Research on Cosmic microwave background Radiation

IHEP.CAS

Hong Li

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BEPC: first run since 1988

Institute of High Energy Physics

Since 1980s

Dayabay neutrino experiment

Beijing Spectrometer III

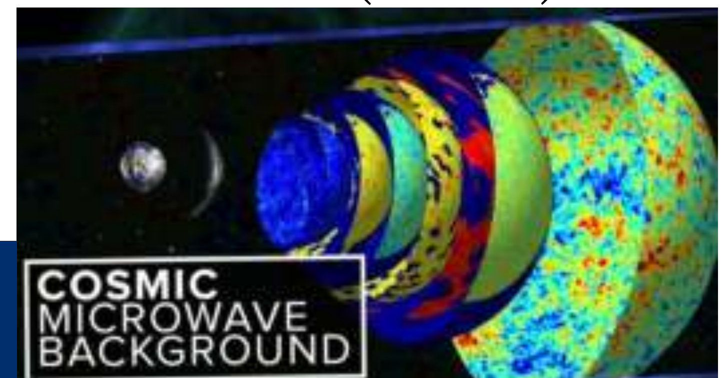
- Particle Astrophysics Division
  - Hard X-ray satellite
  - Cosmic ray experiment
  - AliCPT in Tibet
  - …

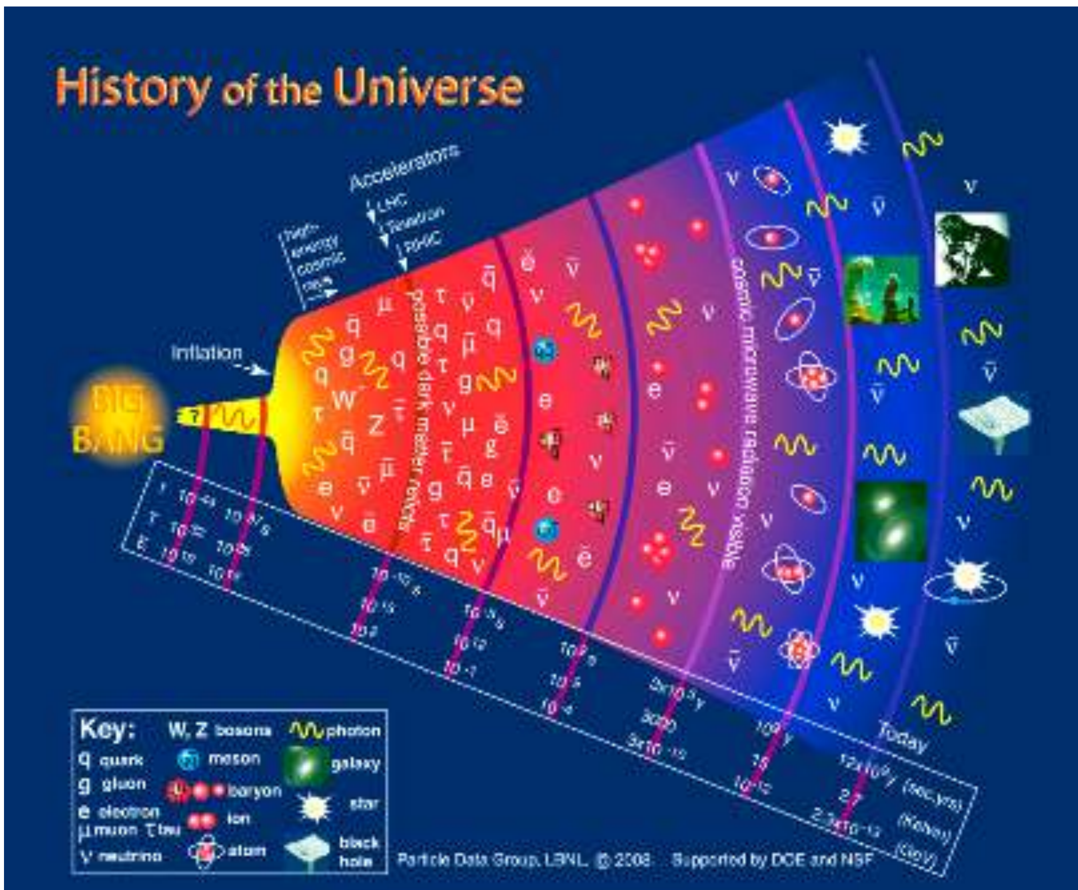
Outline

- What is CMB ?
- Does it exist ?
- Why we are interested ?
- How to observe ?
- Our CMB observation in China – AliCPT

What is CMB ?

- Cosmic Microwave Background radiation (CMB)
  - Relic density from Big Bang
  - CMB is an old fossil !





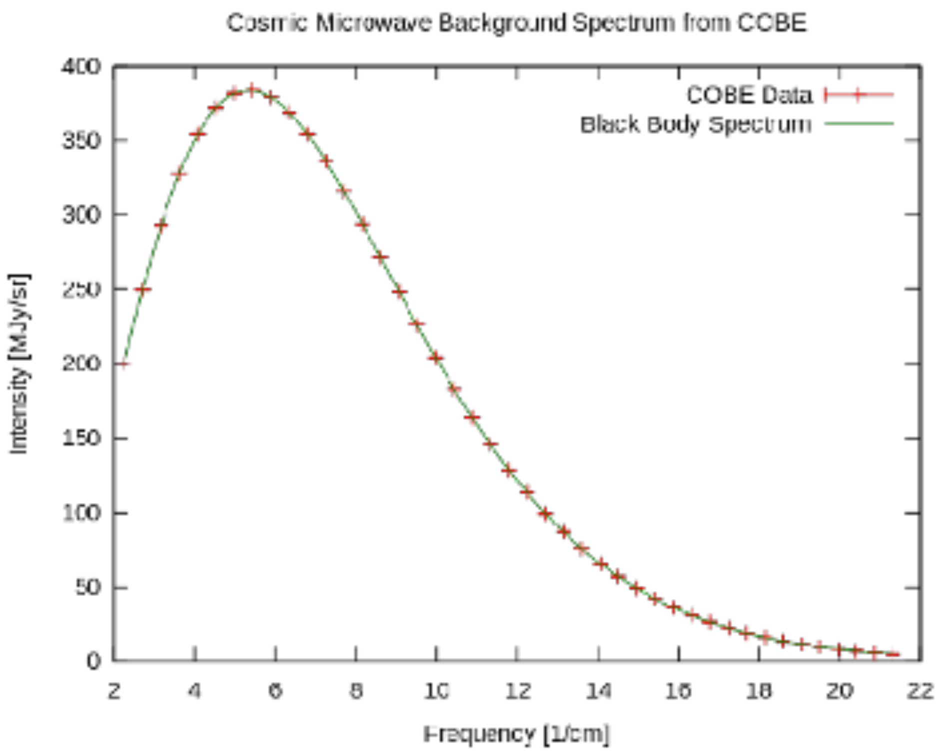
- CMB was discovered in 1965

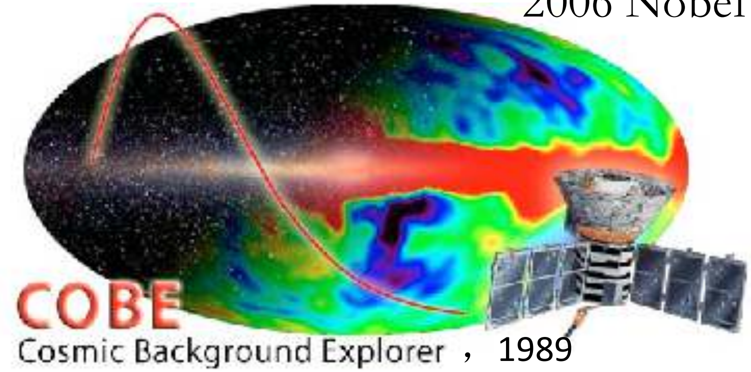
1978 Nobel Prize

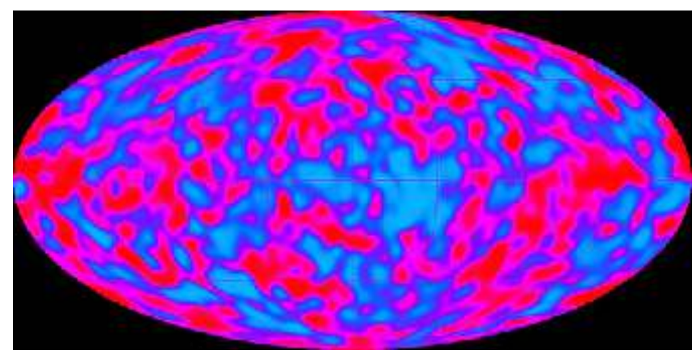
Why we are interested?

2006 Nobel Prize

- 2.73K blackbody spectrum



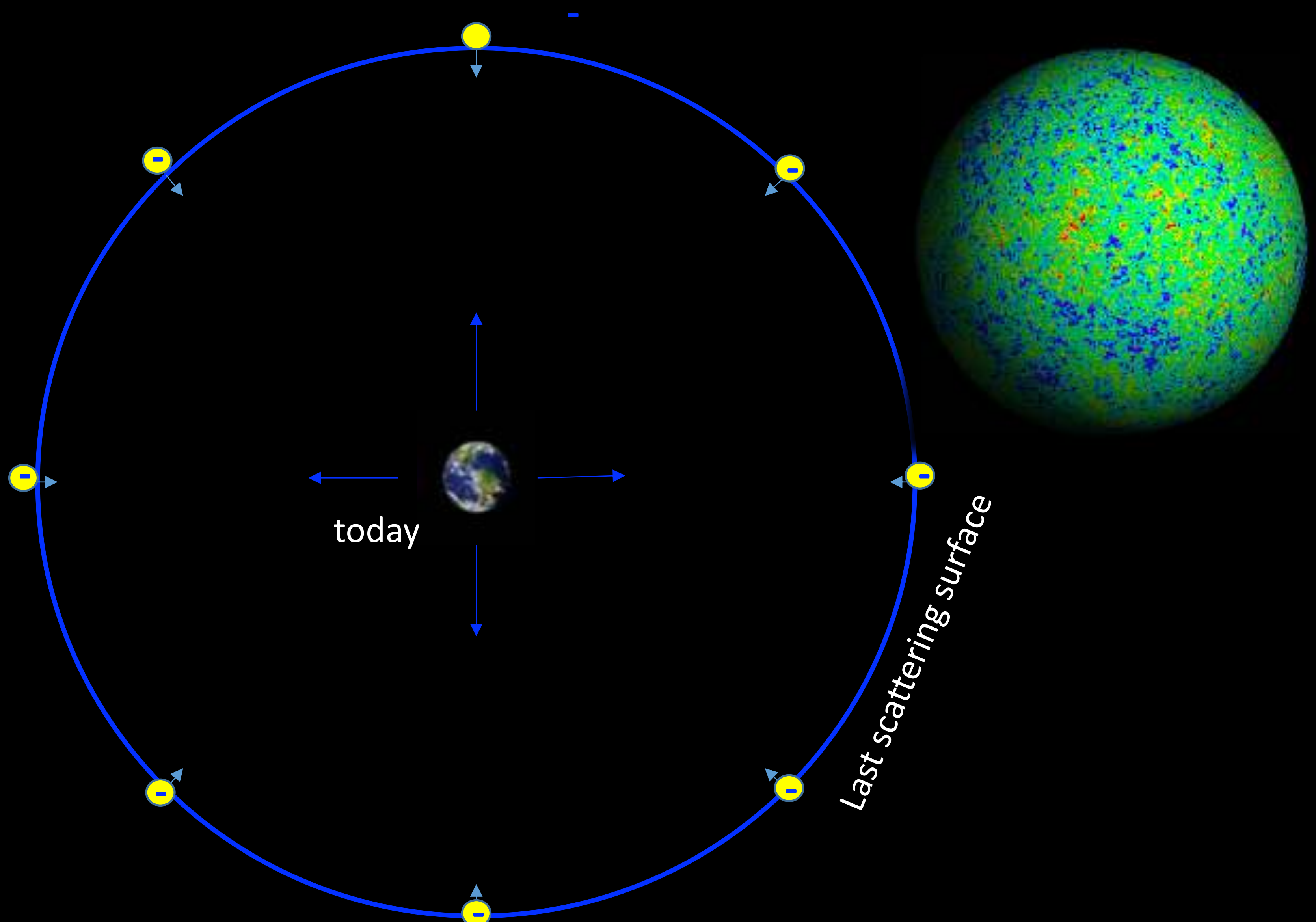




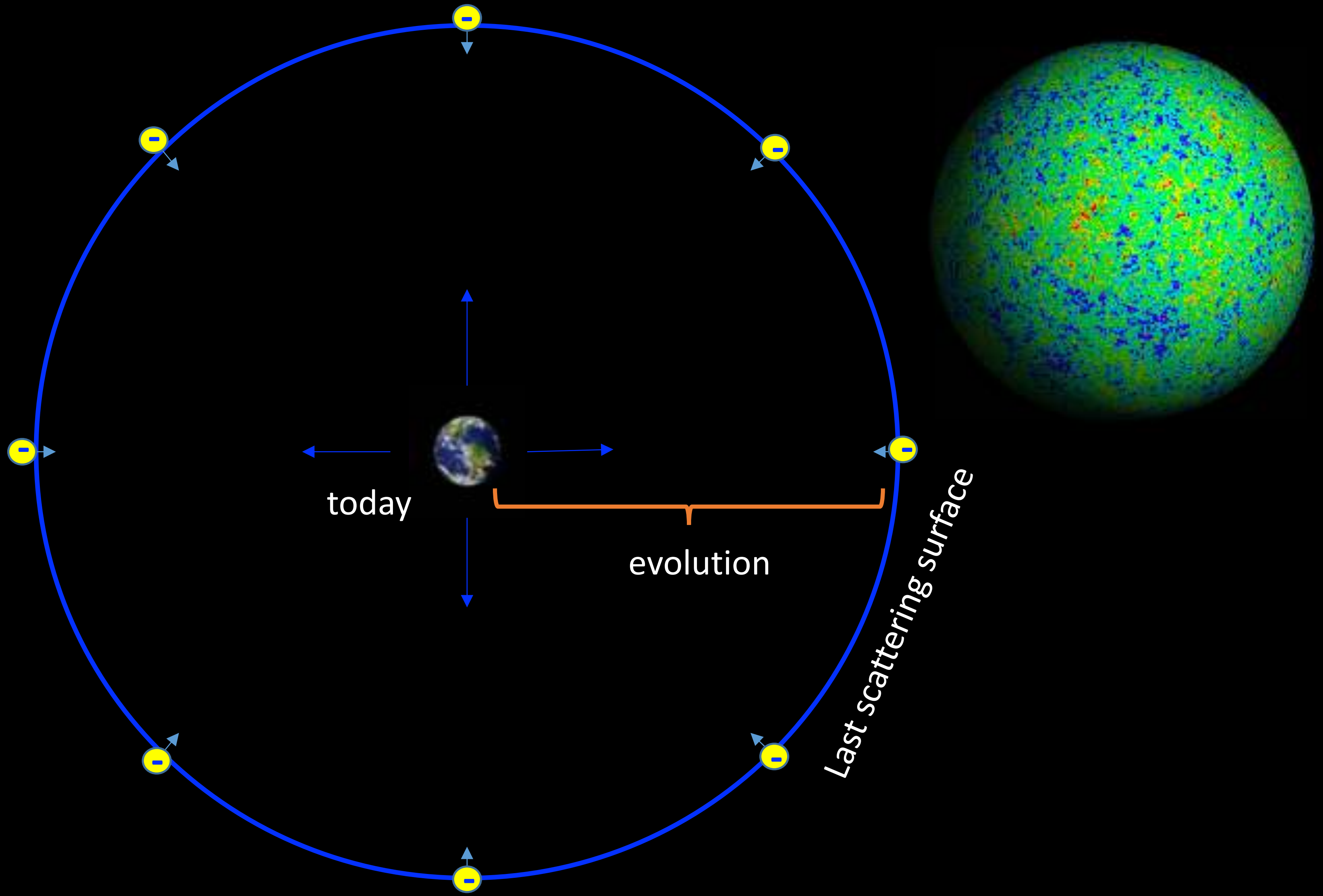
➢ One hundred thousandths temperature fluctuation $\frac{\Delta T}{T} \sim 10^{-5}$

Observation of CMB

Old fossil: we trace back to t~380,000 yrs



Cosmic evolution between: t of [380,000yrs, 138Gyrs]

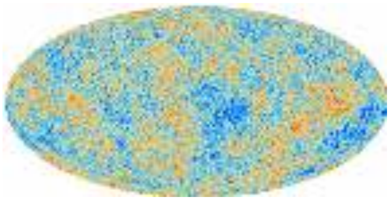


A Precision Cosmological Probe

- Trace back to very early: last scattering

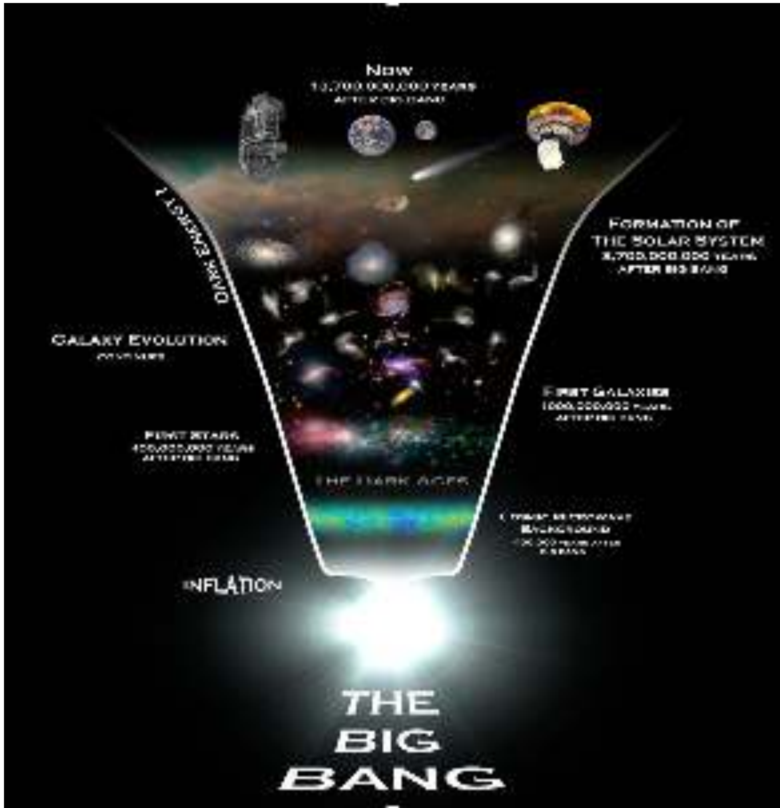
$$t \sim 380{,}000\ yrs, \qquad T \sim 1eV$$

- Tracer is simple and clean: free streaming after decoupling
- Framework is simple: thermal dynamics + linear perturbation theory

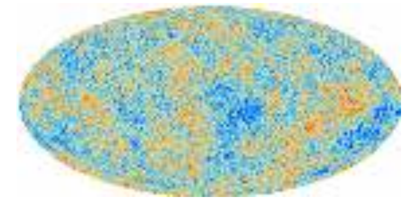


$\frac{\Delta T}{T}$: what can we learn ?

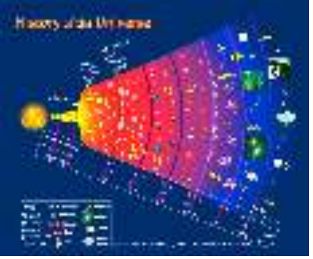
- Early universe: inflation, bouncing⋯
- Geometry: Curvature
- Energy component: baryon, DM, DE⋯
- Late time evolution: cosmic expansion
- ⋯



To solve $\frac{\Delta T}{T}$



- The Guidepost



Background evolution: expansion

- Friedmann-Roberston-Walker (FRW) spacetime

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

or

$$ds^2 = a^2(\eta)(d\eta^2 - \gamma_{ij}dx^i dx^j)$$

η is conformal time $\quad \eta = \int dt/a$

$$x^1 = R\sin\theta\cos\varphi,\ x^2 = x^1 = R\sin\theta\sin\varphi,\ x^3 = R\cos\theta$$

$$\gamma_{ij} = \frac{\delta_{ij}}{(1+\frac{K}{4}x^k x^k)^2} \qquad r = \frac{R}{(1+\frac{K}{4}R^2)^2}$$

Comoving: $\dot{r} = \dot{\theta} = \dot{\varphi} = 0$

Scale factor a(t)

Cosmic evolution: background

- GR equation: dynamics of universe

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = -8\pi G T_{\mu\nu}$$

Perfect fluid $T_{\mu\nu} = (\rho + p) U_\mu U_\nu - p g_{\mu\nu}$ $\quad U_\mu U^\mu = 1$

$U^i = 0, \; U_i = 0$

with cosmic time t	with conformal time η
$U^0 = 1, \; U_0 = 1$	$U^0 = 1/a, \; U_0 = a$
$H^2 + \frac{K}{a^2} = \frac{8\pi G}{3} \rho$	$\mathcal{H}^2 + K = \frac{8\pi G}{3} a^2 \rho$
$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3} (\rho + 3p)$	$\mathcal{H}' = -\frac{4\pi G}{3} a^2 (\rho + 3p)$
$\dot{\rho} + 3H(\rho + p) = 0$	$\rho' + 3\mathcal{H}(\rho + p) = 0$

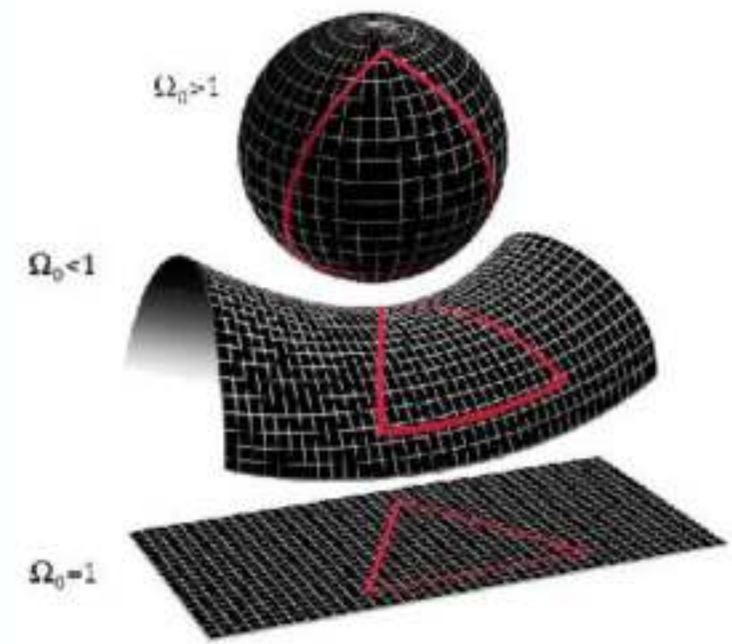
$\omega = p/\rho$ Equation of state is required

Multi components

$$\rho = \sum_i \rho_i,\ p = \sum_i p_i$$

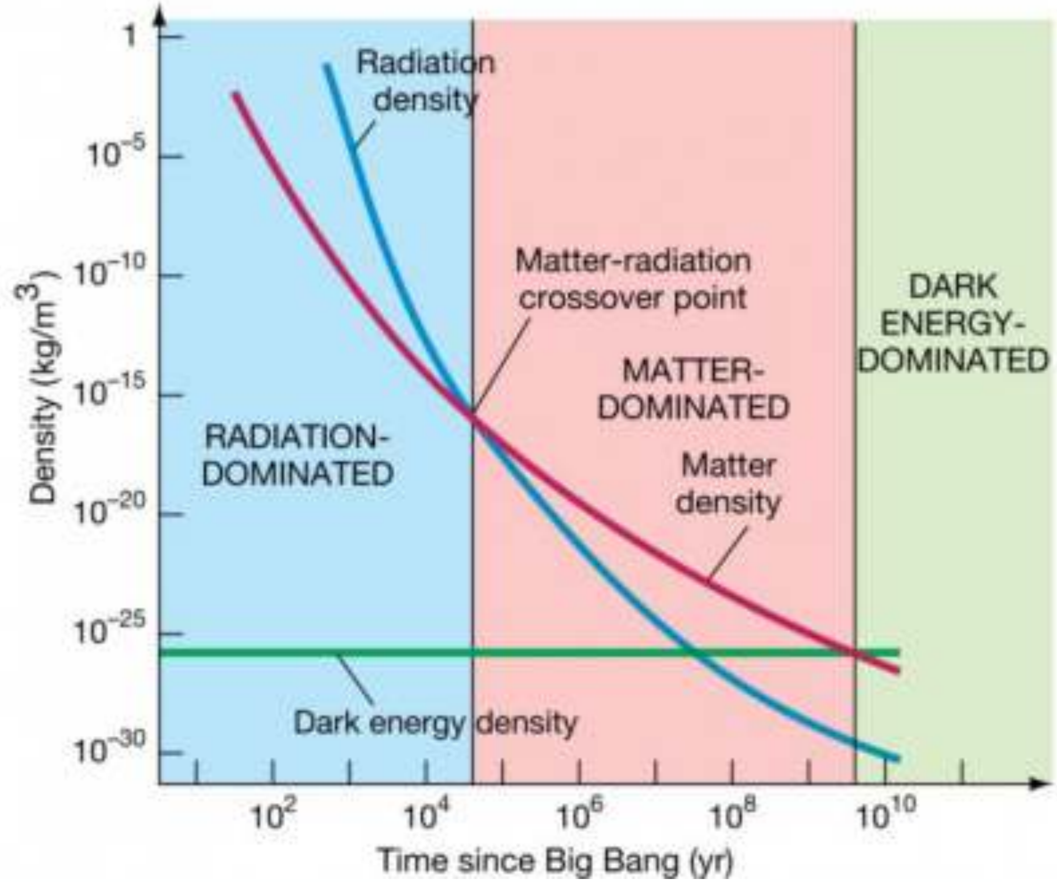
$$1 + \frac{k}{a^2 H^2} = \frac{8\pi G}{3H^2}\rho \equiv \Omega \qquad \Omega = \sum \Omega_i$$

$$\Omega_k \equiv -\frac{k}{a^2 H^2} \qquad \Omega + \Omega_k = 1$$



$$\dot{\rho}_i + 3H(\rho_i + p_i) = 0$$

Continuity equation



$$p_i = p_i(\rho_i) \qquad w_i = \frac{p_i}{\rho_i}$$

With constant EoS $\rho_i \propto a^{-3(1+w_i)}$

Radiation $w_r = 1/3, \rho_r \propto a^{-4}$

Matter (non-relativistic) $w_m = 0, \rho_m \propto a^{-3}$

Cosmological constant $w_\Lambda = -1, \rho_\Lambda = \text{constant}$

Single component universe (K=0)

$$a \propto t^{\frac{2}{3(1+w)}} \quad \text{or} \quad a \propto \eta^{\frac{2}{1+3w}}$$

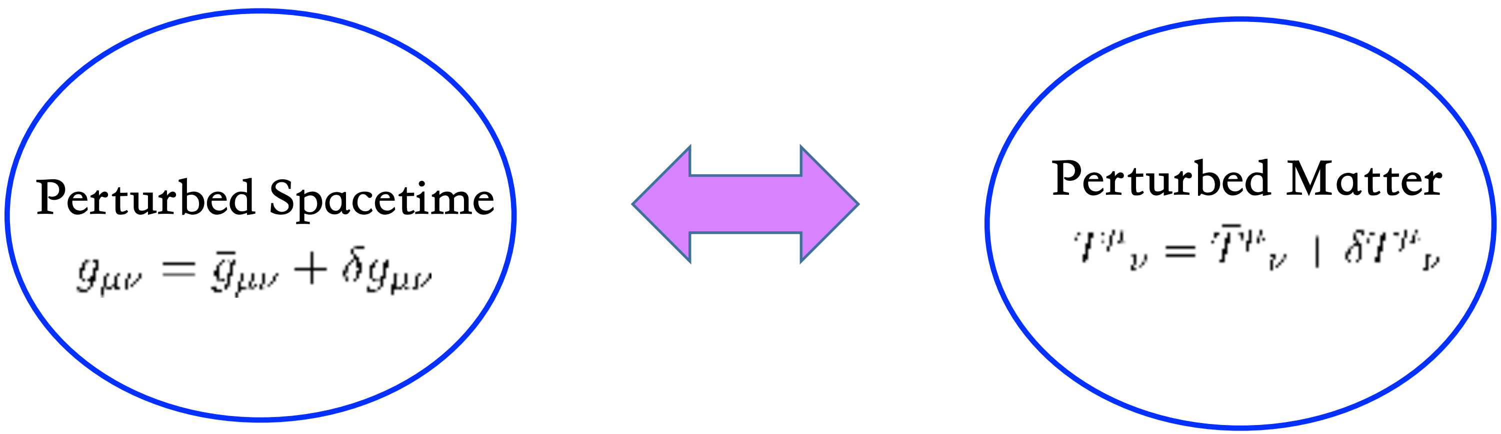
Radiation domination $\quad a \propto t^{\frac{1}{2}} \qquad a \propto \eta$

Matter domination $\quad a \propto t^{\frac{2}{3}} \qquad a \propto \eta^2$

Inflation $\quad a \propto e^{Ht}, \; H = \text{constant}$

$$a = -\frac{1}{H\eta}$$

Linear perturbaton: Cosmic fluctuation



$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$\delta G_{\mu\nu} = 8\pi G \delta T_{\mu\nu}$$

(spacetime)

Spacetime perturbations

$$ds^2 = a(\eta)^2\{(1+2A)d\eta^2 - 2(B_{|i} + S_i)d\eta dx^i - \left[(1-2\psi)\gamma_{ij} + 2E_{|ij} + 2F_{(i|j)} + h_{ij}\right] dx^i dx^j\}$$

$$S^i_{|i} = F^i_{|i} = 0,\ h^i_i = 0,\ h^i_{j|i} = 0$$

Gauge transformations and gauge invariant perturbations

Scalar

$$A \to \tilde{A} = A - \mathcal{H}\xi^0 - \xi^{0'}$$
$$\psi \to \tilde{\psi} = \psi + \mathcal{H}\xi^0$$
$$B \to \tilde{B} = B + \xi^0 - \xi'$$
$$E \to \tilde{E} = E - \xi$$

→

$$\Phi = A + (1/a)[(B - E')a]',$$
$$\Psi = \psi - \mathcal{H}(B - E');$$

Vector

$$\tilde{F}_i = F_i - \eta_i$$
$$\tilde{S}_i = S_i - \eta_i'$$

→

$$\mathcal{F}_i = S_i - F_i'$$

Tensor $\tilde{h}_{ij} = h_{ij}$

(matter)

Matter perturbations $T^\mu_\nu(\eta,\vec{x}) = T^\mu_\nu(\eta) + \delta T^\mu_\nu(\eta,\vec{x})$

$$\delta\tilde{T}^\mu_\nu = \delta T^\mu_\nu - \mathcal{L}_\xi T^\mu_\nu$$

Matter as a fluid

$$T^\mu_\nu = -p\delta^\mu_\nu + (\rho+p)U^\mu U_\nu + \Sigma^\mu_\nu \qquad U^\mu U_\mu = 1 \qquad \Sigma_{\mu\nu}U^\nu = 0\,,\ \ \Sigma^\mu_\mu = 0$$

On background $\rho, p, U^0 = 1/a, U^i = 0$

anisotropic stress due to shear viscosity and heat flow, vanishes on background, gauge invariant perturbations

At linear order $\delta\rho, \delta p,\ \ \delta U^0 = -\frac{A}{a}\,,\ \delta U_0 = aA$

$$U_i = U_{|i} + U_i^{vec}\,,\ \ U_i^{vec|i} = 0$$

$$\Sigma_{00} = 0\,,\ \ \Sigma_{0i} = 0\,,\ \ \Sigma^i_i = 0$$

$$\Sigma_{ij} = -a^2[\Sigma_{|ij} - \frac{1}{3}\nabla^2\Sigma\gamma_{ij} + \Sigma_{(i|j)} + \sigma_{ij}]$$

Scalar

$$\tilde{\delta\rho} = \delta\rho - \rho'\xi^0 \qquad \tilde{U} = U - a\xi^0$$

$$\tilde{\delta p} = \delta p - p'\xi^0 \qquad \tilde{\Sigma} = \Sigma$$

Vector $\quad \tilde{U}_i^{vec} = U_i^{vec} \qquad \tilde{\Sigma}_i = \Sigma_i$

Tensor $\quad \tilde{\sigma}_{ij} = \sigma_{ij}$

Some gauge invariant perturbations

$$^{(gi)}\delta\rho = \delta\rho + \rho'(B - E') \ , \ ^{(gi)}\delta p = \delta p + p'(B - E') \ , \ ^{(gi)}U = U + a(B - E')$$

$$\mathcal{R} = -\psi - \mathcal{H}\frac{\delta\rho}{\rho'} \ , \ \delta p_{nad} \equiv \delta p - \frac{p'}{\rho'}\delta\rho$$

Vector perturbation decay gradually

Vector perturbation

$$k^2\mathcal{F}_i = 16\pi Ga(\rho+p)U_i^{vec} \ ,$$
$$(\mathcal{F}_{i,j}+\mathcal{F}_{j,i})' + 2\mathcal{H}(\mathcal{F}_{i,j}+\mathcal{F}_{j,i}) = 0$$

$$\mathcal{F}_i \propto 1/a^2 \qquad U_i^{vec} \propto 1/[a^3(\rho+p)]$$

$$V_i = V^i = U_i^{vec}/a \propto \frac{1}{a^4(\rho+p)}$$

在辐射为主时期ρ，$p \propto a^{-4}$，因此$V_i = const.$；在物质为主时期ρ，$p \propto a^{-3}$，因此$V_i \propto \frac{1}{a}$是逐渐衰减

- Tensor perturbation: Gravitational wave

$$h''_{ij} + 2\mathcal{H}h'_{ij} + k^2 h_{ij} = 16\pi G a^2 \sigma_{ij}$$

- Scalar perturbation

$$ds^2 = a^2[(1+2\Phi)d\eta^2 - (1-2\Psi)\delta_{ij}dx^i dx^j]$$

$$\left\{\begin{aligned} &3\mathcal{H}(\mathcal{H}\Phi + \Psi') + k^2\Psi = -4\pi G a^2 \delta\rho\ , \\ &\mathcal{H}\Phi + \Psi' = 4\pi G a(\rho + p)U\ , \\ &(2\mathcal{H}' + \mathcal{H}^2)\Phi + \mathcal{H}\Phi' + \Psi'' + 2\mathcal{H}\Psi' + \frac{k^2}{3}(\Psi - \Phi) = 4\pi G a^2 \delta p \\ &k^2(\Psi - \Phi) = 12\pi G a^2(\rho + p)\sigma\ . \end{aligned}\right.$$

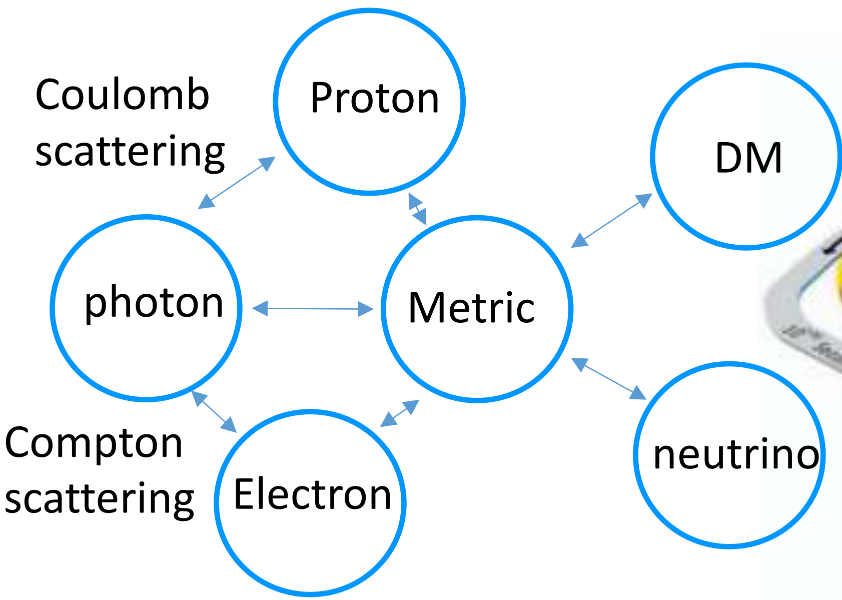
$$\Phi'' + 3\mathcal{H}(1 + c_s^2)\Phi' - c_s^2\nabla^2\Phi + [2\mathcal{H}' + (1 + 3c_s^2)(\mathcal{H}^2 - K)\Phi] = 4\pi G a^2 \delta p_{nad}$$

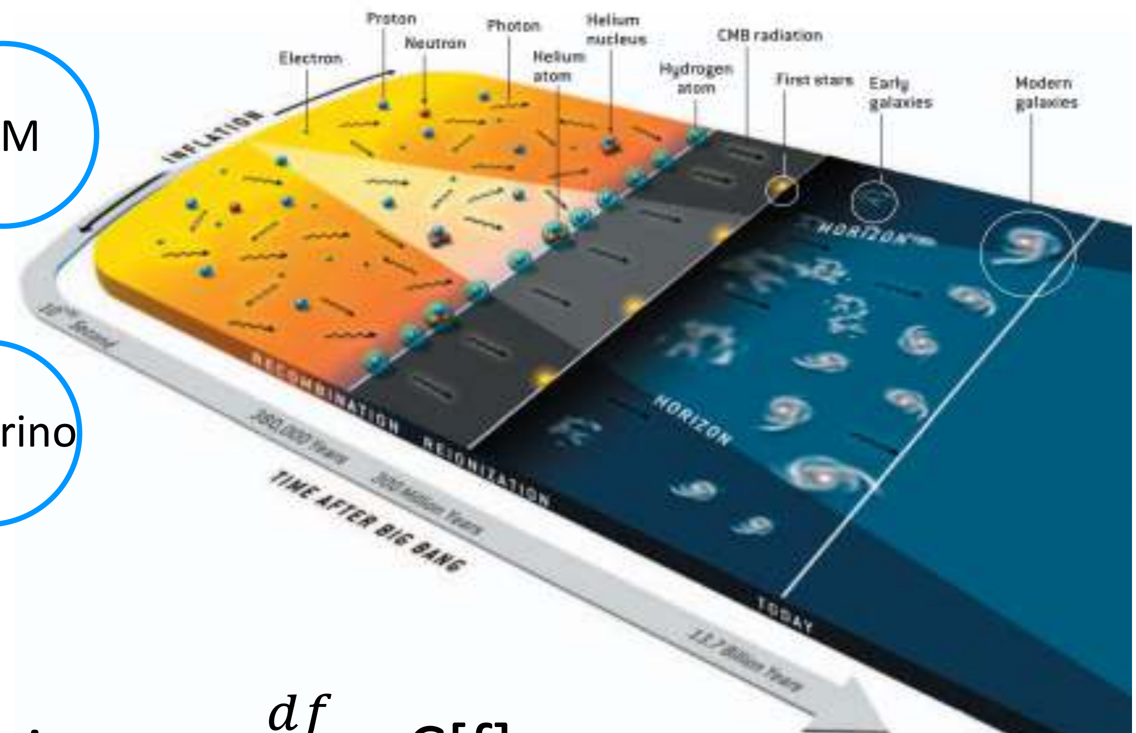
Bardeen parameter $\quad \zeta = -\Phi - \frac{\mathcal{H}}{\bar{\rho}'}\delta\rho,$

$$\zeta' = -\frac{\mathcal{H}}{\bar{\rho} + \bar{p}}\delta p_{nad} + \frac{\nabla^2(\Phi' + \mathcal{H}\Phi)}{12\pi G a^2(\bar{\rho} + \bar{p})}$$

Large scale with adiabatic perturbation:
ζ Conserve !

Coupled system: scattering & interaction





- Boltzmann equation: $\frac{df}{dt}$ = C[f],

$$C[f] = \int d(\text{phase space})[\text{ energy-momentum conservation}] \times |M|^2[\text{emission} - \text{absorption}]$$

- distribution function $f(x^i, P_i, t)$

$$dx^1 dx^2 dx^3 dP_1 dP_2 dP_3$$

$$dN = f dx^1 dx^2 dx^3 dP_1 dP_2 dP_3$$

能动量张量 $T^\mu_\nu = \frac{g}{(2\pi\hbar)^3} \int \frac{dP_1 dP_2 dP_3}{\sqrt{-\det|g|} P^0} P^\mu P_\nu f(x^i, P_j, t)$

In FRW: $\rho = T^0_0 = \frac{g}{(2\pi)^3} \int d^3p E f(\vec{x}, \vec{p}, t)$

$$T^i_j = -P\delta^i_j = \frac{g}{(2\pi)^3} \int \frac{d^3p}{E} (-p^i p^j) f(\vec{x}, \vec{p}, t)$$

$$= -\frac{g}{(2\pi)^3} \int \frac{d^3p}{E} \frac{p^2}{3} f(\vec{x}, p, t) \delta^i_j$$

$$P = \frac{g}{(2\pi)^3} \int \frac{d^3p}{E} \frac{p^2}{3} f(\vec{x}, p, t)$$

$$n = \frac{g}{(2\pi)^3} \int d^3p f(\vec{x}, \vec{p}, t)$$

In thermal equilibrium: $f(\vec{x}, \vec{p}, t) = \frac{1}{\exp\frac{E-\mu}{T} \pm 1}$

Perturbed BE

Newtonian gauge: $$ds^2 = a^2(1+2\phi)d\eta^2 - a^2[(1-2\psi)\delta_{ij} + h_{ij}]dx^i dx^j$$

$$f(x^i, P_j, \eta) = f(x^i, q, n_j, \eta) = f_0(q, \eta) + \delta f(x^i, q, n_j, \eta)$$

Photon: $f(x^i, n_j, \eta) = [exp\left\{\frac{p}{T(\eta)[1+\Delta(x^i, n_j, \eta)]}\right\} - 1]^{-1}$

BE: $$\frac{\partial f}{\partial \eta} + \frac{dx^i}{d\eta}\frac{\partial f}{\partial x^i} + \frac{dq}{d\eta}\frac{\partial f}{\partial q} + \frac{dn_i}{d\eta}\frac{\partial f}{\partial n_i} = (\frac{\partial f}{\partial \eta})_C$$

$$\frac{dx^i}{d\eta} = \frac{P^i}{P^0} = -\frac{q}{\epsilon}(1+\phi+\psi)n_i$$

Geodesic equation

$$P^0\frac{dP^\mu}{d\eta} + \Gamma^\mu_{\alpha\beta}P^\alpha P^\beta = 0 \quad \Rightarrow \quad \frac{dq}{d\eta} = q\psi' - \epsilon n_i \partial_i \phi$$

Perturbed Boltzmann equation

$$\frac{\partial \delta f}{\partial \eta} + i\frac{q}{\epsilon}k\mu\,\delta f + q\frac{\partial f_0}{\partial q}(\psi' - i\frac{\epsilon}{q}k\mu\phi) = (\frac{\partial f}{\partial \eta})_C$$

Equations of the system: 9

- photons:

$$\frac{\partial \Delta_T^{(S)}}{\partial \eta} + ik\mu\Delta_T^{(S)} - \psi' - ik\mu\phi + \dot{\kappa}[-\Delta_T^{(S)} + \Delta_{T0}^{(S)} + i\mu v_b + \frac{1}{2}P_2(\mu)\Pi] \quad (1)$$

$$\frac{\partial \Delta_P^{(S)}}{\partial \eta} + ik\mu\Delta_P^{(S)} - \dot{\kappa}\{-\Delta_P^{(S)} + \frac{1}{2}[1 - P_2(\mu)]\Pi\} \quad (2)$$

$$\Pi = \Delta_{T2}^{(S)} + \Delta_{P2}^{(S)} + \Delta_{P0}^{(S)} \qquad \dot{\kappa} = a n_e X_e \sigma_T \qquad 1 - P_2(\mu) = \frac{3}{2}(1-\mu^2)$$

(3)

- DM:

$$\delta_c' = -kv_c + 3\psi' \quad (4)$$

$$v_c' = -\mathcal{H}v_c + k\phi$$

- Baryon:

$$\delta_b' = -kv_b + 3\psi' \quad (5)$$

$$v_b' = -\mathcal{H}v_b + c_s^2 k\delta_b + \frac{4\rho_\gamma}{3\rho_b}\dot{\kappa}(3\Delta_{T1}^{(S)} - v_b) + k\phi \qquad c_s^2 = \frac{P_b'}{\rho_b'} \quad (6)$$

- Neutrino:

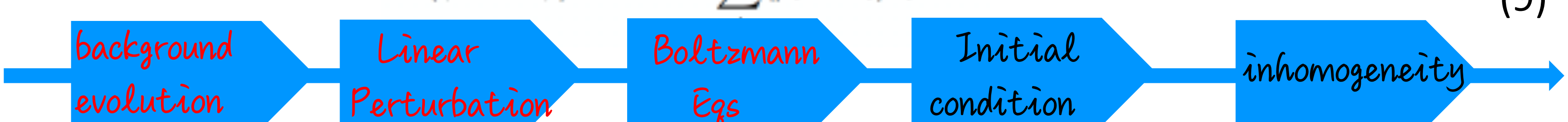
$$\frac{\partial F_\nu}{\partial \eta} + ik\mu F_\nu = 4(\psi' - ik\mu\phi) \quad (7)$$

$$F_\nu(\vec{k}, \hat{n}, \eta) = \frac{\int dq q^3\, \delta f}{\int dq q^3 f_0} = \sum_l (-i)^l (2l+1) F_{\nu l}(\vec{k}, \eta) P_l(\mu)$$

- Einstein EQ:

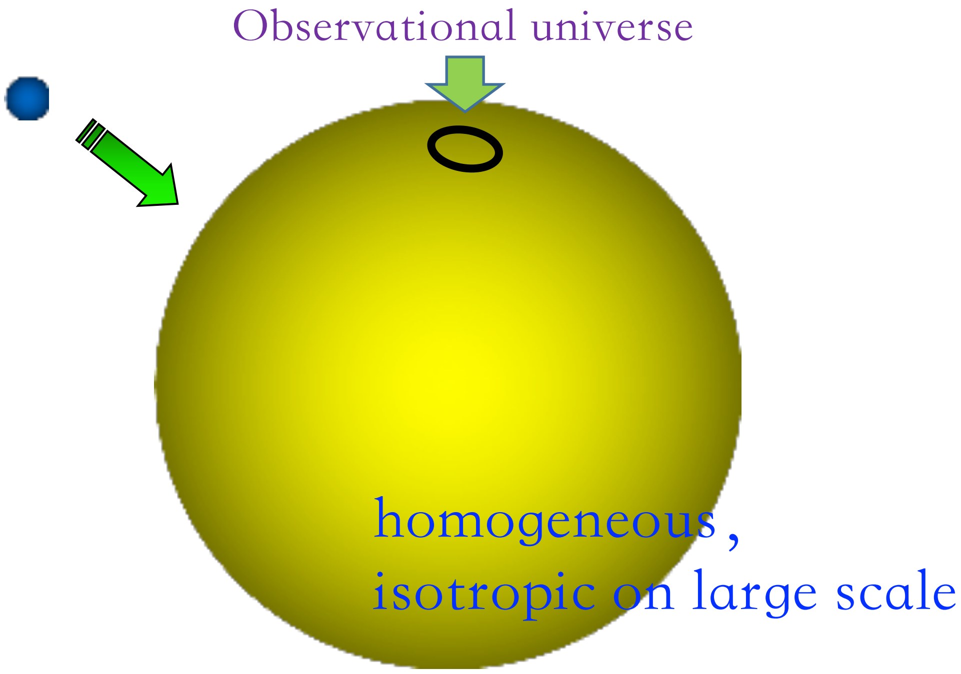
$$k^2\psi + 3\mathcal{H}(\psi' + \mathcal{H}\phi) = -4\pi G a^2 \sum_i \delta\rho_i \quad (8)$$

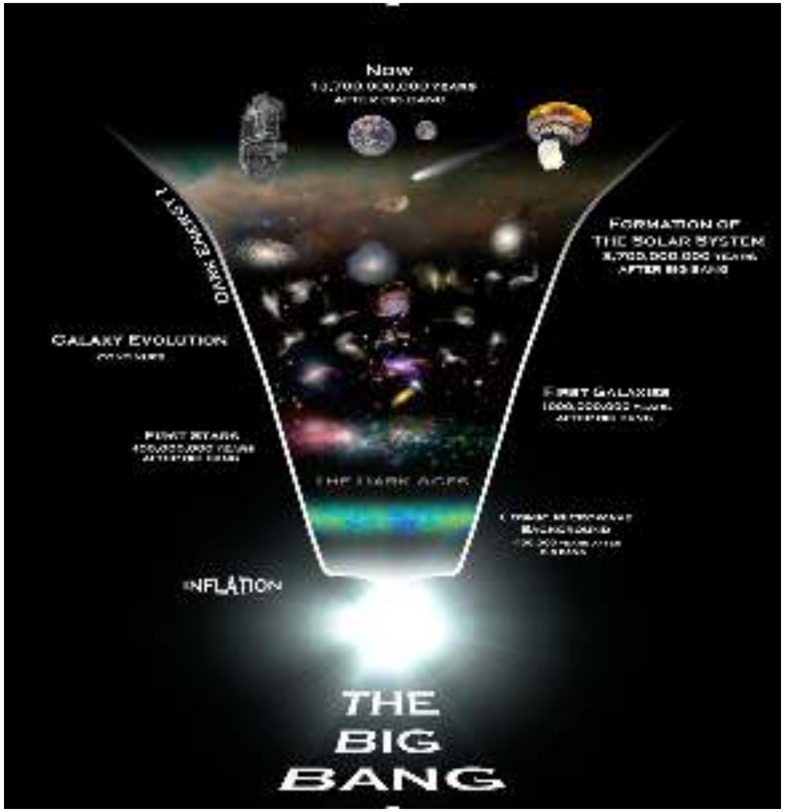
$$k(\psi' + \mathcal{H}\phi) = 4\pi G a^2 \sum (\rho_i + P_i) v_i \quad (9)$$



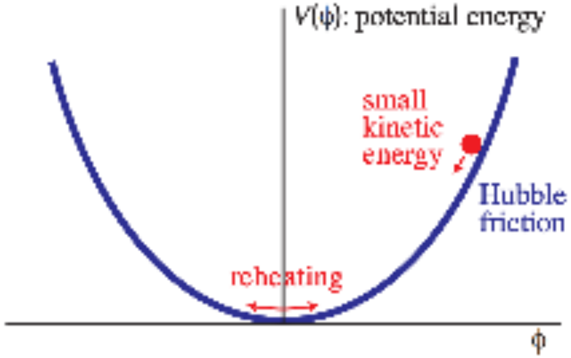
Initial condition: Inflation

- Horizon problem
- Flatness problem

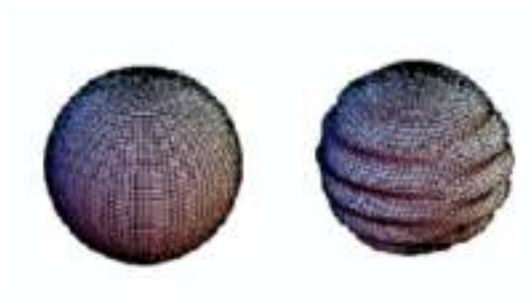




Initial condition



$\delta\phi$

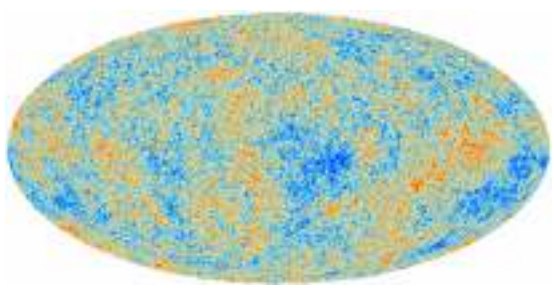


- Initial condition from inflation:

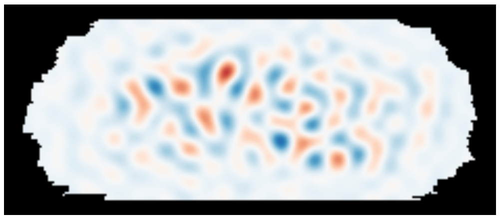
$$\langle \Phi(\vec{\mathrm{k}}) \rangle = 0$$

$$\langle \Phi(\vec{k})\Phi^*(\vec{k'}) \rangle = (2\pi)^3 P_\Phi(k)\delta^3(\vec{k}-\vec{k'})$$

Linear perturbation



temperature



polarization

Initial condition

- Inflation tell you : primordial power spectrum

$$k^3\, P_\Phi(k) = \frac{8\pi}{9}\frac{H^2}{\epsilon m_{pl}^2}\bigg|_{aH=k} \equiv A_S\left(\frac{k}{k_*}\right)^{n_S-1}$$

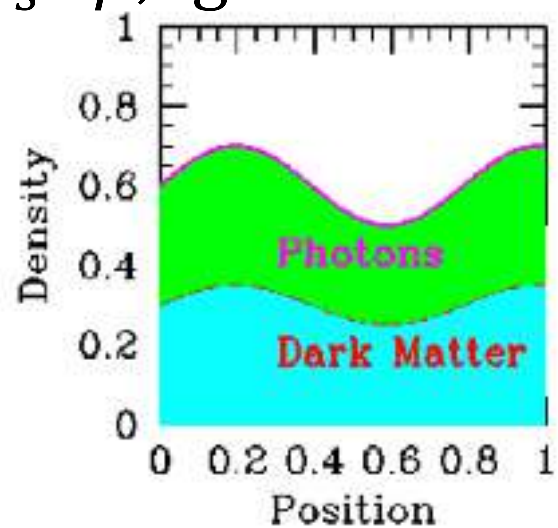
$$k^3\, P_h(k) = 8\pi\frac{H^2}{m_{pl}^2}\bigg|_{aH=k} \equiv A_T\left(\frac{k}{k_*}\right)^{n_T}$$

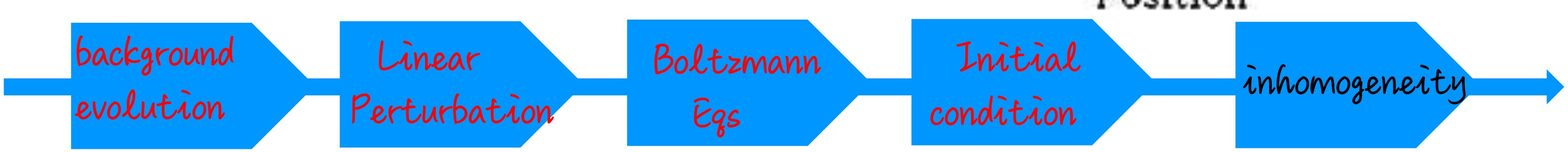
$$r \equiv \frac{A_t}{A_s}$$

- Adiabatic conditions: $\delta p = c_s^2\,\delta\rho$, ignore : δS

$$\delta_c \sim \delta_b \sim 3\,\Delta_T^{(s)}$$

$$\Delta_{T1}^{(s)} = F_{\nu 1} = \frac{i v_b}{3} = \frac{i v}{3}$$





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- Neutrino:

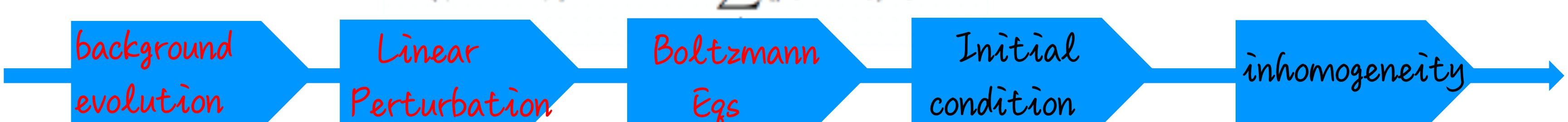
$$\frac{\partial F_\nu}{\partial \eta} + ik\mu F_\nu = 4(\psi' - ik\mu\phi) \quad (7)$$

$$F_\nu(\vec{k}, \hat{n}, \eta) = \frac{\int dqq^3\ \delta f}{\int dqq^3 f_0} = \sum_l (-i)^l(2l+1)F_{\nu l}(\vec{k},\eta)P_l(\mu)$$

- Einstein EQ :

$$k^2\psi + 3\mathcal{H}(\psi' + \mathcal{H}\phi) = -4\pi Ga^2\sum_i \delta\rho_i \quad (8)$$

$$k(\psi' + \mathcal{H}\phi) = 4\pi Ga^2\sum_i(\rho_i + P_i)v_i \quad (9)$$



Focus on : $\frac{\Delta T}{T}$

- Solve BE: multipole expansion， ignore higher order, just keep order of 0 & 1

$$\frac{\partial \Delta_{T0}^{(S)}}{\partial \eta} = -k\Delta_{T1}^{(S)} + \psi'$$

$$\frac{\partial \Delta_{T1}^{(S)}}{\partial \eta} = \frac{k}{3}(\Delta_{T0}^{(S)} - 2\Delta_{T2}^{(S)} + \phi) + \dot{\kappa}(\frac{v_b}{3} - \Delta_{T1}^{(S)})$$

$$\frac{\partial \Delta_{T2}^{(S)}}{\partial \eta} = \frac{k}{5}(2\Delta_{T1}^{(S)} - 3\Delta_{T3}^{(S)}) + \dot{\kappa}(\frac{\Pi}{10} - \Delta_{T2}^{(S)})$$

$$\frac{\partial \Delta_{Tl}^{(S)}}{\partial \eta} = \frac{k}{2l+1}[l\Delta_{T(l-1)}^{(S)} - (l+1)\Delta_{T(l+1)}^{(S)}] - \dot{\kappa}\Delta_{Tl}^{(S)},\ l \geq 3$$

$$\frac{\partial \Delta_{Pl}^{(S)}}{\partial \eta} = \frac{k}{2l+1}[l\Delta_{P(l-1)}^{(S)} - (l+1)\Delta_{P(l+1)}^{(S)}] + \dot{\kappa}[-\Delta_{Pl}^{(S)} + \frac{1}{2}\Pi(\delta_{l0} + \frac{\delta_{l2}}{5})]$$

For strong coupling ($\tau \gg 1$) : $\Delta_l \sim \frac{k\eta}{2\tau}\Delta_{l-1}$

1995: Wayne Hu& …

$$\Delta_0(\eta) + \psi(\eta) \sim [\Delta_0(0) + \psi(0)]\cos(kr_s)$$

$$\Delta_1(\eta) \sim [\Delta_0(0) + \psi(0)]\sin(kr_s)$$

Oscillate …..

From Δ_T to angular power spectrum:

- what inflation predict is the variance of Φ

$$\langle \Phi(\vec{k})\Phi^*(\vec{k'})\rangle = (2\pi)^3 P_\Phi(k)\delta^3(\vec{k}-\vec{k'})$$

- It's useful to do the decomposition into harmonics

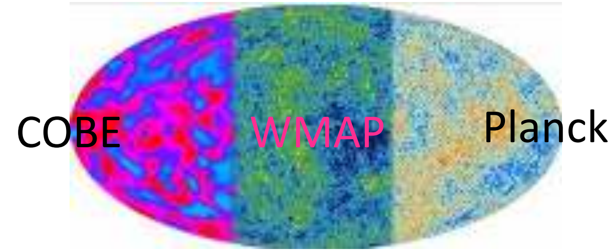
$$\Delta_T(\hat{n}) = \sum_{lm} a_{lm} Y_{lm}(\hat{n})$$

- angular power spectrum

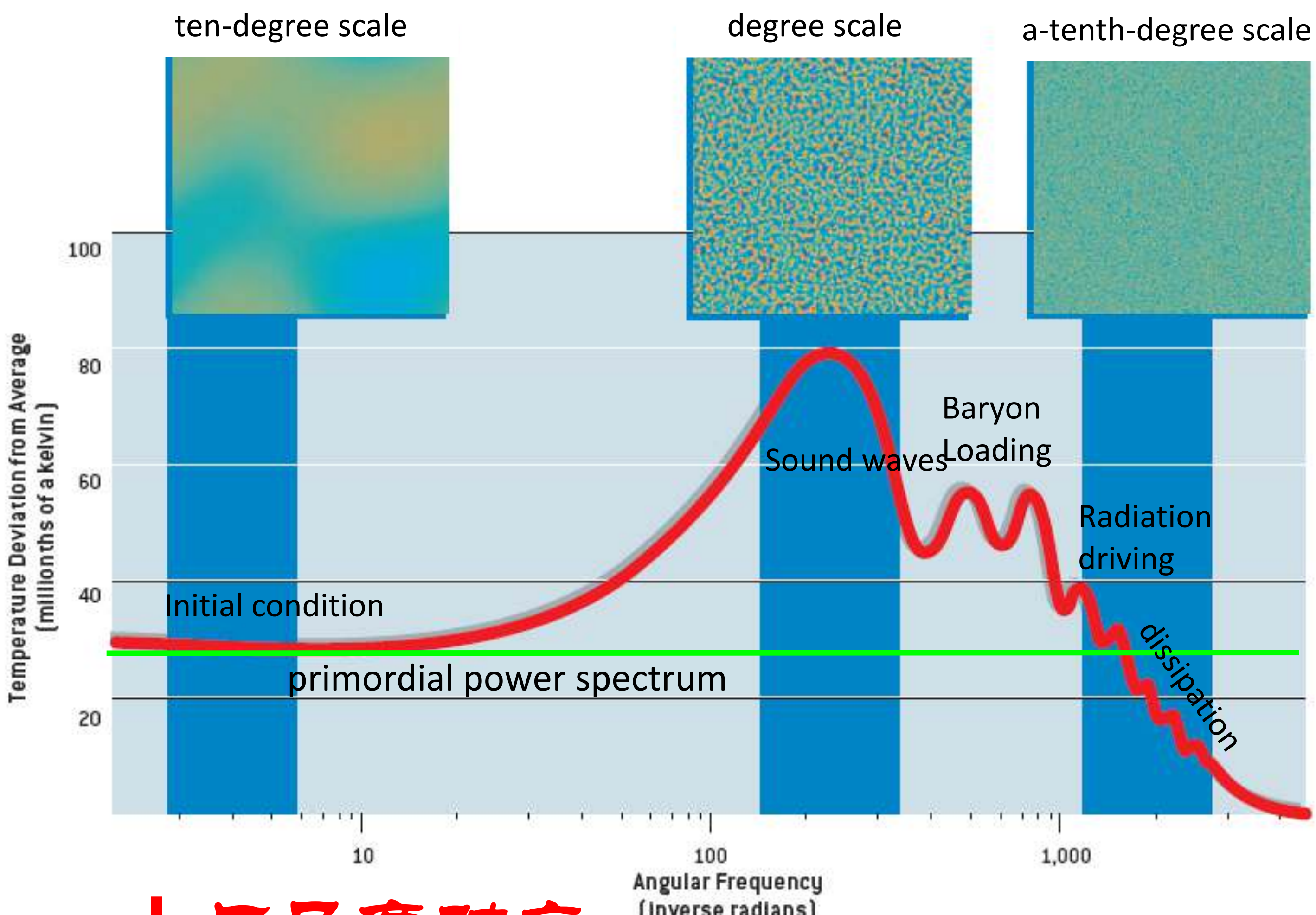
$$< a_{lm} a^*_{lm} > = C_l \delta_{ll'} \delta_{mm'}$$

$$C_l = \delta_{ll'}\delta_{mm'} 4\pi \int d\ln k\, j_l^2(kD_*) \frac{k^3}{2\pi^2} P_{\Phi/h}(k)$$

CMB中的宇宙学信息



TT power spectrum：



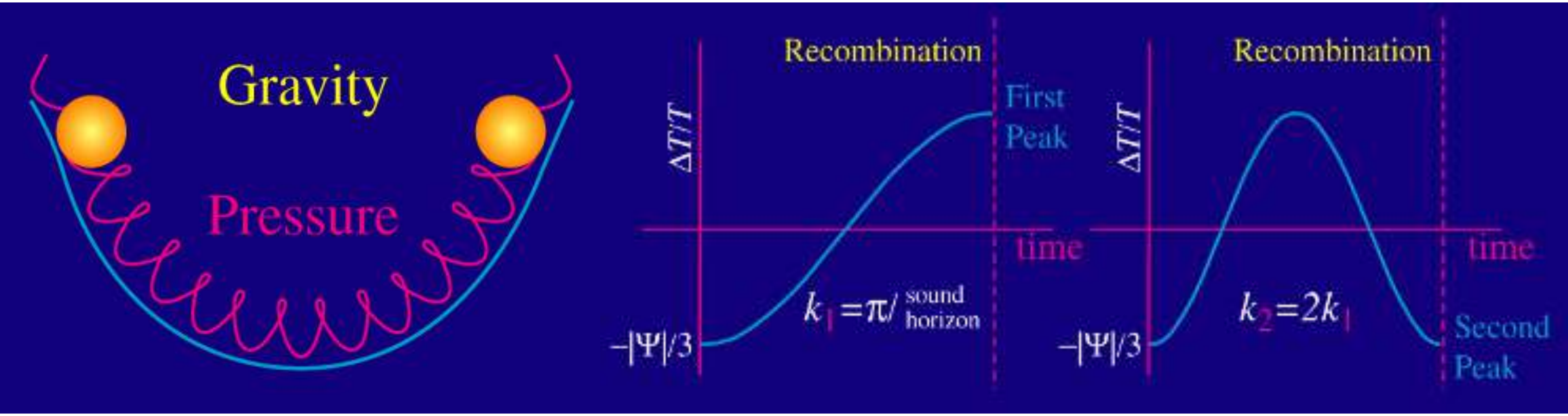
L与尺度对应

CMB中的宇宙学信息

声学振荡：

早期宇宙温度很高，处于等离子体状态，粒子之间相互耦合。扰动以声学振荡的形式在此等离子体中传播，直到光子与重子物质退耦合形成CMB。

声学视界：即到再复合（Recombination）时，声波能够传播的距离

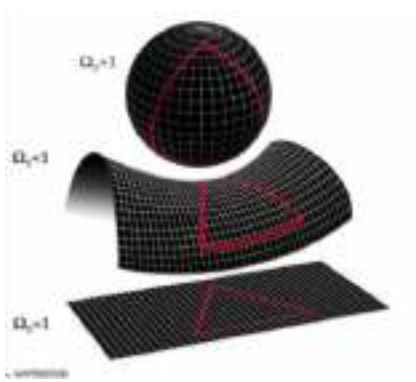


from Wayne Hu

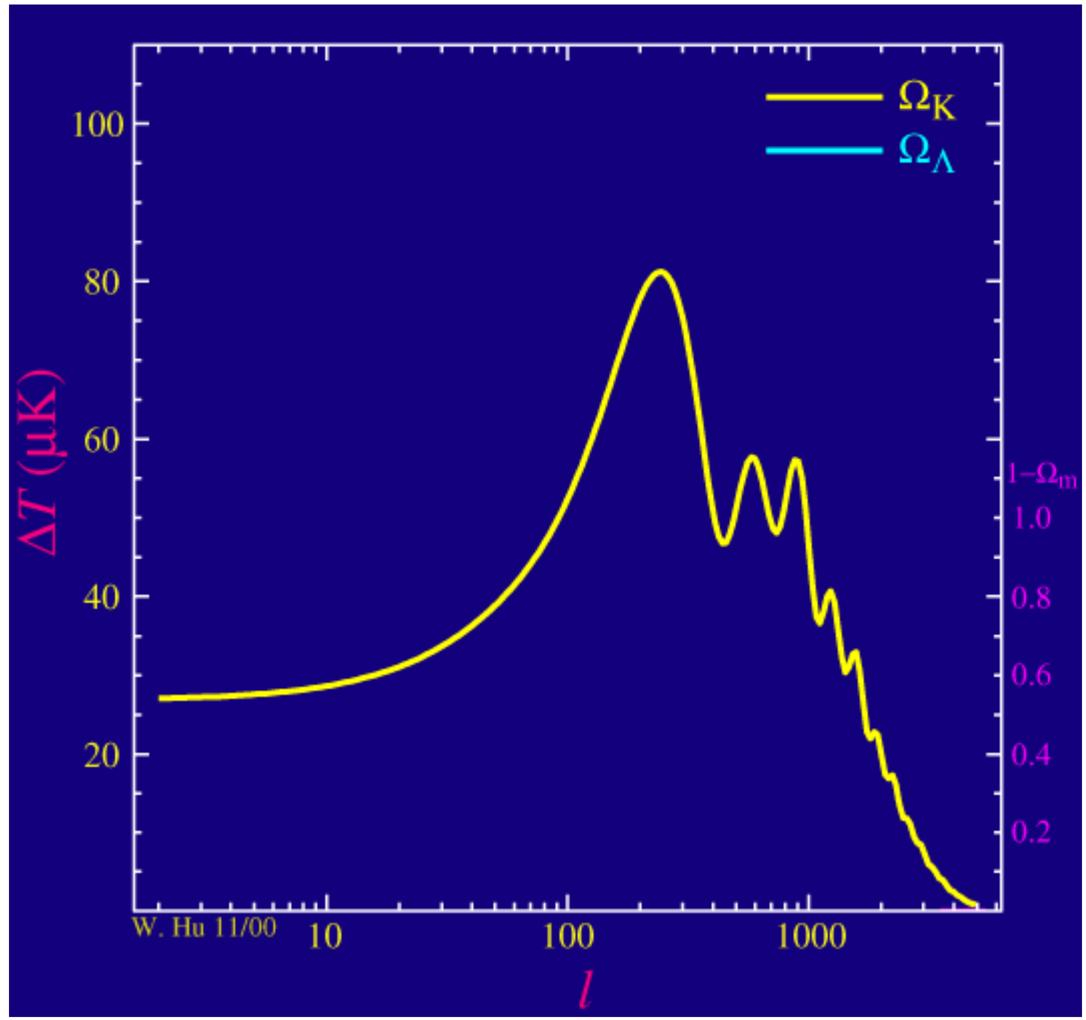
CMB中的宇宙学信息

First peak position:

curvature of universe



$$\sum \Omega_i + \Omega_k = 1$$



from Wayne Hu

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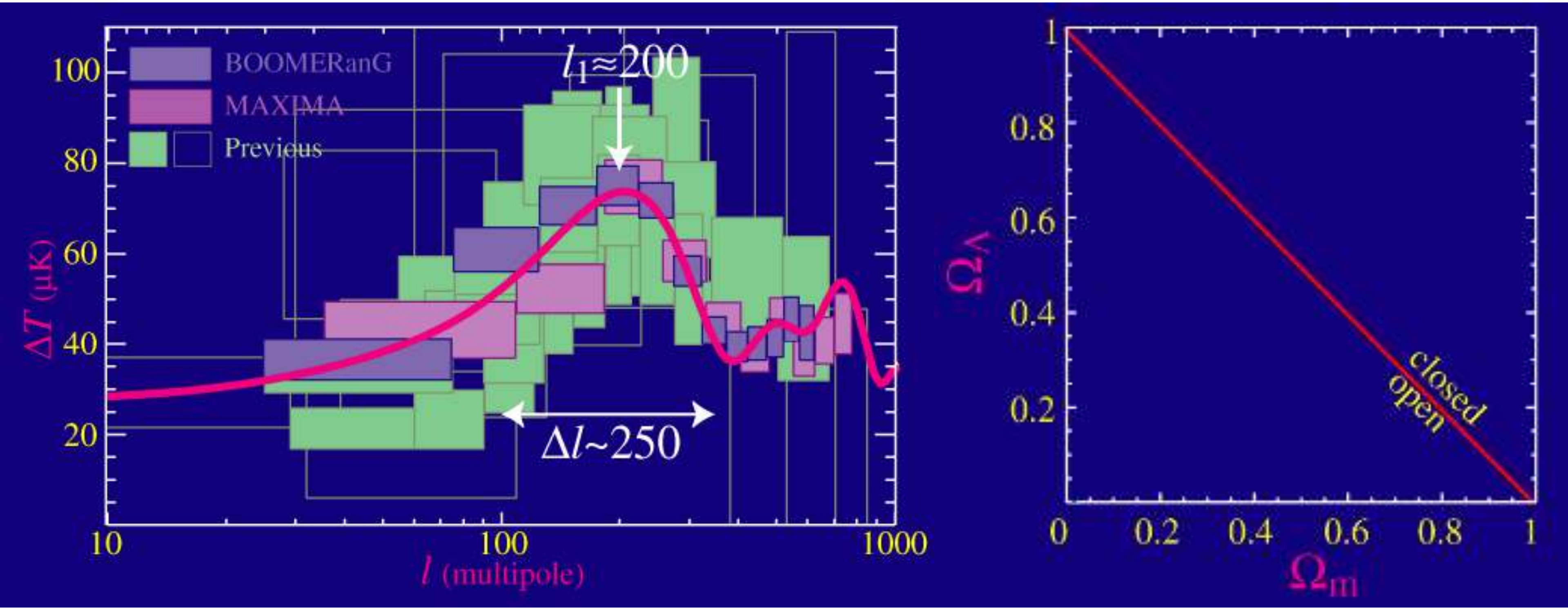


from Wayne Hu

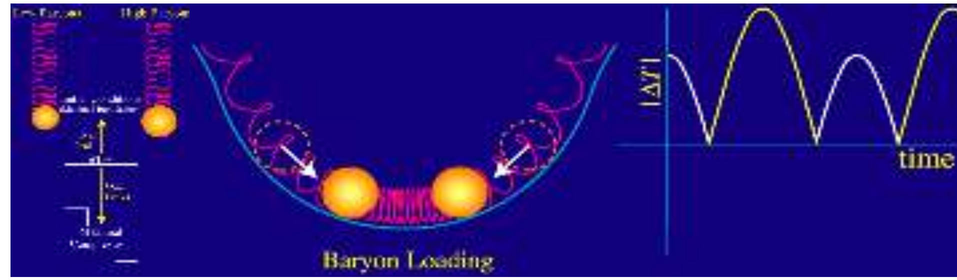
CMB中的宇宙学信息

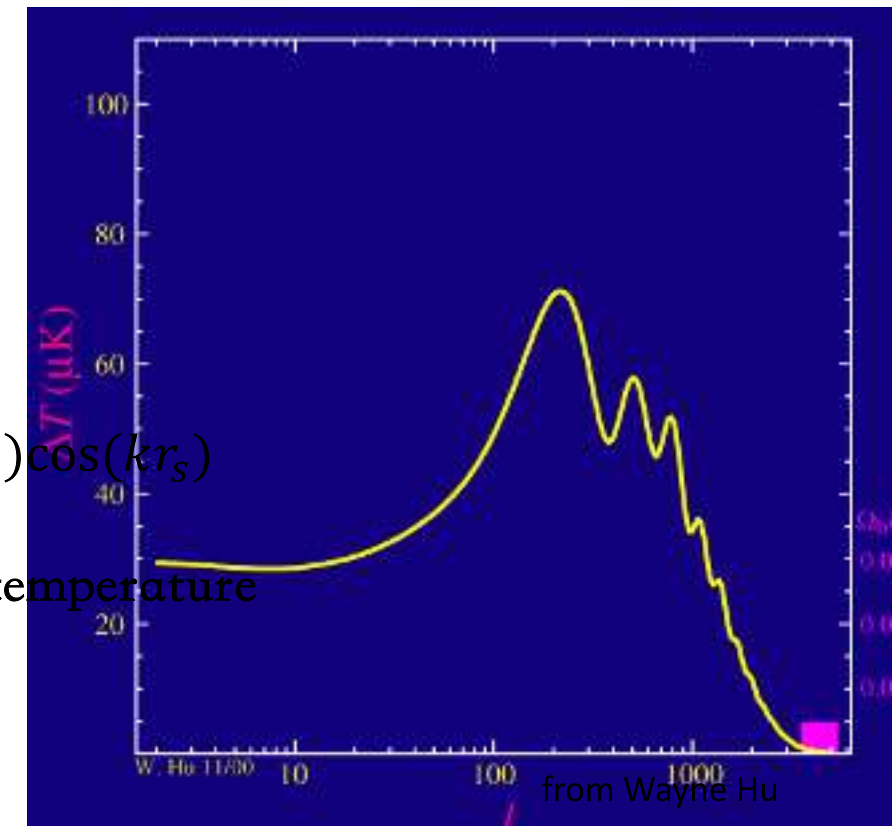
The difference between 2nd and 3rd peaks: baryon !

- Baryon add extra mass to the r-baryon fluid, the controlling parameter is the momentum density ratio

$$R \equiv \frac{p_b + \rho_b}{p_\gamma + \rho_\gamma} \approx 30\Omega_b h^2 \left(\frac{a}{10^{-3}}\right)$$

Which is important at recombination ! Of order unity





from Wayne Hu

➢ Modification to the solution

$$[\Delta_T + (1 + R)\Psi](\eta) = [\Delta_T + (1 + R)\Psi]\ (0)\cos(kr_s)$$

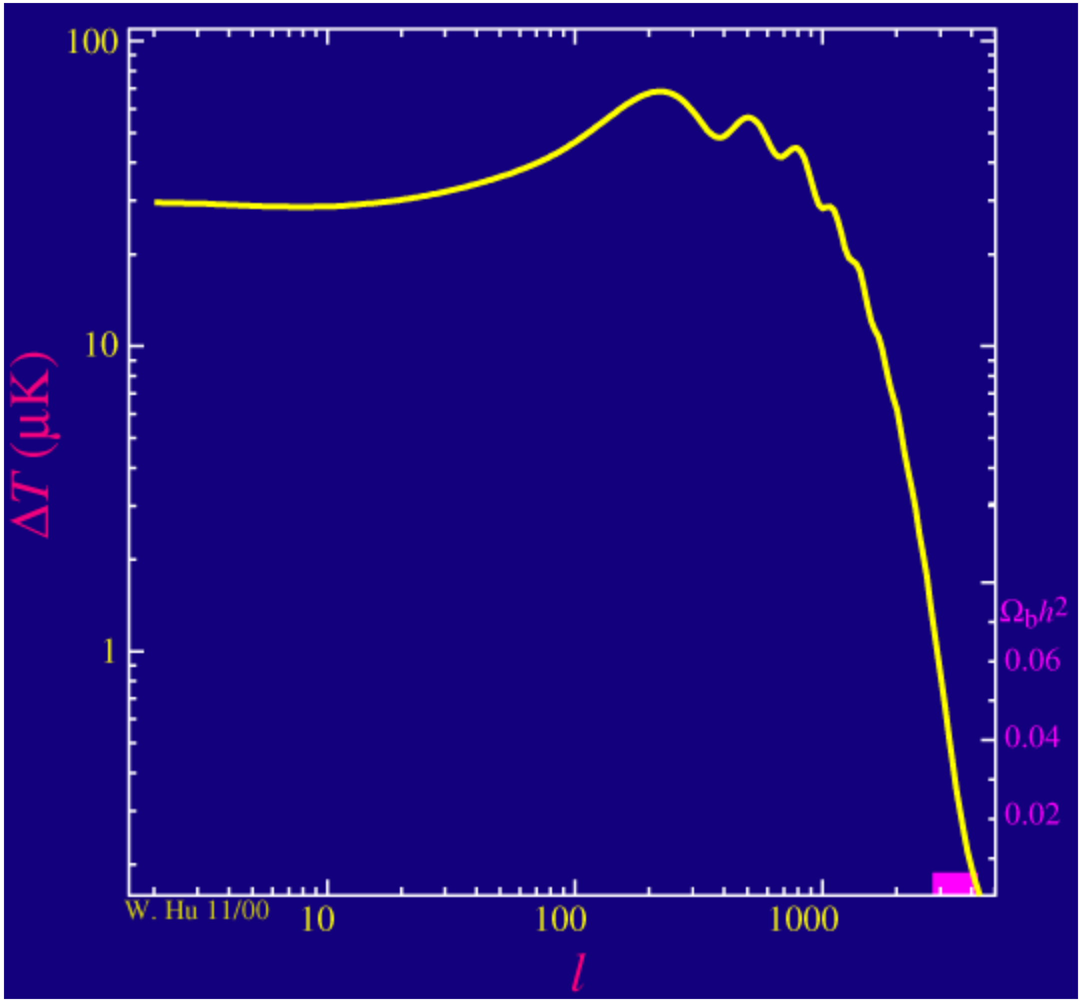
➢ Even-odd peak modulation of effective temperature

$$[\Theta + \Psi]_{\rm peaks} = [\pm(1 + 3R) - 3R]\,\frac{1}{3}\Psi(0)$$

$$[\Theta + \Psi]_1 - [\Theta + \Psi]_2 = [-6R]\frac{1}{3}\Psi(0)$$

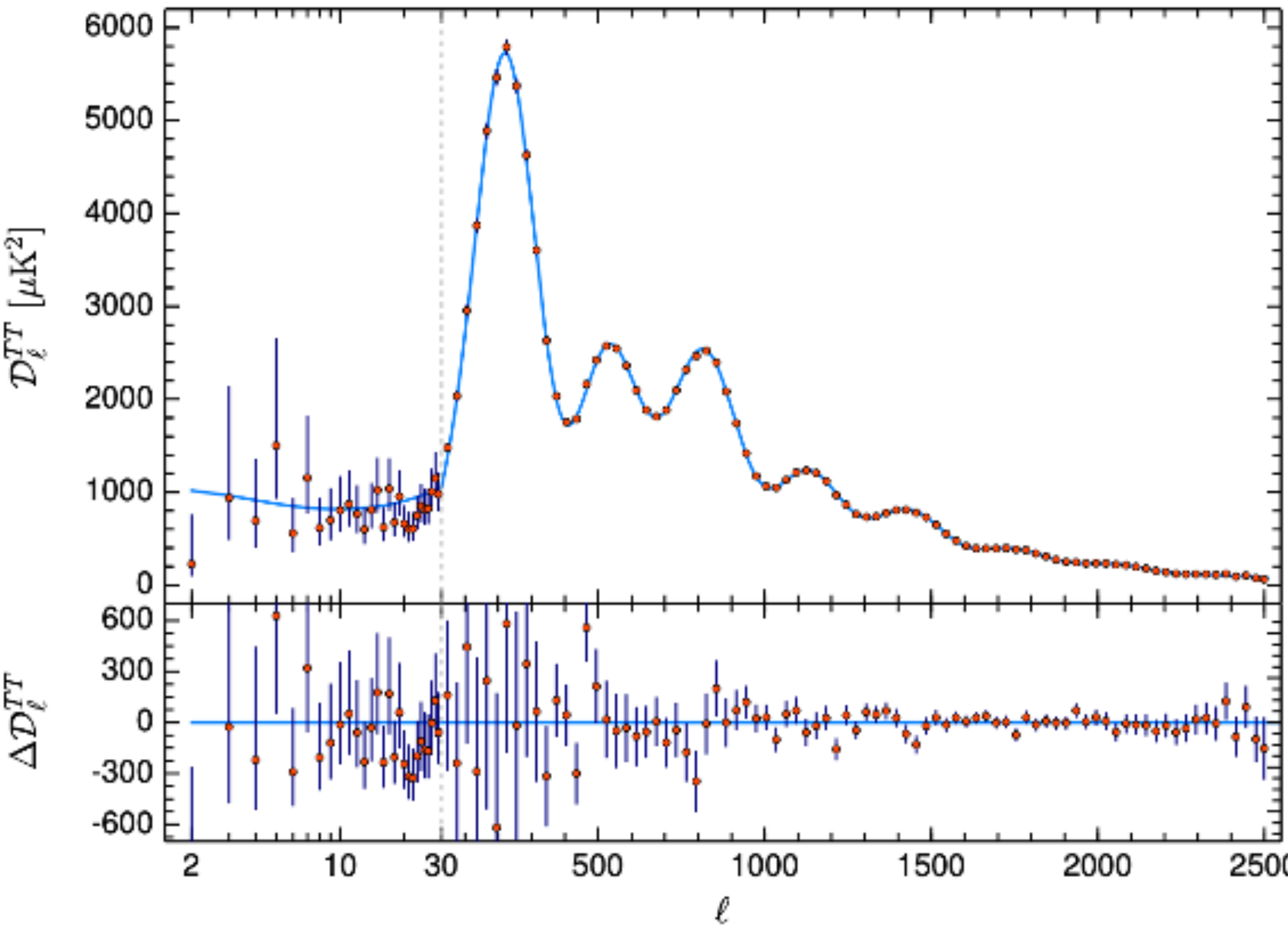
CMB中的宇宙学信息

Damping tail : baryon



from Wayne Hu

The latest measurements

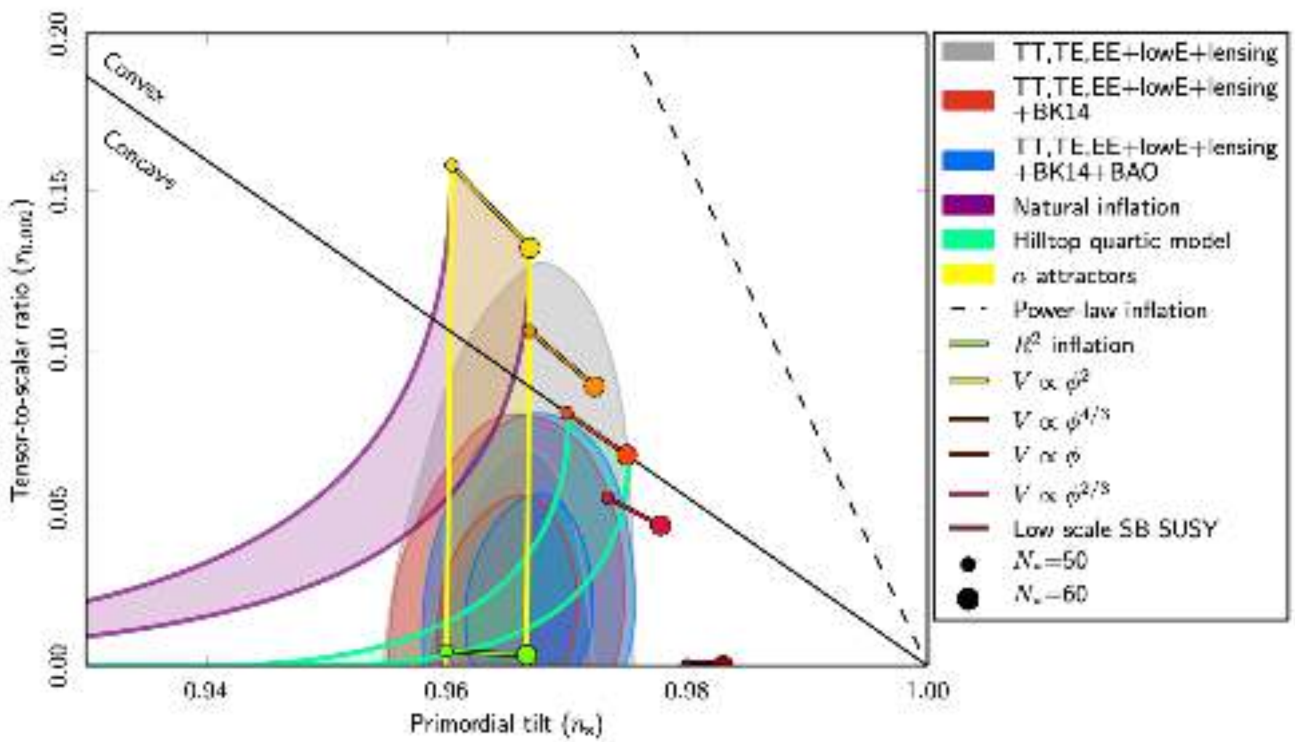


On inflation

- Model parameters : A_S, n_S, r, n_T

$$k^3\, P_\Phi(k) = \frac{8\pi}{9}\frac{H^2}{\epsilon m_{pl}^2}\bigg|_{aH=k} \equiv A_S\left(\frac{k}{k_*}\right)^{n_s-1}, \quad k^3\, P_h(k) = 8\pi\frac{H^2}{m_{pl}^2}\bigg|_{aH=k} \equiv A_T\left(\frac{k}{k_*}\right)^{n_T}$$

$$C_l = \delta_{ll'}\delta_{mm'}4\pi \int d\ln k\, j_l^2(kD_*)\,\frac{k^3}{2\pi^2}\,P_{\Phi,h}(k)$$



$r_{0.002} < 0.044$ (95 % CL, *Planck* TT,TE,EE+lowE+lensing+BK14).

$n_s = 0.9649 \pm 0.0042$ (68 % CL, *Planck* TT,TE,EE+lowE+lensing).

The constraints

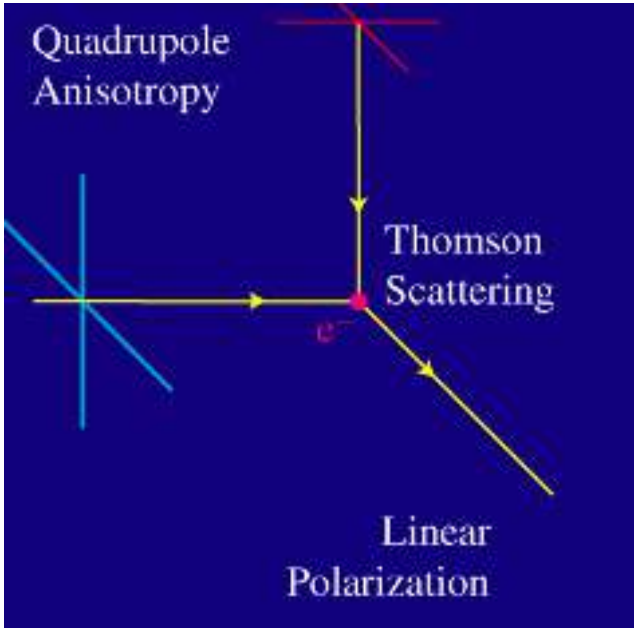
1807.06209

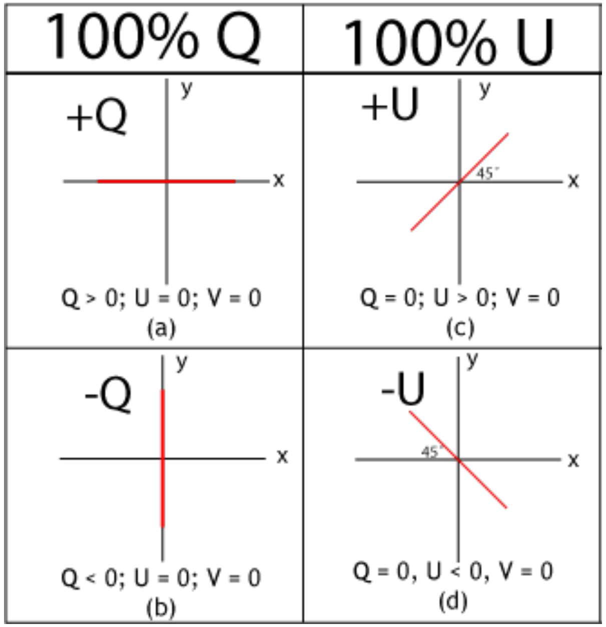
Table 1

Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1206 ± 0.0021	0.1177 ± 0.0020	0.1158 ± 0.0046	0.1202 ± 0.0014	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04077 ± 0.00047	1.04139 ± 0.00049	1.03999 ± 0.00089	1.04090 ± 0.00031	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0522 ± 0.0080	0.0496 ± 0.0085	0.0527 ± 0.0090	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.040 ± 0.016	$3.018^{+0.020}_{-0.018}$	3.052 ± 0.022	3.045 ± 0.016	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9626 ± 0.0057	0.967 ± 0.011	0.980 ± 0.015	0.9649 ± 0.0044	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0 [km s^{-1} Mpc^{-1}]	66.88 ± 0.92	68.44 ± 0.91	69.9 ± 2.7	67.27 ± 0.60	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.679 ± 0.013	0.699 ± 0.012	$0.711^{+0.033}_{-0.026}$	0.6834 ± 0.0084	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.321 ± 0.013	0.301 ± 0.012	$0.289^{+0.026}_{-0.033}$	0.3166 ± 0.0084	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1434 ± 0.0020	0.1408 ± 0.0019	$0.1404^{+0.0034}_{-0.0039}$	0.1432 ± 0.0013	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09589 ± 0.00046	0.09635 ± 0.00051	$0.0981^{+0.0016}_{-0.0018}$	0.09633 ± 0.00029	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8118 ± 0.0089	0.793 ± 0.011	0.796 ± 0.018	0.8120 ± 0.0073	0.8111 ± 0.0060	0.8102 ± 0.0060
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	0.840 ± 0.024	0.794 ± 0.024	$0.781^{+0.052}_{-0.060}$	0.834 ± 0.016	0.832 ± 0.013	0.825 ± 0.011
$\sigma_8 \Omega_m^{0.25}$	0.611 ± 0.012	0.587 ± 0.012	0.583 ± 0.027	0.6090 ± 0.0081	0.6078 ± 0.0064	0.6051 ± 0.0058
z_{re}	7.50 ± 0.82	$7.11^{+0.91}_{-0.75}$	$7.10^{+0.87}_{-0.73}$	7.68 ± 0.79	7.67 ± 0.73	7.82 ± 0.71
$10^9 A_s$	2.092 ± 0.034	2.045 ± 0.041	2.116 ± 0.047	$2.101^{+0.031}_{-0.034}$	2.100 ± 0.030	2.105 ± 0.030
$10^9 A_s e^{-2\tau}$	1.884 ± 0.014	1.851 ± 0.018	1.904 ± 0.024	1.884 ± 0.012	1.883 ± 0.011	1.881 ± 0.010
Age [Gyr]	13.830 ± 0.037	13.761 ± 0.038	$13.64^{+0.16}_{-0.14}$	13.800 ± 0.024	13.797 ± 0.023	13.787 ± 0.020
z_*	1090.30 ± 0.41	1089.57 ± 0.42	$1087.8^{+1.6}_{-1.7}$	1089.95 ± 0.27	1089.92 ± 0.25	1089.80 ± 0.21
r_* [Mpc]	144.46 ± 0.48	144.95 ± 0.48	144.29 ± 0.64	144.39 ± 0.30	144.43 ± 0.26	144.57 ± 0.22
$100\theta_*$	1.04097 ± 0.00046	1.04156 ± 0.00049	1.04001 ± 0.00086	1.04109 ± 0.00030	1.04110 ± 0.00031	1.04119 ± 0.00029
z_{drag}	1059.39 ± 0.46	1060.03 ± 0.54	1063.2 ± 2.4	1059.93 ± 0.30	1059.94 ± 0.30	1060.01 ± 0.29
r_{drag} [Mpc]	147.21 ± 0.48	147.59 ± 0.49	146.46 ± 0.70	147.05 ± 0.30	147.09 ± 0.26	147.21 ± 0.23
k_D [Mpc^{-1}]	0.14054 ± 0.00052	0.14043 ± 0.00057	0.1426 ± 0.0012	0.14090 ± 0.00032	0.14087 ± 0.00030	0.14078 ± 0.00028
z_{eq}	3411 ± 48	3349 ± 46	3340^{+81}_{-92}	3407 ± 31	3402 ± 26	3387 ± 21
k_{eq} [Mpc^{-1}]	0.01041 ± 0.00014	0.01022 ± 0.00014	$0.01019^{+0.00025}_{-0.00028}$	0.010398 ± 0.000094	0.010384 ± 0.000081	0.010339 ± 0.000063
$100\theta_{s,eq}$	0.4483 ± 0.0046	0.4547 ± 0.0045	0.4562 ± 0.0092	0.4490 ± 0.0030	0.4494 ± 0.0026	0.4509 ± 0.0020

CMB polarization:

- Thomson scattering can only form linear polarization, so V = 0.





Stokes parameters

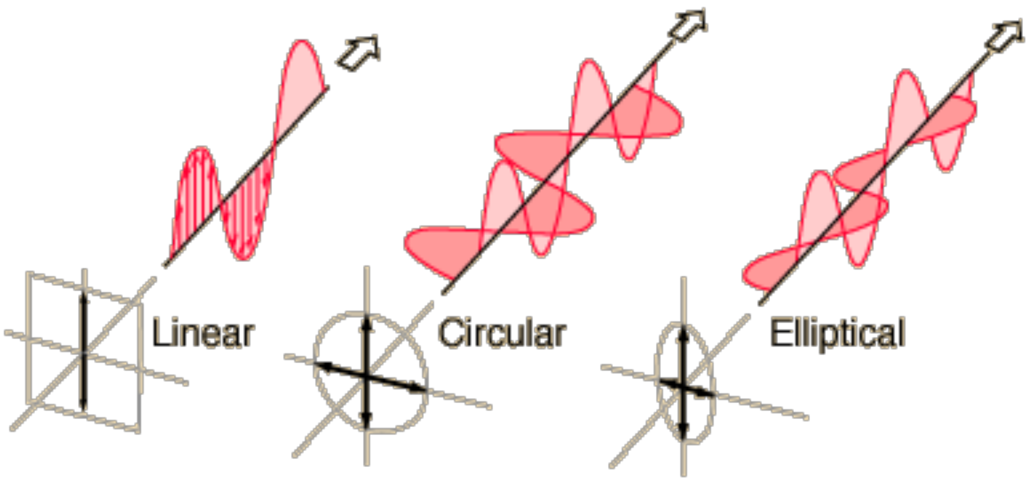
Description

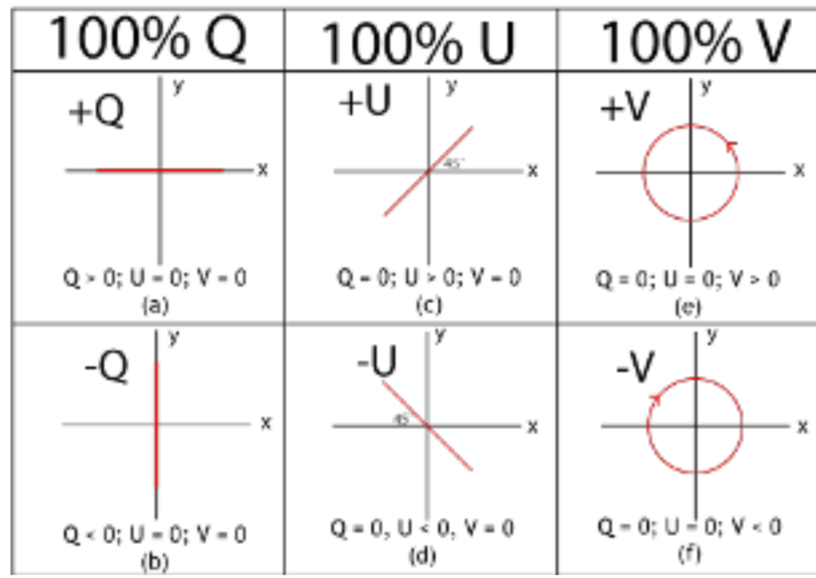
$$E_x = a_x(t)\cos[\omega_0 t - \theta_x(t)] \quad I \equiv \langle a_x^2 \rangle + \langle a_y^2 \rangle, \quad U \equiv \langle 2a_x a_y \cos(\theta_x - \theta_y) \rangle,$$

$$E_y = a_y(t)\cos[\omega_0 t - \theta_y(t)] \quad Q \equiv \langle a_x^2 \rangle - \langle a_y^2 \rangle, \quad V \equiv \langle 2a_x a_y \sin(\theta_x - \theta_y) \rangle.$$

***I*: *intensity* , *Q* and *U*: *linear polarization*, *V*: circular polarization**

- Elliptical polarization is the combination of linear polarization and circular polarization, which is the most general case of photon polarization.





$\theta_x = \theta_y$, linear polarization， V=0

$\theta_x - \theta_y = \frac{\pi}{2}$, $a_x = a_y$, Circular polarization

Degree of polarization: $P \equiv \frac{\sqrt{Q^2+U^2+V^2}}{I}$,

P=0, natural light

Coordinate independent quantities

Q, U are not coordinate invariants

$$Q \pm iU \rightarrow e^{\mp 2i\alpha}(Q \pm iU)$$

E,B decomposition:

$$(Q+iU)(\hat{n}) = \sum_{lm} a_{2,lm\,2}Y_{lm}(\hat{n})$$

$$(Q-iU)(\hat{n}) = \sum_{lm} a_{-2,lm\,-2}Y_{lm}(\hat{n})$$

$$a_{2,lm} = \int d\Omega_2 Y_{lm}^{*}(\hat{n})(Q+iU)(\hat{n})$$

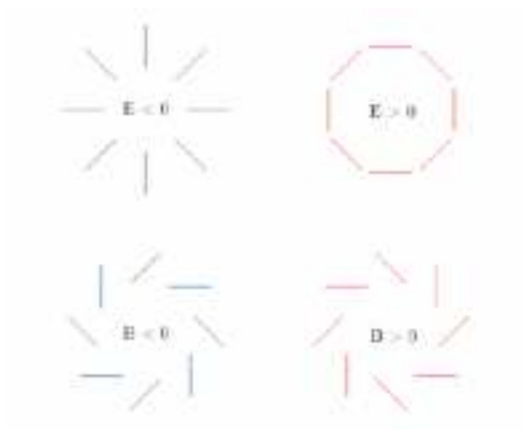
$$= \left[\frac{(l+2)!}{(l-2)!}\right]^{-1/2} \int d\Omega Y_{lm}^{*}(\hat{n})\eth^2(Q-iU)(\hat{n}),$$

$$a_{-2,lm} = \int d\Omega_{-2} Y_{lm}^{*}(\hat{n})(Q-iU)(\hat{n})$$

$$= \left[\frac{(l+2)!}{(l-2)!}\right]^{-1/2} \int d\Omega Y_{lm}^{*}(\hat{n})\eth^2(Q-iU)(\hat{n}).$$

$$a_{E,lm} = -(a_{2,lm} + a_{-2,lm})/2,$$

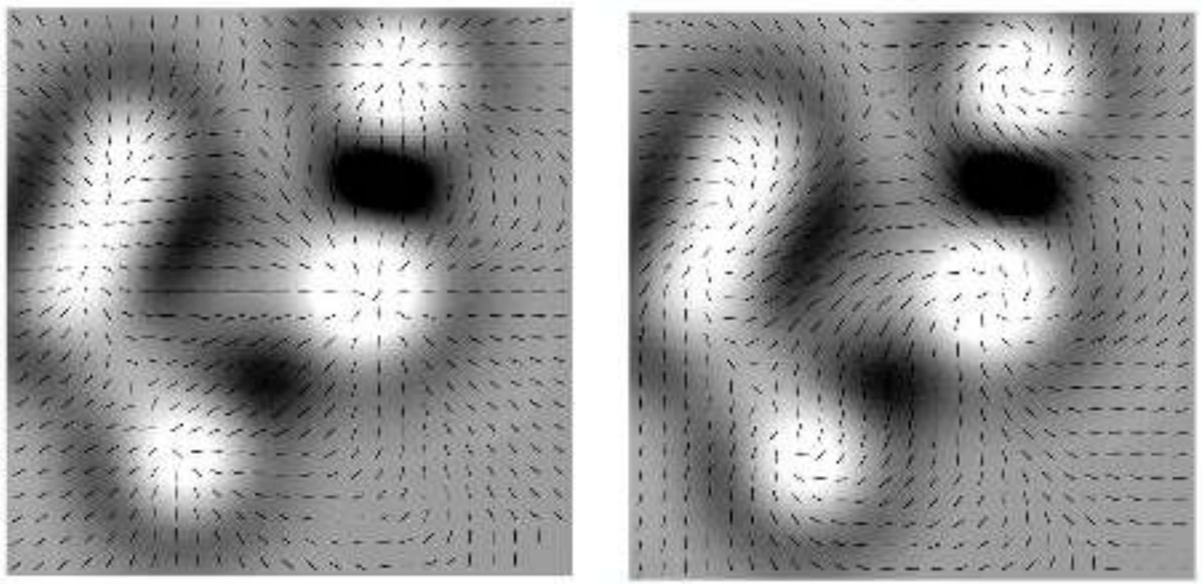
$$a_{B,lm} = i(a_{2,lm} - a_{-2,lm})/2.$$



E： parity even,
E-mode

B: parity odd
B mode

Map of E & B



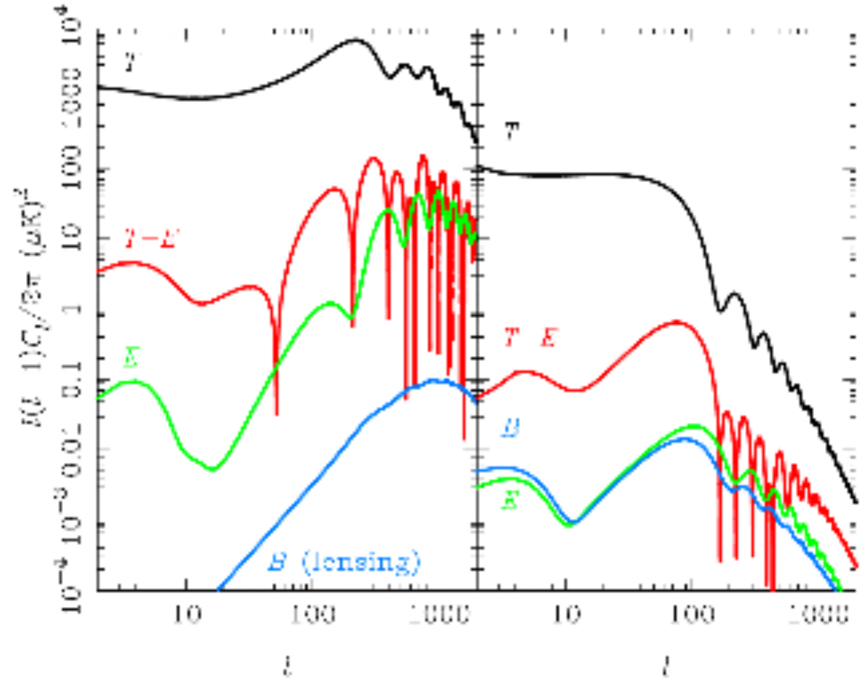
E-mode B-mode

R. Durrer

$$T(\hat{\boldsymbol{n}}) = \sum_{lm} a_{T,lm} Y_{lm}(\hat{\boldsymbol{n}})$$

$$(Q+iU)(\hat{\boldsymbol{n}}) = \sum_{lm} a_{2,lm2} Y_{lm}(\hat{\boldsymbol{n}})$$

$$(Q-iU)(\hat{\boldsymbol{n}}) = \sum_{lm} a_{-2,lm-2} Y_{lm}(\hat{\boldsymbol{n}})$$



From scalar (left)/tensor (right)

Challinor & Peiris, 0903.5158

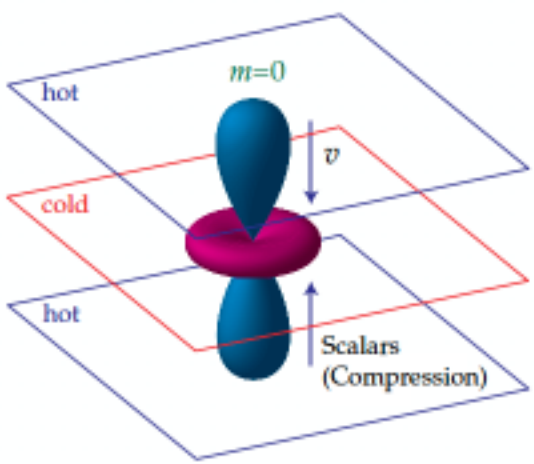
$$< a^*_{T,l'm'} a_{T,lm} >= C_l^{TT} \delta_{ll'} \delta_{mm'} \qquad < E^*_{l'm'} E_{lm} >= C_l^{EE} \delta_{ll'} \delta_{mm'}$$

$$< B^*_{l'm'} B_{lm} >= C_l^{BB} \delta_{ll'} \delta_{mm'} \qquad < a^*_{T,l'm'} E_{lm} >= C_l^{TE} \delta_{ll'} \delta_{mm'}$$

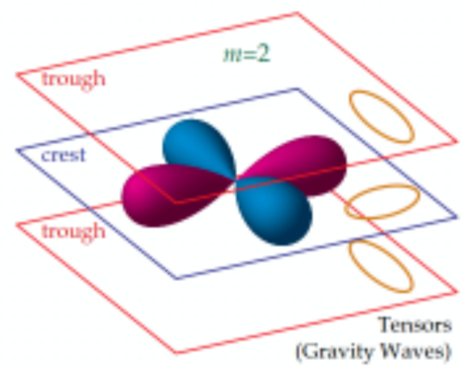
$$< a^*_{T,l'm'} B_{lm} >= C_l^{TB} \delta_{ll'} \delta_{mm'} \qquad < E^*_{l'm'} B_{lm} >= C_l^{EB} \delta_{ll'} \delta_{mm'}$$

B mode: primordial gravitational wave

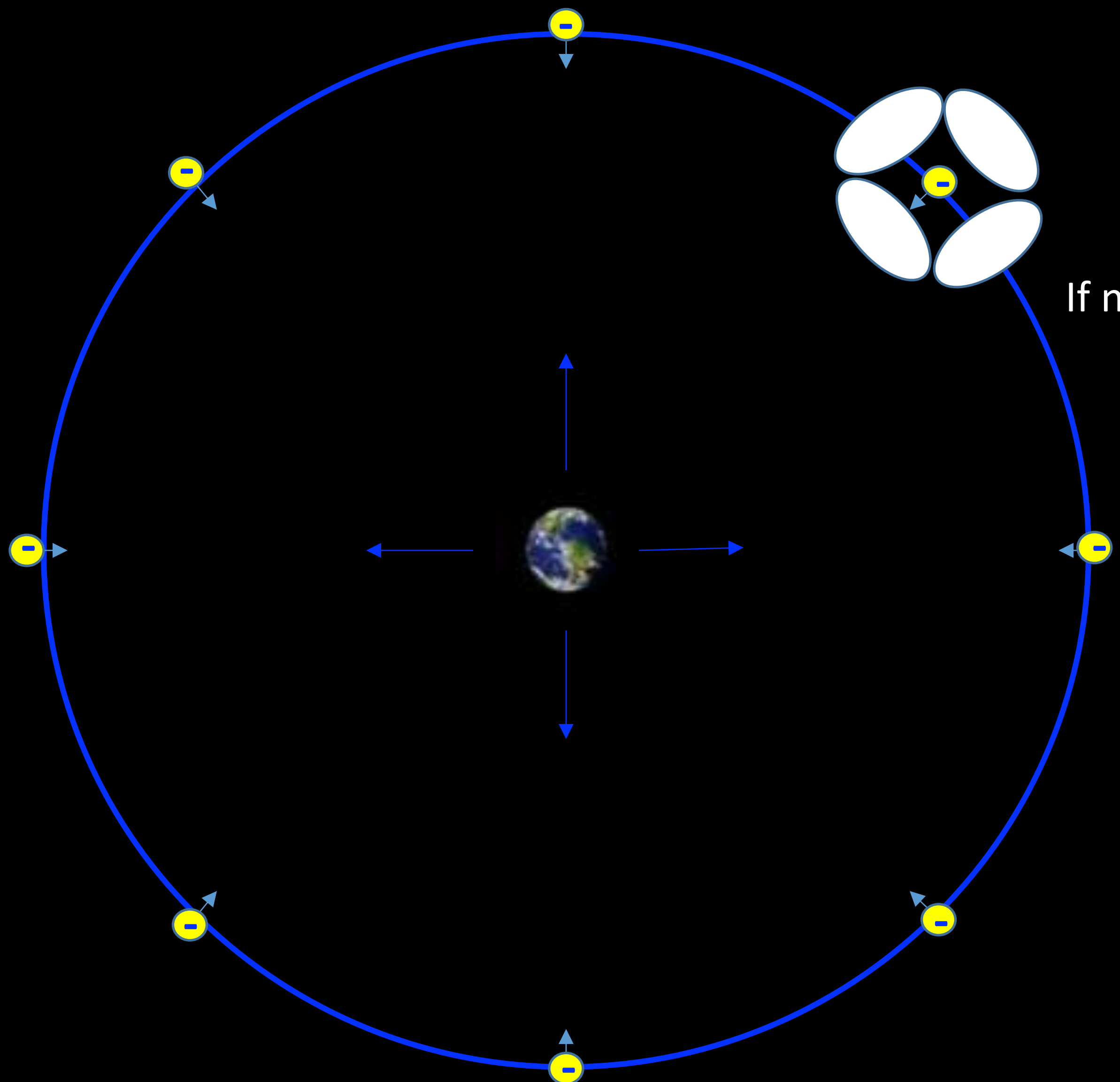
Scalar quadrupole,
azimuthal symmetric
generates T and E



Tensor quadrupole,
without azimuthal symmetry,
generates T, E and B

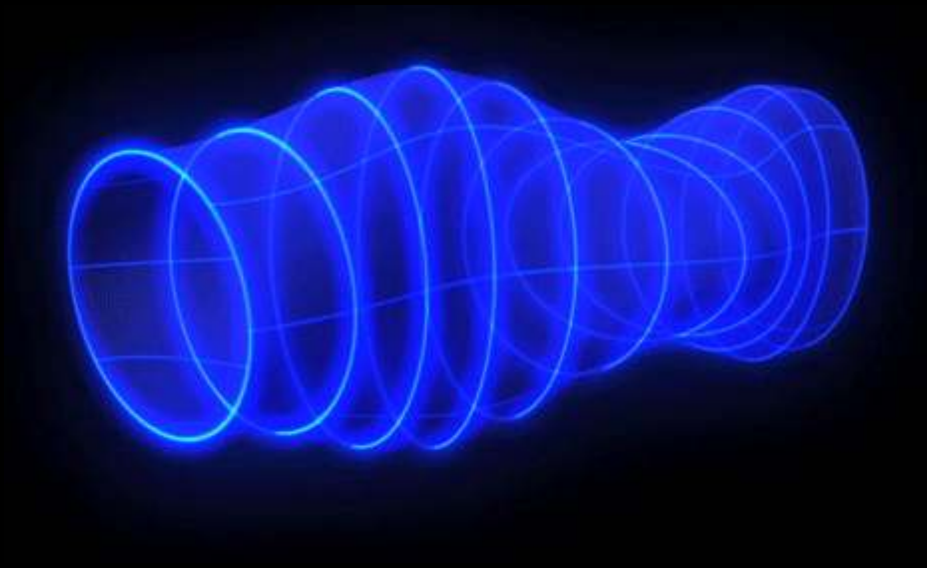


Trace back to last scattering surface, t = 380,000 years

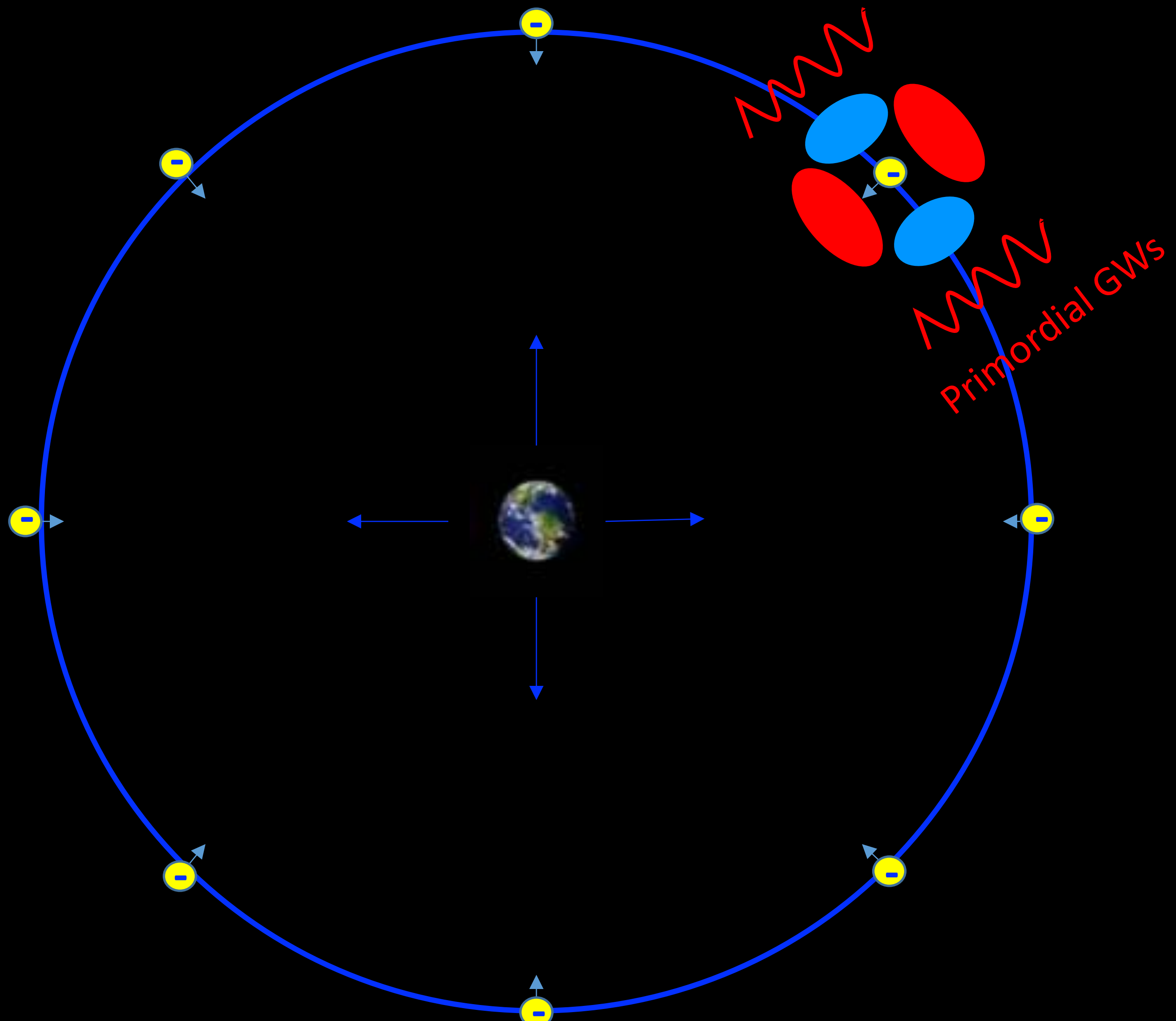


If no perturbation

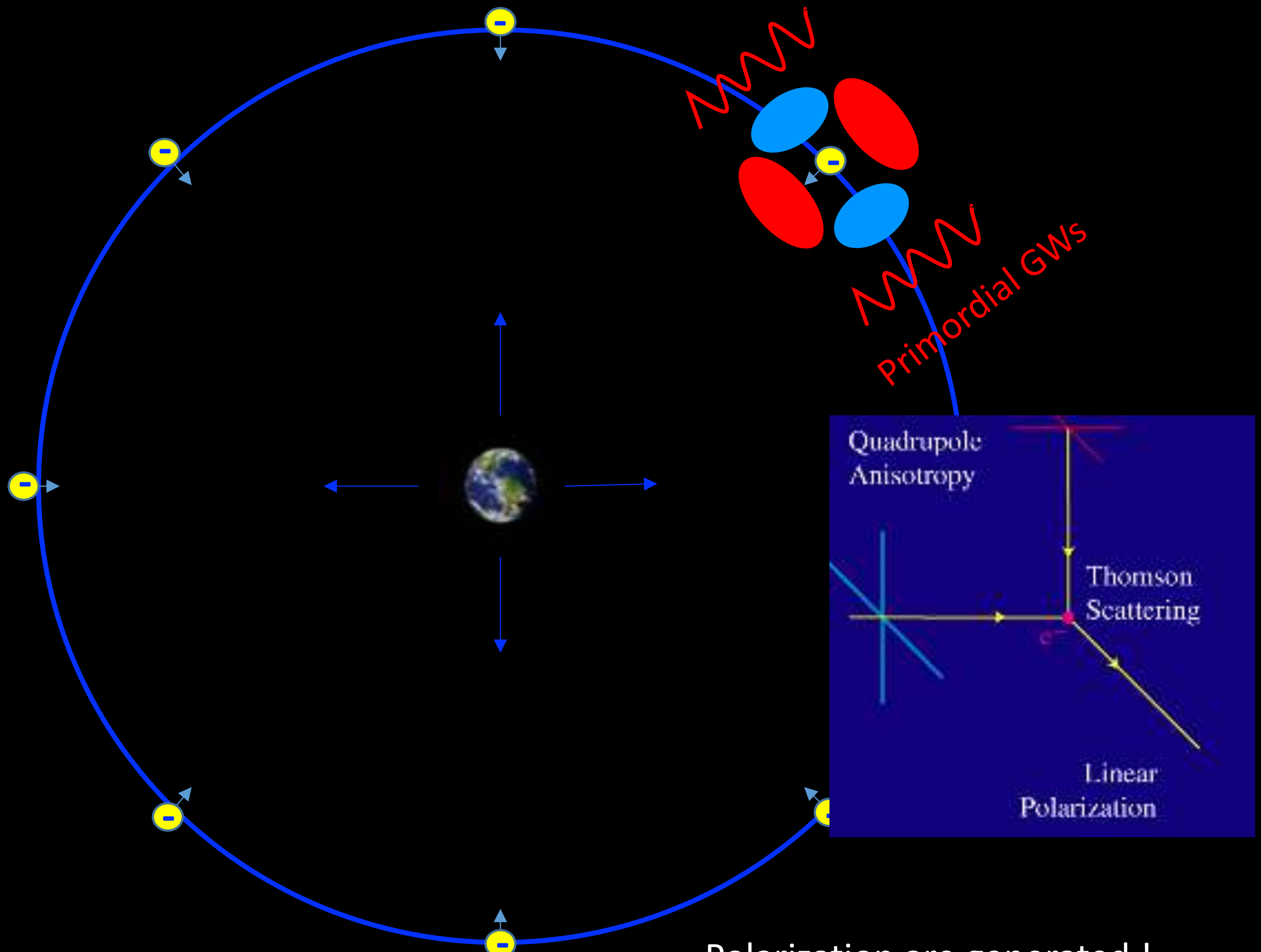
Tensile & compression



Trace back to last scattering surface, t = 380,000 years



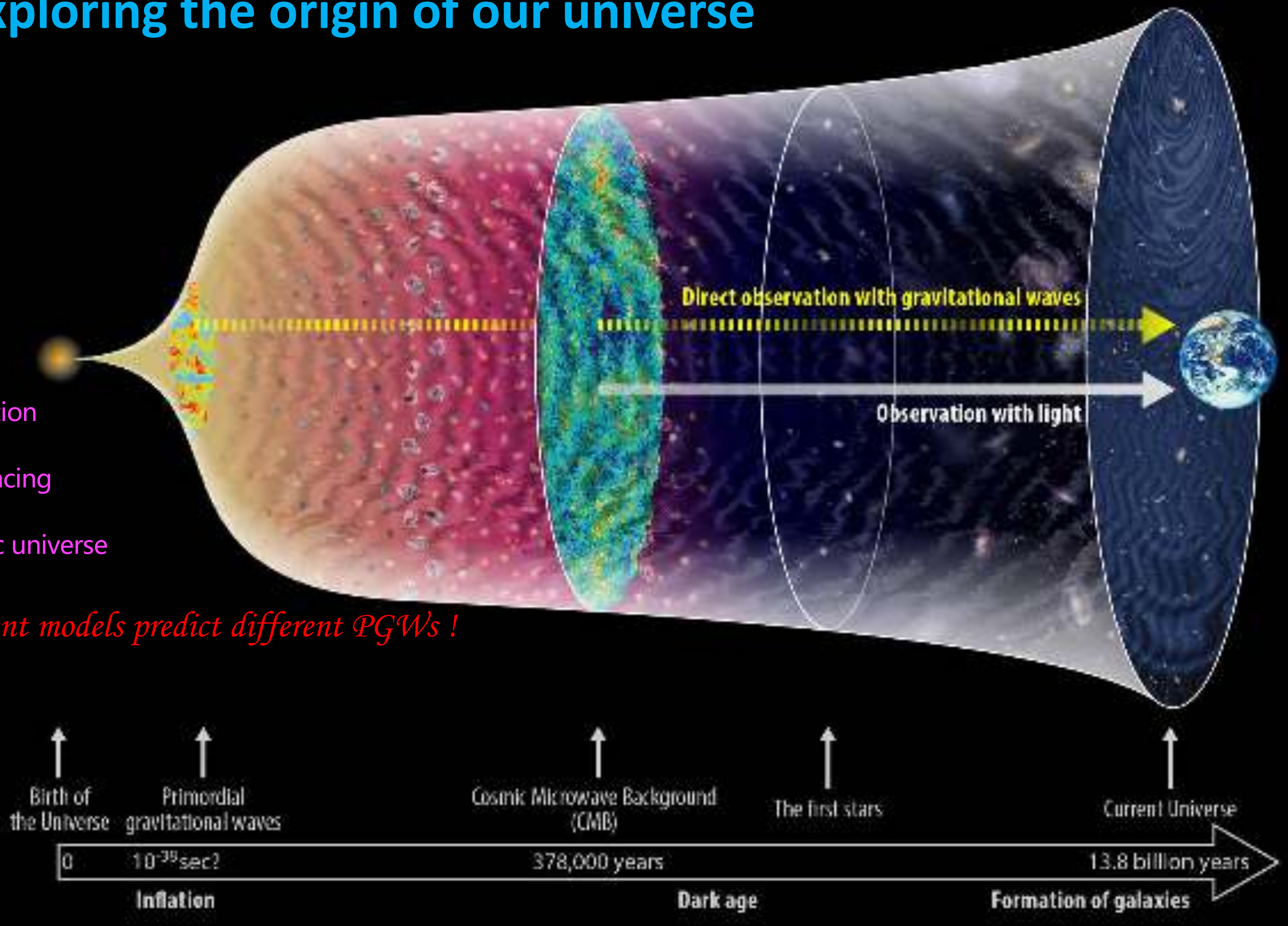
Trace back to last scattering surface, t = 380,000 years



Polarization are generated !

The next goal: Primordial gravitational waves
has not been discovered yet !

Exploring the origin of our universe



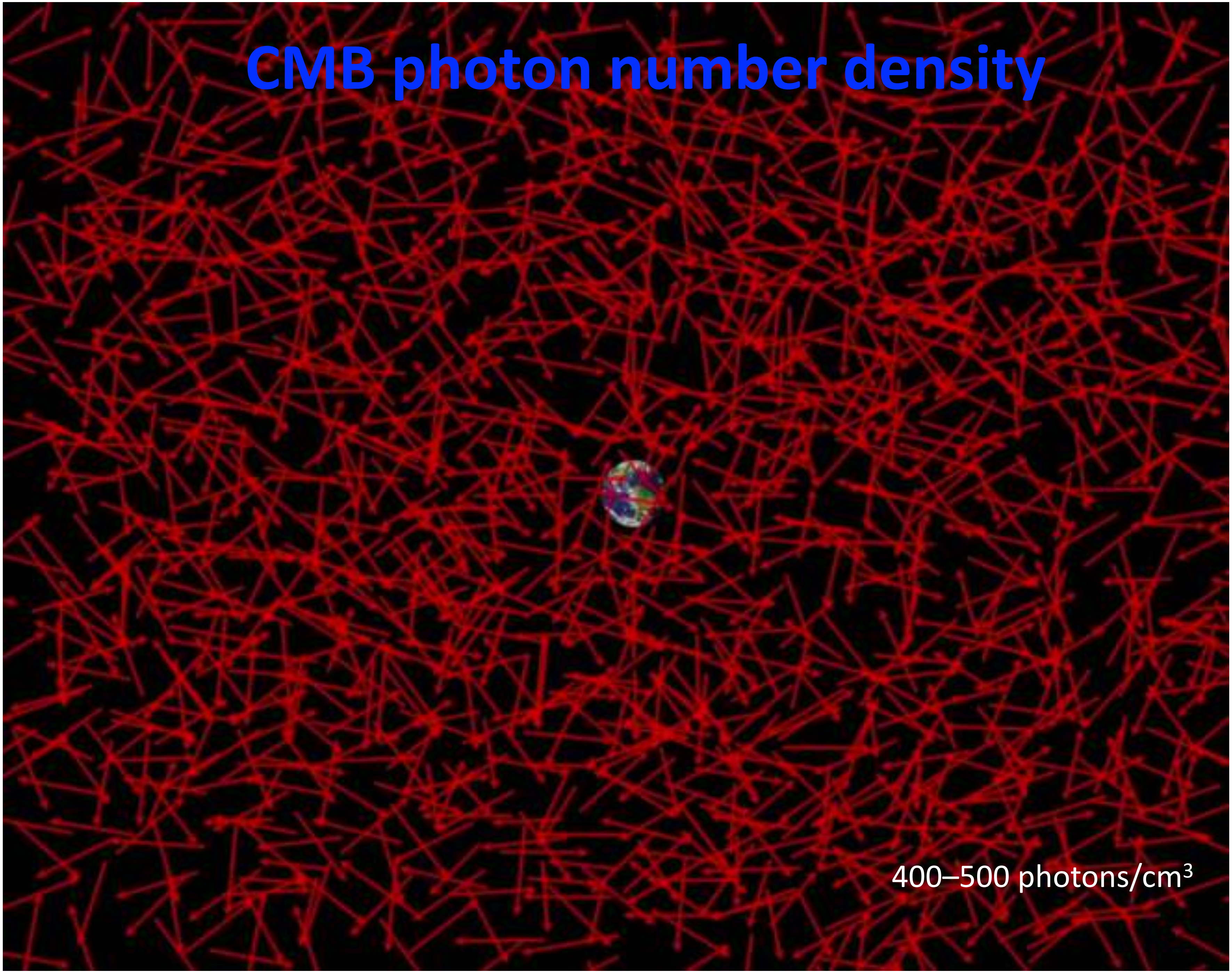
1) inflation

2) bouncing

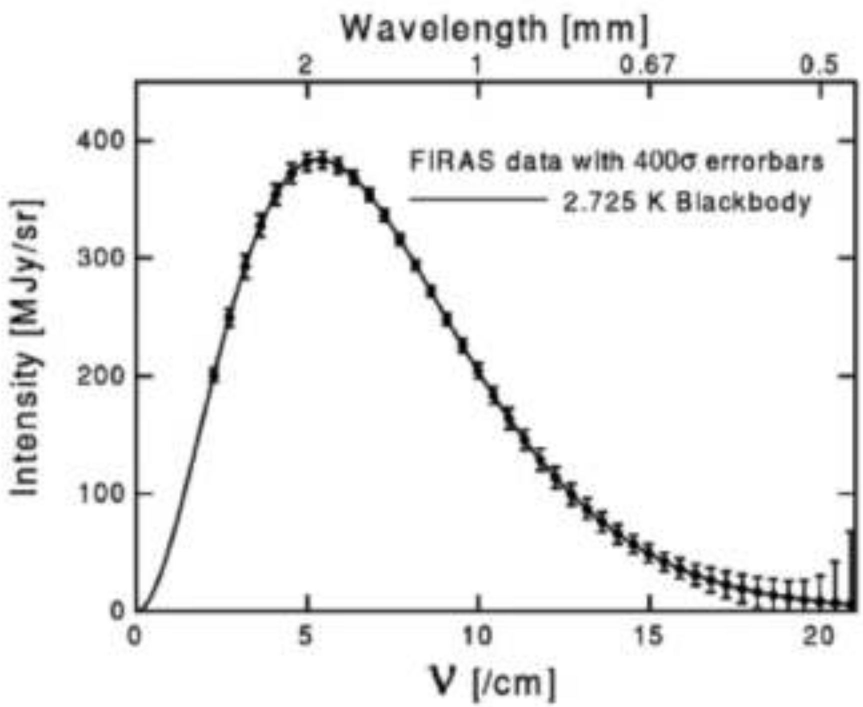
3) cyclic universe

Different models predict different PGWs !

The detection

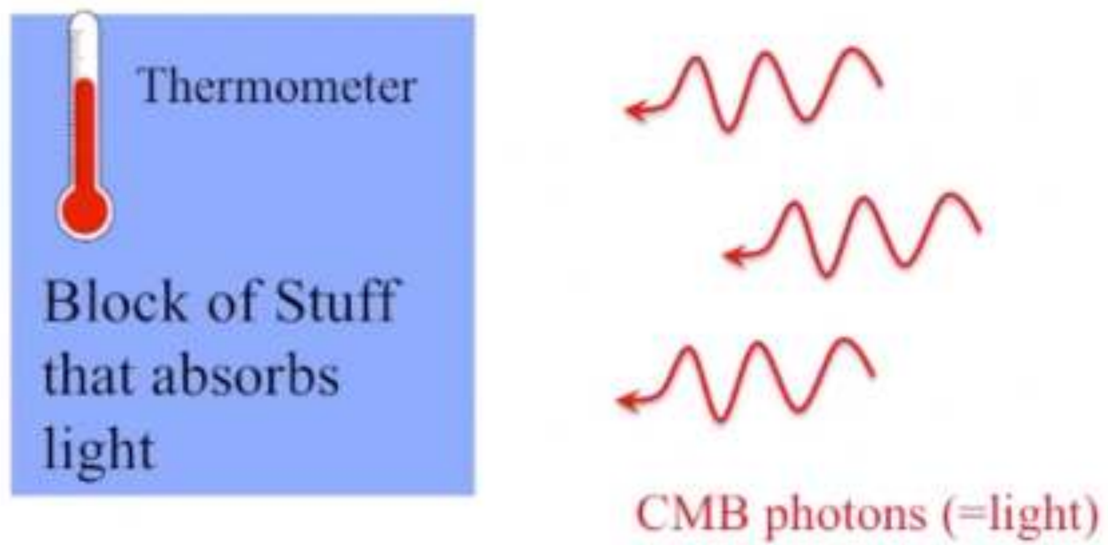

CMB photon number density
400–500 photons/cm3

How weak it is?



- Peak wavelength ： ג=2mm
- CMB Radiation Intensity ： 3.3 microwatts/m^2
- Radiation intensity of human body ： 500 watts/m^2

How to detect ?



Photons get absorbed by block,
Block heats up,
Thermometer senses temperature rise.

How to observe ?

- **Want**

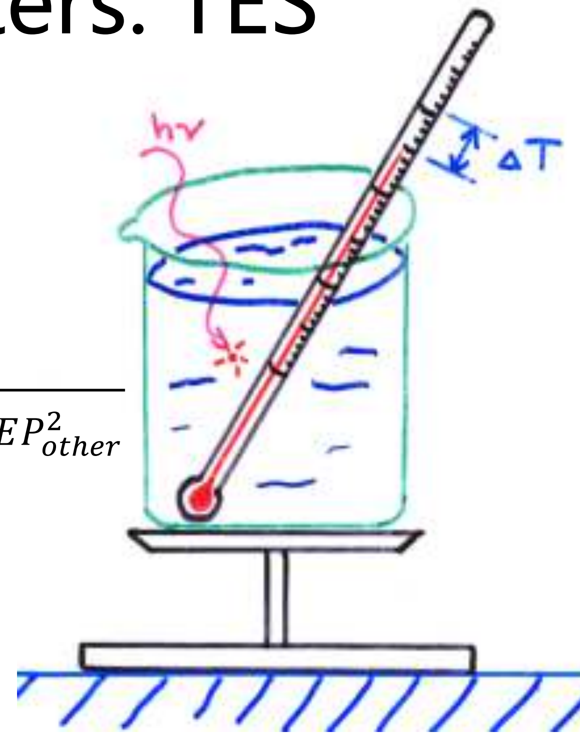
1. Super-sensitive thermometer

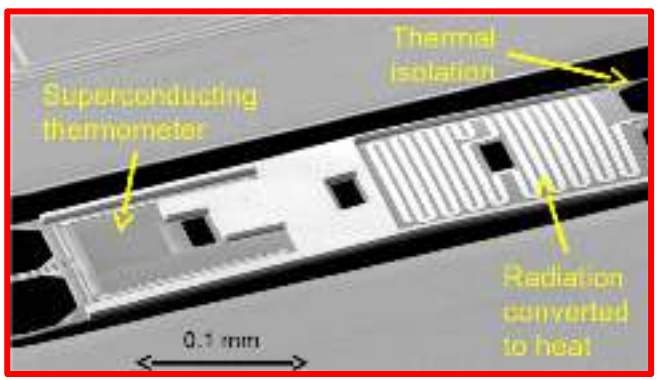
2. Small, very cold, block (so CMB photons heat it up fast)

3. No "extra" photons from our hot environment.

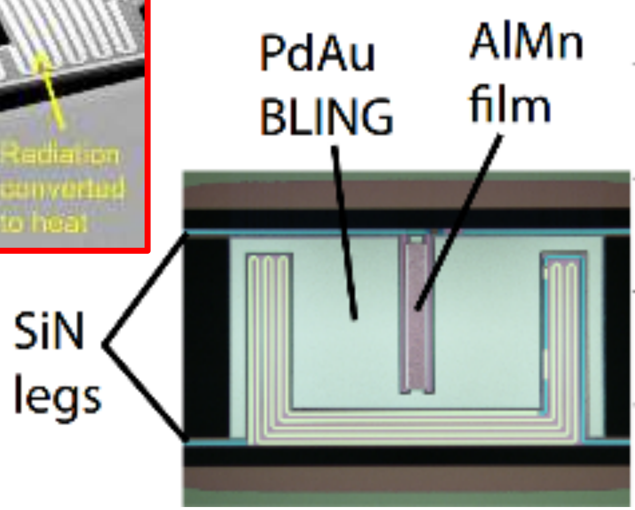
Sensitive Thermometers: TES

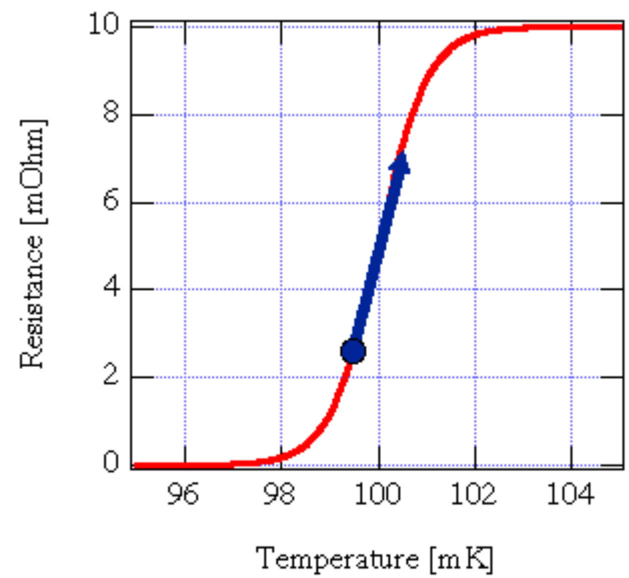
- Optical load :
  - $P_{load} = 2\eta k T_{RJ} \Delta v + P_{internal}$
- Saturation power:
  - $P_{saturation} = T_0 G_0 \frac{(T_c/T_0)^{n+1}-1}{n+1} \sim 2P_{load}$
- Detector noise: $NEP = \sqrt{NEP_{photon}^2 + NEP_{phonon}^2 + NEP_{other}^2}$
  - Photon noise: $NEP_{photon} = \sqrt{2hvP_{load} + \frac{2P_{load}{}^2}{v(\Delta v/v)}}$
  - Phonon noise : $NEP_{phonon} = \sqrt{4k_B G T^2 F}, \quad G = G_0 \left(\frac{T}{T_0}\right)^n$
  - others



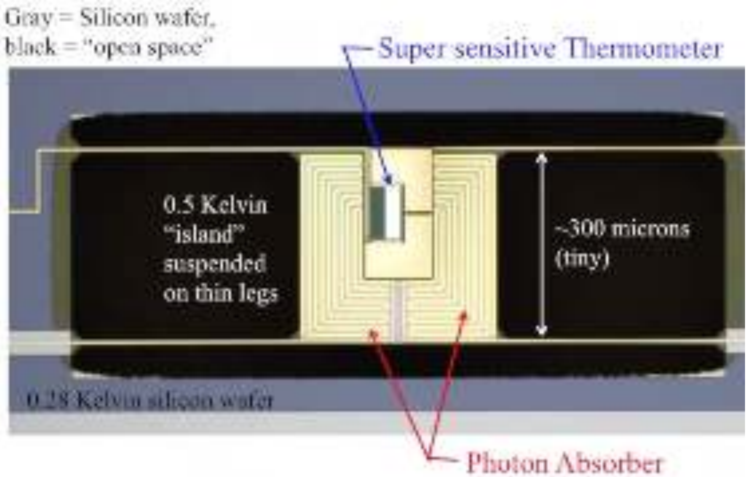


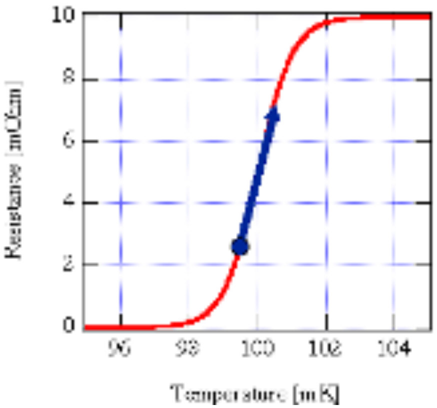
BICEP collaboration

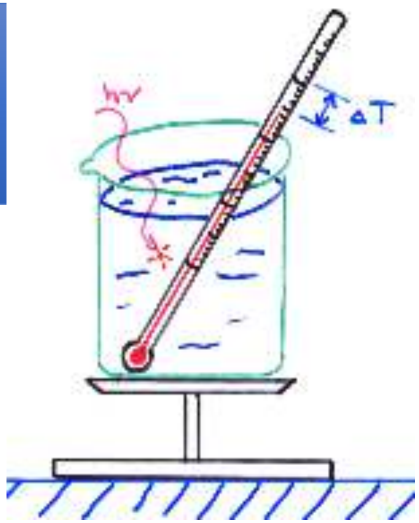




CMB photon detector module

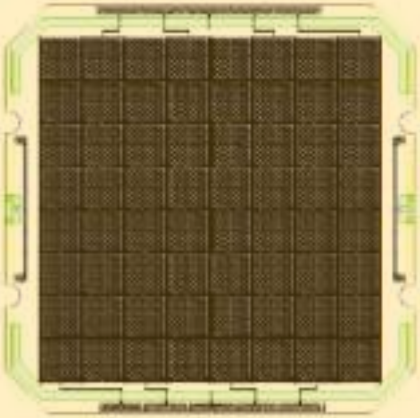




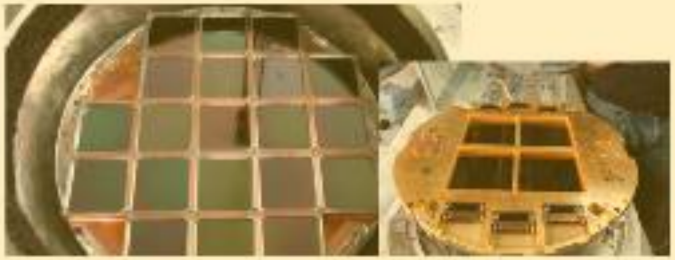


detectors in one module

1 module

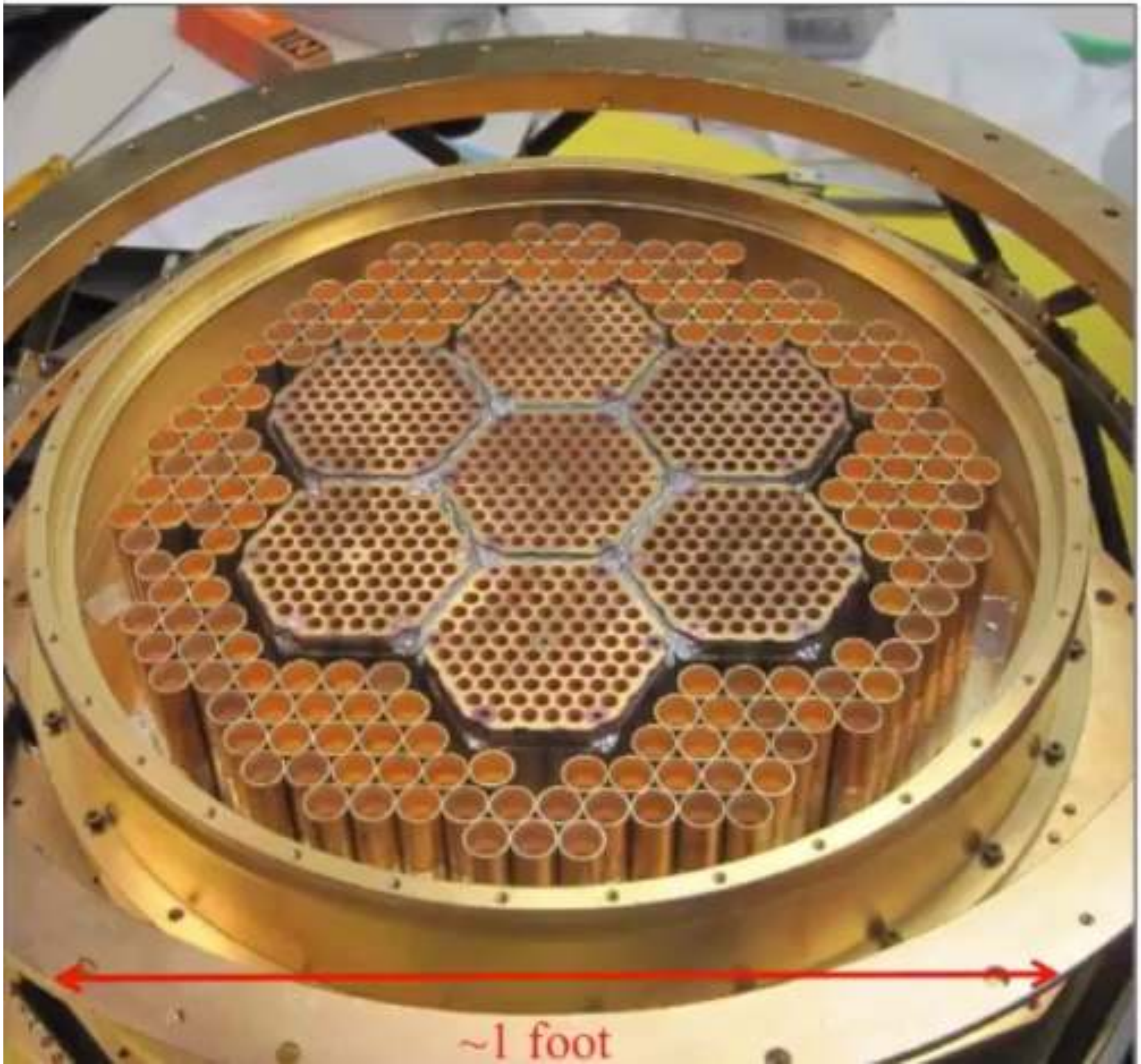


Integrate several modules



Arxiv: 1607.06861, BICEP3 focal plane design and detector performance, BICEP collaboration

SPT Polarization "Camera"



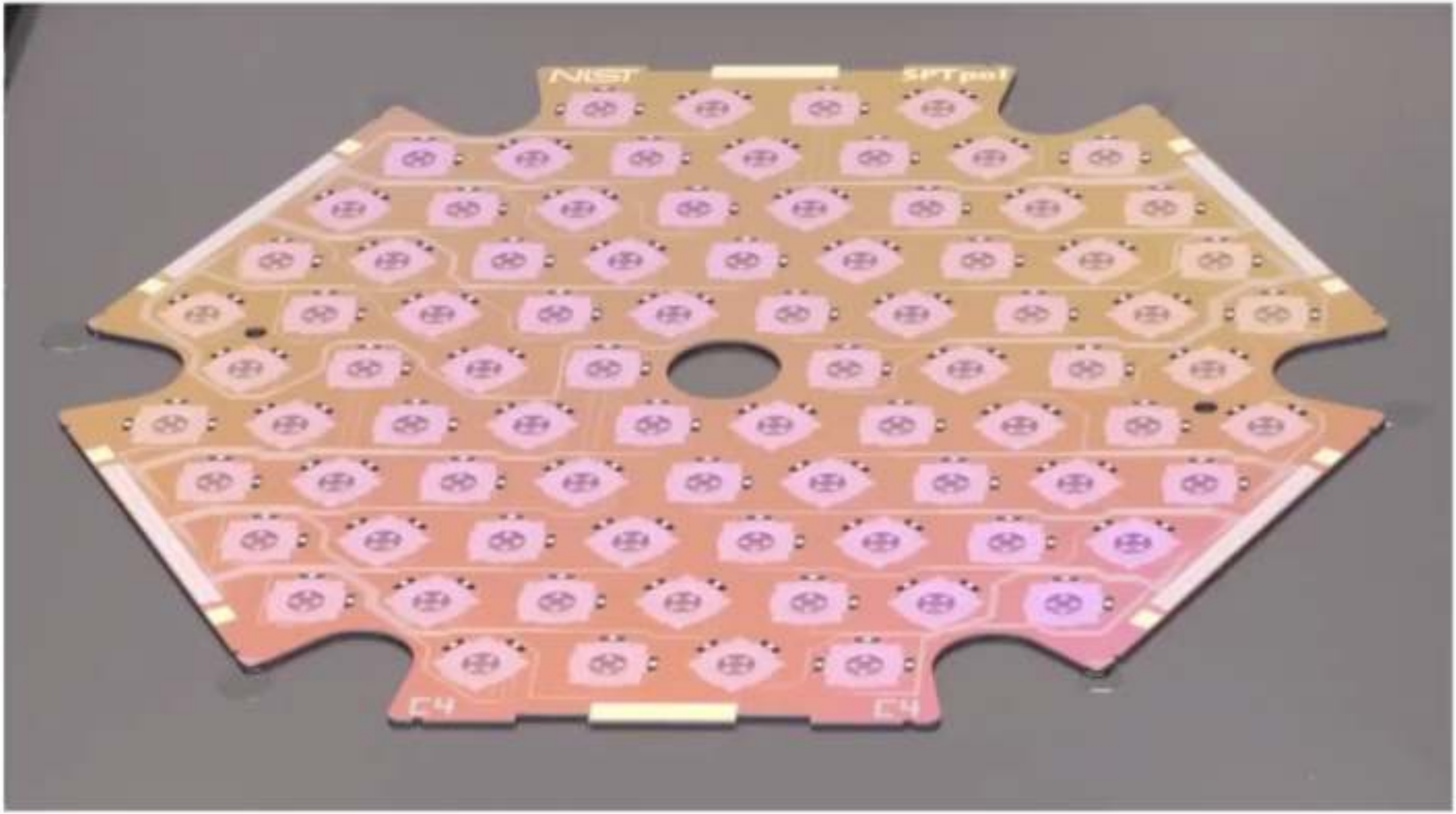
"Pixels" sensitive to 2mm light at the center, and 3mm light (outer set)

Current "state of the art" is around 1000 pixel cameras.

Here you see the "feed horns" that funnel light to the detectors…

From SPT collaboration

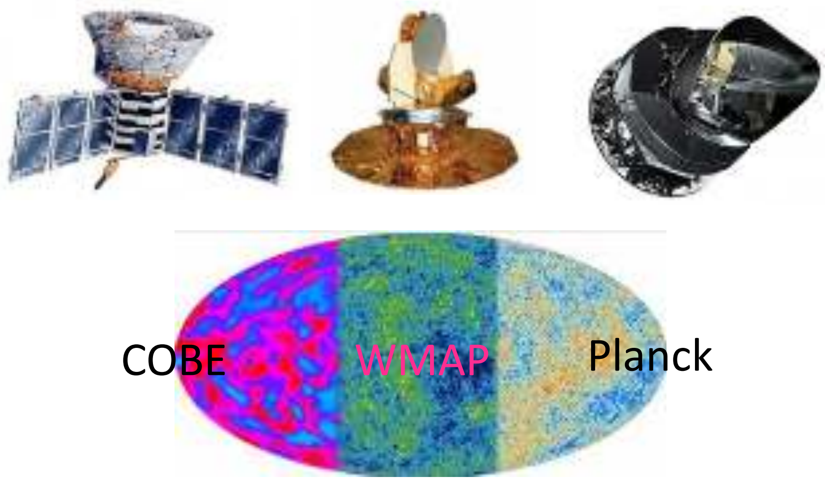
SPTpol 150GHz Detectors
(built in a cleanroom at NIST)

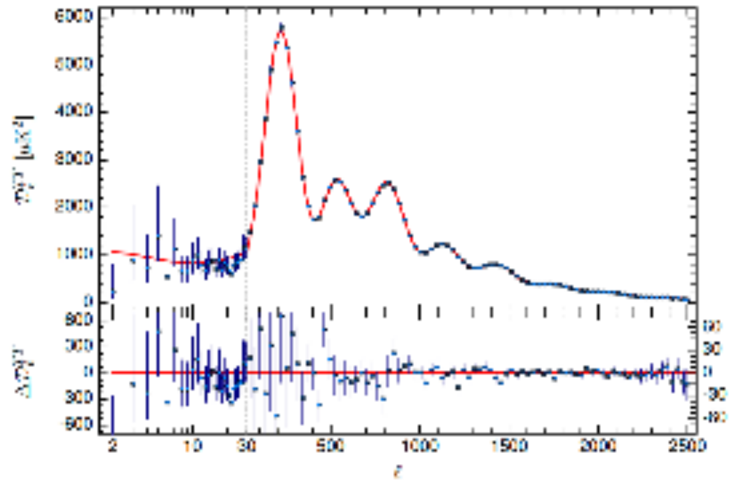


(A few years to develop the ability to make a working first copy, ~1 month for a batch of 2-3 after that. SPTpol has 7 copies.)

From SPT collaboration

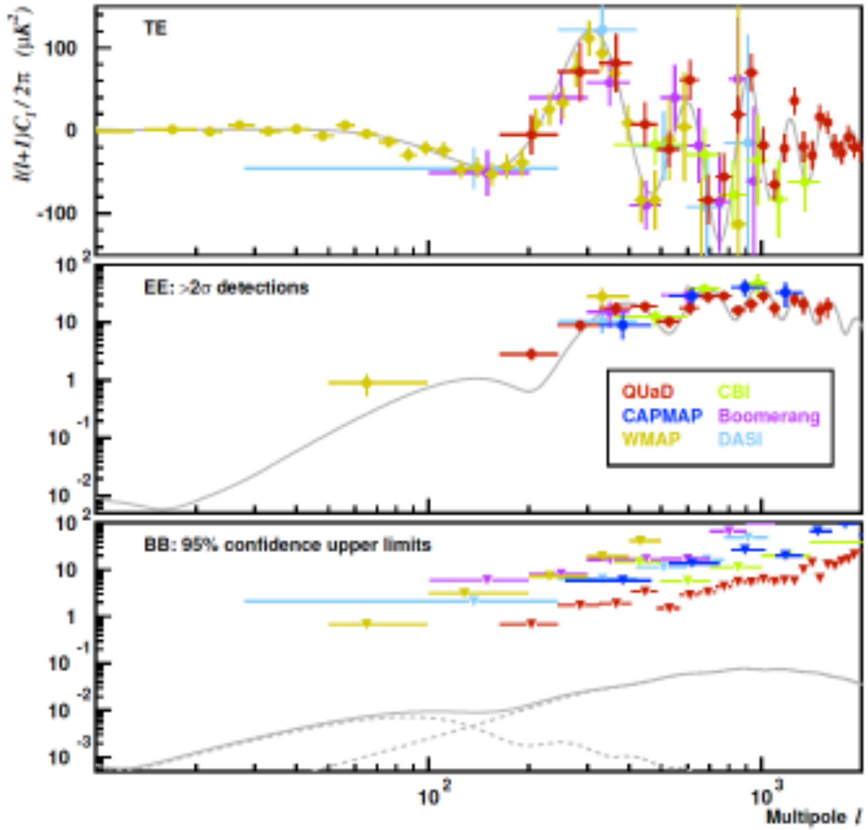
Polarization measurements: experiments

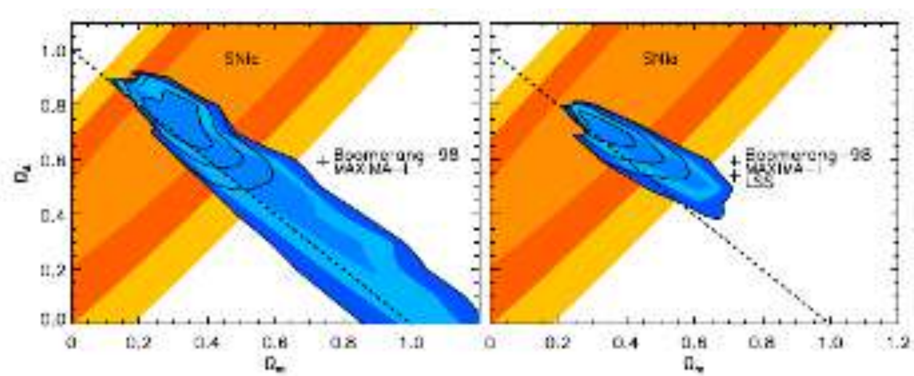




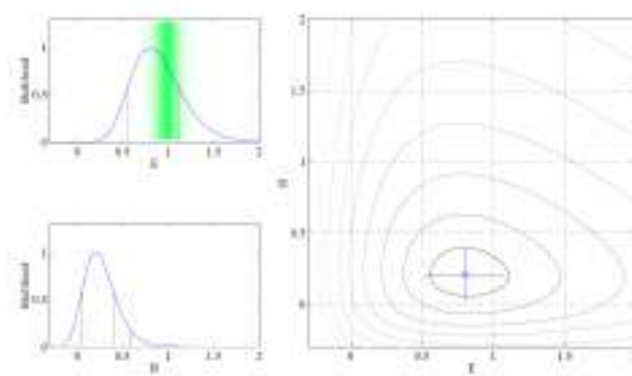
Measurements

- WMAP satellite has mapped the temperature fluctuations over the entire sky, the region around the third peak has been filled in by balloon and ground-based experiments such as BOOMERANG and CBI, and on small scales, ACBAR recently resolved the fourth and fifth acoustic peaks for the first time.
- BOOMERANG: flat universe



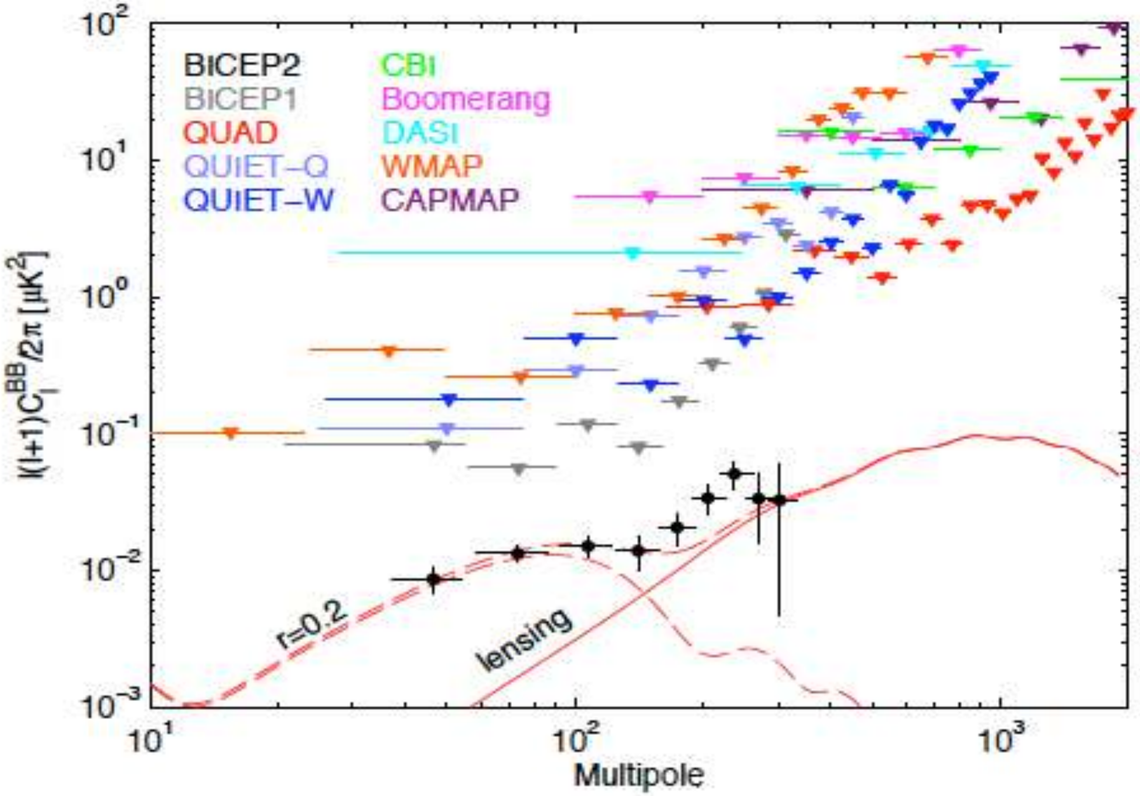


Boomerang collaboration. PRL86 (2001) 3475-3479



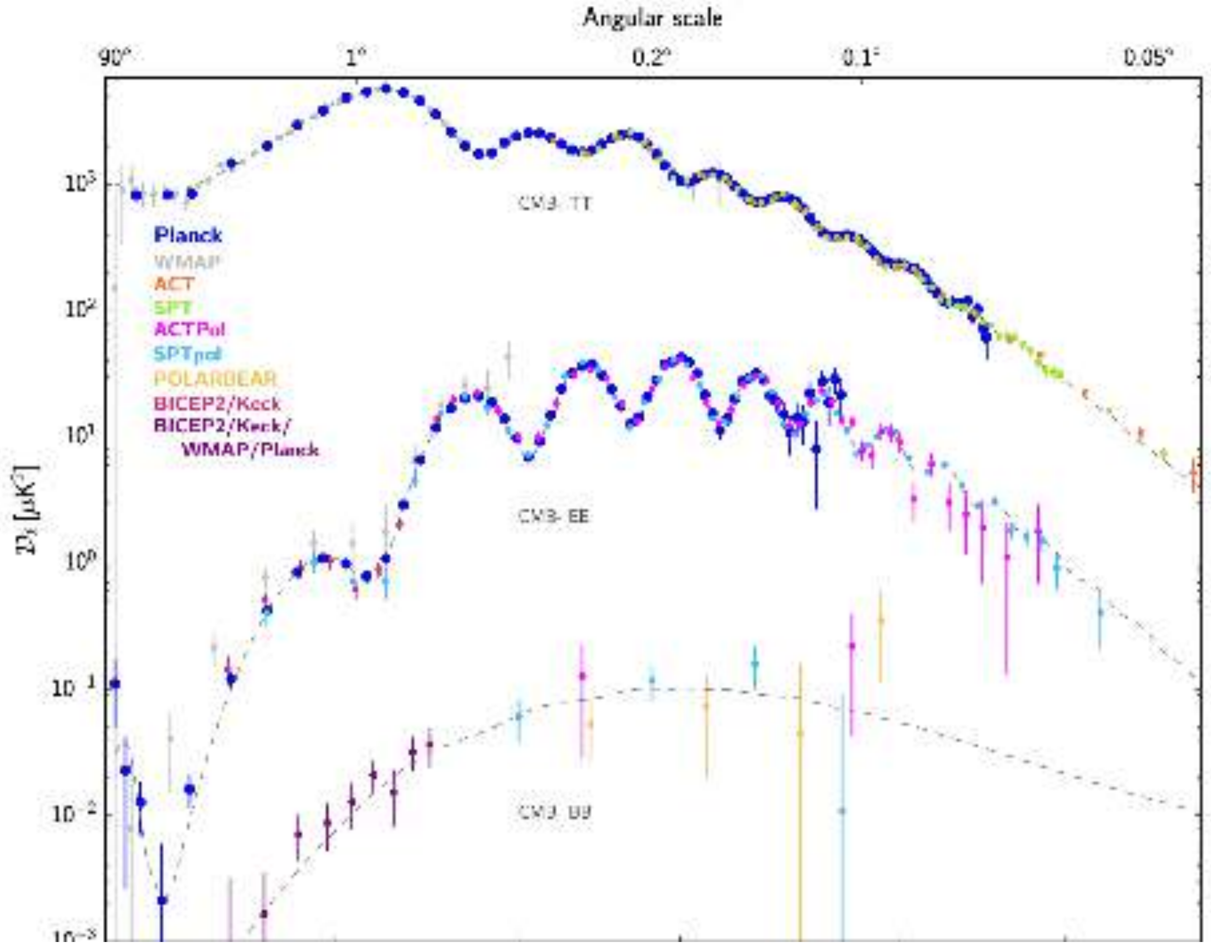
J. Kovac, et al. nature420 (2002), 772

A new stage for BB measurement after BICEP2



- The most accurate measurement of polarization with error bars on BB Spectrum
- Component separation for foreground reduction: dust & syncrotron

What does Planck tell us ?

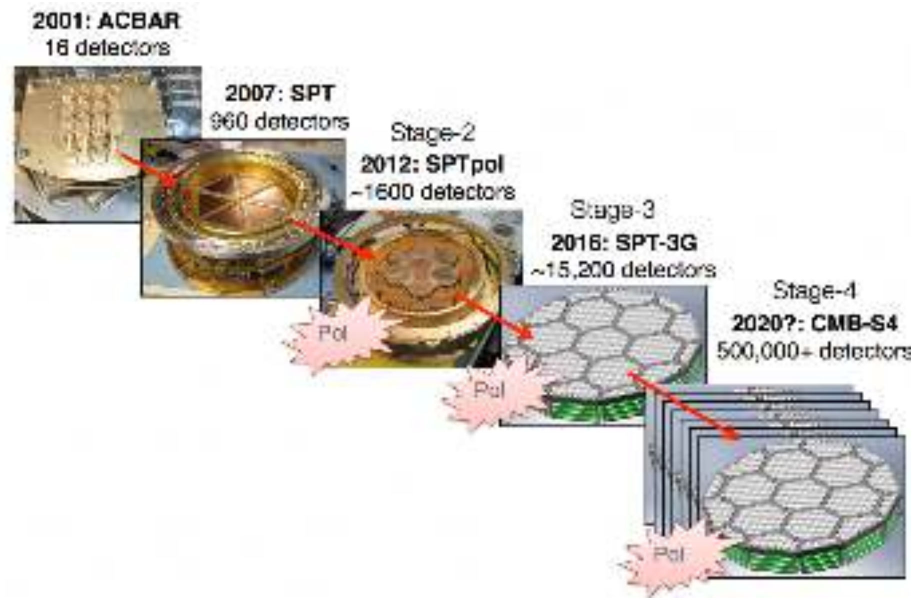


- multi-frequency measurements: 9 bands from 30 – 857 GHz
- precision measurement of T & E

➢ **Contamination from dust can not be ignored !**

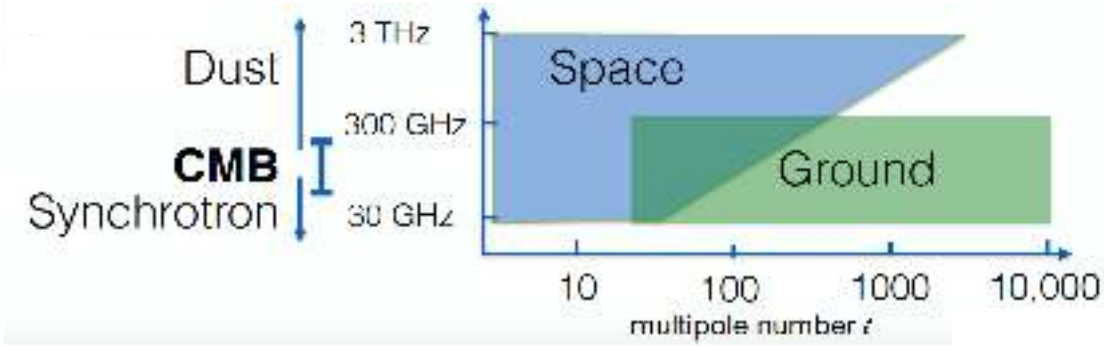
The polarization detection after Planck

- Ground observations will play important role :
  - Litebird may happen in almost 10 years.
  - Ground observation have achieved large stride !

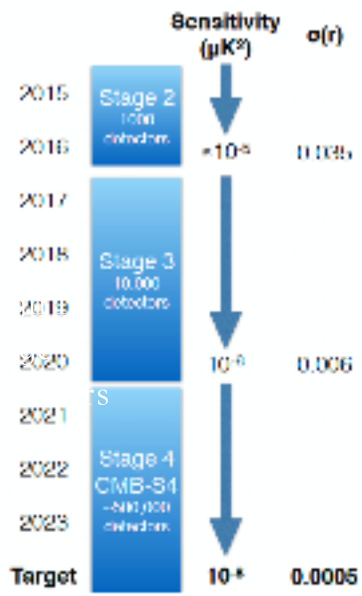


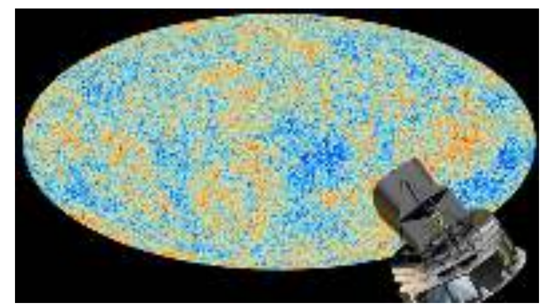
- Ground telescope have many advantages
  - a large amount of TES on the focal plane
  - Array of Telescope is easy

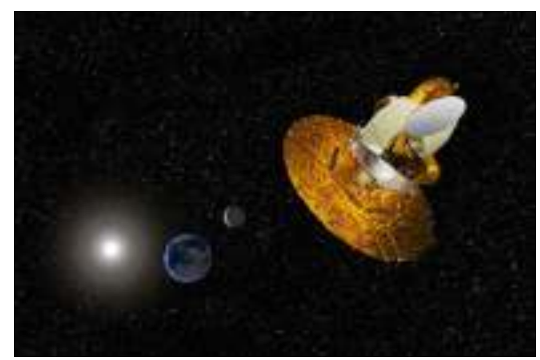
Ground and space are complementary



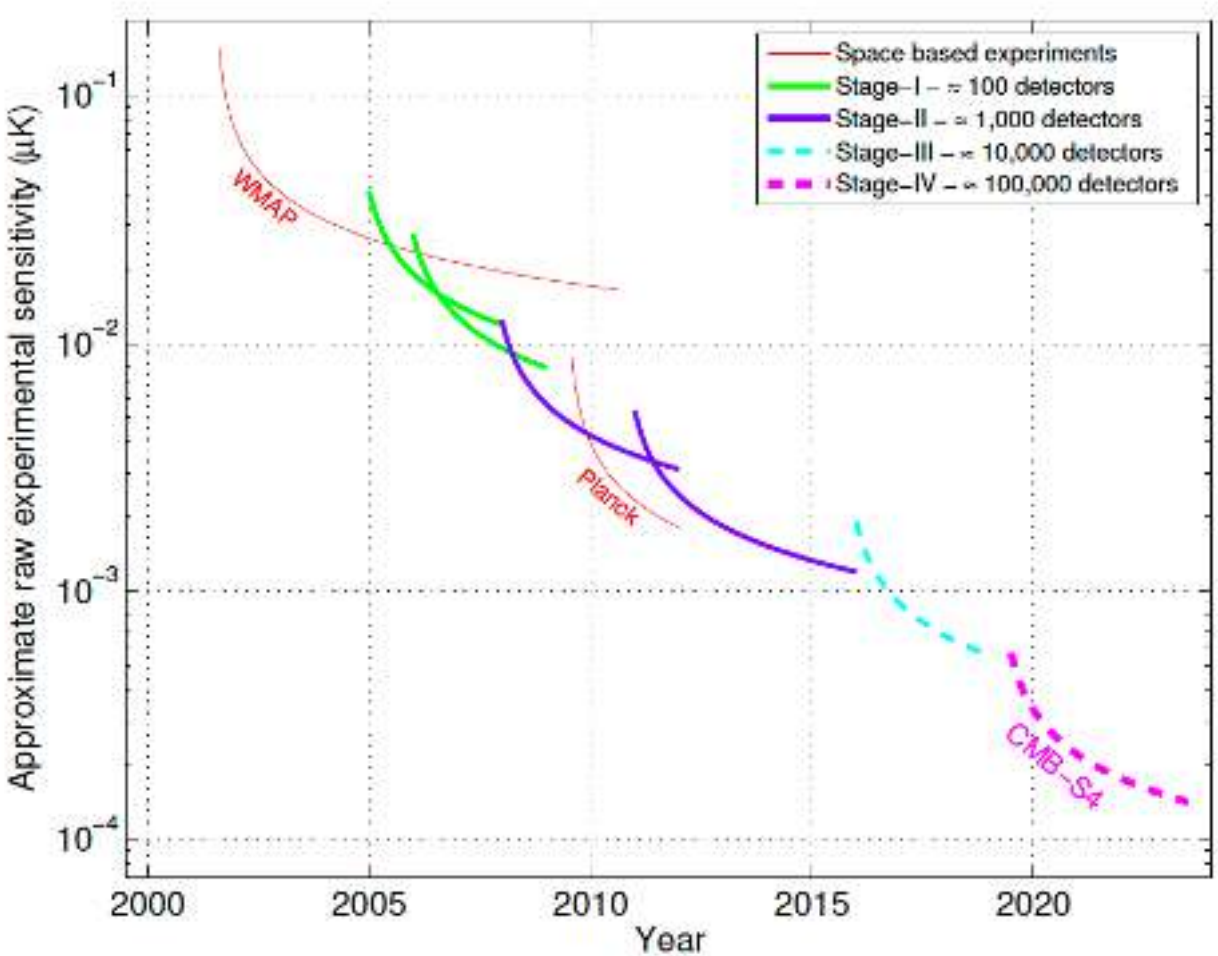
CMB S4:







CMB S4



CMB S4 white paper

CMB physics after Planck

r

- Searching for primordial gravitational waves: constrain the energy scale of inflation and to test alternative models, and to provide insights into quantum gravity;

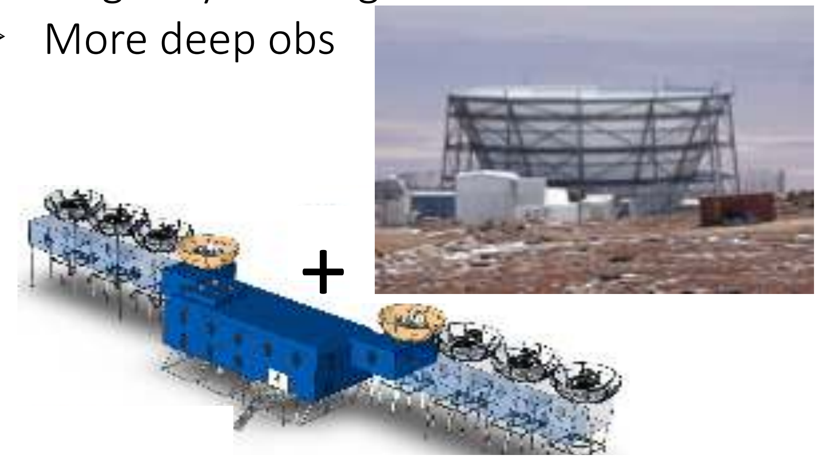
Non-r

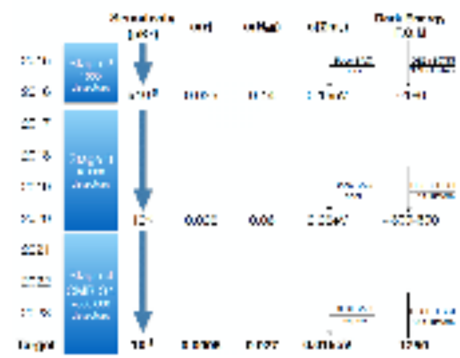
- Measuring effective number of light relativistic species (dark radiation): to search for new light relics, independent tests of BBN and understand the evolution of the Universe at t = 1 sec;
- Sum of the neutrino masses;
- Dark energy study: using secondary CMB anisotropy through its impact on the growth of structure;
- Testing general relativity and constraining alternate theories of gravity on large scales.

CMB S4 white paper

Large + small aperature telescopes:

- ➢ More detectors
- ➢ Large sky coverage
- ➢ More deep obs





Requirement:

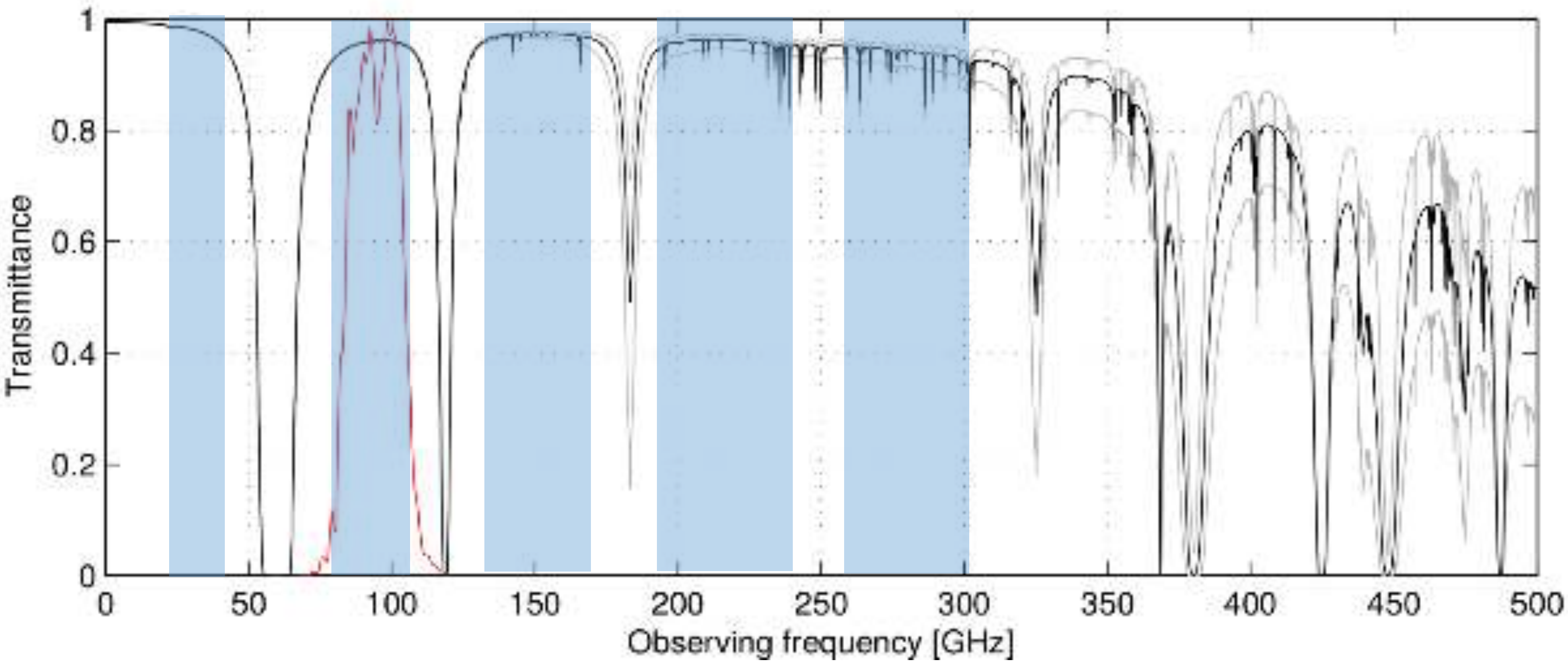
- need sensitivity : 1 uk arcmin
- over half sky,
- four years survey with 500,000 CMB-sensitive detectors;

The way:

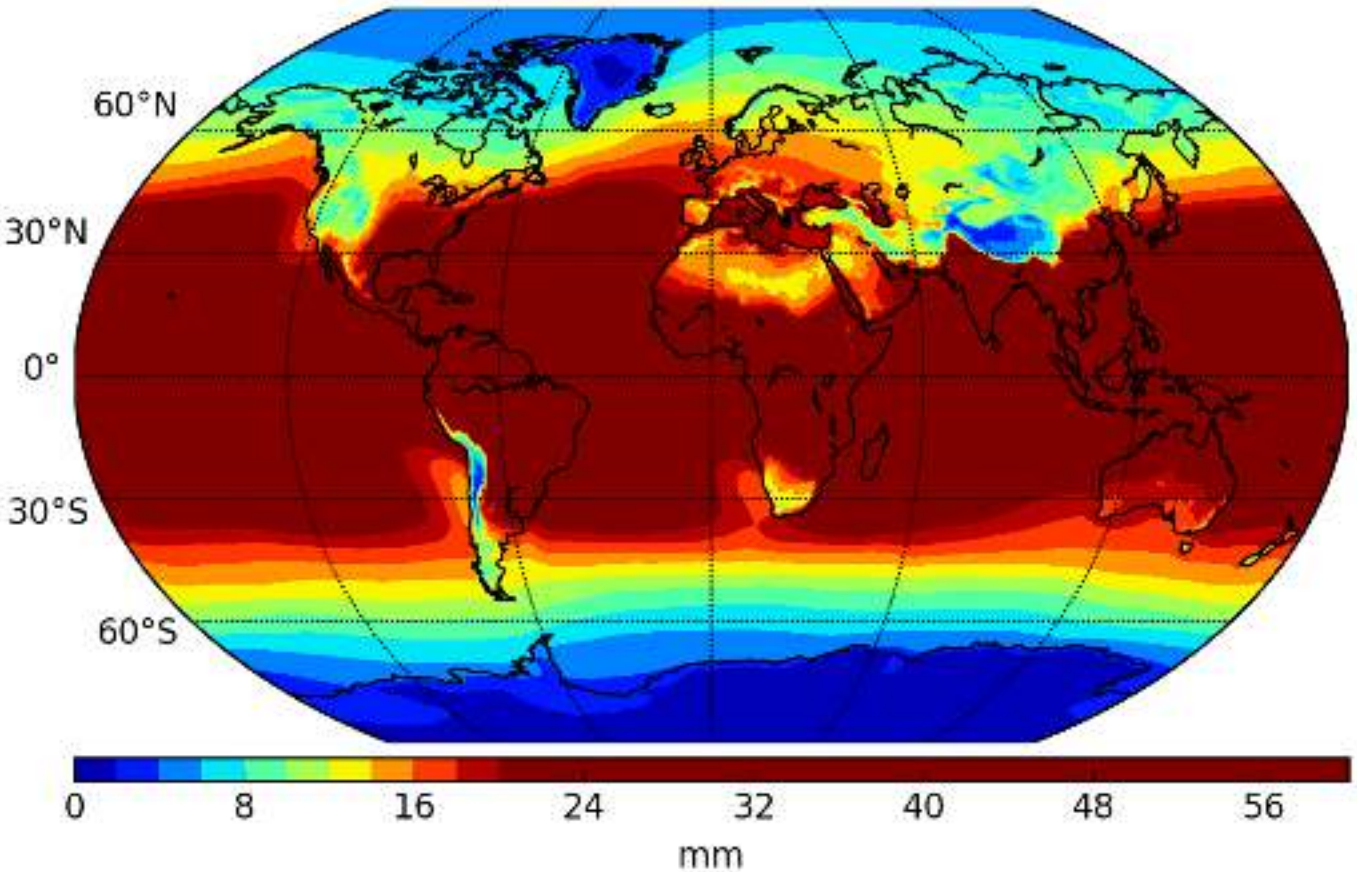
- More sensitive detectors
- Extend to northern sky,
- New telescope: Current telescopes are saturated;

地面CMB探测对台址要求苛刻

- 微波波段大气透射率



地球上有四个台址



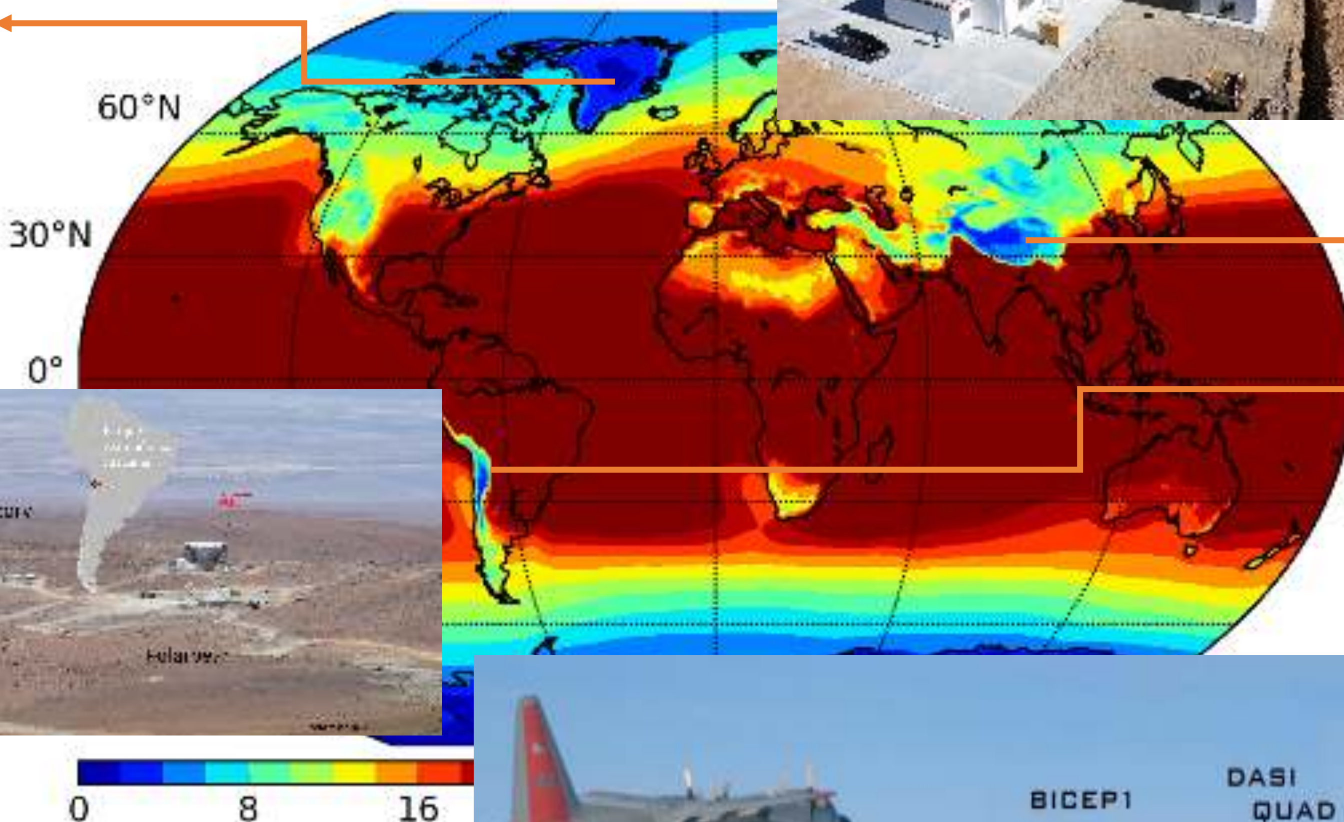
[H. Li *et al* arXiv:1710.03047]()

主要集中于南半球，阿里是北半球唯一

地球上有四个台址

西藏阿里

格陵兰岛



智利阿塔卡马

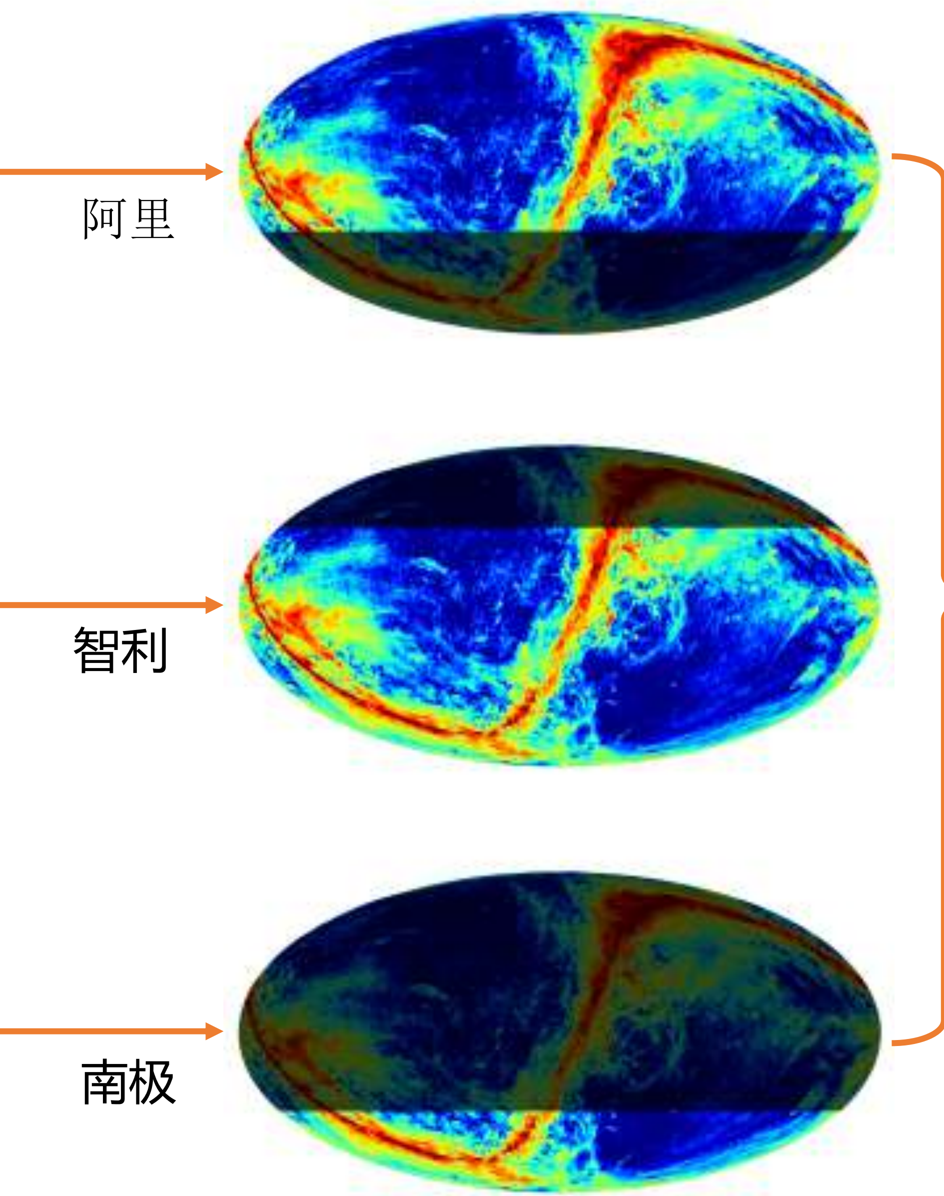
POL

A

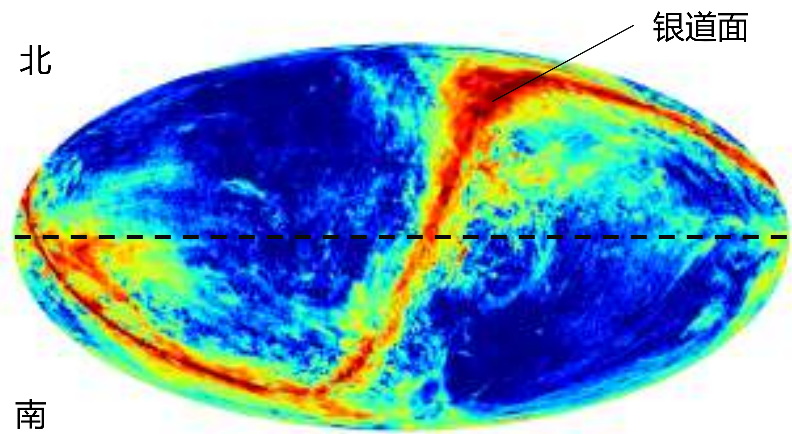
南极

H.

主要集中于南半球



- 阿里望远镜将：
  - 覆盖全部北天区与部分南天区；
  - 覆盖北天区银河系污染较低的天区。



建成后，作为北天的阿里，将与南天的智利、南极一起成为国际地面 CMB 观测、原初引力波探测的三大基地，实现地面 CMB 观测的全天覆盖。

PWV: Datasets

Y.Li, Y.Liu, S.Li, H.Li and X.Zhang,   ArXiv:1709.09053

- Datasets：

Q.Ye,M.Su,H.Li,X.Zhang,   ArXiv:1512.01099
Chao-lin Kuo,   ArXiv:1707.08400

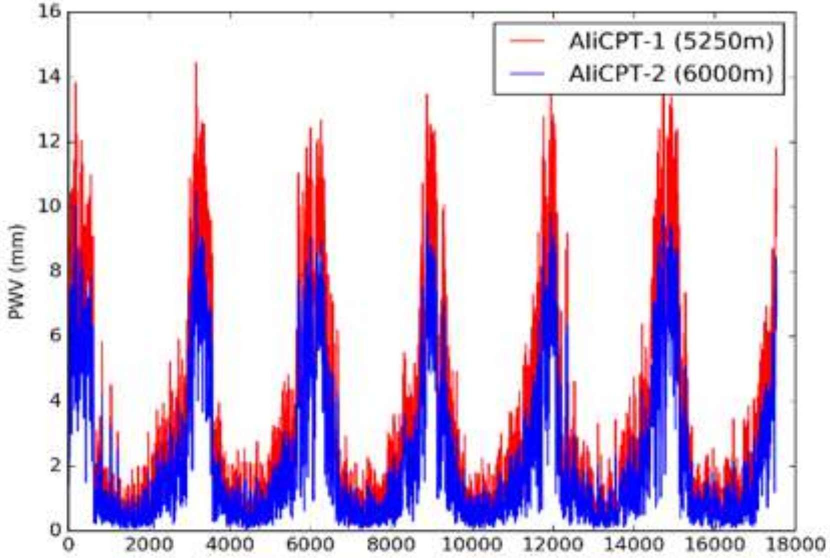
  - MERRA-2 Reanalysis data (NASA)：
    - Spatial Resolution: 0.625lon*0.5lat*72layers
    - Time Resolution: 3hours
    - Data：Relative humidity, Temperature, Pressure, Altitude….
  - Radiosonde data from Ali local weather station：
    - Send the balloon twice a day：07:00 & 19:00
    - Data ：Dew-point temperature, Temperature, Pressure….

Radiosonde

Formula:

$$PWV = \int \rho_\nu dh = \int q_\nu \rho dh = -1/g \int q_\nu dp \approx -1/g \sum_i q_\nu^i \triangle p_i$$

Results:
(1mm/5250m, 0.6mm/6000m)

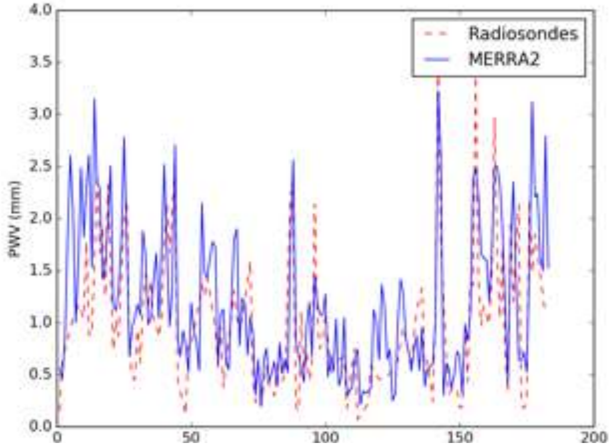


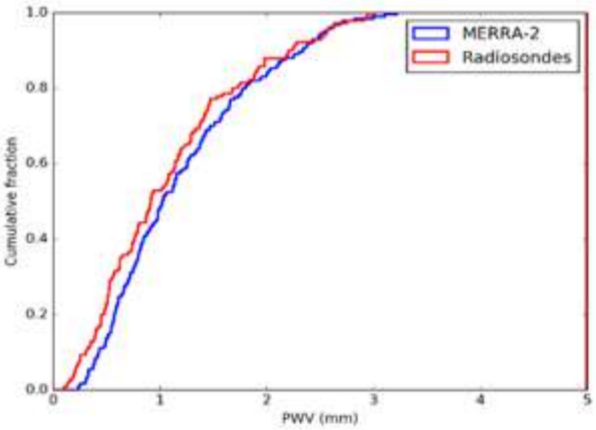
PWV distribution （**MERRA-2**）

- Strong seasonal variation.
- Oct. to Mar: The median value of PWV is

  Radiosonde: 0.92mm/0.56mm

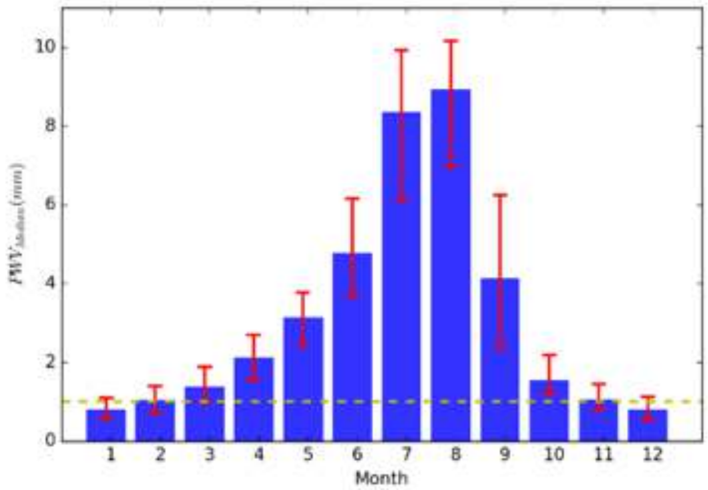
  MERRA-2:   1.07mm/0.62mm
- Results derived from satellite and radiosonde are consistent.



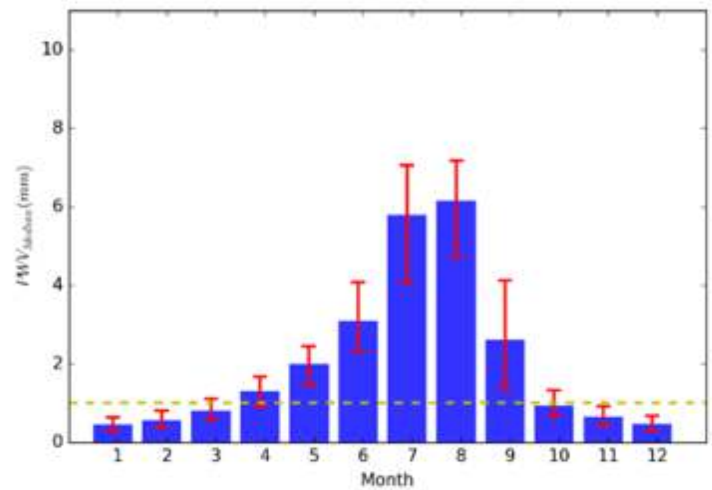


Comparison between MERRA-2 & radiosonde (Oct.-Mar)

- **Observing season:** **Oct. to Mar.**



Monthly distribution **(5250m)**

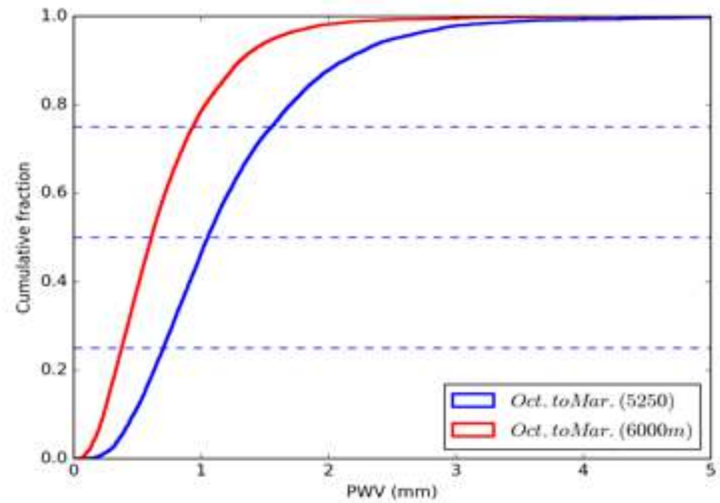


Monthly distribution **(6000m)**

Oct. to Mar: The median value of PWV is

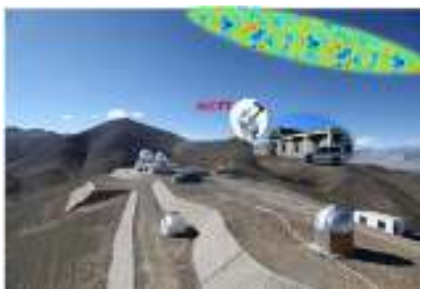
Radiosonde: 0.92mm/0.56mm

MERRA-2: 1.07mm/0.62mm



CMB observation in Tibet

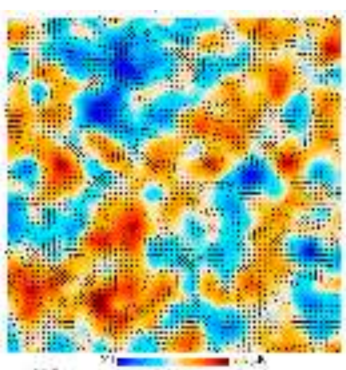
1. **项目概况：**由中科院高能所牵头的国际合作项目。在西藏阿里地区海拔5250米的B1点建设高灵敏的原初引力波探测望远镜（阿里一号，AliCPT-1）。



2. **时间表：**
2014年5月提出；　2016年12月正式启动；
2017年3月奠基；　2018年11月观测仓验收；
预期2020-2021观测季开始观测

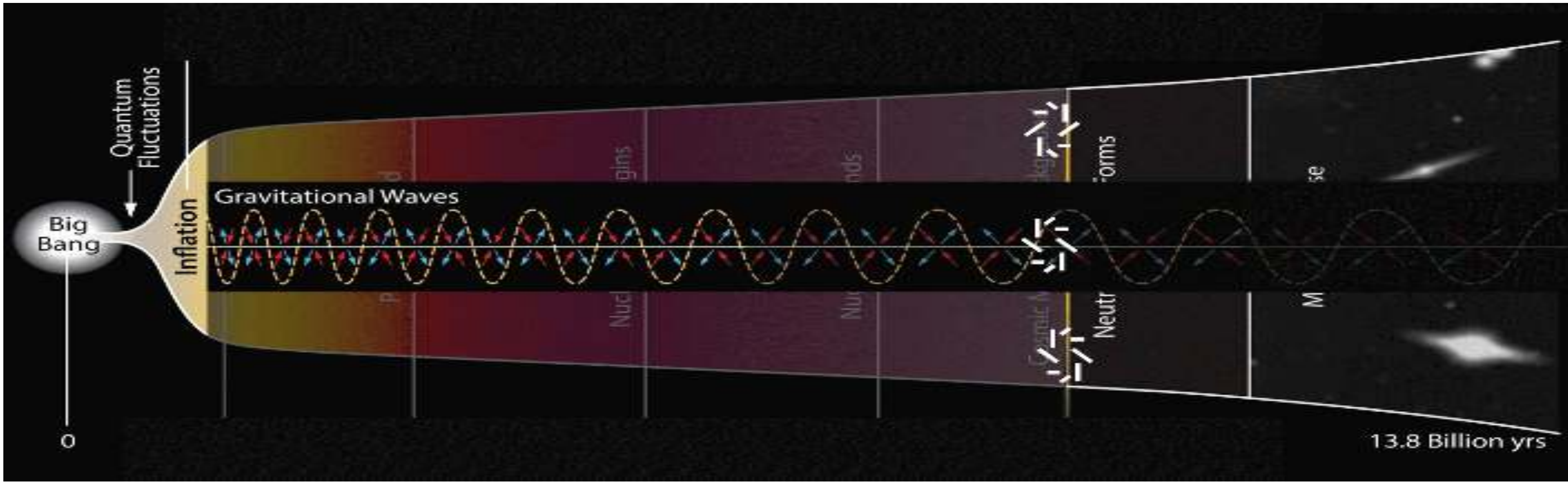
Figure Credit: AliCPT-1 team

3. **科学目标：**
瞄准原初引力波，首次给出对北半球CMB极化的最精确测量，探寻宇宙起源。



建成后，我国的原初引力波研究进入国际前沿
参与国际合作南北协调观测，实现国际上最灵敏的探测
阿里与南极、智利一起成为国际上CMB探测的三大基地

Scientific goal

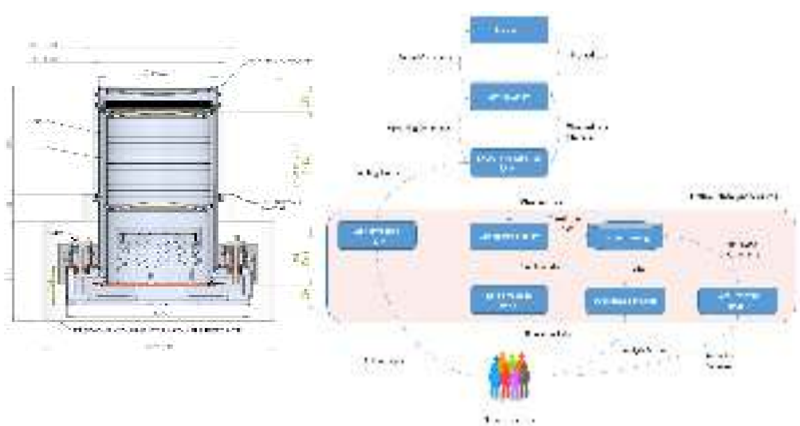


- Probing the primordial gravitational waves (PGWs) with BB spectra.
- Measuring the rotation angle, testing CPT symmetry with TB and EB spectra.
- Investigating the CMB polarization hemispherical asymmetry.
- Studying the cross-correlation between AliCPT and DESI.
- Studying the galactic foreground.

…

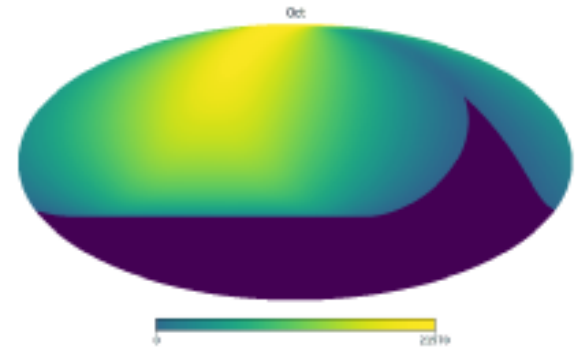
Current status

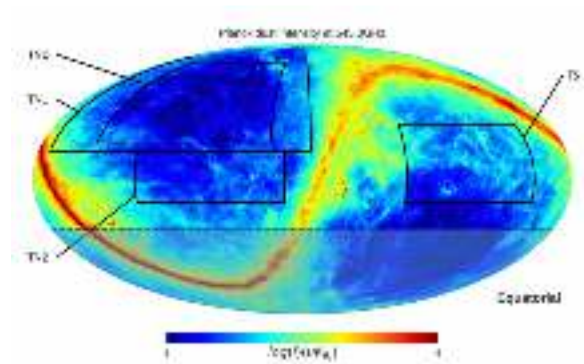
- Finish site construction
- Test mount in factory
- Develop telescope
- Construction for control system, operation system and science analysis platform

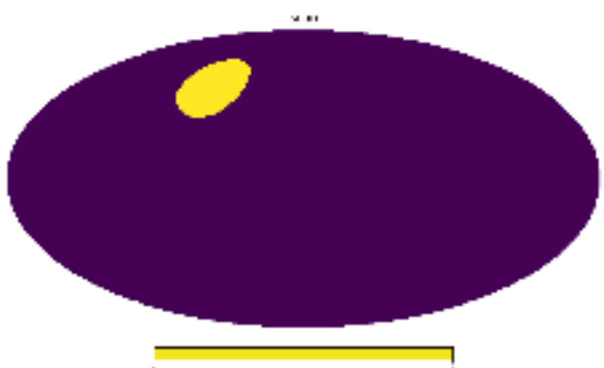


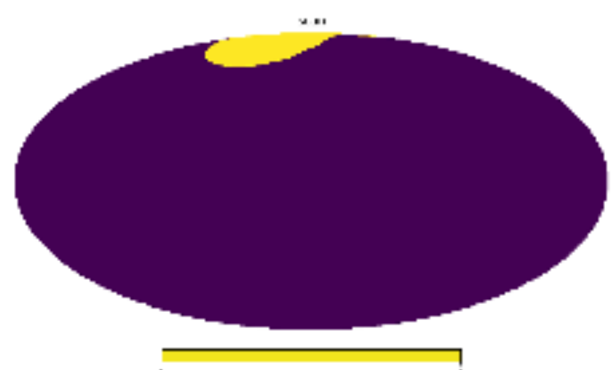
Preliminary concern on Scan strategy

- Observation in Ali
  - Sky move fast: helpful for large sky coverage, but not easy to focus within one small patch.
  - “clean” area in north, also in south: helpful for going deep in north, and cross check in Sourth.





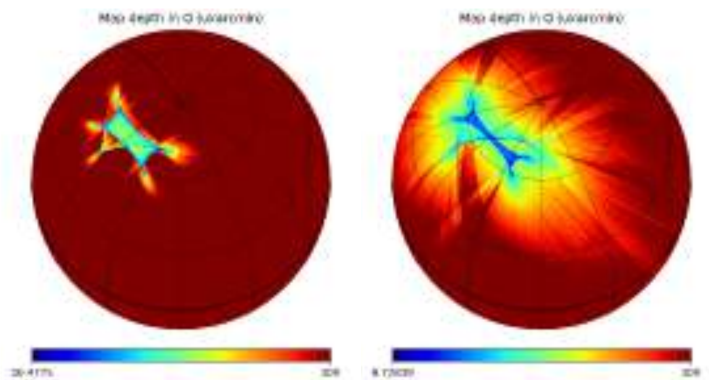




simulation results, Preliminary

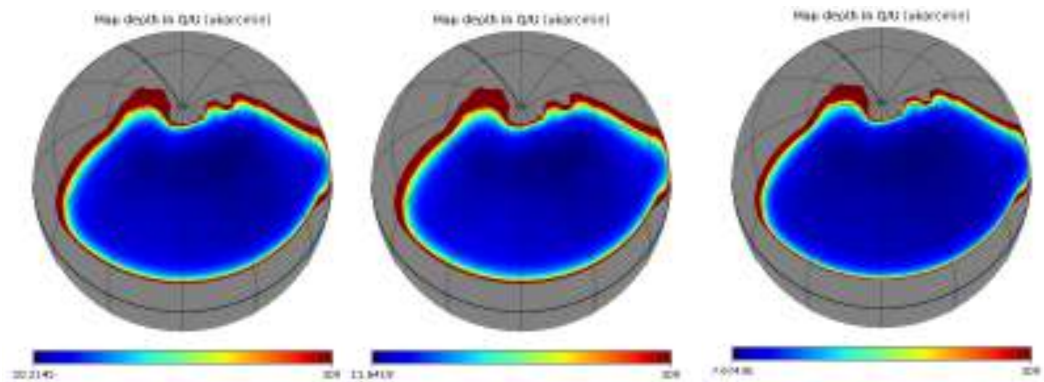
Simulation: sensitivity

AliCPT-1 is designed to have its first light in the winter of 2020



PLANCK 100 GHz & 143 GHz

Pol ~50 uK arcmin in total



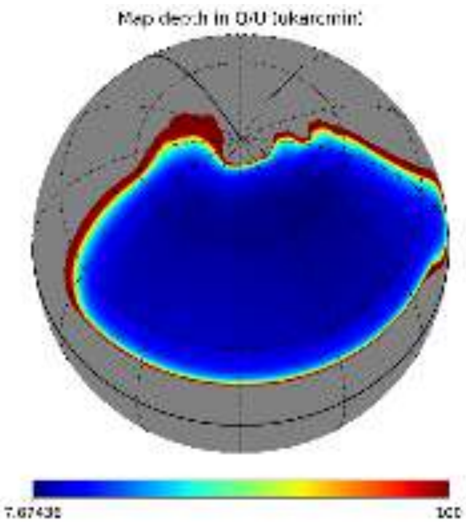
AliCPT 95 GHz & 150 GHz & Total

4 modules 1 season, median map-depth 14 uK arcmin

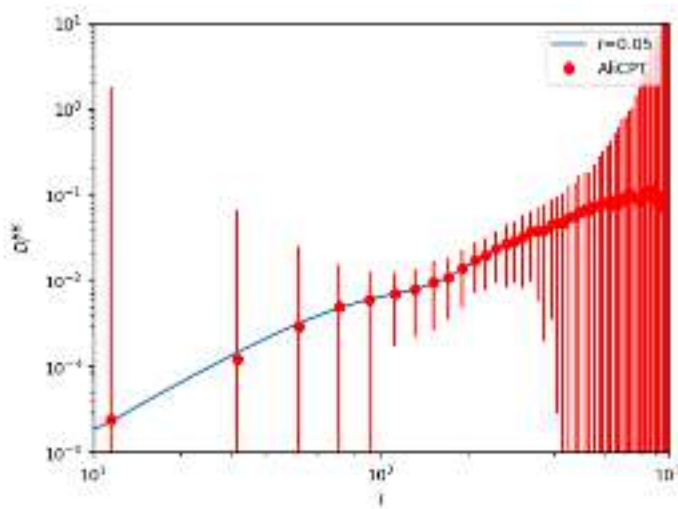
- Probing the primordial gravitational waves (PGWs) with BB spectra.
- Measuring the rotation angle, testing CPT symmetry with TB and EB spectra.
- Studying the cross-correlation between AliCPT and DESI.
- Studying the galactic foreground.
- Investigating the CMB polarization hemispherical asymmetry.
- …

Scientific goal from Xinmin Zhang

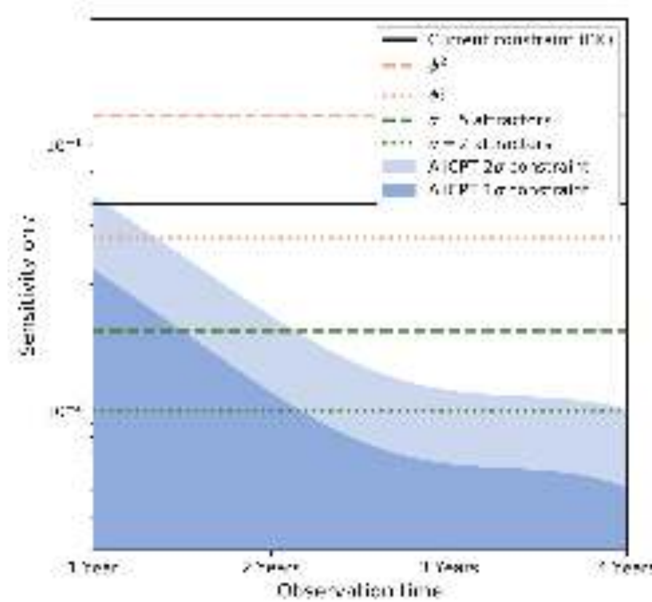
Preliminary results from simulation



Simulation: noise map



Simulation: BB power spectrum

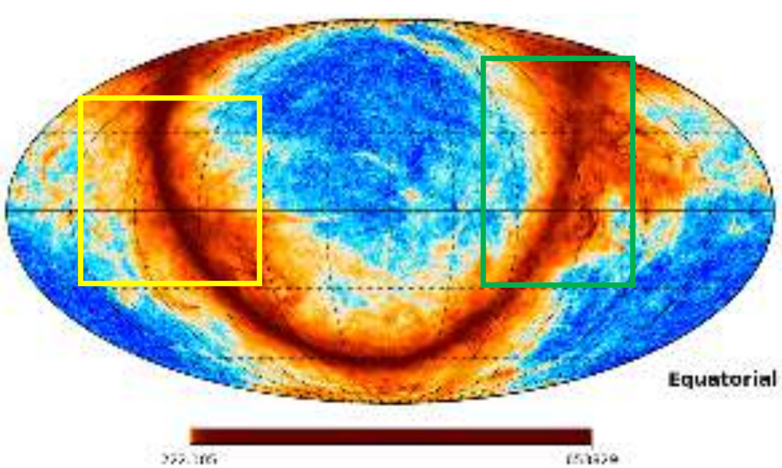


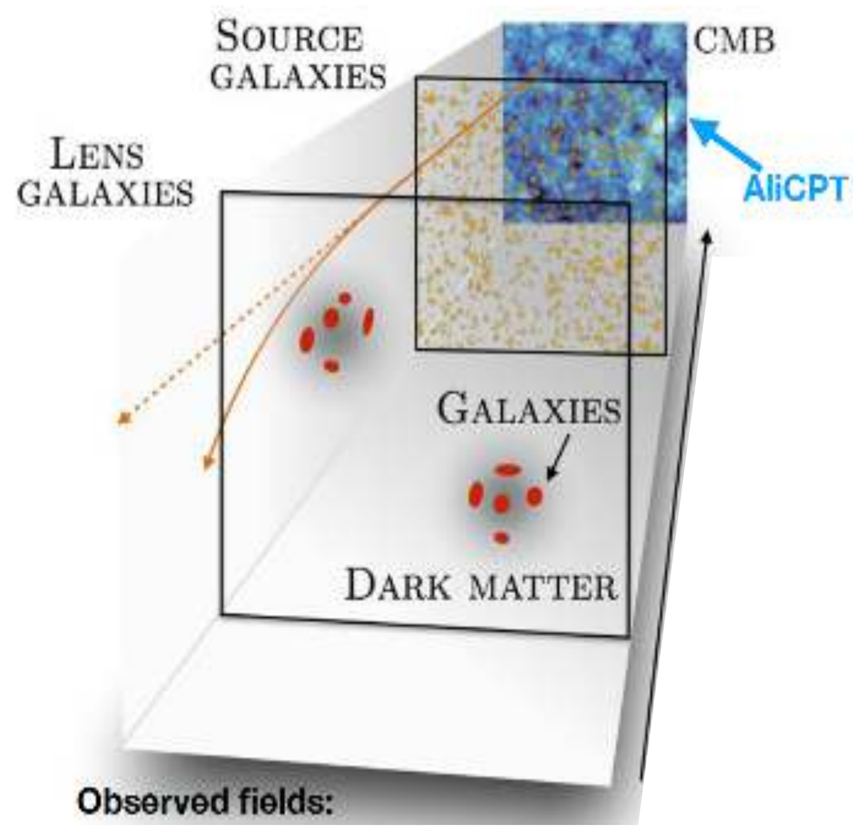
Simulation: r sensitivity

Cosmological study with AliCPT-1

- Cross correlate with DESI

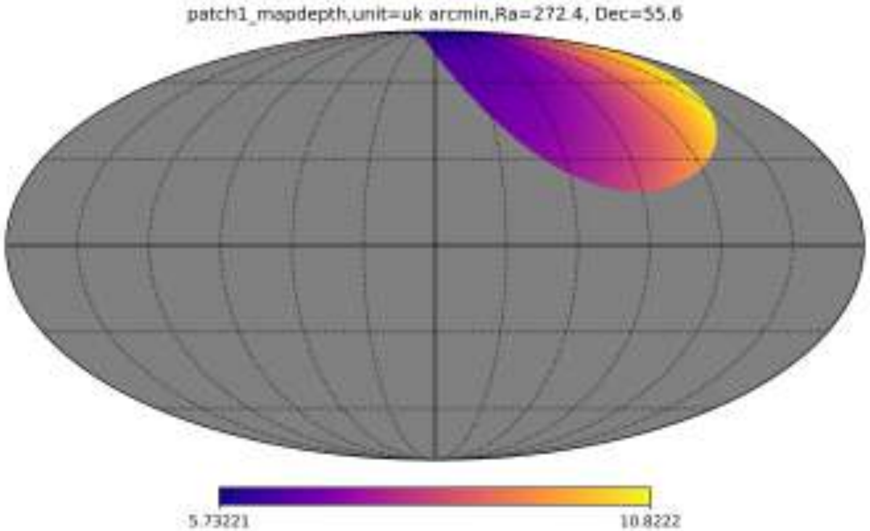
- Scan galaxy: signals for foreground

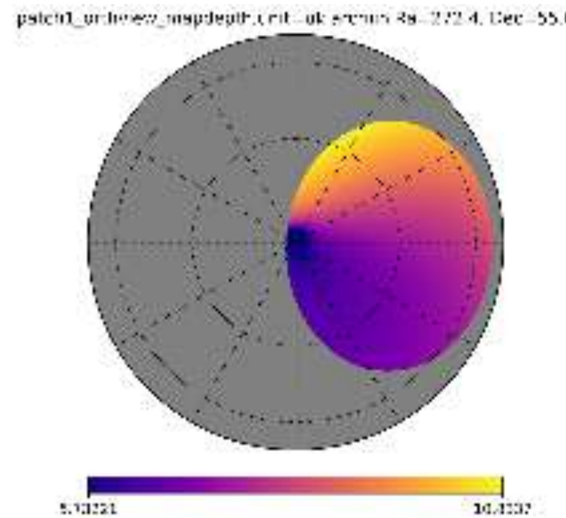


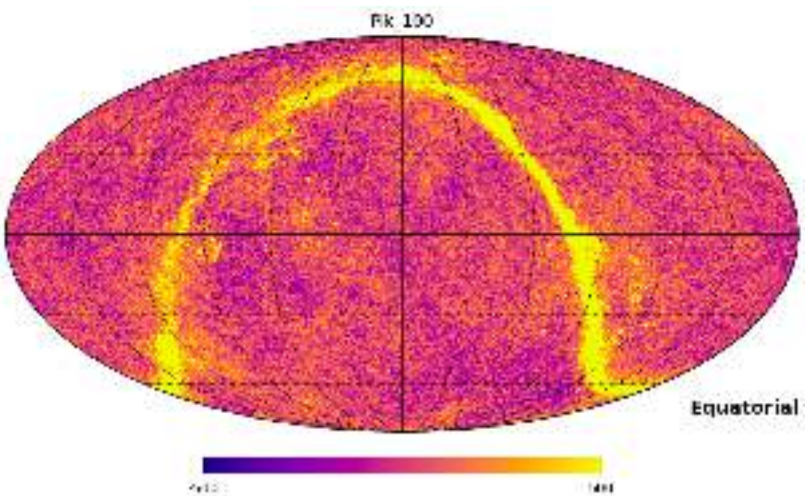


J. Yao

AliCPT-1 map depth







Observational time: 795 h
Minimum map depth: 6.9 $\mu k\ arcmin$
Maximum map depth: 13.8 $\mu k\ arcmin$

Planck map depth: 48 $\mu k\ arcmin$ (all channels)

Thank you