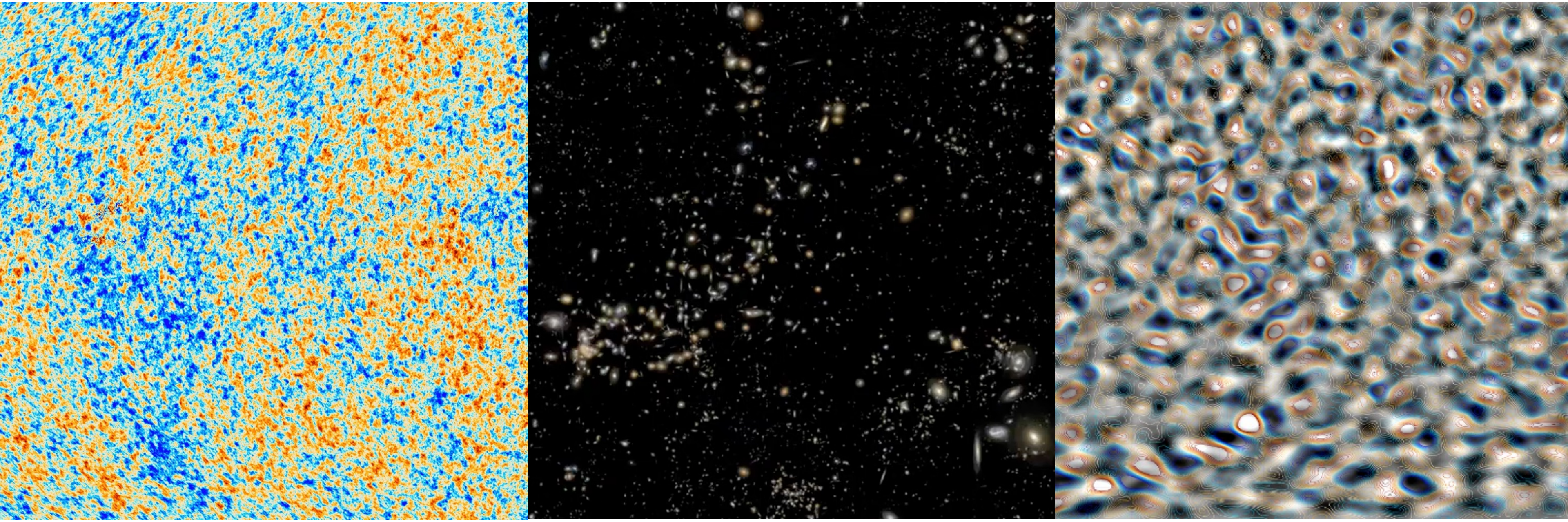
What did we learn from cosmological observations?



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Science & Technology Facilities Council
UK Research and Innovation
European Research Council
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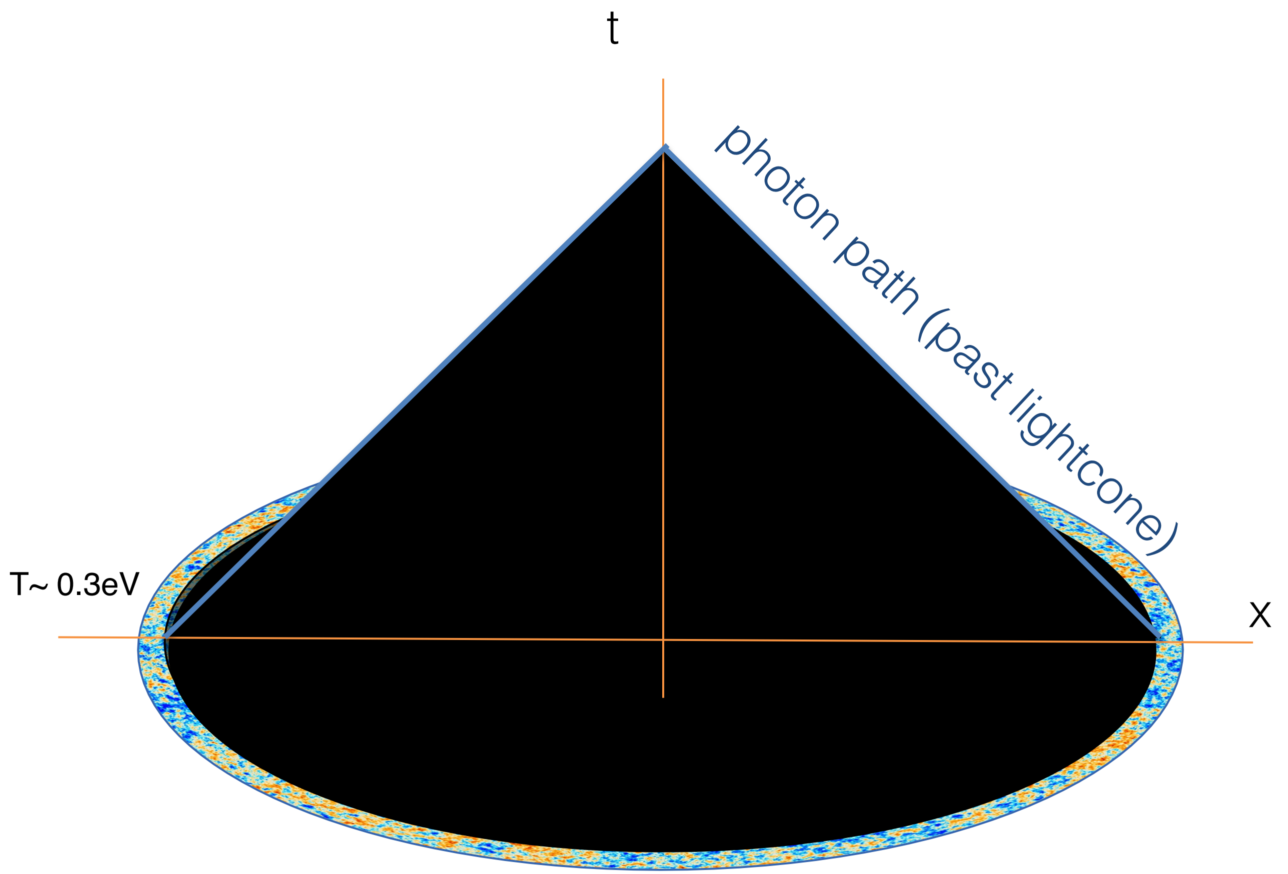
Outline

- The standard cosmological model and the observations that underpin it
- Hubble and S8 tensions: systematics or first cracks in our cosmological model?
- Cosmology as a laboratory for new fundamental physics: r and N_{eff}

Galaxy data from SDSS telescope, video by Miguel Aragon, Mark Subbarao, Alex Szalay

Seeing the Past: Cosmological Observations

No need to speculate about cosmic history: can see it, since the further out we look, the further back in time we look.

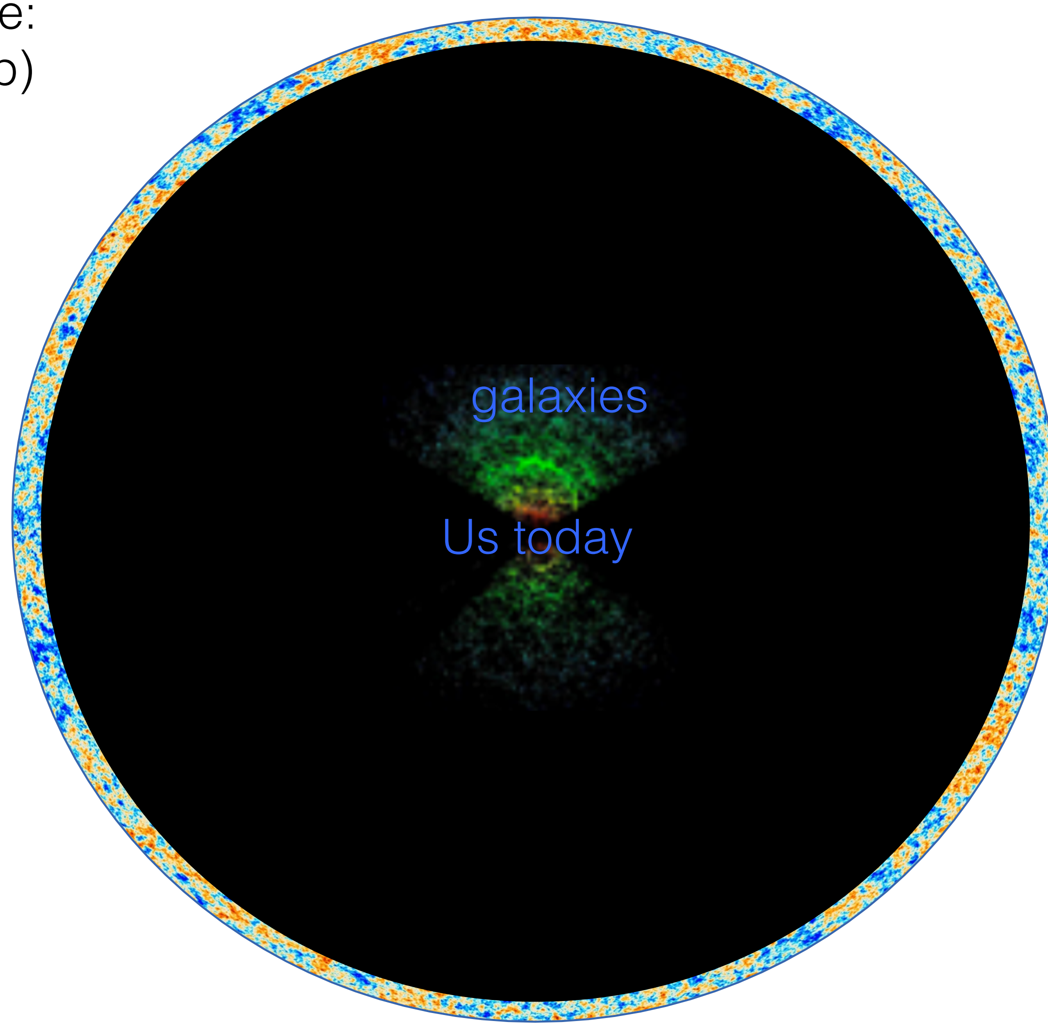


Observations of our universe (typically) on past lightcone surface

Seeing the Past: Cosmological Observations

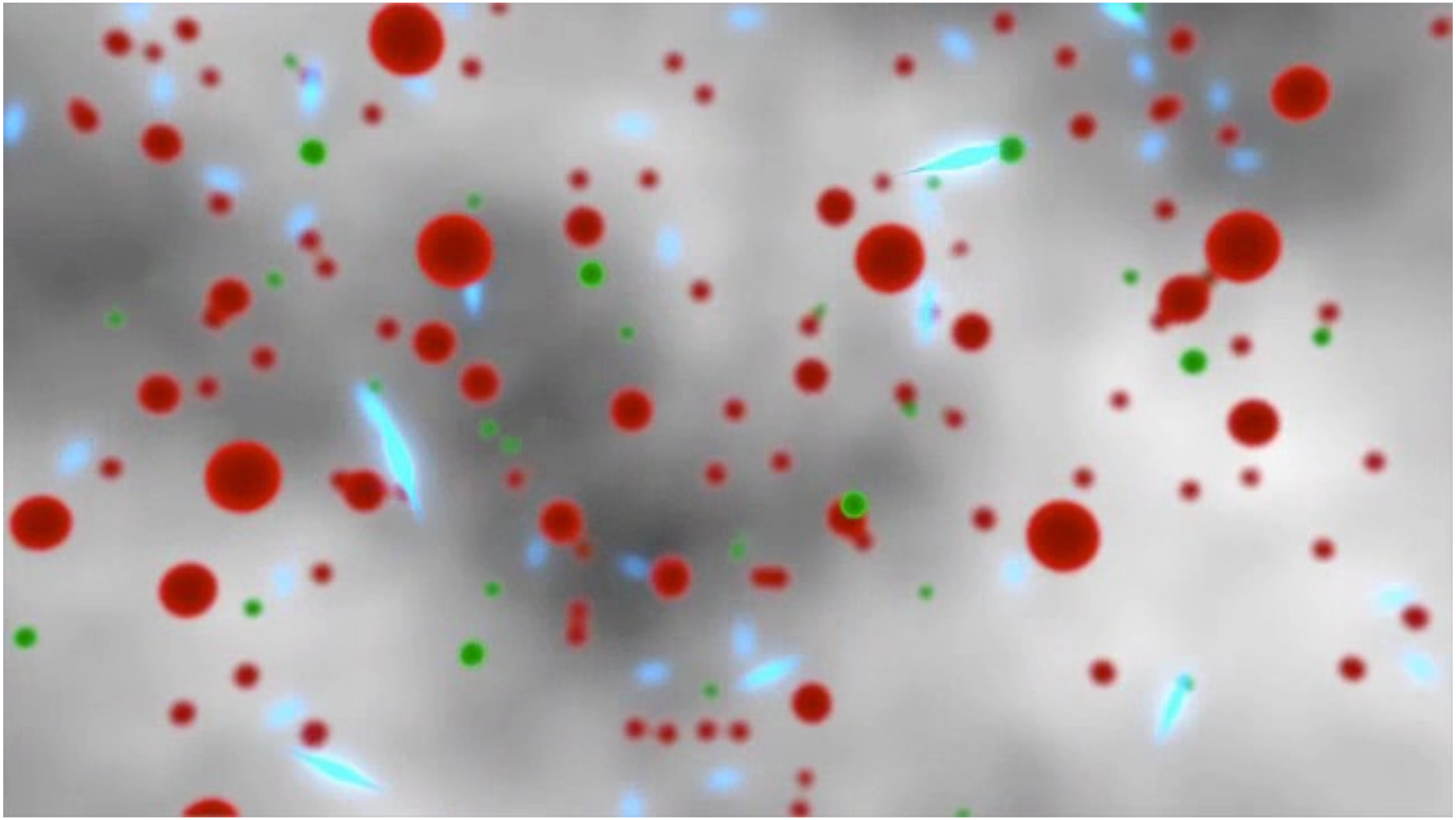
The observable universe:
(lightcone seen from top)

See galaxies nearby; furthest + earliest light source is opaque, glowing plasma, the Cosmic Microwave Background (CMB)



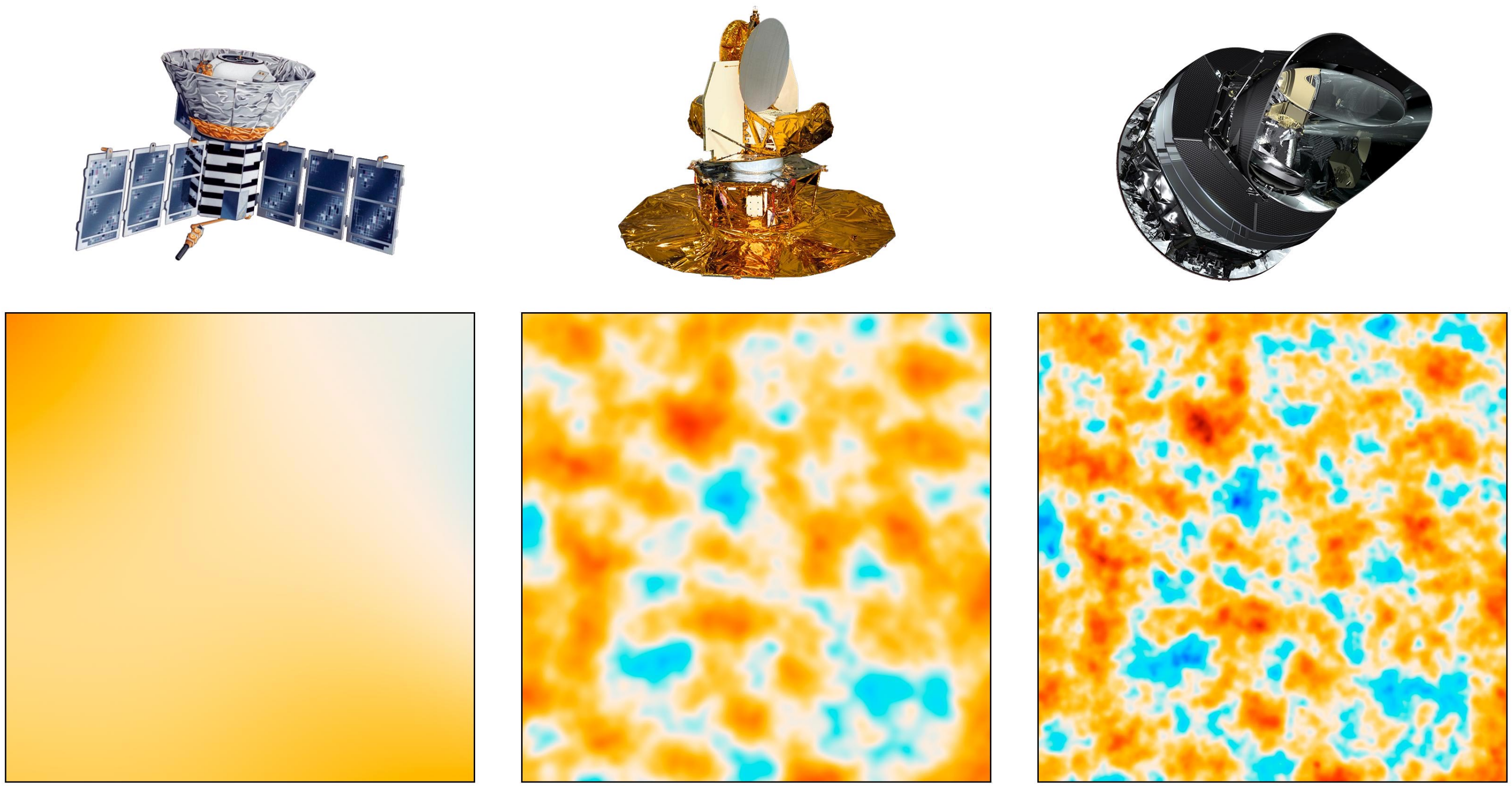
Early universe glowing plasma: emits CMB

(Cartoon, clearly not physical)



CMB Fluctuations – Learning More

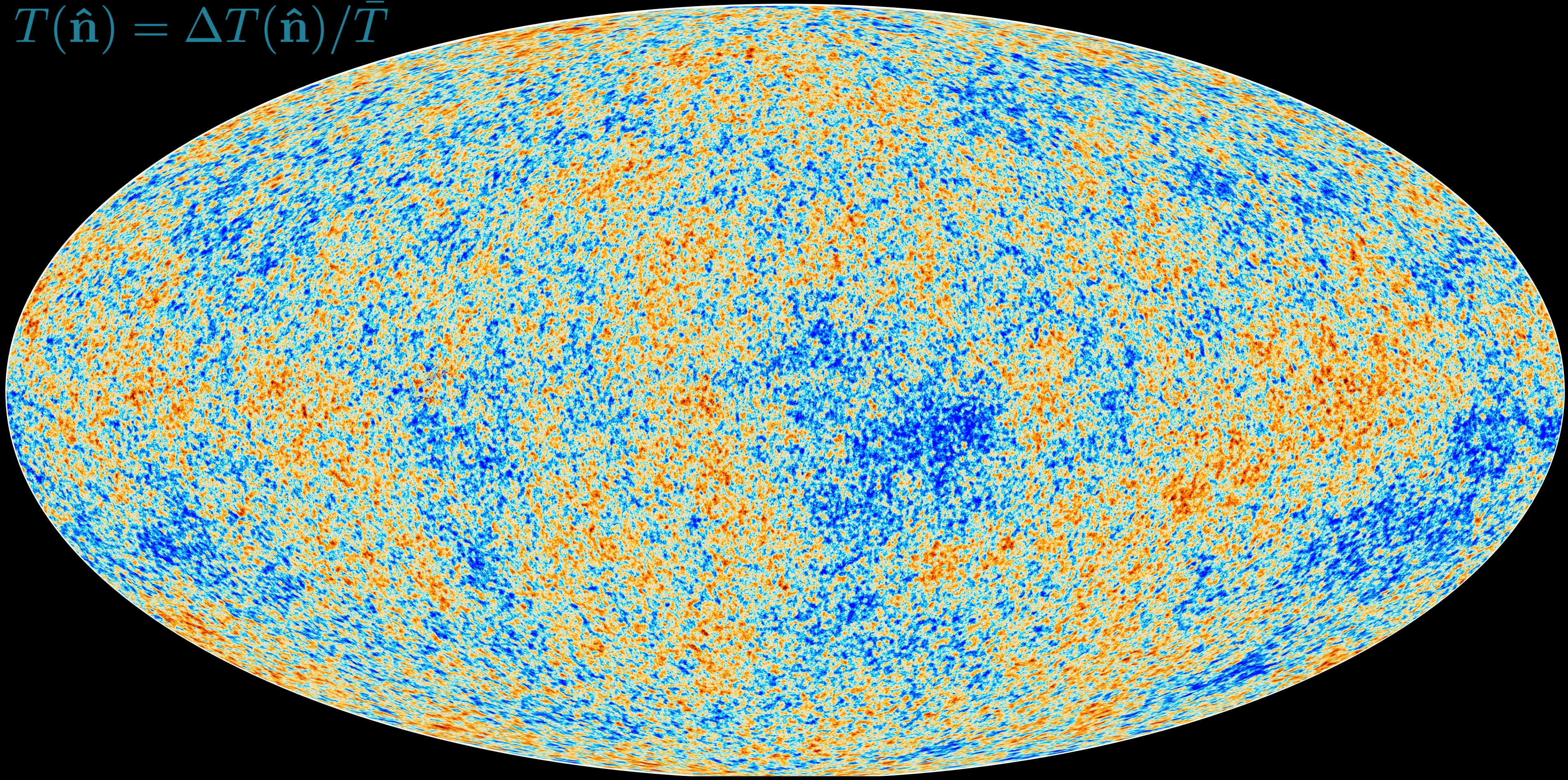
- CMB brightness not uniform! Improving experiments have been making increasingly high-resolution maps of the CMB brightness variation...



COBE WMAP Planck

CMB Fluctuations – Best Picture From Planck Satellite

$$T(\hat{\mathbf{n}}) = \Delta T(\hat{\mathbf{n}})/\bar{T}$$



CMB Brightness Fluctuations

What are we seeing in the CMB maps?

- Most relevant

$$T(\hat{\mathbf{n}}) \sim S(\mathbf{x}_{\text{emision}}, t_{\text{emission}}) \equiv \frac{\delta\rho_r}{4\bar{\rho}_r}(\mathbf{x}_{\text{emision}}, t_{\text{emission}}) + \Phi(\mathbf{x}_{\text{emision}}, t_{\text{emission}})$$

radiation overdensity potential fluctuation

- T depends on initial conditions and causal evolution (linear, translation-invariant, so encoded in transfer function)

$$\tilde{S}(\mathbf{k}, t_{\text{emission}}) = T_S(k, t_{\text{emission}})\Phi_i(\mathbf{k})$$

evolution of perturbations encoded in transfer function

initial potential fluctuations

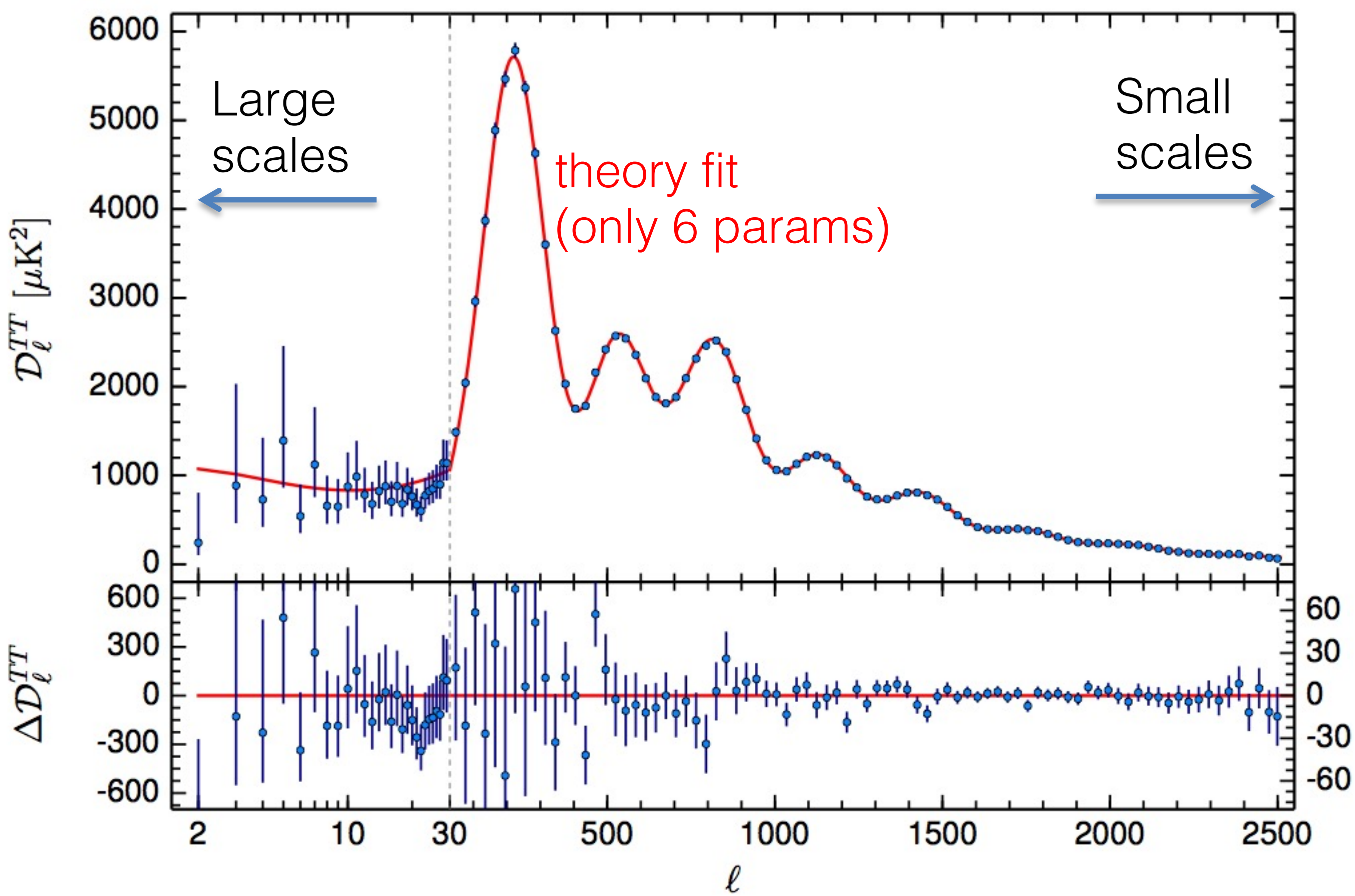
CMB Power Spectrum

- Quantifies fluctuation size^2 vs. (inverse) angular scale
- We can measure it as follows:

$$a_{lm} = \int d^2\hat{\mathbf{n}} Y^*_{lm}(\hat{\mathbf{n}}) T(\hat{\mathbf{n}})$$

$$\hat{C}_l = \Sigma_m |a_{lm}|^2 / (2l+1)$$

Key Measurement: The CMB Power Spectrum



[Planck 2018]

$$\mathcal{D}_l \equiv l(l+1)C_l/2\pi$$

What does the CMB power depend on?

- CMB power spectrum C_l depends on few basic effects

$$\frac{l(l+1)}{2\pi} C_l \sim T_S^2(k = l/\chi_*, t_{\rm emission}) \times \Delta^2_{\Phi_i}(k = l/\chi_*)$$

1. Initial conditions: primordial potential perturbation power spectrum

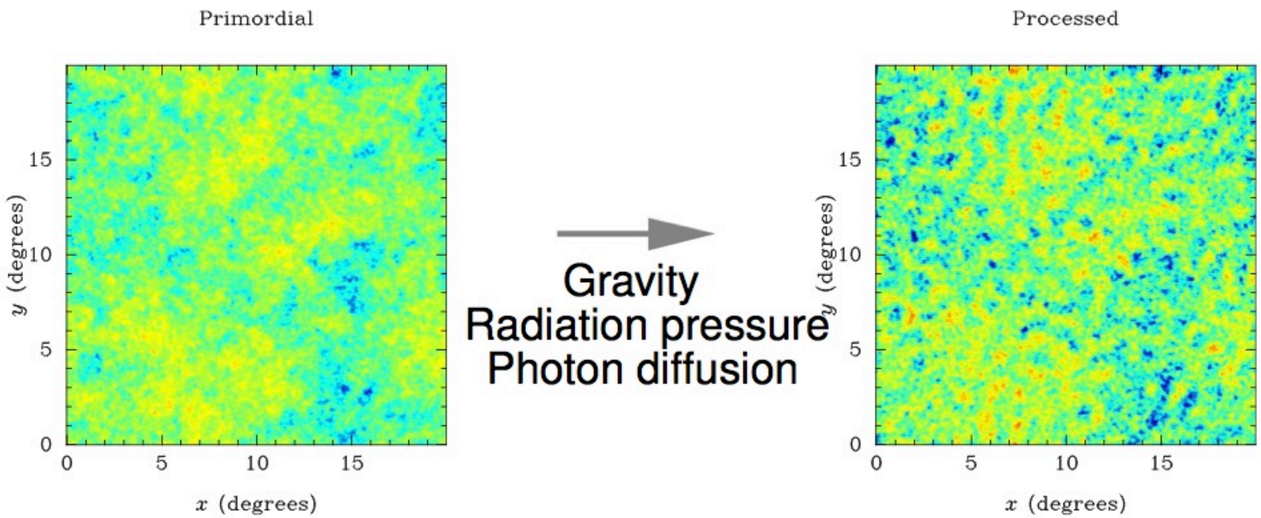
What does the CMB power depend on?

- CMB power spectrum C_l depends on few basic effects

$$\frac{l(l+1)}{2\pi} C_l \sim T_S^2(k = l/\chi_*, t_{\text{emission}}) \times \Delta^2_{\Phi_i}(k = l/\chi_*)$$

2. Evolution/growth: transfer function from linear perturbation theory

1. Initial conditions: primordial potential perturbation power spectrum



Can easily compute based on linearized evolution equations.
Depends on composition of the universe (densities / pressures) + GR

What does the CMB power depend on?

- CMB power spectrum C_l depends on few basic effects

$$\frac{l(l+1)}{2\pi} C_l \sim T_S^2(k = l/\chi_*, t_{\rm emission}) \times \Delta^2_{\Phi_i}(k = l/\chi_*)$$

2. Evolution/growth: transfer function from linear perturbation theory

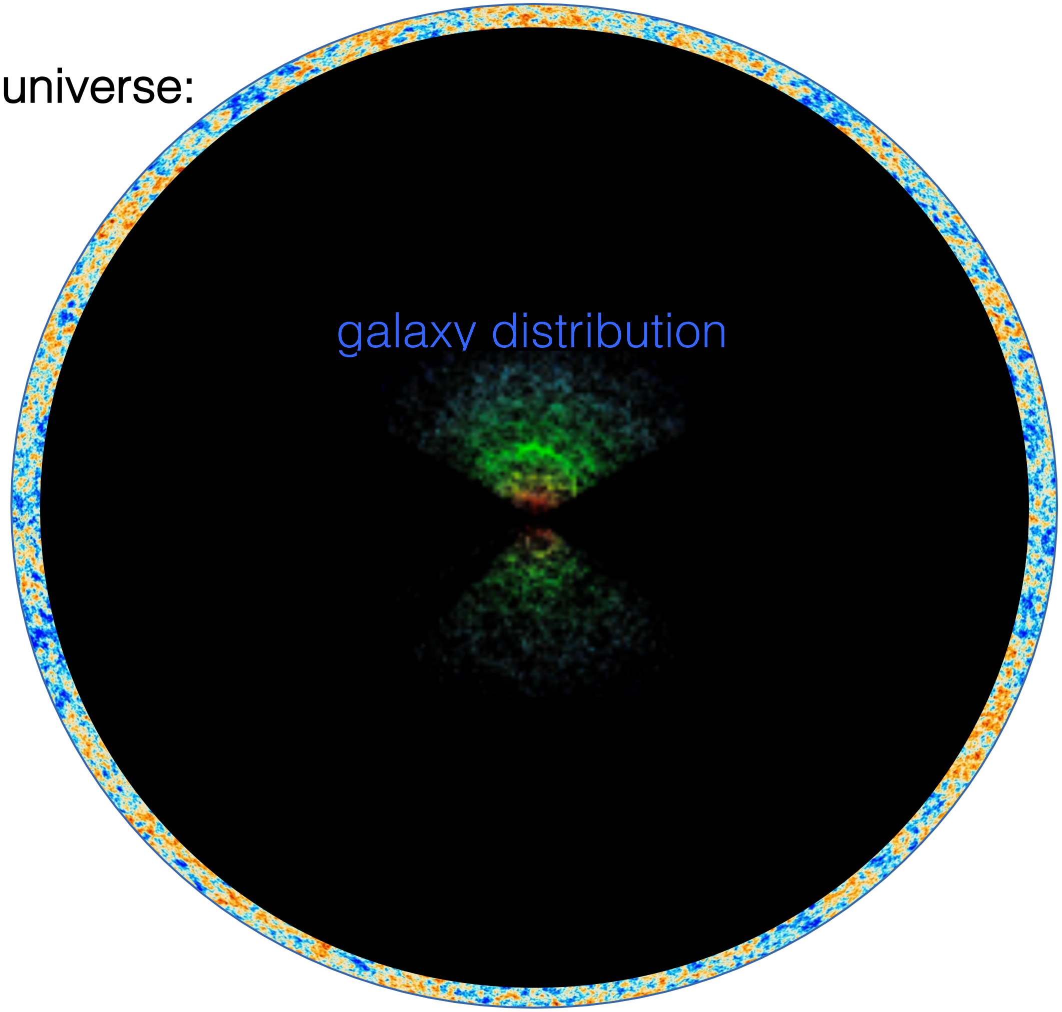
1. Initial conditions: primordial potential perturbation power spectrum

3. Distances: scale to angle projection depends on distance to CMB, χ_*

Also depends on composition of the universe + GR

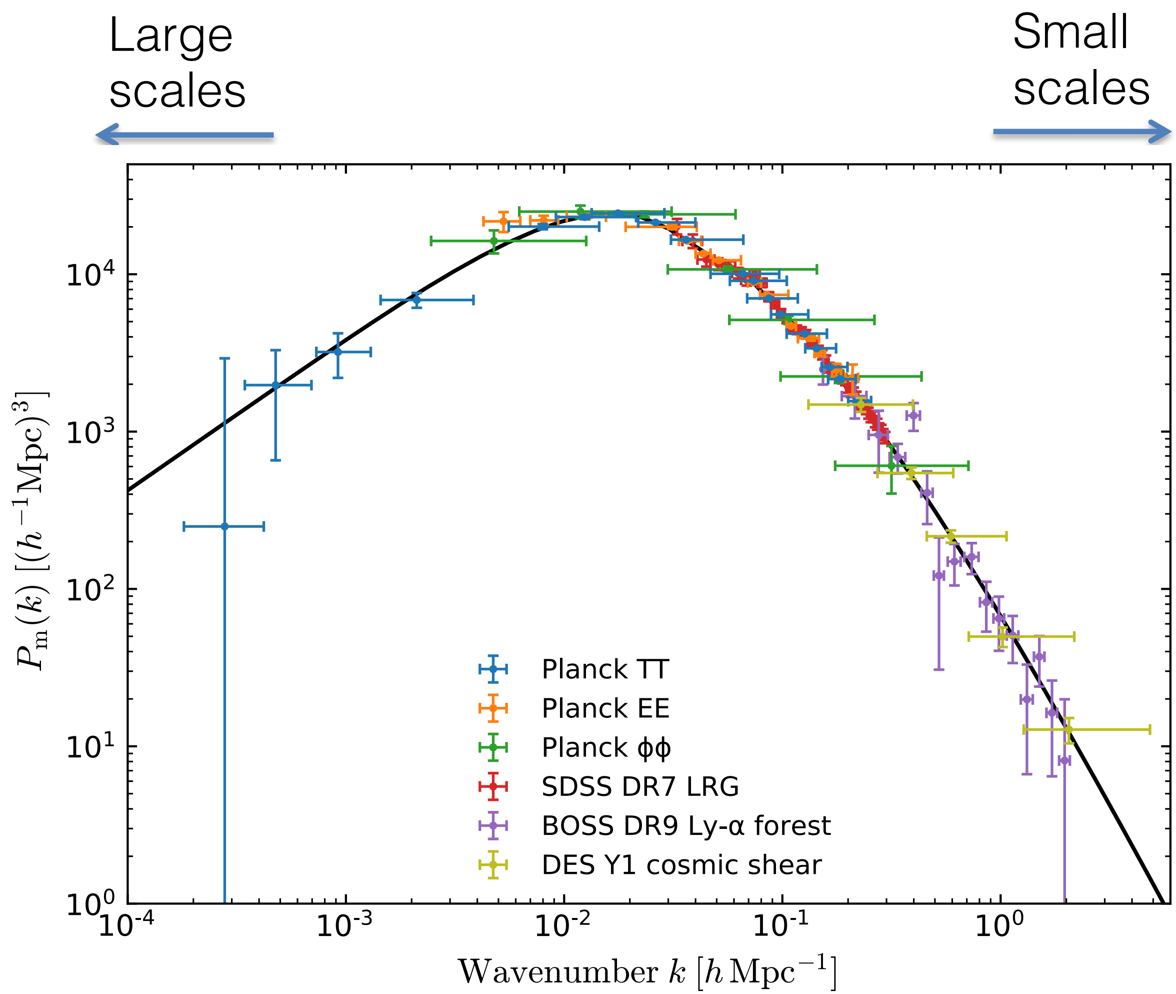
Mapping Large Scale Structure

The observable universe:



Key Measurement: Matter (or Galaxy) Power Spectrum

- Fourier transform galaxy density, square: power spectrum



Same sources of information in large-scale structure

$$C_l^{\kappa\kappa} \sim \int d\chi \Delta_\phi^2(k = l/\chi) T_\kappa^2(t(\chi), k = l/\chi)$$

1. Initial conditions: primordial potential perturbation power spectrum

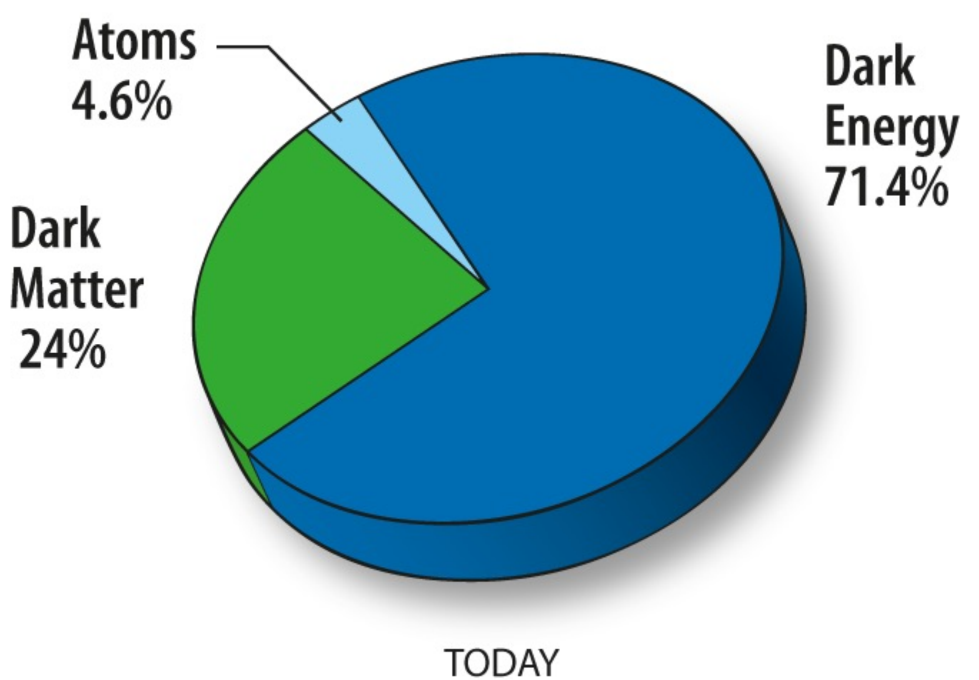
2. Evolution/growth: transfer function from non-linear perturbation theory

3. Distances: scale to angle projection depends on distance to LSS

- Use these to understand the composition + origin of our universe. Cosmology has arrived at a standard model:

Standard Cosmological Model (LCDM): Composition of the Universe

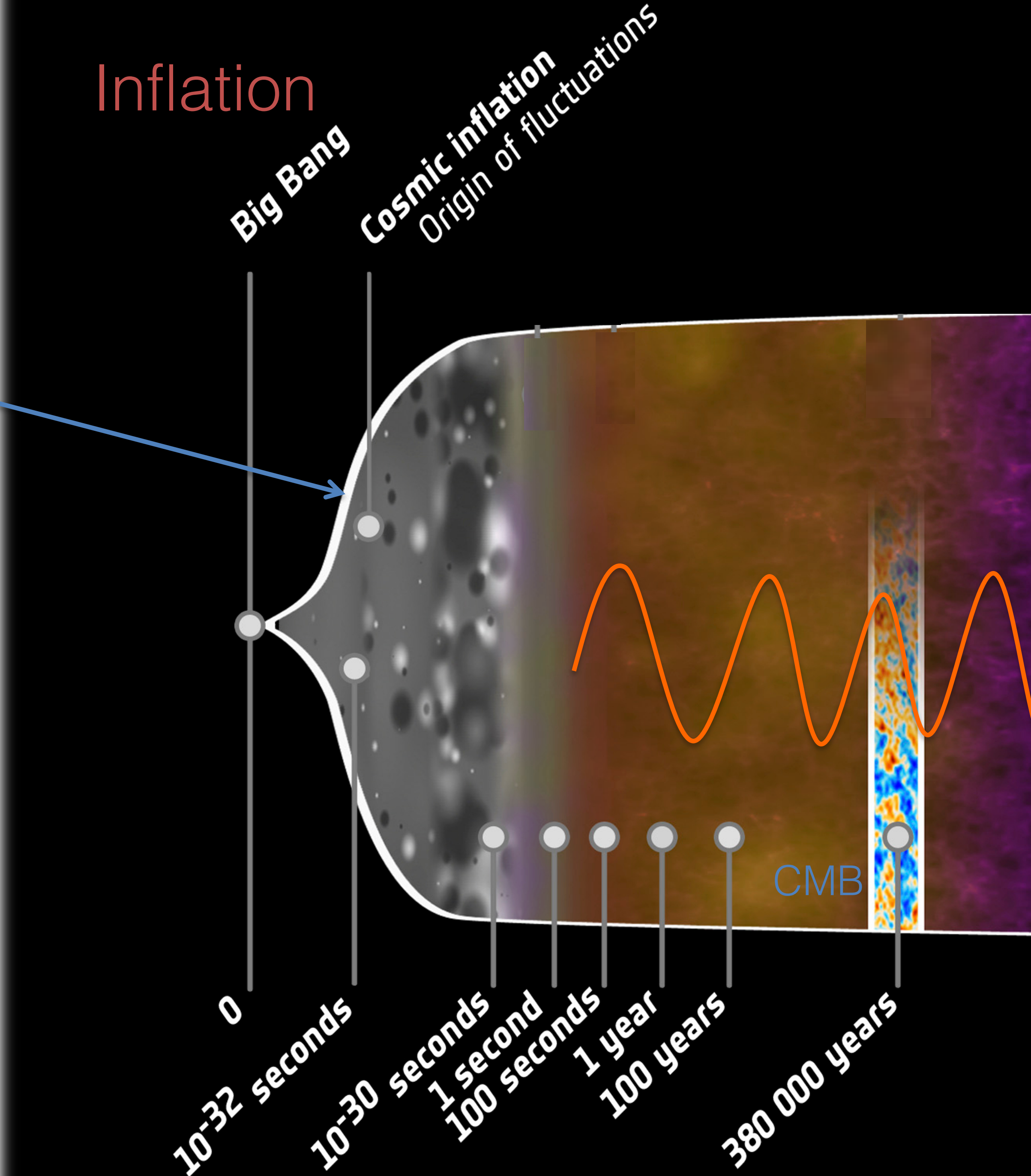
CMB and LSS evolution + distances imply composition:



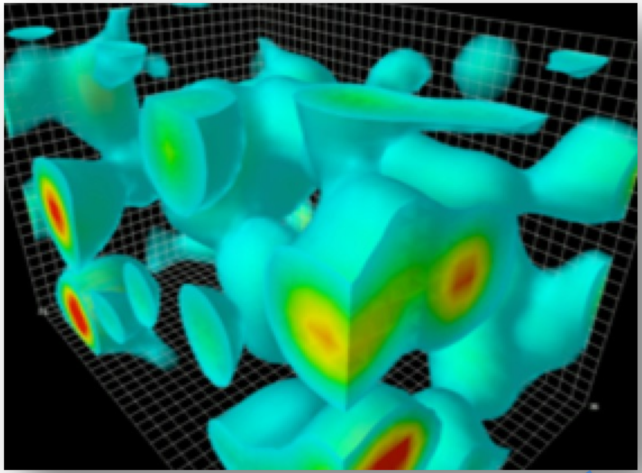
[Planck 2018]

Inflation

- Inflation: initial accelerated cosmic expansion.
- Observational support: evidence of near-scale-invariance, Gaussianity, super-horizon-correlation of initial conditions

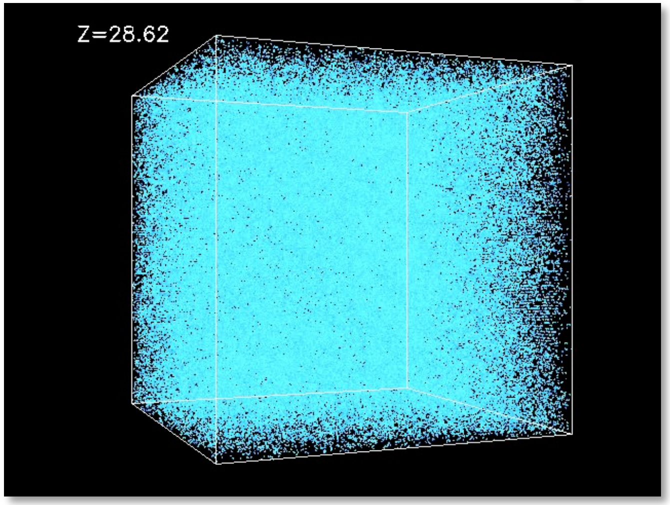


Standard Cosmological Model (LCDM): Inflation Quantum Fluctuations Seed Structure



Inflation quantum fluctuations generate small differences in density

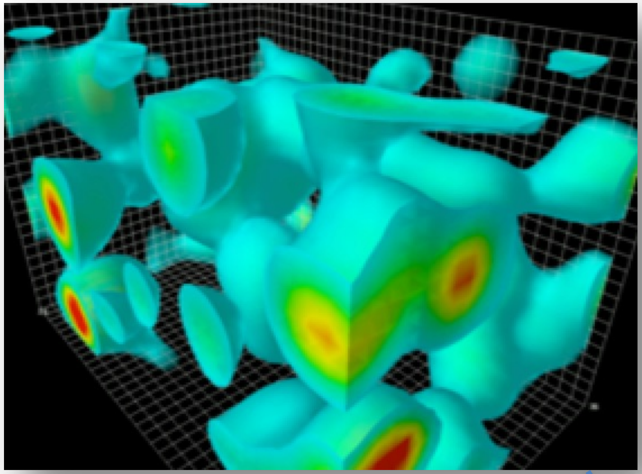
Gravitational collapse, driven by dark matter…



turns these into the stars and galaxies of today!

[A. Kravtsov]

Standard Cosmological Model (LCDM): Inflation Quantum Fluctuations Seed Structure



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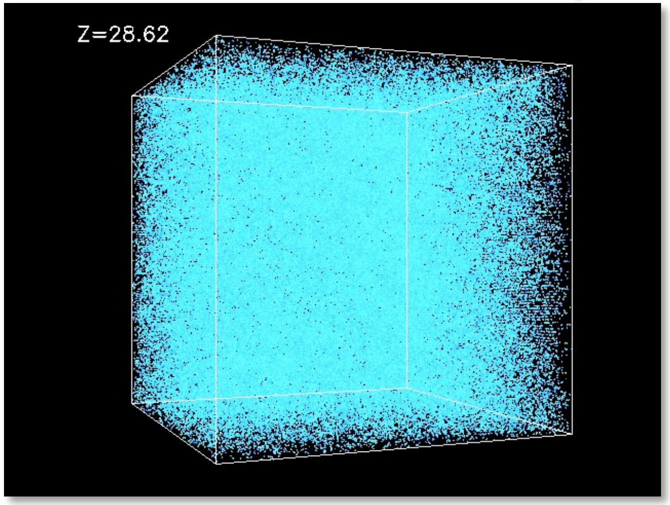
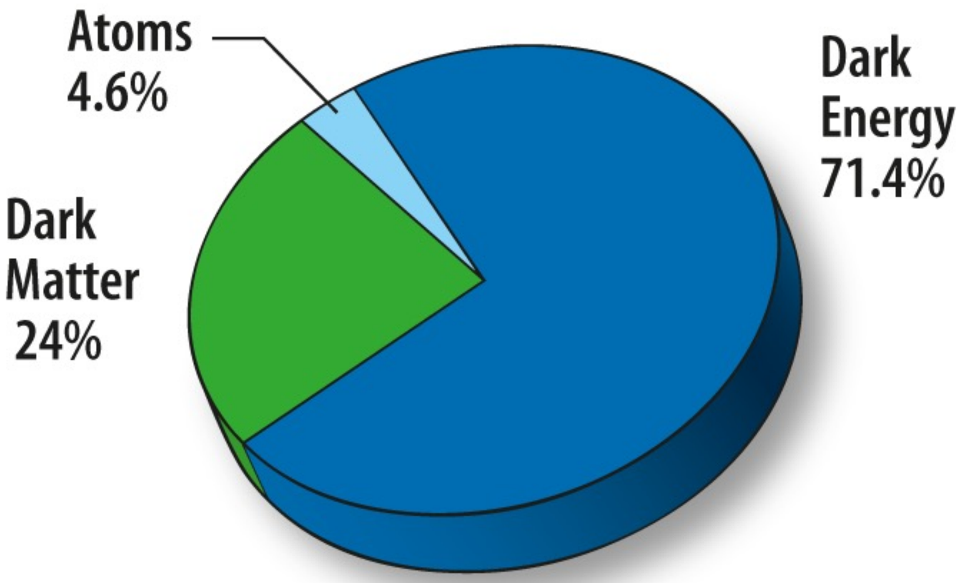


turns these into the stars and galaxies of today!

Observational support: evidence of near-scale-invariance, Gaussianity, super-horizon-correlation of initial conditions

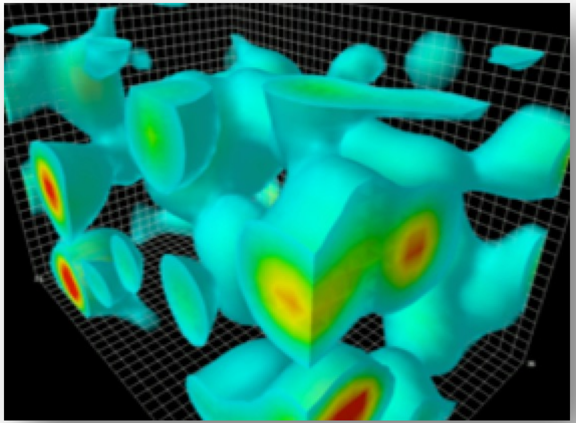
[A. Kravtsov]

Standard Cosmological Model: Simple…



TODAY

A_s, n_s

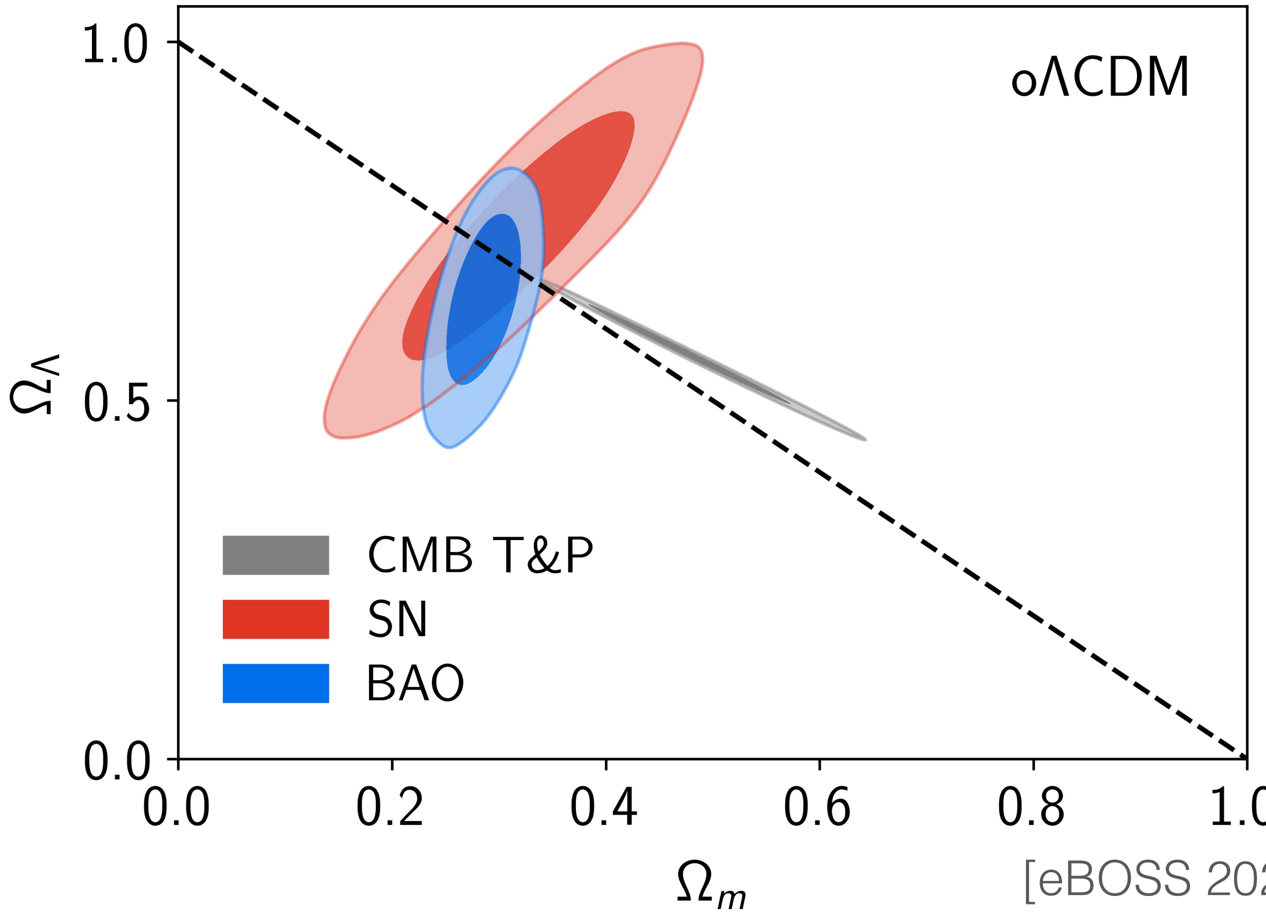


Standard Cosmological Model: robust and difficult to modify…

Can get independent, consistent measurements:

From CMB only OR SNae only OR BAO only

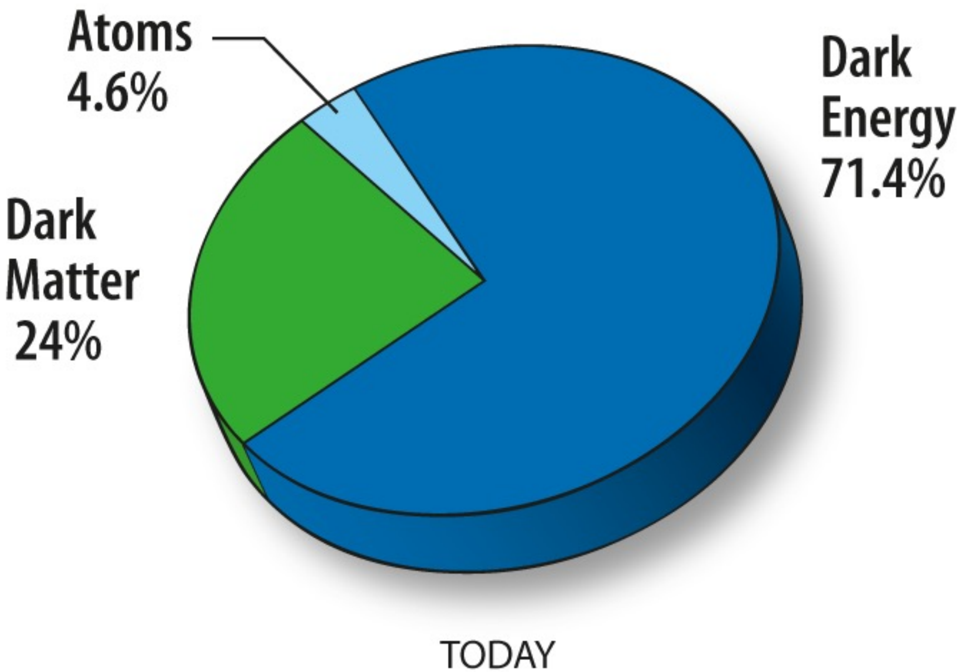
From evolution OR from distance



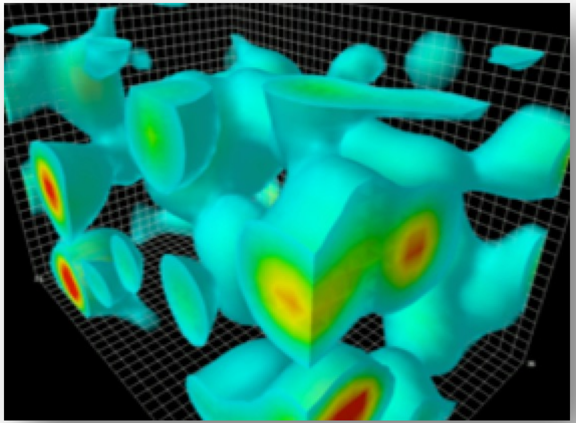
[eBOSS 2021]

Interlocking web of hundreds of -often very robust and well-understood- observations underpinning this model

Standard Cosmological Model:
… but very strange



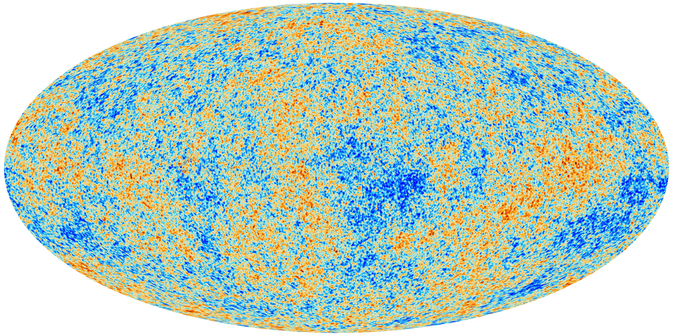
A_s, n_s



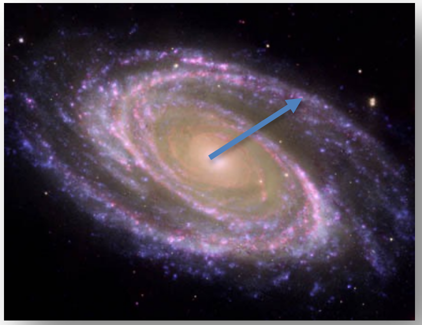
Described by only 5(+1) parameters,
but all of them poorly understood

Recently: claims of tensions in late vs. early-time measurements

- Consistency test:



Fit LCDM model to CMB (early times, t=0.004 Gyr)



Predict expansion (H_0) or structure size (S8) at late times (10-14 Gyr) + compare with observations

Claims of discrepancies in late vs. early measurements:

- Expansion rate of the universe: "Hubble/H_0 tension"
- Growth of structure "S8 tension"

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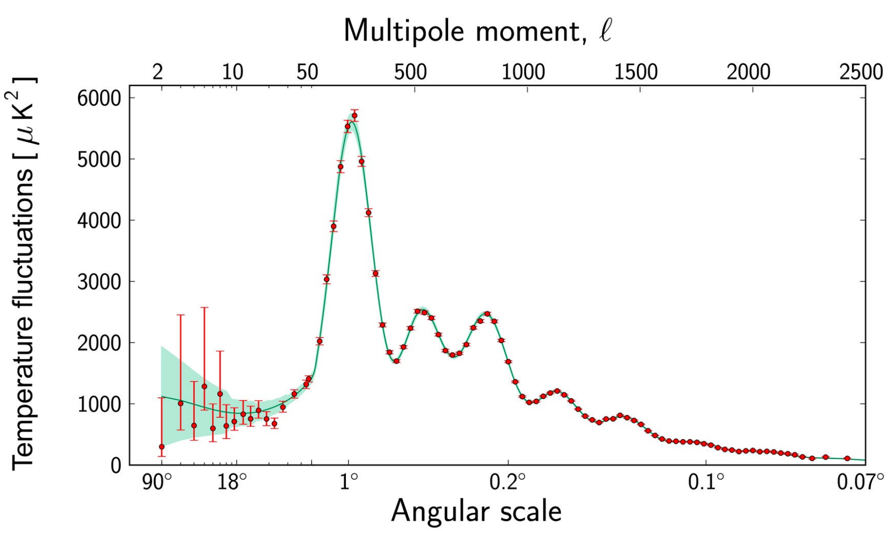
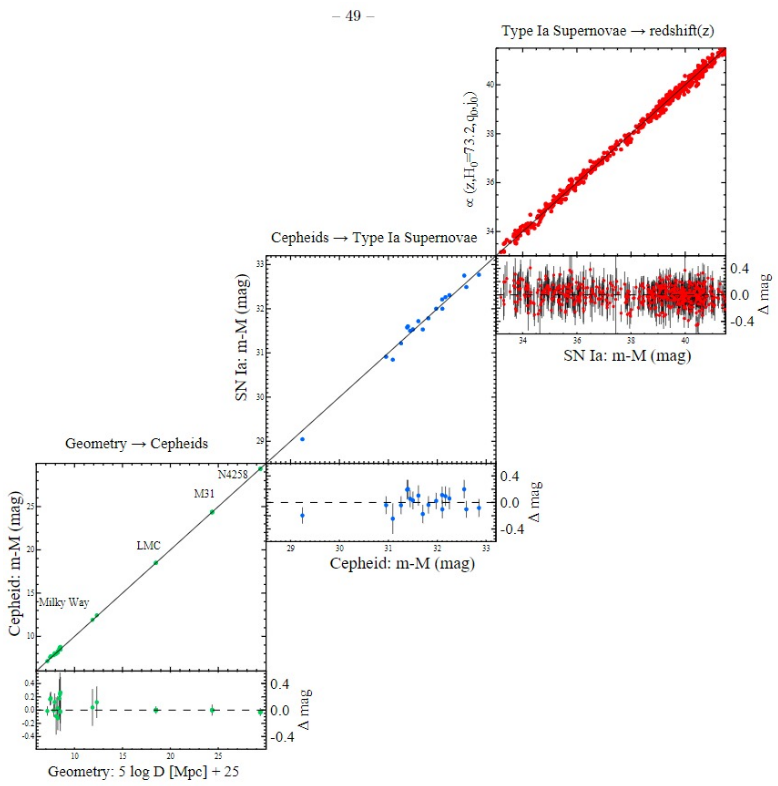
Ways to measure Hubble constant $H_0 = \frac{\dot{a}}{a}$
i.e., expansion rate of Universe

a: scale factor

CMB power spectrum / early / indirect

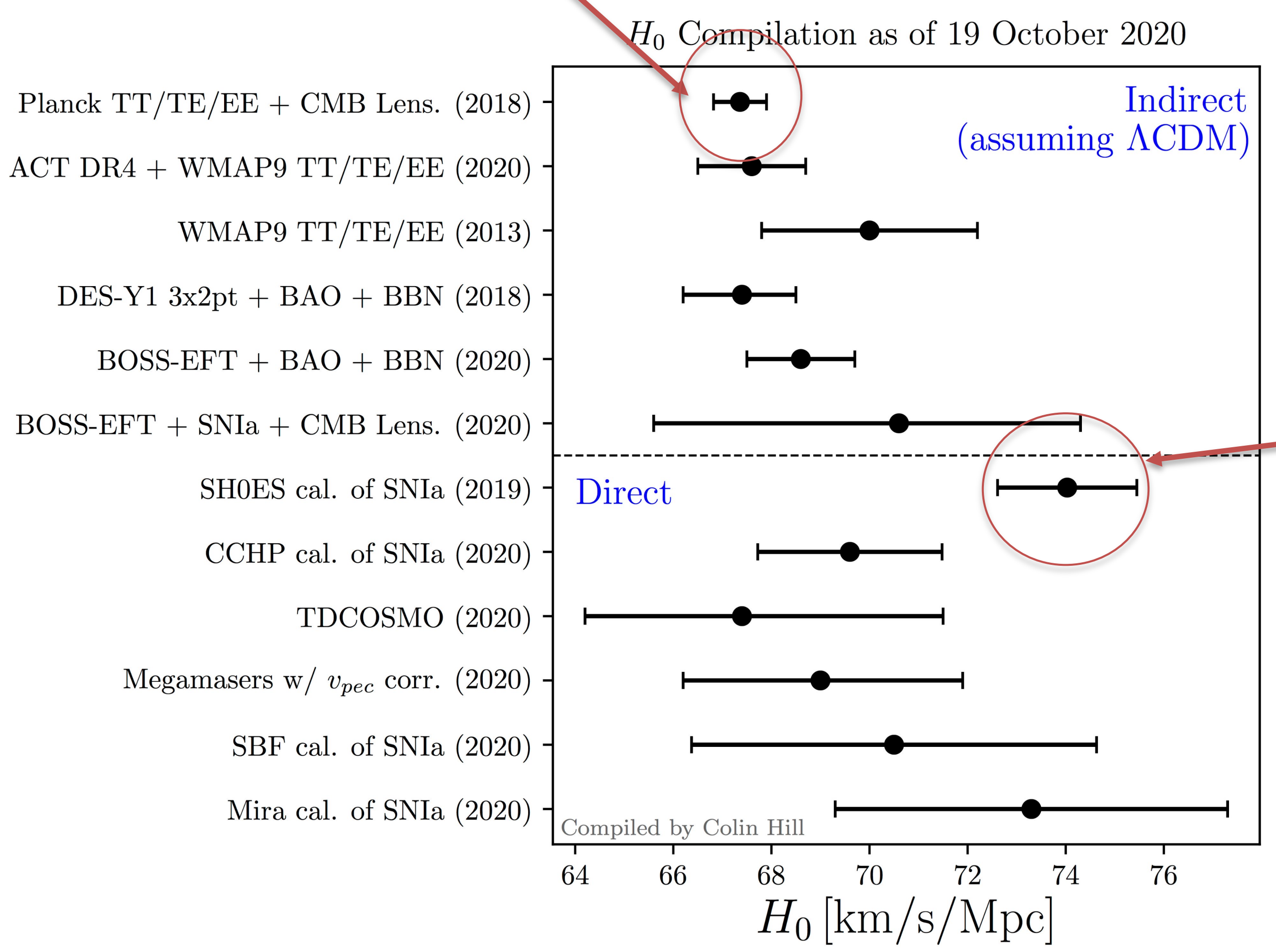


Cosmic distance ladder / late / direct



A big puzzle: the current Hubble constant tension

~68 km/s/Mpc ?



~74 km/s/Mpc ?

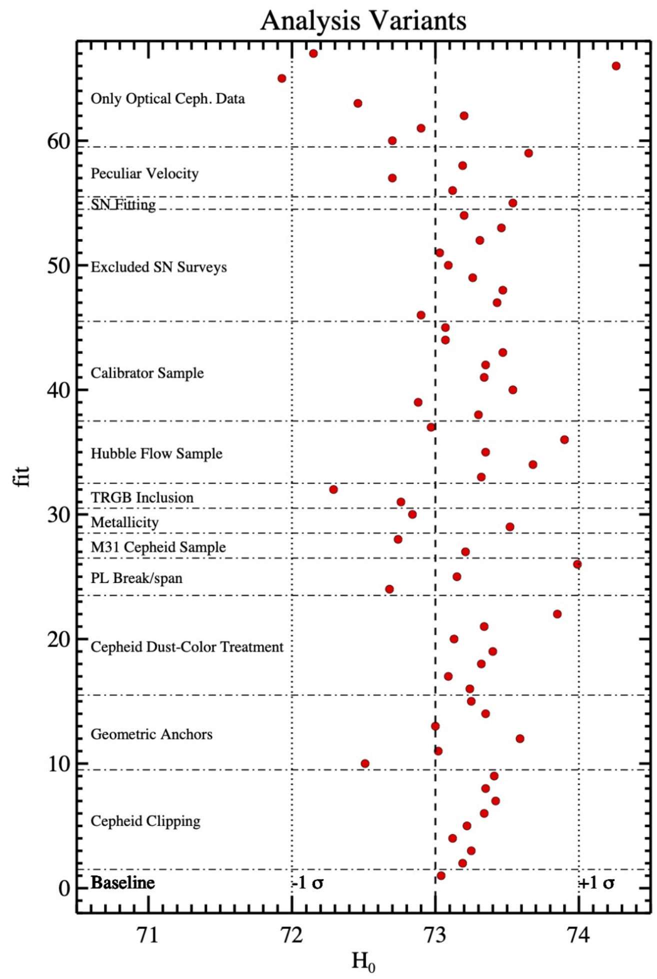
Latest:
73 km/s/Mpc

persistent tension between distance ladder and early-time/indirect measurements

Last week: new distance ladder measurements

[Riess++ 2021]

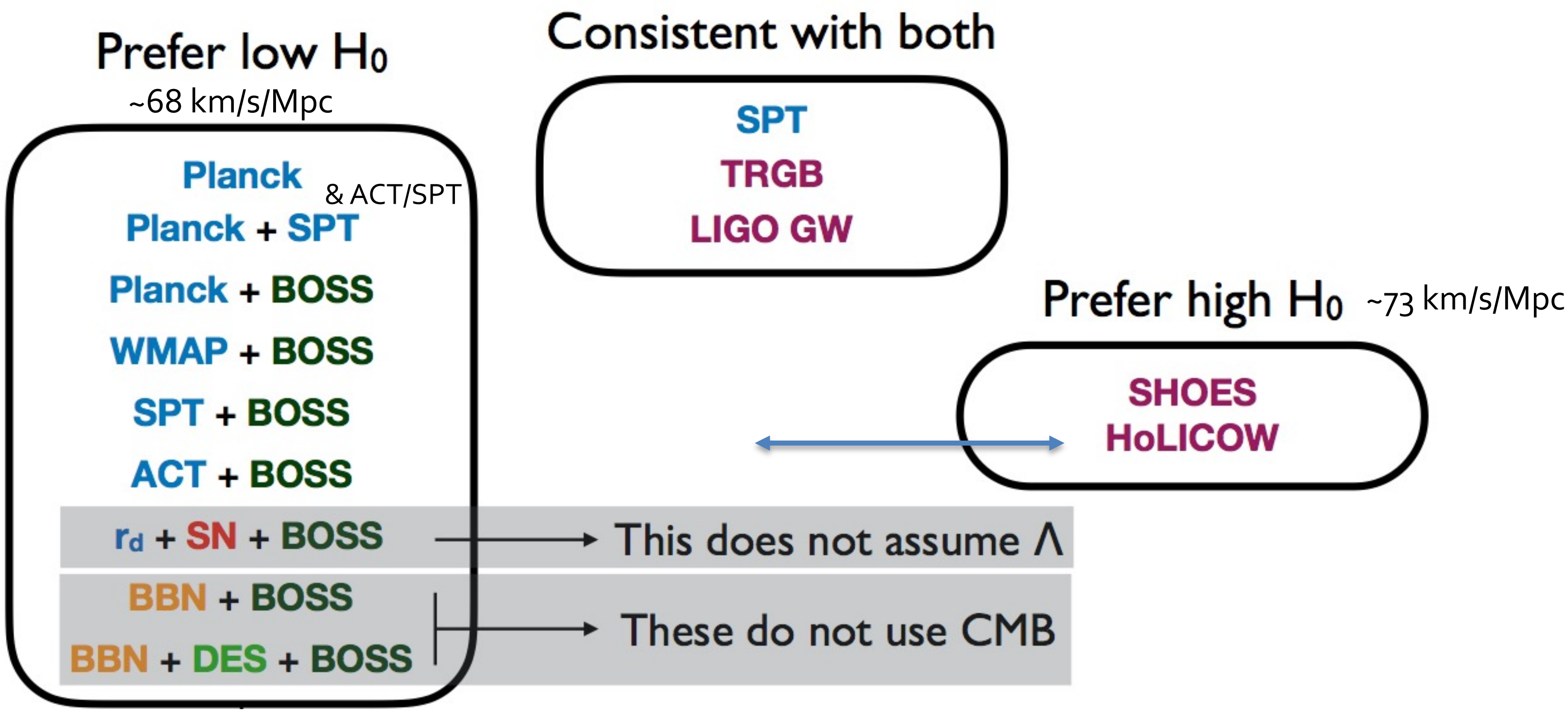
$$H_0 = 73.04 \pm 1.04 \ \text{km s}^{-1} \ \text{Mpc}^{-1}$$



More than doubles cepheid calibrator sample; lots of new checks, result: ~same
Formal claim of 5 sigma tension with Planck.

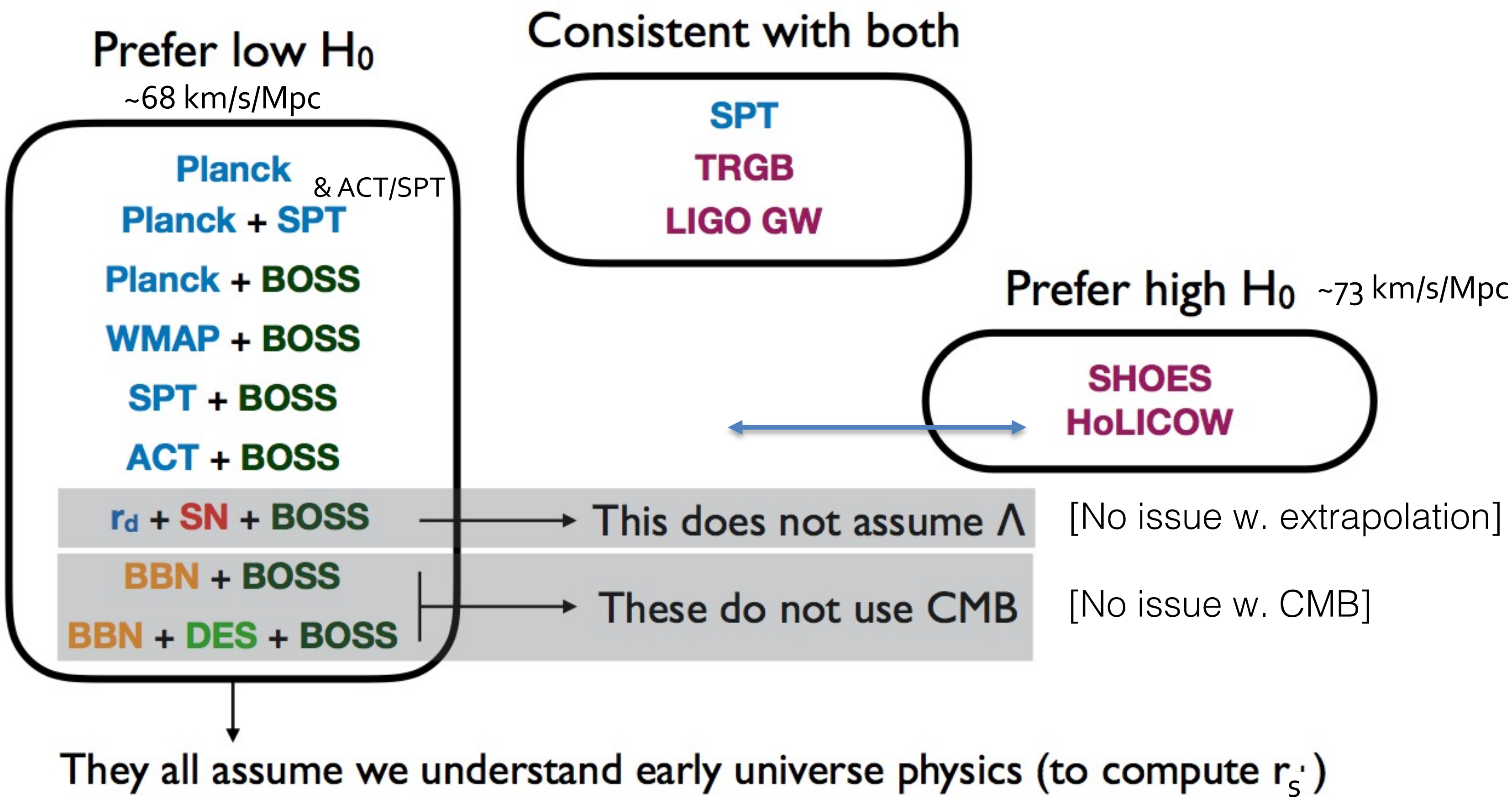
Hubble tension: several cross-checks

Figure credit: A. Font-Ribera

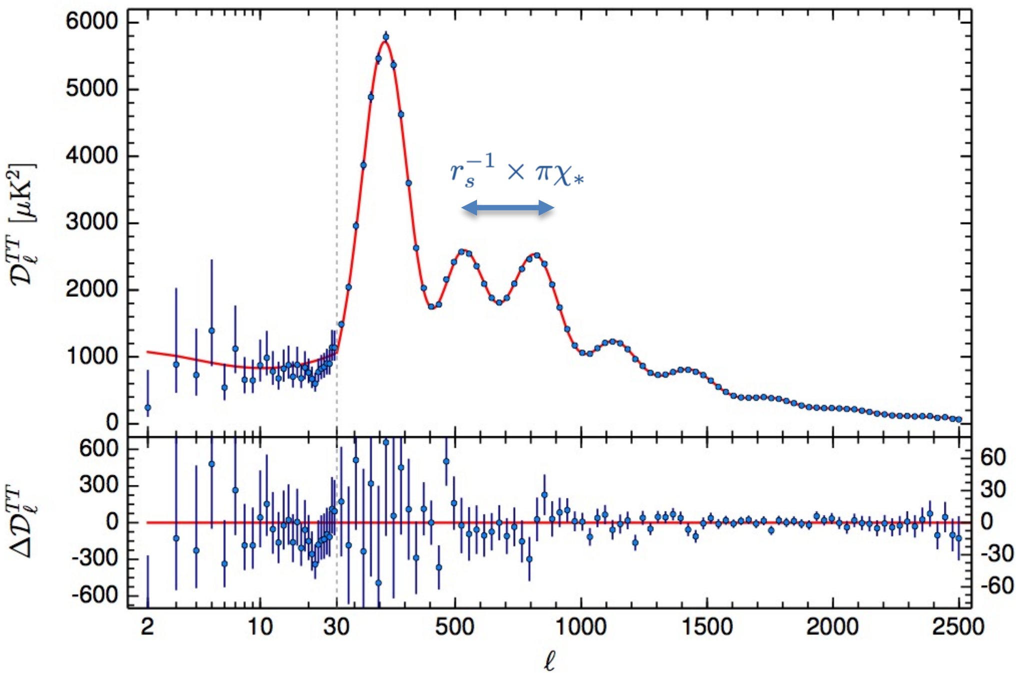


Hubble tension: several cross-checks

Figure credit: A. Font-Ribera



The sound horizon r_s and the CMB



$\mathcal{D}_l \equiv l(l+1)C_l/2\pi$

- Sound horizon: distance a sound wave travels

$$r_s = \int_{z_r}^{\infty} \frac{c_s}{H(z)} dz$$

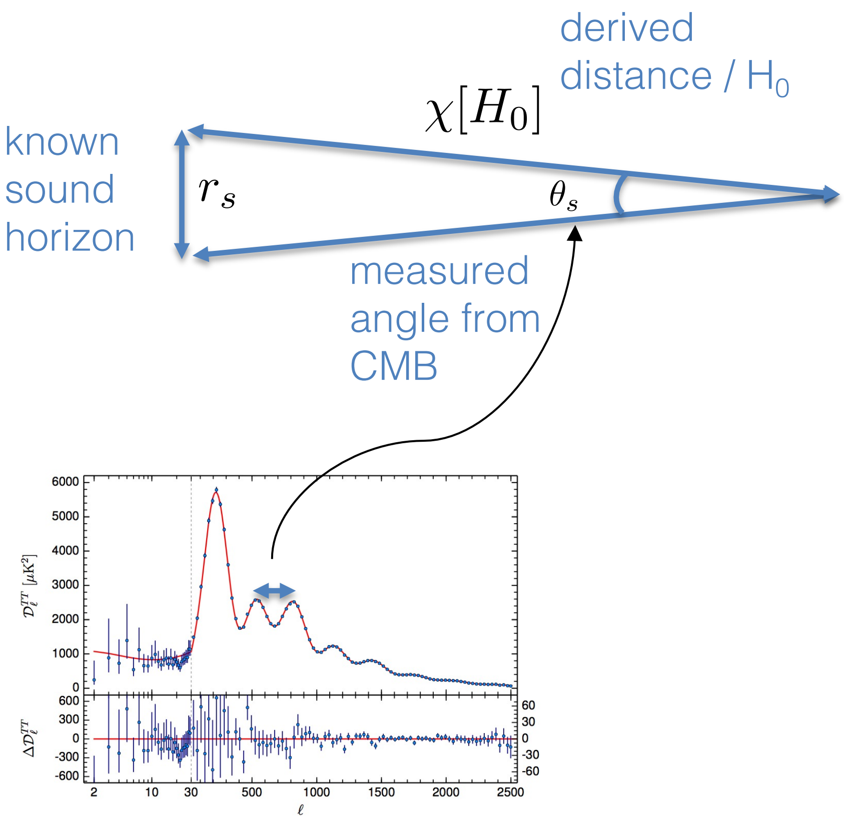
sound speed

redshift

expansion rate

- Characteristic scale imprinted in the CMB peaks and in the matter power spectrum

Measuring Hubble using the CMB



$\mathcal{D}_l \equiv l(l+1)C_l/2\pi$

- Compute (calibr.) sound horizon r_s

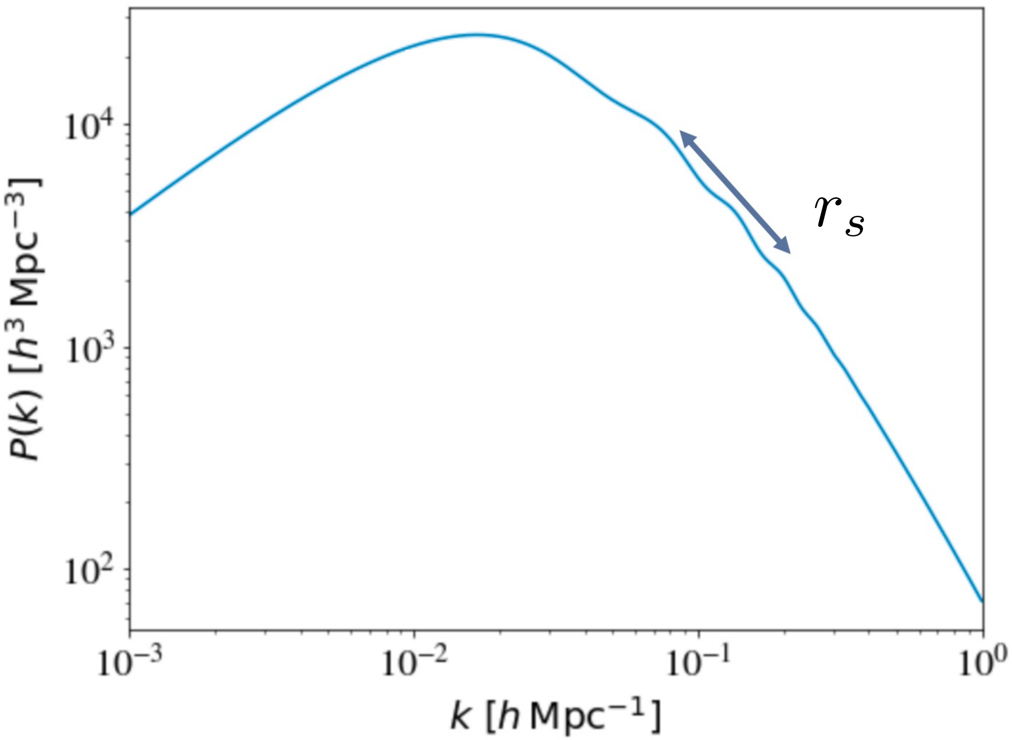
$$r_s = \int_{z_r}^{\infty} \frac{c_s}{H(z)} dz$$

- Measure angle θ_s and infer distance $\chi[H_0] \sim r_s/\theta_s$
- Distance[H_0]

  => H_0 !

Similar: Measuring Hubble using LSS

- Matter power spectrum similar to CMB: Currently mainly get H_0 from BAO scale, imprint of sound horizon on matter.



Idea for resolving tension: is new physics changing r_s?

Possible explanation for tension: New physics has changed the sound horizon

- Arguably simplest new physics solution
- Can shrink sound horizon with new early energy density

The final category is the set of solutions that introduces new components to increase $H(z)$ in the decade of scale factor evolution prior to recombination. We see these as the most likely category of solutions. They are also

$$r_s = \int_{z_r}^{\infty} \frac{c}{H(z)} dz$$

[Knox + Millea 2019]

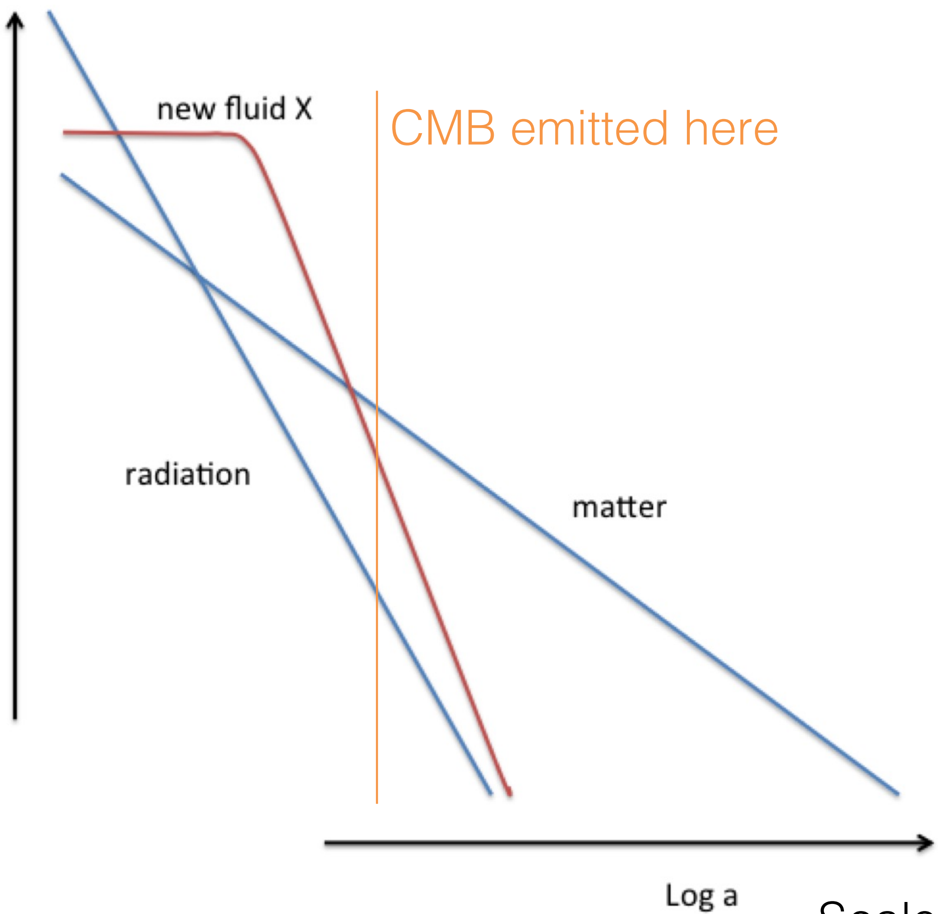
- But note: huge change!

z

Example: Early Dark Energy

[Poulin et al. 2018, ...]

Energy density



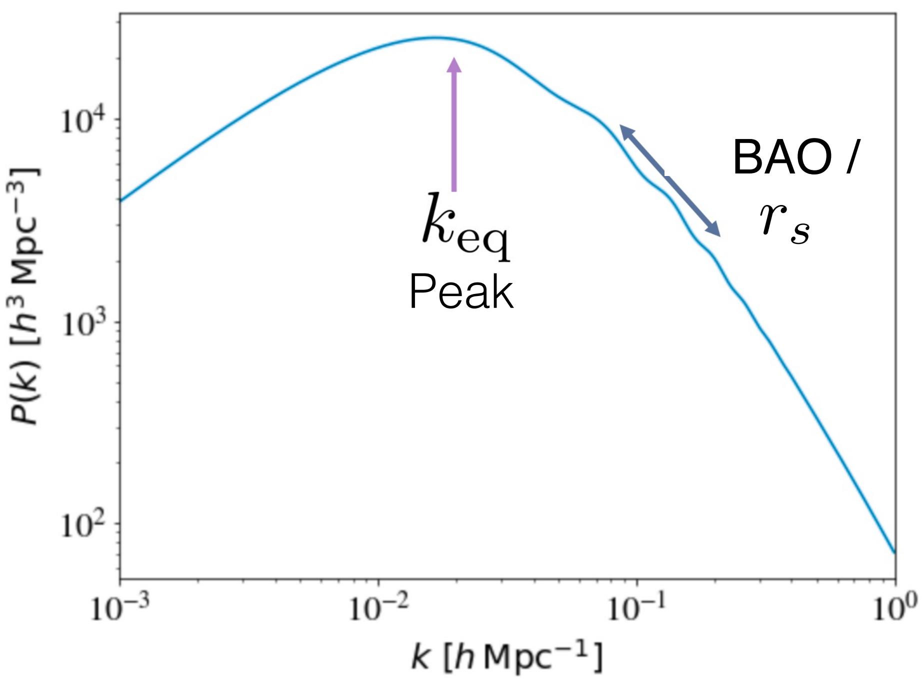
Scale factor ~time

Model actually favored by ACT at ~3 sigma! But: more investigation of systematics needed [Hill++ 21]

Many models (e.g. di Valentino++ 21). Perhaps none entirely compelling?
How to test these kinds of modifications generically?

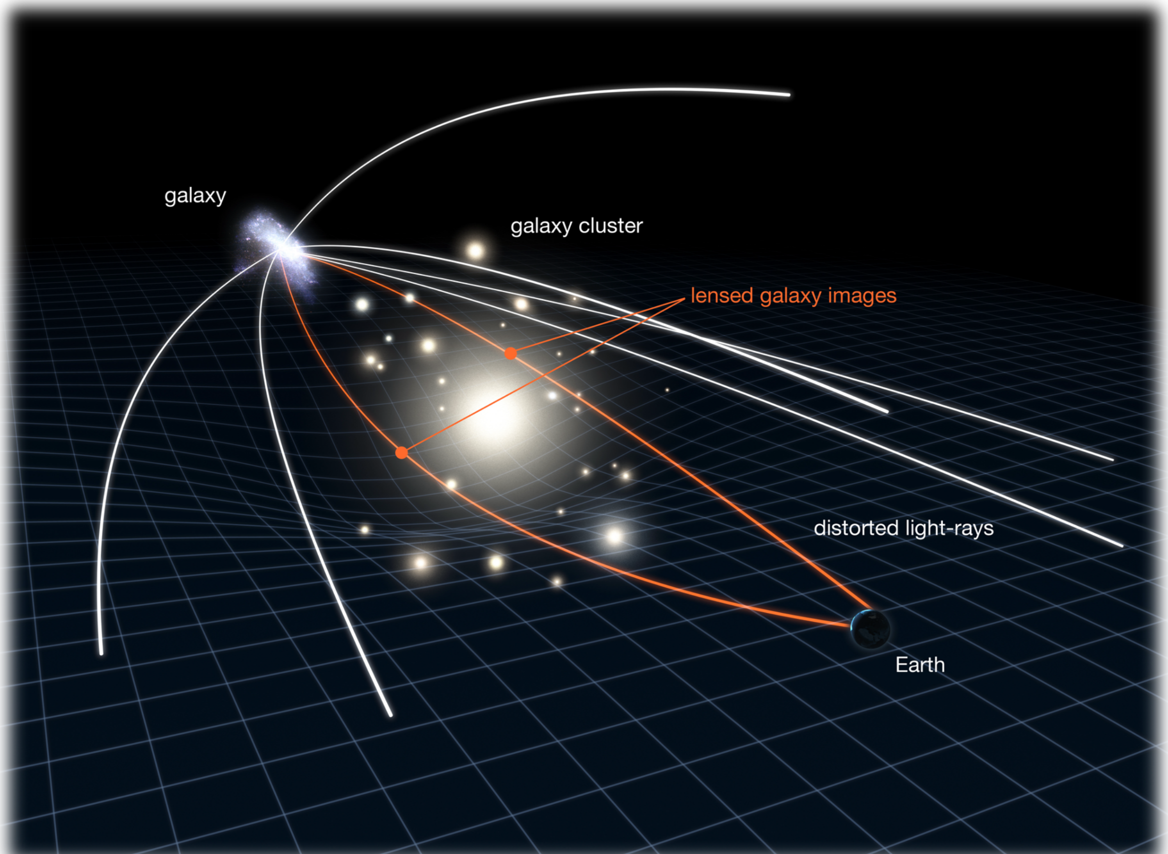
New Ways of Measuring Hubble Constant Needed

- Two scales in the matter power spectrum: sound hor. scale + the matter-radiation equality scale k_{eq}
- Idea: Use k_{eq} to get H_0 without the sound horizon
- For surveys in next few years, great performance, H_0 within 1%, competitive! [Philcox, Sherwin++ 2021, Farren, Philcox, Sherwin in prep.]



S8 Tension: Gravitational Lensing

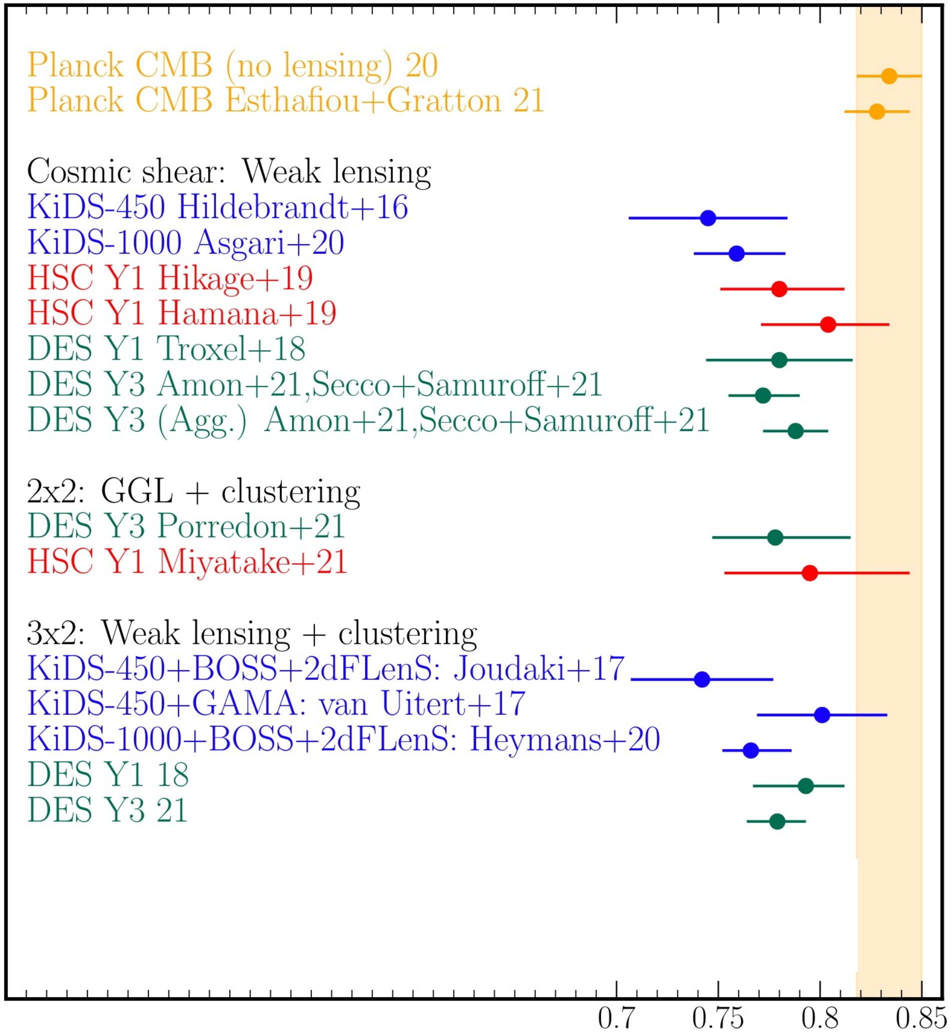
- Distribution of dark matter deflects light from galaxies that passes through. Can measure strength of lensing by warping of galaxy images



S8 tension from galaxy lensing

- Strength of lensing signal depends on how clumpy the mass distribution is (and how much matter there is). Parametrized by S8.

- Problem: S8 measured by lensing at low redshifts is ~2-3 sigma low compared to expectation from Planck.

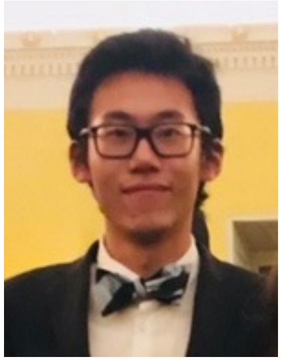


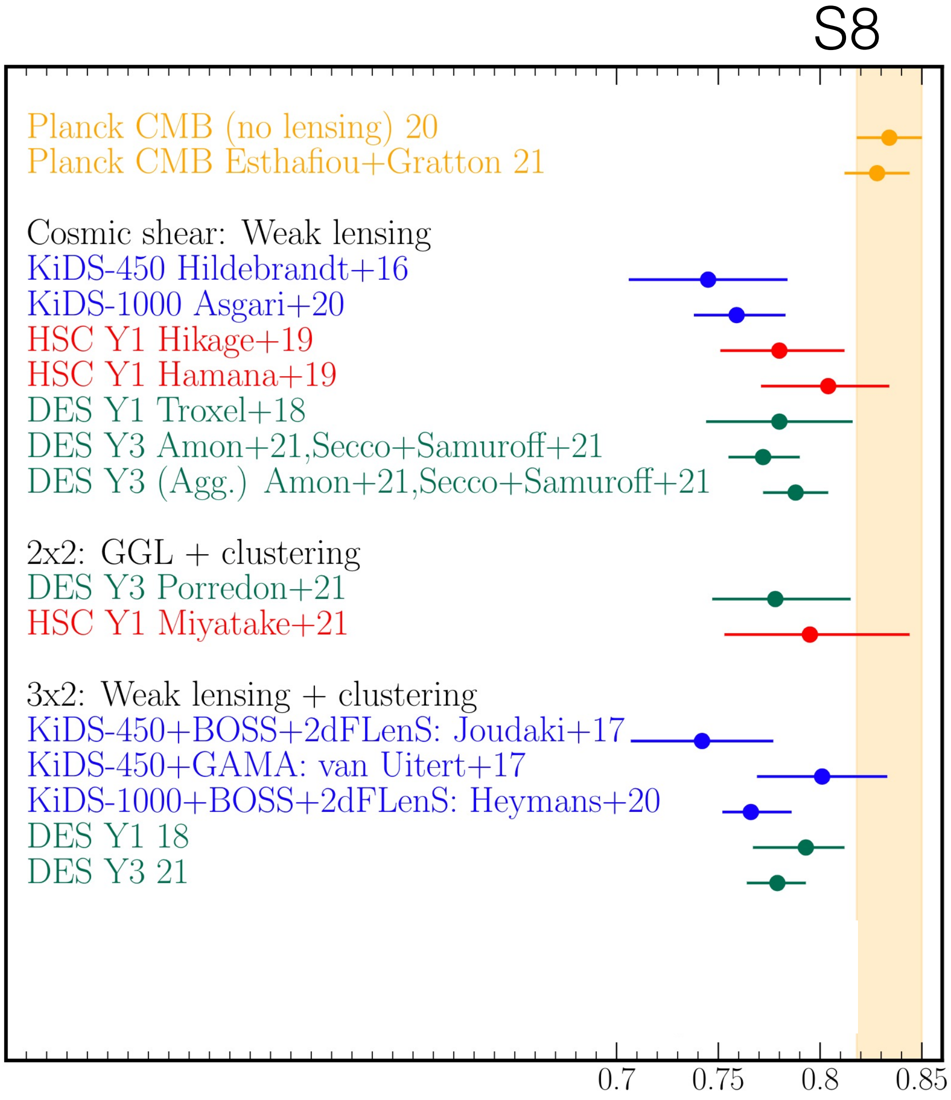
In progress: test S8 tension with CMB lensing

- Galaxy lensing, while powerful, is challenging…

- Want to test further with CMB lensing, as different systematics! Do we also find a low S8?

Frank Qu





CMB Gravitational Lensing

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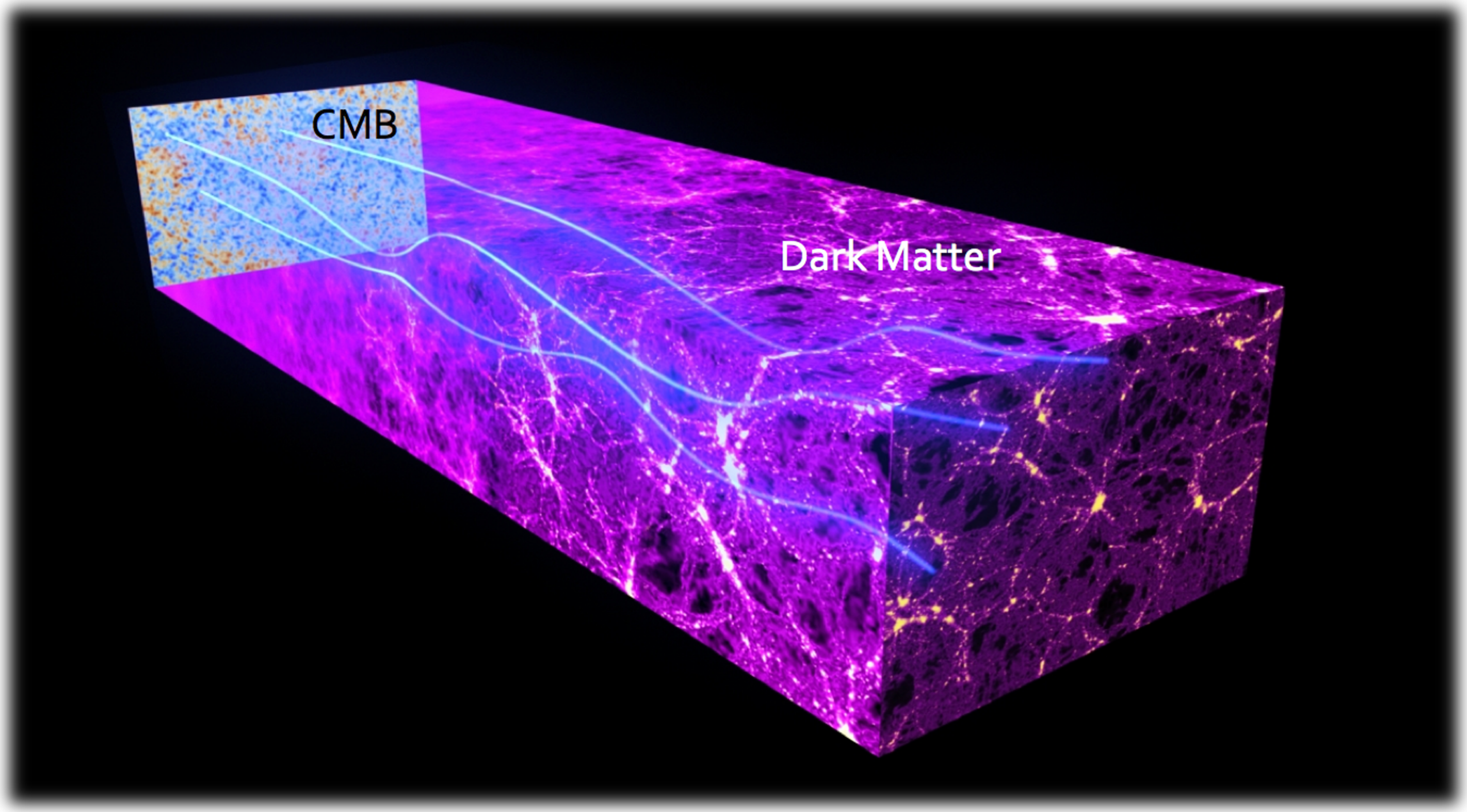
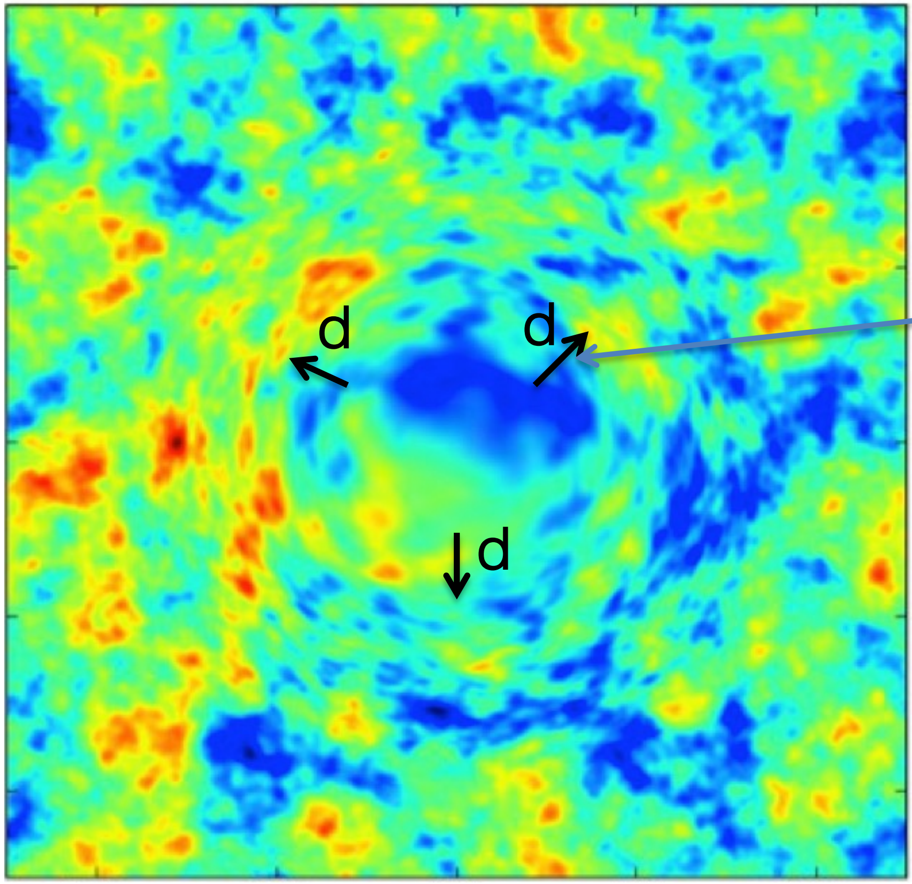


CMB Lensing: An Approximate Picture

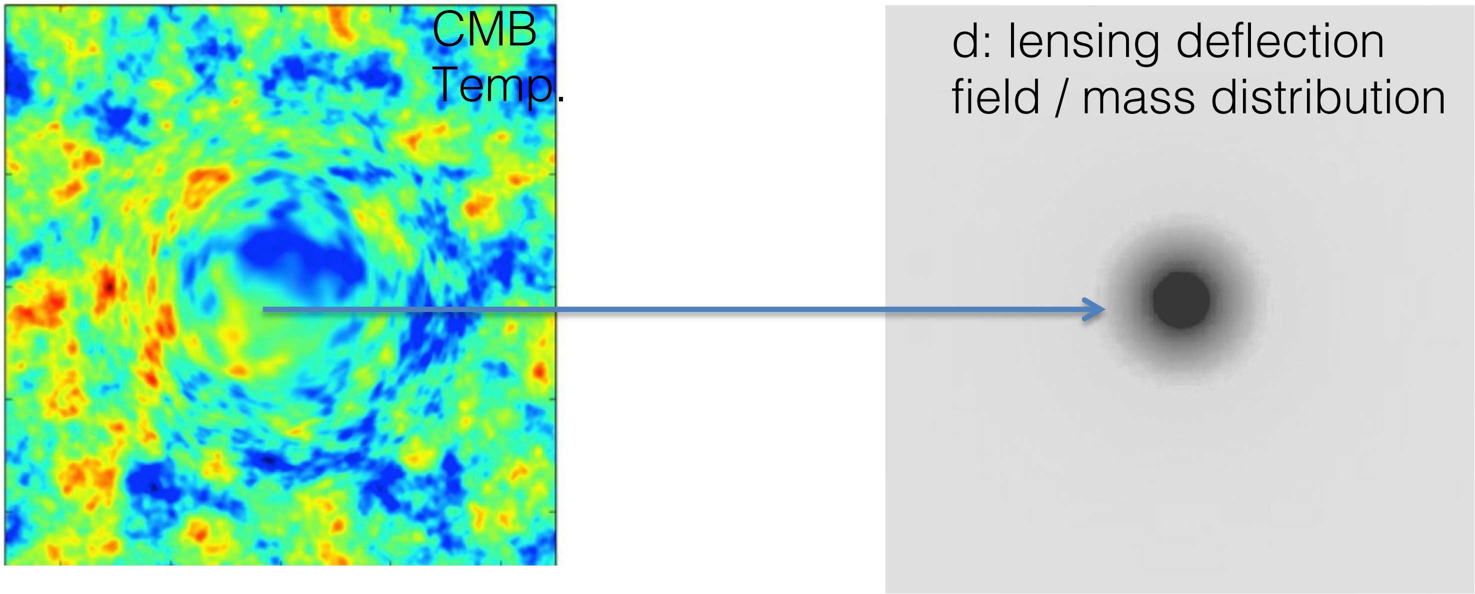


described by **lensing deflection field: d, which probes projected mass**

(very small: here exaggerated by x ~100)

- Dark matter causes lensing magnification feature in the CMB

CMB Lensing Measurement: An Approximate Picture



- Search for lensing by looking for breaking of translation invariance in CMB fluctuations

AdvancedACT
lens. map and spectrum

S16	S17	S18
PA2 @ 150 GHz	MF @ 90 / 150 GHz	LF @ 28 / 41 GHz
PA3 @ 90 / 150 GHz	MF @ 90 / 150 GHz	MF @ 90 / 150 GHz
HF @ 150 / 220 GHz	HF @ 150 / 220 GHz	HF @ 150 / 220 GHz

Mat Madhavacheril

Frank Qu

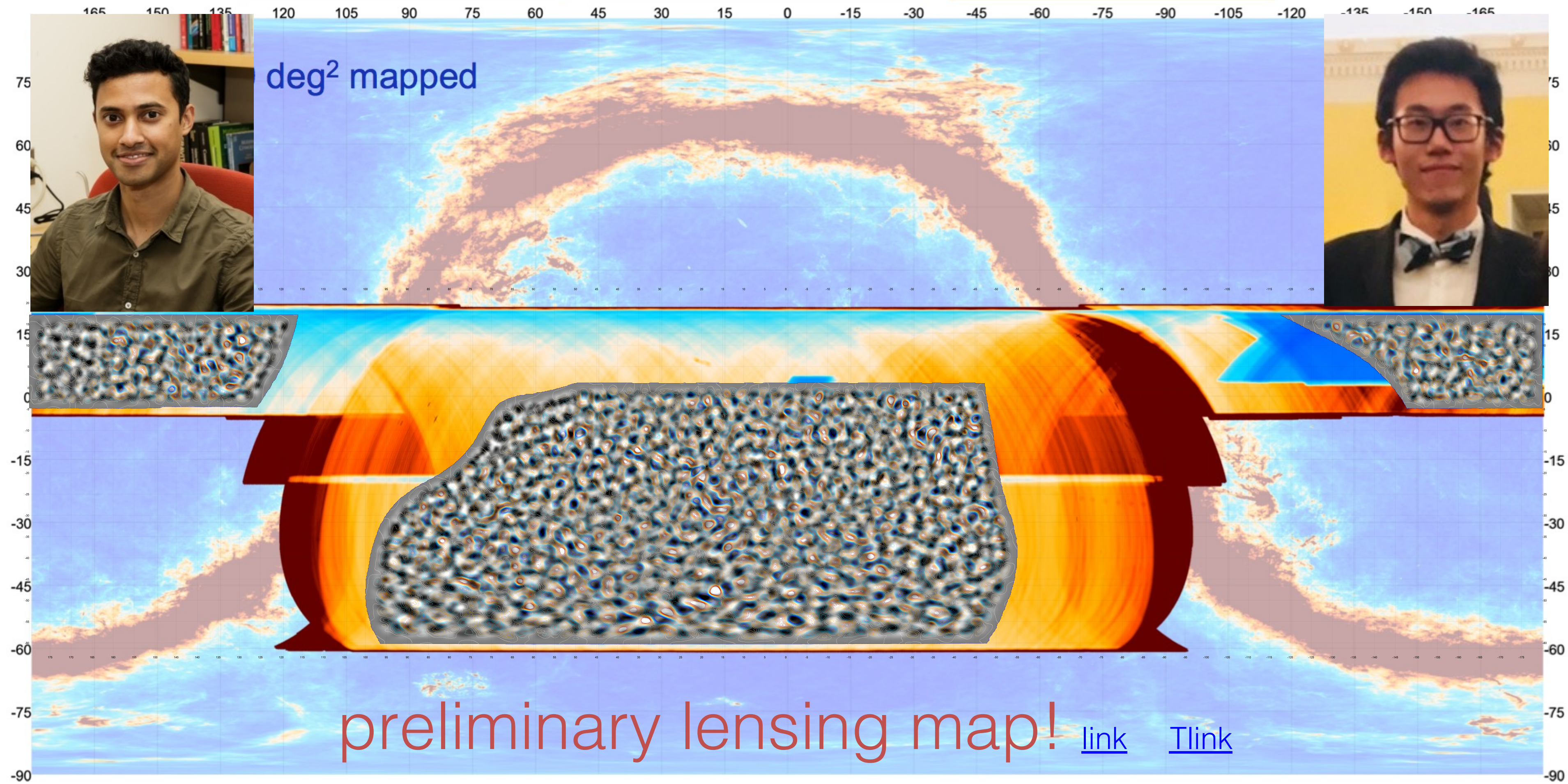
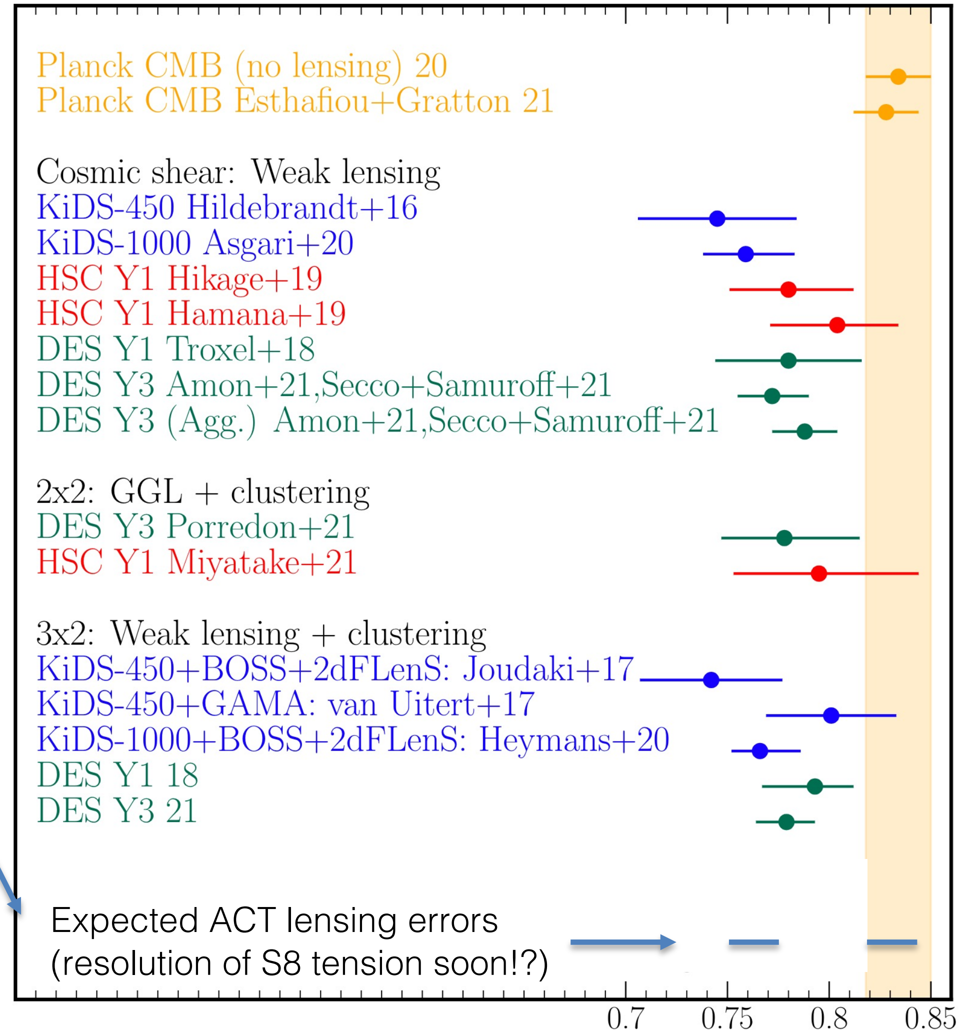


Figure: S. Aiola Map: S. Naess

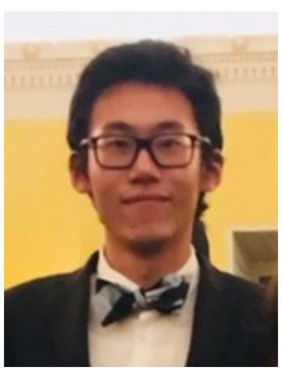
[Qu, Sherwin++ in prep.]

AdvACT lensing power spectra: expected insight into S8 tension

- Significant insights into S8 and neutrino mass coming soon from AdvACT lensing!



Frank Qu



[Qu, Sherwin++ in prep.]

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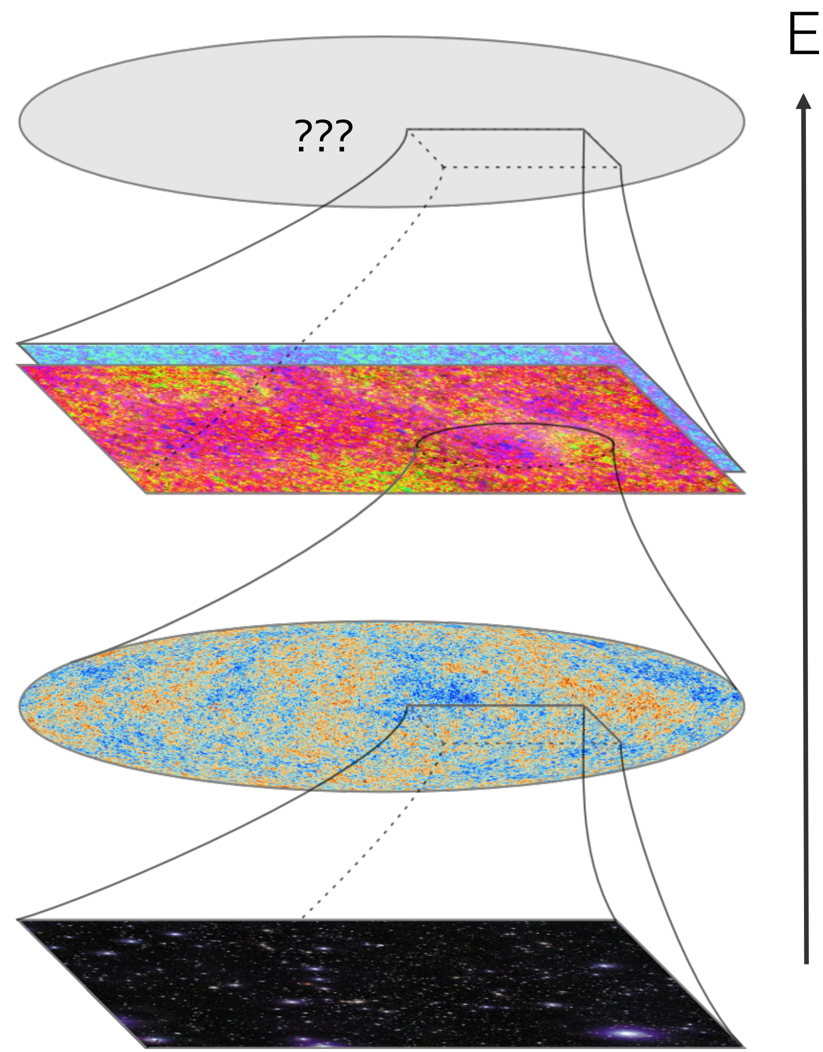
Cosmology: a unique laboratory for fundamental physics

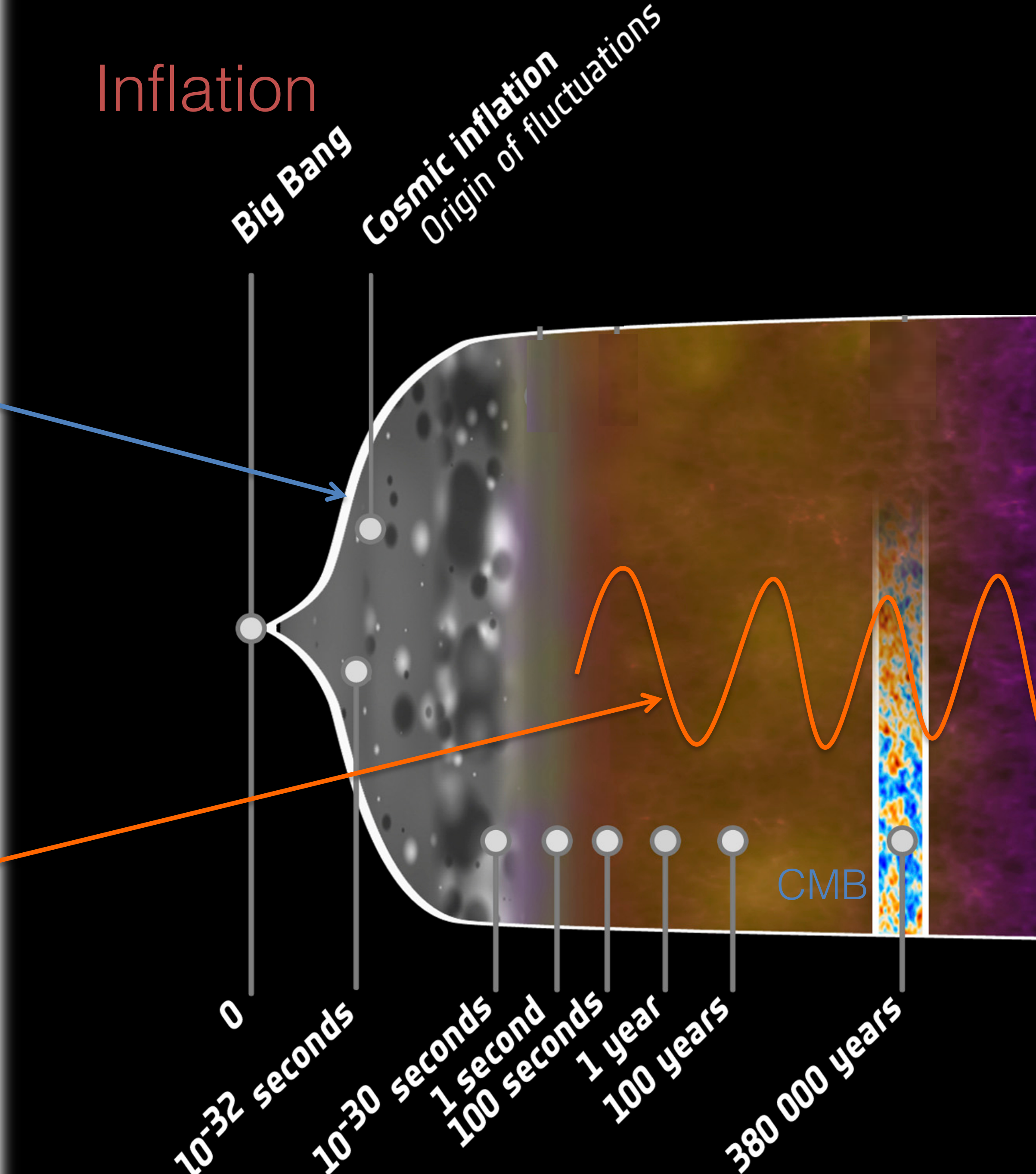
What is the physics at ultra-high-energies?
Probe early universe / inflation via B-modes

Are there new weakly interacting particles?
Probe new particles created in high early-universe densities

[Will leave out: What is dark energy/dark matter? What is neutrino mass? Can we find primordial non-Gaussianity?]



Inflation



- Inflation: initial accelerated cosmic expansion.
- Good evidence for idea – but we don't know for sure
- Many (simple) models make inflationary gravity waves*

*N.B. Some other models also produce GWs

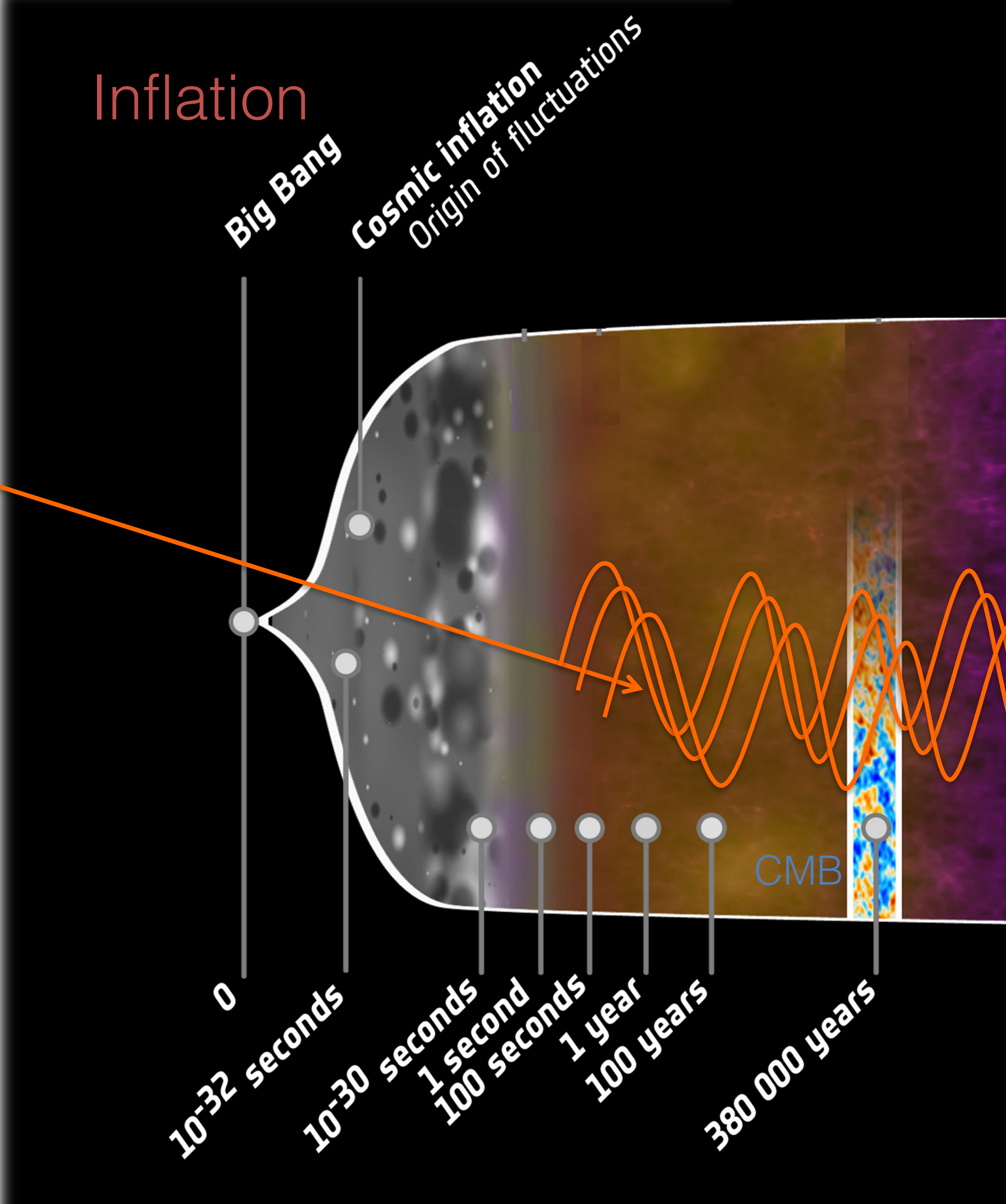
Inflation

- Probe physics at ultra-high energy (at the doorstep of the Planck scale)

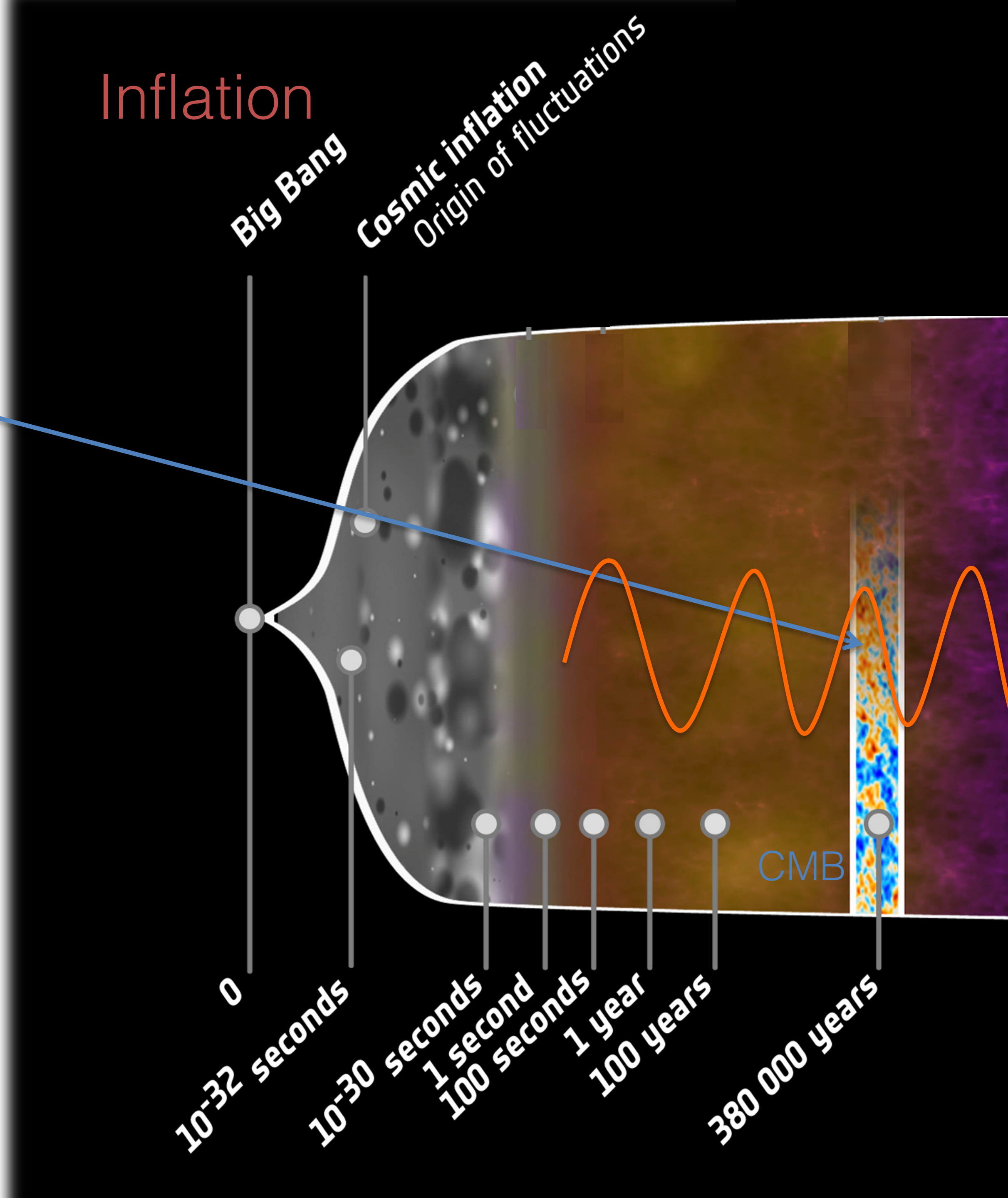
$$V^{1/4} = 1.04 \times 10^{16}\text{GeV}\left(\frac{r_*}{0.01}\right)^{1/4}$$

- The strength of the waves - tensor-to-scalar ratio r - tells us lots about properties of inflation

N.B. Even improved upper limits interesting.

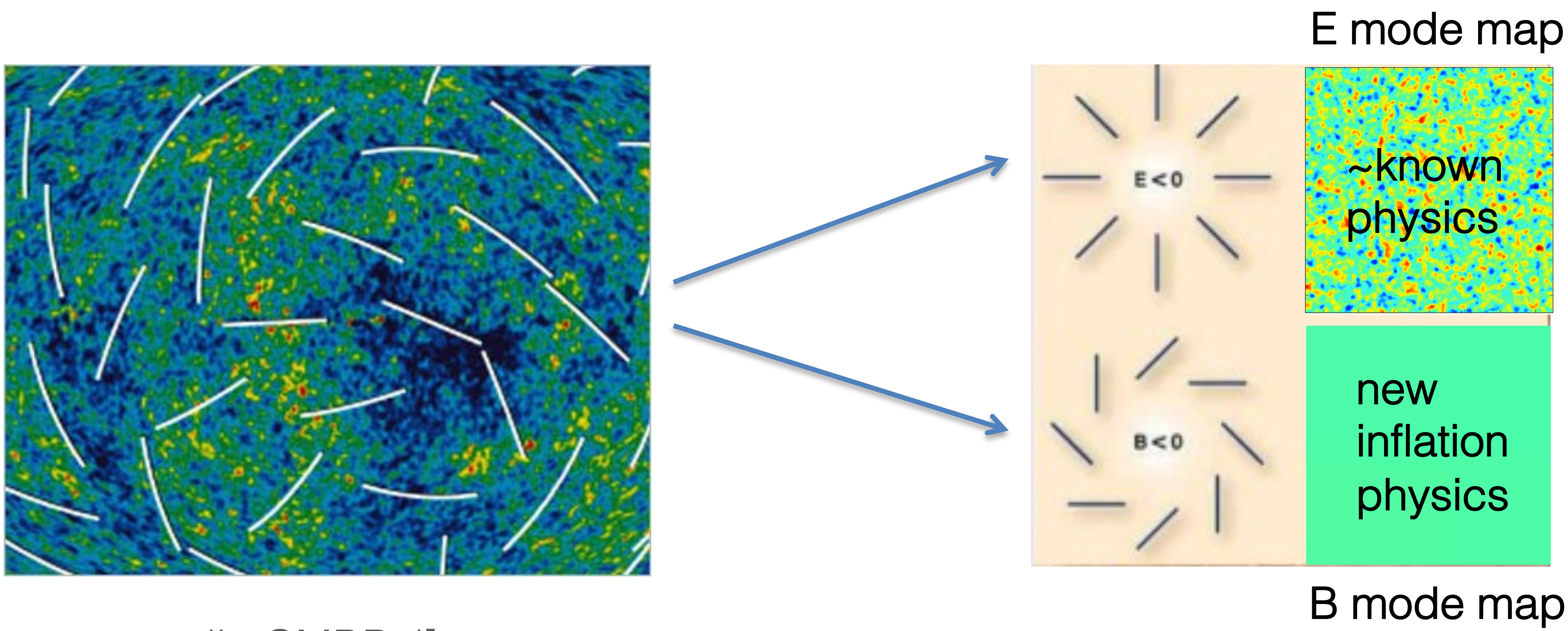


- Leaves a characteristic pattern in the CMB polarization



CMB Polarization Basics

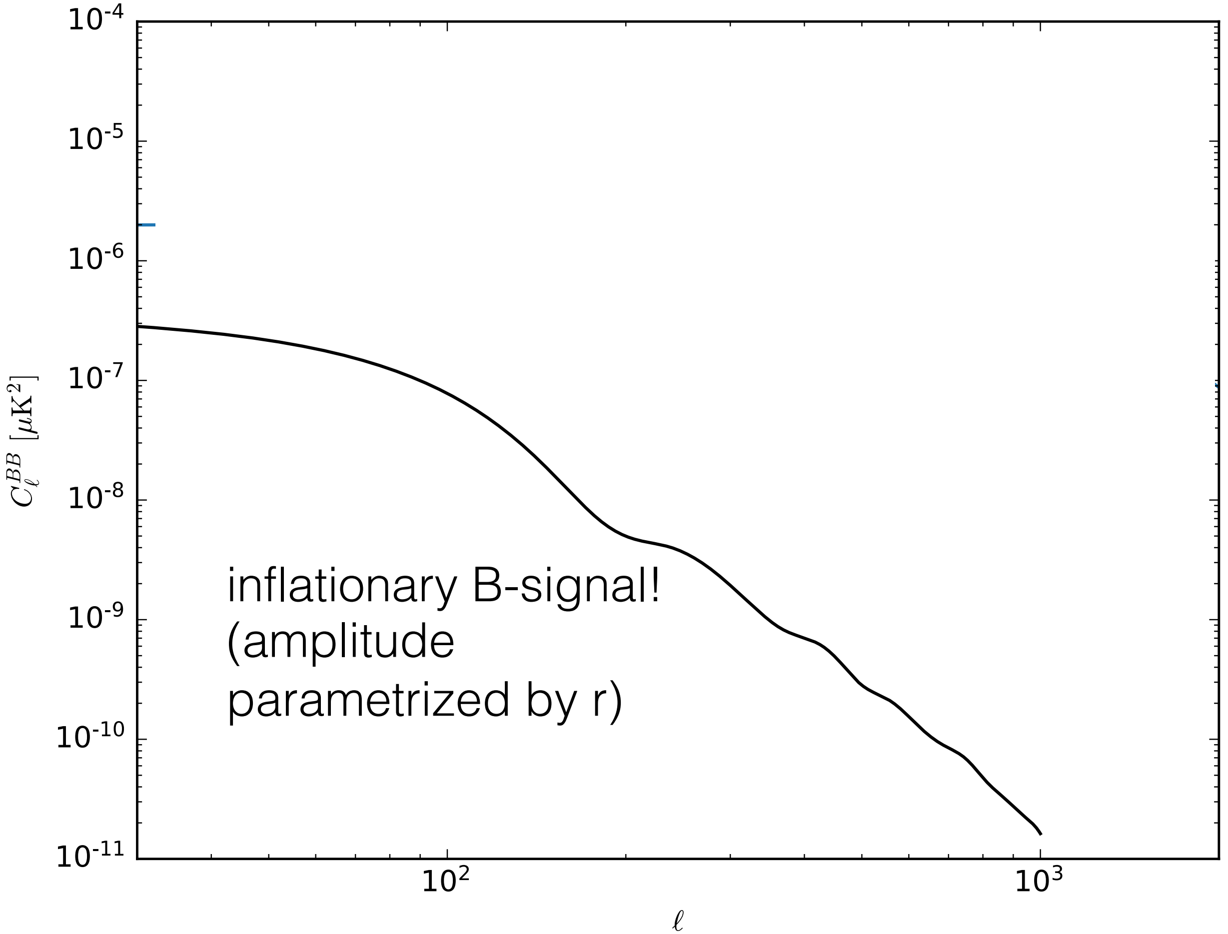
- Any polarization map can be decomposed into E and B mode fields
- <u>B-mode: contains signals from inflation, if there</u>



[Image credit: CMBPol]

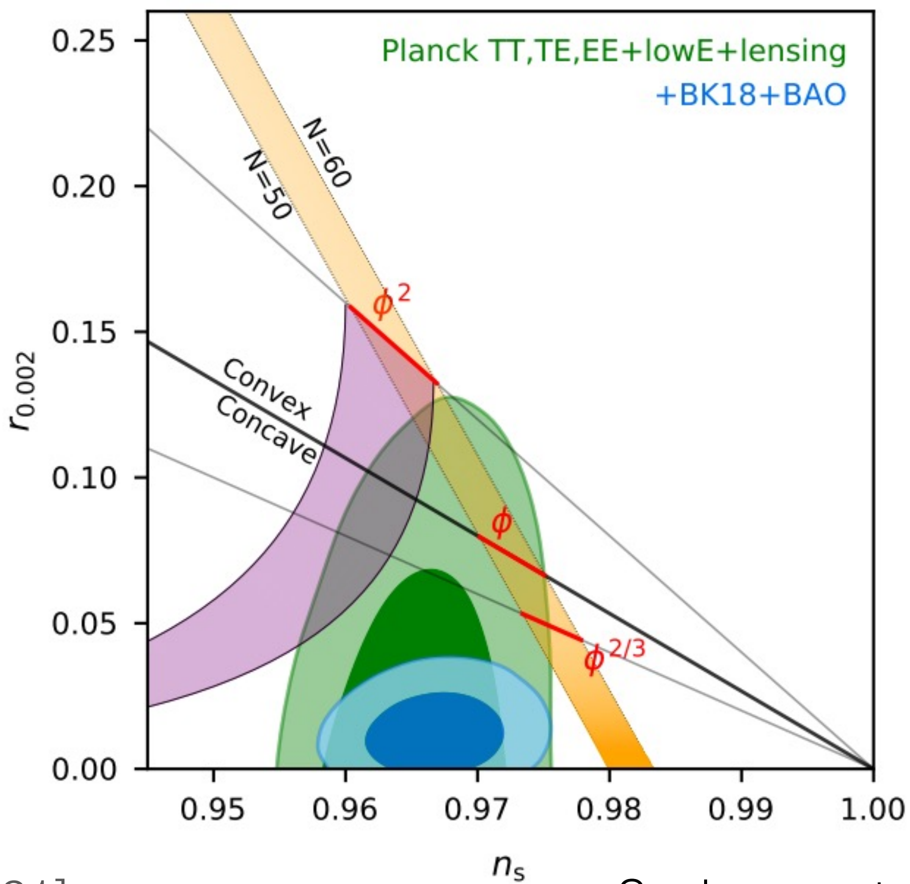
Several surveys searching for primordial B power

B-mode
power



New insights into inflation models

Level of
Inflation
Grav. Waves



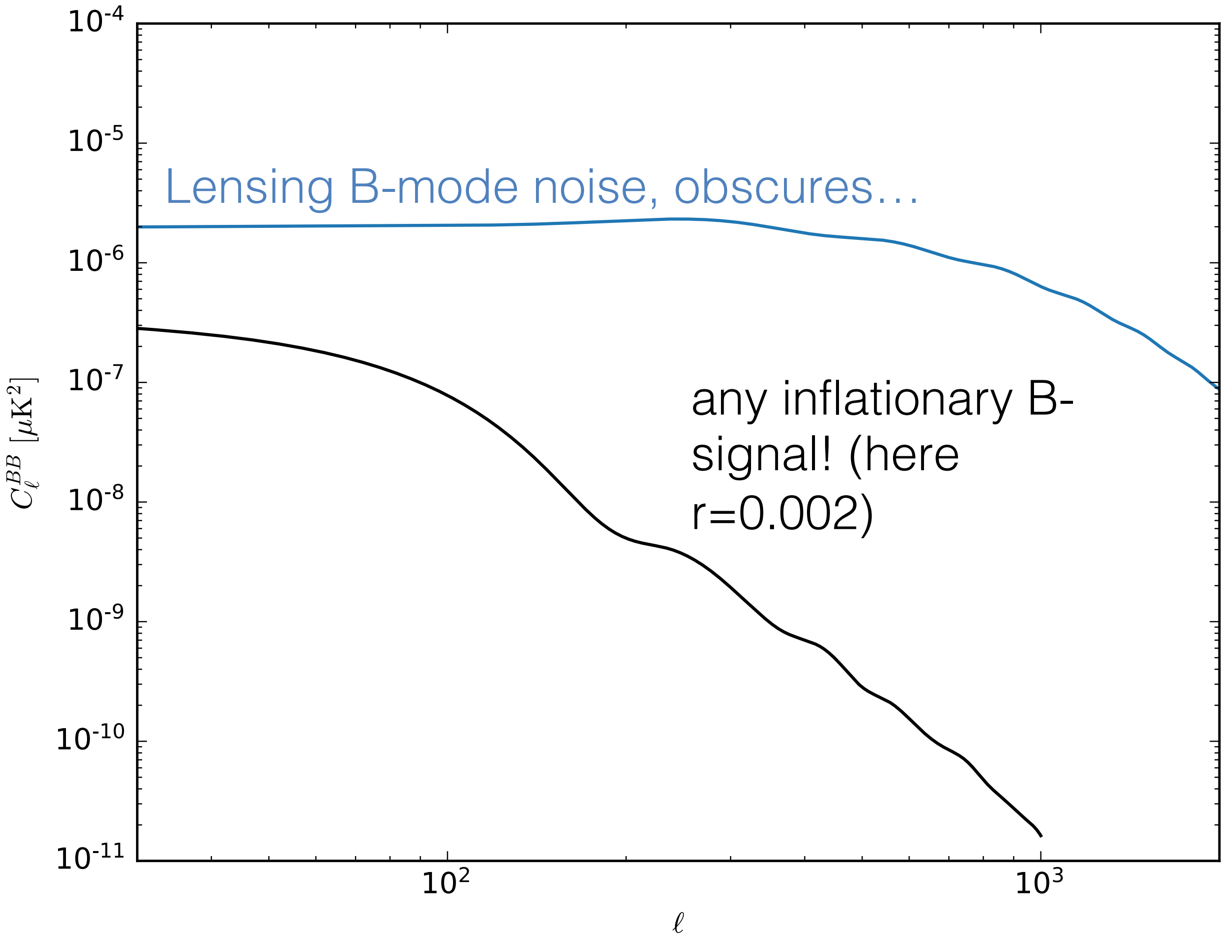
[BICEP/Keck 2021]

Scalar spectral tilt

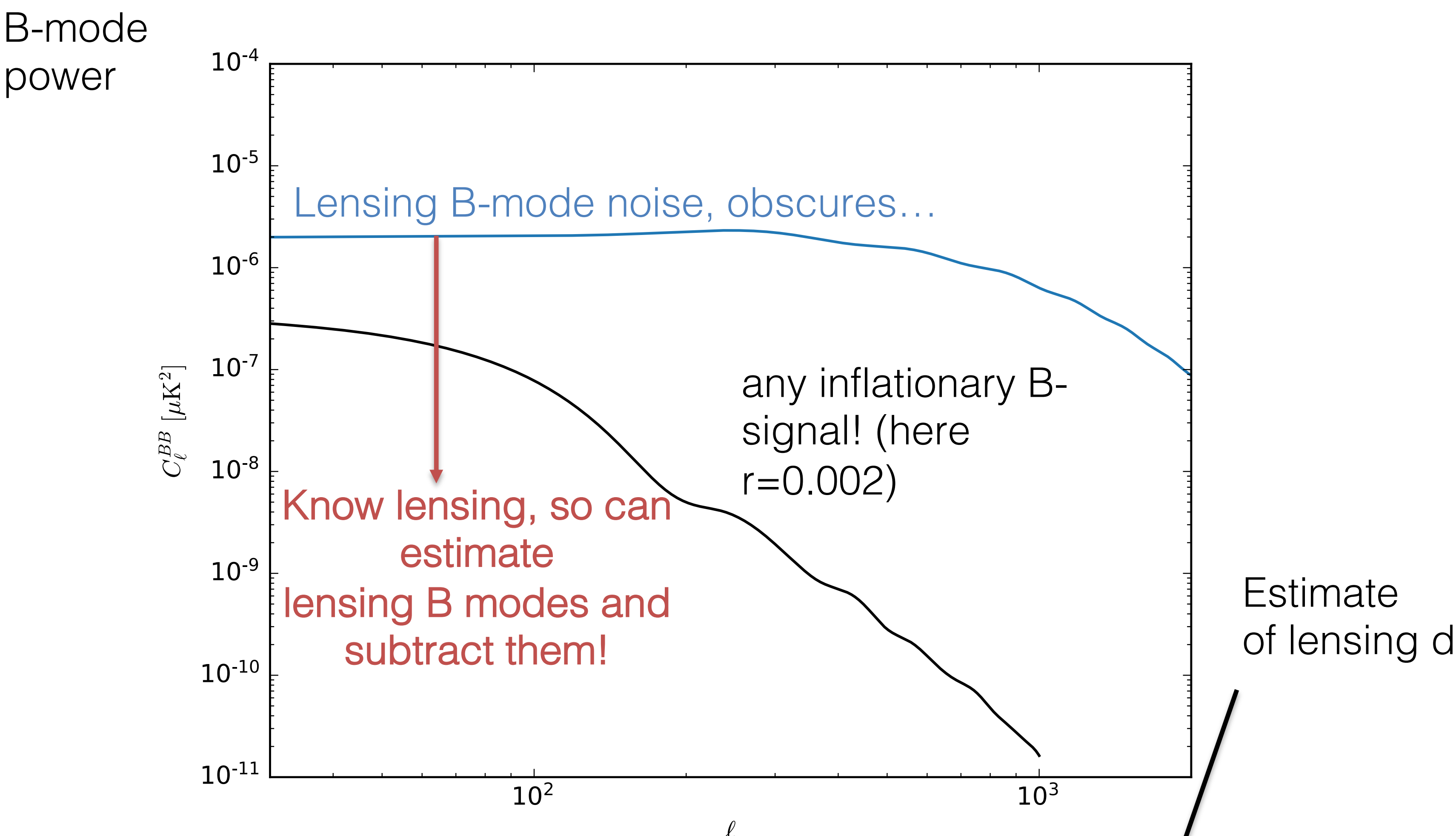
- BICEP/Keck: $r<0.035$. Monomial models strongly disfavored. Require flat potential. Exciting prospects for next 10 years

Lensed CMB B-Polarization: Noise for Inflation-B

B-mode power



Delensing the CMB: Lensing Removal

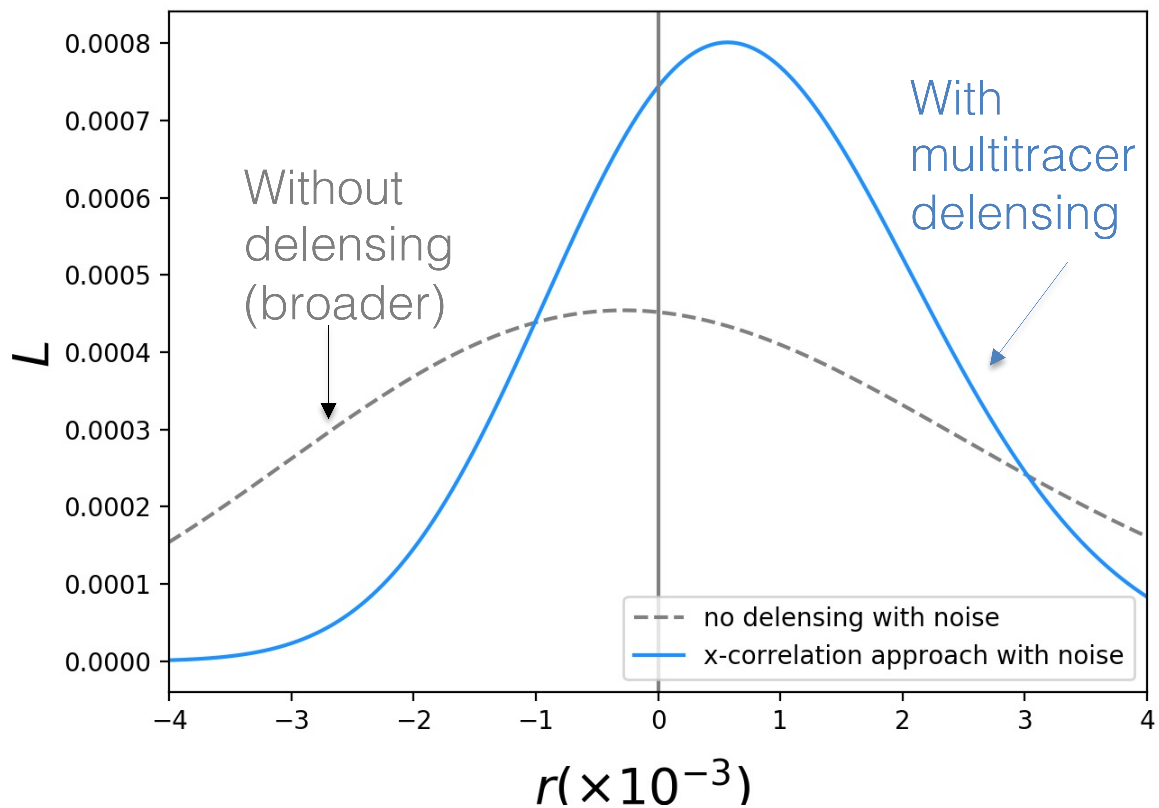


$$B^{data} - \hat{B}^{lens} \sim B^{data} - \int d\mathbf{l}\, W(\mathbf{l}, \mathbf{L}) E(\mathbf{l}) \hat{d}^{filt}(\mathbf{L} - \mathbf{l})$$

New: Delensing Pipeline for Simons Observatory

- New idea: can combined multiple galaxy maps to delens
- Significant improvements appear possible, ~2x improvement in SO r constraints
- Important, as near thresholds from interesting models

Preliminary



[Simons Observatory Collaboration]

Light Relic Particles and Cosmology

- Cosmic Neutrino Background: in radiation era, very large part of the energy density - 41% of total!

- Influences expansion rate H (as extra form of radiation):

$$3M_{\rm pl}^2 H^2 \simeq \rho_\gamma + \rho_\nu$$

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$$3M_{\rm pl}^2 H^2 \simeq \rho_\gamma + \rho_\nu \longleftarrow \qquad N_{\rm eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} \frac{\rho_\nu}{\rho_\gamma}$$

- Energy density parameterized via number of effective neutrino species N_{eff}. Measure via CMB
  - With Planck, we find: $N_{\rm eff} = 3.04 \pm 0.18$

N_{eff} from Cosmology: A Universal Probe for Light Relics

- Not just sensitive to particles with standard model couplings of neutrinos
- Gravity sees everything: cosmology probes all that is neutrino like (radiation, free-streaming)

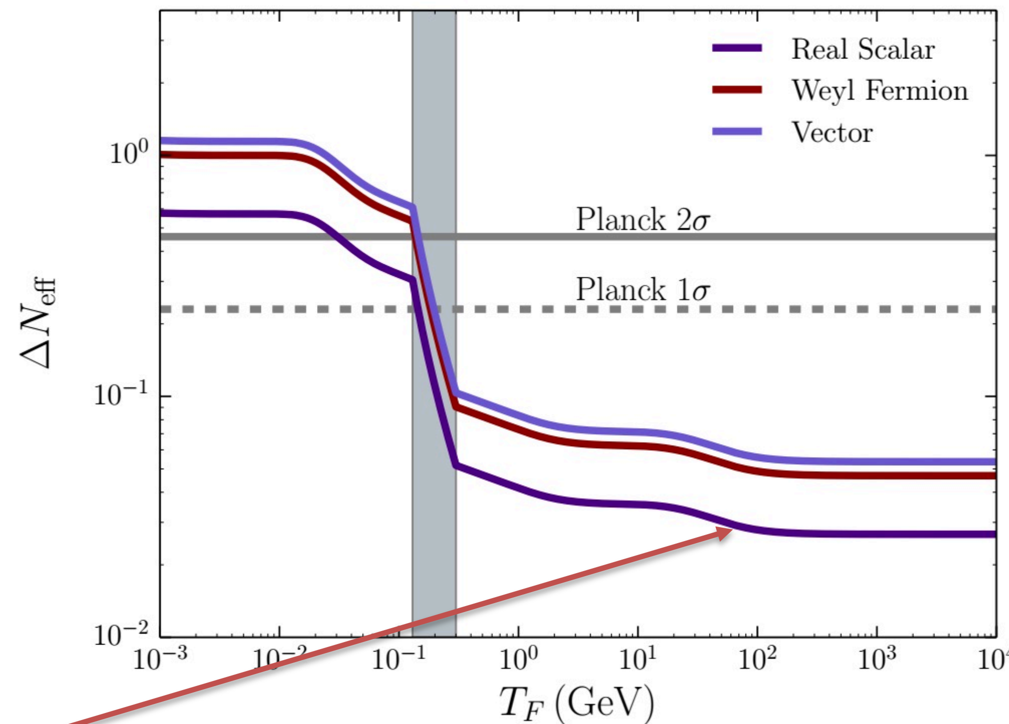
$$3M_{\rm pl}^2 H^2 \simeq \rho_\gamma + \rho_\nu$$

- Can hunt for any new light (relativistic, weakly coupled) particles, created in high density early universe

How Much N_{eff} Does A New Particle Contribute?

- At high freeze-out temperature, the particle misses out on lots of heating, so ΔN_{eff} is very small.

$$N_{\rm eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_\nu}{\rho_\gamma}$$

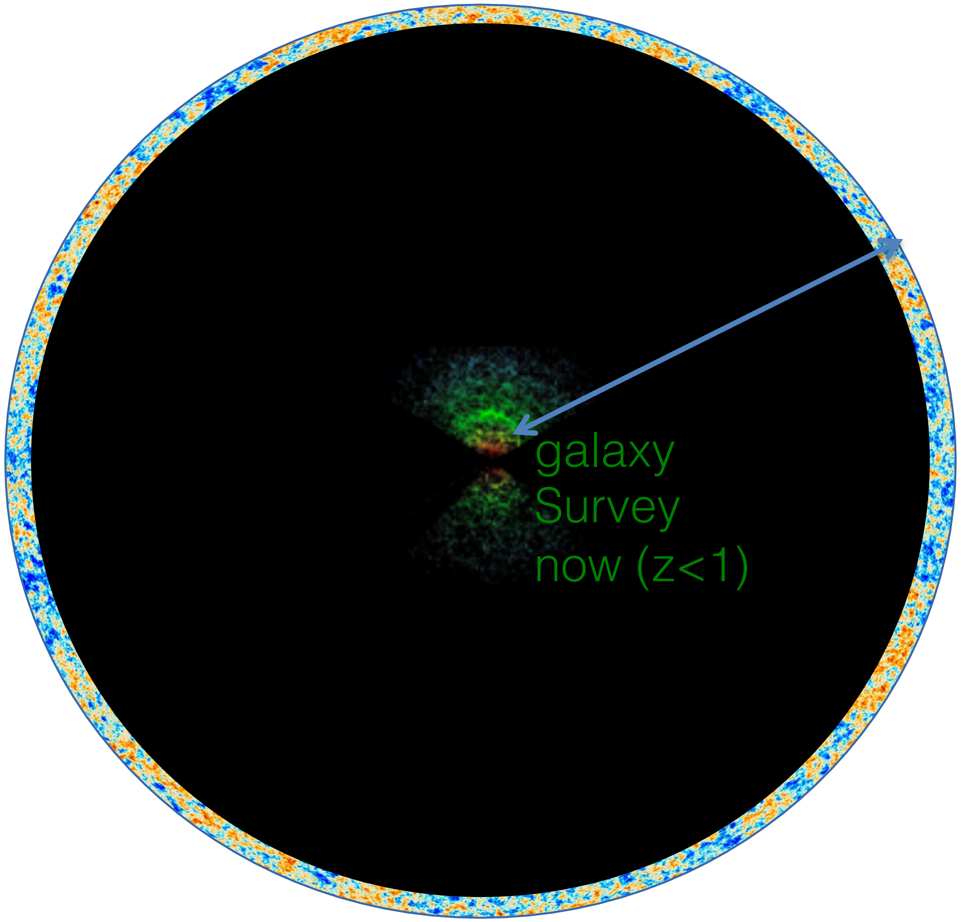


[CMB-S4 science book]

- If we can measure this: **target sensitivity ~0.03,** can see any new light particle that was ever in equilibrium (targeted by CMB-S4 expt.)

2020s and 2030s will be a golden age of large cosmic survey science

Wealth of new Large-scale structure surveys

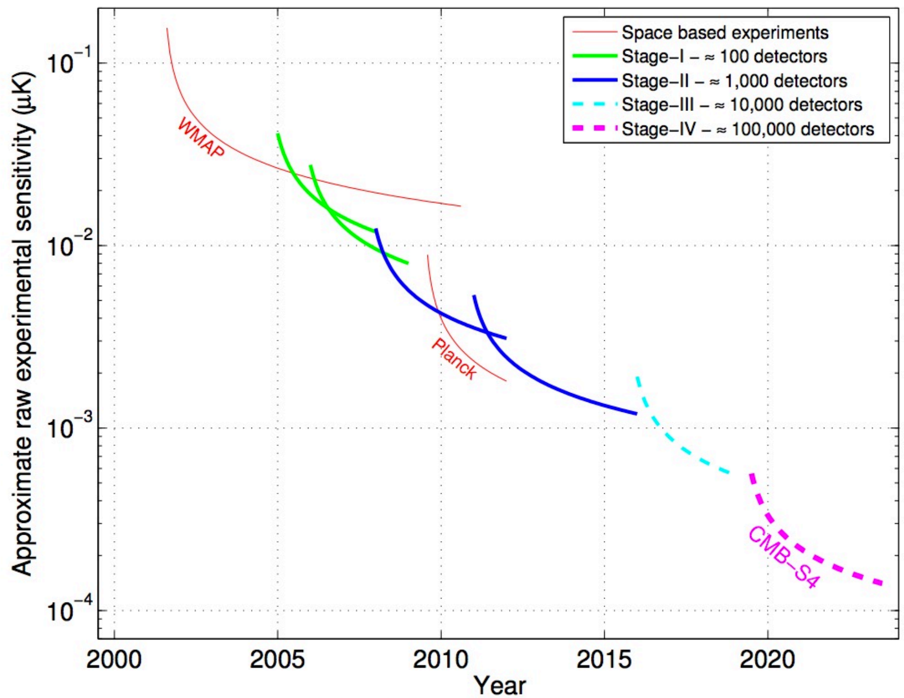


Dark Energy Survey/LSST/Euclid satellite/Spherex/21cm … first mapping of most of the Universe’s volume

2020s and 2030s will be a golden age of large cosmic survey science

Wealth of new CMB data…

CMB Experiment Noise Level



[Abazajian++ 2014]

New CMB surveys Simons Observatory / ACT / S4, will probe new regimes in polarization and on small-scales

Summary

- Network of robust cosmological observations have established a simple but strange standard model
- H_0 and S8 tensions: systematics or first cracks in the model? Need more data – coming soon!
- Cosmology is providing powerful insights into physics at highest energies and with weakest interactions