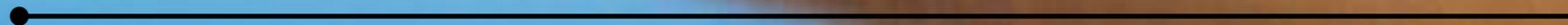
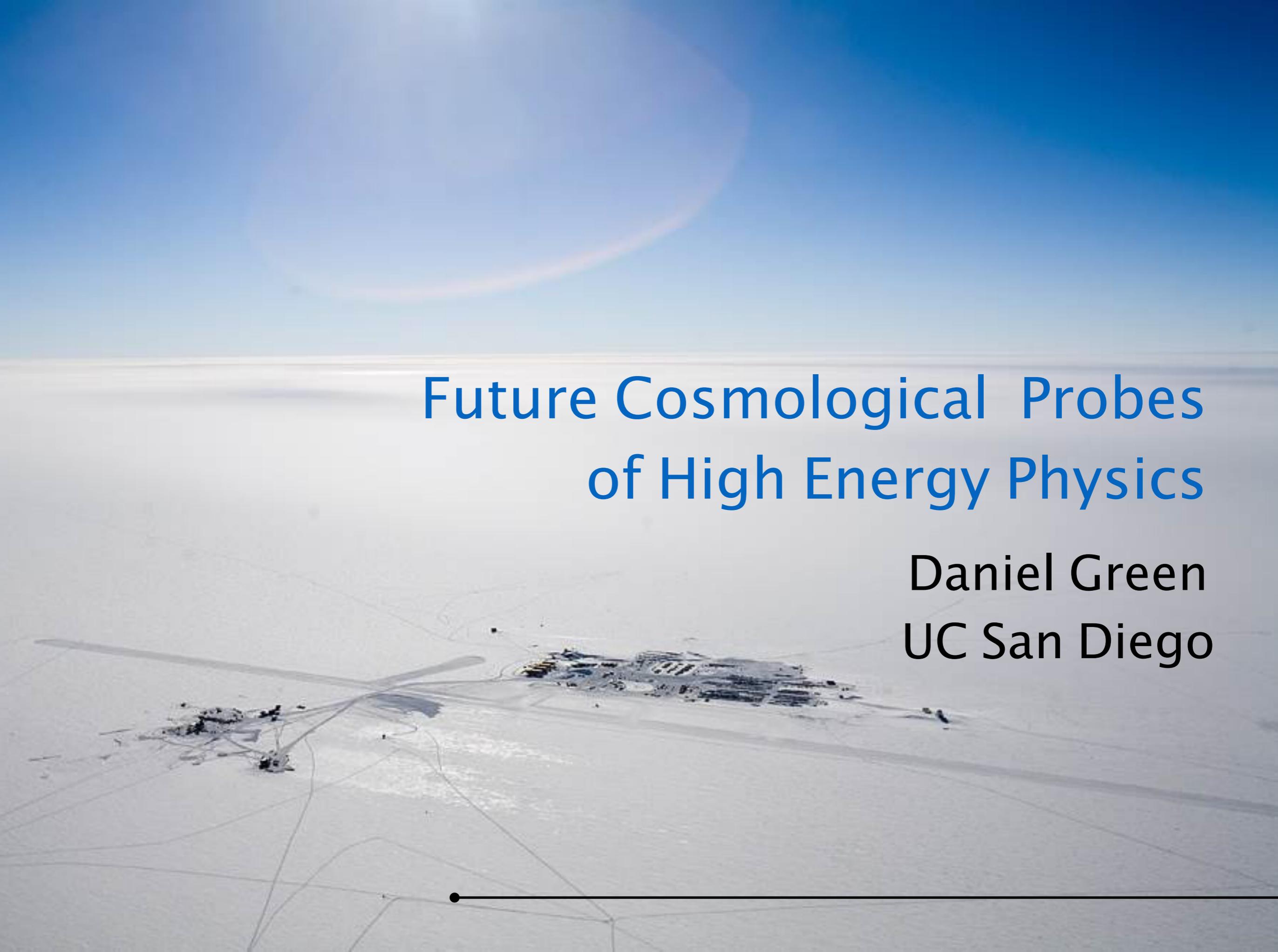
A landscape photograph of a lake reflecting brown hills under a clear blue sky. The lake is in the foreground, reflecting the brown hills and the clear blue sky. The hills are in the middle ground, and the sky is in the background. The overall scene is a serene, natural landscape.

# Future Cosmological Probes of High Energy Physics

Daniel Green  
UC San Diego



An aerial photograph of a vast, flat desert landscape under a clear blue sky. In the center of the image, there is a large, faint, circular structure that appears to be a large-scale scientific experiment or facility, possibly a particle detector or a large-scale astronomical observatory. The structure is composed of many small, interconnected components, forming a complex, circular pattern. The surrounding terrain is flat and sandy, with some sparse vegetation and small structures scattered across the landscape. The sky is a uniform light blue, and the overall scene is brightly lit, suggesting a clear day.

# Future Cosmological Probes of High Energy Physics

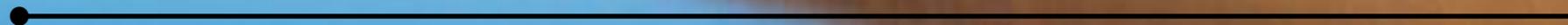
Daniel Green  
UC San Diego

# Outline

1. Future Surveys
2. Inflation and Gravitational Waves
3. Light Particles (old and new)
4. Neutrino Mass
5. Dark Matter



# Future Cosmic Surveys



# Cosmic Microwave Background (CMB)

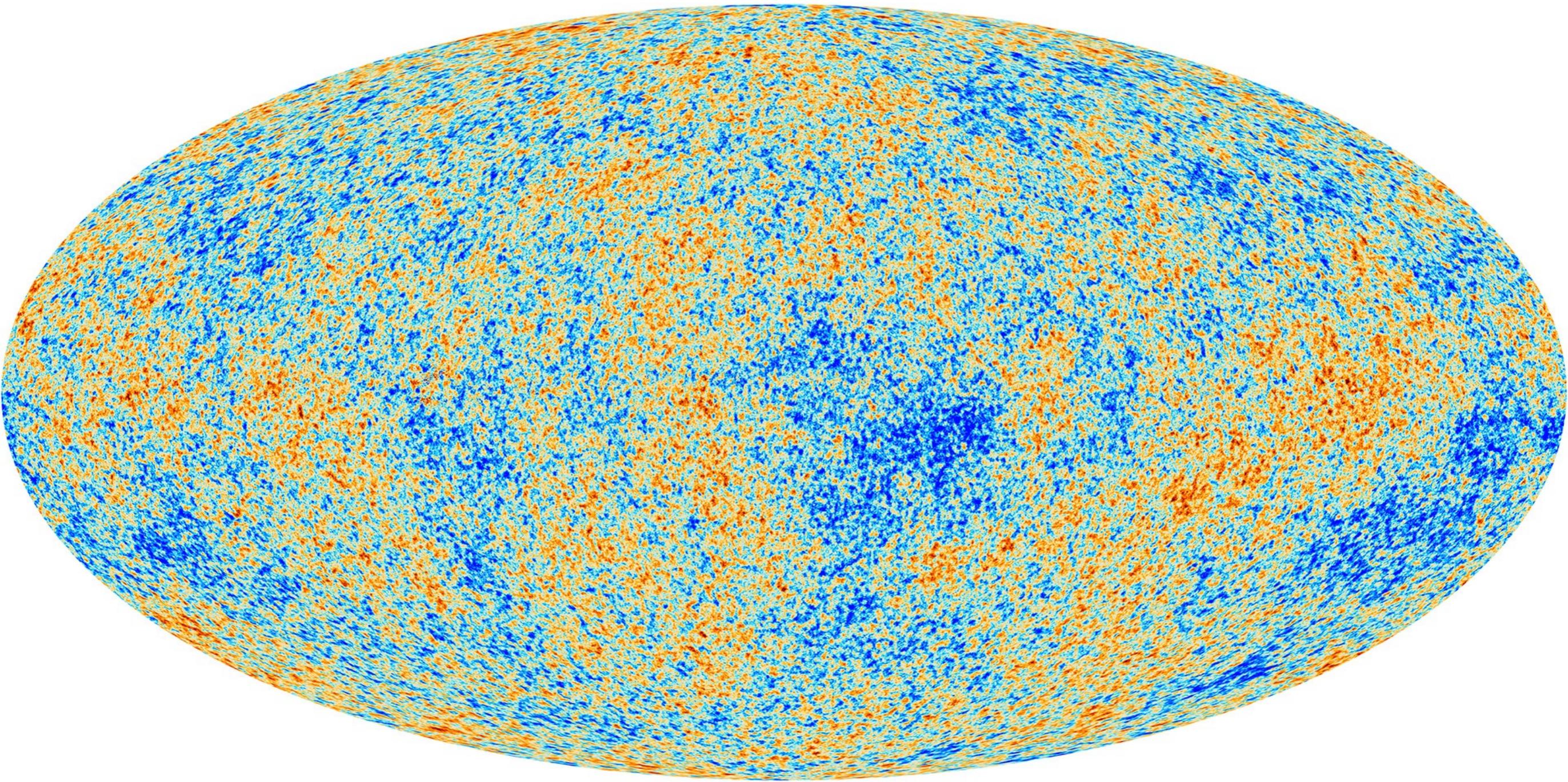


Image from Planck

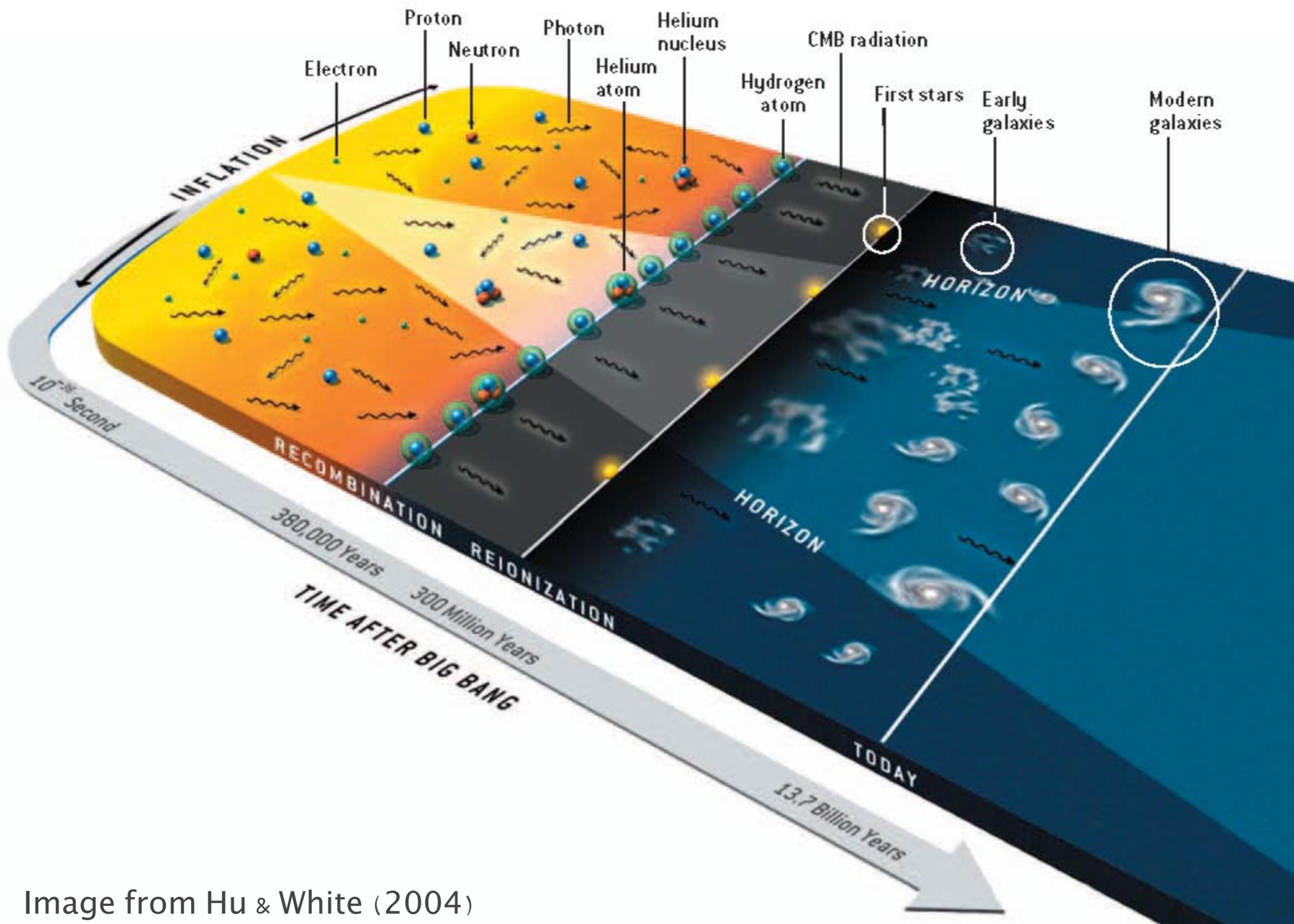


Image from Hu & White (2004)

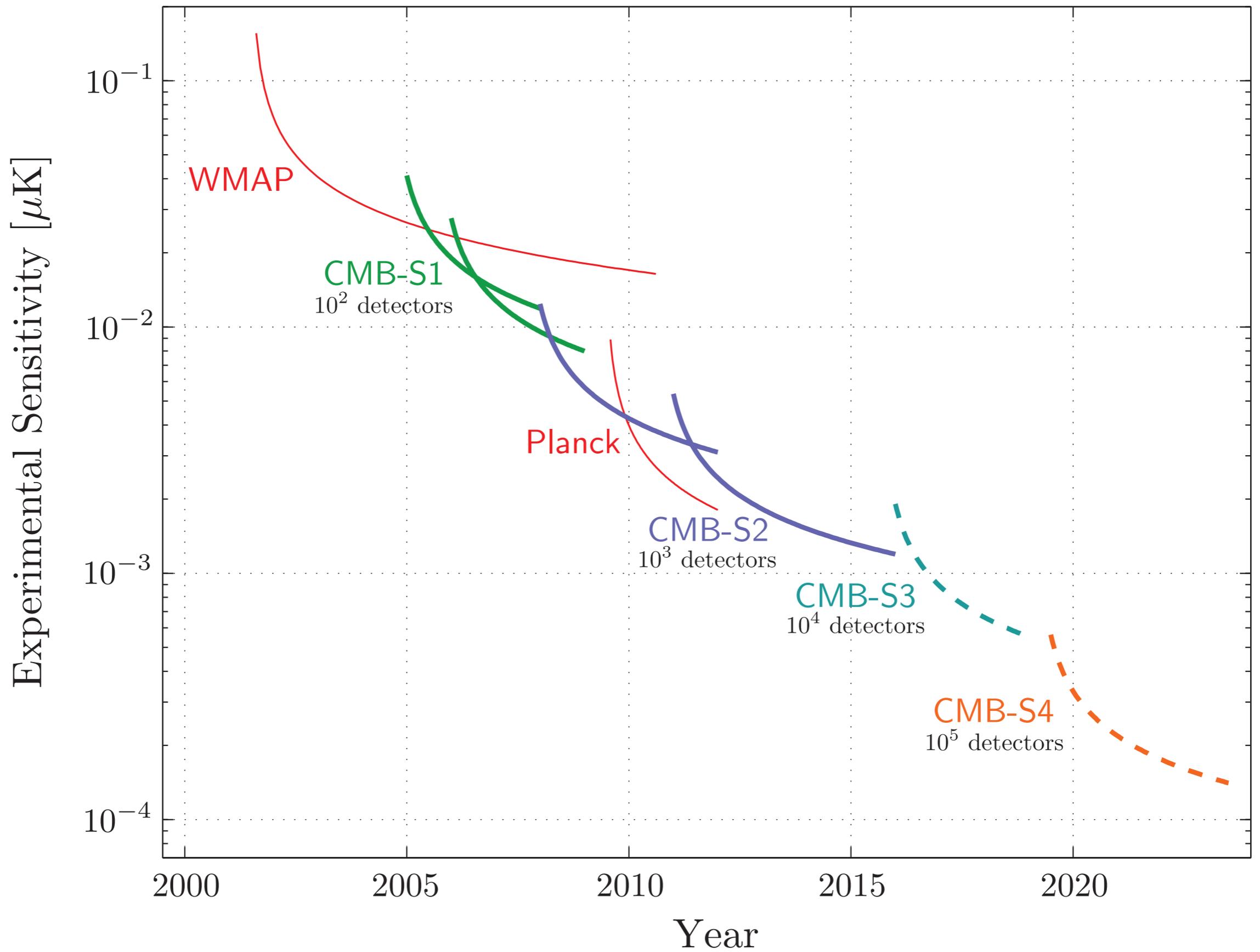
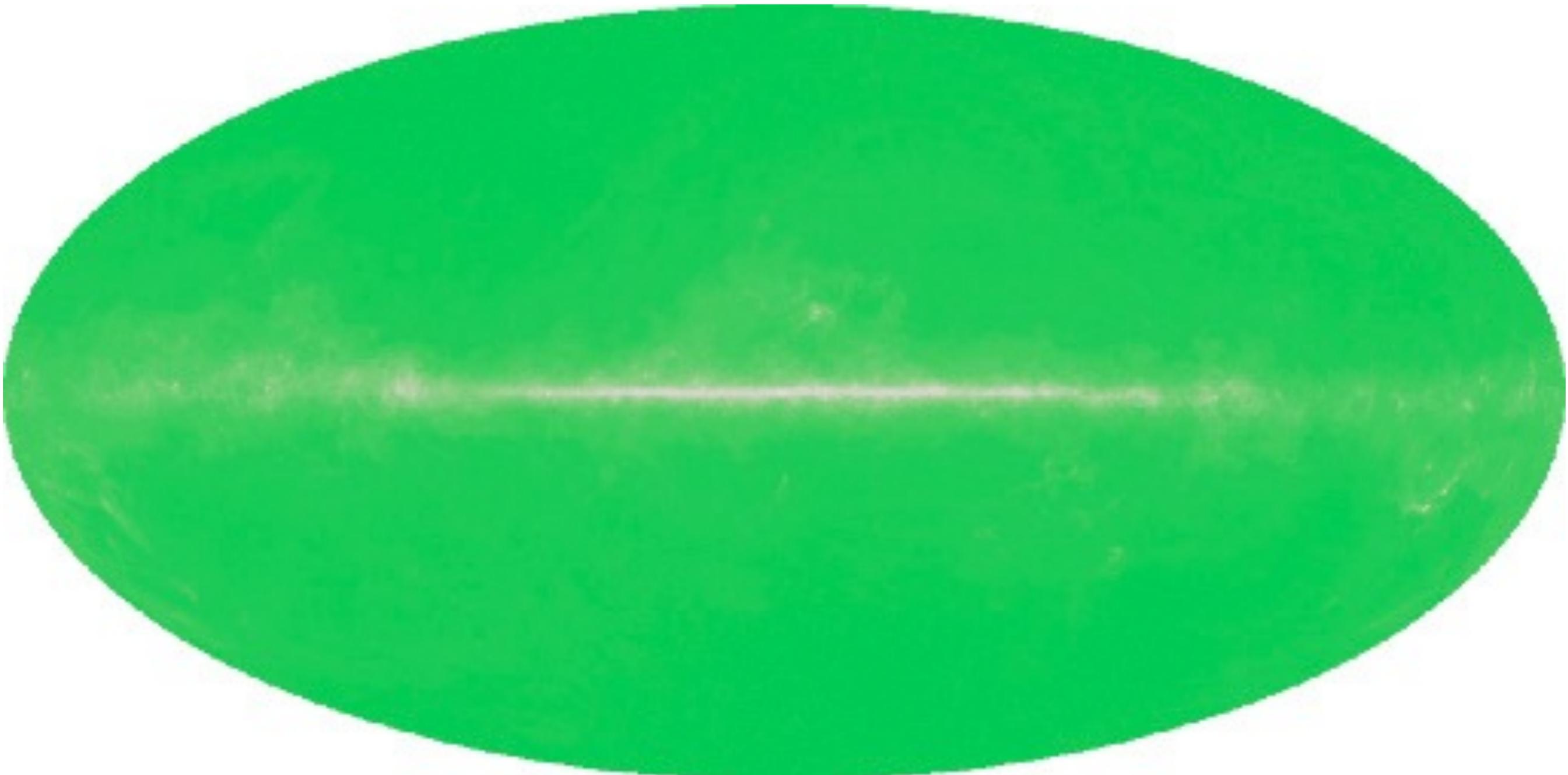
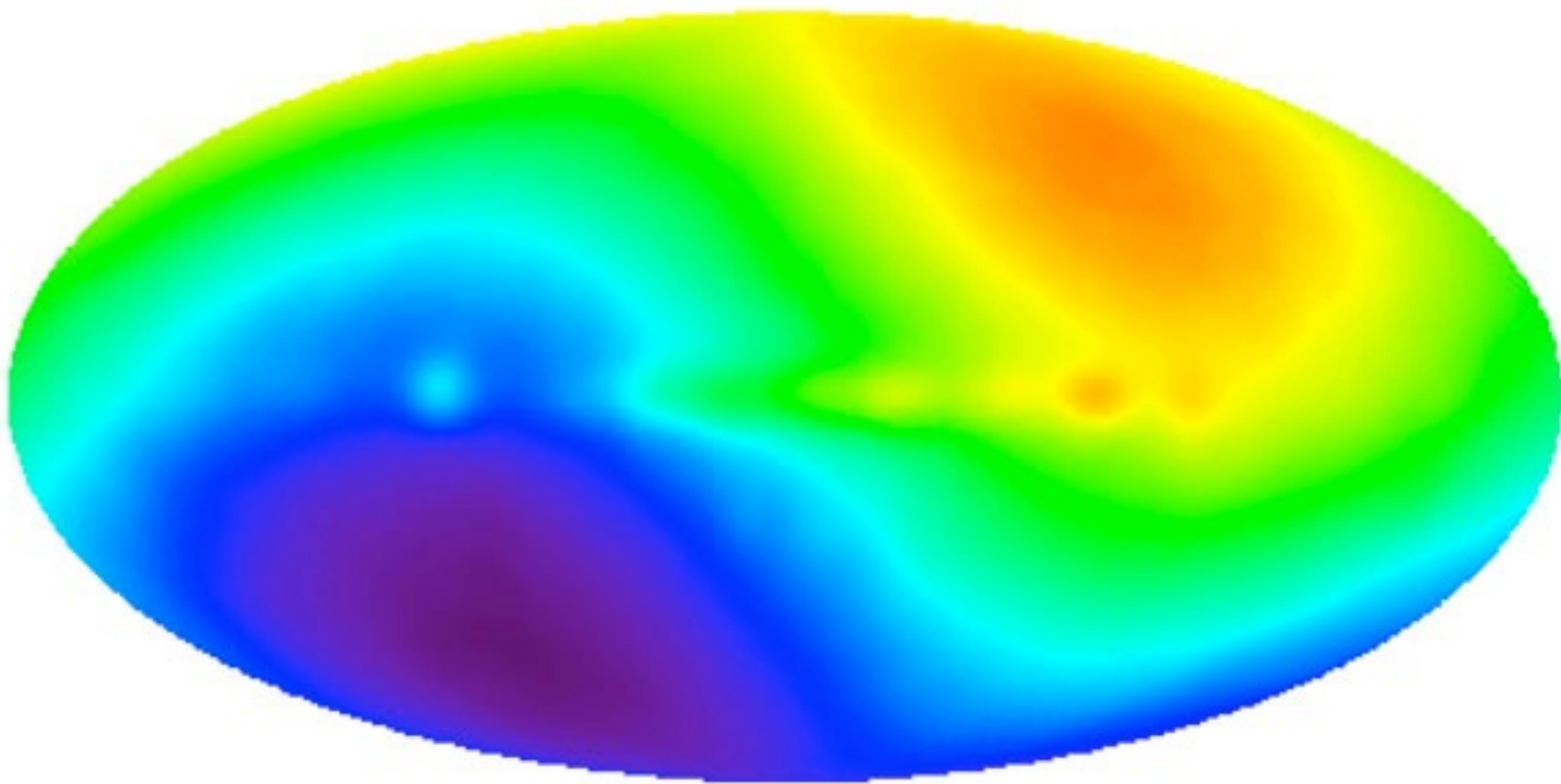


Image from Abazajian et al. (2013)



1965



1969

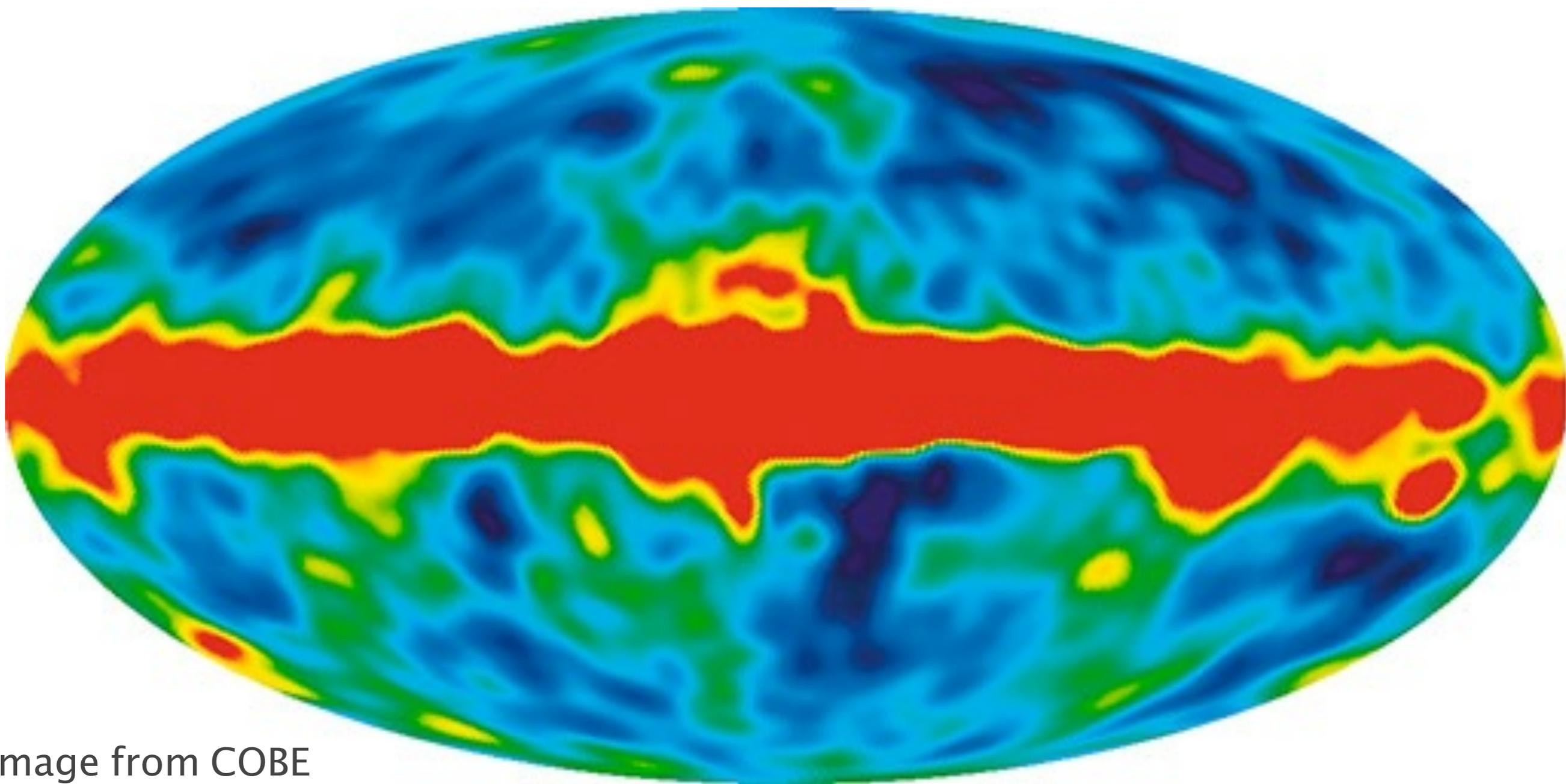


Image from COBE

1992

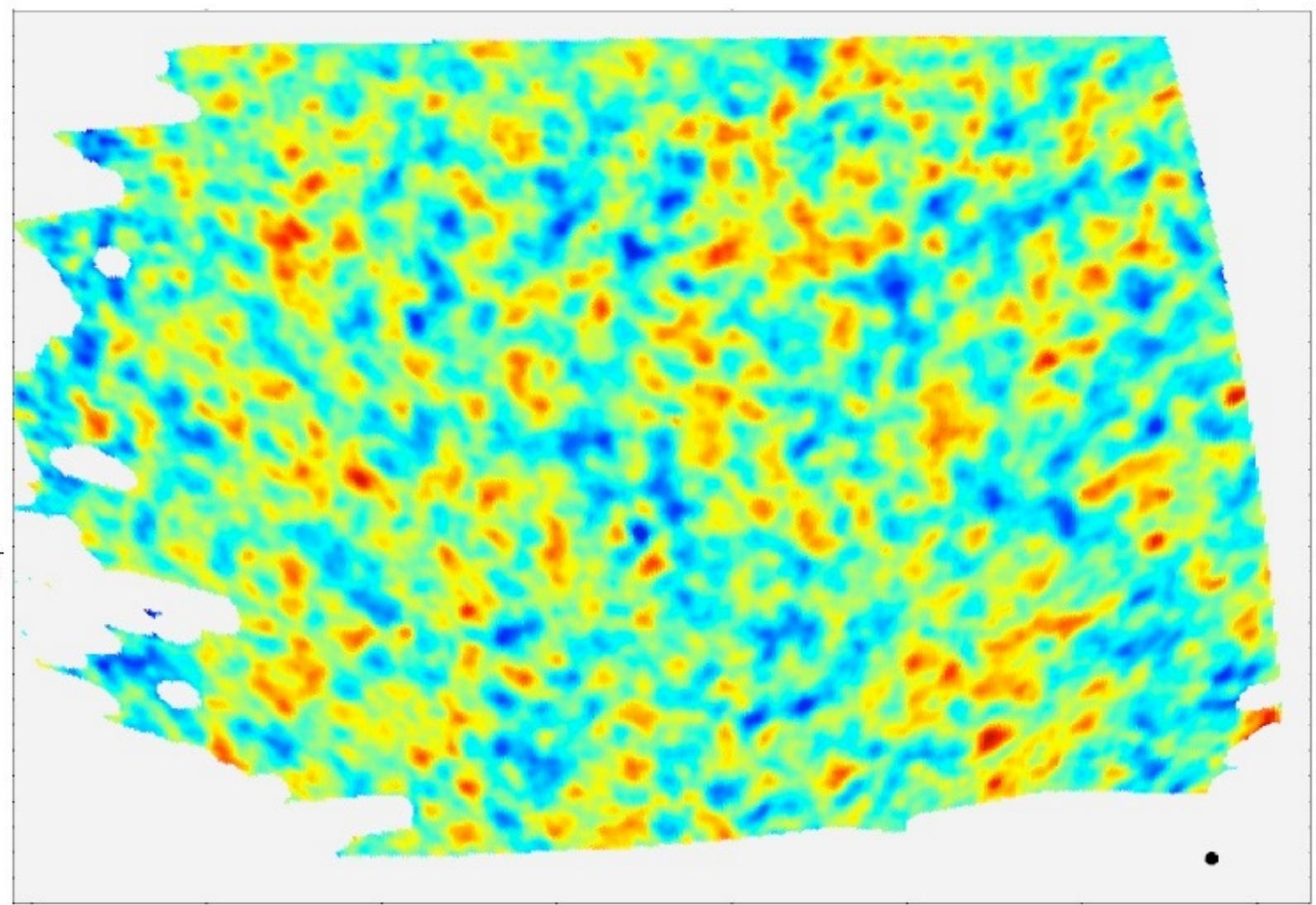
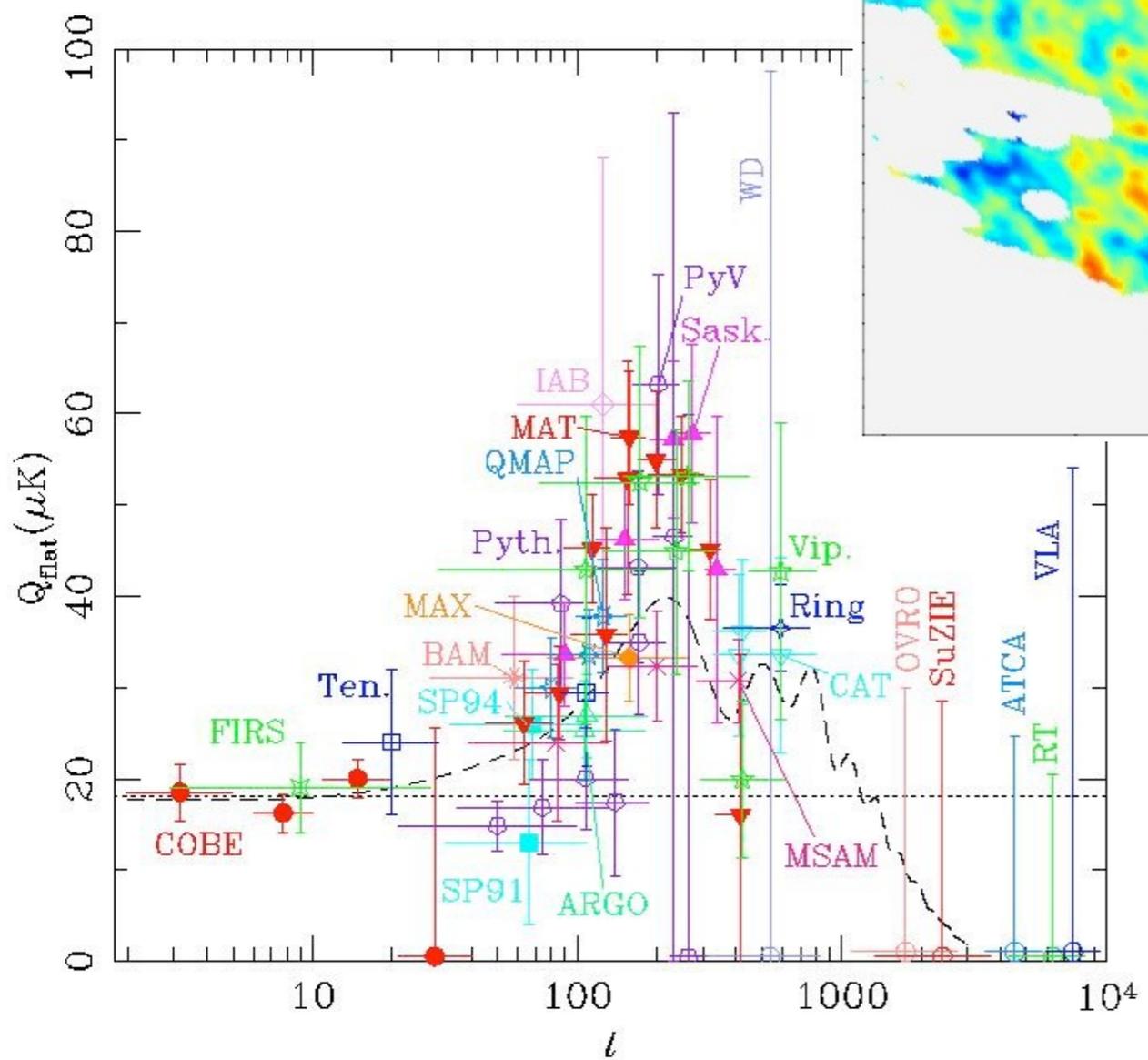


Image from Boomerang

1992-2001

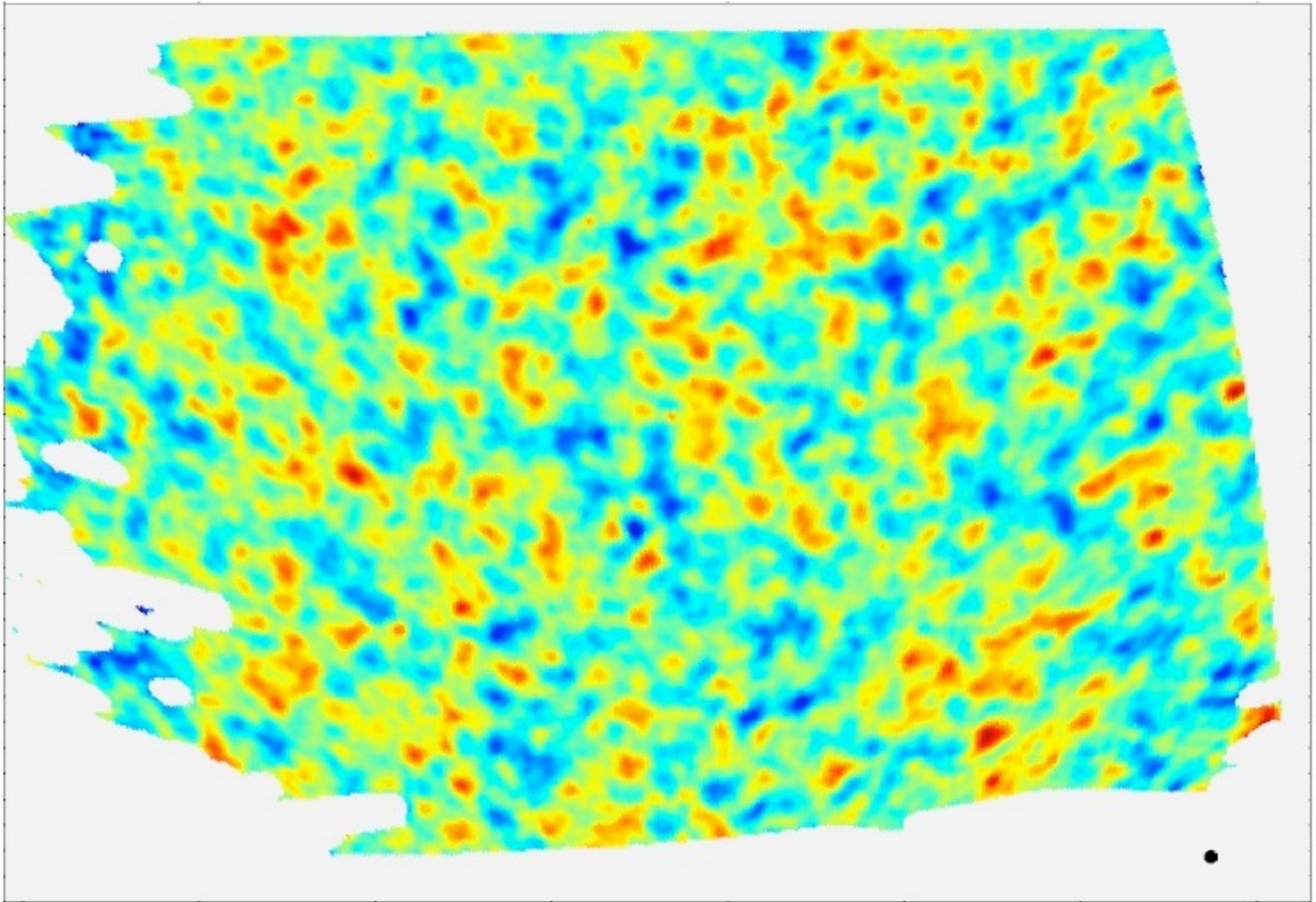
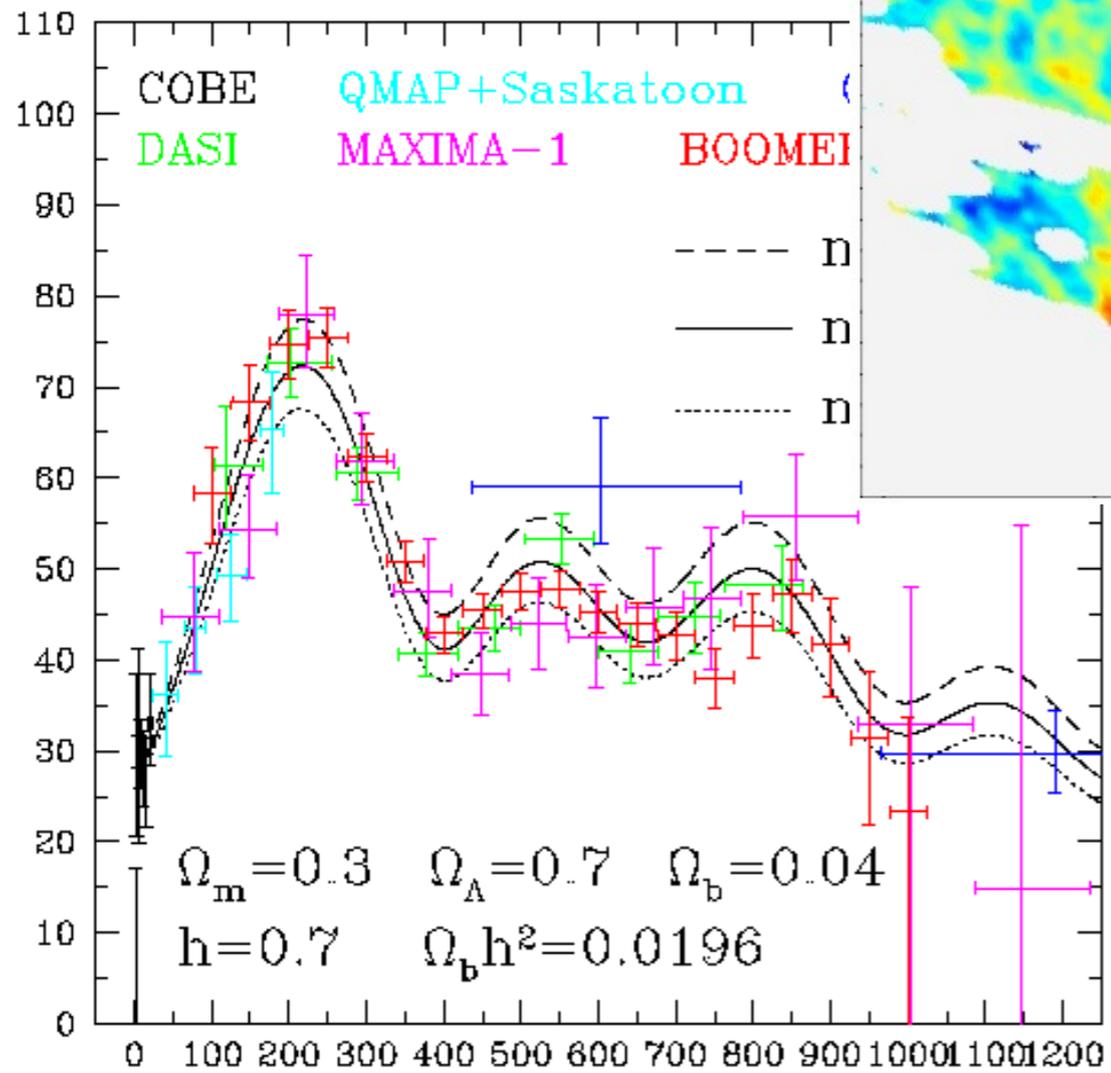


Image from Boomerang

1992-2001



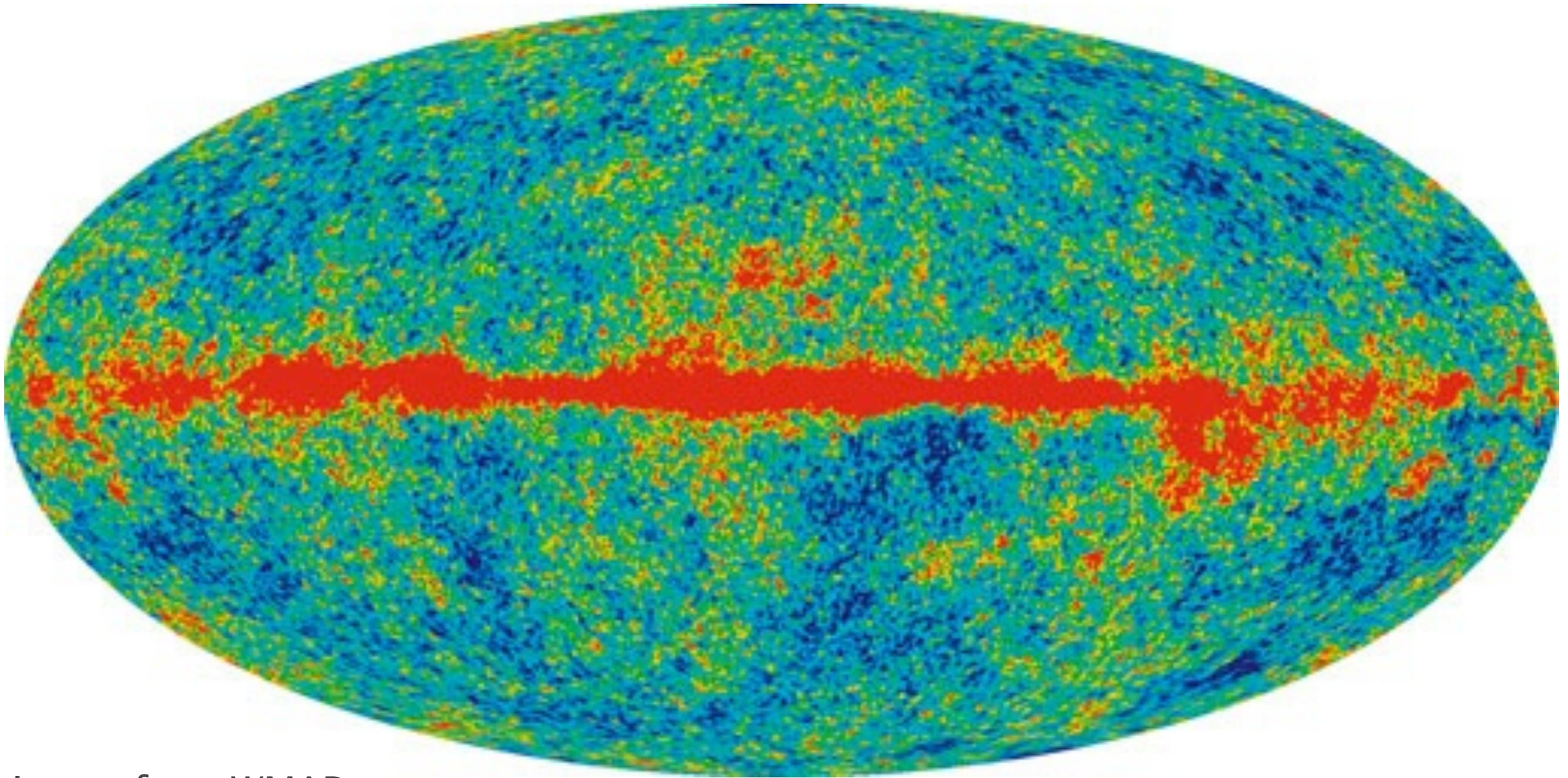


Image from WMAP

2003-2012

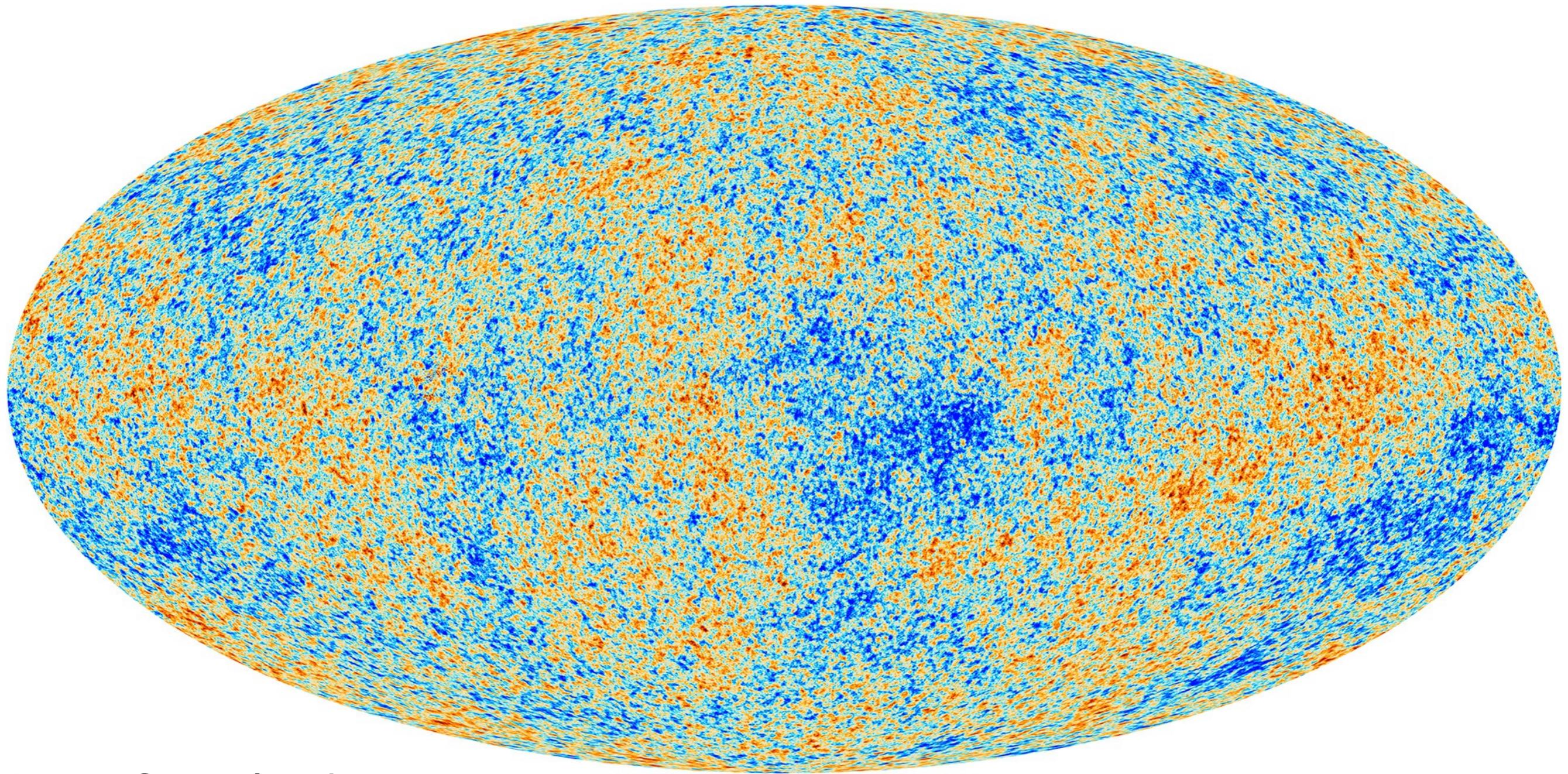


Image from Planck

2013-2018

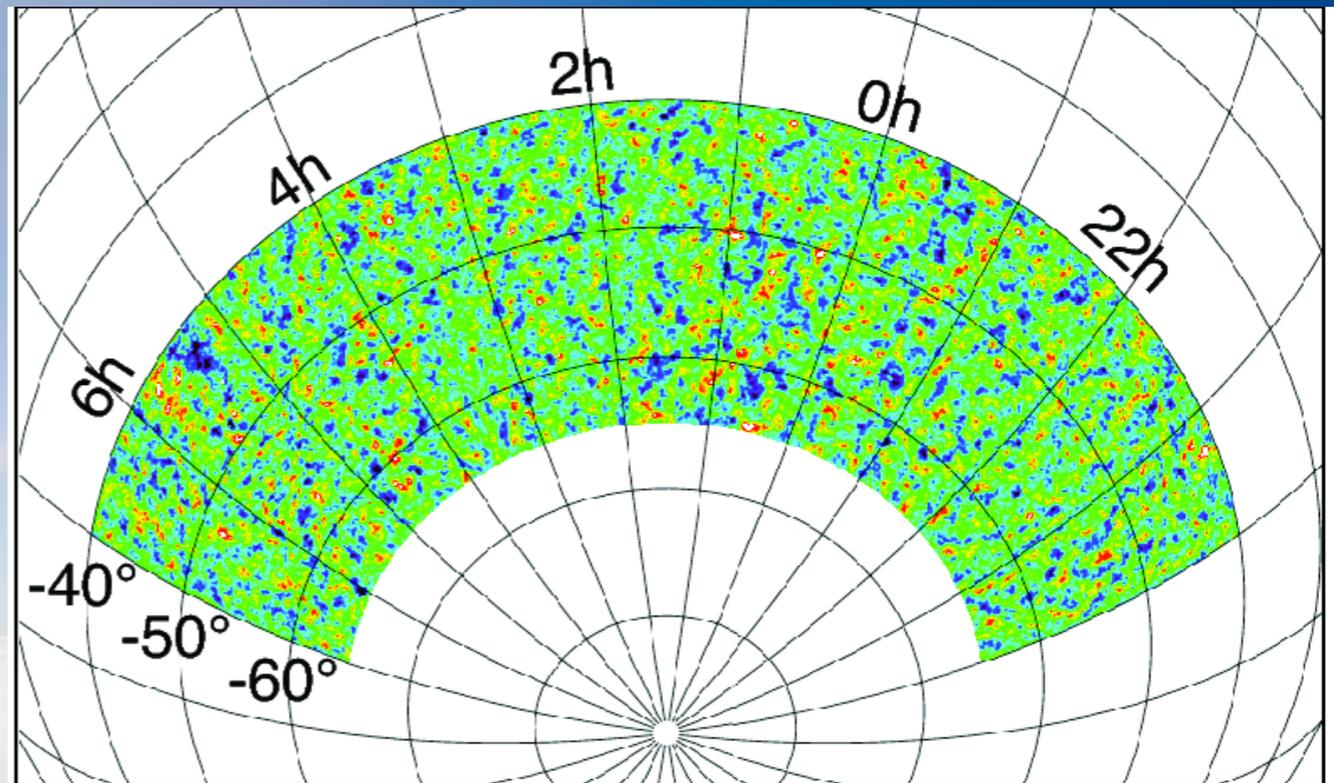
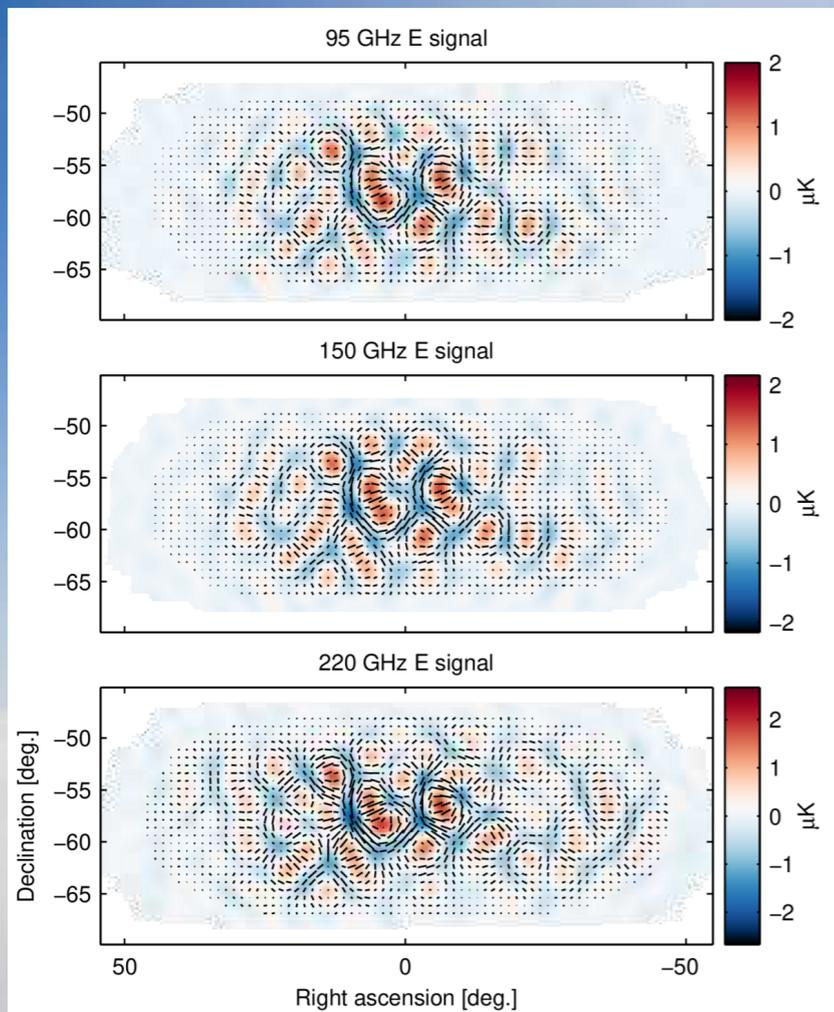


Image from SPT

Image from BICEP/Keck



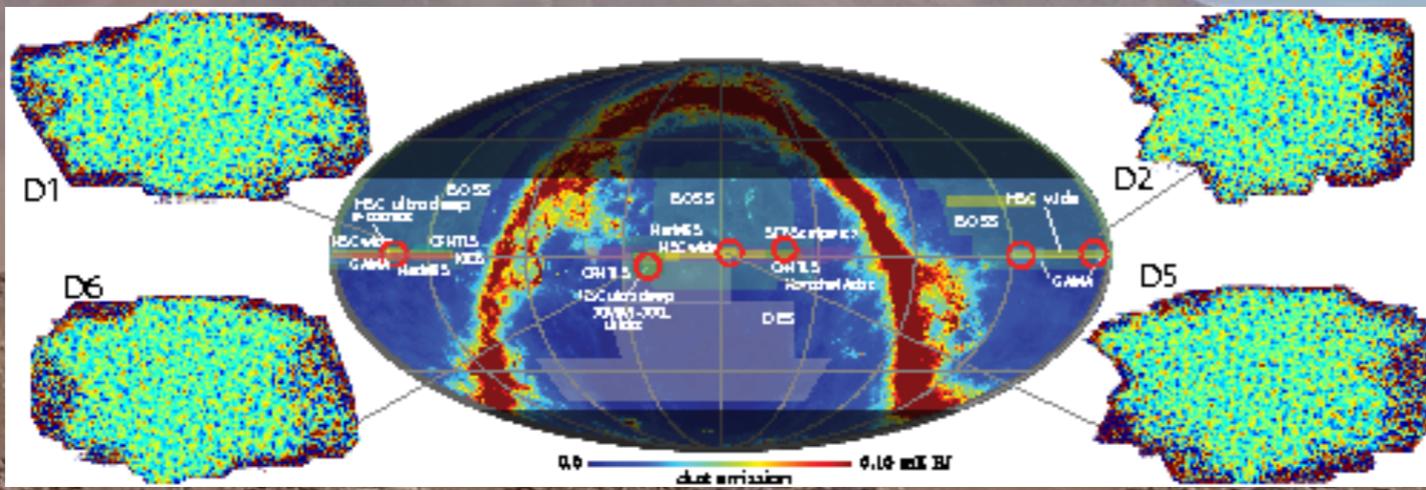
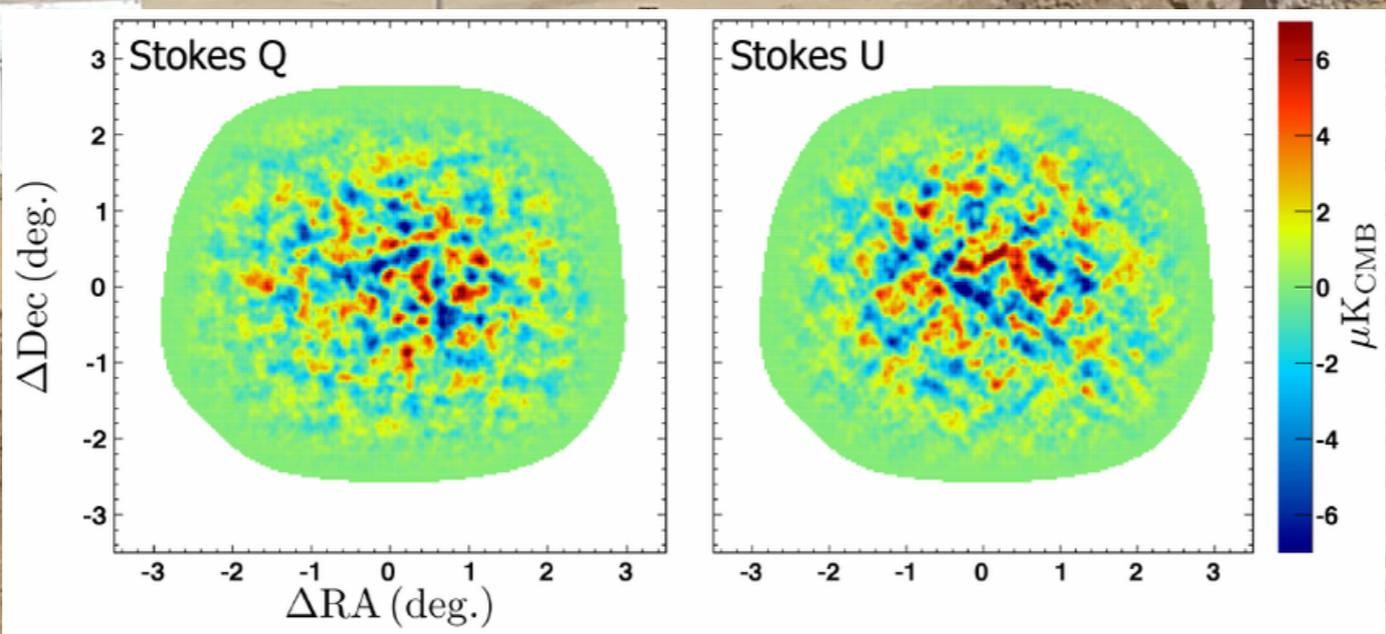


Image from ACTPol



Image from POLARBEAR



Present

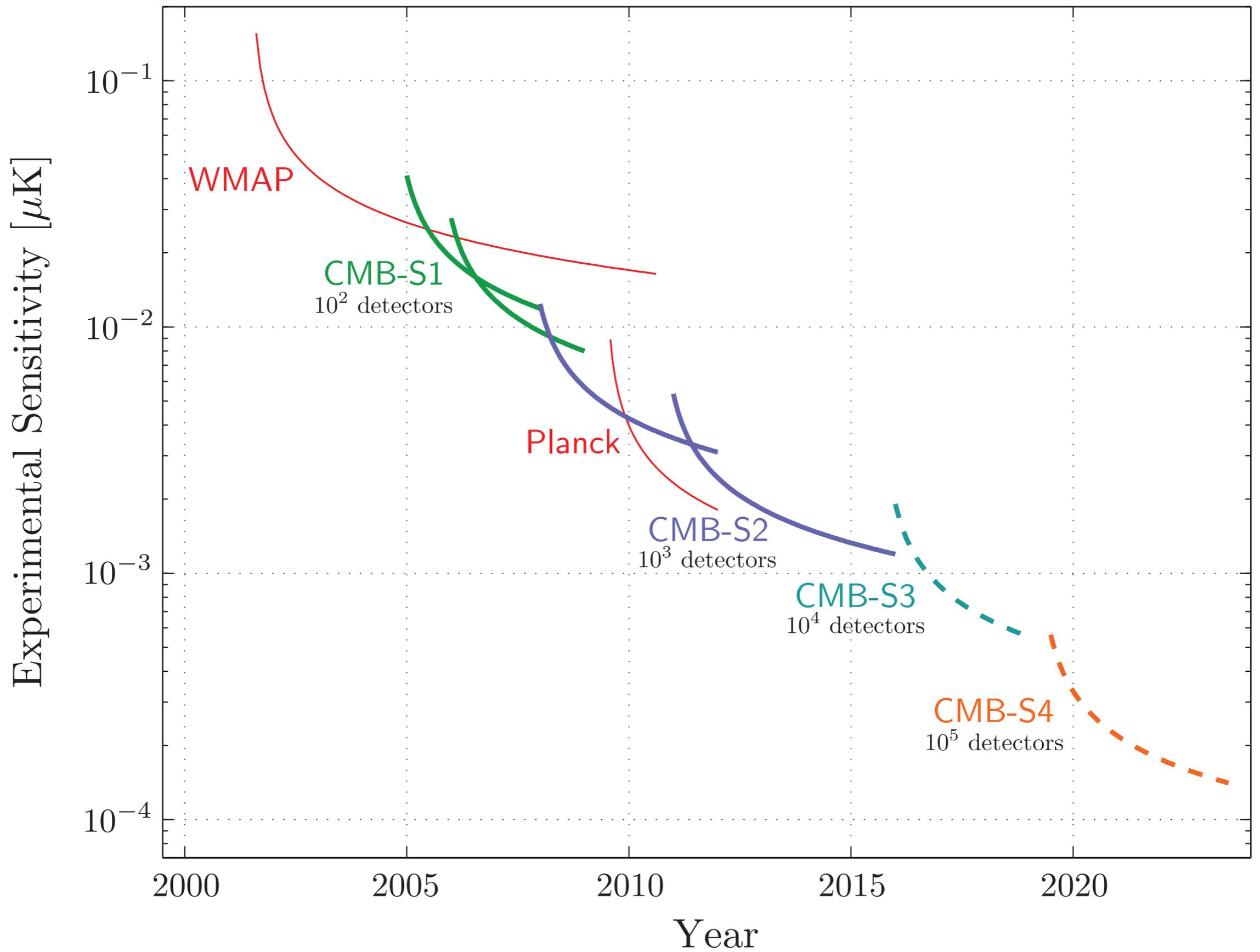
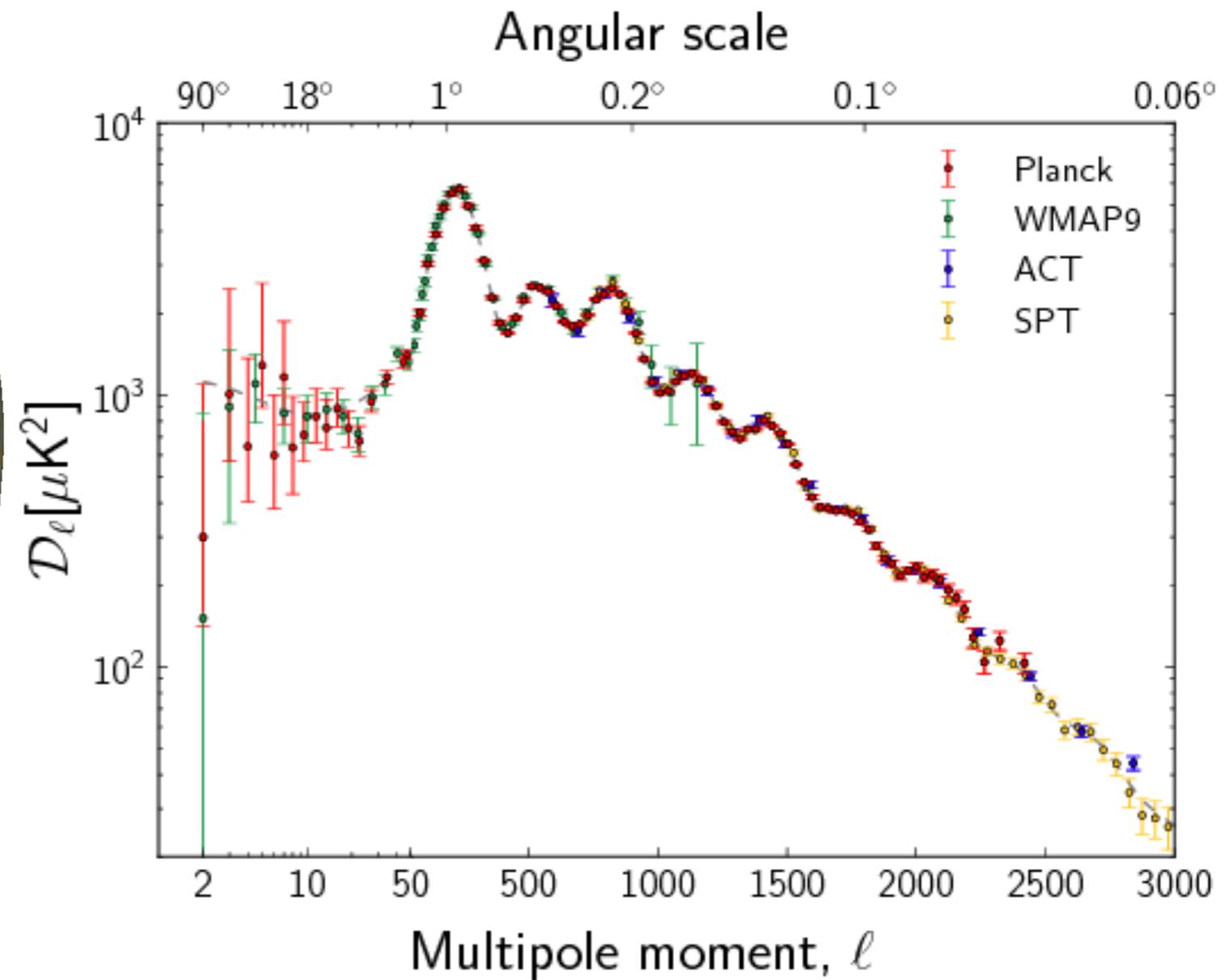
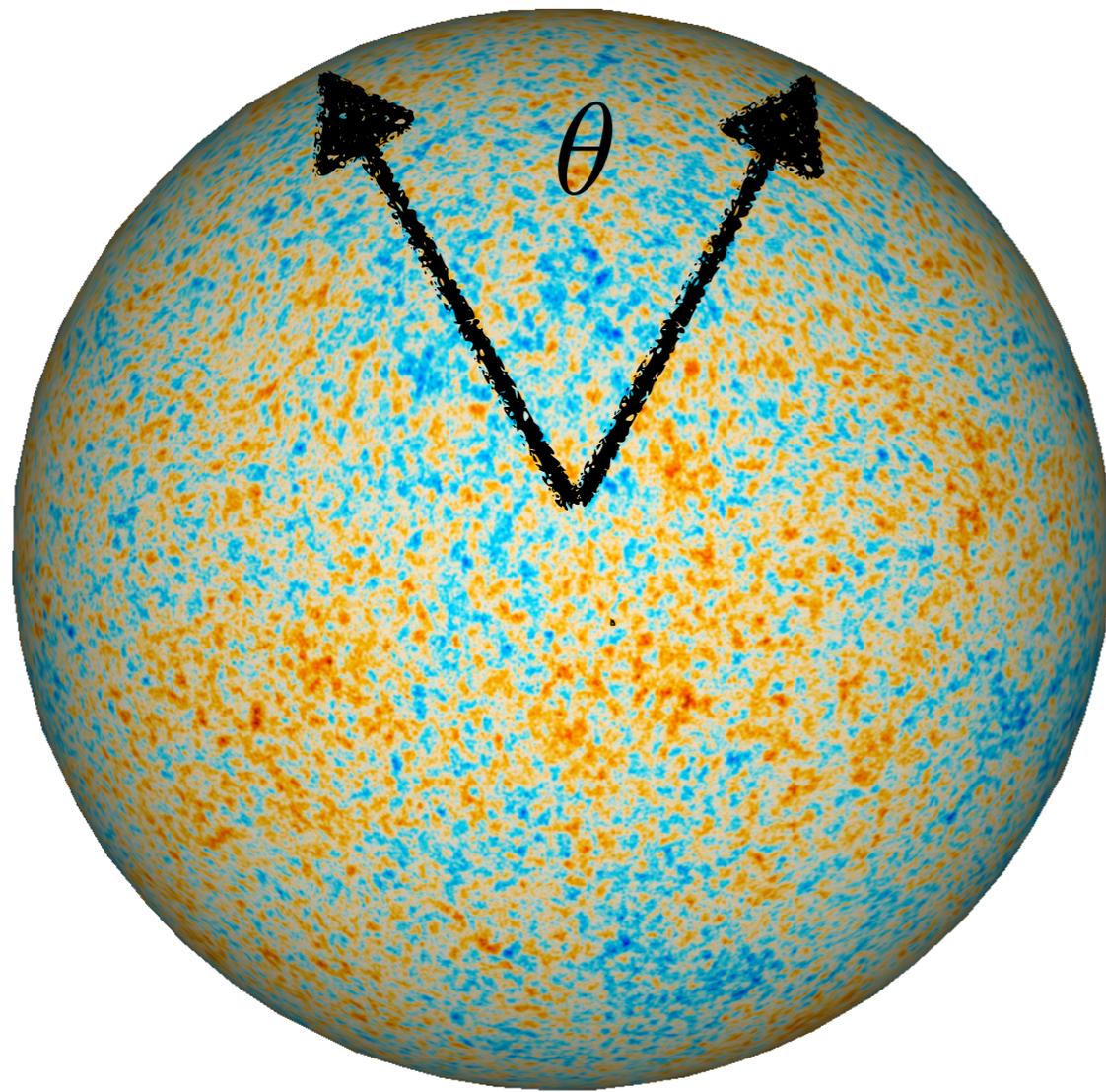
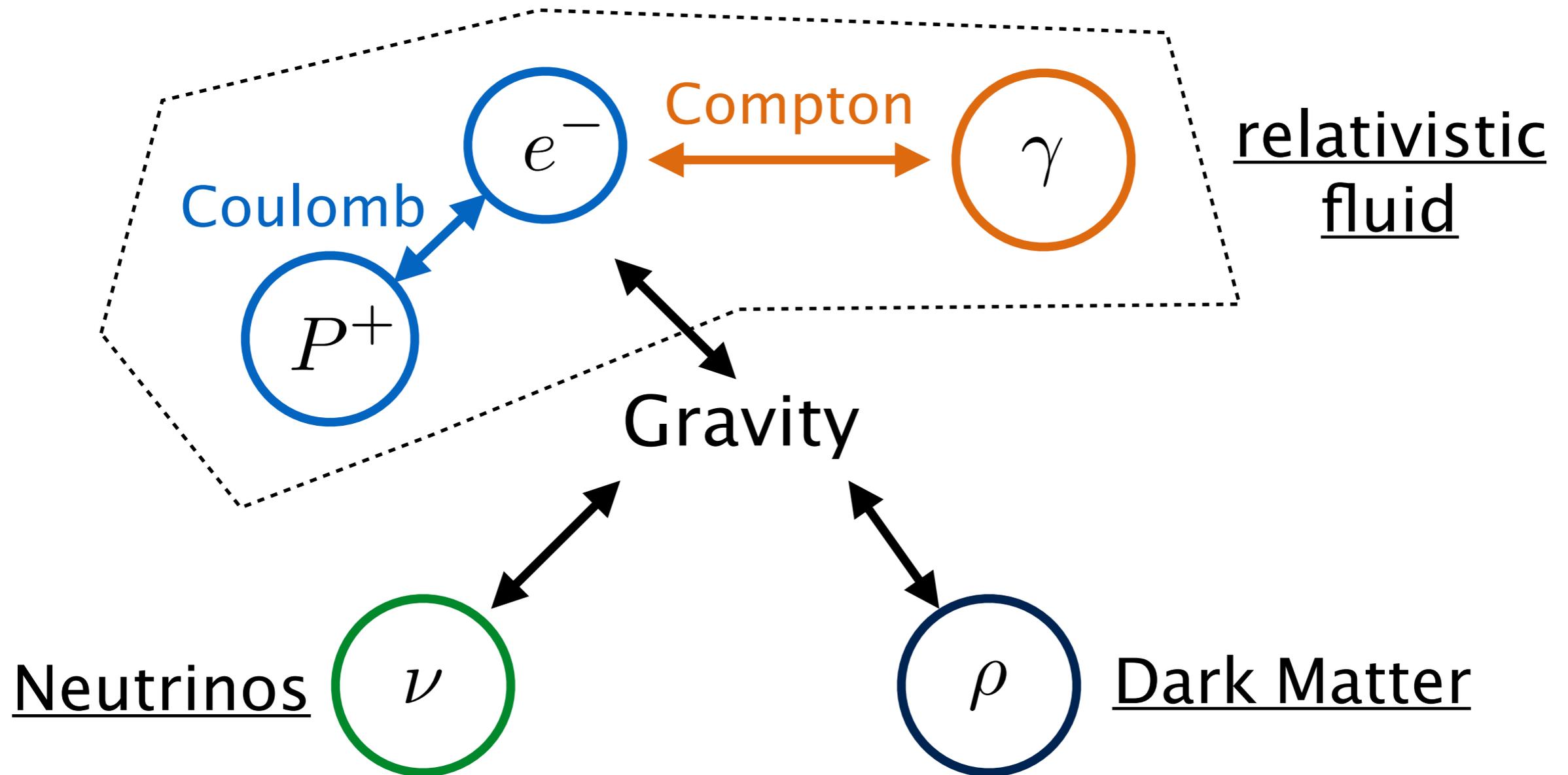


Image from Abazajian et al. (2013)

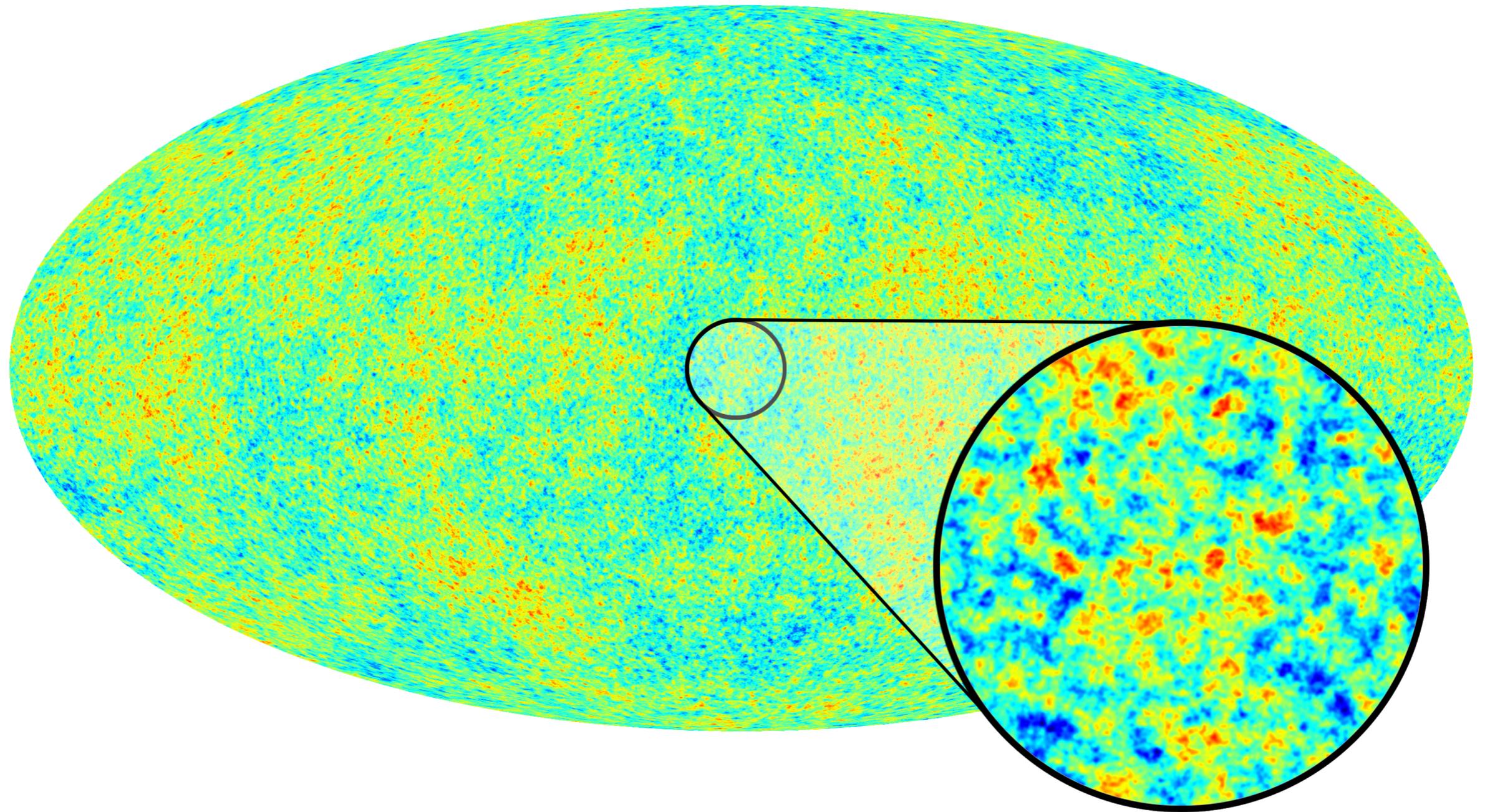
# Cosmic Microwave Background (CMB)

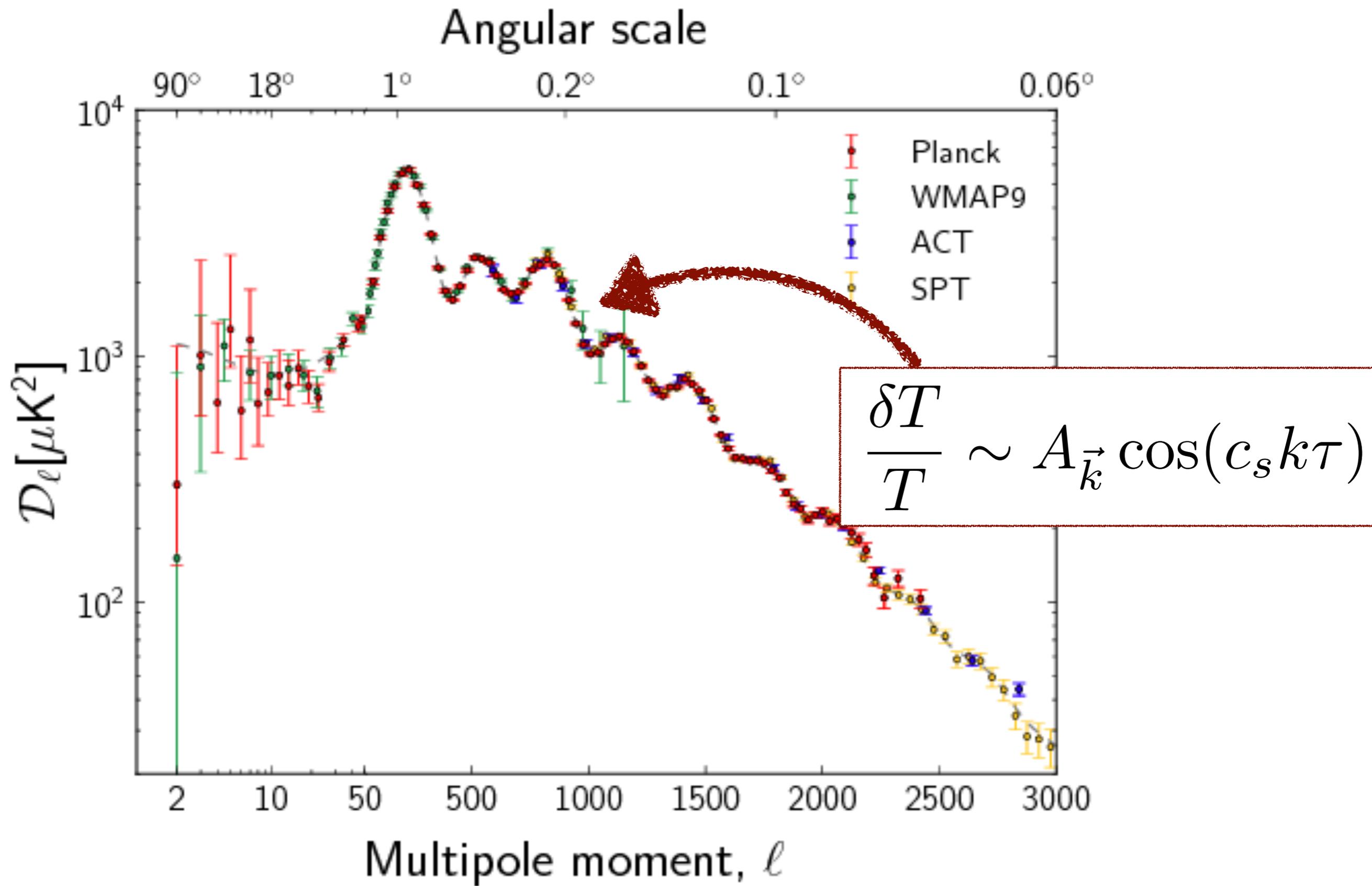


# Cosmic Sound



# Cosmic Sound





# Cosmic Sound

$$\ddot{d}_\gamma - c_s^2 \nabla^2 d_\gamma \approx \nabla^2 \Phi$$

$$d_\gamma \approx A_{\vec{k}} \cos c_s k \tau + \cancel{B_{\vec{k}} \sin c_s k \tau}$$

# Cosmic Sound

Explained if fluctuations were created much earlier

If wavelengths are bigger than curvature radius

$$d_\gamma \approx a_{\vec{k}} + b_{\vec{k}} a^{-3}$$

$$B_{\vec{k}} \sim b_{\vec{k}} a^{-3} \rightarrow 0$$

Inflation needed to make this picture causal & local

# The CMB and Inflation

Curvature scale =  $H^{-1}$

$$H^2 \propto \rho_{m,0} a^{-3} + \rho_{r,0} a^{-4} \rightarrow H \propto a^{-3/2, -2}$$

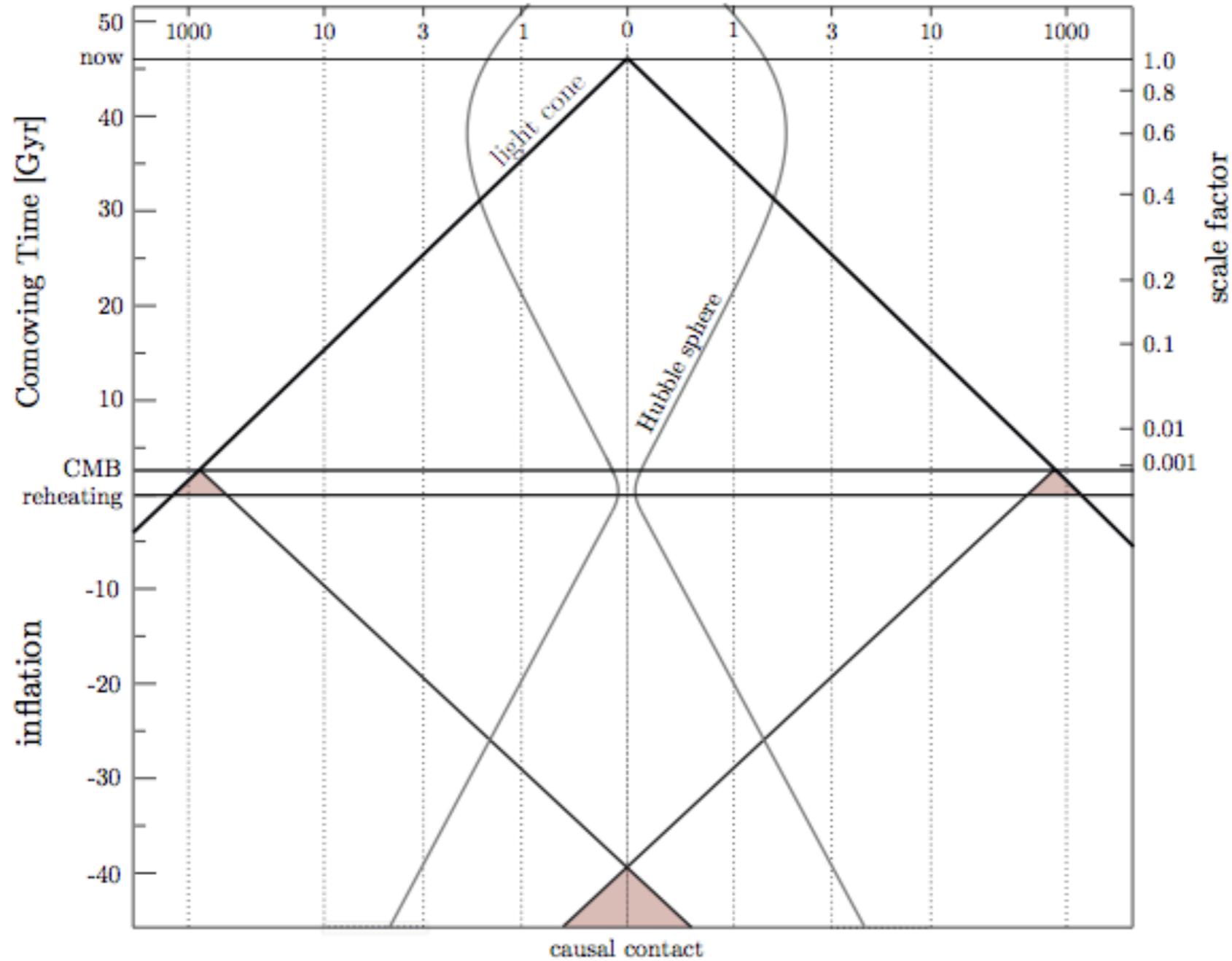
Physical wavelengths:  $\lambda_p^{-1} = k_p = \frac{k}{a}$

Curvature radius increase faster than wavelength

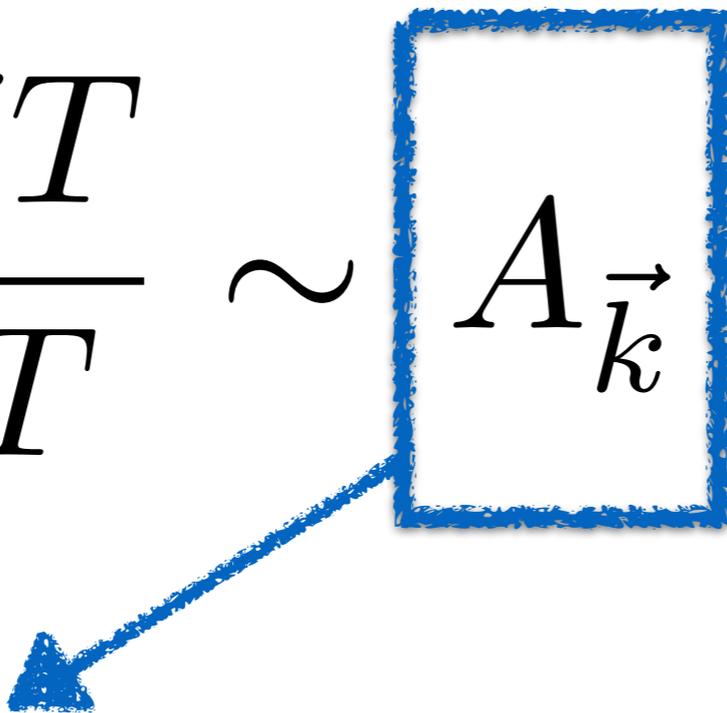
Not true in a universe dominated by vacuum energy

$$H^2 \propto \rho_\Lambda \approx \text{constant}$$

# The CMB and Inflation



Courtesy of Daniel Baumann

$$\frac{\delta T}{T} \sim \boxed{A_{\vec{k}}} \cos(c_s k \tau)$$


“Inflation” : source of initial conditions

$$\langle A_{\vec{k}} A_{\vec{k}'} \rangle = \frac{\Delta^2}{k^{4-n_s}} (2\pi)^3 \delta(\vec{k} + \vec{k}')$$

$$\langle A_{\vec{k}_1} A_{\vec{k}_2} \cdots \rangle = ?$$

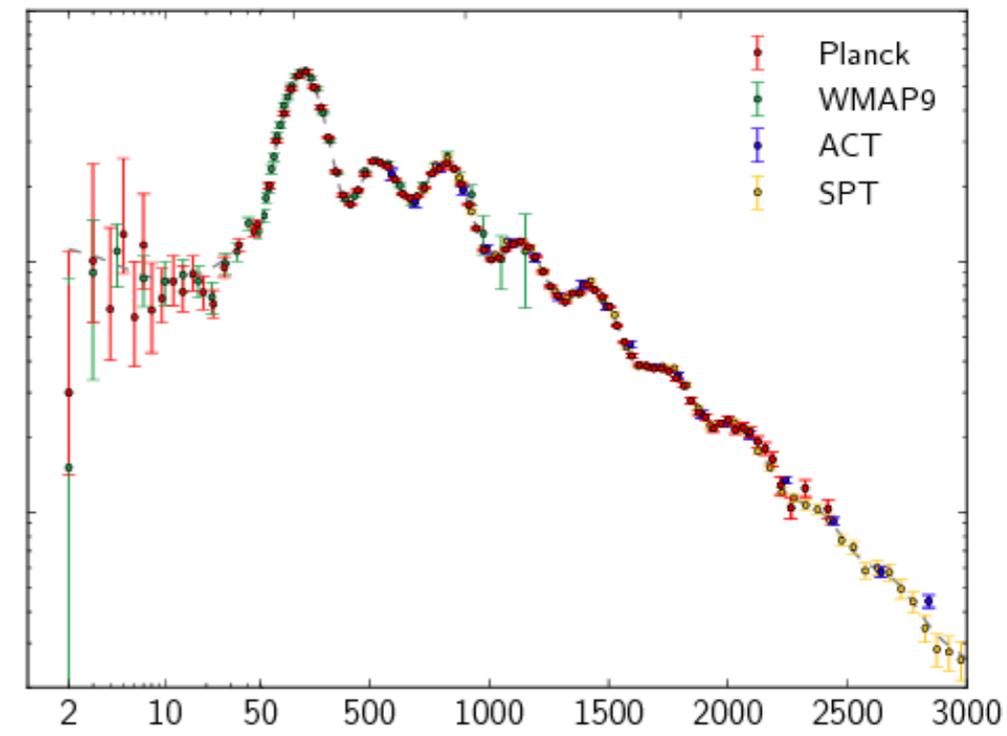
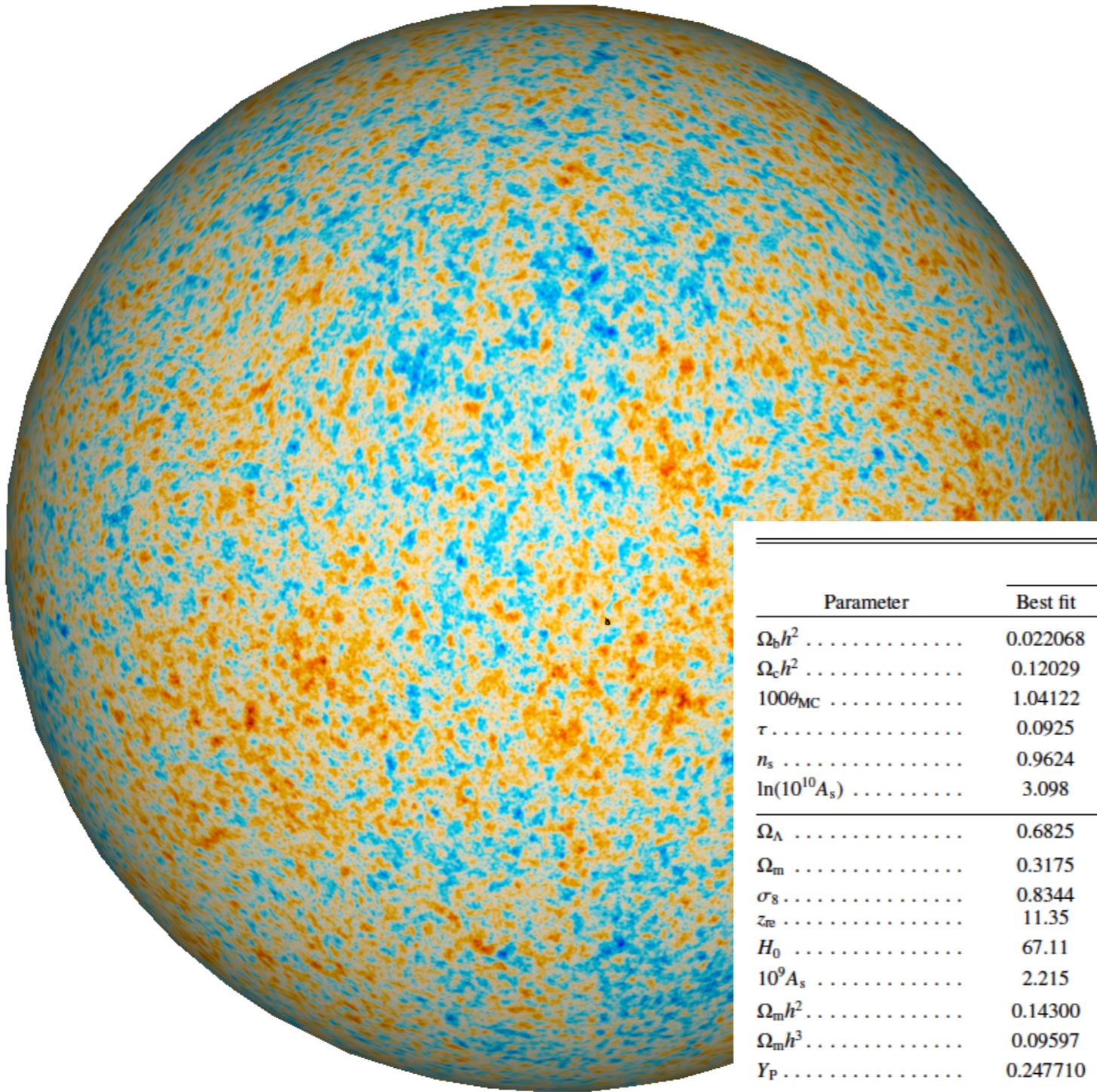
+ Additional Contribution from Gravitational Waves

$$\frac{\delta T}{T} \sim A_{\vec{k}} \cos(c_s k \tau)$$

Recombination:

$$c_s \sim \frac{1}{\sqrt{3(1 + R_b)}}$$

+ diffusion, gravitational forces / redshift, etc.



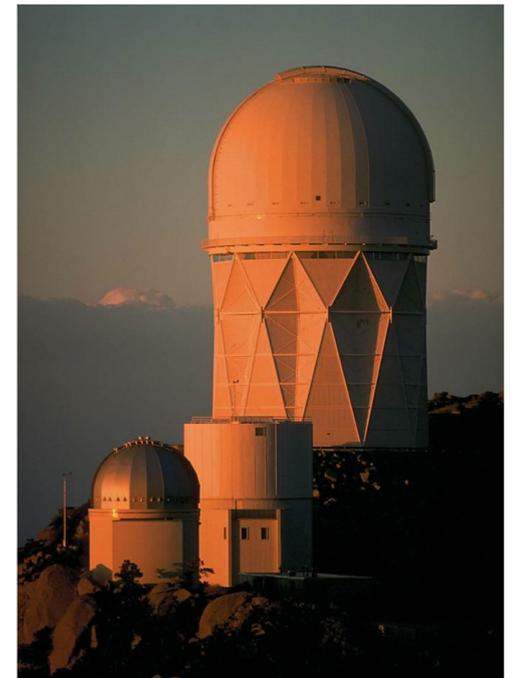
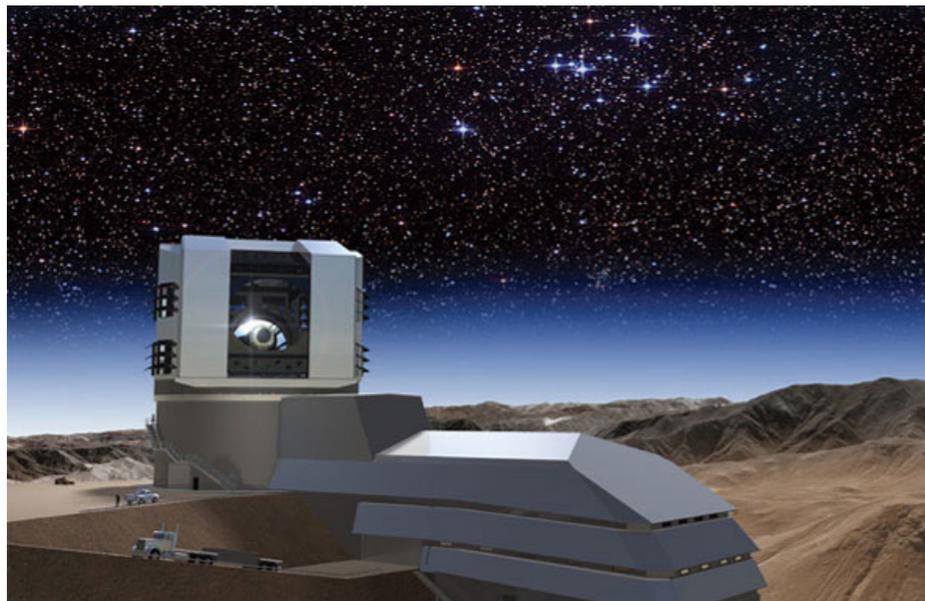
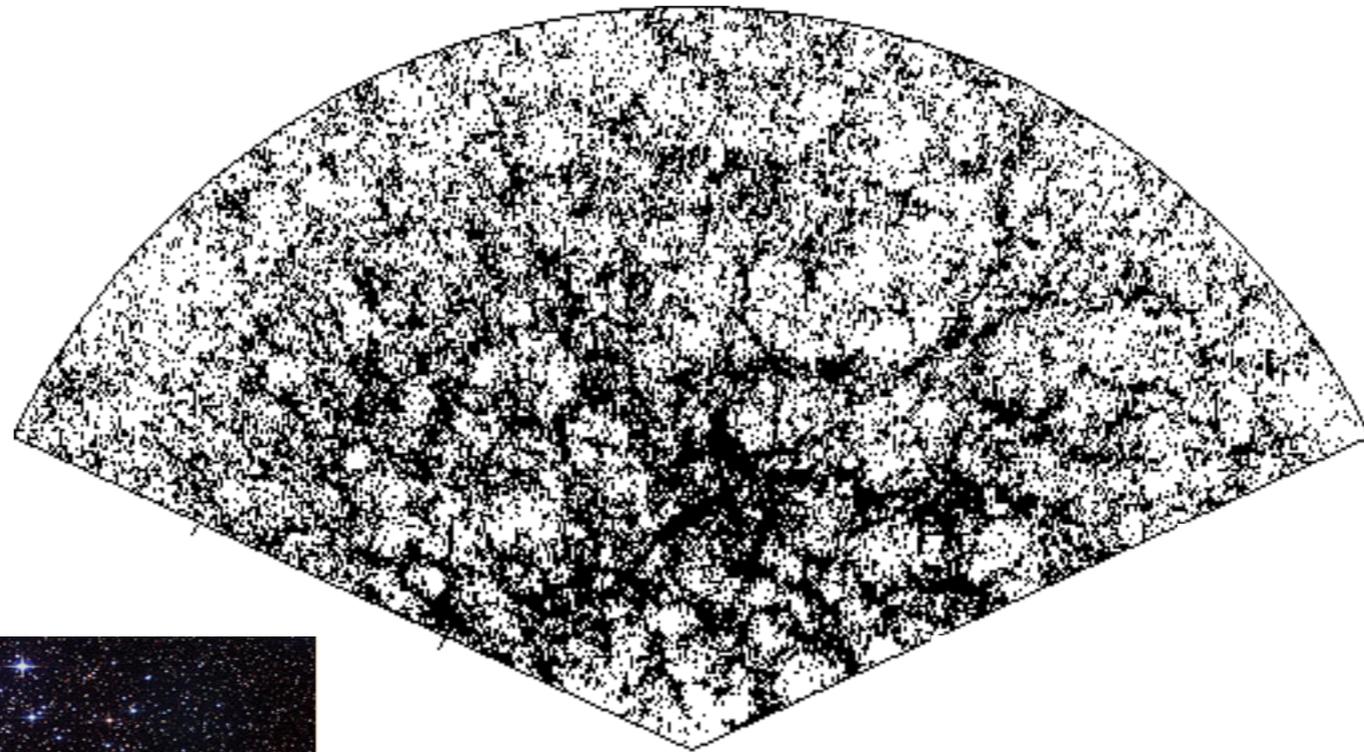
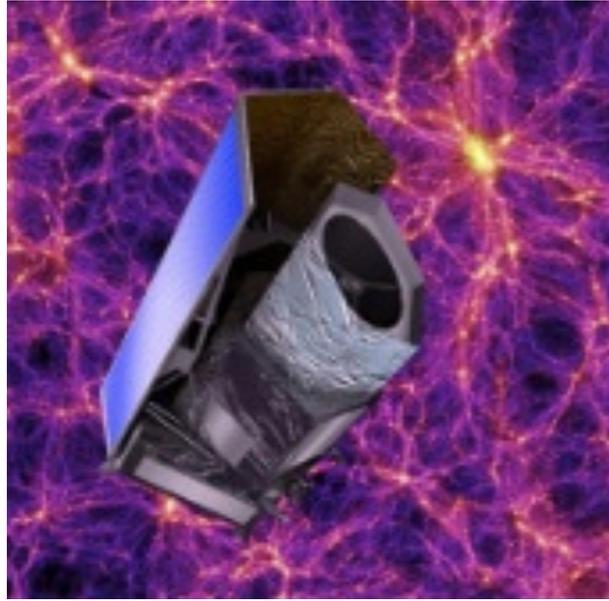
Parameter	Planck		Planck+lensing		Planck+WP	
	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	$0.02207 \pm 0.00033$	0.022242	$0.02217 \pm 0.00033$	0.022032	$0.02205 \pm 0.00028$
$\Omega_c h^2$	0.12029	$0.1196 \pm 0.0031$	0.11805	$0.1186 \pm 0.0031$	0.12038	$0.1199 \pm 0.0027$
$100\theta_{MC}$	1.04122	$1.04132 \pm 0.00068$	1.04150	$1.04141 \pm 0.00067$	1.04119	$1.04131 \pm 0.00063$
$\tau$	0.0925	$0.097 \pm 0.038$	0.0949	$0.089 \pm 0.032$	0.0925	$0.089^{+0.012}_{-0.014}$
$n_s$	0.9624	$0.9616 \pm 0.0094$	0.9675	$0.9635 \pm 0.0094$	0.9619	$0.9603 \pm 0.0073$
$\ln(10^{10} A_s)$	3.098	$3.103 \pm 0.072$	3.098	$3.085 \pm 0.057$	3.0980	$3.089^{+0.024}_{-0.027}$
$\Omega_\Lambda$	0.6825	$0.686 \pm 0.020$	0.6964	$0.693 \pm 0.019$	0.6817	$0.685^{+0.018}_{-0.016}$
$\Omega_m$	0.3175	$0.314 \pm 0.020$	0.3036	$0.307 \pm 0.019$	0.3183	$0.315^{+0.016}_{-0.018}$
$\sigma_8$	0.8344	$0.834 \pm 0.027$	0.8285	$0.823 \pm 0.018$	0.8347	$0.829 \pm 0.012$
$z_{re}$	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	$11.1 \pm 1.1$
$H_0$	67.11	$67.4 \pm 1.4$	68.14	$67.9 \pm 1.5$	67.04	$67.3 \pm 1.2$
$10^9 A_s$	2.215	$2.23 \pm 0.16$	2.215	$2.19^{+0.12}_{-0.14}$	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	$0.1423 \pm 0.0029$	0.14094	$0.1414 \pm 0.0029$	0.14305	$0.1426 \pm 0.0025$
$\Omega_m h^3$	0.09597	$0.09590 \pm 0.00059$	0.09603	$0.09593 \pm 0.00058$	0.09591	$0.09589 \pm 0.00057$
$Y_p$	0.247710	$0.24771 \pm 0.00014$	0.247785	$0.24775 \pm 0.00014$	0.247695	$0.24770 \pm 0.00012$
Age/Gyr	13.819	$13.813 \pm 0.058$	13.784	$13.796 \pm 0.058$	13.8242	$13.817 \pm 0.048$
$z_*$	1090.43	$1090.37 \pm 0.65$	1090.01	$1090.16 \pm 0.65$	1090.48	$1090.43 \pm 0.54$
$r_*$	144.58	$144.75 \pm 0.66$	145.02	$144.96 \pm 0.66$	144.58	$144.71 \pm 0.60$
$100\theta_*$	1.04139	$1.04148 \pm 0.00066$	1.04164	$1.04156 \pm 0.00066$	1.04136	$1.04147 \pm 0.00062$
$z_{drag}$	1059.32	$1059.29 \pm 0.65$	1059.59	$1059.43 \pm 0.64$	1059.25	$1059.25 \pm 0.58$
$r_{drag}$	147.34	$147.53 \pm 0.64$	147.74	$147.70 \pm 0.63$	147.36	$147.49 \pm 0.59$
$k_D$	0.14026	$0.14007 \pm 0.00064$	0.13998	$0.13996 \pm 0.00062$	0.14022	$0.14009 \pm 0.00063$
$100\theta_D$	0.161332	$0.16137 \pm 0.00037$	0.161196	$0.16129 \pm 0.00036$	0.161375	$0.16140 \pm 0.00034$
$z_{eq}$	3402	$3386 \pm 69$	3352	$3362 \pm 69$	3403	$3391 \pm 60$
$100\theta_{eq}$	0.8128	$0.816 \pm 0.013$	0.8224	$0.821 \pm 0.013$	0.8125	$0.815 \pm 0.011$
$r_{drag}/D_V(0.57)$	0.07130	$0.0716 \pm 0.0011$	0.07207	$0.0719 \pm 0.0011$	0.07126	$0.07147 \pm 0.00091$

Courtesy of thecmb.org

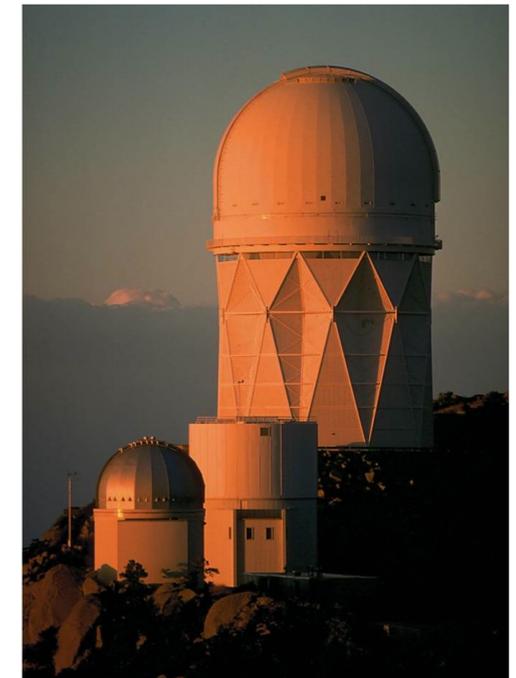
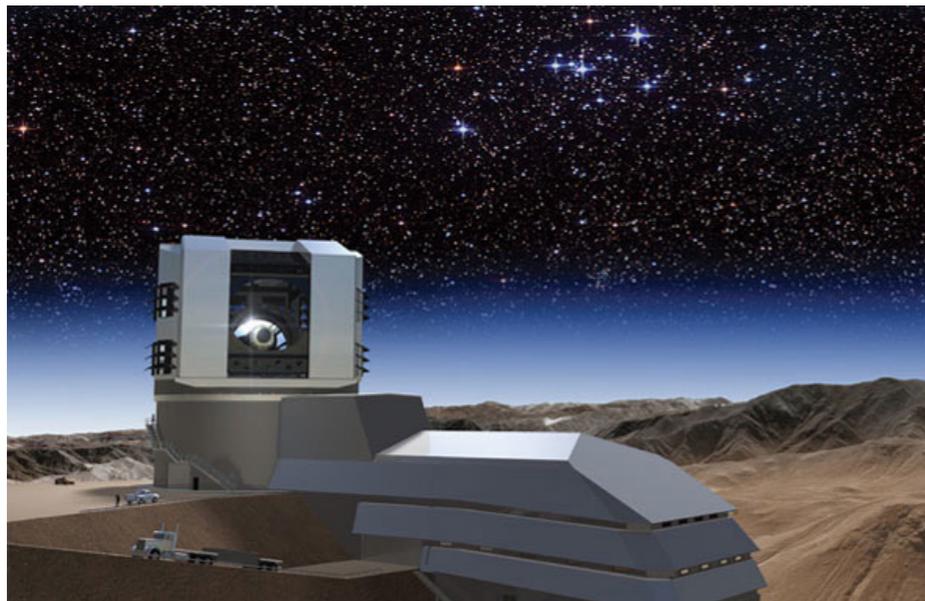
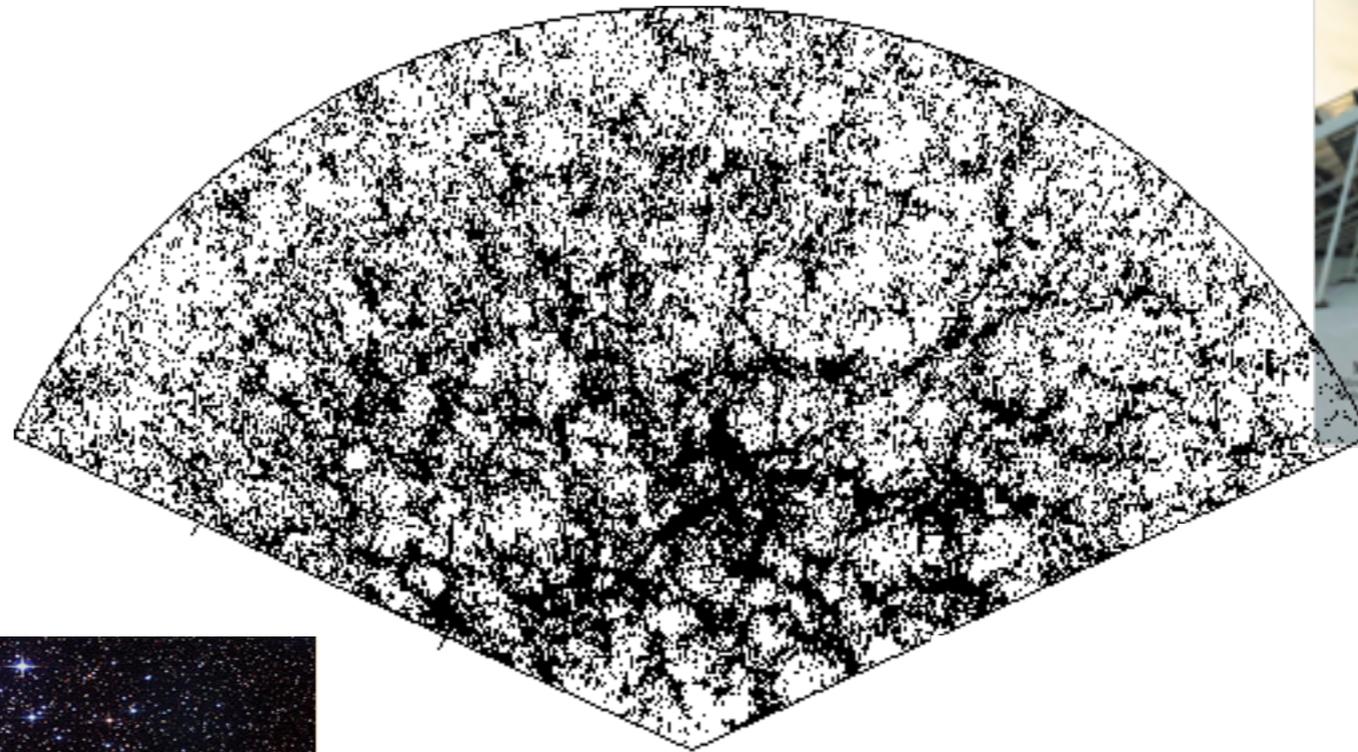
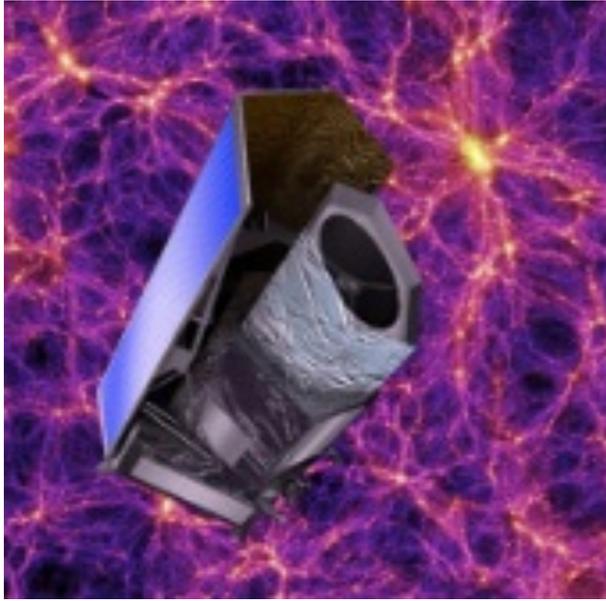
# Science Targets for Future CMB

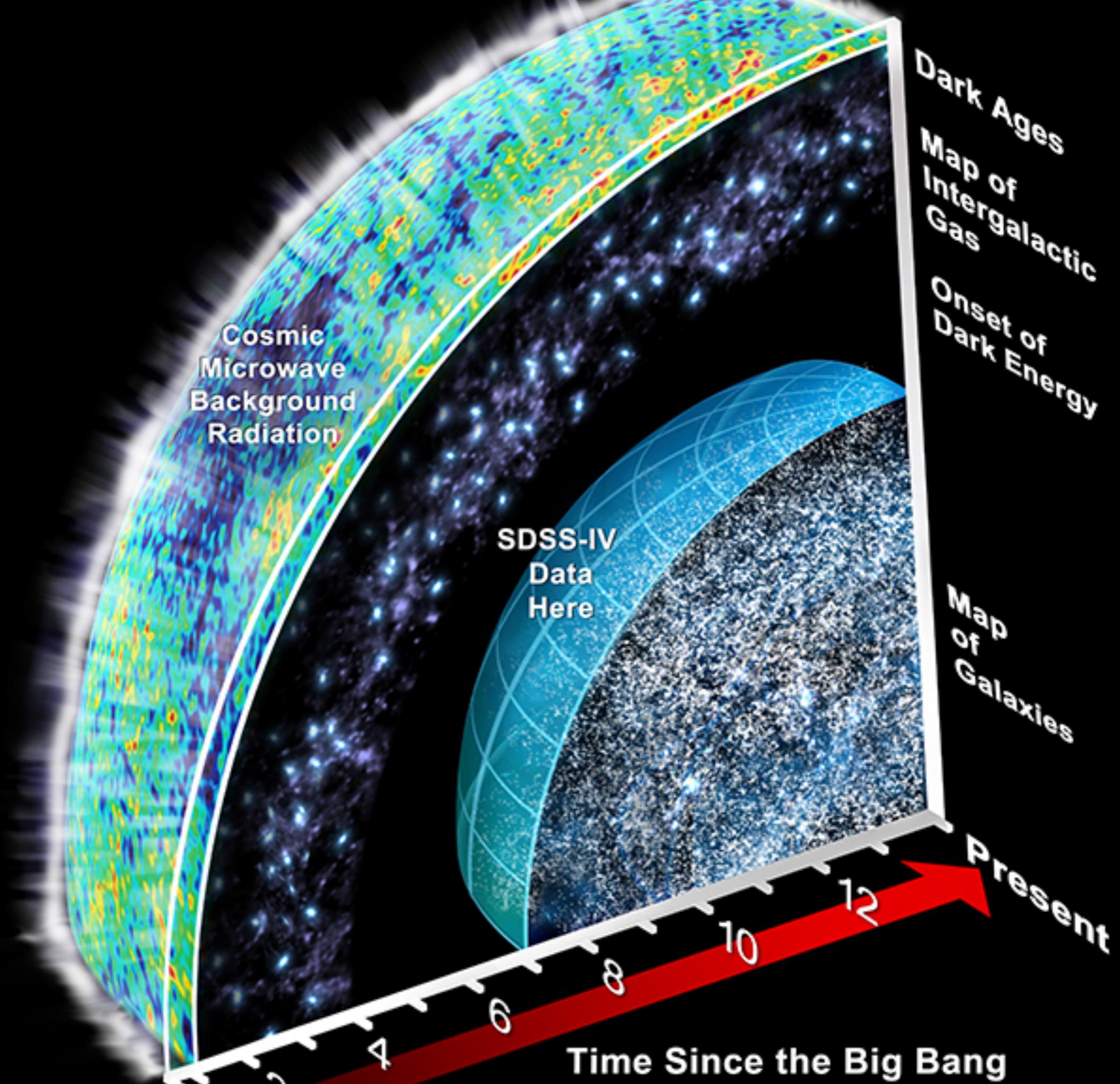
- Gravitational Waves from Inflation
- Light Relics ( $N_{\text{eff}}$ )
- Neutrino Mass
- Dark Matter Interactions / Properties
- Lensing maps
- Galaxy clusters
- Reionization

# Large Scale Structure

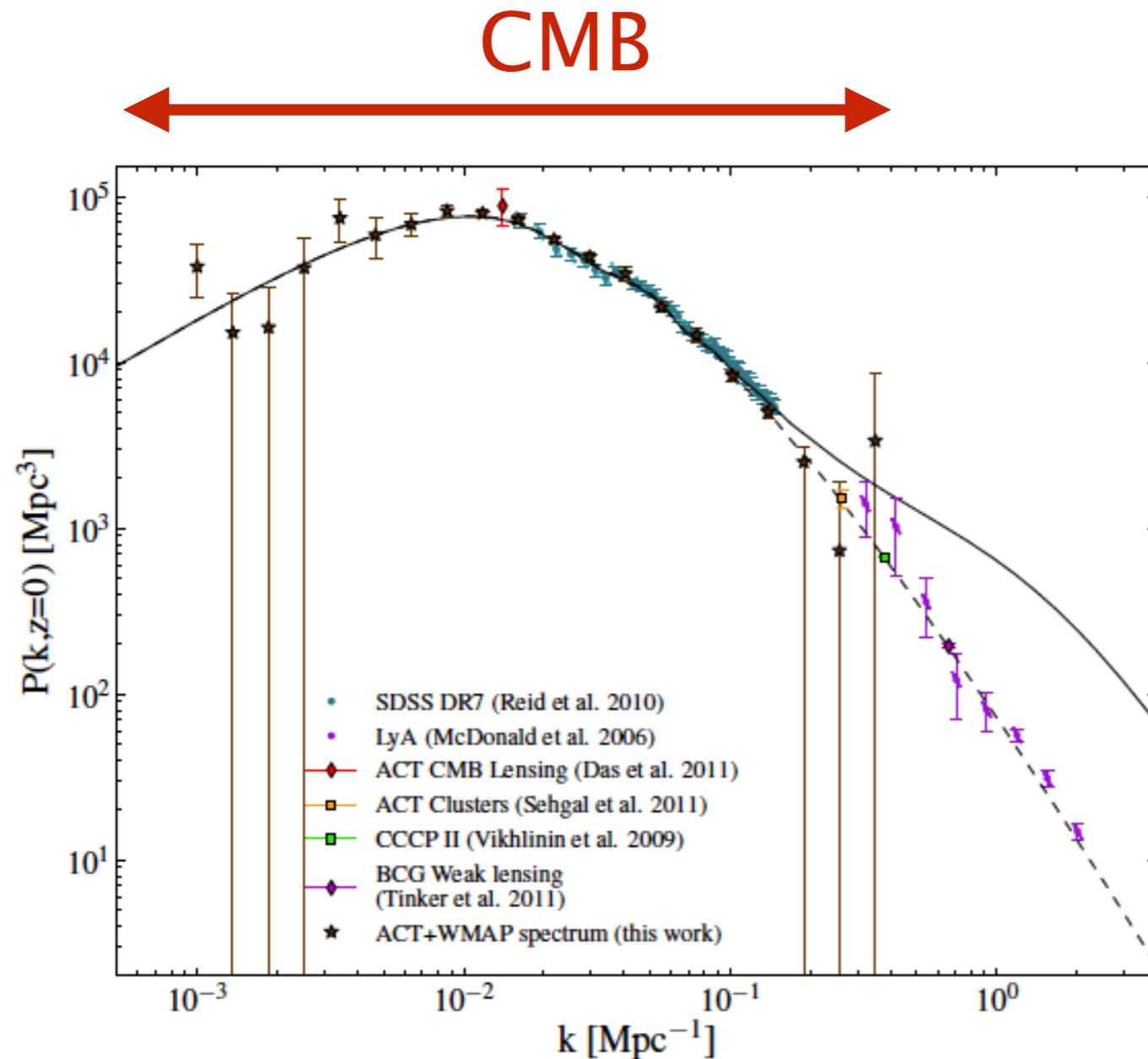


# Large Scale Structure





# Large Scale Structure



$$N_{\text{modes}}^{\text{CMB}} \sim \left( \frac{k_{\text{max}}}{k_{\text{min}}} \right)^2$$

$$N_{\text{modes}}^{\text{LSS}} \sim \left( \frac{k_{\text{max}}}{k_{\text{min}}} \right)^3$$

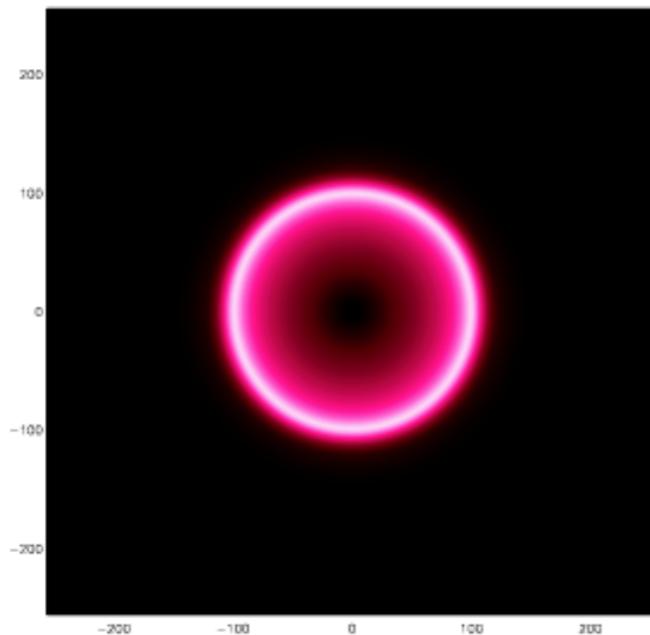
Linear regime of LSS (at high- $z$ )

# Large Scale Structure

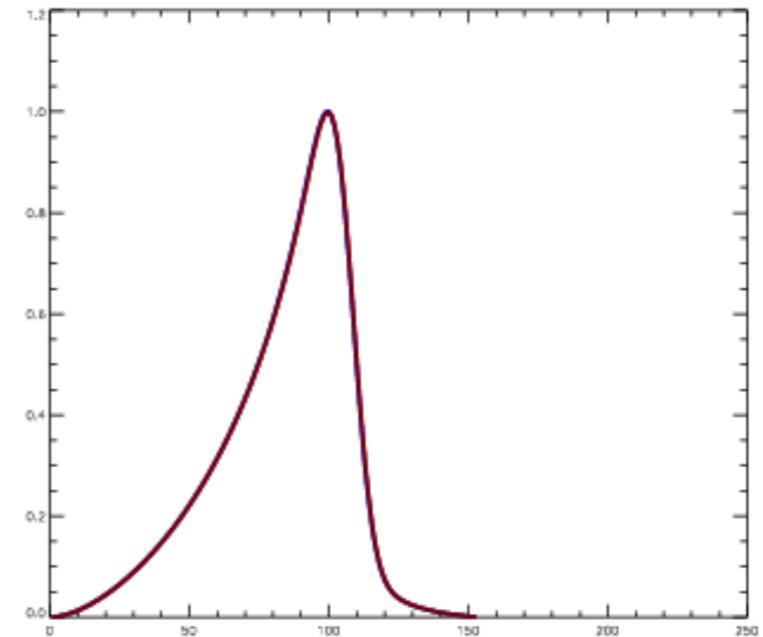
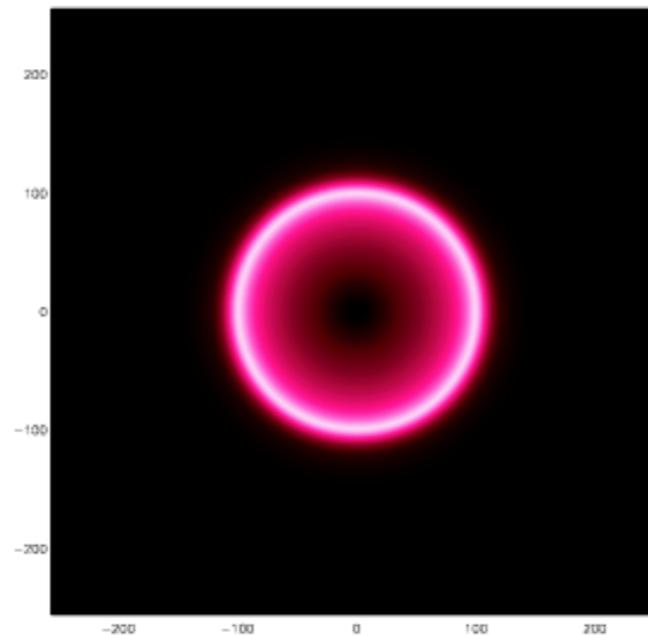
Most surveys are driven by dark energy science

Goal: map the BAO peak over cosmic time

“Baryons”



photons



Courtesy of Martin White

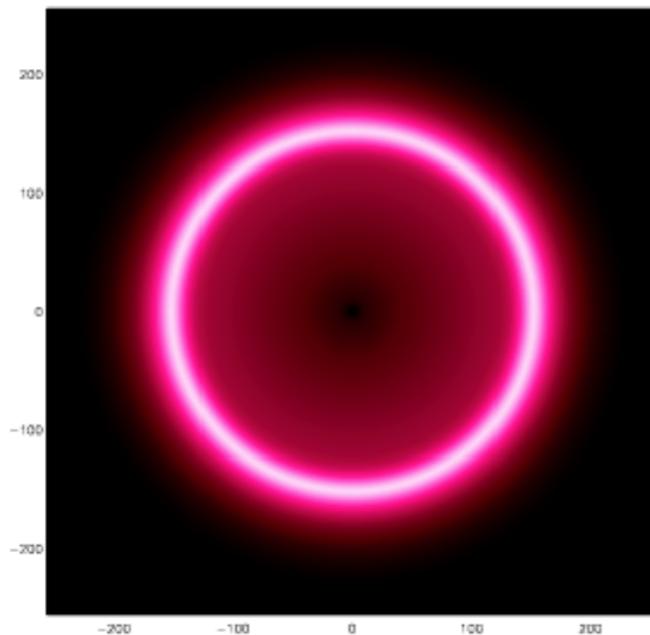
Pre-CMB – Photons support sound wave

# Large Scale Structure

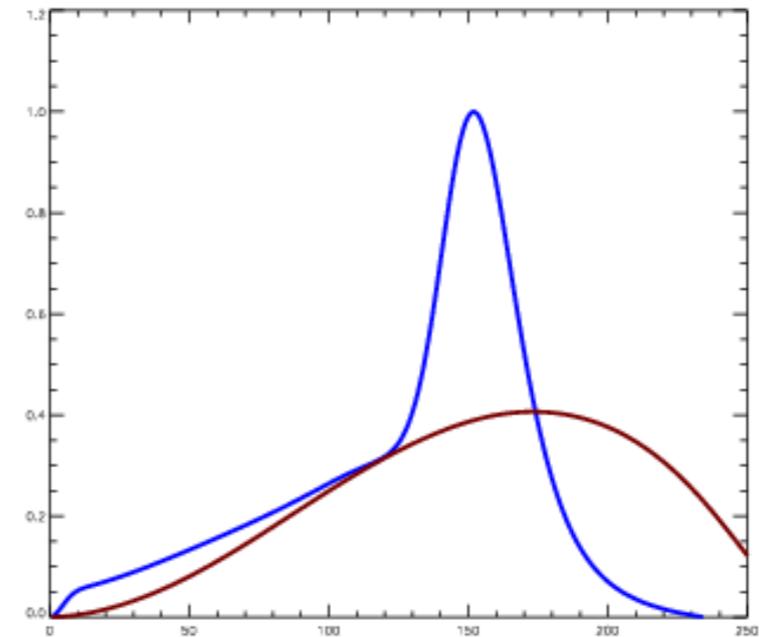
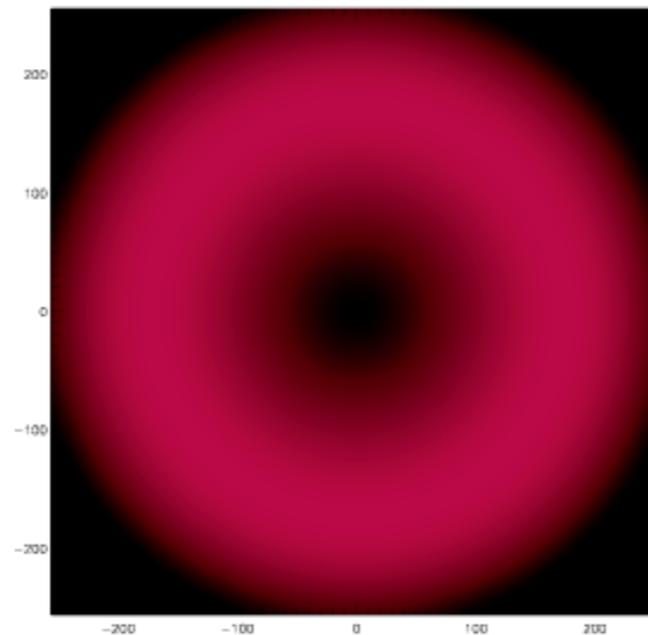
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Courtesy of Martin White

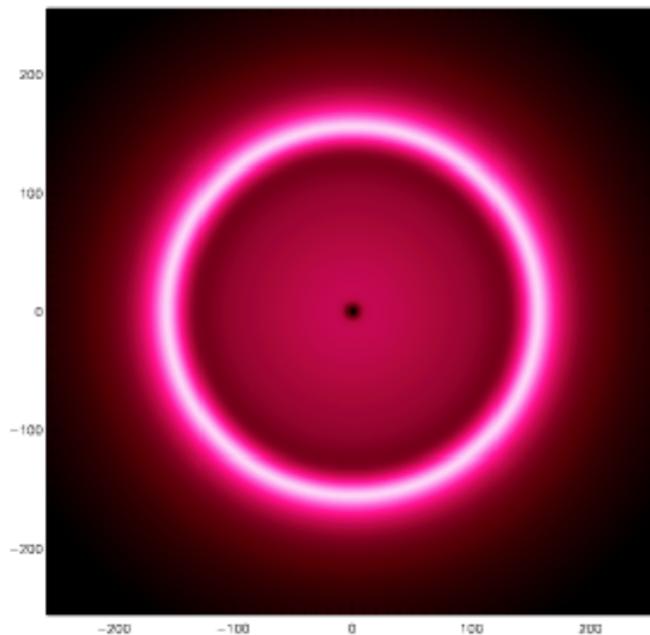
Post-CMB – Photons free-stream

# Large Scale Structure

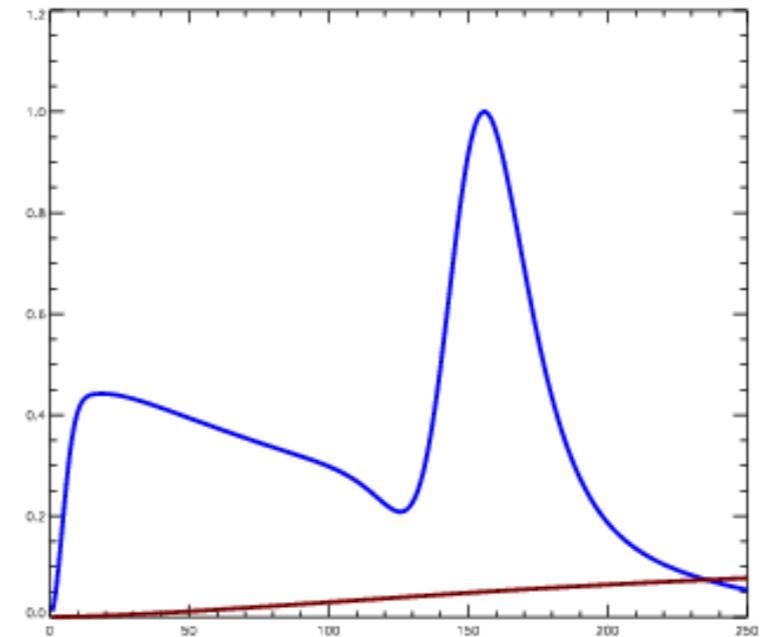
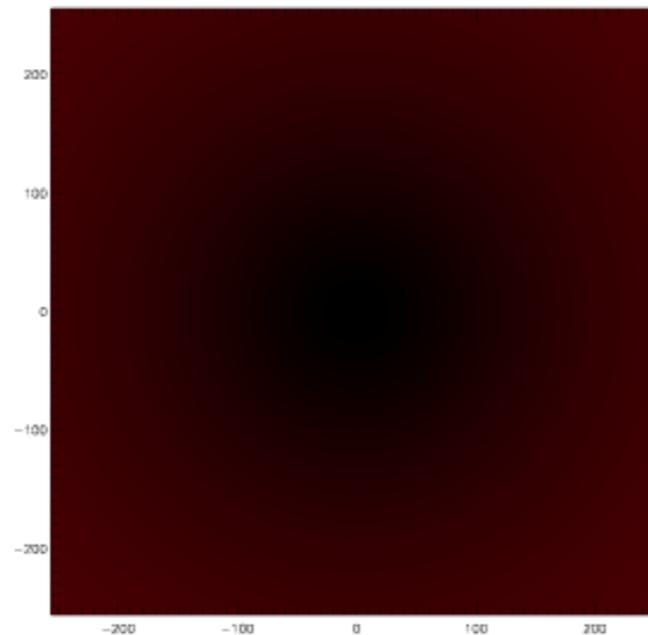
Most surveys are driven by dark energy science

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photons



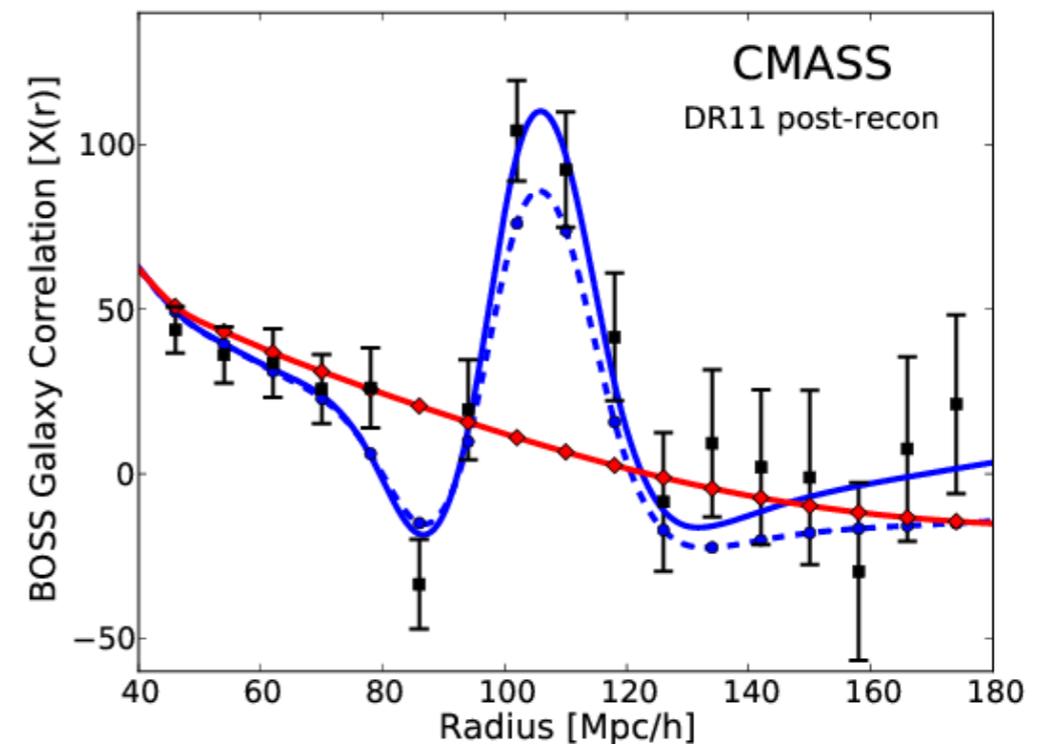
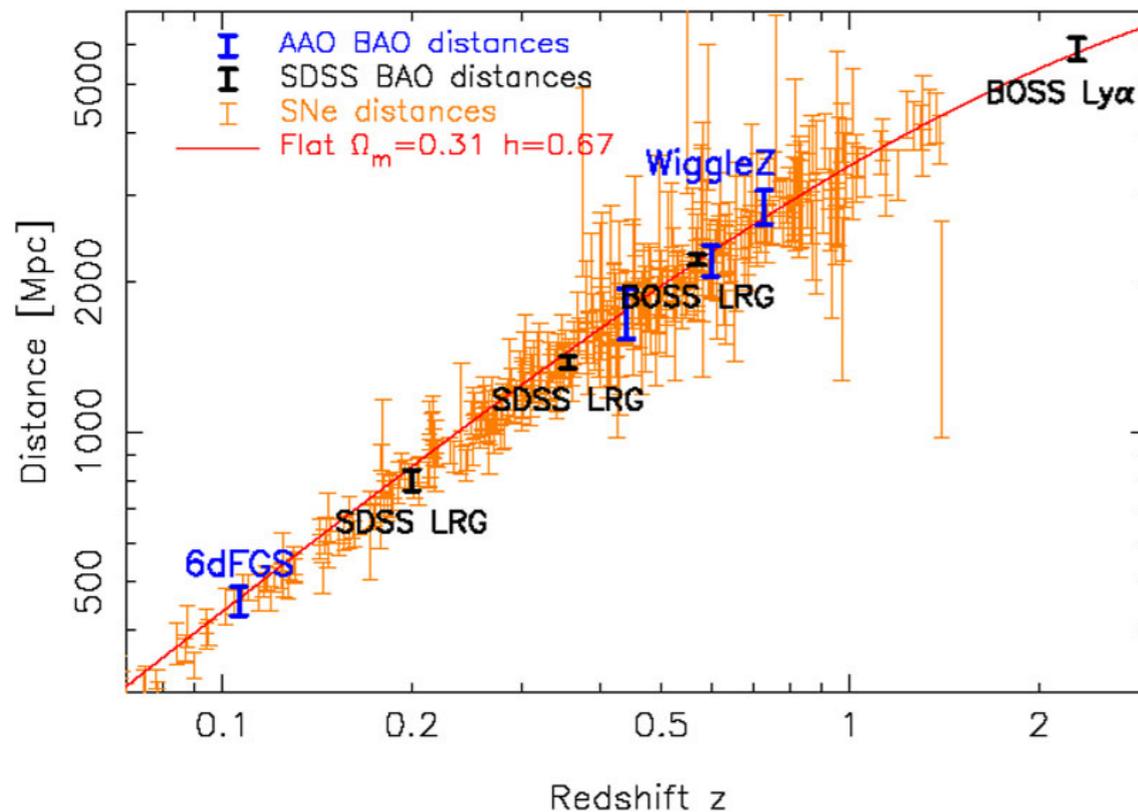
Courtesy of Martin White

Post-CMB – Baryon peak frozen in place

# Large Scale Structure

Most surveys are driven by dark energy science

Goal: map the BAO peak over cosmic time



Peak is a standard ruler for measuring  $H(z)$

# Large Scale Structure

## BAO peak in position - oscillation in power spectrum

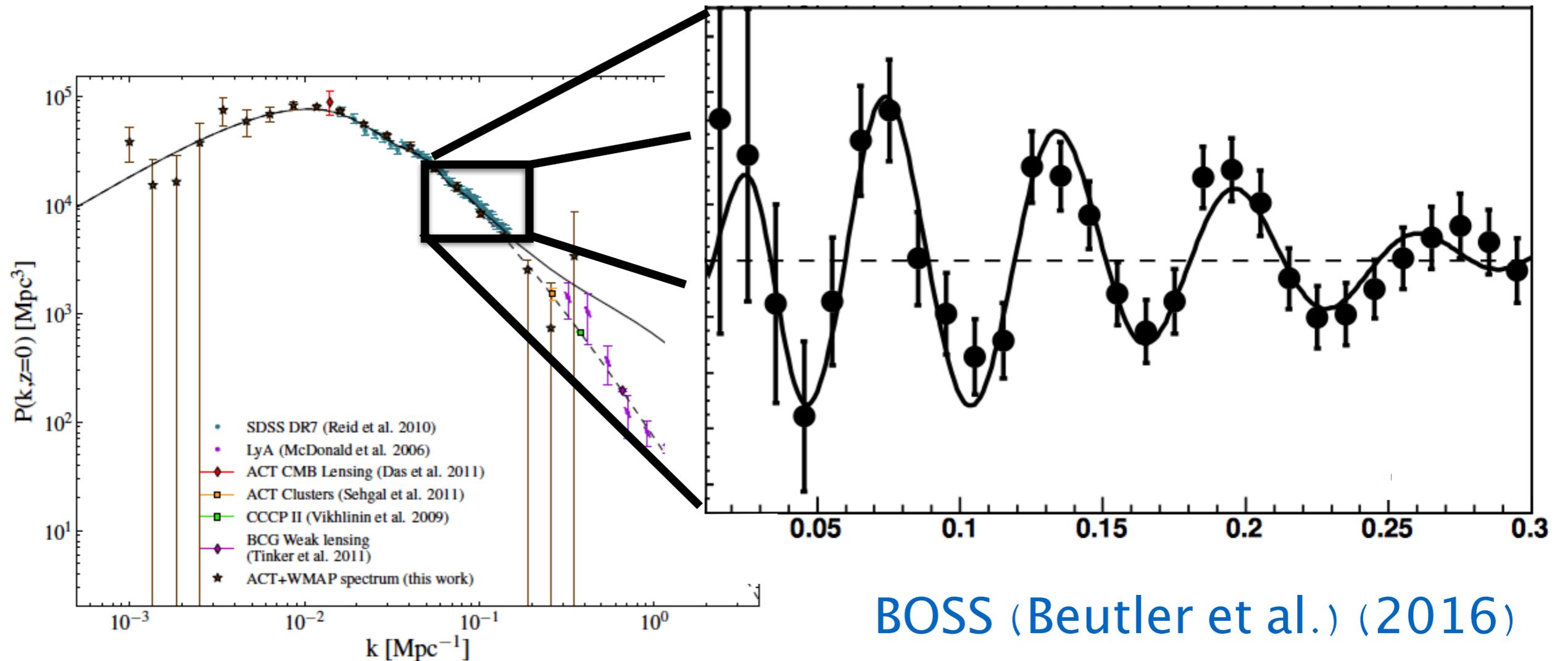
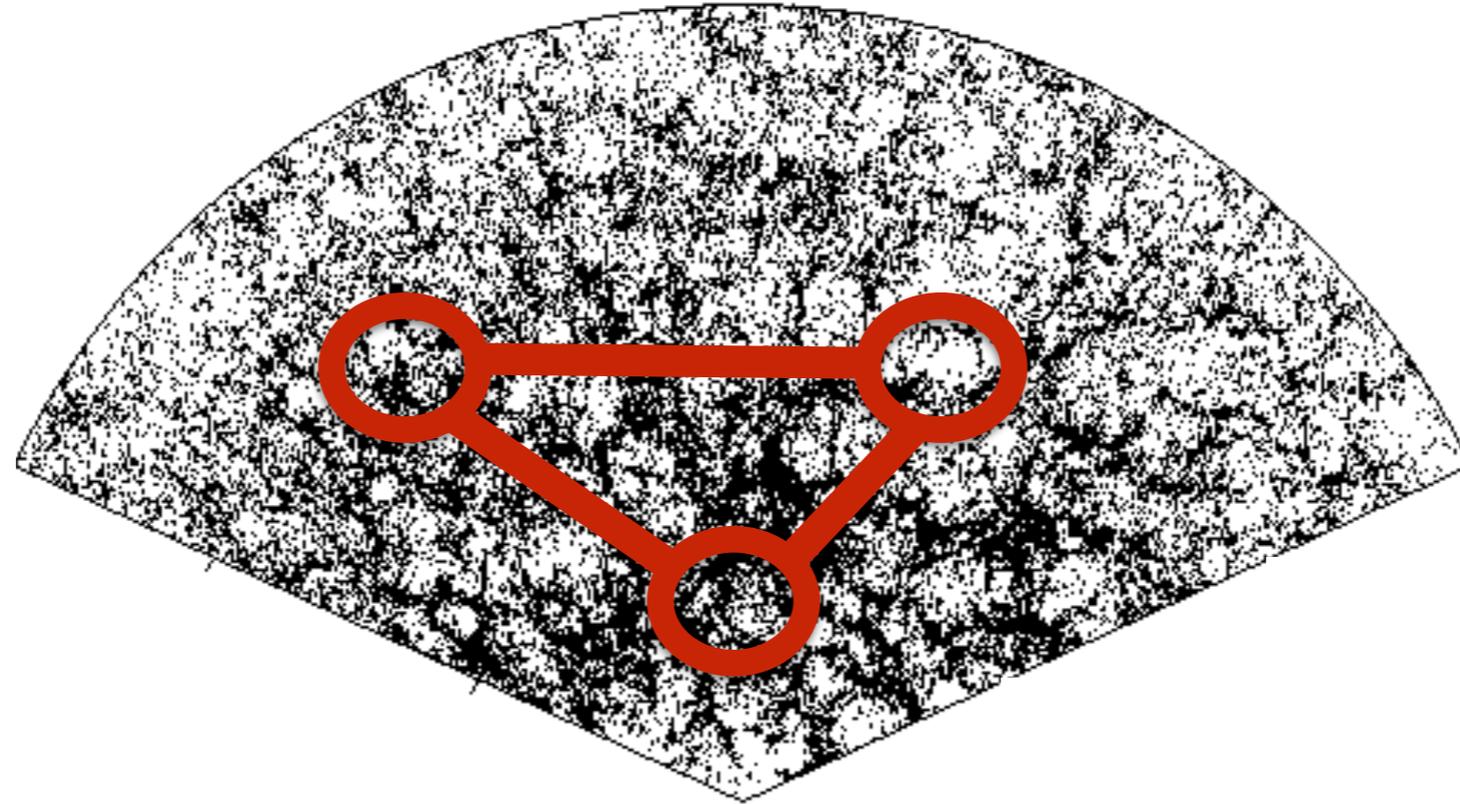


Figure from Hlozek et al.

# Large Scale Structure

Realizing the potential of LSS requires more



The BAO is a huge compression of the information

Other information hard to separate from nonlinearity

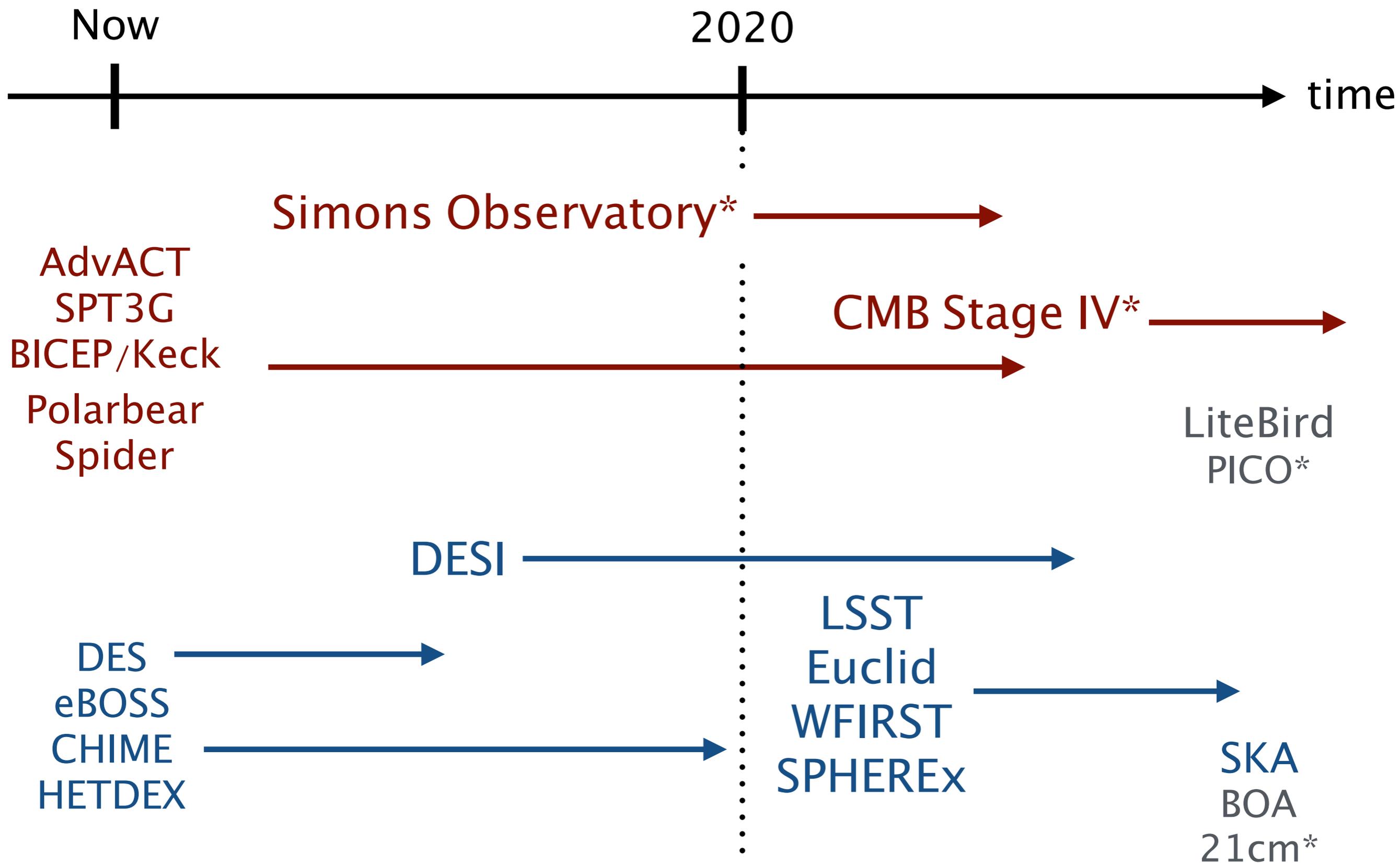
LSS is the proton collider to the CMB  $e^+e^-$  collider

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# Science Targets for Future Surveys

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- Expansion History
  - Neutrino Mass
  - Interactions / Particle Content during Inflation
  - Dark Matter Interactions / Properties
  - Lensing maps
  - Galaxy formation / properties
  - Time-domain Astronomy
-



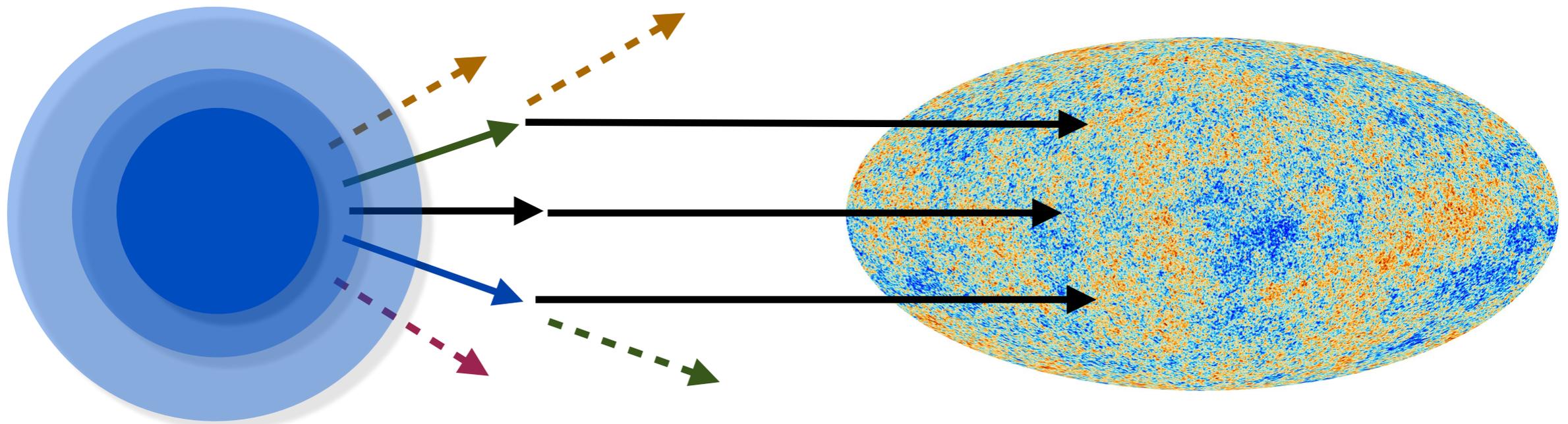
\* DG member



# Inflation and Gravitational Waves

# Inflation

Inflation is indirectly tied to high energy physics



Everything is excited during inflation

# Inflation

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Gravitational Waves determines energy scale

$$H < 10^{14} \text{ GeV}$$

A detection would imply very high scale inflation

Non-gaussian correctors determine interactions

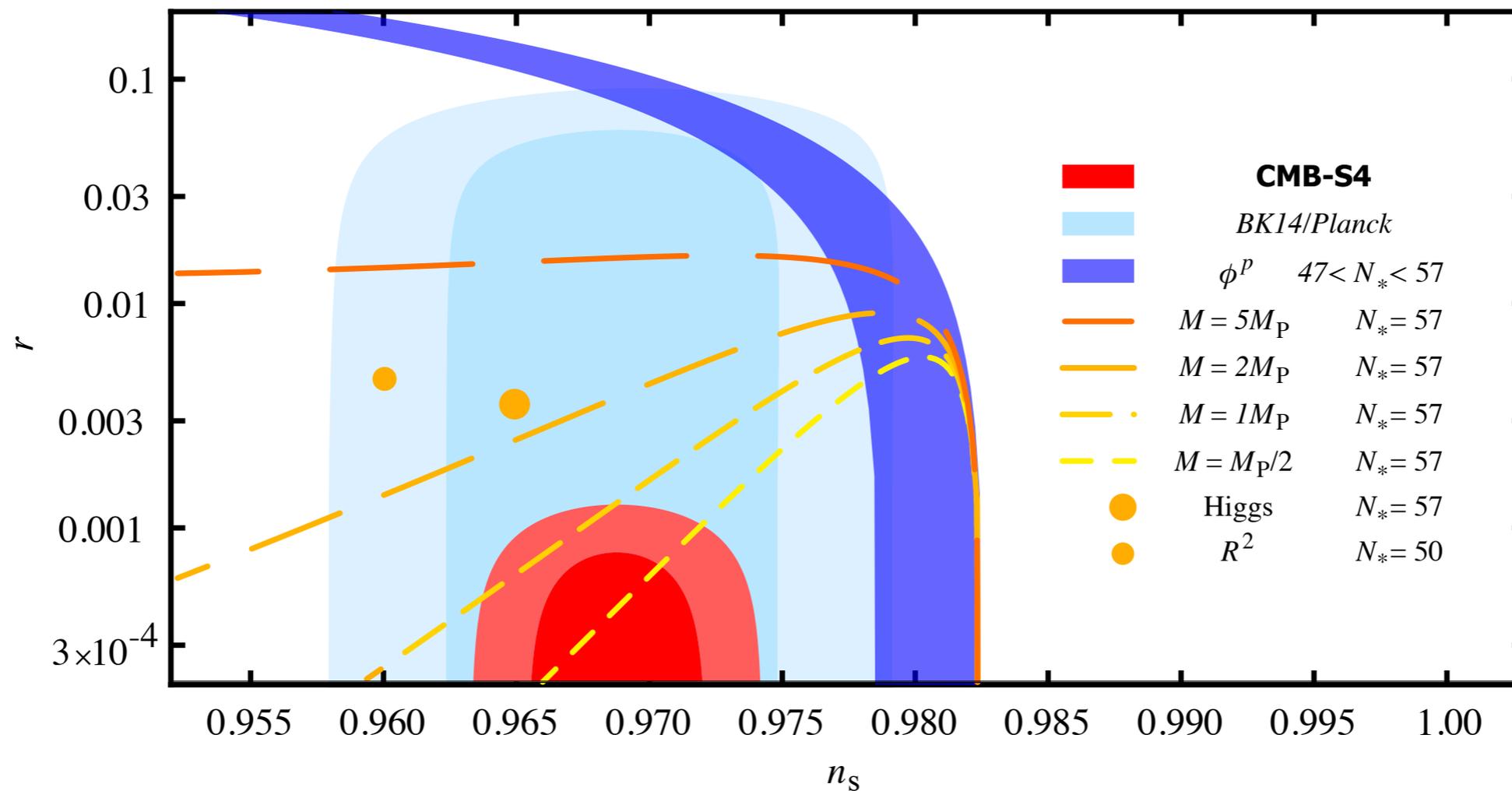
$$3\text{-point} \propto \frac{H^2}{\Lambda^2}$$

Encodes mass, spin and couplings of all particles

---

# Inflation

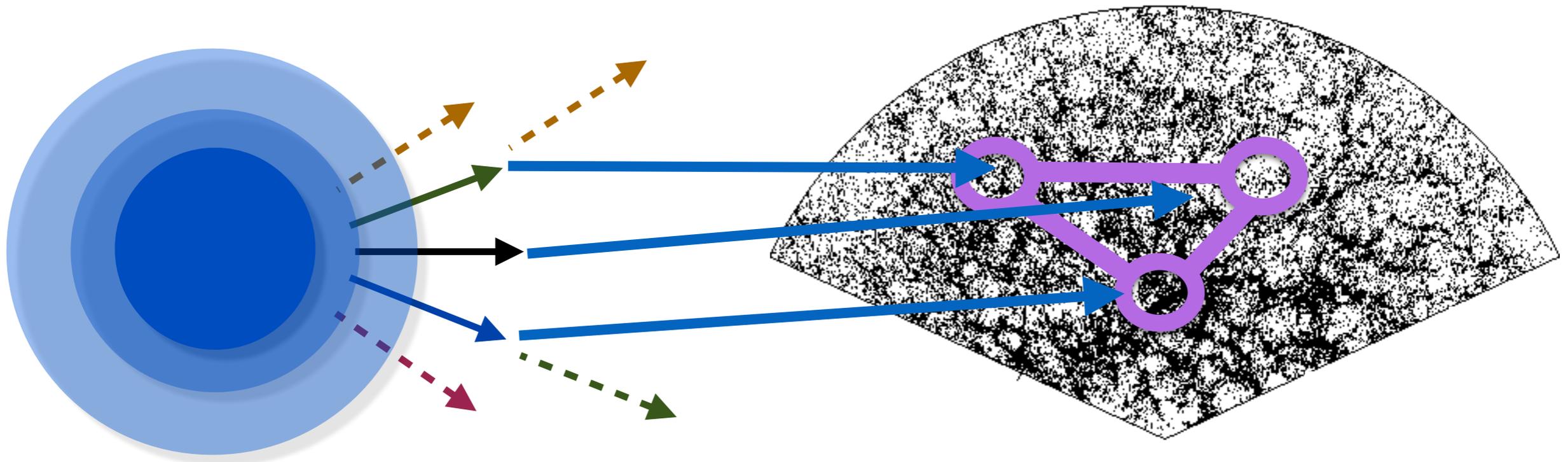
CMB will make significant improvements in GWs



Driven by (unique!) B-mode polarization signal

# Large Scale Structure

LSS is the frontier for interactions / spectroscopy

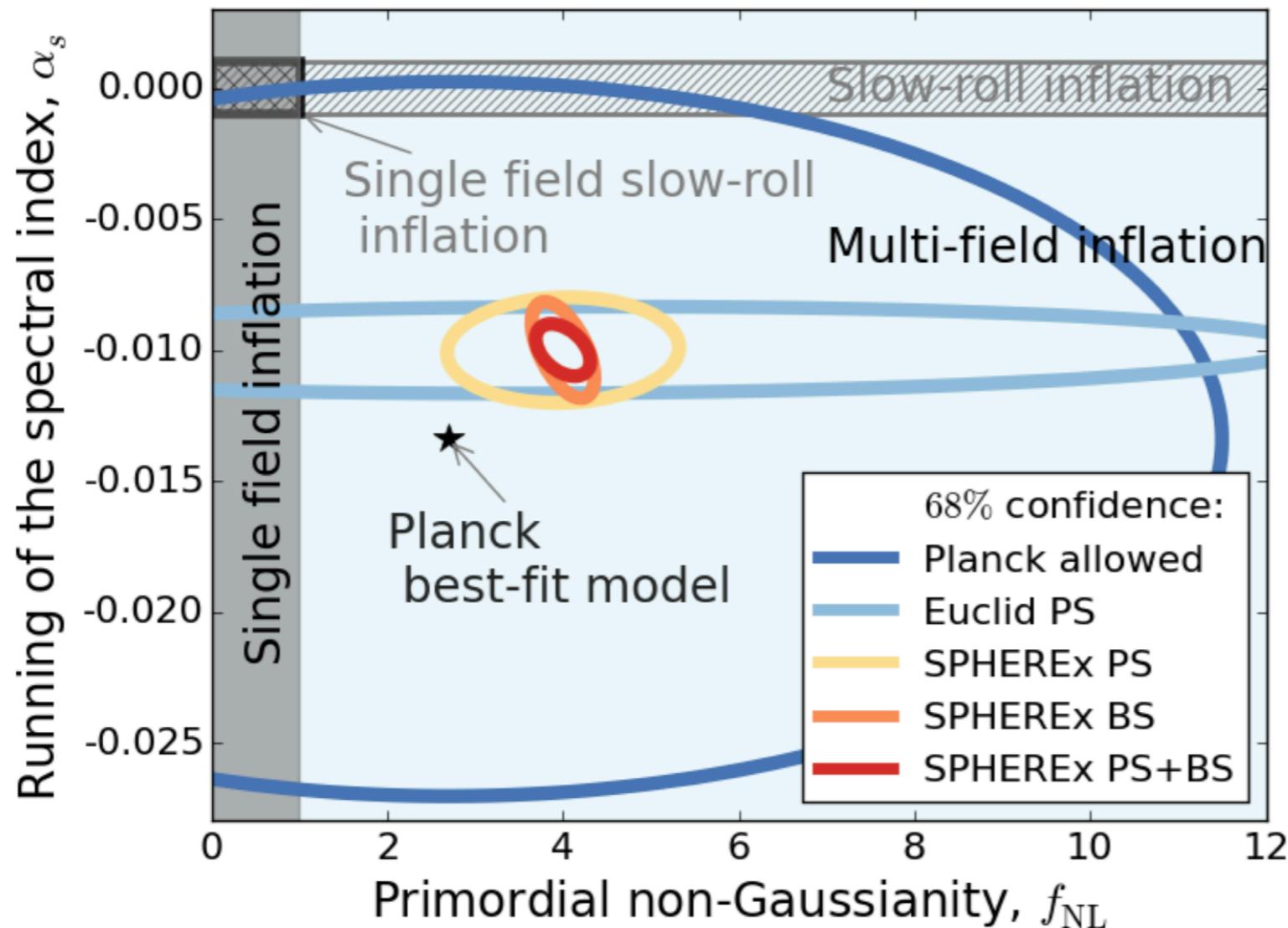


Need the raw statistical power from # of modes

Need significant improvements in modeling/analysis

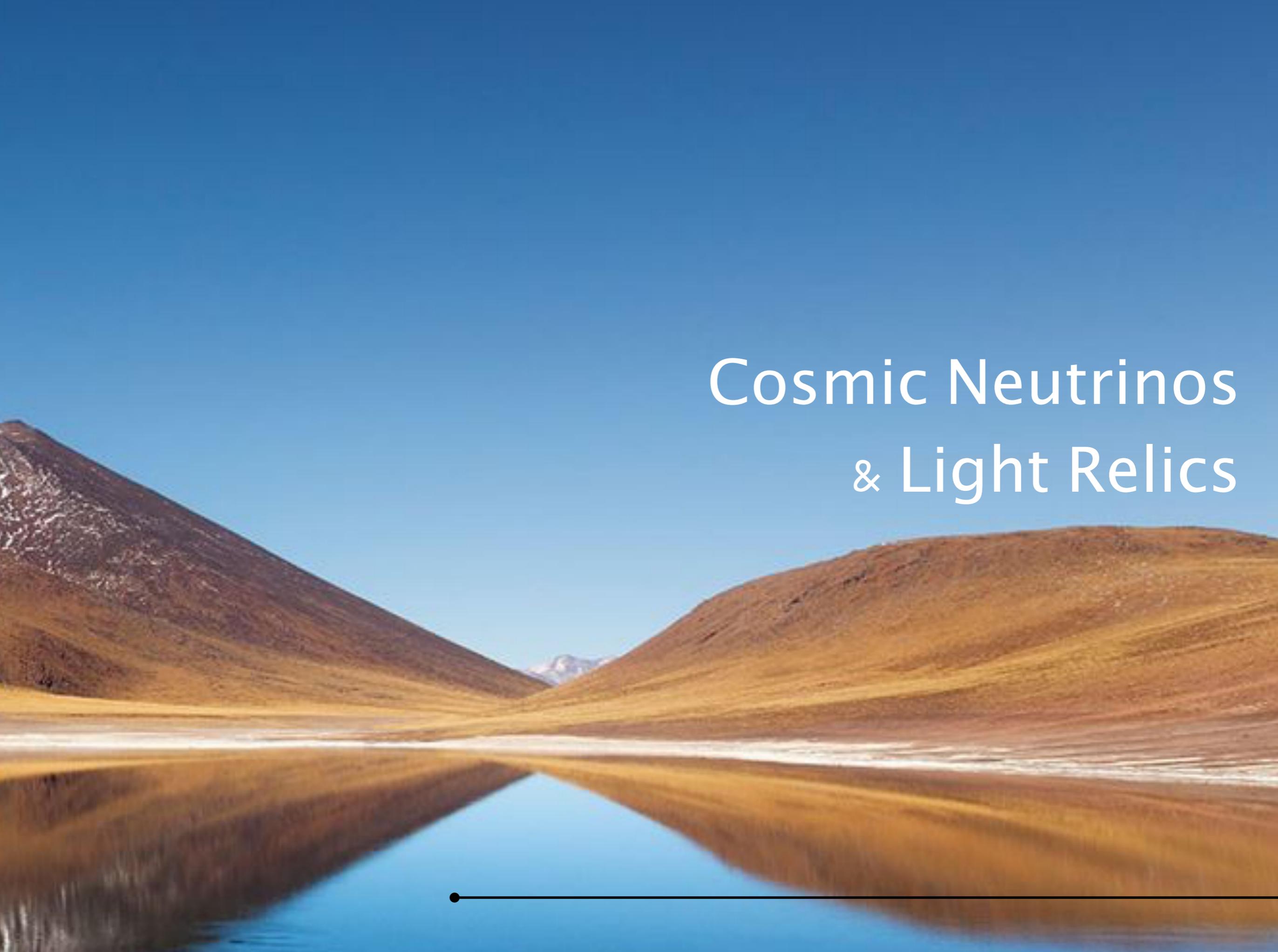
# Large Scale Structure

SPHEREx (NASA MIDEX, announced on Feb 13)



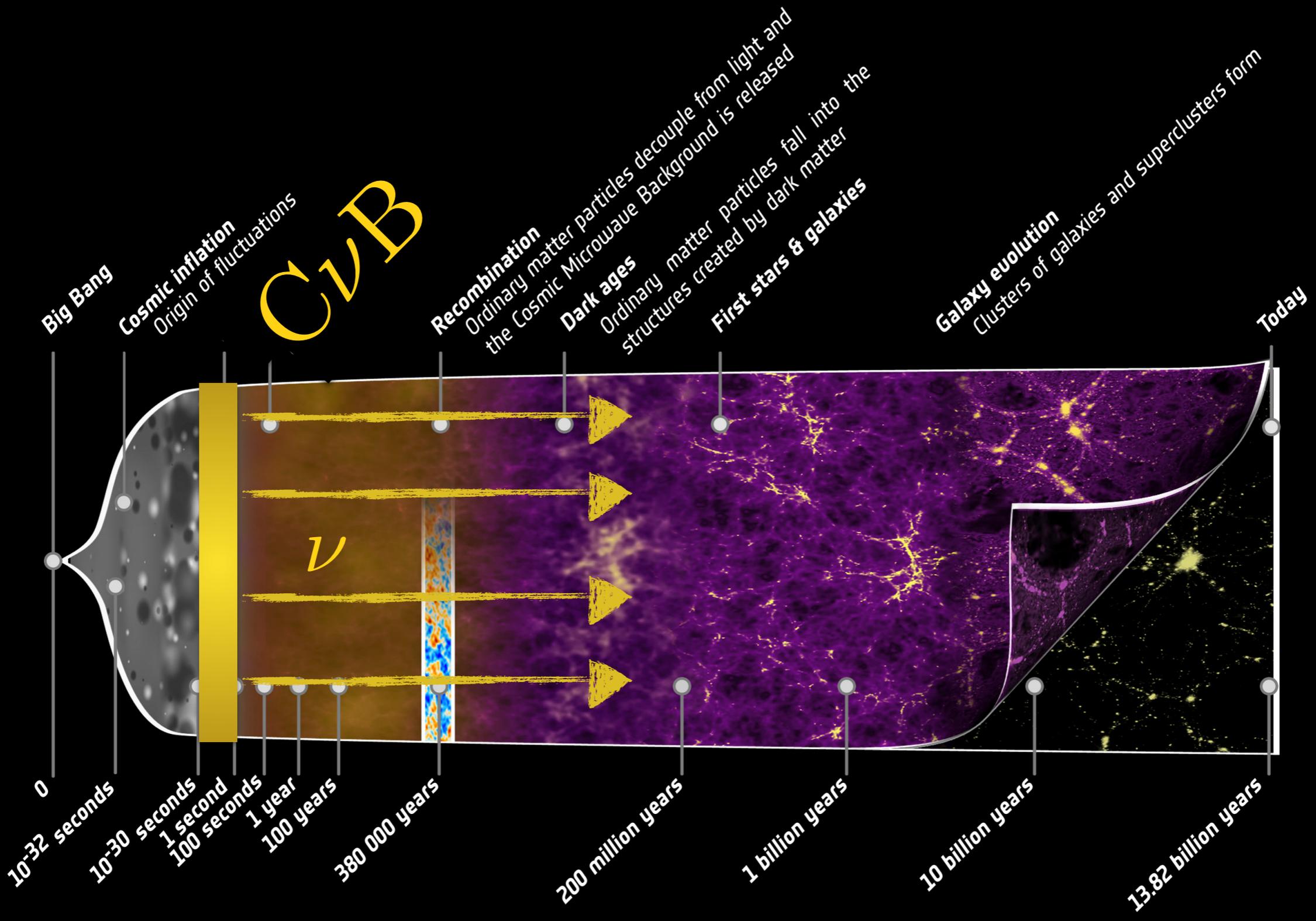
Doré et al. (2014)

Primary science goals require these improvements

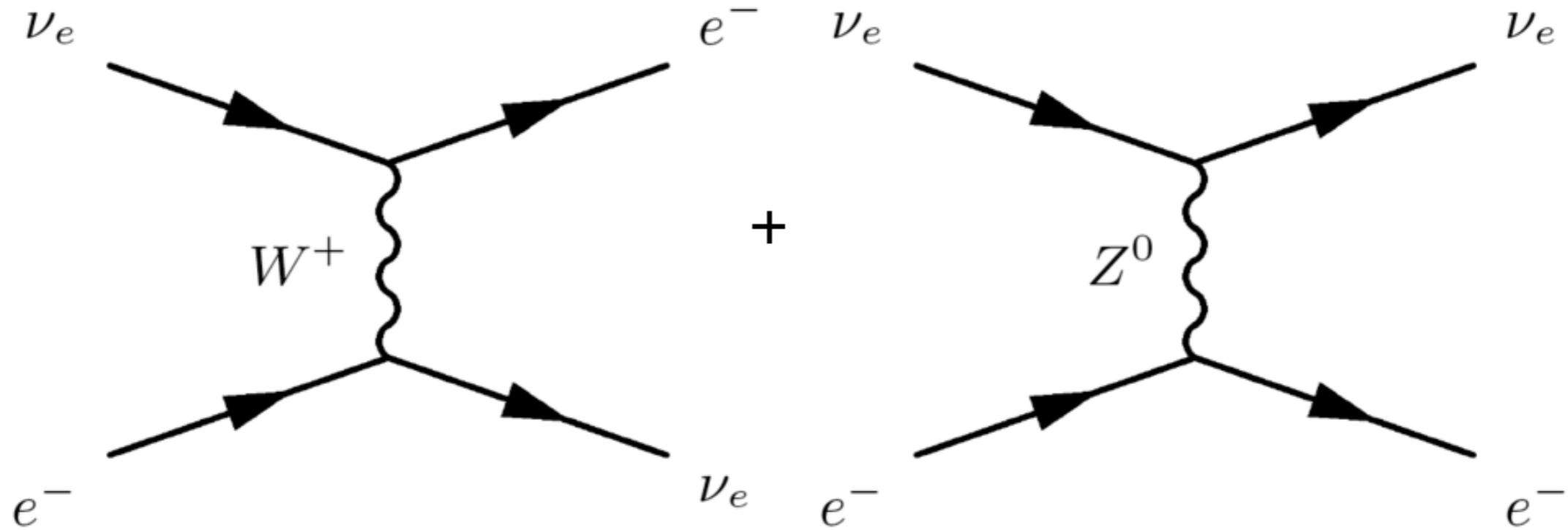
A landscape photograph showing a wide valley with a river in the foreground. The river reflects the surrounding brown and tan hills and the clear blue sky. In the distance, snow-capped mountains are visible. The overall scene is serene and natural.

# Cosmic Neutrinos & Light Relics



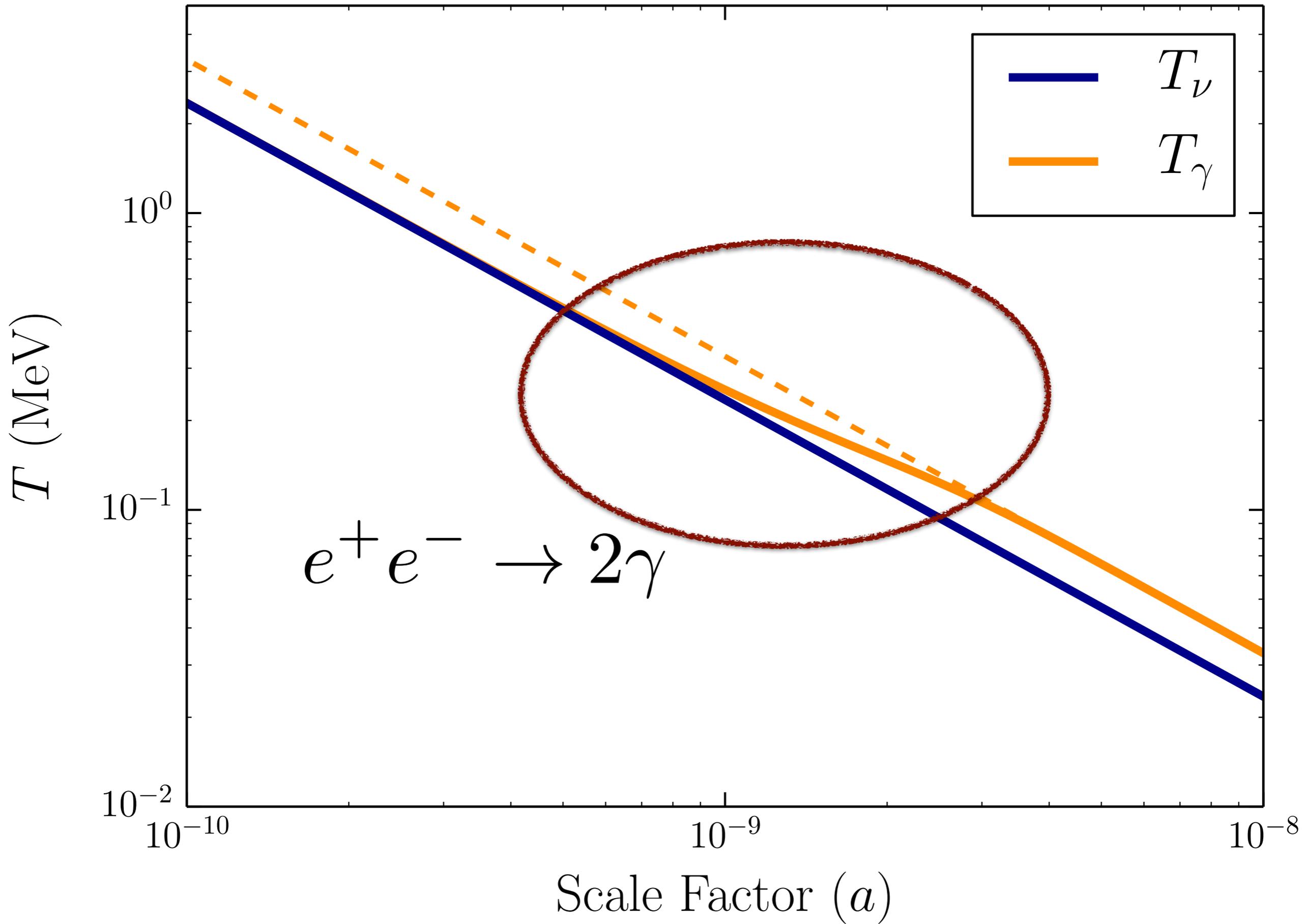


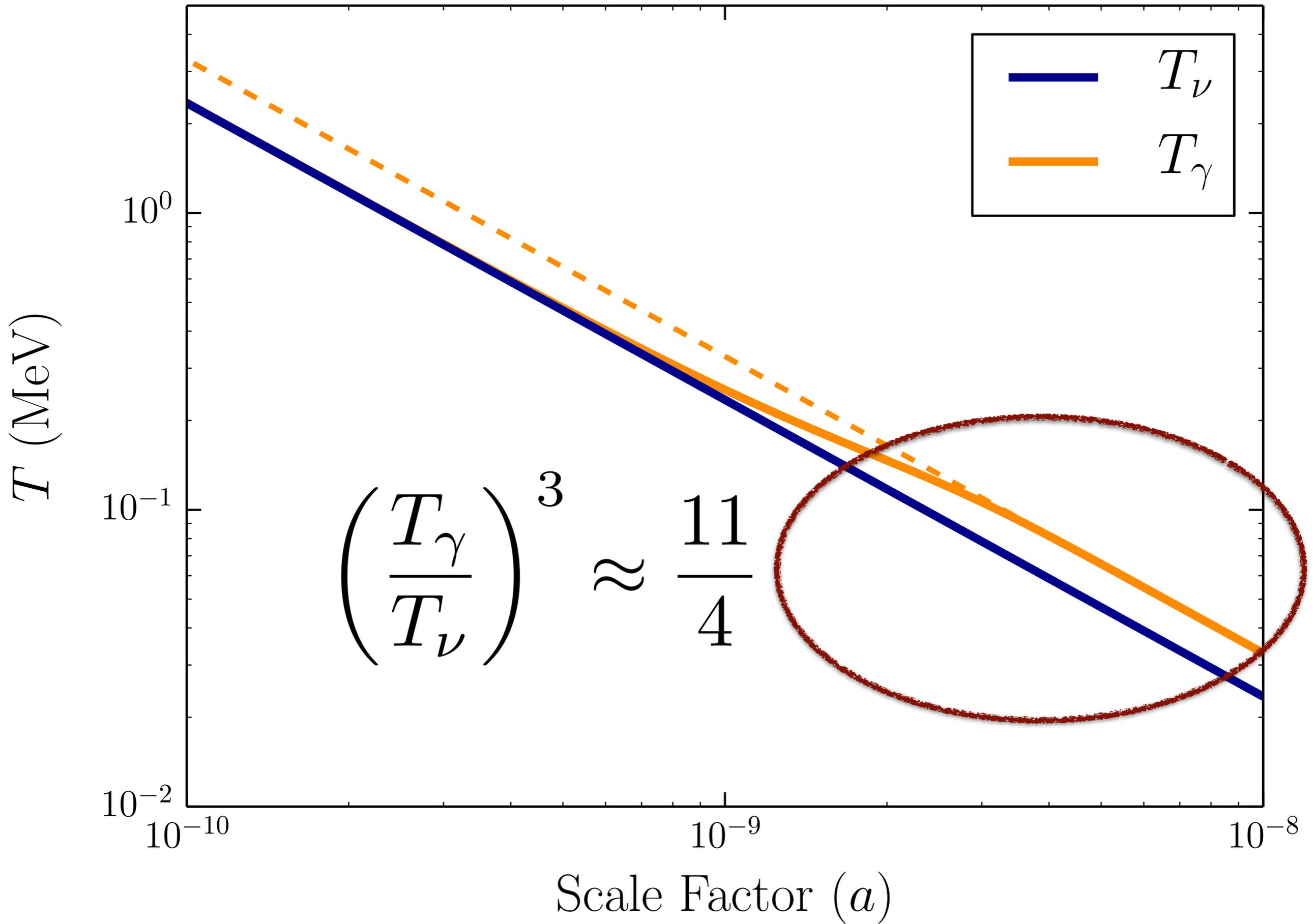
# Cosmic Neutrino Background



**Equilibrium :**

$$\Gamma \sim G_F^2 T^5 > H \sim \frac{T^2}{M_{\text{pl}}}$$





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

Perfect decoupling :

$$N_{\text{eff}} = 3.$$

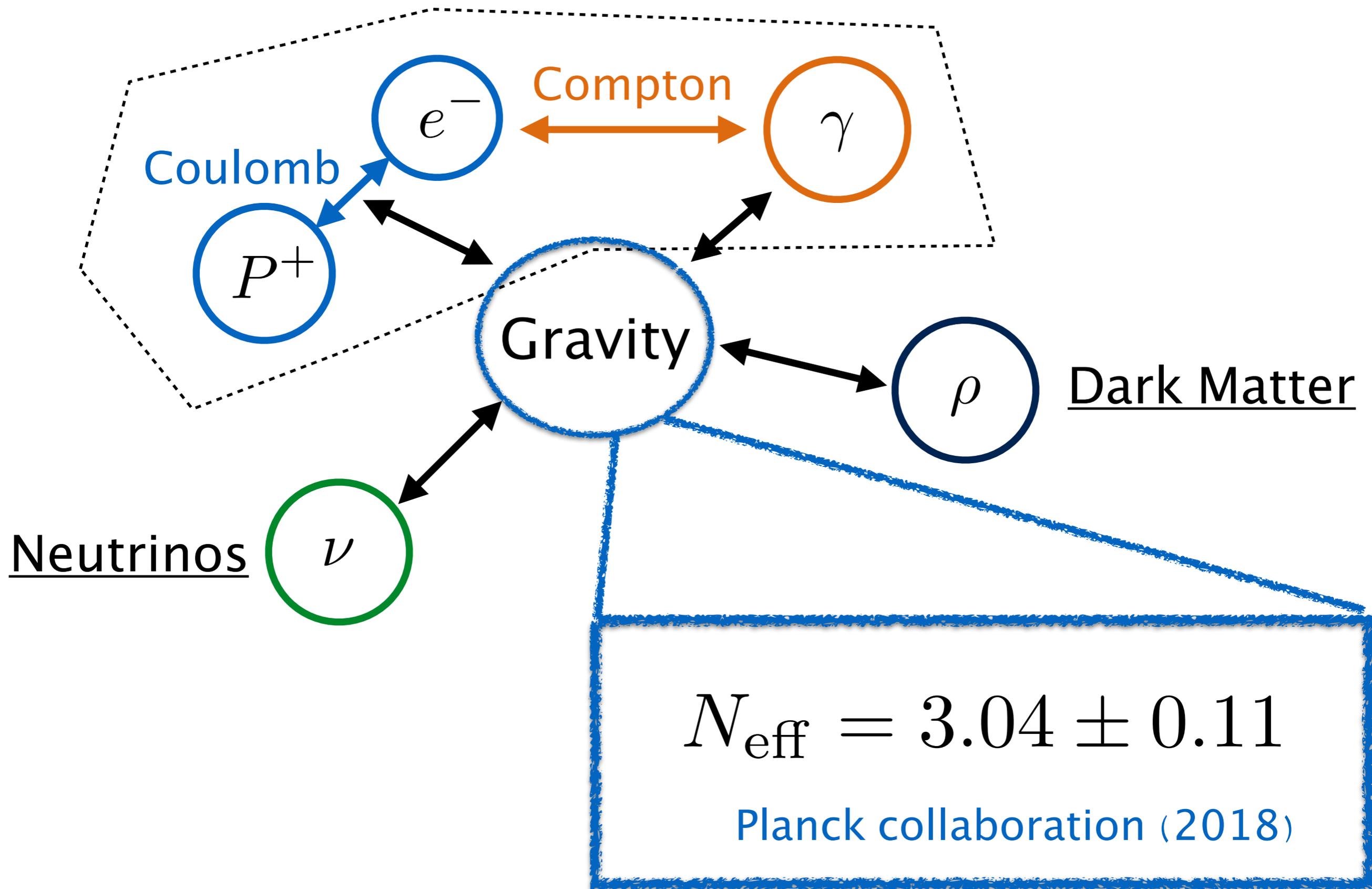
Imperfect decoupling :

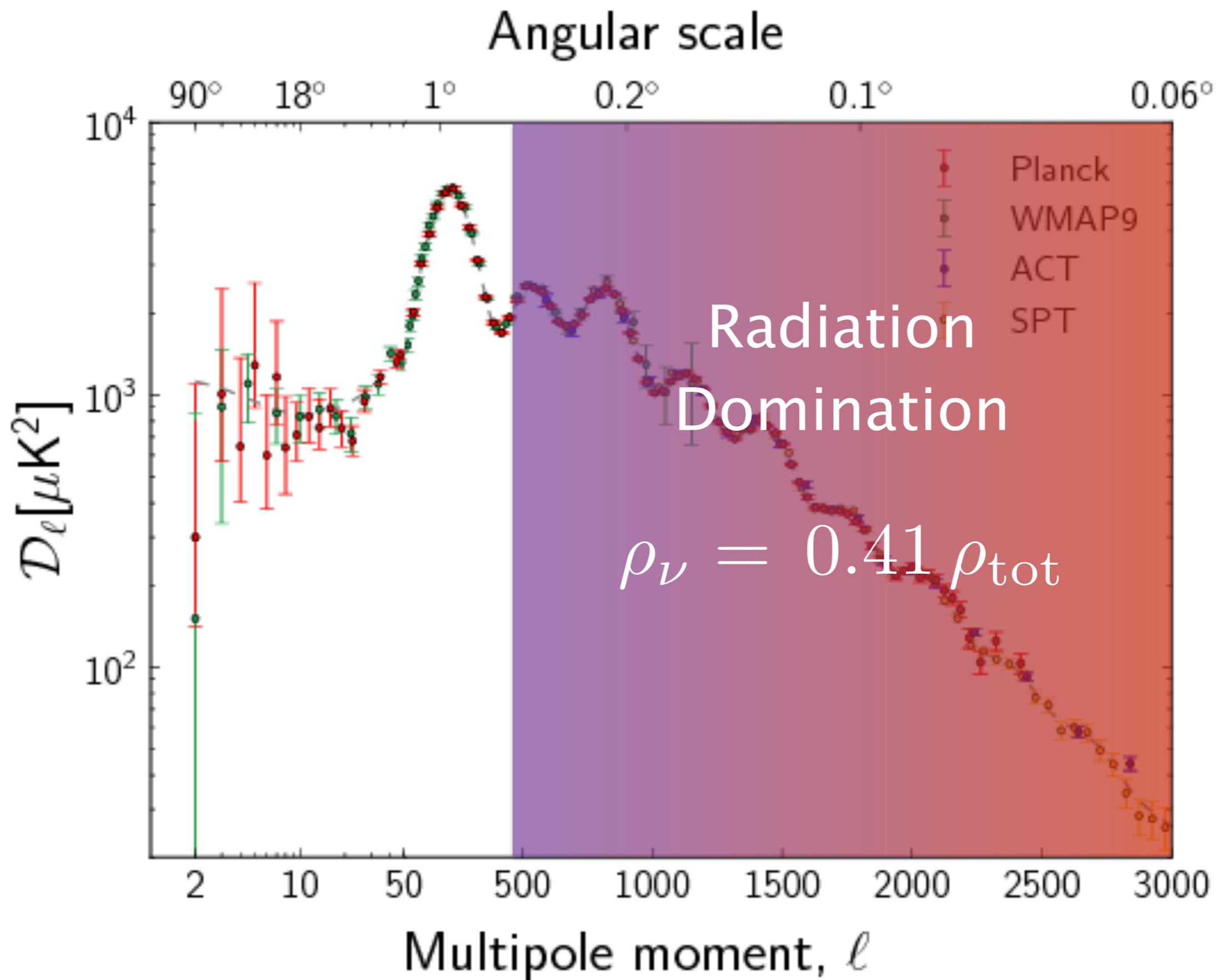
$$N_{\text{eff}} = 3.035$$

Imperfect decoupling + QED :

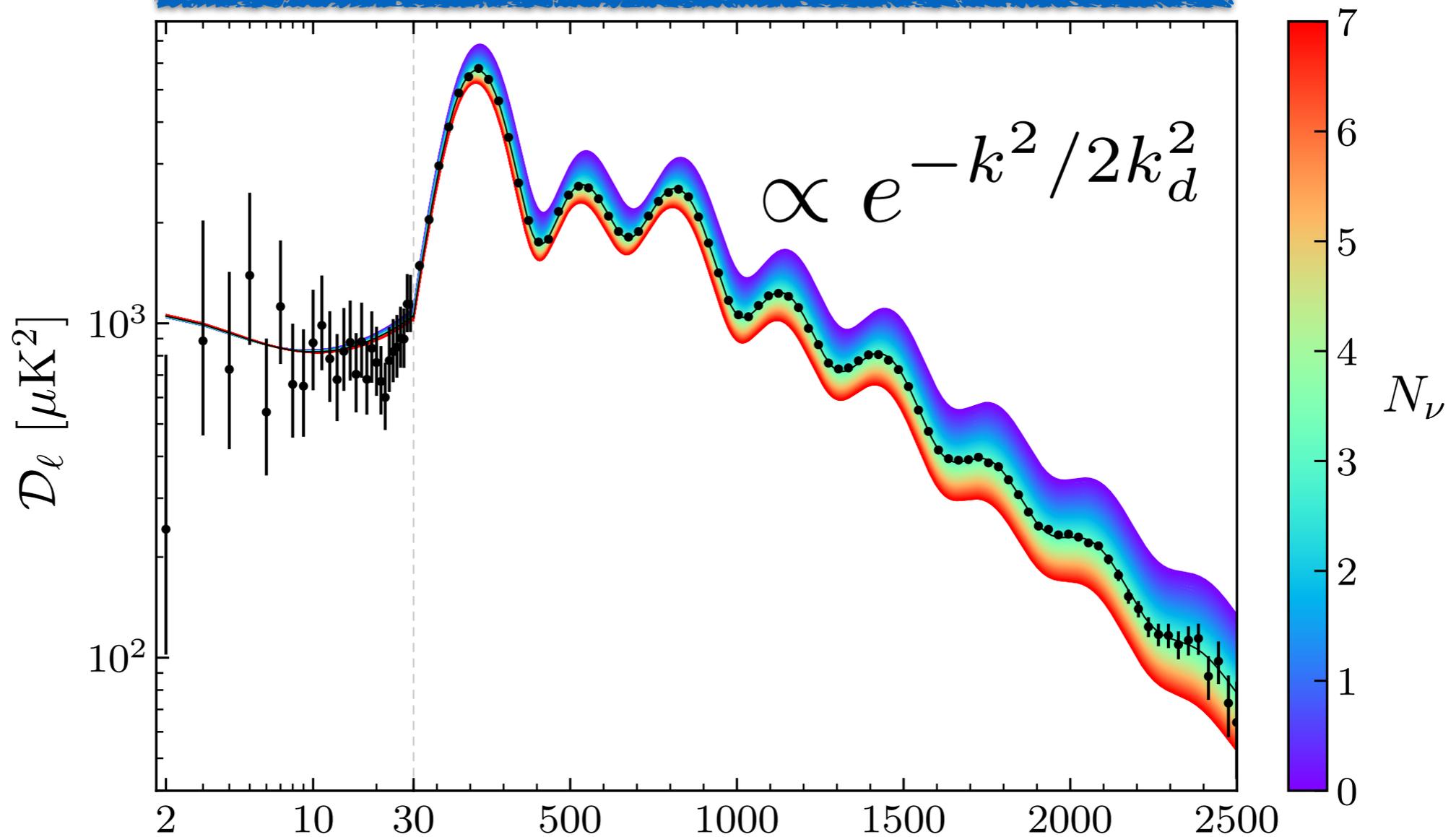
$$N_{\text{eff}} = 3.045$$

Salas & Pastor (2016);  
Mangano et al. (2005)





$$3M_{\text{pl}}^2 H^2 = \rho_\gamma + \rho_\nu$$



$$\frac{1}{k_d^2} \sim \langle \Delta x^2 \rangle \propto t \quad t \propto \frac{1}{H}$$

What **exactly** is this measuring?

Totally different from the Z-width:

$$N_\nu = 2.9840 \pm 0.0082$$

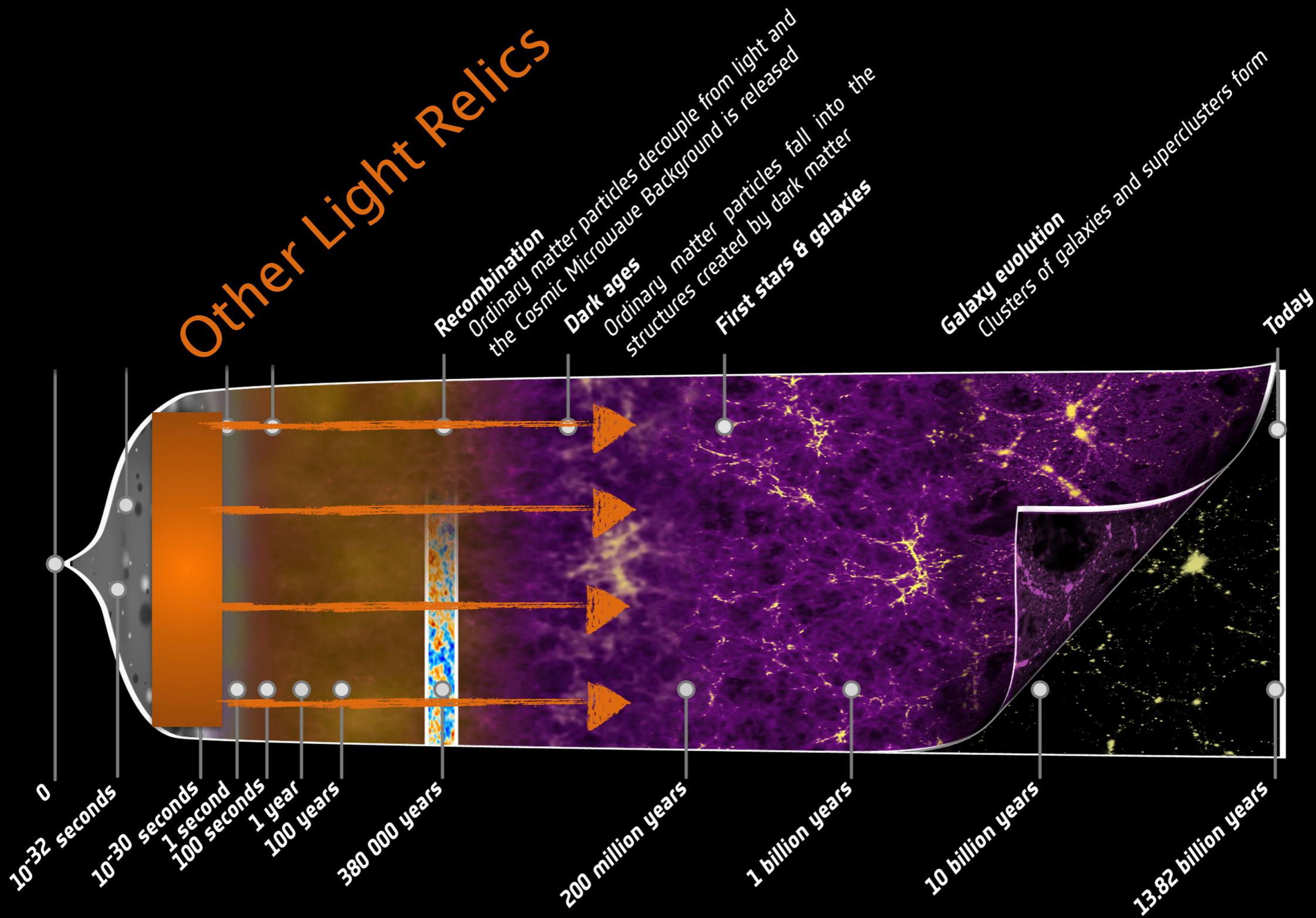
Lab measures **Standard Model** interactions

Cosmology measures gravitational interactions

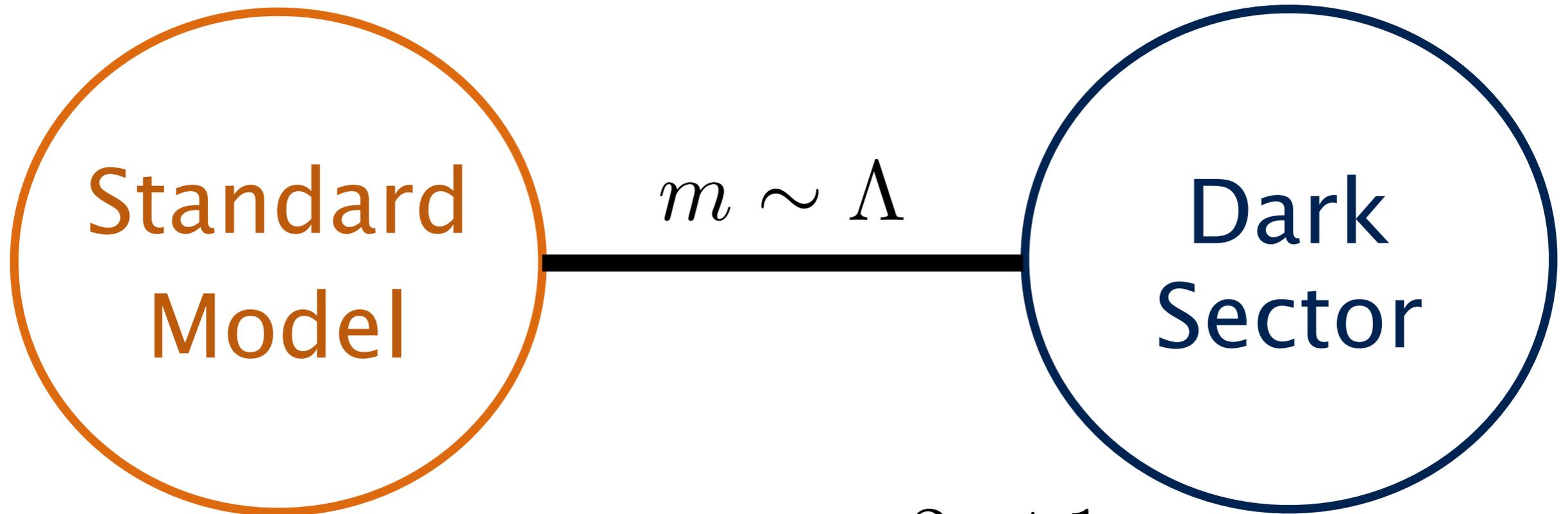
**Measures energy density of neutrino-like particles**

E.g. Sensitive to any other light thermal relic

# Other Light Relics



# Dark/Hidden Sectors



$$\Gamma_{\text{prod}} \sim \frac{T^{2n+1}}{\Lambda^{2n}}$$

E.g.

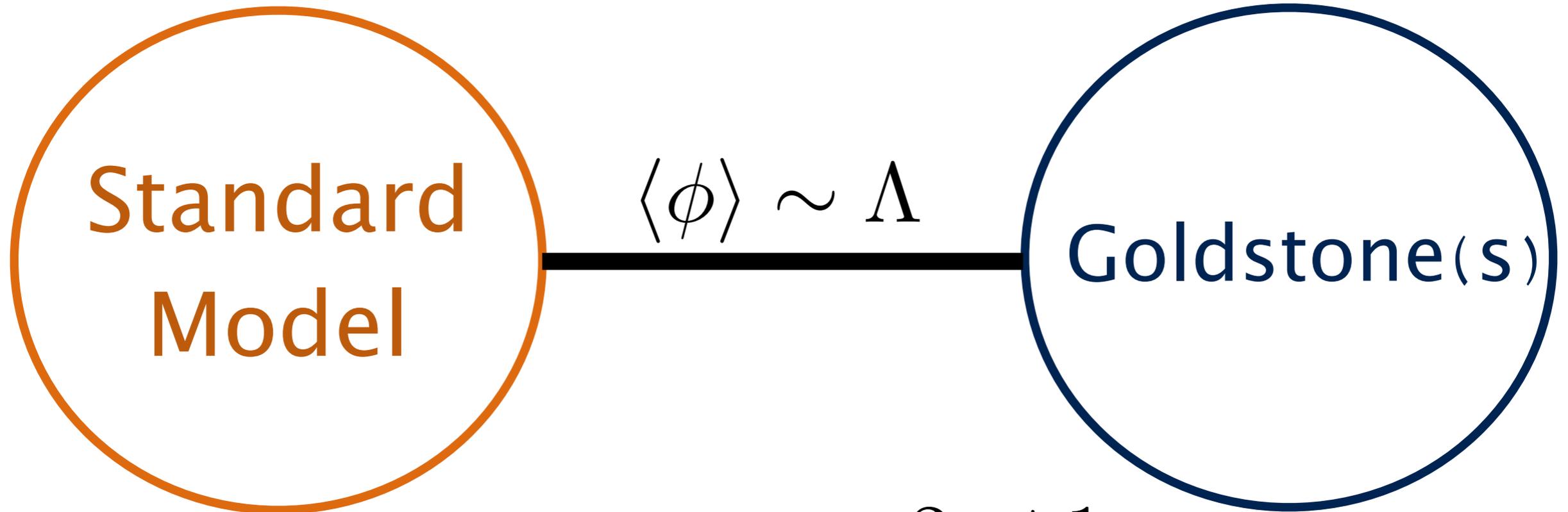
Dark Sectors

Neutral naturalness

Nnaturalness

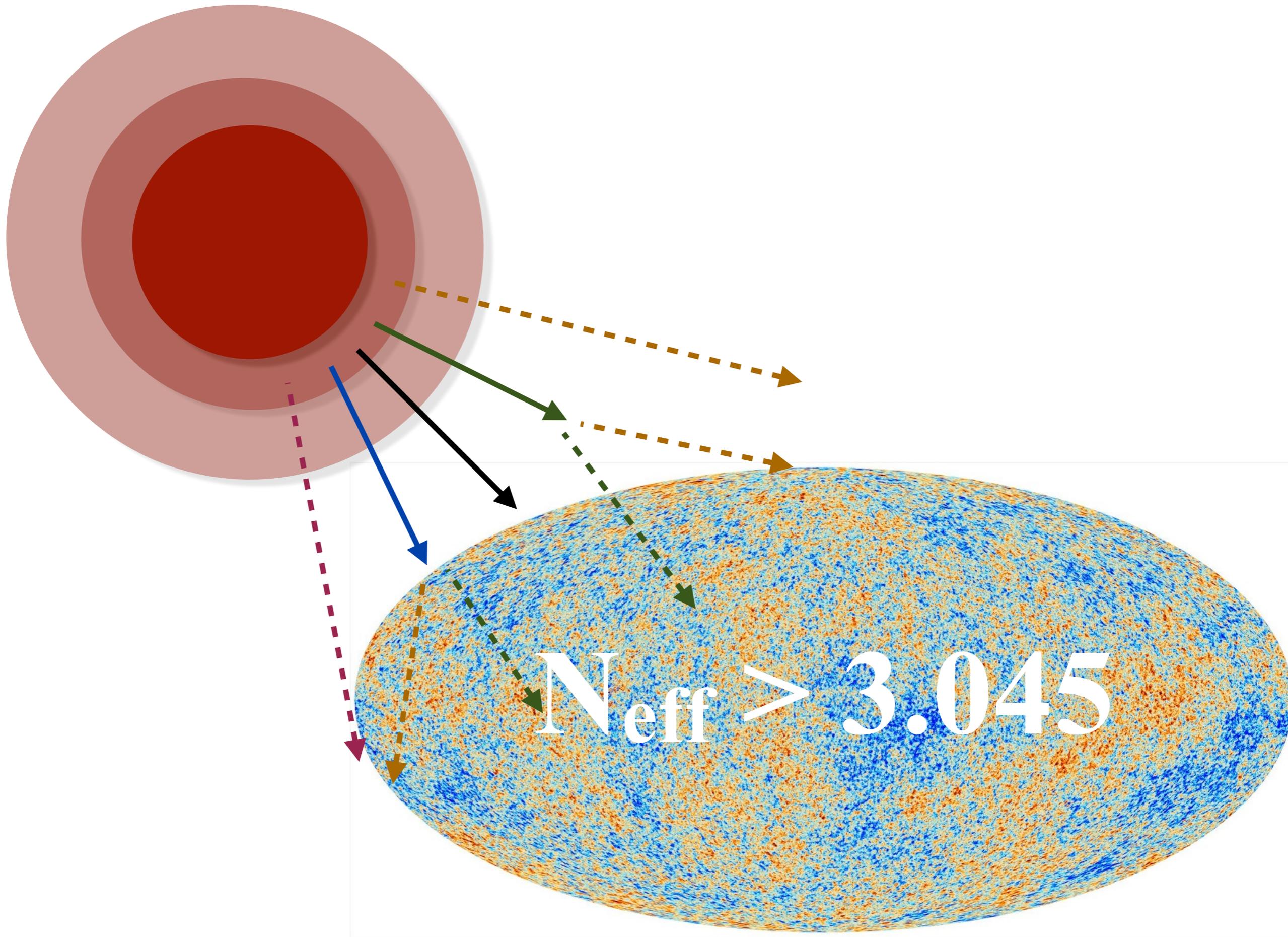
Hidden Valleys

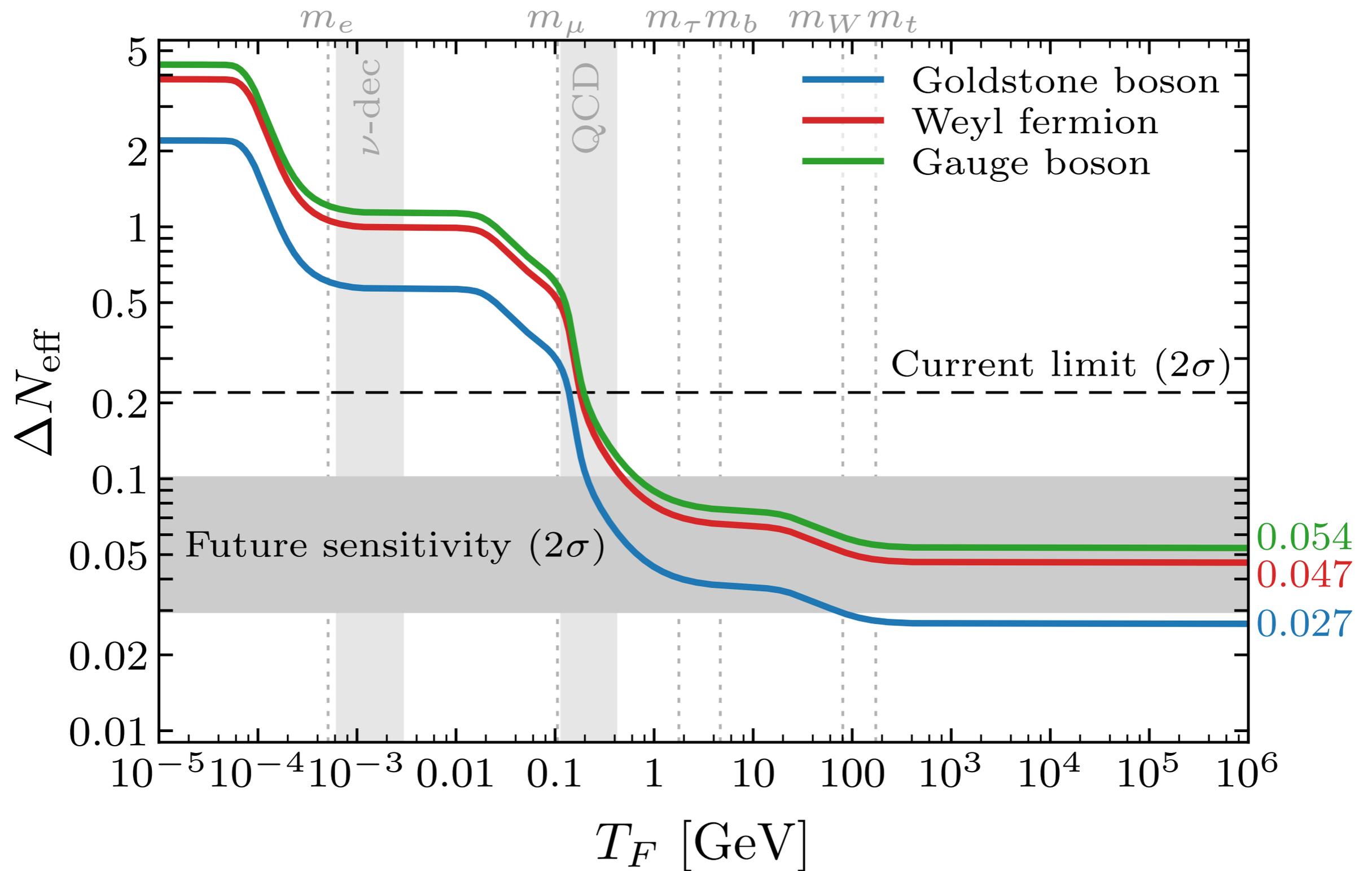
# (pseudo) Goldstone Bosons



$$\Gamma_{\text{prod}} \sim \frac{T^{2n+1}}{\Lambda^{2n}}$$

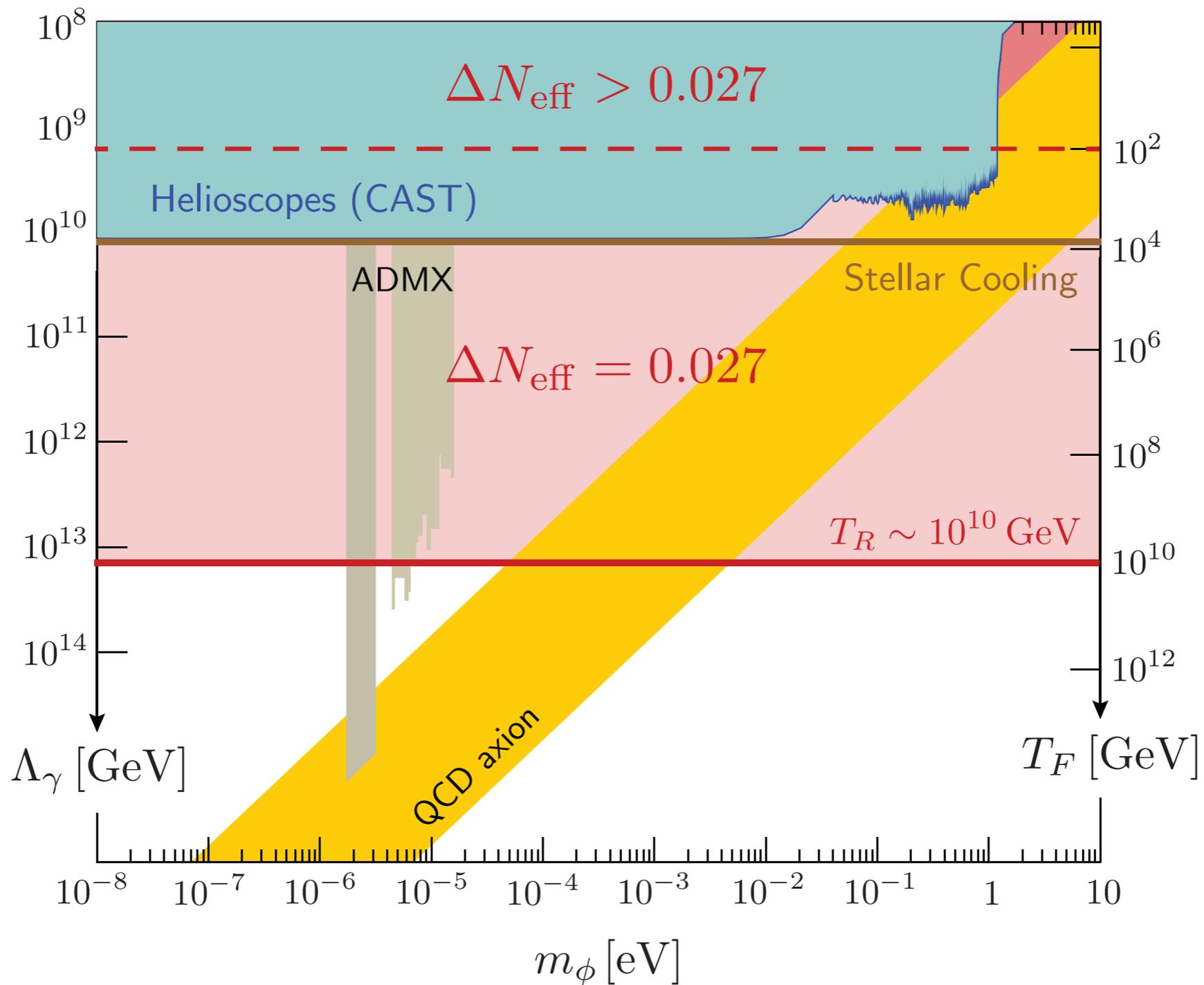
E.g.  
Axions  
Relaxions  
Familions  
Gravitino\*





# Implications for Axions

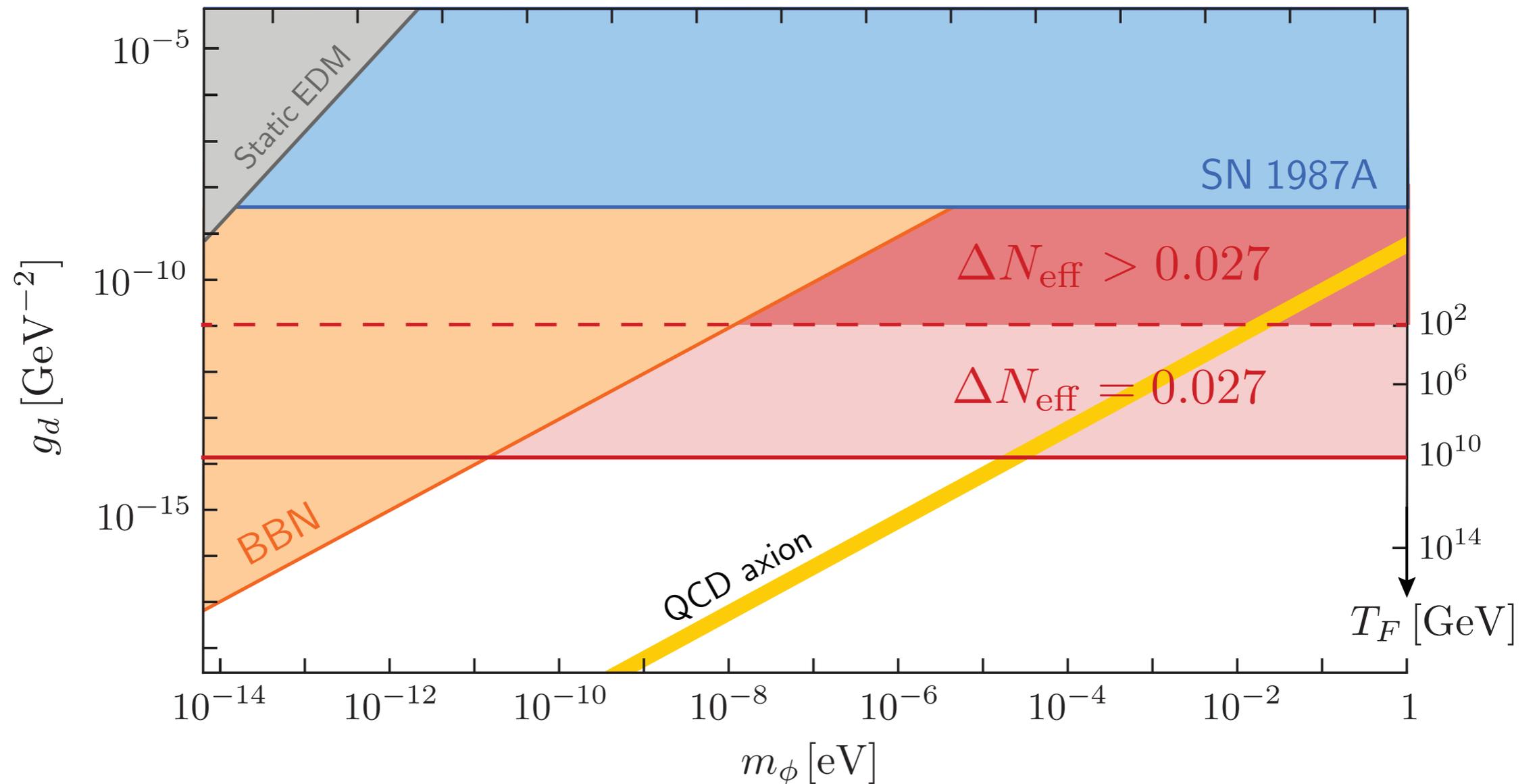
$\Lambda_\gamma$



Baumann, DG & Wallisch (2016)

# Implications for Axions

$$g_d \sim \frac{10^{-4}}{\text{GeV}} \frac{1}{\Lambda_g}$$



Baumann, DG & Wallisch (2016)

# Realistic Goals

CMB experiments like CMB-S4 & PICO can reach

$$\sigma(N_{\text{eff}}) = 0.030$$

- This is a primary science target for future CMB
- 100 GeV freeze-out for particles with spin
- Probes prior to QCD for any particle

Futuristic LSS surveys + CMB might reach

$$\sigma(N_{\text{eff}}) = 0.015$$

# Neutrino Mass



# Neutrino Mass

Neutrinos have mass

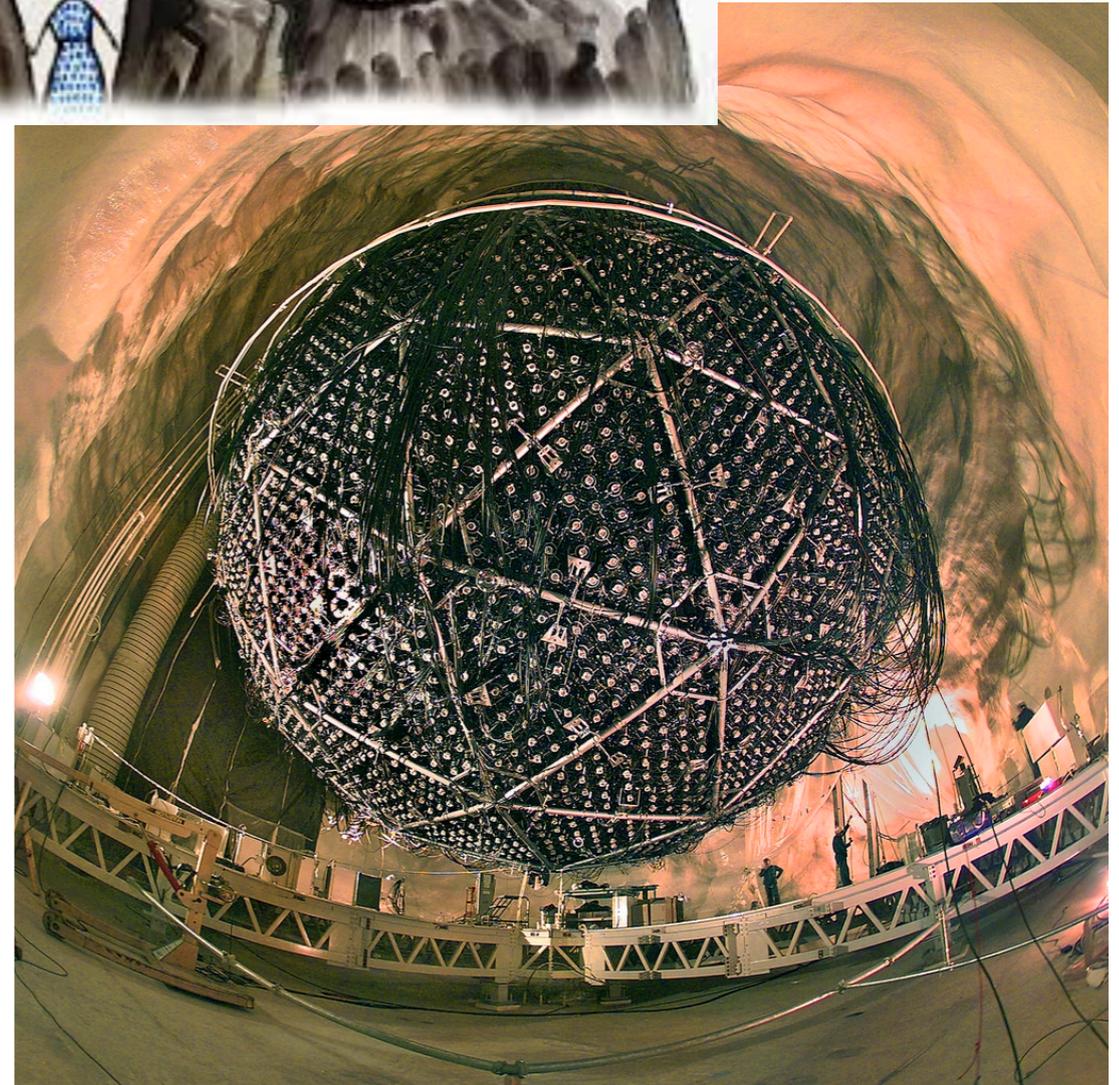
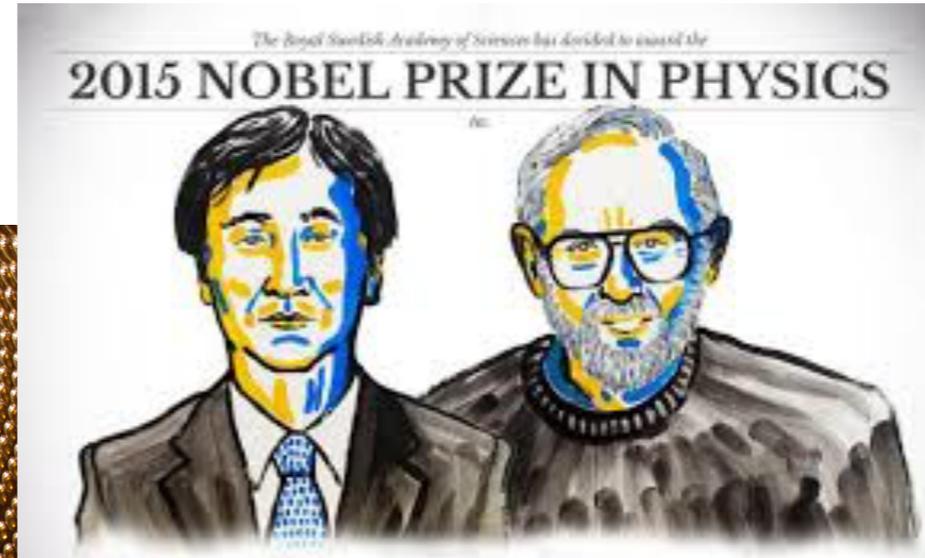
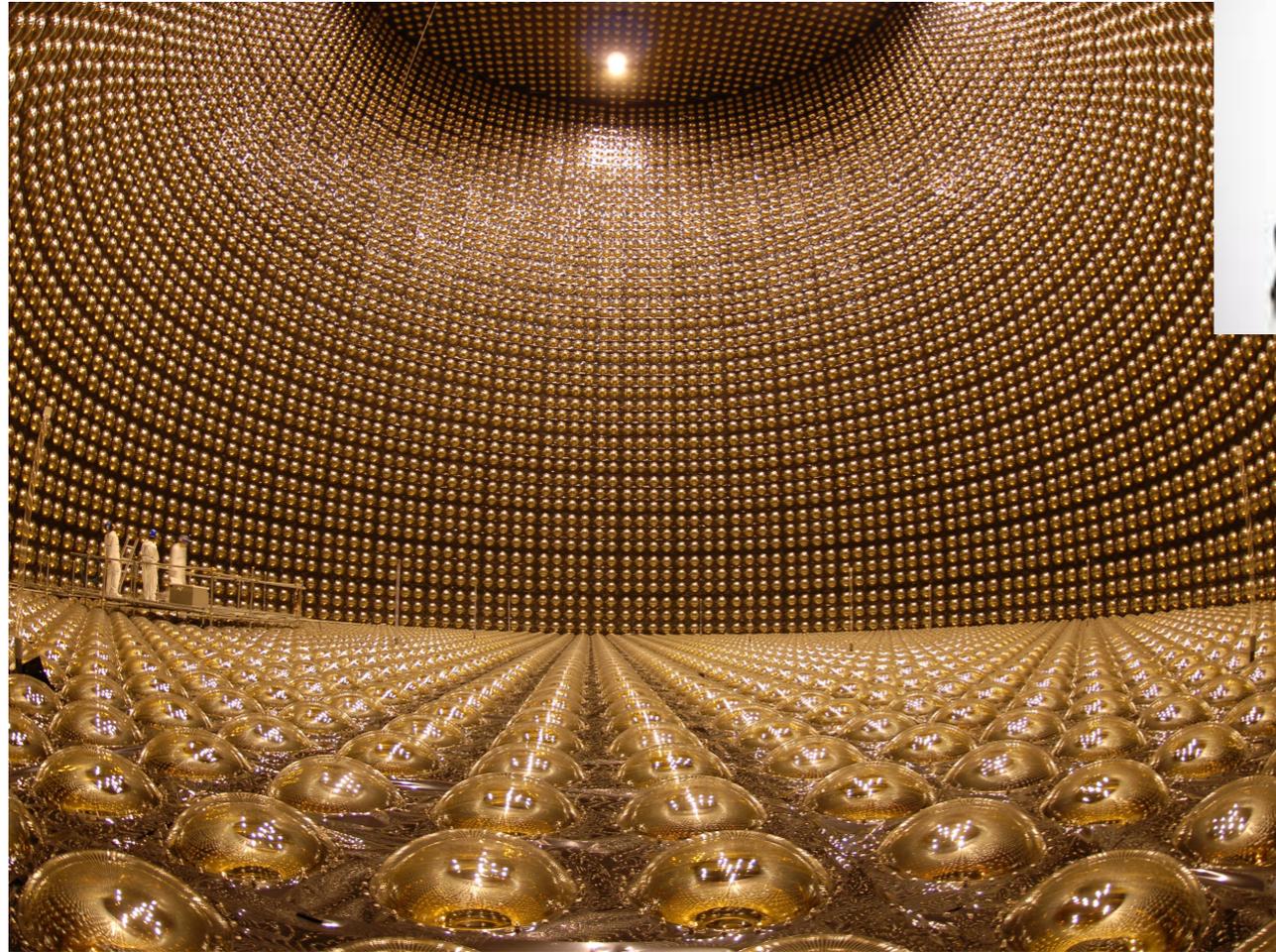
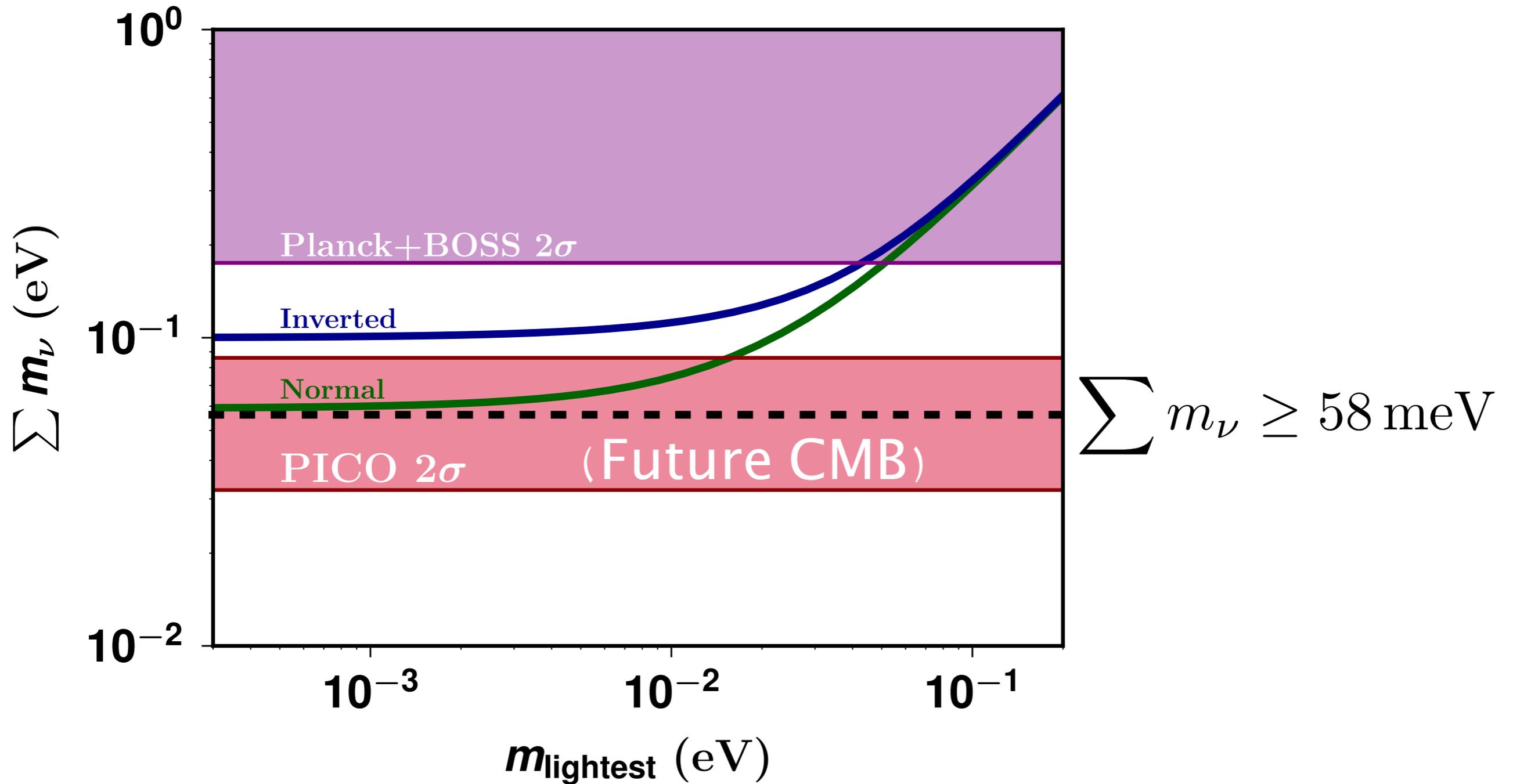


Image from Super-K ; SNO

# Neutrino Mass



# Neutrino Mass

Massive neutrinos free stream / suppress growth

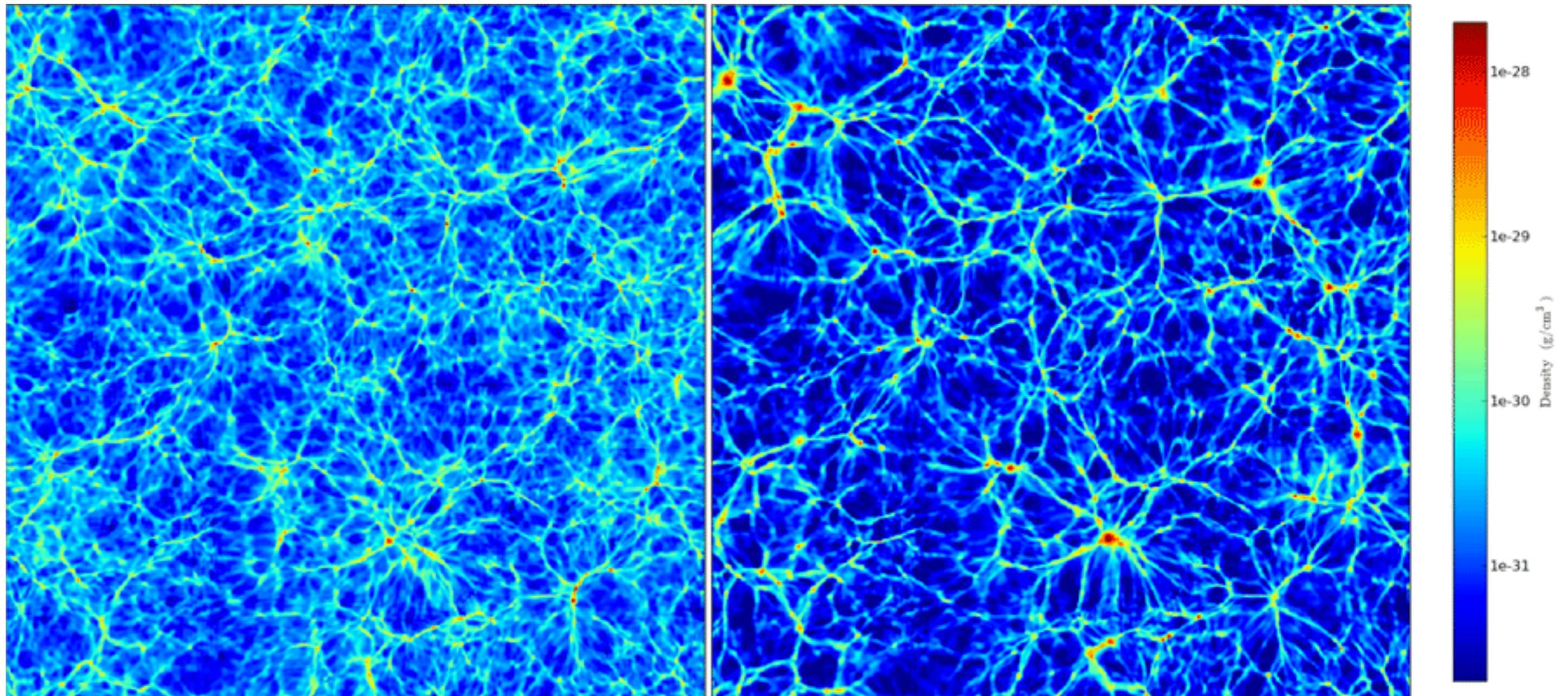
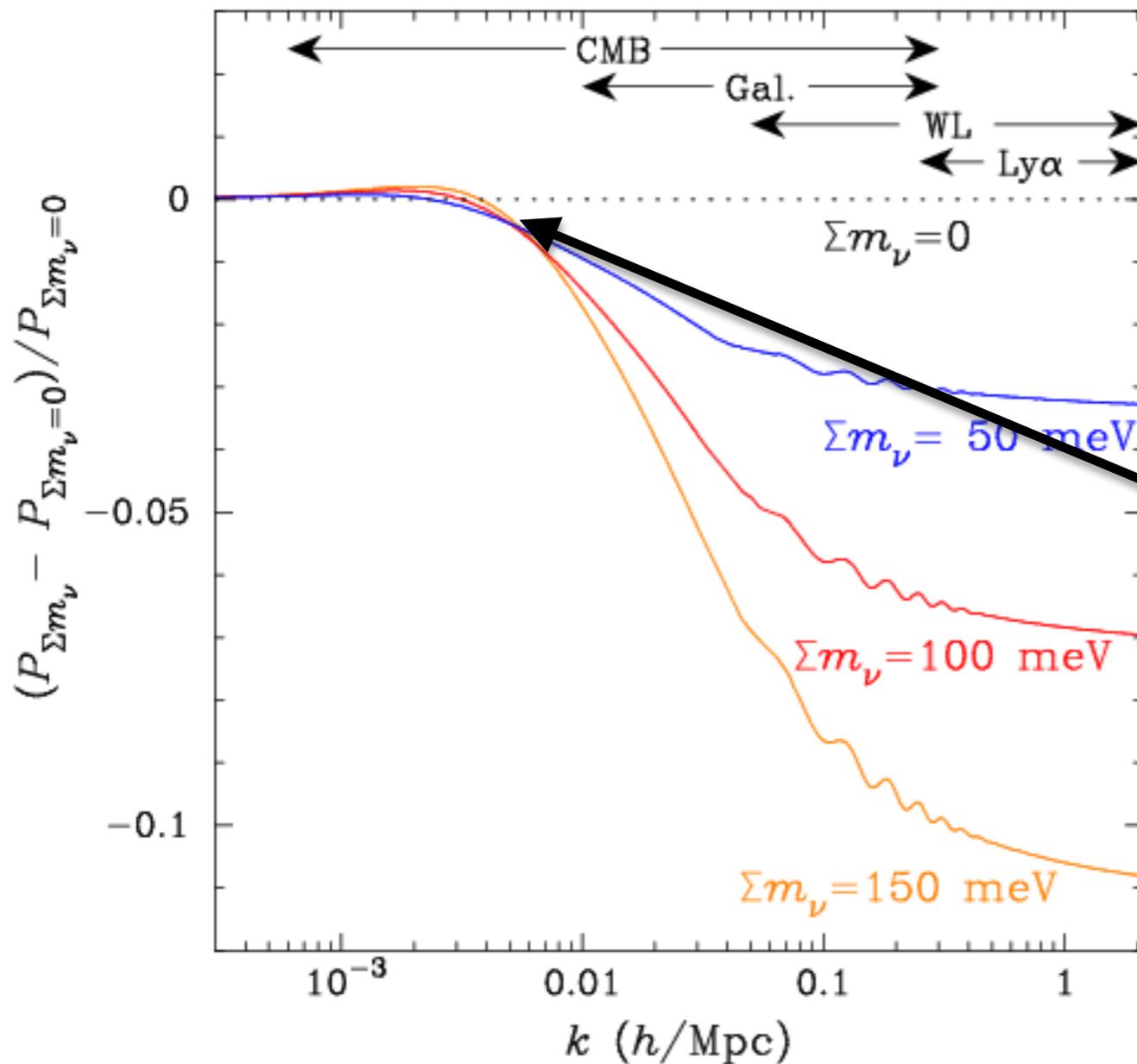


Image from Agarwal & Feldman (2010)

# Neutrino Mass

Massive neutrinos free stream / suppress growth

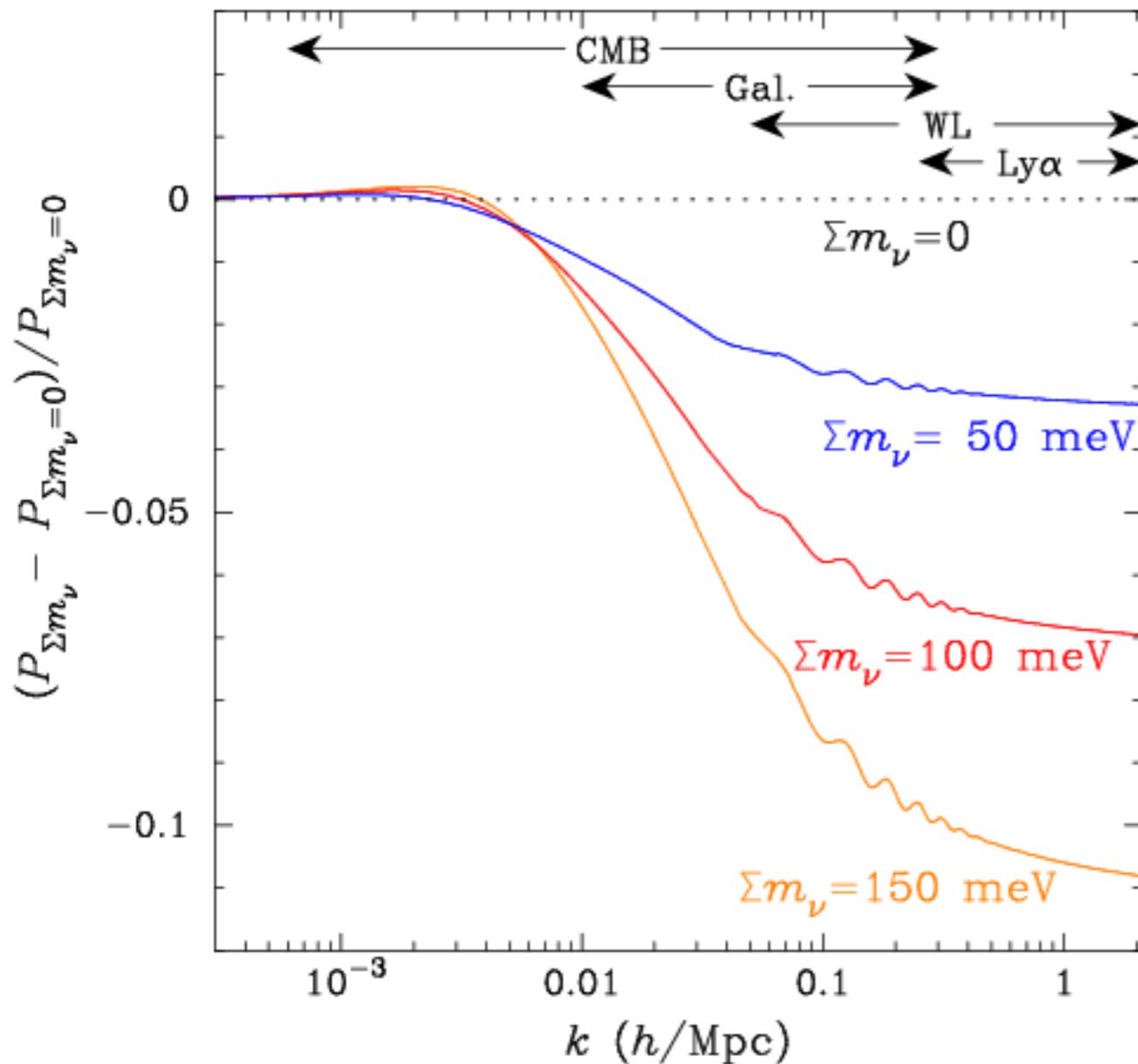


$$k_{\text{fs}} \approx 0.01 \frac{h}{\text{Mpc}} \left( \frac{m_\nu}{0.05 \text{ eV}} \right)$$

Abazajian et al (2016)

# Neutrino Mass

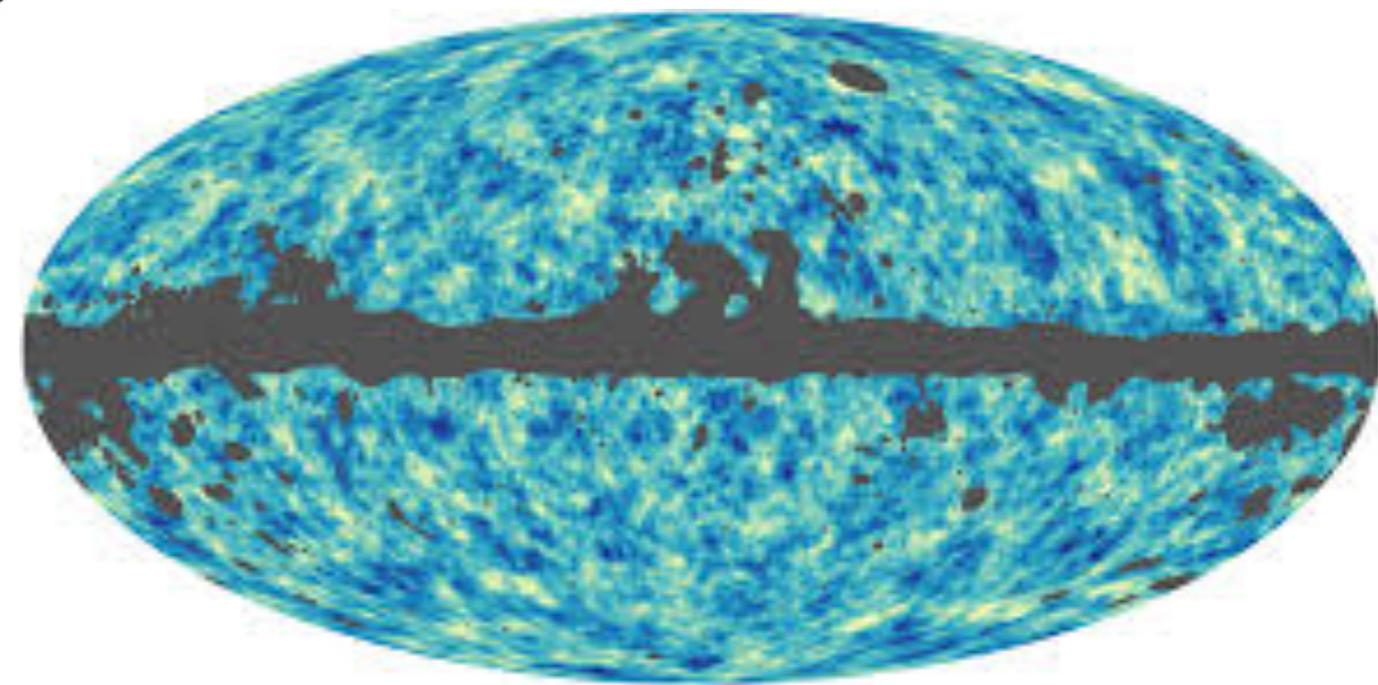
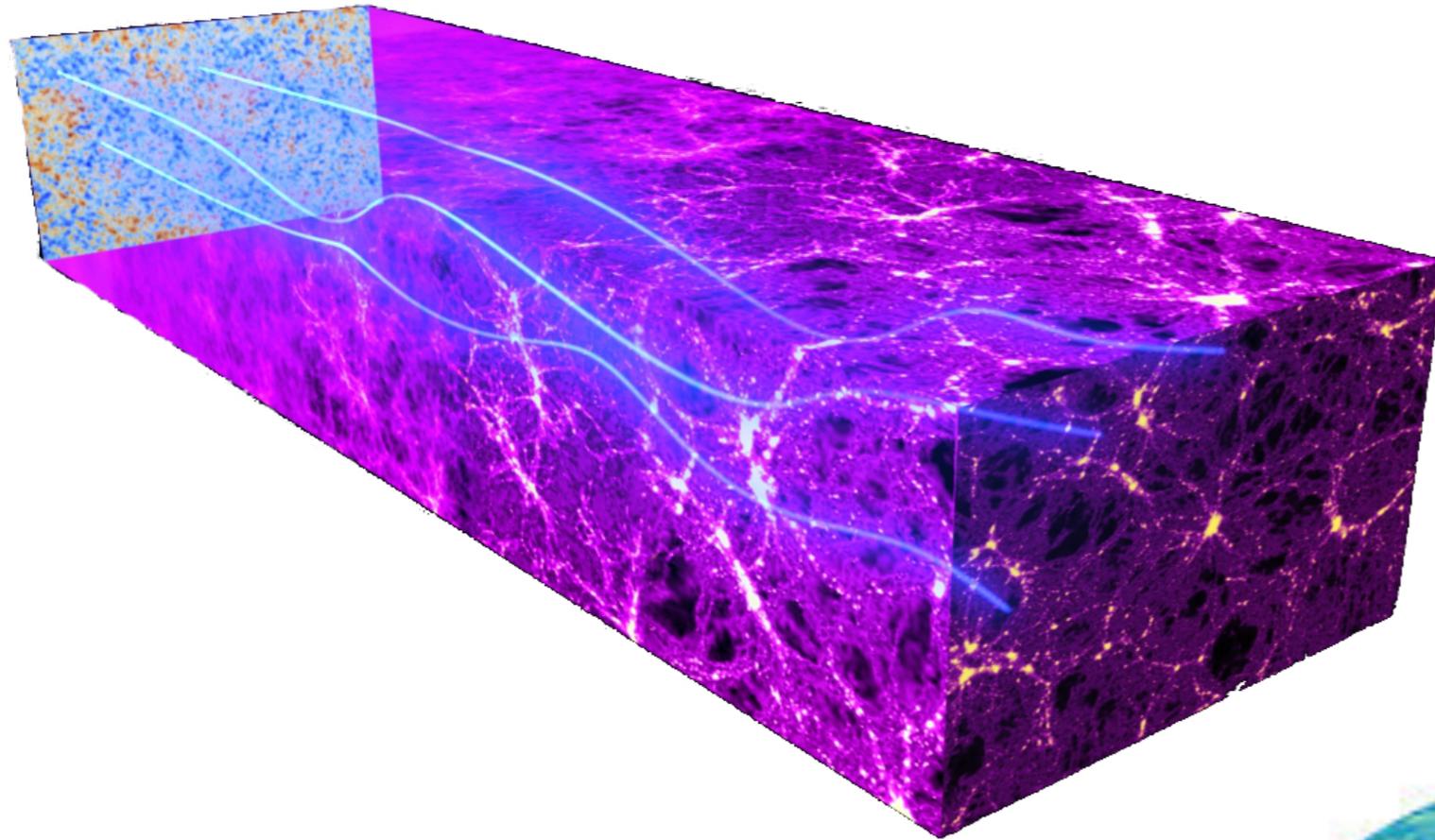
Massive neutrinos free stream / suppress growth



$$\approx -\frac{6}{\Omega_m h^2} \frac{\Sigma m_\nu}{93 \text{ eV}}$$

Abazajian et al (2016)

# Cosmological Observables

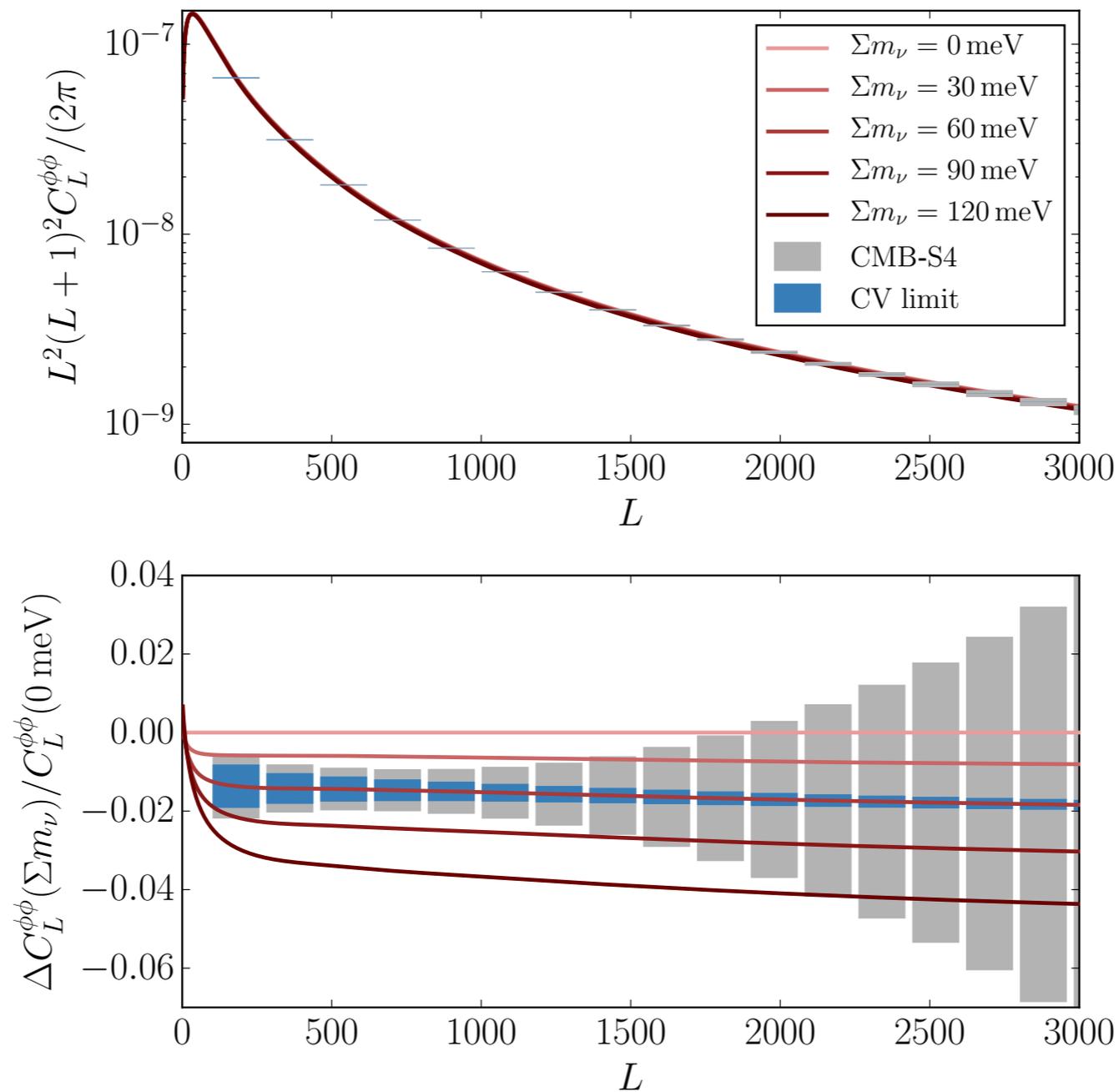


Images from ESA



# Cosmological Observables

Hard because we don't measure  $k_{fs}$



# Cosmological Observables

We need to measure 3 numbers:

(1) (dark) matter power spectrum – lensing

$$P_{\text{lensing}} \propto \Omega_m^2 \times A_s$$

(2) High accuracy matter abundance – BAO

(3) Primordial Amplitude of Fluctuations – CMB

With planned observations: 1–3 are easiest–hardest

# Realistic Goals

Data we have in hand + DESI BAO can reach

$$\sigma\left(\sum m_\nu\right) \approx 30 \text{ meV}$$

95% exclusion of  $\sum m_\nu = 0$  for minimum mass

With improved measurements of reionization:

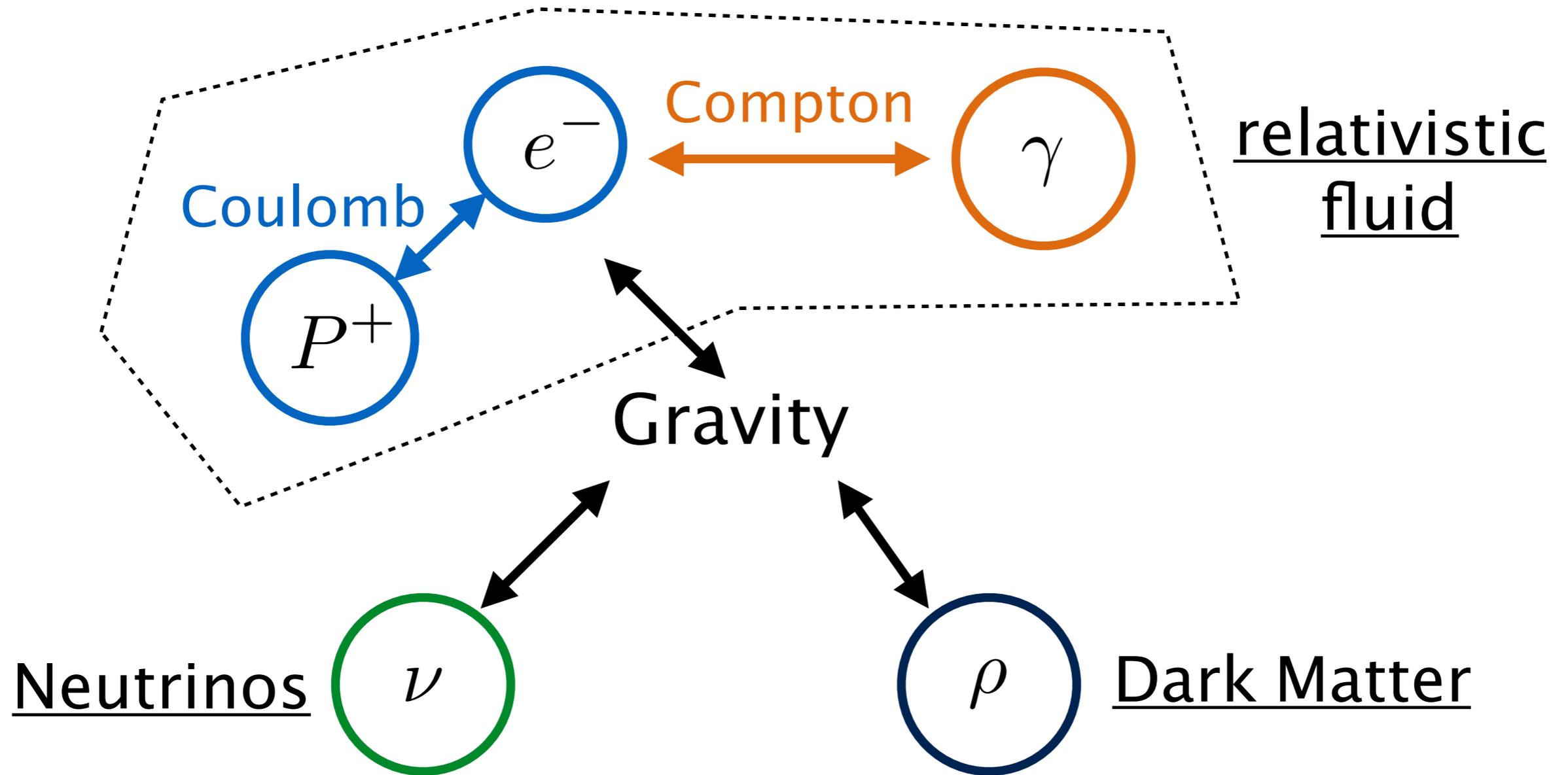
$$\sigma\left(\sum m_\nu\right) < 15 \text{ meV}$$

Possible with a CMB satellite (e.g. LiteBird, PICO)

# Dark Matter

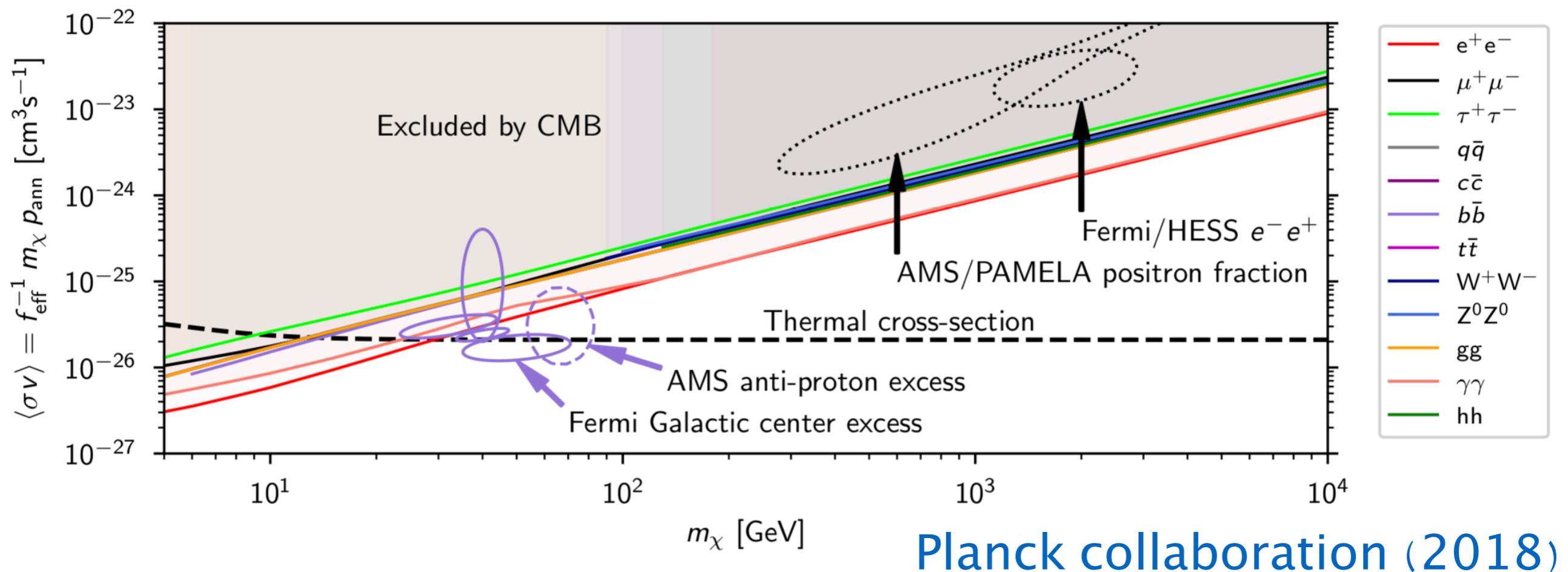


# Dark Matter Interactions



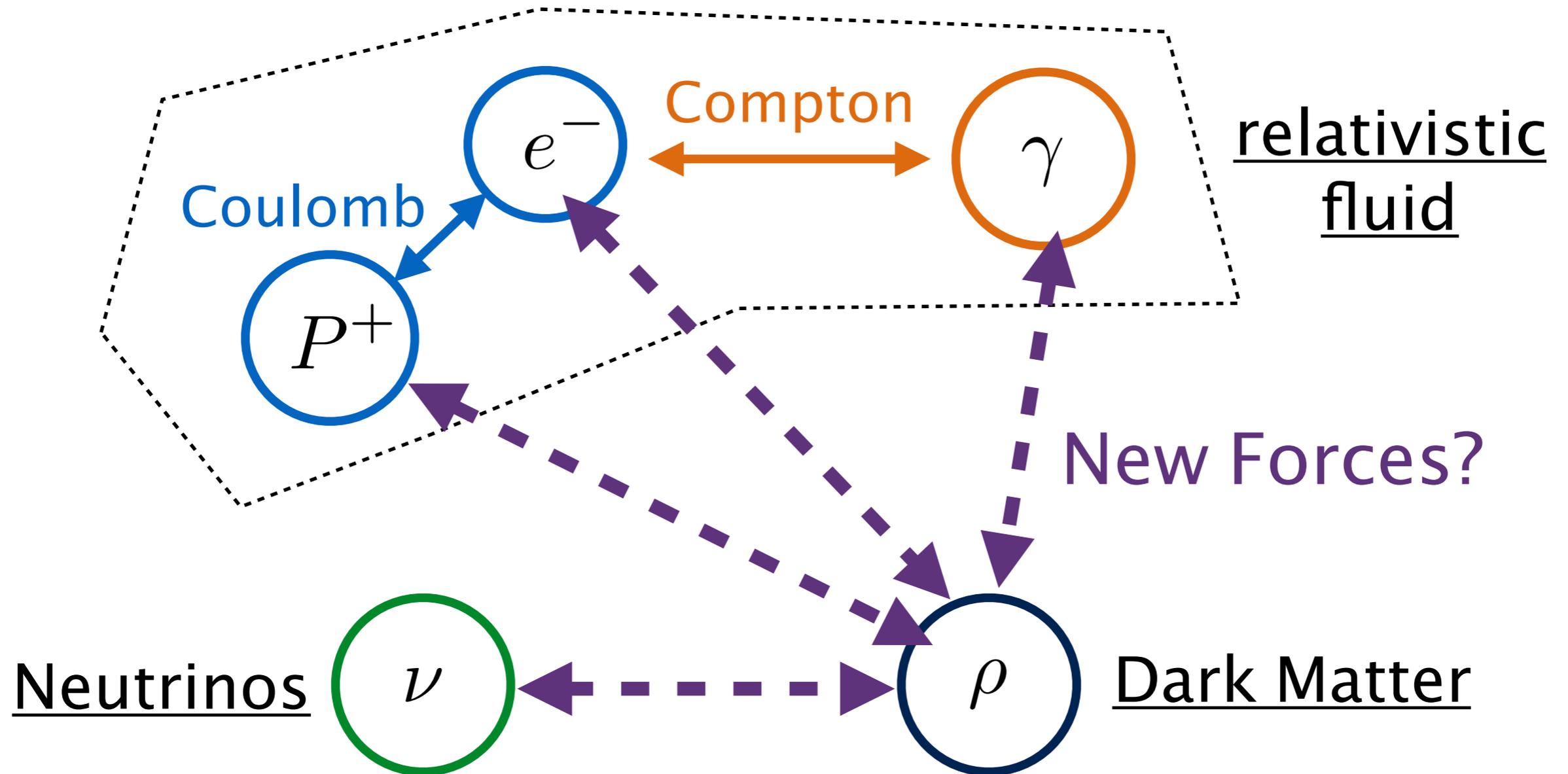
# Dark Matter Annihilation

CMB gives a powerful model-independent constraint

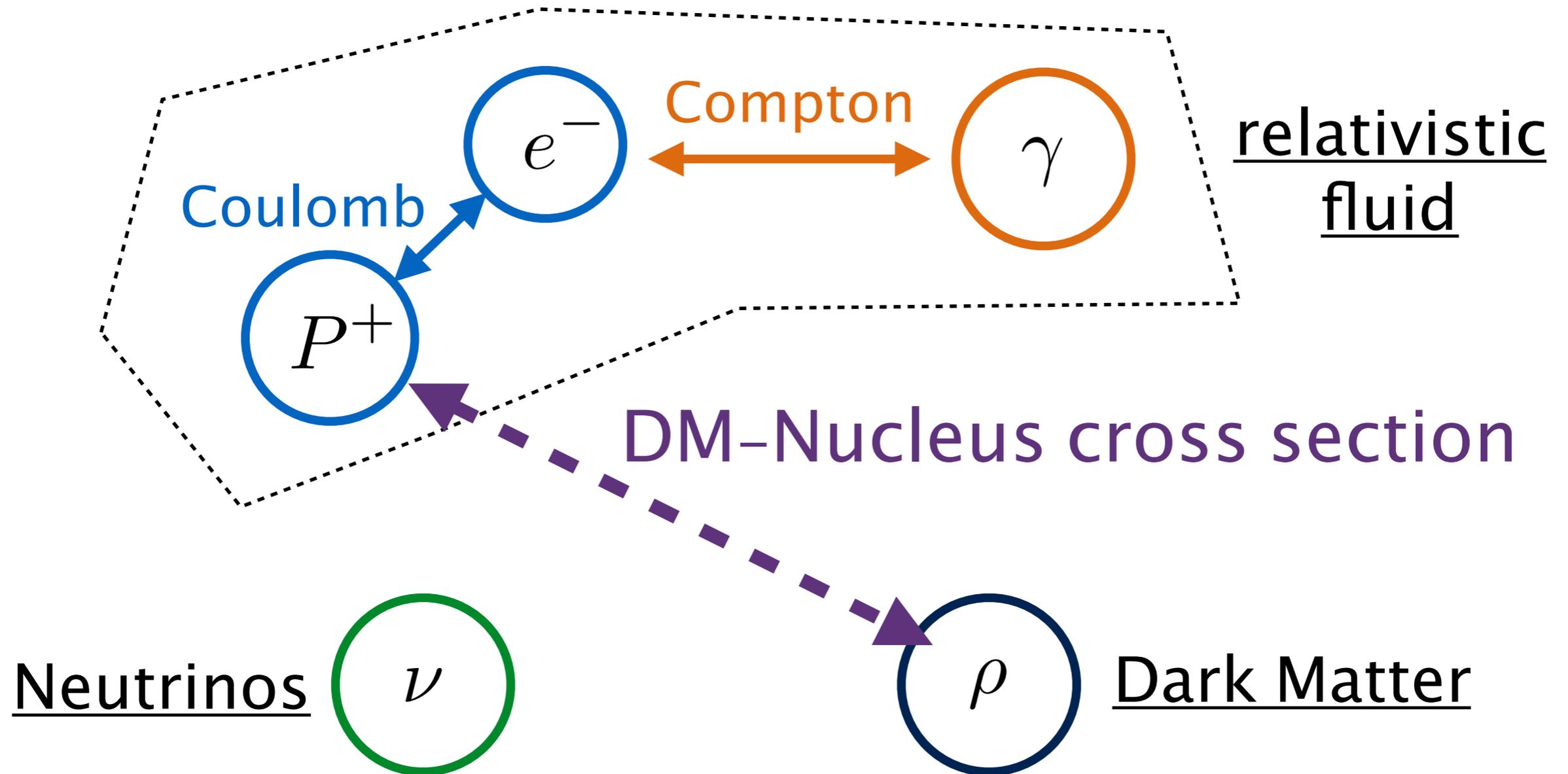


Planck has saturated CMB capabilities

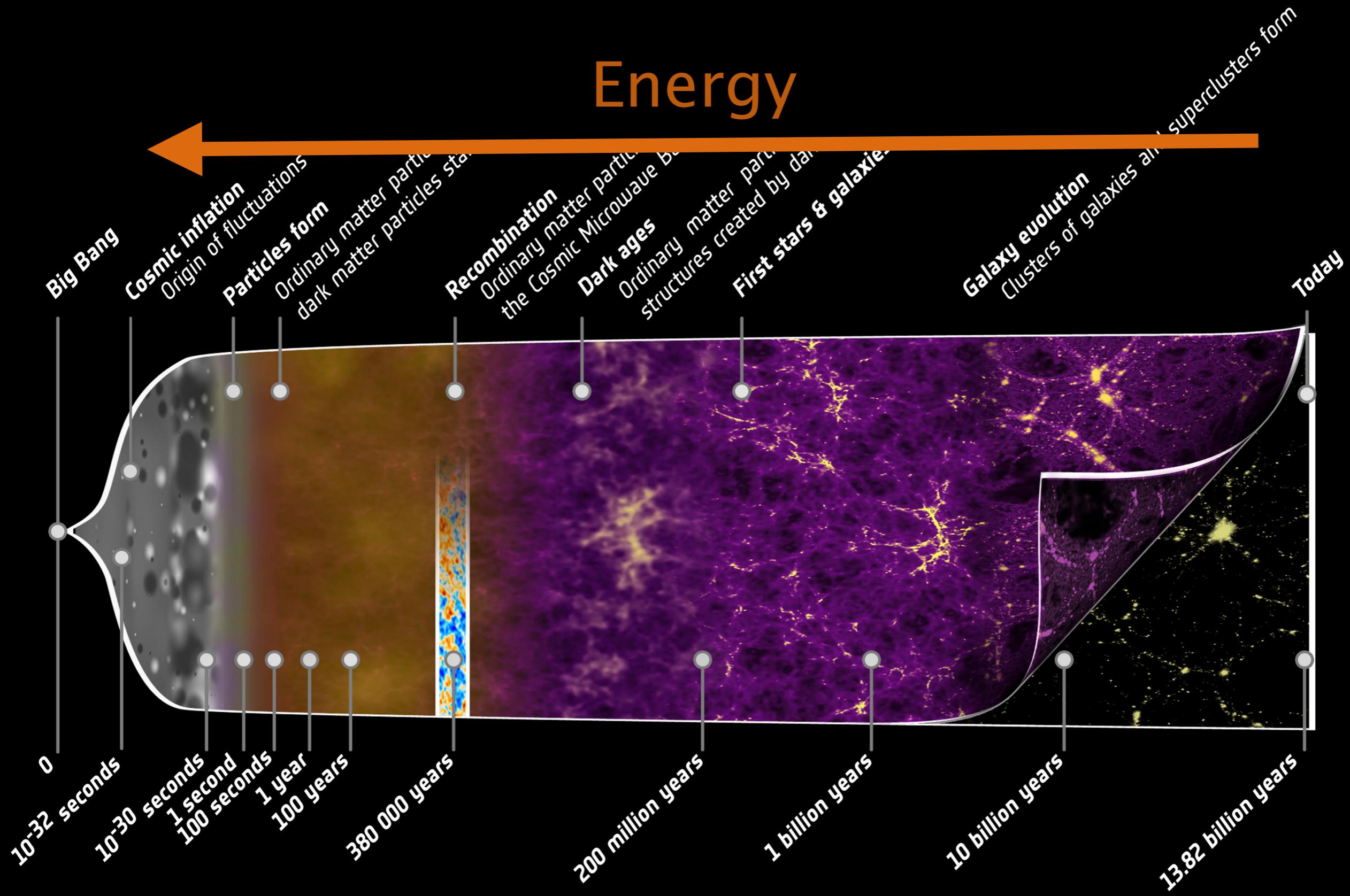
# Dark Matter Interactions

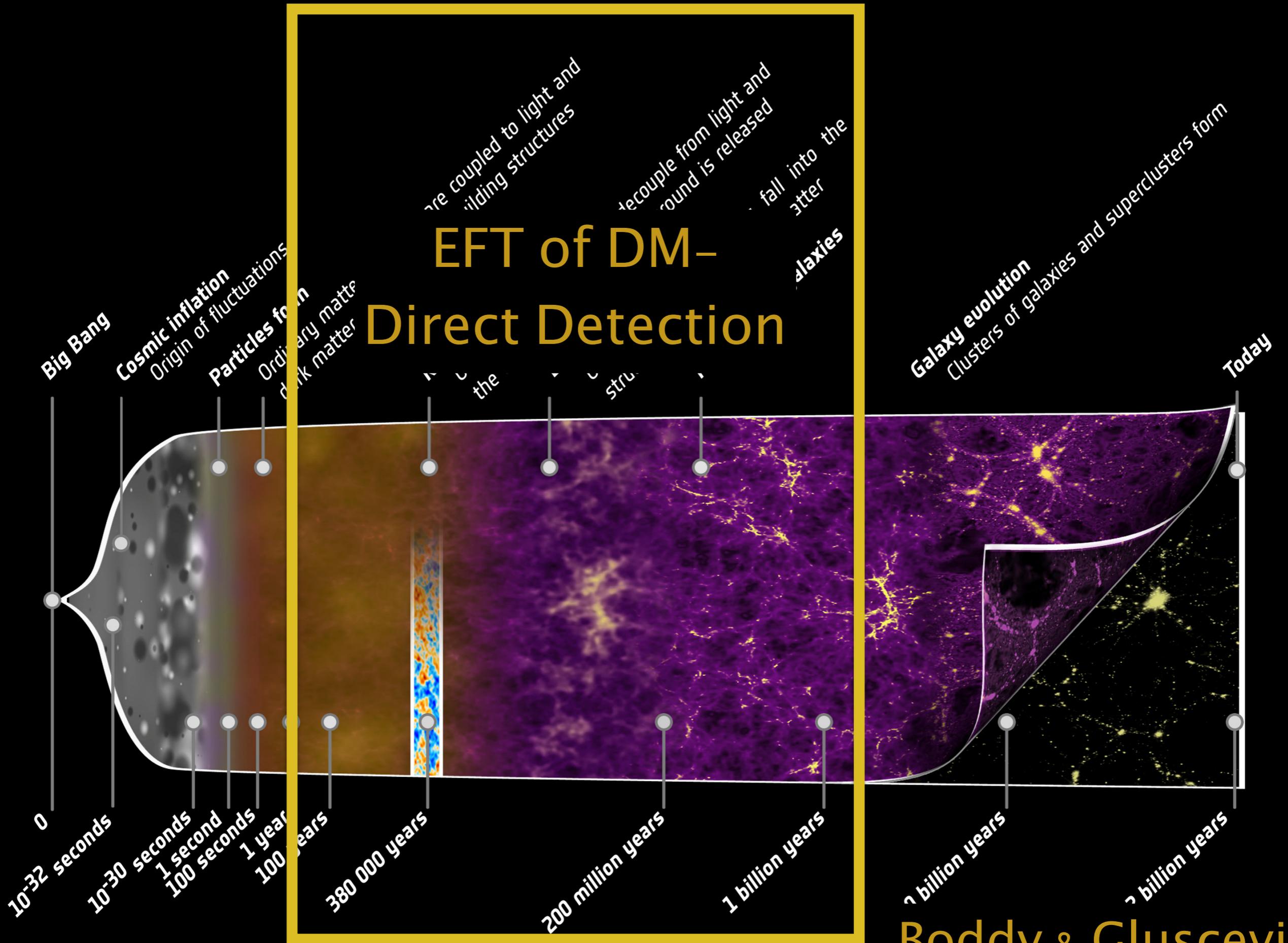


# DM-Baryon Scattering



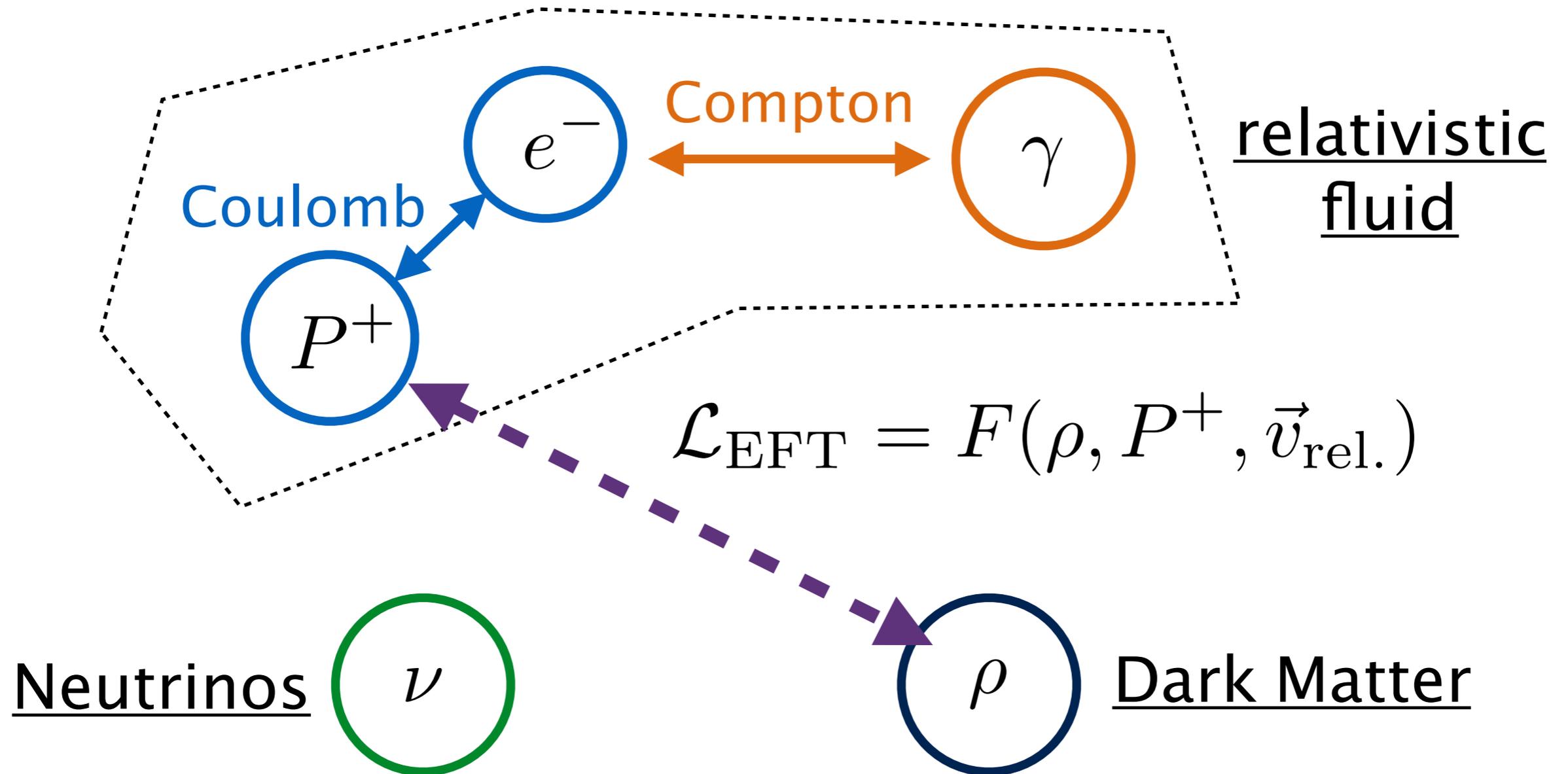
# Energy



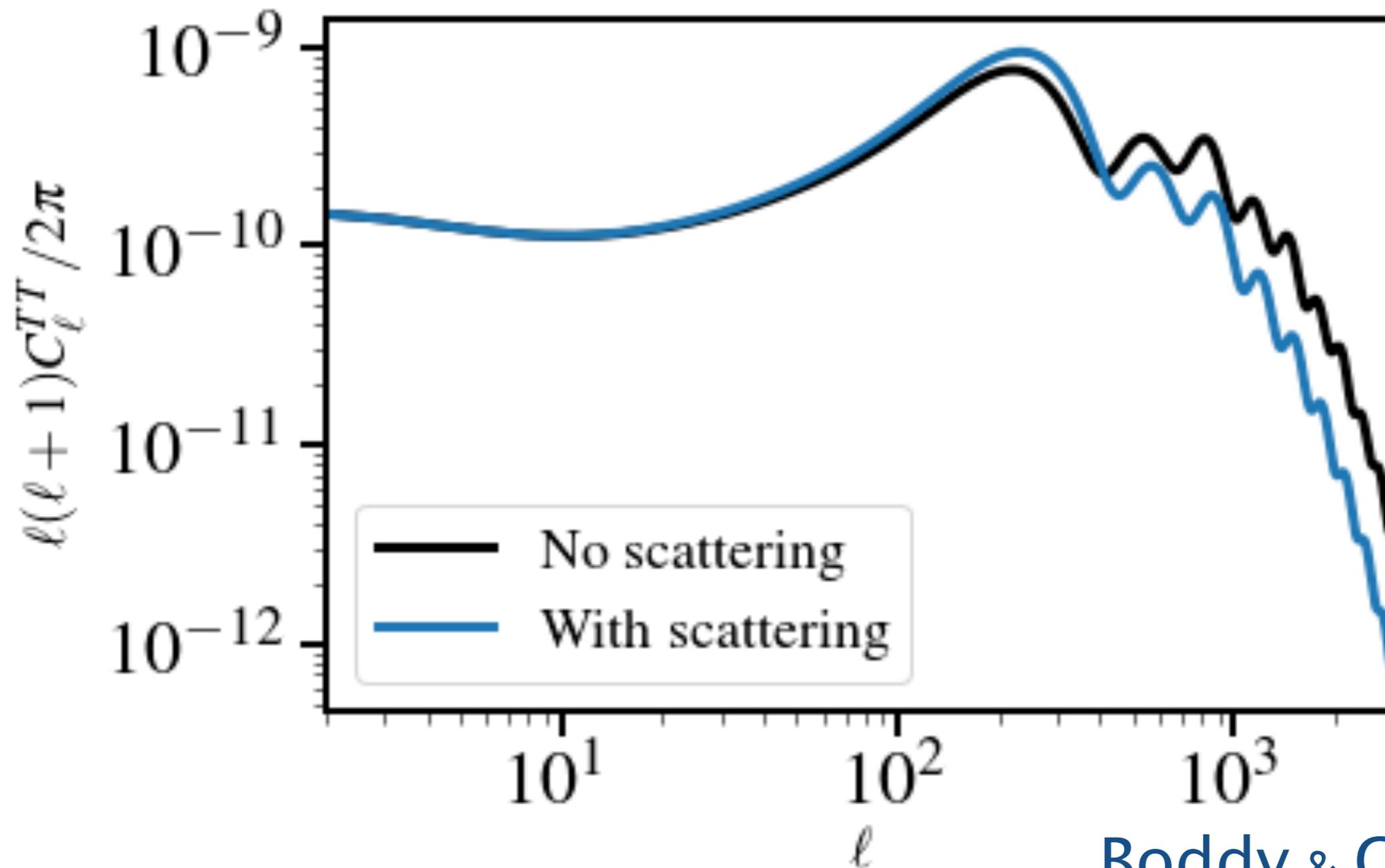


**Boddy & Gluscevic**

# EFT of DM-Direct Detection



# EFT of DM-Direct Detection



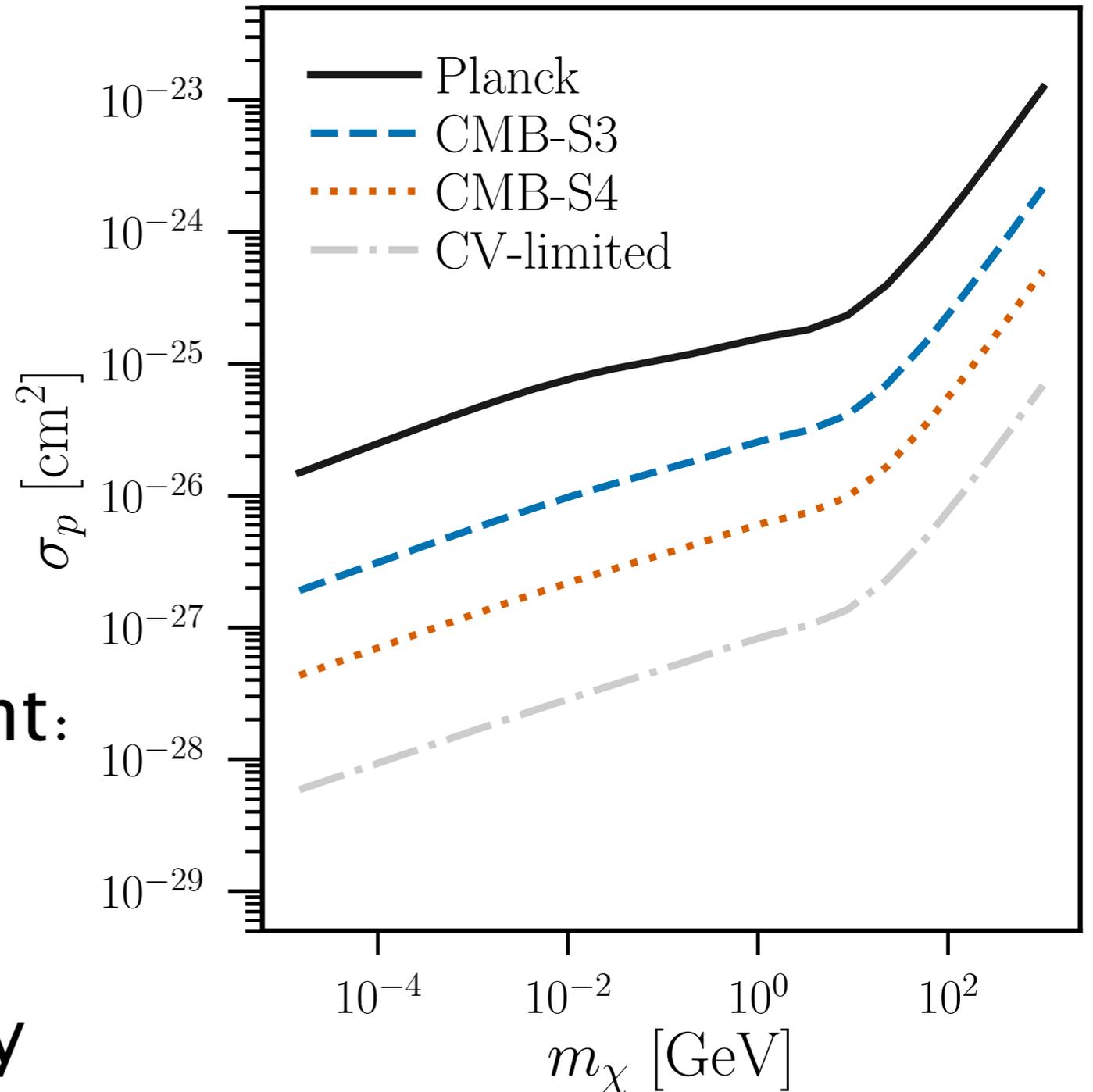
Boddy & Gluscevic

# EFT of DM-Direct Detection

Significant Improvements  
expected in CMB

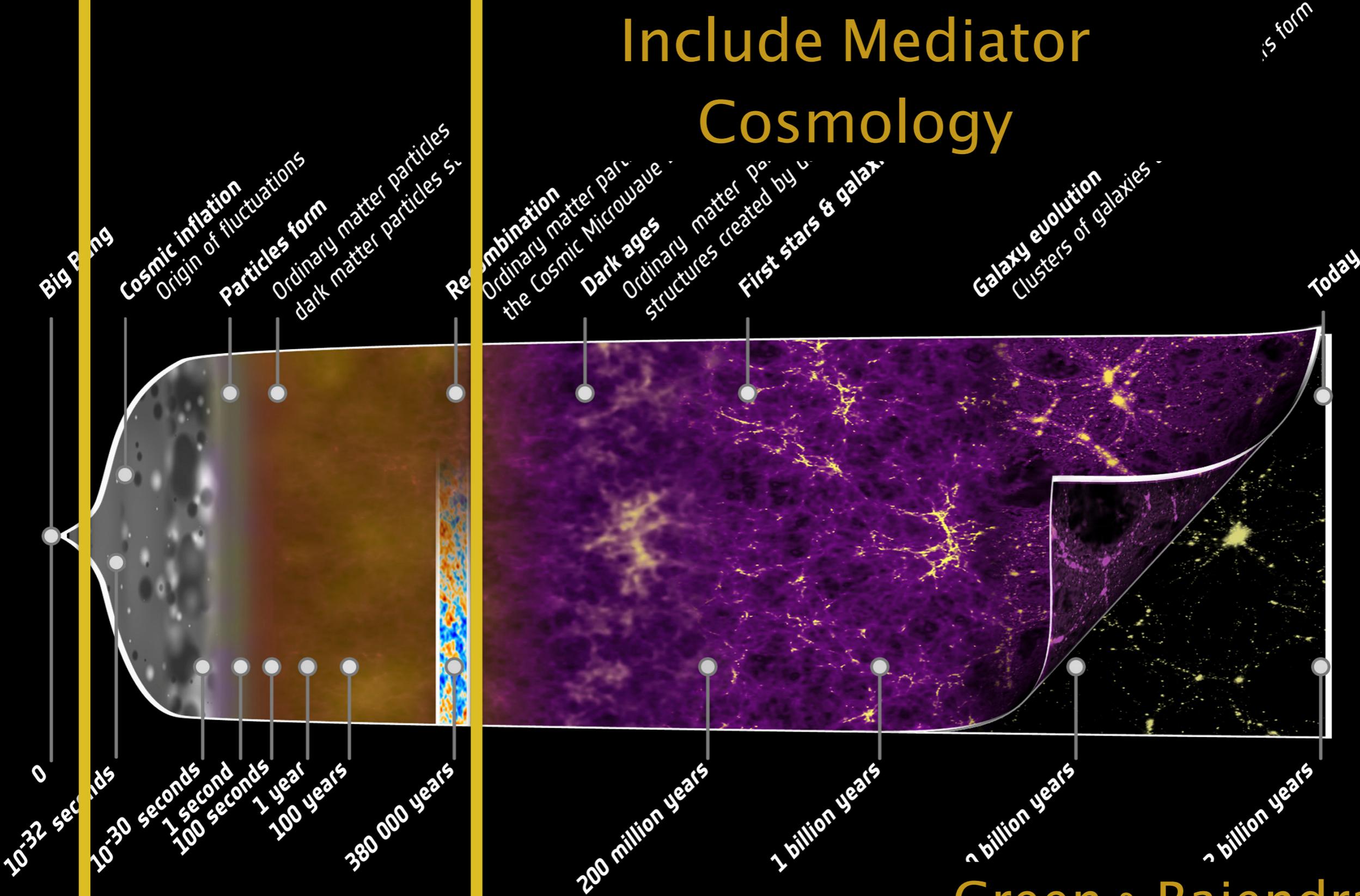
Driven by lensing maps +  
tighter LCDM params

Totally model independent:  
Literally measuring DM-B  
cross-section. No  
uncertainty on DM density



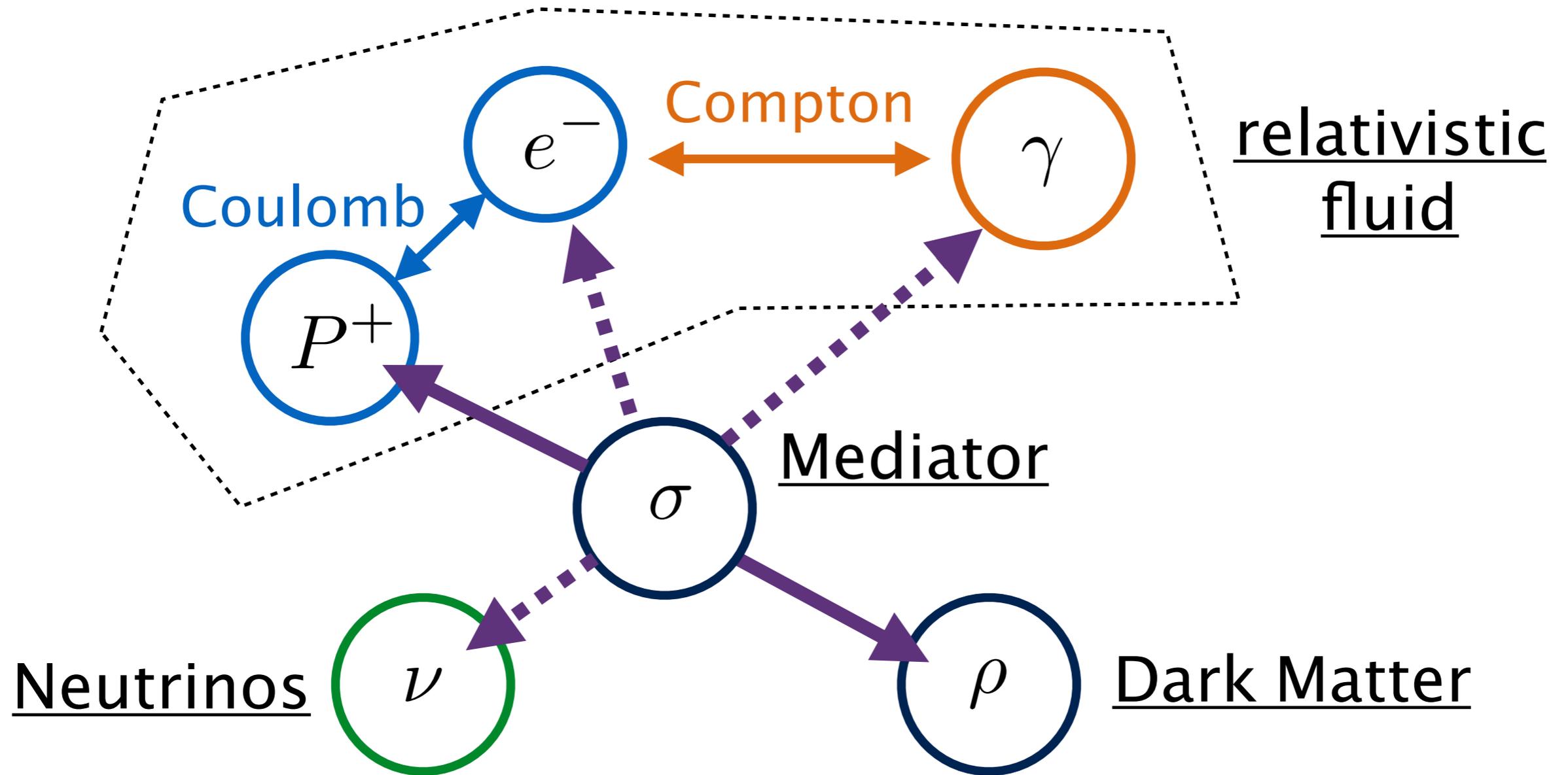
Boddy & Gluscevic

# Simplified Models: Include Mediator Cosmology



Green & Rajendran

# Simplified Models: Include Mediator



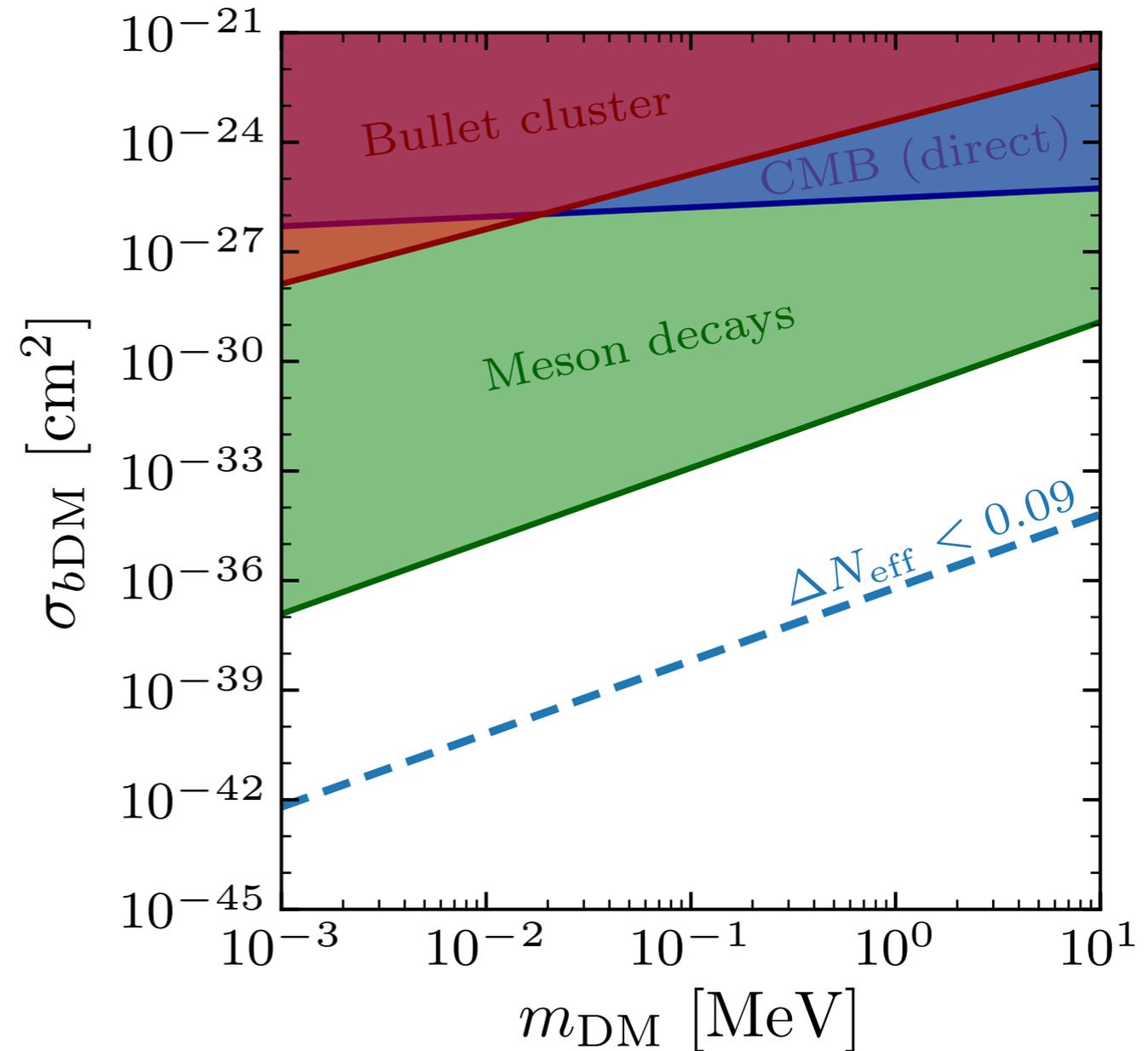
# Simplified Models: Include Mediator

More model dependent:  
Constraint depends on  
mediator

Current data strongly limits  
electron and photon  
couplings

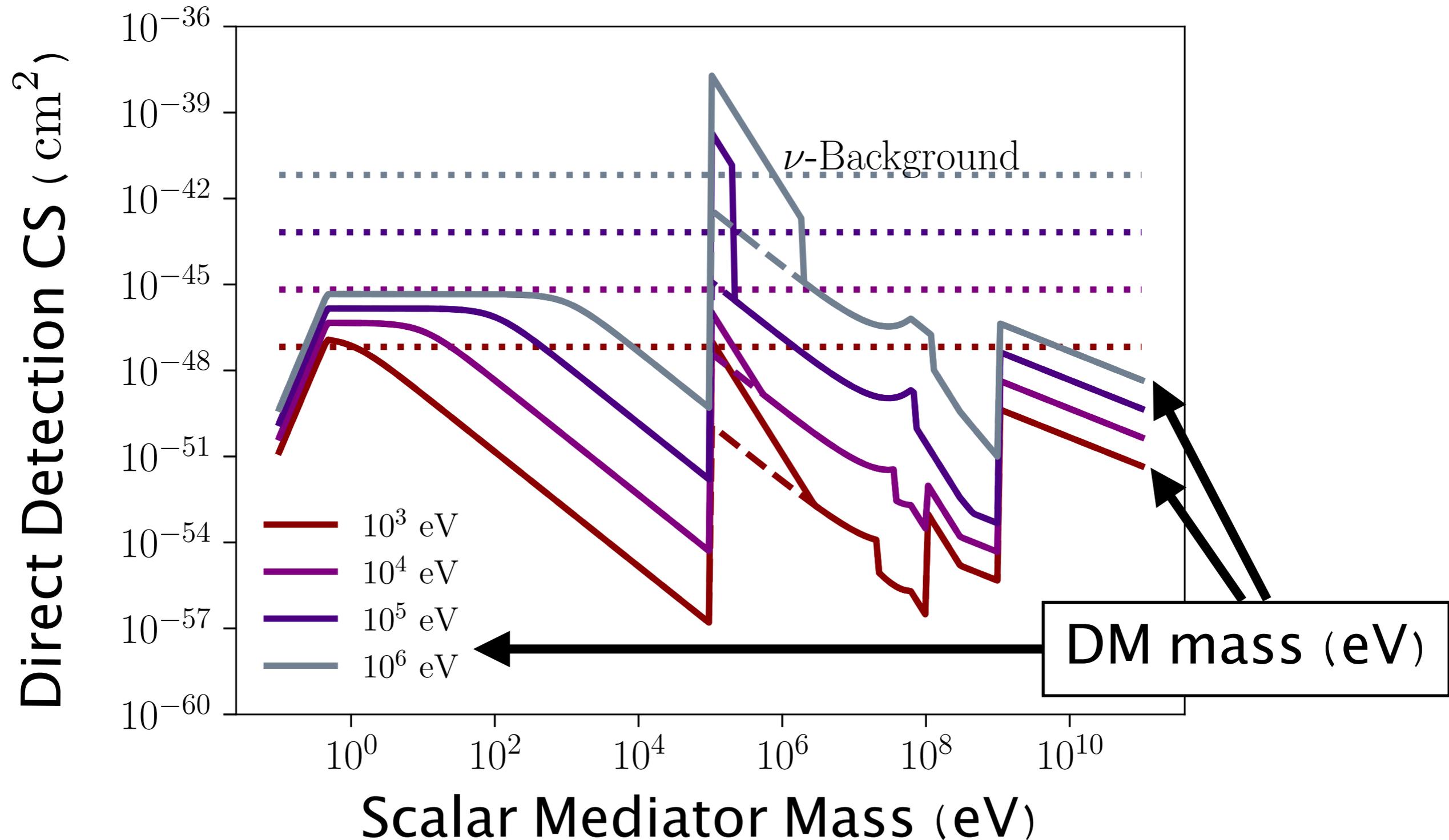
Future will strongly limit  
nuclear couplings

Complimentary probe



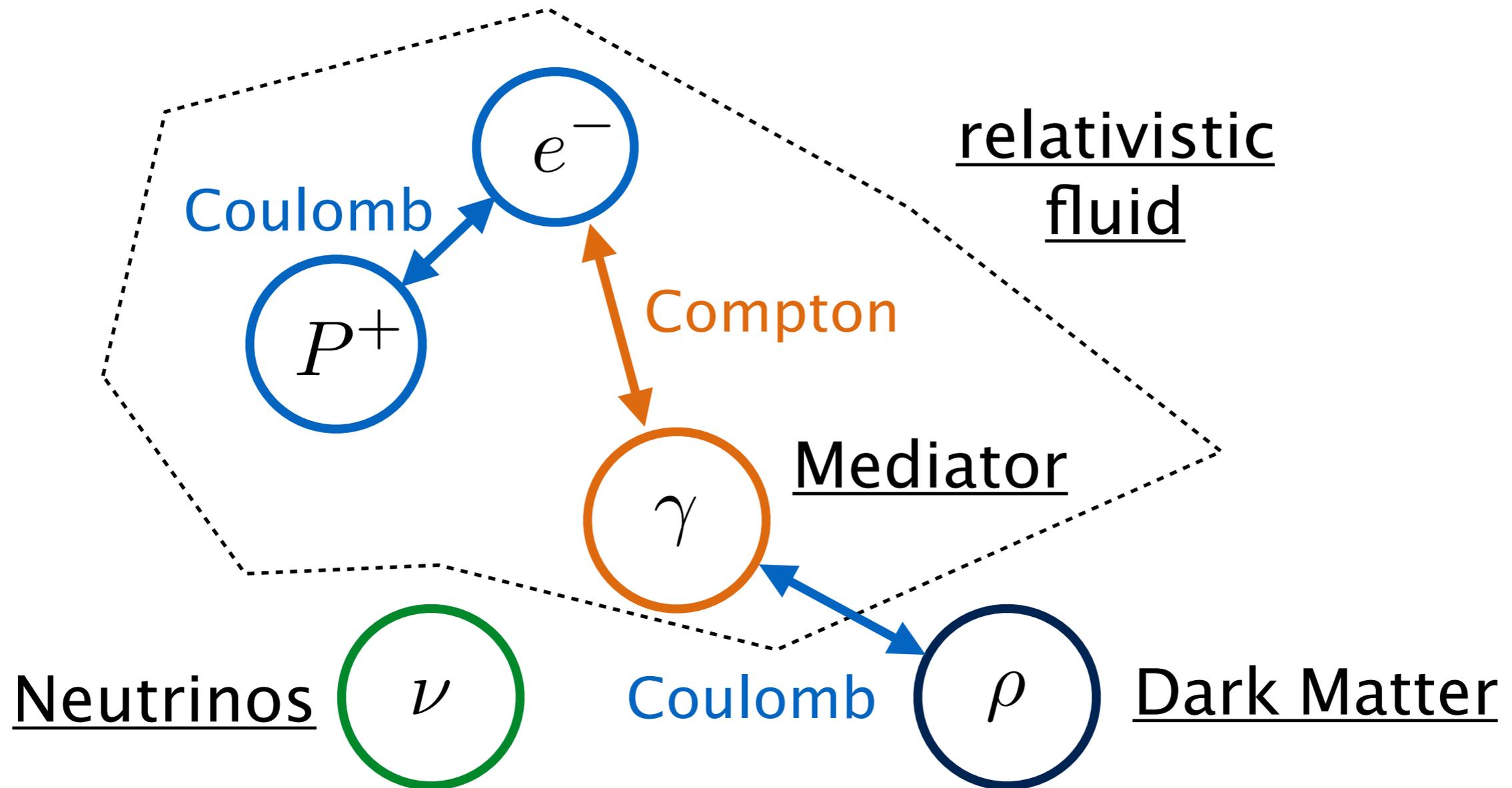
DG & Rajendran

# Simplified Models: Include Mediator



DG & Rajendran

# Milli-charged Dark Matter



# Milli-charged Dark Matter

Evades constraint from thermalizing mediator  
Only viable DM model for EDGES 21cm signal

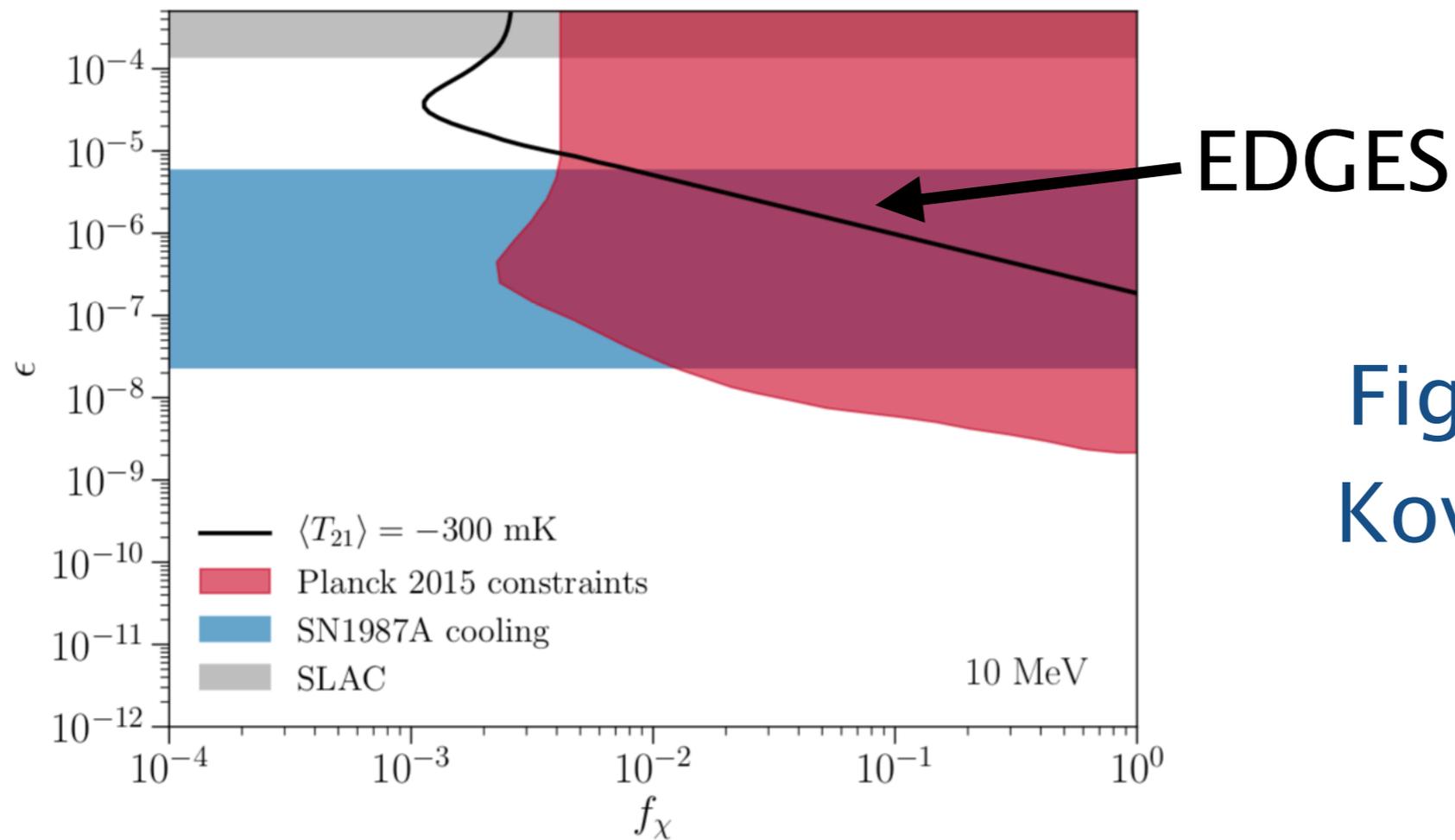


Figure from  
Kovetz et al.

Strongly constrained by the CMB

de Putter et al.; Kovetz et al.

# Future Directions

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Cosmology is a clean laboratory for Dark Matter

New applications are emerging with data quality

Partly a response to evolution of the field

Usually a CMB constraint for any new idea

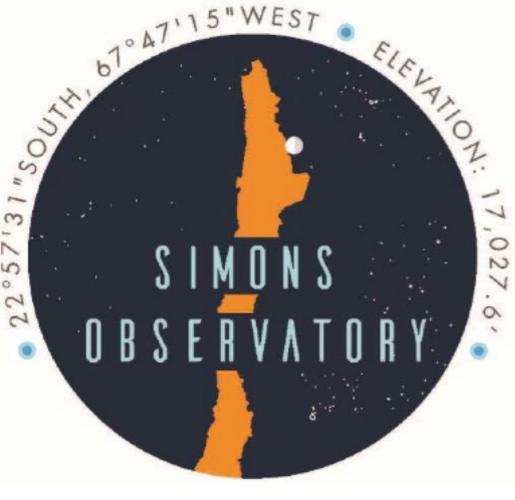
Notice no mention of DM annihilation:

Current bounds are strong, but will not improve

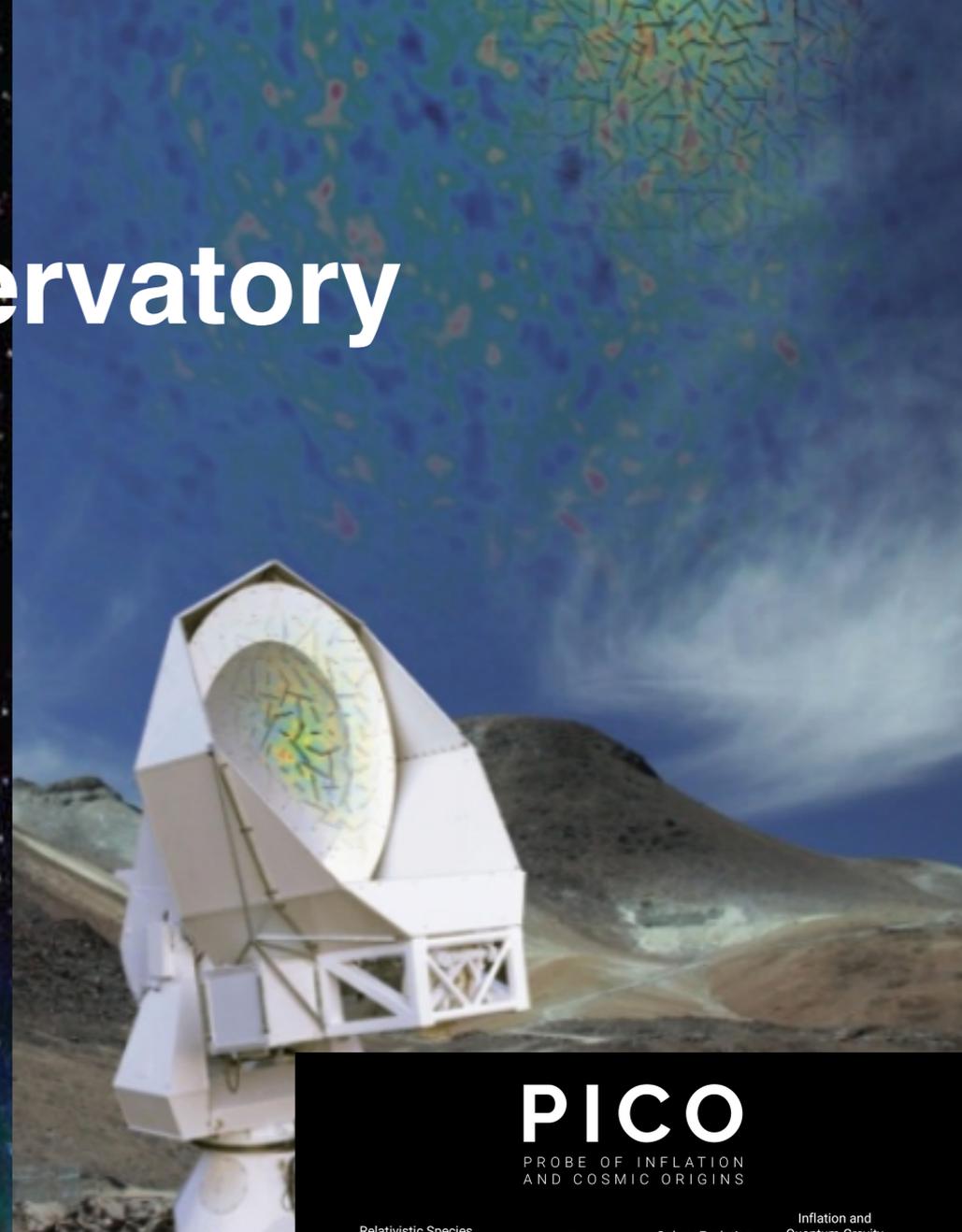
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An aerial photograph of a vast, flat, snow-covered landscape under a clear blue sky. In the lower center, there is a small, dark, rectangular structure, possibly a building or a small settlement, surrounded by tracks and some debris. The horizon is visible in the distance, and the overall scene is desolate and open.

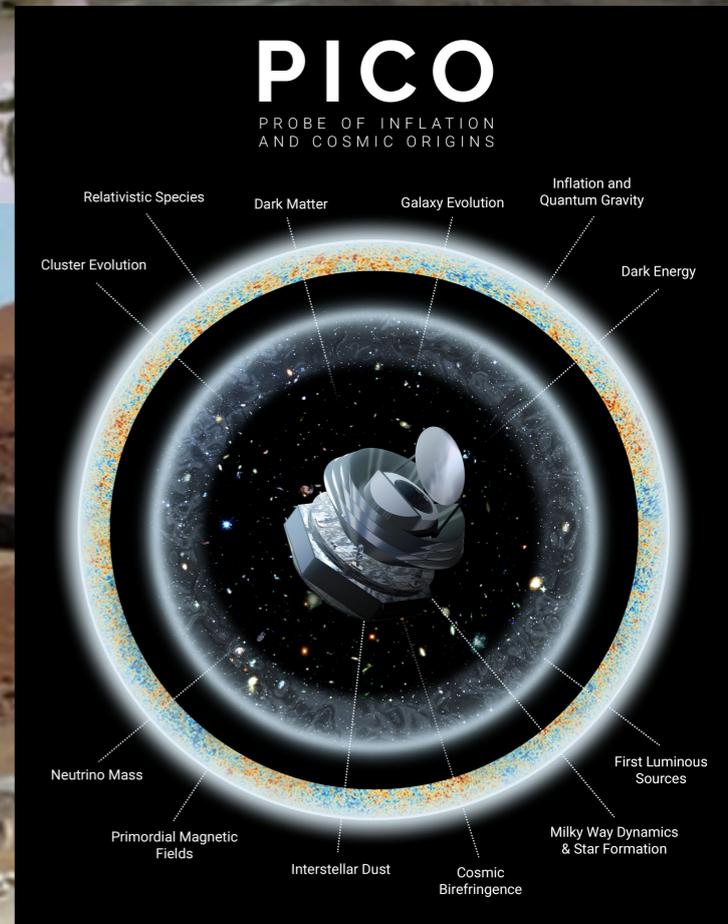
# Summary

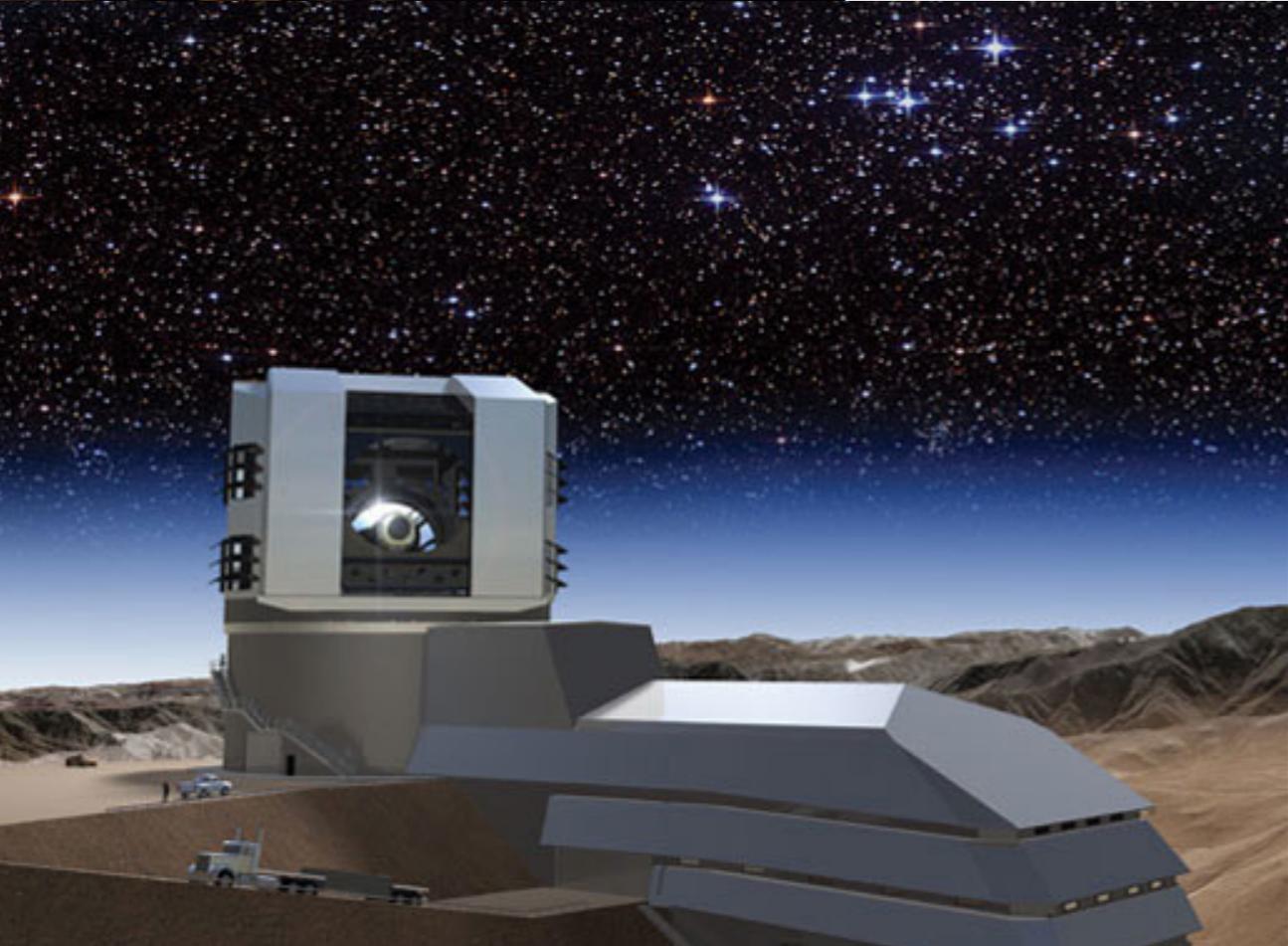
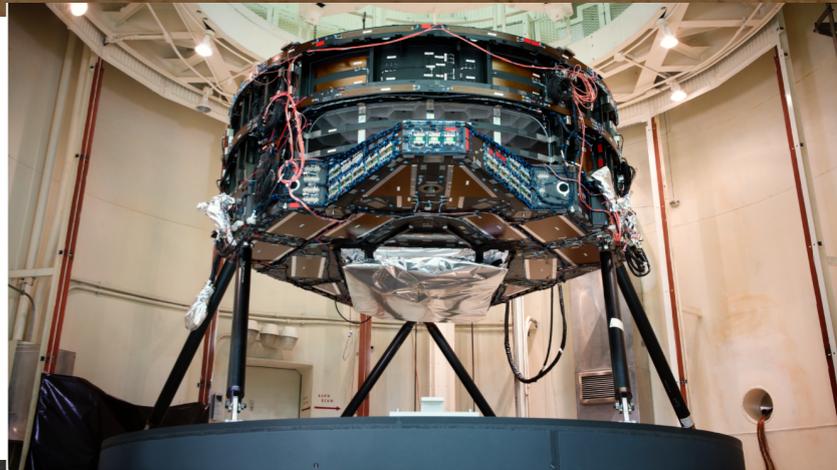
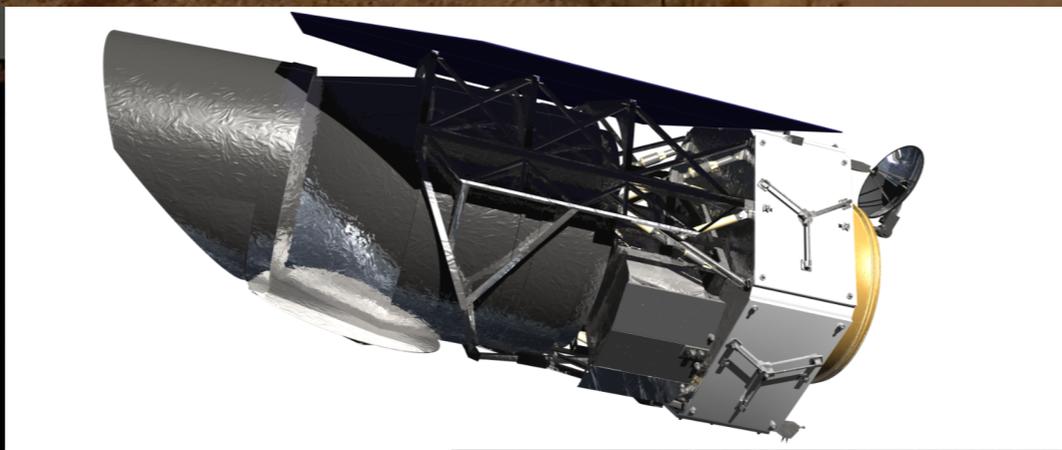


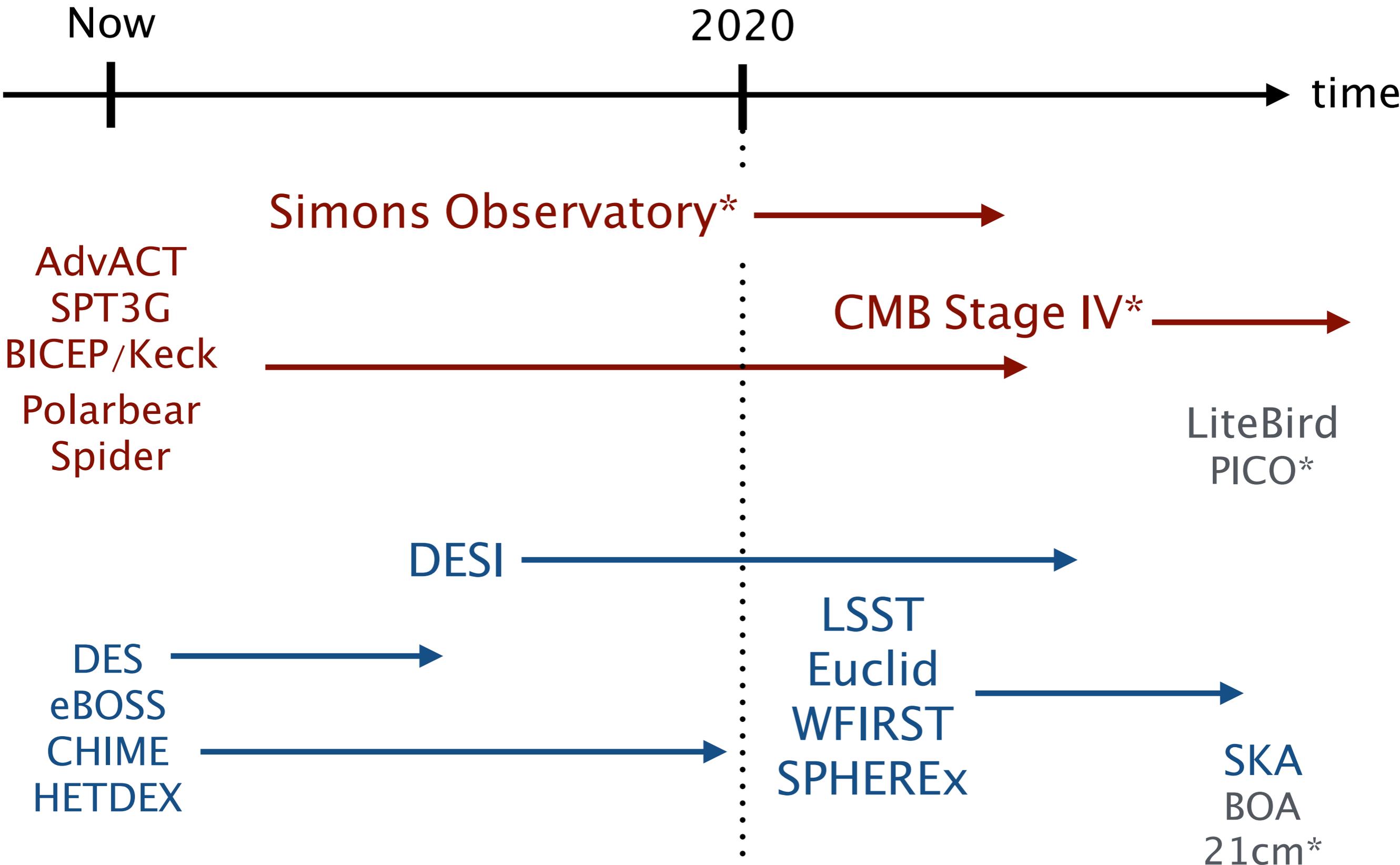
# The Simons Observatory



**CMB-S4**  
Next Generation CMB Experiment







\* DG member

# Summary

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## CMB:

Gravitational Waves and Inflation

Light relics, dark matter, helium abundance, etc.

## Lensing (CMB & galaxy):

Neutrino mass, dark matter properties

## Galaxy surveys:

Inflationary particle content & interactions

Expansion history (BAO), light relics, dark forces

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Thank you