Imperial College London

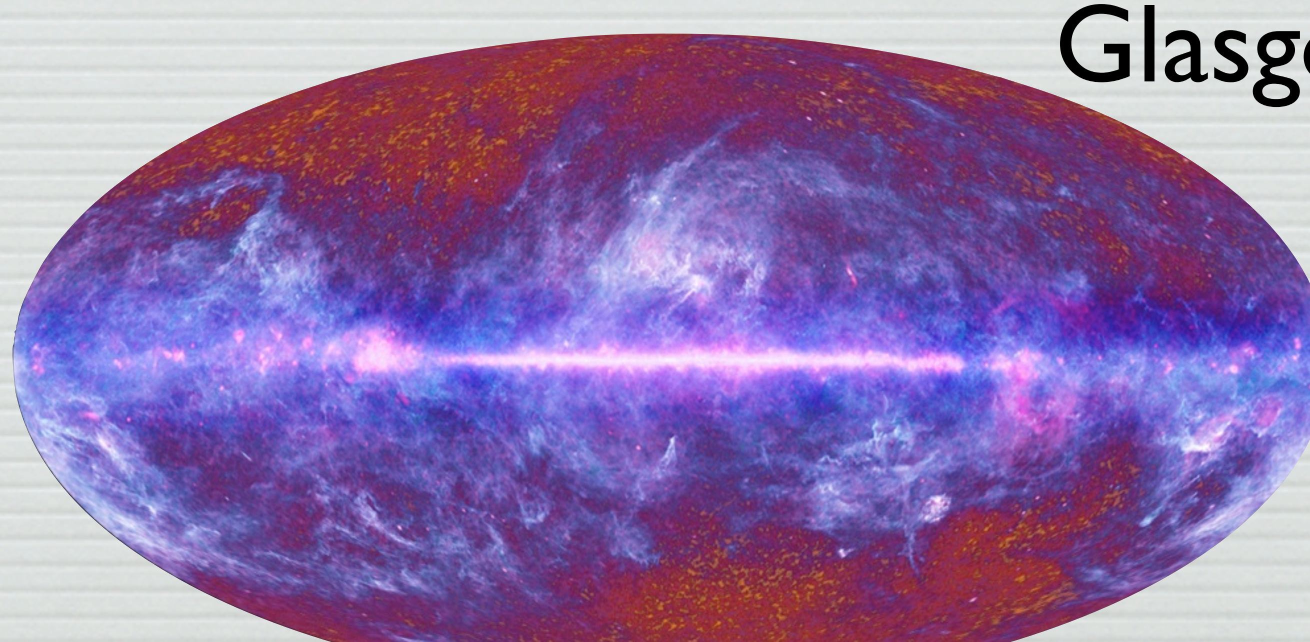
The Cosmic Microwave Background

Andrew Jaffe, Imperial College

Science & Technology Facilities Council

Summer School 2011

Glasgow



Imperial College London

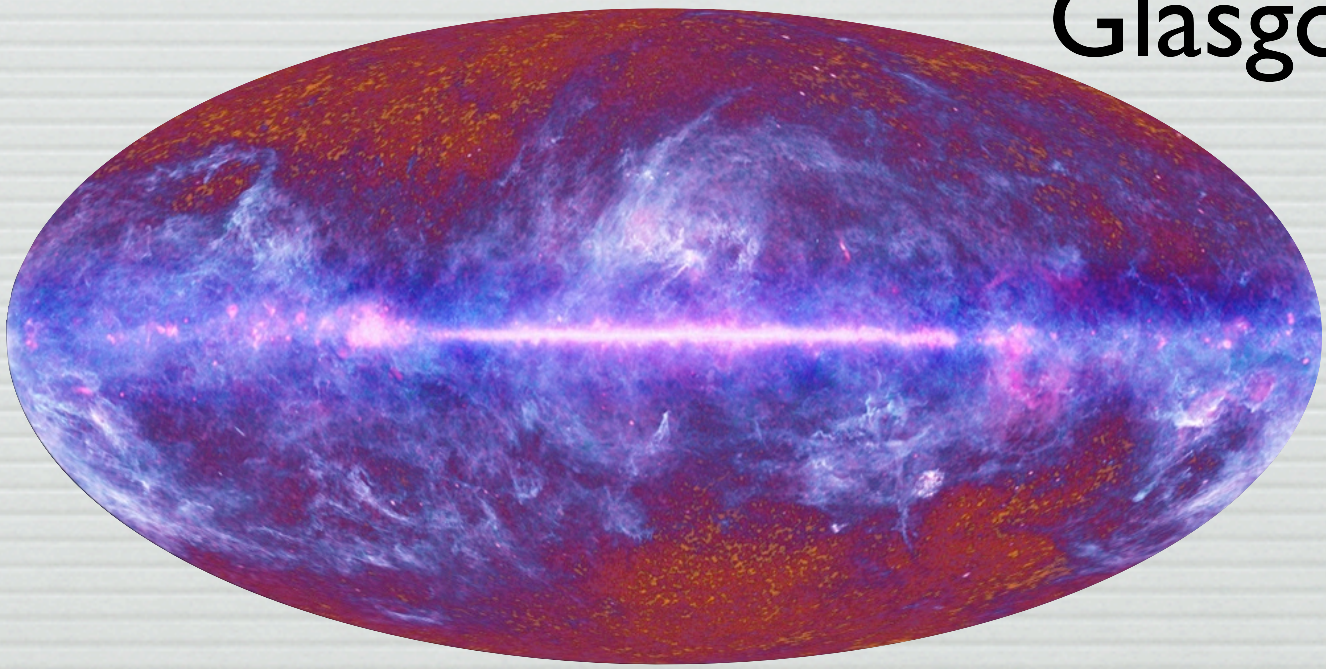
The Cosmic Microwave Background

Andrew Jaffe, Imperial College

Science & Technology Facilities Council

Summer School 2011

Glasgow



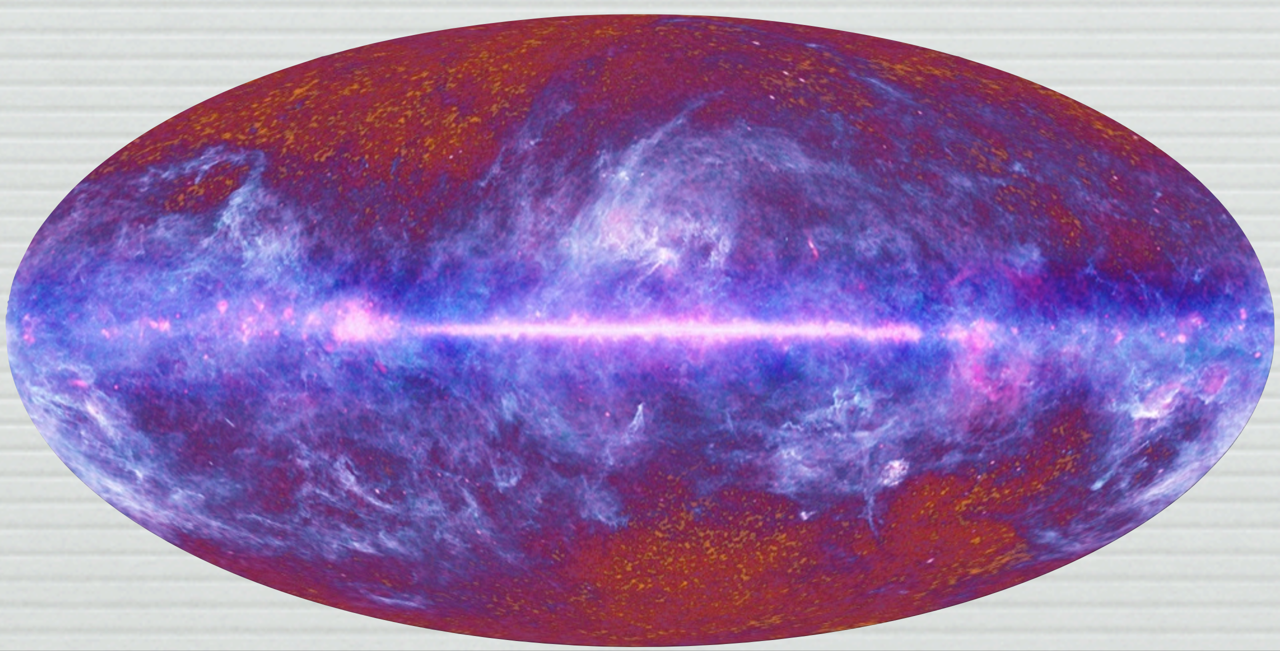
Imperial College London

The CMB

Andrew Jaffe

Sept 2011

Science & Technology Facilities Council



J. A. Tauber[36], N. Mandolesi[45], J.-L. Puget[52], T. Banos[82], M. Bersanelli[32], F. R. Bouchet[51], R. C. Butler[45], J. Charra[52], G. Crone[37],
J. Dodsworth[38], G. Efstathiou[90], R. Gispert[52], G. Guyot[52], A. Gregorio[93], J. J. Juillet[82], J.-M. Lamarre[66], R. J. Laureijs[36], C. R. Lawrence[61],
H. U. Nørgaard-Nielsen[35], T. Passvogel[37], J. M. Reix[82], D. Texier[39], L. Vibert[52], A. Zacchei[46], P. A. R. Ade[6], N. Aghanim[52], B. Aja[18], E. Alippi[84],
L. Aloy[37], P. Armand[82], M. Arnaud[7], A. Arondel[52], A. Arreola-Villanueva[61], E. Artal[18], E. Artina[84], A. Arts[37], M. Ashdown[89], J. Aumont[9],
M. Azzaro[40], A. Bacchetta[83], C. Baccigalupi[5], M. Baker[37], M. Balasini[84], A. Balbi[33], A. J. Banday[67,12], G. Barbier[64], R. B. Barreiro[58],
M. Bartelmann[67,95], P. Battaglia[84], E. Battaner[91], K. Benabed[51], J.-L. Beney[63], R. Beneyton[51], K. Bennett[36], A. Benoit[64], J.-P. Bernard[12],
P. Bhandari[61], R. Bhatia[61], M. Biggi[74], R. Biggins[38], G. Billig[38], Y. Blanc[14], H. Blavot[52], J. J. Bock[61], A. Bonaldi[49], R. Bond[13], J. Bonis[63],
J. Borders[61], J. Borrill[88], L. Boschini[84], F. Boulanger[52], J. Bouvier[64], M. Bouzit[52], R. Bowman[61], E. Bréelle[4], T. Bradshaw[77], M. Braghin[37],
M. Bremer[36], D. Brienza[34], D. Broszkiewicz[4], C. Burigana[45], M. Burkhalter[73], P. Cabella[33], T. Cafferty[61], M. Cairola[83], S. Caminade[52],
P. Camus[53], C. M. Cantalupo[65], B. Cappellini[32], J.-F. Cardoso[4], R. Carr[39], A. Catalano[4], L. Cayón[23], M. Cesa[83], M. Chaigneau[52], A. Challinor[90],
A. Chamballu[43], J. P. Chambelland[82], M. Charra[52], L.-Y. Chiang[55], G. Chlewicki[83], P. R. Christensen[71], S. Church[24], E. Ciancietta[83],
M. Cibrario[83], R. Cizeron[63], D. Clements[43], B. Collaudin[82], J.-M. Colley[4,51], S. Colombi[51], A. Colombo[37], F. Colombo[84], O. Corre[82],
F. Couchot[63], B. Cougrand[52], A. Coulais[66], P. Couzin[82], B. Crane[52], B. Crill[61], M. Crook[77], D. Crumb[61], F. Cuttaia[45], U. Dörl[67], P. da Silva[51],
R. Daddato[37], C. Damasio[37], L. Danese[5], G. d'Aquino[37], O. D'Arcangelo[60], K. Dassas[52], R. D. Davies[62], W. Davies[73], R. J. Davis[62],
P. De Bernardis[34], D. de Chambure[37], G. de Gasperis[33], M. L. De la Fuente[18], P. De Paco[81], A. De Rosa[45], G. De Troia[33], G. De Zotti[49],
M. Dehamme[63], J. Delabrouille[4], J.-M. Delouis[51], F.-X. Désert[64], G. di Girolamo[38], C. Dickinson[62], E. Doelling[38], K. Dolag[67], I. Domken[11],
M. Douspis[52], D. Doyle[37], S. Du[63], D. Dubruel[82], C. Dufour[4], C. Dumesnil[52], X. Dupac[39], P. Duret[52], C. Eder[63], A. Elfving[37], T. A. Enßlin[67],
P. Eng[52], K. English[61], H. K. Eriksen[10,56], P. Estaria[37], M. C. Falvella[2], F. Ferrari[84], F. Finelli[45], A. Fishman[61], S. Fogliani[46], S. Foley[38],
A. Fonseca[61], G. Forma[82], O. Forni[12], P. Fosalba[87], J.-J. Fourmond[52], M. Frailis[46], C. Franceschet[32], E. Franceschi[45], S. François[52],
M. Frerking[61], M. F. Gómez-Reñasco[57], K. M. Górski[61], T. C. Gaier[61], S. Galeotta[48], K. Ganga[4], J. García Lázaro[39], A. Garnica[61], M. Gaspard[63],
E. Gavila[82], M. Giard[12], G. Giardino[36], G. Gienger[38], Y. Giraud-Heraud[4], J.-M. Glorian[12], M. Griffin[6], A. Gruppuso[45], L. Guglielmi[4],
D. Guichon[82], B. Guillaume[37], P. Guillouet[4], J. Haissinski[63], F. K. Hansen[10,56], J. Hardy[61], D. Harrison[90], A. Hazell[76], M. Hechler[38],
V. Heckenauer[52], D. Heinzer[38], R. Hell[67], S. Henrot-Versillé[63], C. Hernández-Monteagudo[67], D. Herranz[58], J. M. Herreros[57], V. Hervier[52],
A. Heske[37], A. Heurtel[63], S. R. Hildebrandt[57], R. Hills[89], E. Hivon[51], M. Hobson[89], D. Hollert[61], W. Holmes[61], A. Hornstrup[35], W. Hovest[67],
R. J. Hoyland[57], G. Huey[61], K. M. Huffenberger[92], N. Hughes[94], U. Israelsson[61], B. Jackson[37], A. Jaffe[43], T. R. Jaffe[62], T. Jagemann[39],
N. C. Jessen[35], J. Jewell[61], W. Jones[22], M. Juvela[72], J. Kaplan[4], P. Karlman[61], F. Keck[38], E. Keihänen[21], M. King[61], T. S. Kisner[65], P. Kletzkine[37],
R. Kneissl[67], J. Knoche[67], L. Knox[26], T. Koch[61], M. Krassenburg[37], H. Kurki-Suonio[21,42], A. Lähteenmäki[68], G. Lagache[52], E. Lagorio[64],
P. Lami[52], J. Lande[12], A. Lange[61], F. Langlet[52], R. Lapini[74], M. Lapolla[84], A. Lasenby[89], M. Le Jeune[4], J. P. Leahy[62], M. Lefebvre[52],
F. Legrand[51], G. Le Meur[63], R. Leonardi[27], B. Leriche[52], C. Leroy[52], P. Leutenegger[84], S. M. Levin[61], P. B. Lilje[10,56], C. Lindensmith[61],
M. Linden-Vørnle[86], A. Loc[61], Y. Longval[52], P. M. Lubin[27], T. Luchik[61], I. Luthold[37], J. F. Macias-Perez[96], T. Maciaszek[14], C. MacTavish[43],
S. Madden[37], B. Maffei[62], C. Magneville[8], D. Maino[32], A. Mambretti[84], B. Mansoux[63], D. Marchioro[84], M. Maris[46], F. Marliani[37],
J.-C. Marrucho[63], J. Martí-Canales[37], E. Martínez-González[58], A. Martín-Polegre[37], P. Martin[82], C. Marty[12], W. Marty[12], S. Masi[34],
M. Massardi[49], S. Matarrese[31], F. Matthai[67], P. Mazzotta[33], A. McDonald[38], P. McGrath[61], A. Mediavilla[18], P. R. Meinhold[27], J.-B. Mélin[8],
F. Melot[96], L. Mendes[39], A. Mennella[32], C. Mervier[52], L. Meslier[52], M. Miccolis[84], M.-A. Miville-Deschenes[52], A. Moneti[51], D. Montet[82],
L. Montier[12], J. Mora[61], G. Morgante[45], G. Morigi[45], G. Morinaud[52], N. Morisset[59], D. Mortlock[90], S. Mottet[51], J. Mulder[61], D. Munshi[90],
A. Murphy[70], P. Murphy[61], P. Musi[83], J. Narbonne[12], P. Naselsky[71], A. Nash[61], F. Nati[34], P. Natoli[33], B. Netterfield[13], J. Newell[61], M. Nexon[12],
C. Nicolas[52], P. H. Nielsen[85], N. Ninane[11], F. Noviello[52], D. Novikov[43], I. Novikov[71], I. J. O'Dwyer[61], P. Oldeman[37], P. Olivier[37], L. Ouchet[82],
C. A. Oxborrow[35], L. Pérez-Cuevas[37], L. Pagan[84], C. Paine[61], F. Pajot[52], R. Paladini[80], F. Pancher[64], J. Panh[14], G. Parks[61], P. Parnaudeau[51],
B. Partridge[41], B. Parvin[61], J. P. Pascual[18], F. Pasian[46], D. P. Pearson[61], T. Pearson[61], M. Pecora[84], O. Perdereau[63], L. Perotto[96], F. Perrotta[5],
F. Piacentini[34], M. Piat[4], E. Pierpaoli[20], O. Piersanti[37], E. Plaige[63], S. Plaszczynski[63], P. Platania[60], E. Pointecouteau[12], G. Polenta[1],
N. Ponthieu[52], L. Popa[54], G. Poulleau[52], T. Poutanen[21,42,68], G. Prézeau[61], L. Pradell[16], M. Prina[61], S. Prunet[51], J. P. Rachen[67], D. Rambaud[12],
F. Rame[83], I. Rasmussen[37], J. Rautakoski[37], W. T. Reach[50], R. Rebolo[57], M. Reinecke[67], J. Reiter[61], C. Renault[96], S. Ricciardi[79], P. Rideau[82],
T. Riller[67], I. Ristorcelli[12], J. B. Riti[82], G. Rocha[61], Y. Roche[82], R. Pons[12], R. Rohlfs[59], D. Romero[61], S. Roose[11], C. Rosset[63], S. Rouberol[51],
M. Rowan-Robinson[43], J. A. Rubiño-Martín[57], P. Rusconi[84], B. Rusholme[50], M. Salama[61], E. Salerno[15], M. Sandri[45], D. Santos[96], J. L. Sanz[58],
L. Sauter[51], F. Sauvage[82], G. Savini[75], M. Schmelzel[61], A. Schnorhk[37], W. Schwarz[61], D. Scott[19], M. D. Seiffert[61], P. Shellard[89], C. Shih[61],
M. Sias[83], J. I. Silk[29], R. Silvestri[84], R. Sippel[3], G. F. Smoot[25], J.-L. Starck[8], P. Stassi[96], J. Sternberg[36], F. Stivoli[79], V. Stolyarov[90], R. Stompor[4],
L. Stringhetti[45], D. Strommen[61], T. Stute[3], R. Sudiwala[6], R. Sugimura[61], R. Sunyaev[67], J.-F. Sygnet[51], M. Türler[59], E. Taddei[84], J. Tallon[61],
C. Tamiatto[52], M. Taurigna[63], D. Taylor[39], L. Terenzi[45], S. Thuerey[37], J. Tillis[61], G. Tofani[44], L. Toffolatti[17], E. Tommasi[2], M. Tomasi[32],
E. Tonazzini[15], J.-P. Torre[52], S. Tosti[52], F. Touze[63], M. Tristram[63], J. Tuovinen[69], M. Tuttlebee[38], G. Umana[47], L. Valenziano[45], D. Vallée[4],
M. van der Vlis[37], F. Van Leeuwen[90], J.-C. Vanel[4], B. Van-Tent[51], J. Varis[69], E. Vassallo[38], C. Vescovi[64], F. Vezzu[64], D. Vibert[51], P. Vielva[58],
J. Vierra[61], F. Villa[45], N. Vittorio[33], C. Vuerli[46], L. A. Wade[61], A. R. Walker[19], B. D. Wandelt[28], C. Watson[38], D. Werner[38], M. White[30],
S. D. M. White[67], A. Wilkinson[62], P. Wilson[61], A. Woodcraft[6], B. Yoffo[4], M. Yun[61], V. Yurchenko[70], D. Yvon[8], B. Zhang[61], O. Zimmermann[64],
A. Zonca[48], and D. Zorita[78]

The CMB at #STFC2011

- The Physics of the CMB
  - Last scattering and beyond
- The state of the art (WMAP and suborbital)
  - A Standard Cosmological Model?
- Planck
  - An all-sky ***telescope*** with 9 frequency bands: 30GHz to 857 GHz, sensitive to
    - dust in the solar system, our galaxy and other galaxies
    - synchrotron radiation
    - cold, molecular gas
    - and the cosmic microwave background!
- Beyond Planck
  - Suborbital 2011-2015
  - A future Satellite?

A standard cosmological model?

$$ds^2 = c^2dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2d\theta^2 + r^2\sin^2\theta\, d\phi^2\right]$$

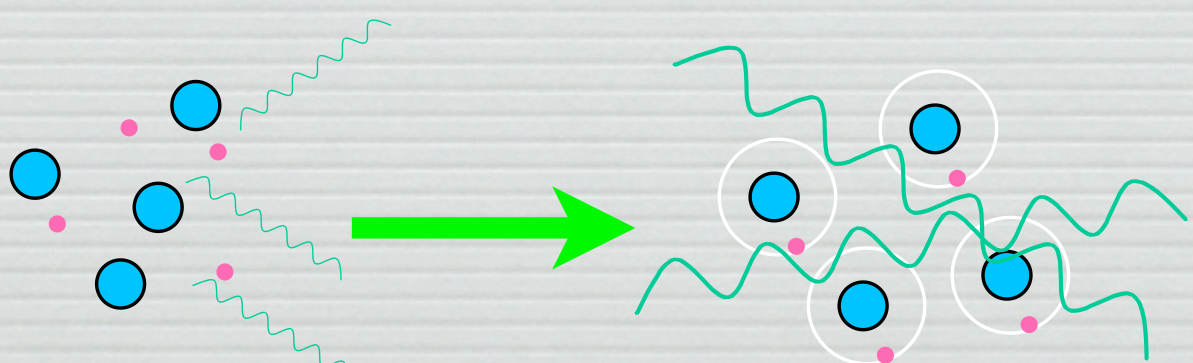
- *Predictions:* ("pillars of the Big Bang")
  - Expansion (Hubble)
- Hot big bang
  - Light element abundances (BBN)
  - Recombination (CMB)

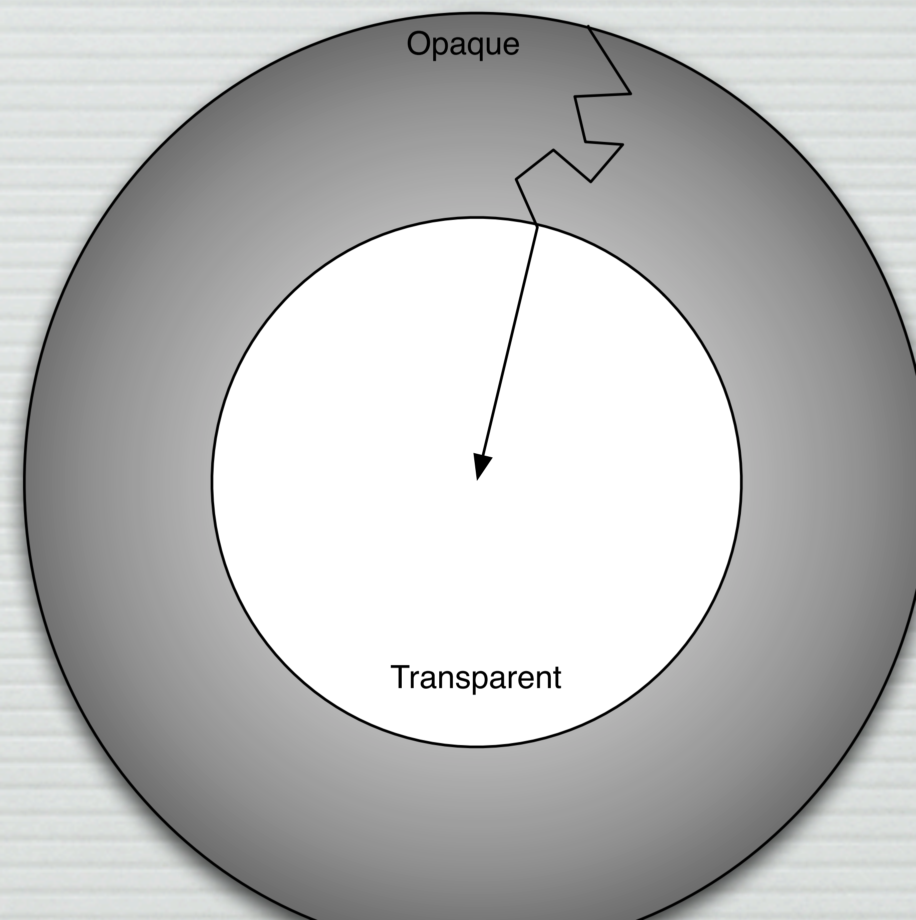
- Friedmann-Robertson-Walker metric with:
  - radiation ($p/\rho\equiv w=1/3$)
    baryons ($w\simeq 0$)
    dark matter ($w=0$)
    dark energy ($w<-1/3$ [$w=-1$?])
    - Age t_0, expansion rate H_0
    - Curvature: Ω_k (=0?)
    - Densities:
      $\Omega_r \sim 10^{-5}$, $\Omega_b \approx 0.04$,
      $\Omega_c \approx 0.23$, $\Omega_{DE} \approx 0.73$ (w_{DE})
- small perturbations
  - seemingly Gaussian, acausal, adiabatic
    - Initial power spectrum of scalar density perturbations
      $$P(k) \simeq Ak^{n_s}$$
    - (and similar for tensor gravitational waves)
  - small non-Gaussianity f_{NL}

Inflation?

Evidence & Observations: Cosmic Microwave Background

- 400,000 years after the Big Bang, the temperature of the Universe was $T \sim 3{,}000$ K
- Hot enough to keep hydrogen atoms *ionized* until this time
  - ***proton + electron → Hydrogen*** + *photon* [$p^+ + e^- \rightarrow H + \gamma$]
  - ***charged plasma → neutral gas***
    - depends on *entropy* of the Universe
- Photons (light) can't travel far in the presence of charged particles
  - ***Opaque → transparent***



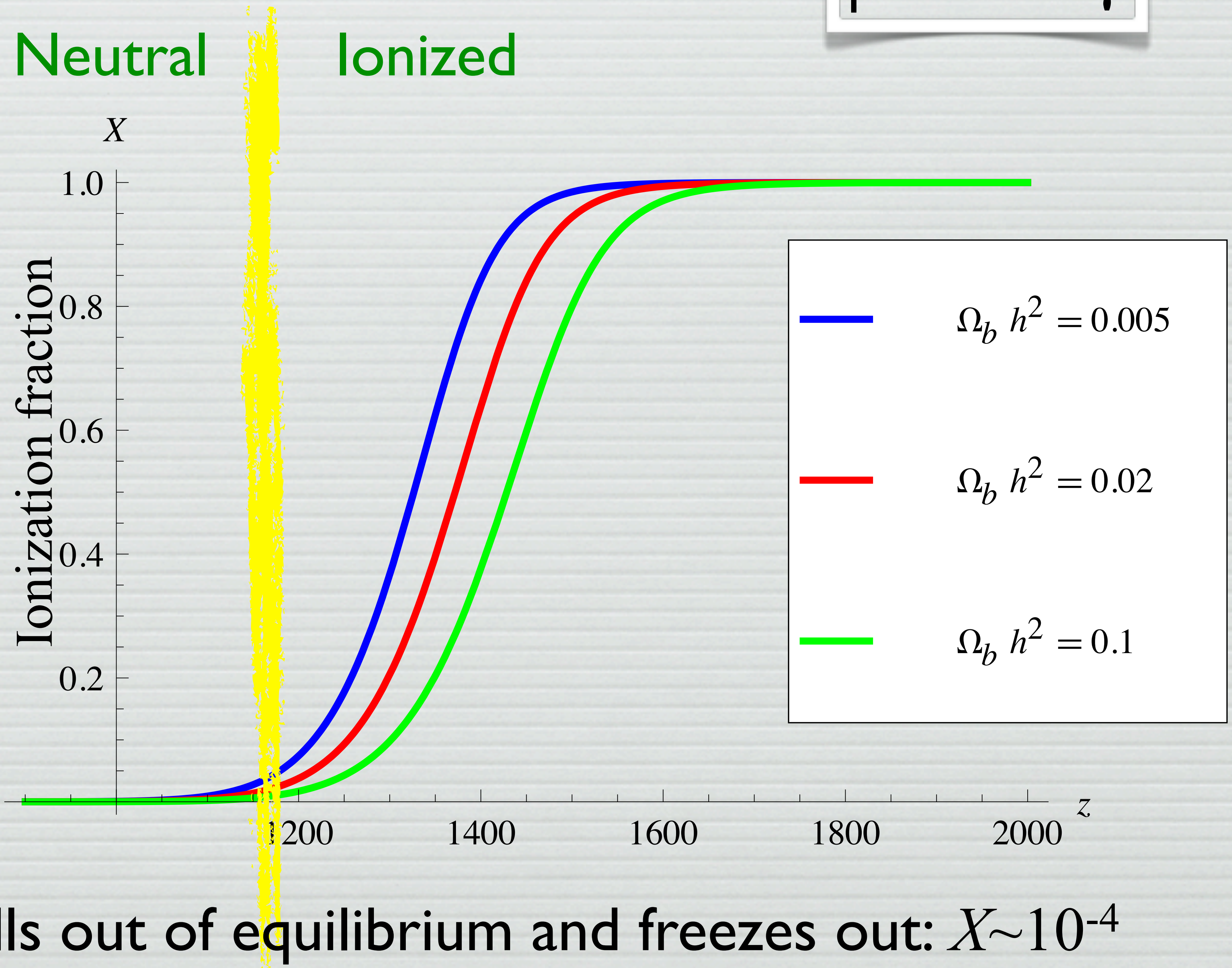


Ionization fraction: Equilibrium

- tiny baryon-to-photon ratio $\eta = n_b/n_\gamma \cong 10^{-9}$ key to "delay" to $kT \sim 1\,\text{eV} \ll 13.6\,\text{eV}$

p+e → H+γ

- Solve *Saha Equation* equilibrium ioniz'n balance
- really should follow many levels, species

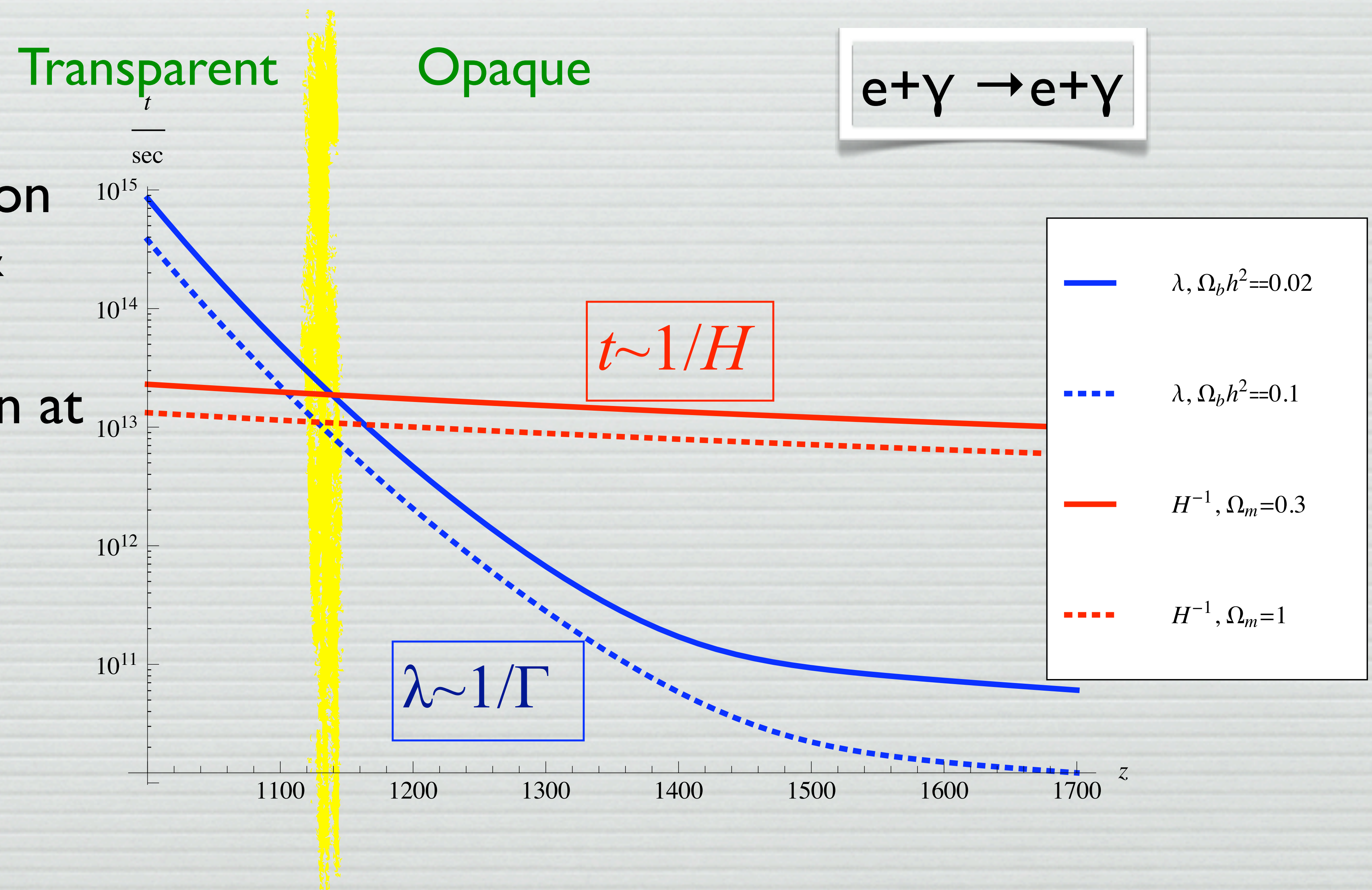


Not shown: interaction falls out of equilibrium and freezes out: $X \sim 10^{-4}$

Photon Decoupling

- Freeze-out when interaction rate = $\Gamma < H$ = expansion rate

- Evolution of photon-baryon plasma depends on expansion rate & densities
- Apparent horizon at recombination: *approximate* standard ruler

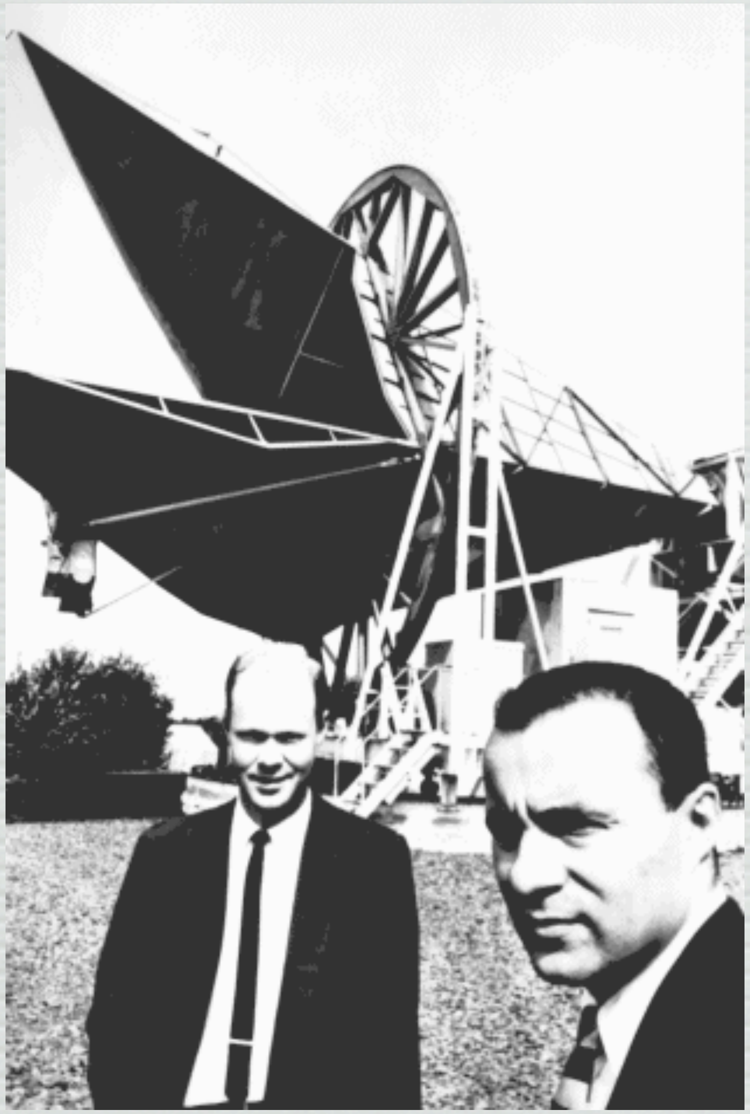


History

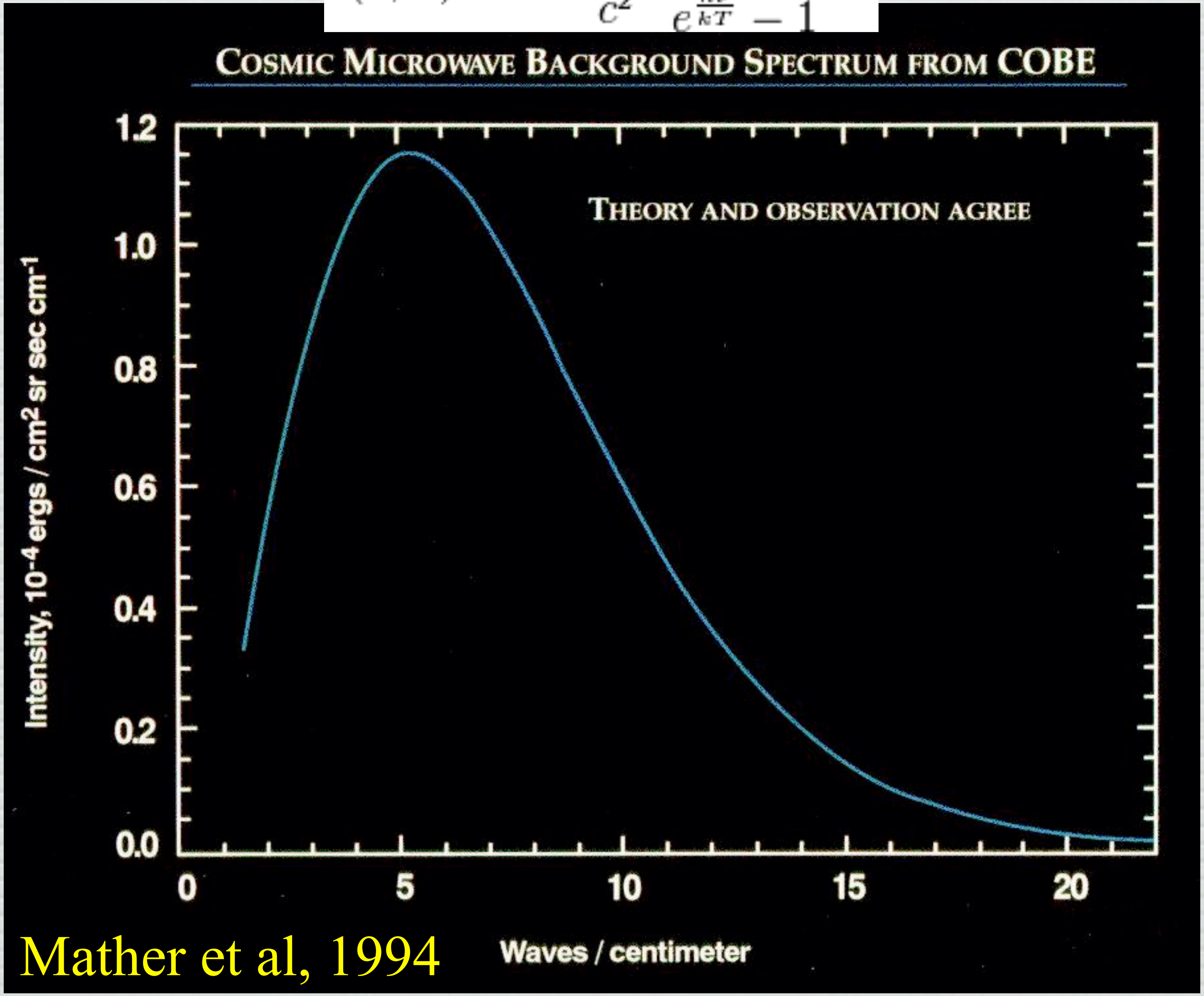
- *1948*: Alpher, Gamow, Herman predict the existence of the CMB
- *1964*: Dicke, Peebles, Roll & Wilkinson (Princeton) start looking for it...
- *1964*: Penzias & Wilson (AT&T Bell Labs) accidentally find it
  - $T = 3K$, constant over sky
- *1969-70s*: 0.1% variations
  - Doppler Shift from our motion through the CMB
- *1990s*: 10^{-5} variations
  - Sign of the large-scale structure of the universe at early times

Black Body radiation from the Early Universe

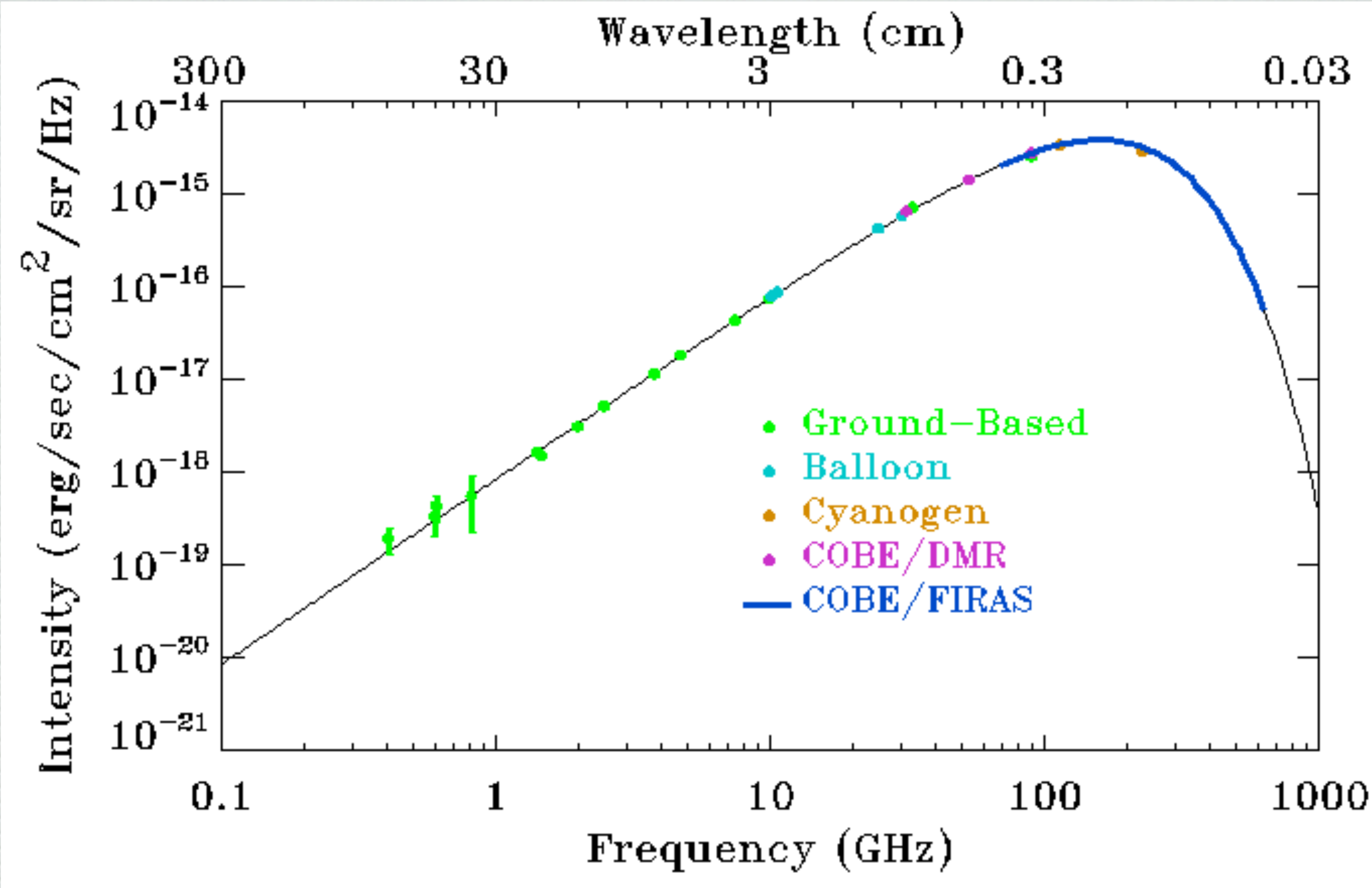
$$I(\nu,T)d\nu = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}}-1}d\nu$$



Penzias & Wilson



Black Body radiation from the Early Universe

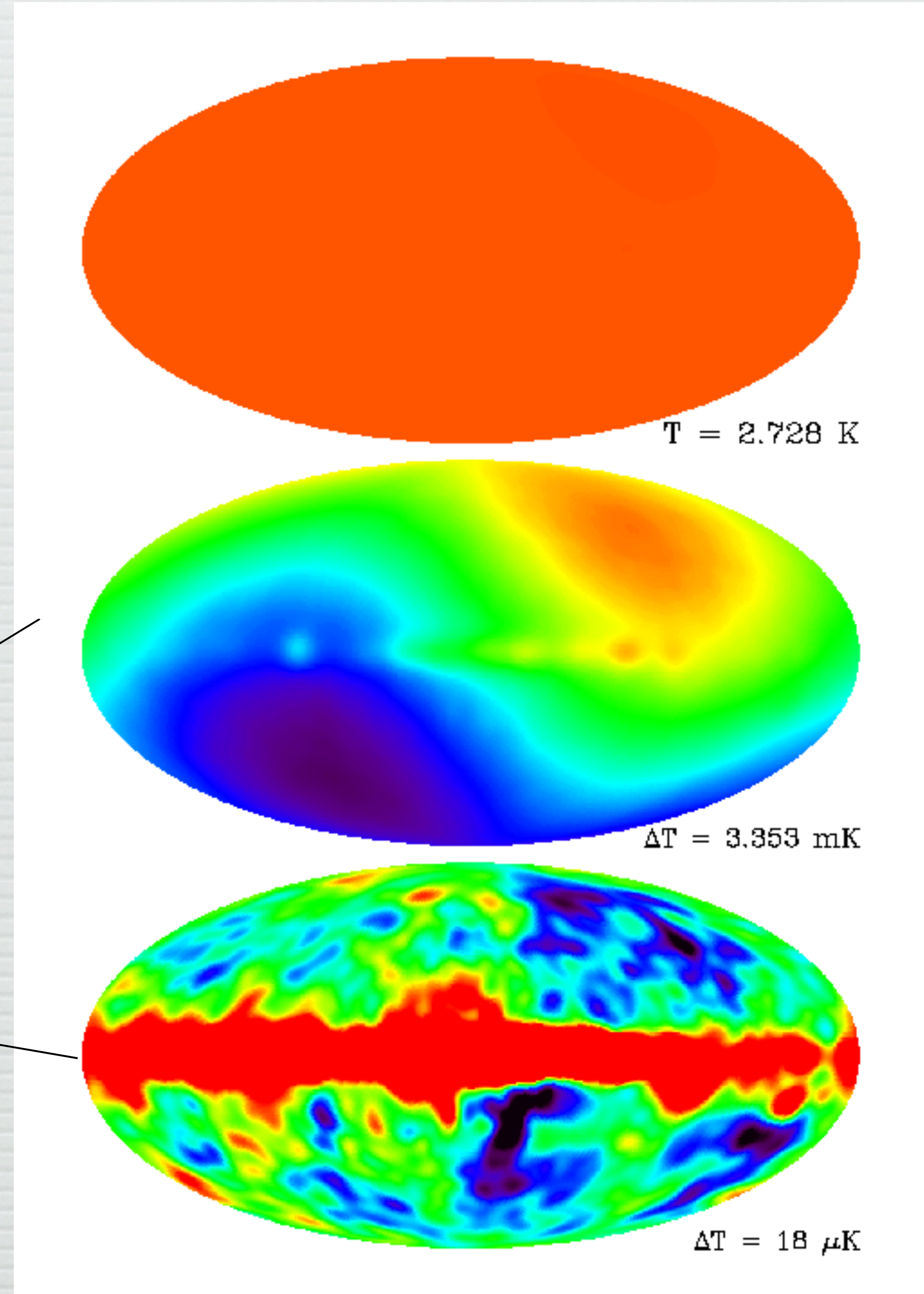


Al Kogut, ARCADE, http://arcade.gsfc.nasa.gov/cmb_spectrum.html

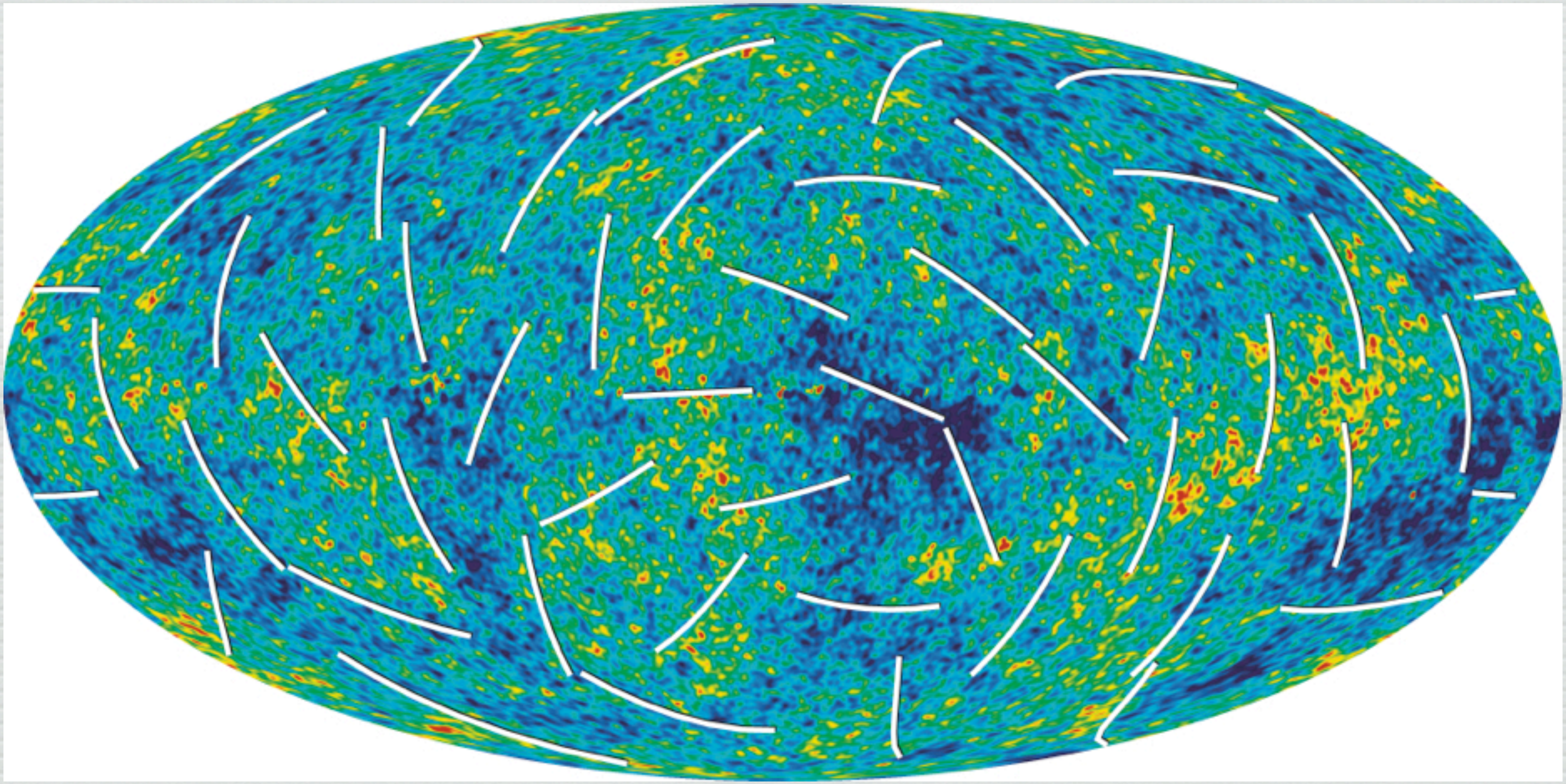
Fluctuations in the CMB

CMB "Dipole"

Cosmological & galactic fluctuations



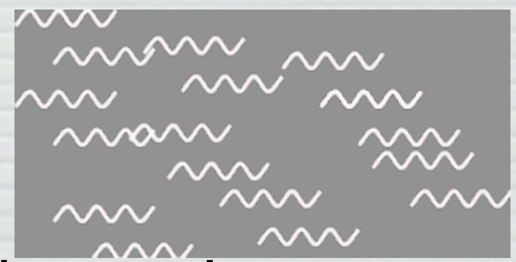
Temperature and polarization from WMAP



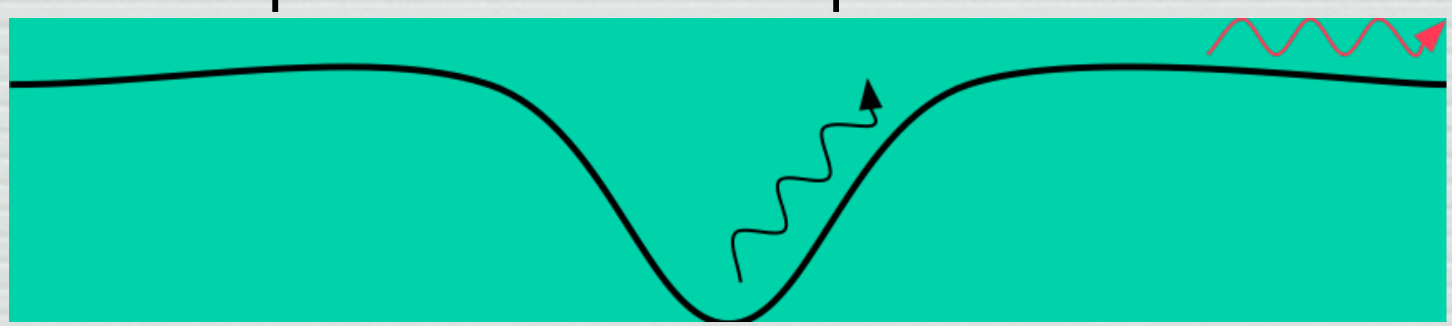
What affects the CMB temperature?

$$\frac{\Delta T}{T}(\hat{x}) \simeq \frac{1}{4}\frac{\delta \rho_\gamma}{\rho_\gamma} + v \cdot \hat{x} + \int_{\eta_{rec}}^{\eta_0} d\eta \, \dot{h}_{ij} \hat{x}_i \hat{x}_j$$

- Initial temperature (density) of the photons

Cooler   Hotter

- Doppler shift due to movement of baryon-photon plasma
- Gravitational red/blue-shift as photons climb out of potential wells or fall off of underdensities



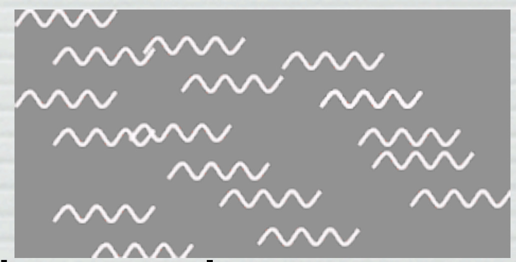
- Photon path from LSS to today
- All linked by initial conditions ⇒ 10^{-5} fluctuations

What affects the CMB temperature?

$$\frac{\Delta T}{T}(\hat{x}) \simeq \frac{1}{4}\frac{\delta\rho_\gamma}{\rho_\gamma} + v\cdot\hat{x} + \int_{\eta_{rec}}^{\eta_0} d\eta\, \dot{h}_{ij}\hat{x}_i\hat{x}_j$$

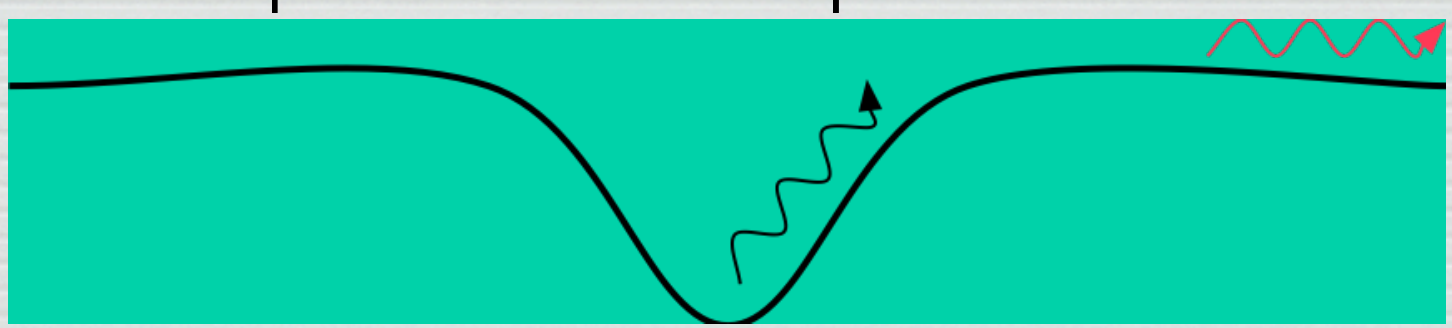
- Initial temperature (density) of the photons

Cooler



Hotter

- Doppler shift due to movement of baryon-photon plasma
- Gravitational red/blue-shift as photons climb out of potential wells or fall off of underdensities



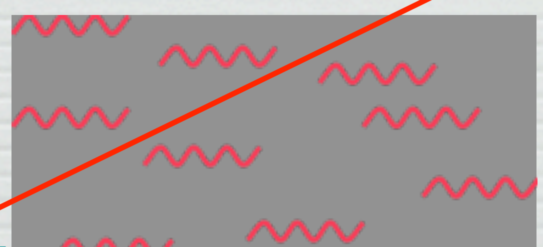
- Photon path from LSS to today
- All linked by initial conditions ⇒ 10^{-5} fluctuations

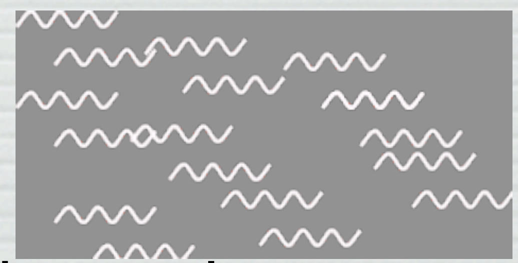
What affects the CMB temperature?

$$\frac{\Delta T}{T}(\hat{x}) \simeq \frac{1}{4}\frac{\delta\rho_\gamma}{\rho_\gamma} + v\cdot\hat{x} + \int_{\eta_{rec}}^{\eta_0} d\eta\, \dot{h}_{ij}\hat{x}_i\hat{x}_j$$

- Initial temperature (density) of the photons

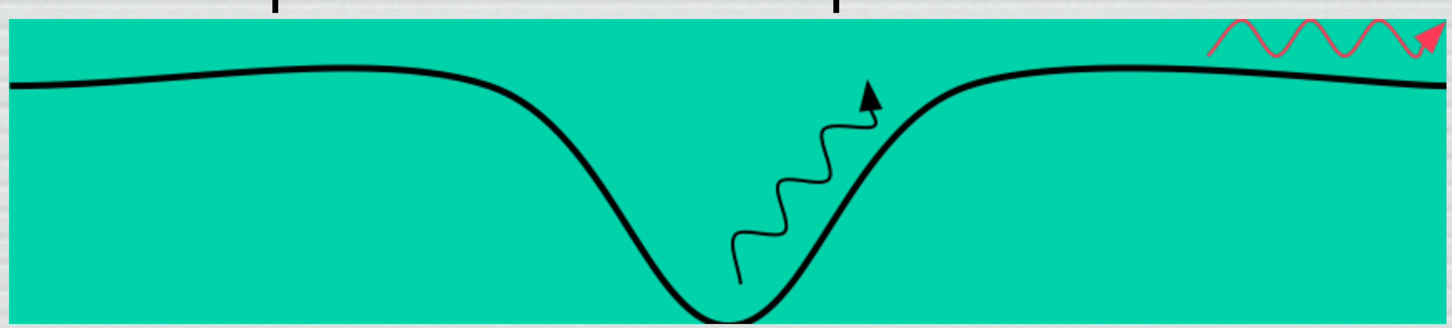
Cooler





Hotter

- Doppler shift due to movement of baryon-photon plasma
- Gravitational red/blue-shift as photons climb out of potential wells or fall off of underdensities



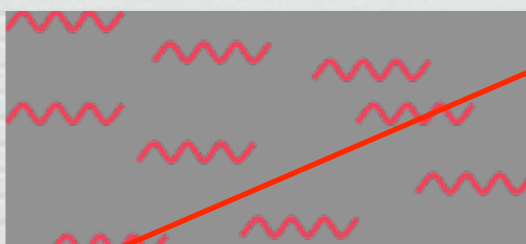
- Photon path from LSS to today
- All linked by initial conditions ⇒ 10^{-5} fluctuations

What affects the CMB temperature?

$$\frac{\Delta T}{T}(\hat{x}) \simeq \frac{1}{4}\frac{\delta\rho_\gamma}{\rho_\gamma} + v\cdot\hat{x} + \int_{\eta_{rec}}^{\eta_0} d\eta\, \dot{h}_{ij}\hat{x}_i\hat{x}_j$$

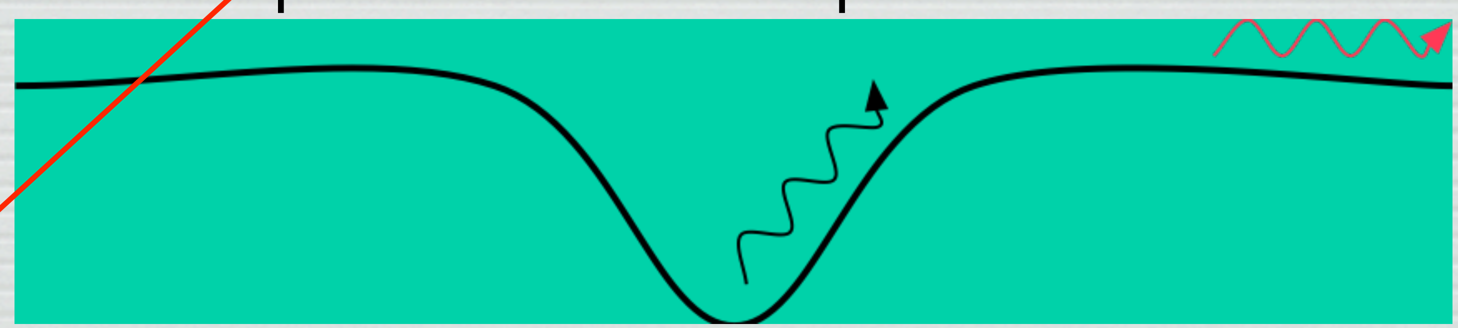
- Initial temperature (density) of the photons

Cooler



Hotter

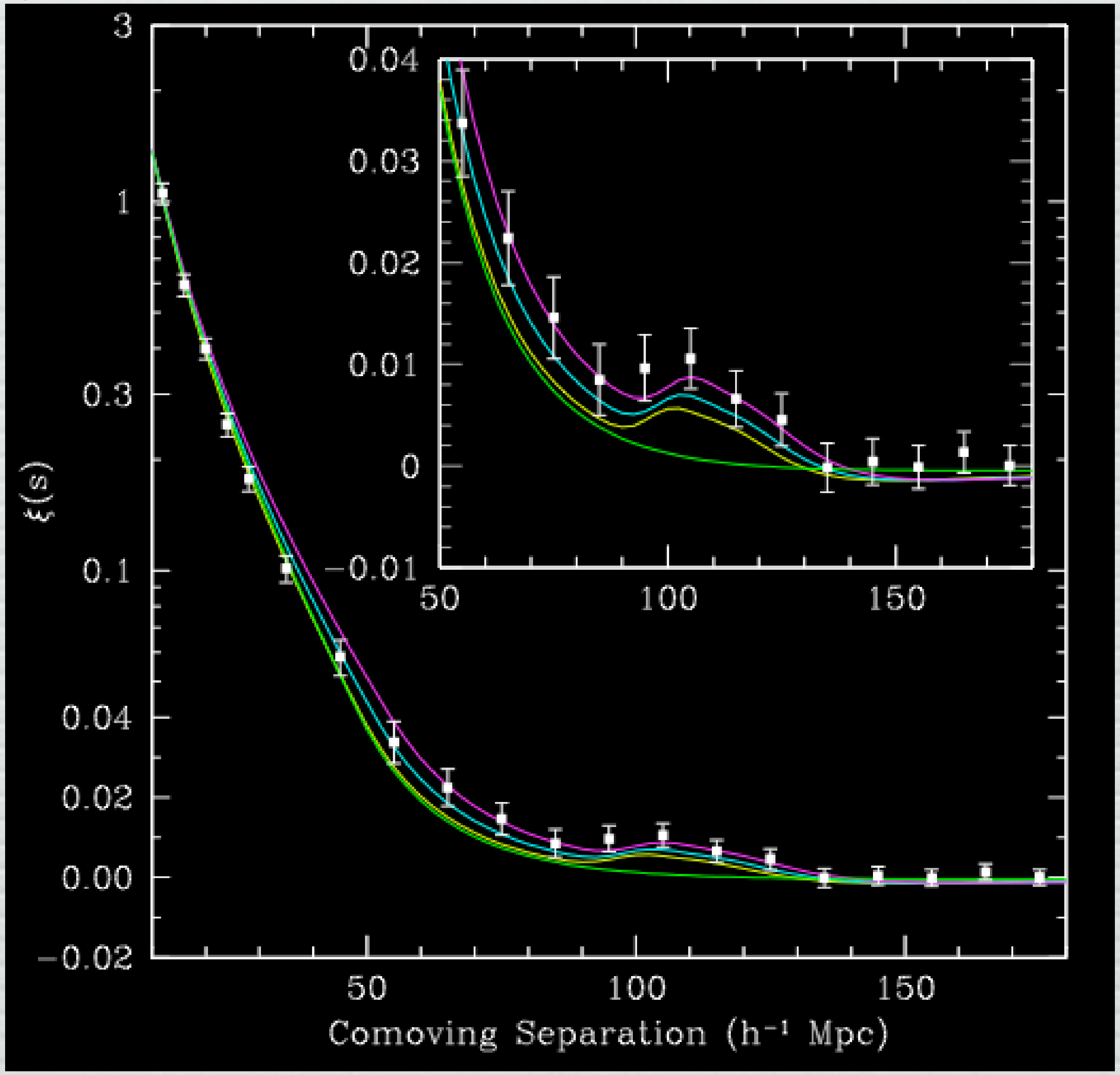
- Doppler shift due to movement of baryon-photon plasma
- Gravitational red/blue-shift as photons climb out of potential wells or fall off of underdensities



- Photon path from LSS to today
- All linked by initial conditions ⇒ 10^{-5} fluctuations

Baryon Acoustic Oscillations

- Before recombination, baryons supported by radiation pressure: sounds waves in the plasma (Jeans analysis)
- See characteristic scale of sound horizon at recombination $\sim c_s t_{\rm dec} \sim 100{\rm Mpc}$
  - Hence useful as distance indicator (measure *w*)
- After recombination: fluctuations frozen in, evolve via ~ linear evolution
- Same thing we see in ***the CMB***



The horizon at last scattering

- The particle (light) horizon at last scattering, corresponds to about 1 degree on the sky
  - $d_A = D/\theta = a_e r_e = a_o r_e (a_e/a_o) = a_o r_e/(1+z)$ for $D = d_H$
  - so $\theta = D/d_A$
- But fluctuations in the CMB are *sound waves*, so

$$d_{\rm sound} = \frac{1}{H_0(1+z)} \int_z^\infty \frac{dz' \; c_s}{E(z')}$$

for $c_s \simeq c/\sqrt{3}$ (mostly radiation):

- $d_{\rm sound} \simeq d_H/\sqrt{3}$
  - numerical calculations take full evolution of dark matter, baryons, radiation into account

Large scales: the Sachs-Wolfe effect

- Outside the horizon (greater than a degree)
  - velocity term is negligible
  - metric (potential) term looks like

$$\int_{\rm rec}^{t_0} dt\,\dot\phi \simeq \phi_{\rm rec} - \phi_0$$

  - $\phi \approx$const for linear evolution in a flat MD universe
  - Further, the *potential* is related to the *density* term, so

$$\frac{\Delta T}{T} = \phi_{\rm rec} - \frac{2}{3}\phi_{\rm rec} = \frac{1}{3}\phi_{\rm rec}$$

- "Integrated Sachs-Wolfe effect" occurs when ϕ varies (e.g., nonlinear evolution, Λ)

Oscillations in primordial plasma: Acoustic Peaks

- Before recombination, a tightly-coupled plasma of matter (p, e) and photons
- Primordial/inflationary perturbations on all scales–can only collapse when in causal contact
- Pressure determined by mix of baryons and radiation (~10^9 photons/baryon): baryon "doping" lowers c_s from $1/\sqrt{3}$.
- Higher Ω_b decreases rebound force; decreases relative amplitude on smaller scales (2^{nd} C_ℓ peak relative to first)

CMB Statistics

z~1300: p+e→H & Universe becomes transparent.

$$\frac{T(\hat{x}) - \bar{T}}{\bar{T}} \equiv \frac{\Delta T}{T}(\hat{x}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{x})$$

Determined by **temperature**, **velocity** and **metric** on the last scattering surface.

Power Spectrum:

$$\langle a^*_{\ell m} a_{\ell' m'} \rangle = \delta_{\ell \ell'} \delta_{m m'} \, C_\ell$$

Multipole ℓ ~ angular scale $180°/\ell$

For a **Gaussian** theory, C_ℓ completely determines the statistics of the temperature.

The CMB transfer function

- Linear evolution from approximately Gaussian ICs $\Rightarrow$ ~ all information in the power spectrum:

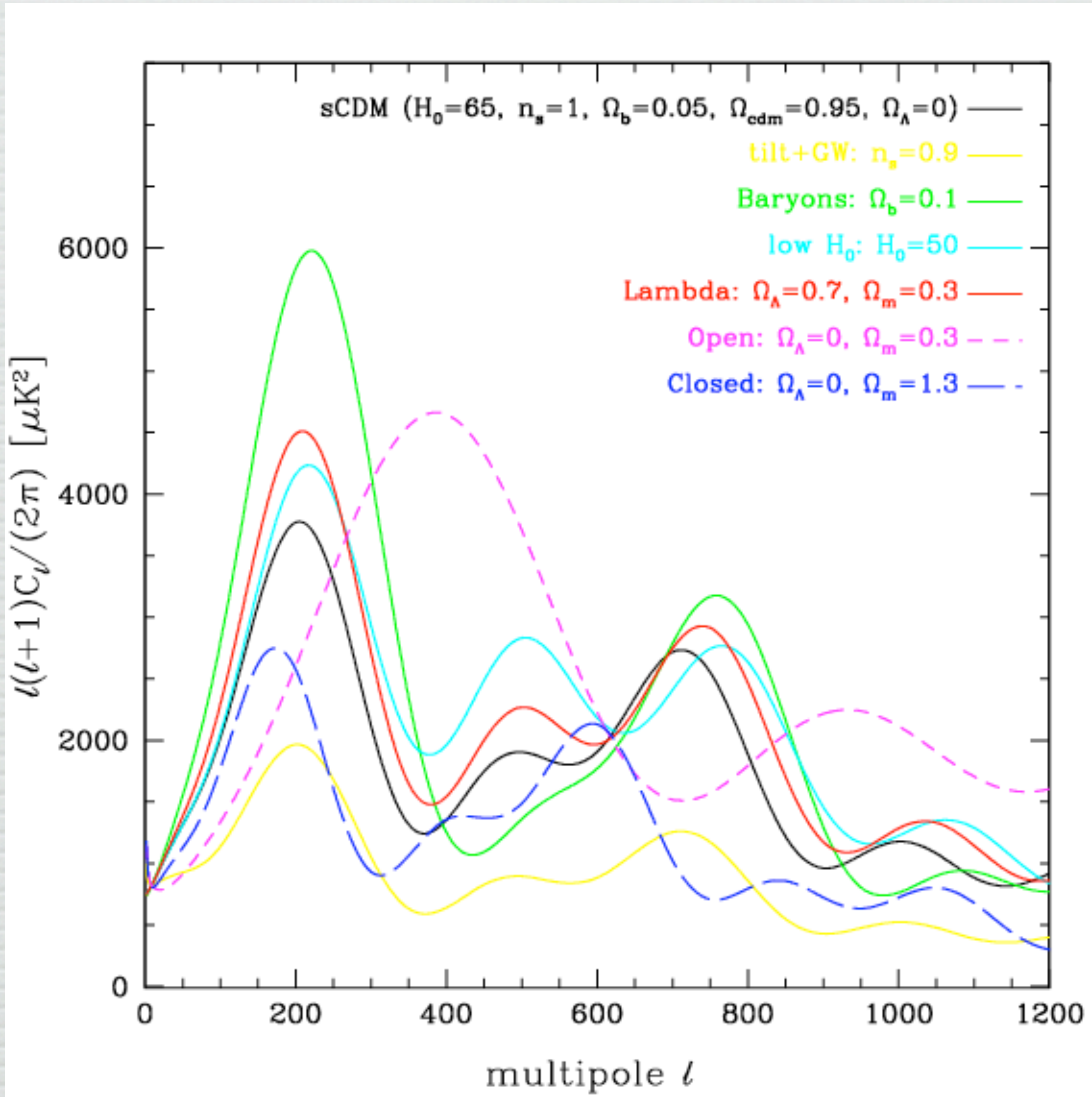
$$C_\ell = \int P_i(k) T_\ell^2(k)\, dk$$

- compare density spectrum: $P(k) = P_i(k)T^2(k)$
- The transfer function depends on the "cosmological parameters". For example:
  - matter density—determines sound speed in baryon/ photon fluid
  - curvature—determines angular-diameter distance to horizon

  - Actually solve Boltzmann Equation over thickness of Last-Scattering surface – e.g., `CMBFAST, CAMB`

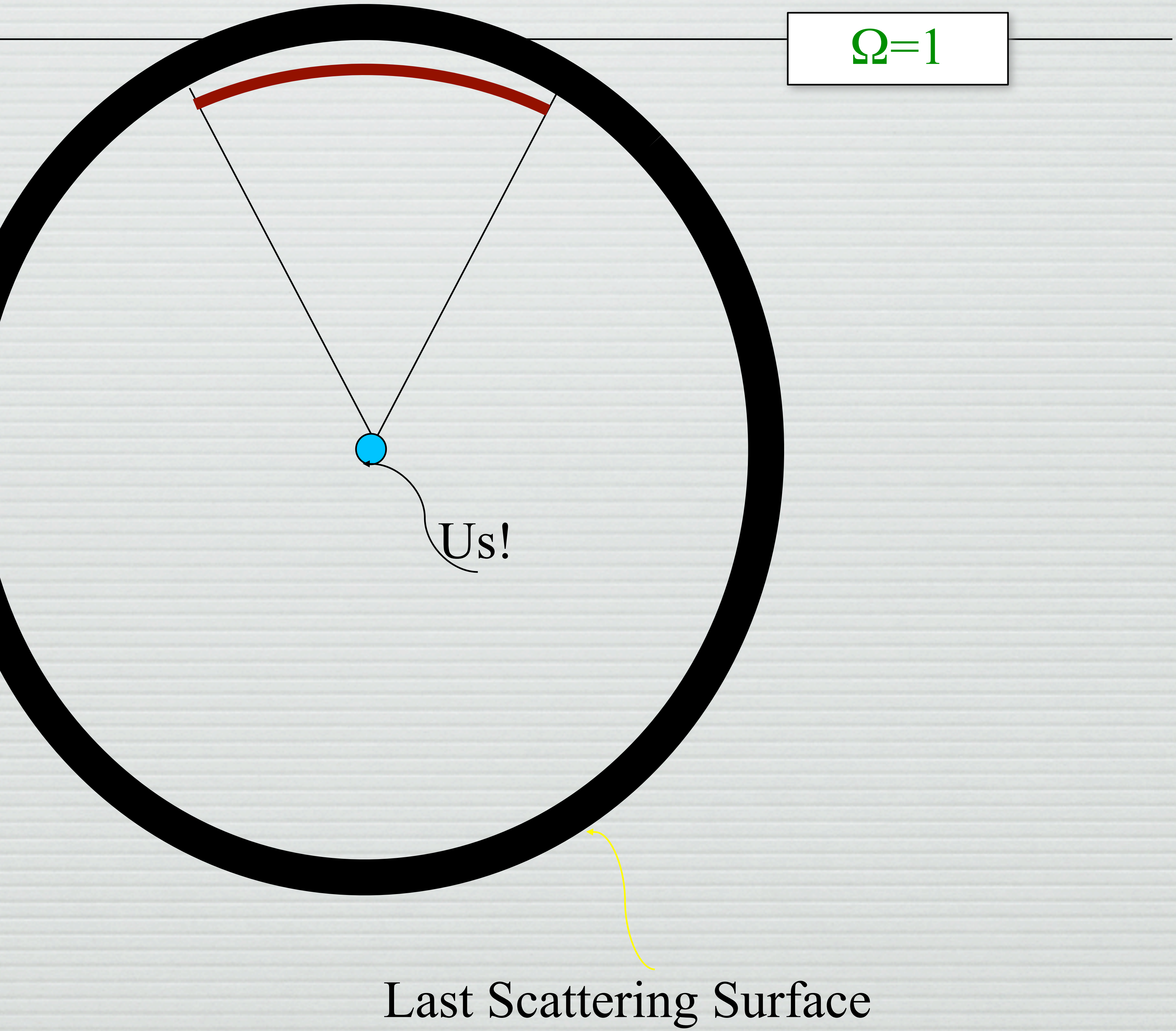
Theoretical Predictions

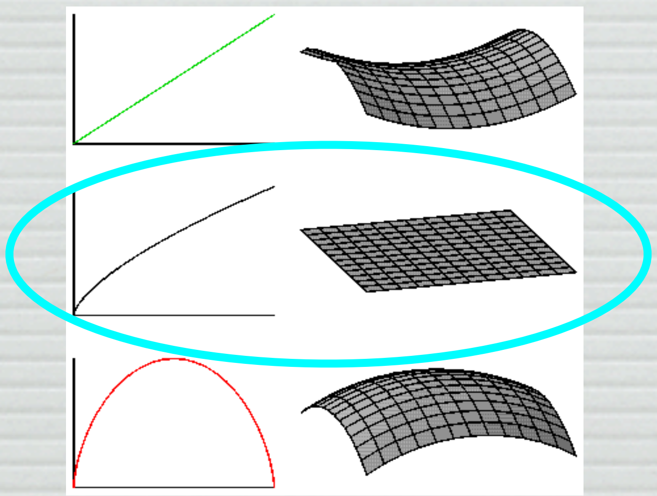
Mean square fluctuation amplitude



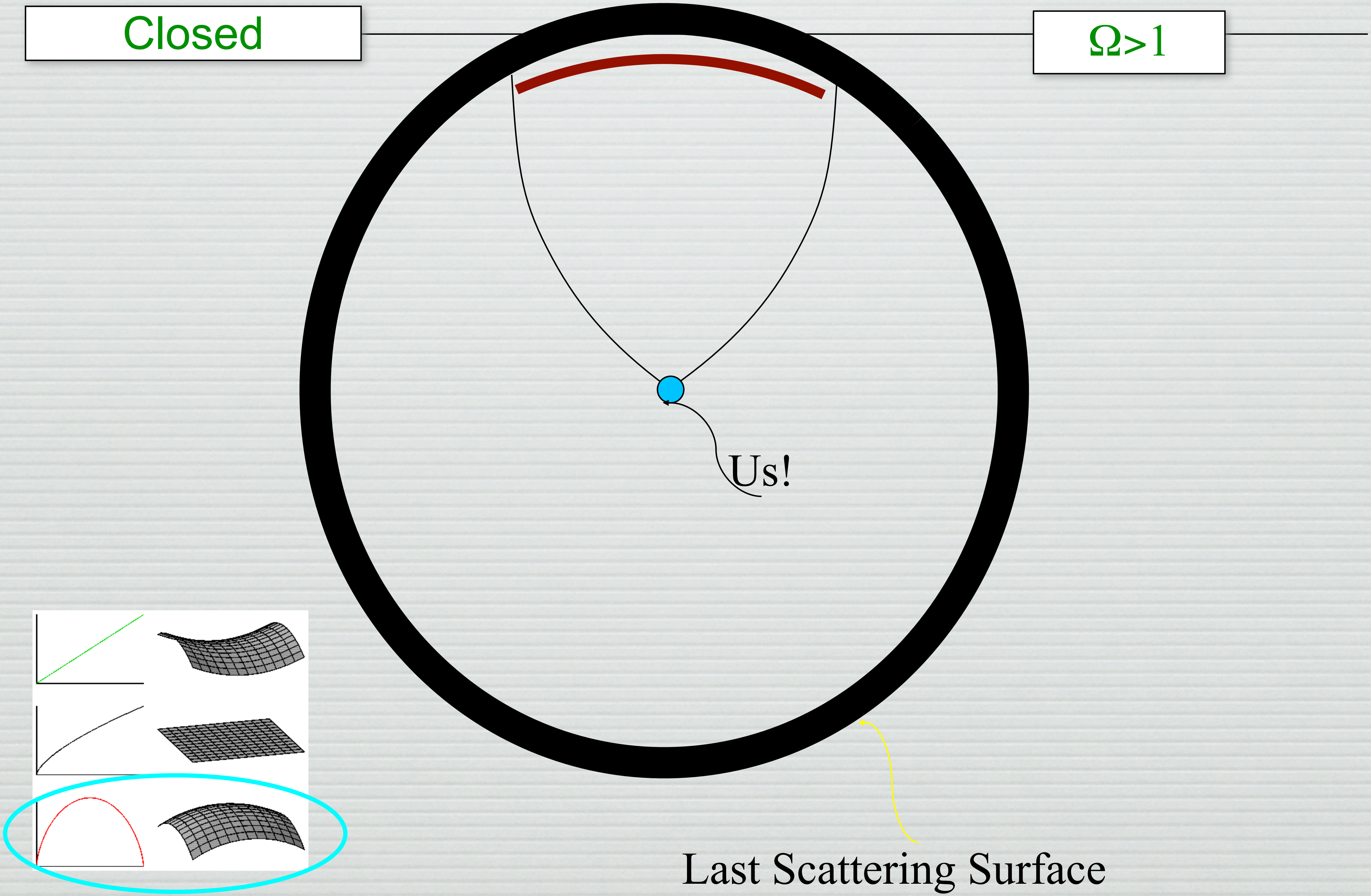
~180°/Angular scale

Measuring Curvature with the CMB

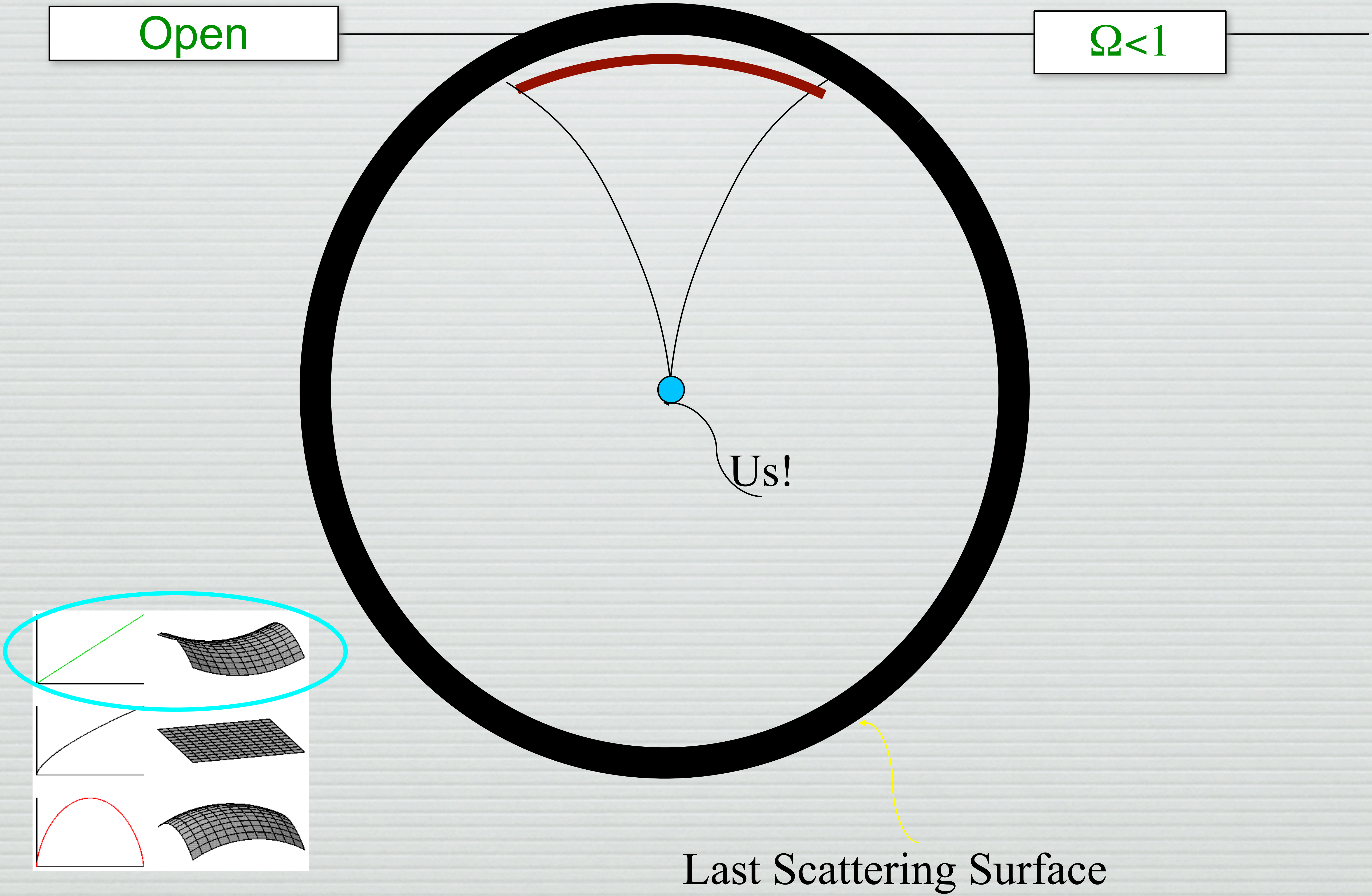


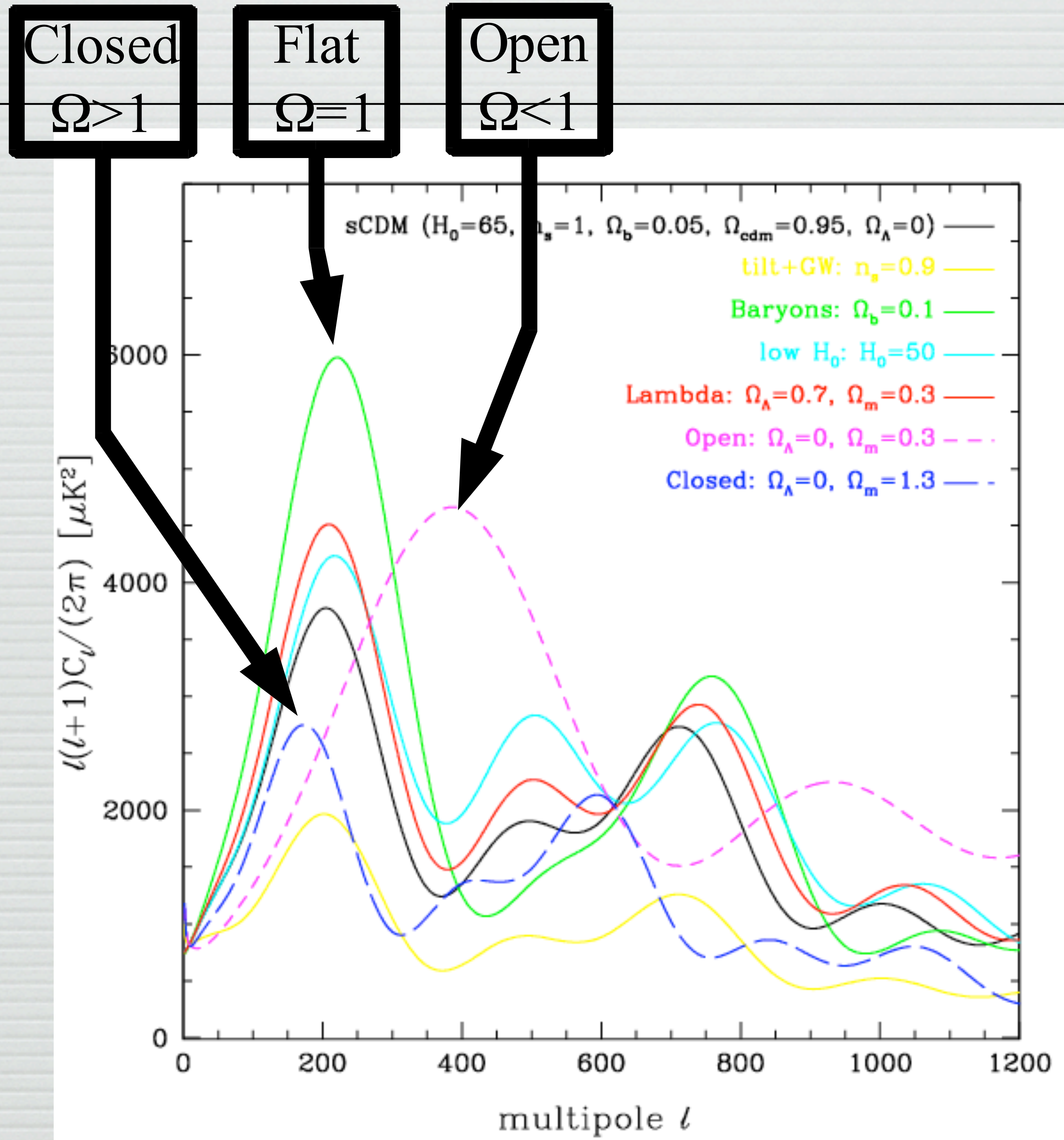


Measuring Curvature with the CMB

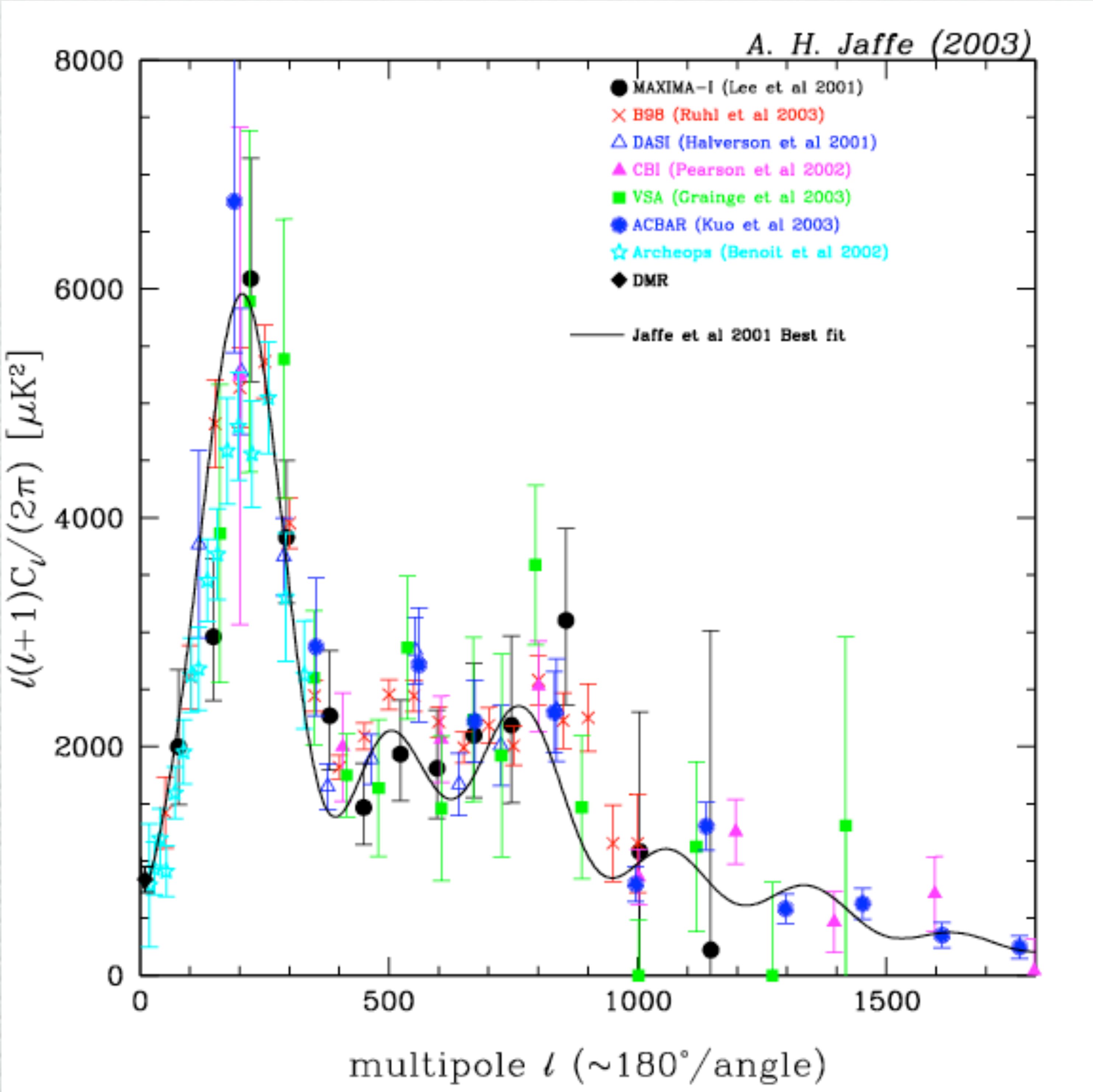


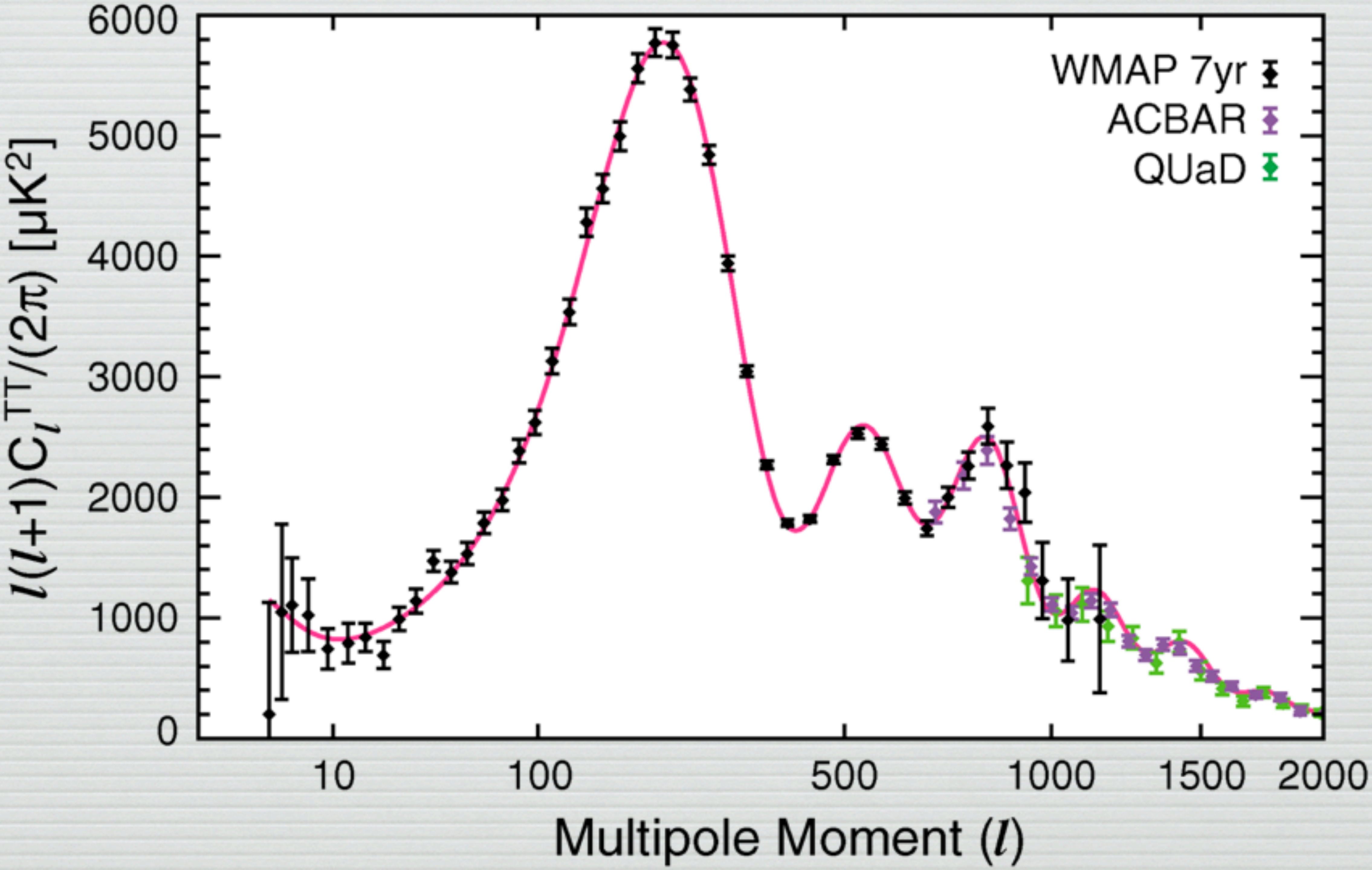
Measuring Curvature with the CMB




Closed $\Omega>1$
Flat $\Omega=1$
Open $\Omega<1$
sCDM (H_0=65, $_s$=1, Ω_b=0.05, Ω_{cdm}=0.95, Ω_Λ=0)
tilt+GW: n_s=0.9
Baryons: Ω_b=0.1
low H_0: H_0=50
Lambda: Ω_Λ=0.7, Ω_m=0.3
Open: Ω_Λ=0, Ω_m=0.3
Closed: Ω_Λ=0, Ω_m=1.3
$\ell(\ell+1)C_\ell/(2\pi)$ [μK^2]
multipole ℓ
0
2000
4000
200
400
600
800
1000
1200

January, 2003

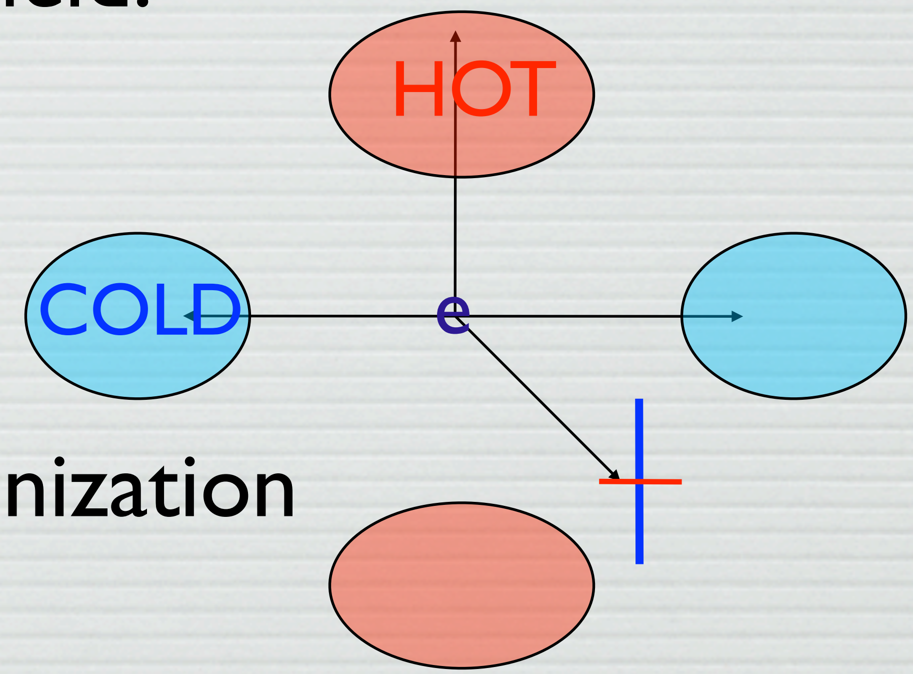




Komatsu et al 2011

CMB Polarization: Generation

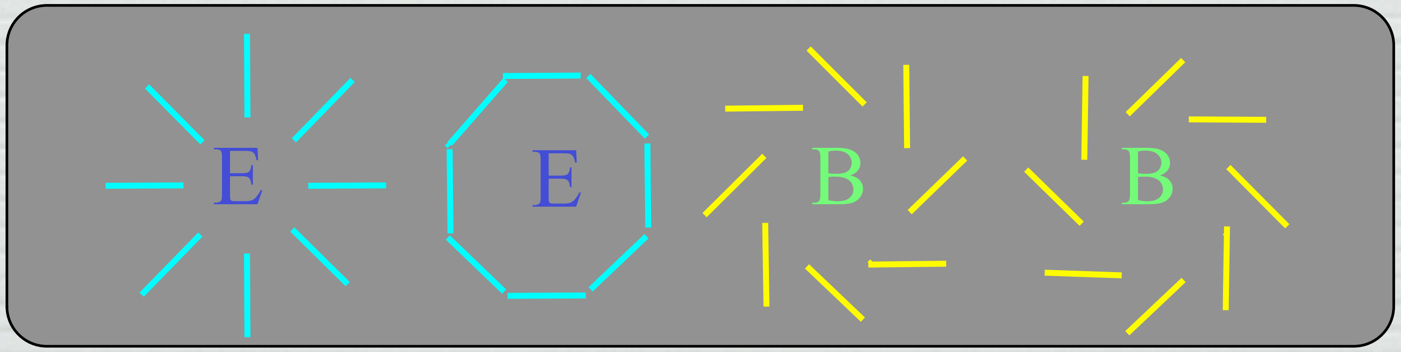
- Ionized plasma + quadrupole radiation field:



- Unlike intensity, only generated when ionization fraction, $0<x<1$ (*i.e.*, during transition)
- Scalar perturbations: traces ~gradient of velocity
  - same initial conditions as temperature and density fluctuations
- Tensor perturbations: independent of density fluctuations
  - +,× patterns of quadrupoles (impossible to form via linear scalar perturbations)
  - at last-scattering, from primordial background of gravitational radiation, predicted by inflation

CMB Polarization: E/B Decomposition

- 2-d (headless) vector field on a sphere
- Spin-2/tensor spherical harmonics
- grad/scalar/E + curl/pseudoscalar/B patterns



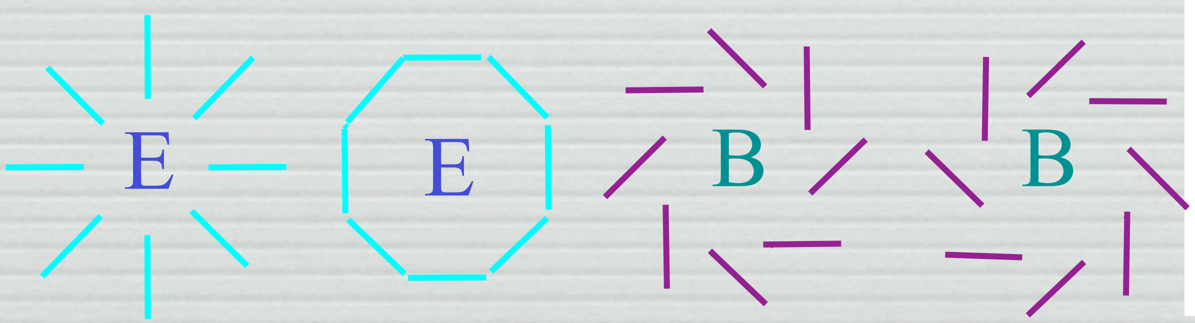
- NB. From polarization pattern⇒ E/B

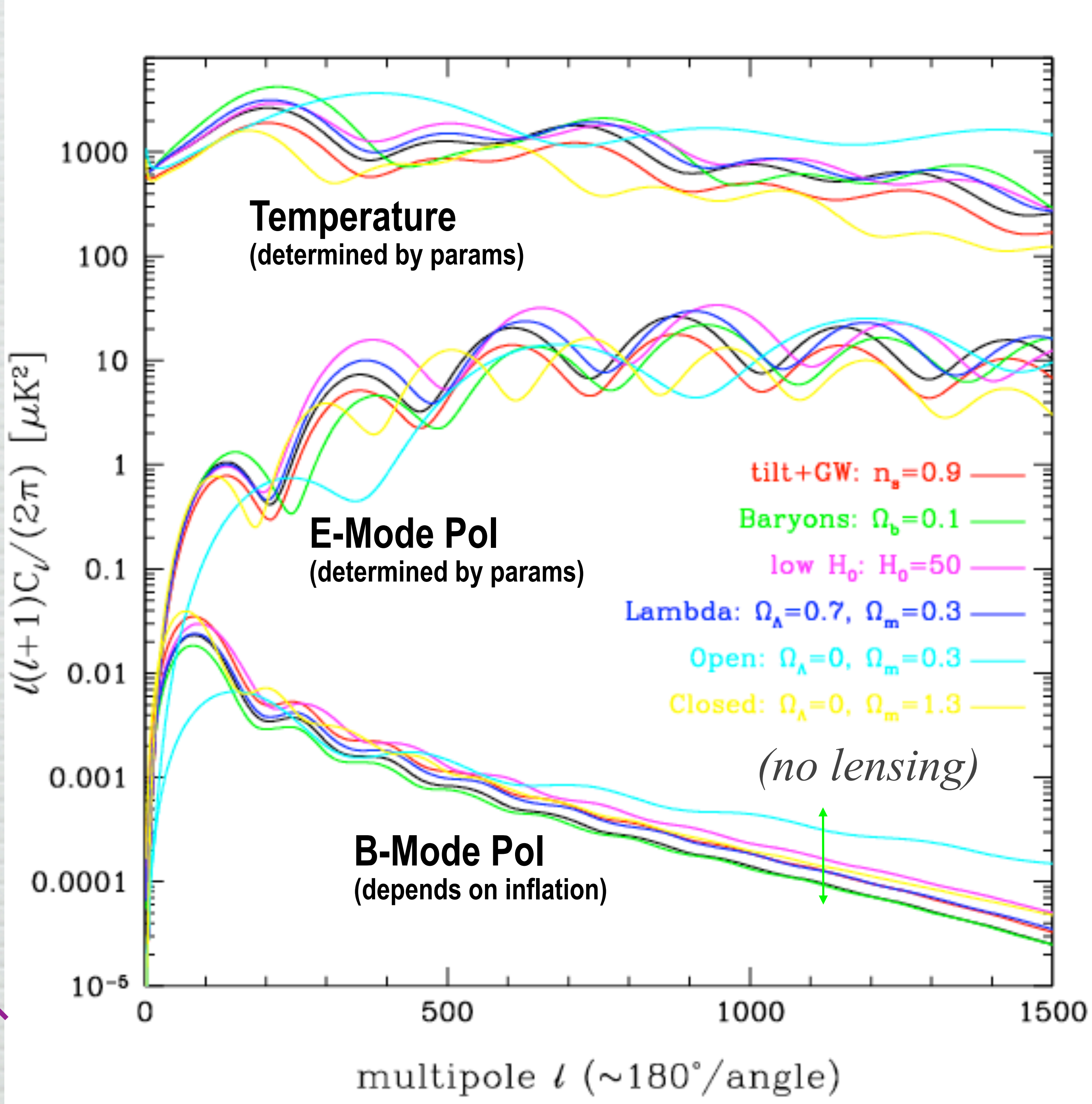
  decomposition requires integration (*non-local*) or differentiation (*noisy*)
  - (data analysis problems)

Kamionkowski, Kosowsky, Stebbins
Seljak & Zaldarriaga

Polarization of the CMB

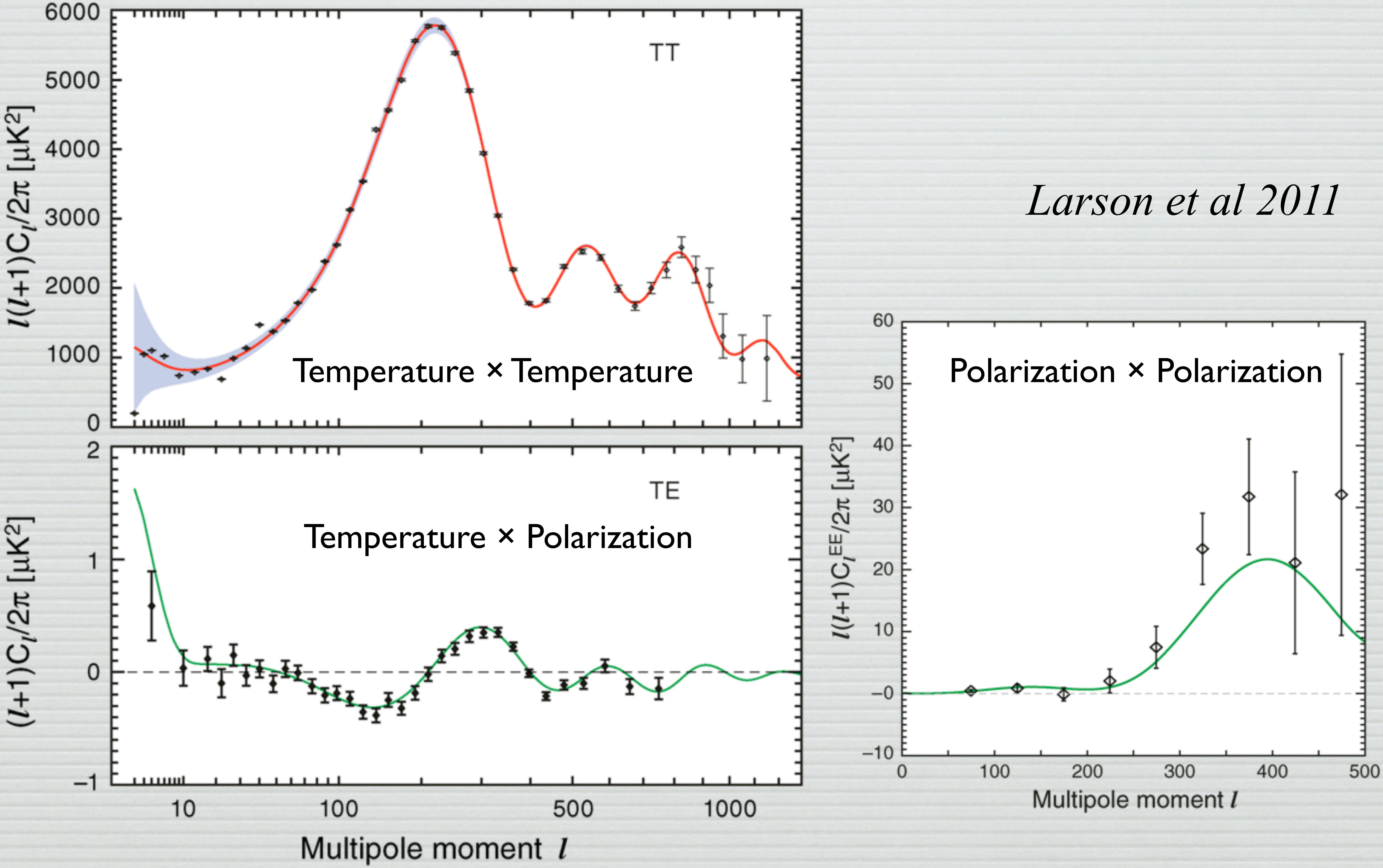
- Causal physics — scattering in baryon-photon plasma — same as intensity, E-mode polarization
  - Specific predictions given primordial P(k) & parameters





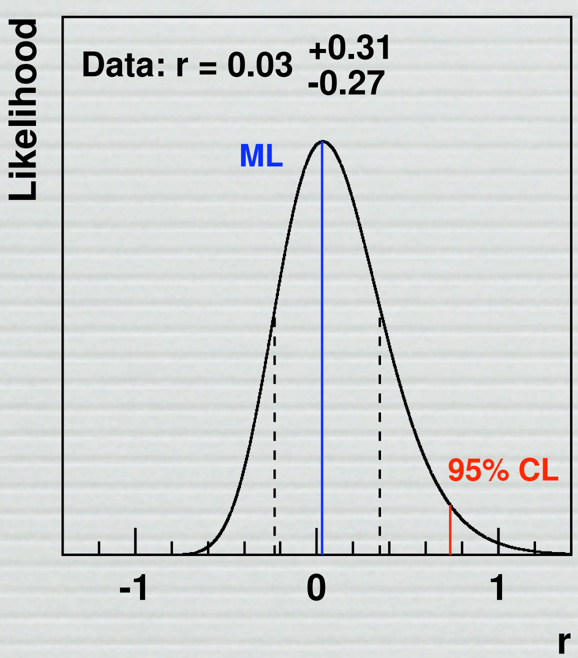
WMAP

Larson et al 2011

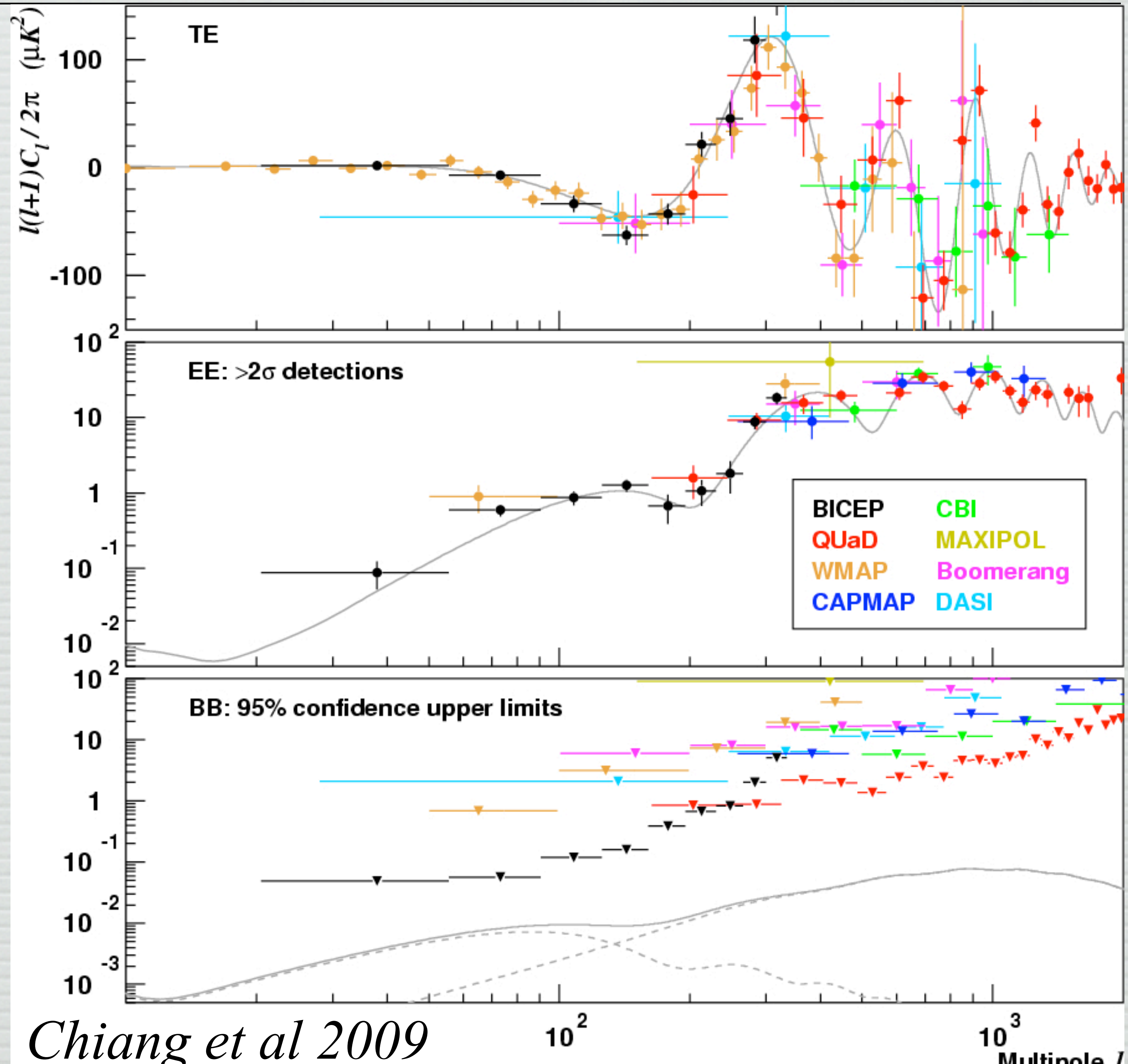


Polarization Measurements: State of the Art

WMAP "All CMB"
Tensor/Scalar power
$r < 0.36$ 95%
model-dependent

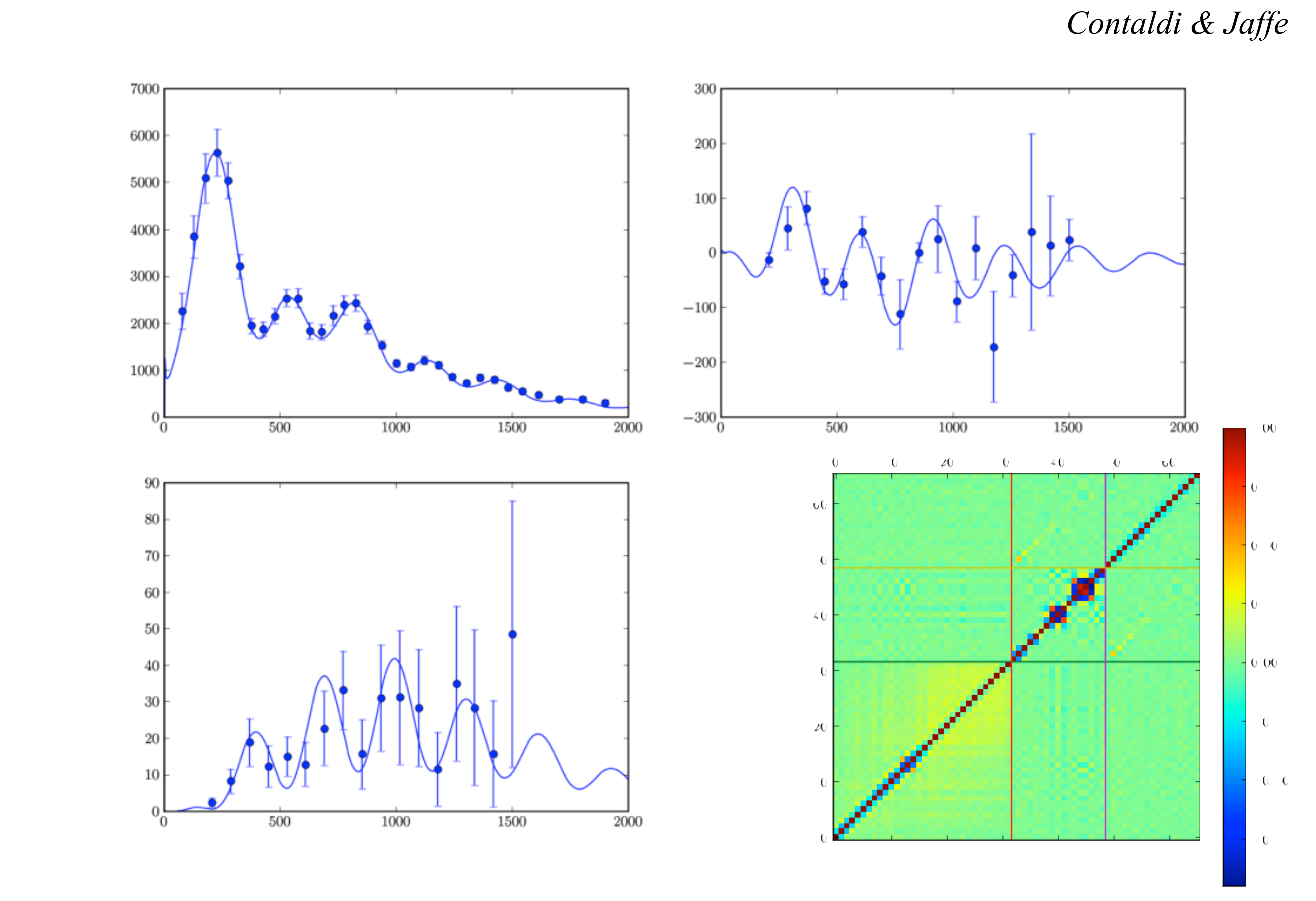


BB alone:
$r < 0.73$ 95%



Chiang et al 2009

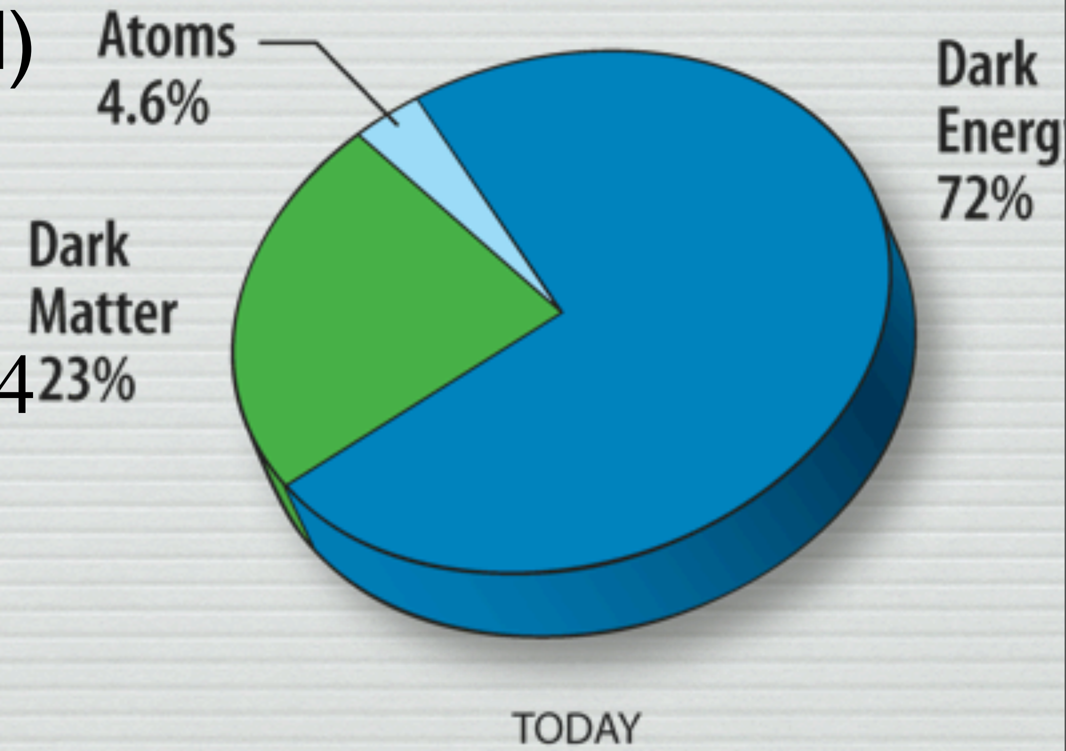
The "unified" spectrum



Cosmology C. 2011

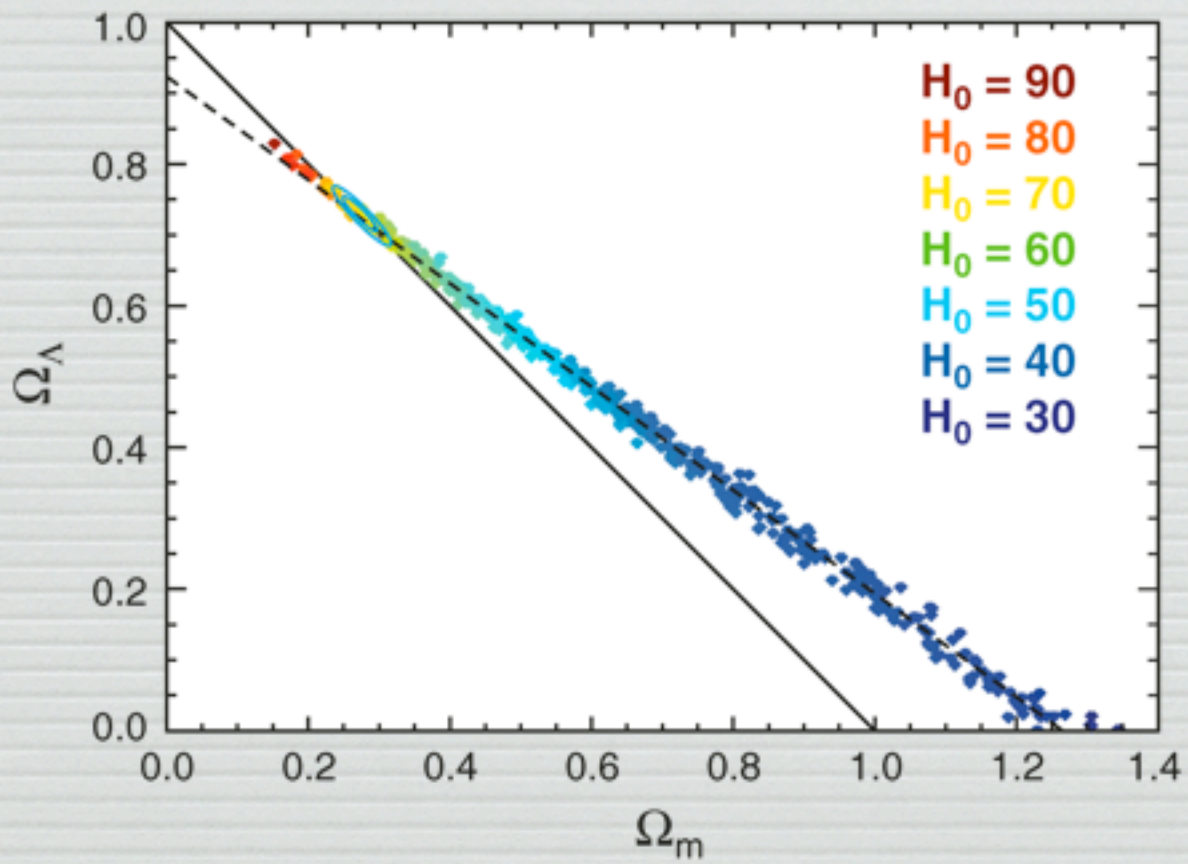
- WMAP Corroborates (and improves upon) existing data (MAXIMA, BOOMERaNG, &c.)
- ΛCDM: (Komatsu et al 2010)
  - Ω=1: Flat Universe
  - $n_s \approx 0.97 \pm 0.01$: *not-exactly* scale-invariant initial perturbations
  - $\Omega_m = 0.27 \pm 0.01$, $\Omega_{\Lambda/DE} = 0.73$: Dark matter, dark energy
  - $\Omega_b = 0.045 \pm 0.001$ (baryon density; BBN) $H_0 = 72 \pm 2$ km/s/Mpc (Hubble constant)
  - Better limits on non-Gaussianity
  - Dark energy eq. of state $w = -1.10 \pm 0.14$
  - Bayesian: known correlation structure
  - Details (errors!) depend on priors

precision cosmology, but not in the same ballpark as what people here are doing!



Cosmological Parameters

- *Detailed* parameter estimates depend upon
  - Data considered
  - Theoretical context (i.e., prior information)
- General picture ~robust (at least w/in nearly-scale-invariant, moderately expanding FRW models)
  - still scope for admixtures of strings, isocurvature, etc.



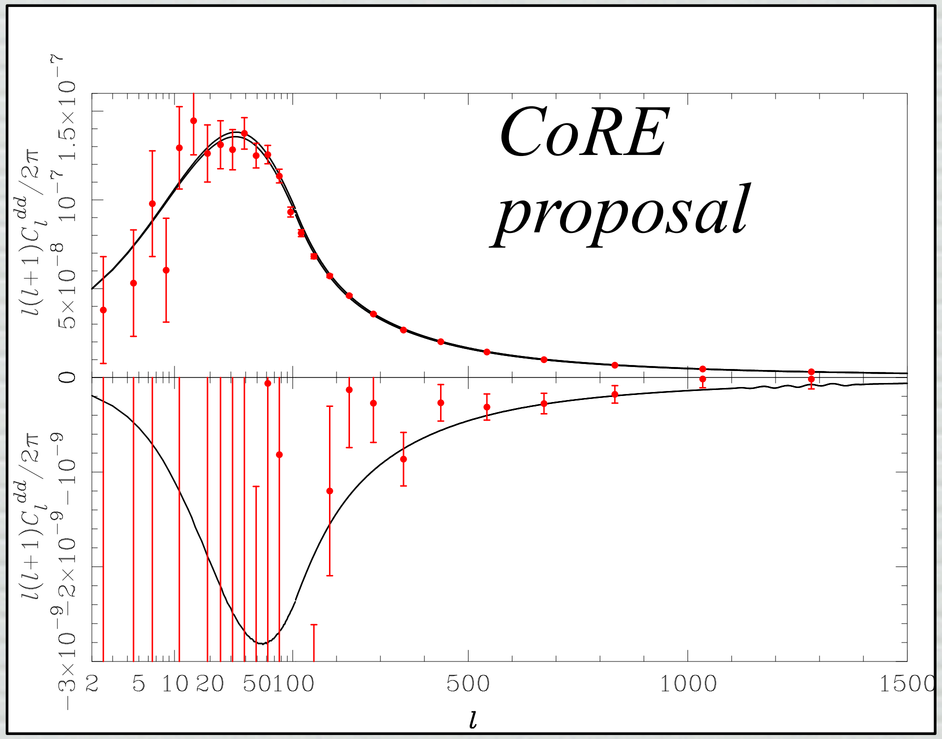
WMAP+BAO+SNe

	Flat ΛCDM	Curved ΛCDM
Ω_{tot}	1	1.005±0.006
Ω_m	0.278±0.015	0.282±0.016
Ω_Λ	0.72±0.015	0.72±0.016
H_0	69.9±1.3 km/s/Mpc	68.5±2.0 km/s/Mpc

WMAP Science team

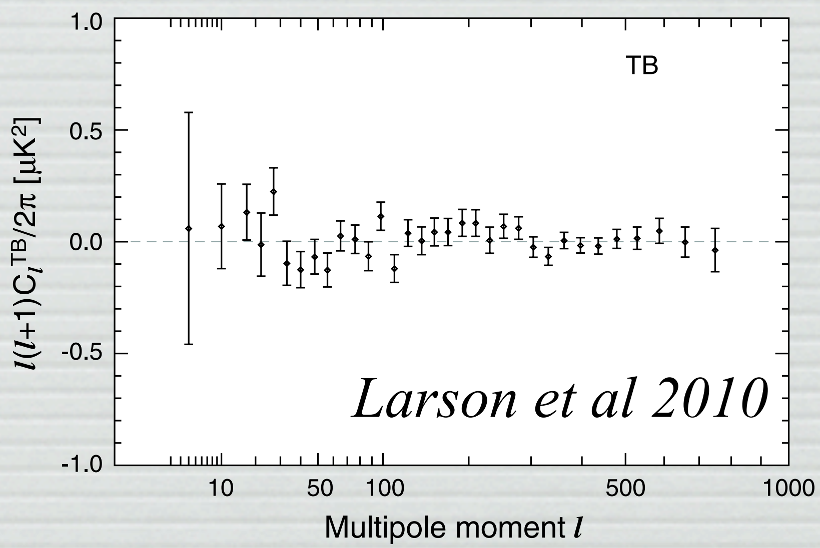
Neutrinos (and other light particles)

- Depending on mass, contribute to relativistic degrees of freedom (N_{eff}) and matter density
- Sensitive to absolute mass, not differences
  - If m≳0.5eV, non-relativistic at decoupling
  - If relativistic at early times:
    - changes matter-radiation equality
    - free-streaming ⇒ anisotropic stress
    - (CMB alone is degenerate with matter density, so need to combine with other measurements of $\Omega_m h^2$)
      - N_{eff} = 4.34±0.88
  - In future, neutrino effect on CMB *lensing* may be strongest test



Fundamental Physics with the CMB: Parity violation

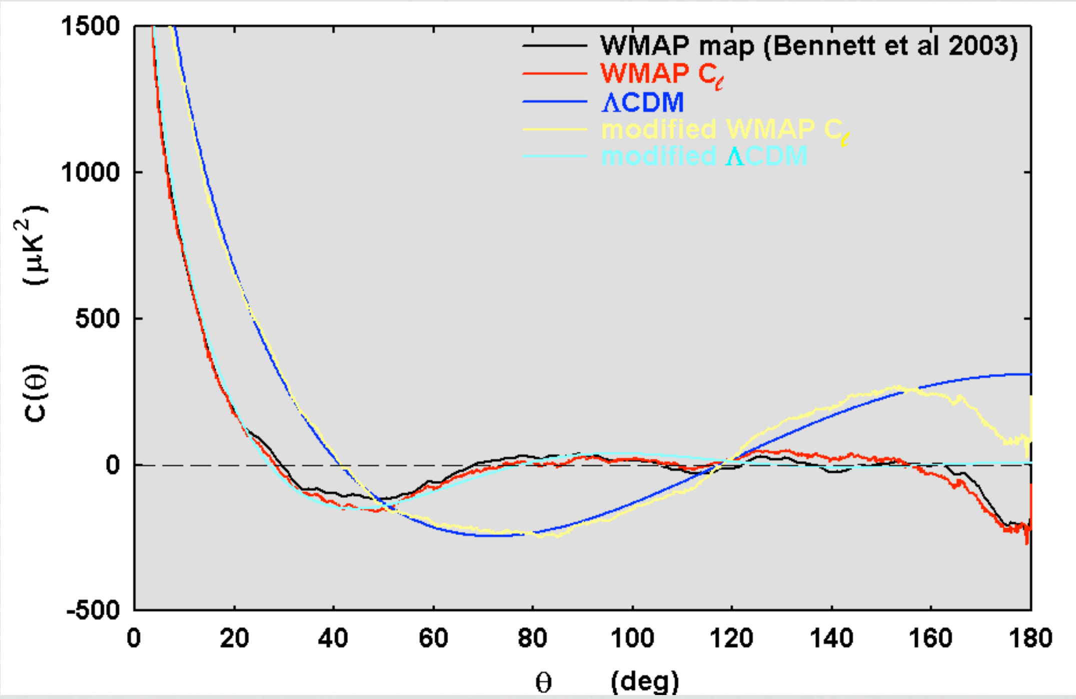
- Parity conservation of EM interactions:
  - $\langle \mathrm{EB} \rangle = \langle \mathrm{TB} \rangle = 0$
- "Cosmic birefrigence" (M. Kamionkowsi et al)
  - $\frac{\phi}{M}\mathbf{E}\cdot\mathbf{B} \propto F\tilde{F}$ in Lagrangian (nb. these **are** EM fields…)
  - different velocities for left and right circular polzn
  - rotates E⇒B by angle $\alpha \sim \phi/M$
  - non-detection of $\langle \mathrm{TB} \rangle$: $\alpha \lesssim 1°$
    - (WMAP 7-year + small-scale expts)

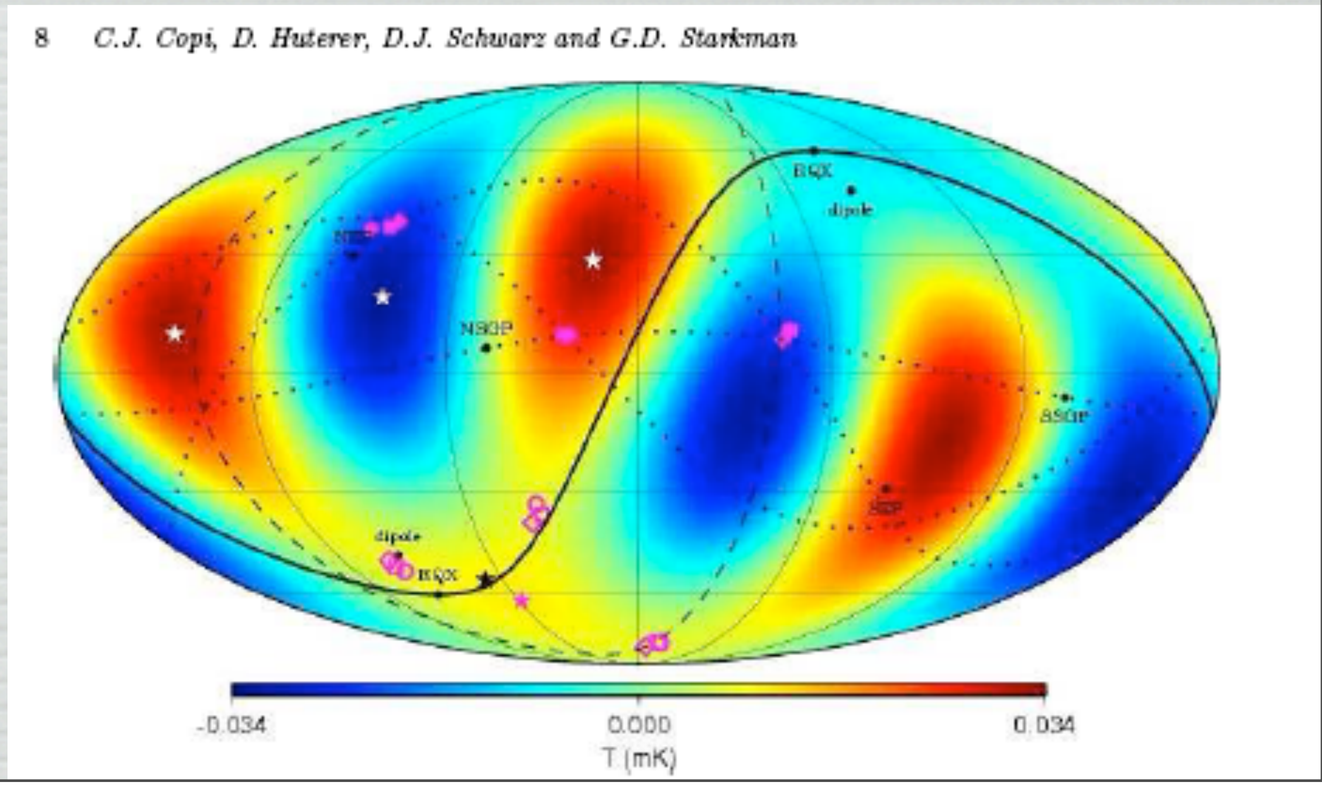


- Long distance to last scattering:
  - $c_L = c_R(1 \pm 10^{-30})$

"Anomalies"

- However….
- Low quadrupole (cf DMR)
  - +Niarchou et al
- Aligned multipoles
  - (+Tegmark et al, Land & Magueijo, Copi et al…)
  - "Unlikely" distribution of low-ℓ $a_{\ell m}$…
    - Aligned w/ astrophysics…
      - Ecliptic, dipole
  - Bianchi models?
- Anisotropic Distribution of power
- Cold spot
- Topology? (Simple cases ruled out)
- (see also Pontzen & Peiris 2010)





Planck: Launched 2009

- Nominal mission: 14 Months
  (already extended ~2x, will also incorporate "warm extension" for LFI)

Planck launch, 14 May 2009

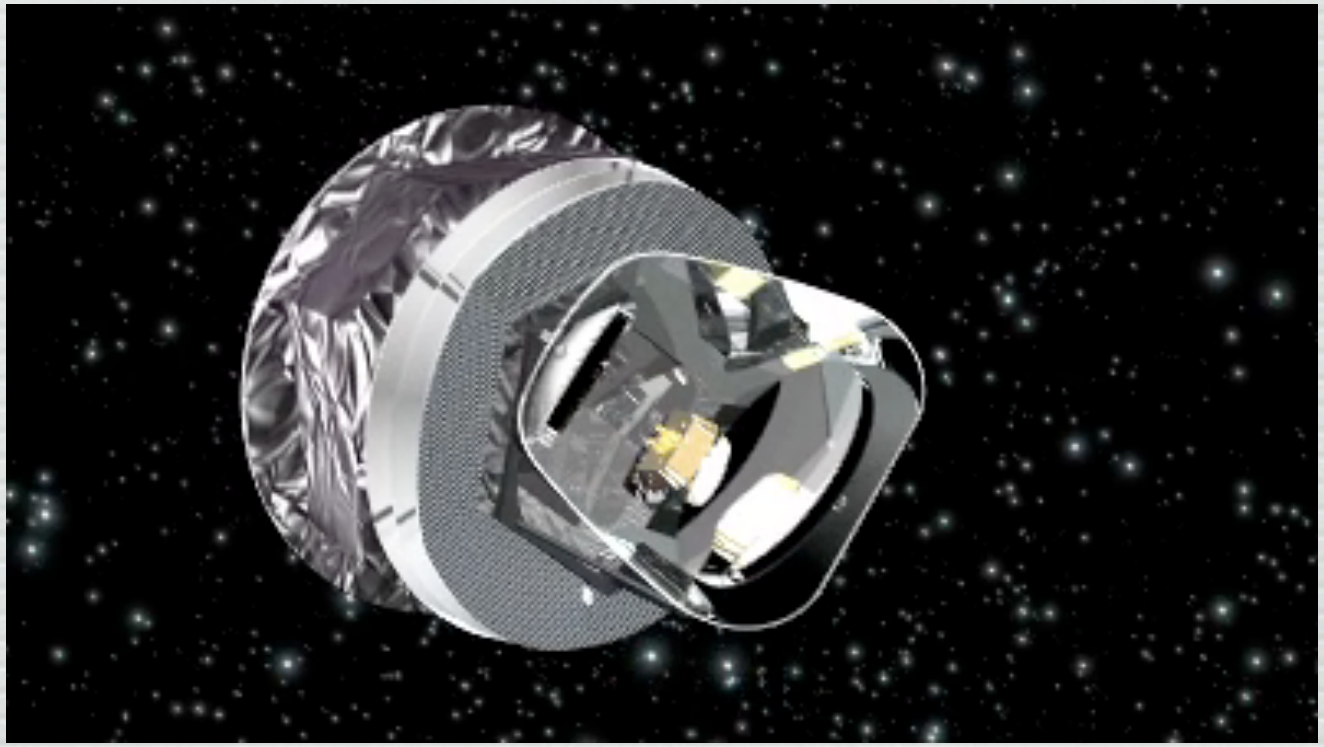
Planck in orbit (animation)

Planck: Launched 2009

- Nominal mission: 14 Months
  (already extended ~2x, will also incorporate "warm extension" for LFI)

Planck launch, 14 May 2009

Planck in orbit (animation)

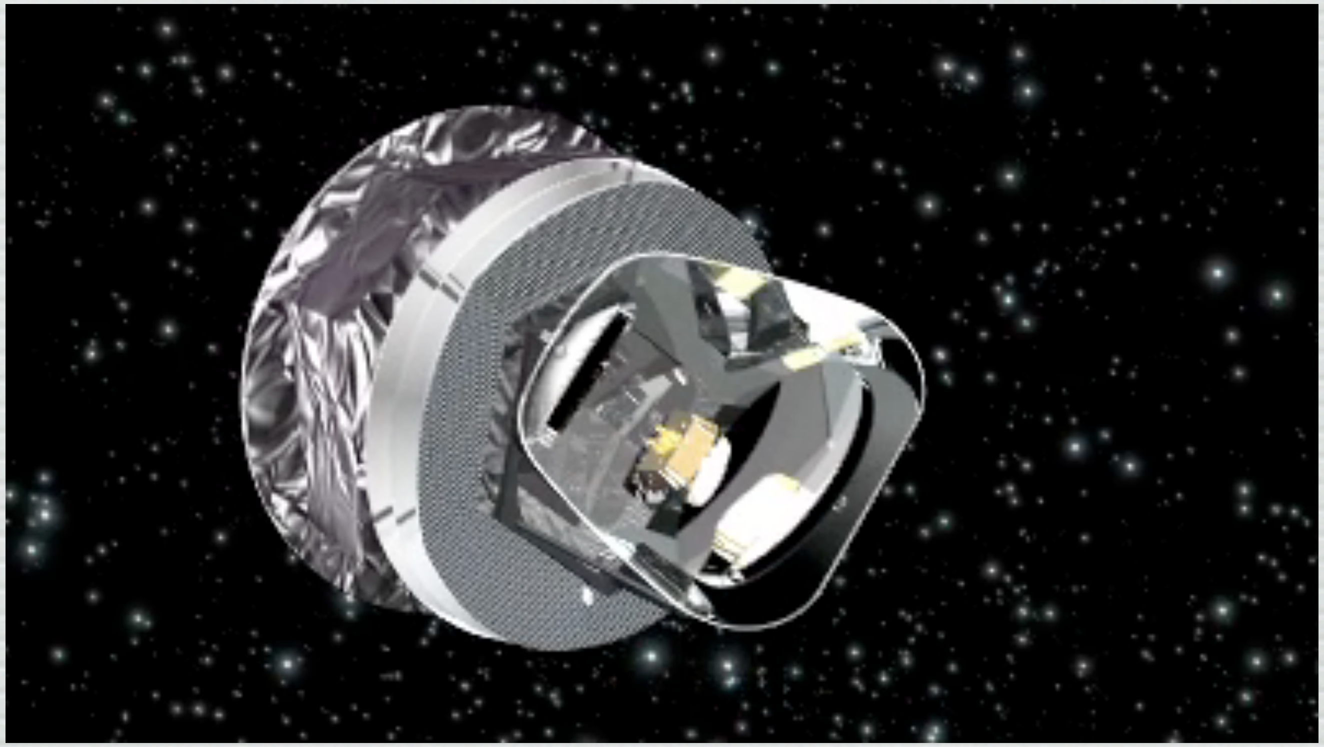


Planck: Launched 2009

- Nominal mission: 14 Months (already extended ~2x, will also incorporate "warm extension" for LFI)

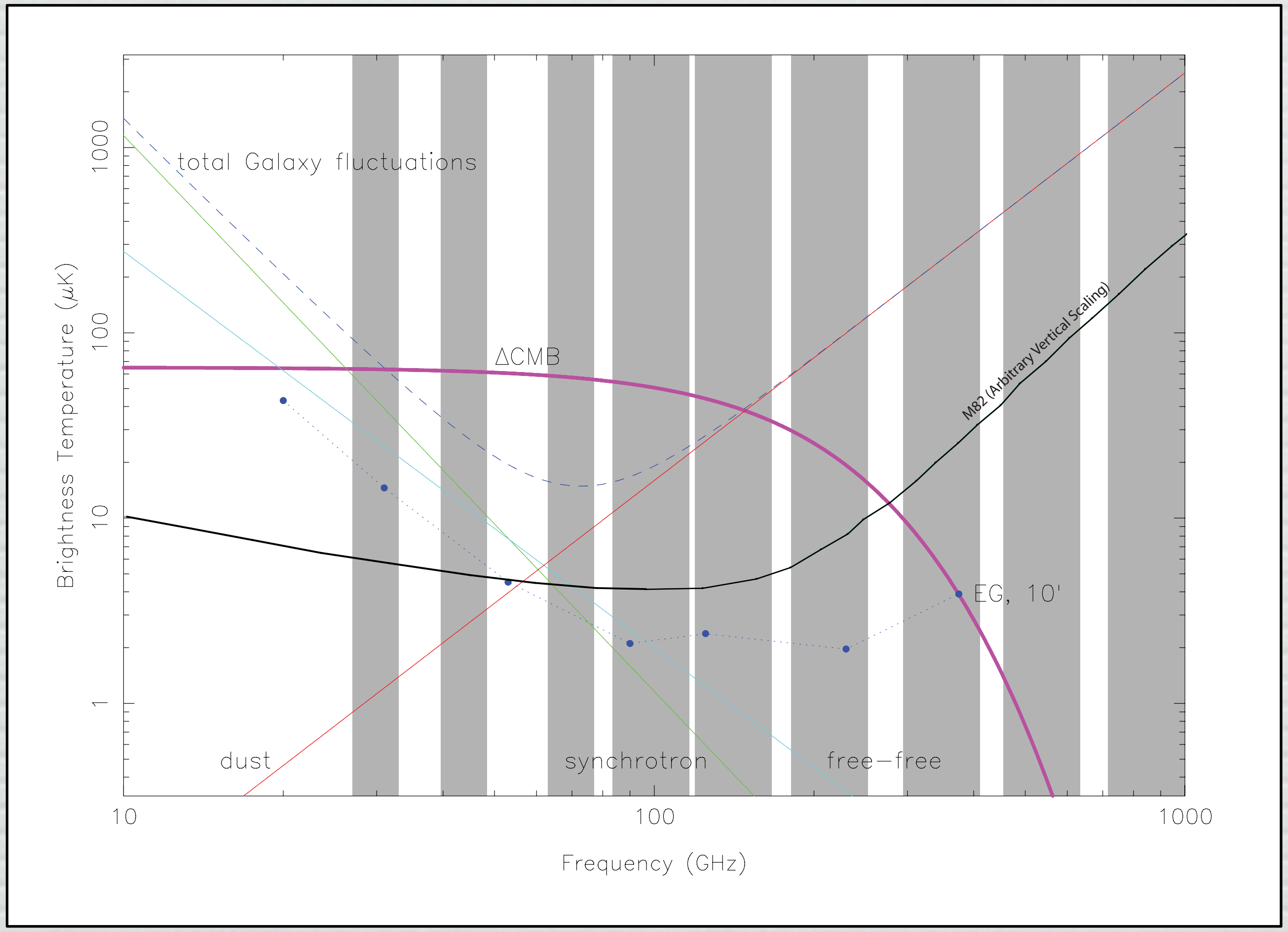
Planck launch, 14 May 2009

Planck in orbit (animation)



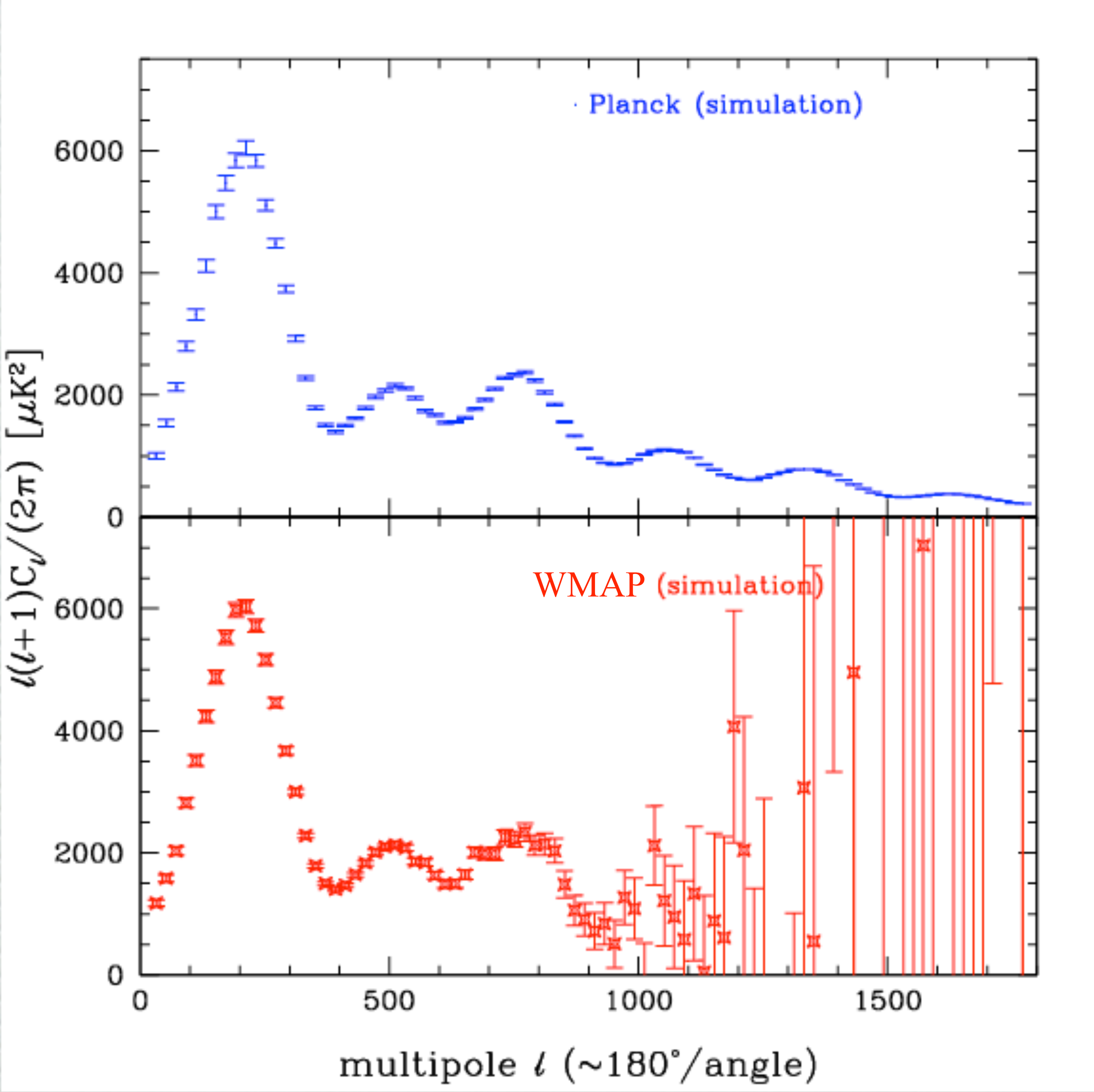
Future (soon) spectra

- Planck gets ~all of T, most of E
- Wide frequency coverage for "foreground" removal



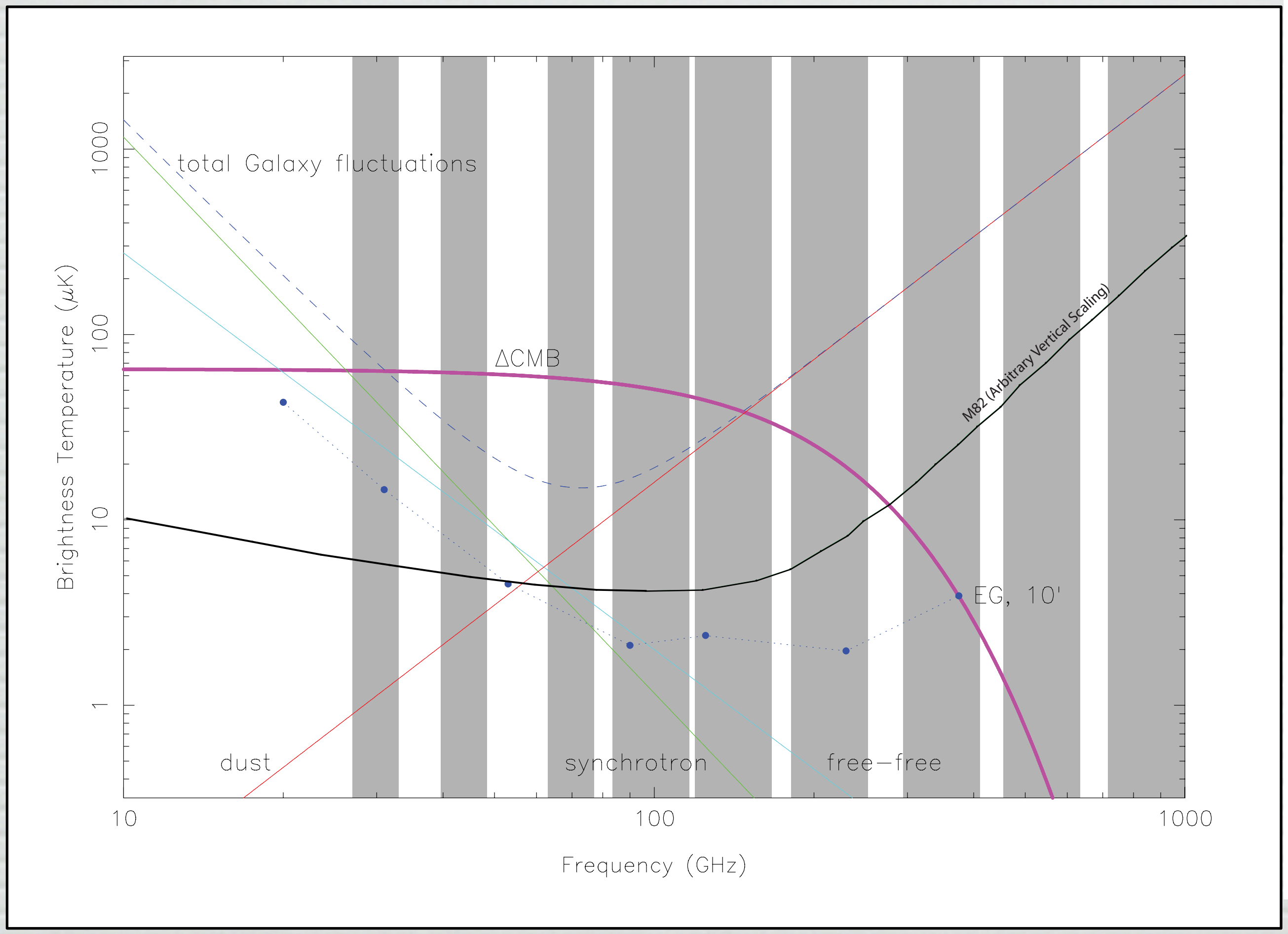
- Breaks "conceptual" degeneracies (do we have the overall model correct?); most parameters better determined by factor of ~few.

- Planck cosmology: Jan 2013



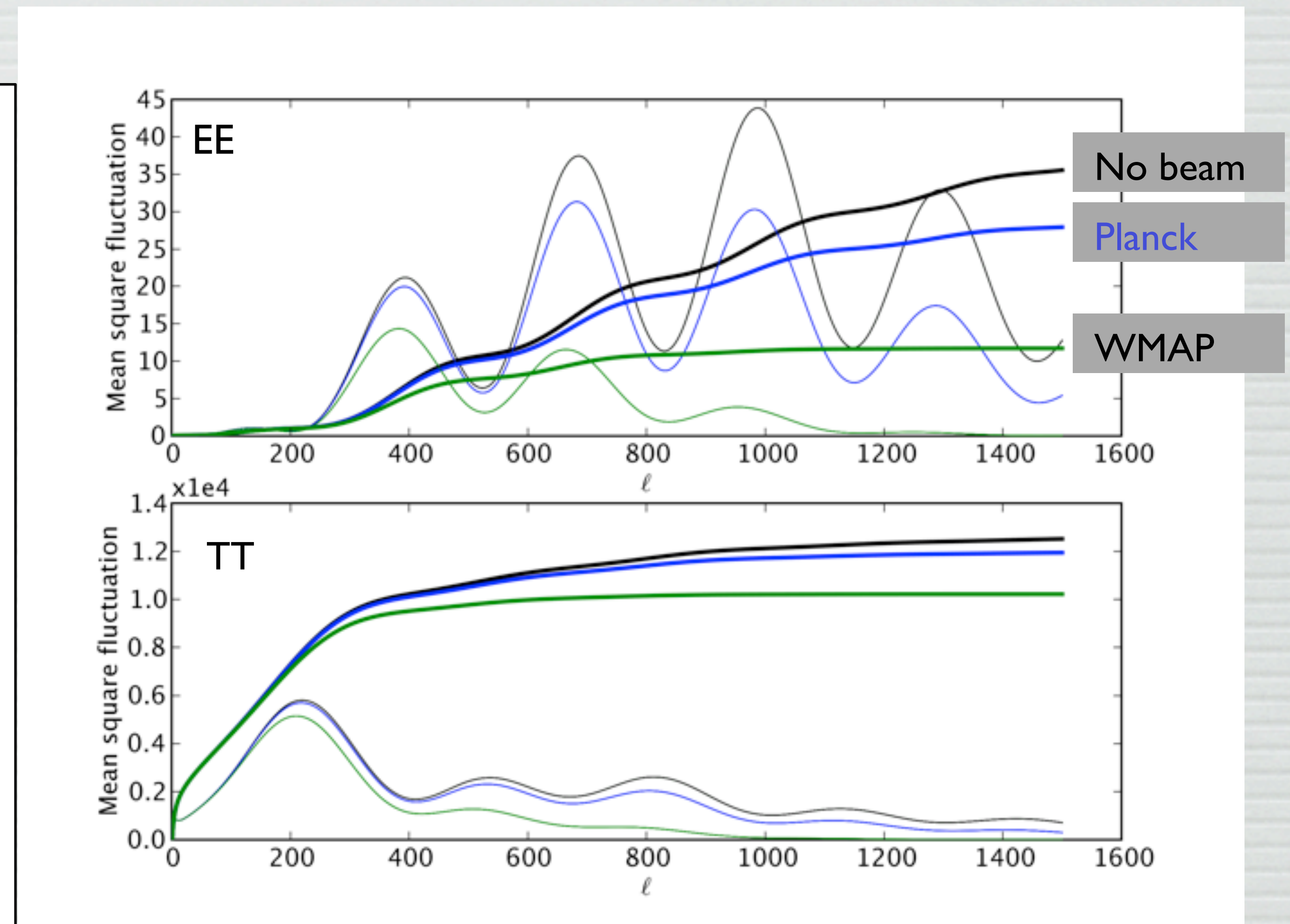
Future (soon) spectra

- Planck gets ~all of T, most of E
- Wide frequency coverage for "foreground" removal



- Breaks "conceptual" degeneracies (do we have the overall model correct?); most parameters better determined by factor of ~few.

- Planck cosmology: Jan 2013



Planck Data

- The Early Release Compact Source Catalog

- Two Subcatalogs
  - The Early Sunyaev-Zeldovich Catalog
  - The Early Cold Cores Catalog

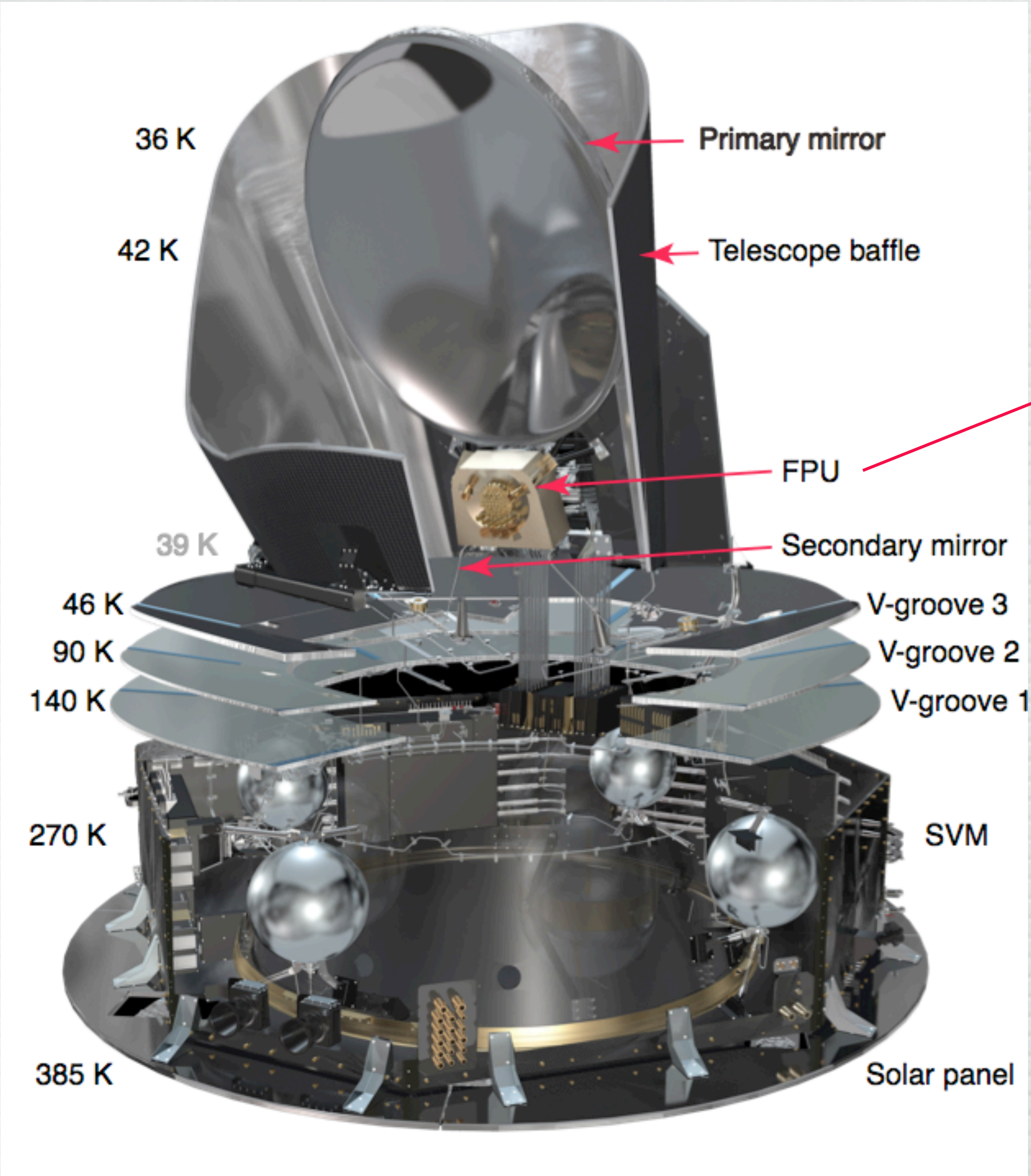
  - `http://www.sciops.esa.int/index.php?project=planck&page=Planck_Legacy_Archive`

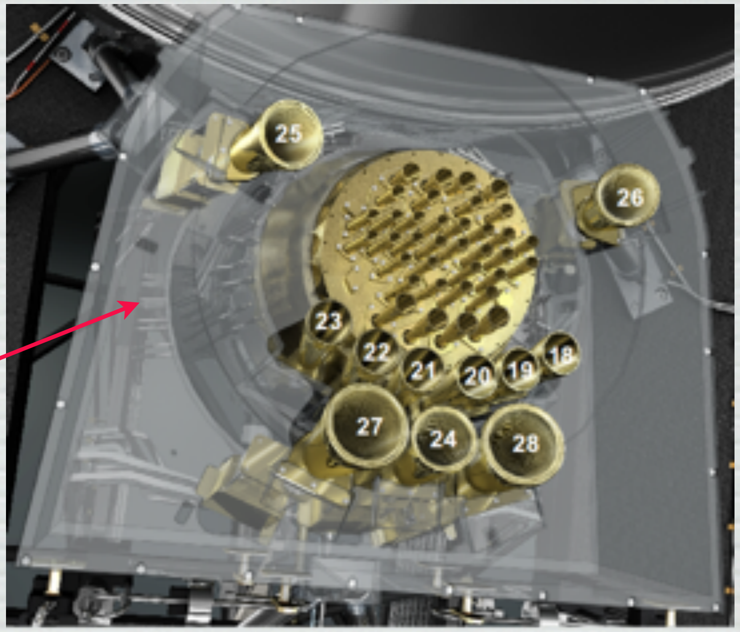
Planck Early Papers

- 25 Papers, submitted to A&A
- "The Planck Collaboration 2011a-y"
  - Overview, hardware performance, data analysis
  - Data product descriptions
  - First scientific results
    - The Milky Way
    - Galaxies
    - Clusters

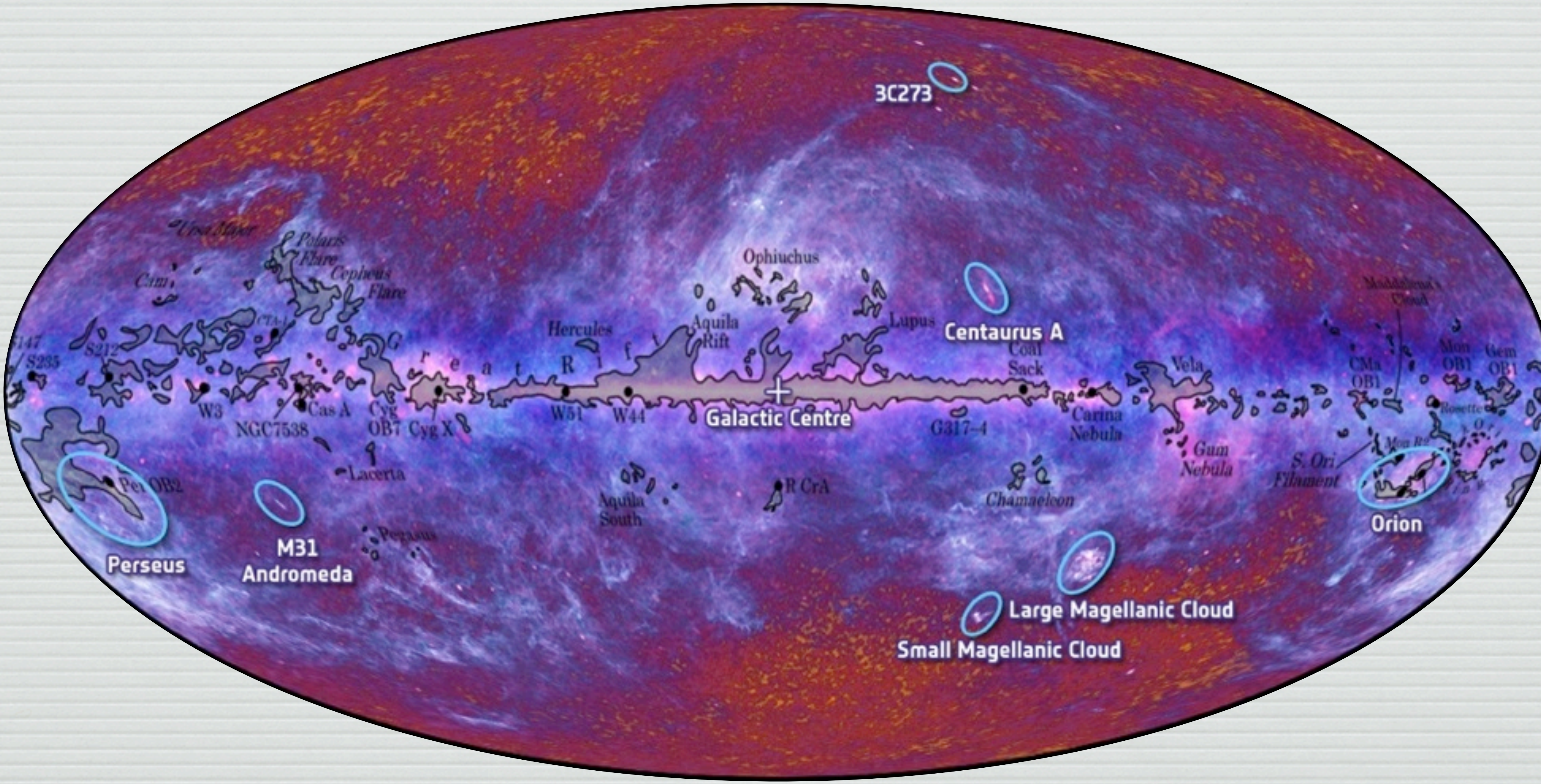
- http://www.sciops.esa.int/index.php?project=PLANCK&page=Planck_Published_Papers

The coldest (known) object in space





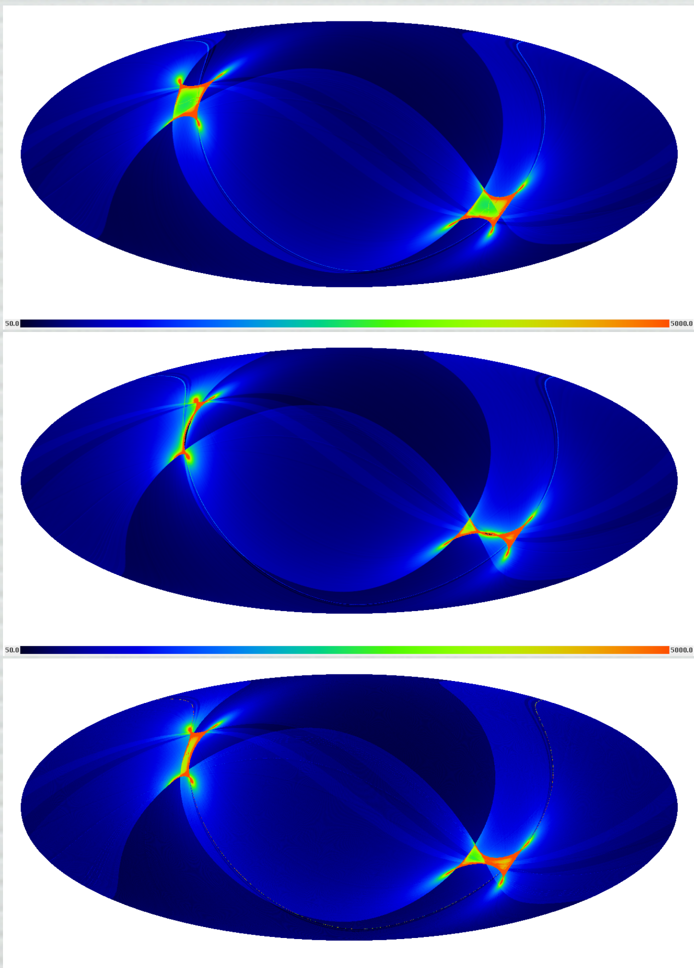
The Planck Sky — Previewed

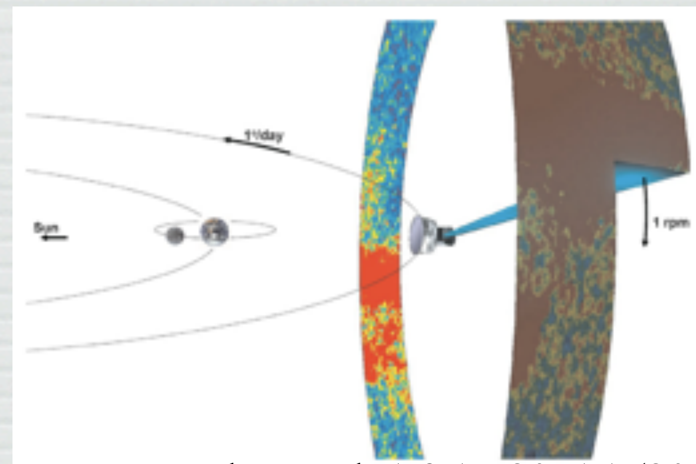


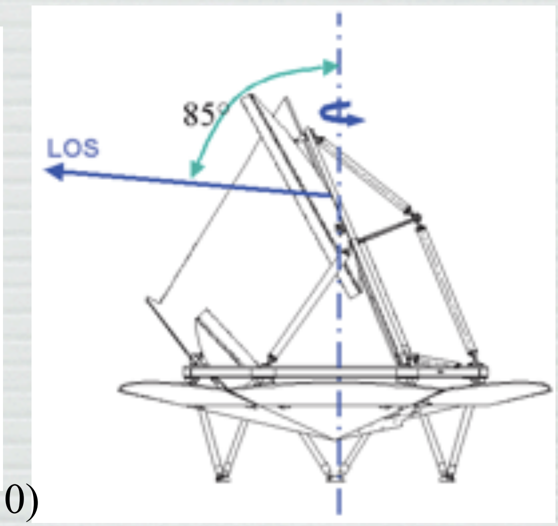
Planck Early Papers

- ***The hardware and software***
  - The Planck mission
  - The thermal performance of Planck
  - First assessment of the Low Frequency Instrument in-flight performance
  - First assessment of the High Frequency Instrument in-flight performance
  - The Low Frequency Instrument data processing
  - The High Frequency Instrument data processing
- ***The data***
  - The Early Release Compact Source Catalogue
  - The all-sky early Sunyaev-Zeldovich cluster sample
  - The Galactic cold core population revealed by the first all-sky survey
- ***Clusters***
  - XMM-Newton follow-up for validation of Planck cluster candidates
  - Statistical analysis of Sunyaev-Zeldovich scaling relations for X-ray galaxy clusters
  - Calibration of the local galaxy cluster Sunyaev-Zeldovich scaling relations
  - Cluster Sunyaev-Zeldovich optical scaling relations
- ***Galaxies***
  - Statistical properties of extragalactic radio sources in the Planck Early Release Compact Source Catalogue
  - Early Release Compact Source Catalogue validation and extreme radio sources
  - Spectral energy distributions and radio continuum spectra of northern extragalactic radio sources
  - The Planck view of nearby galaxies
  - Origin of the submillimetre excess dust emission in the Magellanic Clouds
  - The power spectrum of cosmic infrared background anisotropies
- ***The Milky Way***
  - All-sky temperature and dust optical depth from Planck and IRAS – constraints on the "dark gas" in our Galaxy
  - New light on anomalous microwave emission from spinning dust grains
  - Properties of the interstellar medium in the Galactic plane
  - The submillimetre properties of a sample of Galactic cold clumps
  - Dust in the diffuse interstellar medium and the Galactic halo
  - Thermal dust in nearby molecular clouds

Planck: the stats







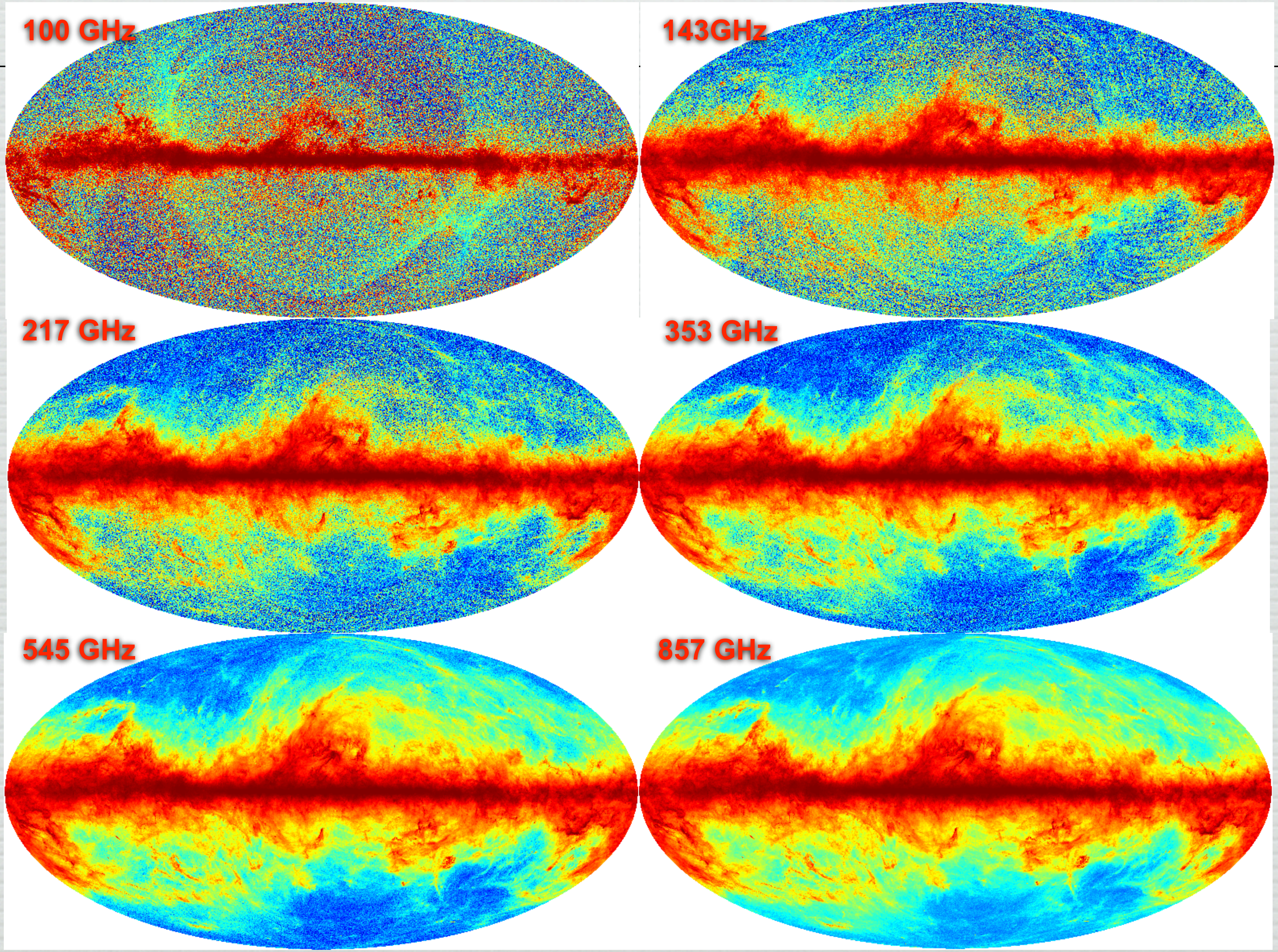
Tauber et al, A&A 520, A1 (2010)

Table 3. *Planck* performance parameters determined from flight data.

Channel	$N_{detectors}$ [a]	ν_{center} [b] [GHz]	Mean Beam[c] FWHM	Mean Beam[c] Ellipticity	White-noise[d] Sensitivity [μK_{RJ} $s^{1/2}$]	White-noise[d] Sensitivity [μK_{CMB} $s^{1/2}$]	Calibration[e] Uncertainty [%]	Faintest Source[f] in ERCSC $\|b\| > 30°$ [mJy]
30 GHz	4	28.5	32.65	1.38	143.4	146.8	1	480
44 GHz	6	44.1	27.92	1.26	164.7	173.1	1	585
70 GHz	12	70.3	13.01	1.27	134.7	152.6	1	481
100 GHz	8	100	9.37	1.18	17.3	22.6	2	344
143 GHz	11	143	7.04	1.03	8.6	14.5	2	206
217 GHz	12	217	4.68	1.14	6.8	20.6	2	183
353 GHz	12	353	4.43	1.09	5.5	77.3	2	198
545 GHz	3	545	3.80	1.25	4.9	. . .	7	381
857 GHz	3	857	3.67	1.03	2.1	. . .	7	655

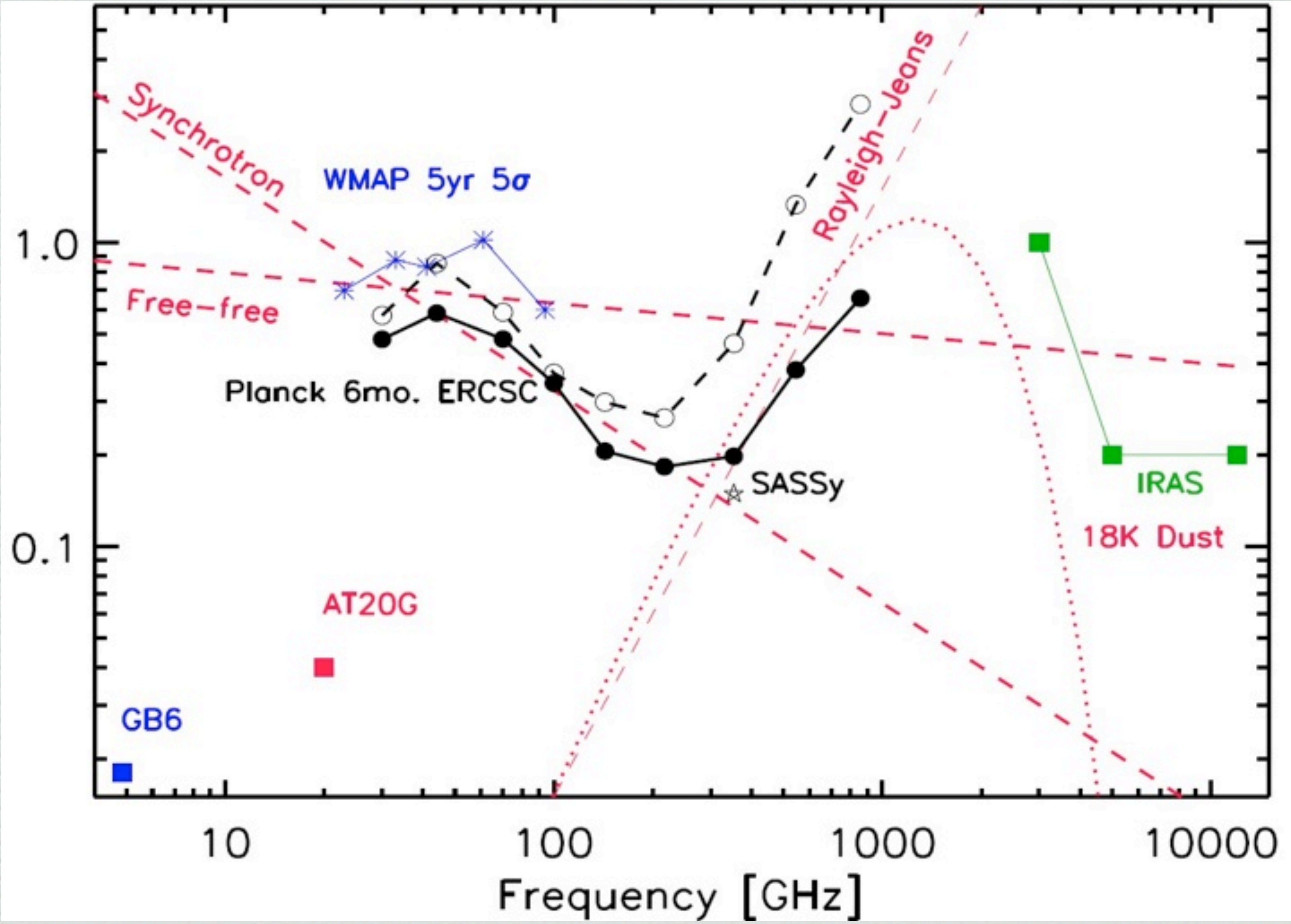
- Working at or beyond requirements for sensitivity and resolution.
- Unexpected: very high cosmic ray glitch rate (solar min):
  - 15% of HFI data contaminated by direct hits;
  - also, energy deposited directly into 100mK stage

Maps from HFI (CMB-removed!)

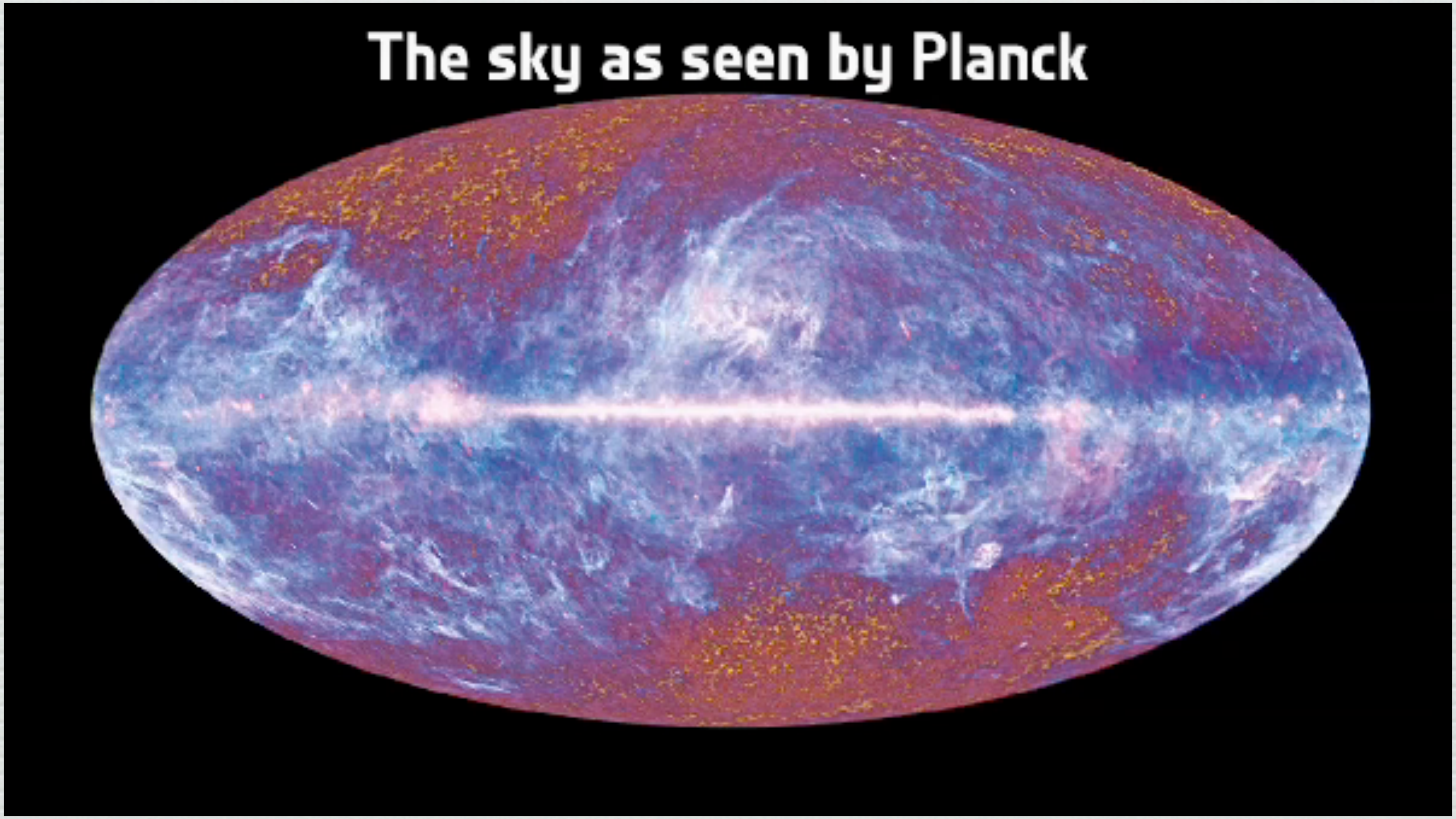


The Early-Release Compact Source Catalog

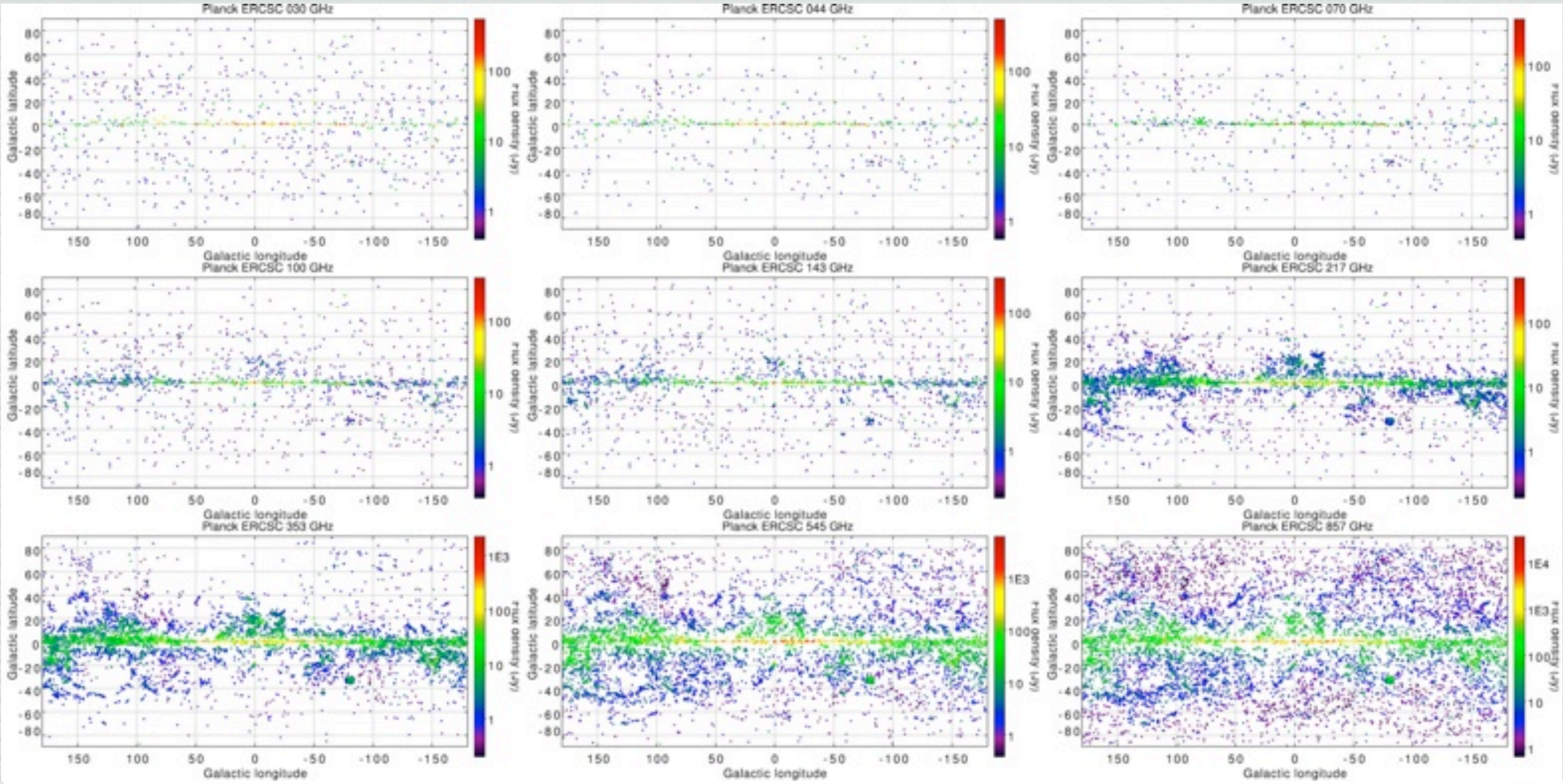
- ERCSC Sensitivity



The Early-Release Compact Source Catalog



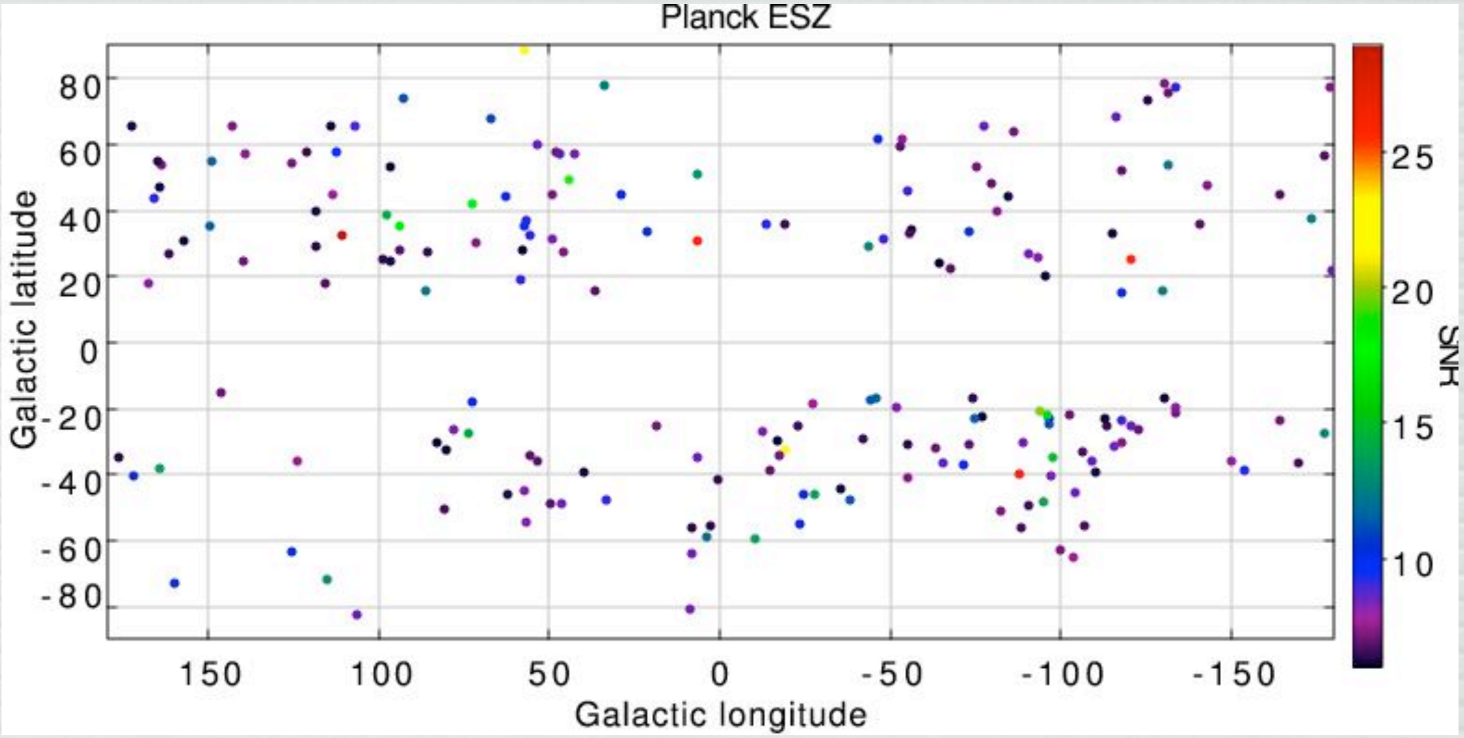
The Early-Release Compact Source Catalog

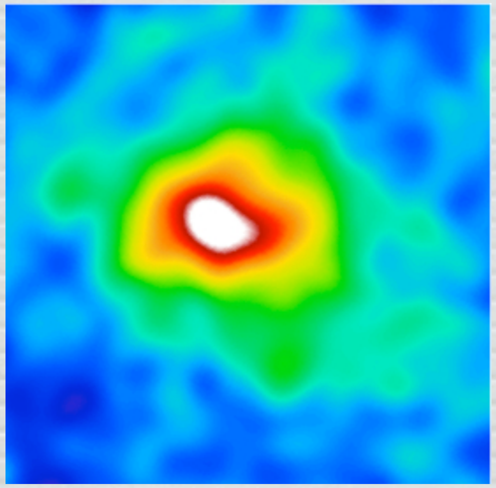


Freq [GHz]	30	44	70	100	143	217	353	545	857
$\lambda(\mu m)$	10000	6818	4286	3000	2098	1382	850	550	350
Sky Coverage (%)	99.96	99.98	99.99	99.97	99.82	99.88	99.88	99.80	99.79
Beam FWHM (′)[a]	32.65	27.00	13.01	9.94	7.04	4.66	4.41	4.47	4.23
# of Sources	705	452	599	1381	1764	5470	6984	7223	8988
# of $\|b\| > 30°$ Sources	307	143	157	332	420	691	1123	2535	4513
10σ[b] (mJy) median	1173	2286	2250	1061	750	807	1613	2074	2961
10σ[c] (mJy) faint	487	1023	673	500	328	280	249	471	813
Flux Density Limit[d] (mJy)	480	585	481	344	206	183	198	381	655

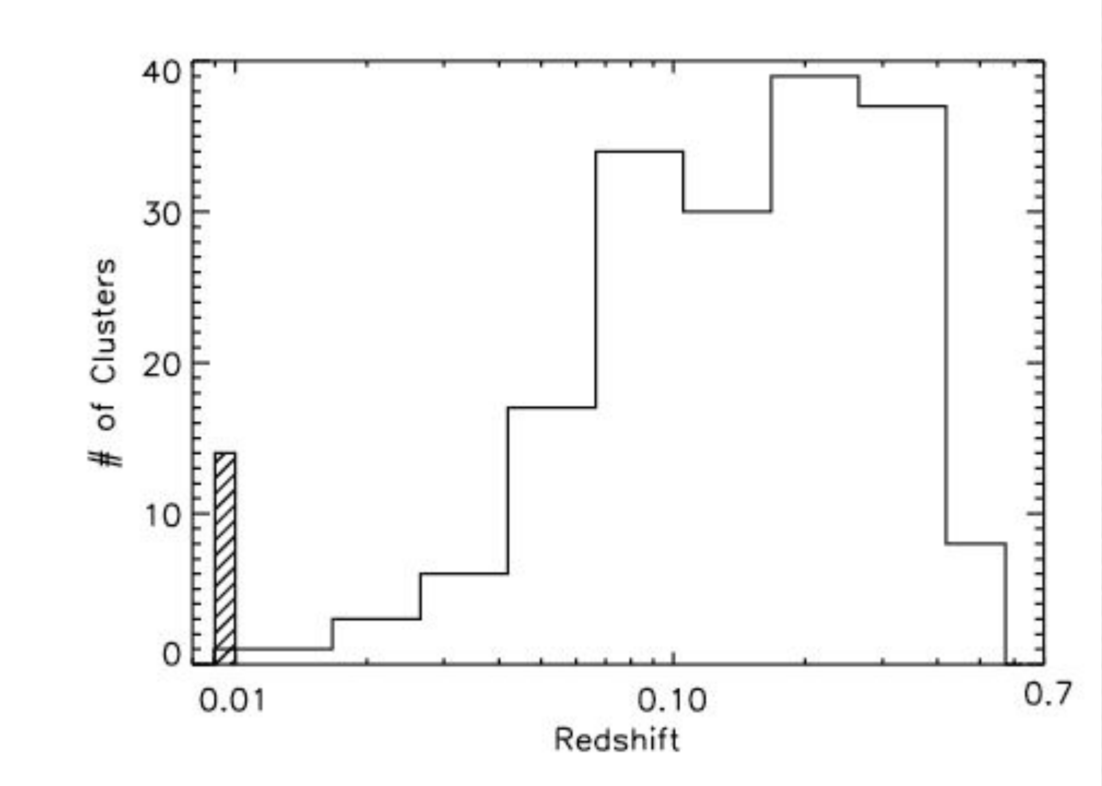
The Early SZ Catalog

- Sunyaev-Zeldovich effect:
  - inverse-Compton upscattering of CMB photons by hot cluster gas
- 189 high-reliability SZ candidates (S/N from 6 to 29)
  - 20 new clusters
  - new SZ detections for 80% of known clusters
  - 86% z<0.3
  - up to $M \sim 10^{15}\, M_\odot$



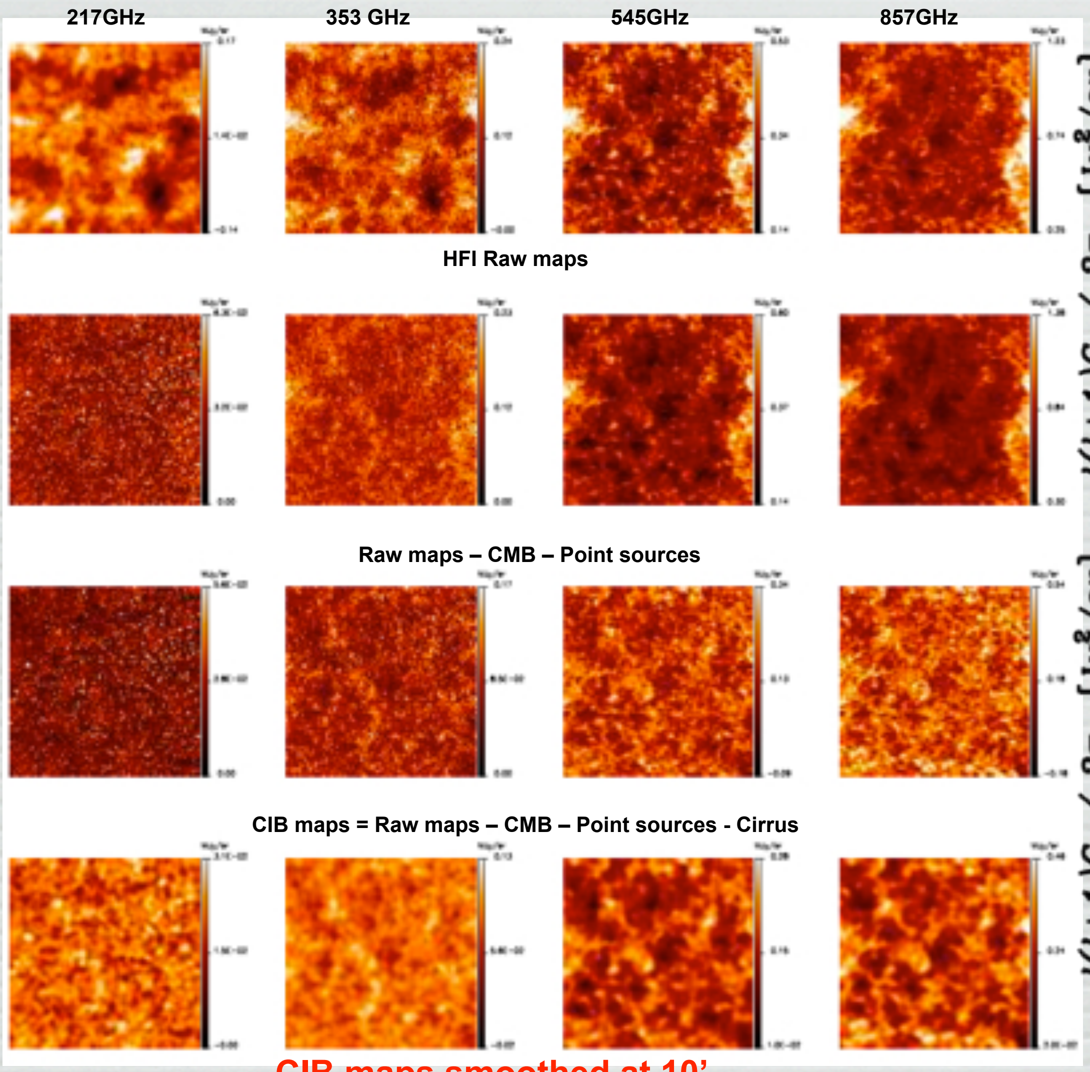


Planck reconstructed y-map of Coma on a ~3°x3° patch

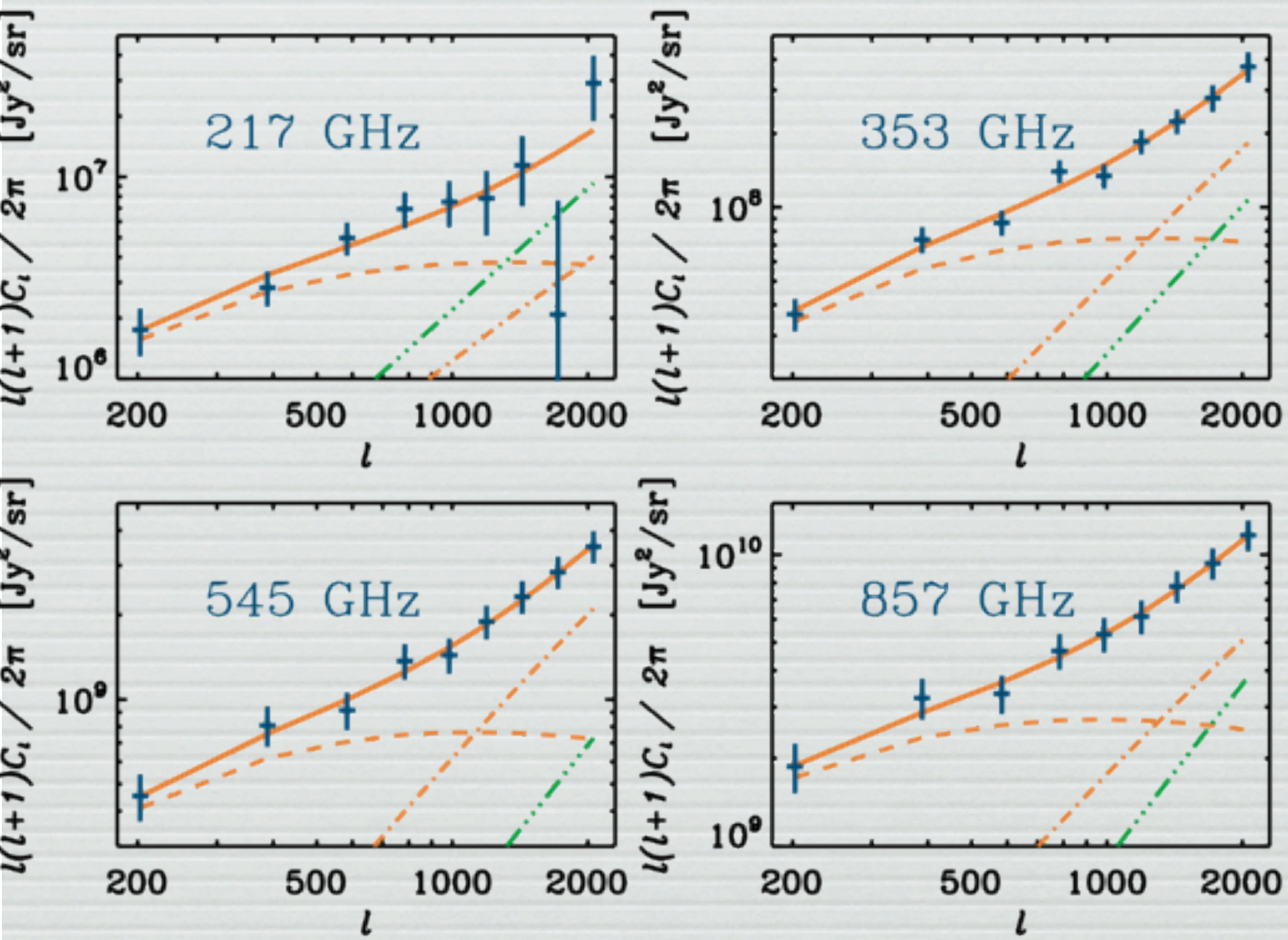


The Cosmic Infrared Background

- Unresolved galaxies ("confusion")



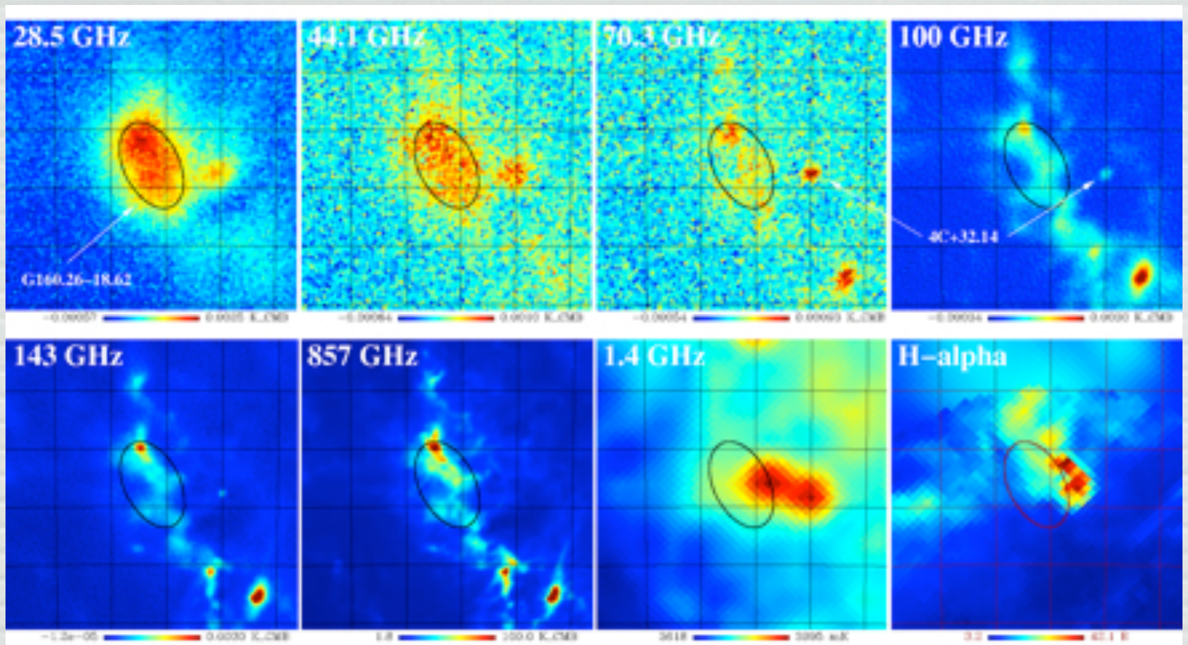
CIB maps smoothed at 10'



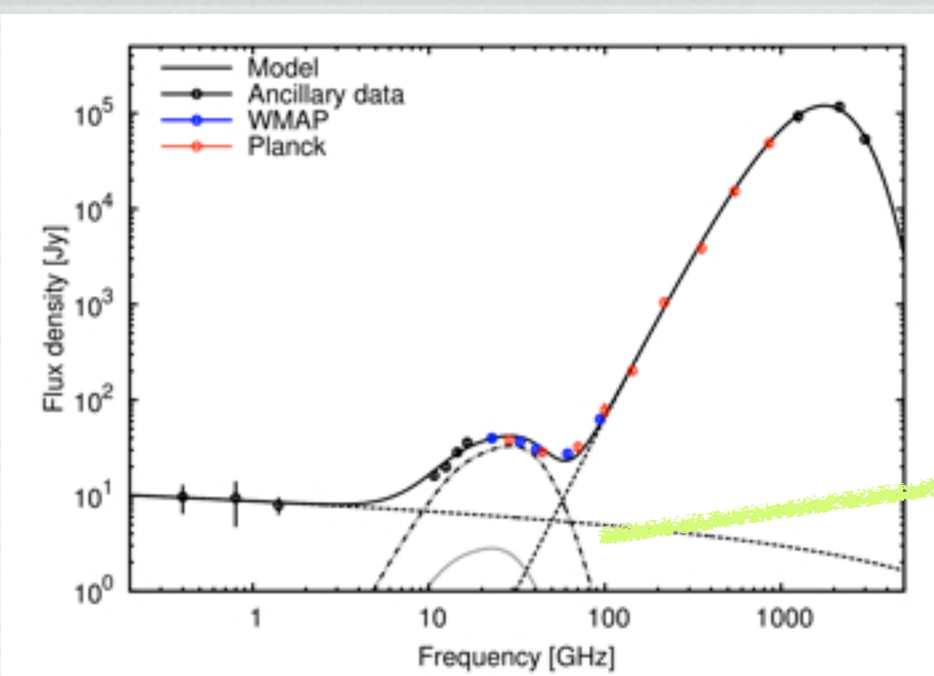
Model:
1-halo + 2-halo + shot noise

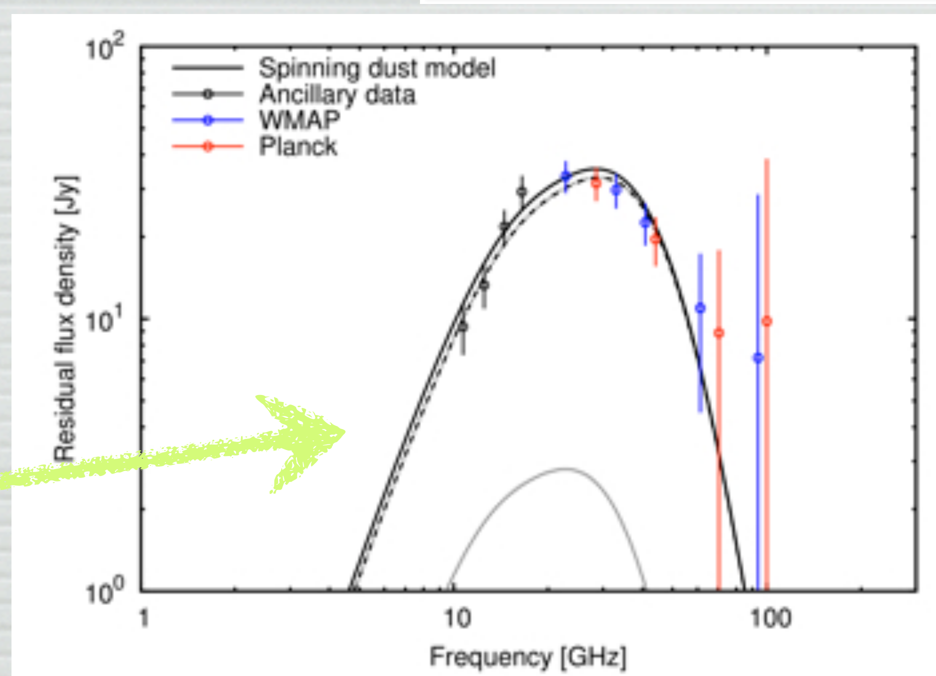
The Milky Way: Anomalous Emission and Spinning Dust

Maps and spectra: Perseus Molecular Cloud



Gas state	Molecular	Atomic	Ionized
		Perseus	
N_H [10^{21} cm^{-2}]	11.7	1.3	0.4
n_H [cm^{-3}]	250	30	1
z [pc]	15.1	14.0	…
G_0	1	2	…
T [K]	40	100	8×10^3
x_H [ppm]	112	410	10^6
x_C [ppm]	<1	100	…
y	1	0.1	…
a_0 [nm]	0.58	0.53	…
b_C [ppm]	68	68	…
β	…	1.65	…
T_d [K]	…	18.5	…
τ_{250}	…	9.4×10^{-4}	…
		ρ Ophiuchus	
N_H [10^{21} cm^{-2}]	17.1	0.35	0.4
n_H [cm^{-3}]	2×10^4	200	0.5
z [pc]	0.3	0.6	…
G_0	0.4	400	…
T [K]	20	10^3	8×10^3
x_H [ppm]	9.2	373	10^6
x_C [ppm]	<1	100	…
y	1	0.1	…
a_0 [nm]	0.58	0.35	…
b_C [ppm]	65	50	…
β	…	1.72	…
T_d [K]	…	20.4	…
τ_{250}	…	2.6×10^{-3}	…





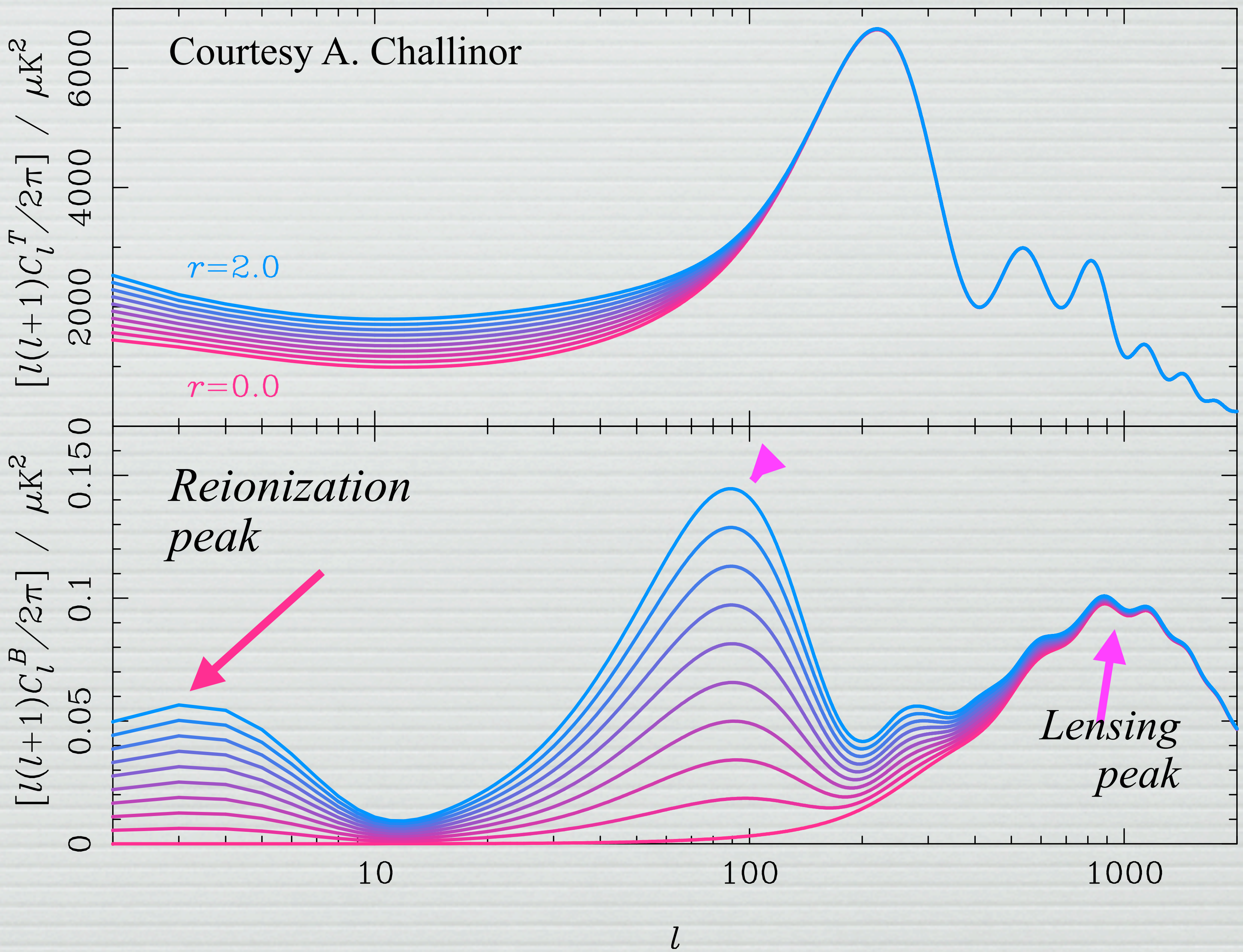
Lots More!

- Galactic and extragalactic science:
  - Nearby Galaxies: Dave Clements' talk
  - Dark Gas & star formation: Jennifer Hatchell's talk

- Papers on astro-ph and submitted to A&A
- Planck catalogs and papers available online:
- www.sciops.esa.int/index.php?project=PLANCK
- Catalog can be searched online
- Some extant followup data on AGN also available at this site

The CMB after Planck: Gravitational Radiation

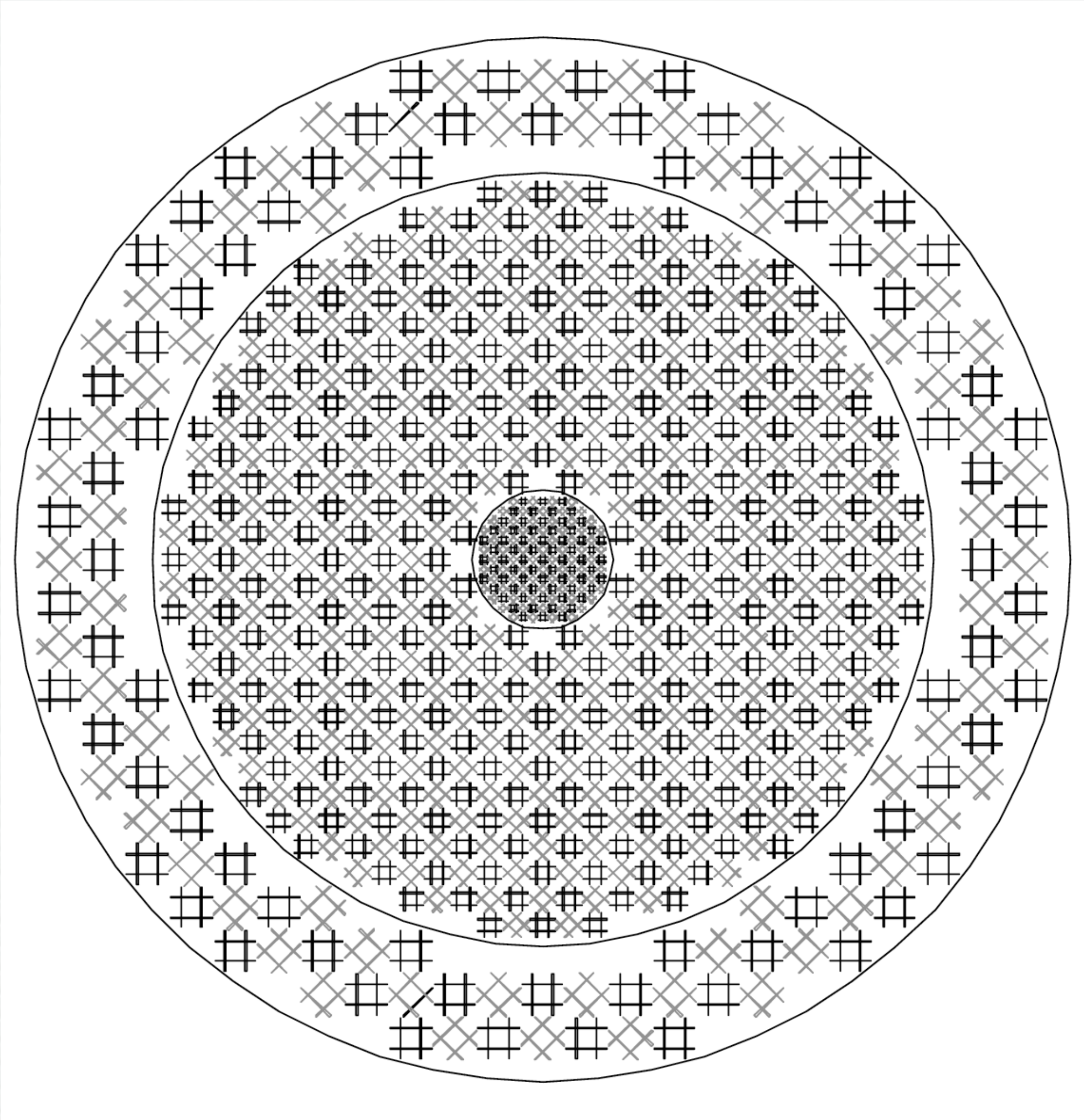
- Last scattering: "direct" effect of tensor modes (primordial GWs) on the primordial plasma
  - inflationary potential
- dominated by *lensing of E* ⇒ *B* for $\ell \gtrsim 200$
- Reionization peak $\ell \lesssim 20$
  - need ~full-sky. Difficult for single suborbital experiments
- Fundamental physics:
  - sensitive to $m_\nu \lesssim 0.06$eV
    - (i.e., hot dark matter)
- *Limits depend on full set of parameters*



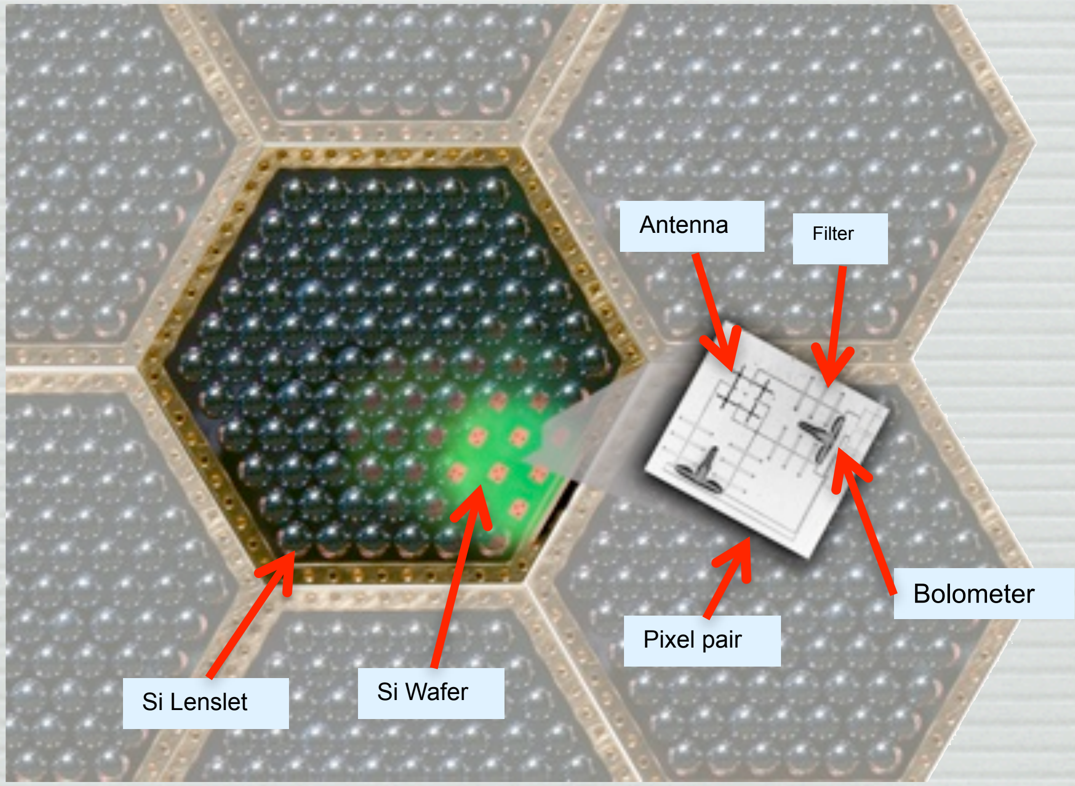
Suborbital experiments target $\ell \sim 100$ peak: require order-of-magnitude increase in sensitivity over Planck

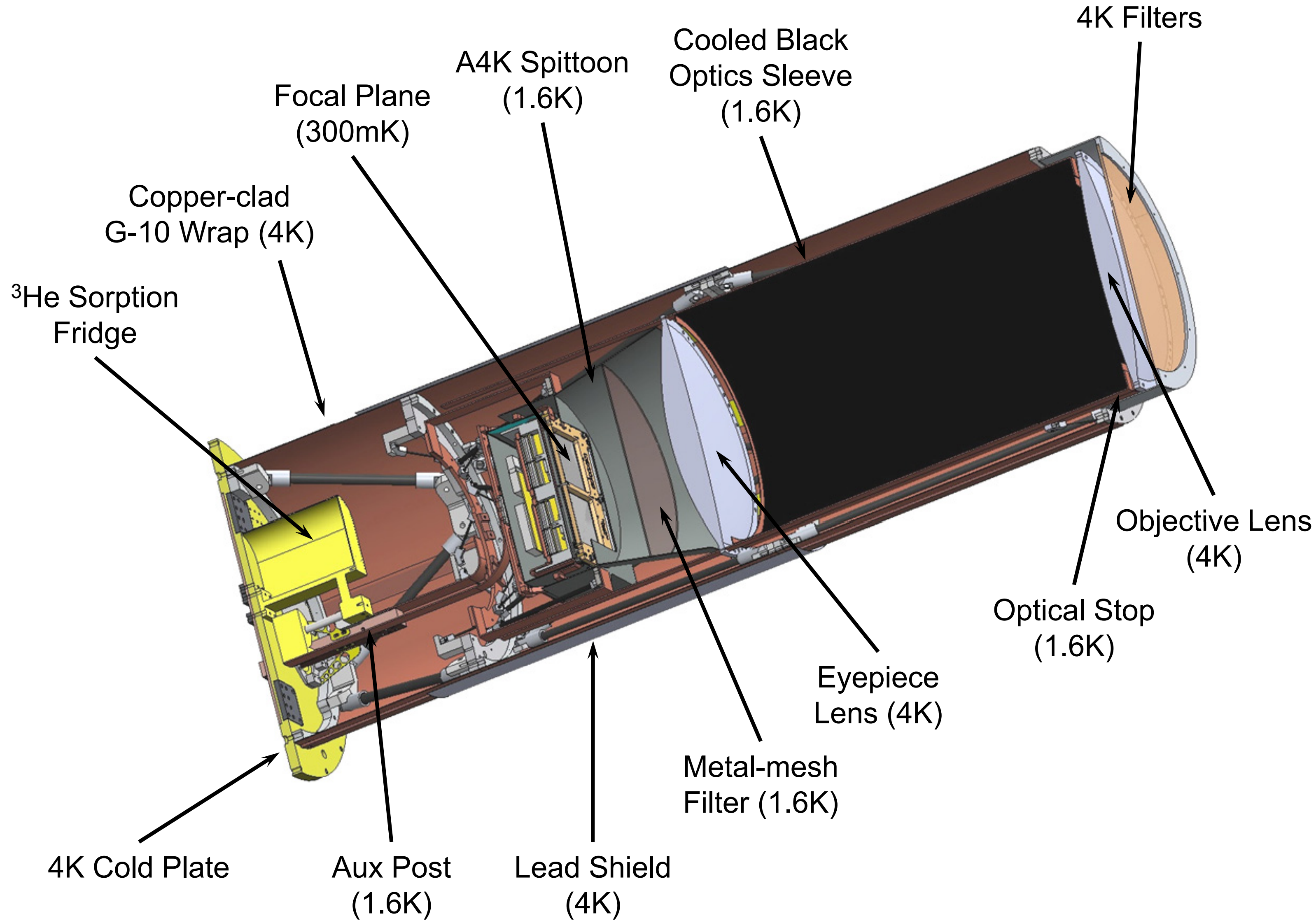
Beyond Planck: New Technologies

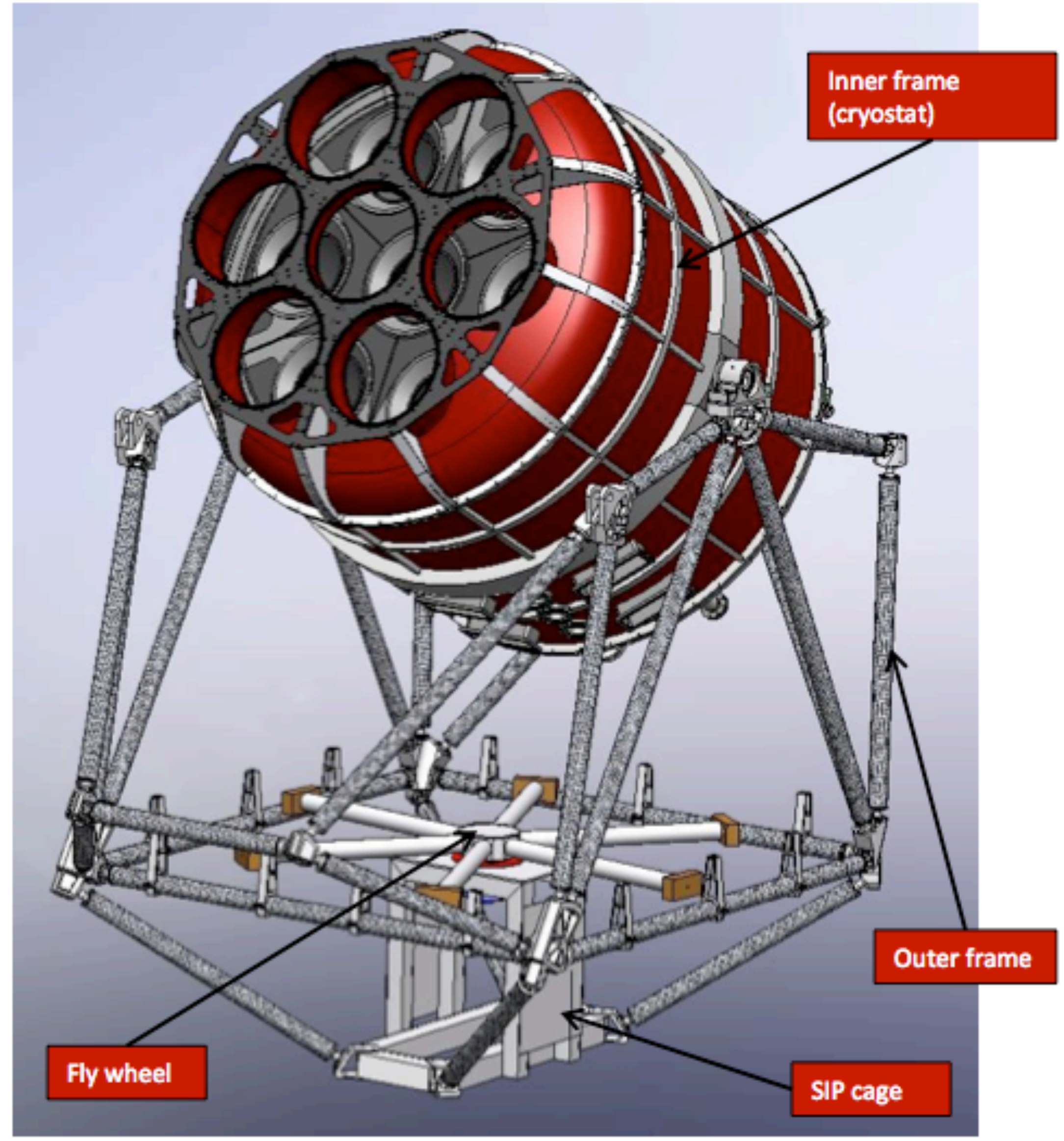
- PolarBear - AT Lee (Berkeley)



- Antenna-coupled bolometers
- ~900 pixels @ 150 GHz, 3000 bolometers
- Full use of useful 150 GHz Field-of-view
- New challenges: 1000s of bolometers (central limit theorem to the rescue????)



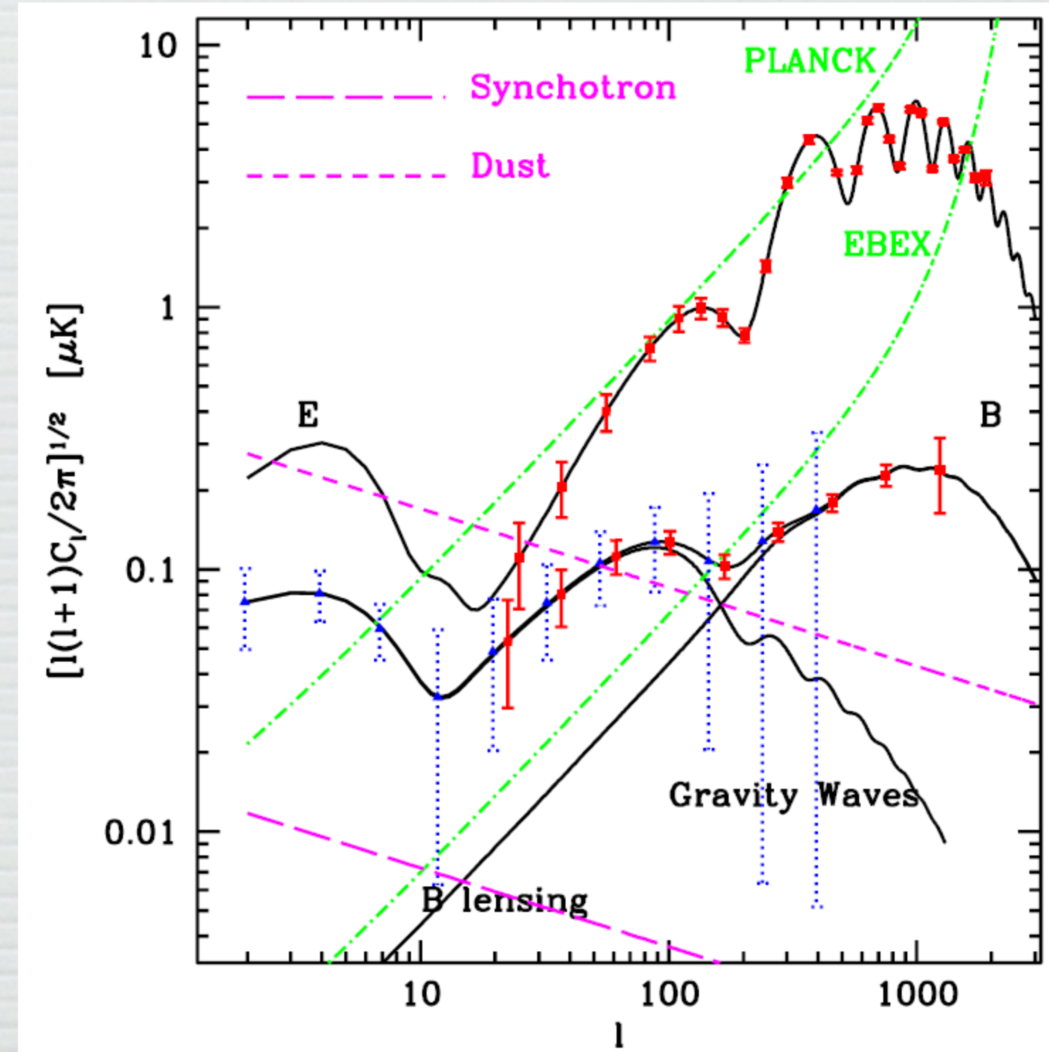

4K Filters
Cooled Black
Optics Sleeve
(1.6K)
A4K Spittoon
(1.6K)
Focal Plane
(300mK)
Copper-clad
G-10 Wrap (4K)
^{3}He Sorption
Fridge
Objective Lens
(4K)
Optical Stop
(1.6K)
Eyepiece
Lens (4K)
Metal-mesh
Filter (1.6K)
4K Cold Plate
Aux Post
(1.6K)
Lead Shield
(4K)


Inner frame
(cryostat)
Outer frame
Fly wheel
SIP cage

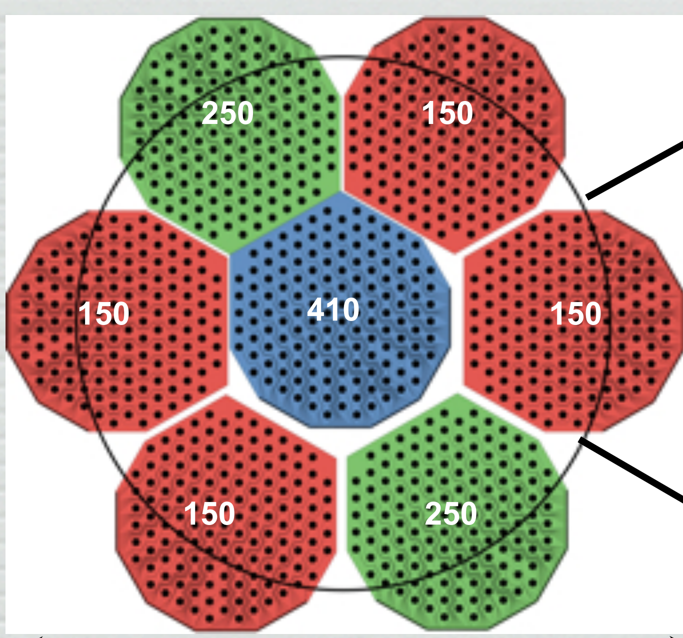
EBEX

From individual bespoke detectors to 1,500 fabricated en masse

Full focal plane will be sensitive to $r \simeq 0.01$

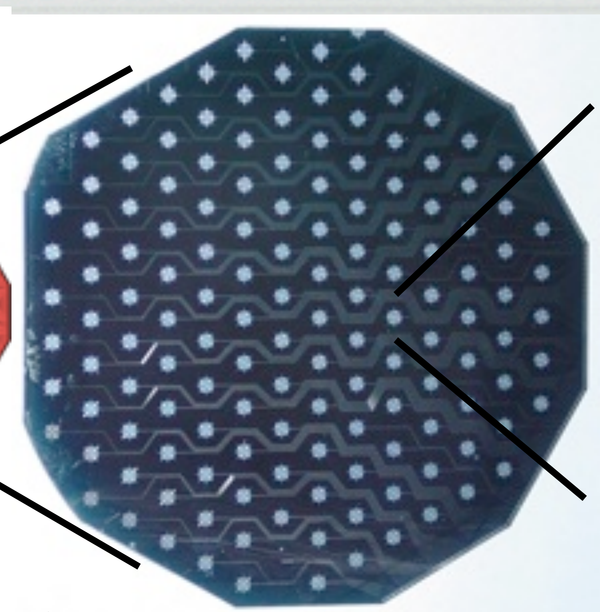


738 element array



30 cm

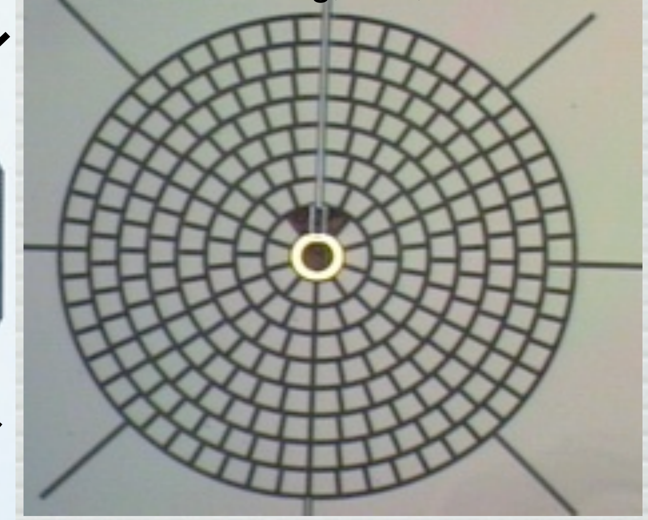
139 element decagon



8.6 cm

Single TES

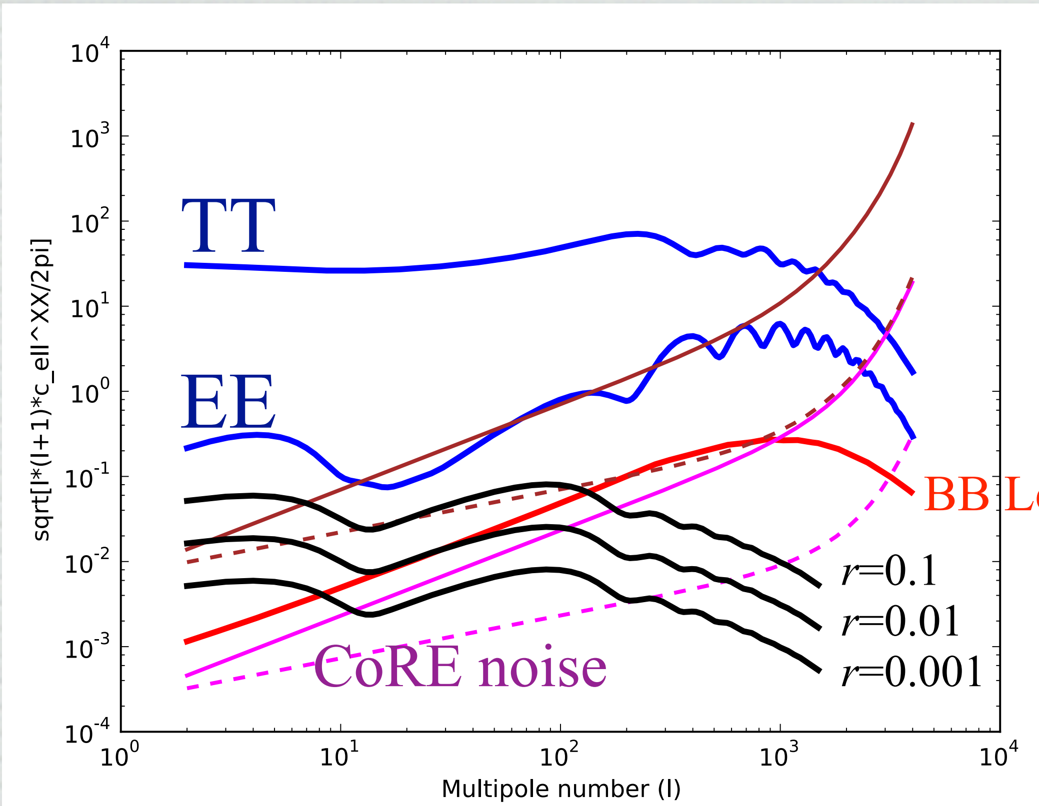
Meng, Lee, UCB



2.1 mm

COrE

Cosmic Origins Explorer



ν (GHz)	θ_{fwhm} (arcmin)	n_{det}	Temp (I) μK·arcmin RJ	Temp (I) CMB	Pol (Q,U) μK·arcmin RJ	Pol (Q,U) CMB
23	52.8	2	413	418	584	592
33	39.6	2	413	424	584	600
41	30.6	4	365	381	516	539
61	21.0	4	438	481	619	681
94	13.2	8	413	516	584	729

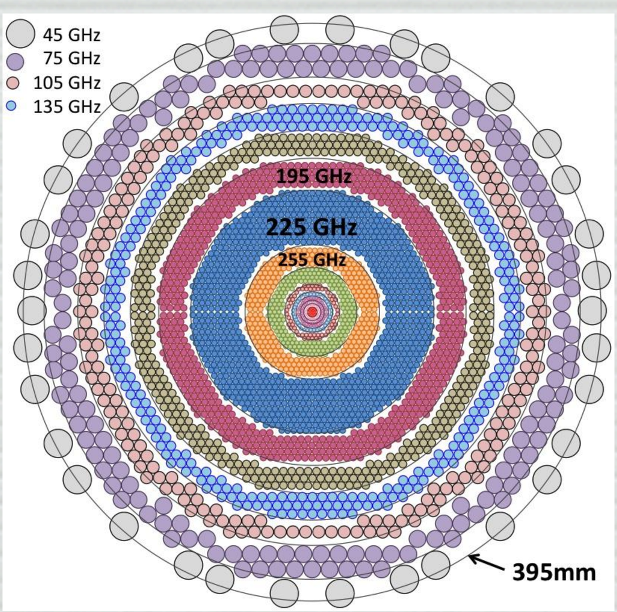
WMAP (9 year mission)

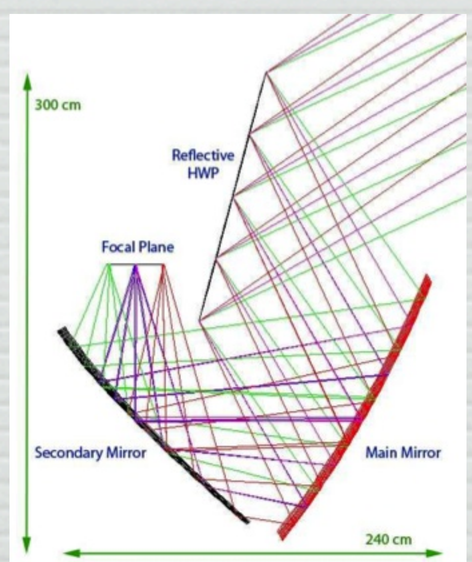
ν (GHz)	n_{unpol}	n_{pol}	θ_{fwhm} (arcmin)	Temp (I) μK·arcmin RJ	Temp (I) CMB	Pol (Q,U) μK·arcmin RJ	Pol (Q,U) CMB
30	4	4	32.7	198.5	203.2	280.7	287.4
44	6	6	27.9	228.0	239.6	322.4	338.9
70	12	12	13.0	186.5	211.2	263.7	298.7
100	8	8	9.9	23.9	31.3	33.9	44.2
143	11	8	7.2	11.9	20.1	19.7	33.3
217	12	8	4.9	9.4	28.5	16.3	49.4
353	12	8	4.7	7.6	107.0	13.2	185.3
545	3	0	4.7	6.8	1.1×10^3	—	—
857	3	0	4.4	2.9	8.3×10^4	—	—

PLANCK (30 month mission)

ν (GHz)	($\Delta\nu$) (GHz)	n_{det}	θ_{fwhm} (arcmin)	Temp (I) μK·arcmin RJ	Temp (I) CMB	Pol (Q,U) μK·arcmin RJ	Pol (Q,U) CMB
45	15	64	23.3	4.98	5.25	8.61	9.07
75	15	300	14.0	2.36	2.73	4.09	4.72
105	15	400	10.0	2.03	2.68	3.50	4.63
135	15	550	7.8	1.68	2.63	2.90	4.55
165	15	750	6.4	1.38	2.67	2.38	4.61
195	15	1150	5.4	1.07	2.63	1.84	4.54
225	15	1800	4.7	0.82	2.64	1.42	4.57
255	15	575	4.1	1.40	6.08	2.43	10.5
285	15	375	3.7	1.70	10.1	2.94	17.4
315	15	100	3.3	3.25	26.9	5.62	46.6
375	15	64	2.8	4.05	68.6	7.01	119
435	15	64	2.4	4.12	149	7.12	258
555	195	64	1.9	1.23	227	3.39	626
675	195	64	1.6	1.28	1320	3.52	3640
795	195	64	1.3	1.31	8070	3.60	22200

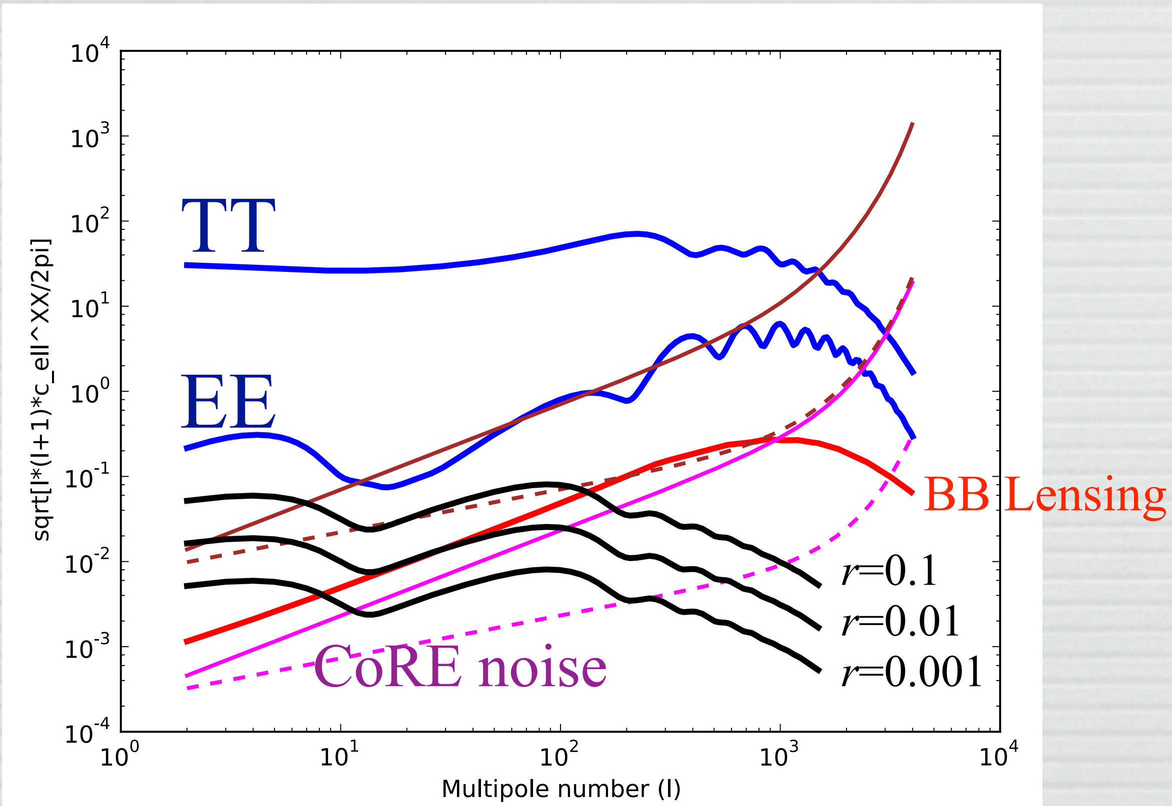
COrE summary (4 year mission)



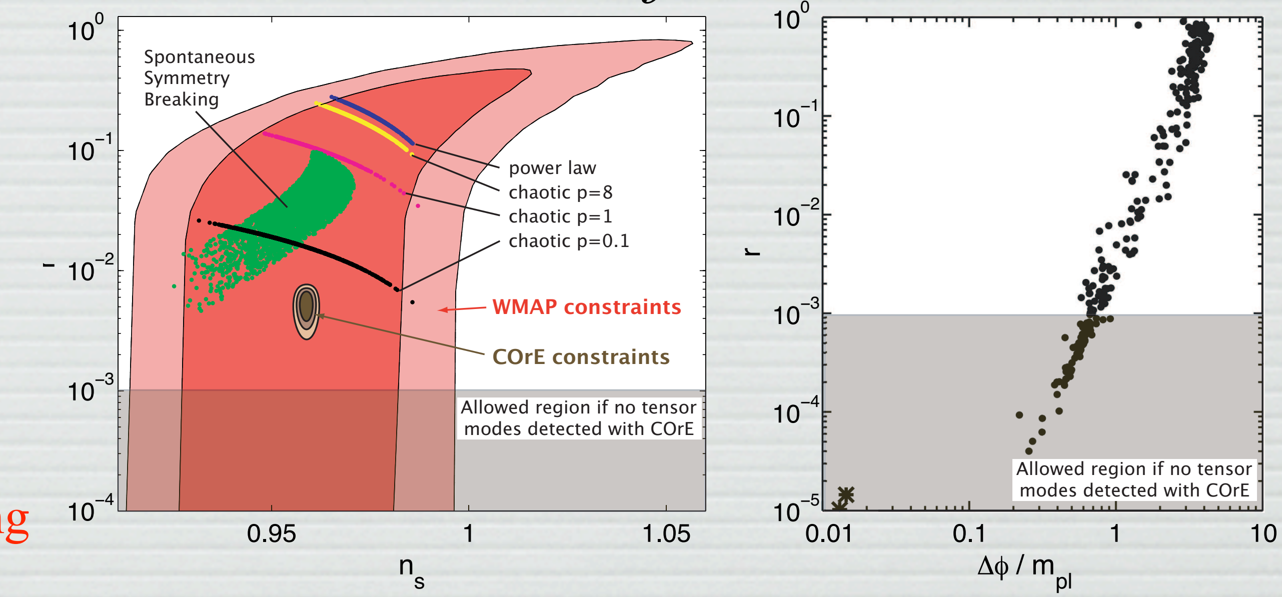


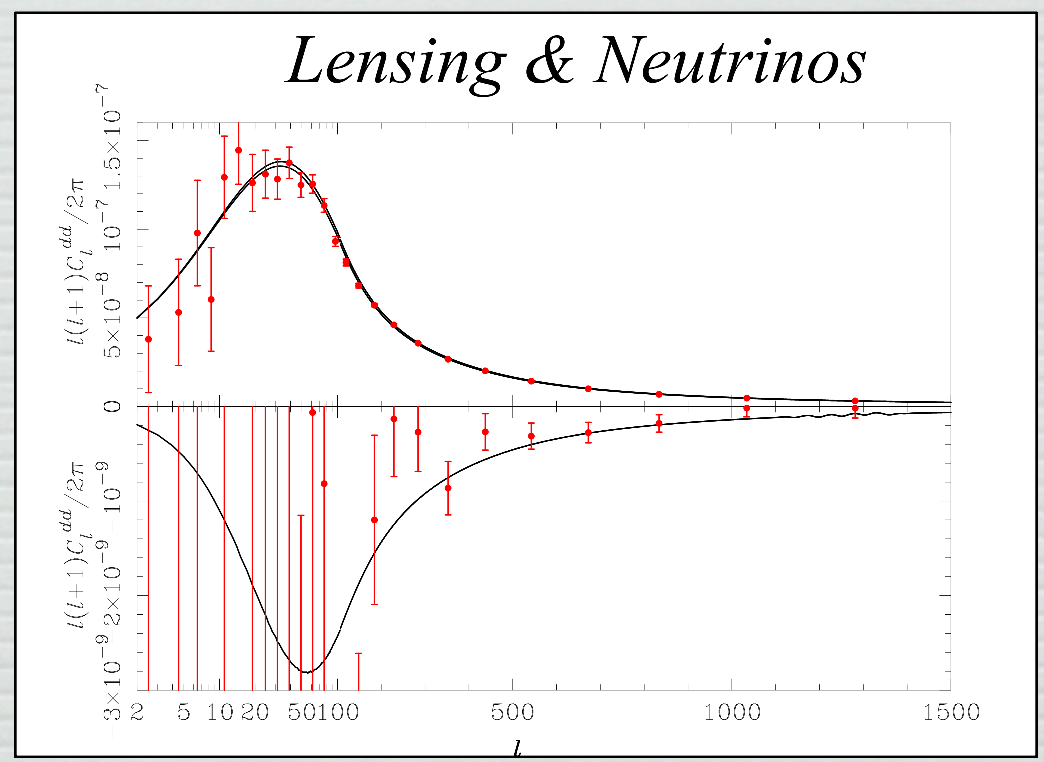
6400 Detectors, 45-800 GHz

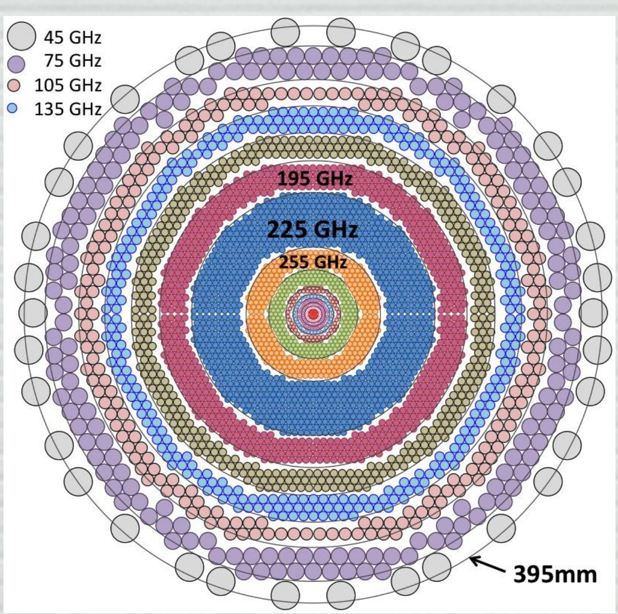
COrE
Cosmic Origins Explorer

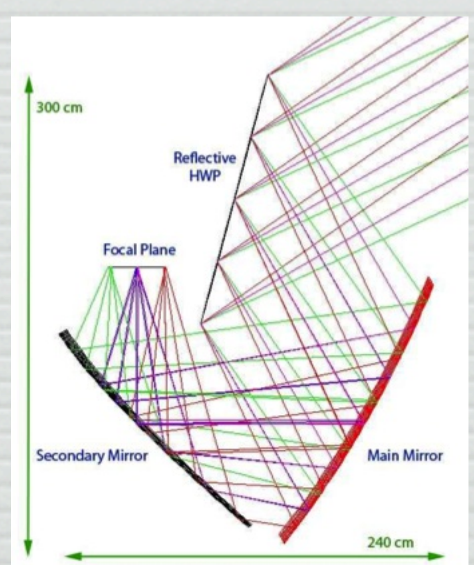


Inflation







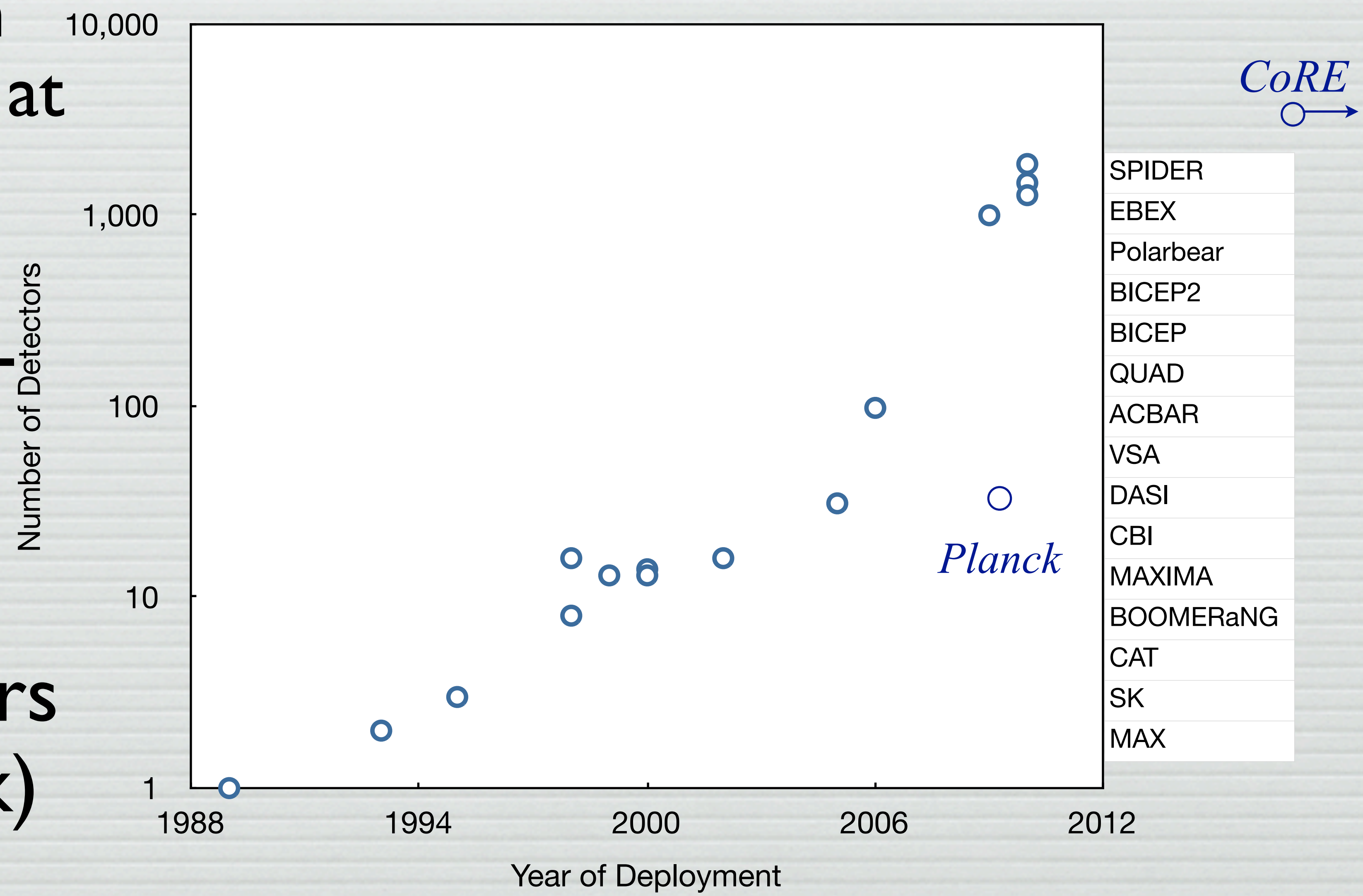


6400 Detectors, 45-800 GHz

Technological Evolution

- Current generation (EBEX, Spider, BICEP2, Polarbear)
  - detectors at quantum limit (for bolometers at *f* >90 GHz)
  - From "bespoke" detectors to multiple-detector fabrication
    - from *tens* to *thousands* of detectors
- Space-based detectors (DMR, WMAP, Planck) usually lag behind

- Signal-to-noise is not the problem:



The CMB in 2011 and beyond

- The intensity and polarization of the CMB encodes a wealth of cosmological information
- Current data support the inflationary paradigm
- Full results depend on external data and priors
- Planck will capture all of the primary intensity information on the sky, and much of the scalar polarization signal
- Planck is the most sensitive full-sky astronomical observatory over a factor of 30 in frequency
- Ongoing experiments with 1000s of detectors will probe polarization orders of magnitude deeper