Cosmology for Particle Physicists

Axions - inflation, primordial black holes, chiral gravitational waves, and cosmic birefringence

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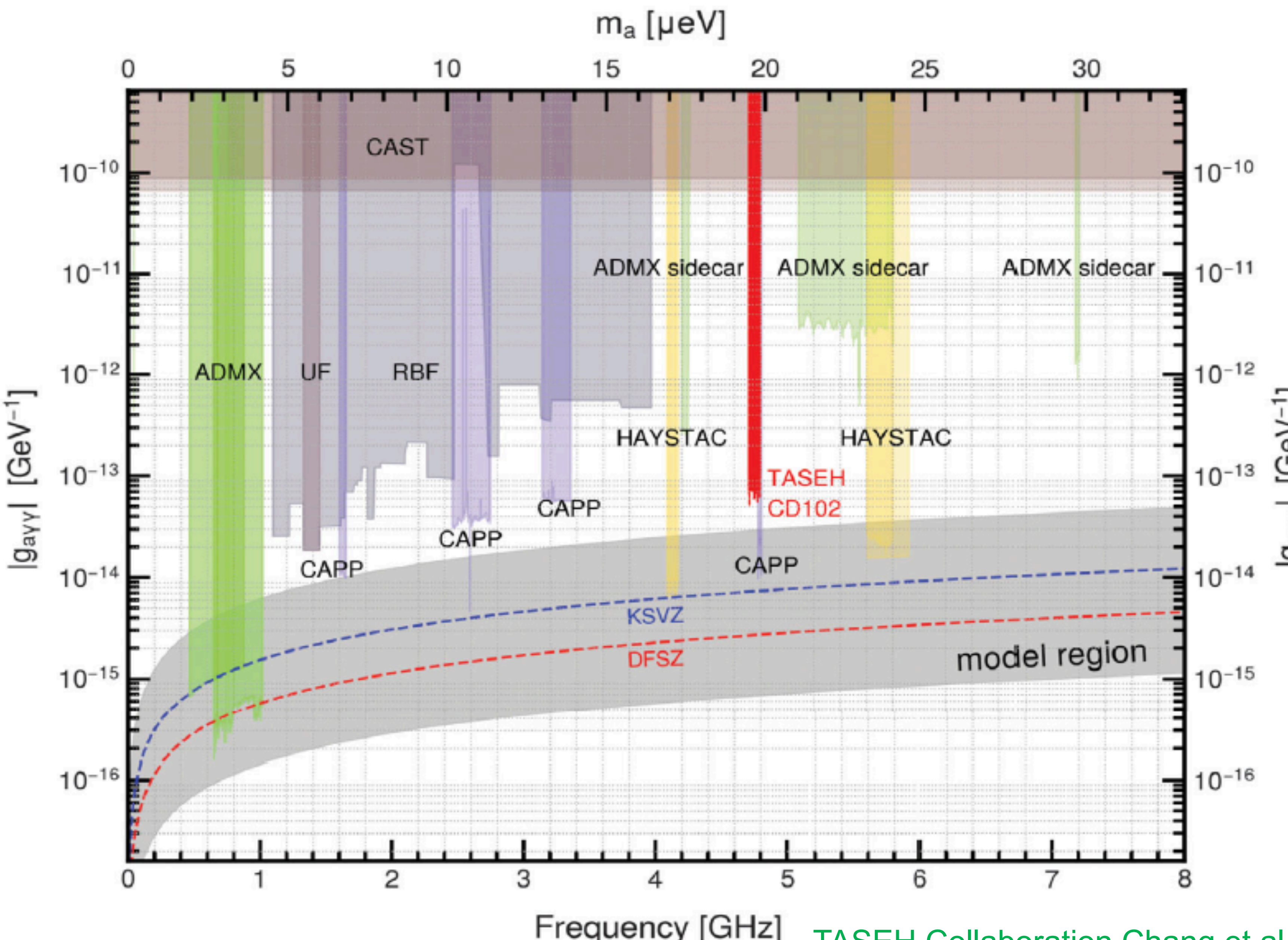
Outline

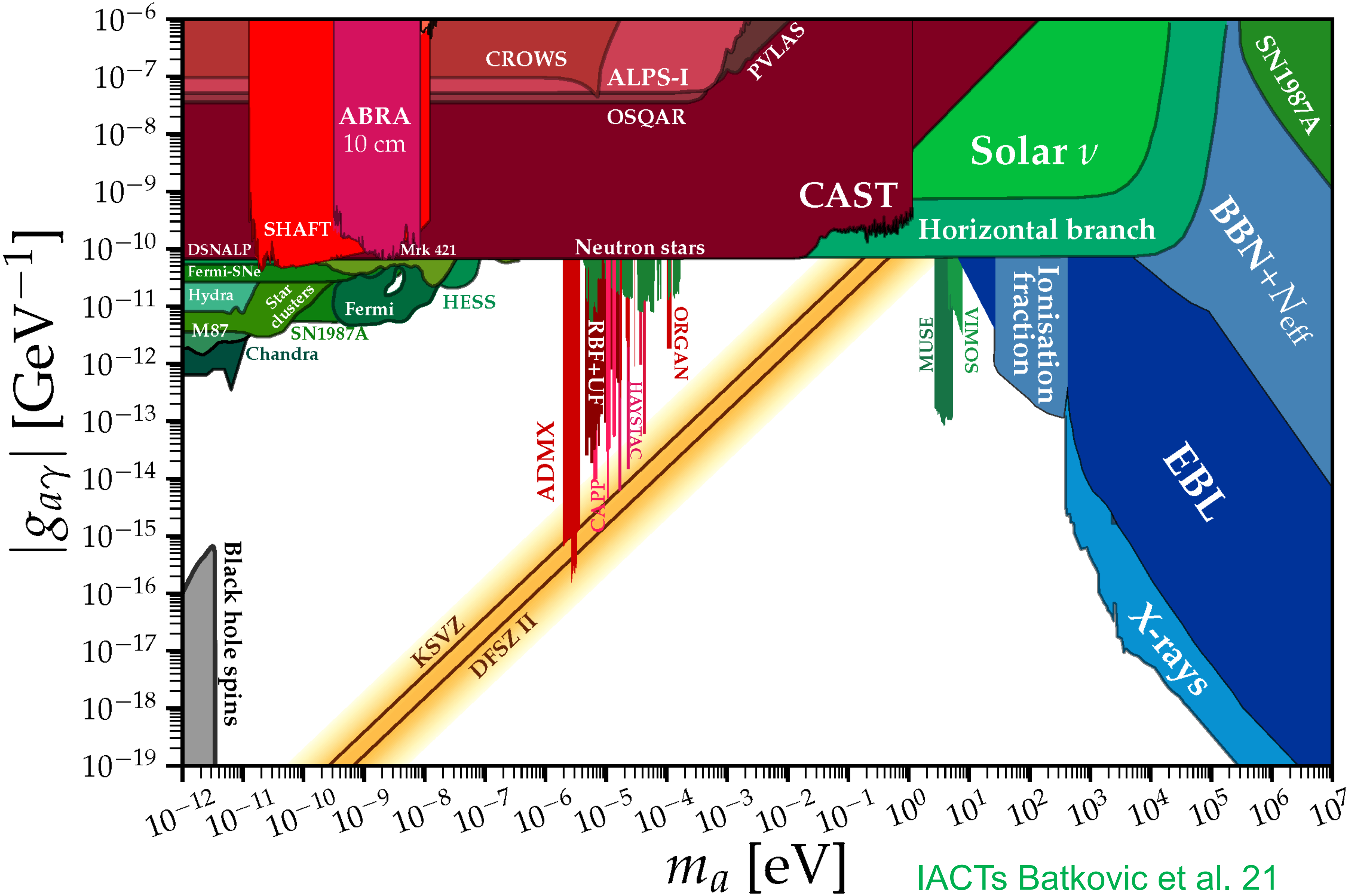
- Axions with mass and breaking scale (m_a, f_a)
- Assume an axion-photon coupling $aF\tilde{F}$
- Cosmic birefringence due to axionic dark matter / dark energy / string-wall networks and CMB B-mode polarization
- Axion inflation – PBH seeds and chiral gravitational waves
- Conclusion

Axion experimental search



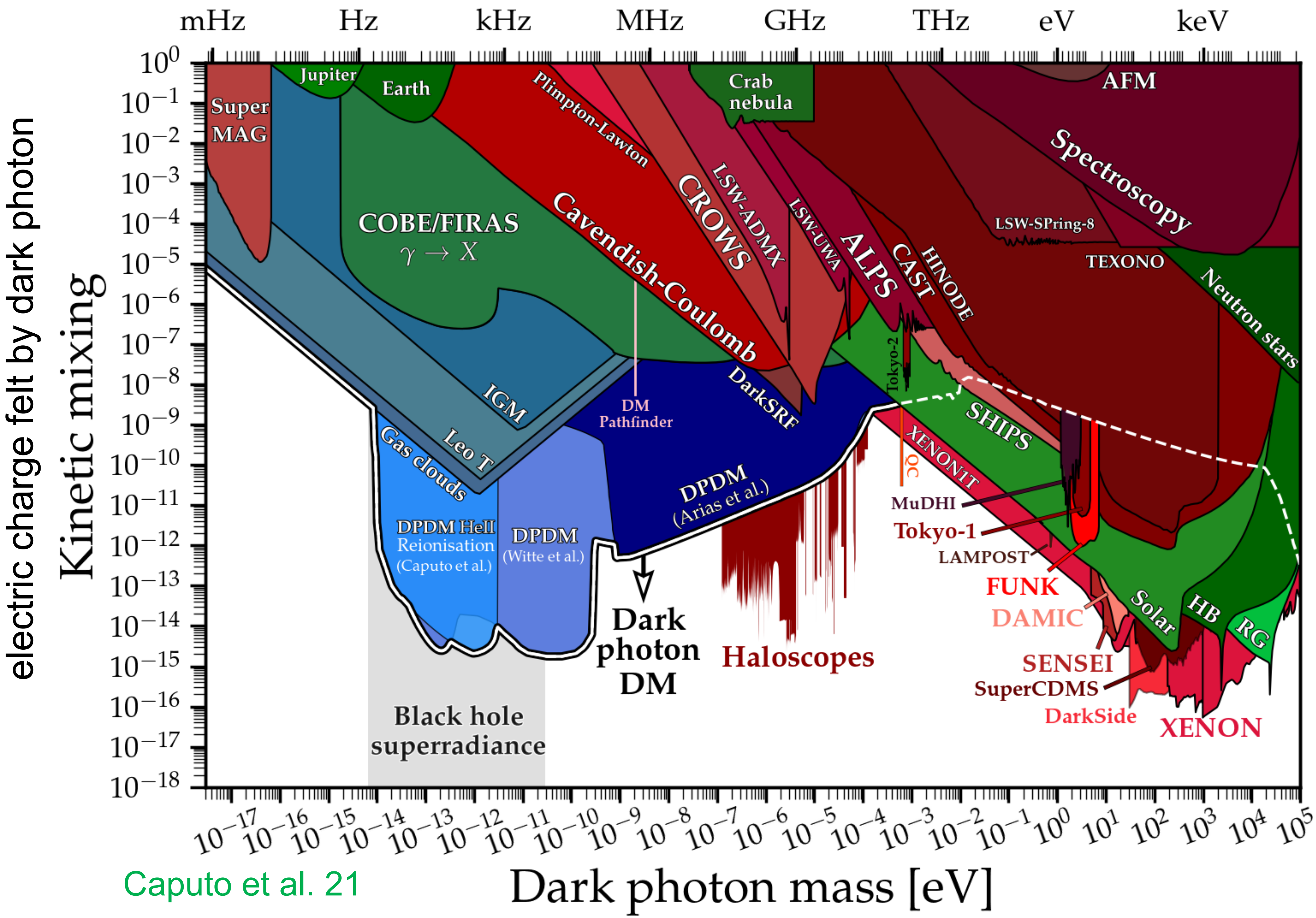
TASEH Collaboration Chang et al. 22

Ultralight axion constraints from experiments, astrophysics, and cosmology



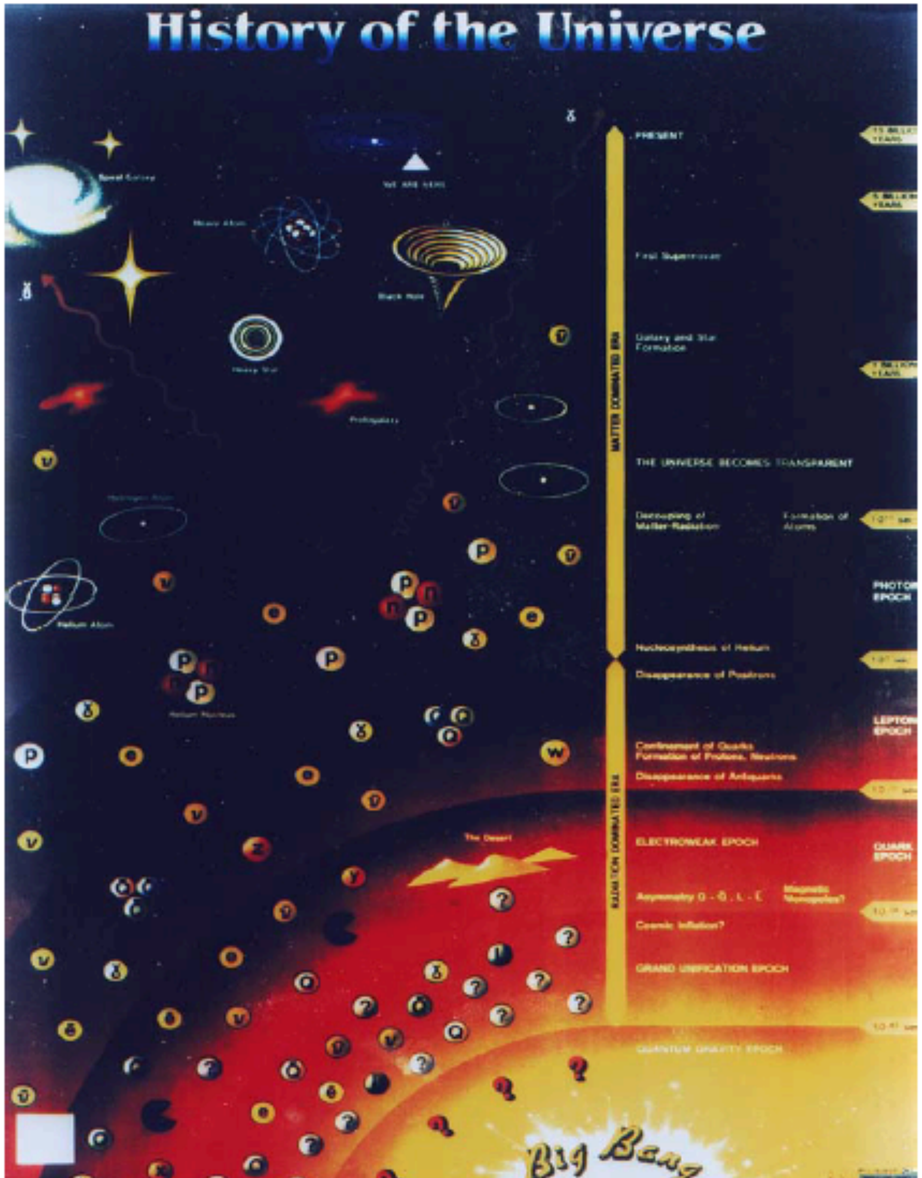
IACTs Batkovic et al. 21

Search for Dark Photon (massive almost-charge-blind photon-like particles)



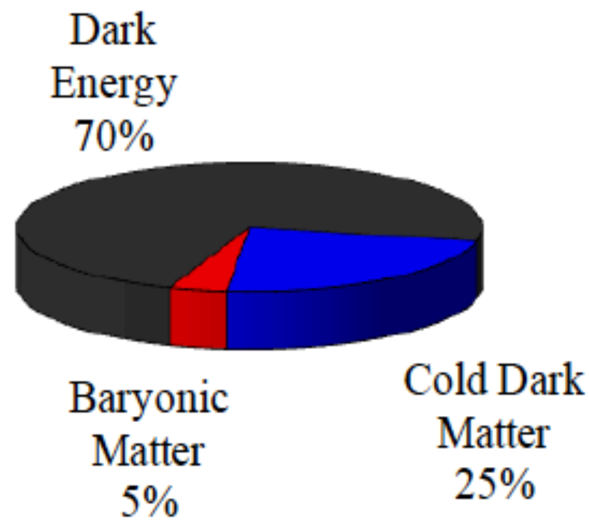
Caputo et al. 21

The Hot Big Bang Model



Fermilab Image 01-582D

Cosmic Budget



What is CDM?
Weakly interacting but can gravitationally clump into halos

What is DE??
Inert, smooth, anti-gravity!!

Axion-like DE and CDM

(too many references to list)

- Weak equivalence principle plus spin dictates a universal pseudoscalar (Ni 77)
- There exists at least one fundamental scalar – the Higgs boson !
- Axion monodromy – large-field inflation
- Peccei-Quinn symmetry breaking – QCD axion CDM
- Problems in small-scale structures – 10^{-22} eV scalar (maybe pseudoscalar) fuzzy CDM
- String axiverse – a plentitude of axions with a vast mass range 10^{-33} eV - 10^{-10} eV
- Extended string axiverse – axions as DE

Cosmic Expansion Equations and Cosmological Parameters

expansion rate | total energy | curvature

$$H^2 = 8\pi G\,(\rho_M+\rho_{DE})\,/\,3 - k\,/\,R^2$$

G	Newton's constant
R	scale factor or radius
$H \equiv \dot{R}/R$	Hubble parameter
ρ	energy density
p	pressure
k=1, 0, -1	closed, flat, open

$$1 = \Omega_M + \Omega_{DE} - k\,/\,(R^2H^2) \Leftarrow \Omega \equiv 8\pi G\rho/\,3H^2$$

The goal of modern cosmology is to determine the cosmological parameters h, k, Ω_M, Ω_{DE}…where matter contains baryons, cold dark matter, neutrinos, photons…

H_0=100 h km s^{-1} Mpc^{-1}

acceleration | total pressure

$$\ddot{R}\,/\,R = -4\pi G\,(\rho_M+\rho_{DE}+3p_M+3p_{DE})\,/\,3$$

de-acceleration parameter

$$q \equiv -\ddot{R}R\,/\,\dot{R}^2$$

equation of state $w \equiv p\,/\rho$

$$2q = \Omega_M\,(1+3w_M) + \Omega_{DE}(1+3w_{DE}) \Leftarrow$$

$\Omega_M \approx \Omega_{CDM}=0.25$, $w_{CDM}\approx 0$; $\Omega_{DE}\approx\Omega_\Lambda=0.7$, $w_\Lambda \approx -1$ $\Rightarrow$ $q<0$ ***Universe is accelerating*** !!

Scalar field model for DE/DM

kinetic energy X

potential energy

$$S = \int d^4x \, [f(\varphi)\, \partial_\mu\varphi\partial^\mu\varphi/2 - V(\varphi)]$$

Equation of State $w = p/\varepsilon = (X-V)/(X+V)$

Sound speed $c_s^2 = 1$

Assume a spatially homogeneous scalar field $\varphi(t)$

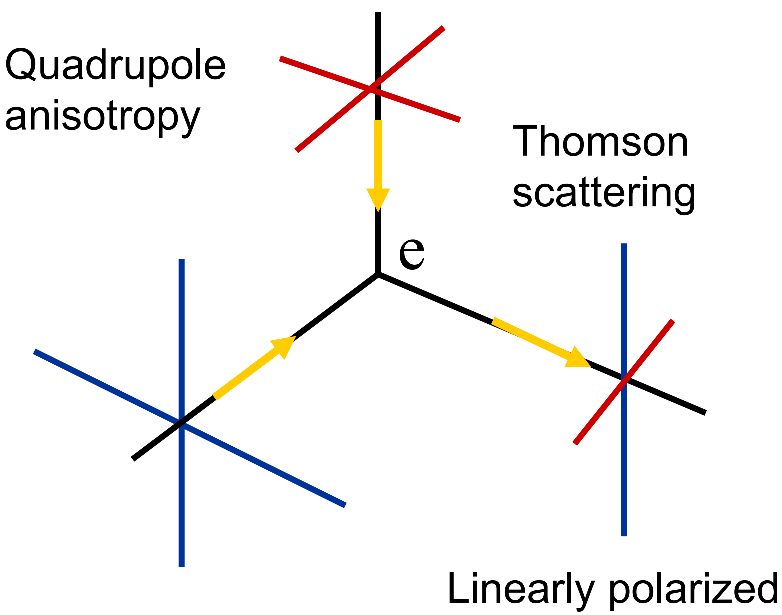
- $f(\varphi)=1 \rightarrow X=\dot{\varphi}^2/2 \rightarrow \quad -1 < w < 1$ *quintessence*
- any $f(\varphi) \rightarrow$ negative $X \rightarrow \quad w < -1$ *phantom*
- $V(\varphi) = m^2\varphi^2/2$, $m >> H_{eq}$ cold dark matter

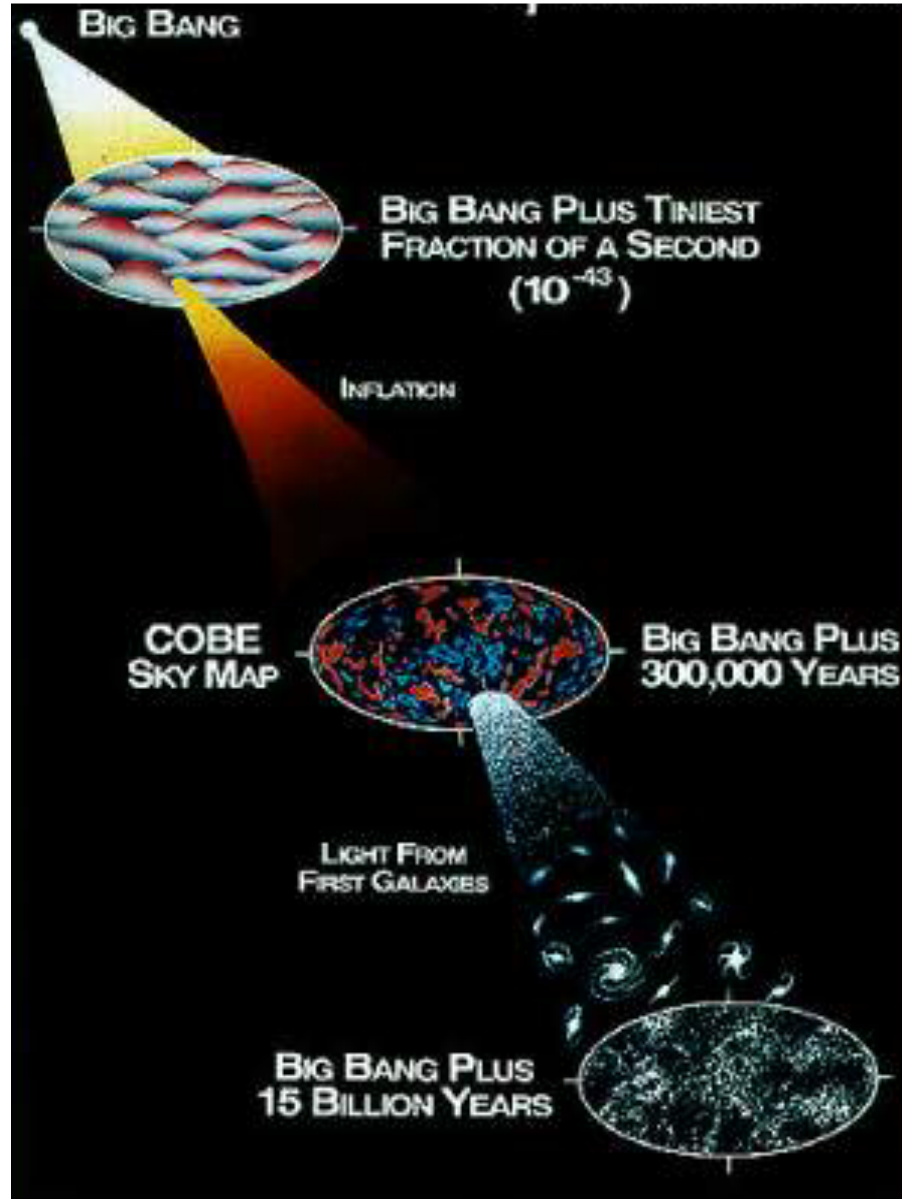
$V(\varphi)$ →

$m^2\phi^2, \lambda\phi^4$	Frieman et al (1995)
$V_0/\phi^\alpha, \alpha > 0$	Ratra & Peebles (1988)
$V_0 \exp(\lambda\phi^2)/\phi^\alpha$	Brax & Martin (1999,2000)
$V_0(\cosh\lambda\phi - 1)^p$	Sahni & Wang (2000)
$V_0 \sinh^{-\alpha}(\lambda\phi)$	Sahni & Starobinsky (2000), Ureña-López & Matos (2000)
$V_0(e^{\alpha\kappa\phi} + e^{\beta\kappa\phi})$	Barreiro, Copeland & Nunes (2000)
$V_0(\exp M_p/\phi - 1)$	Zlatev, Wang & Steinhardt (1999)
$V_0[(\phi - B)^\alpha + A]e^{-\lambda\phi}$	Albrecht & Skordis (2000)

CMB Anisotropy and Polarization

- On large angular scales, matter imhomogeneities generate gravitational redshifts
- On small angular scales, acoustic oscillations in plasma on last scattering surface generate Doppler shifts
- Thomson scatterings with electrons generate polarization



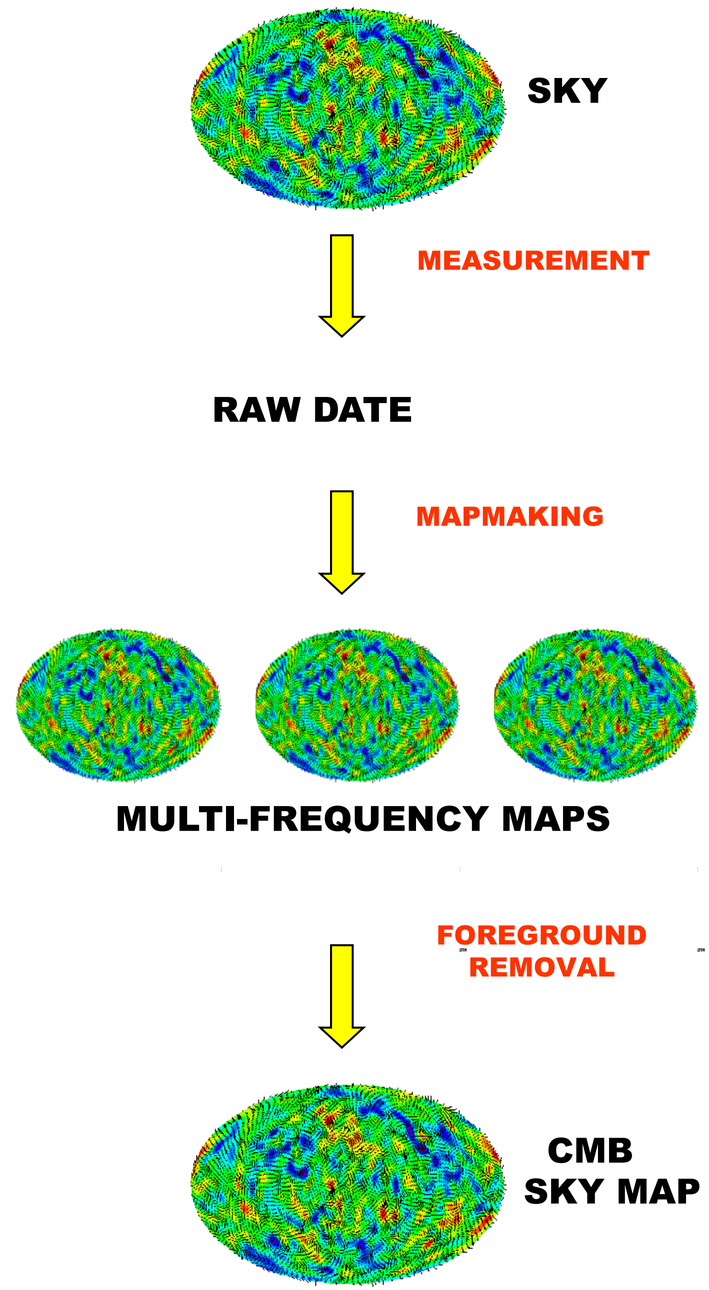


CMB Measurements

- Point the telescope to the sky
- Measure CMB Stokes parameters:

  $T = T_{CMB} - T_{mean}$,

  $Q = T_{EW} - T_{NS}$, $U = T_{SE\text{-}NW} - T_{SW\text{-}NE}$
- Scan the sky and make a sky map
- Sky map contains CMB signal, system noise, and foreground contamination including polarized galactic and extra-galactic emissions
- Remove foreground contamination by multi-frequency subtraction scheme
- Obtain the CMB sky map



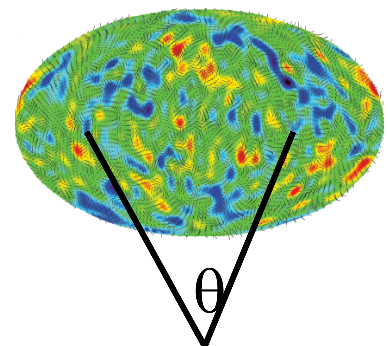
CMB Anisotropy and Polarization Angular Power Spectra

Decompose the CMB sky into a sum of spherical harmonics:

$$T(\theta,\varphi) = \Sigma_{lm}\ a_{lm}\, Y_{lm}\, (\theta,\varphi)$$

$$(Q - iU)\,(\theta,\varphi) = \Sigma_{lm}\ a_{2,lm}\ {}_{2}Y_{lm}\, (\theta,\varphi)$$

$$(Q + iU)\,(\theta,\varphi) = \Sigma_{lm}\ a_{-2,lm}\ {}_{-2}Y_{lm}\, (\theta,\varphi)$$



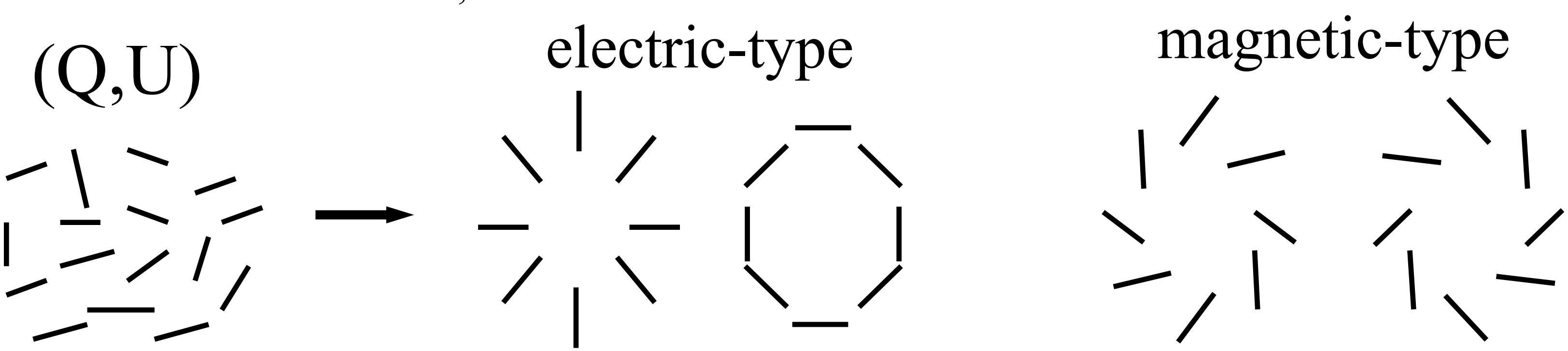
l = 180 degrees/ θ

$C^{TT}_{l} = \Sigma_m (a^*_{lm}\, a_{lm})$ Anisotropy power spectrum

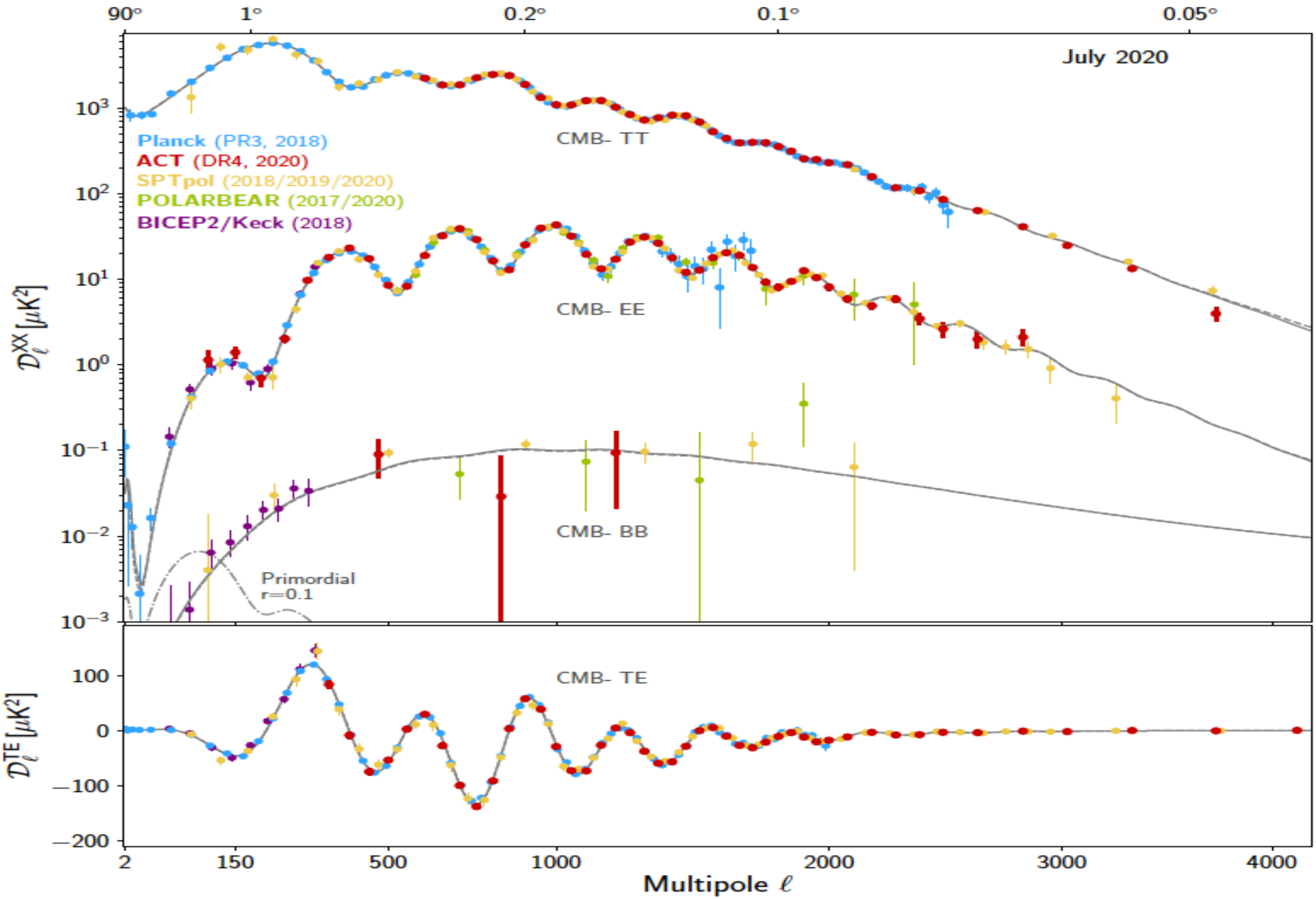
$C^{EE}_{l} = \Sigma_m (a^*_{2,lm}\, a_{2,lm} + a^*_{2,lm}\, a_{-2,lm})$ E-polarization power spectrum

$C^{BB}_{l} = \Sigma_m (a^*_{2,lm}\, a_{2,lm} - a^*_{2,lm}\, a_{-2,lm})$ B-polarization power

$C^{TE}_{l} = -\Sigma_m (a^*_{lm}\, a_{2,lm})$ TE correlation power spectrum



Latest report on CMB measurements



Planck best-fit 6-parameter ΛCDM model 2018

Density perturbation (scalar) power spectrum

Spectral index $\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$

$k_0 = 0.05 \mathrm{Mpc}^{-1}$

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
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

ΛCDM model + 1-parameter extension

r = Tensor (GWB) / Scalar
= $P_h(k)$ / $P_R(k)$ at k=0.002 Mpc^{-1}

Spectral index $\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s-1}$

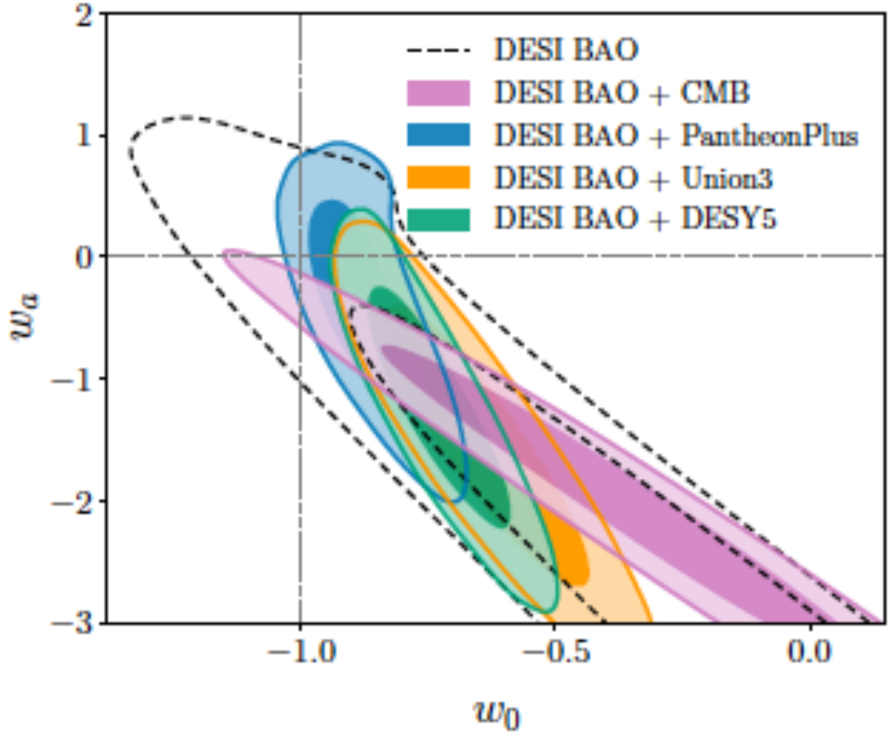
Planck best-fit 7-parameter 2018

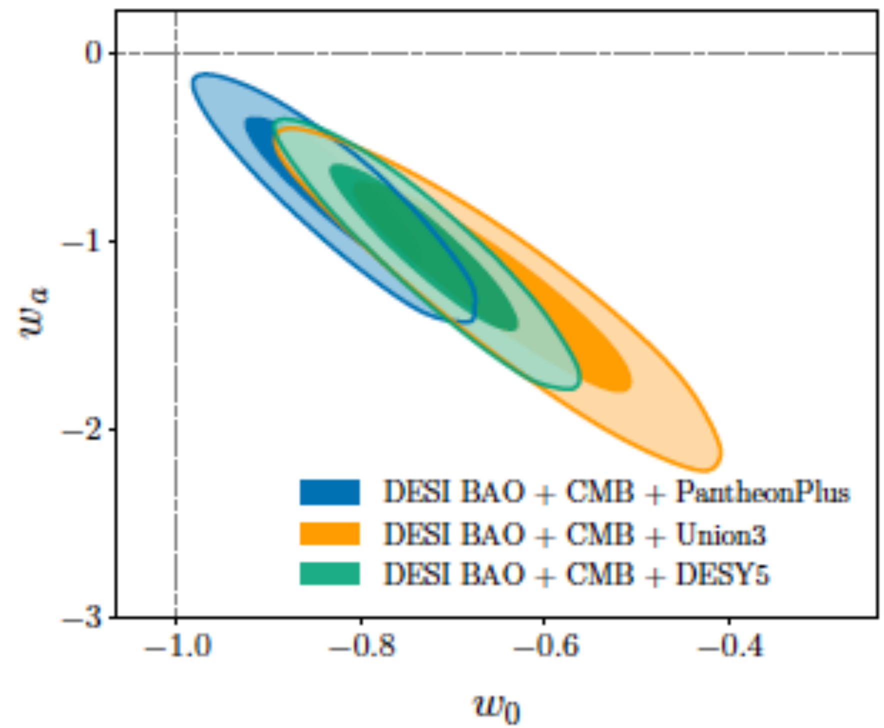
Parameter	TT+lowE	TT, TE, EE+lowE	TT, TE, EE+lowE+lensing	TT, TE, EE+lowE+lensing+BAO
Ω_K	$-0.056^{+0.044}_{-0.050}$	$-0.044^{+0.033}_{-0.034}$	$-0.011^{+0.013}_{-0.012}$	$0.0007^{+0.0037}_{-0.0037}$
Σm_ν [eV]	< 0.537	< 0.257	< 0.241	< 0.120
$N_{\rm eff}$	$3.00^{+0.57}_{-0.53}$	$2.92^{+0.36}_{-0.37}$	$2.89^{+0.36}_{-0.38}$	$2.99^{+0.34}_{-0.33}$
$Y_{\rm P}$	$0.246^{+0.039}_{-0.041}$	$0.240^{+0.024}_{-0.025}$	$0.239^{+0.024}_{-0.025}$	$0.242^{+0.023}_{-0.024}$
$dn_s/d\ln k$	$-0.004^{+0.015}_{-0.015}$	$-0.006^{+0.013}_{-0.013}$	$-0.005^{+0.013}_{-0.013}$	$-0.004^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.102	< 0.107	< 0.101	< 0.106
w_0	$-1.56^{+0.60}_{-0.48}$	$-1.58^{+0.52}_{-0.41}$	$-1.57^{+0.50}_{-0.40}$	$-1.04^{+0.10}_{-0.10}$

Joint Planck+WMAP+BICEP/Keck Array constraint 2021
$r_{0.05} < 0.036$ at 95% c.l.

The 2024 DESI galaxy survey measurement of

$w(z) = w_0 + w_a z/(1+z)$





$$(z_{\rm p}, w_{\rm p}) = \begin{cases} (0.57, -1.094 \pm 0.070) & \text{(DESI+CMB)} \\ (0.26, -0.982 \pm 0.028) & \text{(DESI+CMB+PantheonPlus)} \\ (0.33, -0.960 \pm 0.038) & \text{(DESI+CMB+Union3)} \\ (0.26, -0.946 \pm 0.026) & \text{(DESI+CMB+DESY5).} \end{cases}$$

Time-evolving Dark Energy !!

DE/DM Coupling to Electromagnetism

$$\mathcal{L}_N = -\frac{1}{4}\sqrt{-g}B_{F\tilde{F}}(\phi)F_{\mu\nu}\tilde{F}^{\mu\nu}\,, \quad \text{where} \quad \phi \equiv \frac{\Phi}{M}\,, \qquad M = M_{Pl}/\sqrt{8\pi}$$

This leads to photon dispersion relation Carroll, Field, Jackiw 90

$$n_\pm = \varepsilon \mp \frac{1}{2}\frac{\partial B_{F\tilde{F}}}{\partial\phi}\left(\frac{\partial\phi}{\partial\eta} + \vec{\nabla}\phi\cdot\hat{n}\right)$$

$(\varepsilon, \vec{n})$ is the photon four-momentum

$\pm$ left/right handed $\quad$ η conformal time

vacuum birefringence

then, a rotational speed of polarization plane

$$\omega = \frac{1}{2}(n_+ - n_-) = -\frac{1}{2}\frac{\partial B_{F\tilde{F}}}{\partial\phi}\left(\frac{\partial\phi}{\partial\eta} + \vec{\nabla}\phi\cdot\hat{n}\right)$$

If $B=\beta\varphi$, cooling of horizontal branch stars would imply $\beta<10^7$

For homogenous field ϕ(t), cosmic birefringence induces a constant rotation angle α

ical birefringence". The rotated angle of the polarization direction for an observed source would then be given by

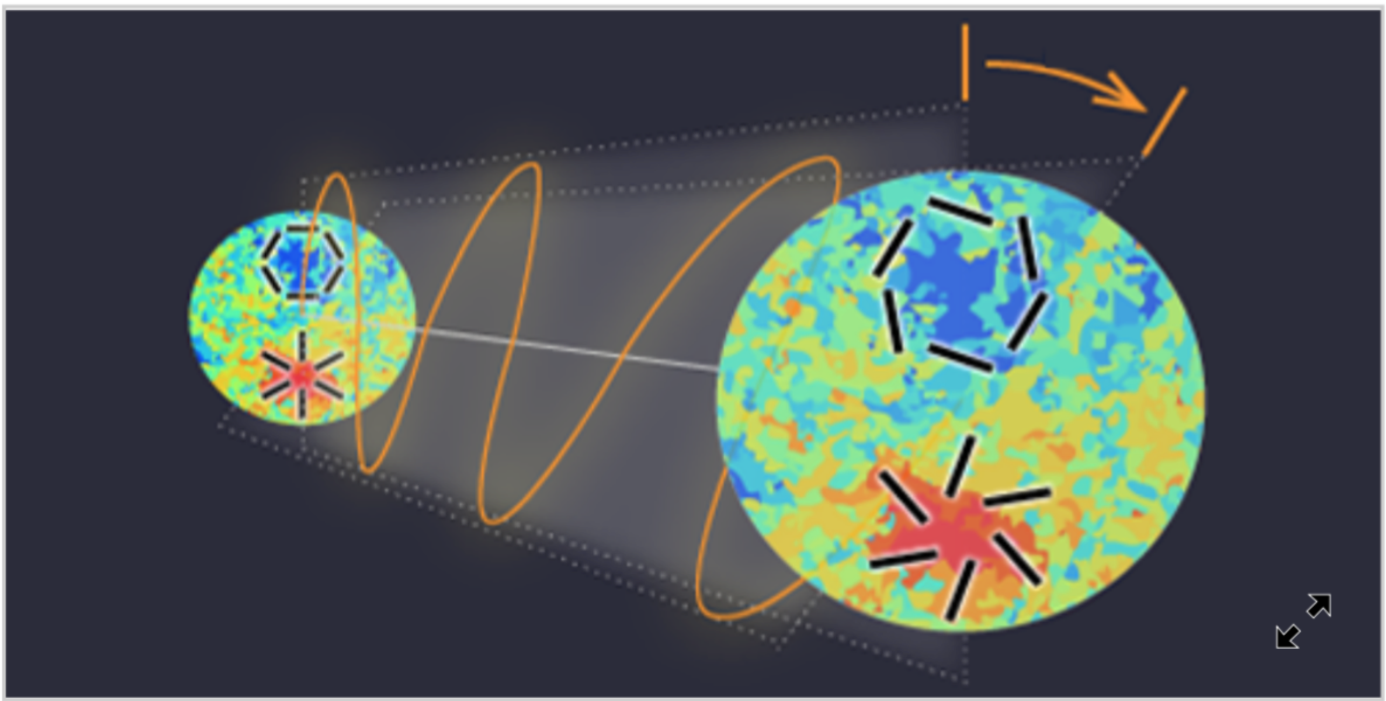
$$\boxed{\bar{\alpha} = \int_z^0 \bar{\omega}(\eta) d\eta = -\frac{1}{2}\beta_{F\tilde{F}}\Delta\bar{\phi},} \tag{25}$$

where $\Delta\bar{\phi}$ is the change in $\bar{\phi}$ between the redshift z of the source and today. Measure-

Hints of Cosmic Birefringence?

November 23, 2020 • *Physics* 13, s149

A new analysis of the cosmic microwave background shows that its polarization may be rotated by exotic effects indicating beyond-standard-model physics.



Y. Minami/KEK

Rotation angle

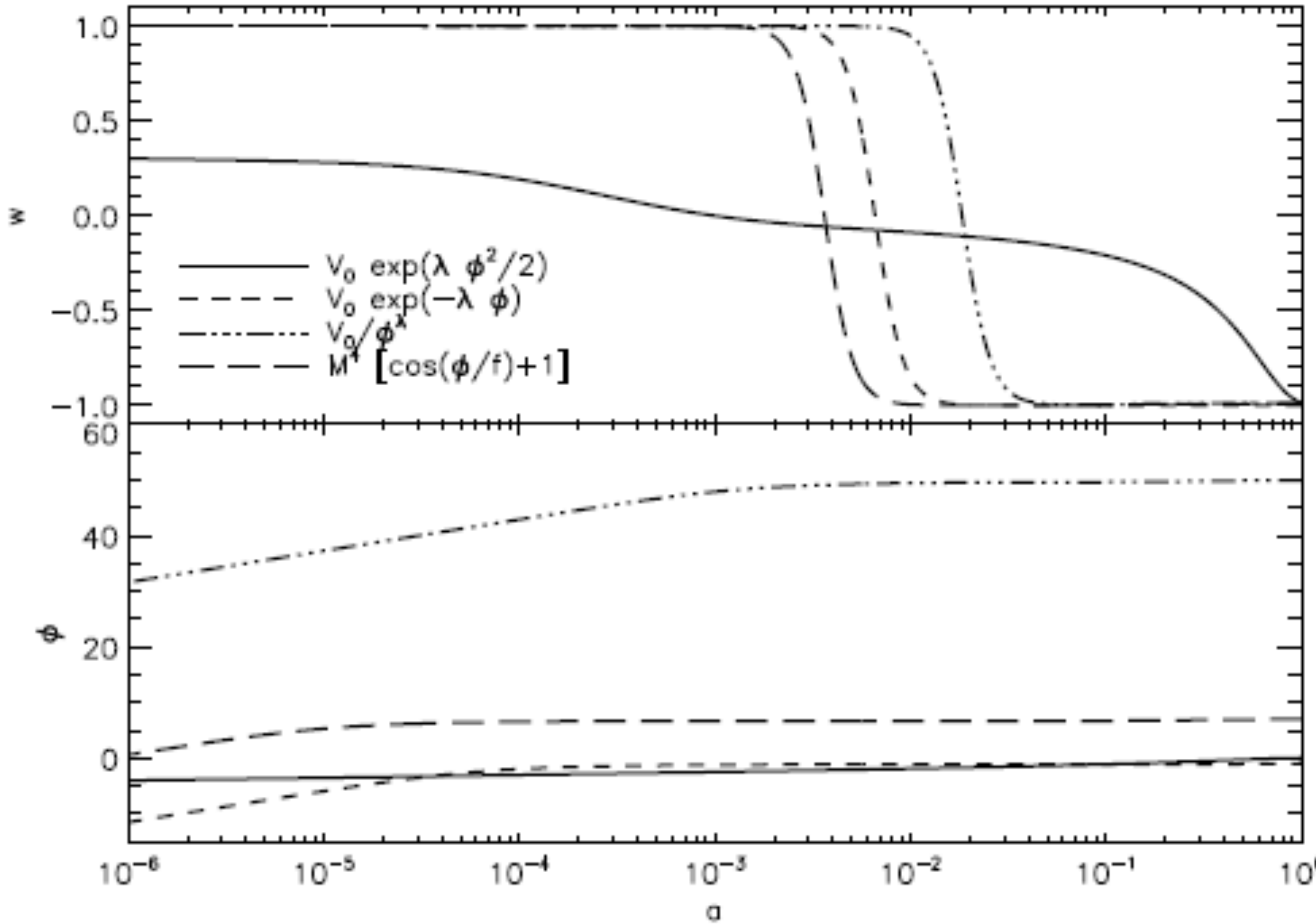
$$\alpha = -0.342^{\circ}{}^{+0.094^{\circ}}_{-0.091^{\circ}} \;(68\%\ \mathrm{CL})$$

Y. Minami and E. Komatsu, "New extraction of the cosmic birefringence from the Planck 2018 polarization data," **Phys. Rev. Lett. 125, 221301 (2020)**.

B. Feng, M. Li, J.-Q. Xia, X. Chen, and X. Zhang, Phys. Rev. Lett. **96**, 221302 (2006).

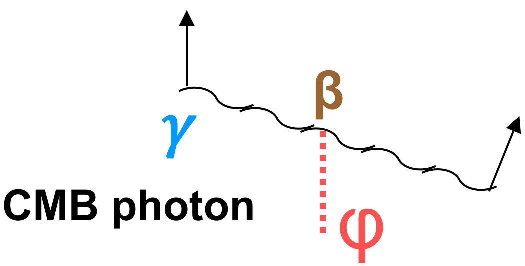
Systematics?

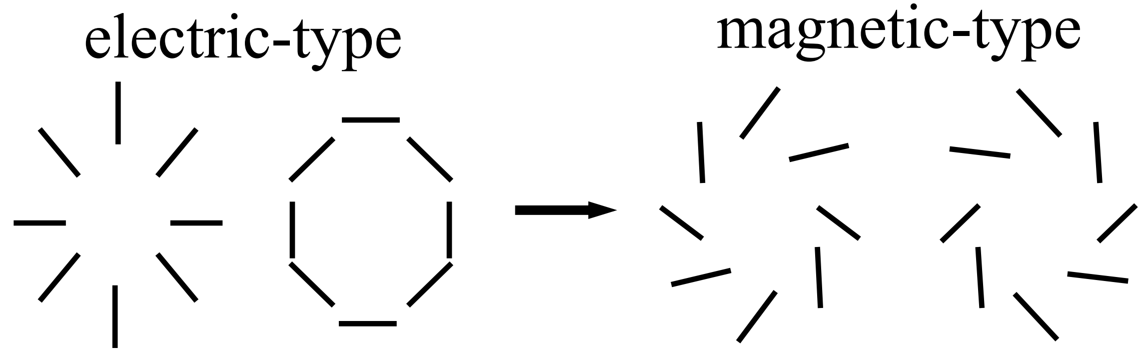
We Tried Many Scalar Dark Energy Models

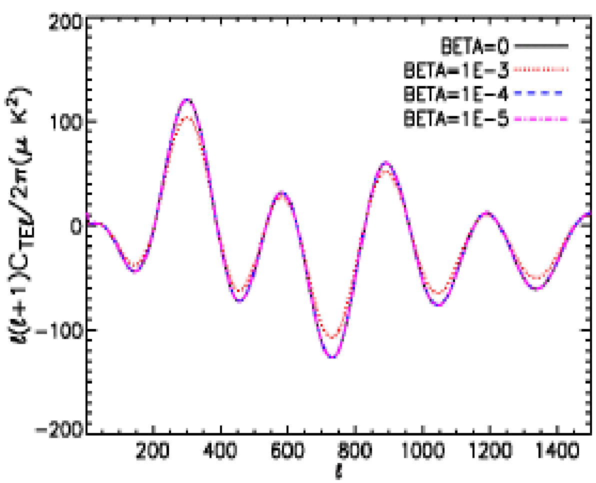


DE mean field induced vacuum birefringence – cosmic rotation of CMB polarization

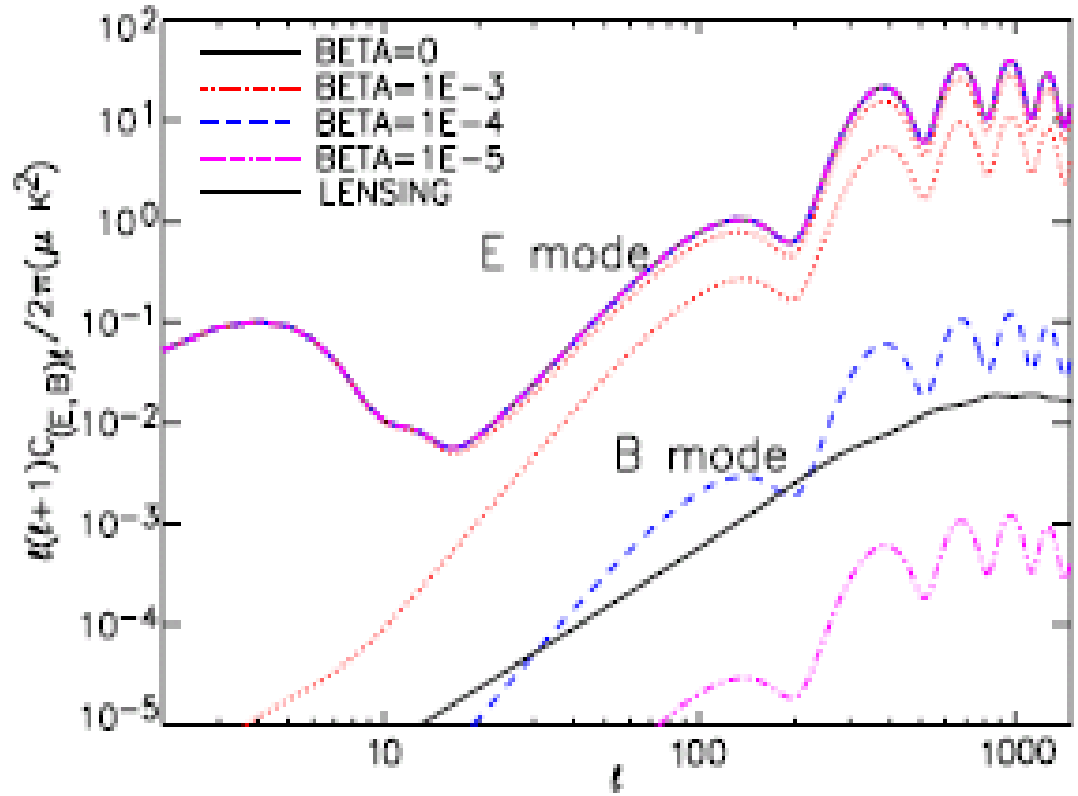
Zhang et al 06
Liu,Lee,Ng 06



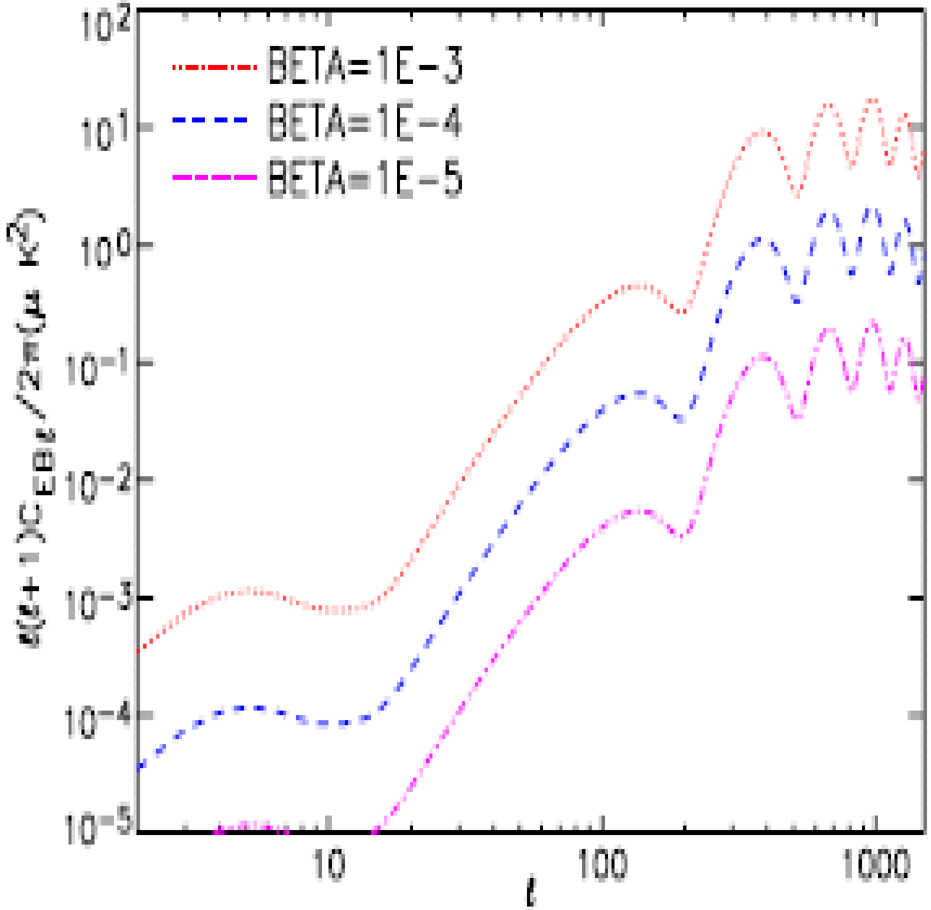


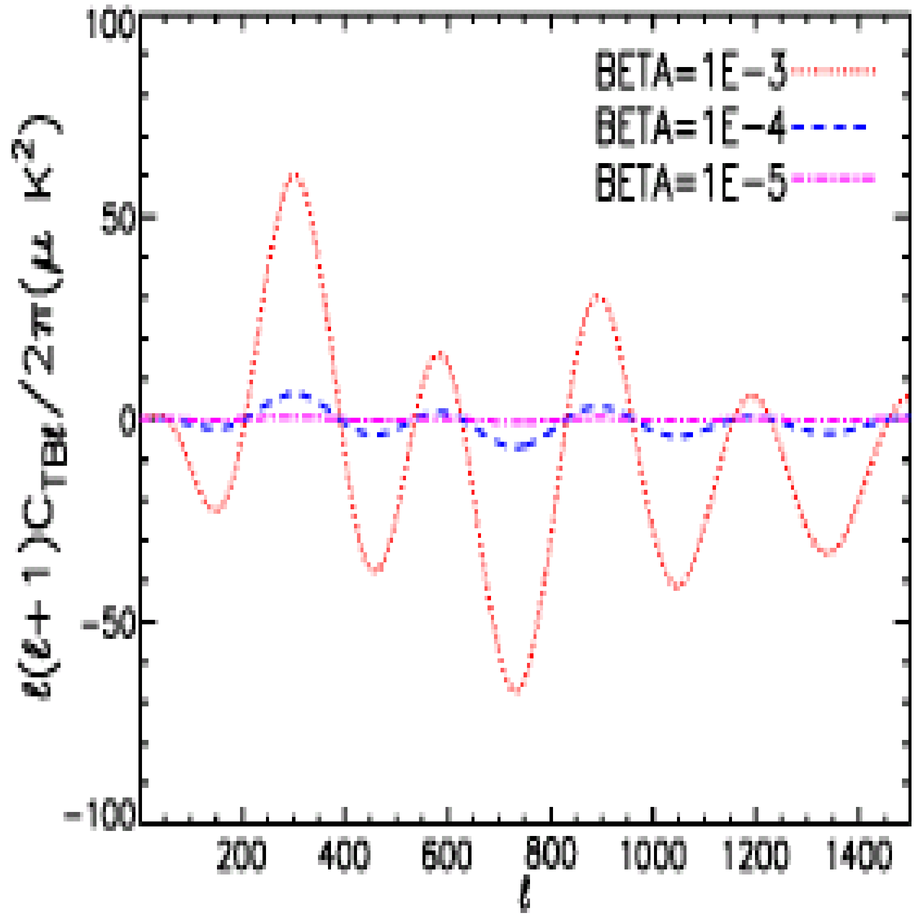


TE spectrum



Parity violating EB,TB cross power spectra – cosmic parity violation





Including Dark Energy Perturbation

Dark energy perturbation $\phi(\eta,\vec{x}) = \bar{\phi}(\eta) + \delta\phi(\eta,\vec{x})$ $\quad \delta\phi(\eta,\vec{x}) = \frac{1}{\sqrt{(2\pi)^3}} \int \delta\phi(\vec{k}',\eta) e^{i\vec{k}'\cdot\vec{x}} d^3k'$

time and space dependent rotation $\quad \omega = -\frac{1}{2}\frac{\partial B_{F\tilde{F}}}{\partial\phi}\left(\frac{\partial\phi}{\partial\eta} + \vec{\nabla}\phi\cdot\hat{n}\right)$

$$\dot{\Delta}_{Q\pm iU}(\vec{k},\eta) + ik\mu\Delta_{Q\pm iU}(\vec{k},\eta) = n_e\sigma_T a(\eta)\Big[-\Delta_{Q\pm iU}(\vec{k},\eta) \times \sum_m \sqrt{\frac{6\pi}{5}}\, {}_{\pm2}Y_2^m(\hat{n}) S_P^{(m)}(\vec{k},\eta)\Big] \mp i2\frac{1}{\sqrt{(2\pi)^3}}\int d\vec{k}'\, \tilde{\omega}(\vec{k}-\vec{k}',\eta)\Delta_{Q\pm iU}(\vec{k}',\eta)$$

$$\tilde{\omega}(\vec{k},\eta) = -\frac{1}{2}\frac{\partial B_{F\tilde{F}}}{\partial\bar{\phi}}\left[\dot{\delta\phi}_{\vec{k}}(\eta) + i\vec{k}\cdot\hat{n}\,\delta\phi_{\vec{k}}(\eta)\right]$$

- Perturbation induced polarization power spectra in general quintessence models are small
- Interestingly, in nearly ΛCDM models (no time evolution of the mean field), birefringence generates <BB> while <TB>=<EB>=0

Cosmic Birefringence (CB) Fluctuations

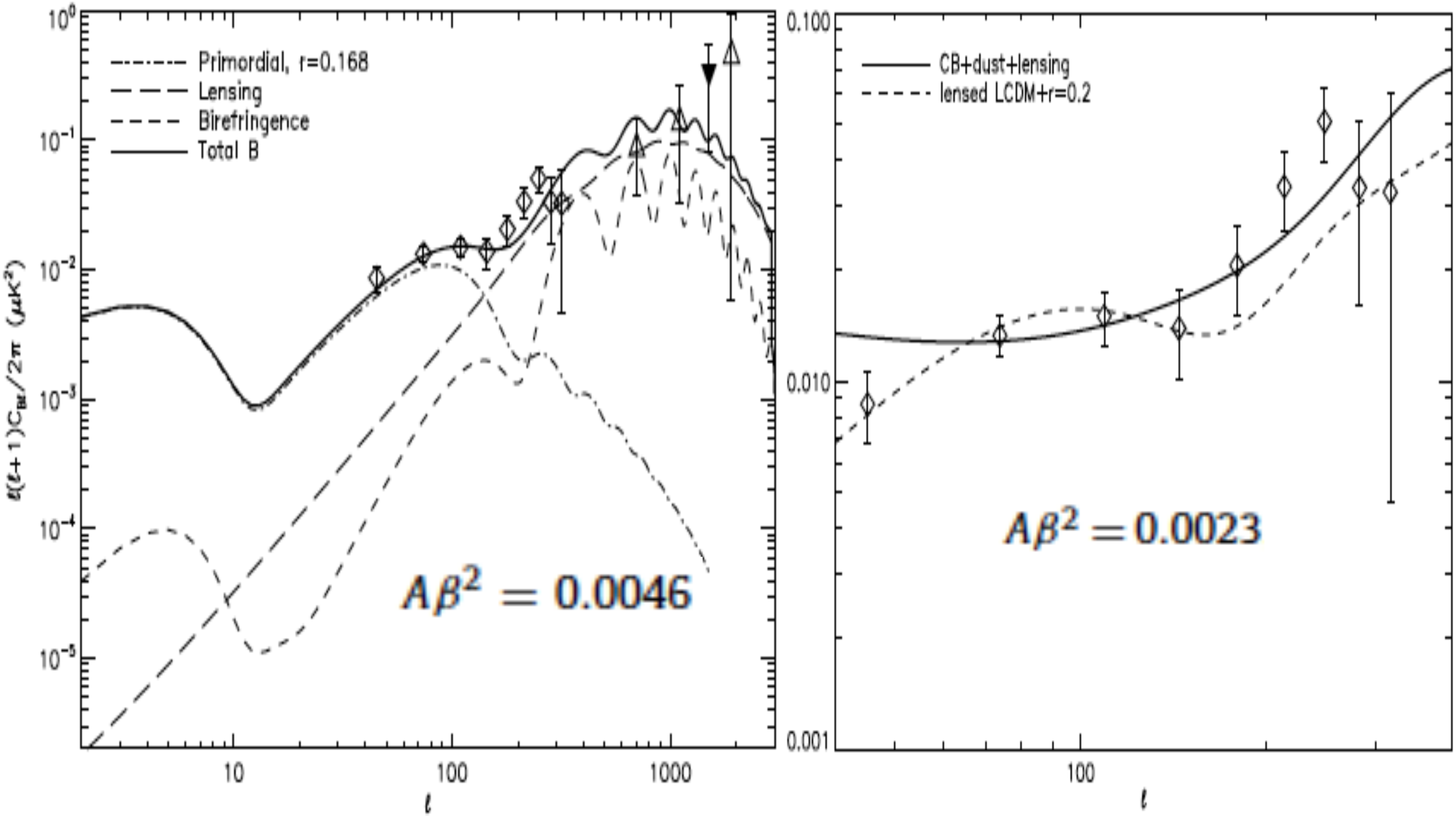
Nearly massless pseudo scalar

$$\left\langle \delta\phi_{\vec{k},i}\delta\phi_{\vec{k}',i}\right\rangle = (2\pi^2/k^3)P_{\delta\phi}(k)\,\delta(\vec{k}-\vec{k}')$$

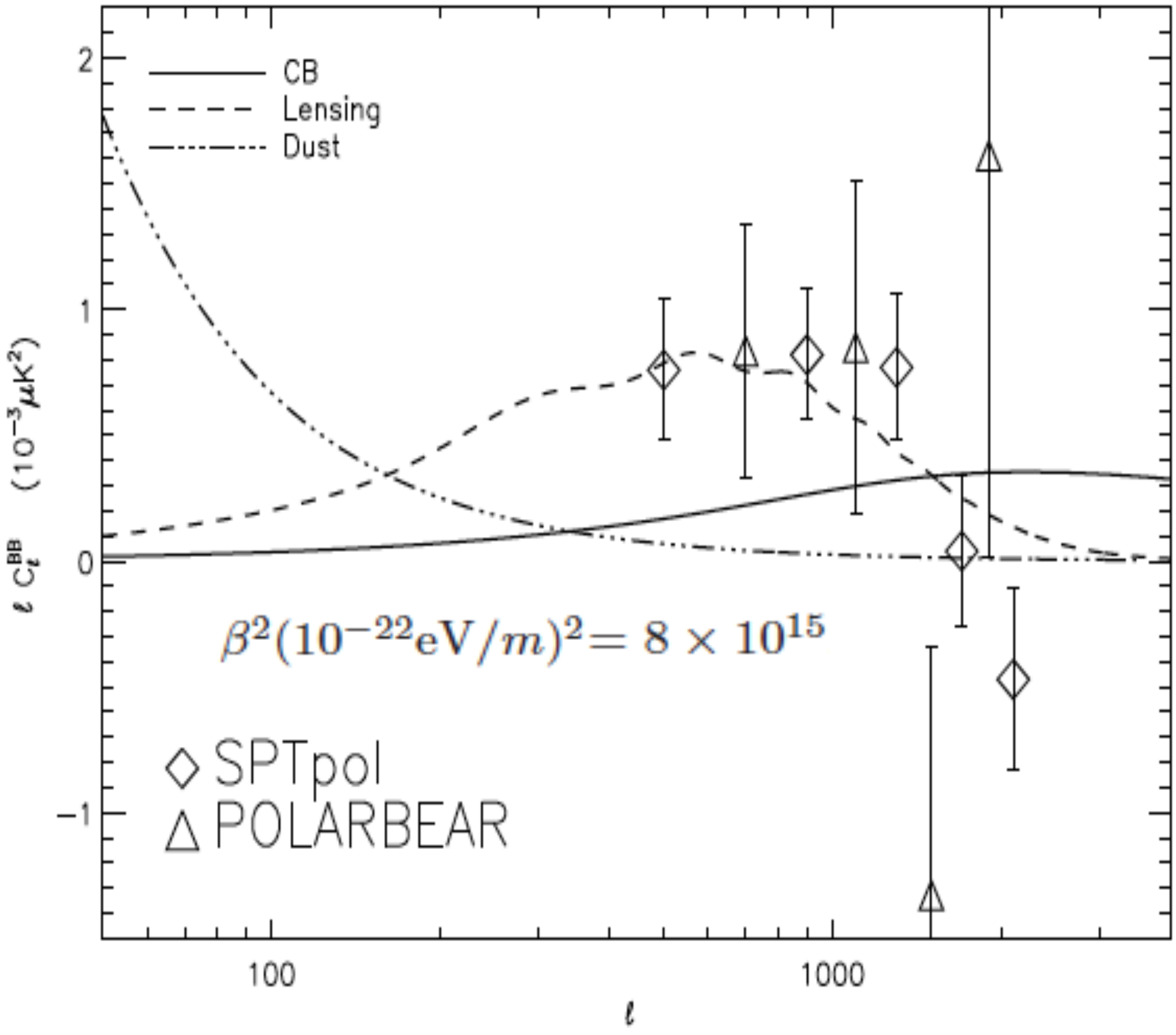
$$P_{\delta\phi}(k) = Ak^{n-1}$$

Pospelov et al. 08

Lee, Liu, Ng14



Axion (m~10^{-22}eV) CDM curvature perturbation



$\delta\rho_\phi/\rho_\phi = \delta\rho/\rho$

$$\rho_\phi = m_\phi^2\phi^2$$

$$\frac{\delta\rho_\phi}{\rho_\phi} = 2\frac{\delta\phi}{\phi}$$

$$\frac{\delta\phi}{M} = \frac{\delta\phi}{\phi}\frac{\phi}{M}$$

$$\phi = \phi_m\left(\frac{a_m}{a}\right)^{\frac{3}{2}}$$

$$H(a_m) = m$$

Liu, Ng 17

Ultra-light Axionic string-wall networks

[55] P. Agrawal, A. Hook, and J. Huang, JHEP **07**, 138 (2020), arXiv:1912.02823 [astro-ph.CO].

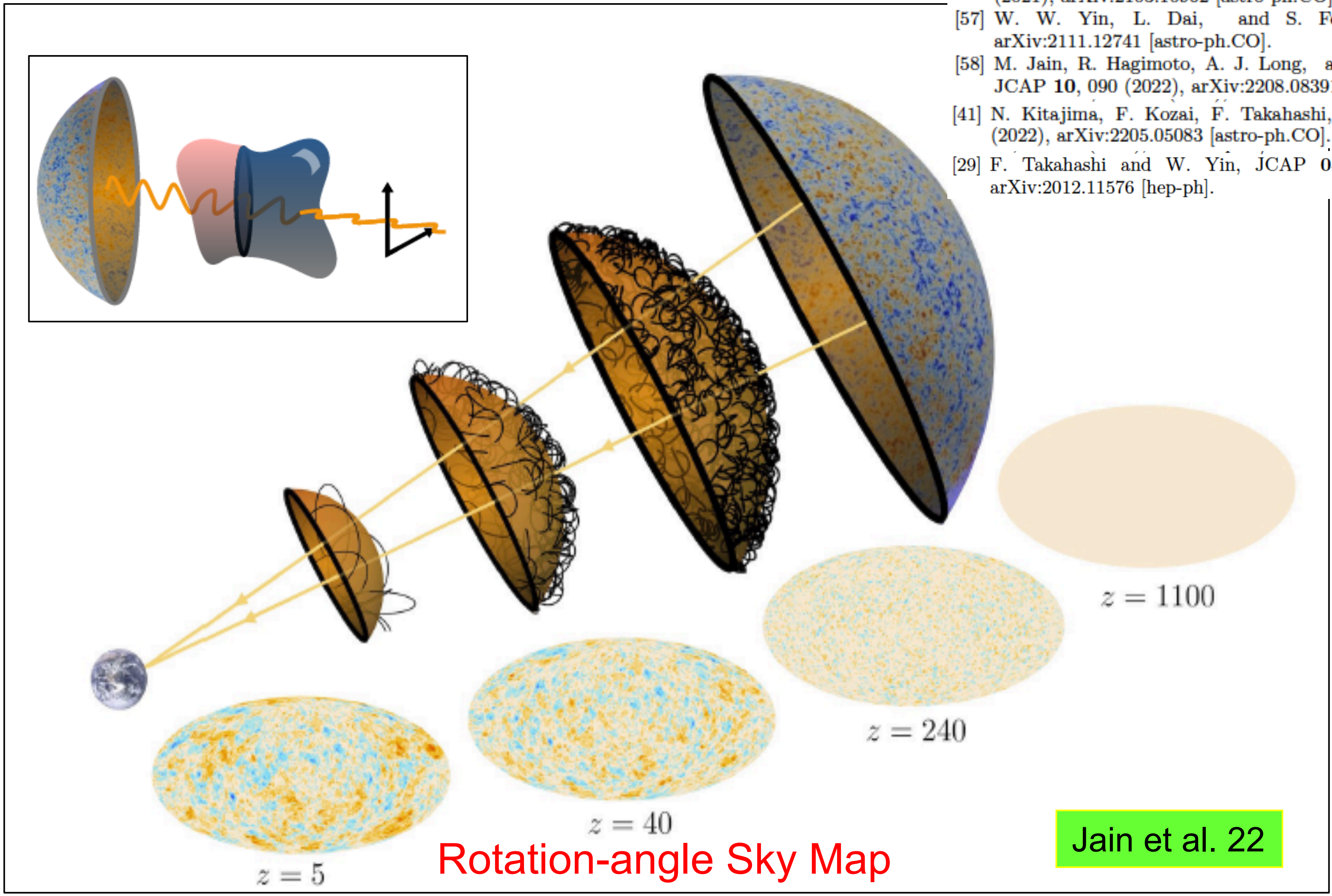
[56] M. Jain, A. J. Long, and M. A. Amin, JCAP **05**, 055 (2021), arXiv:2103.10962 [astro-ph.CO].

[57] W. W. Yin, L. Dai, and S. Ferraro, (2021), arXiv:2111.12741 [astro-ph.CO].

[58] M. Jain, R. Hagimoto, A. J. Long, and M. A. Amin, JCAP **10**, 090 (2022), arXiv:2208.08391 [astro-ph.CO].

[41] N. Kitajima, F. Kozai, F. Takahashi, and W. Yin, (2022), arXiv:2205.05083 [astro-ph.CO].

[29] F. Takahashi and W. Yin, JCAP **04**, 007 (2021), arXiv:2012.11576 [hep-ph].



Rotation-angle Sky Map

Jain et al. 22

Axion Inflation

We consider a version of the trapped inflation driven by a pseudoscalar φ that couples to a $U(1)$ gauge field A_μ:

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\frac{M_p^2}{2}R - \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - V(\varphi) - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{\alpha}{4f}\varphi\tilde{F}^{\mu\nu}F_{\mu\nu}\right], \quad (3)$$

Sorbo, Barnaby, Namba, Peloso, Meerburg, Pager, Unal,….

$$\varphi = \phi(\eta) + \delta\varphi(\eta, \vec{x})$$

Under the temporal gauge, $A_\mu = (0, \vec{A})$, we decompose $\vec{A}(\eta, \vec{x})$ into its right and left circularly polarized Fourier modes, $A_\pm(\eta, \vec{k})$, whose equation of motion is then given by

$d\eta = dt/a$

$$\left[\frac{d^2}{d\eta^2} + k^2 \mp 2aHk\xi\right]A_\pm(\eta, k) = 0, \quad \xi \equiv \frac{\alpha}{2fH}\frac{d\phi}{dt}. \quad (5)$$

$k/(aH) < 2|\xi|$

Spinoidal instability

Background

$$\frac{d^2\phi}{dt^2} + 3H\frac{d\phi}{dt} + \frac{dV}{d\phi} = \frac{\alpha}{f}\langle \vec{E}\cdot\vec{B}\rangle,$$

$$3H^2 = \frac{1}{M_p^2}\left[\frac{1}{2}\left(\frac{d\phi}{dt}\right)^2 + V(\phi) + \frac{1}{2}\langle \vec{E}^2 + \vec{B}^2\rangle\right]$$

$$\boxed{\begin{aligned} \langle \vec{E}\cdot\vec{B}\rangle &\simeq -2.4\cdot 10^{-4}\frac{H^4}{\xi^4}\,\mathrm{e}^{2\pi\xi}, \\ \left\langle\frac{\vec{E}^2+\vec{B}^2}{2}\right\rangle &\simeq 1.4\cdot 10^{-4}\frac{H^4}{\xi^3}\,\mathrm{e}^{2\pi\xi}. \end{aligned}}$$

$$\frac{1}{2}\langle \vec{E}^2 + \vec{B}^2\rangle = \int \frac{dk\,k^2}{4\pi^2 a^4}\sum_{\lambda=\pm}\left(\left|\frac{dA_\lambda}{d\eta}\right|^2 + k^2|A_\lambda|^2\right),$$

$$\langle \vec{E}\cdot\vec{B}\rangle = -\int \frac{dk\,k^3}{4\pi^2 a^4}\frac{d}{d\eta}\left(|A_+|^2 - |A_-|^2\right).$$

Perturbation

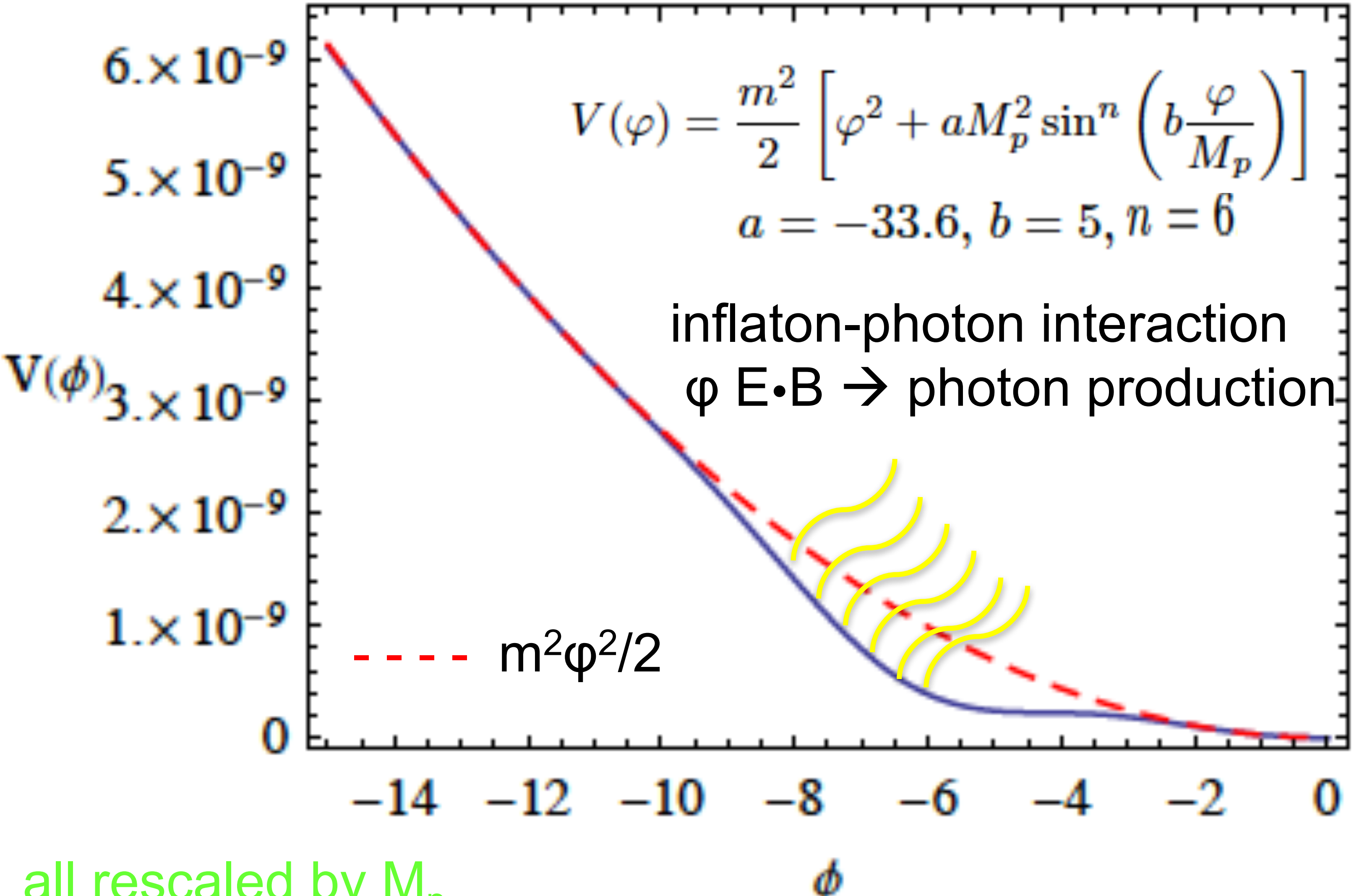
$$\left[\frac{\partial^2}{\partial t^2} + 3\beta H\frac{\partial}{\partial t} - \frac{\vec{\nabla}^2}{a^2} + \frac{d^2V}{d\phi^2}\right]\delta\varphi(t,\vec{x}) = \frac{\alpha}{f}\left(\vec{E}\cdot\vec{B} - \langle\vec{E}\cdot\vec{B}\rangle\right)$$

$$\delta\varphi = \frac{\alpha}{3\beta f H^2}\left(\vec{E}\cdot\vec{B} - \langle\vec{E}\cdot\vec{B}\rangle\right)$$

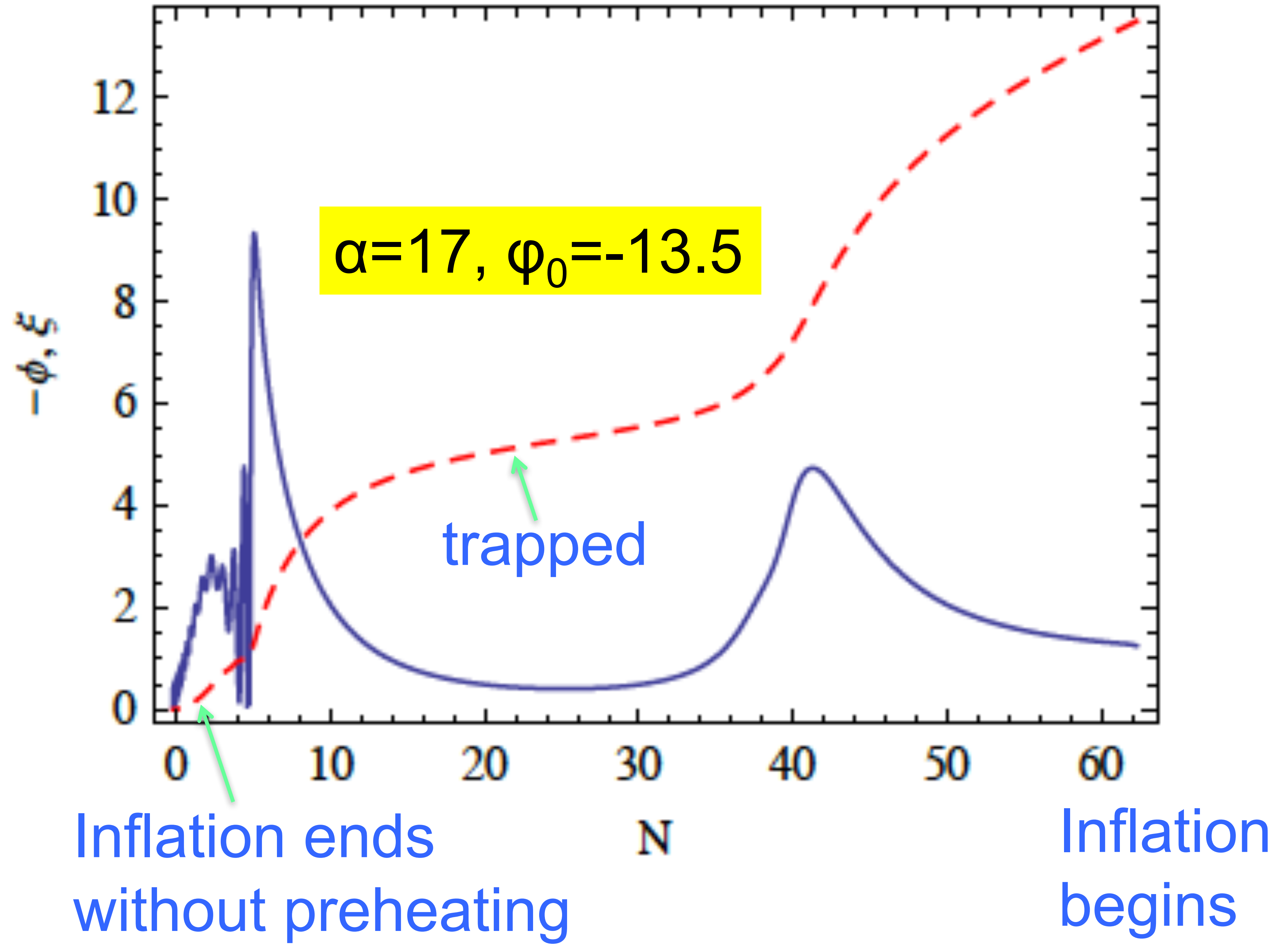
$$\boxed{\beta \equiv 1 - 2\pi\xi\frac{\alpha}{f}\frac{\langle\vec{E}\cdot\vec{B}\rangle}{3H(d\phi/dt)}}$$

$$\Delta_\zeta^2(k) = \langle\zeta(x)^2\rangle = \frac{H^2\langle\delta\varphi^2\rangle}{(d\phi/dt)^2} = \left[\frac{\alpha\langle\vec{E}\cdot\vec{B}\rangle}{3\beta f H(d\phi/dt)}\right]^2$$

e.g. Axion inflation with a steep potential Cheng, Lee, Ng 16



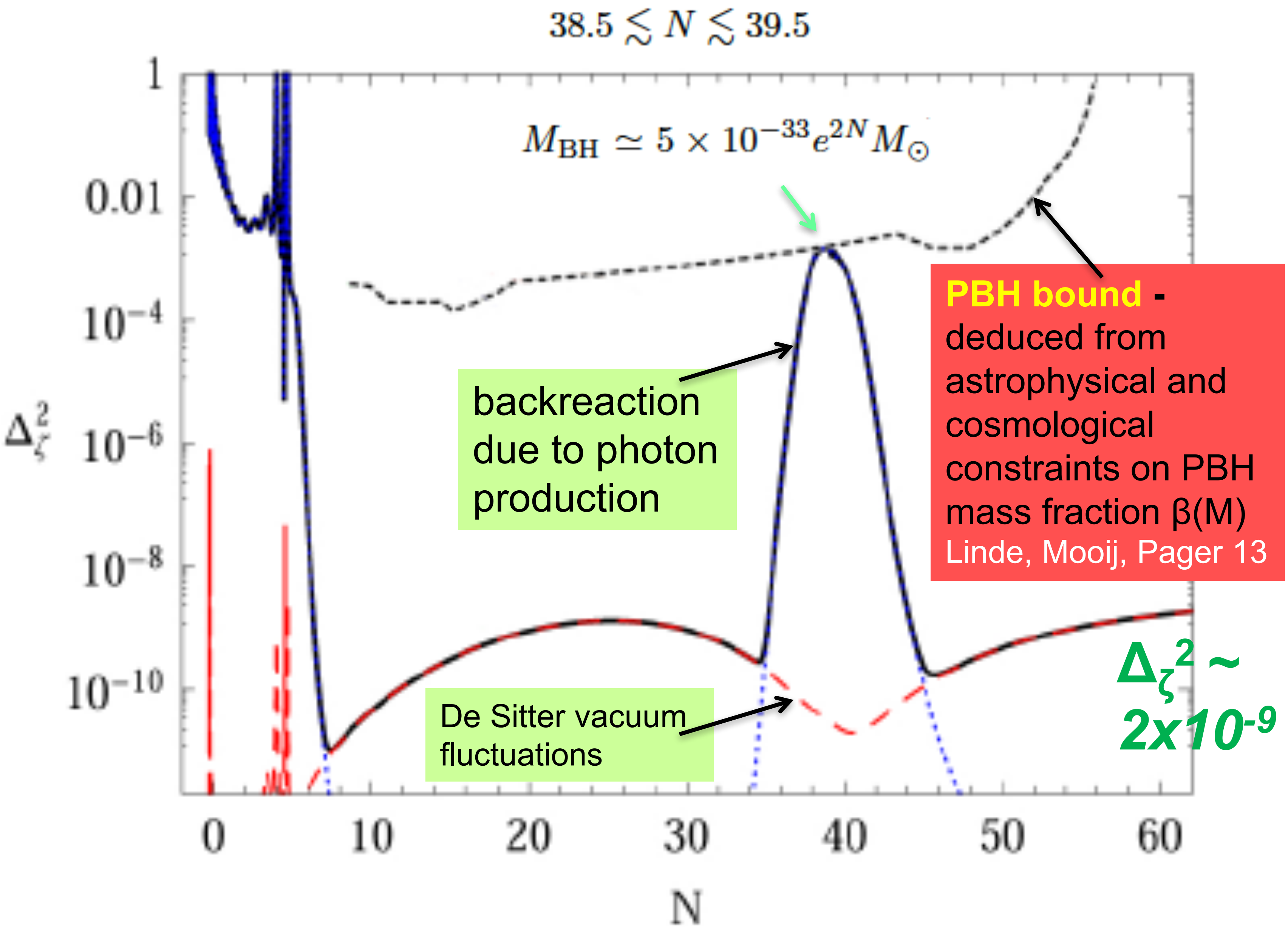
all rescaled by M_p



α=17, φ0=-13.5
trapped
Inflation ends without preheating
Inflation begins
−ϕ, ξ
N
0
2
4
6
8
10
12
0
10
20
30
40
50
60

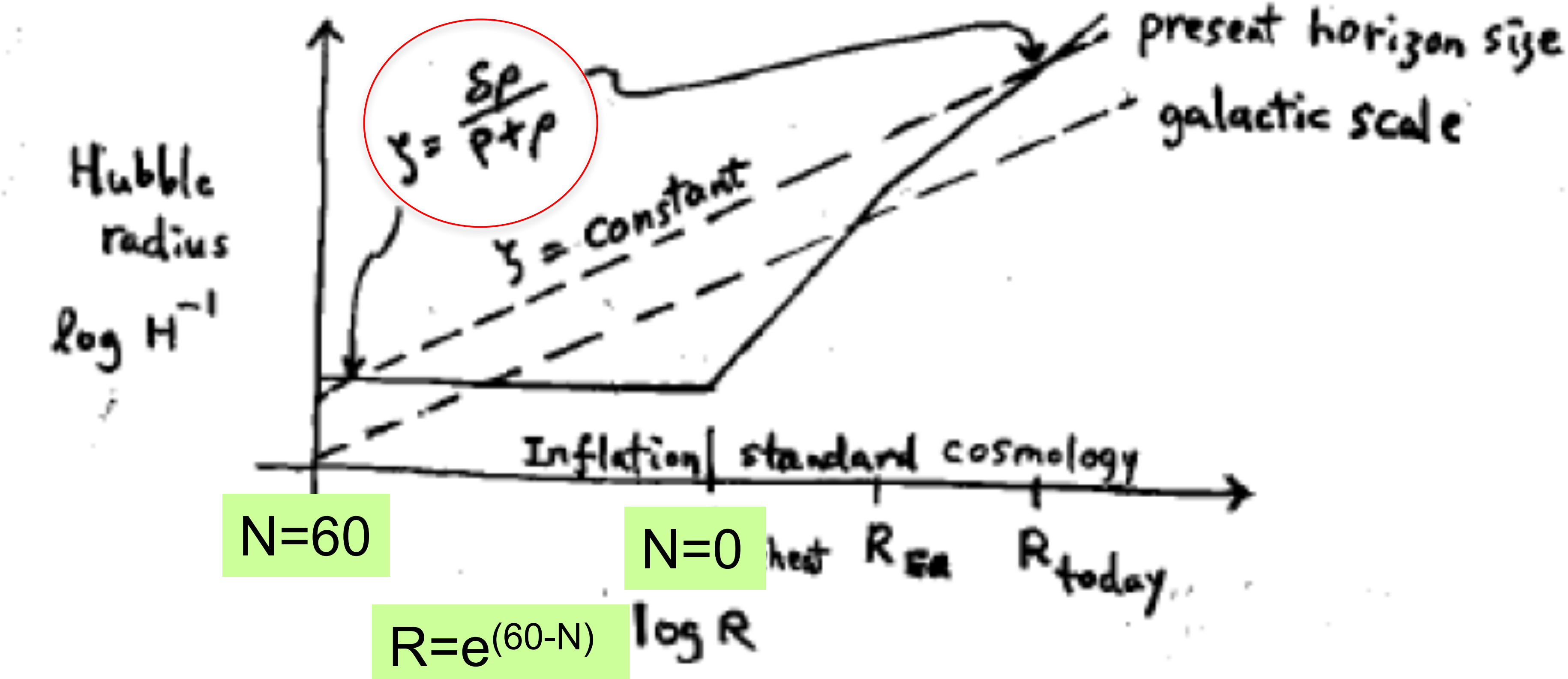
Production of 10-100$M_\odot$ PBHs

Curvature perturbation $P_R = \Delta_\zeta^2 = \langle\zeta\zeta\rangle = (\delta\rho/\rho)^2$



Production of PBHs in inflation

Evolution of cosmological density perturbation

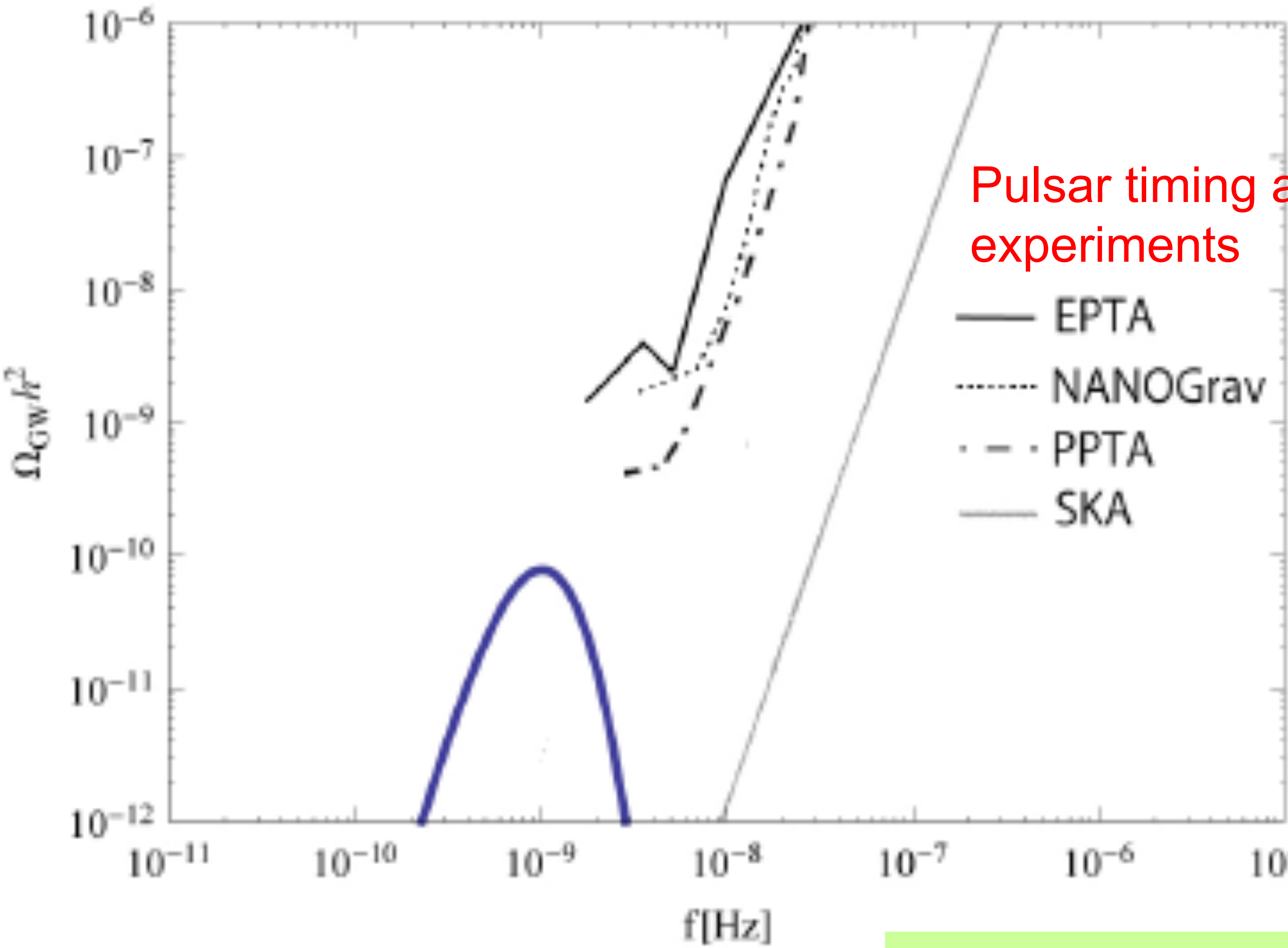


$$M_{\rm BH} = \frac{4\pi M_p^2}{H} e^{2N} = 2.74 \times 10^{-38} e^{2N} \left(\frac{M_p}{H}\right) M_\odot$$

N is e-foldings before the end of inflation

Associated Chiral Gravitational Waves in Axion Inflation

Spectral energy density



$$\left[\frac{\partial^2}{\partial\eta^2} + \frac{2}{a}\frac{da}{d\eta}\frac{\partial}{\partial\eta} - \vec{\nabla}^2\right] h_{ij} = \frac{2a^2}{M_p^2}\left(-E_iE_j - B_iB_j\right)^{TT}$$

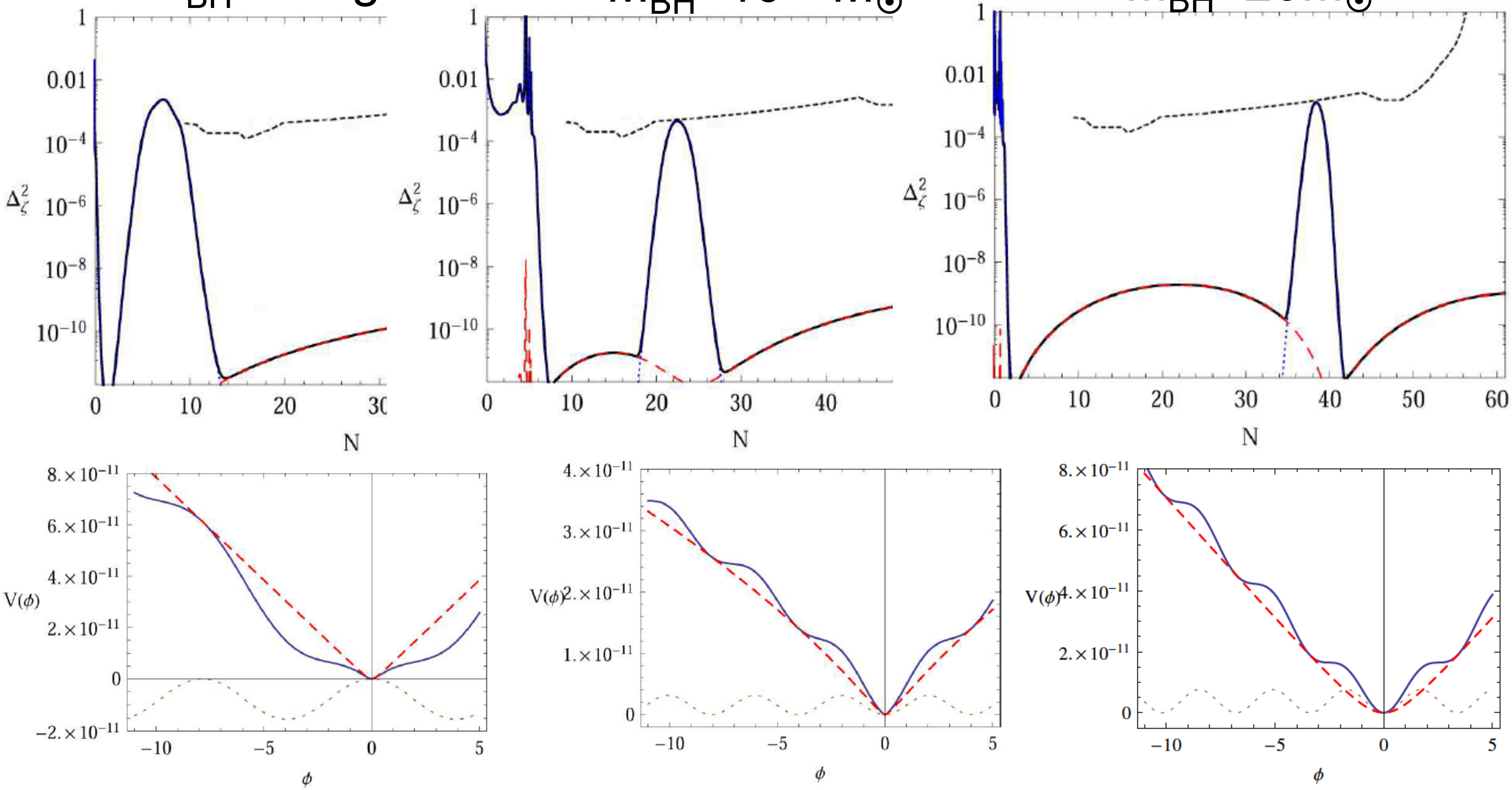
Transverse traceless part of photon energy-momentum

<E·E> ~ <E·B> ~ ζ

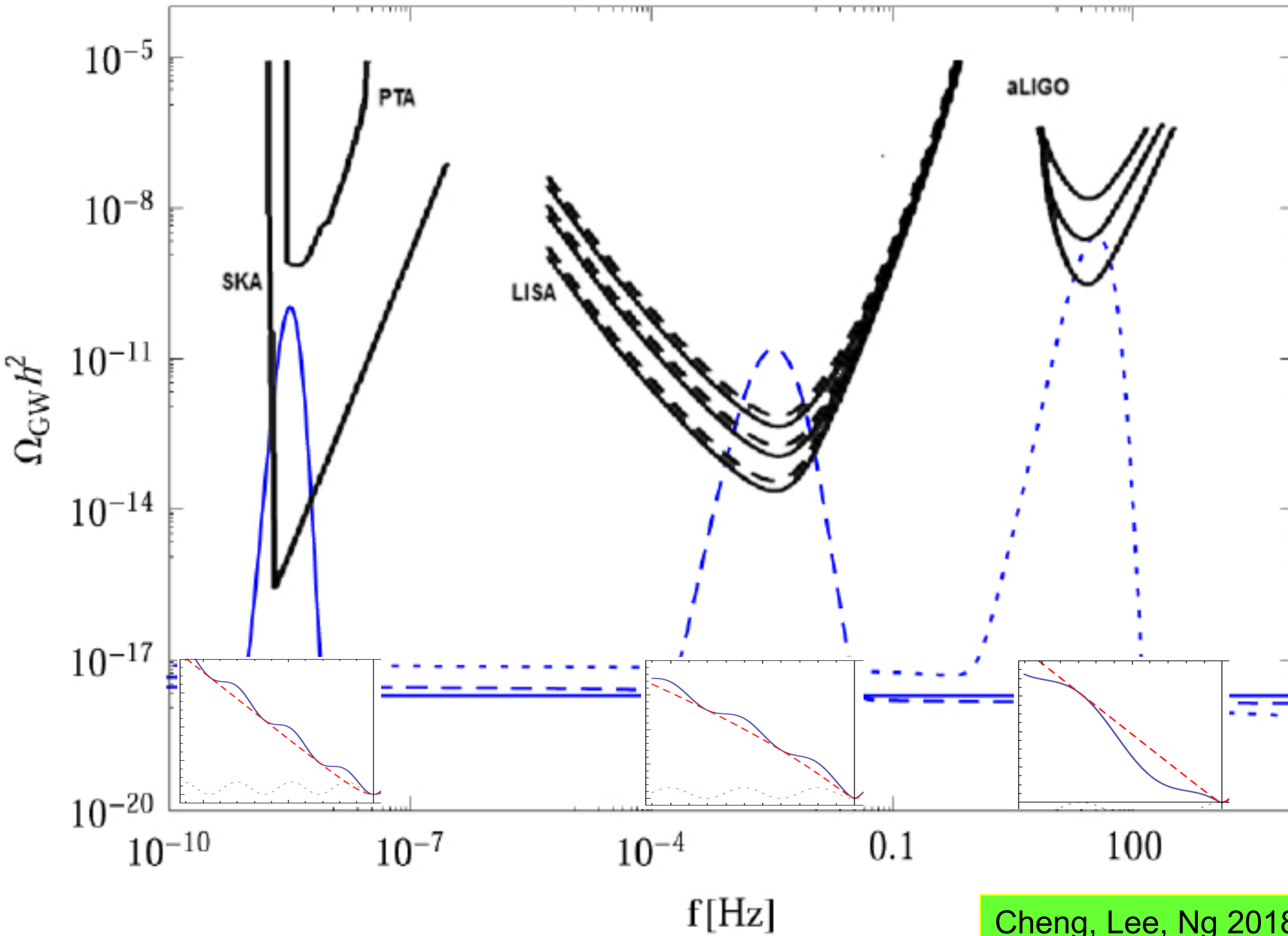
Chiral GWs Sorbo 11 Chiral photons

Production of PBHs realized in axion monodromy inflation with sinusoidal modulations

$M_{BH} \sim 10^8$ g $\quad$ $M_{BH} \sim 10^{-13} M_\odot$ $\quad$ $M_{BH} \sim 20 M_\odot$



Chiral GWs associated with PBHs in modulated axion inflation



Cheng, Lee, Ng 2018

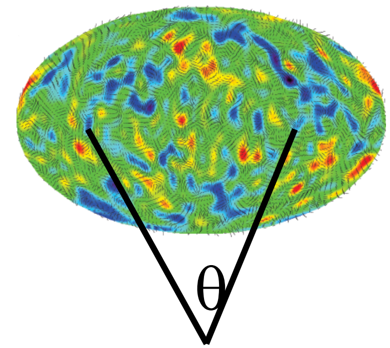
GWB Anisotropy and Polarization Angular Power Spectra

Decompose the GWB sky into a sum of spherical harmonics:

$$T(\theta,\varphi) = \Sigma_{lm}\ a_{lm}\, Y_{lm}\,(\theta,\varphi),\quad V(\theta,\varphi) = \Sigma_{lm}\ b_{lm}\, Y_{lm}\,(\theta,\varphi)$$

$$(Q - iU)\,(\theta,\varphi) = \Sigma_{lm}\ a_{4,lm}\ {}_{4}Y_{lm}\,(\theta,\varphi)$$

$$(Q + iU)\,(\theta,\varphi) = \Sigma_{lm}\ a_{-4,lm}\ {}_{-4}Y_{lm}\,(\theta,\varphi)$$



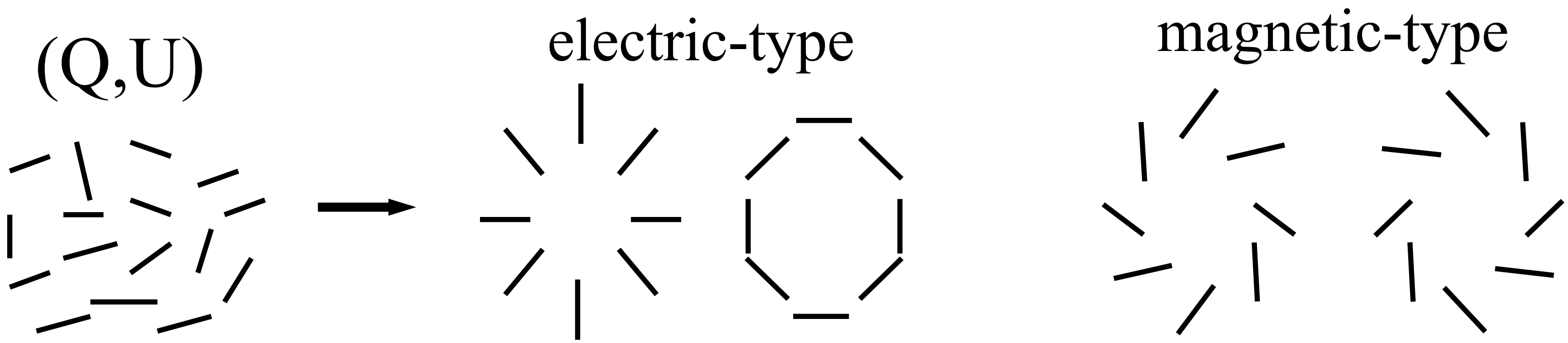
l = 180 degrees/ θ

$C^T_l = \Sigma_m (a^*_{lm}\, a_{lm})$ anisotropy power spectrum

$C^V_l = \Sigma_m (b^*_{lm}\, b_{lm})$ circular polarization power spectrum

$C^E_l = \Sigma_m (a^*_{4,lm}\, a_{4,lm} + a^*_{4,lm}\, a_{-4,lm})$ E-polarization power spectrum

$C^B_l = \Sigma_m (a^*_{4,lm}\, a_{4,lm} - a^*_{4,lm}\, a_{-4,lm})$ B-polarization power spectrum



Current gravitational-wave detectors

LIGO-
Virgo-
KAGRA
Collaboration

ASIOP has joined
LIGO and KAGRA

Concluding remarks

- T. D. Lee and C. N. Yang, C. S. Wu 1957

  Parity symmetry is broken in sub -atomic world - weak interaction is left-handed

- Is there any parity violation in the cosmos on the sky?

  CMB polarization, chiral GWs

- Search for Cosmic Parity Violation via axions