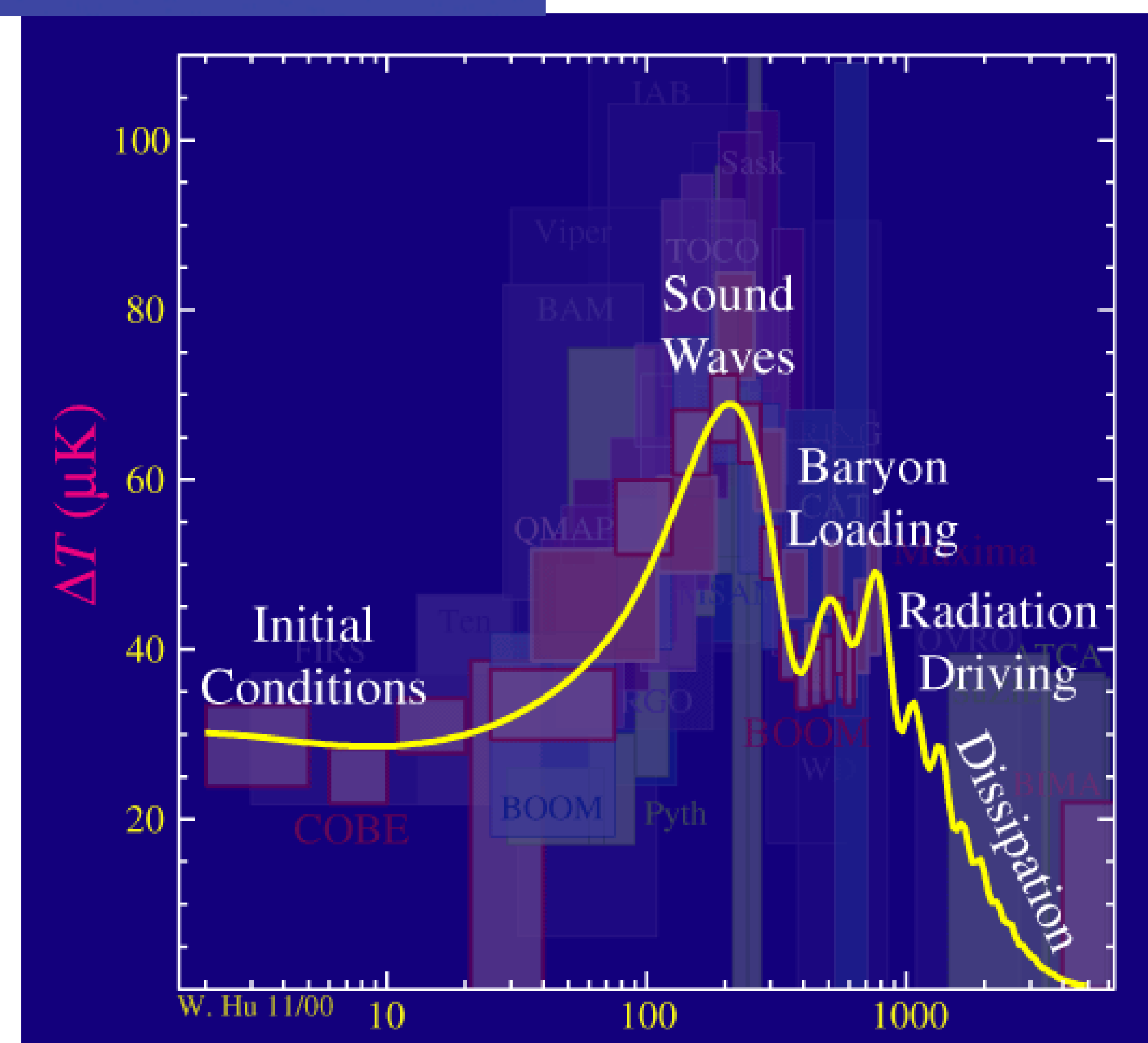


On large scales:

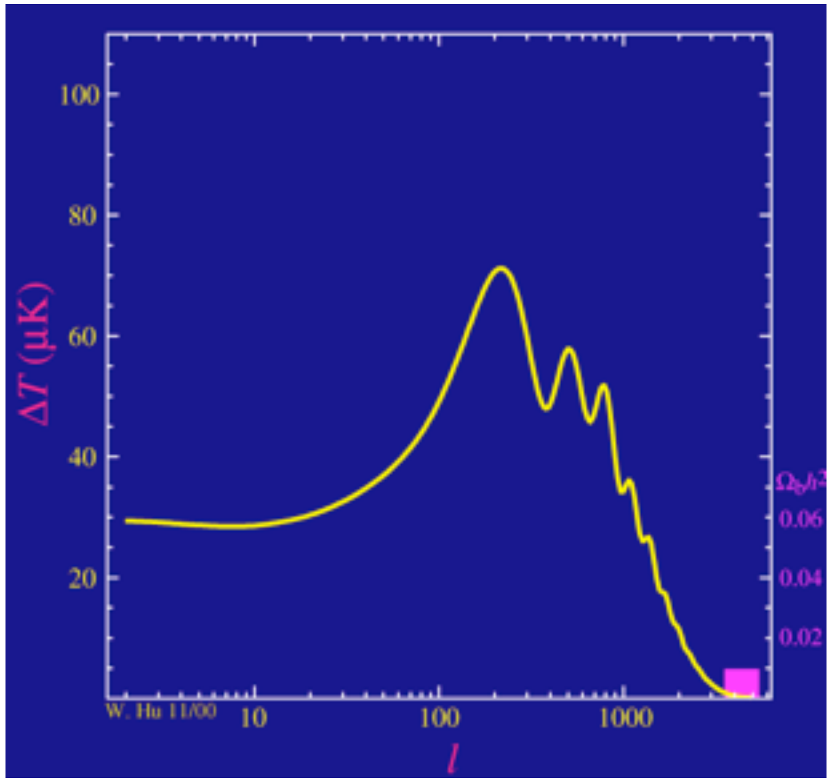
density fluctuations at last scattering + gravitational redshift (SW effect)

On intermediate scales:

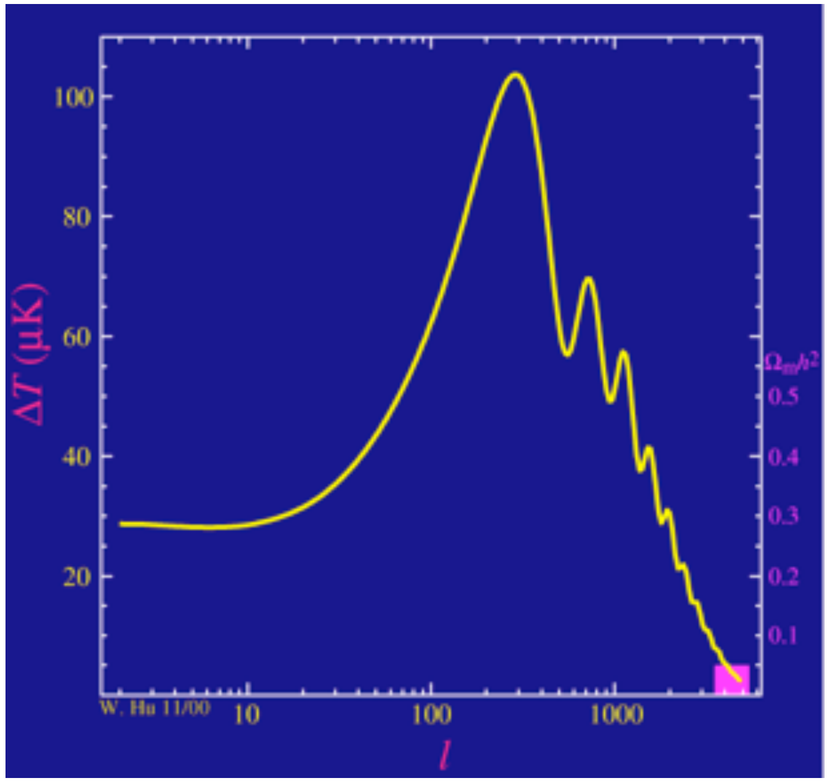
acoustic oscillations



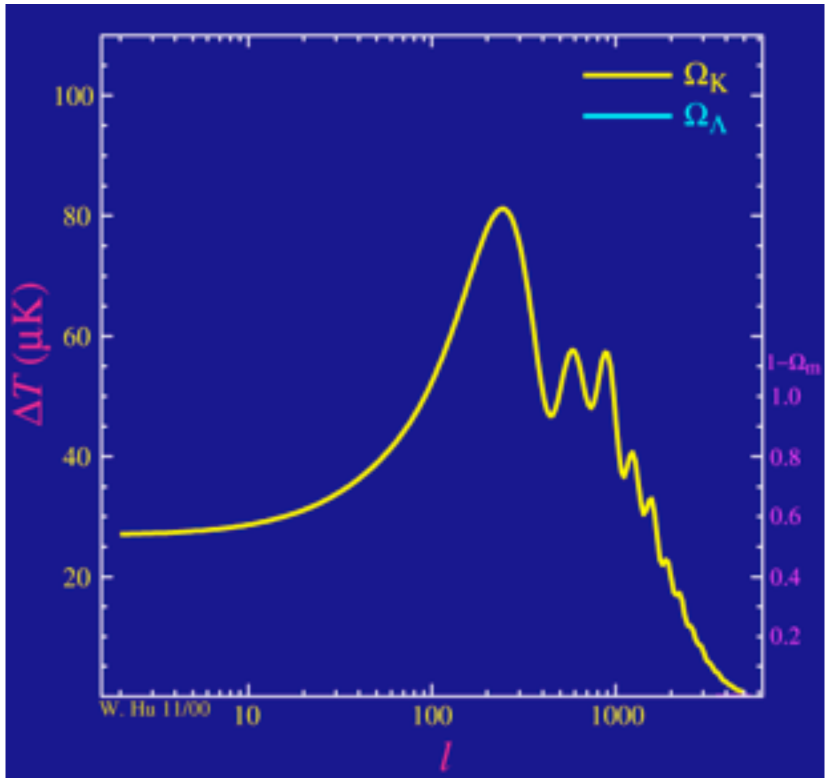
Cosmological Parameter Dependence



baryons

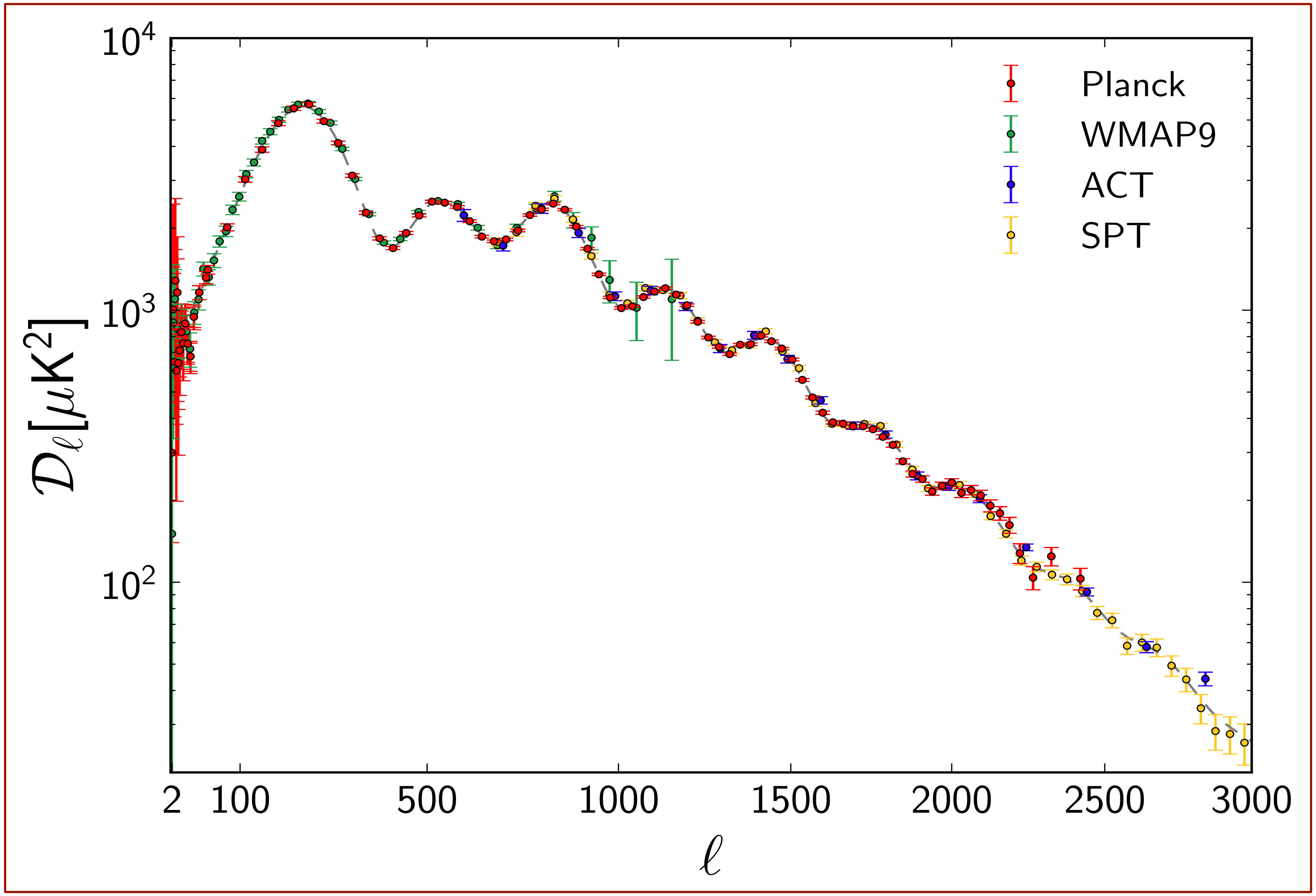


dark matter



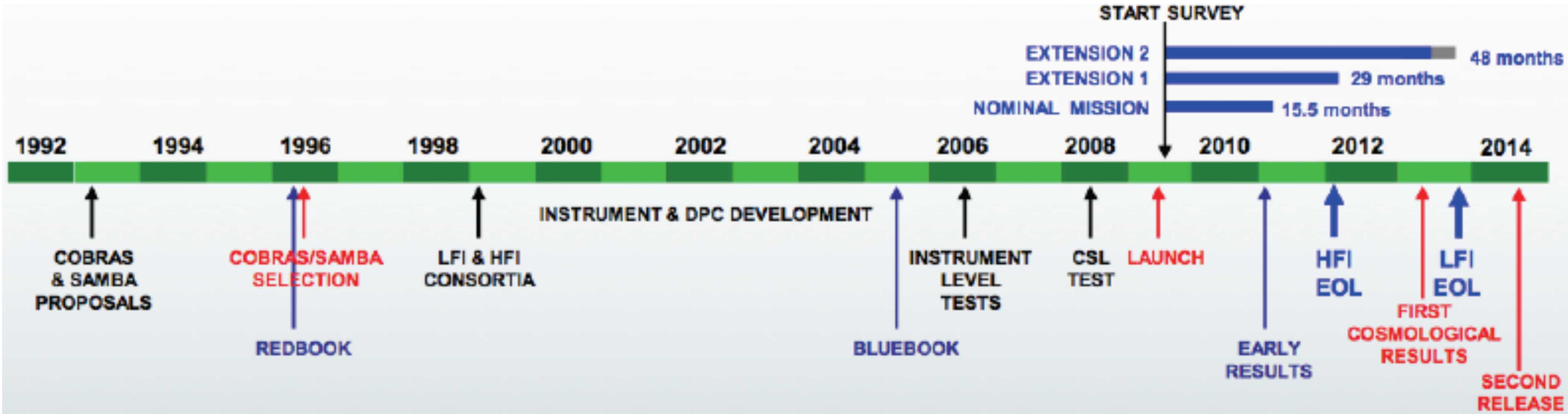
dark energy/
curvature

CMB today

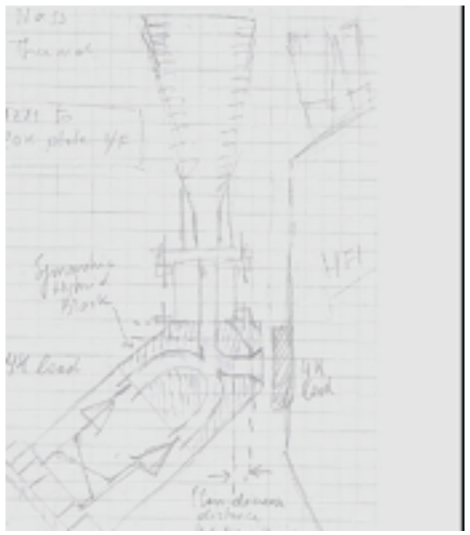


9 peaks measured!!
(up to l~3000)

The Planck Mission

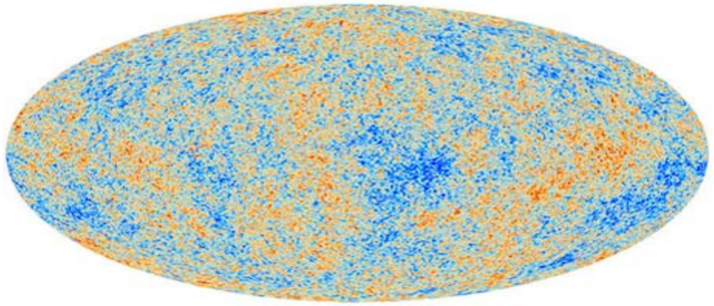


a 20 year old story...



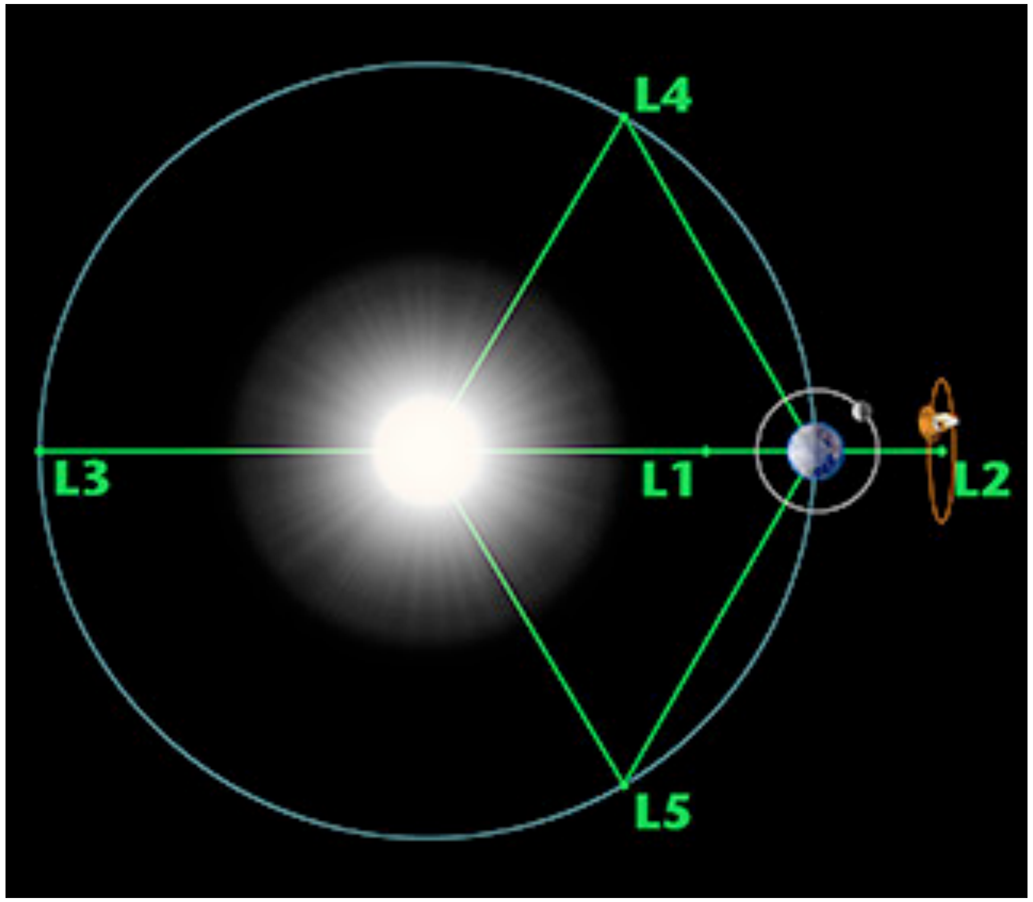
1992: COBRAS/SAMBA

May 14th 2009

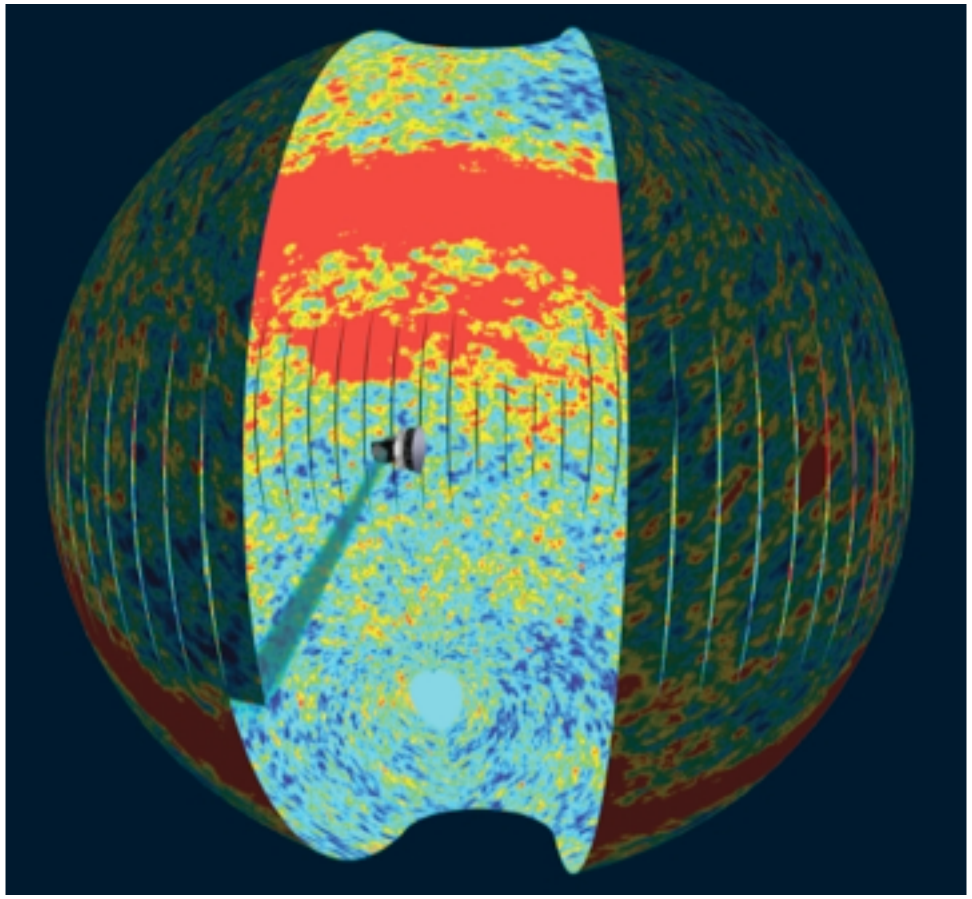


March 21st 2013

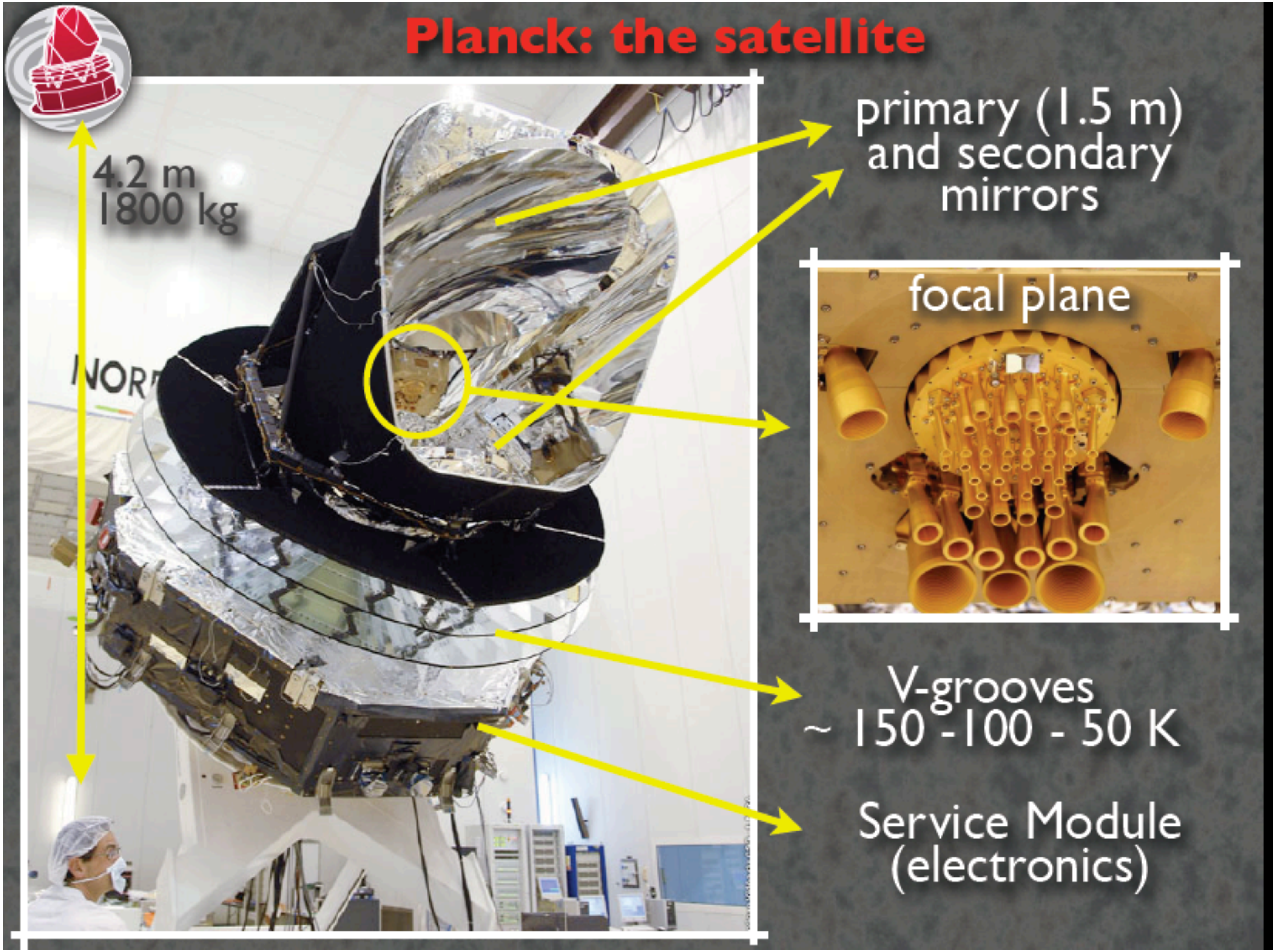
Orbit and scanning



Lagrange point L2



a full sky in 6 months
3 skys published
5(8) completed

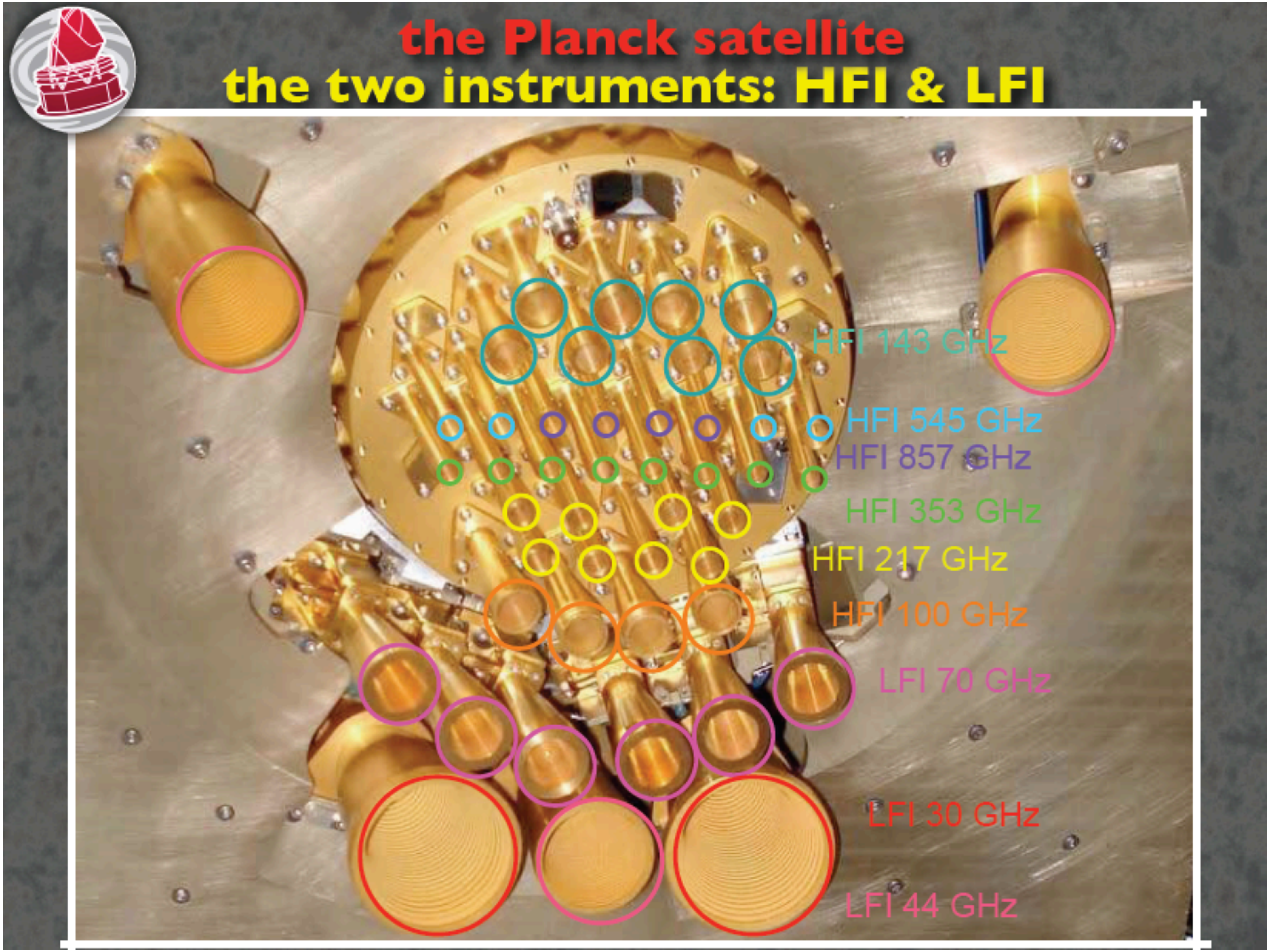


Mass 1'800 kg
Power 1'600 W
Size 4.2 × 4.2 m
Cost 600×10^6 €

50'000 Electronic components
36'000 l ^{4}He
12'000 l ^{3}He
(HFI cooled down to 0.1 K)

2 instruments & consortia
16 countries
400 researchers

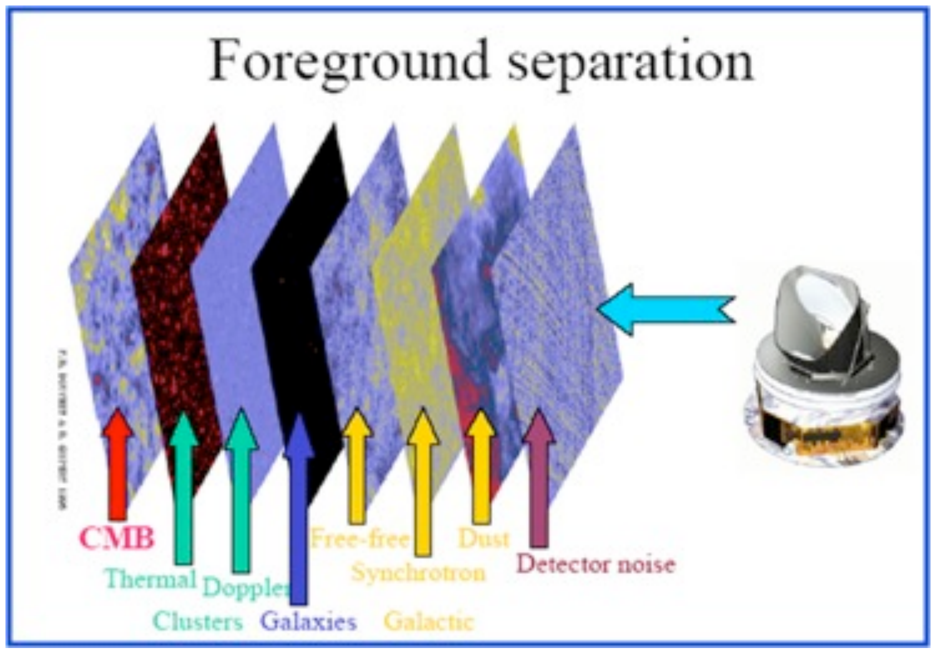
from S. Donzelli

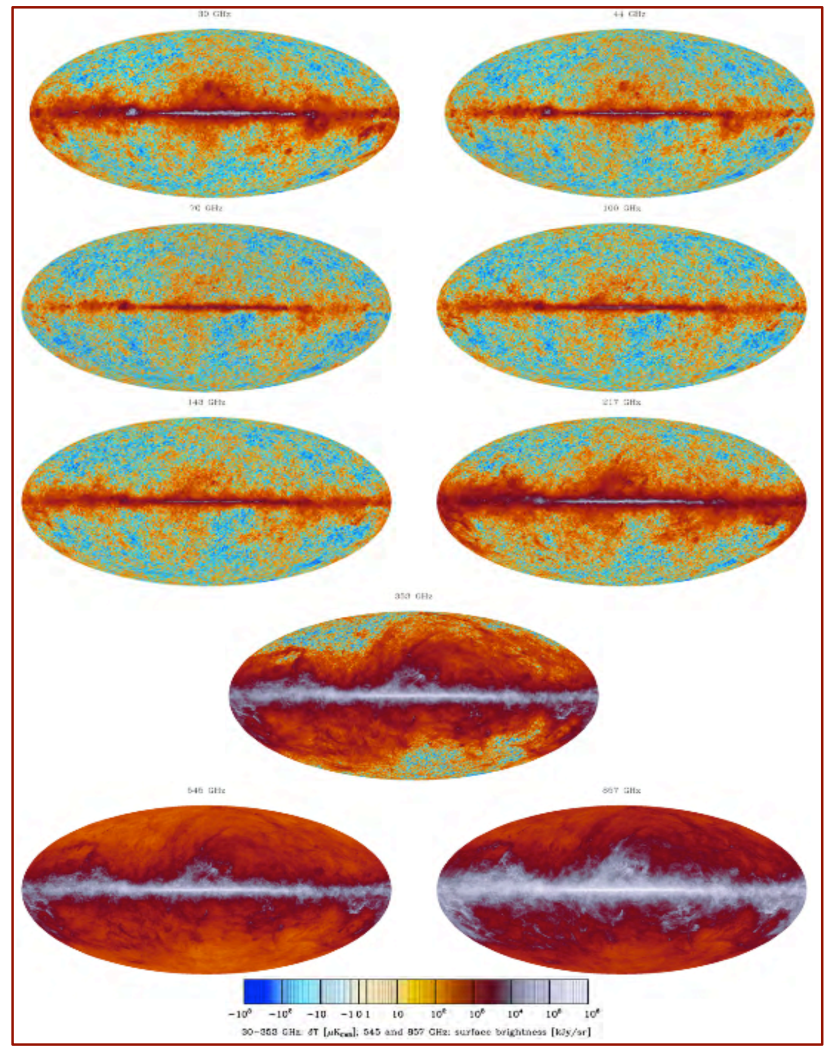


2 instruments, 9 frequency channels

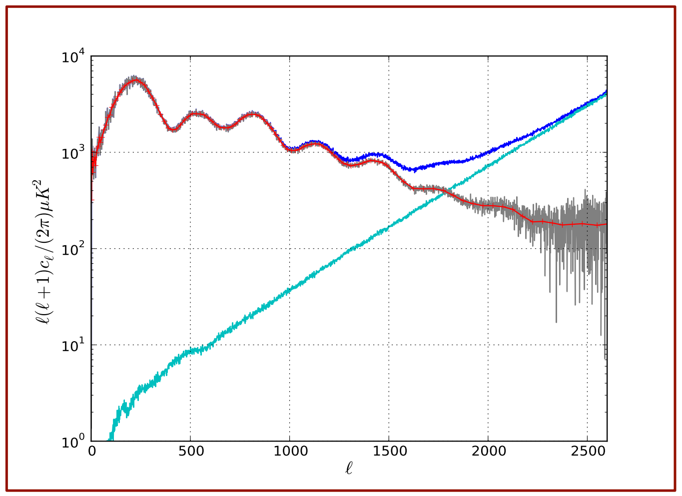
from S. Donzelli

Foregrounds





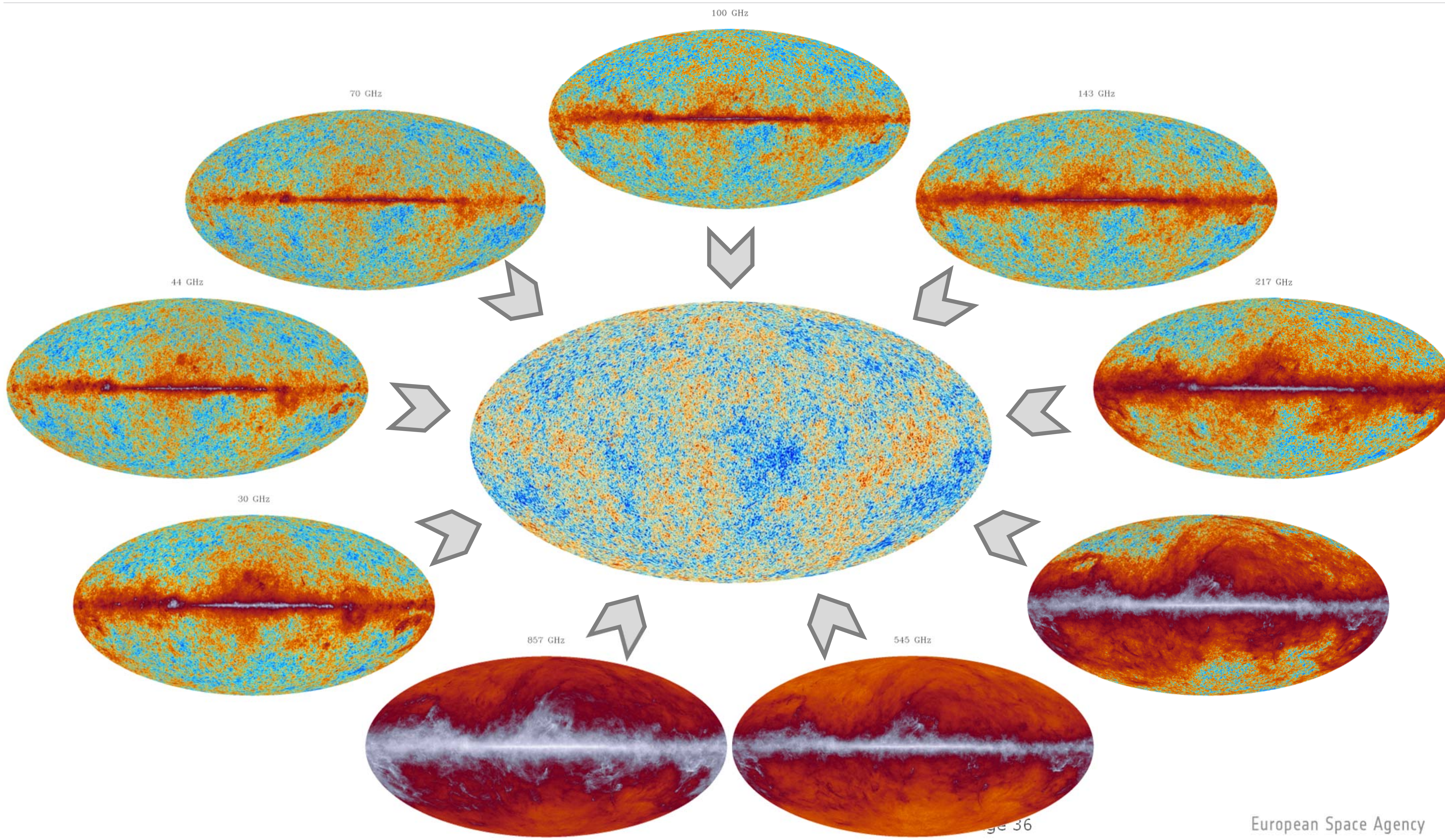
9 frequency maps



signal/noise

Cleaning byproducts contain a lot of (astro)physics: catalogs of compact sources, clusters, synchrotron emission,...

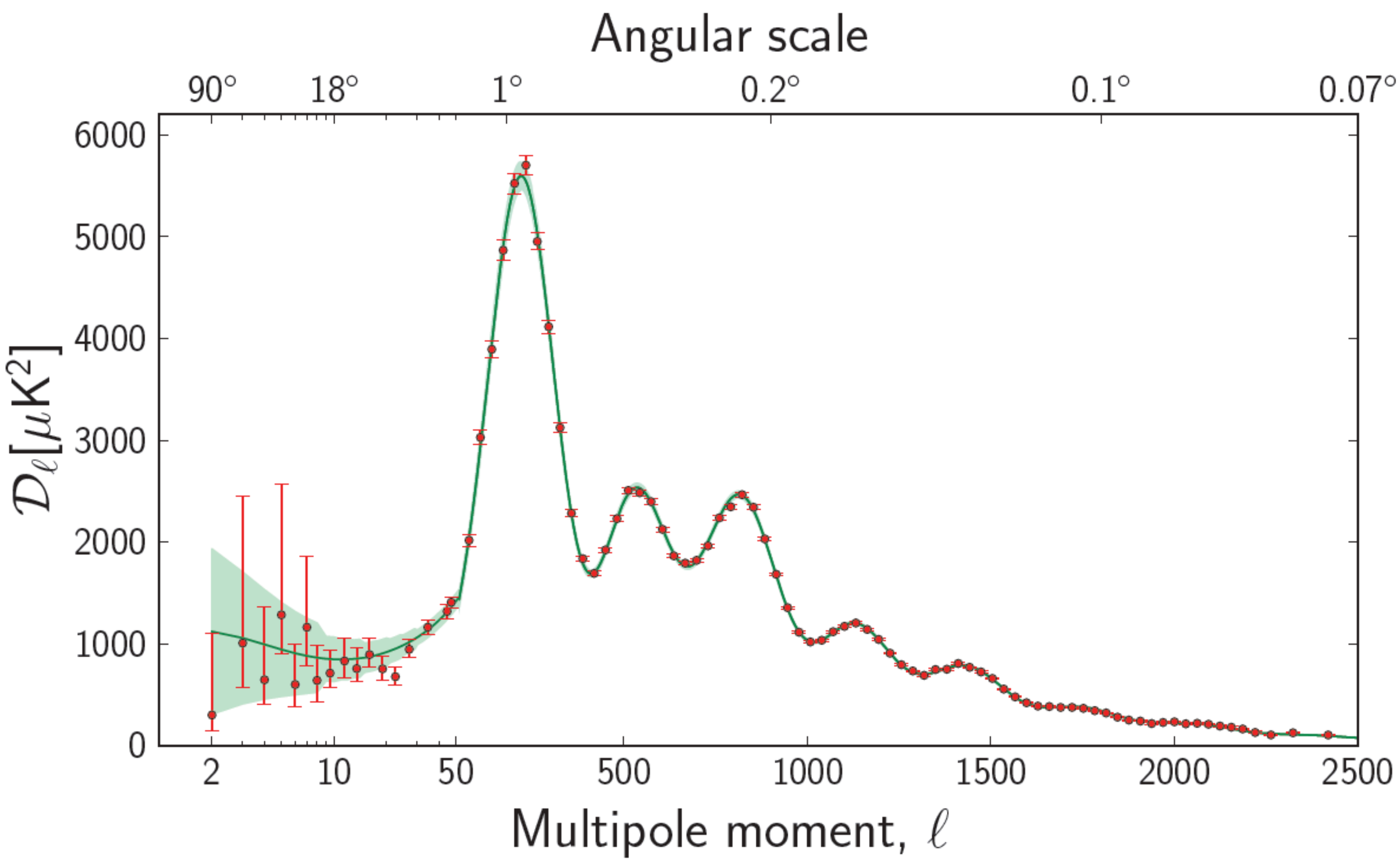
Cleaning the foregrounds



François R. Bouchet "Planck mission overview"

3% of the CMB sky replaced by a Gaussian Random realisation

The CMB Power Spectrum (Planck alone)



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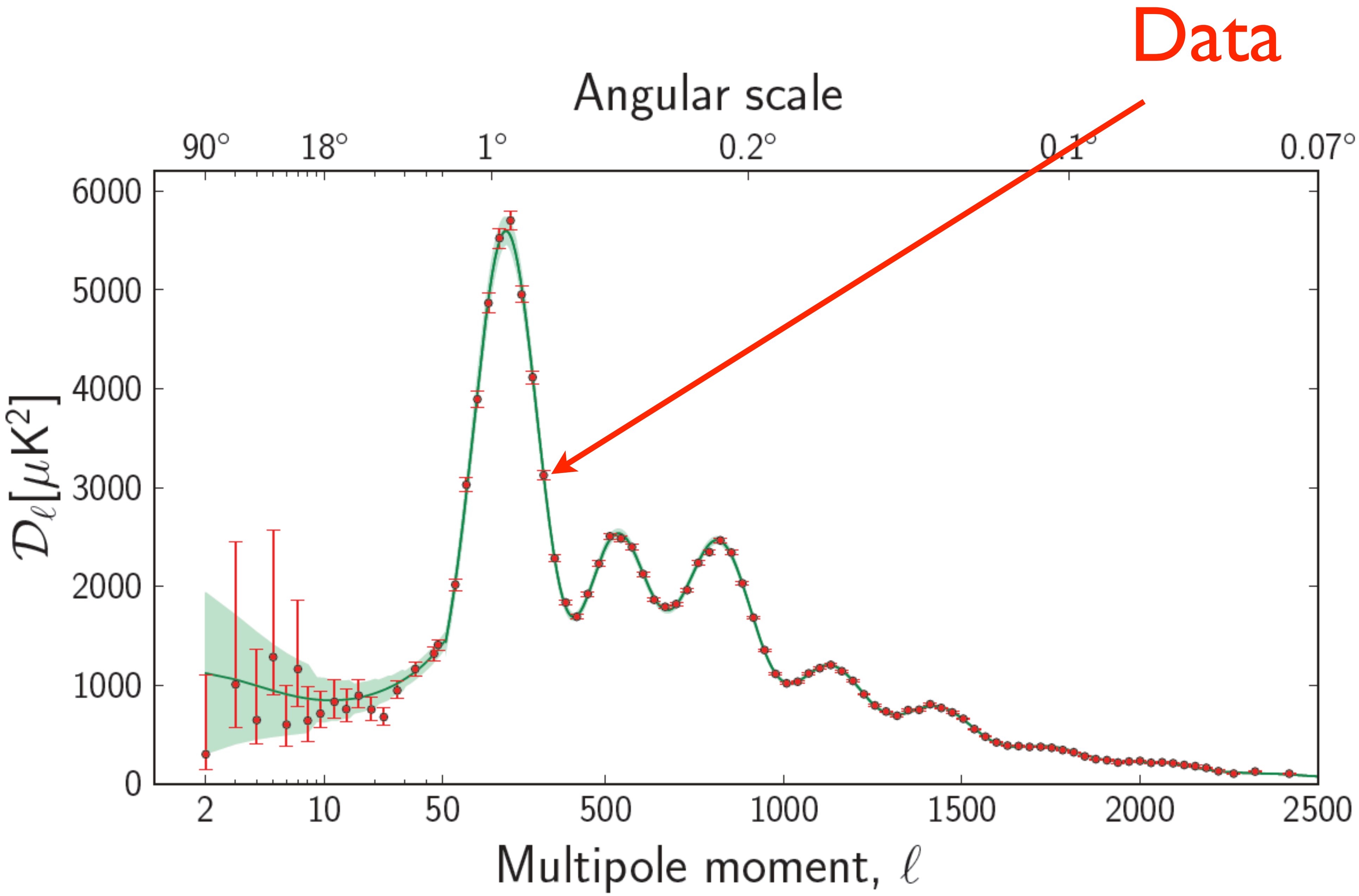

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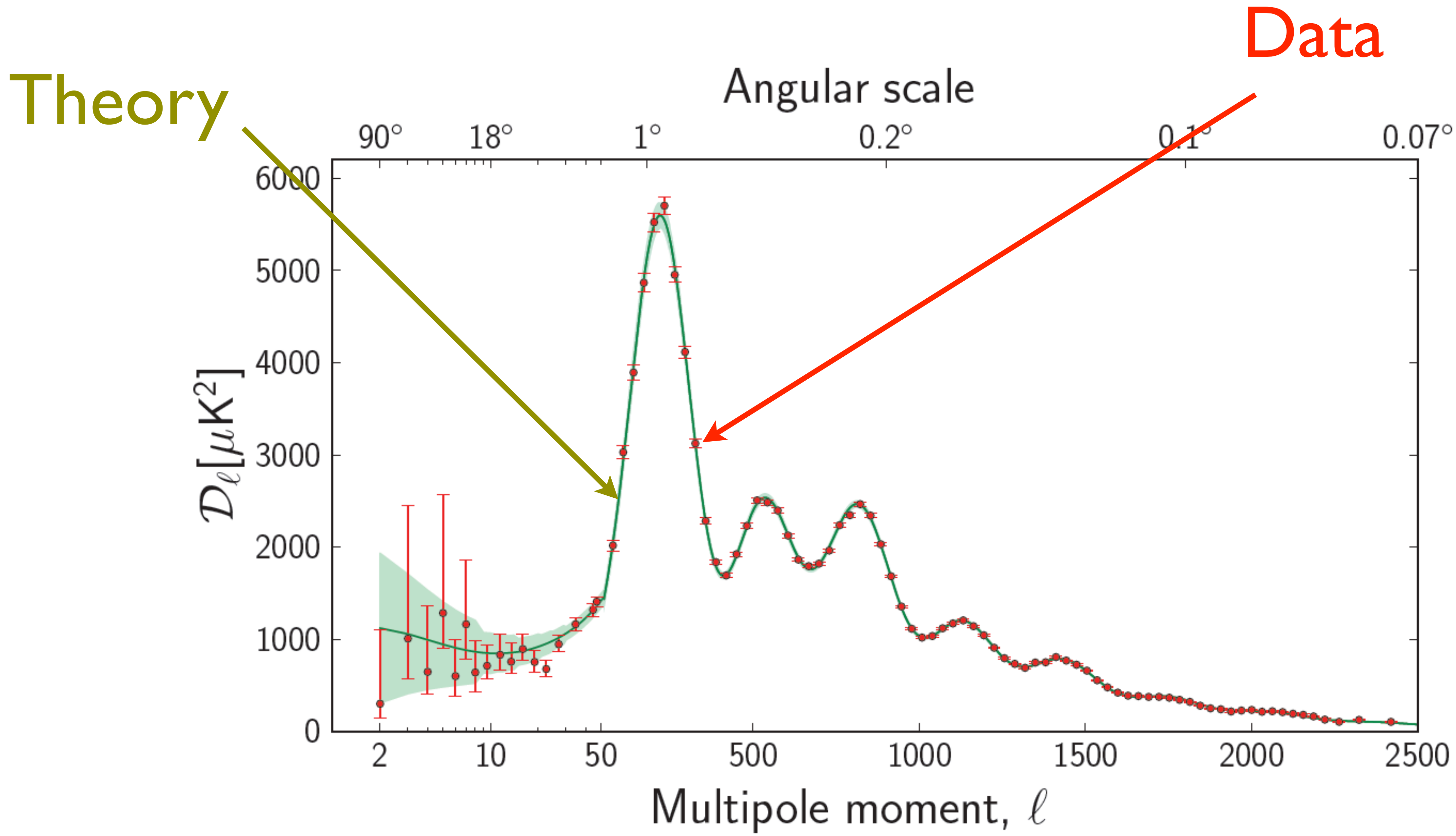

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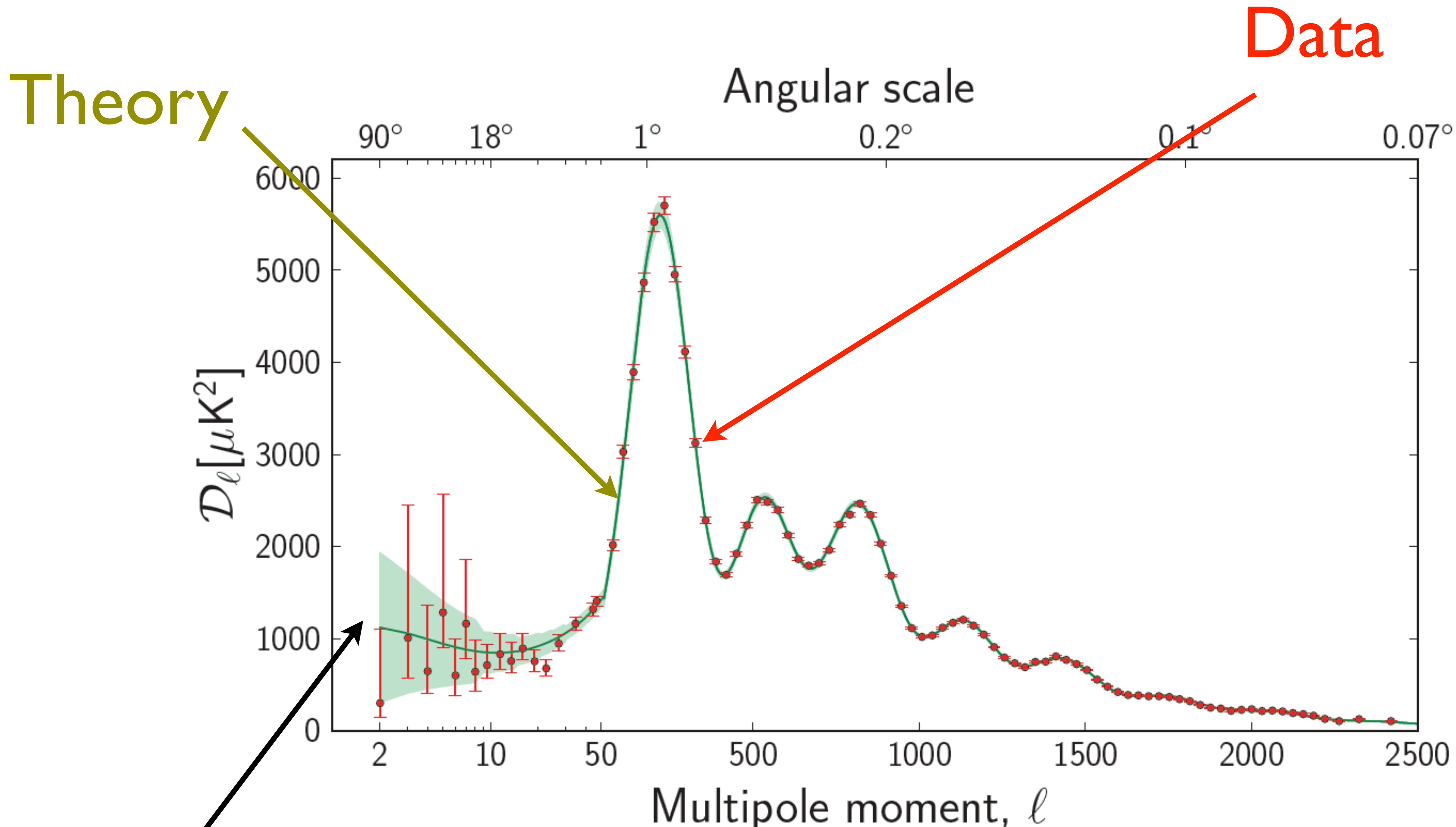

"Cosmic variance":

$$\Delta T = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

$$C_\ell^T = \langle |a_{\ell m}|^2 \rangle$$

$$\frac{\sigma_{C_l}}{C_l^T} = \sqrt{\frac{2}{(2l+1) f_{sky}}}$$

The Standard Model of Cosmology

- Gravity is described by General Relativity on all scales
- Background Geometry is spatially flat
- Matter content: baryons, photons, 3 neutrino species, Dark Matter, Cosmological Constant
- Primordial (adiabatic) density perturbations: $\Delta T/T \sim 10^{-5}$ on all scales with a nearly (but not exactly) scale-invariant spectrum

The Standard Model Parameters

	Planck alone		Planck + others	
	Planck (CMB+lensing)		*Planck*+WP+highL+BAO	
Parameter	Best fit	68 % limits	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025

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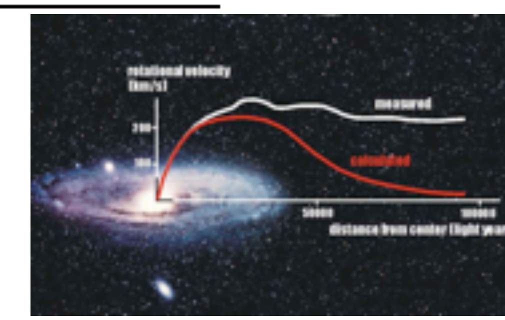
DM/b ~5.4   CMB is the strongest evidence for Dark Matter



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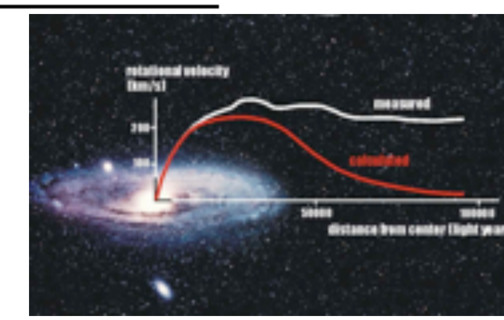

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Sound horizon (peaks position) measured at 0.05%

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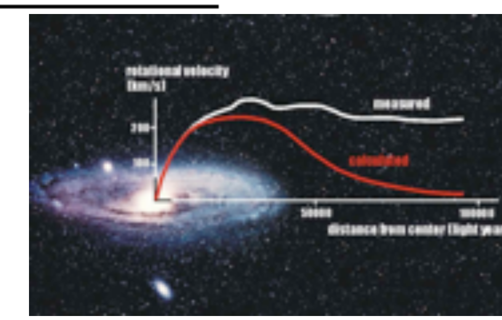

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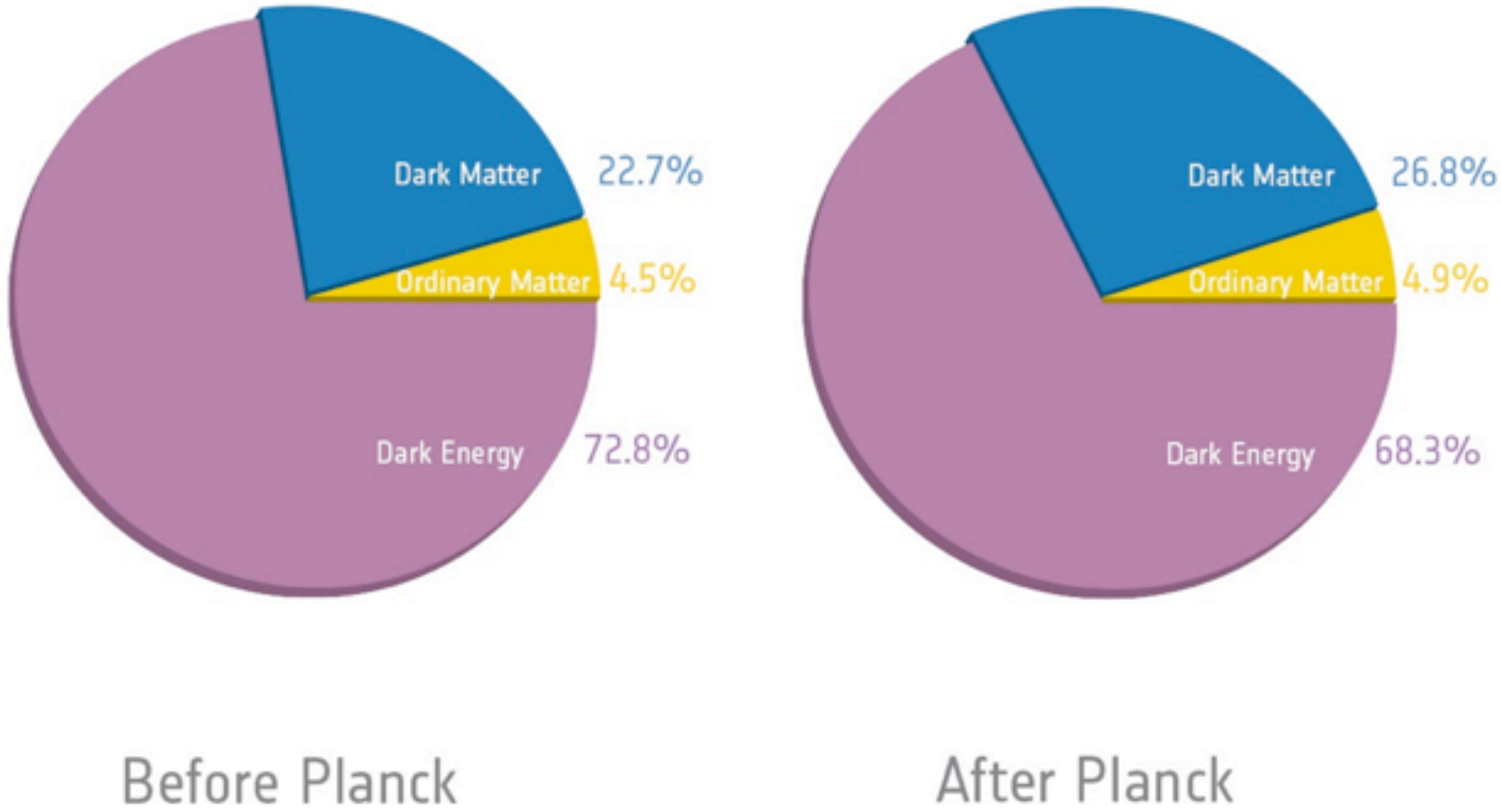
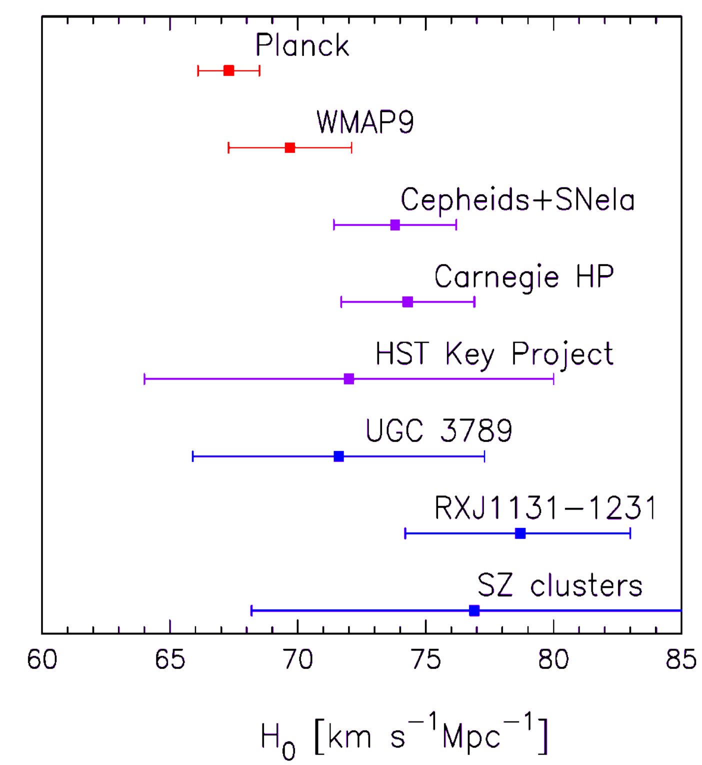
Sound horizon (peaks position) measured at 0.05%

$n_s - 1 \neq 0$ at 6 sigmas, expected from inflation

The Energy Budget Today

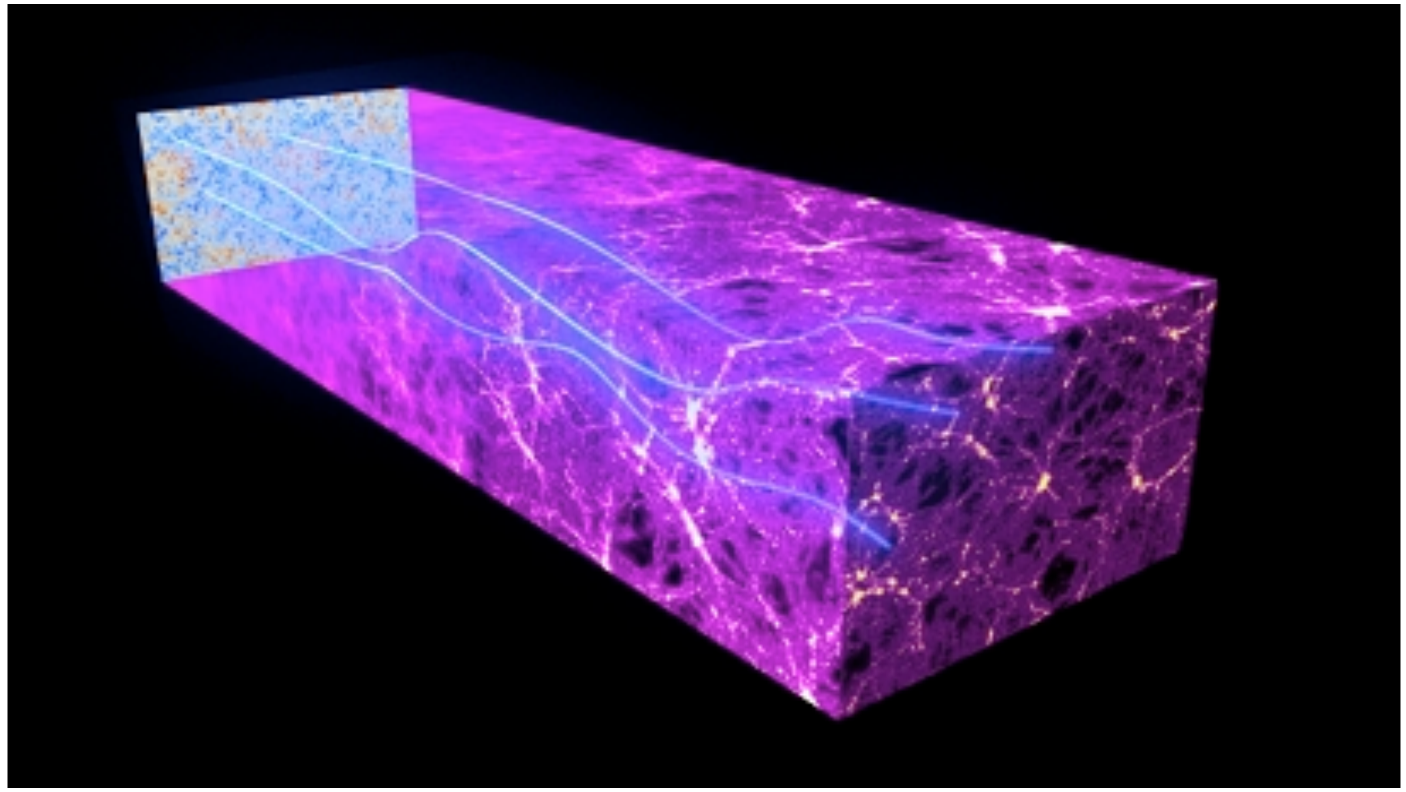


credits: F. Bouchet



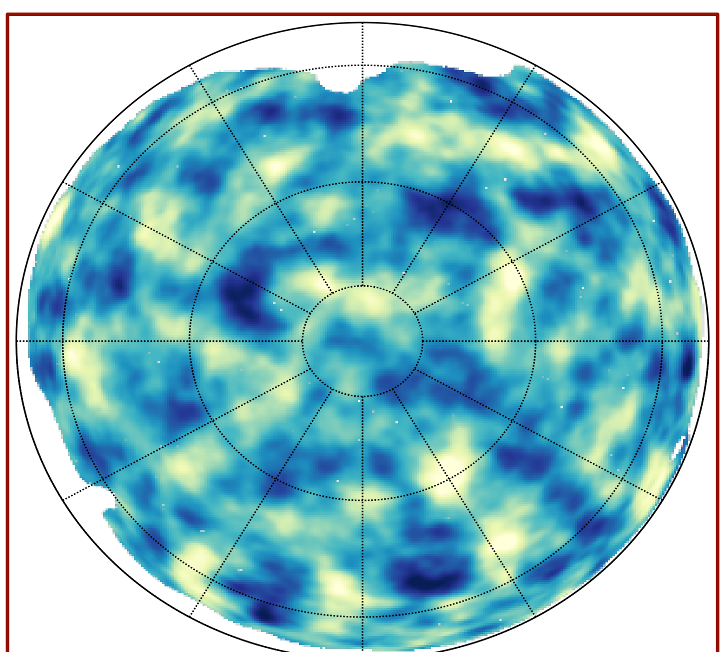
Age of the Universe: t_0 = 13.796 ± 0.058 Gyr
(Slight tension with astrophysical determinations)

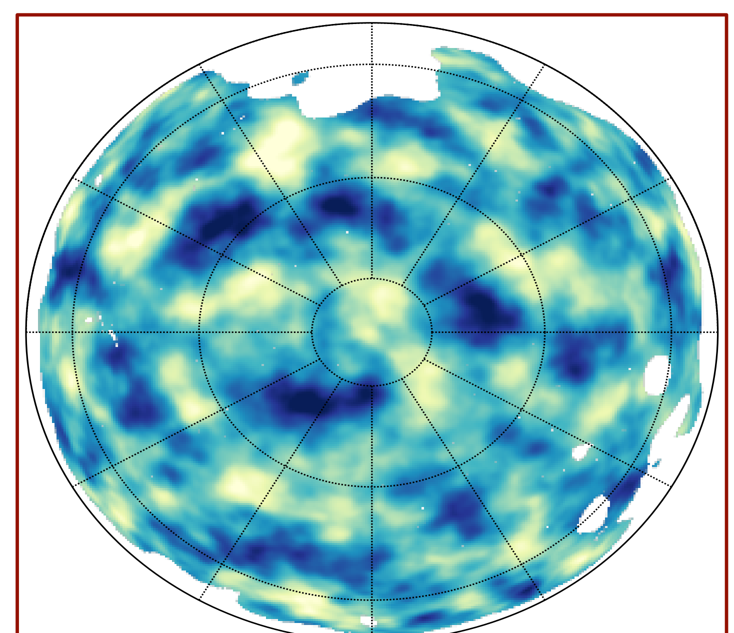
Gravitational Lensing of the CMB



Large scale structure between the last scattering surface and the observer gravitationally lenses the CMB anisotropies

Effect detected at more than 10 sigma!





Projected maps of the matter (baryon + dark) distribution between the last scattering surface and us!!

Neutrinos

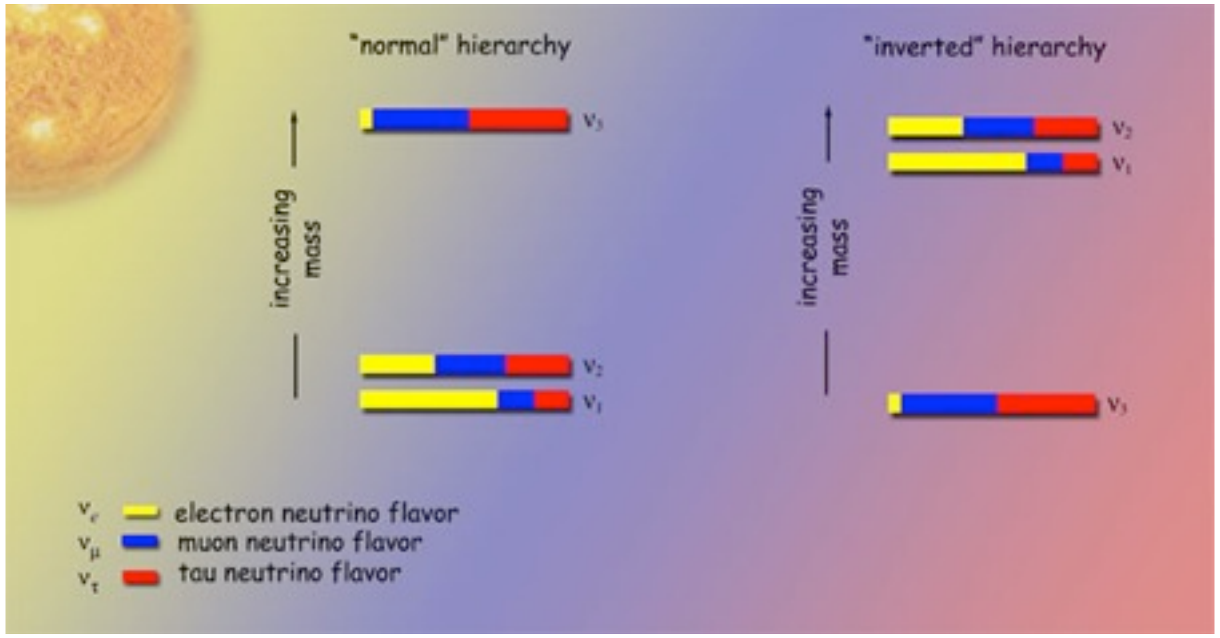
SM (of particle physics): 3 neutrino species

Neutrino masses:

$$|\Delta m_{12}^2| = (5.4 - 9.5) \times 10^{-5}\,\mathrm{eV}^2 \qquad \text{solar}$$

$$|\Delta m_{23}^2| = (1.2 - 4.8) \times 10^{-3}\,\mathrm{eV}^2 \qquad \text{atmosferic}$$

$$m_{\nu_e} < 2.5\,\mathrm{eV} \qquad {}^3H\,\beta\,\text{decay}$$



Cosmic neutrino background: - decouple at T~1 MeV

- today $\left.\frac{n_{\nu i}}{n_\gamma}\right|_{T<0.5\,\mathrm{MeV}} = \frac{3}{11}$ $\quad n_{\nu_i} \simeq 200\ \mathrm{cm}^{-3}$

Neutrinos and the CMB

Massive neutrinos below free streaming scale do not cluster, thus the gravitational potential decays at small scales

Thanks to the detection of gravitational lensing the upper bound on the total neutrino mass becomes considerably stronger than before (WMAP)

$$\sum m_\nu < 0.66\,\mathrm{eV} \quad (95\%;\ Planck\text{+WP+highL})$$

stronger than laboratory limits!!

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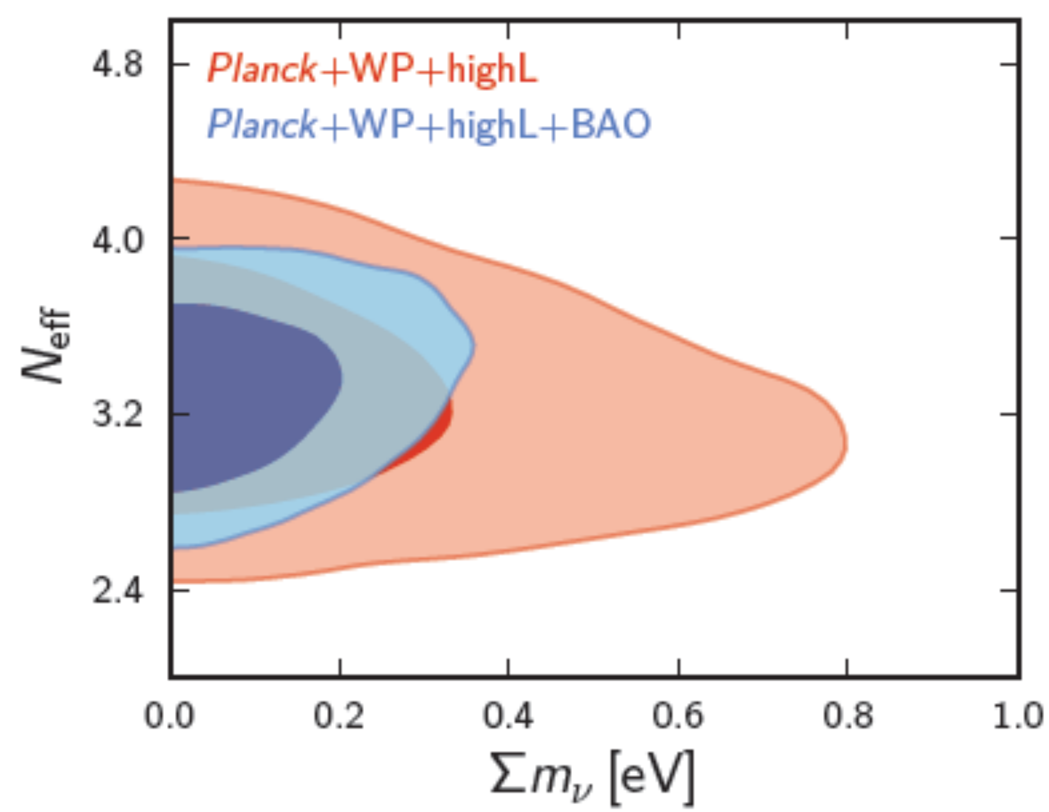
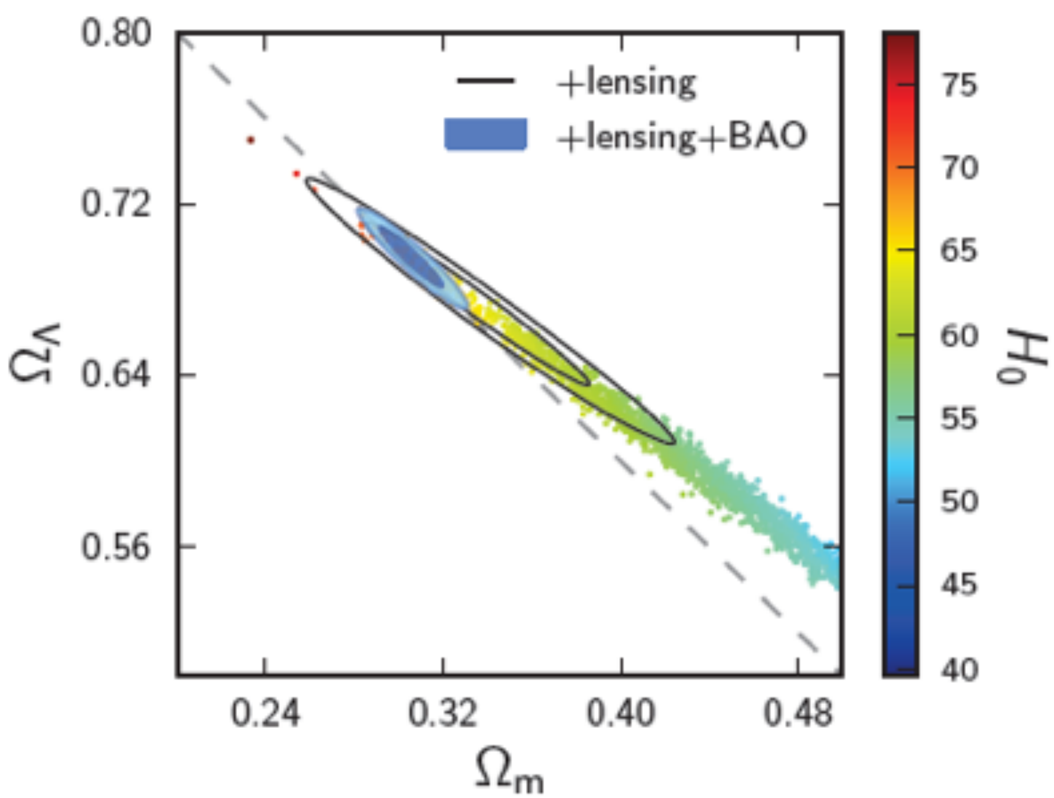
No evidence for extra neutrino species

$$N_{\text{eff}} = 3.36^{+0.68}_{-0.64} \quad (95\%;\ \textit{Planck}\text{+WP+highL}).$$



Dark Energy From Planck



Dark Energy required by CMB alone (lensing) independently of astrophysical observations (SNeIa)

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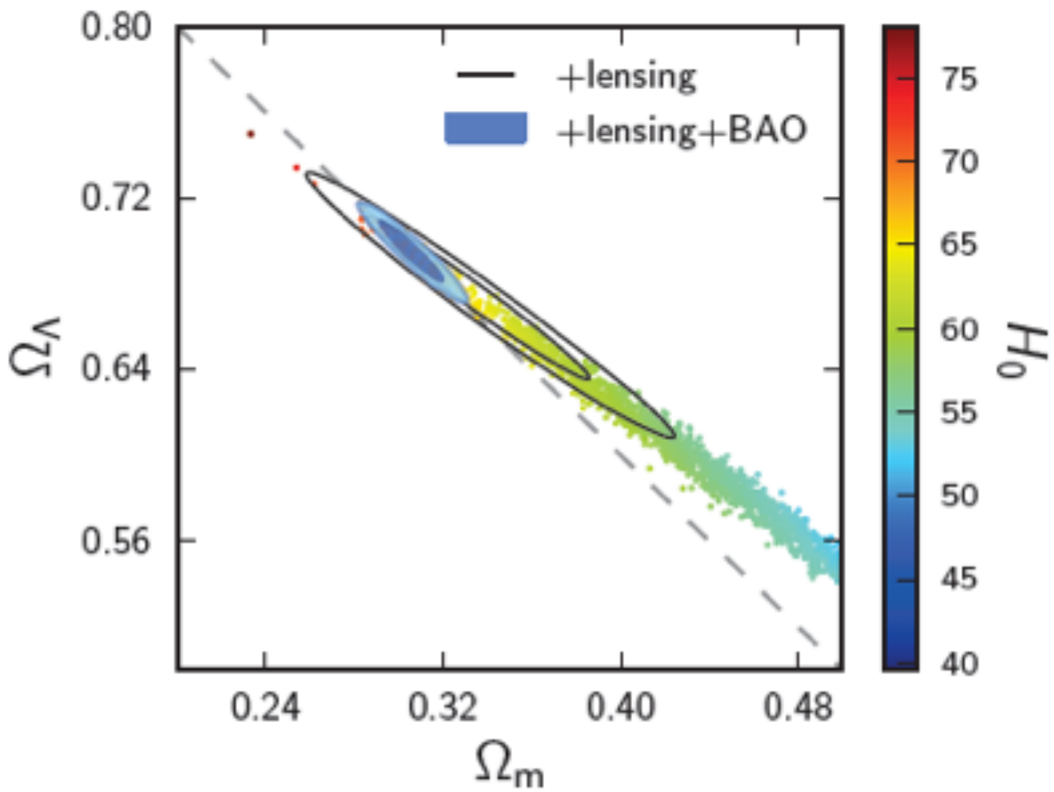
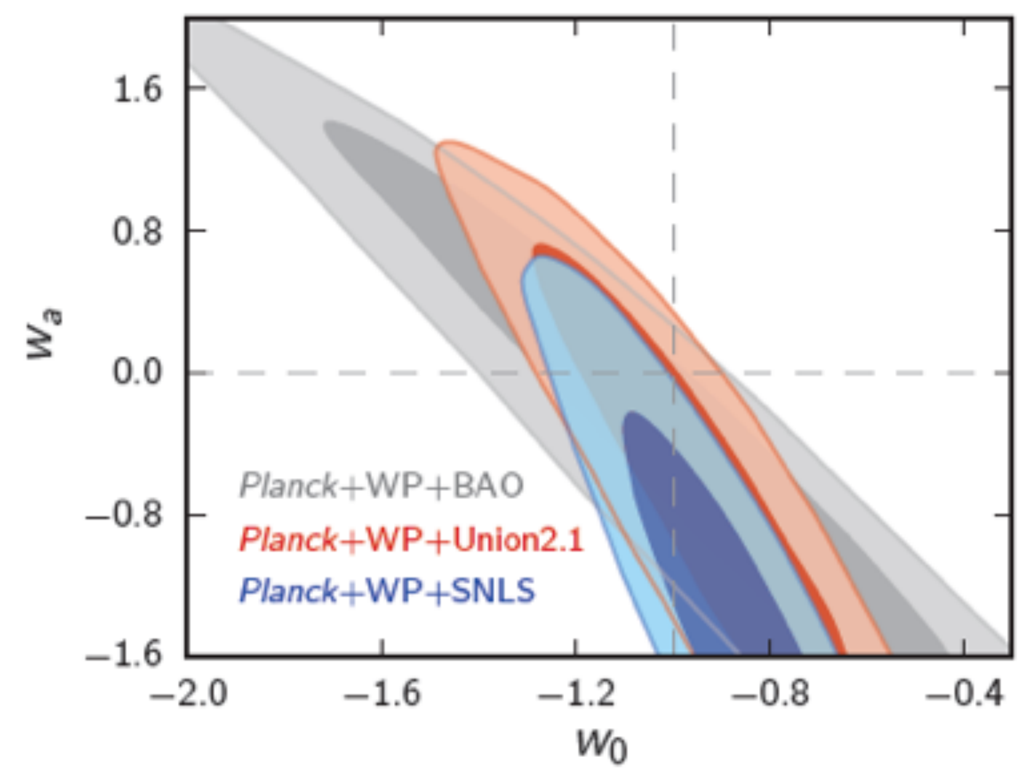


Dark Energy required by CMB alone (lensing) independently of astrophysical observations (SNeIa)



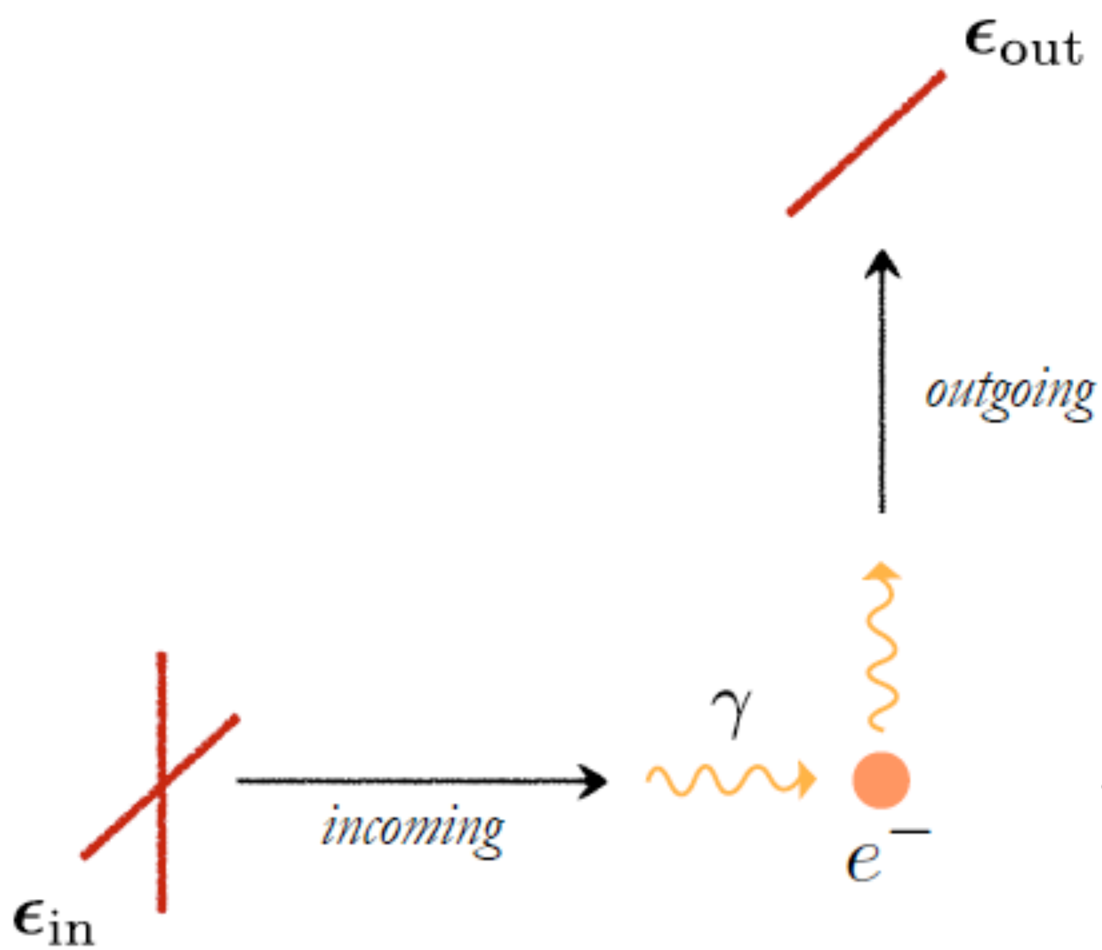
Assuming the simple DE parametrization $p_{DE}=w(a)\rho_{DE}$ with $w(a) = w_0 + w_a(a_0-a)$

Planck finds (95%; Planck+WP+BAO):
$w_0 = -1.04\ (+0.72/-0.69)$
$w_a < 1.32$

Cosmological constant: $w_0=-1$, $w_a=0$

CMB polarization

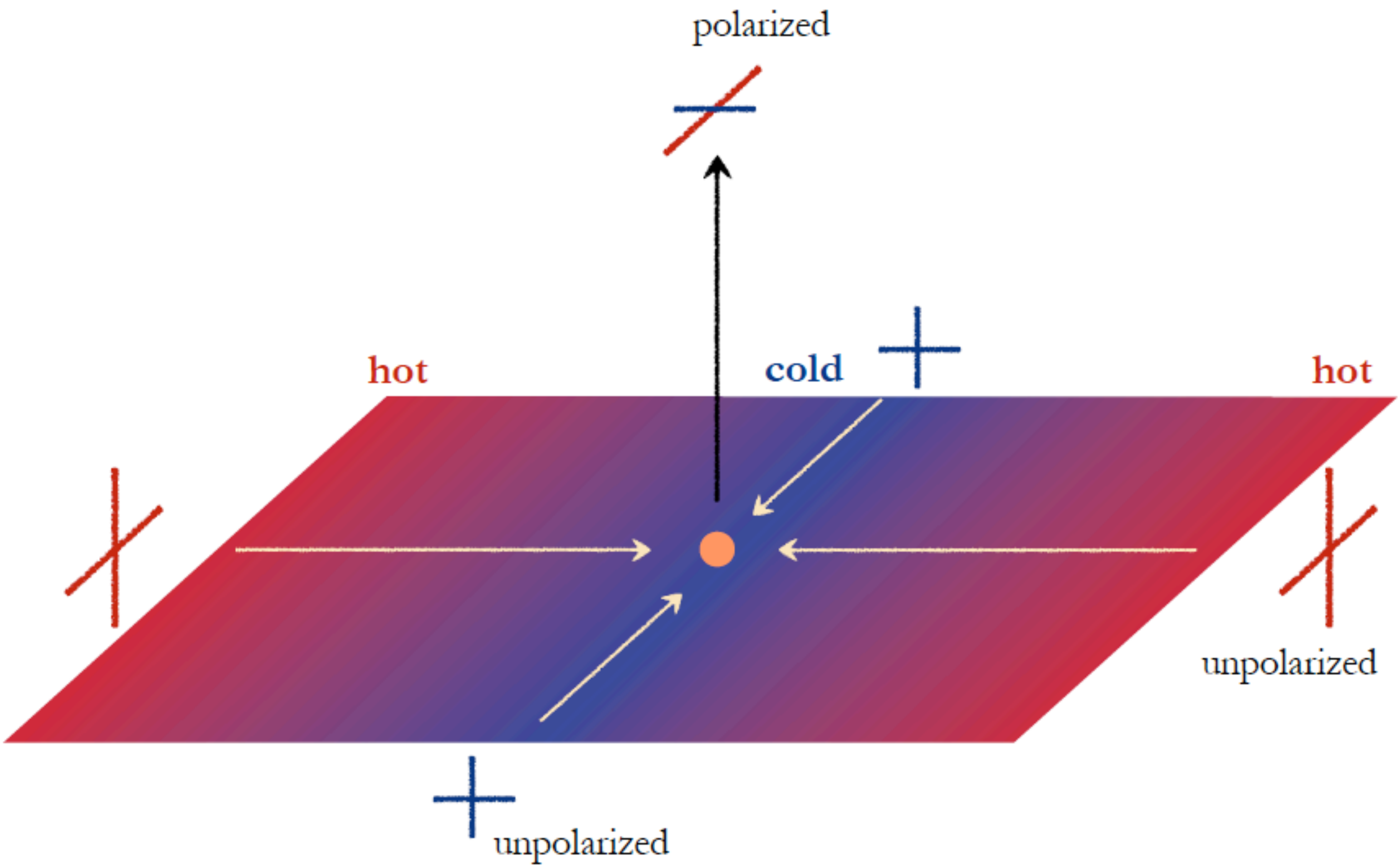
Thomson scattering is anisotropic:



$$\frac{d\sigma}{d\Omega} \propto \left| \epsilon_{in} \cdot \epsilon_{out} \right|^2$$

from D. Baumann

Quadrupolar temperature anisotropy leads to linear polarization:



from D. Baumann

A quadrupolar temperature anisotropy can be generated by

I) Anisotropies in the density of photons sorrounding the electron (scalar perturbations)

II) A quadrupolar stretching of space due to a passing gravitational wave (tensor perturbations)

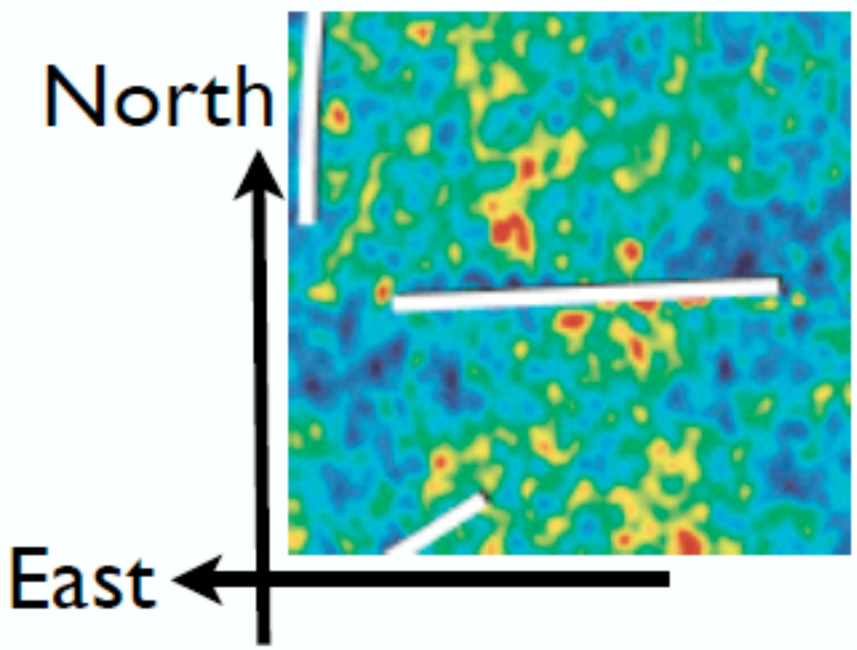
$$dl^2 = a^2(t)e^{2\zeta(x,t)}[e^h]_{ij}dx^i dx^j$$

$$= a^2(t)[1+2\zeta(x,t)+\ldots][\delta_{ij}+h_{ij}(x,t)+\ldots]dx^i dx^j$$

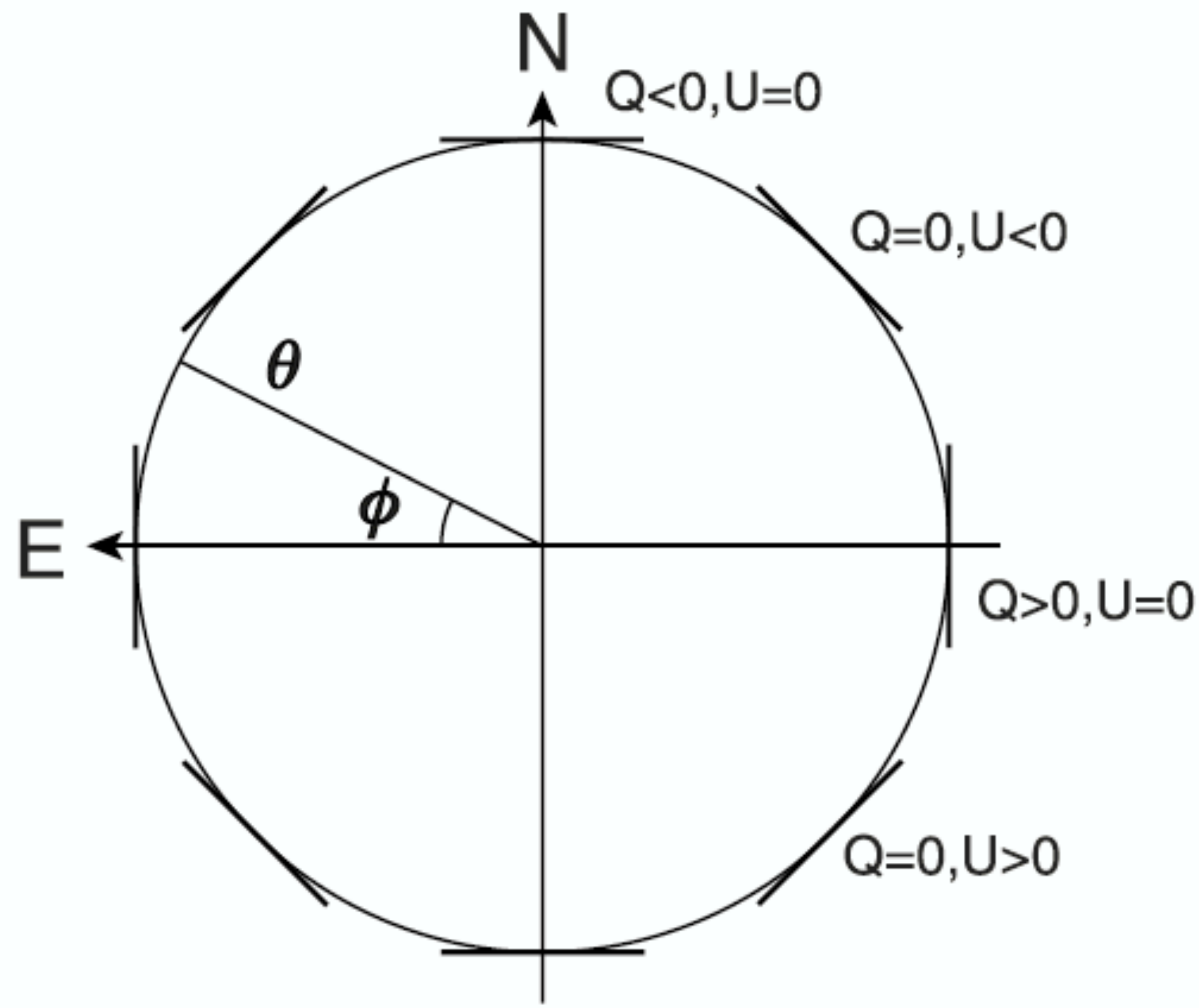
$\left(\frac{\delta T}{T} = -\frac{\zeta}{5}\right)$ scalar (curvature) tensor (gravitational wave)

can we distinguish between them?

“Stokes Parameters”

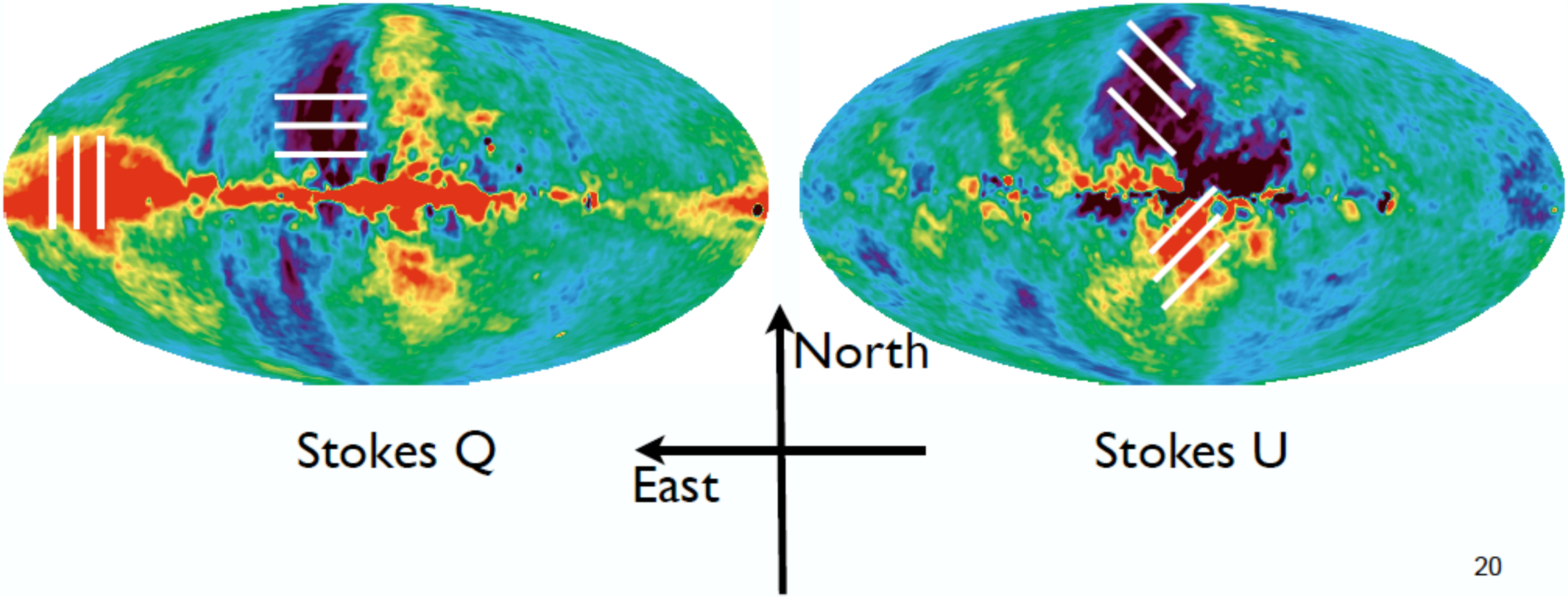


Q<0; U=0



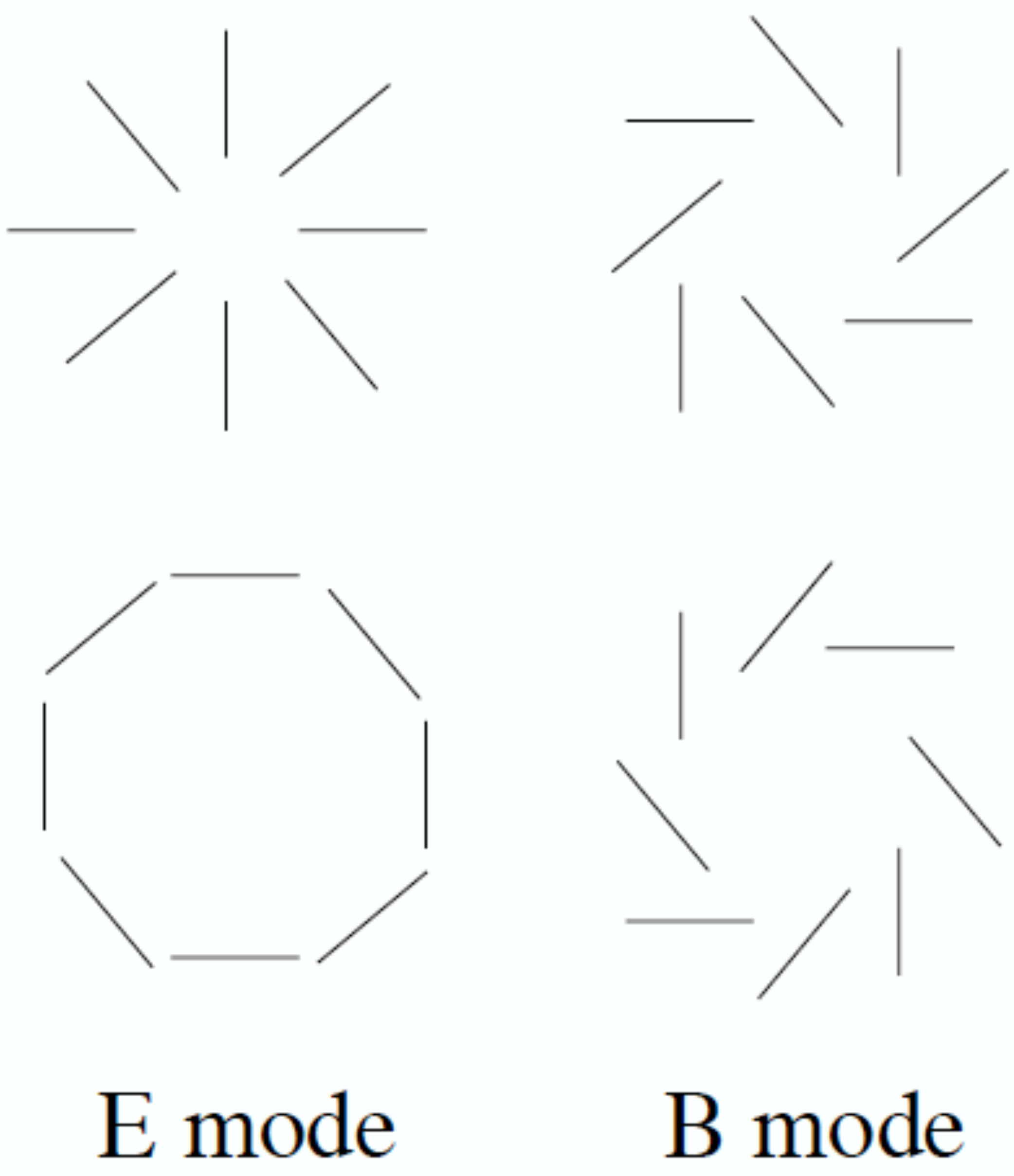
from E. Komatsu

23 GHz [polarized]



from E. Komatsu

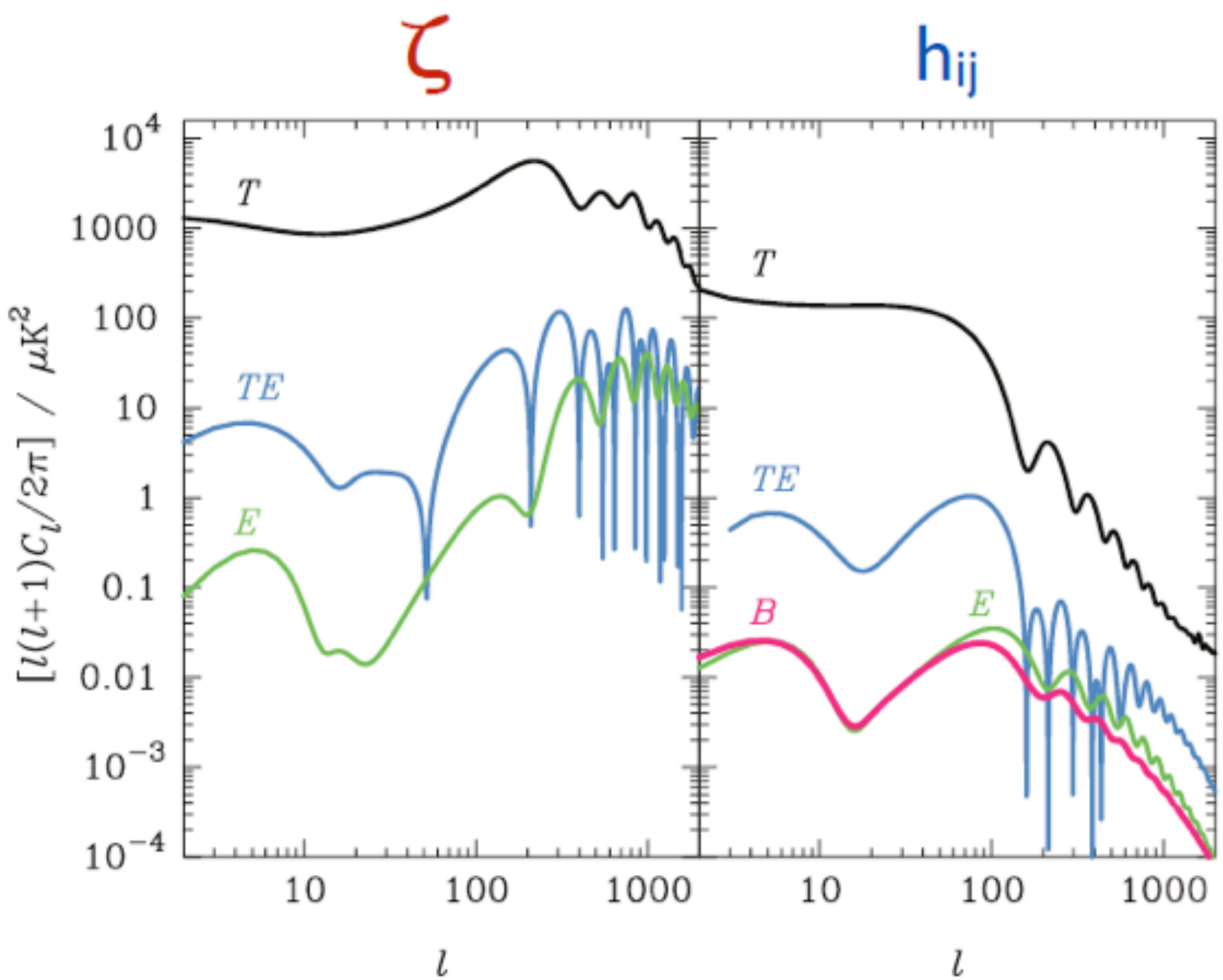
E-mode and B-mode



- Gravitational potential can generate the E-mode polarization, but not B-modes. (scalar)
- **Gravitational waves** can generate both E- and B-modes! (tensor)

from E. Komatsu

We predict the following power spectra for scalar and tensor perturbations:



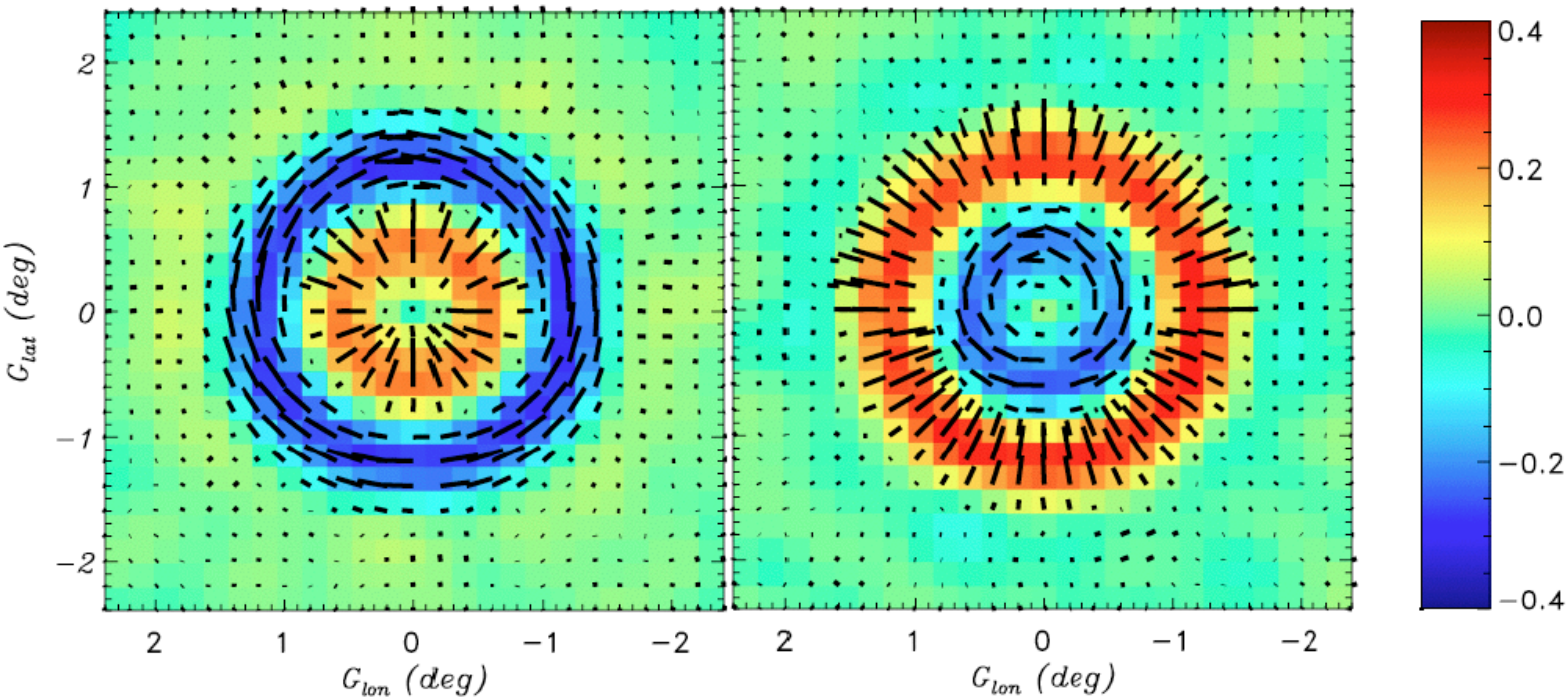
B-modes are unique to tensors.

Challinor

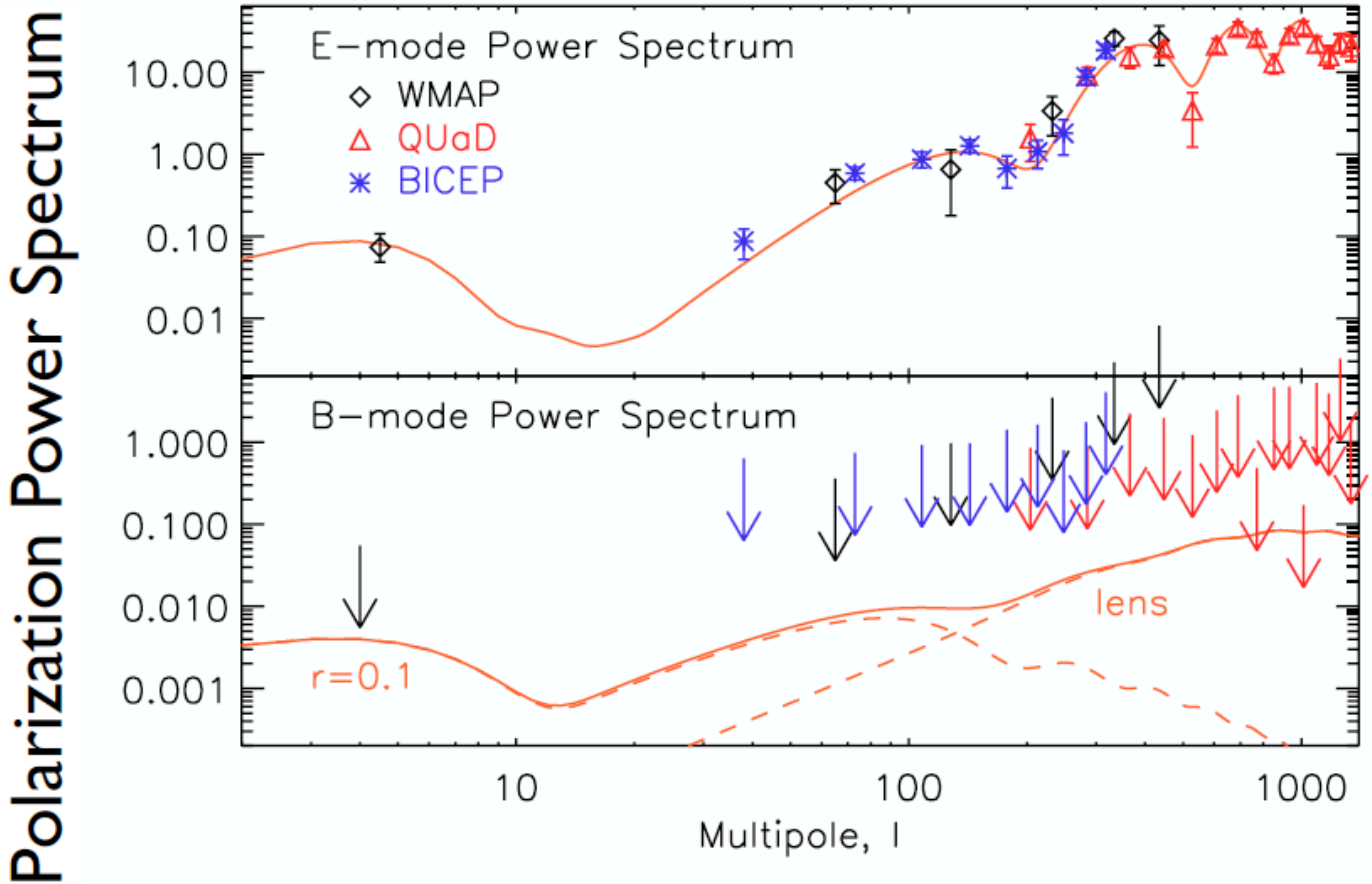
E-modes

Planck Collaboration I (2013)

Planck Data!



Q_r (cold spots) Q_r (hot spots)



- No detection of B-mode polarization at degree scales, *before March 17*

“Tensor-to-scalar Ratio,” r

r = [Power in Gravitational Waves]

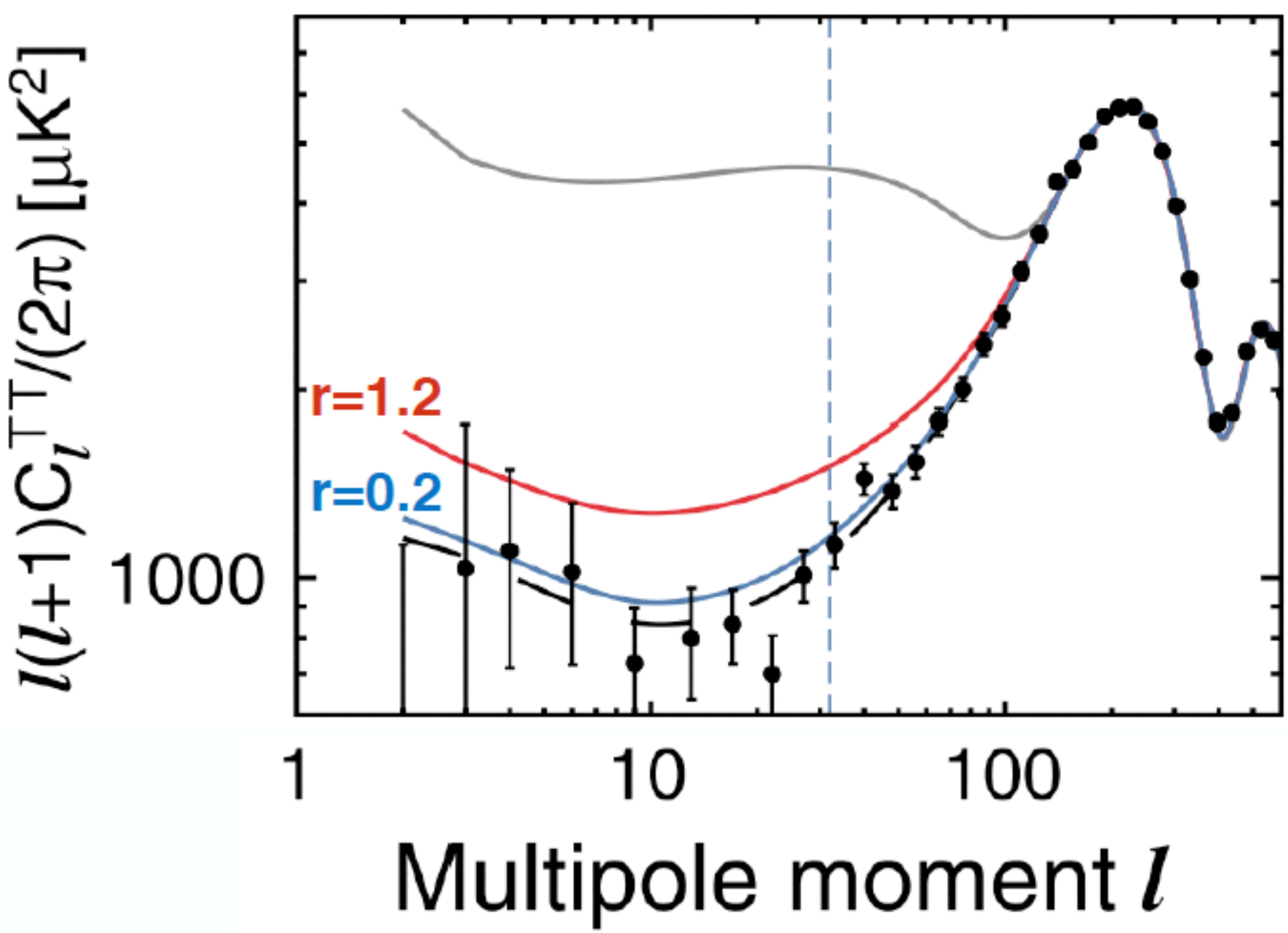
/ [Power in Curvature Perturbation]

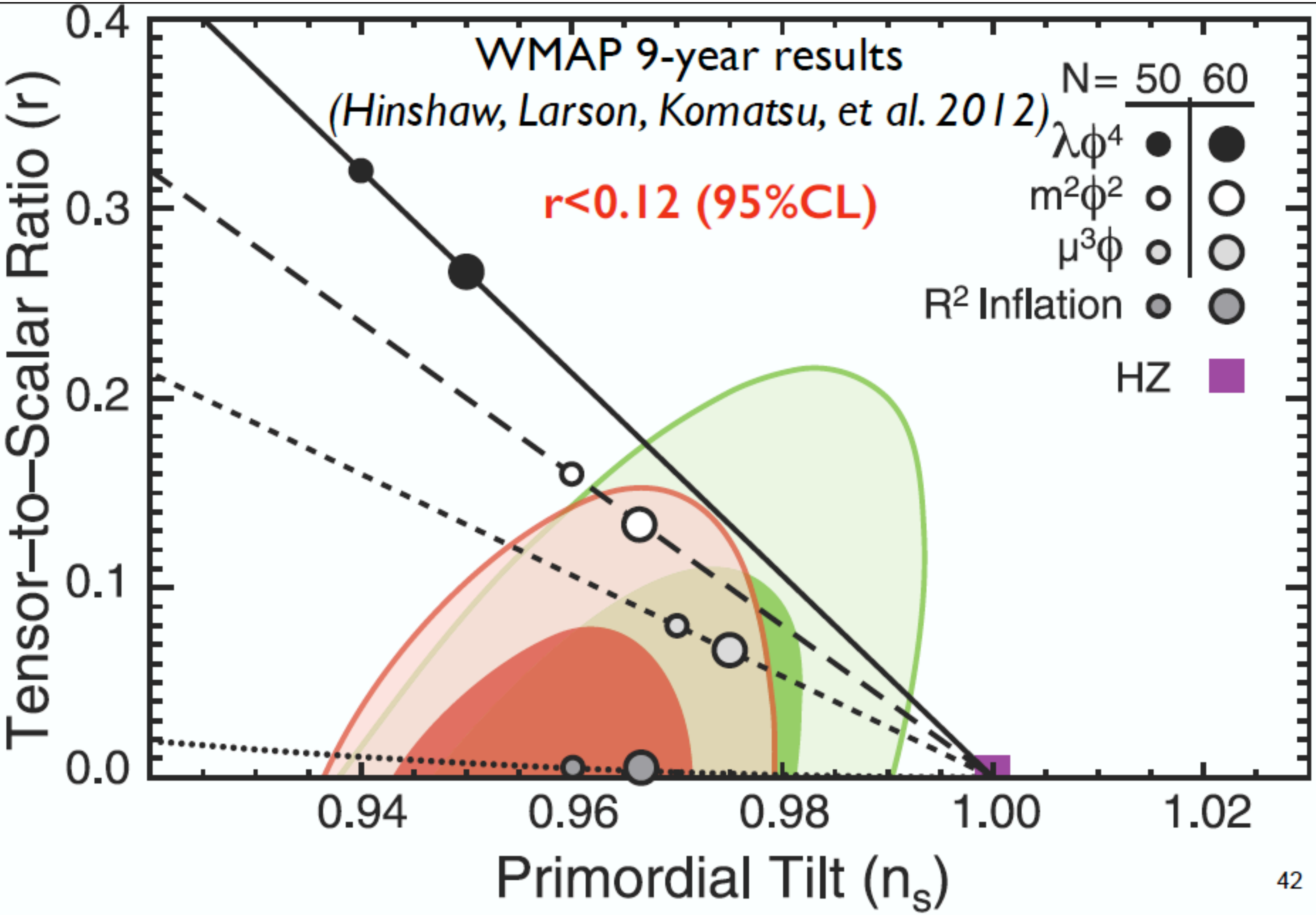
$= \langle h_{ij,k0} h^{ij,k0*} \rangle / \langle |\zeta_{k0}|^2 \rangle$ at k_0=0.002 Mpc^{-1}

Inflation predicts r <~ 1

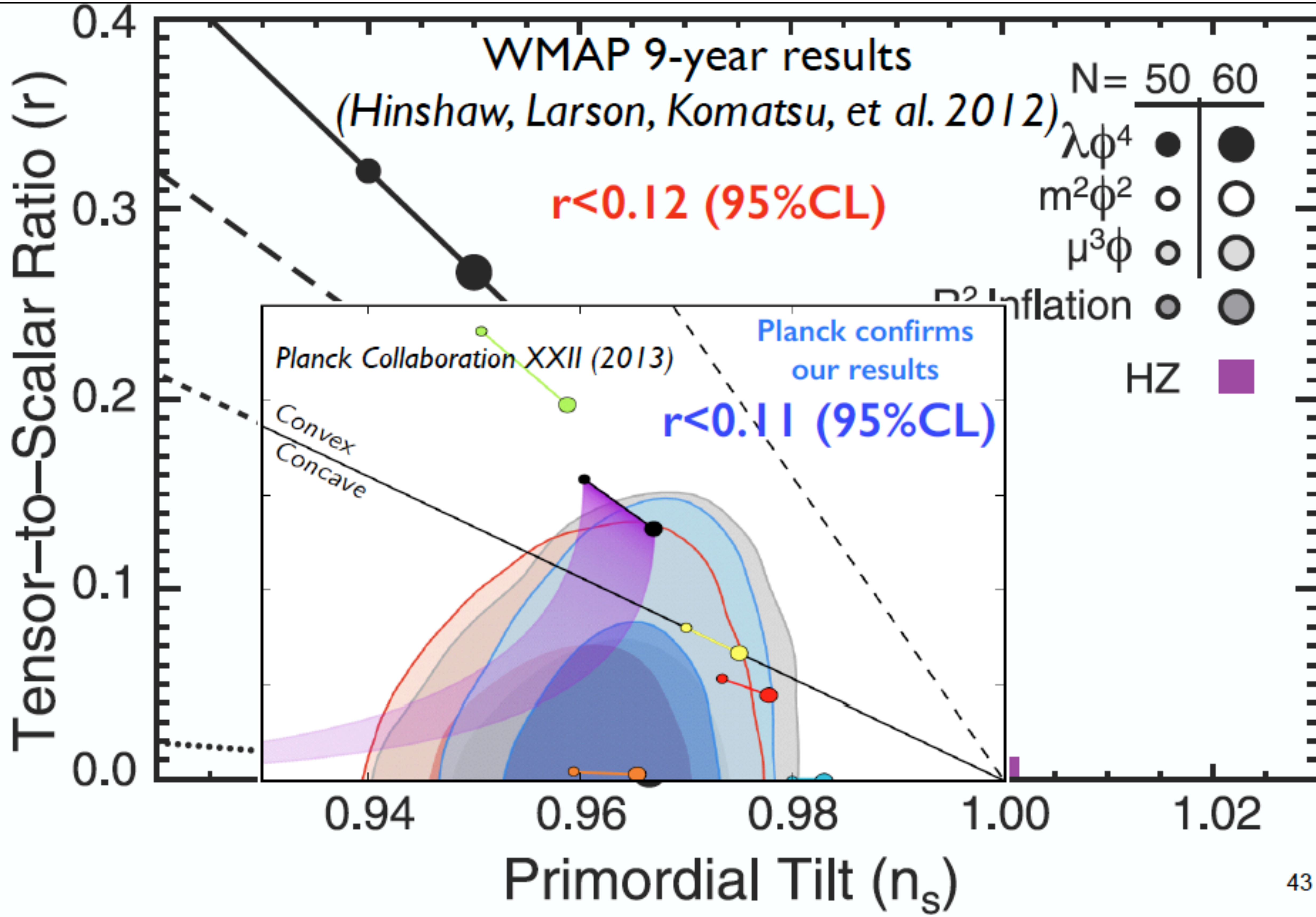
WMAP5

Limit from Temperature

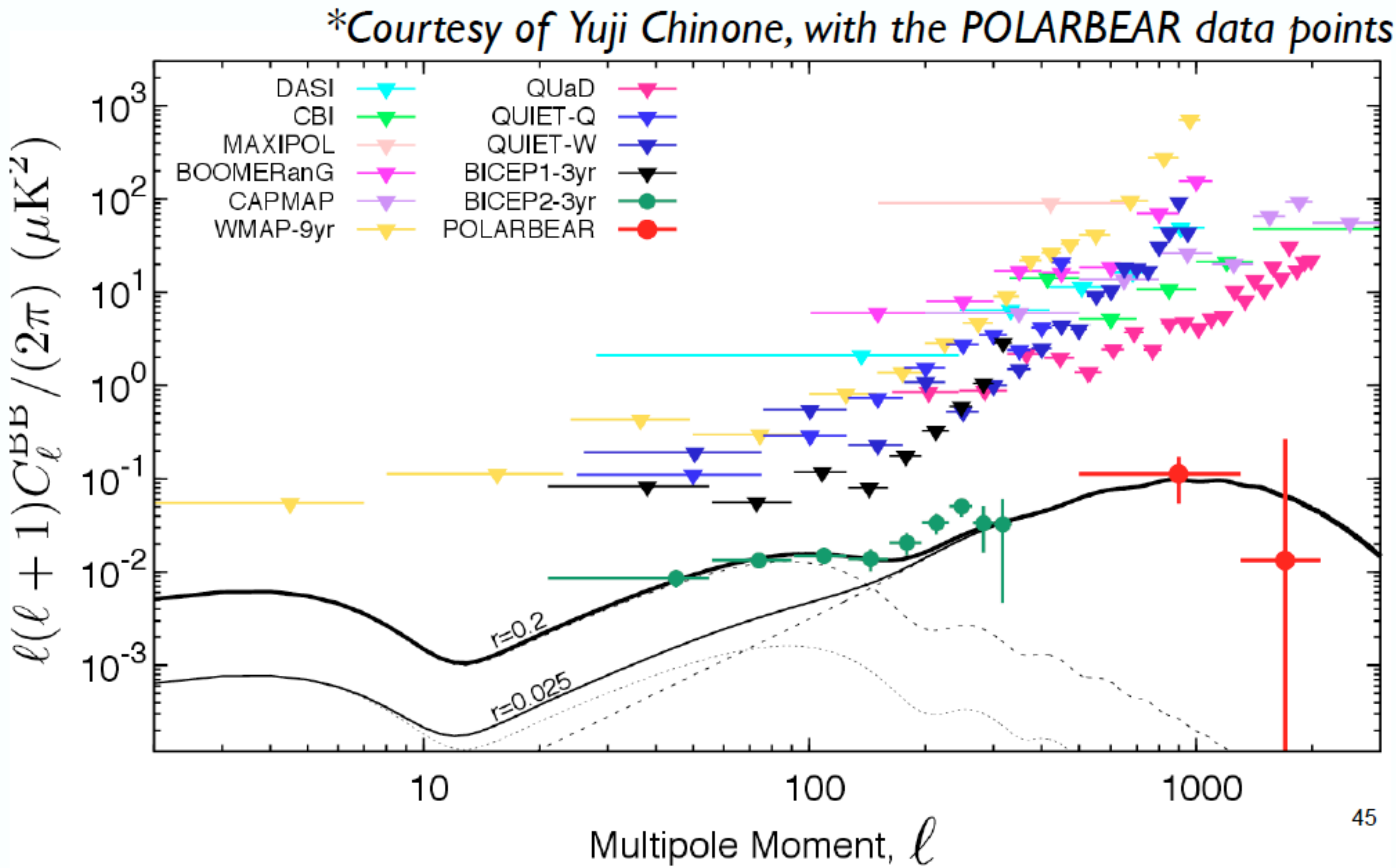




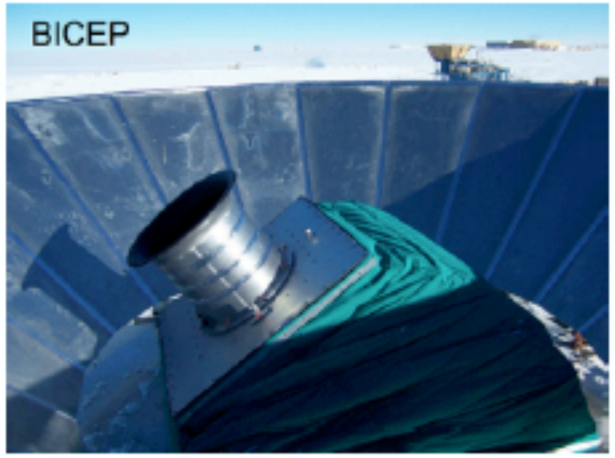
WMAP 9-year results
(Hinshaw, Larson, Komatsu, et al. 2012)
r<0.12 (95%CL)
N= 50 60
λφ⁴
m²φ²
μ³φ
R² Inflation
HZ
Tensor-to-Scalar Ratio (r)
Primordial Tilt (n_s)
0.0
0.1
0.2
0.3
0.4
0.94
0.96
0.98
1.00
1.02


WMAP 9-year results
(Hinshaw, Larson, Komatsu, et al. 2012)
r<0.12 (95%CL)
N= 50 60
λφ⁴
m²φ²
μ³φ
R² Inflation
HZ
Planck Collaboration XXII (2013)
Planck confirms our results
r<0.11 (95%CL)
Convex
Concave
Tensor-to-Scalar Ratio (r)
Primordial Tilt (n_s)
0.0
0.1
0.2
0.3
0.4
0.94
0.96
0.98
1.00
1.02

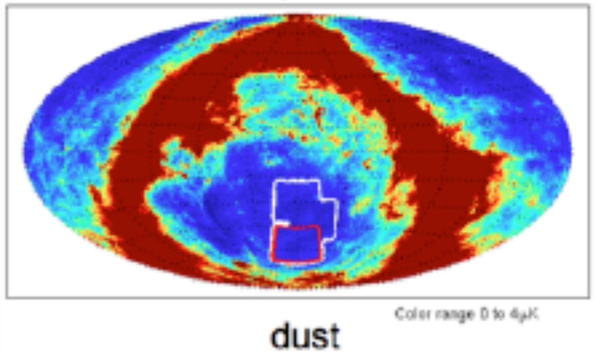
March 17, 2014 BICEP2!



What is BICEP2?

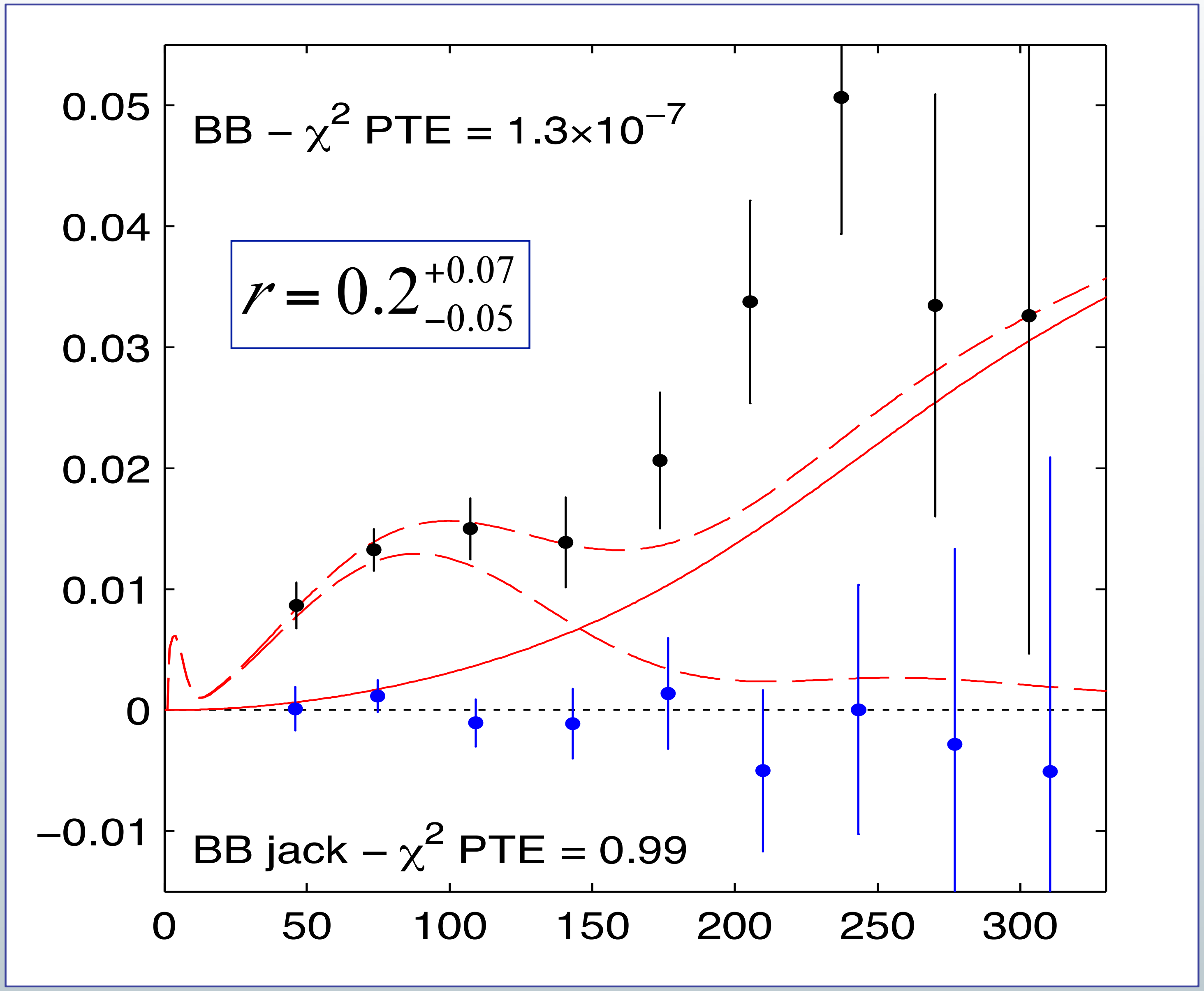


- A small [26 cm] refractive telescope at South Pole
- 512 bolometers working at 150 GHz



- Observed 380 square degrees for three years [2010-2012]
- Previous: BICEP1 at 100 and 150 GHz [2006-2008]
- On-going: Keck Array = 5 x BICEP2 at 150 GHz [2011-2013] and additional detectors at 100 and 220 GHz [2014-]

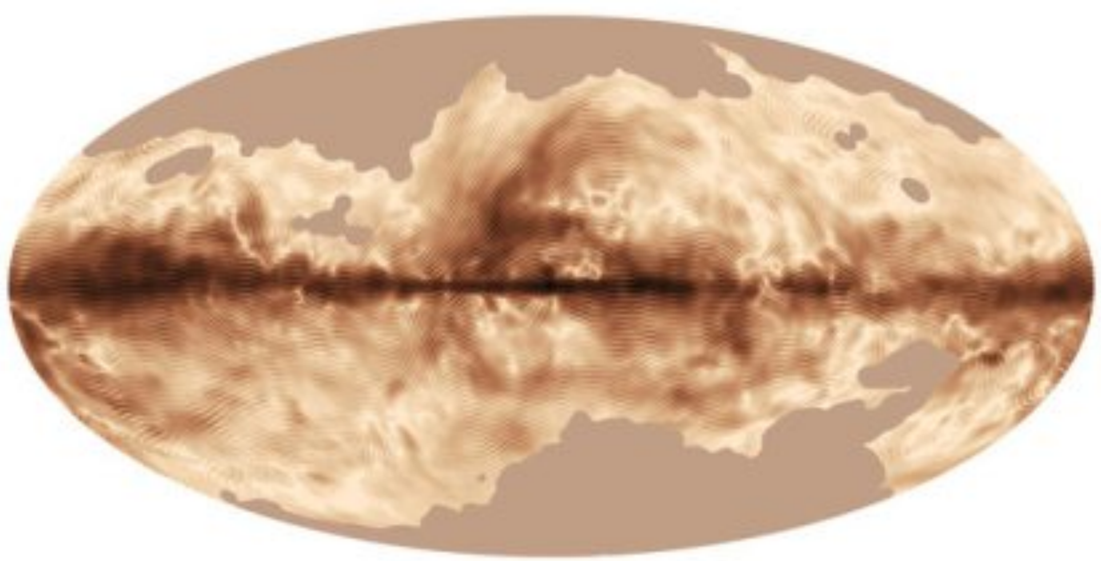
BICEP2 results: BB power spectrum



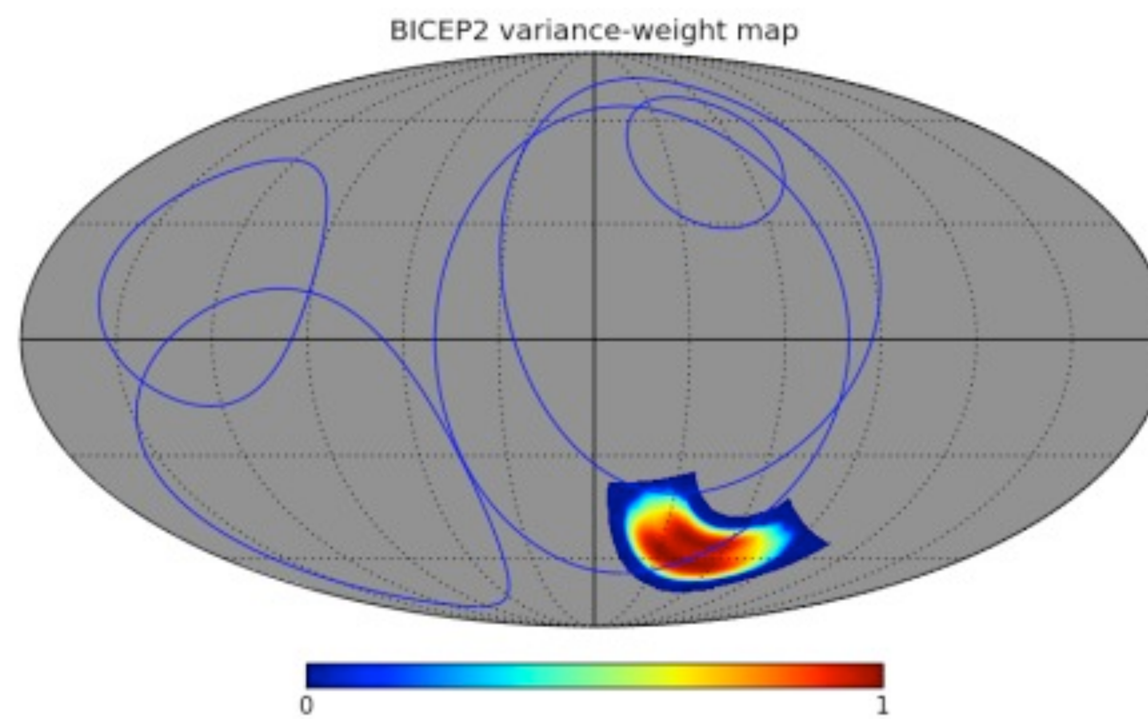
r=0 excluded at the 5.9 σ level

Has Bicep2 observed the cosmological primordial B modes?

Main weak point: only one frequency (150 GHz) need more frequencies to definitely separate the foreground emission from Galaxy



Planck, May 5th, 2014
polarization at 353 GHz
(mostly from galactic dust)



Bicep2 corner of sky

Wait for more frequencies/more sky (Planck, Keck,...)

If Bicep2 ha observed the cosmological primordial B modes, what do we learn?

1) Inflation happened

1.1) Inflation happened at a scale ~2×10^{16} GeV
1.2) many models of Inflation are ruled out

2) Gravitons were produced during Inflation: gravity is a quantum theory!!

gravitons in an expanding Universe

$$ds^2=a^2(\tau)[-d\tau^2+(\delta_{ij}+h_{ij}(\underline{x},\tau))\,dx^i\,dx^j]$$

traceless, symmetric h_{ij}, satisfies the equation of motion

$$h''_{ij}+2\frac{a'}{a}h'_{ij}-\nabla^2 h_{ij}=0$$

$' = d/d\tau$

$$h_{ij}(\vec{x},\tau)=\int\frac{d^3k}{(2\pi)^3}e^{i\vec{k}\cdot\vec{x}}\varphi(\vec{x},\tau)\varepsilon_{ij}(\vec{k})$$

$$\varphi''+2\frac{a'}{a}\varphi'+k^2\varphi=0$$

polarization tensor

free massless, minimally coupled scalar field

behaviour:

k « aH (outside the horizon) φ ≈ **const + decaying mode**

k » aH (inside the horizon) $\varphi \approx e^{\pm ik\tau}/a$ gravitational wave; it freely streams, experiencing redshift and dilution, like a free photon)

k (comoving momentum) is constant

Inflation defined by d(aH)/dt >0: microscopic scales grow and eventually become larger than the horizon (1/aH)

quantize h_{ij} : plane waves become gravitons.

Redshift by Inflationary expansion turns them into classical gravitational waves

Models for Inflation

``Large field'' models

$$V(\phi) \propto \phi^{\alpha}$$

typical of ``caothic inflation scenario''
(Linde `83)

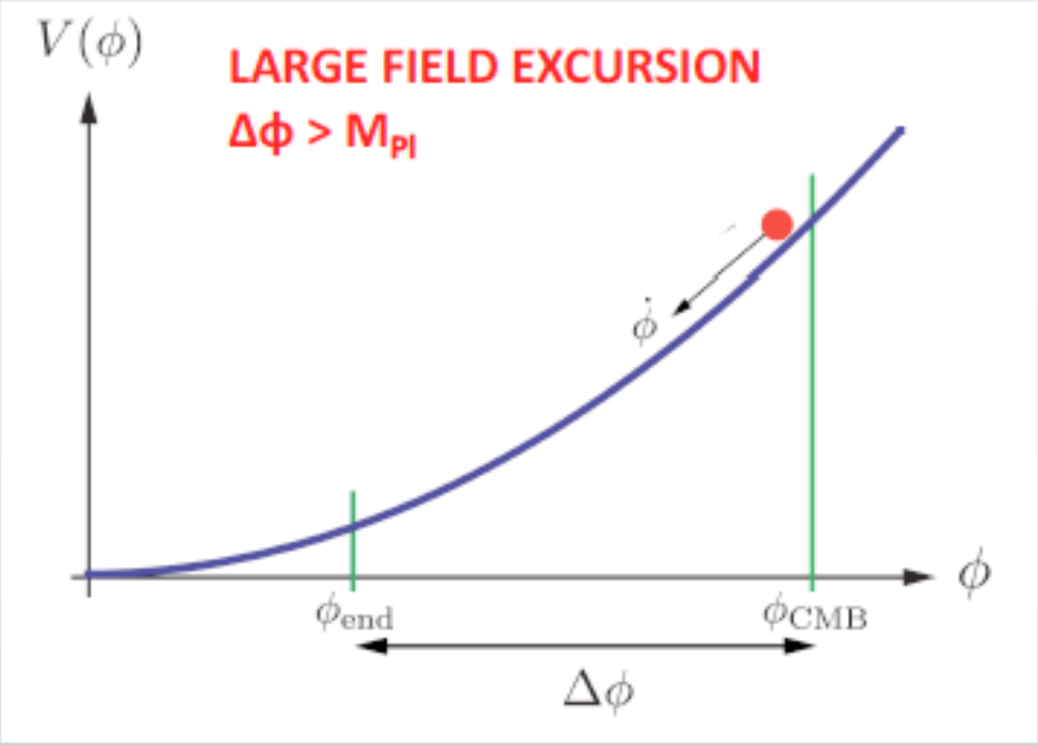
$$V(\phi) \propto \exp[\phi/\mu]$$

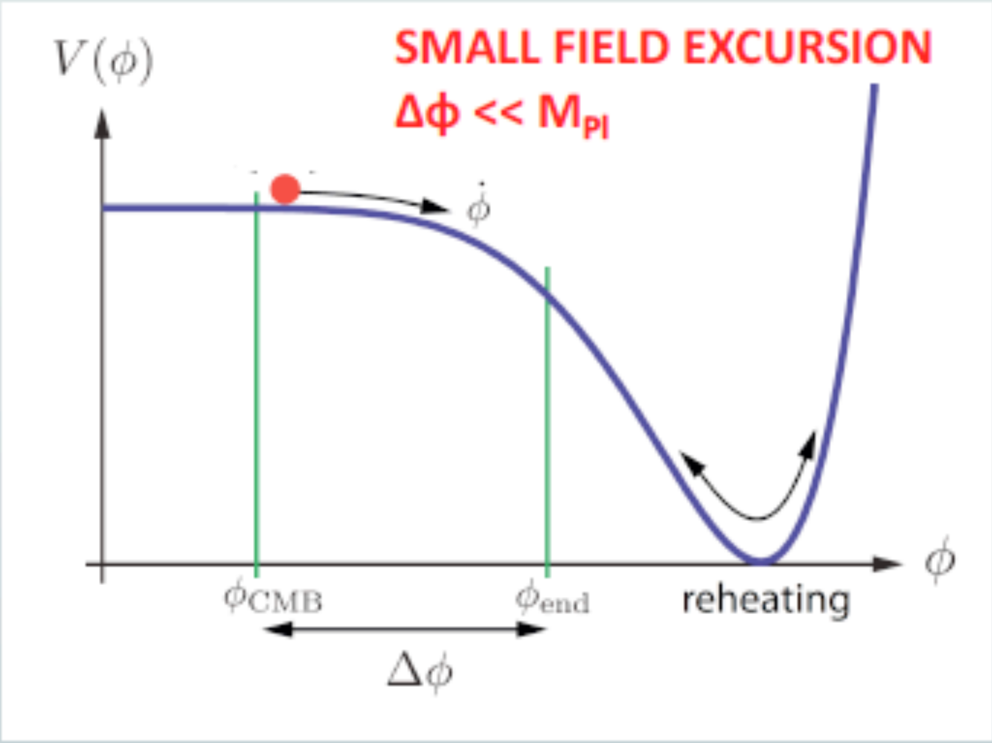
``power law inflation'' (Lucchin, Matarrese'85)

``Small field'' models

$$V(\phi) = V_0 \left[1 - \left(\frac{\phi}{\mu}\right)^p\right] \qquad \phi < \mu < M_{\rm Pl}$$

from spontaneous symmetry breaking or Goldstone, axion models (Linde; Albrecht, Steinhardt `82; Freese et al '90)





Slow roll Inflation: parameters and observables

$$\epsilon = \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2$$

$$\eta = M_P^2\left(\frac{V''}{V}\right)$$

$$\xi^2 = M_P^2 V' V''' / V^2$$

$$M_P \equiv (8\pi G_N)^{-1/2}$$

scalar (comoving curvature) perturbation power-spectrum

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{1}{2M_P^2\epsilon}\left(\frac{H_*}{2\pi}\right)^2\left(\frac{k}{aH_*}\right)^{n_{\mathcal{R}}-1}$$

Measured by Planck

scalar spectral index $n_R - 1 = -6\varepsilon + 2\eta$

"running" $dn_R / d\ln k = -2\xi + 16\varepsilon\eta - 24\varepsilon^2$

tensor (gravity-wave) perturbation power-spectrum

$$\mathcal{P}_T(k) = \frac{k^3}{2\pi^2}\langle h_{ij}^* h^{ij}\rangle = \frac{8}{M_P^2}\left(\frac{H_*}{2\pi}\right)^2\left(\frac{k}{aH_*}\right)^{n_T}$$

almost independent on V
directly related to H_* !!

tensor-to-scalar ratio $r = \frac{\mathcal{P}_T}{\mathcal{P}_{\mathcal{R}}} = 16\epsilon$

tensor spectral index $n_T = -2\epsilon$

"Large field" models can produce a high level of gravity waves ($r>0.01$)

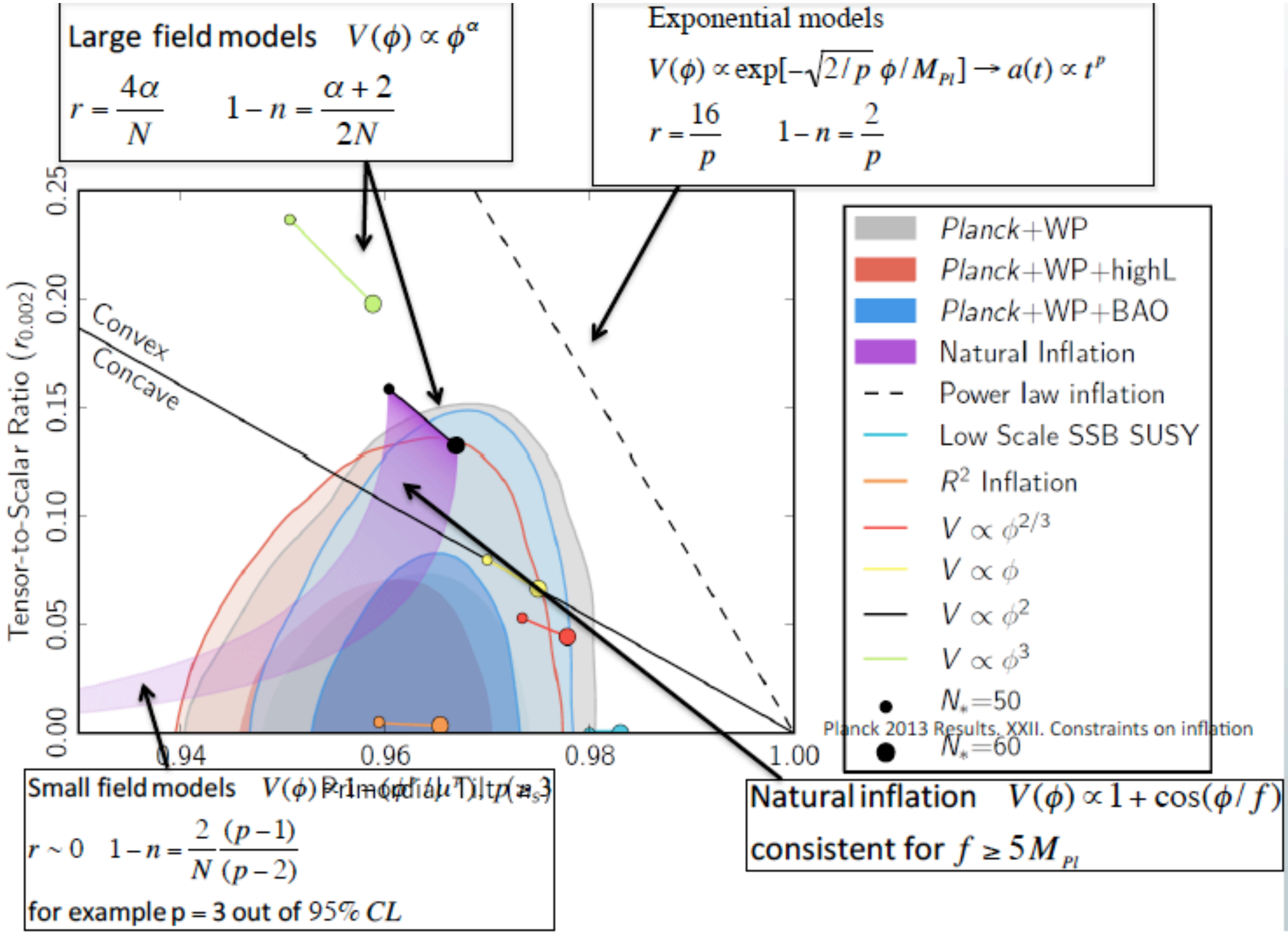
"Small field" models produce a low level of gravity waves ($r<0.01$)

$$\frac{\Delta\phi}{m_{\rm Pl}} \simeq \left(\frac{N}{30}\right) \times \left(\frac{r}{0.01}\right)^{1/2}$$

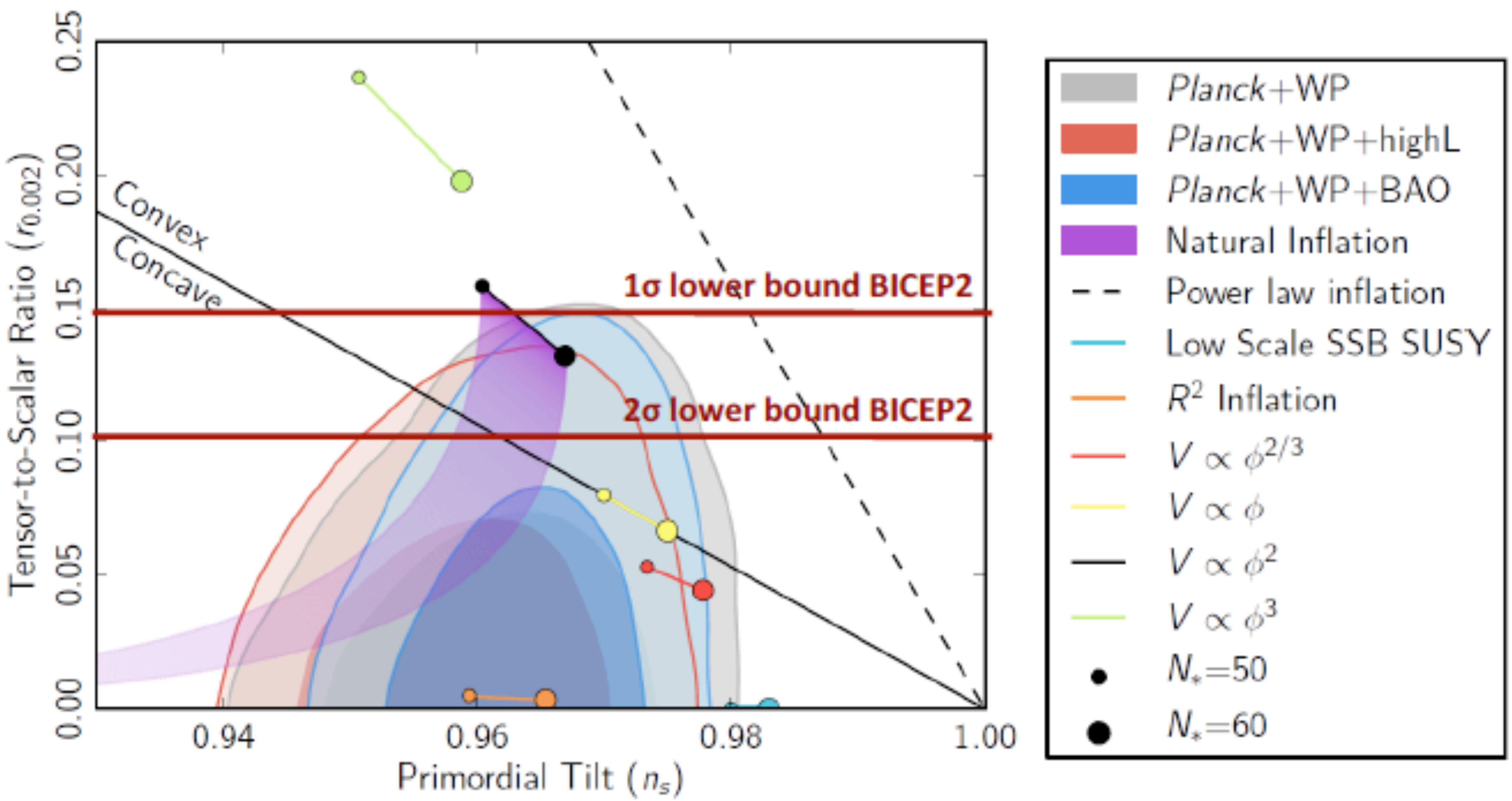
$30 \leq N \leq 60.$

So the bigger the field excursion during inflation the bigger the amplitude of gravity waves

Mapping models on the ns-r plane



Constraints after Planck+Bicep2



"small field" models (e.g. Higgs inflation, Starobinsky,...) predict r~0.003: ruled out!

Tension Bicep2-Planck?

- Planck: $r<0.11$, Bicep2: $r\sim 0.1\text{-}0.2$
- If the higher value from Bicep2 is confirmed, the two can be reconciled by including some form of scale dependence: maybe contrived, but possible).
- In any case, let's wait for Planck!

Conclusions

- A standard model of cosmology has been identified, at ~% accuracy or better
- The model is based on General Relativity + standard interactions (e.m., weak) and requires substantial amounts of Dark Matter and Dark Energy
- Bicep2 result, if confirmed, means that Nature is Quantum up to M_{Planck}, or, at least, $M \sim M_{GUT} \sim 10^{16}$ GeV: QFT-like "problems" like explaining the Hierarchy M_W/M_{Planck} now on firmer grounds
- A lot of New Physics out there: Inflaton, Dark Matter, Dark Energy, neutrino masses, Baryon asymmetry... modifications of GR?
- Luckily, a lot of new experiments/observations, too: Planck, Keck, Euclid,..., LHC, underground,....