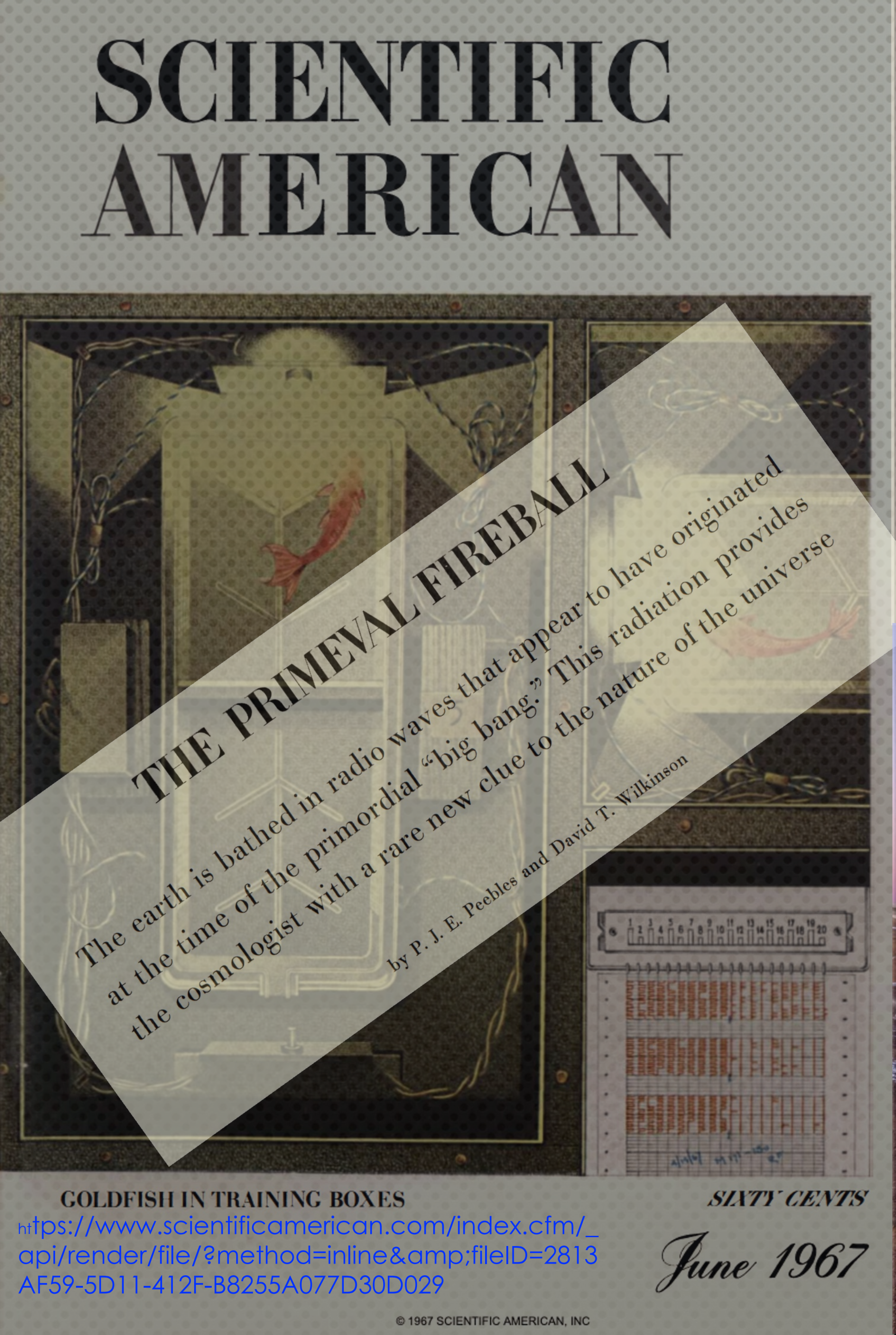
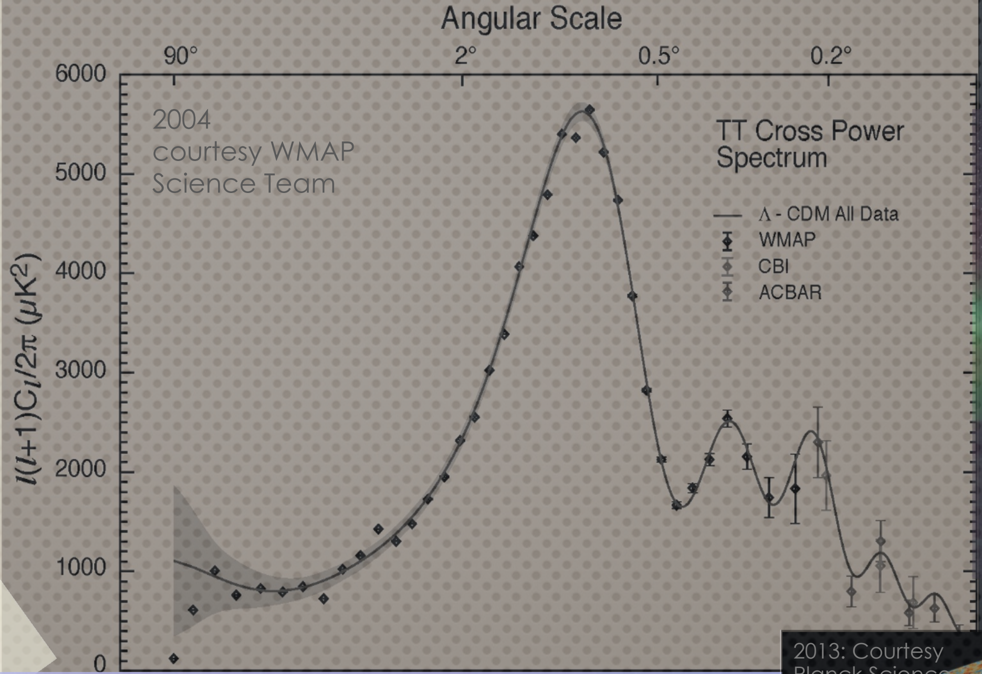
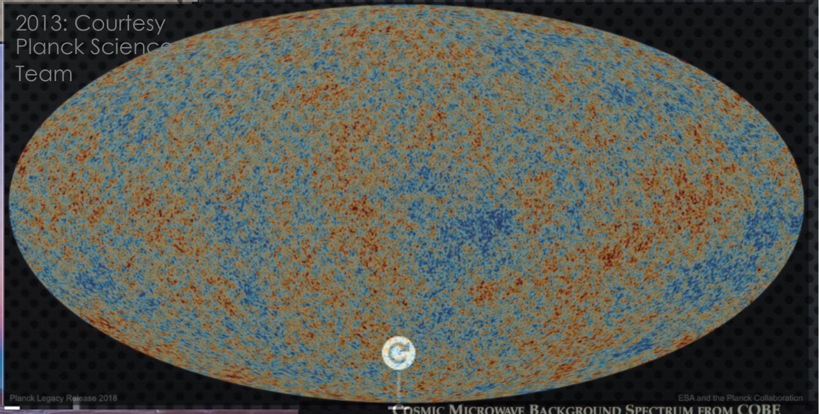
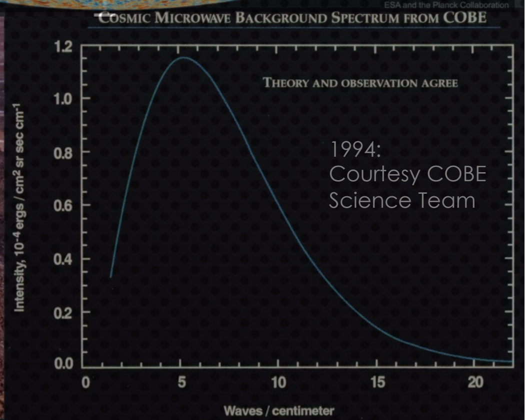


https://www.scientificamerican.com/index.cfm/_api/render/file/?method=inline&fileID=2813AF59-5D11-412F-B8255A077D30D029





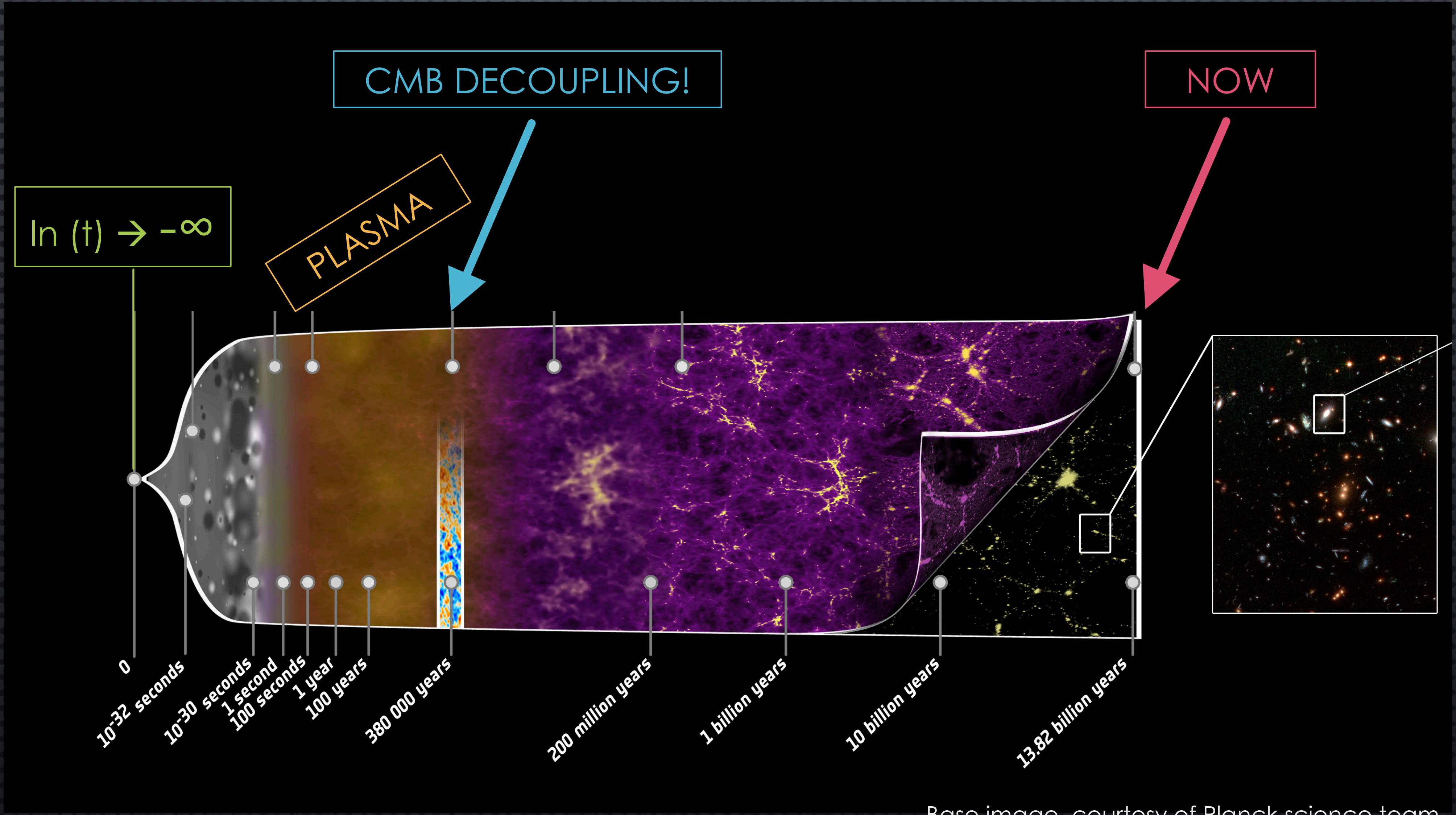


CMB PHYSICS

Suzanne Staggs

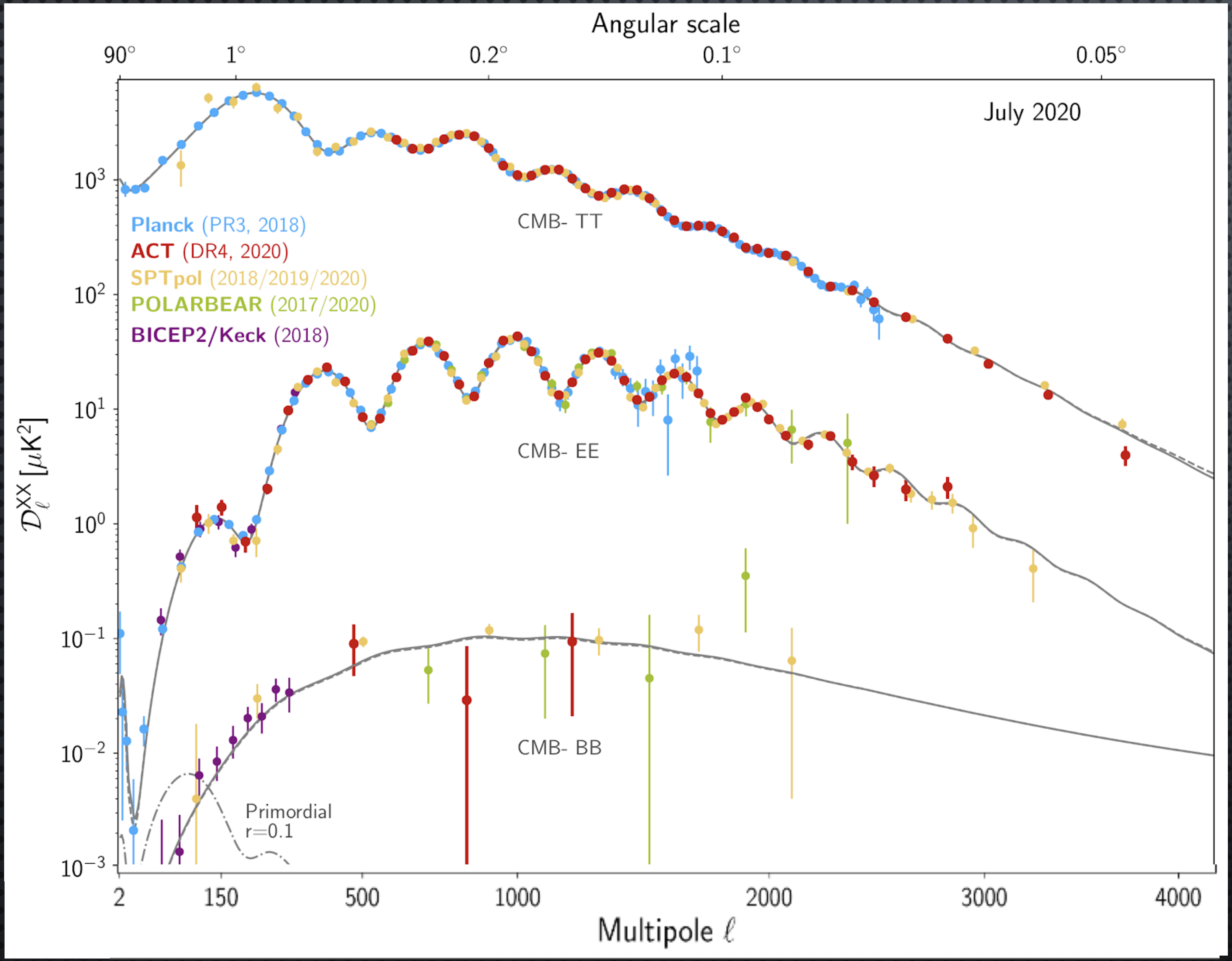
6 June 2022 @ PPC

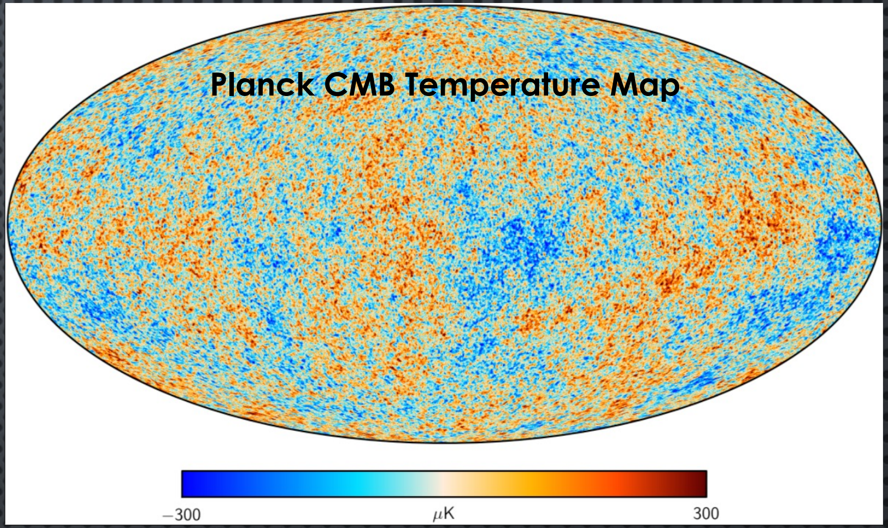
THE COSMIC MICROWAVE BACKGROUND IN CONTEXT



Base image courtesy of Planck science team

THE ALL-MIGHTY CMB POWER SPECTRA



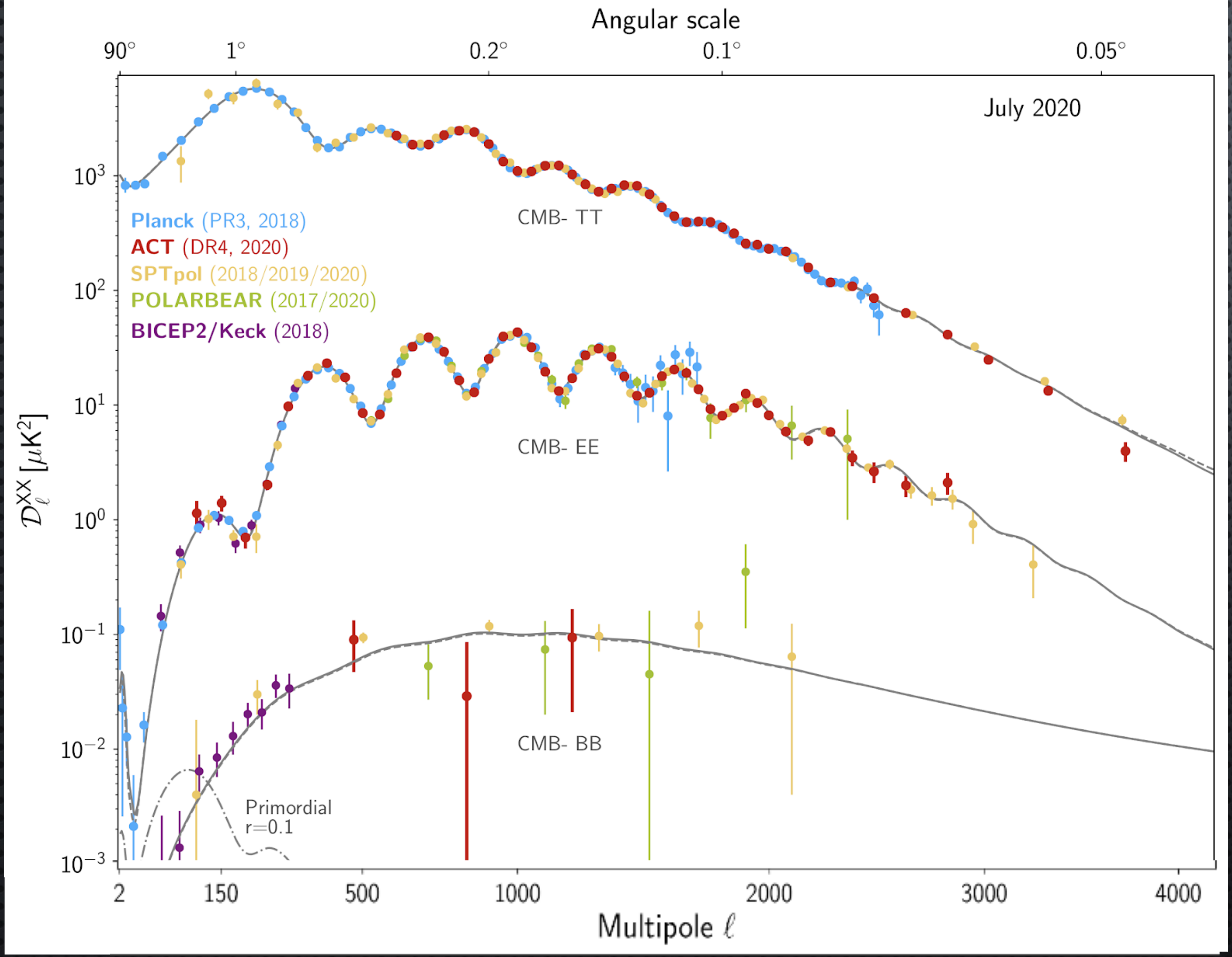


The CMB appears forgettable in maps but remarkable in harmonic space

TT: intensity fluctuations
EE, BB: polarization fluctuations

Compilation from Choi et al, 2020
DOI: 10.1088/1475-7516/2020/12/045)
but already there are more data, and more coming!

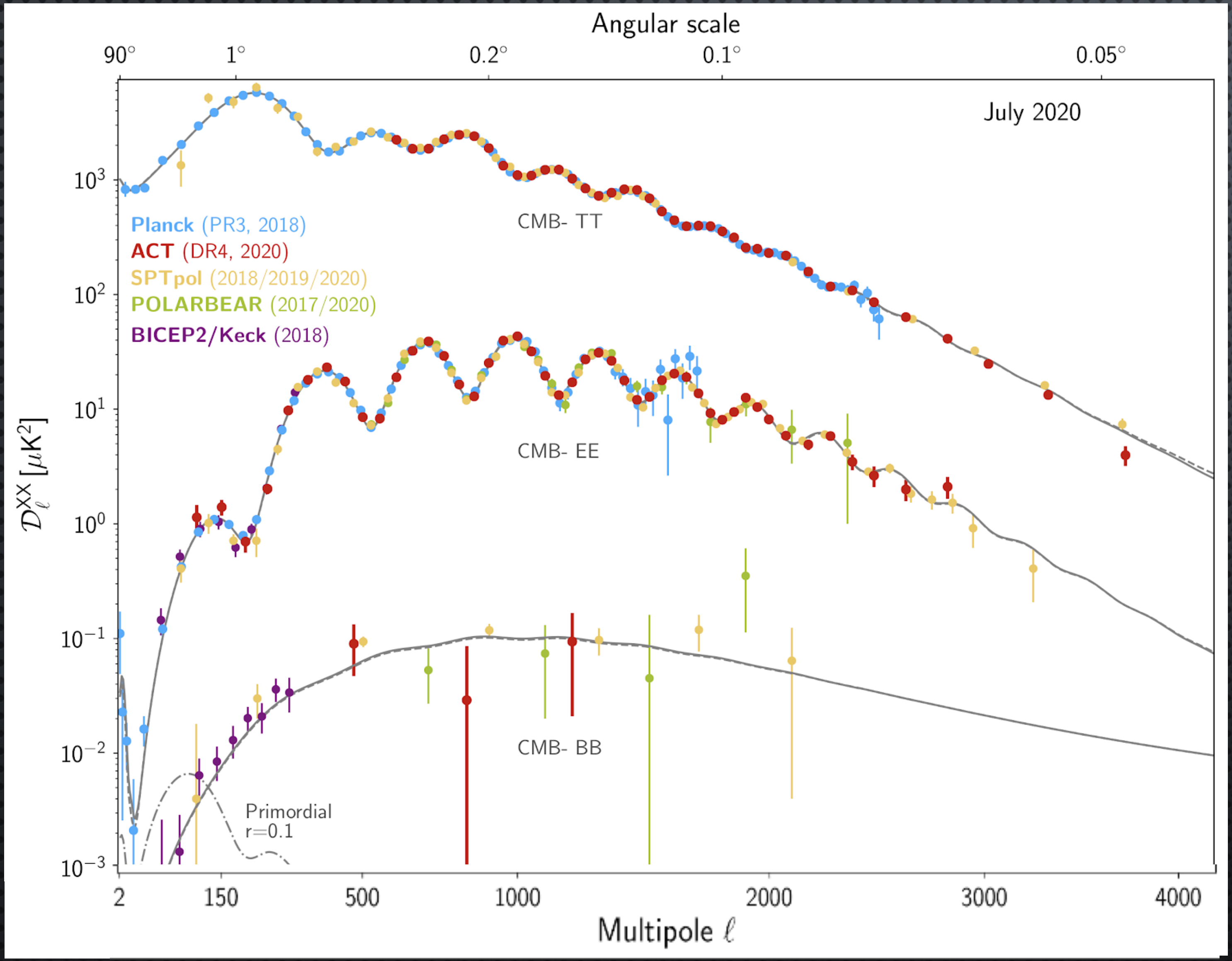
STRUCTURE IN THE CMB POWER SPECTRA



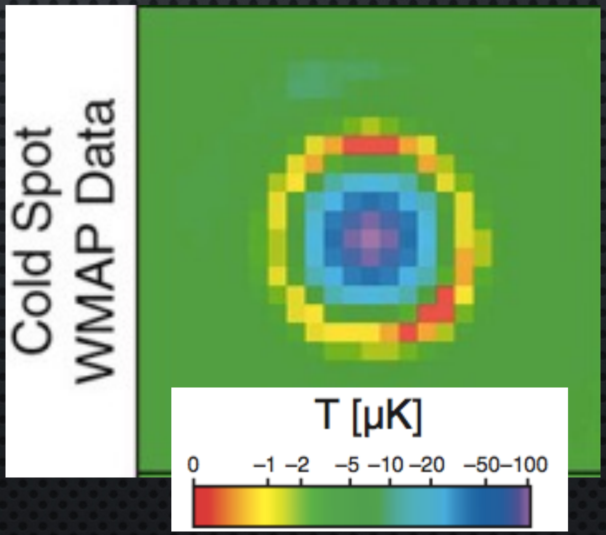
1. INFLATION* engenders dark matter density fluctuations on SUPERhorizon scales.
2. TIME reveals these previously superhorizon dimples in the metric … at time t*, a superhorizon fourier mode of k* is revealed.
3. ACOUSTIC OSCILLATIONS ensue: quasi simple harmonic motion of the photon-baryon fluid associated with mode k*. The plasma is sucked into the metric dimples by gravity and forced out by radiation pressure.
4. COOLING of the expanding universe congeals the plasma, releasing the CMB radiation, bearing patterns of the SHM oscillations.

* Or other

STRUCTURE FROM ACOUSTIC OSCILLATIONS

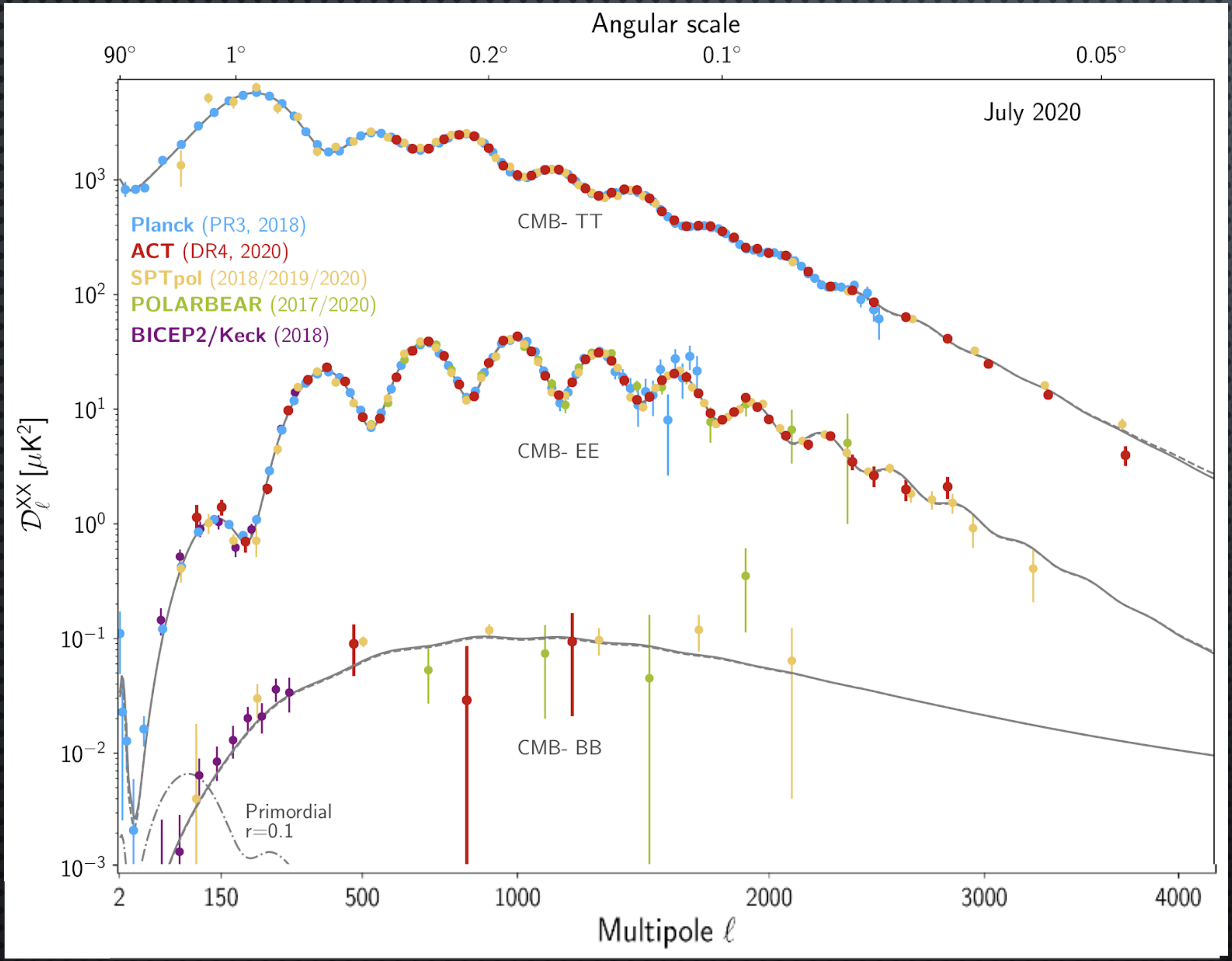


Structure:



WMAP7 stacking on overdense spots; Komatsu et al, 2011.

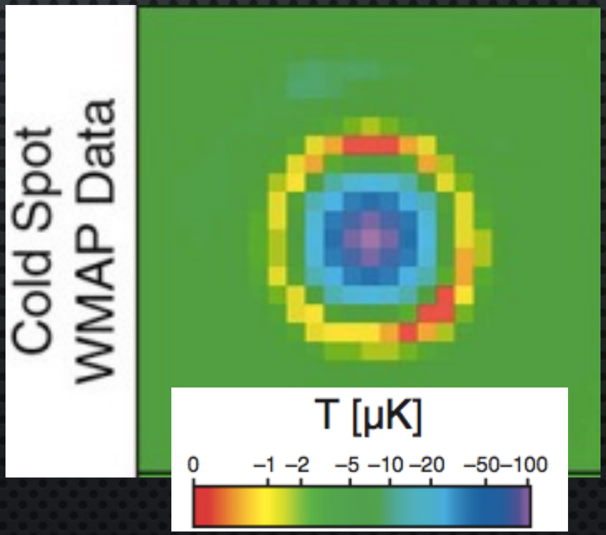
TRANSFER FUNCTION ON INITIAL INITIAL CONDITIONS



Structure in the form of transfer function assumed to act on:

$$P(k) = A_S \left(\frac{k}{k_0}\right)^{\tilde{n}_s - 1},$$

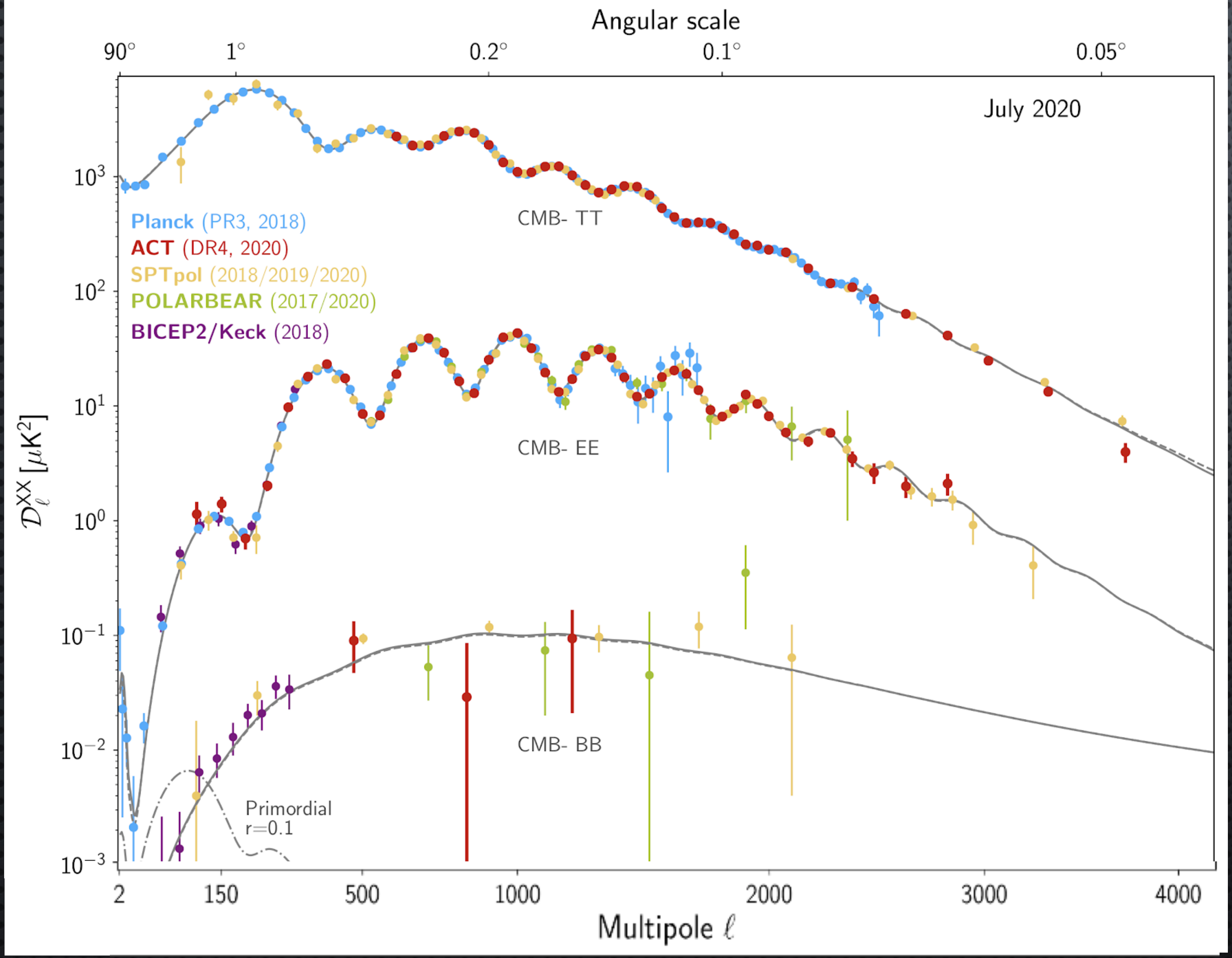
k = 3d wave-vector in the then universe



5^0x5^0 patch

WMAP7 stacking on overdense spots; Komatsu et al, 2011.

TRANSFER FUNCTION ITSELF COMMUNICATES INITIAL CONDITIONS



Structure in the form of transfer function assumed to act on:

$$P(k) = A_S \left(\frac{k}{k_0}\right)^{\tilde{n}_s - 1},$$

2 params

k = 3d wave-vector in the then universe

ACOUSTIC OSCILLATIONS :
Then density of baryons
Then density of dark matter

2 params

ADDITIONAL EFFECTS:
Rescattering due to reionization
Geometry (if flat → dark energy)

2 params

+1: Damping tail, running, etc

CMB SPECTRA AND SIX BASIC COSMOLOGY PARAMETERS

Planck 2018 Paper I; Planck + BAO Results – **including EE, TE, & Lensing**

$\Omega_b h^2$	baryon density	2.24% +/-0.01%
$\Omega_c h^2$	cold dark matter density	11.93% +/-0.09%
Θ	angular scale of acoustic horizon at decoupling	0.5965^0 +/- 1"
τ	reionization optical depth	0.056 +/- 0.007
n_s	spectral index of primordial adiabatic fluctuations	0.966 +/-0.004
A_s	amplitude of perturbations	3.047 +/-0.014

where H_0 = h * 100 km/s/Mpc, and the geometry is taken as flat.

From the above, in the context of ΛCDM, can derive Ω_Λ, Ω_m, σ_8, t_0, H_0.

Ω_Λ = 68.9% +/- 0.6%; Ω_m = 31.1% +/- 0.6%; σ_8 =0.810 +/- 0.006; t_0 = 13.79 +/- 0.02 Gyr; H_0 = 67.7+/- 0.4 km/s/Mpc

CMB SPECTRA AND SIX BASIC COSMOLOGY PA

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CMB SPECTRA AND ~~SIX BASIC~~ 6+1 COSMOLOGY PARAMETERS

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$\Omega_c h^2$	cold dark matter density	11.93% +/-0.09%
Θ	angular scale of acoustic horizon at decoupling	0.5965^0 +/- 1”
τ	reionization optical depth	0.056 +/- 0.007
n	spectral index of primordial adiabatic fluctuations	0.966 +/-0.004
A_s	amplitude of perturbations	3.047 +/-0.014

$dn_s/d\ln k = -0.005 +/- 0.007$

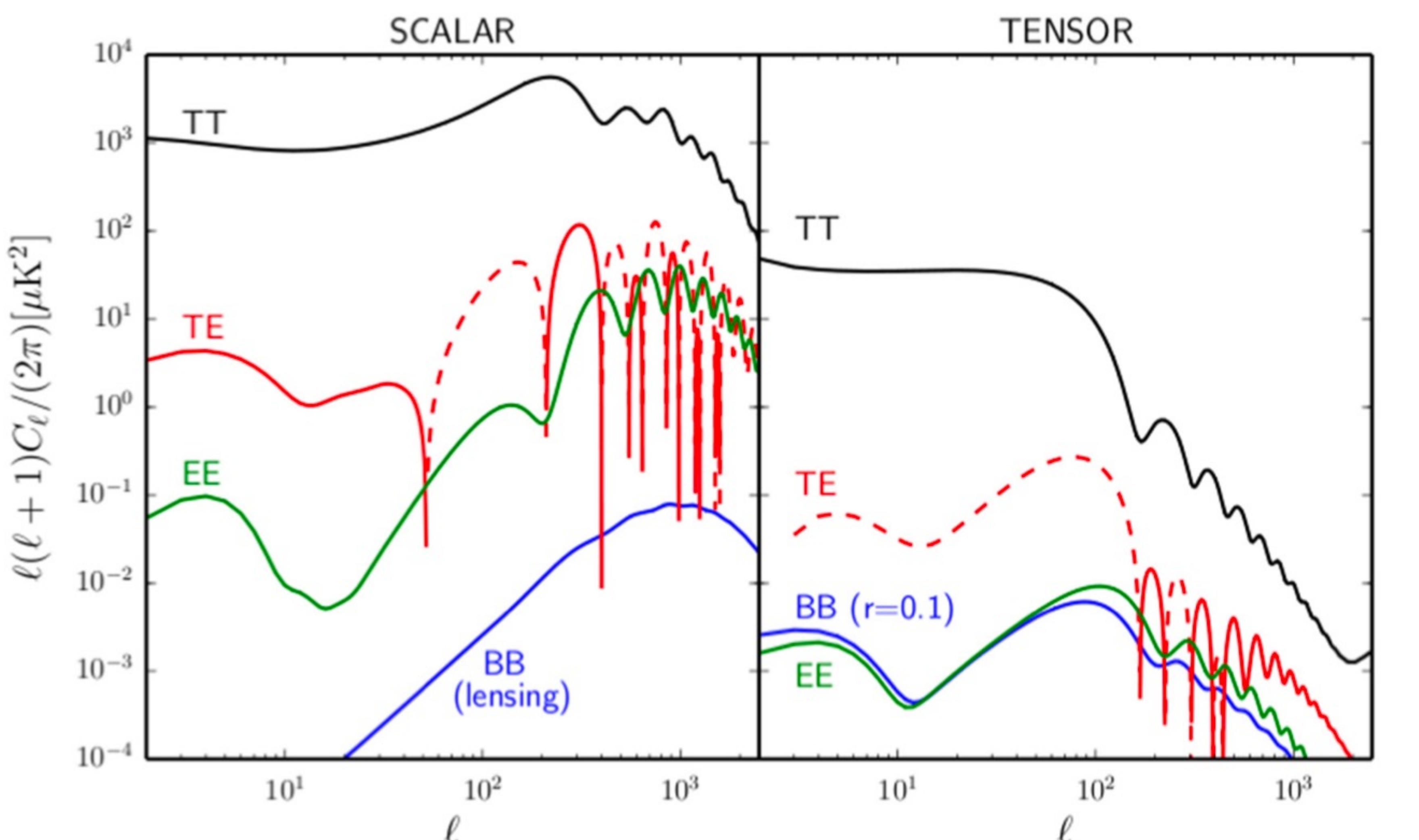
and <2% variance isocurvature

where $H_0 = h * 100$ km/s/Mpc, and the geometry is taken as flat.

From the above, in the context of ΛCDM, can derive Ω_Λ, Ω_m, σ_8, t_0, H_0.

Ω_Λ = 68.9% +/- 0.6%; Ω_m = 31.1% +/- 0.6%; σ_8 =0.810 +/- 0.006; t_0 = 13.79 +/- 0.02 Gyr; H_0 = 67.7+/- 0.4 km/s/Mpc

TENSOR PERTURBATIONS (GRAVITATIONAL WAVES)

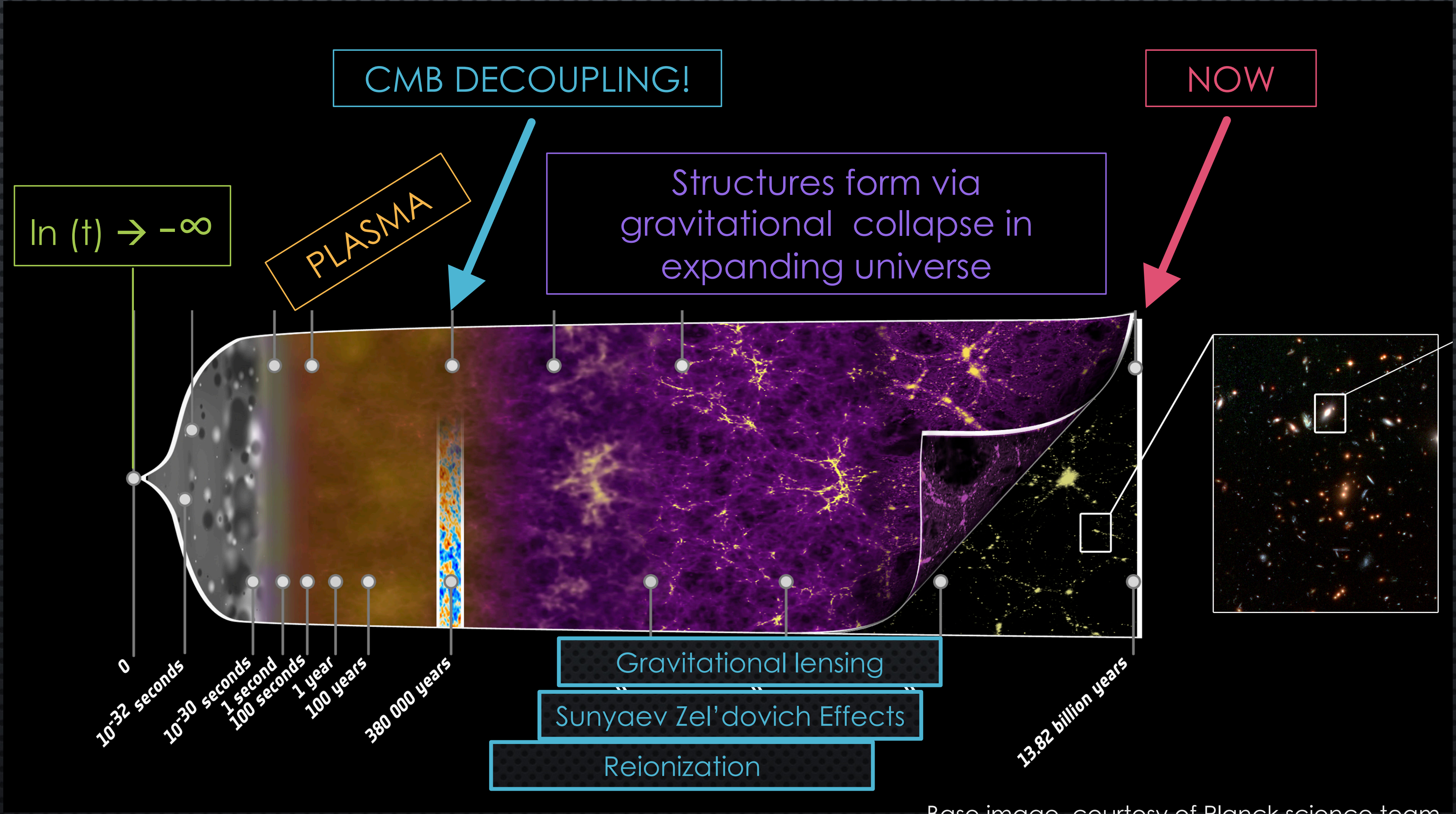


Staggs, Dunkley, Page 2017

r < 0.035 (BB from BICEP/Keck only, 2021z0

r < 0.056 (BB with TT, EE, TE from Planck, Tristram et al 2021)

THE CMB: INITIAL CONDITIONS & BEYOND



Base image courtesy of Planck science team

COSMOLOGY & CONTENTS OF UNIVERSE

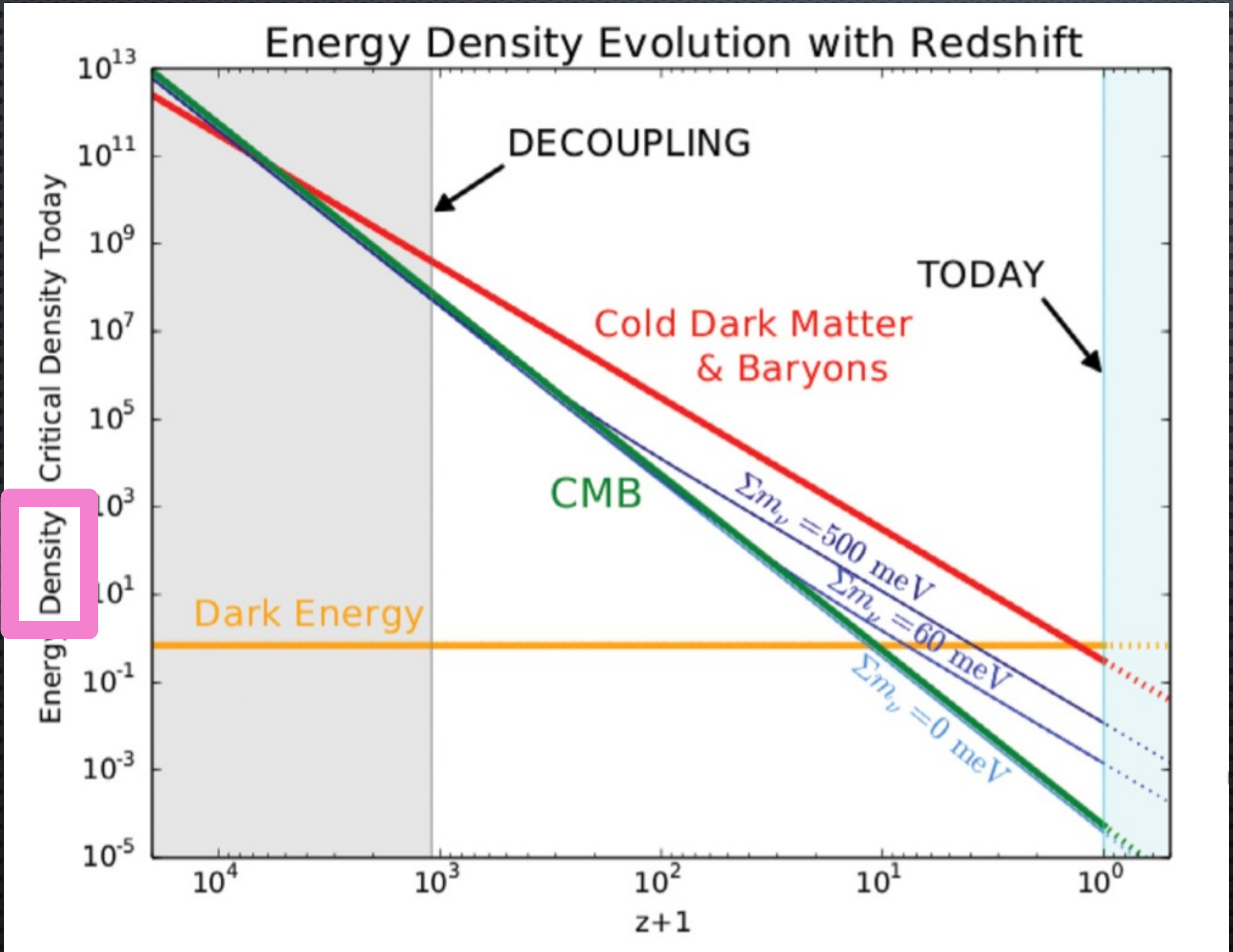


Figure from Staggs, Page & Dunkley, RoPP, 2018.

$$H^2 = \frac{8\pi}{3} G\rho$$

In FLRW universe: but see upcoming talk from Subir Sarkar

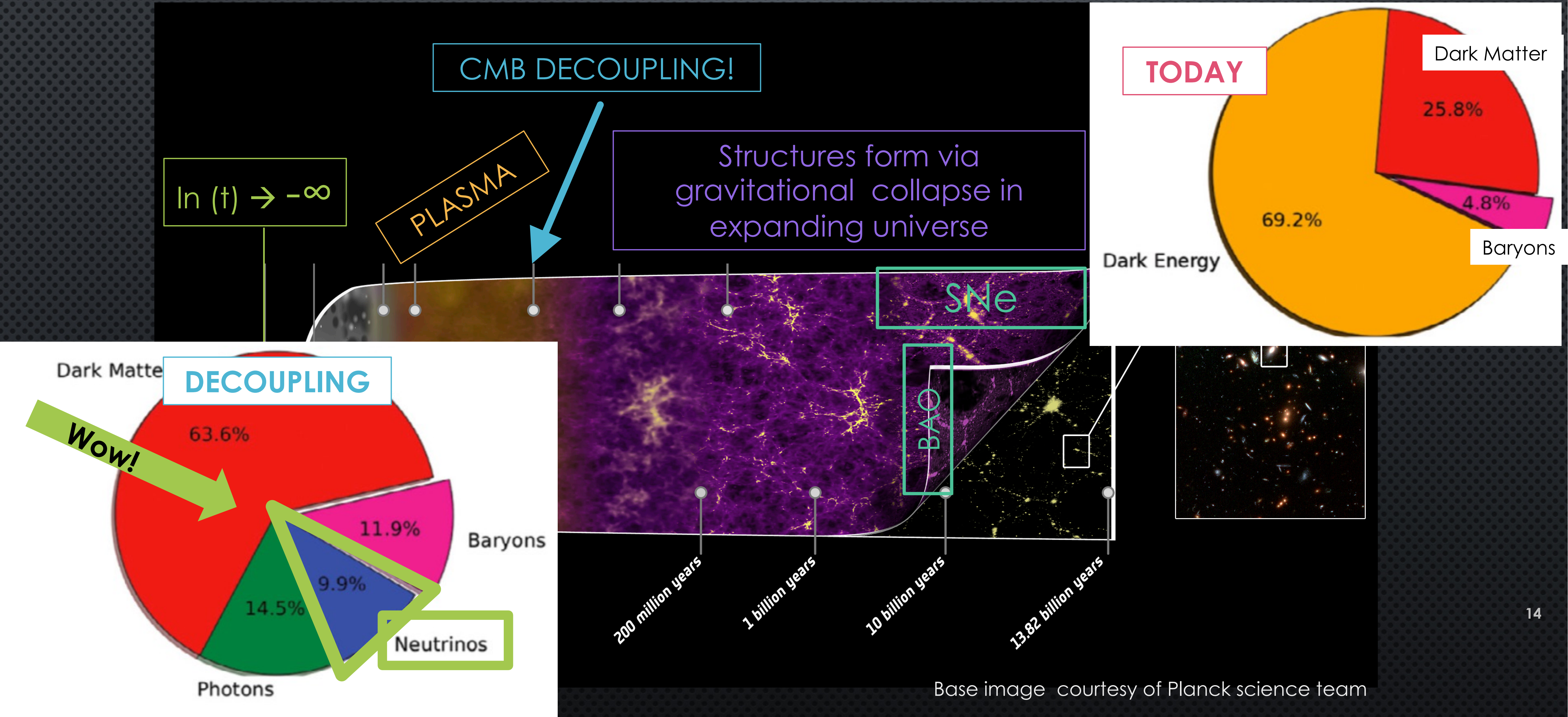
H(t) dynamics depend on ρ(t)

NEUTRINOS AND OTHER LIGHT PARTICLES ARE RELATIVISTIC IN THE EARLY HOT UNIVERSE → RADIATION

Σm_ν matters later!

See upcoming talk from Shun Saito.

THE COSMIC MICROWAVE BACKGROUND IN CONTEXT



Base image courtesy of Planck science team

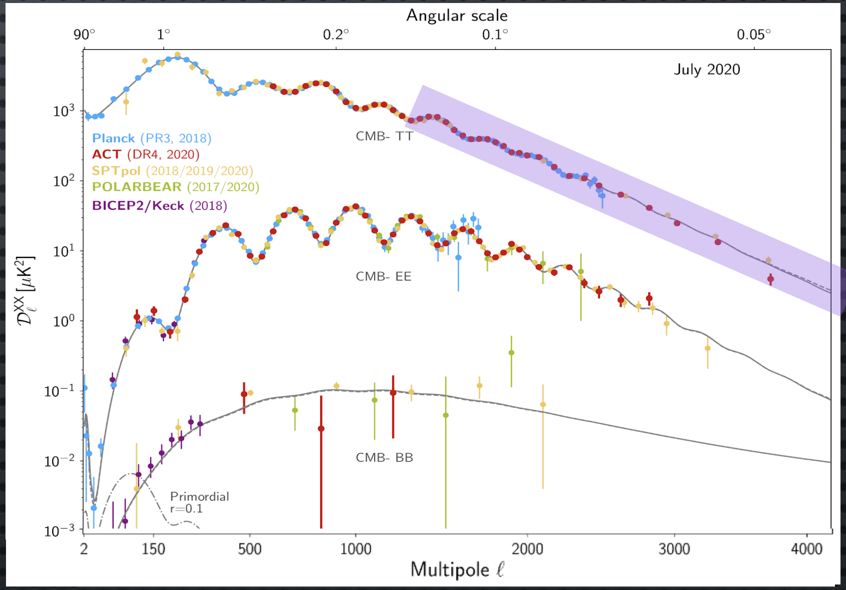
HIGH RESOLUTION SPECTRA: NEUTRINOS AND LIGHT RELICS

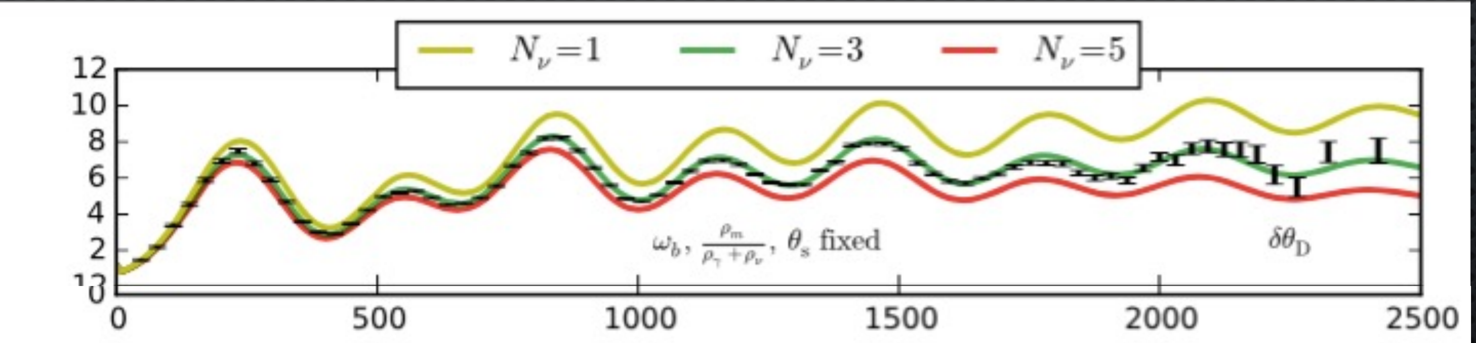
Definition of N_{eff}

$$\rho_R = \frac{\pi^2}{15} T_\gamma^4 (1+z)^4 \left[1 + \frac{7}{8} N_{\text{eff}} \left(\frac{4}{11}\right)^{4/3}\right]$$

Planck 2018 (1807.06209)
N_{eff} = 2,99 +/- 0.17 (95% CL)
(cf 3.046 for SM neutrinos)

4/11 assumes instantaneous decoupling of the neutrinos…





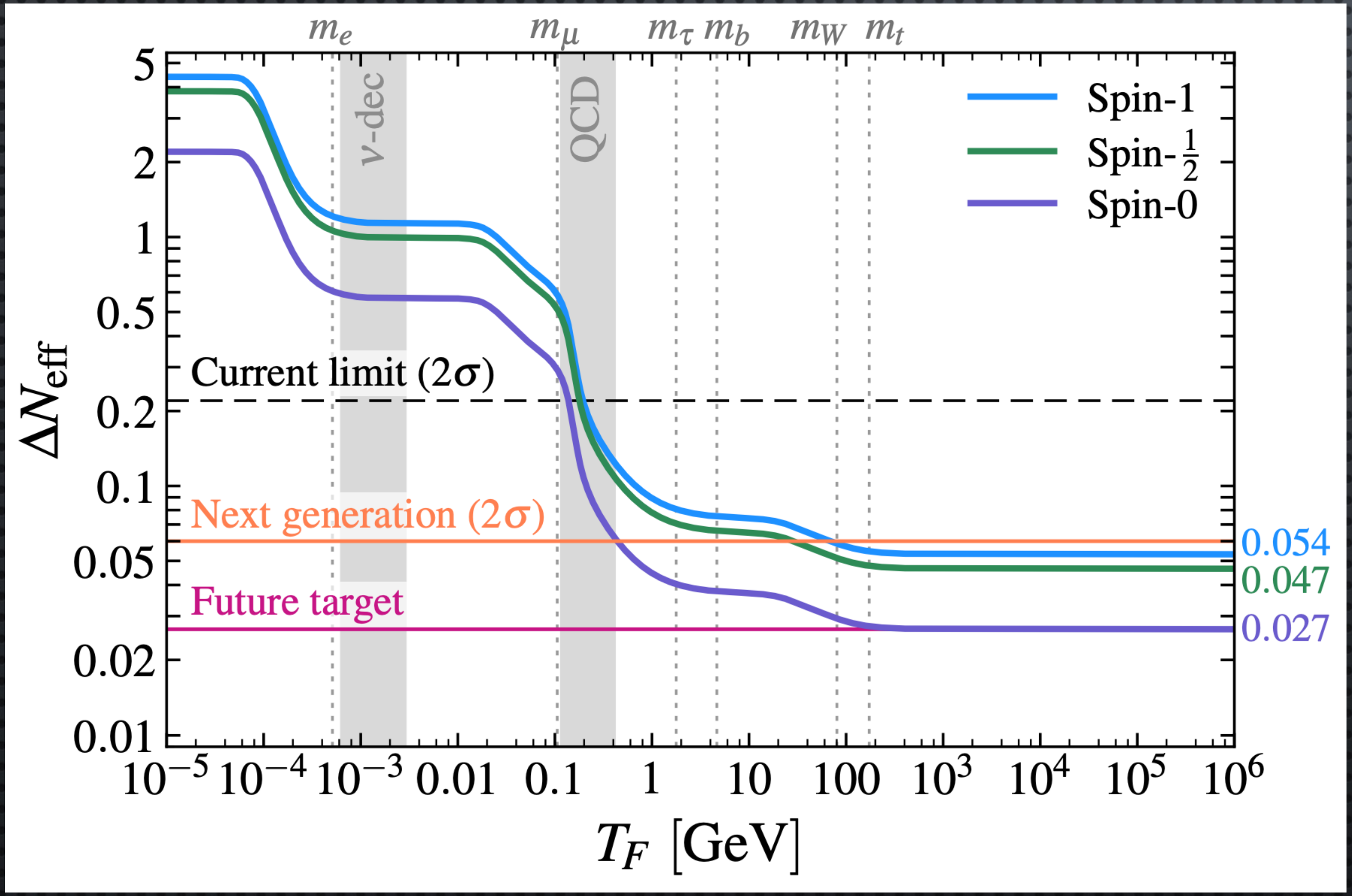
Follin et al, PRL, 2015

(Plot has damping tail suppressed.)

Damping tail envelope from photon diffusion. Higher ρ_R → later matter domination → shallower potential wells.

DISCOVERY POTENTIAL FOR LIGHT RELICS

AXIONS, STERILE NEUTRINOS, HIDDEN PHOTONS, GRAVITINOS



D. Green et al 2019, Astro2020 White Paper

$$\rho_R = \frac{\pi^2}{15} T_\gamma^4 (1+z)^4 \left[1 + \frac{7}{8} N_{\rm eff} \left(\frac{4}{11}\right)^{4/3}\right]$$

$N_{\rm eff}$ does not have to be an integer with this definition!

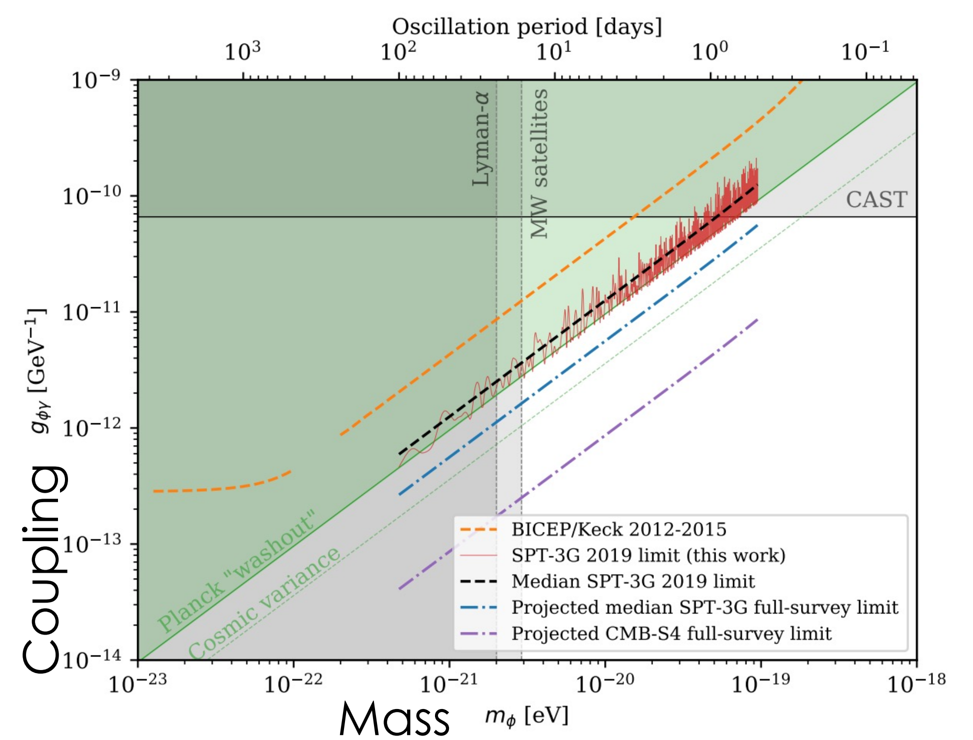
Particles that decouple earlier will end up relatively colder but can still contribute!

Saturates at 0.03/DOF.

"light" means < 0.1 eV

THE CMB & BIREFRINGENCE

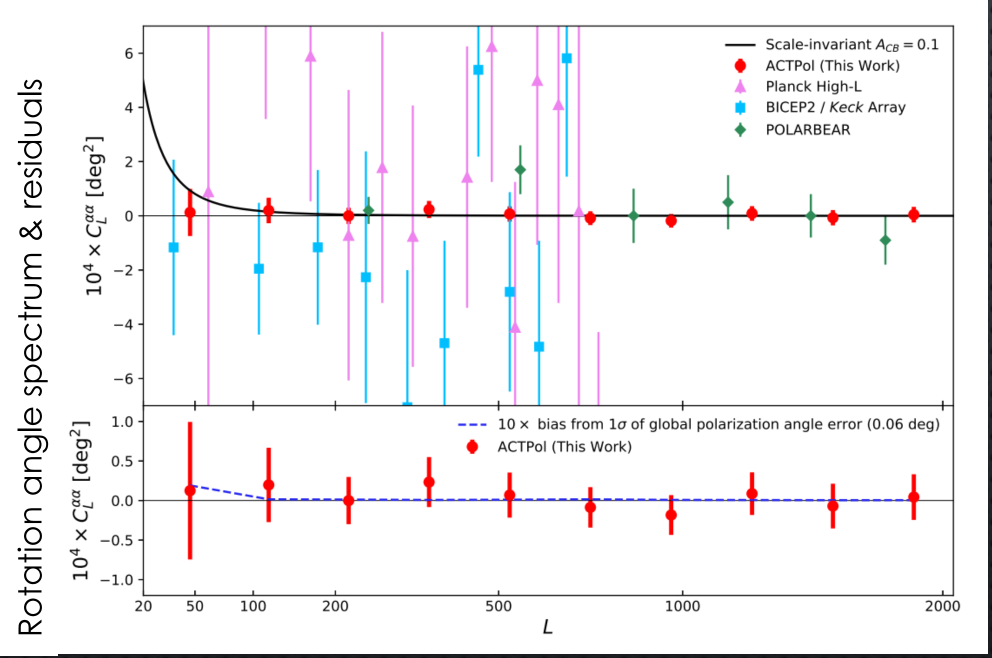
Axion-Like Dark Matter
(nonthermally produced)



BICEP/Keck XII, 2020

Ferguson et al, 2022, 2203.16567.pdf

Birefringence Angular Power Spectrum



Namikawa et al, 2020, DOI: 10.1103/PhysRevD.101.083527

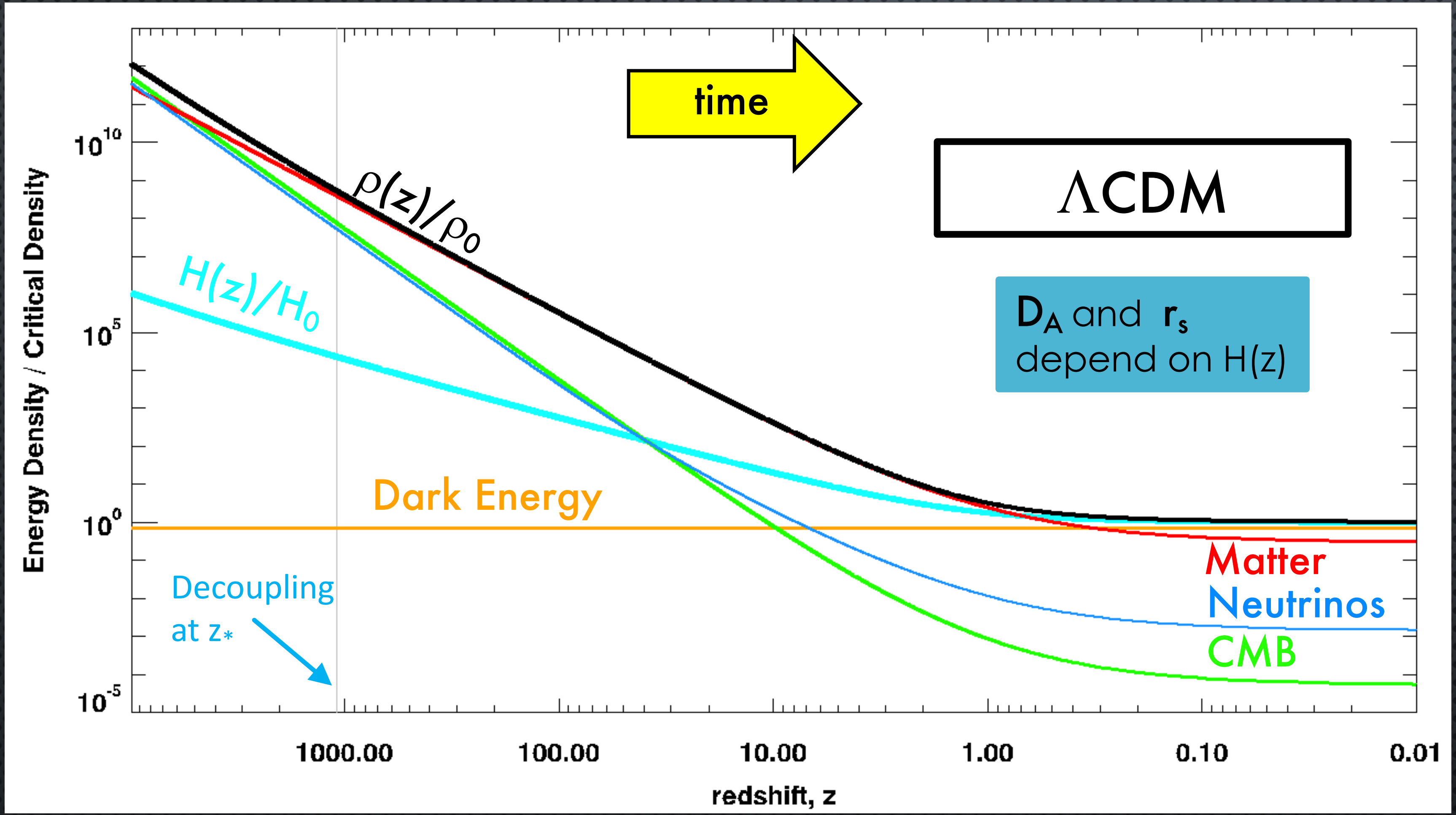
Also a monopole limit from Planck + WMAP:

$\beta = 0.34^\circ$ +/- 0.09°

(Eskilt & Komatsu, 2022, 2205.13962.pdf)

See later talks in this meeting!

THE CMB & H_0



$$H^2 = \frac{8\pi}{3} G\rho$$

r_s = sound horizon

$$r_s^\star = \int_0^{t_\star} \frac{dt}{a(t)}\, c_s(t) = \int_{z_\star}^{\infty} \frac{dz}{H(z)}\, c_s(t)$$

Sound horizon depends on dynamics **before** decoupling.

D_A = angular diameter distance

$$D_A^* = \int_0^{z^*} \frac{dz}{H(z)}$$

D_A depends on dynamics **after.**

Sound speed c_s depends on baryon density ofc (but BBN!)

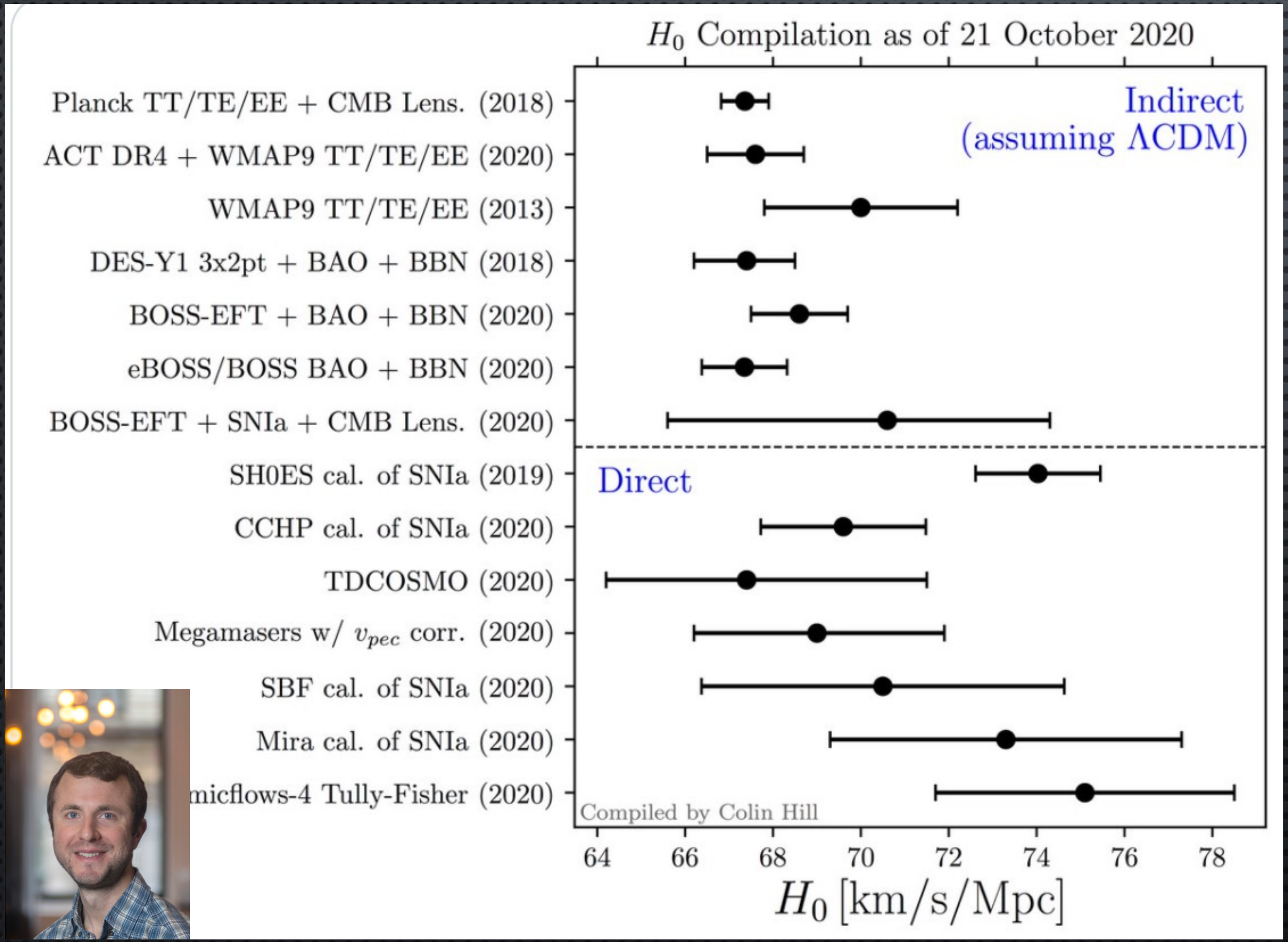
Recall $a = (1+z)^{-1}$

CMB spectra determine θ_s

$D_A = r_s/\theta_s$

See also Knox & Millea, Phys. Rev. D 101, 043533 (2020); arXiv:1908.03663

WHAT NOW?



Recall the plan:

- CMB defines initial contents of the universe
- Which determines how the universe expands
- Which lets the CMB predict the future

Interpretation of status:

- Tension!
- And: all the measurements are (still) hard
- And: it doesn't have to be the CMB that sets the initial conditions
- But: maybe the model needs more!

See upcoming talk by Adam Riess

https://twitter.com/jcolinhill/status/1319415667095949312

WHAT MIGHT BRIDGE THE GAP?

Quoting Colin Hill quoting Knox & Millea (2020):
"We single out the set of solutions that increase the expansion rate in the decade of scale factor expansion just prior to recombination as the least unlikely [to be successful]."

$D_A = r_s/\theta_s$

CMB spectra determine θ_s

r_s = sound horizon

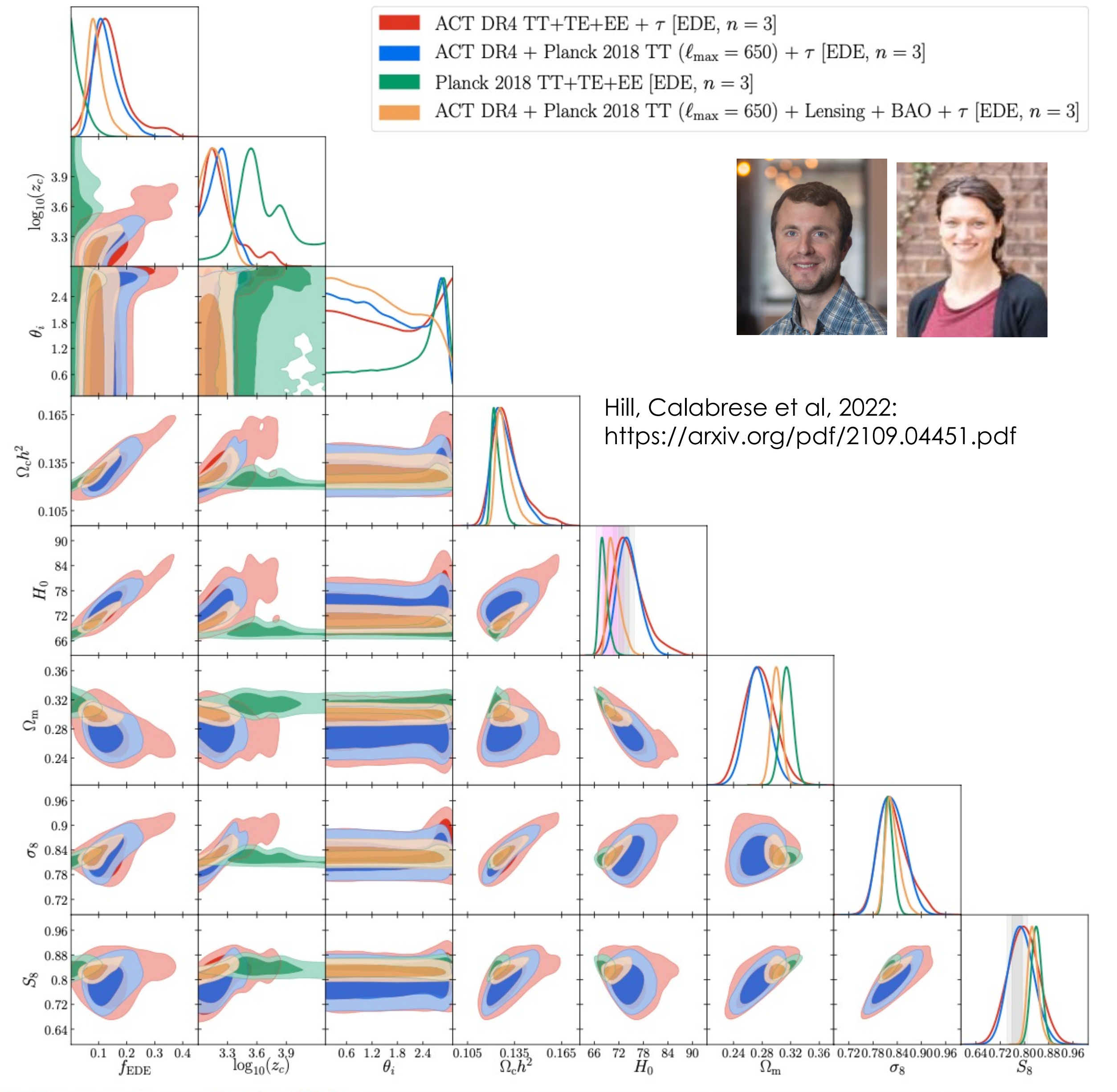
$$r_s^\star = \int_0^{t_\star} \frac{dt}{a(t)}\, c_s(t) = \int_{z_\star}^{\infty} \frac{dz}{H(z)}\, c_s(t)$$

Sound horizon depends on dynamics **before** decoupling.

Early Dark Energy (EDE) postulates a scalar field with a potential defined so as to cause additional expansion before decoupling, decreasing r_s & thus D_A, leading to increased H_0.

Hill, Calabrese et al, 2022: https://arxiv.org/pdf/2109.04451.pdf

STATUS: INTERESTING BUT NOT HIGH S/N YET



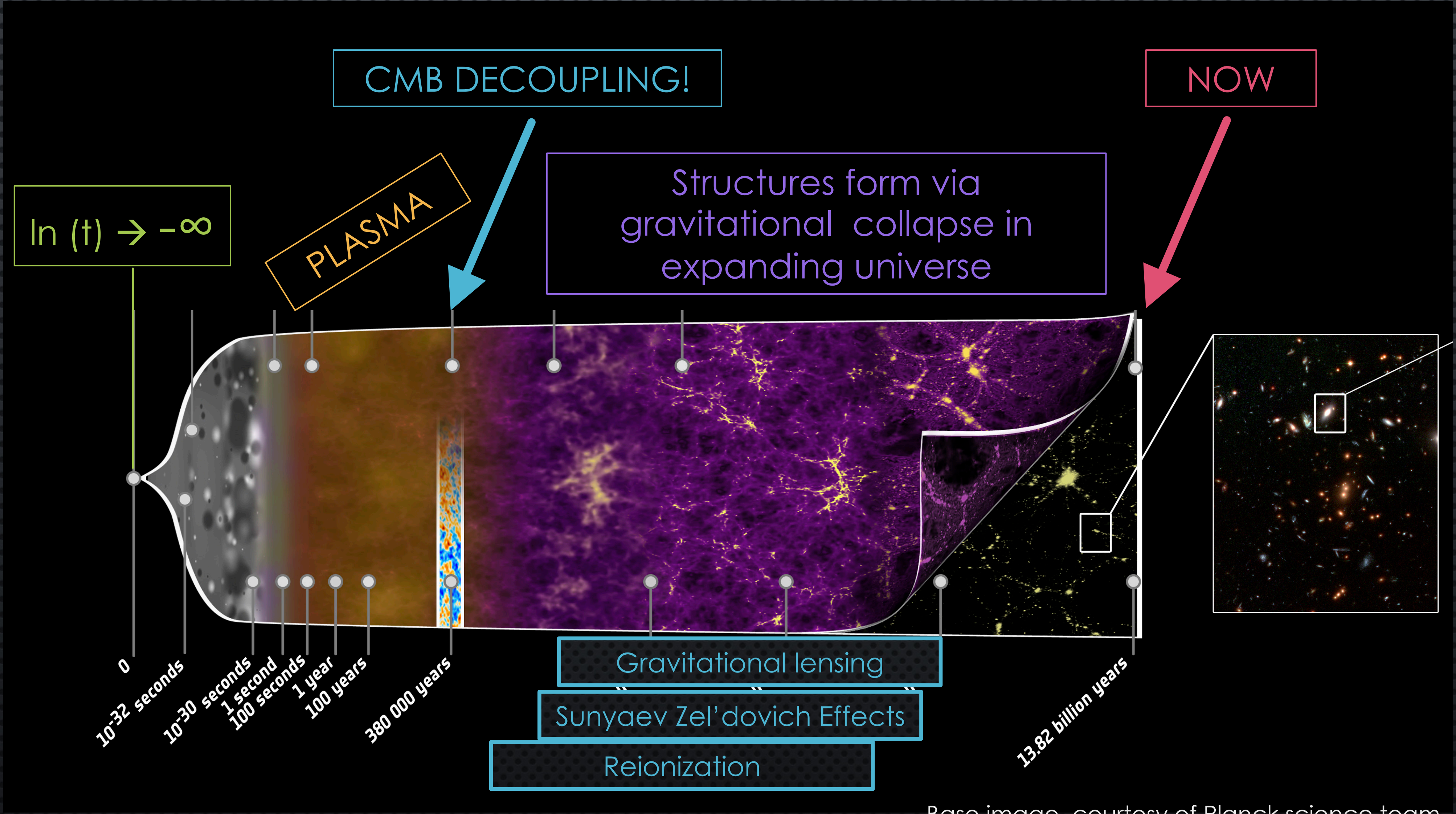
Hill, Calabrese et al, 2022:
https://arxiv.org/pdf/2109.04451.pdf

Planck does not need EDE
ACT alone and ACT + low-ell and
ACT + low-ell + ext data alll show
slight preference for EDE
Planck does not need EDE

Check out the paper for lots
of detail and explanations!

Upcoming ACT DR6 is coming!
We have >~4x more data in the wide regions.

THE CMB: INITIAL CONDITIONS & BEYOND



Base image courtesy of Planck science team

Coming up from ACT, Simons Observatory (SO) & CMB-S4:

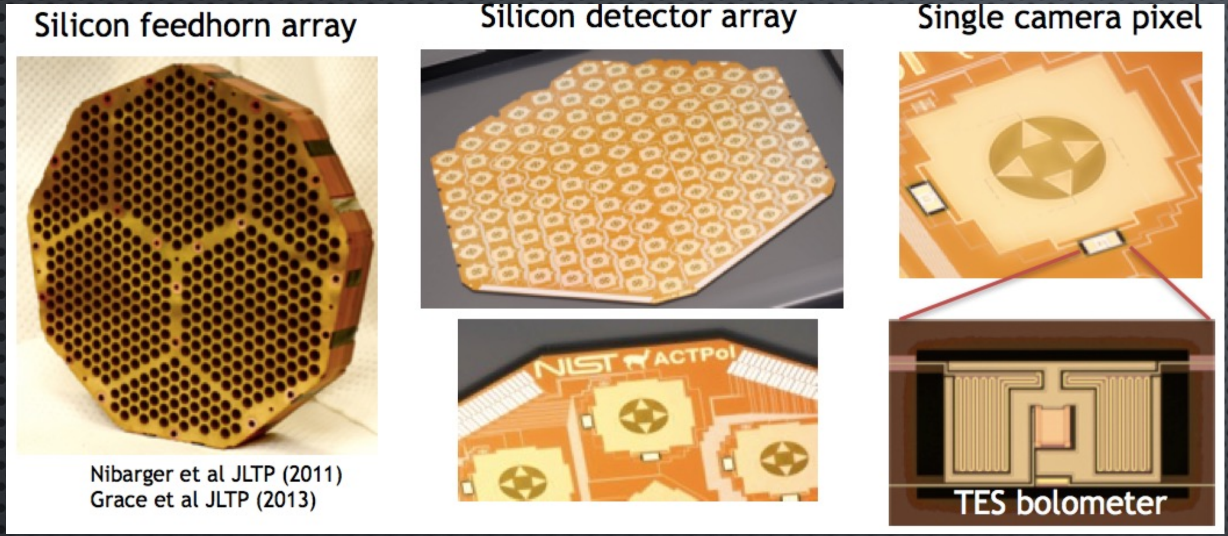
HUGE MAPS OF THE CMB WITH HIGH ANGULAR RESOLUTION

- PRIMORDIAL INITIAL CONDITIONS:
  - CMB POWER SPECTRA
- EVOLVING UNIVERSE:
  - CMB LENSING
  - CLUSTERS (tSZ signatures)
  - LARGE SCALE MOTIONS (kSZ)
  - REIONIZATION (kSZ)
- BONUSES:
  - DUSTY STAR-FORMING GALAXIES
  - RADIO SOURCES
  - TRANSIENT SCIENCE

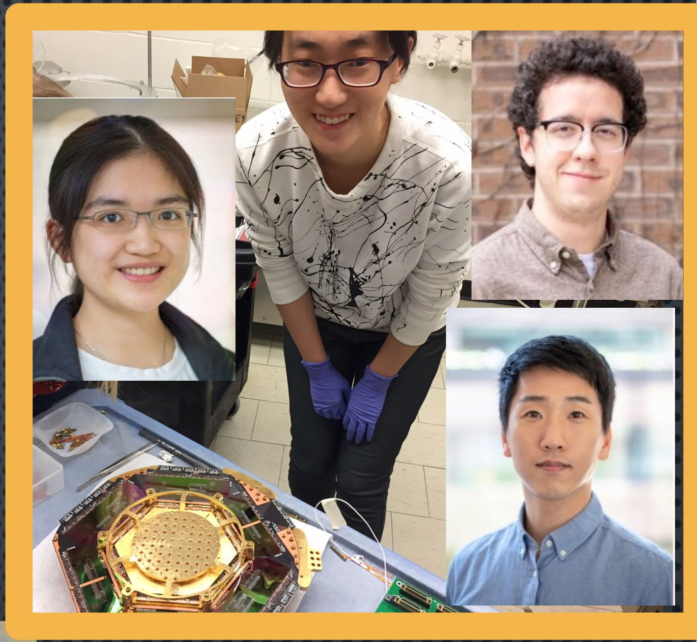
New light relics: N_{eff}
Primordial gravitational waves → new fields
First cosmic ruler (H_0)
Fundamental constants' constancy

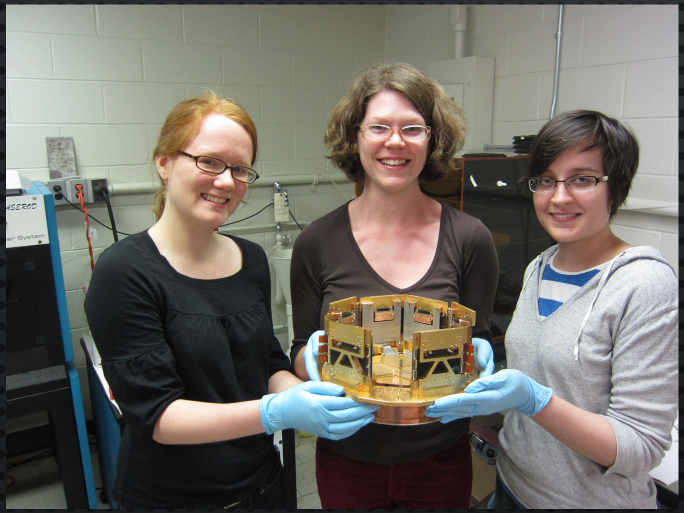
Neutrino masses: Σm_ν
Growth rate of structure → GR
Growth rate of structure → H(a) → DE
Reionization → baryon distribution
Structure formation → physics thereof

THE ACTPOL/ADVACT CAMERA



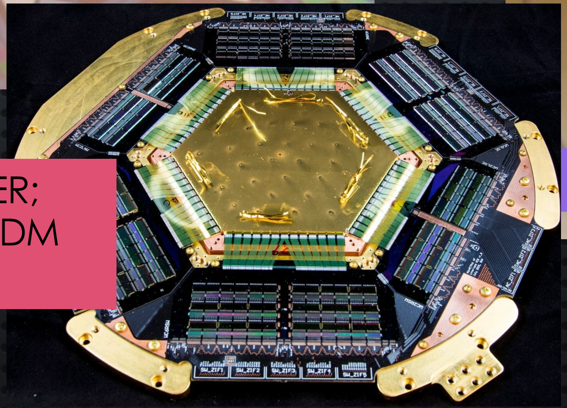
Advanced ACTPol Focal Plane Array:



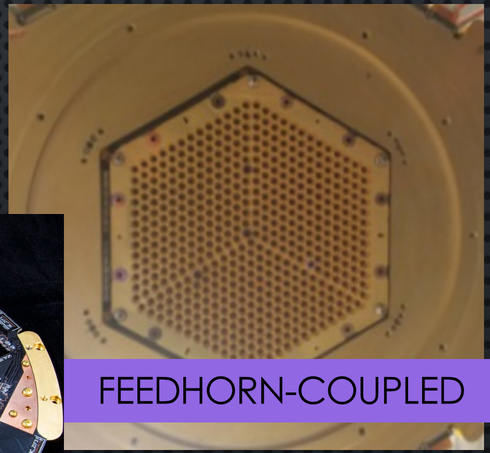


Superconducting devices fabricated at NIST

ACTPol Focal Plane Array



150 mm WAFER; SQUID-BASED TDM READOUT



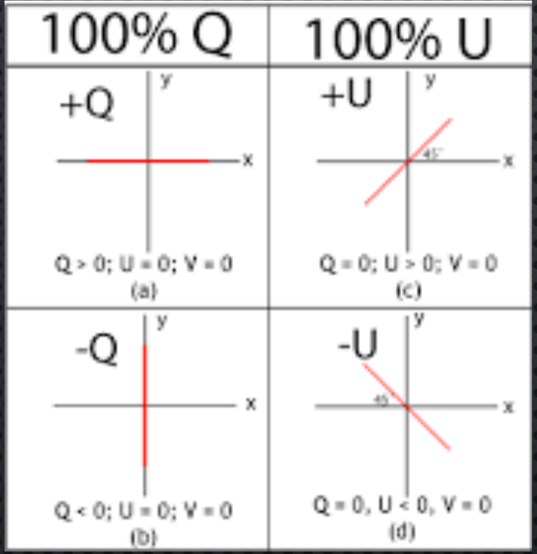
FEEDHORN-COUPLED

MULTIPLE FREQUENCY BANDS BETWEEN 30 and 280 GHz


END SLIDE
Staggs Lab

CMB POLARIZATION: E-MODES & B-MODES

STOKES PARAMETERS

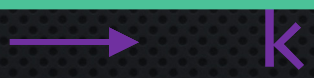


E-modes are symmetric wrt rotations around the wavevector…

ACOUSTIC OSCILLATIONS (SCALAR MODES) PRODUCE **ONLY** E-MODES!

Kamionkowski, Kosowsky & Stebbins; 1997

Seljak & Zaldarriaga 1997



E & B are GLOBAL not LOCAL since they are fundamentally defined in harmonic (not position) space.

NEUTRINOS & HIGH RESOLUTION CMB SPECTRA

NEUTRINOS

DECOUPLING: t ~ 1 s (T ~ 1 MeV)
PRESENT DENSITY: n ~ 100 / cm^3
PRESENT TEMPERATURE: T ~ 2K (~ 0.2 meV)
PRESENT ENERGY EACH: E ~ m > 58 meV
PRESENT ENERGY DENSITY: r_n > 5.8 eV/ cm^3

PHOTONS

DECOUPLING: t ~ 380 kyr (T ~ 1 MeV)
PRESENT DENSITY: n ~ 400 / cm^3
PRESENT TEMPERATURE: T ~ 3K (~ 0.3 meV)
PRESENT ENERGY EACH: E ~ T~ 0.3 meV
PRESENT ENERGY DENSITY: r_g ~ 0.2 eV/ cm^3