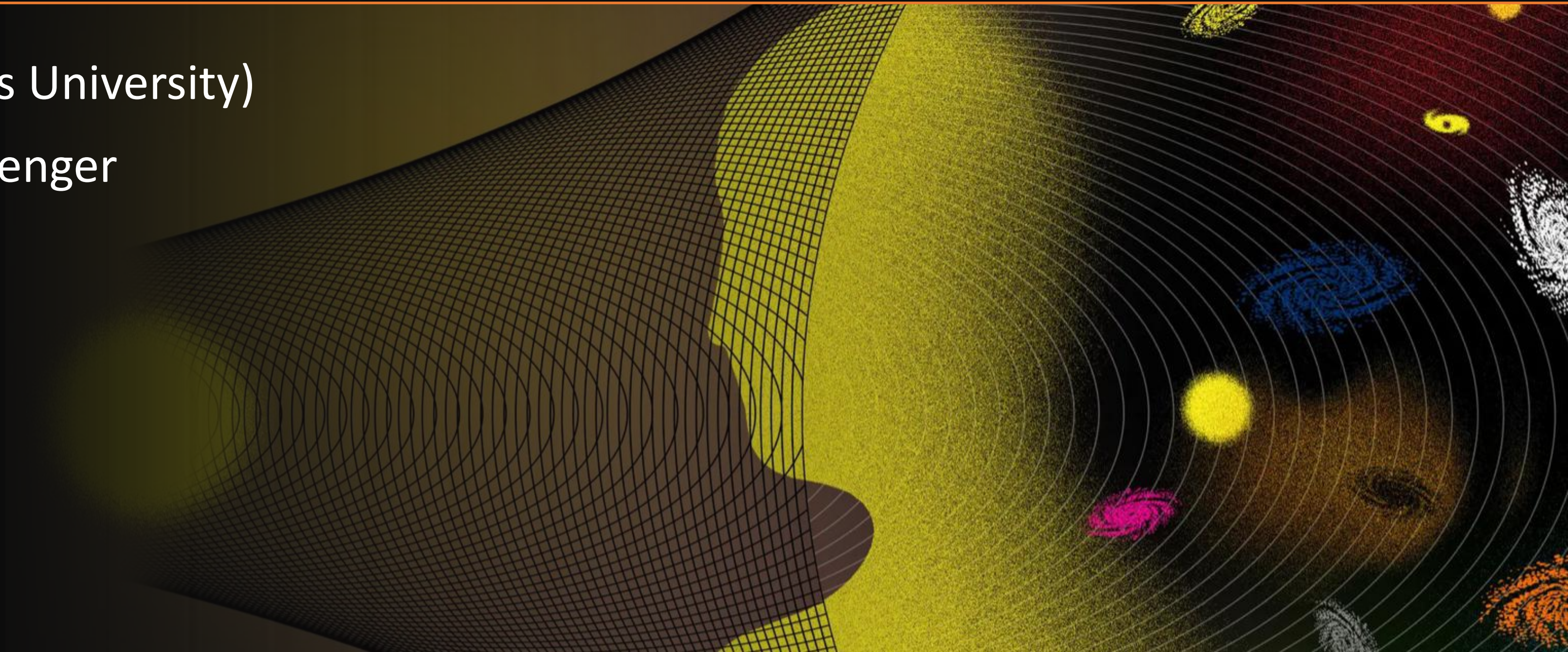
Cosmology puzzles (2024)

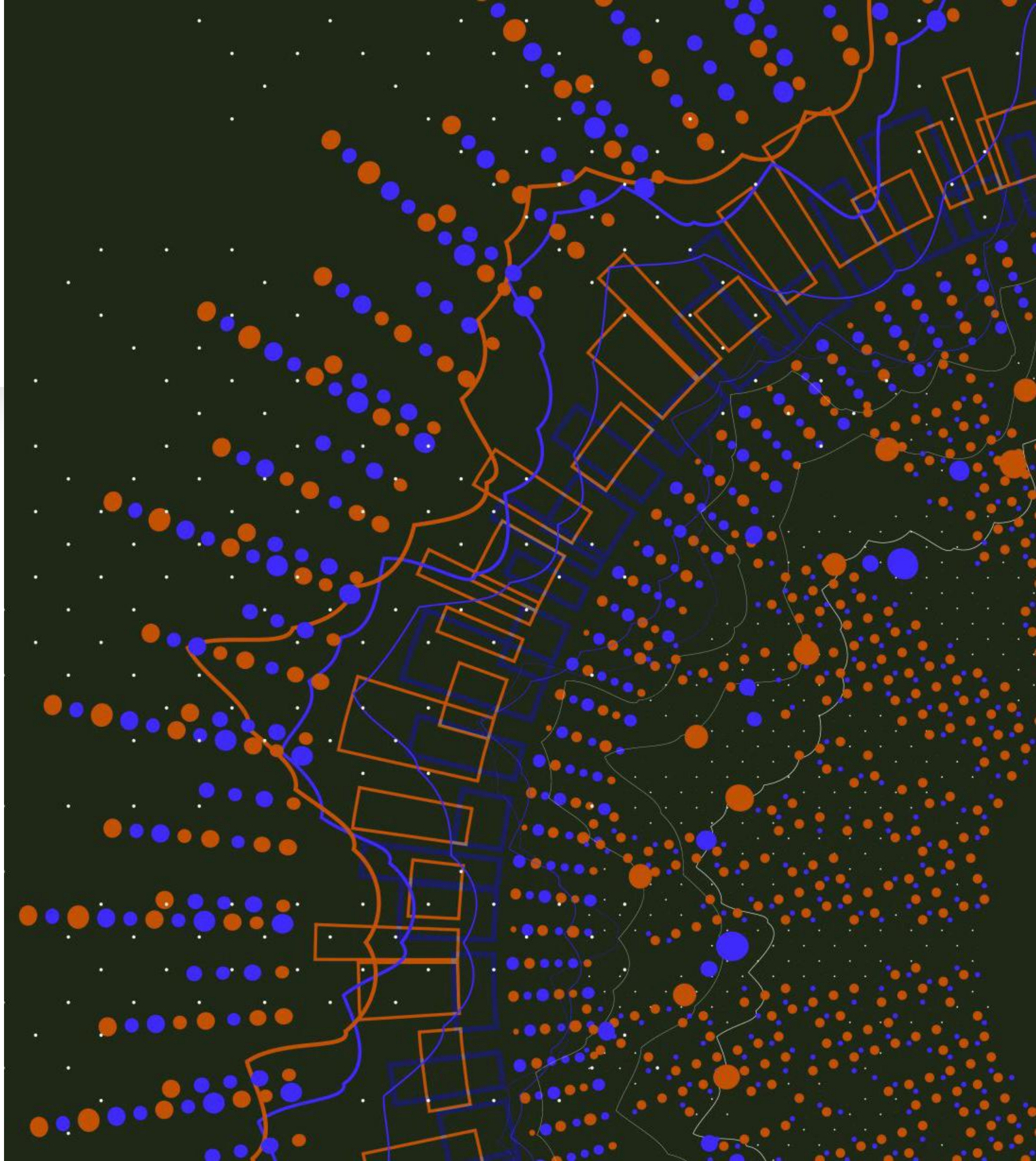
Marc Kamionkowski (Johns Hopkins University)

n3as summer school on multimessenger astrophysics , santa cruz, july 2024



Topics

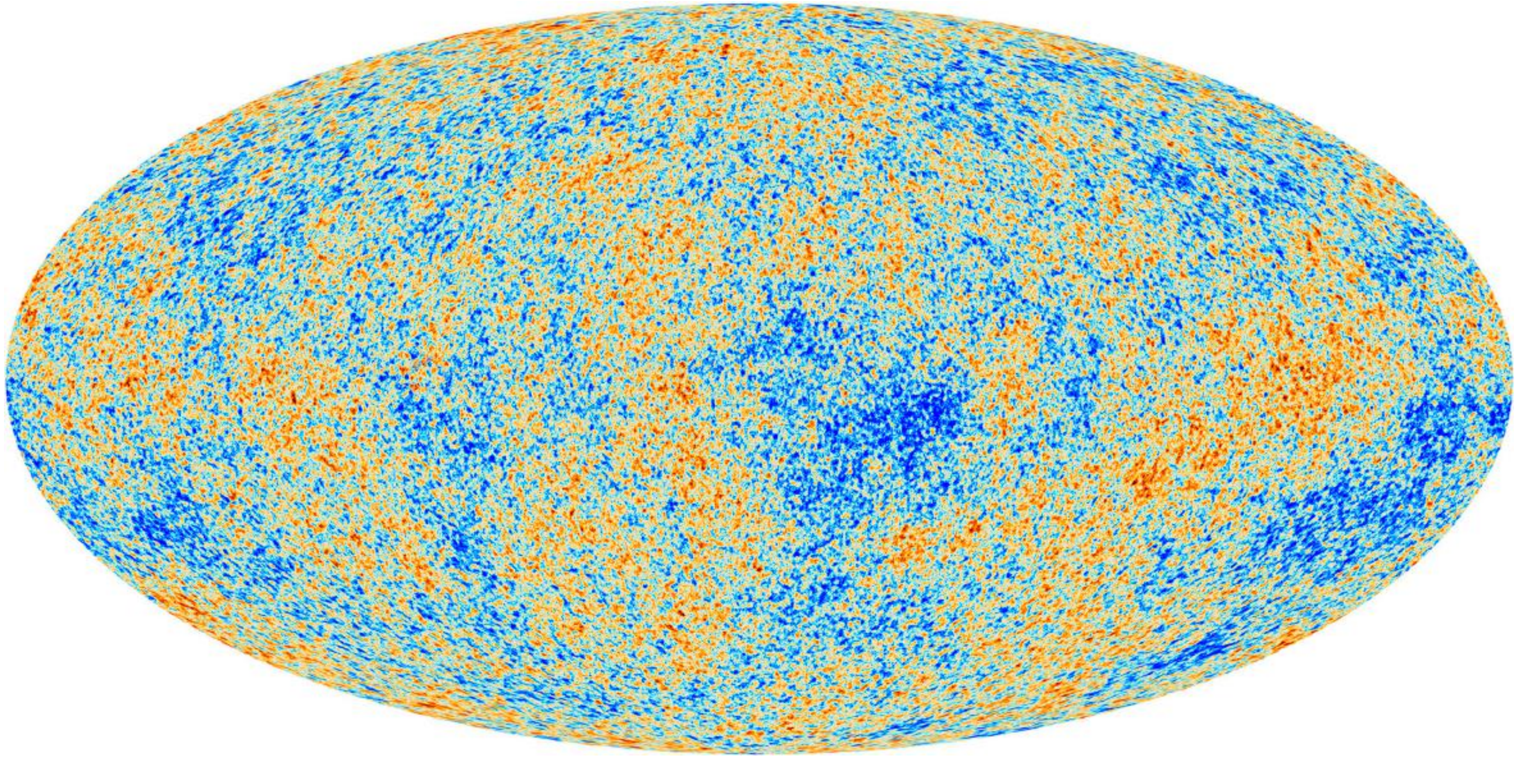
- Cosmology overview
- Hubble tension
- Parity in the CMB



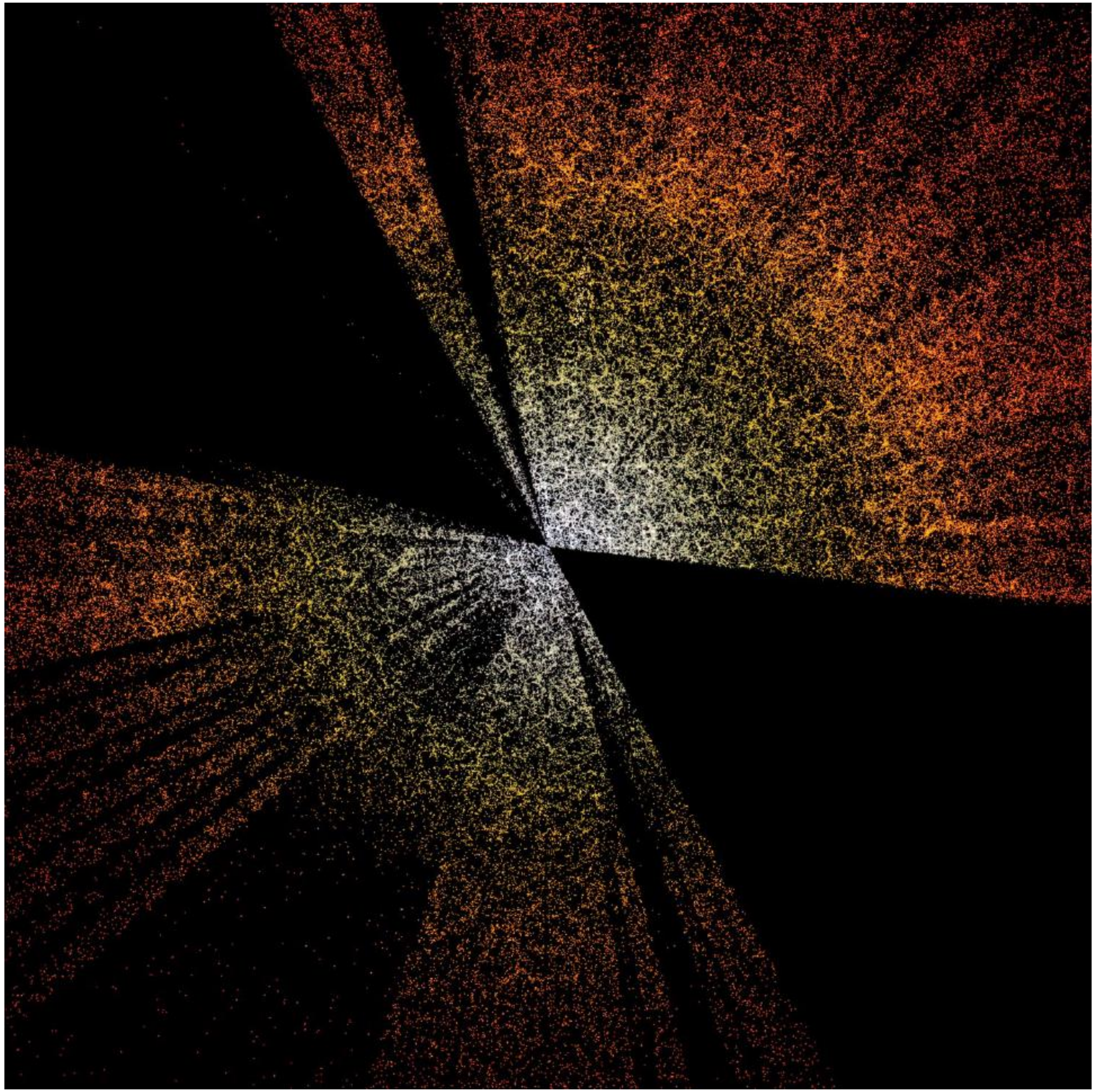
Cosmology

Study of origin and evolution of the Universe

Primary observables: CMB



Primary observables: Galaxy surveys



Quantitative observables

Statistical measures of mass distribution

Matter power spectrum P(k)

CMB angular power spectrum C_l

…..also lensing of galaxies, cmb, RSDs….

Classical measures

Direct measures of expansion rate (Hubble constant) H_0

Angular-diameter distances

….also age of Universe, Alcock-Paczynski, linear-theory growth factor…..

ΛCDM: the cosmological standard model

Flat (rather than open or closed) FRW Universe

4% baryons (i.e., protons, neutrons, electrons)

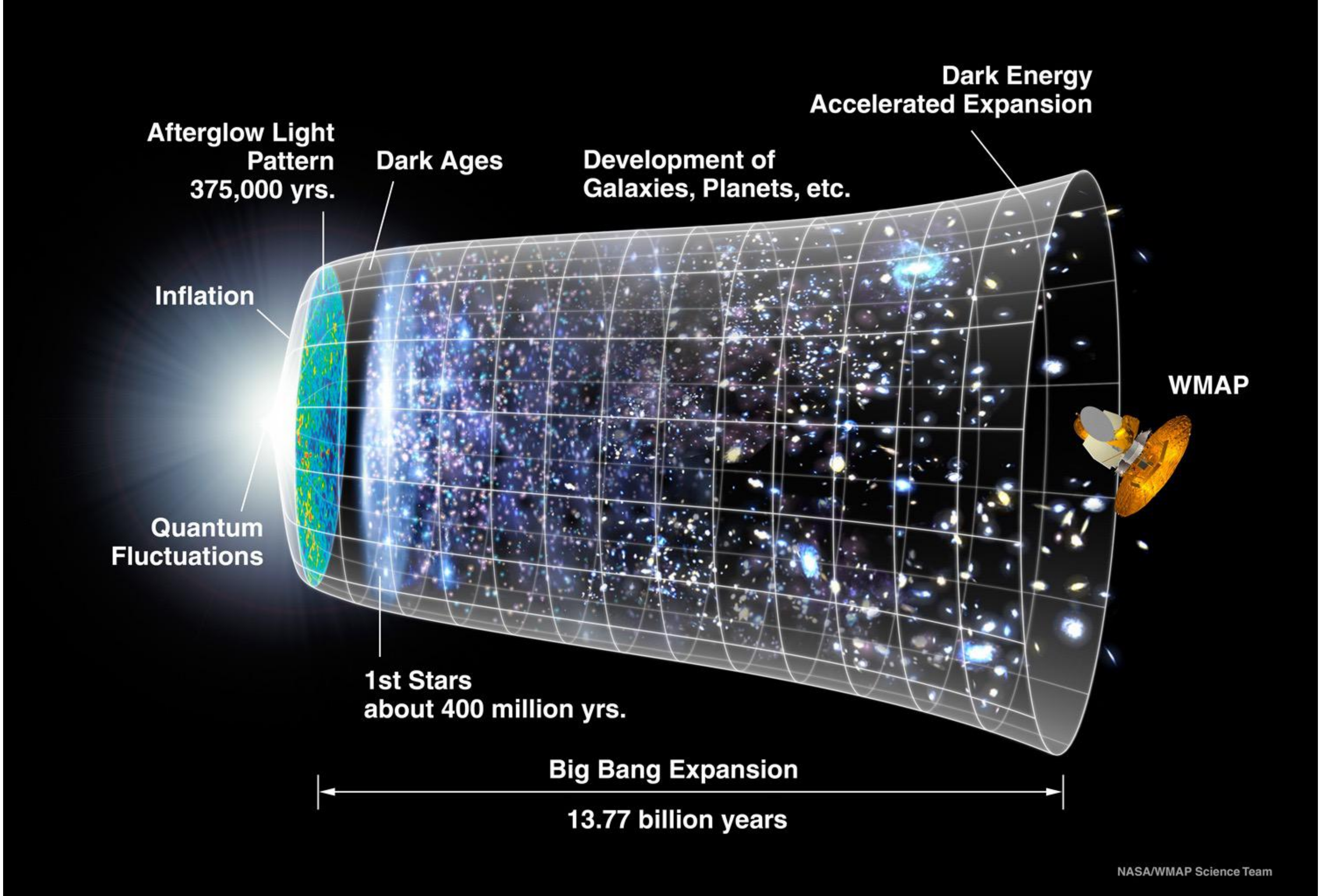
- With light-element abundances given by big-bang nucleosynthesis (BBN)

27% CDM: cold (i.e., slowly moving) dark (i.e., interacts only gravitationally) matter

69% cosmological constant

nearly scale-invariant spectrum of *adiabatic* and *gaussian* primordial density perturbations (as expected from simplest inflationary models)

H_0=67.4 km/sec/Mpc



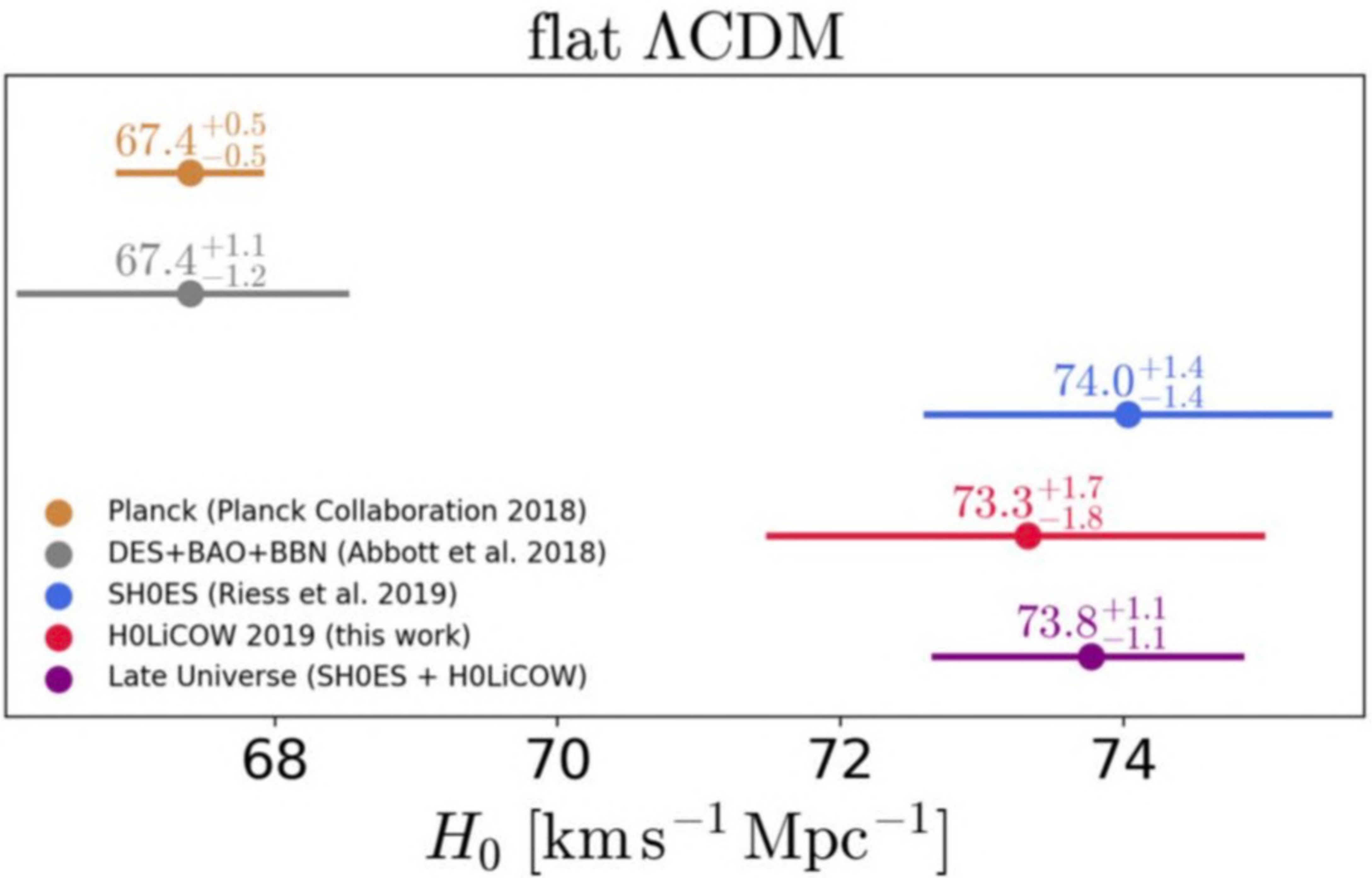
Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years
NASA/WMAP Science Team

Cosmological questions

- What is the dark matter
- What is responsible for accelerated cosmic expansion
- What is the physics of (or alternative to) inflation?
- Why a baryon asymmetry?
- What can we say about neutrinos

Some others

- Why does H_0 from CMB/LSS disagree with the directly observed value
- Does the Universe have a handedness?
- Why do the two halves of the CMB sky look different?

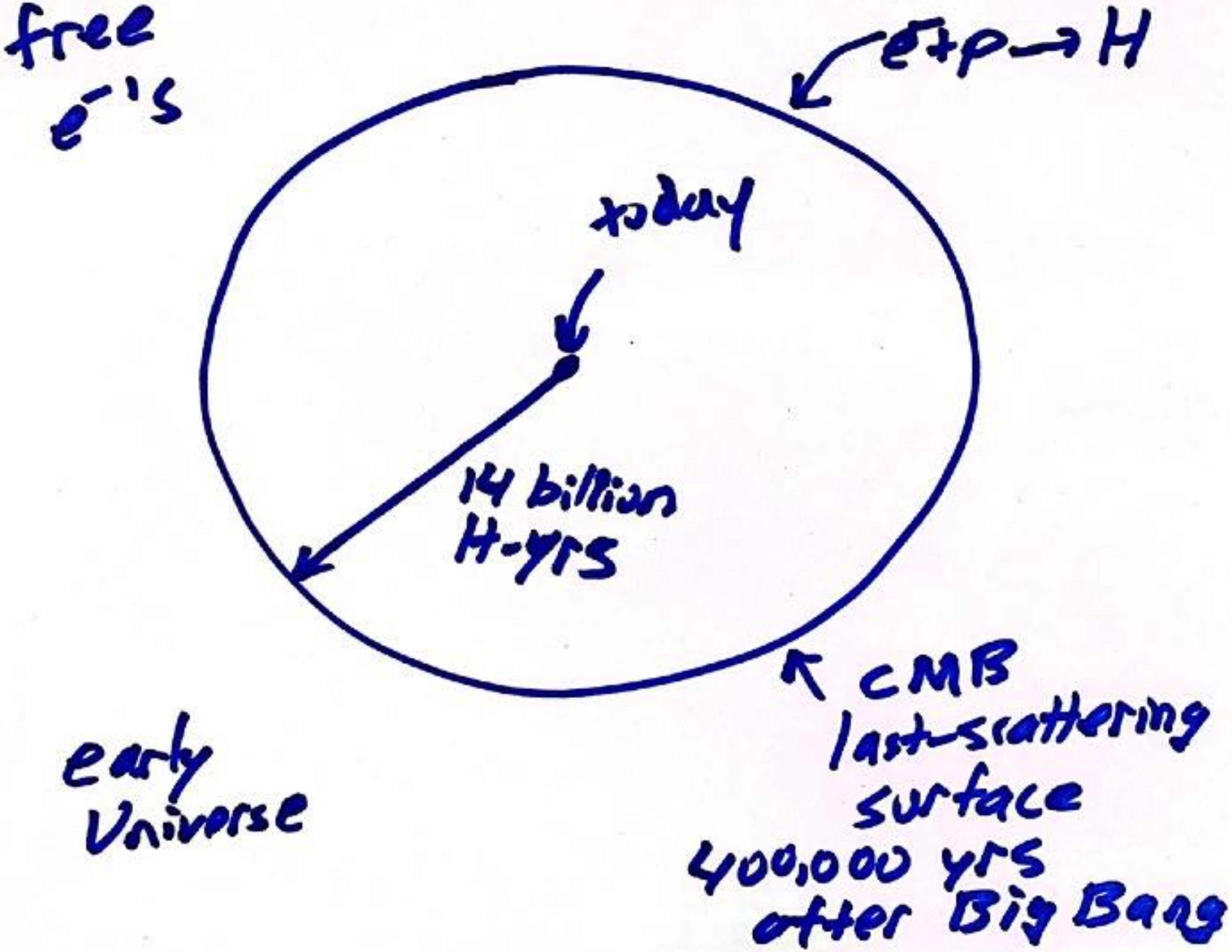

flat ΛCDM
$67.4^{+0.5}_{-0.5}$
$67.4^{+1.1}_{-1.2}$
$74.0^{+1.4}_{-1.4}$
$73.3^{+1.7}_{-1.8}$
$73.8^{+1.1}_{-1.1}$
Planck (Planck Collaboration 2018)
DES+BAO+BBN (Abbott et al. 2018)
SH0ES (Riess et al. 2019)
H0LiCOW 2019 (this work)
Late Universe (SH0ES + H0LiCOW)
68
70
72
74
H_0 [km s^{-1} Mpc^{-1}]

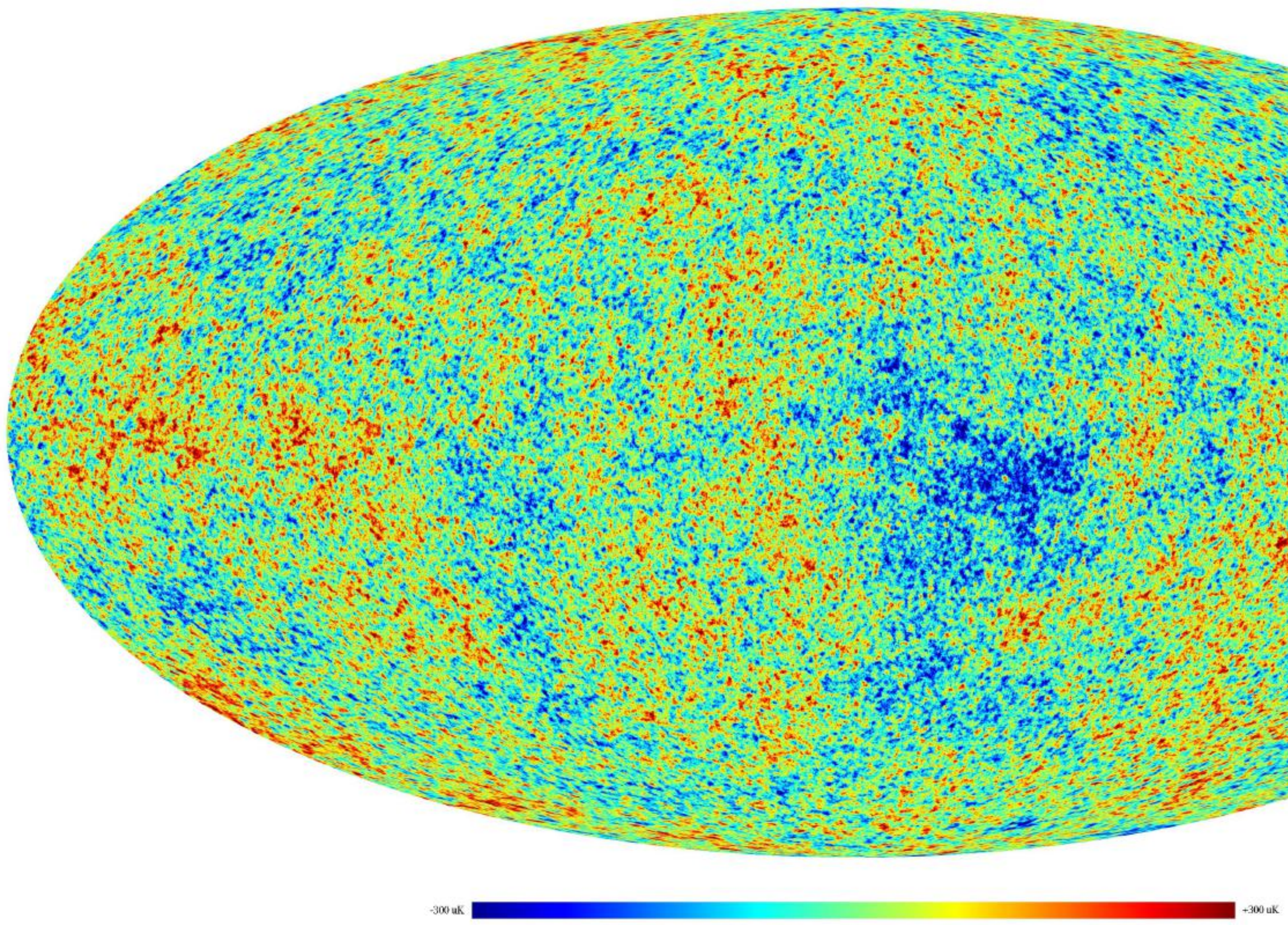
The Hubble "tension": Why does the expansion rate inferred from the CMB differ from that observed locally?

- Problem with local measurements?
- Problem with CMB measurements?
- Problems with both?
- New physics?

The Hubble "tension": Why does the expansion rate inferred from the CMB differ from that observed locally?

- Problem with local measurements?
- Problem with CMB measurements?
- Problems with both?
- New physics? ☑


free e⁻'s
e⁻+p → H
today
14 billion lt-yrs
CMB last scattering surface 400,000 yrs after Big Bang
early Universe

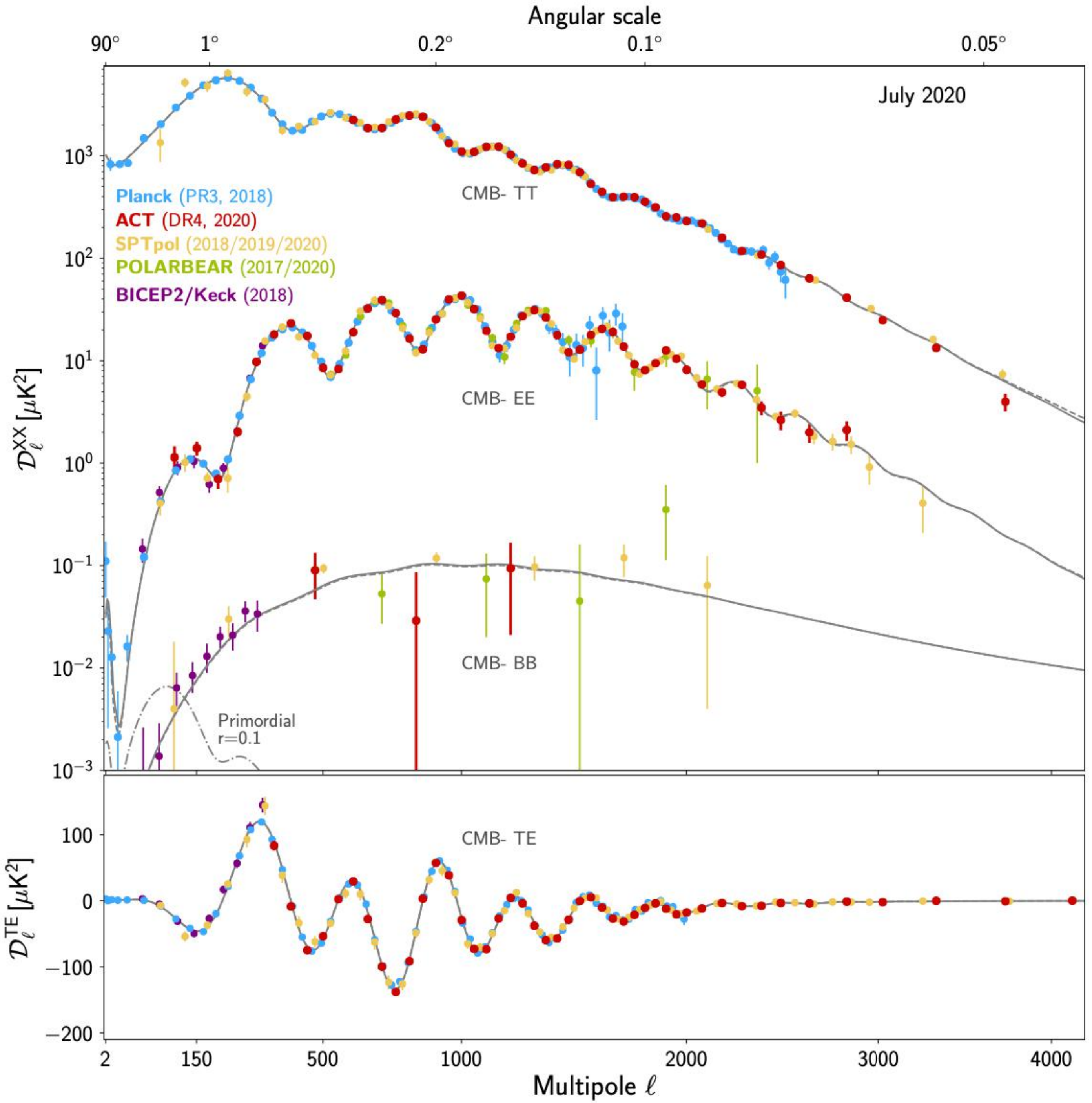

-300 uK
+300 uK

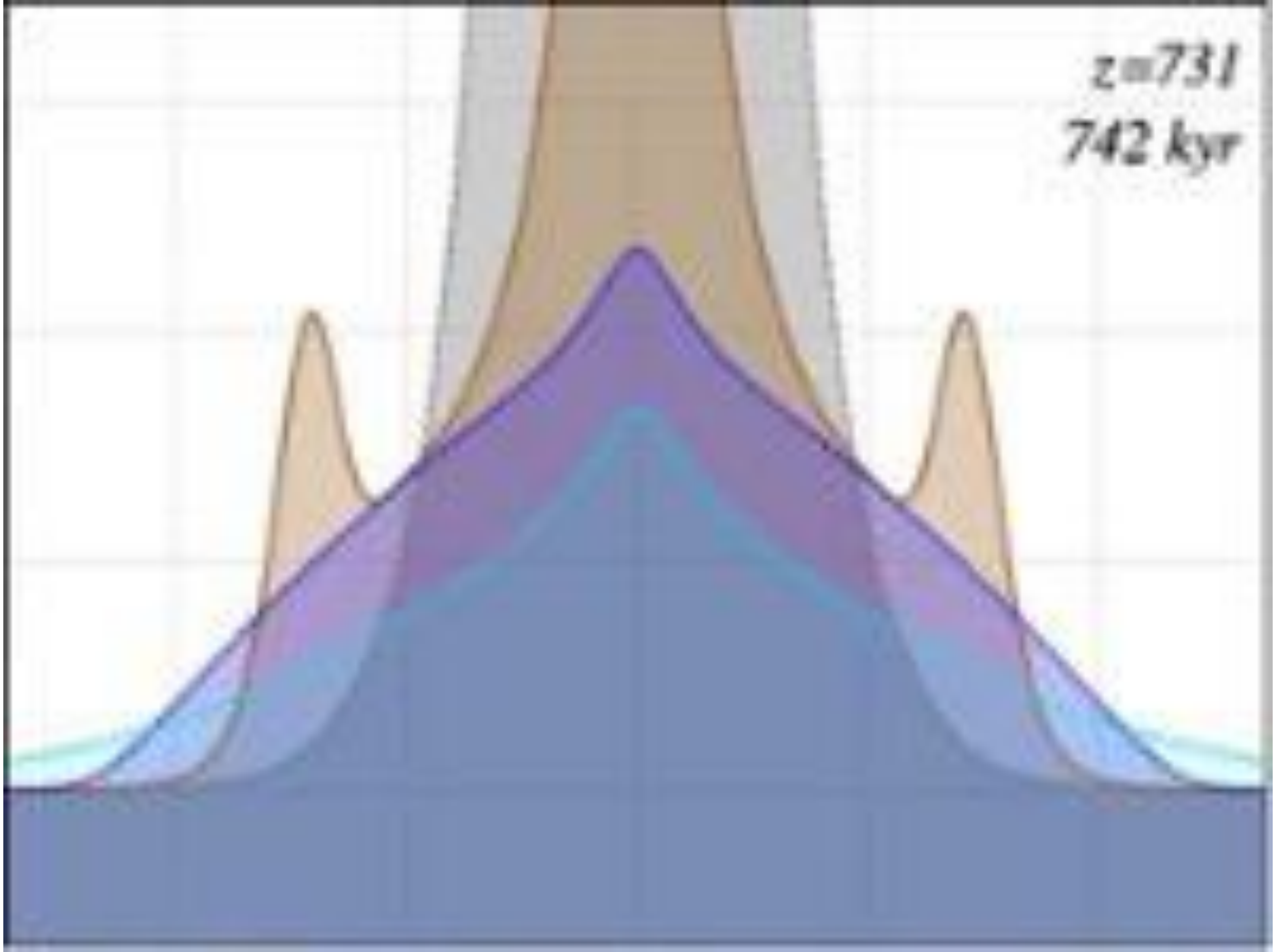
H_0 inferred from CMB from three angles:

- Sound-horizon angle θ_s
- Damping-scale angle θ_d
- Equality angle θ_{eq}

CMB power spectrum:

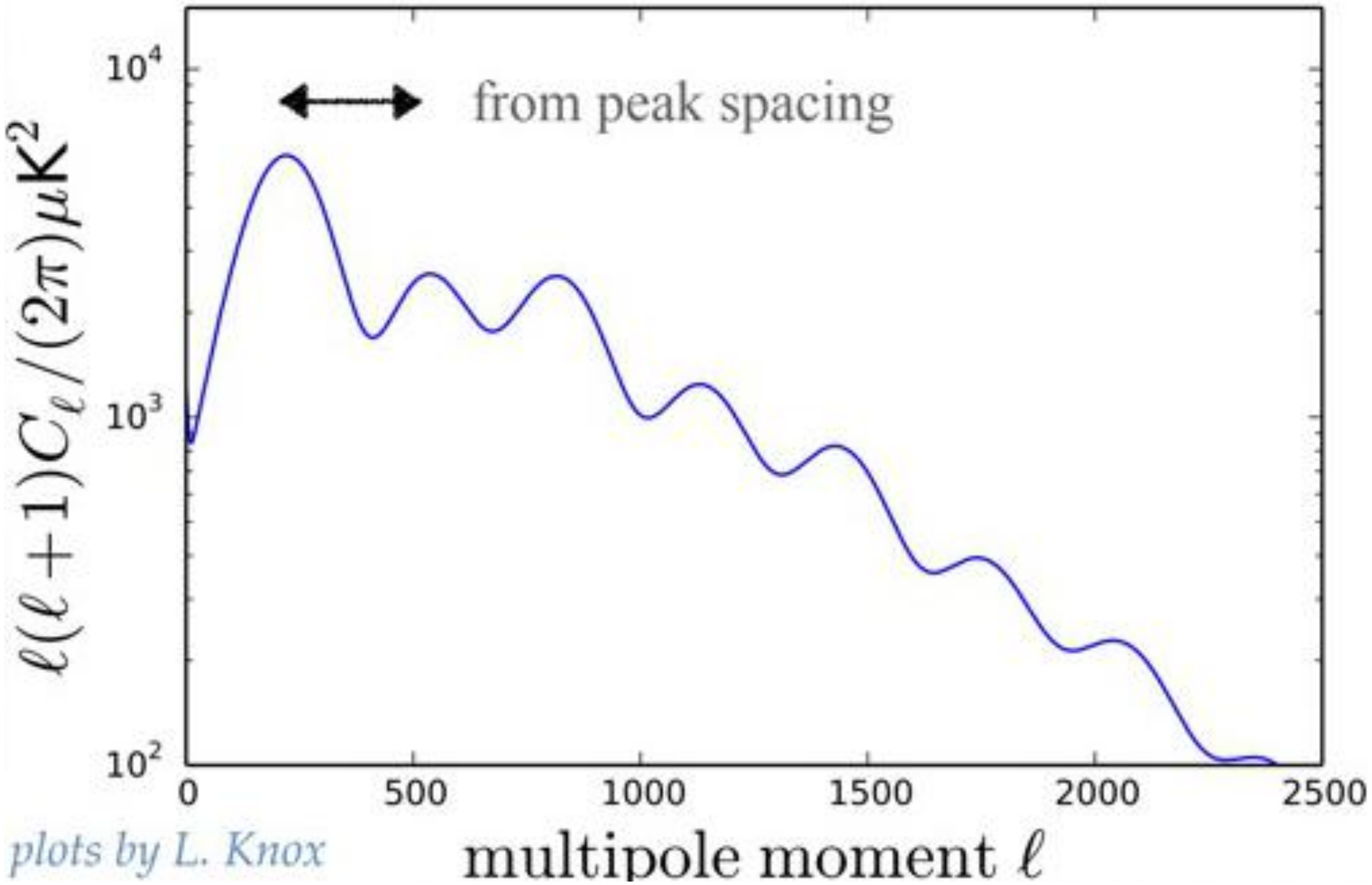
~ |Fourier transform|^2




z=731
742 kyr

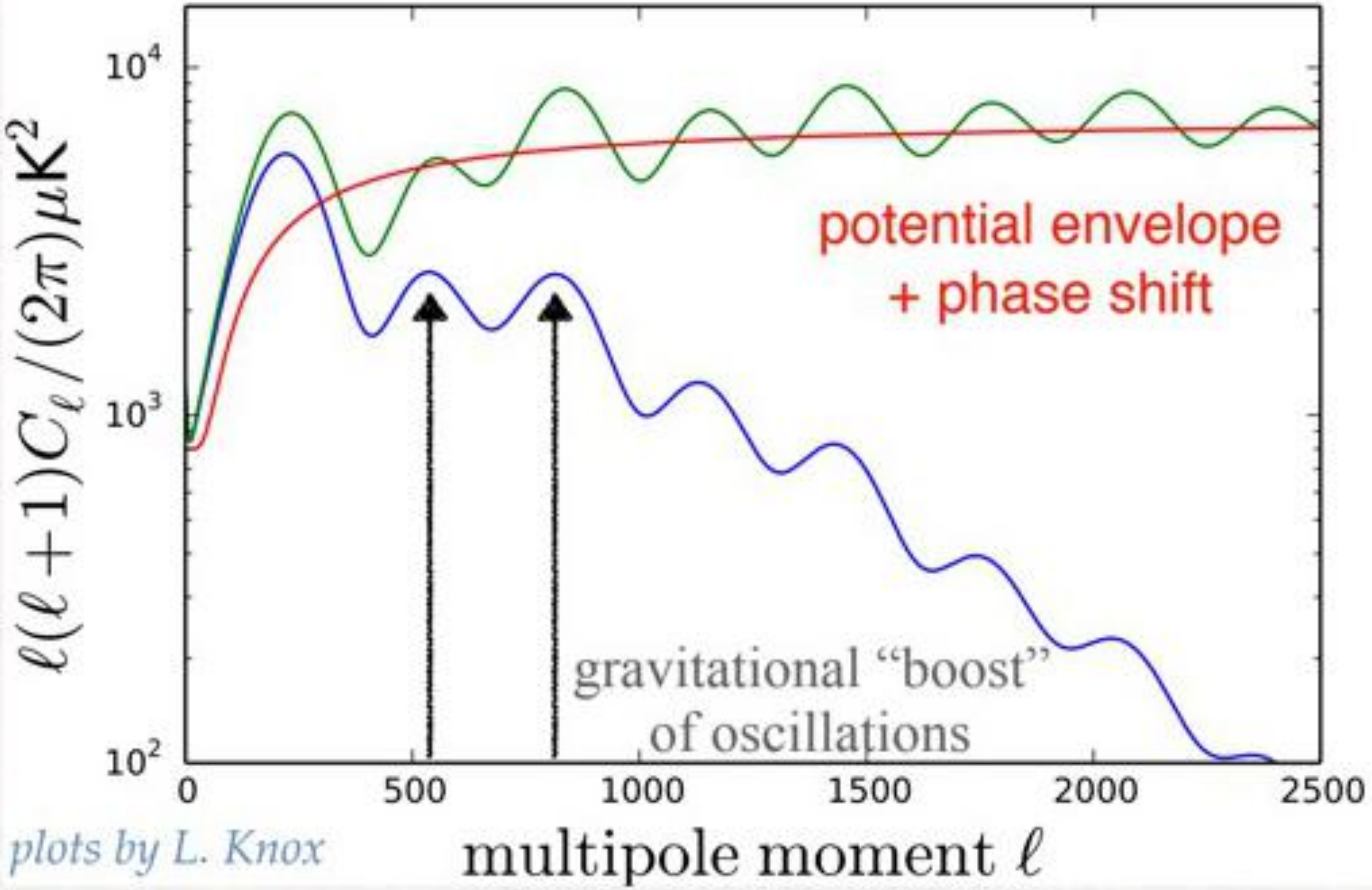
Acoustic peaks come from Fourier-space ”ringing” of these spherical shells

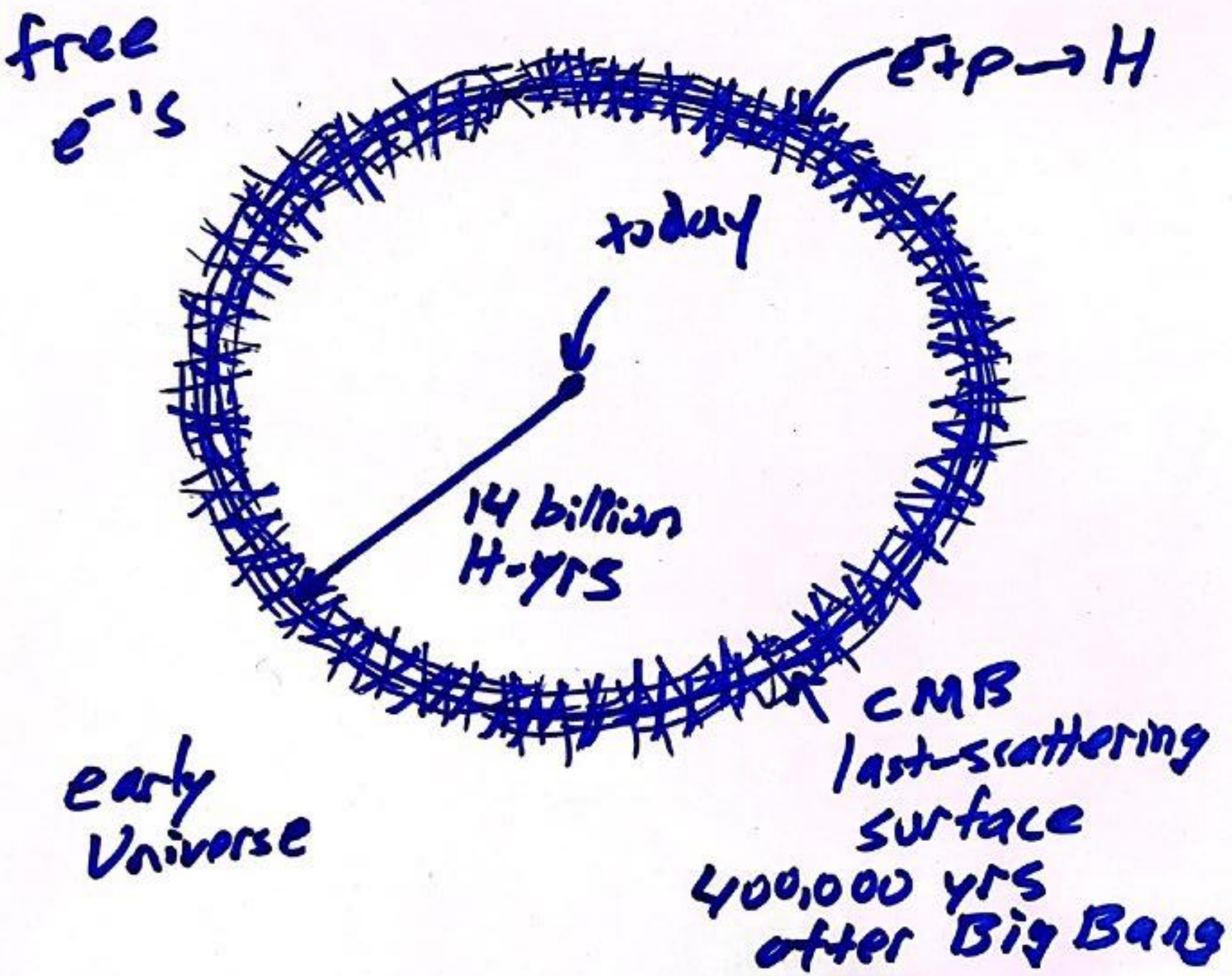
Wavenumber (l) $\propto$ (sound horizon)$^{-1}$



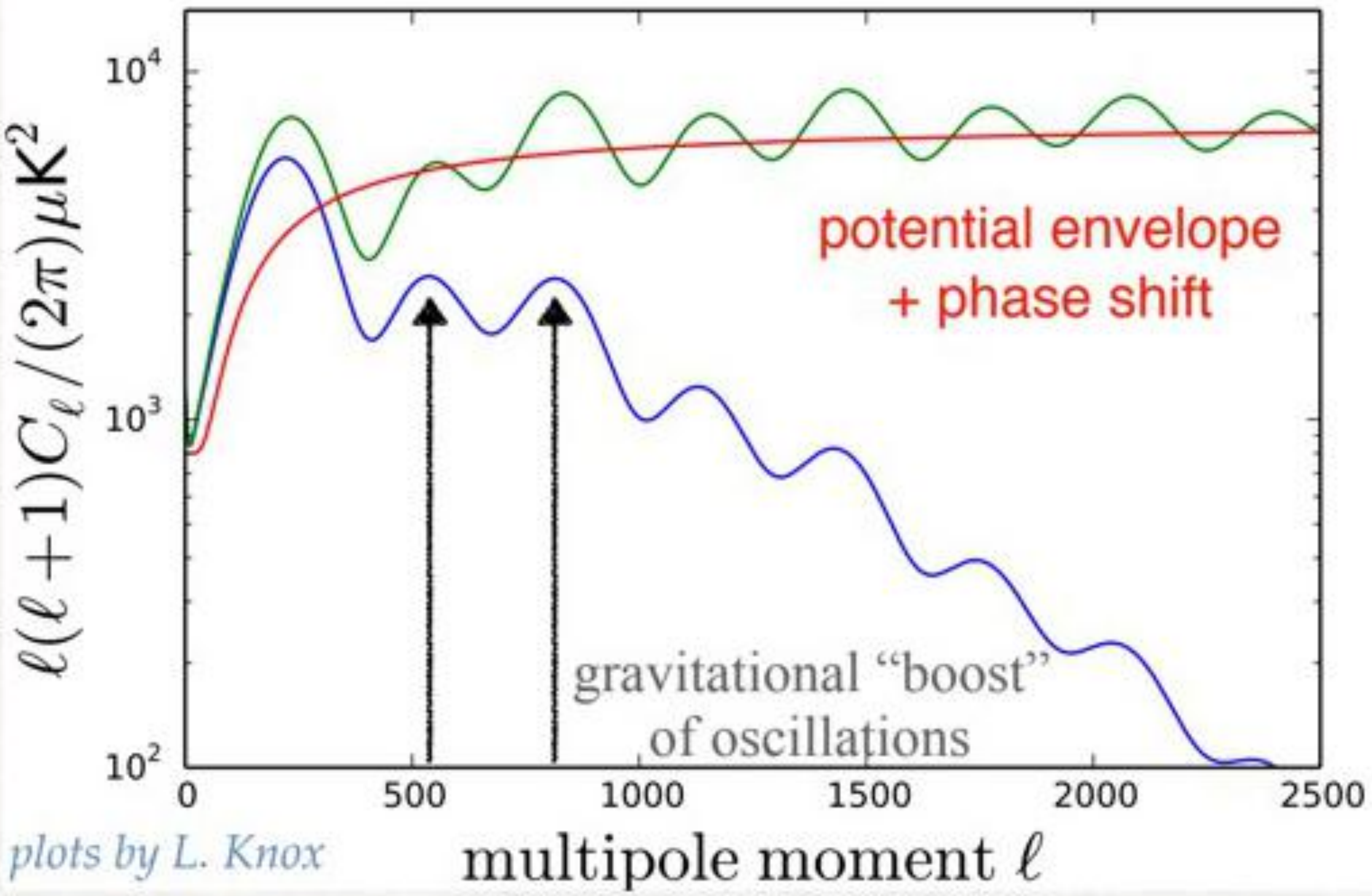
from peak spacing
$\ell(\ell+1)C_\ell/(2\pi)\mu K^2$
10^4
10^3
10^2
0
500
1000
1500
2000
2500
multipole moment ℓ
plots by L. Knox

θ_{eq} horizon size at matter-radiation equality ~ 0.81




free
e⁻'s
e+p→H
today
14 billion
lt-yrs
early
Universe
CMB
last-scattering
surface
400,000 yrs
after Big Bang

θ_{eq} horizon size at matter-radiation equality ~ 0.81



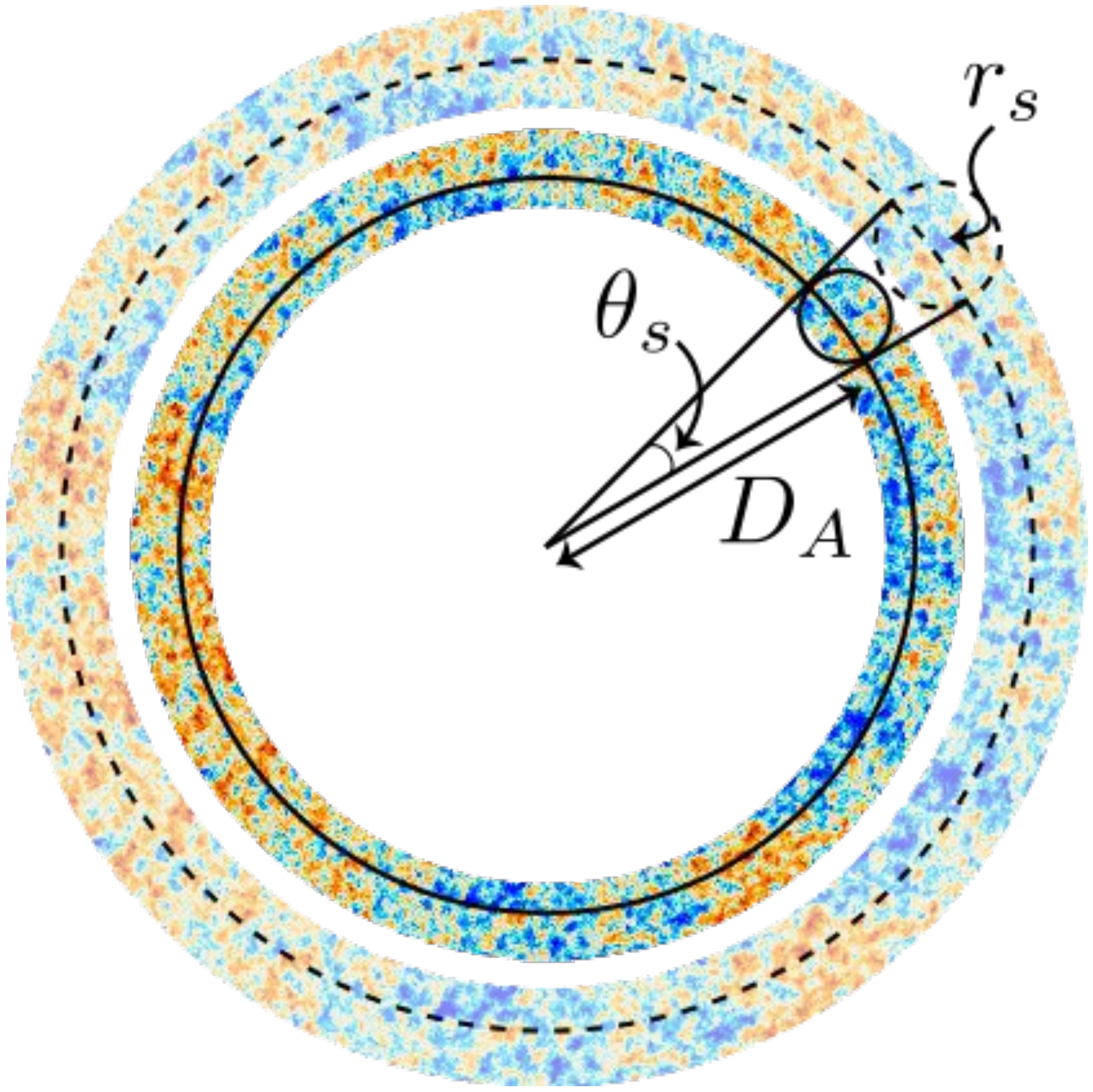
plots by L. Knox

- Three angles:
  - sound horizon
  - damping scale
  - MR equality

- depend on
  - dark-matter density
  - baryon density
  - Hubble constant

- Of three angles, sound-horizon angle determined best (1 part in 10^4)

$$\theta_s = \frac{r_s}{D_A}$$



$$D_A = \frac{c}{H_0} \int_{t_{rec}}^{t_0} \frac{dt/t_0}{[\rho(t)/\rho_0]^{1/2}}$$

$$r_s = \frac{1}{H_{\rm rec}} \int_0^{t_{\rm rec}} \frac{c_s(t)\, dt/t_{\rm rec}}{[\rho(t)/\rho(t_{\rm rec})]^{1/2}}$$

$$H_0 = H_{\rm rec} \frac{\int_{t_{\rm rec}}^{t_0} \frac{c\,dt/t_0}{[\rho(t)/\rho_0]^{1/2}}}{\int_0^{t_{\rm rec}} \frac{c_s(t)\,dt/t_{\rm rec}}{[\rho(t)/\rho(t_{\rm rec})]^{1/2}}}$$

To increase H_0, can

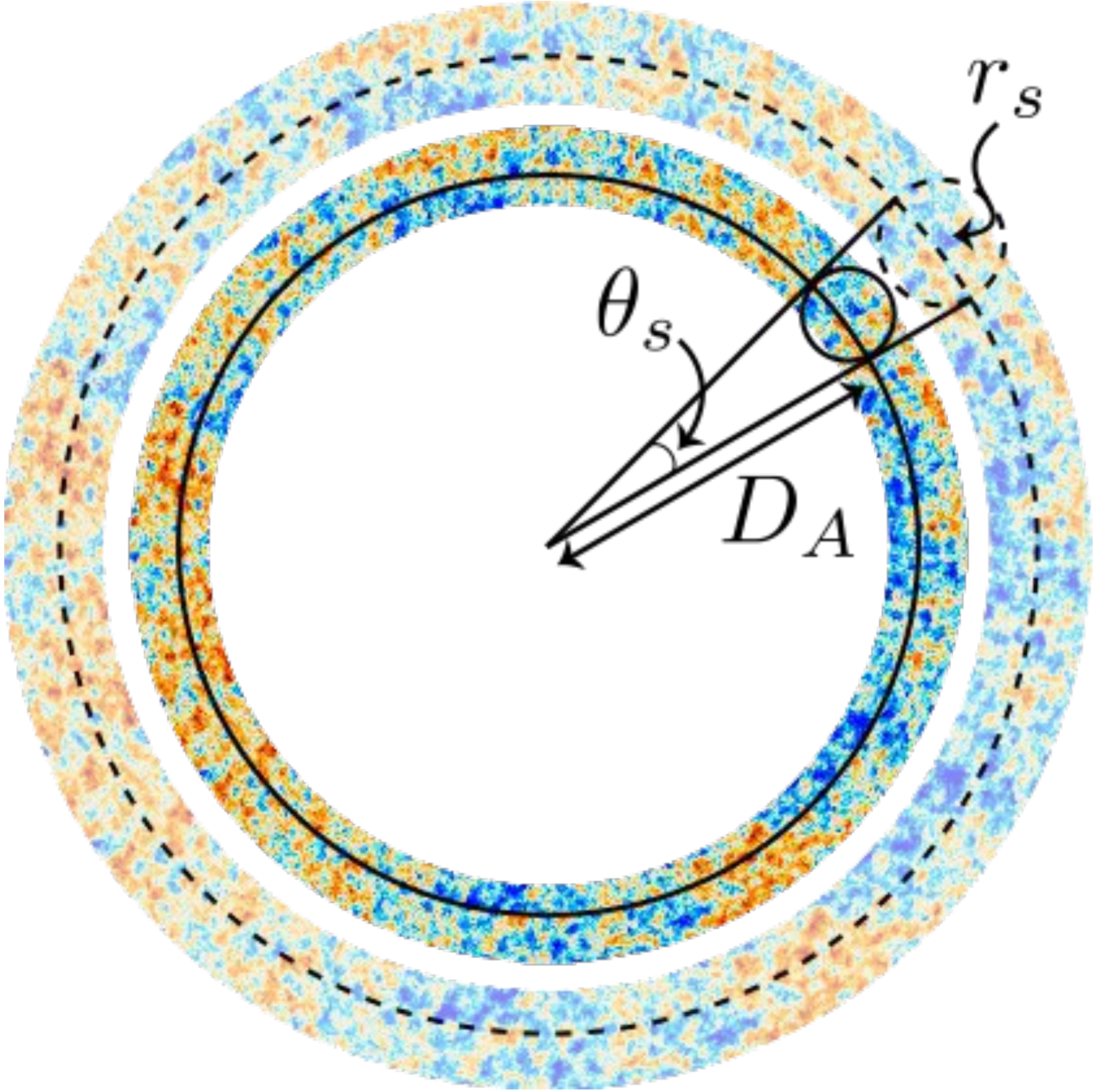
- Decrease matter density at late times
- Decrease sound speed in early Universe
- Increase matter density at early times

$$H_0 = H_{\rm rec} \frac{\int_{t_{\rm rec}}^{t_0} \frac{c\, dt/t_0}{[\rho(t)/\rho_0]^{1/2}}}{\int_0^{t_{\rm rec}} \frac{c_s(t)\, dt/t_{\rm rec}}{[\rho(t)/\rho(t_{\rm rec})]^{1/2}}}$$

To increase H_0, can

- Decrease matter density at late times (late-time solutions)
- Decrease sound speed in early Universe
- Increase matter density at early times

$$H_{\rm cmb} \propto \frac{1}{D_A} \propto \frac{\theta_s}{r_s}$$



$$\theta_s = \frac{r_s}{D_A}$$

Late-time solutions

Modify late expansion history to increase D_A

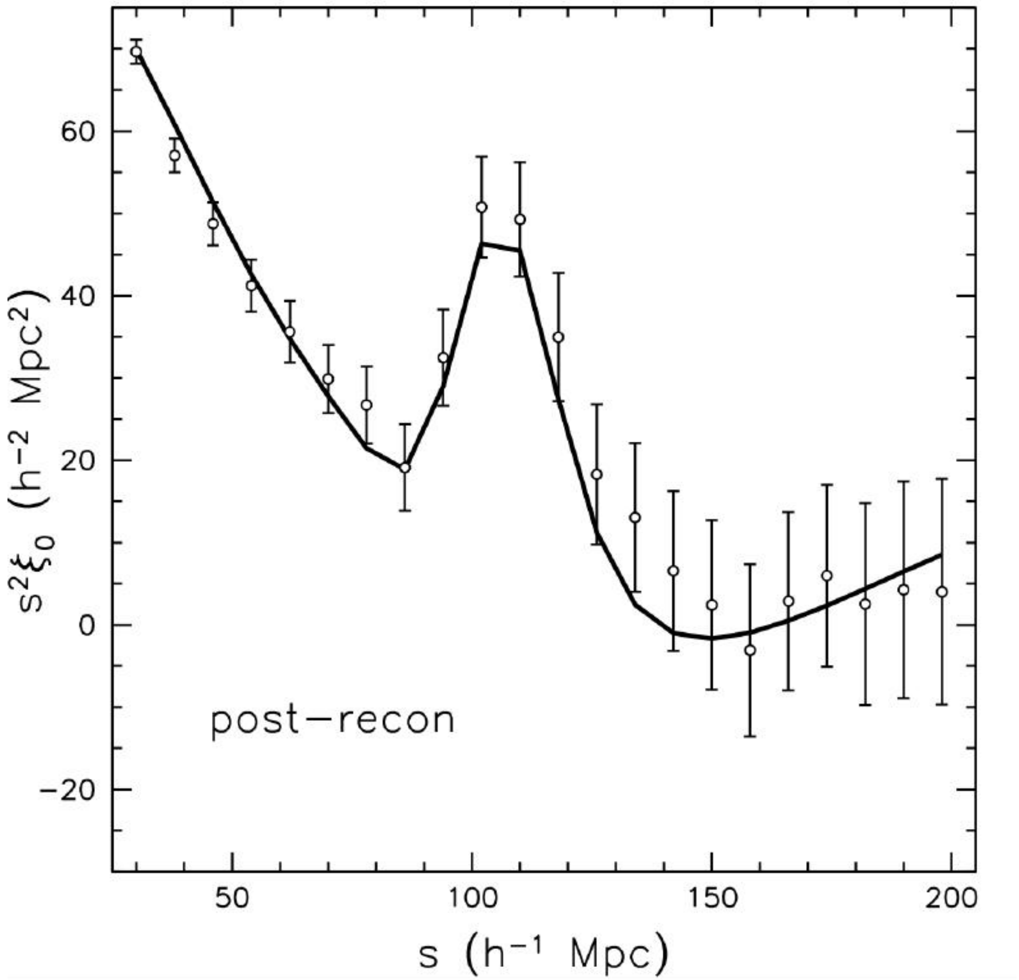
e.g., exotic dark energy; phantom energy; exotic dark matter;

Requires energy density *smaller* than in standard model: negative-density matter?!?! Violation of null energy condition?!?!

Late-time solutions: Empirically disfavored by BAO in galaxy distribution

Sound horizon imprinted on galaxy distribution measured in “redshift space”

Provides standard ruler to infer H_0 --> lower H_0



SDSS-BOSS Collaboration
Anderson et al. 2013

$$H_0 = H_{\rm rec} \frac{\int_{t_{\rm rec}}^{t_0} \frac{c\, dt/t_0}{[\rho(t)/\rho_0]^{1/2}}}{\int_0^{t_{\rm rec}} \frac{c_s(t)\, dt/t_{\rm rec}}{[\rho(t)/\rho(t_{\rm rec})]^{1/2}}}$$

To increase H_0, can

- Decrease matter density at late times (late-time solutions)
- Decrease sound speed in early Universe
- Increase matter density at early times

$$H_0 = H_{\rm rec} \frac{\int_{t_{\rm rec}}^{t_0} \frac{c\,dt/t_0}{[\rho(t)/\rho_0]^{1/2}}}{\int_0^{t_{\rm rec}} \frac{c_s(t)\,dt/t_{\rm rec}}{[\rho(t)/\rho(t_{\rm rec})]^{1/2}}}$$

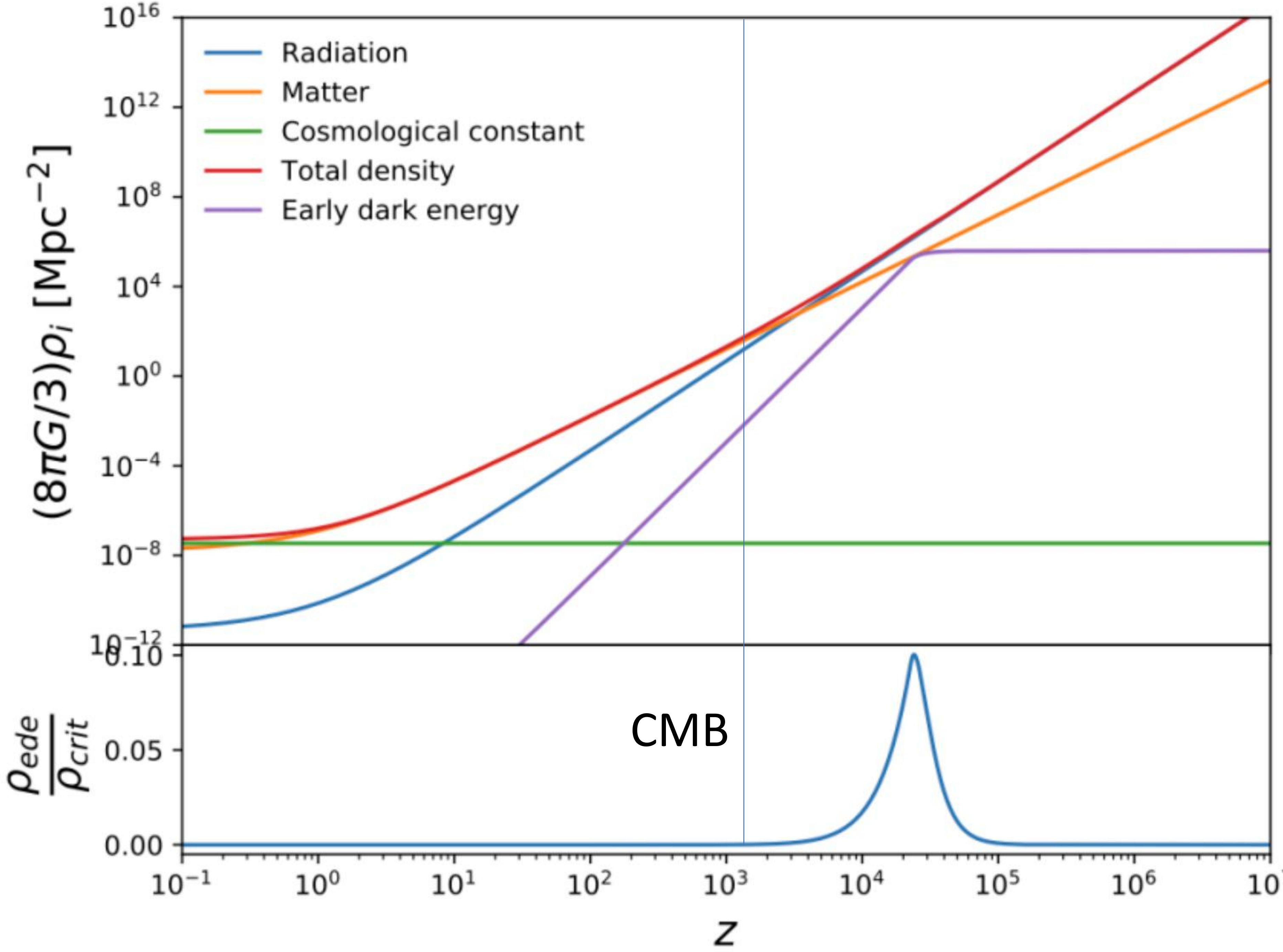
To increase H_0, can

- Decrease matter density at late times (late-time solutions)
- Decrease sound speed in early Universe
- Increase matter density at early times *(early dark energy)*

Possible solution: Early dark energy

(Karwal,MK, 2016)

- Suppose early Universe expands faster
- Then less time for sound waves to propagate
- Smaller sound horizon
- Larger H_0 inferred from CMB



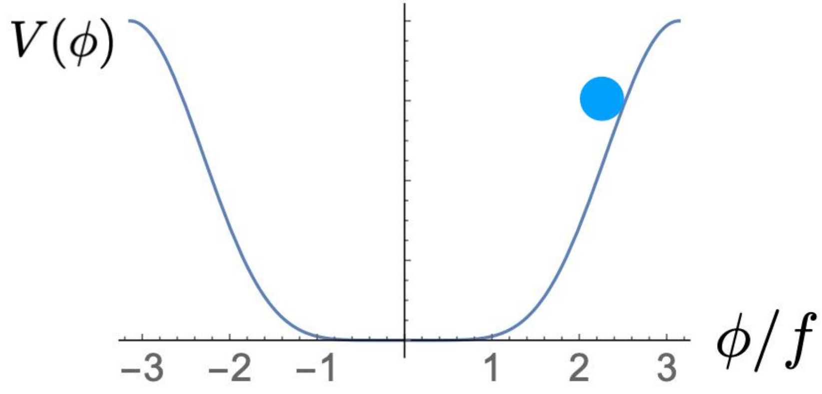
Radiation
Matter
Cosmological constant
Total density
Early dark energy
$(8\pi G/3)\rho_i$ [Mpc^{-2}]
10^{16}
10^{12}
10^{8}
10^{4}
10^{0}
10^{-4}
10^{-8}
10^{-12}
$\frac{\rho_{ede}}{\rho_{crit}}$
0.10
0.05
0.00
CMB
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
z

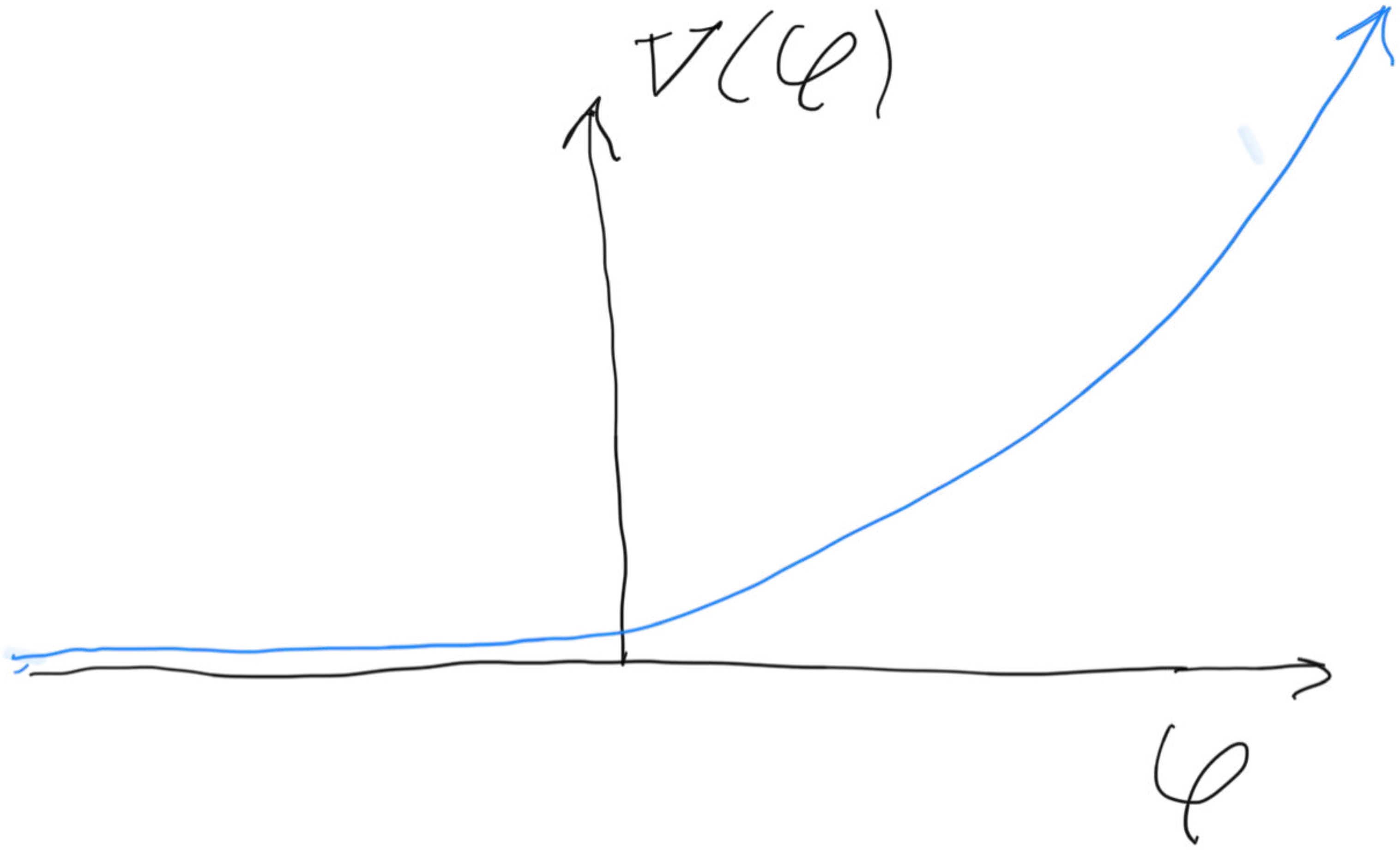
- Behaves like cosmological constant at late times; decays as

$$(\text{scale factor})^{(2n-2)/(2n+2)}$$

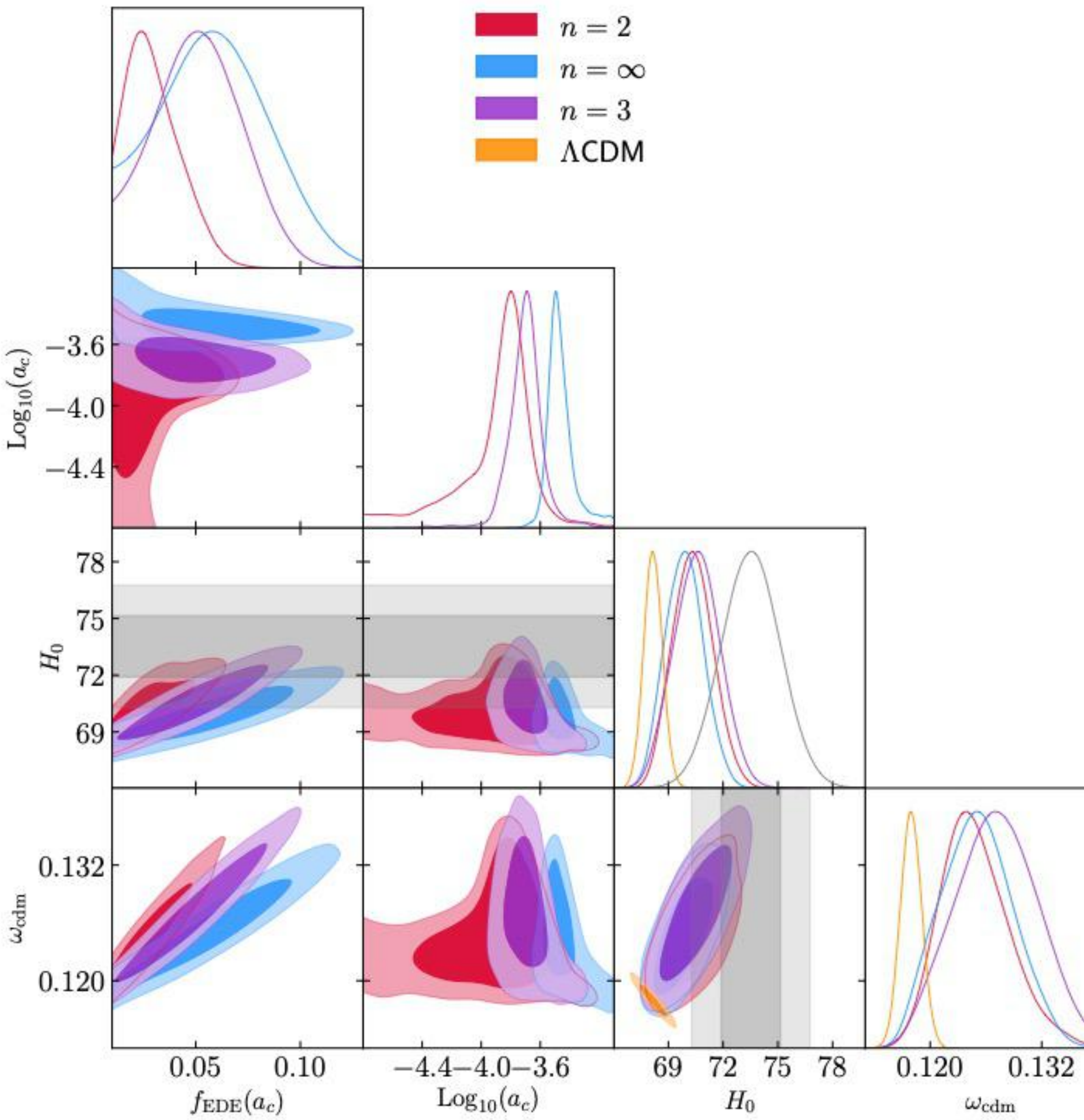
at late times (MK, Pradler & Walker, 2014)

$$V(\phi) \propto \left[1 - \cos\left(\frac{\phi}{f}\right)\right]^n$$





$V(\varphi)$
φ

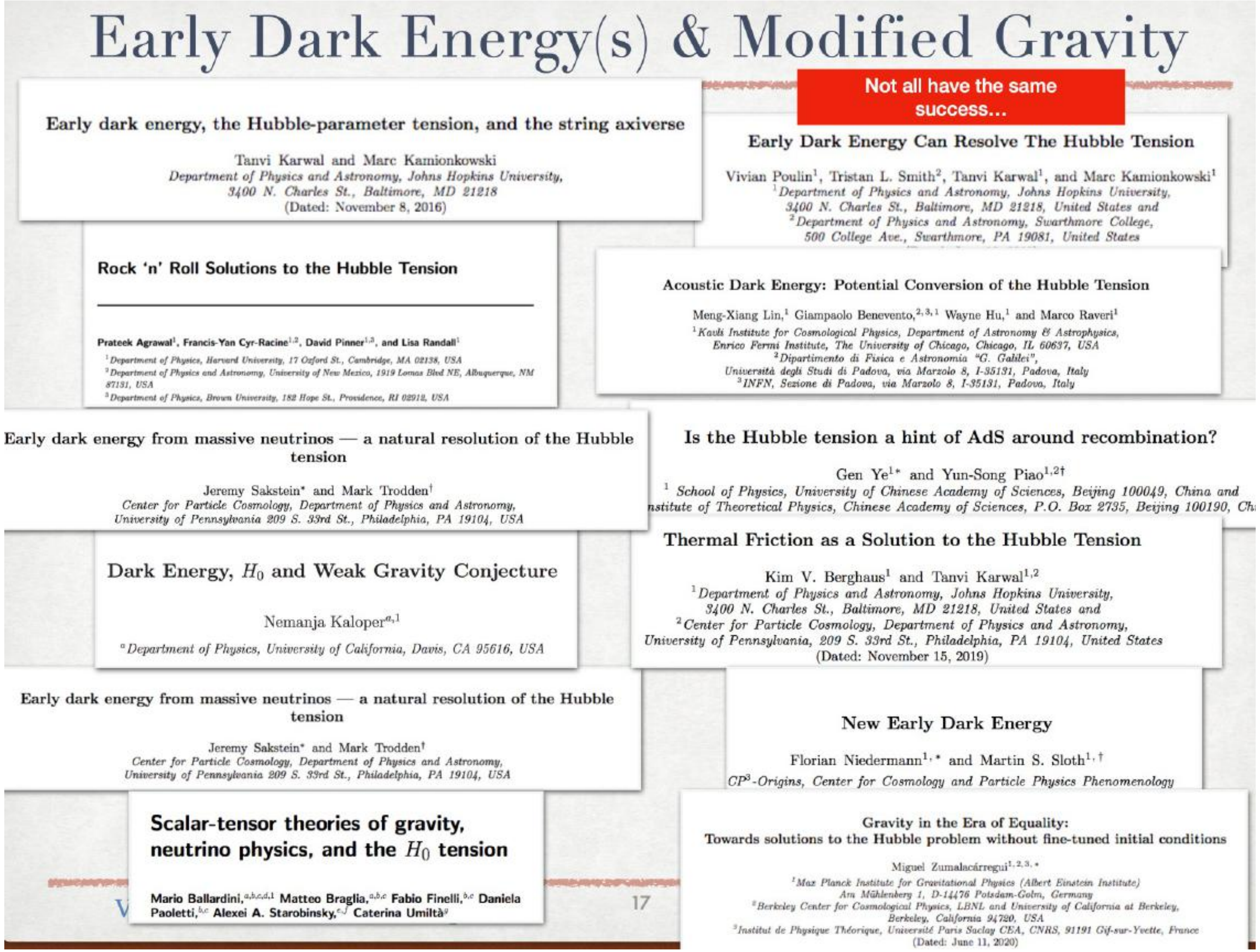


Poulin et al. 2018

New tests of scenario:

Measurements of fine-grain features of CMB polarization by ACTPol/SPT3G/Simons/CMB-S4/etc

Since then…..tons of EDE models



Since then….new measurements from SPT-3G, ACTPol, DES, etc. tend to disfavor EDE, but do not necessarily “rule it out”.

Other possibilities:

- Change to recombination
- Variable electron mass

  (Hart, Chluba, 2019++; Lee, Ali-Haimoud, Schoneburg, Poulin, 2024; Lynch, Knox, Chluba 2024)

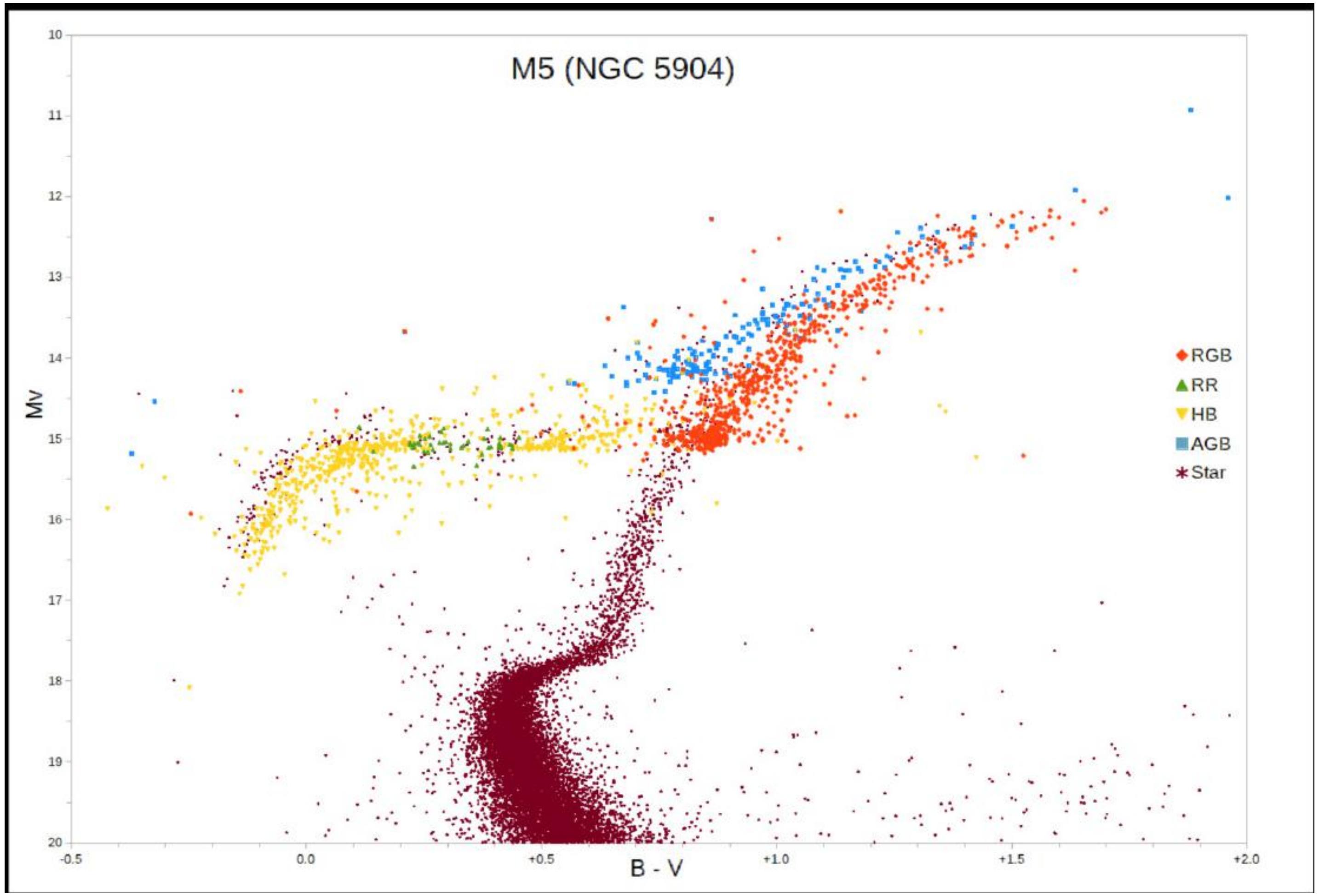
- Primordial magnetic fields
  (Jedamzik, Pogosian, 2020++)

- Variable m_e and spatial curvature works pretty well
  (Poulin, Smith, et al., in prep)

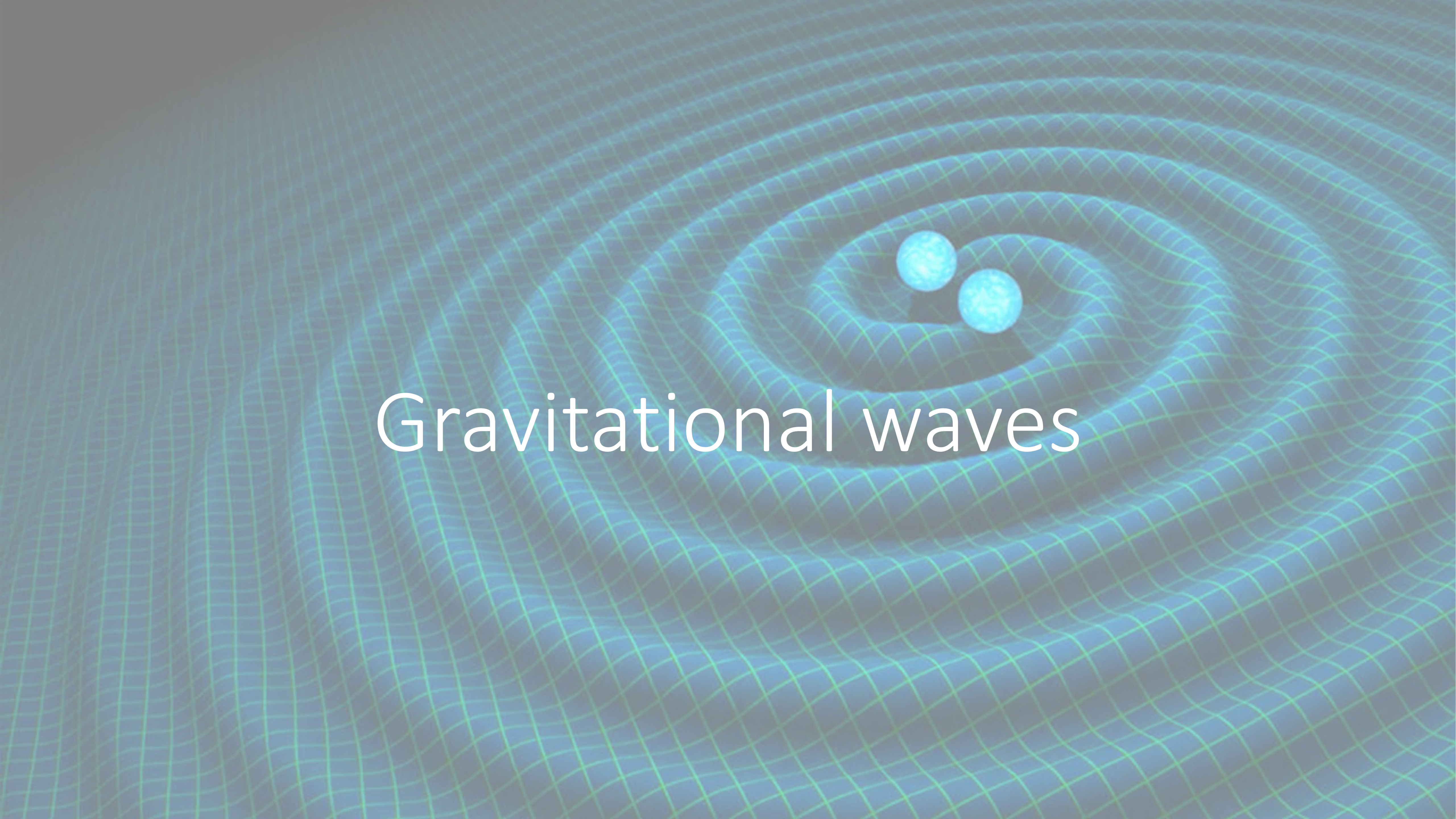
What to look forward to

Gravitational lensing time delays

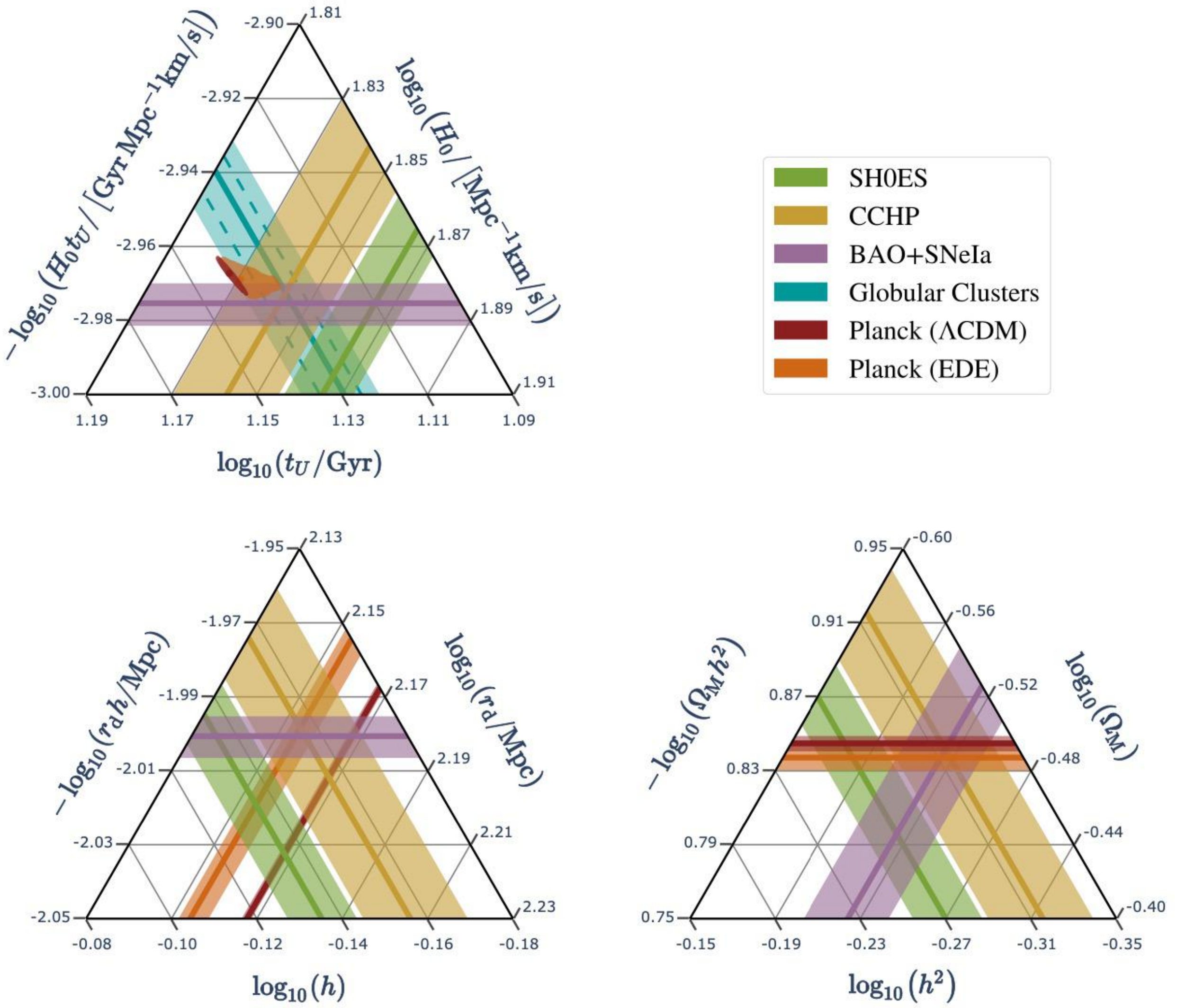
Tip of the red-giant branch



Gravitational waves



Globular-cluster ages (Bernal et al. 2021)

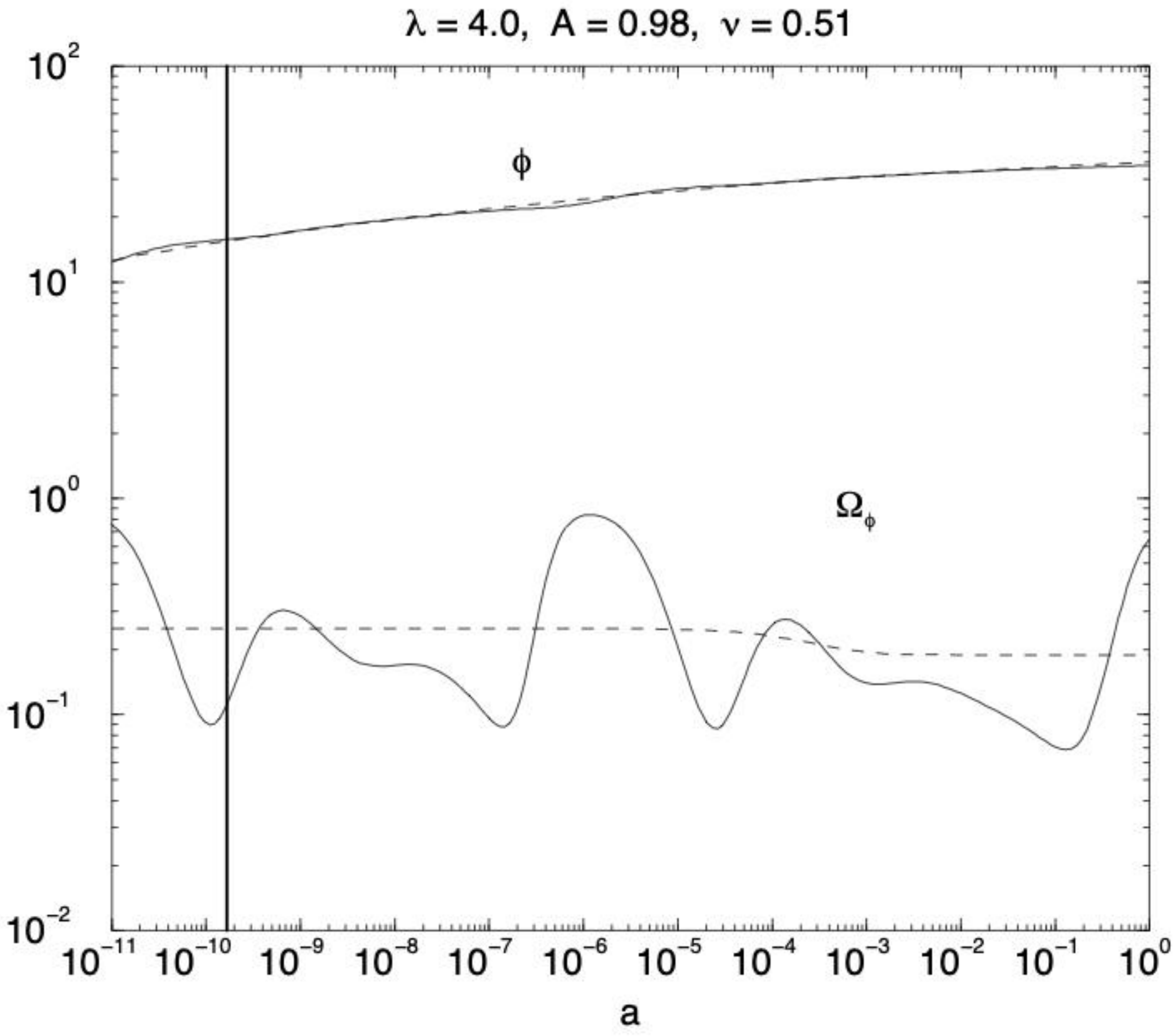


Recurrent dark energy?

- $\Lambda \neq 0$ today
- Inflation → $\Lambda \neq 0$ in the early Universe
- EDE (if this is what's going on) → $\Lambda \neq 0$ at z ~ 10,000

- Recurring periods of "Λ-like" behavior throughout cosmic history?

E.g. tracking oscillating energy (Dodelson, Kaplinghat, Stewart, astro-ph/0002360; Griest, astro-ph/0202052)

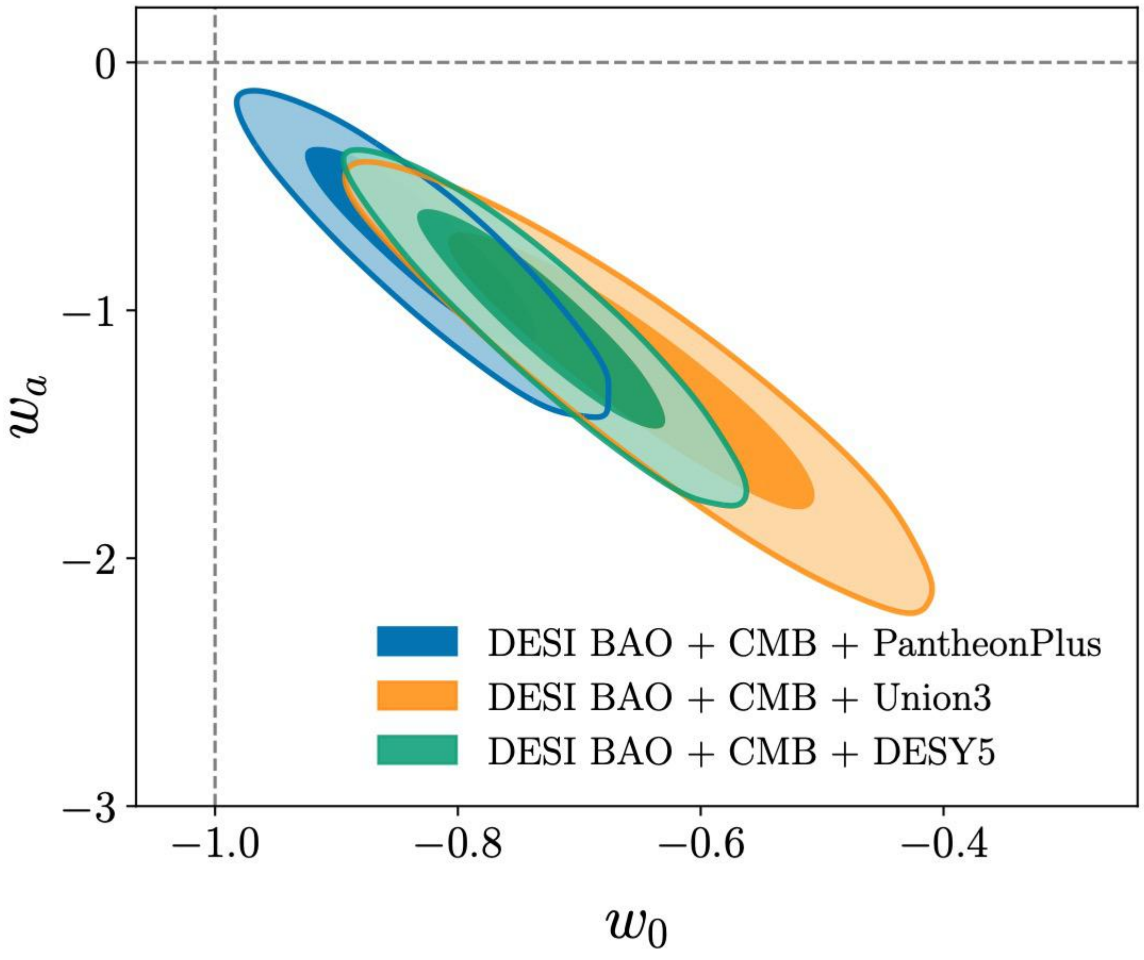


String Axiverse? (MK, Pradler, Walker, 2014; based on Arvanitaki et al., 2009; Svrcek & Witten, 2006)

- ~100 axion fields
  - masses distributed logarithmically

- At each Log(Hubble time) , chance that axion field may act like dark energy

Recent results: DESI 2024



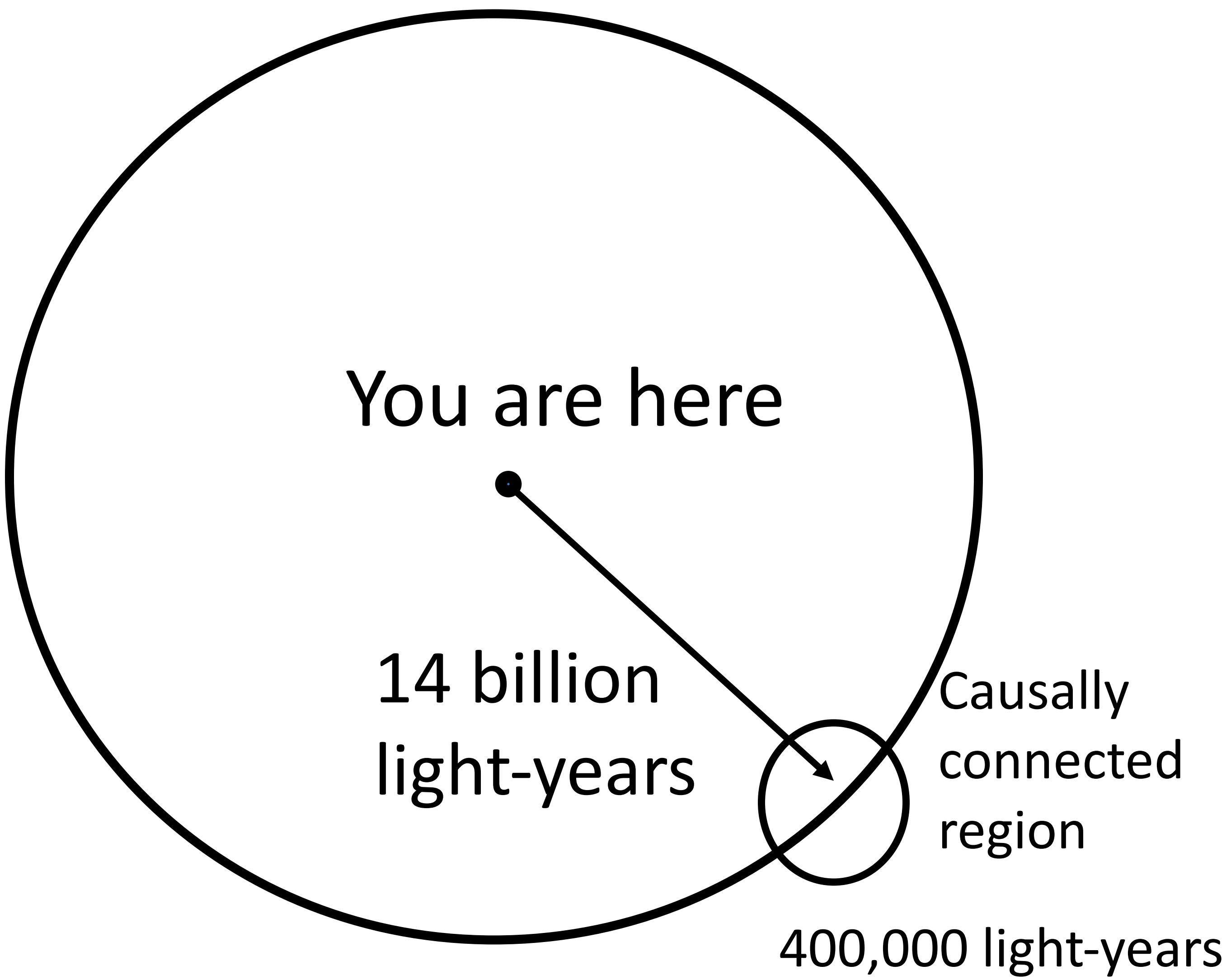
A little bit about inflation

Marc Kamionkowski (Johns Hopkins)

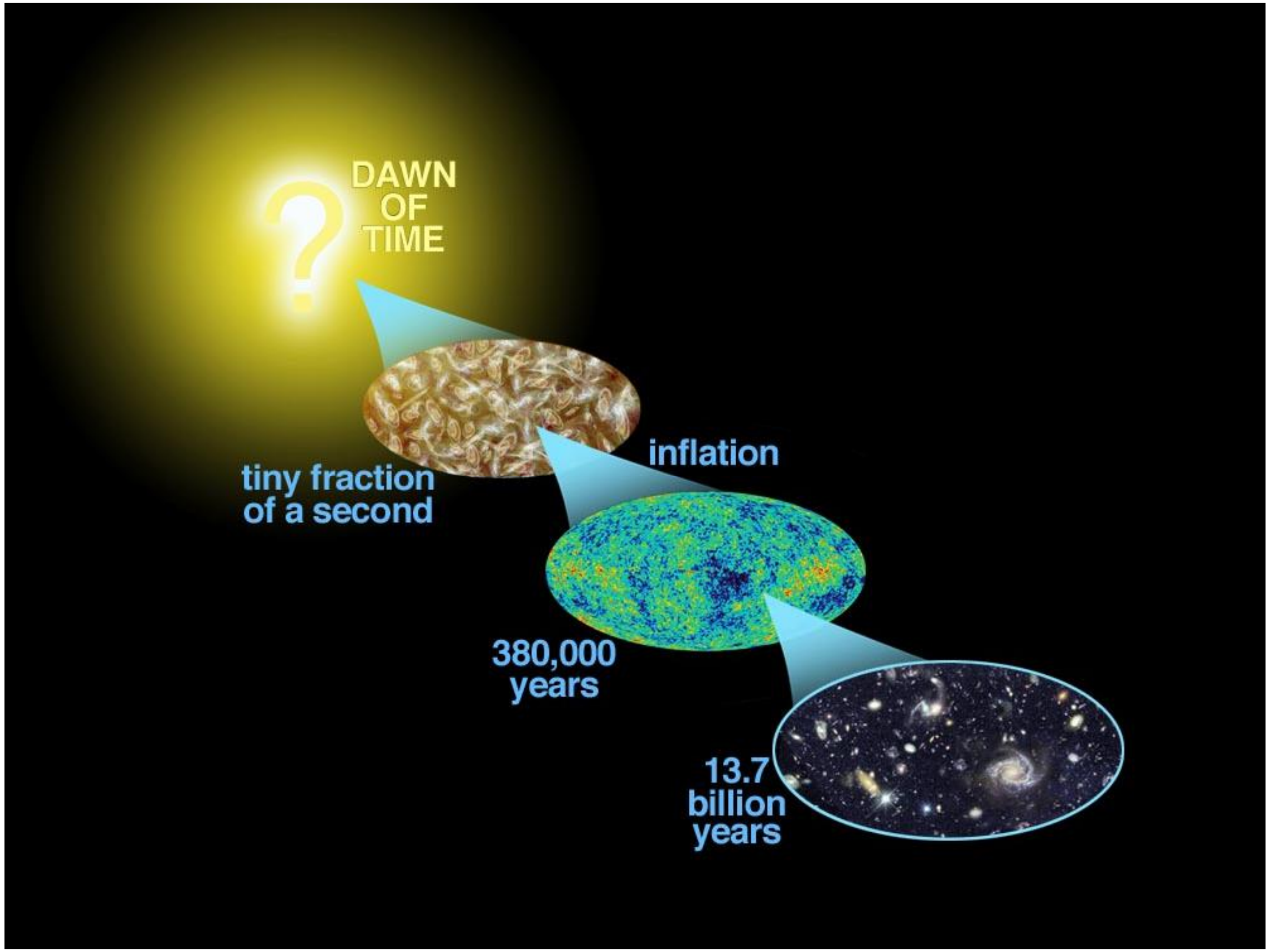
n3as summer school

15 July 2024

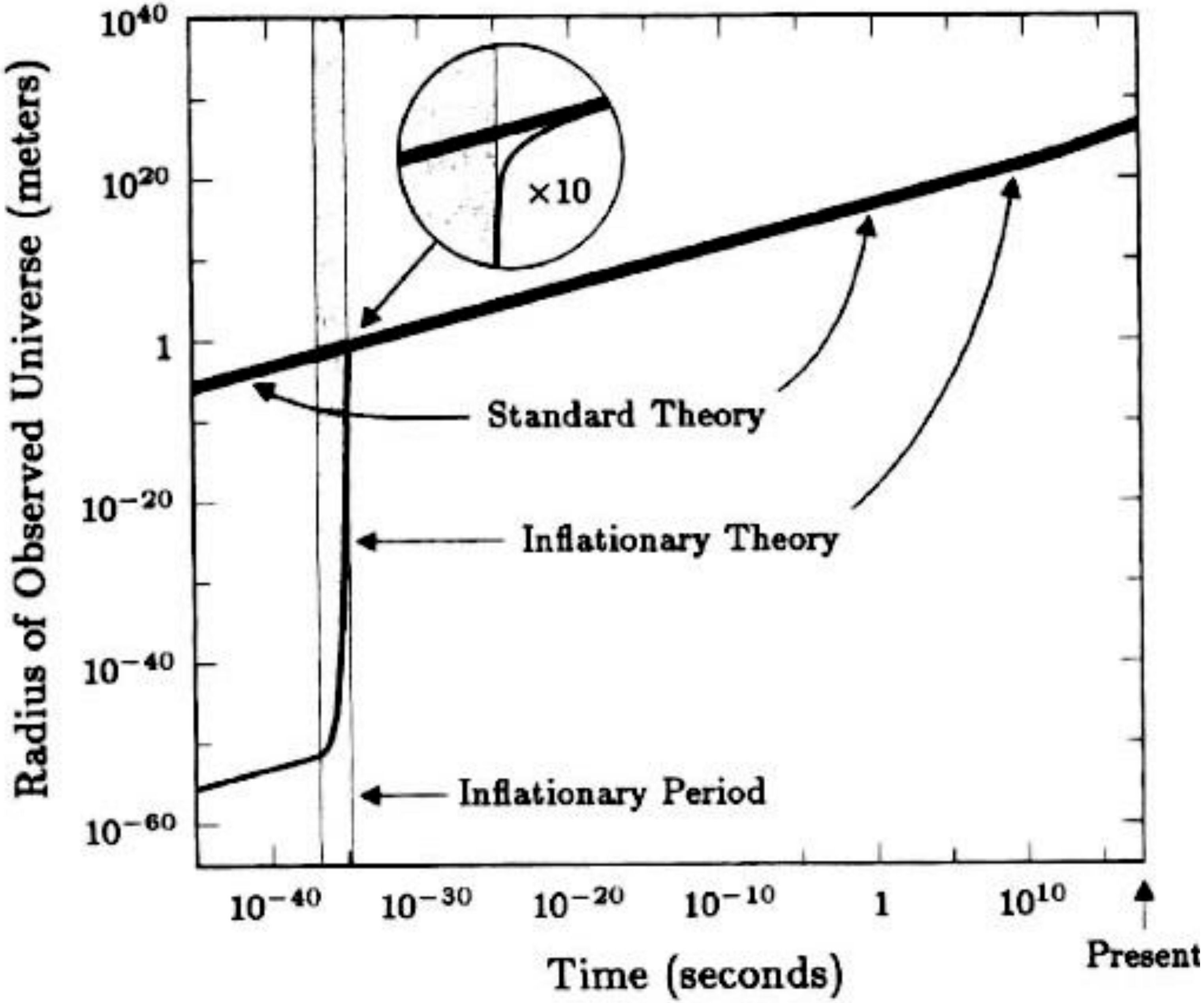
Cosmology <1980: Isotropy Problem



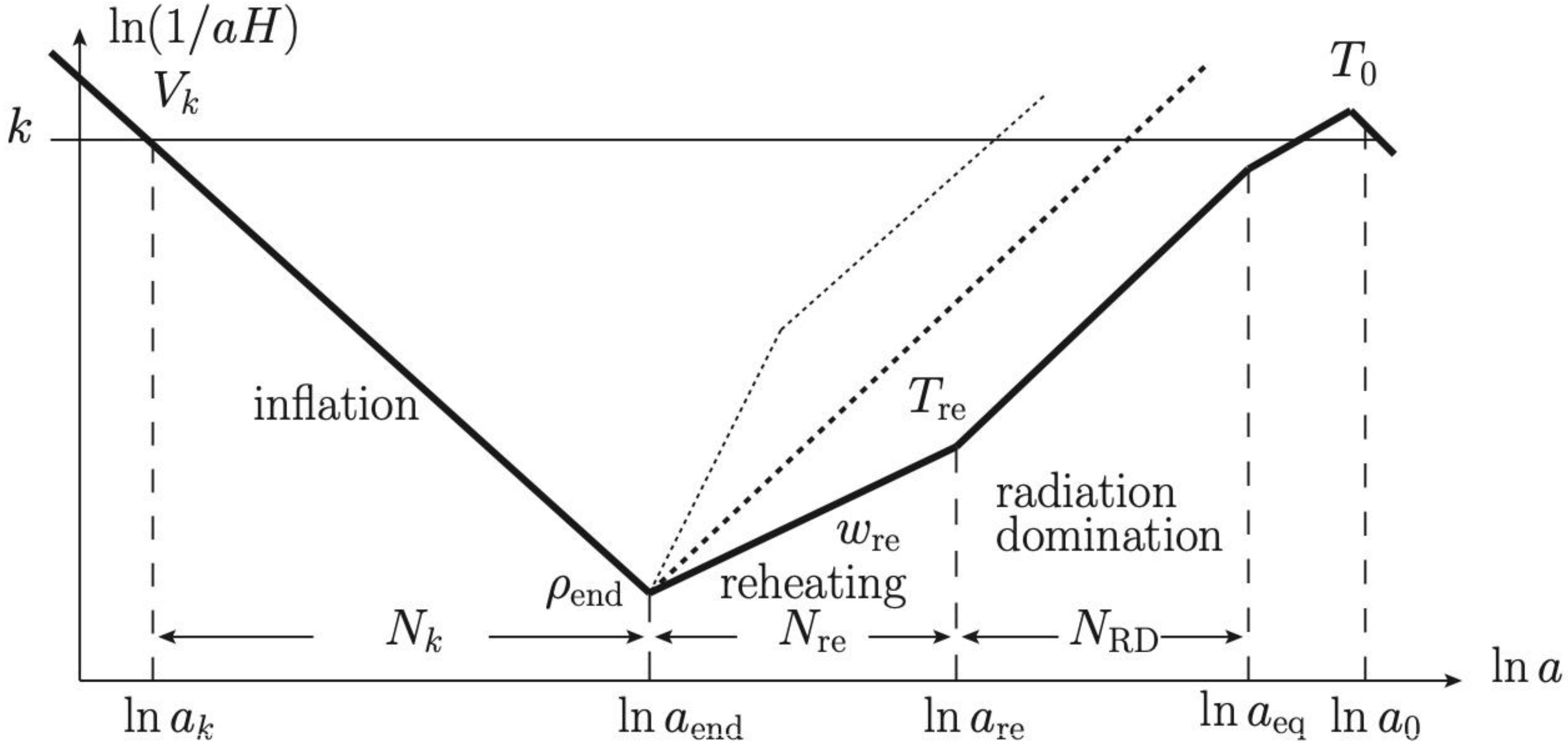
Inflation (~1980)



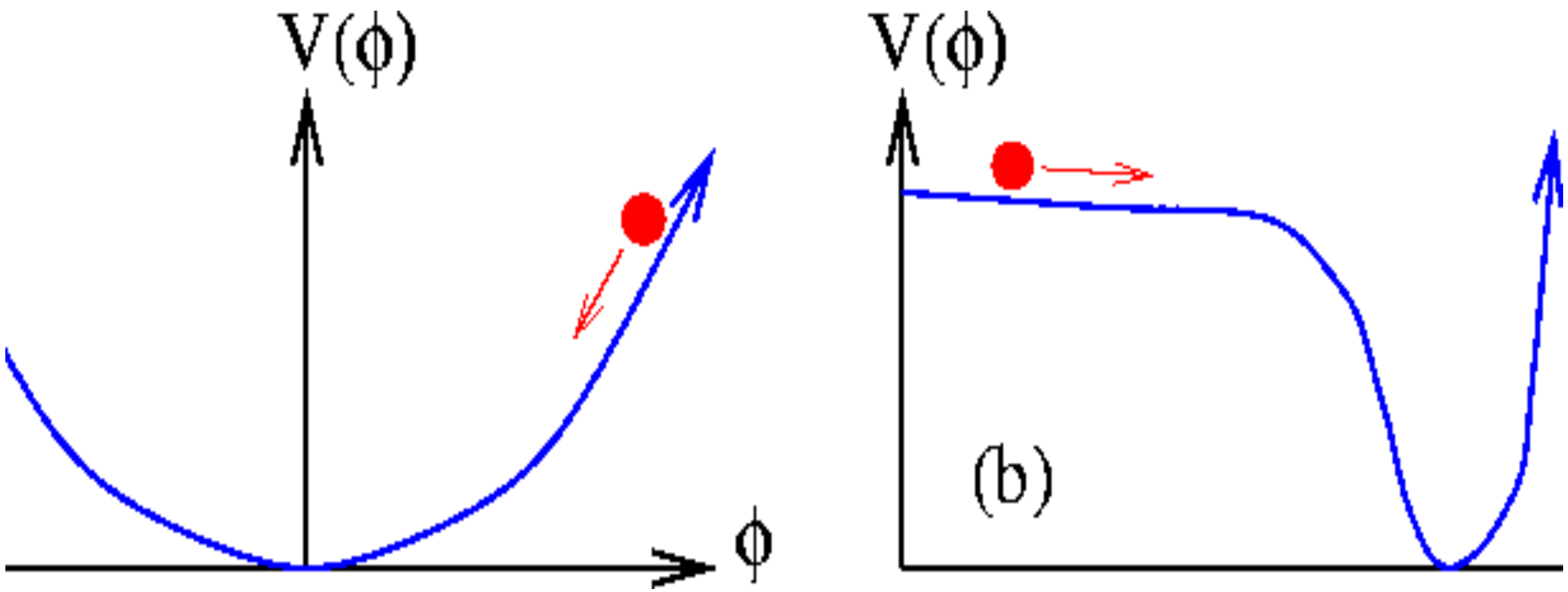
Guth, Linde, Albrecht-Steinhardt, Sato, Kazanas, Starobinsky, Englert-Brout-Gunzig….



10^{40}
10^{20}
1
10^{-20}
10^{-40}
10^{-60}
Radius of Observed Universe (meters)
×10
Standard Theory
Inflationary Theory
Inflationary Period
10^{-40}
10^{-30}
10^{-20}
10^{-10}
1
10^{10}
Present
Time (seconds)


ln(1/aH)
V_k
k
T_0
inflation
T_re
radiation
domination
w_re
reheating
ρ_end
N_k
N_re
N_RD
ln a
ln a_k
ln a_end
ln a_re
ln a_eq
ln a_0

The Mechanism:



new scalar field ("inflaton") $\phi(\vec{x}, t)$

Standard Predictions of Inflation

- A flat Universe

”Slow-roll” evolution

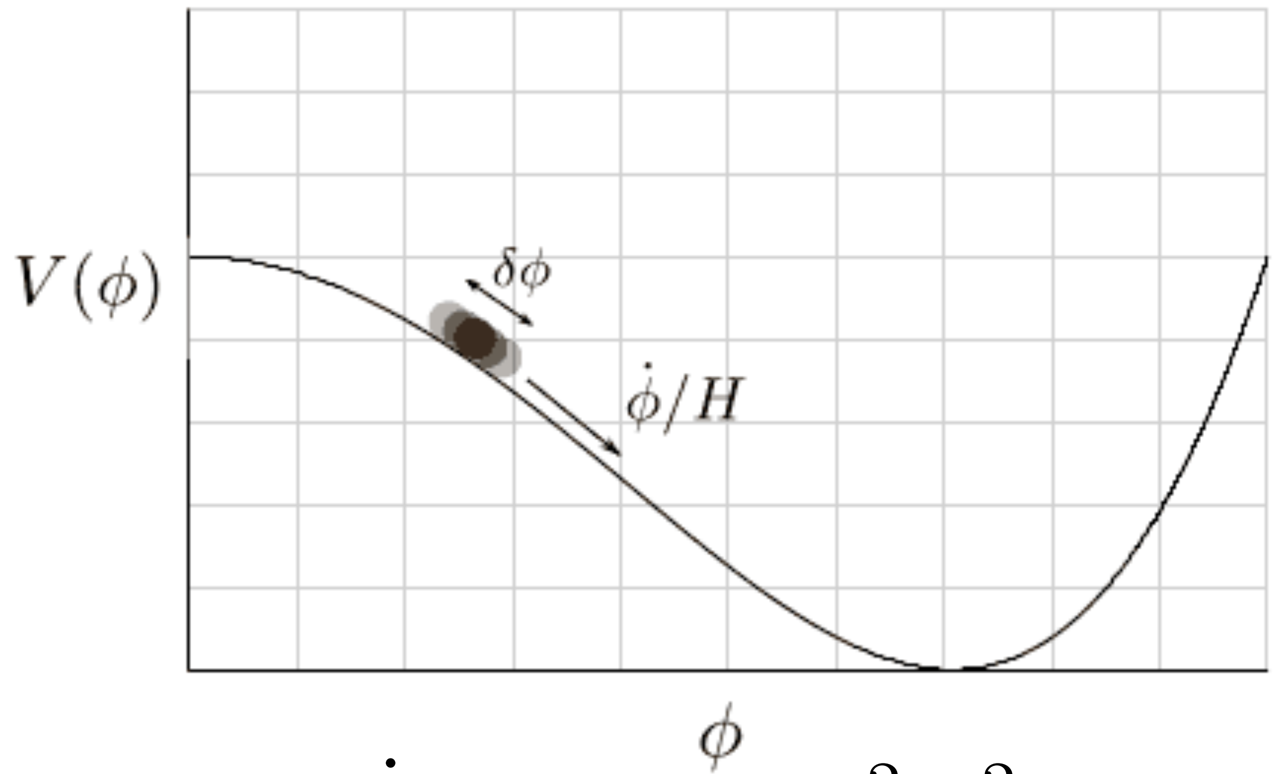
$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0 \qquad \rightarrow \qquad 3H\dot{\phi} \simeq -V'(\phi)$$

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi\rho}{3m_{\mathrm{Pl}}^2} - \frac{k}{a^2}$$

$$\rho \simeq V \simeq \text{constant} \quad \rightarrow \quad k/a^2 \rightarrow 0 \quad \rightarrow \quad \text{Universe flat}$$

Standard Predictions of Inflation

- A flat Universe
- “Adiabatic” primordial density fluctuations
- Nearly scale-invariant spectrum of primordial density fluctuations
- Very nearly Gaussian primordial density fluctuations



$$\ddot{\delta}\phi(\vec{x},t) + 3H\dot{\delta}\phi(\vec{x},t) + a^{-2}\nabla^2\delta\phi(\vec{x},t) = 0$$

$$\ddot{\delta}\phi_{\vec{k}}(t) + 3H\dot{\delta}\phi_{\vec{k}}(t) + (k/a)^2\delta\phi(\vec{x},t) = 0$$

At early times, is SHO, which has nonzero zero-point amplitude

At late times, $\delta\phi_k$ → constant → quantum-generated density perturbation

$$P_\phi(k) = \left(\frac{H}{2\pi}\right)^2\bigg|_{k=aH}.$$

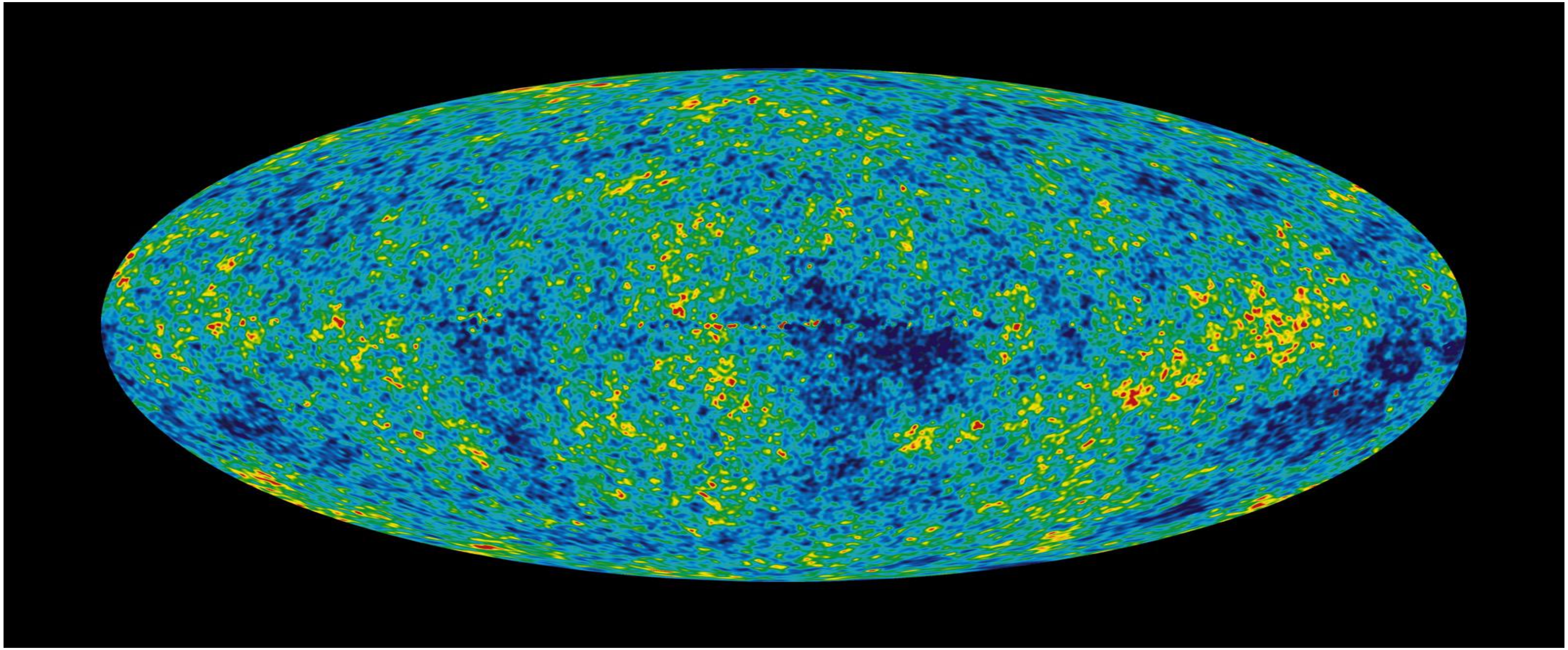
$$\delta V \simeq V'(\phi)\delta\phi$$

$$\nabla^2\Phi = 4\pi G\delta\rho$$

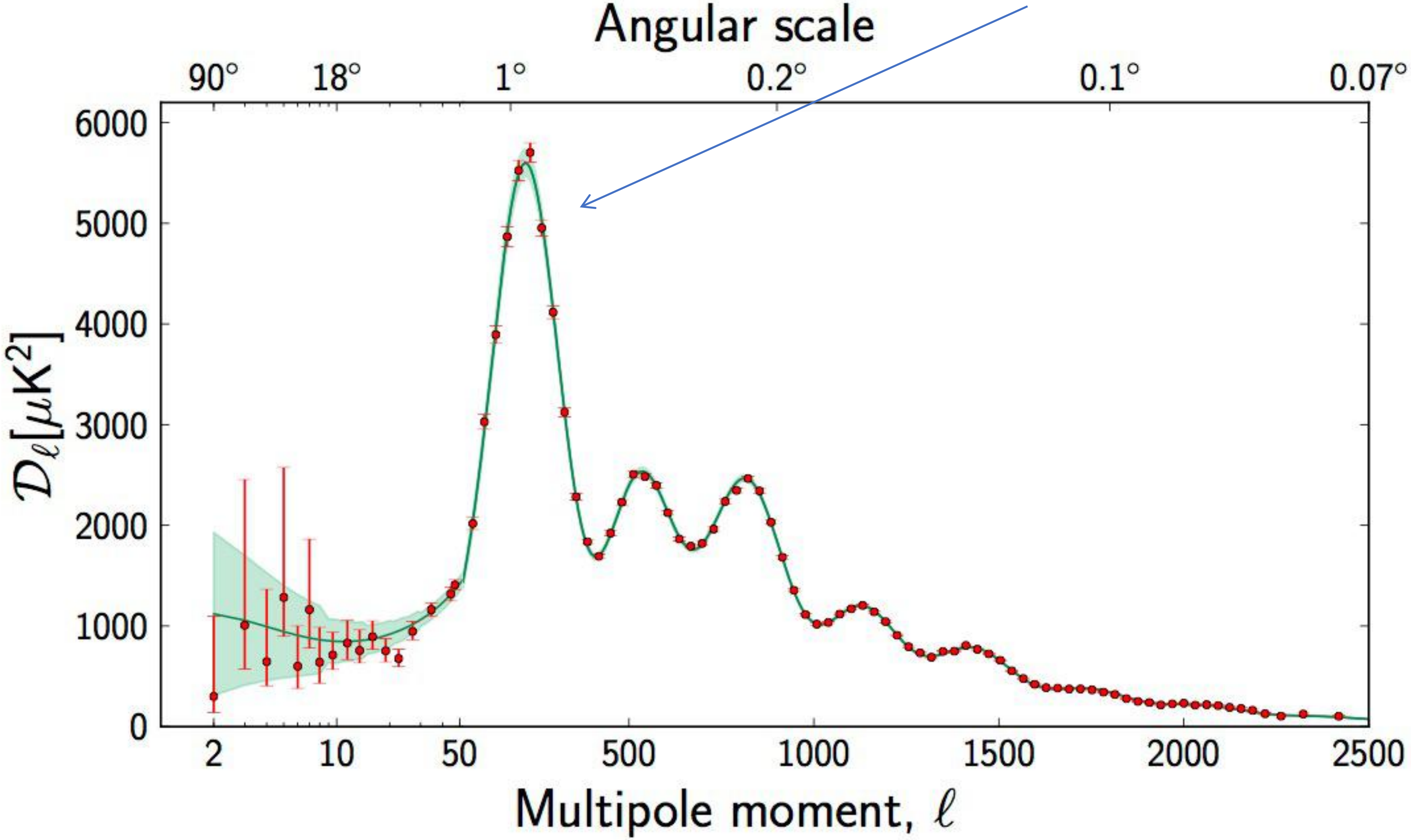
$$\Delta\Phi^2(k) = \frac{128\pi V^3}{m_{\rm Pl}^6 (V')^2} = \frac{8}{3\pi^2}\frac{V}{m_{\rm Pl}^2\epsilon},$$

$$\epsilon \simeq 0.01$$

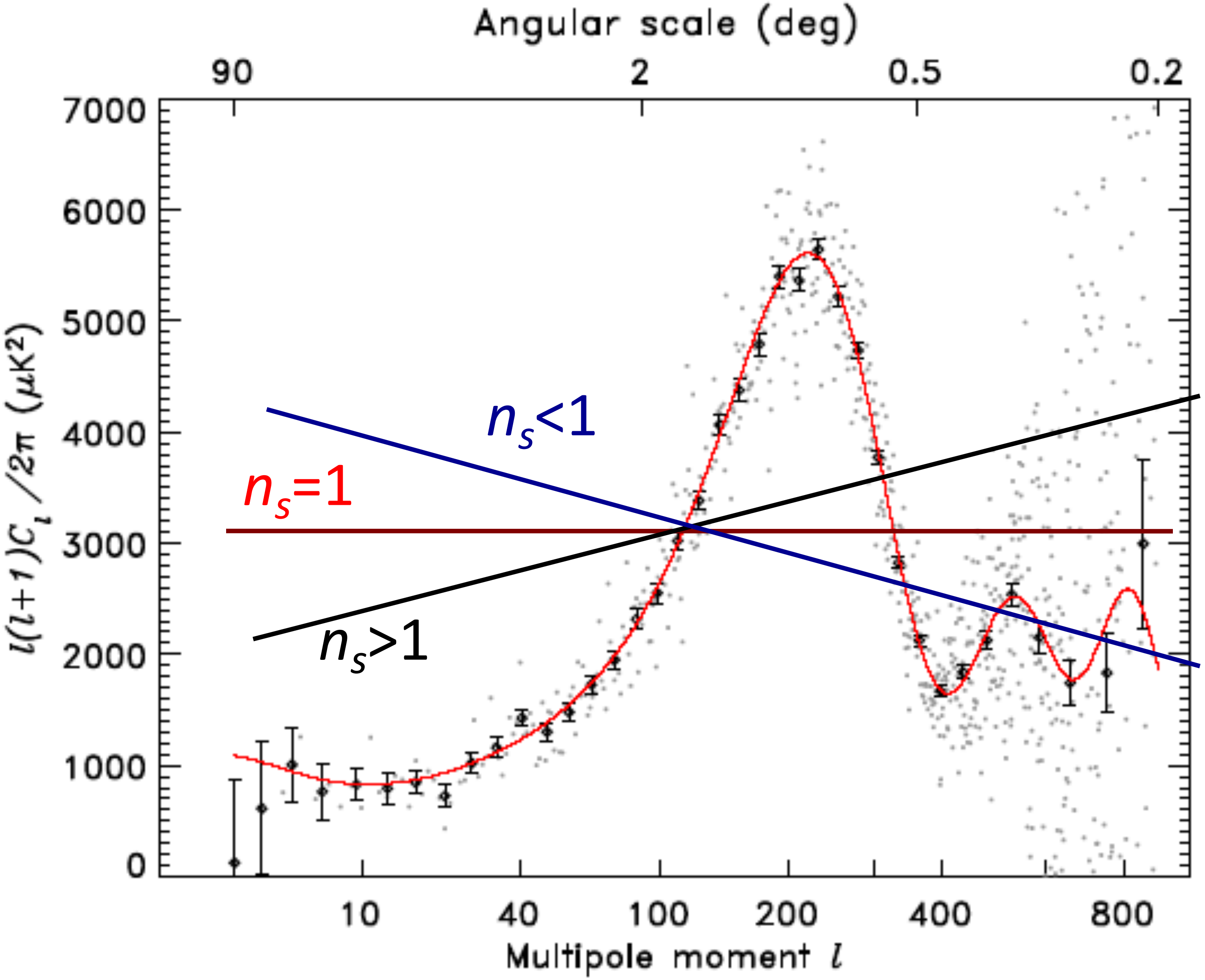
A flat Universe?



Universe is flat!



Nearly (but not precisely) scale-invariant primordial perturbations



Angular scale (deg)
90
2
0.5
0.2
7000
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ (μK^2)
$n_s<1$
$n_s=1$
$n_s>1$
10
40
100
200
400
800
Multipole moment l

WMAP

But not *precisely* scale-invariant….

$$n_s = 0.968 \pm 0.006$$

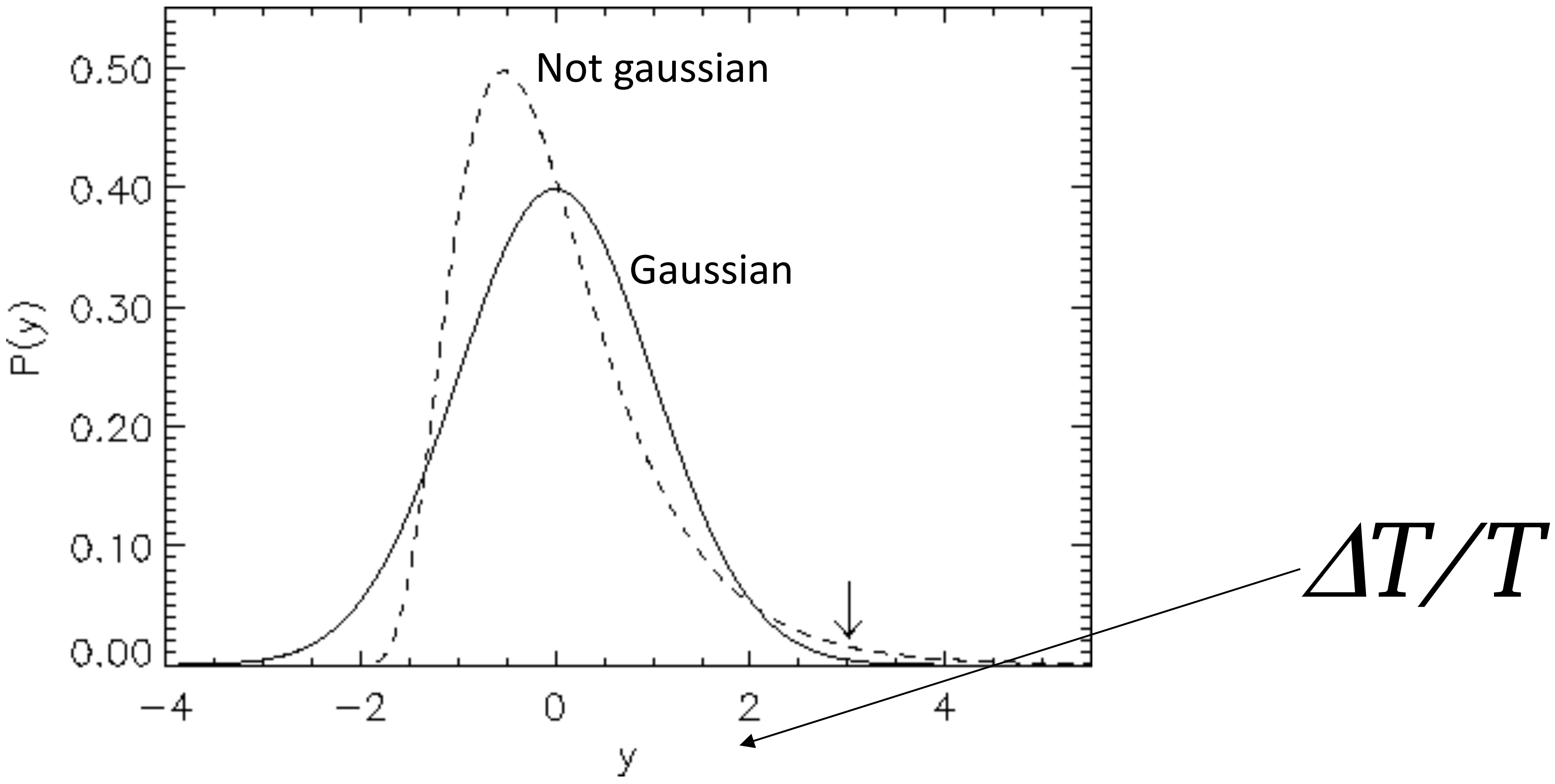
Very nearly Gaussian fluctuations

- Gravitational potential (e.g., Verde, Wang, Heavens, MK, 2000)

$$\Phi = \phi + f_{\rm NL}\phi^2$$

with f_{NL}<<1 (Wang & MK, 2000)

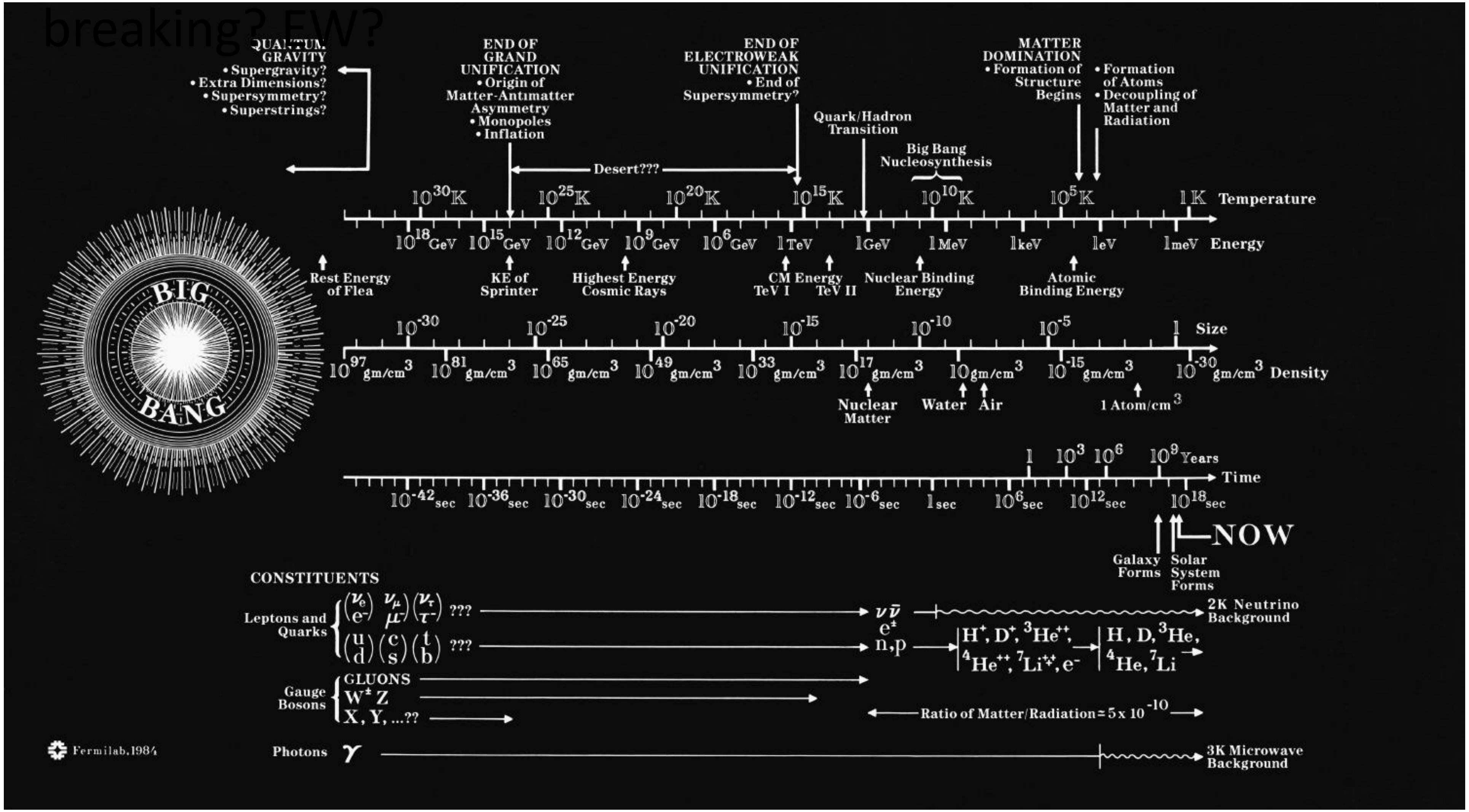
Gaussian field



Current constraints

$|f_{nl}|<10$

But what is the new physics responsible for inflation? Quantum gravity? GUT? PQ symmetry breaking? SUSY breaking? EW?



What is the energy scale of inflation??

Gravitational waves

- Arise from same Hawking-like process during inflation as density perturbations (GW amplitude h also satisfies KG equation)
- Have amplitude ("tensor-to-scalar ratio")

$$r \simeq 0.1 \left(\frac{E_{\mathrm{infl}}}{2 \times 10^{16}\,\mathrm{GeV}} \right)^4$$

Current limits to"tensor-to-scalar ratio" $r<0.03$ or $E_{infl}<(2x10^{16}$ GeV)

But r could also be as small as 0.000000…..00001 !!

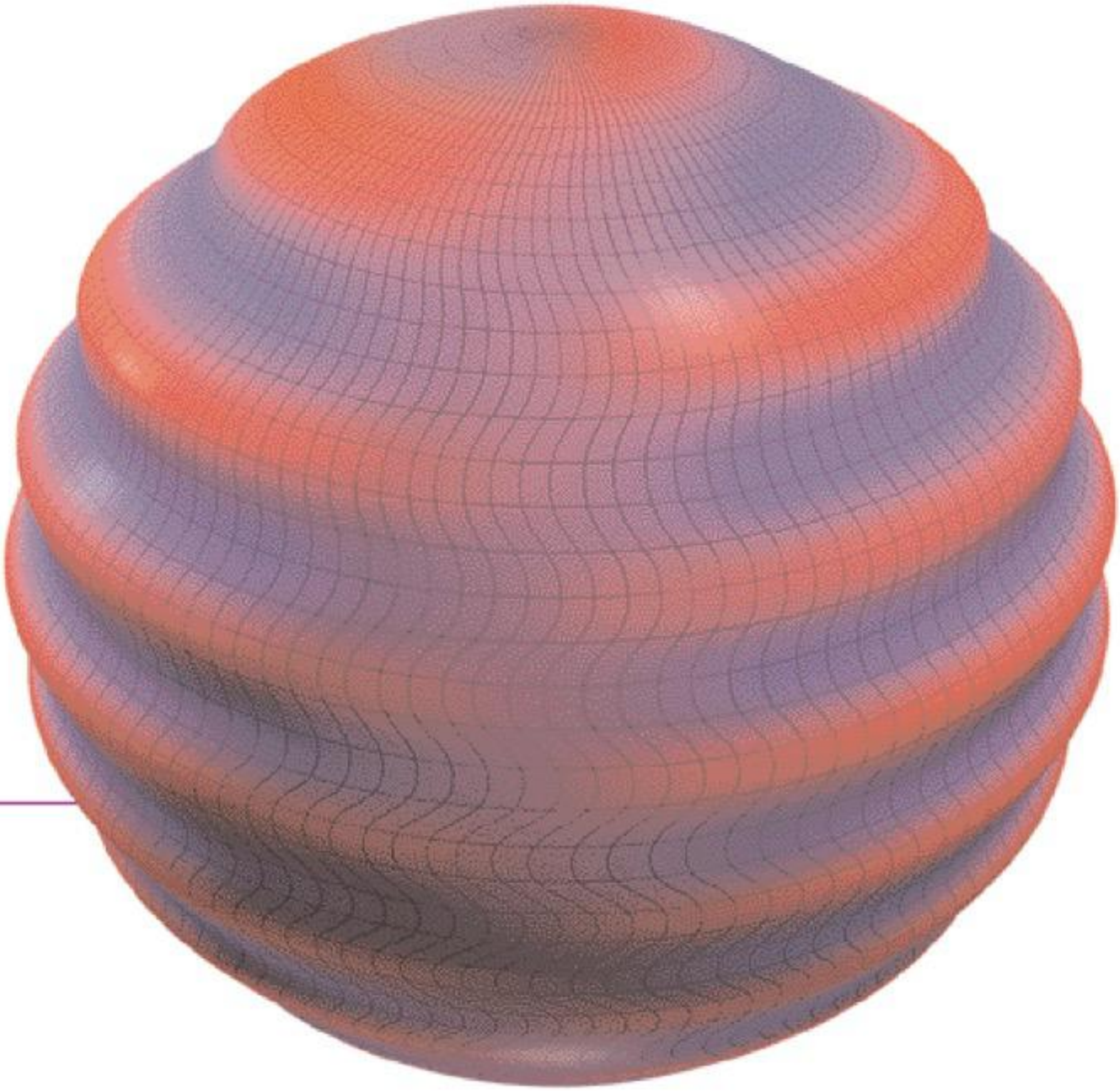
But there are reasons to suspect r not too small!!!

$$n_s \simeq 1 - 6\epsilon + 2\eta, \quad n_t \simeq -2\epsilon,$$

with

$$\epsilon \equiv \frac{m_{\mathrm{Pl}}^2}{16\pi}\left(\frac{V'(\phi)}{V(\phi)}\right)^2, \quad \eta \equiv \frac{m_{\mathrm{Pl}}^2}{8\pi}\frac{V''(\phi)}{V(\phi)},$$

and $r = 16\epsilon$

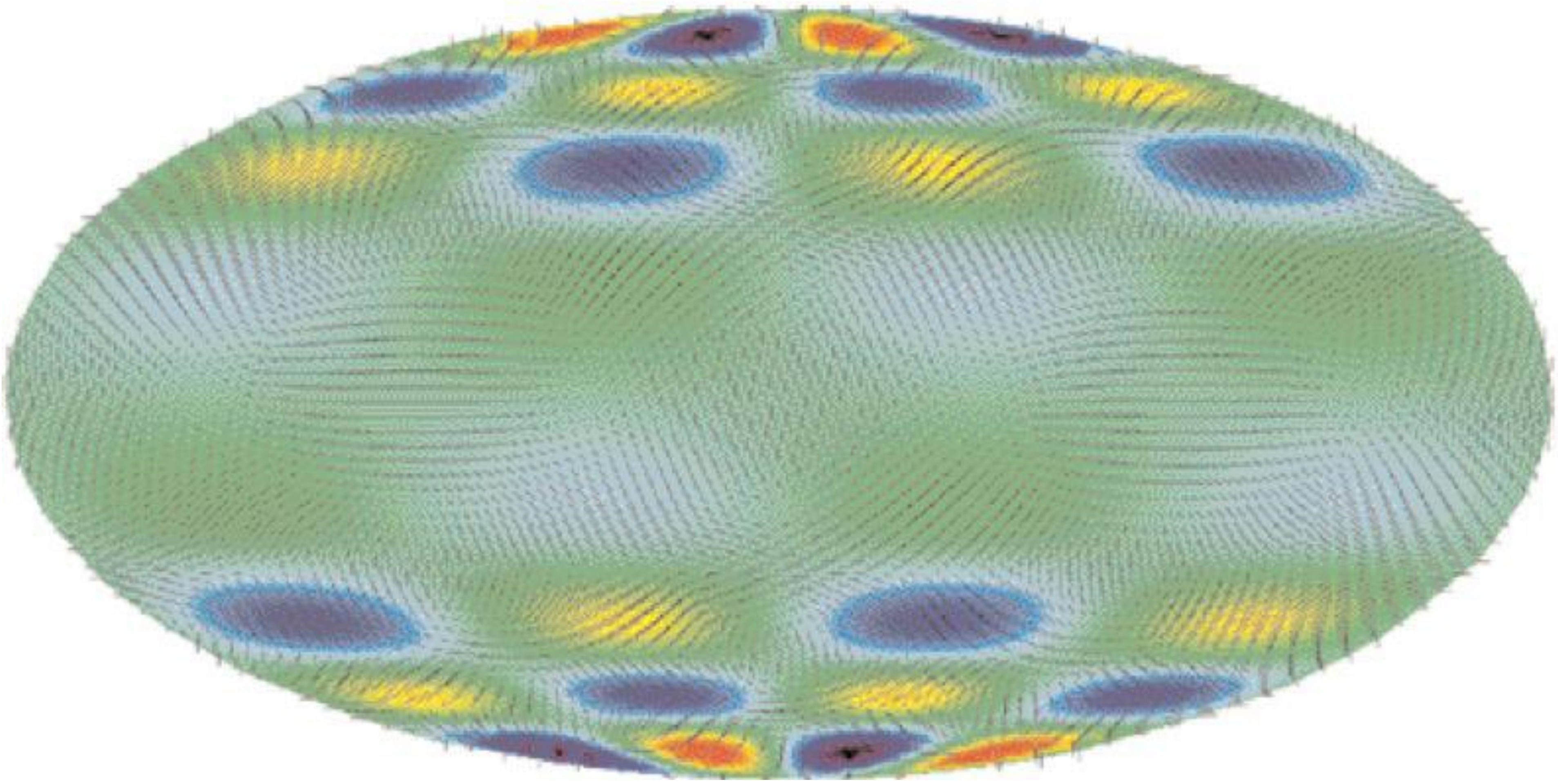


DISTORTED UNIVERSE

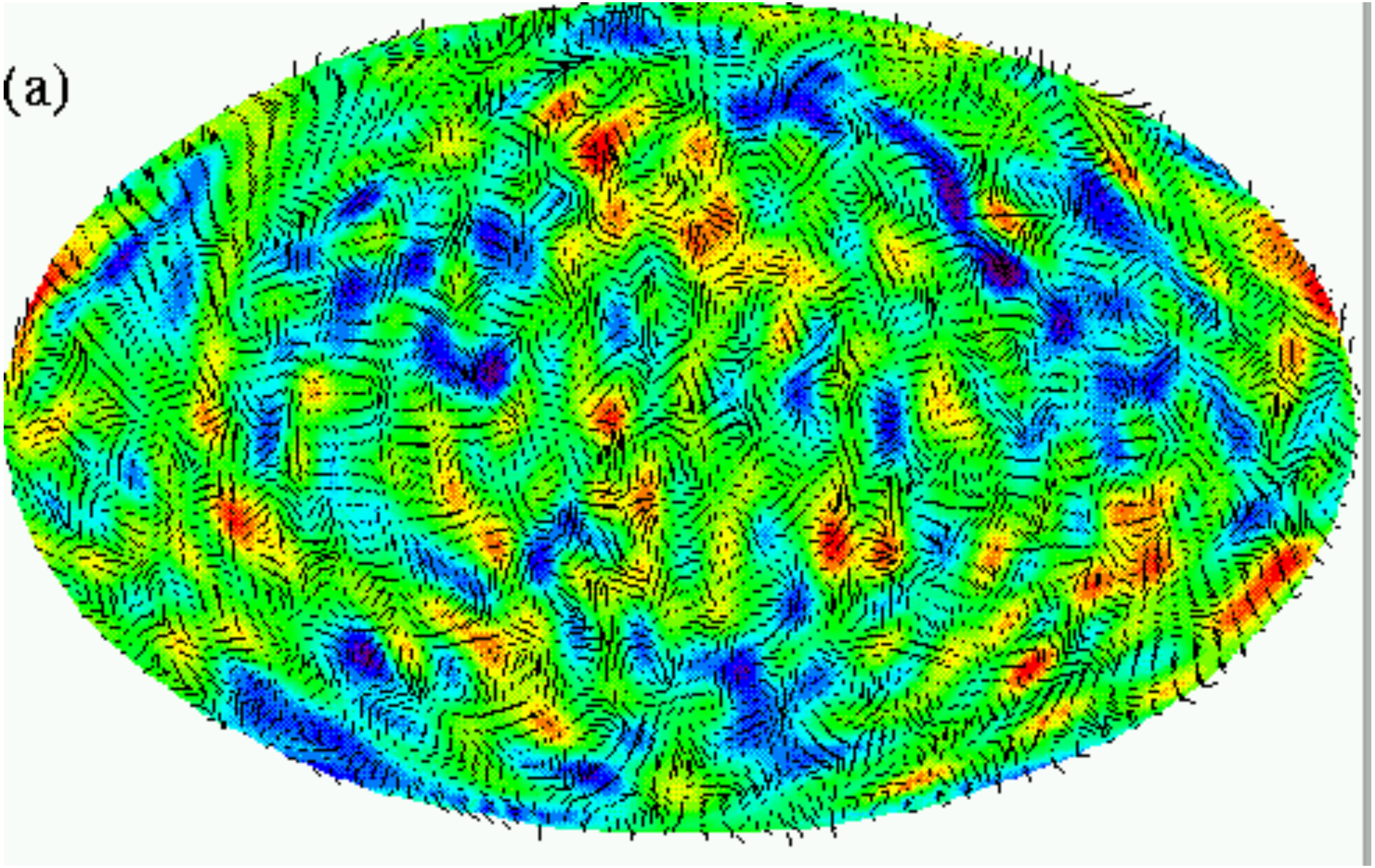
But GWs also induce polarization in CMB

(Polnarev 1987)

GWs also induce polarization in CMB



(a)



Detection of gravitational waves with CMB polarization

(MK, Kosowsky, Stebbins 1997; Seljak & Zaldarriaga 1997)

Temperature map: $T(\hat{n})$ "E modes"

Polarization Map: $\vec{P}(\hat{n}) = \vec{\nabla} E + \vec{\nabla} \times \vec{B}$

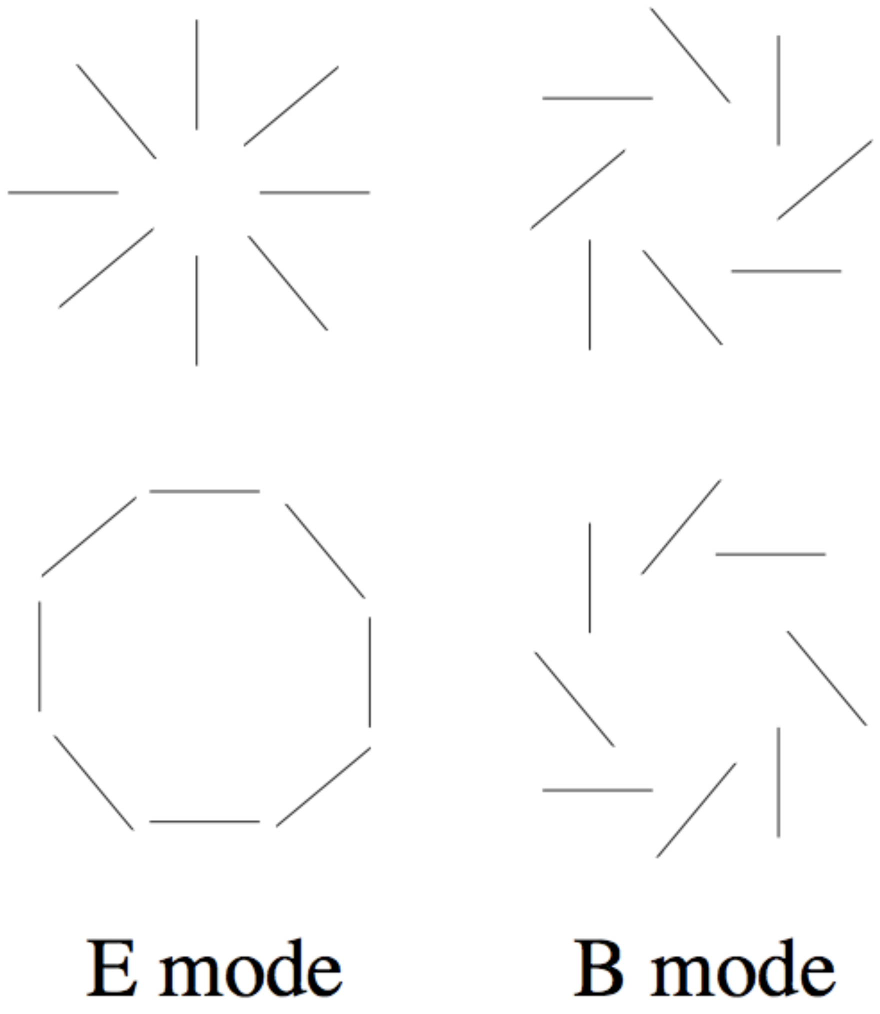
"B modes"

Density perturbations have no "handedness" so they can*not* produce a polarization with a curl

Gravitational waves do have a handedness, so they can (and do) produce a curl

→ **A "smoking gun" for inflation**

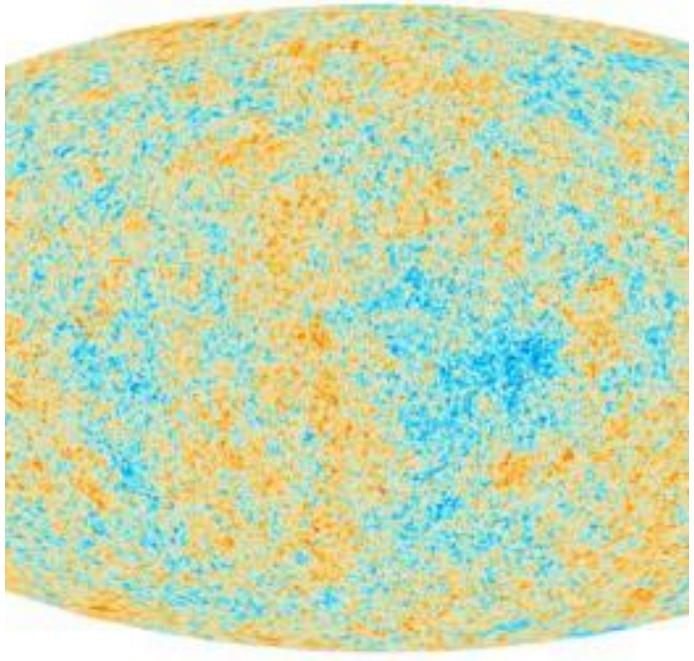
E-mode and B-mode

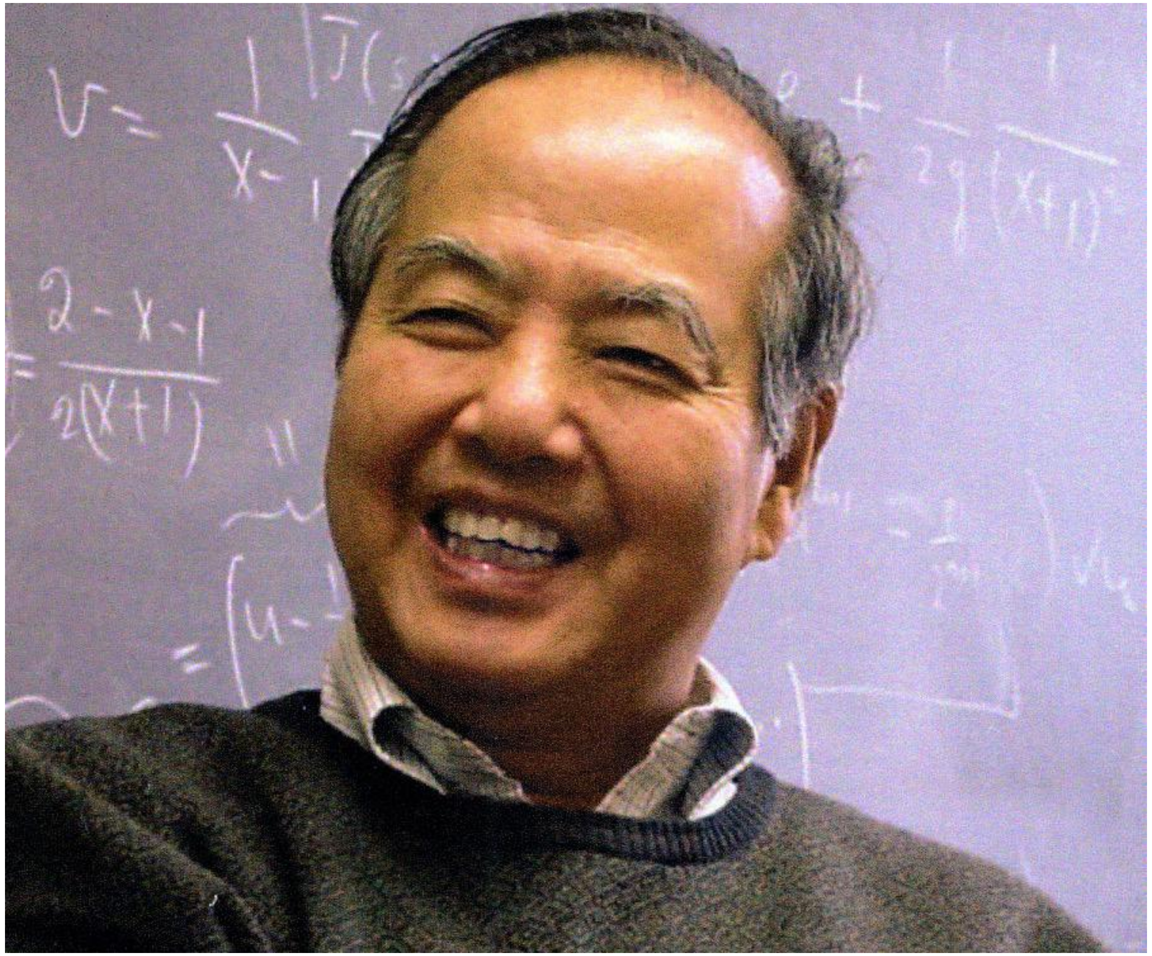


- Gravitational potential can generate the E-mode polarization, but not B-modes.
- **Gravitational waves** can generate both E- and B-modes!



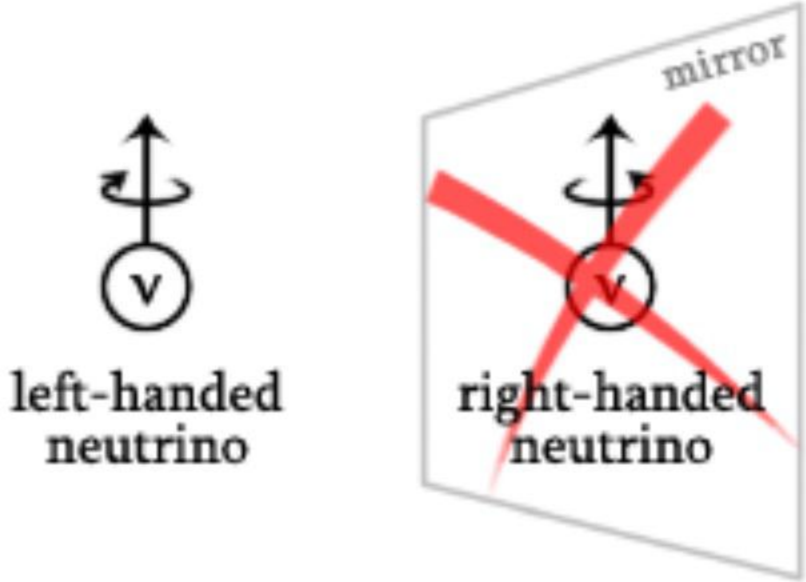
$$\phi R\tilde{R}$$



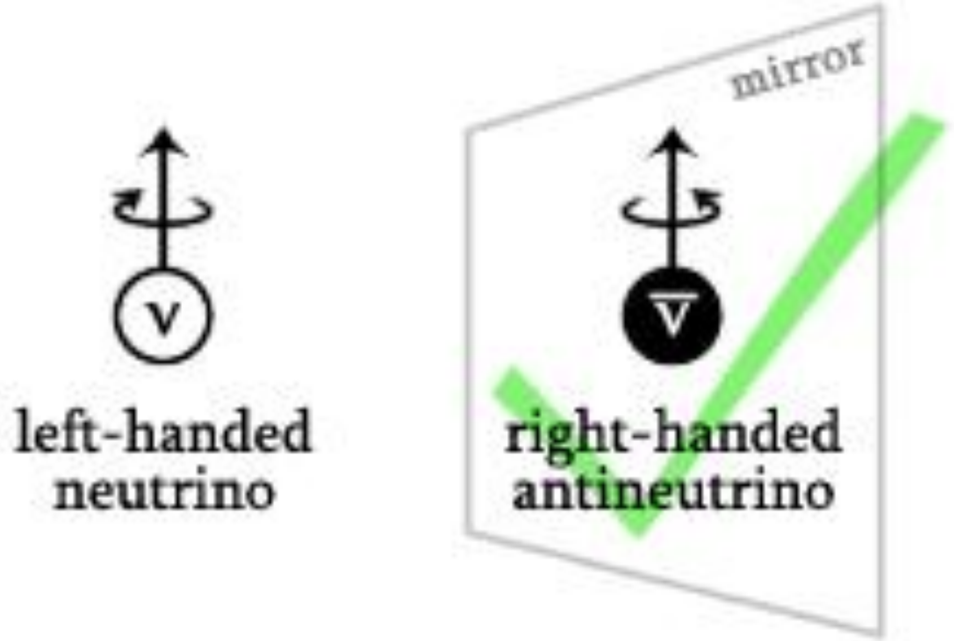


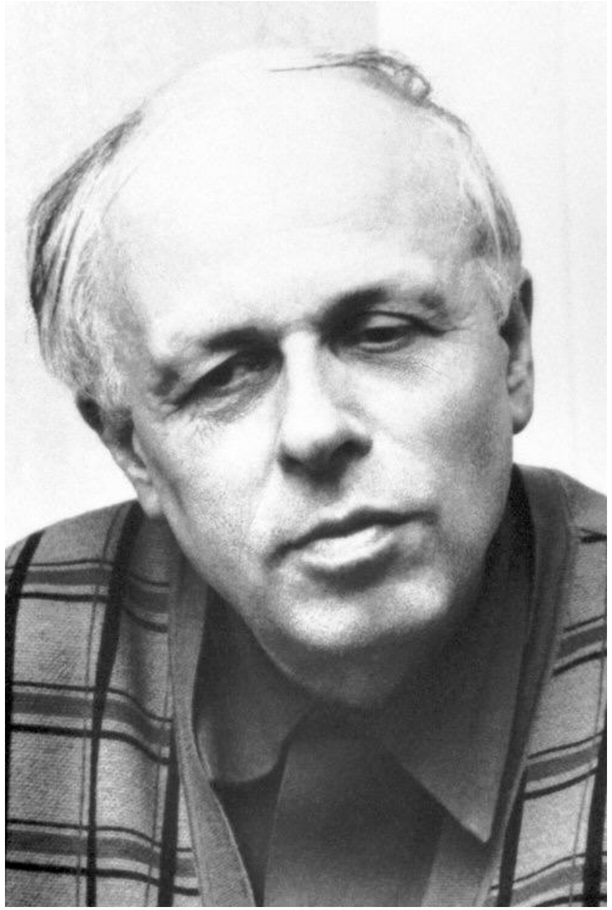

2021
Chien-Shiung Wu
Nuclear Physicist
Forever
USA

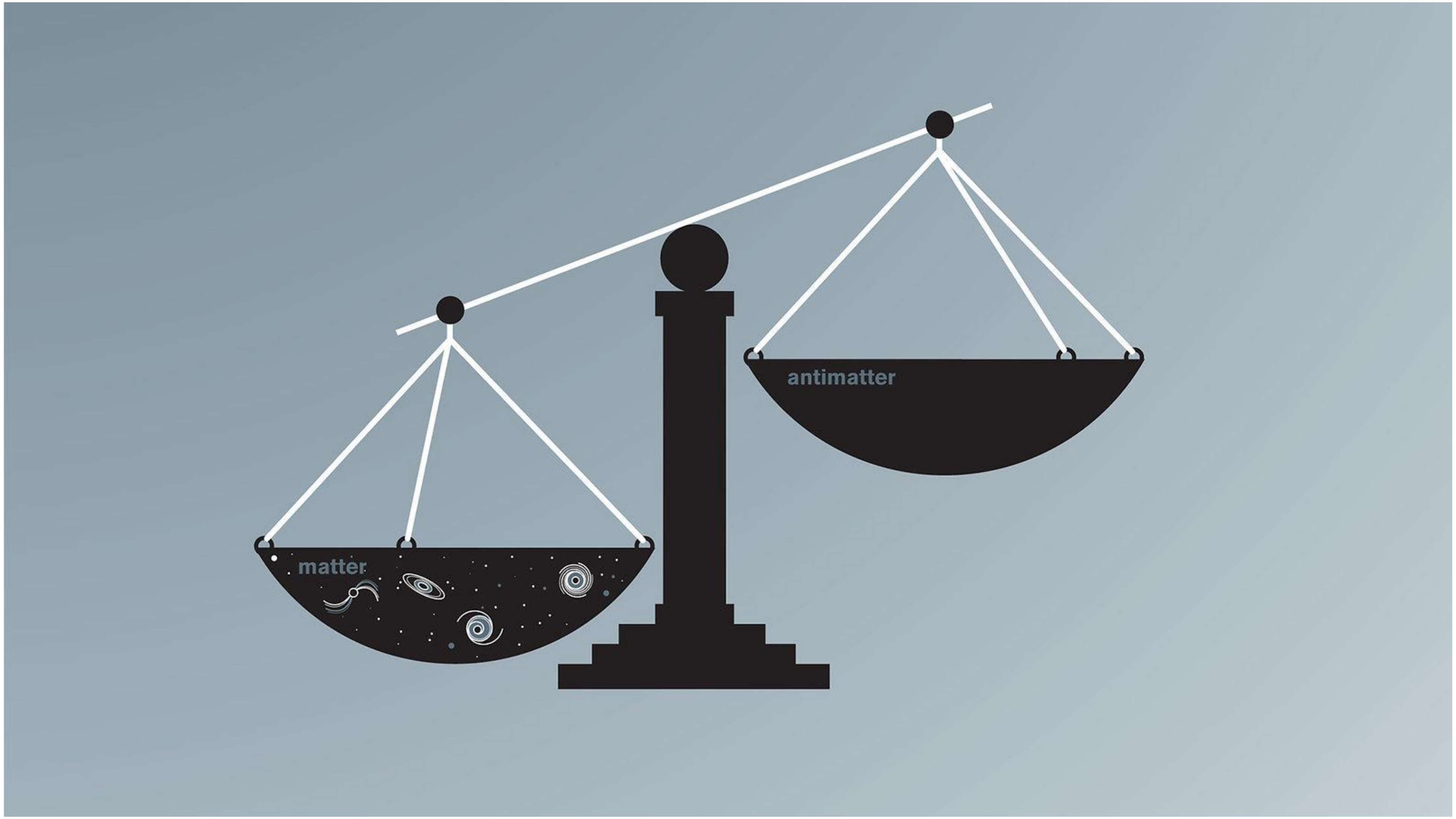
Neutrinos Violate P-Symmetry



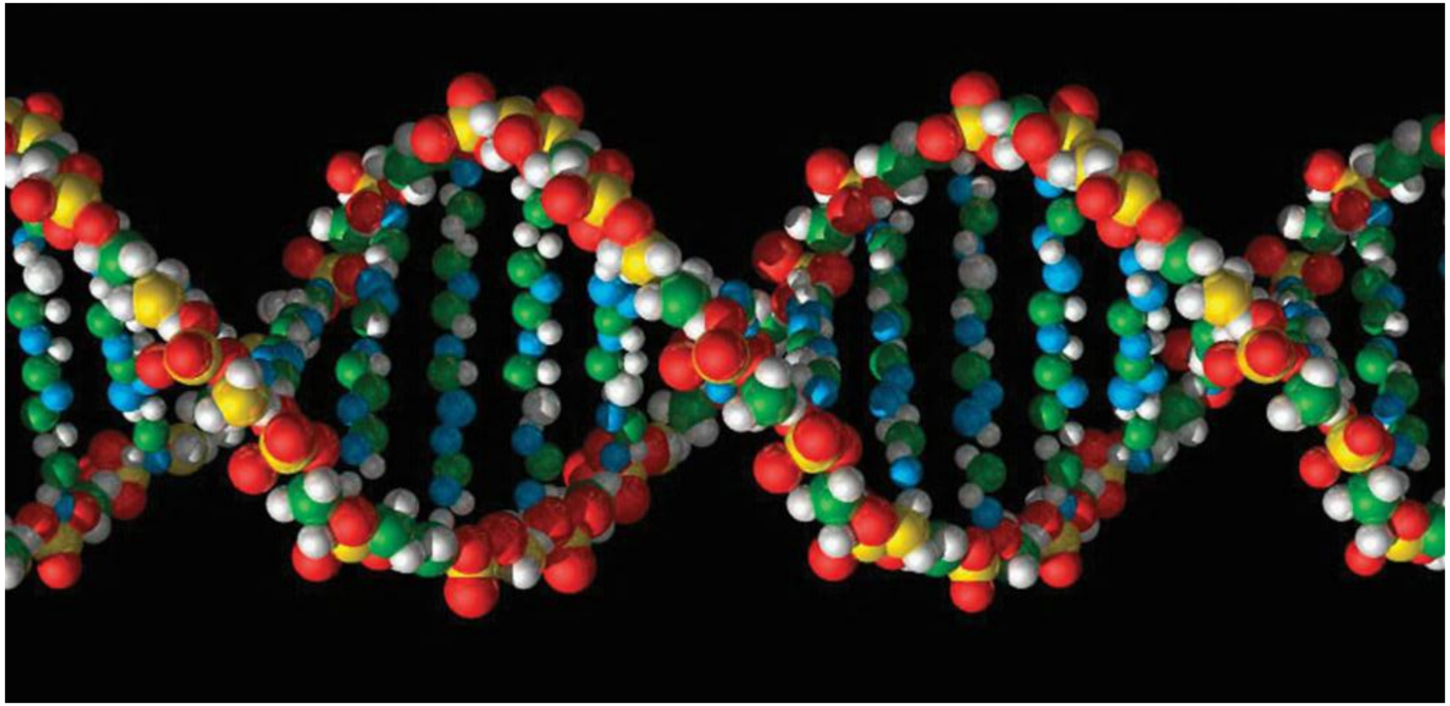
Neutrinos and CP Symmetry



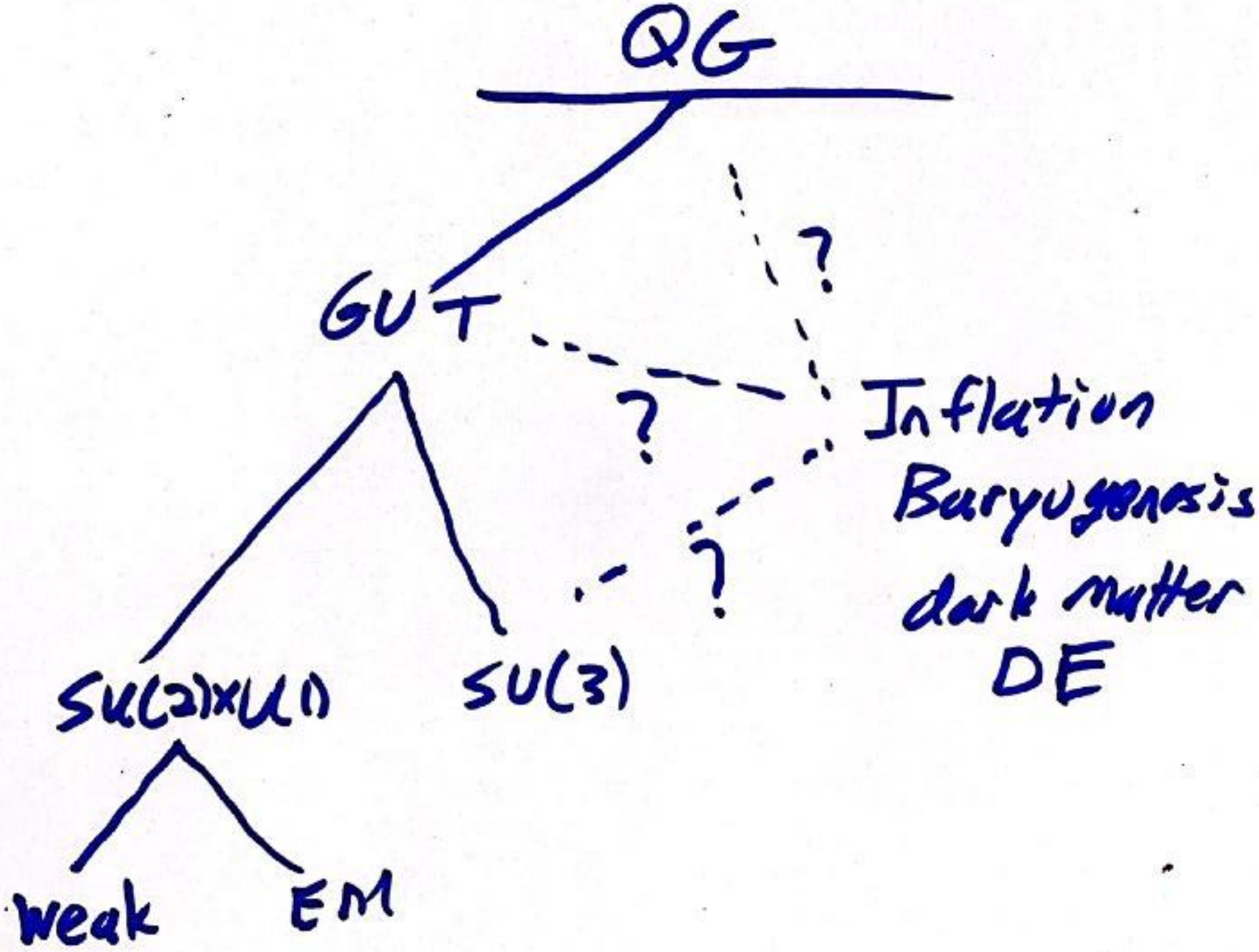



antimatter
matter

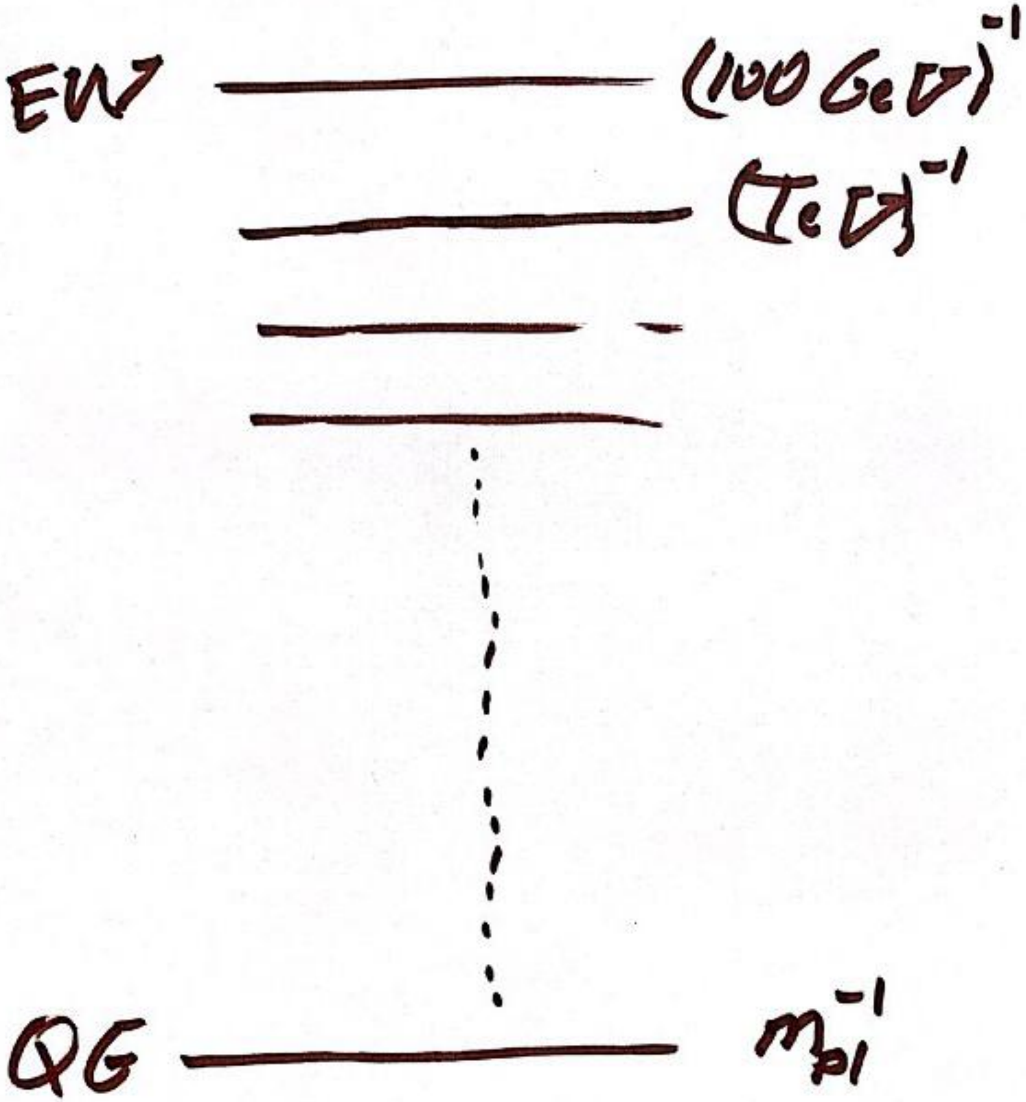
Biology is parity breaking



People are parity breaking



QG
GUT
?
?
?
Inflation
Baryogenesis
dark matter
DE
SU(2)xU(1)
SU(3)
Weak
EM


EW
(100 GeV)⁻¹
(TeV)⁻¹
QG
m_pl⁻¹

Is parity respected on cosmological scales?

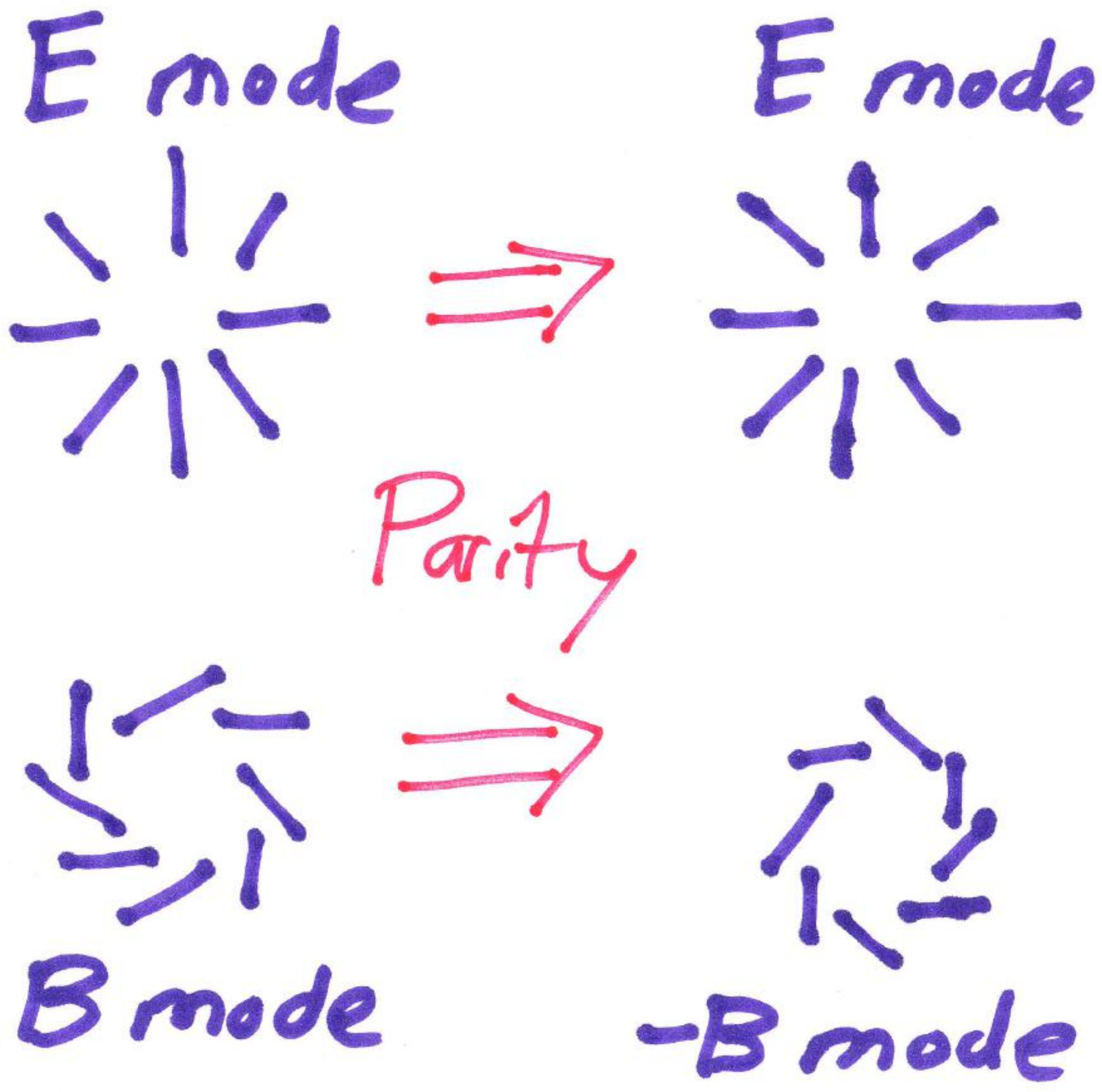
Need new physics for….

- Primordial density perturbations from inflation
- Dark energy
- Early dark energy
- Dark matter
- Baryogenesis
- Neutrino physics

Cosmological Birefringence

(Lue, Wang, MK 1999; Lepora 1999; MK 2008; Gluscevic, MK, Cooray, 2009; MK 2010)

- Is new cosmological physics (e.g., inflation, dark energy) parity violating?
- Polarization E and B modes have opposite parity; EB correlation therefore signature of parity violation


E mode
E mode
Parity
B mode
-B mode

Cosmological birefringence

•E.g., if quintessence field *Φ(t)* couples to E&M through:

$$\mathcal{L} = \frac{1}{4}F^2 + \frac{\phi}{M_*}F\tilde{F}$$

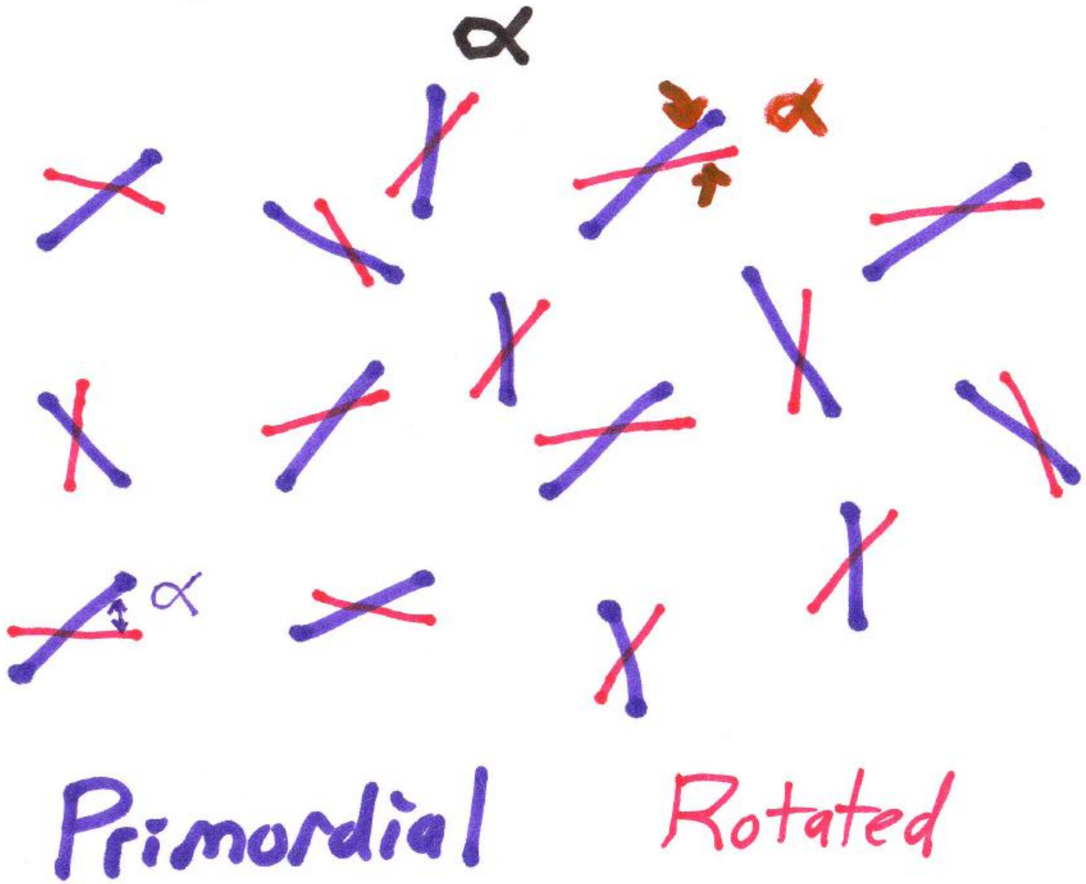
Time evolution of *Φ(t)* leads to rotation, by angle α, of CMB polarization as photons propagate from CMB surface of last scatter (Harari & Sikivie 1992; Carroll, Field, Jackiw 1998)

Rotation induces EB cross-correlation (Lue, Wang, MK 1999)

WMAP/BOOMERanG/QUaD searches: α<few degrees

(Feng et al., astro-ph/0601095; Komatsu et al. 2008; Wu et al. 2008)

Uniform Rotation



Parity-breaking CMB power spectra

$$C_\ell^{\mathrm{TB}} \qquad C_\ell^{\mathrm{EB}}$$

Cosmic Birefringence from the *Planck* Data Release 4

P. Diego-Palazuelos,[1,2,*] J. R. Eskilt,[3,†] Y. Minami,[4] M. Tristram,[5] R. M. Sullivan,[6] A. J. Banday,[7,8] R. B. Barreiro,[1] H. K. Eriksen,[3] K. M. Górski,[9,10] R. Keskitalo,[11,12] E. Komatsu,[13,14] E. Martínez-González,[1] D. Scott,[6] P. Vielva,[1] and I. K. Wehus[3]

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We search for the signature of parity-violating physics in the cosmic microwave background, called cosmic birefringence, using the *Planck* data release 4. We initially find a birefringence angle of $\beta = 0.30° \pm 0.11°$ (68% C.L.) for nearly full-sky data. The values of β decrease as we enlarge the Galactic mask, which can be interpreted as the effect of polarized foreground emission. Two independent ways to model this effect are used to mitigate the systematic impact on β for different sky fractions. We choose not to assign cosmological significance to the measured value of β until we improve our knowledge of the foreground polarization.

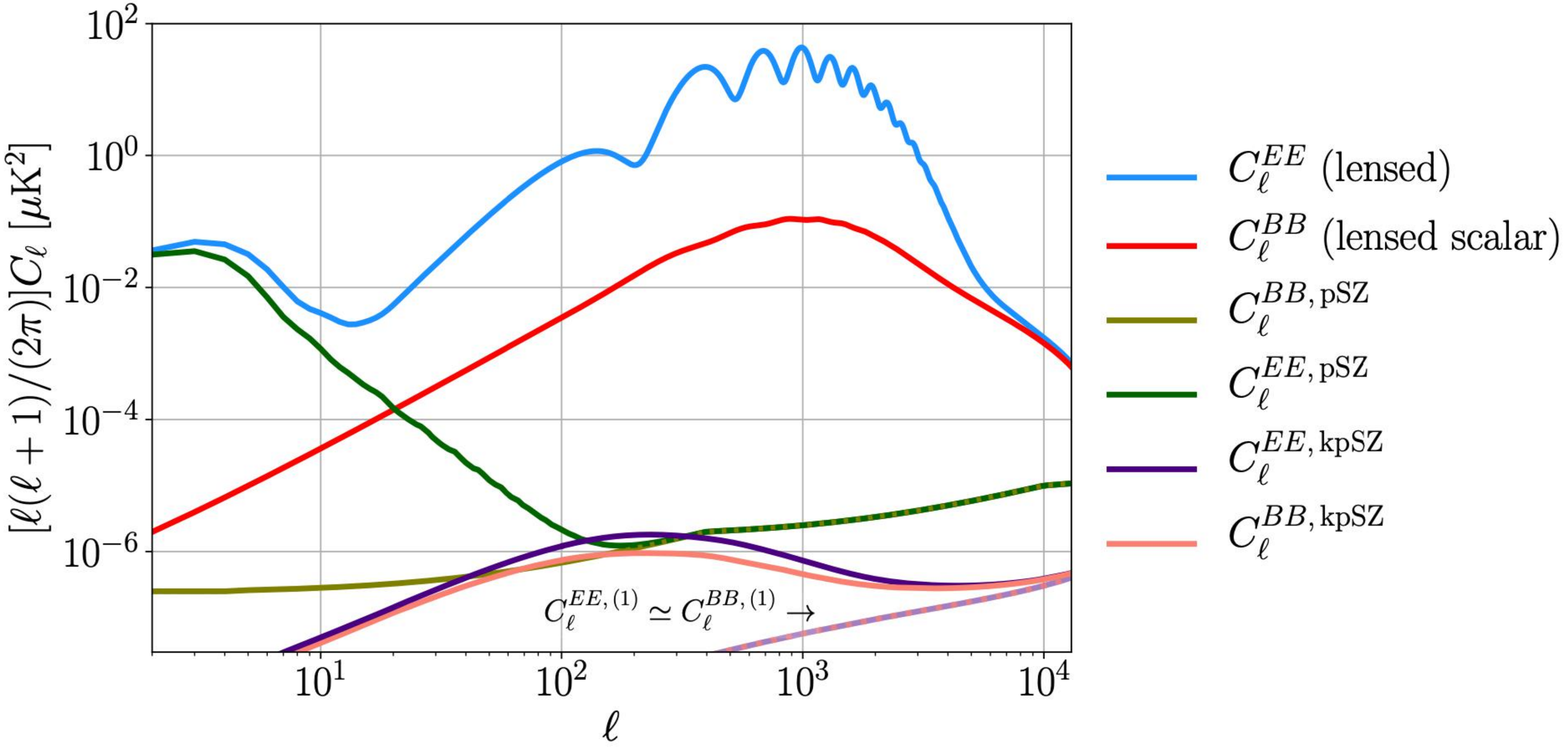
Redshift dependence from kinetic polarized SZ effect

(Hotinli, Holder, Johnson, MK 2204.12503)

Cross-correlation of small-scale CMB polarization with galaxy surveys allows you to isolate the polarization induced by scattering from free electrons.

CB observables can then be applied to polarized sources at different redshifts

Where does the rotation take place?

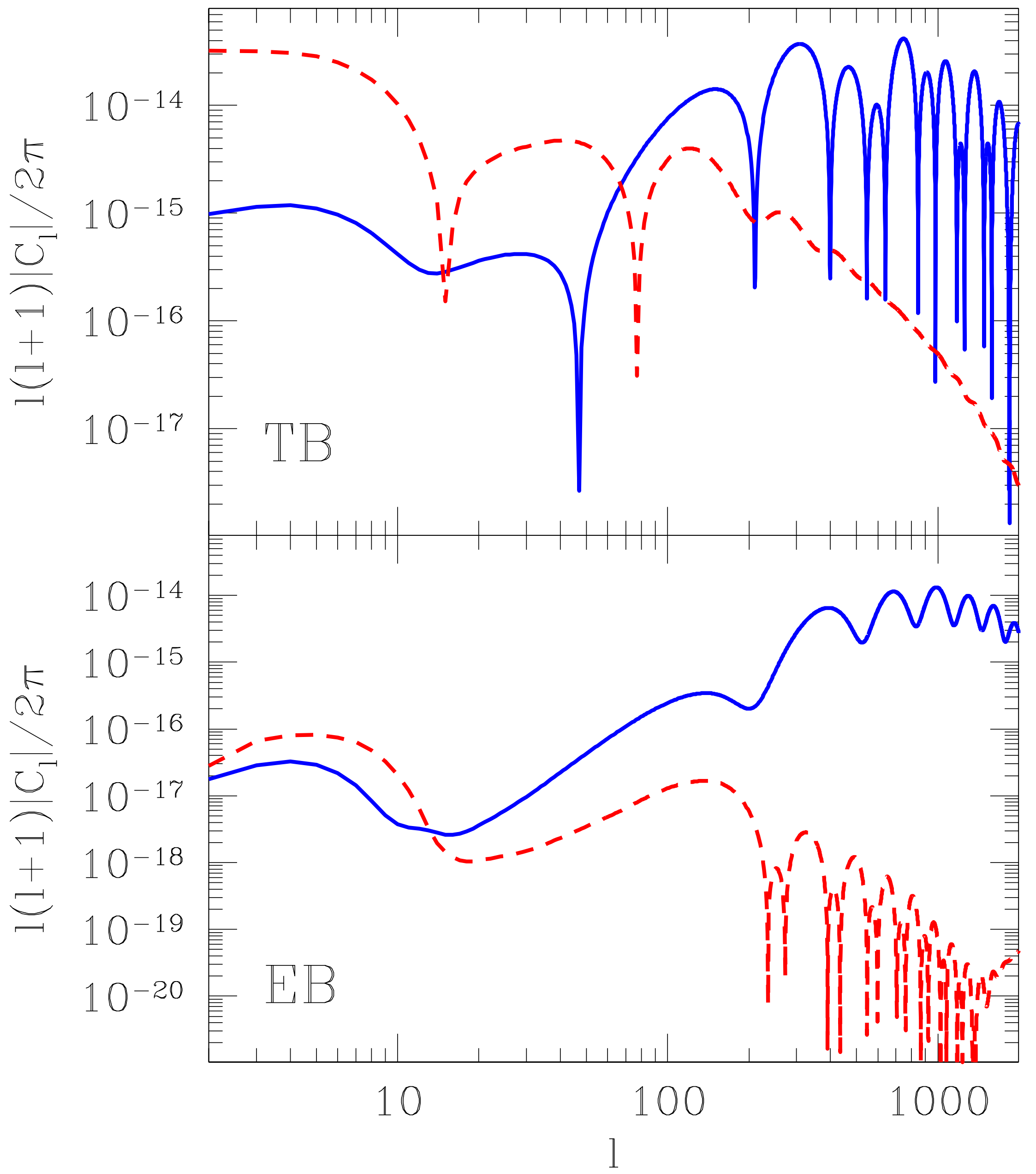


Chiral gravitational waves (amplitude birefringence)
(Lue, Wang, MK, 1999)

- Chern-Simons gravity during inflation

$$\phi R\tilde{R}$$

- May lead to right/left asymmetry and thus to EB/TB cross-correlation

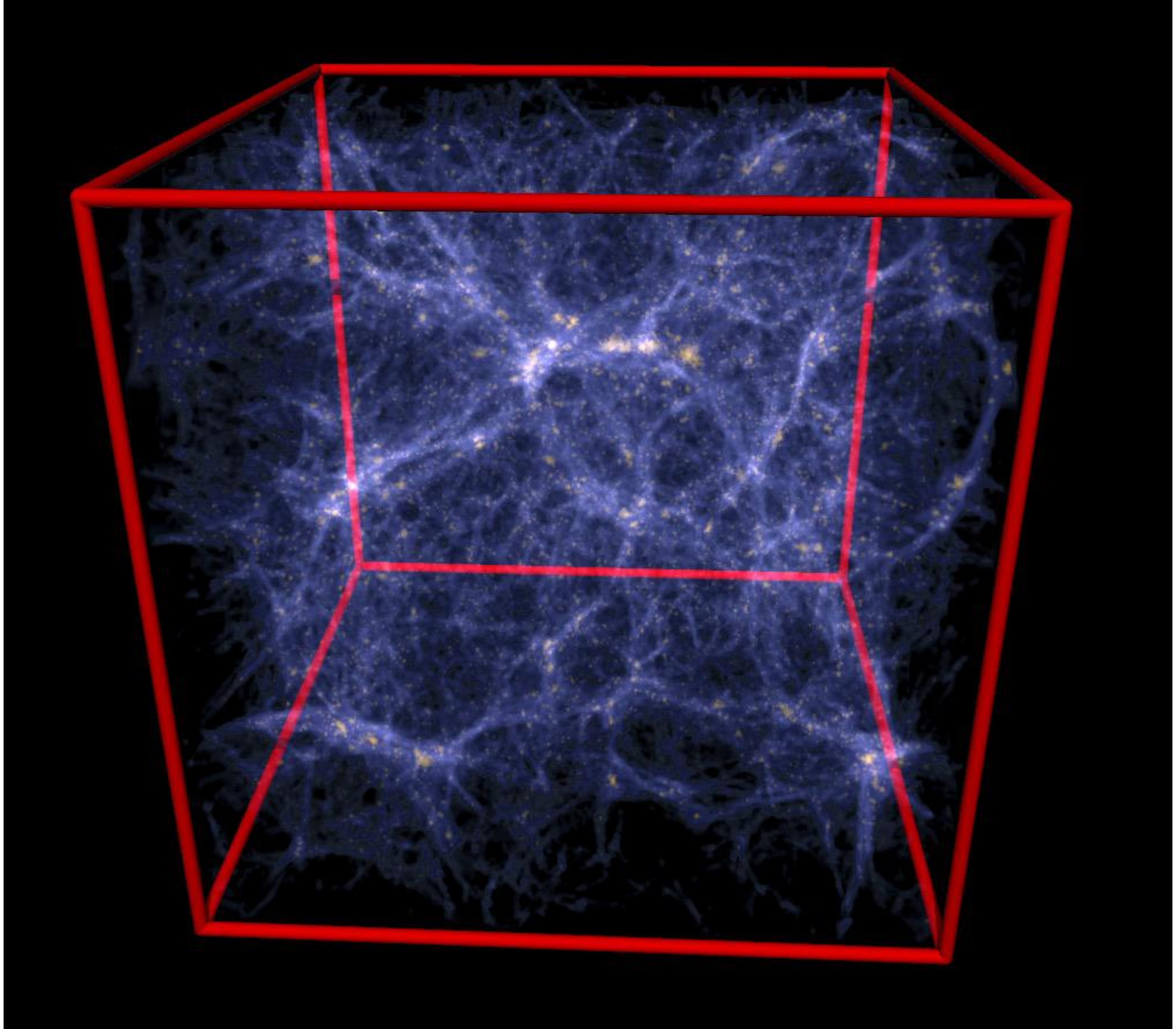


10^{-14}
10^{-15}
10^{-16}
10^{-17}
TB
$l(l+1)|C_l|/2\pi$
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
EB
$l(l+1)|C_l|/2\pi$
10
100
1000
l

B modes and parity tests for galaxy surveys

Jeong & MK 2012

Dai, Jeong, MK 2013



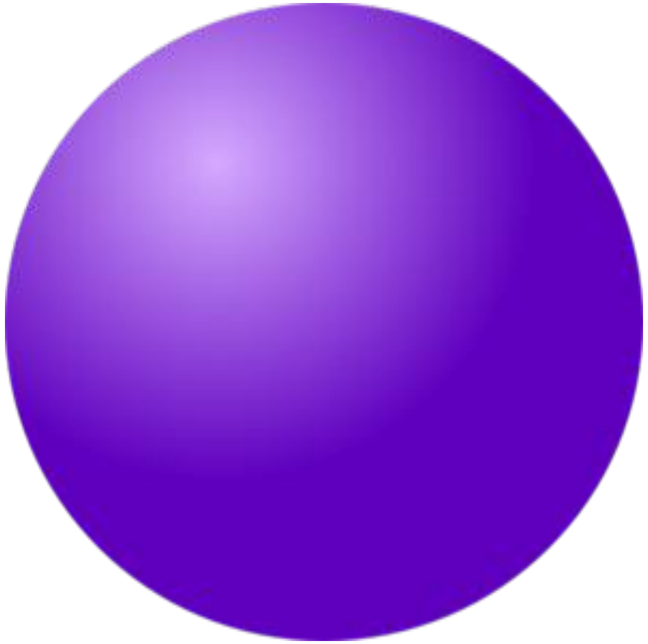
$$\rho(\vec{x})$$

$$\langle\rho(\vec{x})\rho(\vec{x}+\vec{r})\rangle = \xi(r)$$

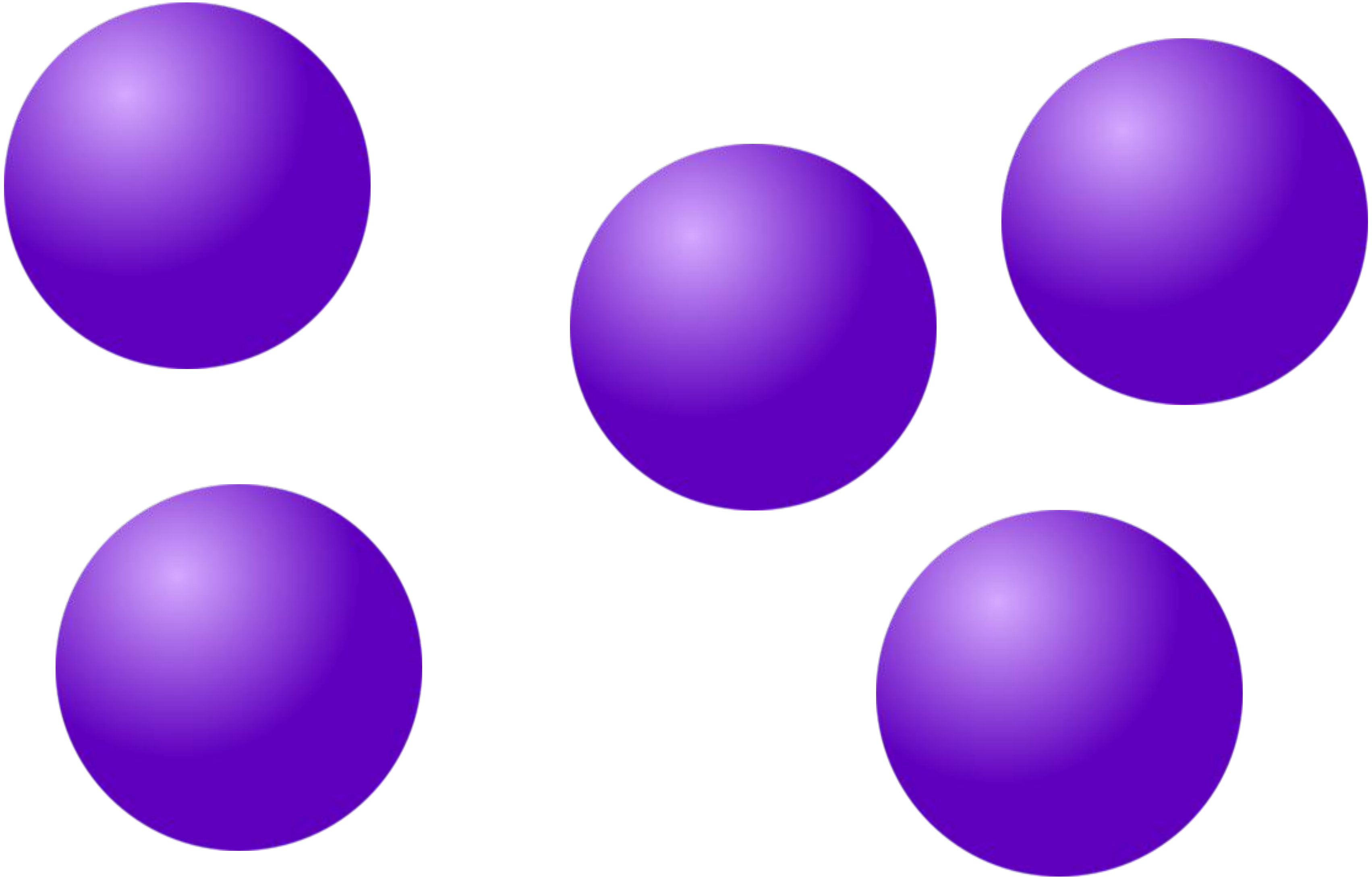
Two-point autocorrelation function

Statistically isotropy and homogeneity
(translational/rotational invariance)

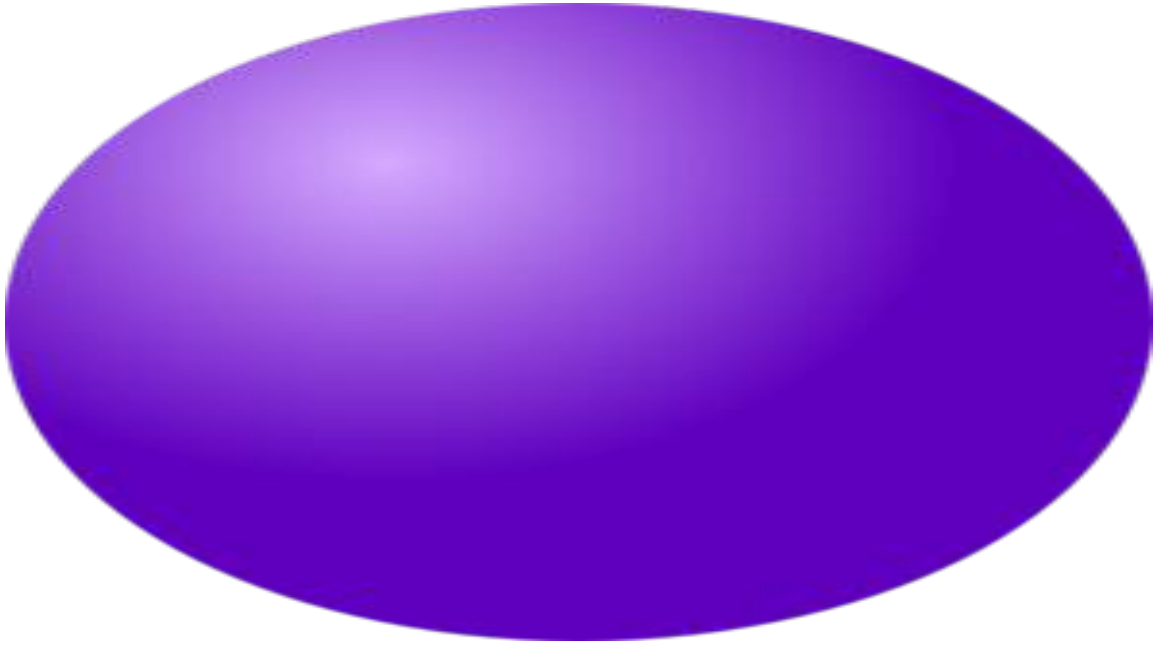
Iso-correlation contours



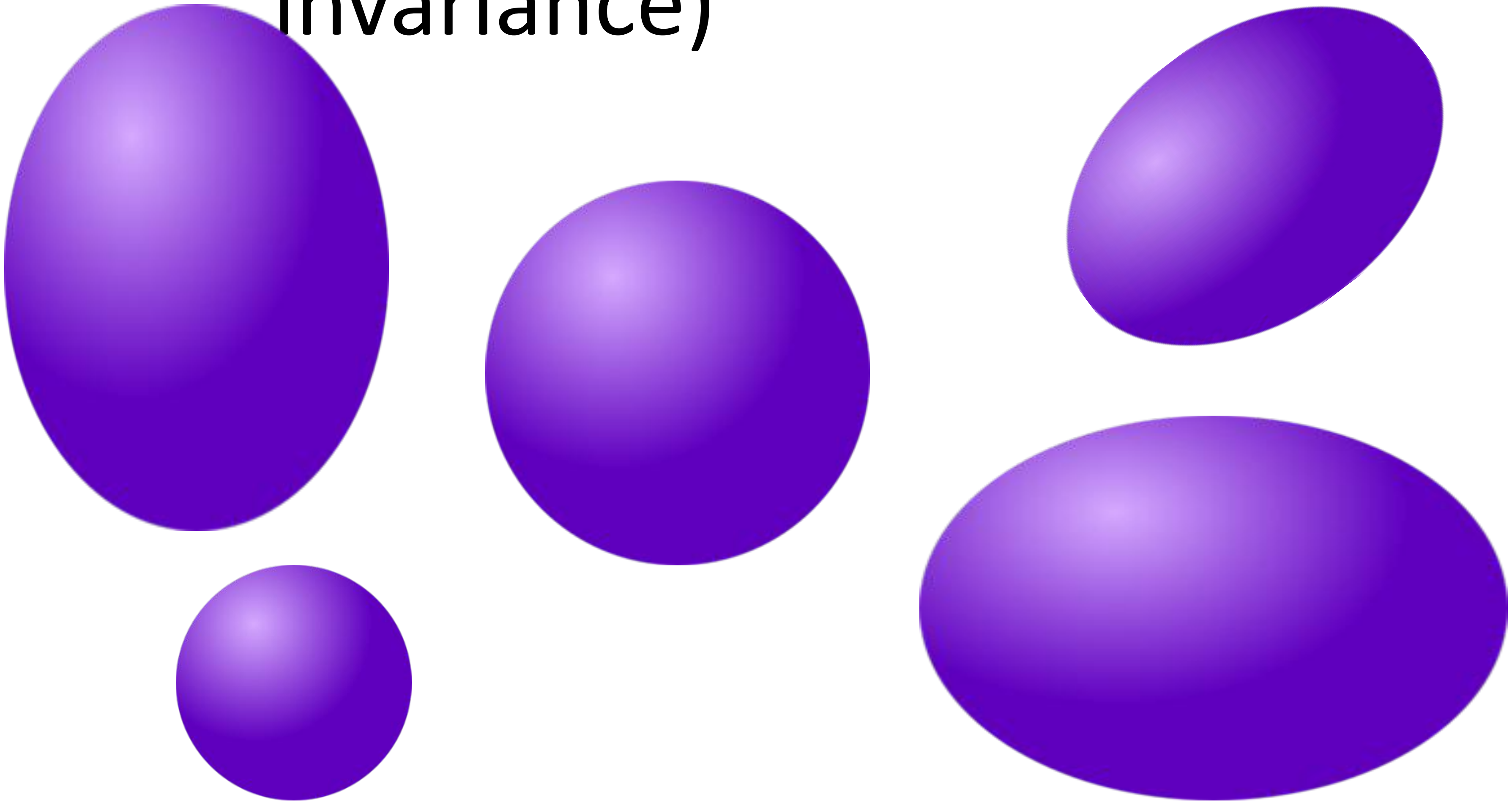
Iso-correlation contours



But departure from statistical isotropy (rotational invariance) is conceivable



As is departure from statistical homogeneity (translational invariance)



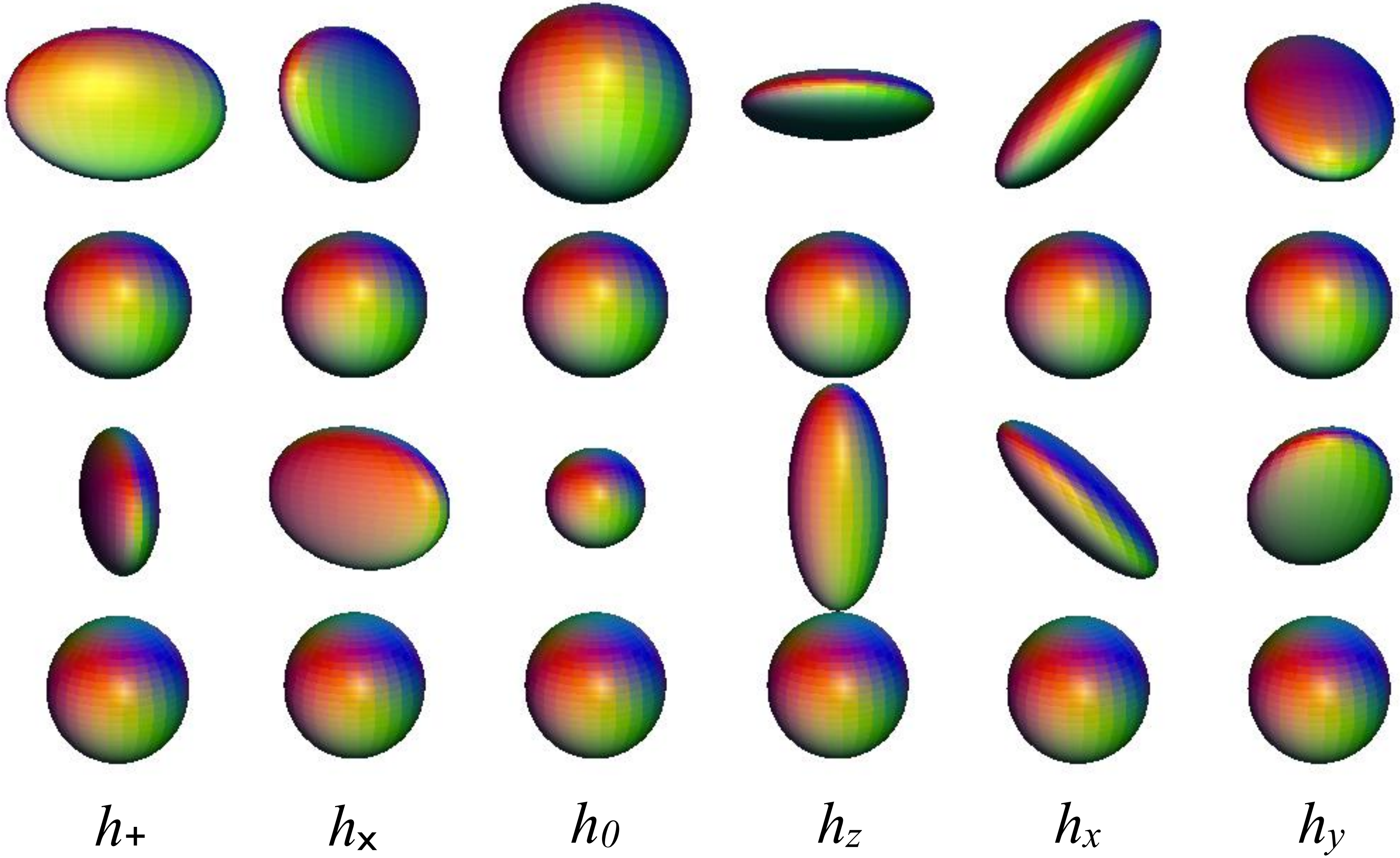
Elongations of iso-correlation contours ~ CMB polarization

Ellipticity in 3d

5 degrees of freedom

Elongation in 2d

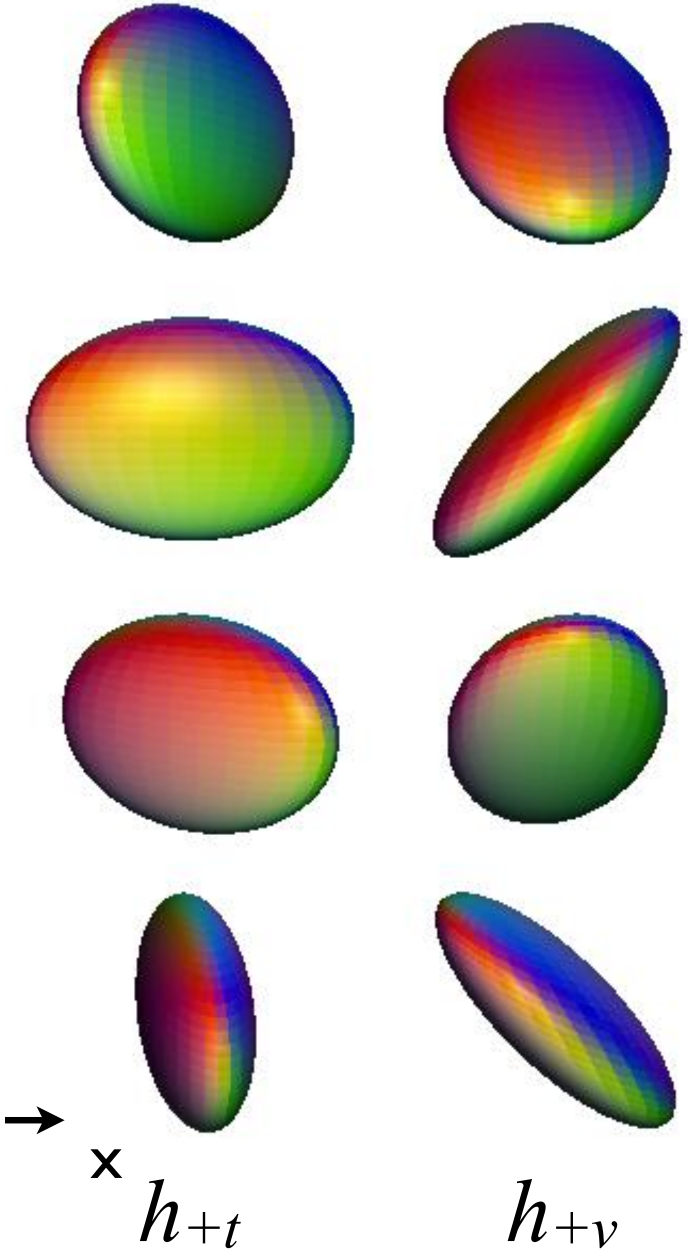
2 degrees of freedom


h_+
$h_\times$
h_0
h_z
h_x
h_y

parity

$$h^t_{R,L} = (h_+ \pm i h_\times)/\sqrt{2}$$

$$h^v_{R,L} = (h_x \pm i h_y)/\sqrt{2}$$


×
h_{+t}
h_{+v}

Again, are effectively parametrization
of 4-pt functions

Recent results: Parity probes

Improved Constraints on Cosmic Birefringence from the *WMAP* and *Planck* Cosmic Microwave Background Polarization Data

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(Dated: September 13, 2022)

The observed pattern of linear polarization of the cosmic microwave background (CMB) photons is a sensitive probe of physics violating parity symmetry under inversion of spatial coordinates. A new parity-violating interaction might have rotated the plane of linear polarization by an angle β as the CMB photons have been traveling for more than 13 billion years. This effect is known as "cosmic birefringence." In this paper, we present new measurements of cosmic birefringence from a joint analysis of polarization data from two space missions, *Planck* and *WMAP*. This dataset covers a wide range of frequencies from 23 to 353 GHz. We measure $\beta = 0.342^\circ\,{}^{+0.094^\circ}_{-0.091^\circ}$ (68% C.L.) for nearly full-sky data, which excludes $\beta = 0$ at 99.987% C.L. This corresponds to the statistical significance of 3.6σ. There is no evidence for frequency dependence of β. We find a similar result, albeit with a larger uncertainty, when removing the Galactic plane from the analysis.

Recent results: Parity probes

In galaxy 4-pt correlation!!

Hou, Slepian, Cahn 2022; Philcox 2022

But see Krolewski, Smith, May, Hopkins, last week