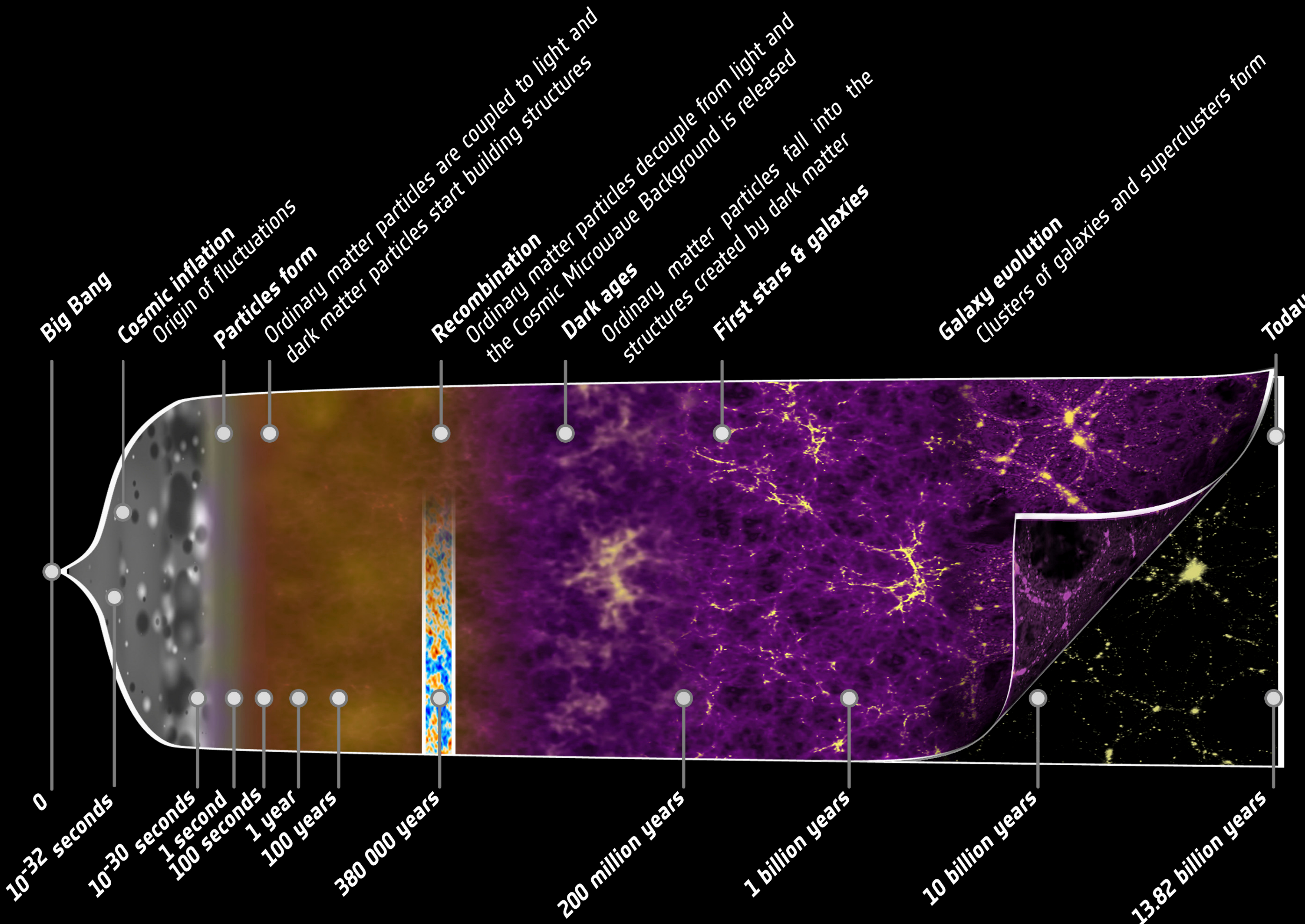
Messengers from the Early Universe

Daniel Green
UC San Diego

Outline

1. Cosmic History
2. Cosmic Sound
3. Cosmic Neutrinos and Light Relics
4. Neutrino Mass

Cosmic History



Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years


THE HISTORY AND FATE OF THE UNIVERSE
Four eras and eight major stages in the evolution of the universe
The Big Bang and Expanding Universe
History of the Universe
Cosmology and Relics of History
The Fate of the Universe
Our Cosmic Address
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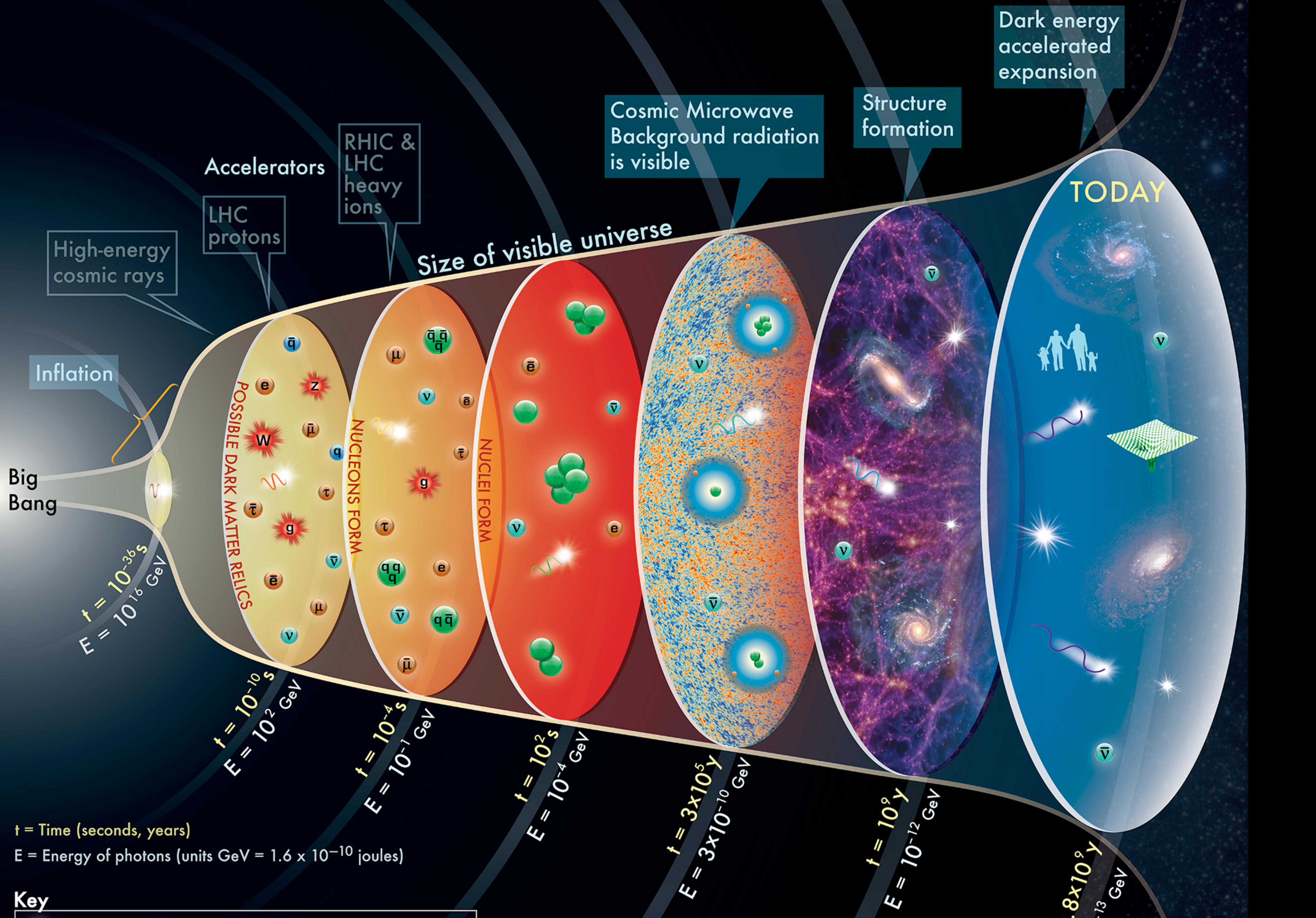
HISTORY OF THE UNIVERSE

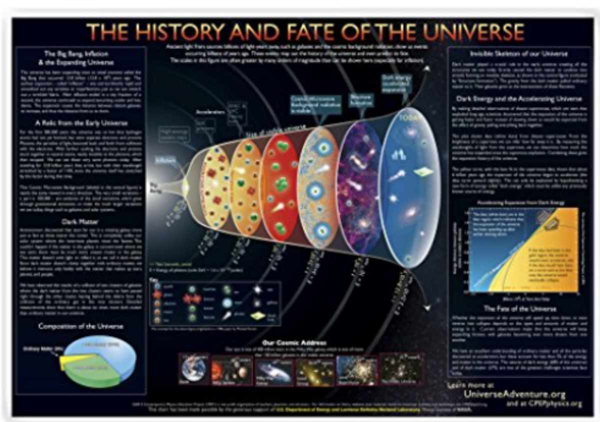


t = Time (seconds, years)

E = Energy of photons (units GeV = 1.6×10^{-10} joules)

Key

Industrial & Scientific › Science Education



Roll over image to zoom in

by Contemporary Physics Education Project (CPEP)

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History and Fate of the Universe II Laminated Placemat

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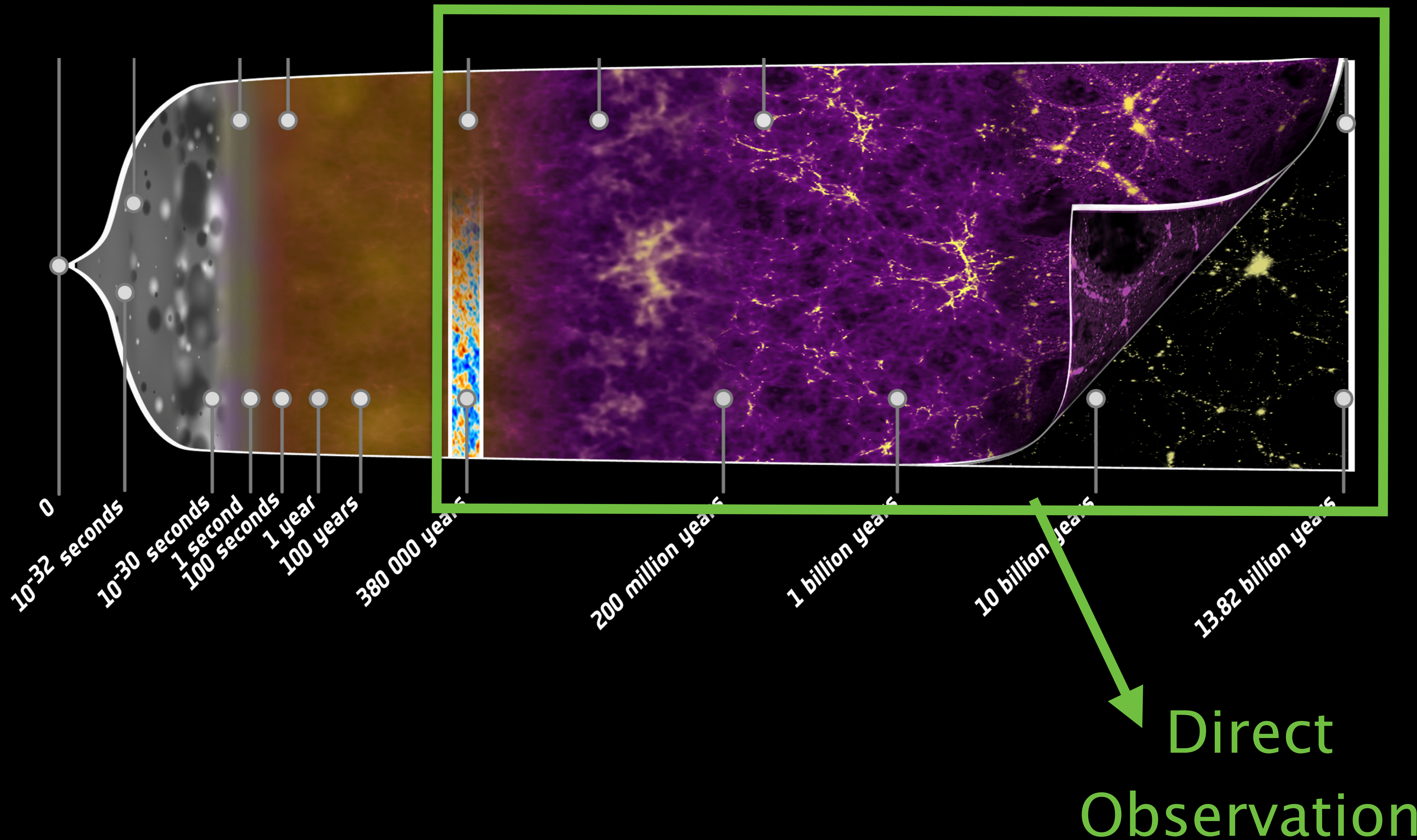
History of the Universe

Suggests a complete story

1. Early phase of inflation
2. Reheating up to $T \gg 1\,\mathrm{TeV}$
3. Standard model cools through expansion
4. (Perhaps) WIMP Dark Matter freeze-out

This story is plausible but hardly proven



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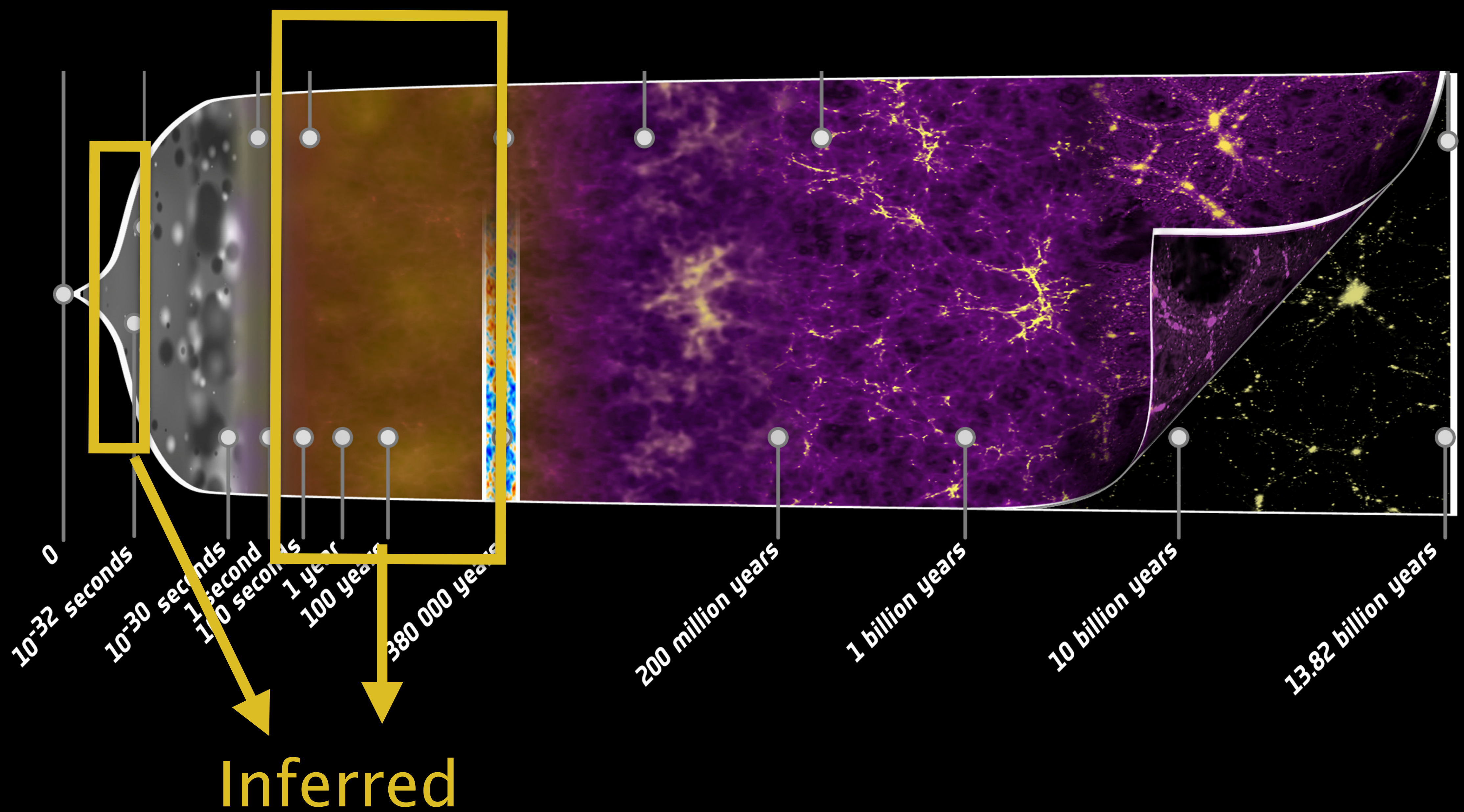
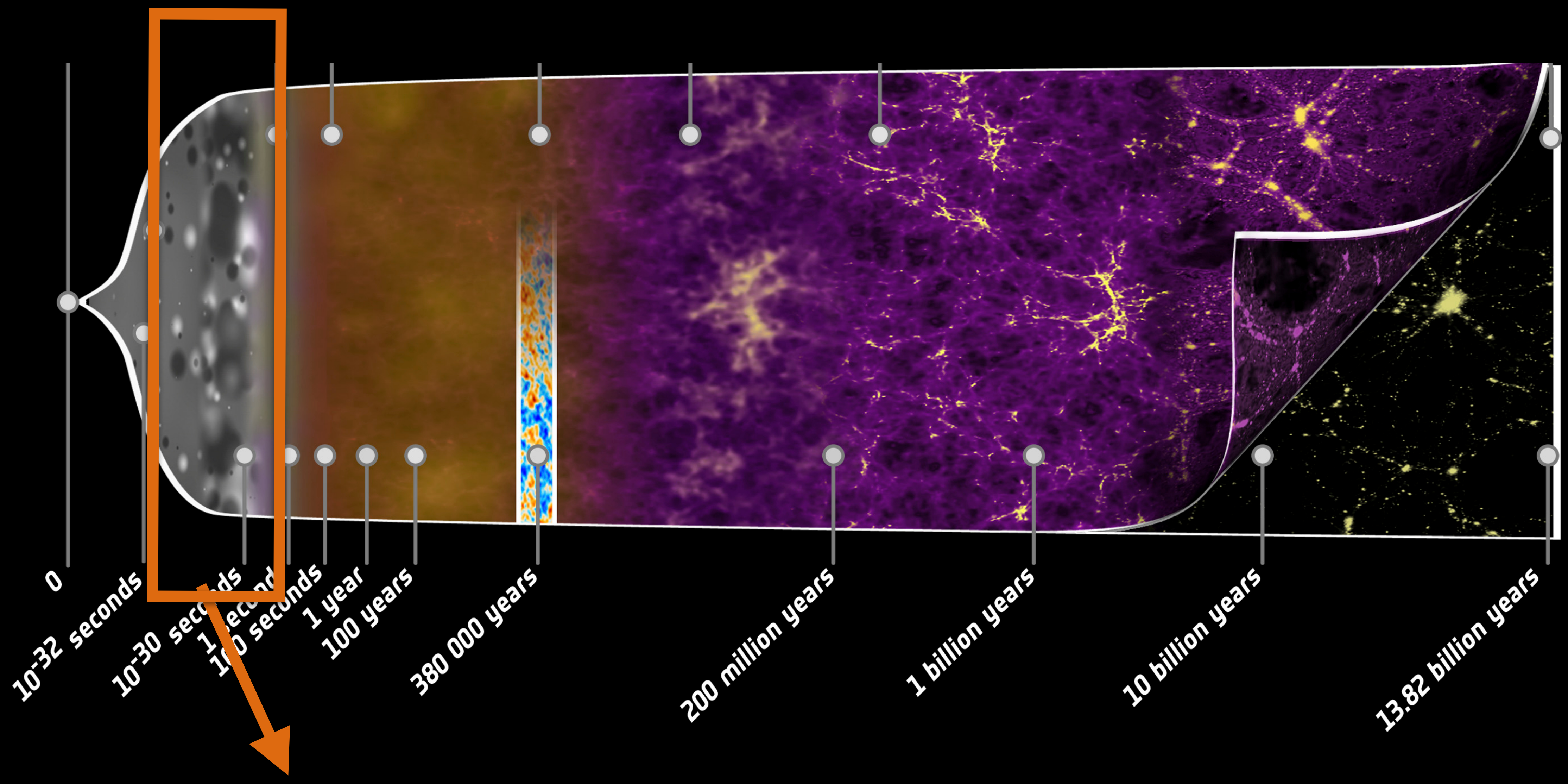
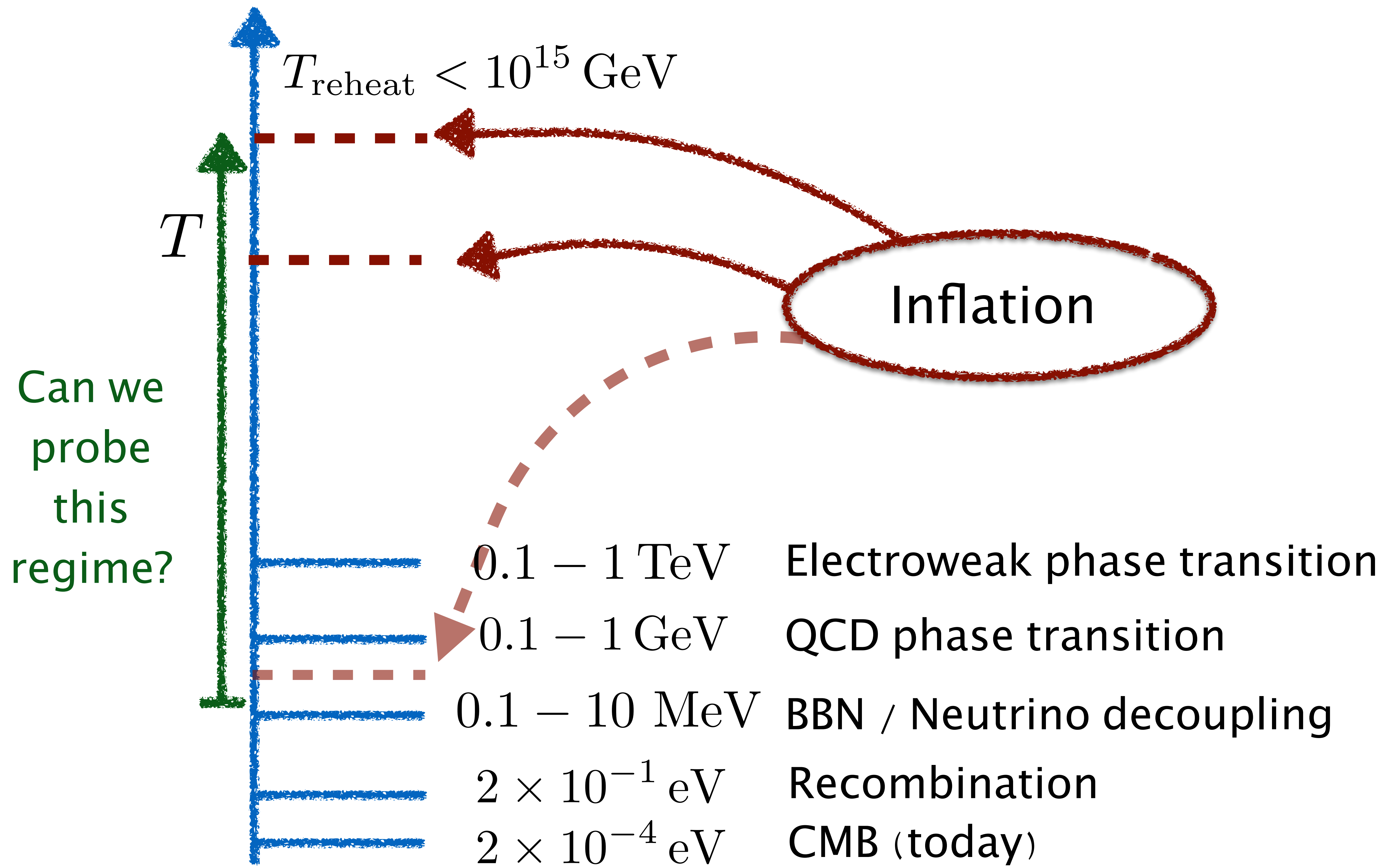


This story is plausible but hardly proven



Unproven(?)



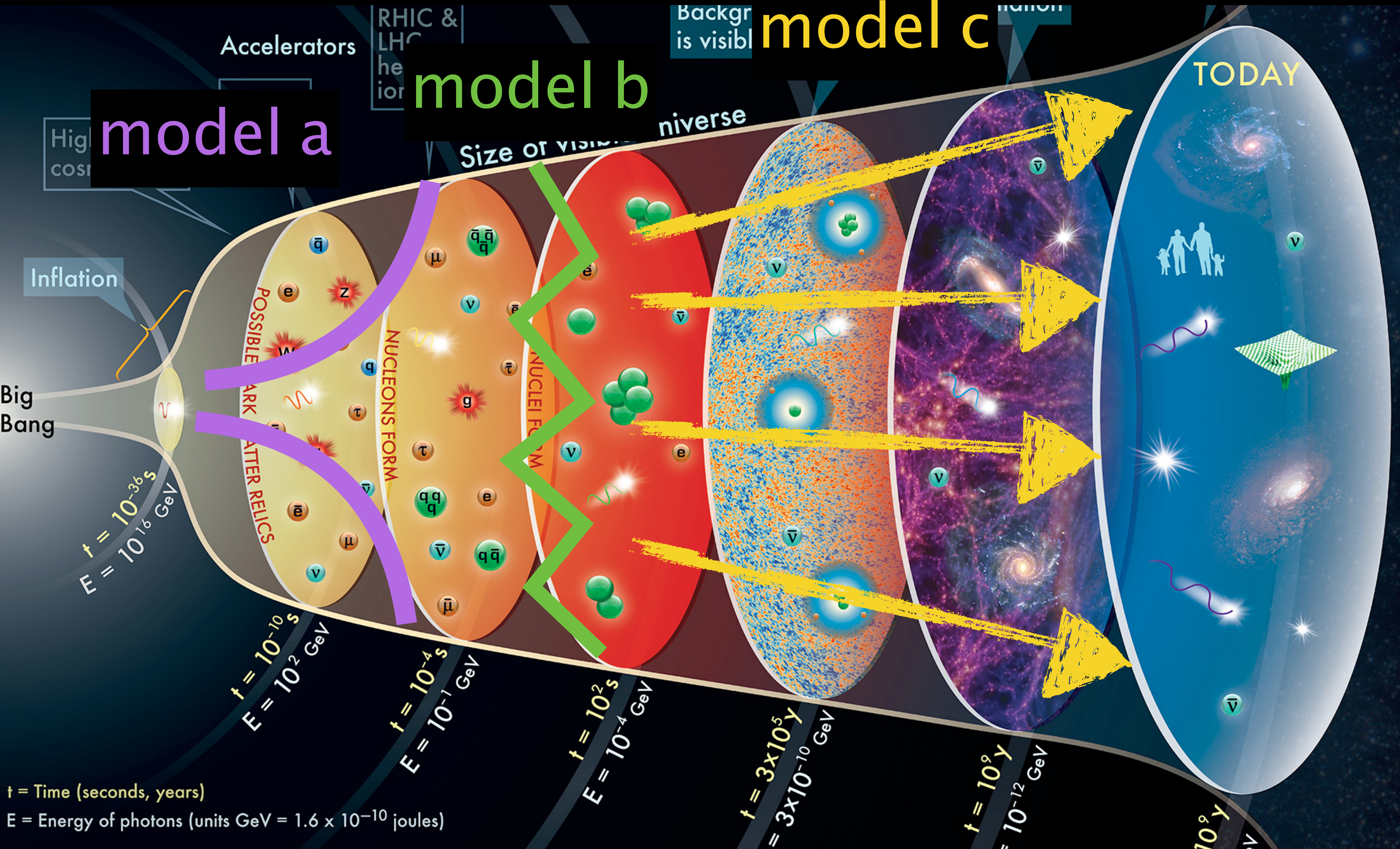
$T_{\rm reheat} < 10^{15}\,{\rm GeV}$
T
Inflation
Can we probe this regime?
$0.1 - 1\,{\rm TeV}$
Electroweak phase transition
$0.1 - 1\,{\rm GeV}$
QCD phase transition
$0.1 - 10\ {\rm MeV}$
BBN / Neutrino decoupling
$2 \times 10^{-1}\,{\rm eV}$
Recombination
$2 \times 10^{-4}\,{\rm eV}$
CMB (today)

Does it matter?

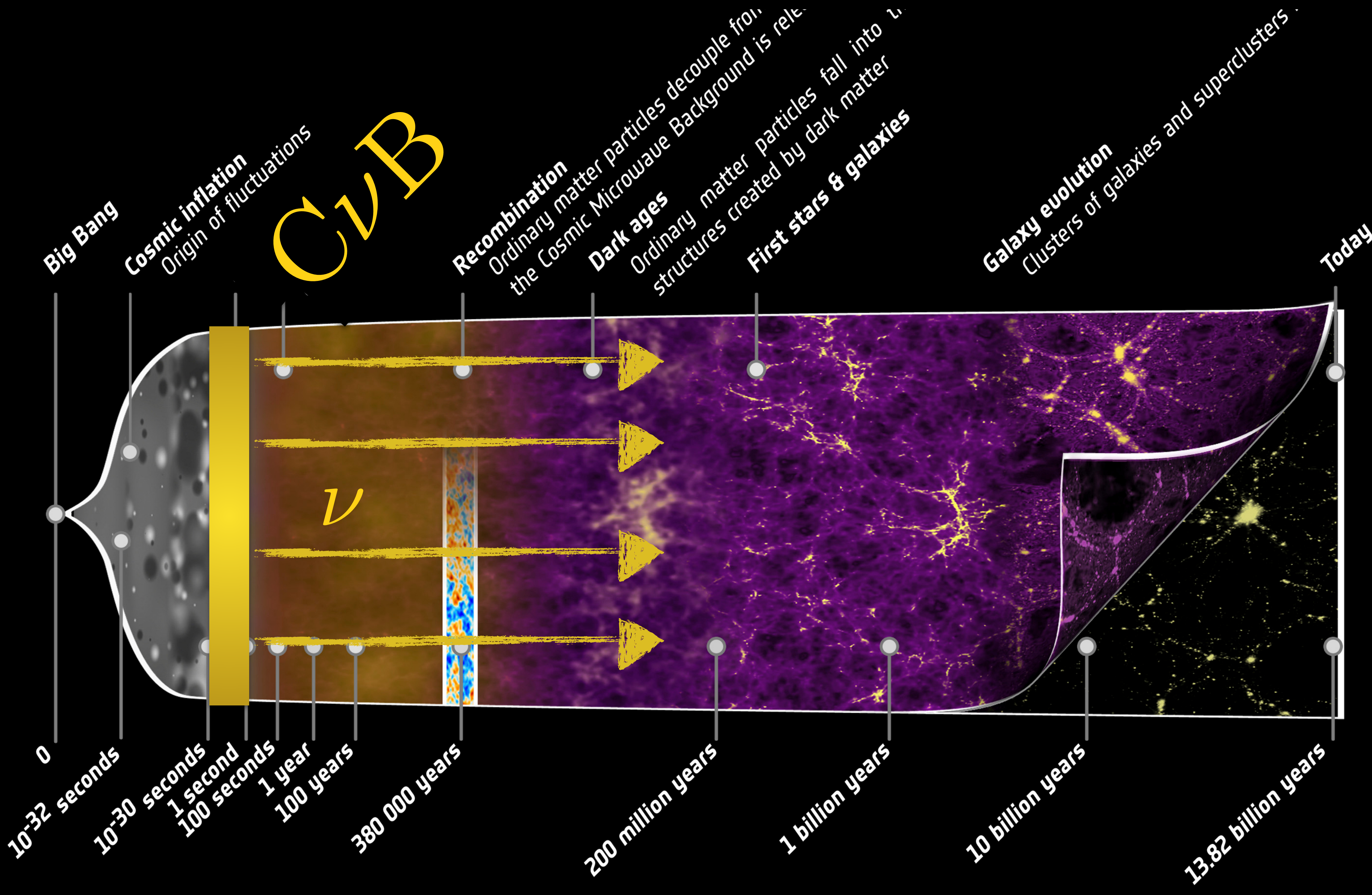
Cosmology is tied to every basic problem

- Cosmological Constant
- Dark Matter / Dark Sectors
- Solution to strong CP problem (axion)
- Cosmological solutions to Hierarchy Problem
- Relics from new symmetries (e.g. gravitino)
- Origin of structure, baryogenesis, B-fields, ...

Ideas are not consistent with a single cosmic history



I will focus on two related goals:



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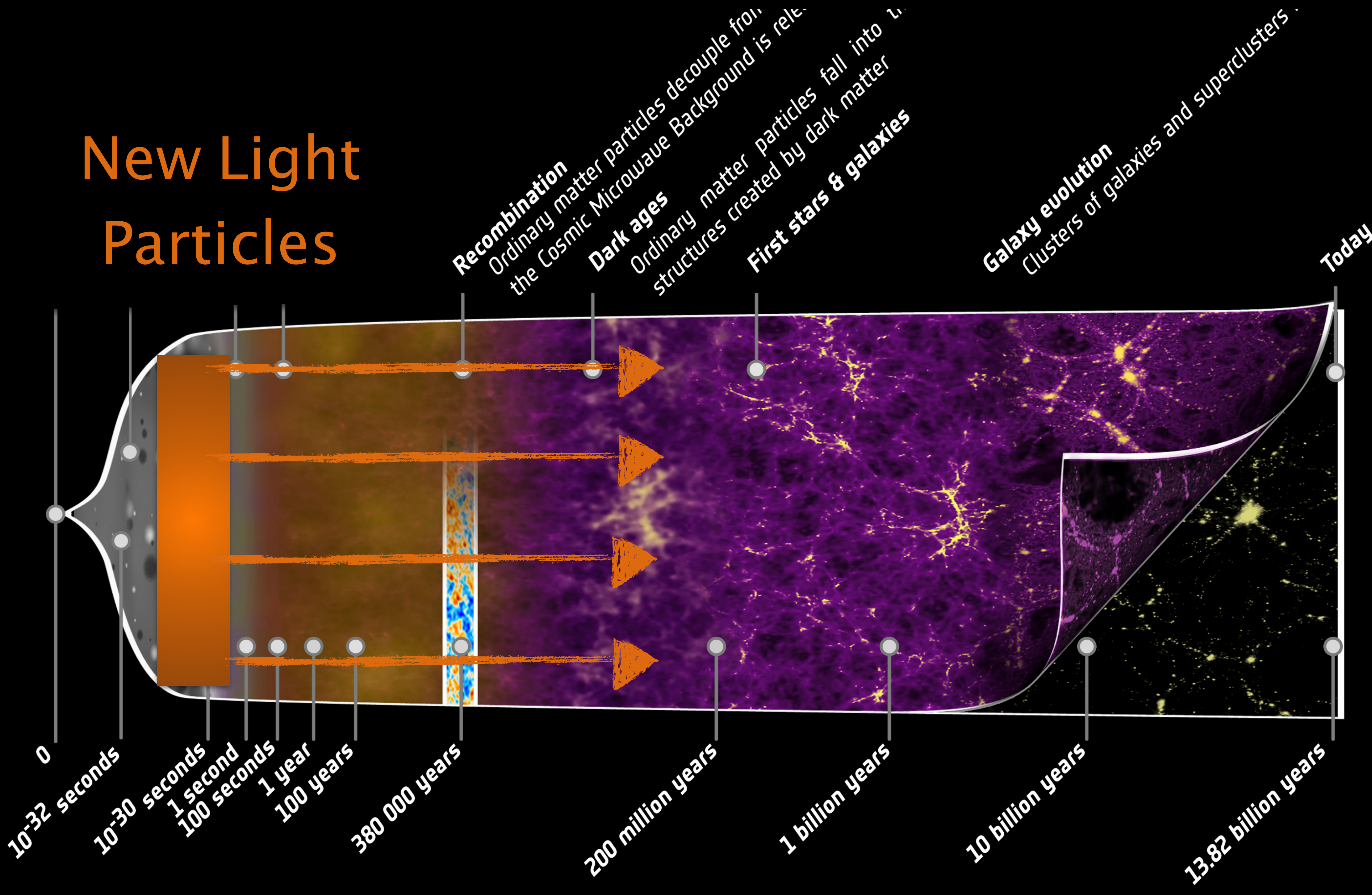


Does it matter?

Observations will be relevant to:

- Cosmological Constant
- Dark Matter / Dark Sectors ✓
- Solution to strong CP problem (axion) ✓
- Cosmological solutions to Hierarchy Problem ✓
- Relics from new symmetries (e.g gravitino) ✓
- Origin of structure, baryogenesis, B-fields, …


Cosmic Sound

Cosmic Microwave Background (CMB)

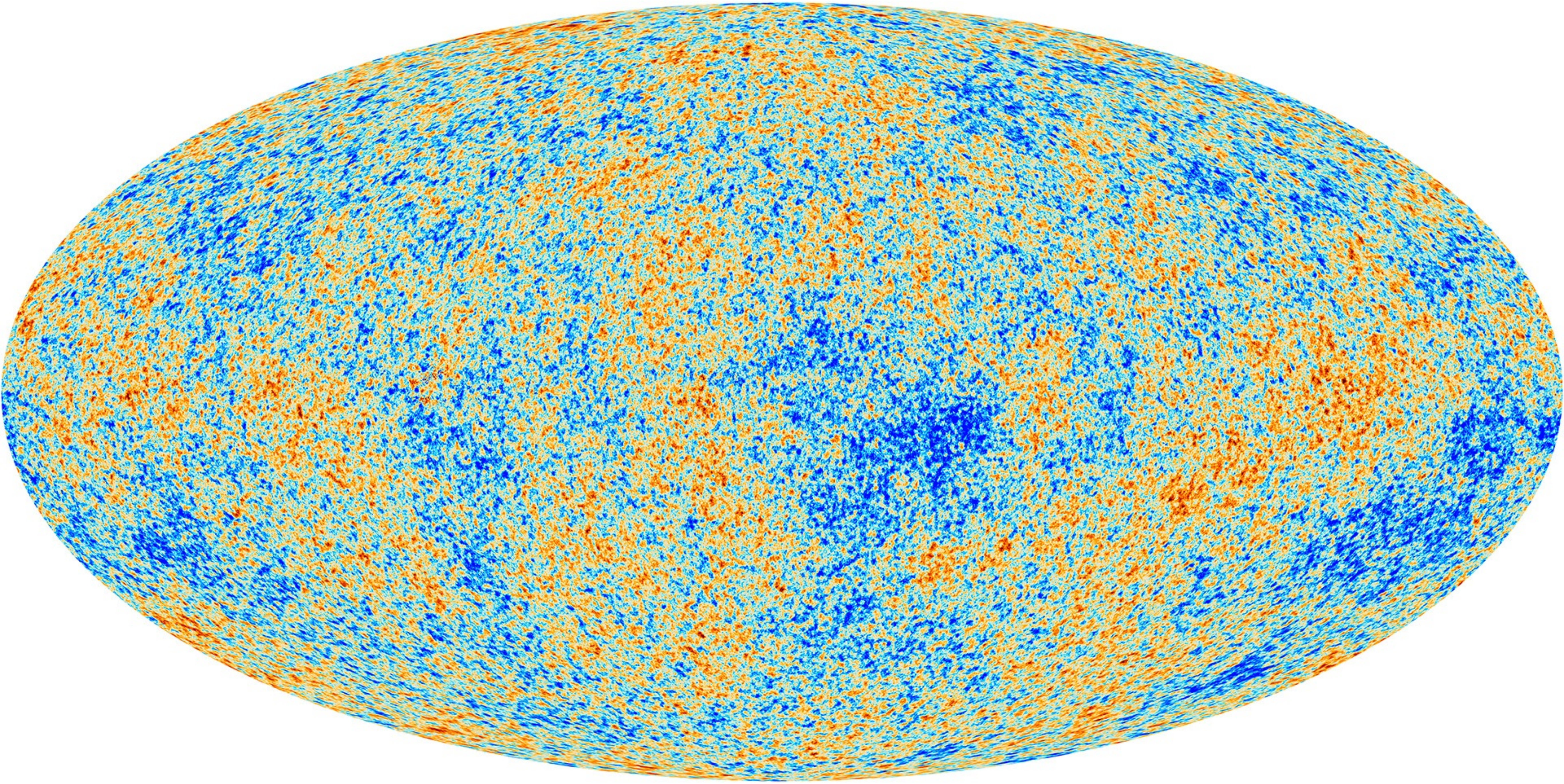


Image from Planck

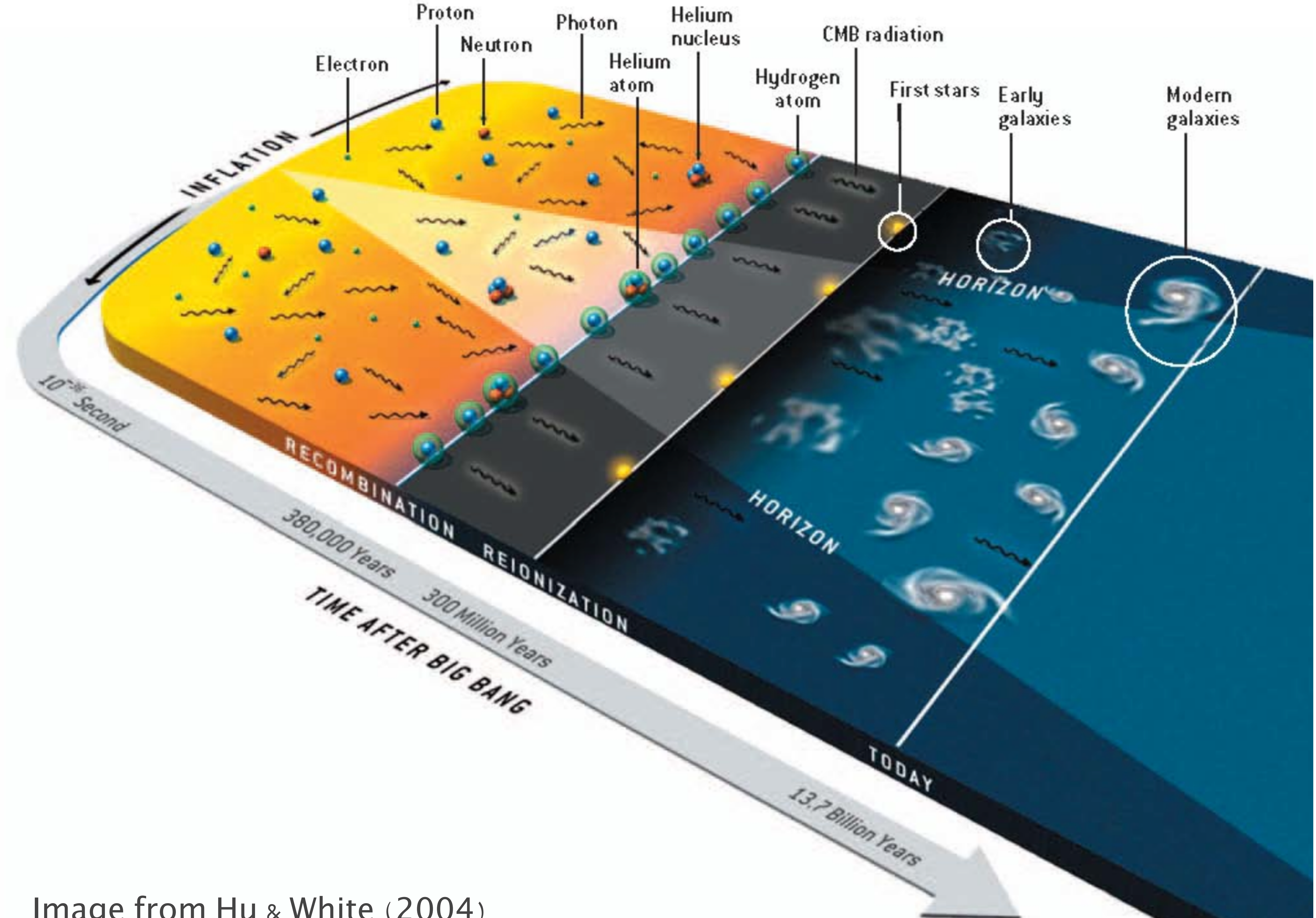
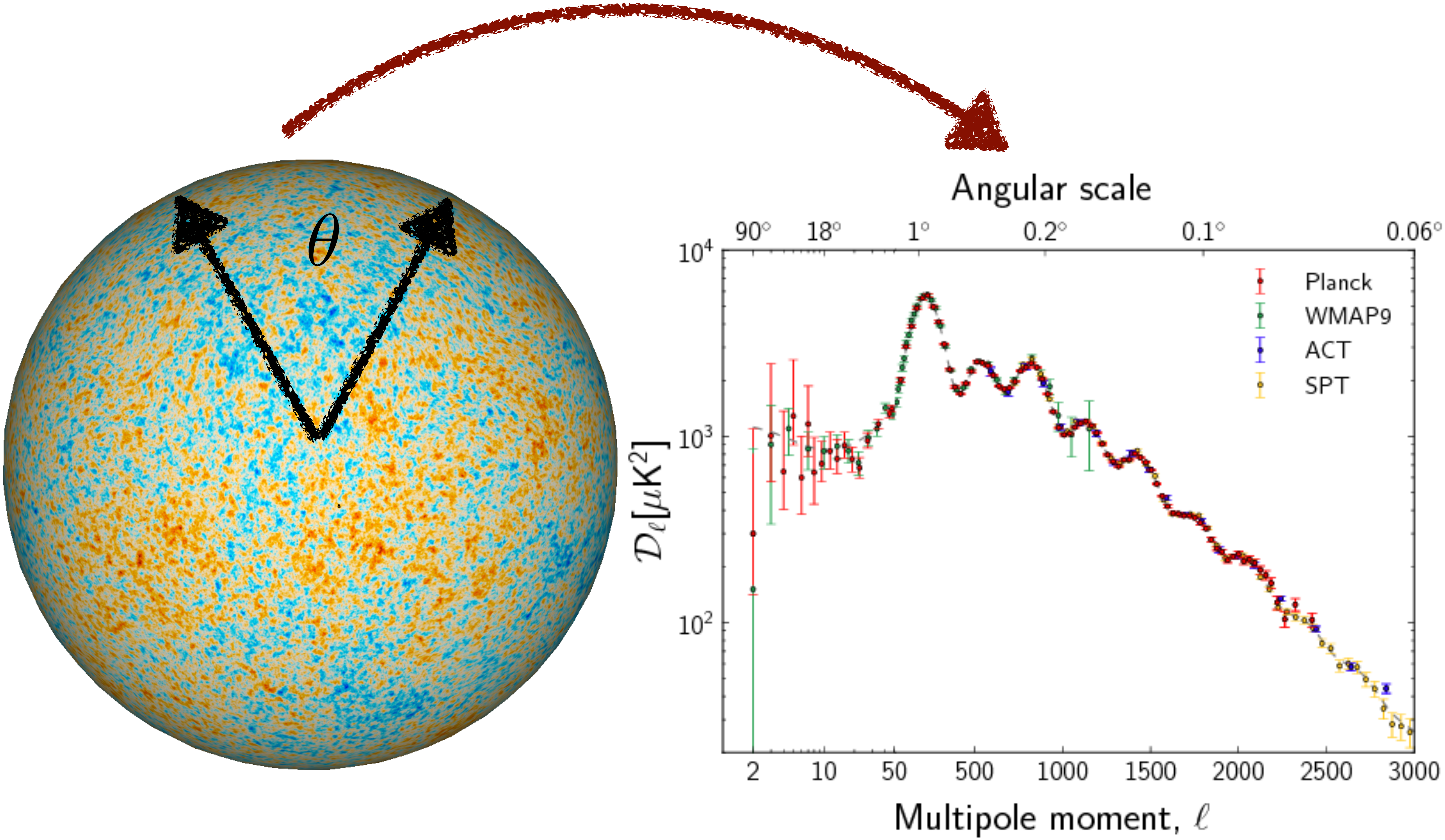
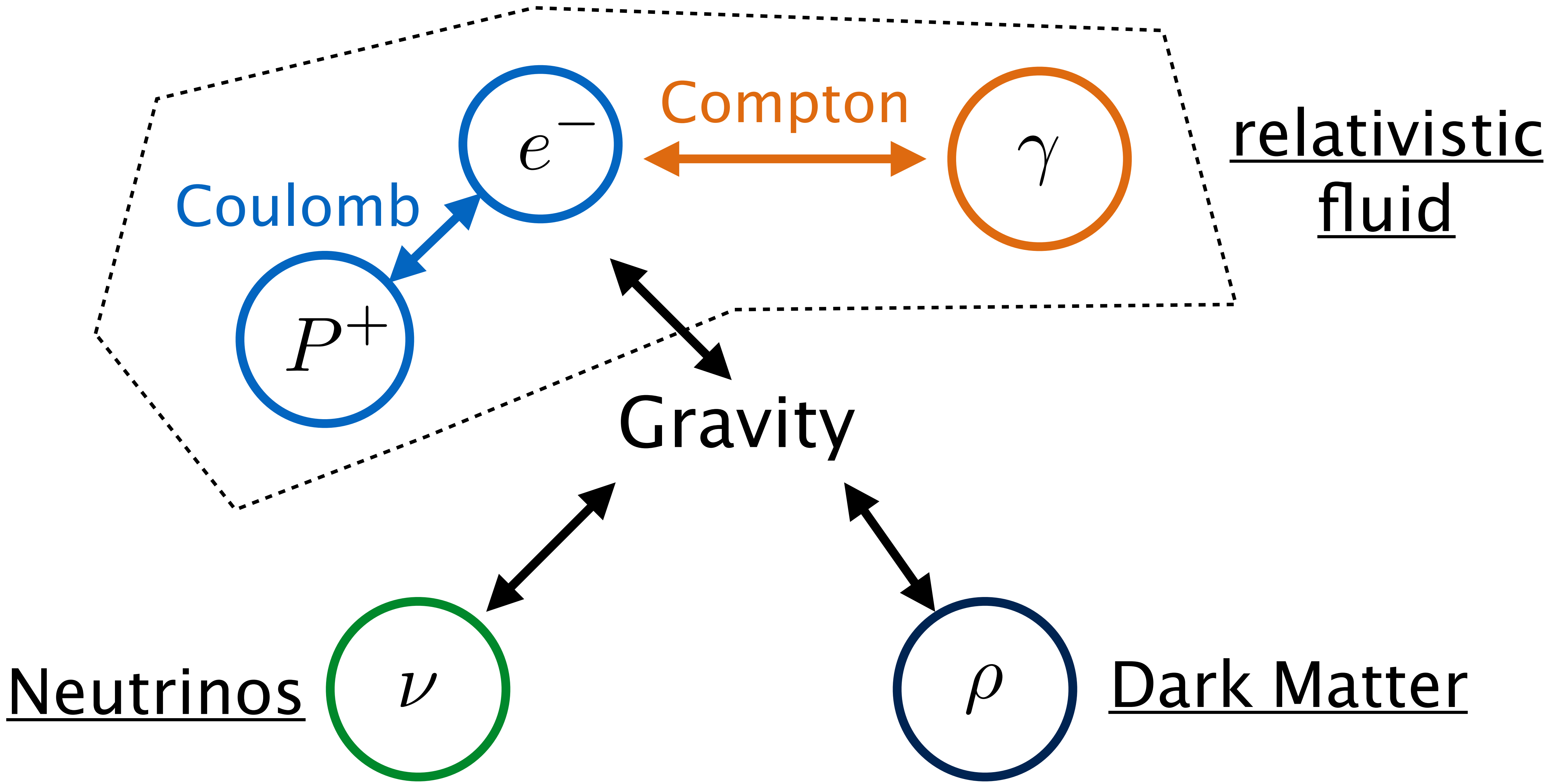


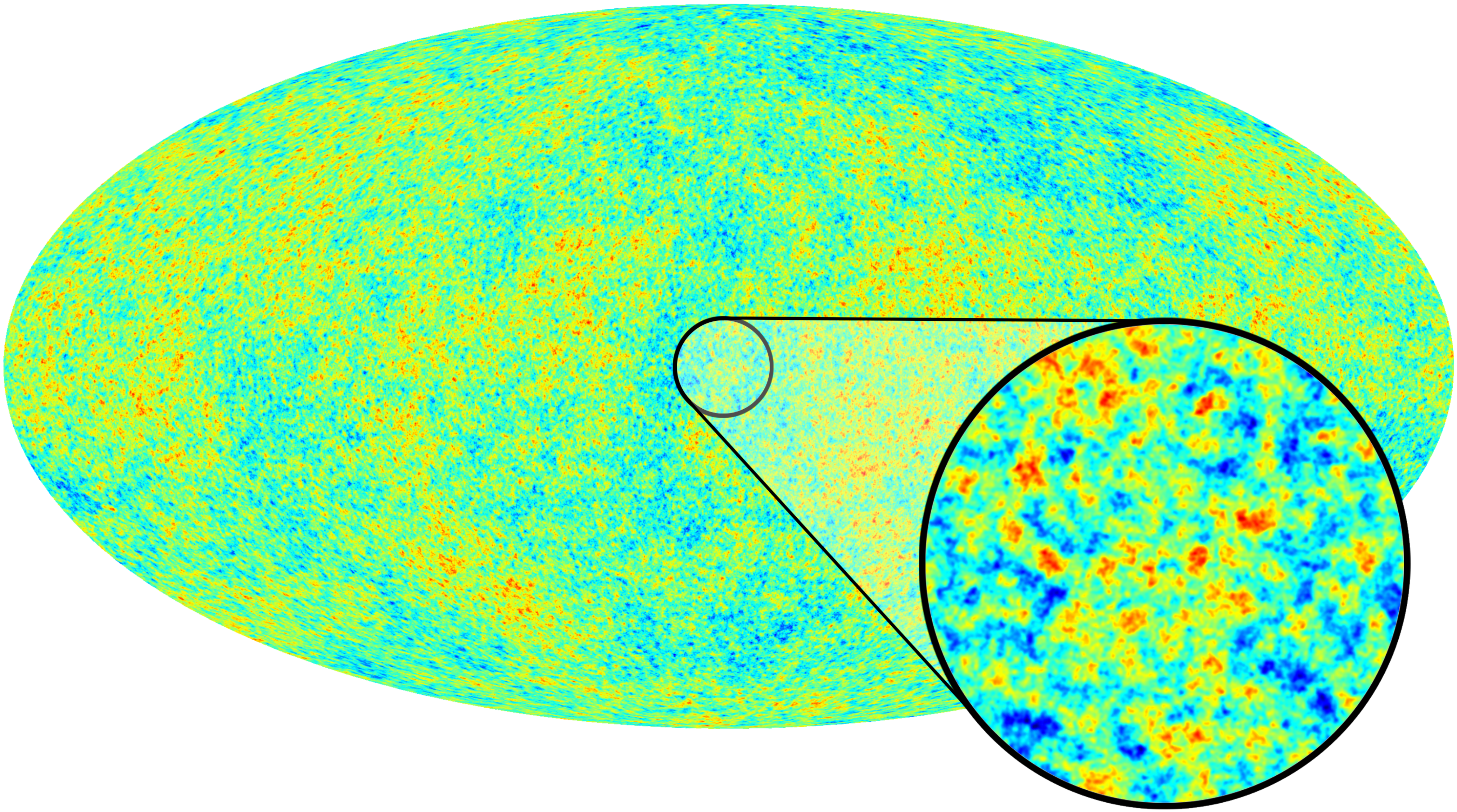
Image from Hu & White (2004)

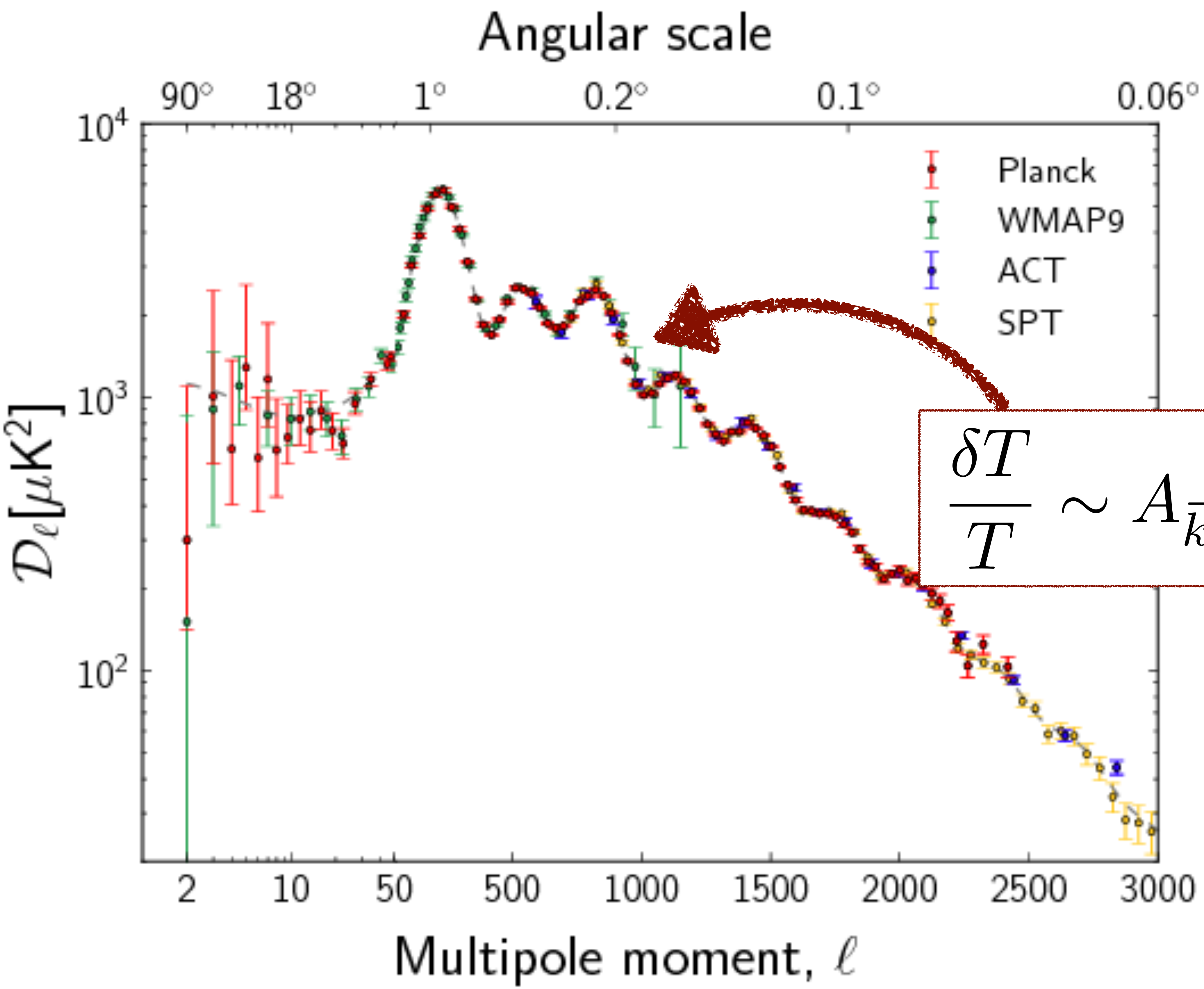


Courtesy of thecmb.org



Compton
e^-
γ
relativistic
fluid
Coulomb
P^+
Gravity
Neutrinos
ν
ρ
Dark Matter





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

Cosmic Sound

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

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

Cosmic Sound

But we have to **Match** to long wavelength

$$k_{\text{physical}} \propto a^{-1} \qquad H \propto a^{-2}$$

In the past $$k_{\text{physical}} \ll H$$

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

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

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

"Inflation" : source of initial conditions

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

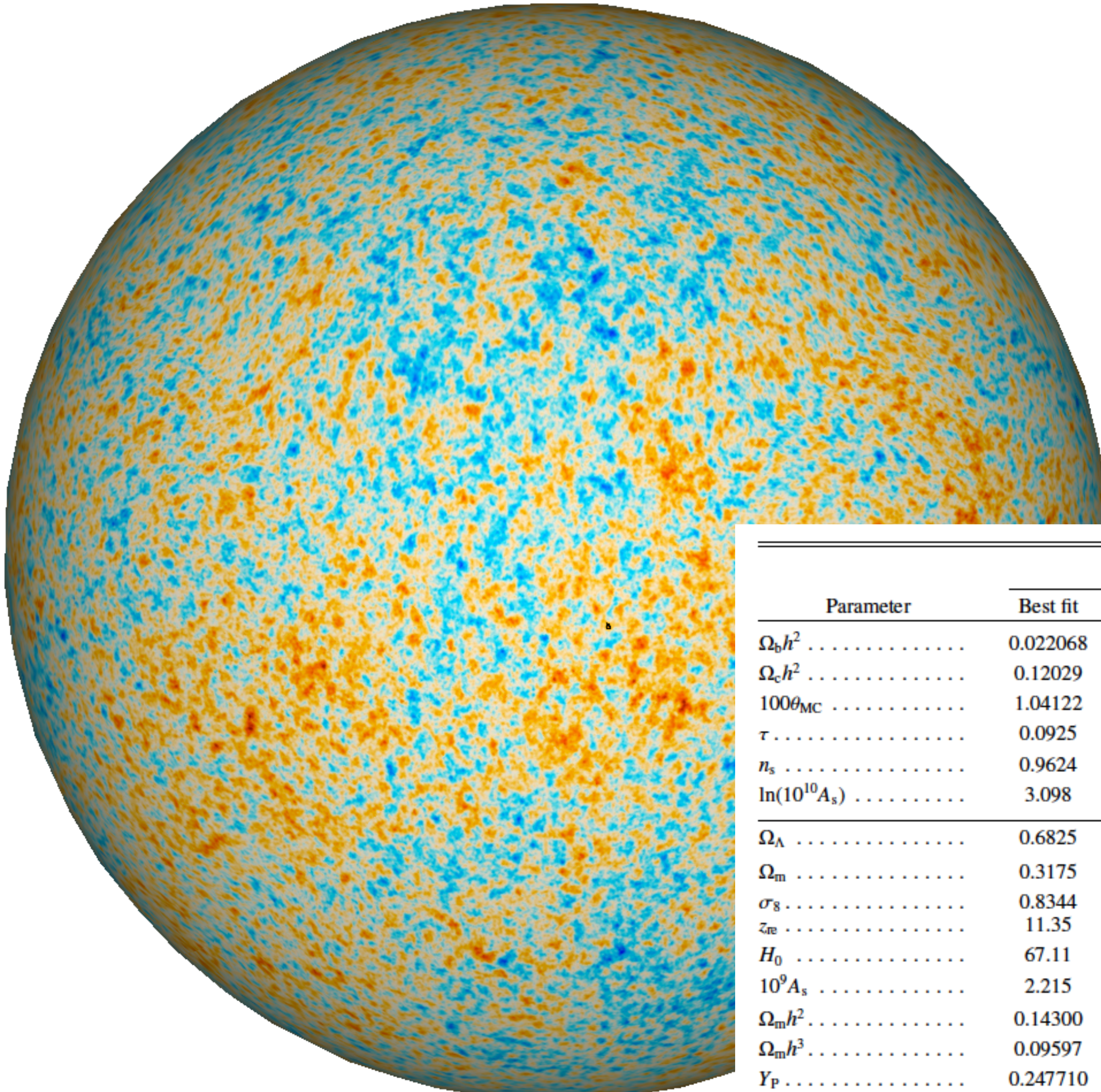
$$\langle A_{\vec{k}_1} A_{\vec{k}_2} \cdots \rangle = \text{?}$$

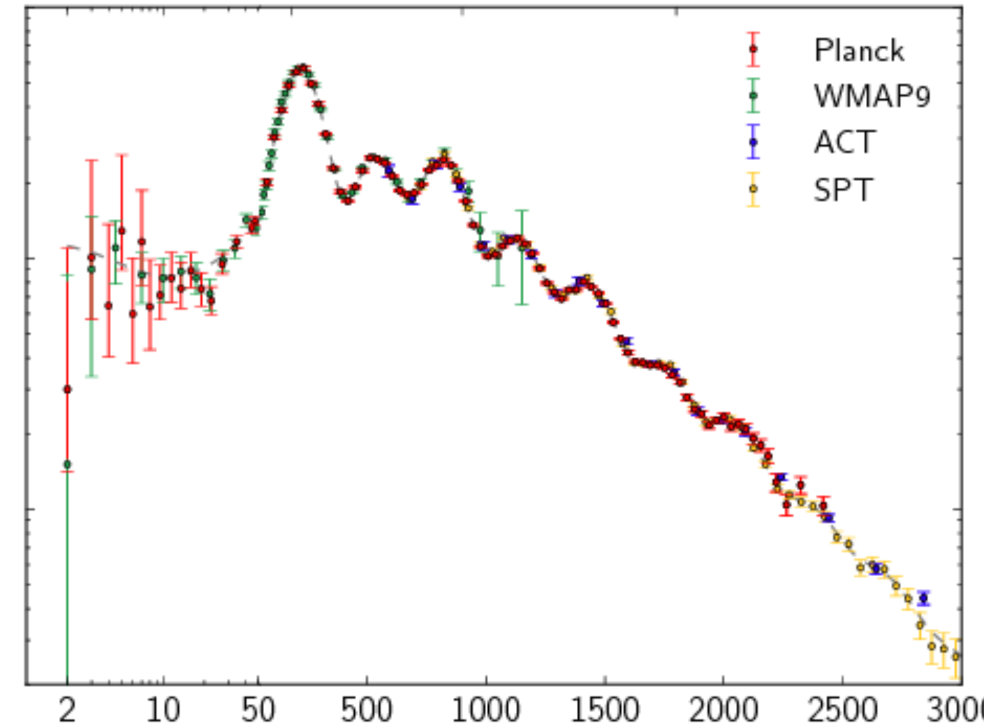
$$\frac{\delta T}{T} \sim A_{\vec{k}} \cos(c_s k \tau)$$

Recombination:

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

+ diffusion, gravitational forces / redshift, etc.

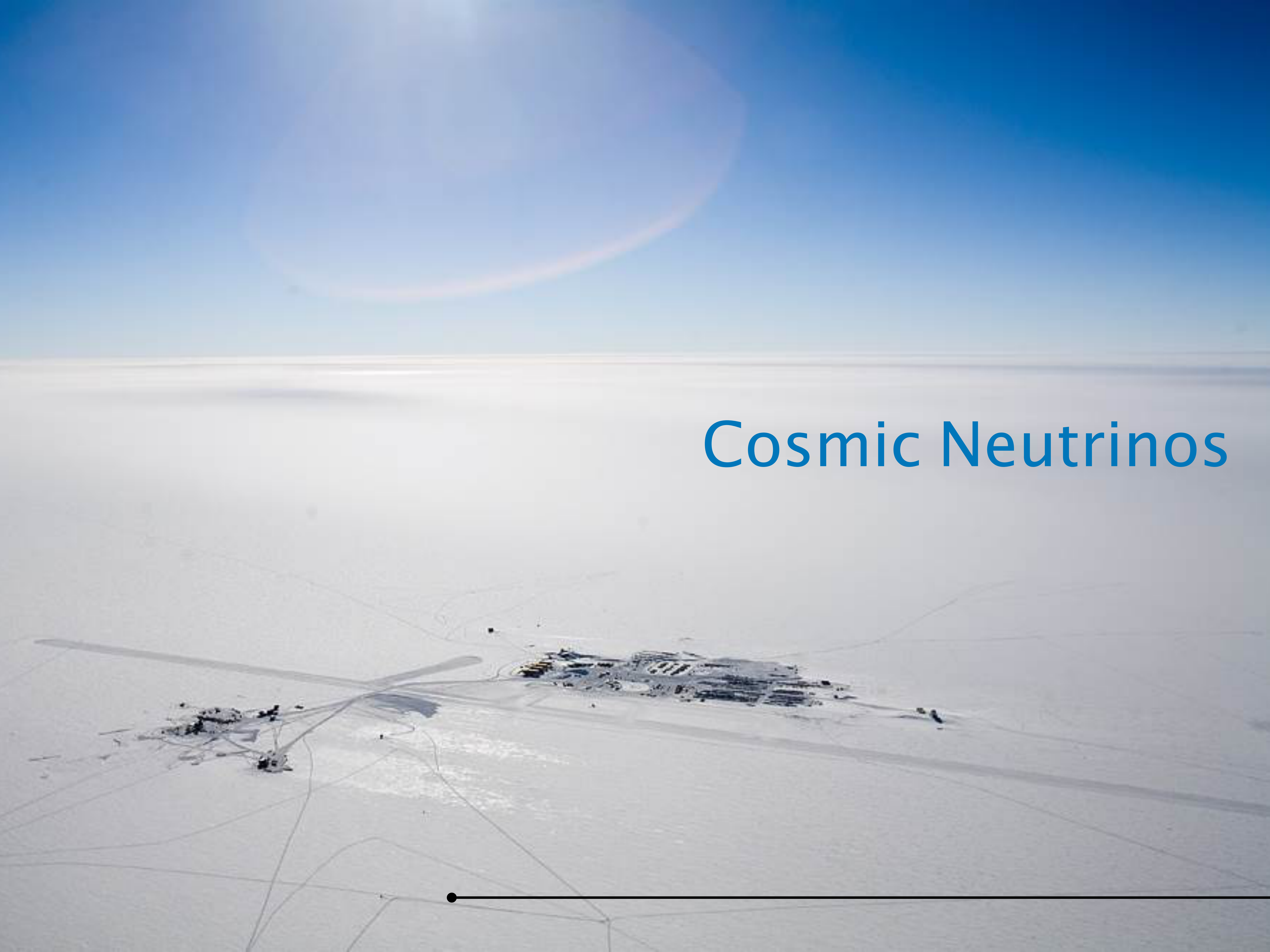


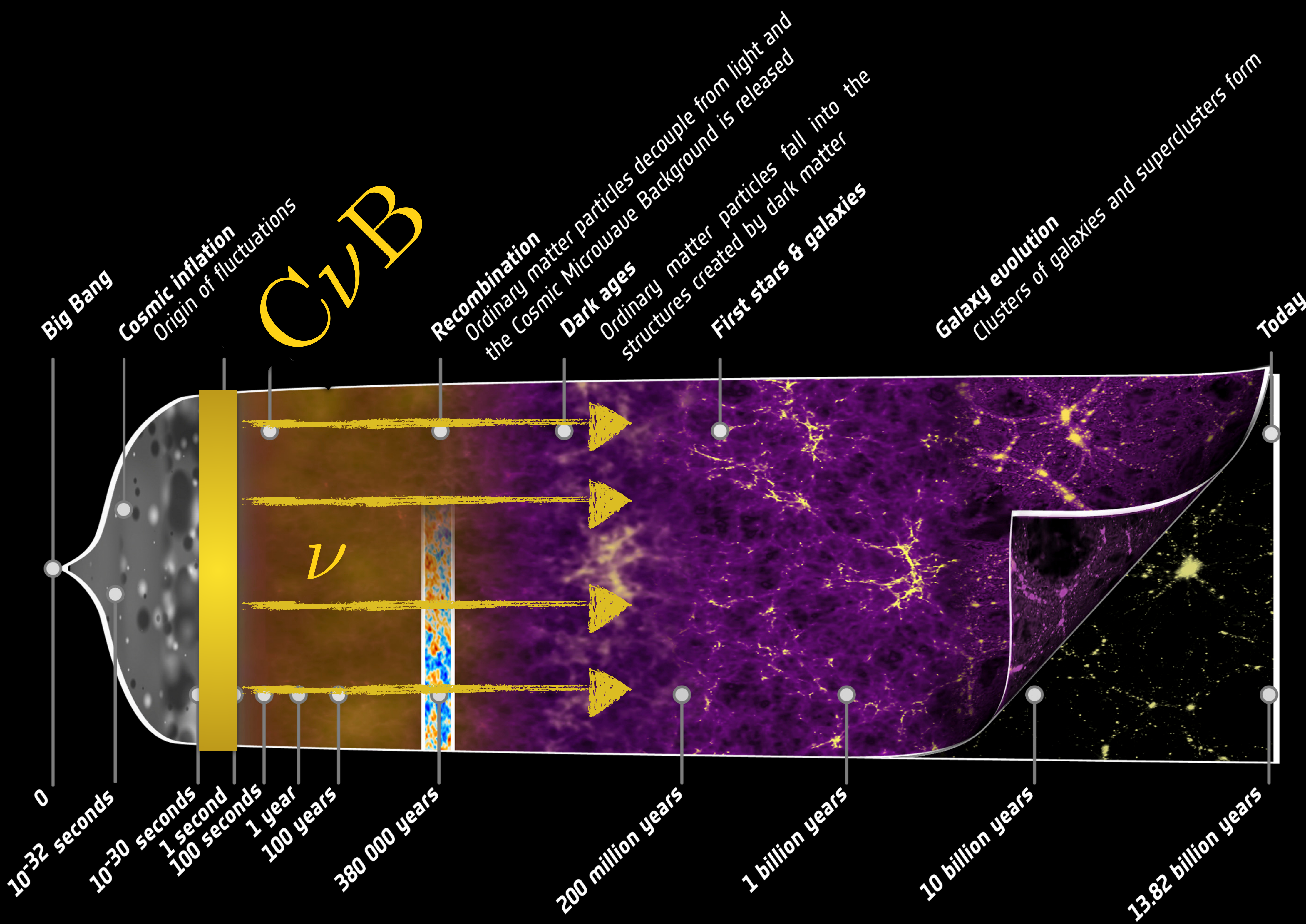


Parameter	*Planck* Best fit	*Planck* 68% limits	*Planck*+lensing Best fit	*Planck*+lensing 68% limits	*Planck*+WP Best fit	*Planck*+WP 68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 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 ± 0.0029	0.14094	0.1414 ± 0.0029	0.14305	0.1426 ± 0.0025
$\Omega_m h^3$	0.09597	0.09590 ± 0.00059	0.09603	0.09593 ± 0.00058	0.09591	0.09589 ± 0.00057
Y_P	0.247710	0.24771 ± 0.00014	0.247785	0.24775 ± 0.00014	0.247695	0.24770 ± 0.00012
Age/Gyr	13.819	13.813 ± 0.058	13.784	13.796 ± 0.058	13.8242	13.817 ± 0.048
z_*	1090.43	1090.37 ± 0.65	1090.01	1090.16 ± 0.65	1090.48	1090.43 ± 0.54
r_*	144.58	144.75 ± 0.66	145.02	144.96 ± 0.66	144.58	144.71 ± 0.60
$100\theta_*$	1.04139	1.04148 ± 0.00066	1.04164	1.04156 ± 0.00066	1.04136	1.04147 ± 0.00062
z_{drag}	1059.32	1059.29 ± 0.65	1059.59	1059.43 ± 0.64	1059.25	1059.25 ± 0.58
r_{drag}	147.34	147.53 ± 0.64	147.74	147.70 ± 0.63	147.36	147.49 ± 0.59
k_D	0.14026	0.14007 ± 0.00064	0.13998	0.13996 ± 0.00062	0.14022	0.14009 ± 0.00063
$100\theta_D$	0.161332	0.16137 ± 0.00037	0.161196	0.16129 ± 0.00036	0.161375	0.16140 ± 0.00034
z_{eq}	3402	3386 ± 69	3352	3362 ± 69	3403	3391 ± 60
$100\theta_{eq}$	0.8128	0.816 ± 0.013	0.8224	0.821 ± 0.013	0.8125	0.815 ± 0.011
$r_{drag}/D_V(0.57)$	0.07130	0.0716 ± 0.0011	0.07207	0.0719 ± 0.0011	0.07126	0.07147 ± 0.00091

Courtesy of thecmb.org

Cosmic Neutrinos





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Cosmic inflation
Origin of fluctuations
CνB
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Today
ν
0
10-32 seconds
10-30 seconds
1 second
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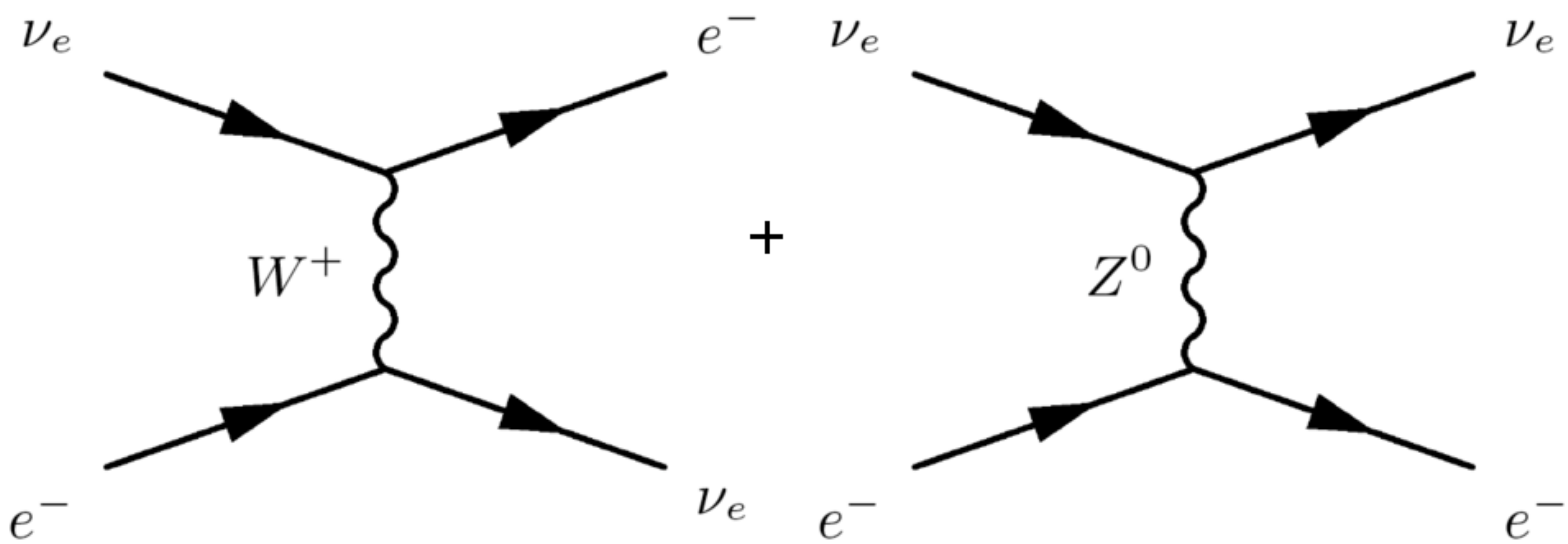
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

Cosmic Neutrino Background



Equilibrium :

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

Decoupling: $T^3 \sim G_{\rm F}^{-2}/M_{\rm pl} = \mathcal{O}(1\,{\rm MeV})$

Cosmic Neutrino Background

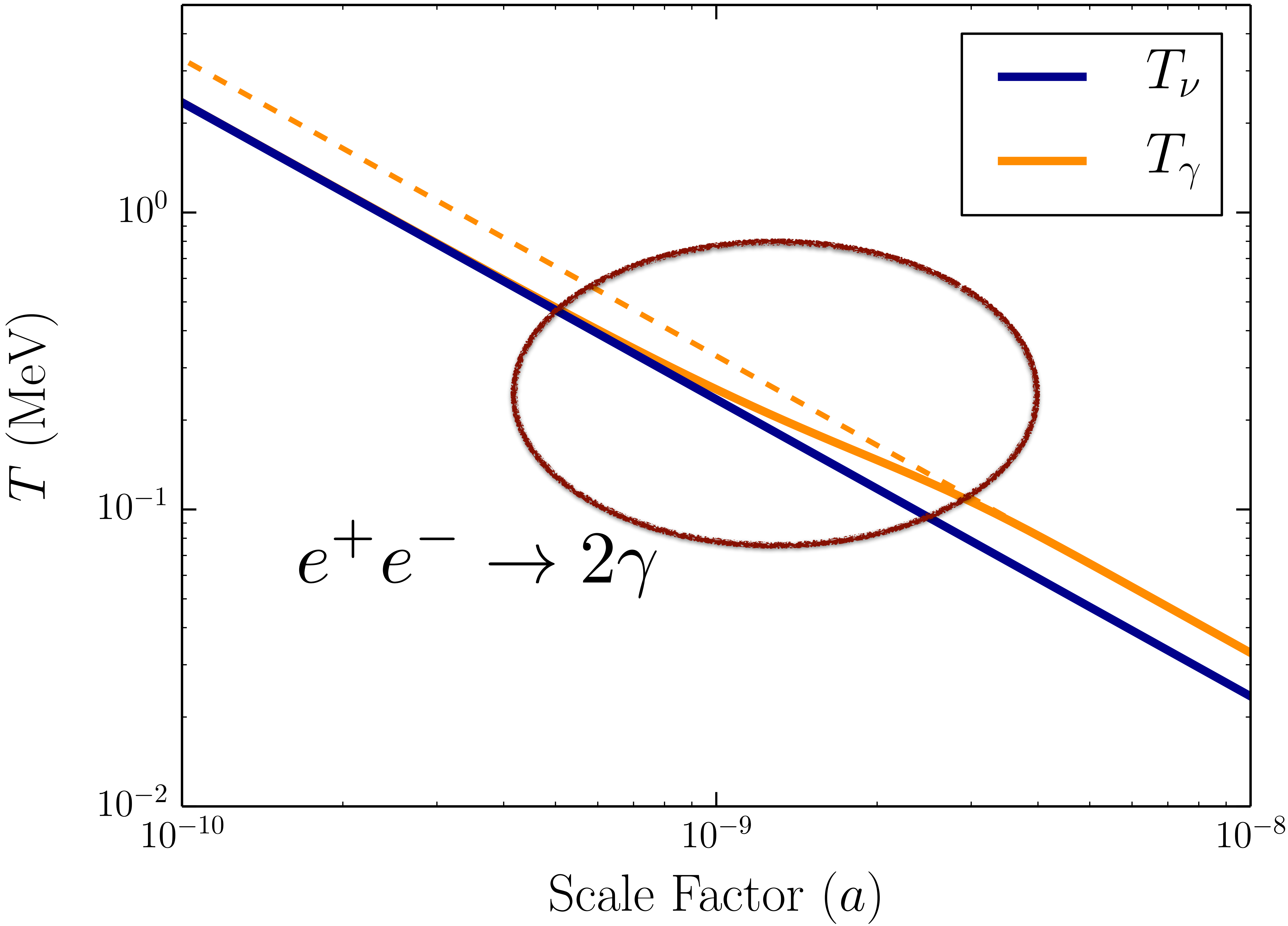
In equilibrium, light fields share entropy evenly

$$s \propto g_\star(T) T^3 \qquad g_\star \approx N_{\rm bosons} + \frac{7}{8} N_{\rm fermions}$$

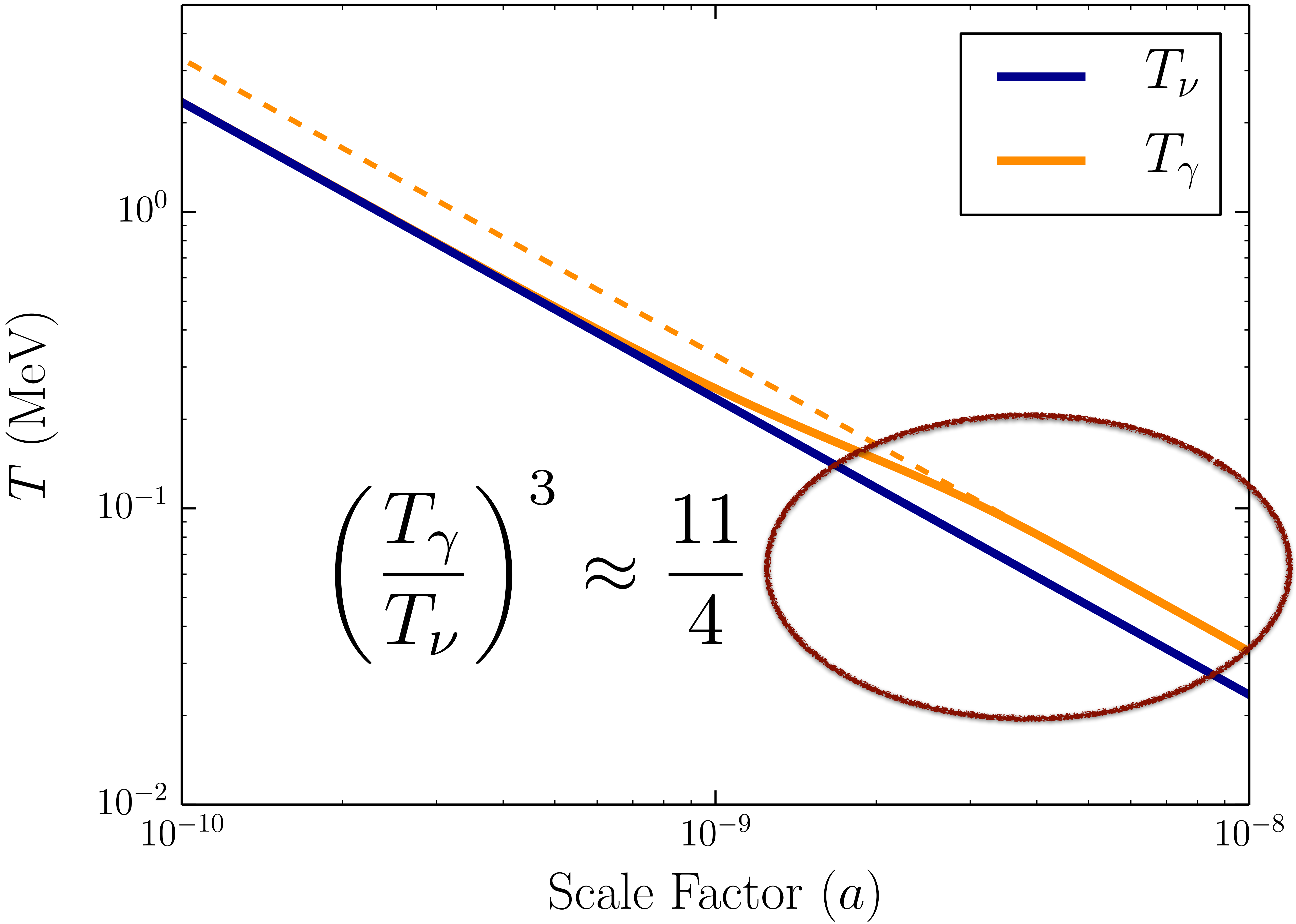
Neutrino number density $\approx$ photon number density

All the power of cosmology starts here

The Universe prepares for us a pristine, high-density state of neutrinos



T_ν
T_γ
10^0
10^{-1}
10^{-2}
T (MeV)
$e^+e^- \to 2\gamma$
10^{-10}
10^{-9}
10^{-8}
Scale Factor (a)



T_ν
T_γ
T (MeV)
10^0
10^{-1}
10^{-2}
10^{-10}
10^{-9}
10^{-8}
Scale Factor (a)
$\left(\frac{T_\gamma}{T_\nu}\right)^3 \approx \frac{11}{4}$

Cosmic Neutrino Background

Cosmology sensitive to the neutrino energy density

Conventional to define

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

Perfect decoupling : $N_{\mathrm{eff}} = 3.$

Imperfect decoupling + QED : $N_{\mathrm{eff}} = 3.045$

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

Cosmic Neutrino Background

After decoupling the state doesn't change

$$f(p,t) = \frac{1}{e^{p/T_\nu} + 1}$$

where $T_\nu, p \propto a^{-1}$

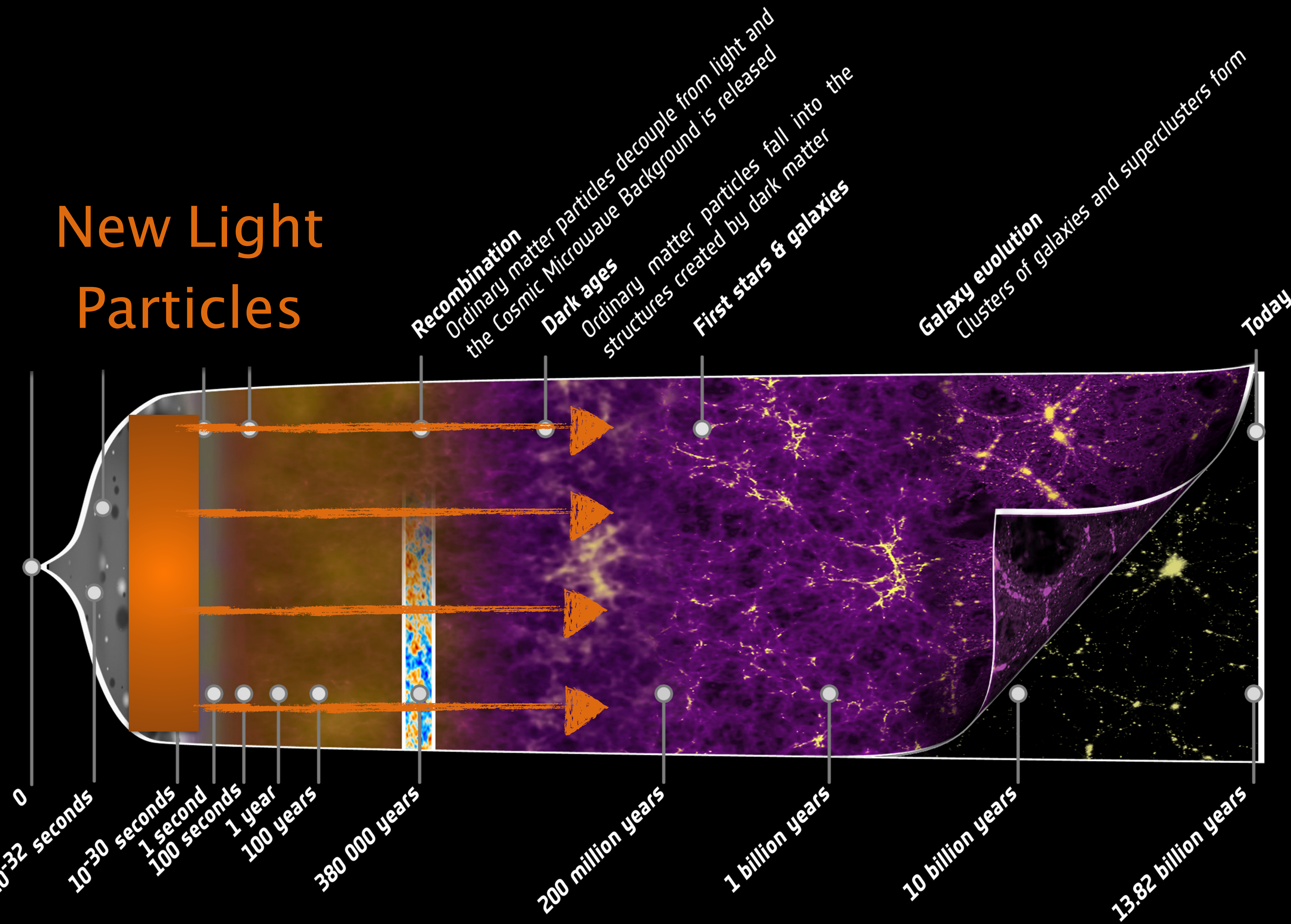
Neutrino temperature redshifts like CMB

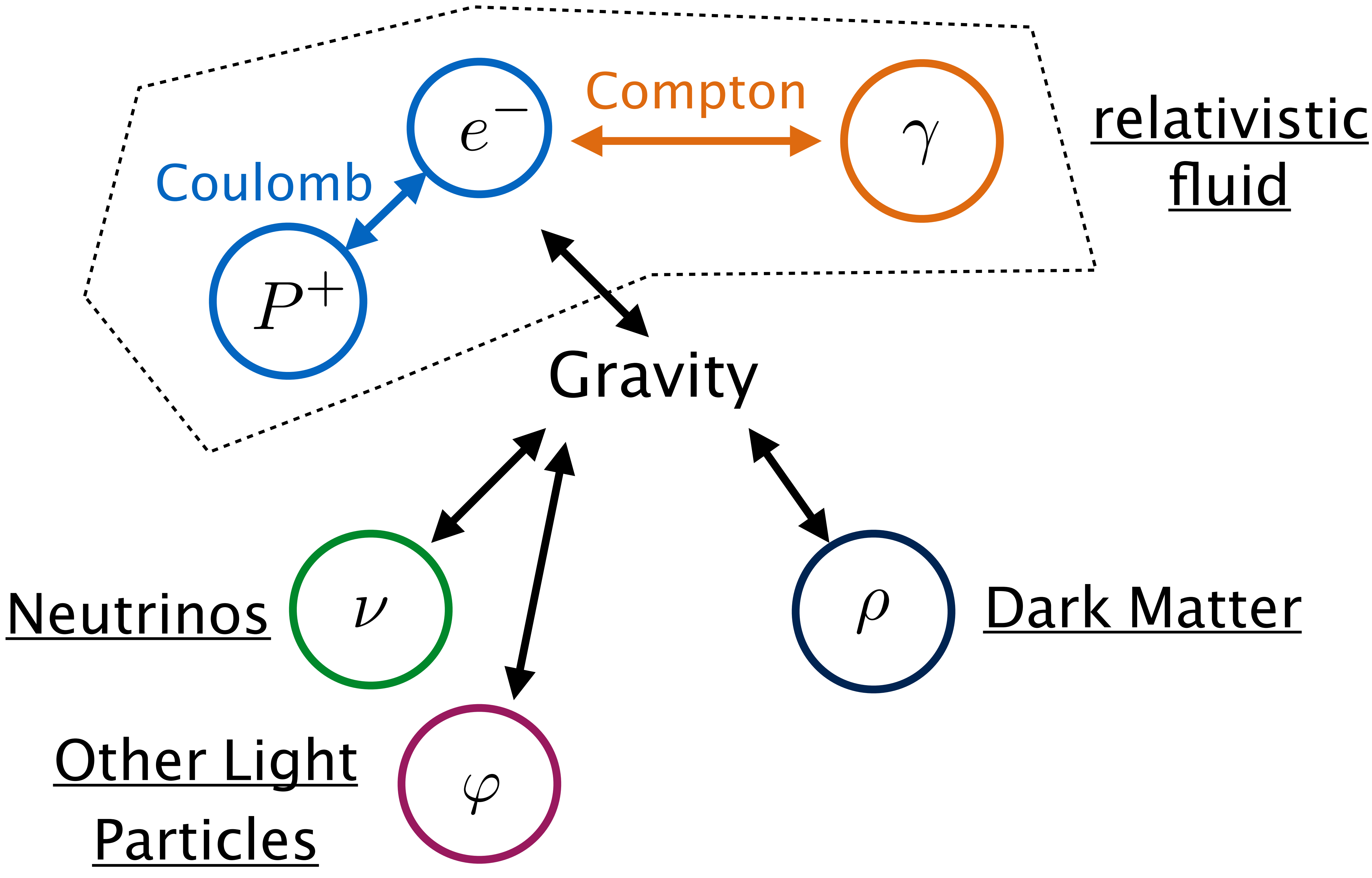
$$T_{\mathrm{CMB}} = 2.72\,\mathrm{K} \quad \rightarrow \quad T_\nu = 1.95\,\mathrm{K}$$

Today, these are very low energy neutrinos

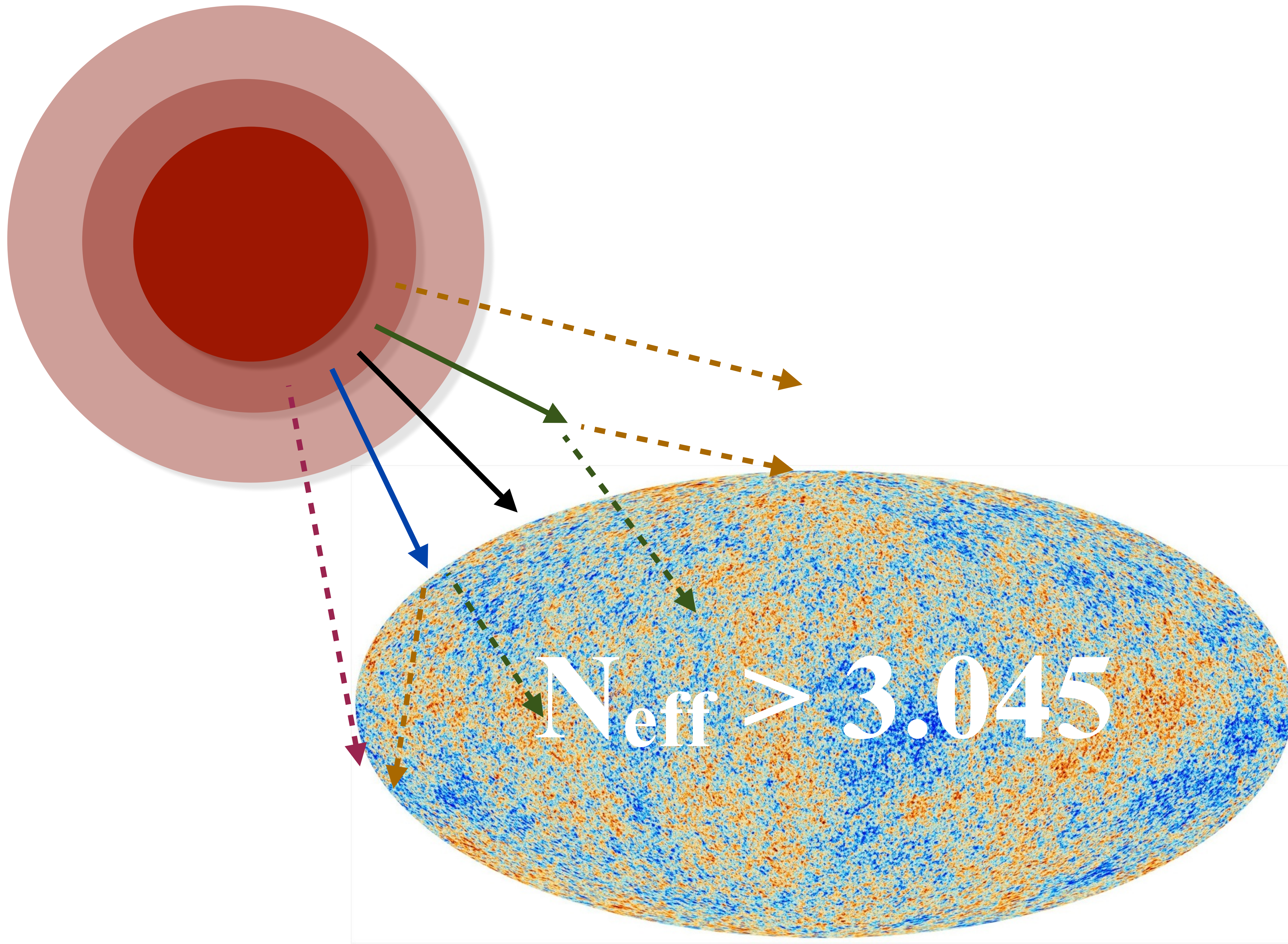
Light Relics

New Light Particles





Coulomb
e^-
Compton
γ
relativistic fluid
P^+
Gravity
Neutrinos
ν
ρ
Dark Matter
Other Light Particles
φ


$N_{eff} > 3.045$

Light Relics

Any light thermalized particle looks like a neutrino

If a light particle decouples at temperature T_F

Only diluted by annihilation after decoupling

$$\Delta N_{\rm eff} = N_{\rm eff} - 3.045 = g_s \frac{4}{7} \left(\frac{43}{4 g_\star(T_F)} \right)^{4/3}$$

Light relics degrees of freedom

Standard Model degrees of freedom

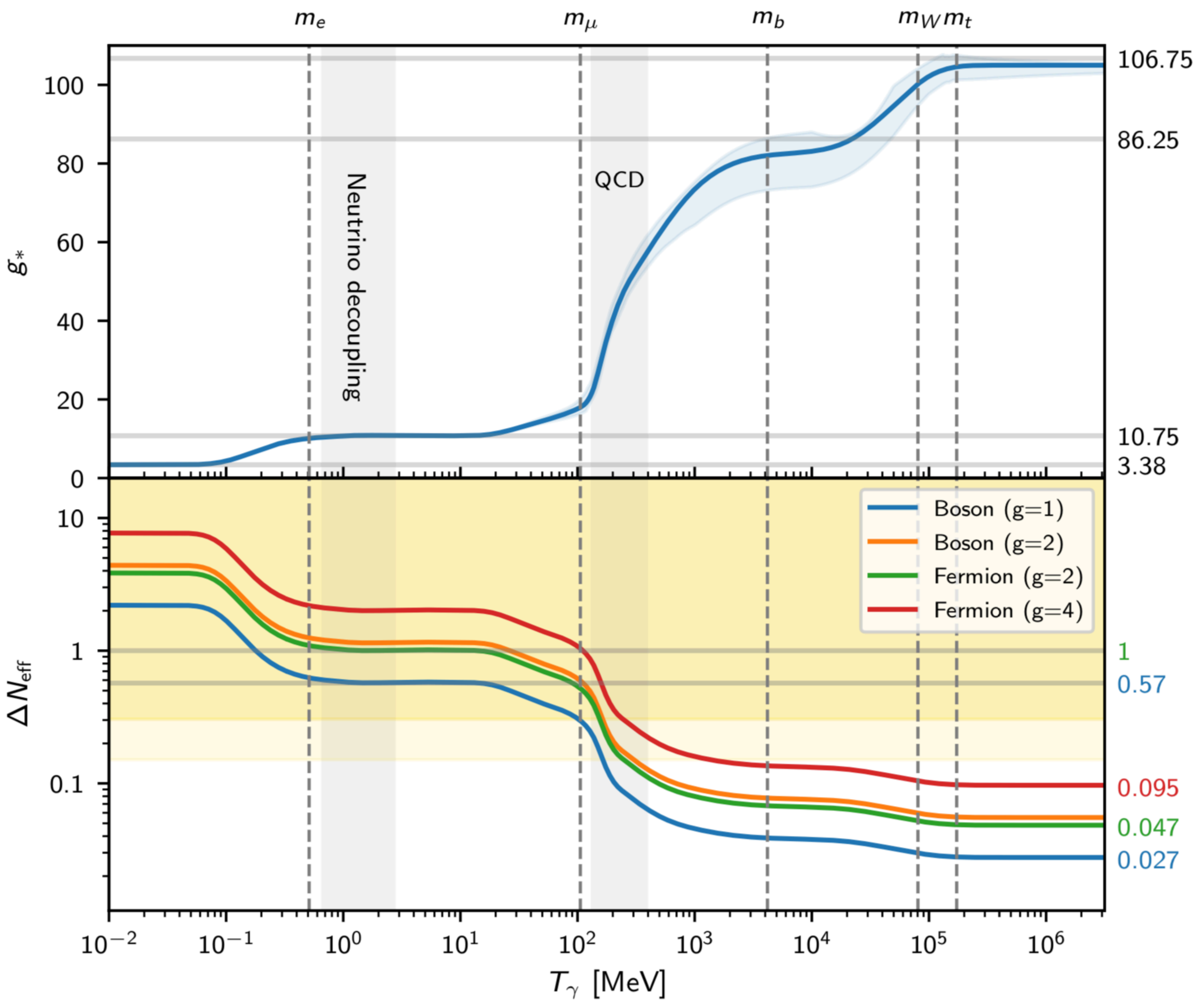


Image from Planck 2018

Light Relics

Coming generations will make a lot of progress

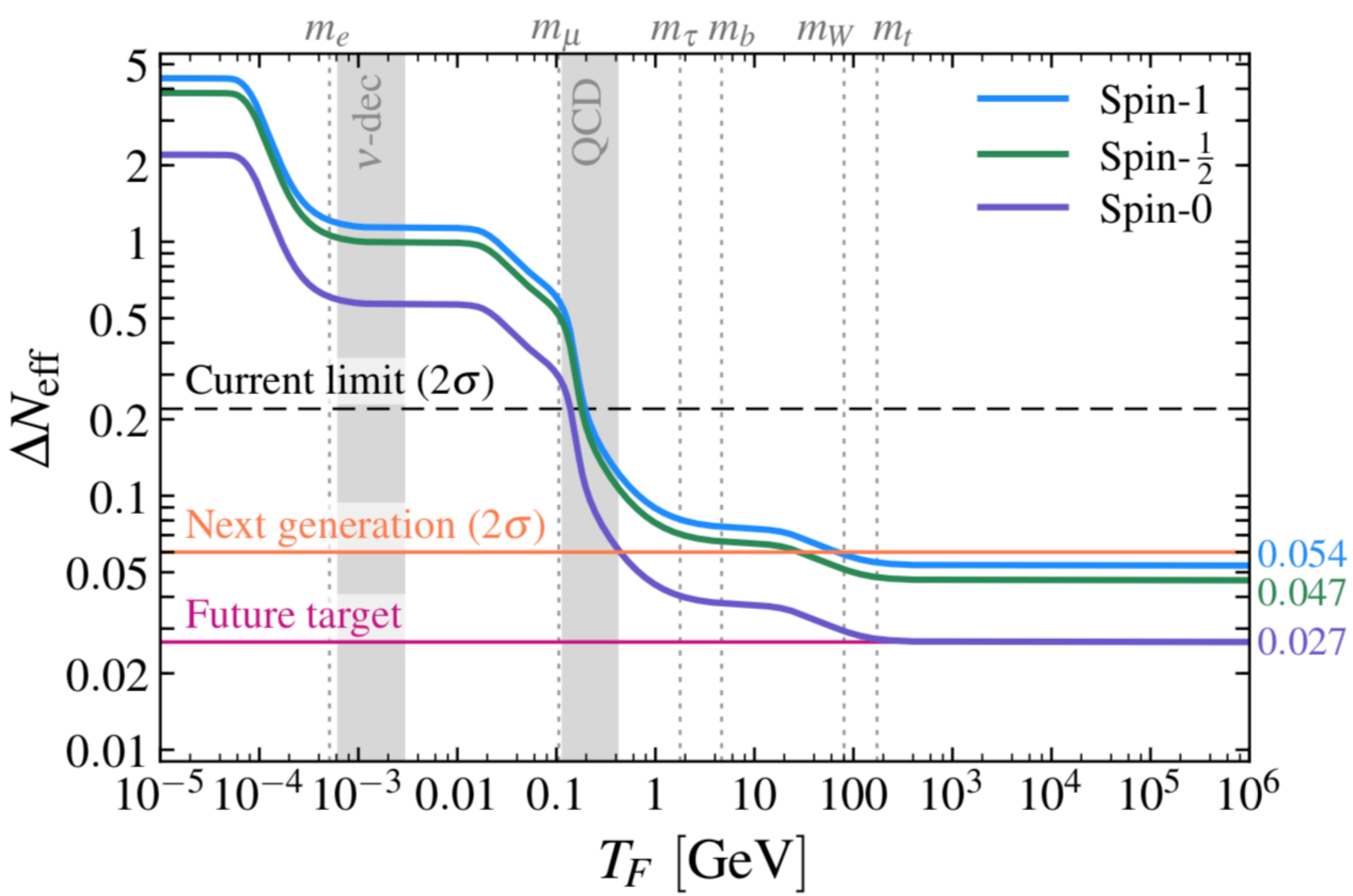
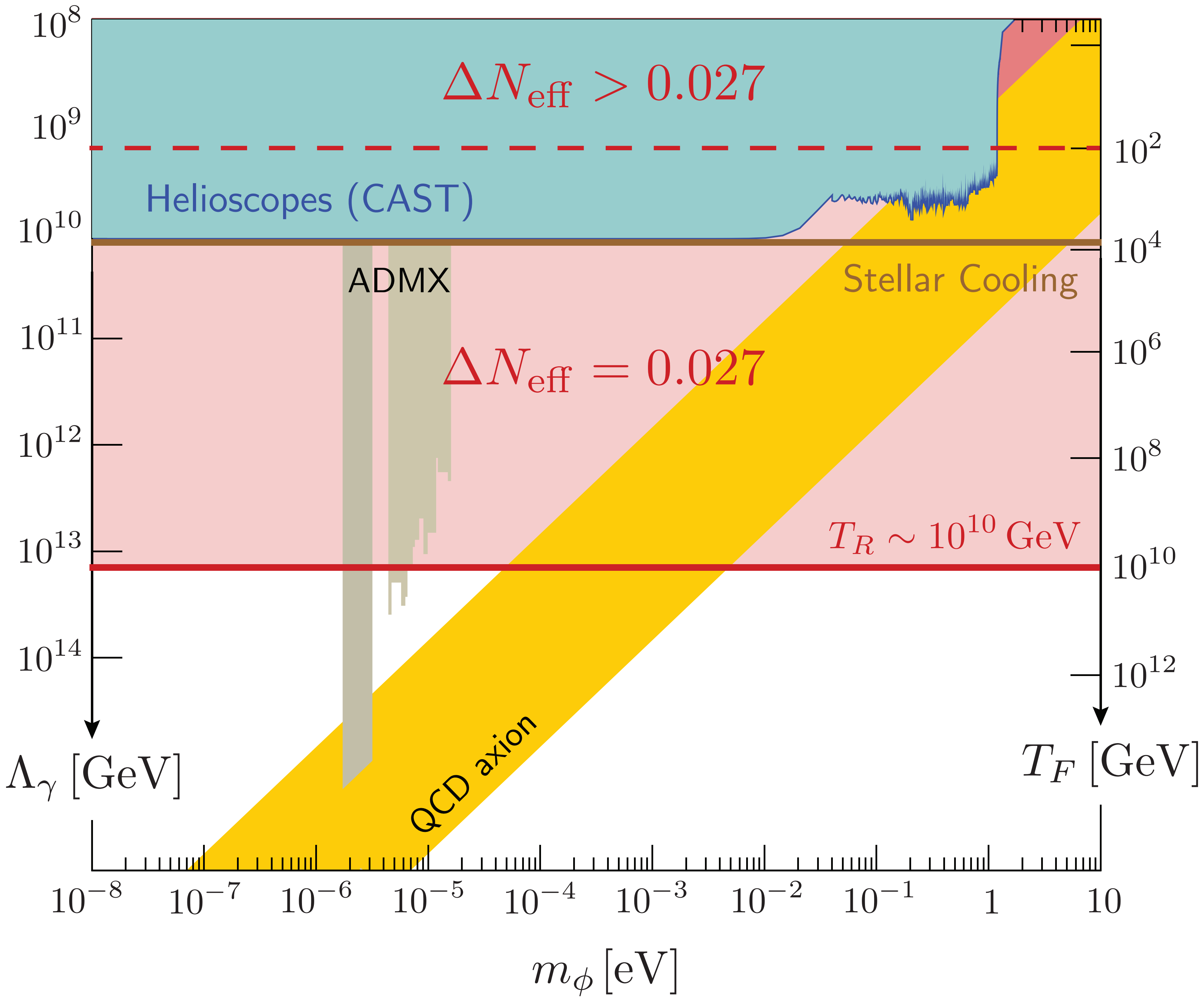


Image from DG et al. 2019

Implications for Axions

Λ_γ



Baumann, DG & Wallisch (2016)

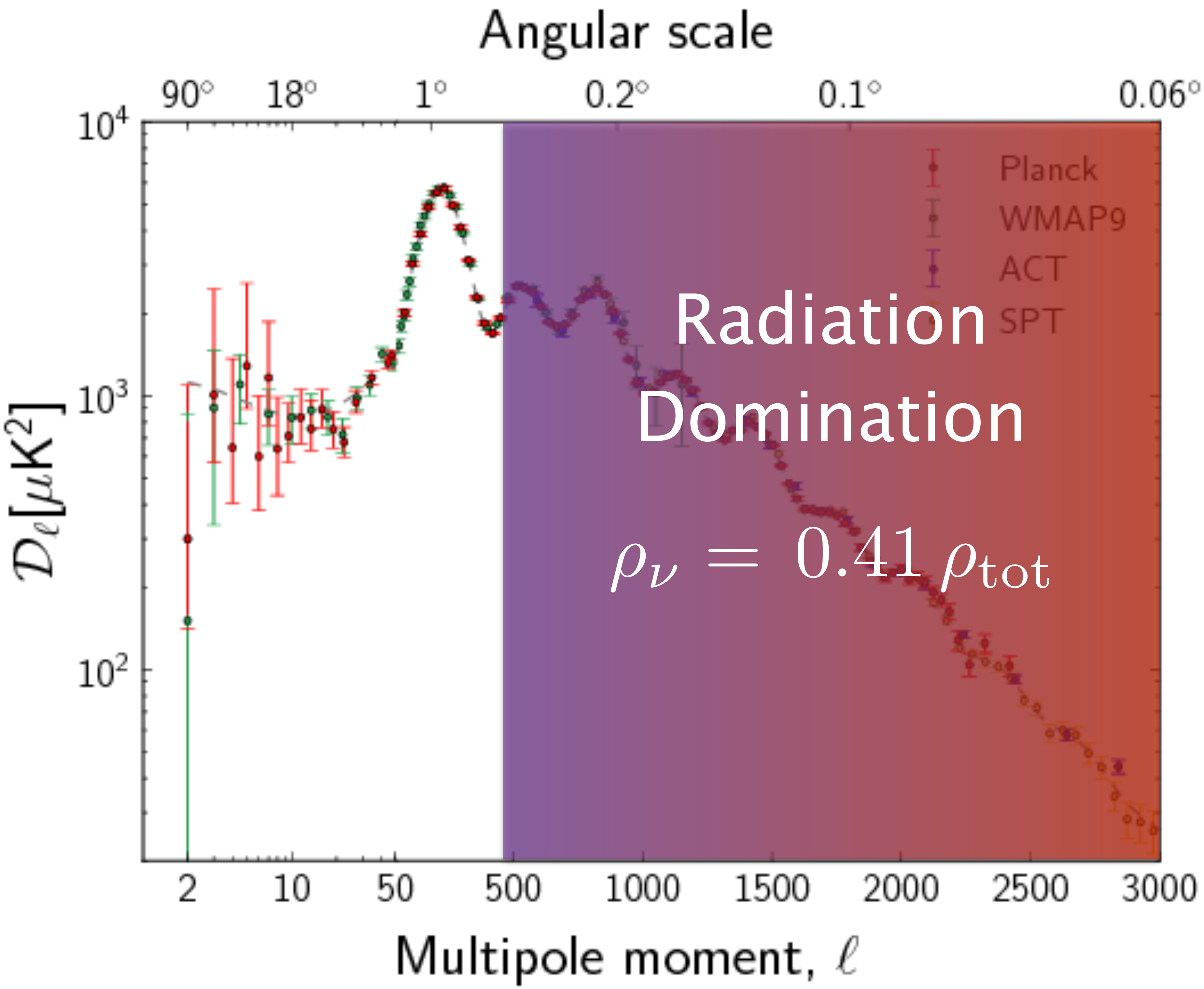
Implications for Axions

	Current Constraints		Future CMB Constraints		
Coupling	Bound [GeV]	Origin	Freeze-Out [GeV]	Freeze-In [GeV]	$\Delta\tilde{N}_{\rm eff}$
Λ_{ee}	1.2×10^{10}	White dwarfs	6.0×10^{7}	2.7×10^{6}	1.3
$\Lambda_{\mu\mu}$	2.0×10^{6}	Stellar cooling	1.2×10^{10}	3.4×10^{7}	0.5
$\Lambda_{\tau\tau}$	2.5×10^{4}	Stellar cooling	2.1×10^{11}	9.5×10^{7}	0.05
Λ_{bb}	6.1×10^{5}	Stellar cooling	9.5×10^{11}	–	0.04
Λ_{tt}	1.2×10^{9}	Stellar cooling	3.5×10^{13}	–	0.03
$\Lambda^{V}_{\mu e}$	5.5×10^{9}	$\mu^+ \to e^+ \phi$	6.2×10^{9}	4.8×10^{7}	0.5
$\Lambda_{\mu e}$	3.1×10^{9}	$\mu^+ \to e^+ \phi \gamma$	6.2×10^{9}	4.8×10^{7}	0.5
$\Lambda_{\tau e}$	4.4×10^{6}	$\tau^- \to e^- \phi$	1.0×10^{11}	1.3×10^{8}	0.05
$\Lambda_{\tau\mu}$	3.2×10^{6}	$\tau^- \to \mu^- \phi$	1.0×10^{11}	1.3×10^{8}	0.05
Λ^{A}_{cu}	6.9×10^{5}	D^0-$\bar{D}^0$	1.3×10^{11}	2.0×10^{8}	0.05
Λ^{A}_{bd}	6.4×10^{5}	B^0-$\bar{B}^0$	4.8×10^{11}	3.7×10^{8}	0.04
Λ_{bs}	6.1×10^{7}	$b \to s\phi$	4.8×10^{11}	3.7×10^{8}	0.04
Λ_{tu}	6.6×10^{9}	Mixing	1.8×10^{13}	2.1×10^{9}	0.03
Λ_{tc}	2.2×10^{9}	Mixing	1.8×10^{13}	2.1×10^{9}	0.03

Baumann, DG & Wallisch (2016)

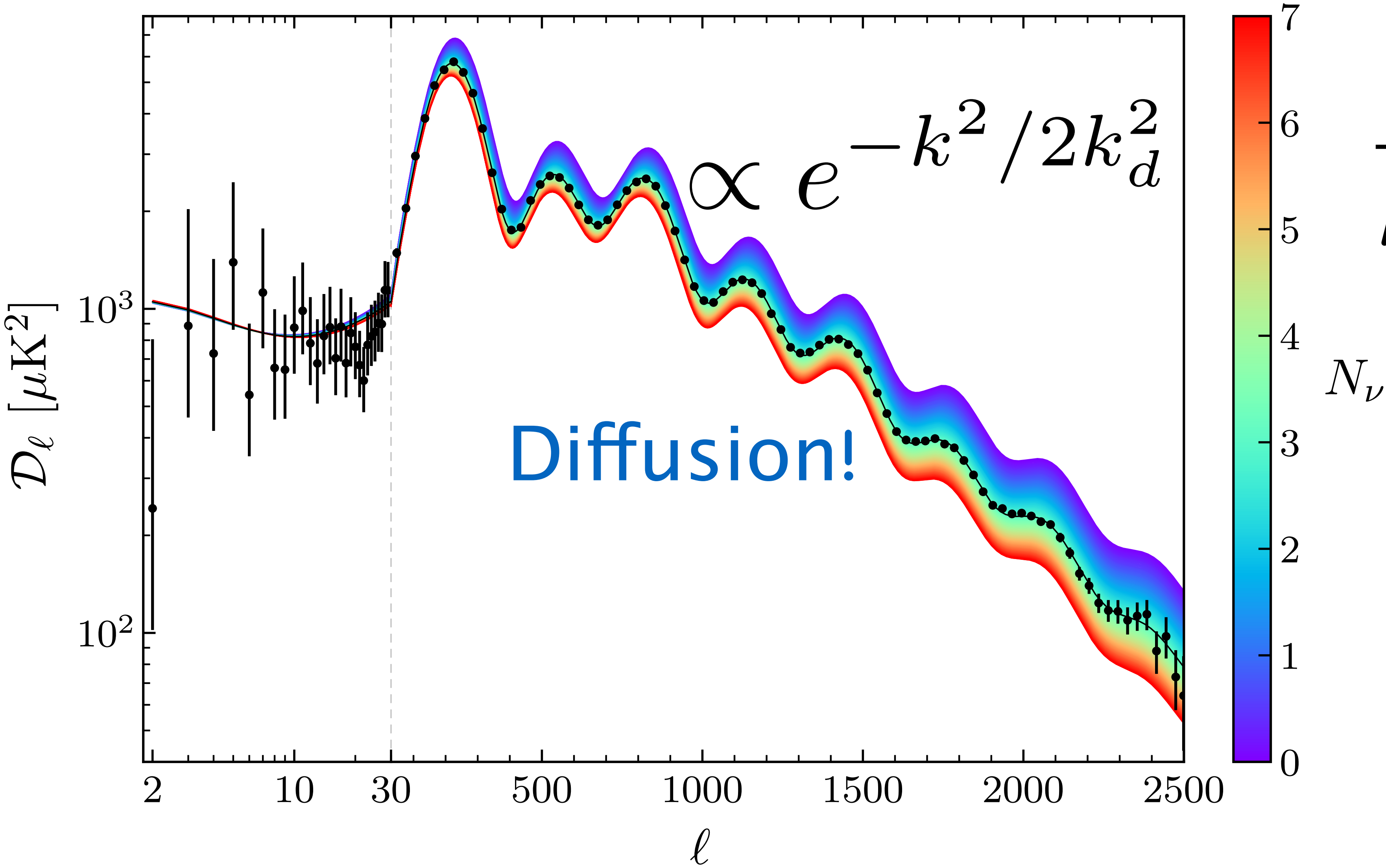
Signals in the CMB

Cosmic Microwave Background



Cosmic Microwave Background

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



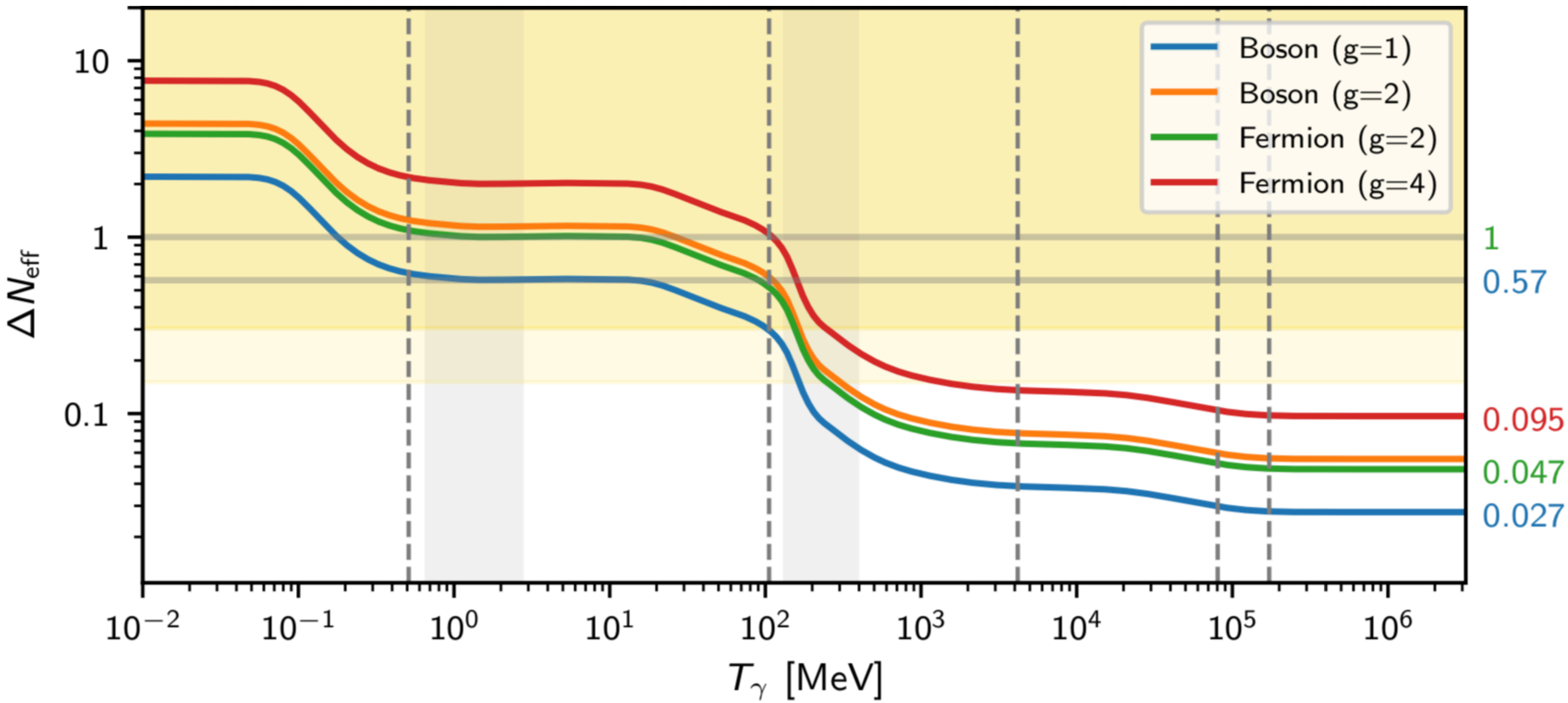
$$\frac{1}{k_d^2} \sim \langle \Delta x^2 \rangle \propto t$$

$$t \propto \frac{1}{H}$$

Cosmic Microwave Background

Damping drives the constraints for $\Lambda\mathrm{CDM} + N_{\mathrm{eff}}$

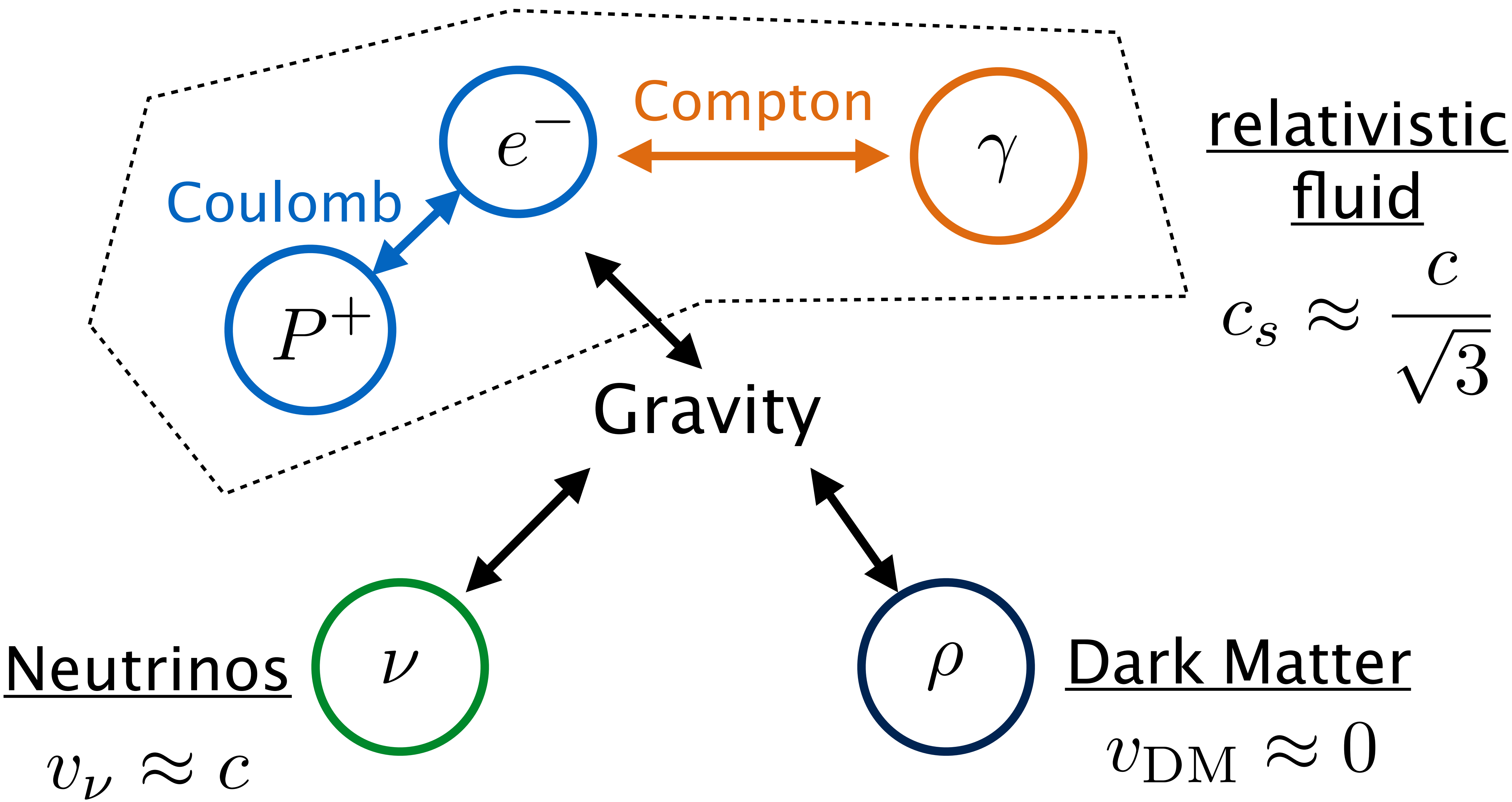
$$N_{\mathrm{eff}} = 2.99 \pm 0.17\,(\mathrm{TTTEEE} + \mathrm{BAO} + \kappa\kappa)$$



Planck 2018

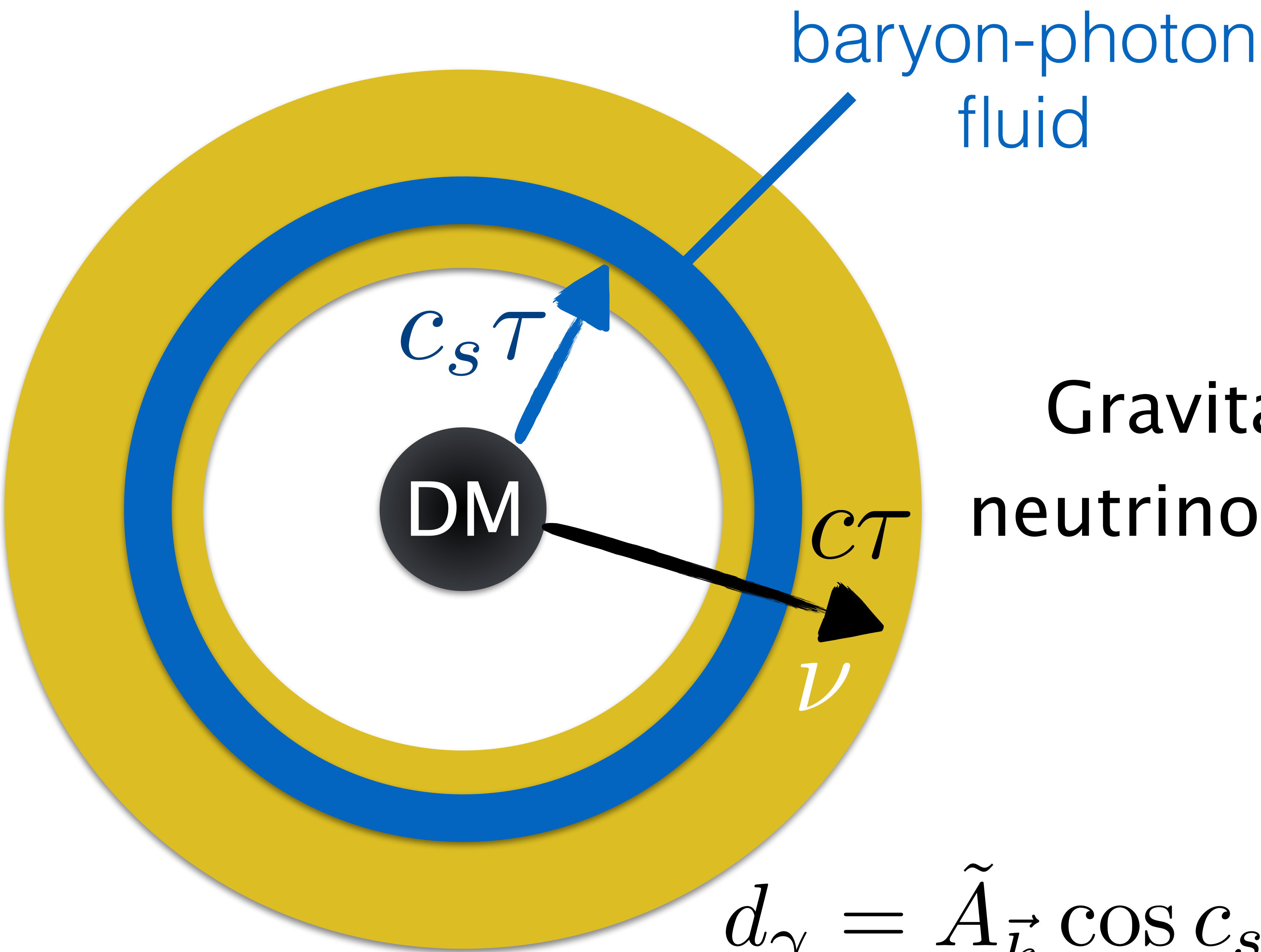
Phase Shift

Neutrinos fluctuations move faster than sound



Phase Shift

Information propagates ahead of the sound horizon



Gravitational force of neutrinos regenerates sin

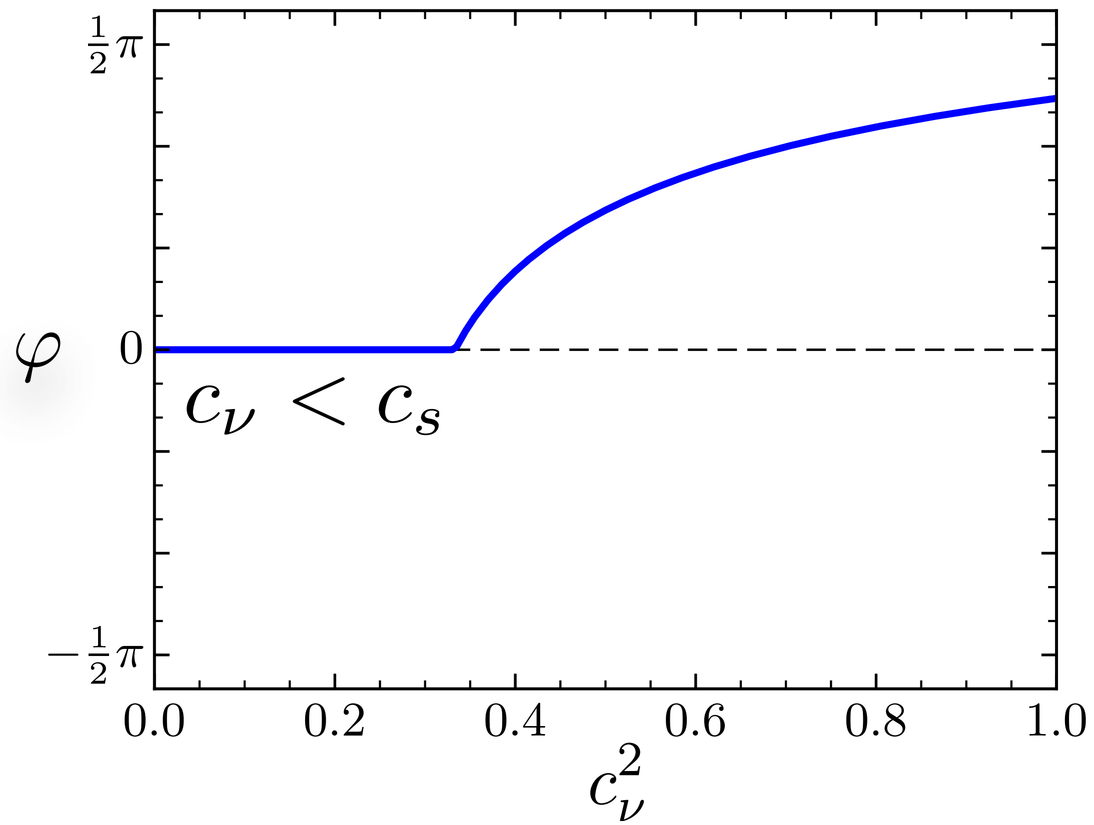
$$d_\gamma = \tilde{A}_{\vec{k}} \cos c_s k\tau + B_{\vec{k}} \sin c_s k\tau$$

Phase Shift

The sine is equivalent to a phase shift

$$\cos(kr_s) \to \cos(kr_s + \varphi) \qquad \varphi \sim B/\tilde{A}$$

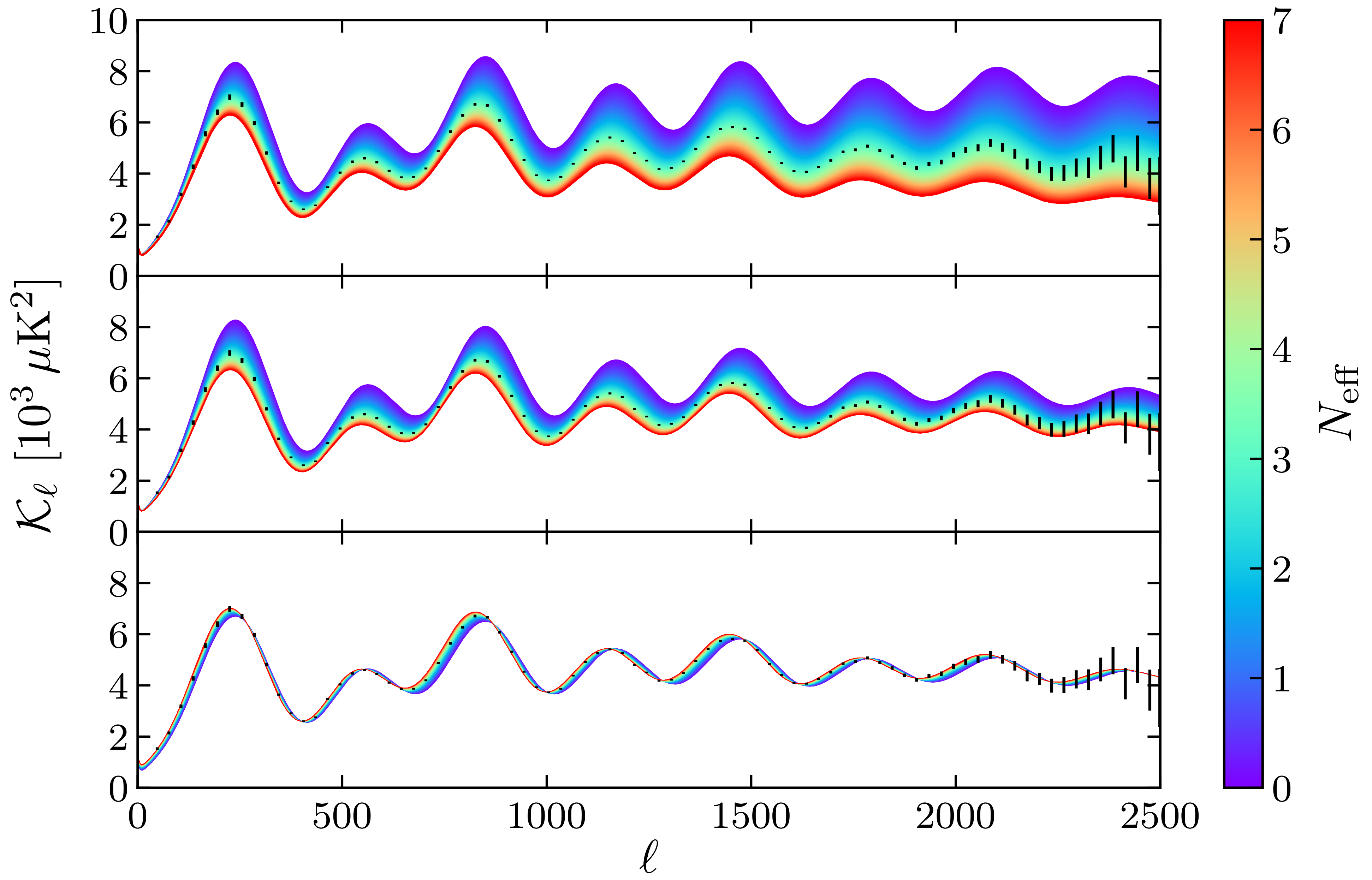
Supersonic fluctuations encoded in phase shift



Bashinsky & Seljak (2003); Baumann, DG, Meyers, Wallisch (2015)

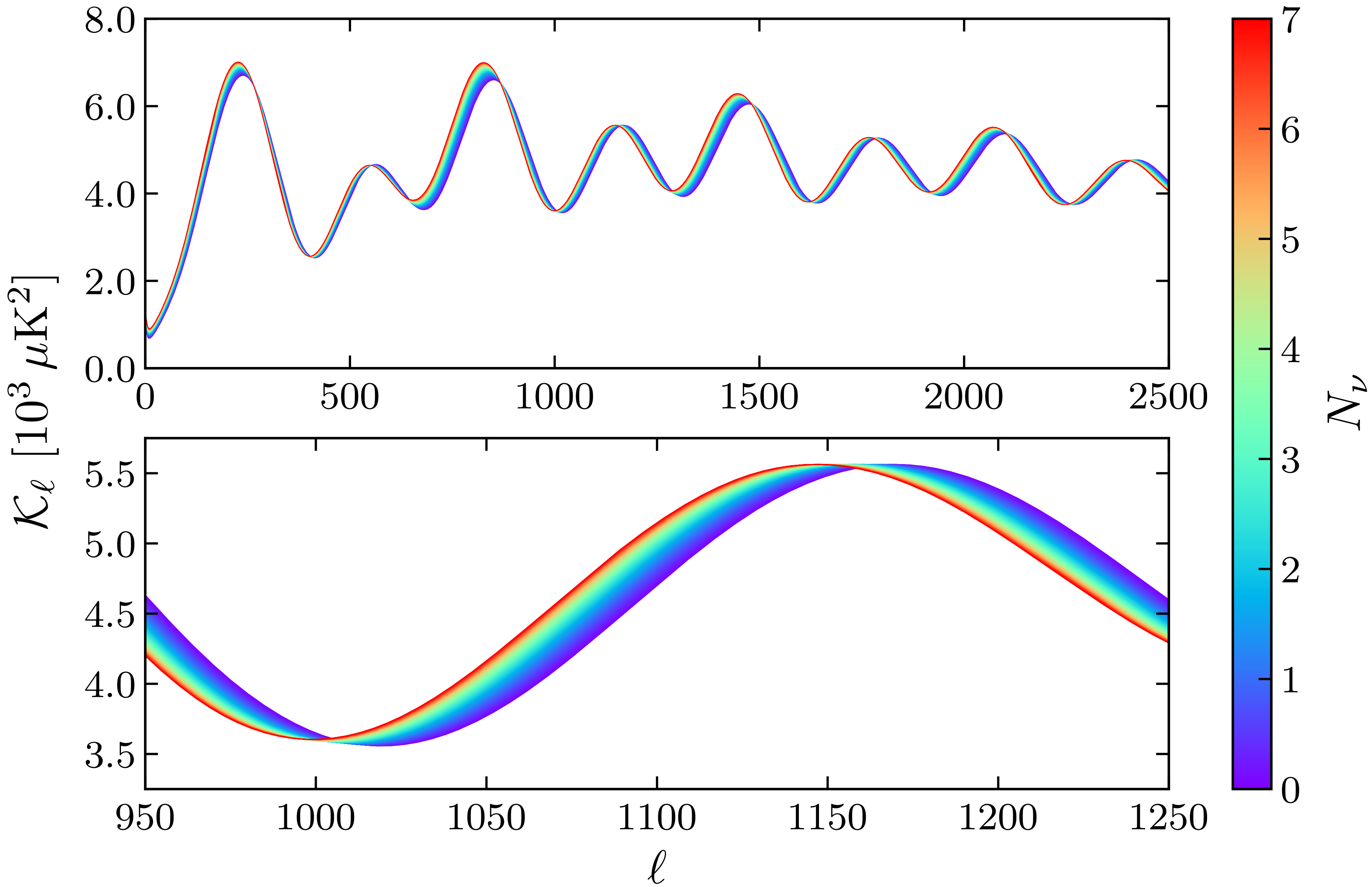
Phase Shift

Neutrinos produce a unique shift in the CMB



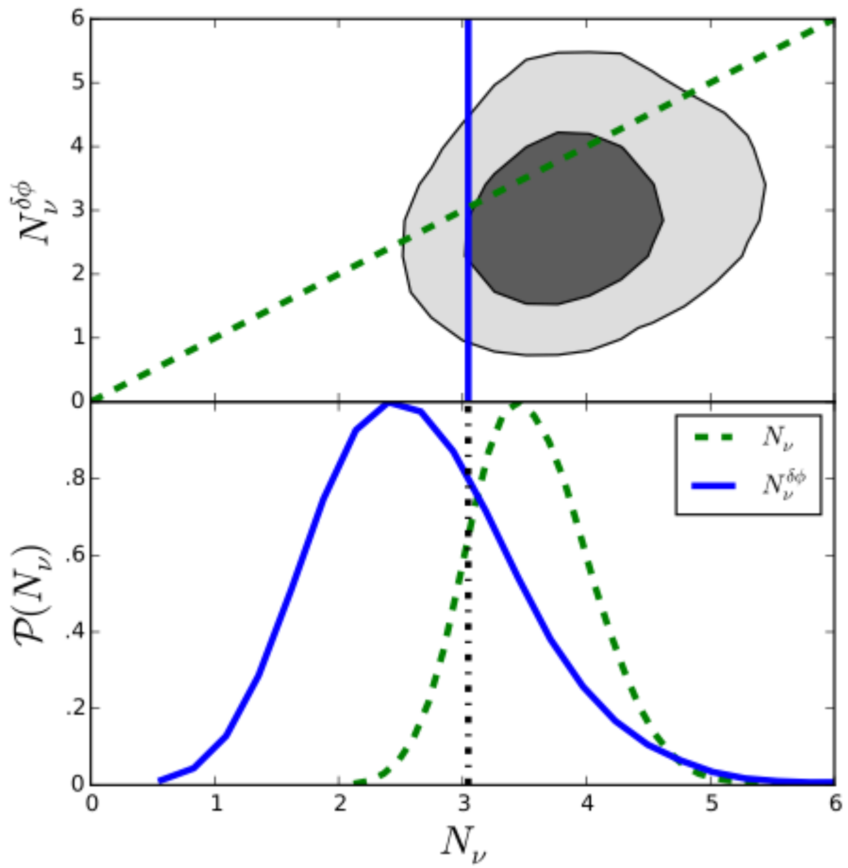
Phase Shift

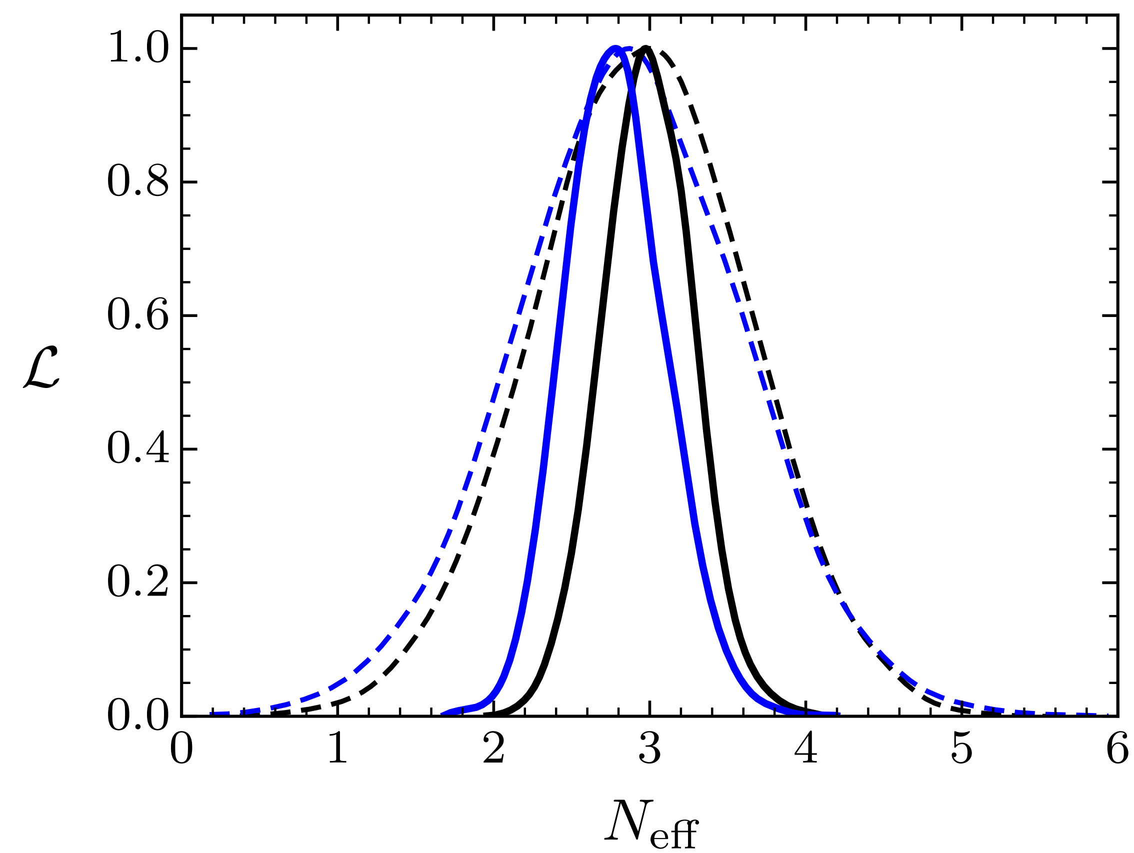
Neutrinos produce a unique shift in the CMB



Phase Shift

This phase shift is detected in the CMB





$$N_{\rm eff}^{\rm phase} = 2.3^{+1.1}_{-0.4}$$

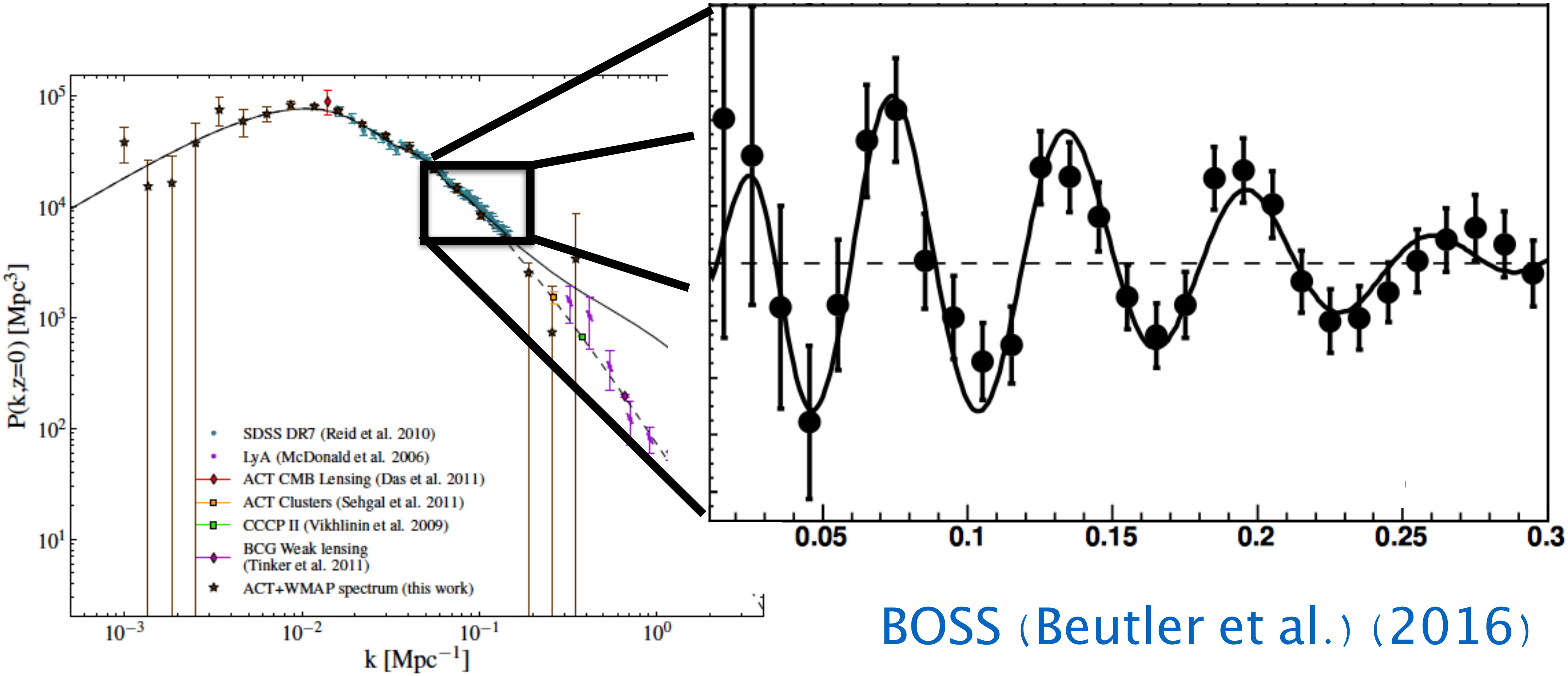
$$N_{\rm eff}^{\rm phase} = 2.68^{+0.29}_{-0.33}$$

Follin et al. (2015)

Baumann, DG, Meyers, Wallisch (2015); Brust, Cui, Sigurdson (2017)

Baryon Acoustic Oscillations (BAO)

Signal is frozen in distribution of galaxies / matter

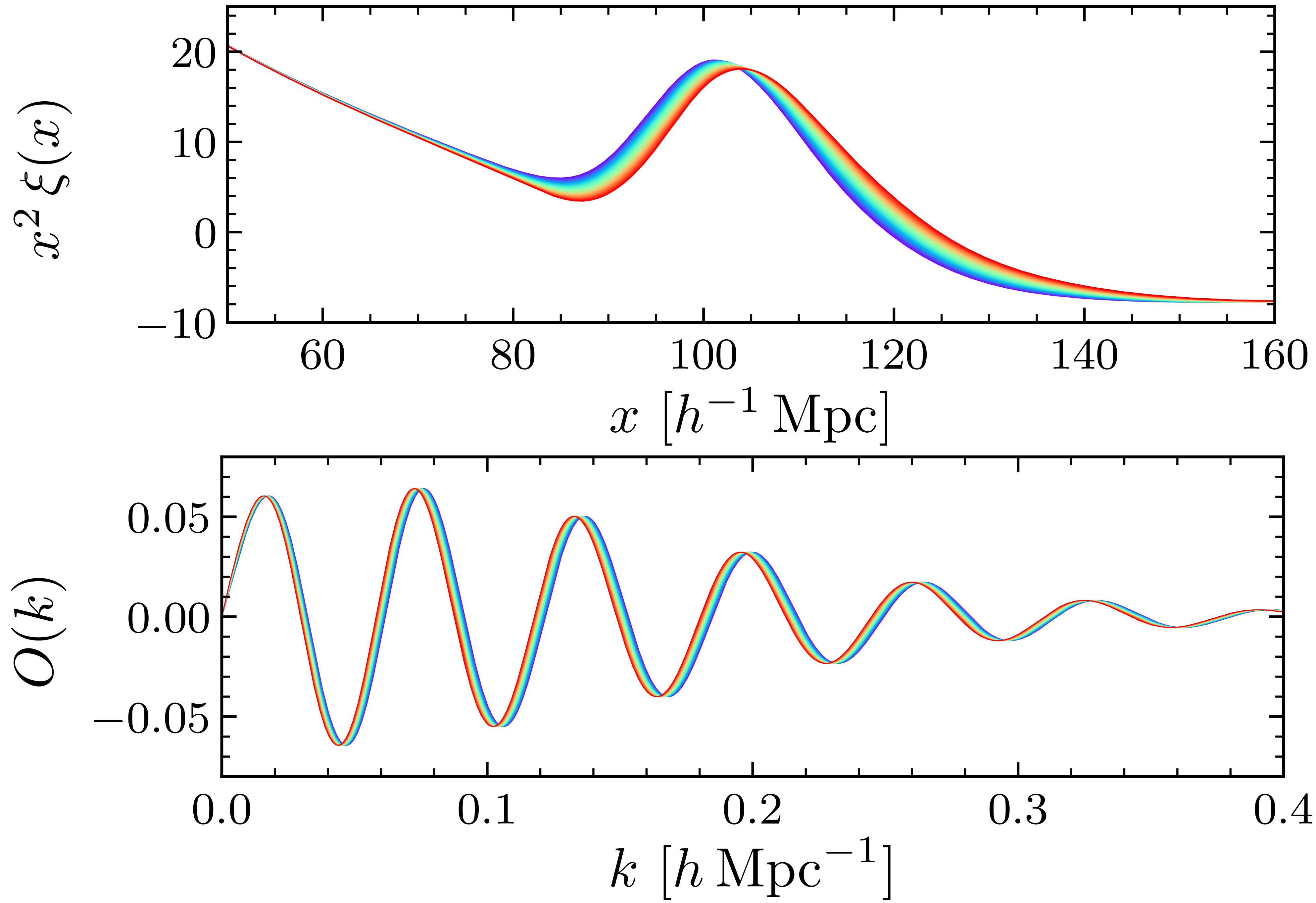


BOSS (Beutler et al.) (2016)

Figure from Hlozek et al.

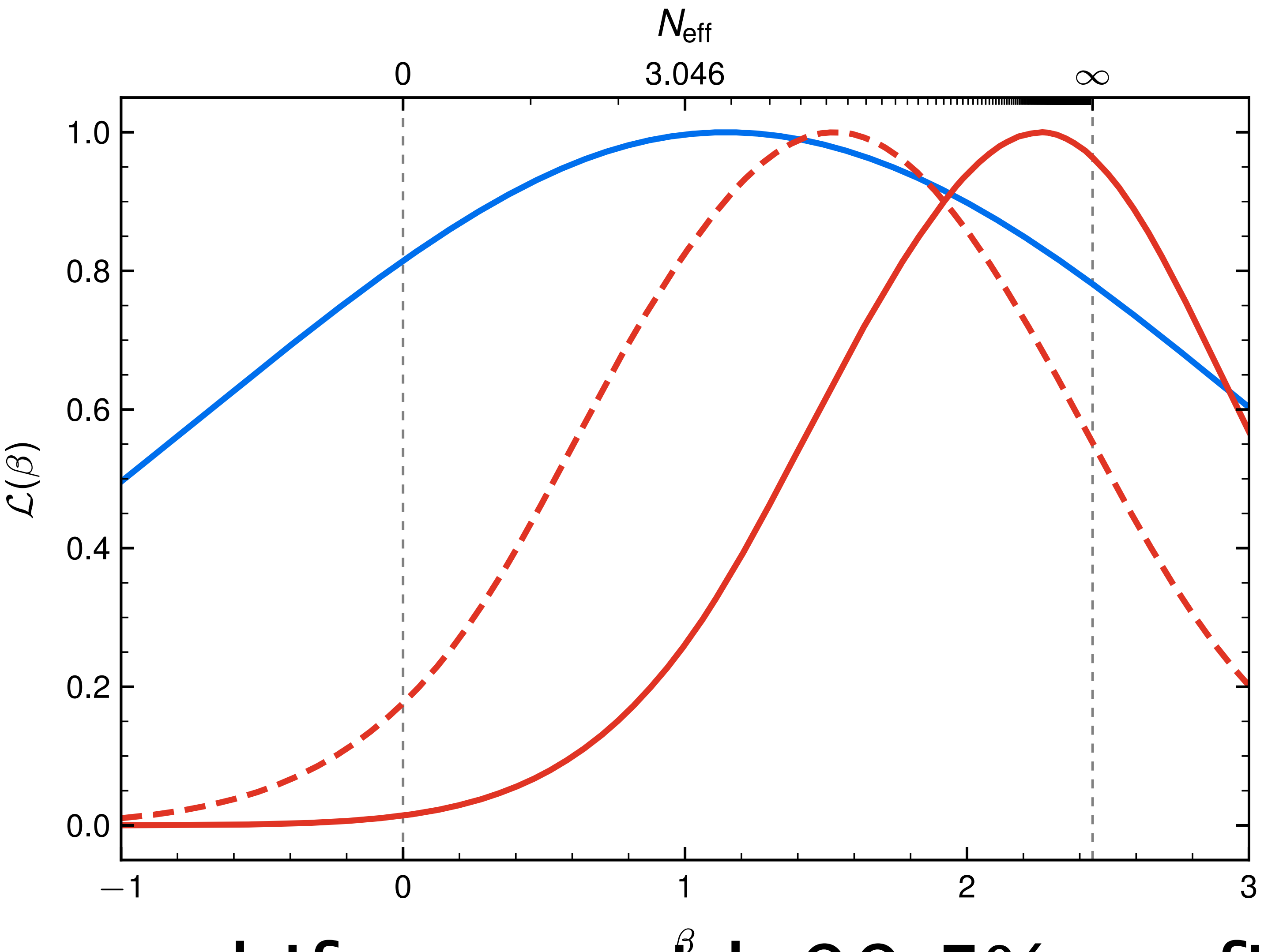
BAO Phase Shift

Phase shift appears in BAO



BAO Phase Shift

Applying same idea to BOSS data



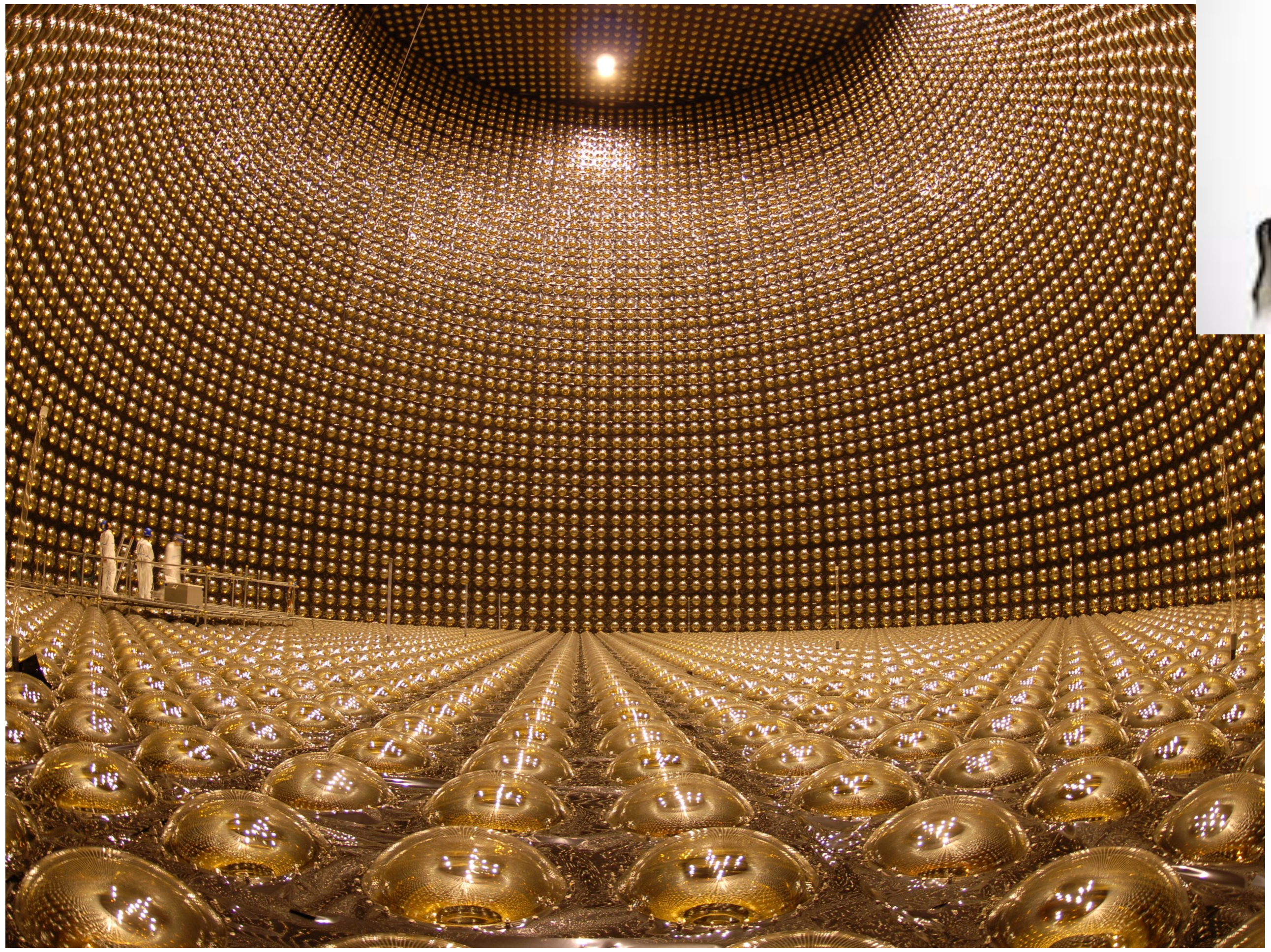
Positive phase shift seen with 99.5% confidence

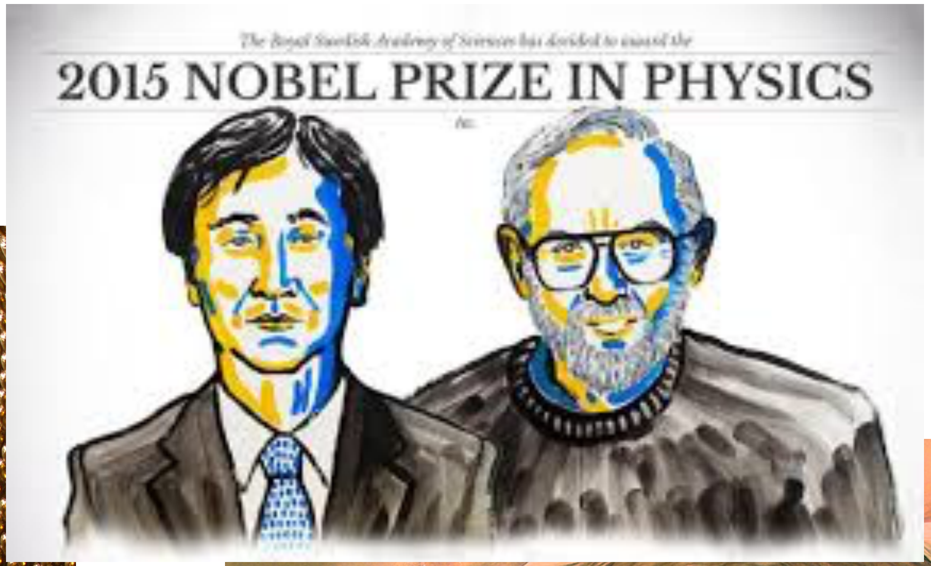
Baumann et al. (2018)

Neutrino Mass

Neutrino Mass

Neutrinos have mass





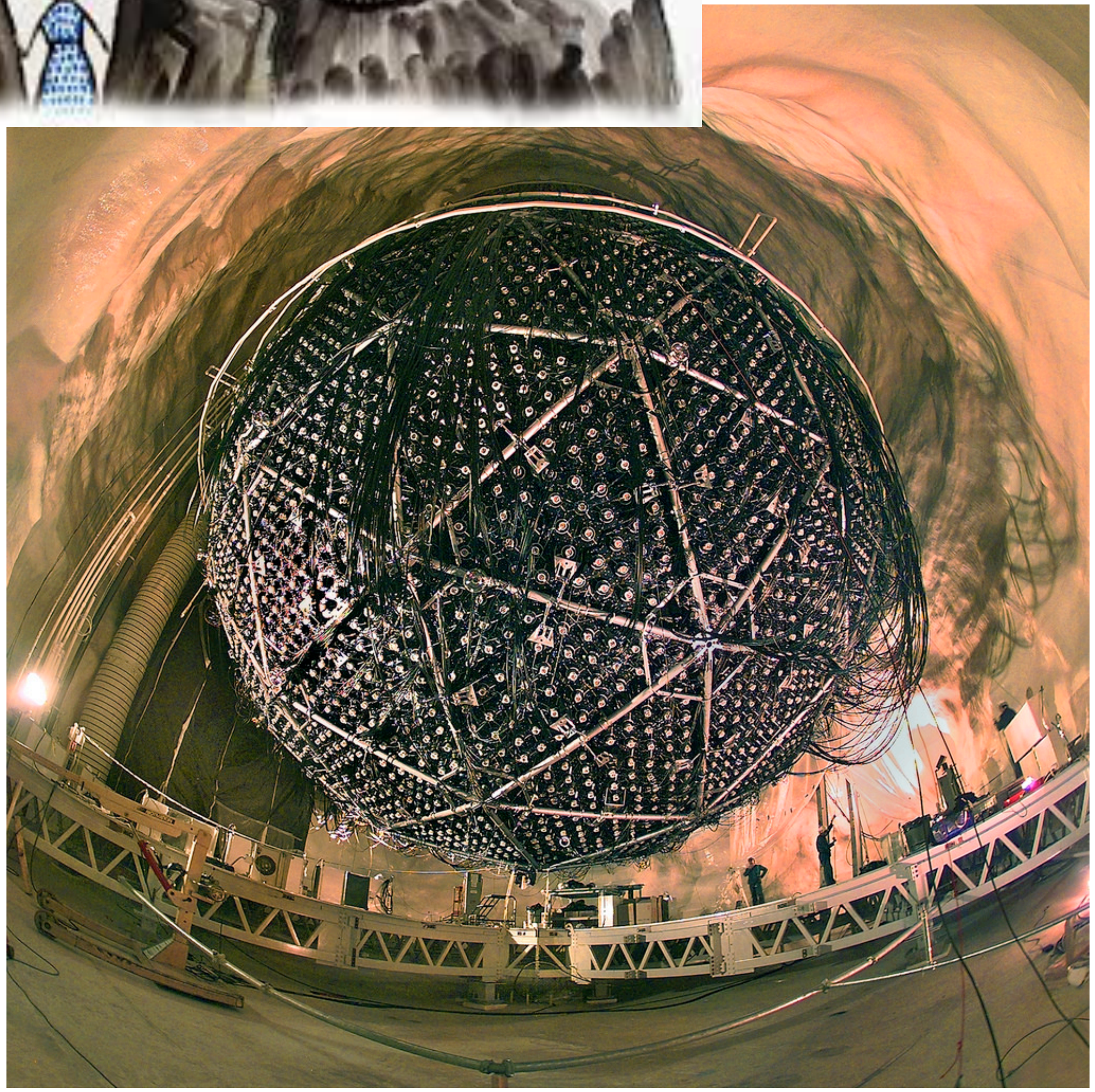
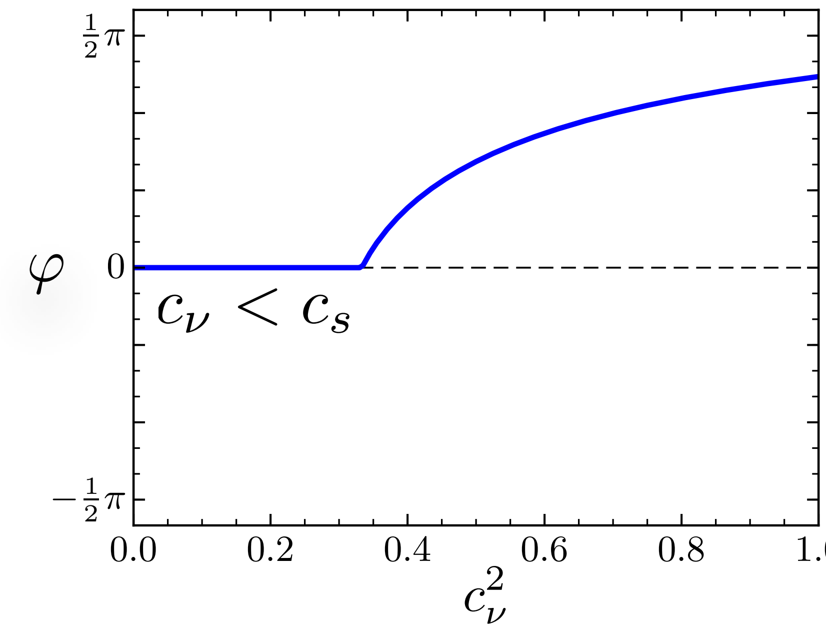


Image from Super-K ; SNO

Neutrino Mass

We know neutrinos were relativistic at recombination

If is wasn't, then $c_\nu \approx \frac{3T_\nu}{m_\nu} \ll 1$



Phase shift doesn't arise when non-relativistic

$$T_{\rm CMB}(z_{\rm recomb.}) \approx 0.25\,{\rm eV}$$

$$\sum m_\nu < 0.26\,{\rm eV}\;(95\%)$$

Planck TTTEEE (2018)

We can still improve by going to lower redshift

Neutrino Mass

Massive neutrinos free stream / suppress growth

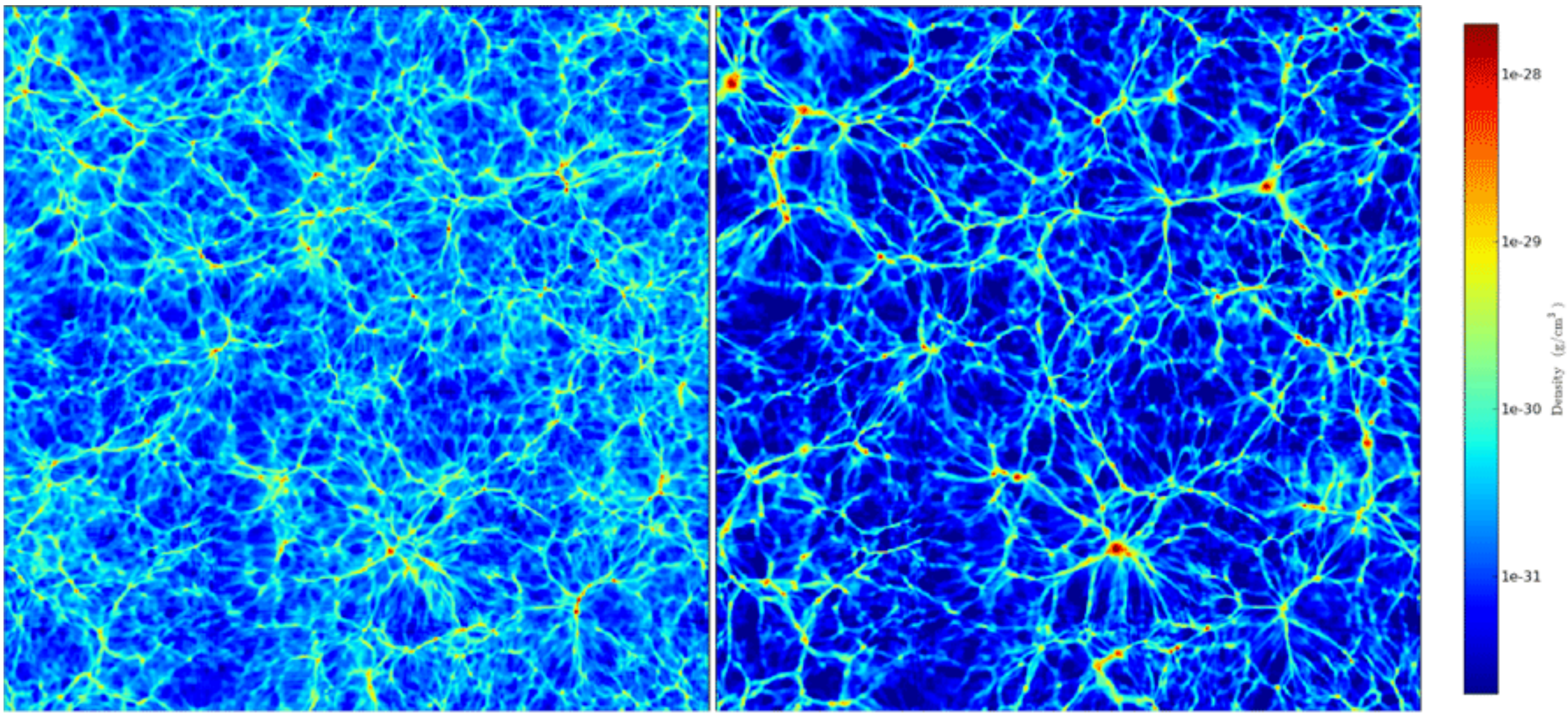
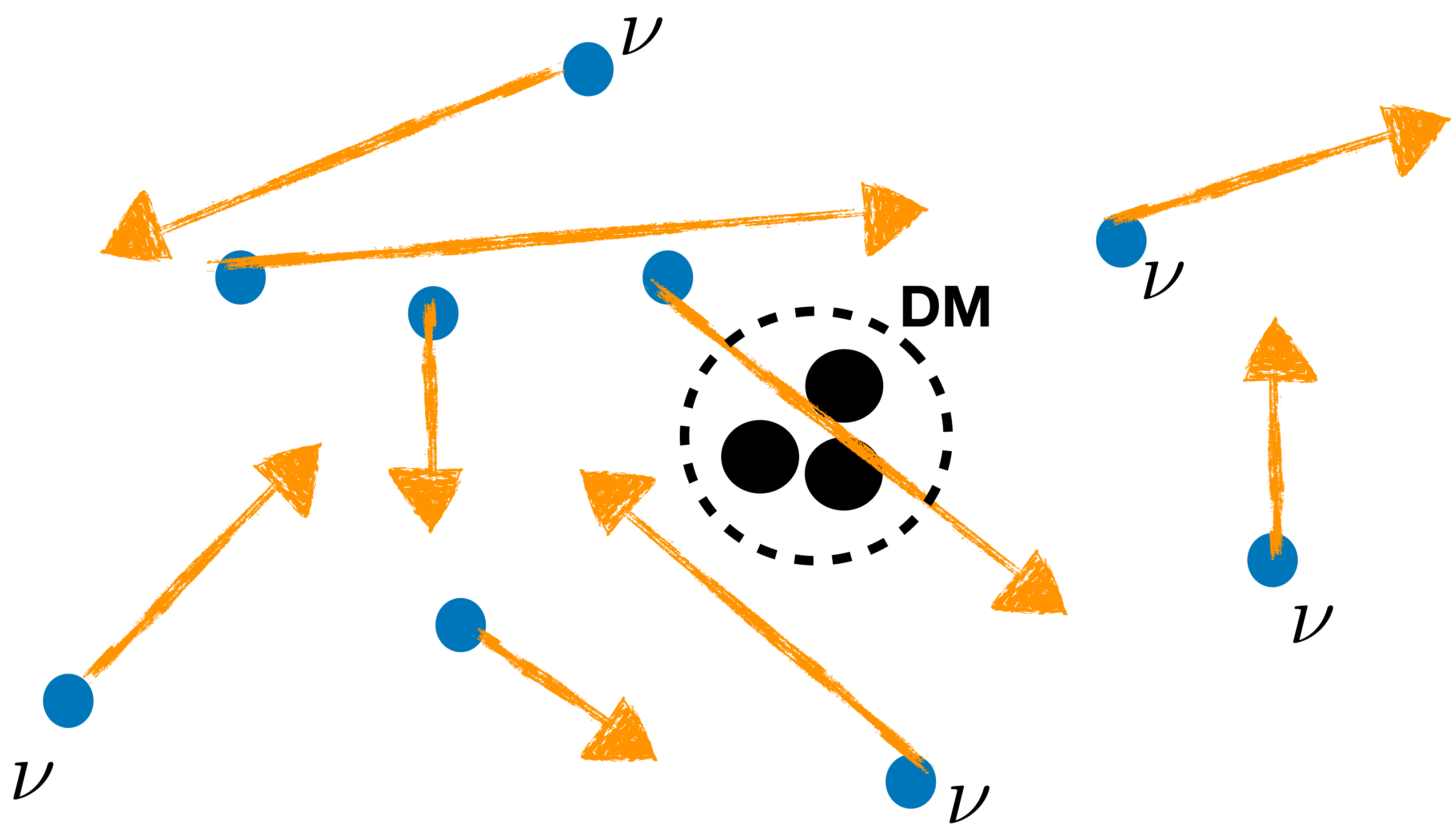


Image from Agarwal & Feldman (2010)

Neutrino Mass

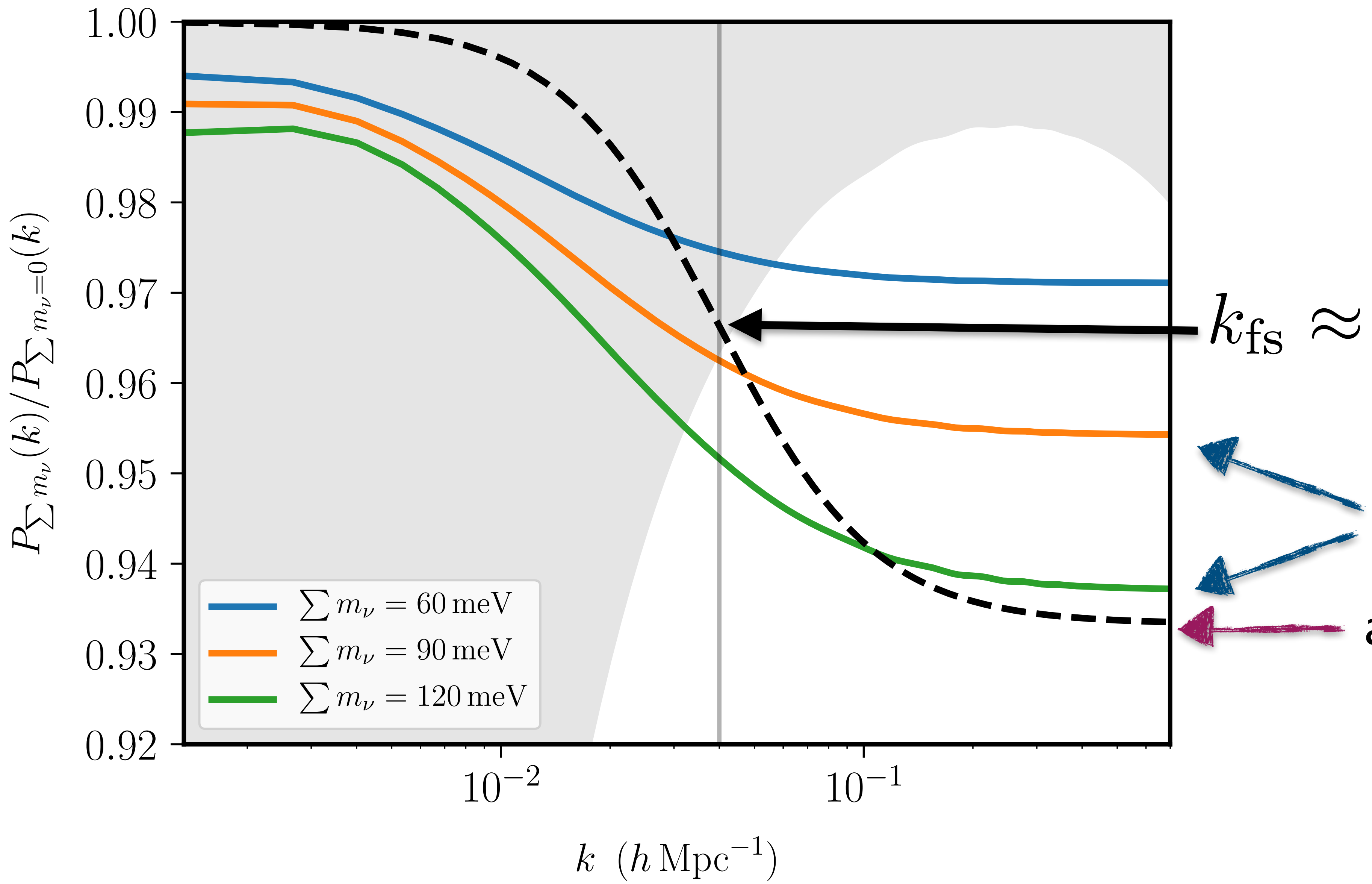
Massive neutrinos free stream / suppress growth

$$c_\nu \approx 8.7 \times 10^{-3} c \, \frac{1}{1+z} \left(\frac{58\,\mathrm{meV}}{\sum m_\nu} \right) \qquad c_{\mathrm{dm}} \approx 0$$



Neutrino Mass

Massive neutrinos free stream / suppress growth



$$k_{\rm fs} \approx 0.04 \frac{h}{\rm Mpc} \left(\frac{m_\nu}{50\,\rm meV}\right)$$

Neutrino Mass

Suppression is really two separate effects:

1. Neutrinos redshift like matter but don't cluster

At fixed, total matter density

$$P_m[m_\nu \neq 0] \approx (1 - 2f_\nu)P_m[m_\nu \neq 0]$$

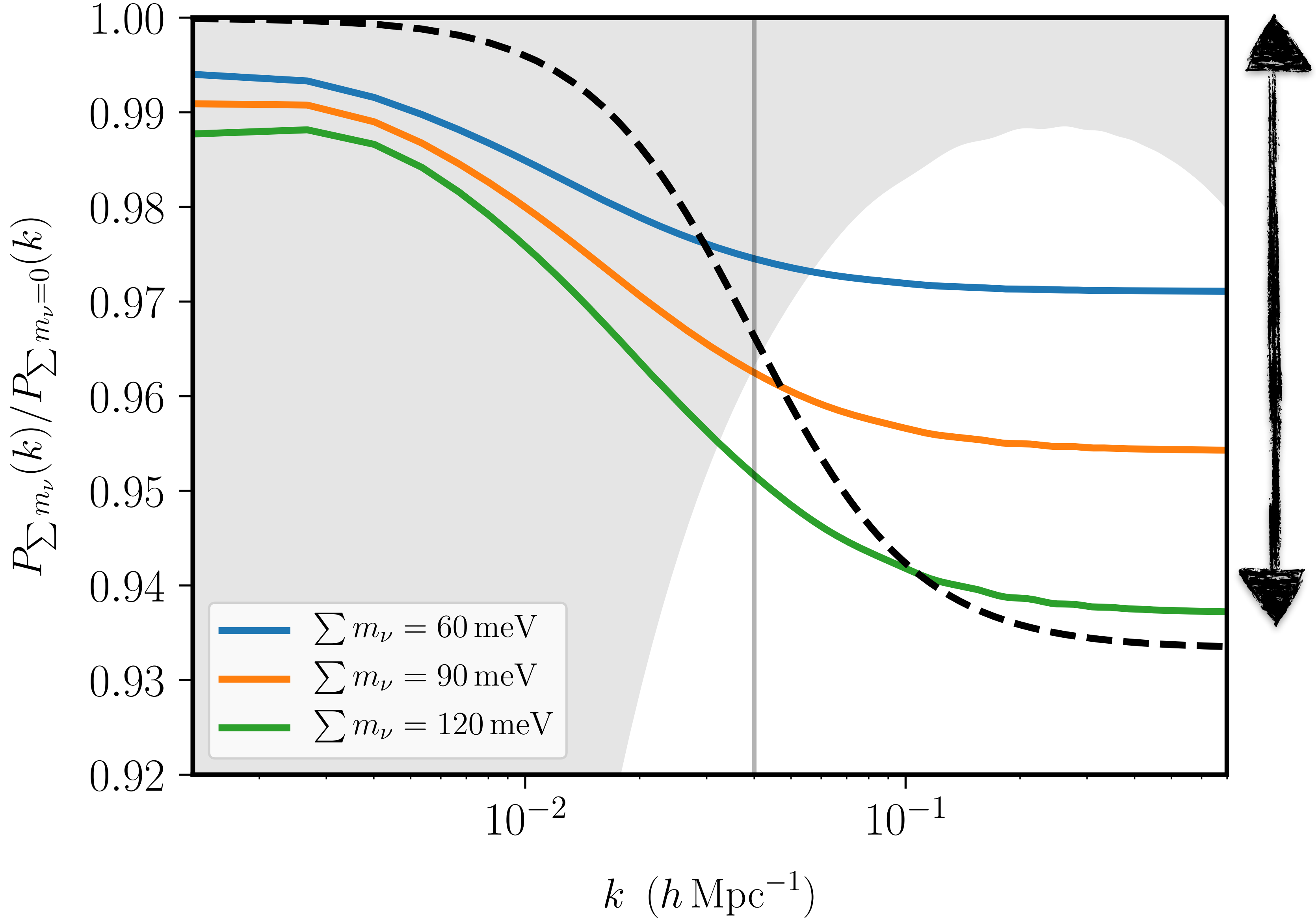
2. Dark matter clusters more slowly

$$P_m[m_\nu \neq 0] \approx (1 - \frac{3}{5} f_\nu \log \frac{1+z_{\rm NR}}{1+z}) P_m[m_\nu \neq 0]$$

Enhanced by a large log (time of growth)

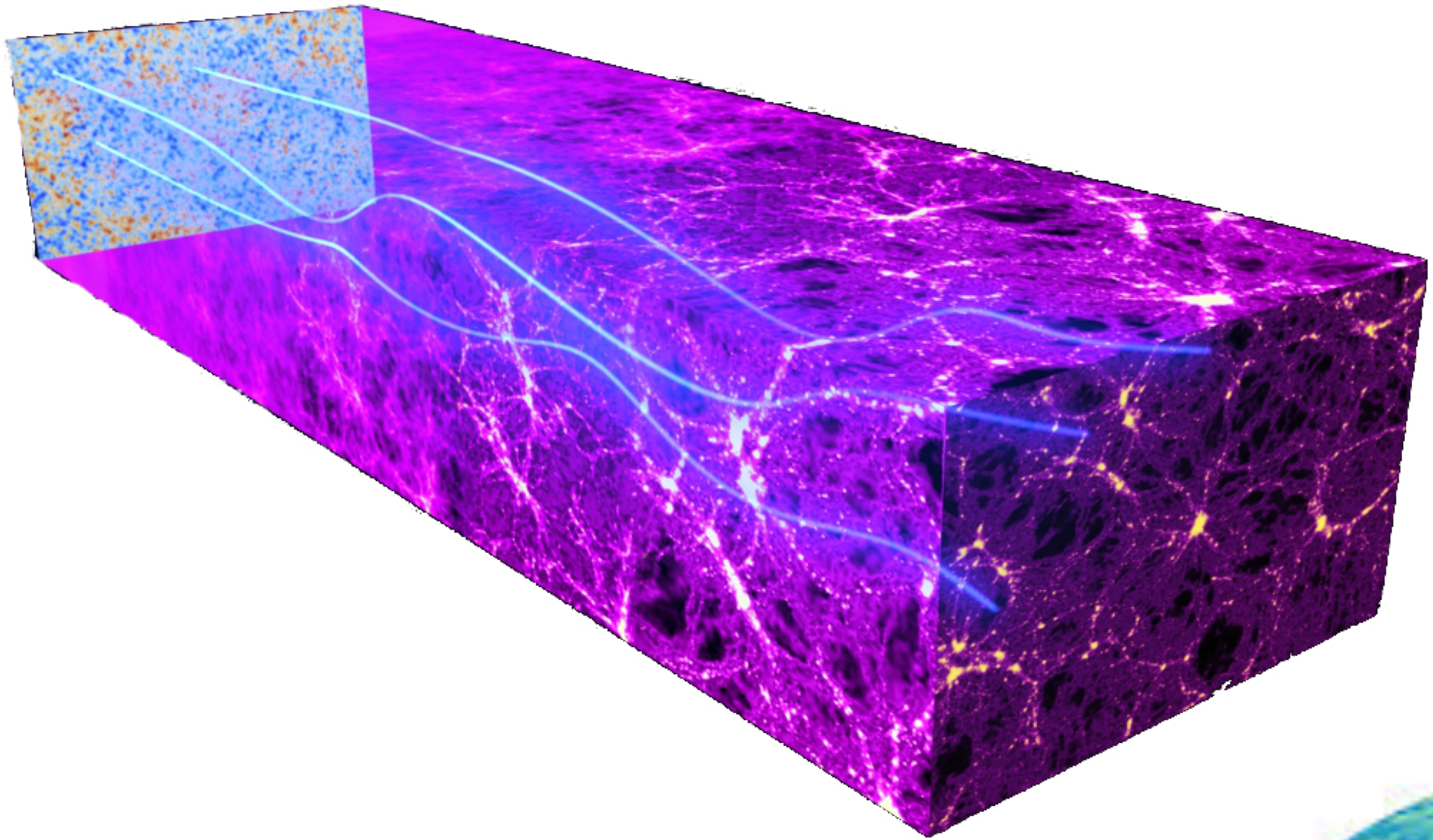
Neutrino Mass

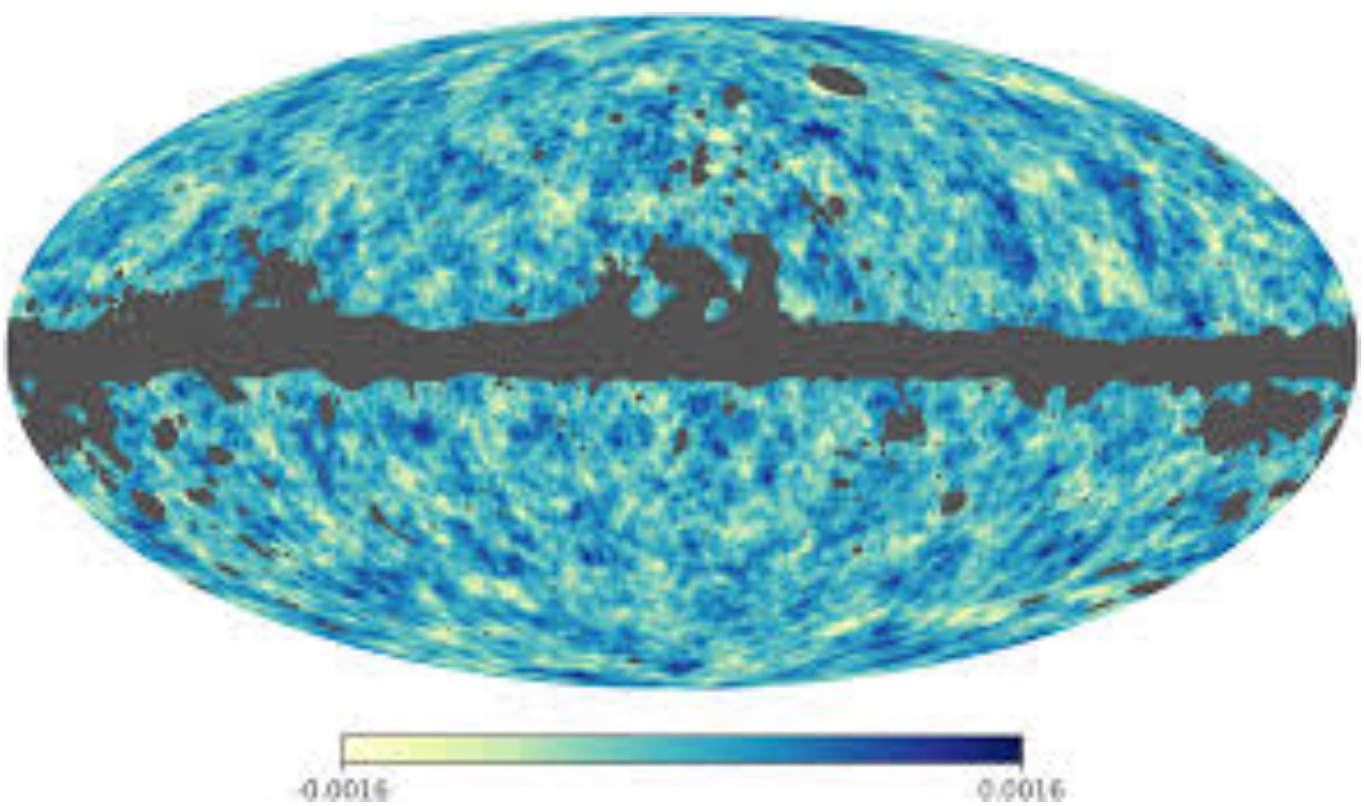
Combine to give a large suppression



$$\approx -8\frac{\Omega_\nu h^2}{\Omega_m h^2}$$

Cosmological Observables

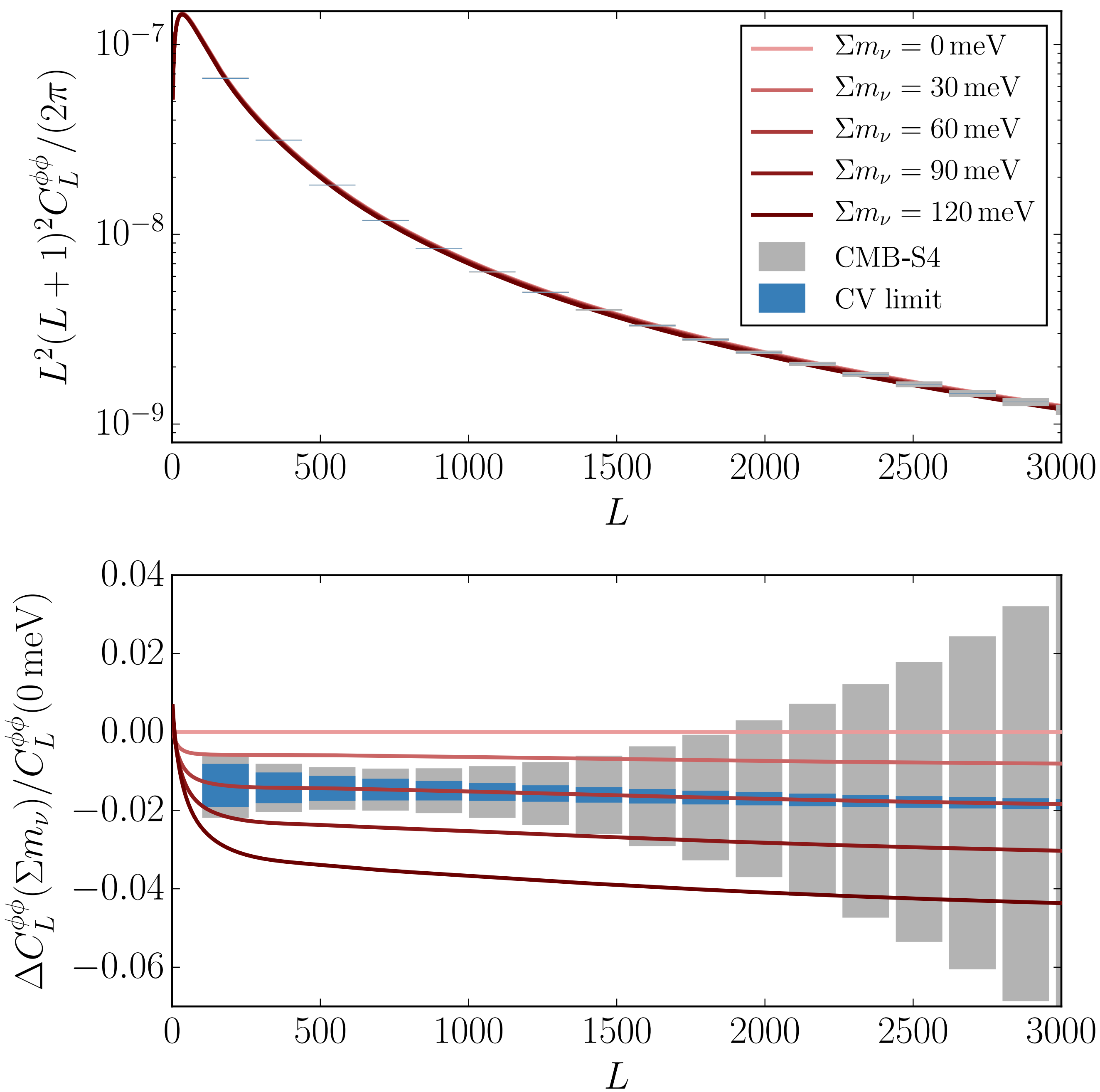




Images from ESA

Cosmological Observables

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



Cosmological Observables

We need to measure 3 numbers:

(1) (dark) matter power spectrum – lensing

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

(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

$$\sigma(\sum m_\nu) \approx 30\,\mathrm{meV}$$

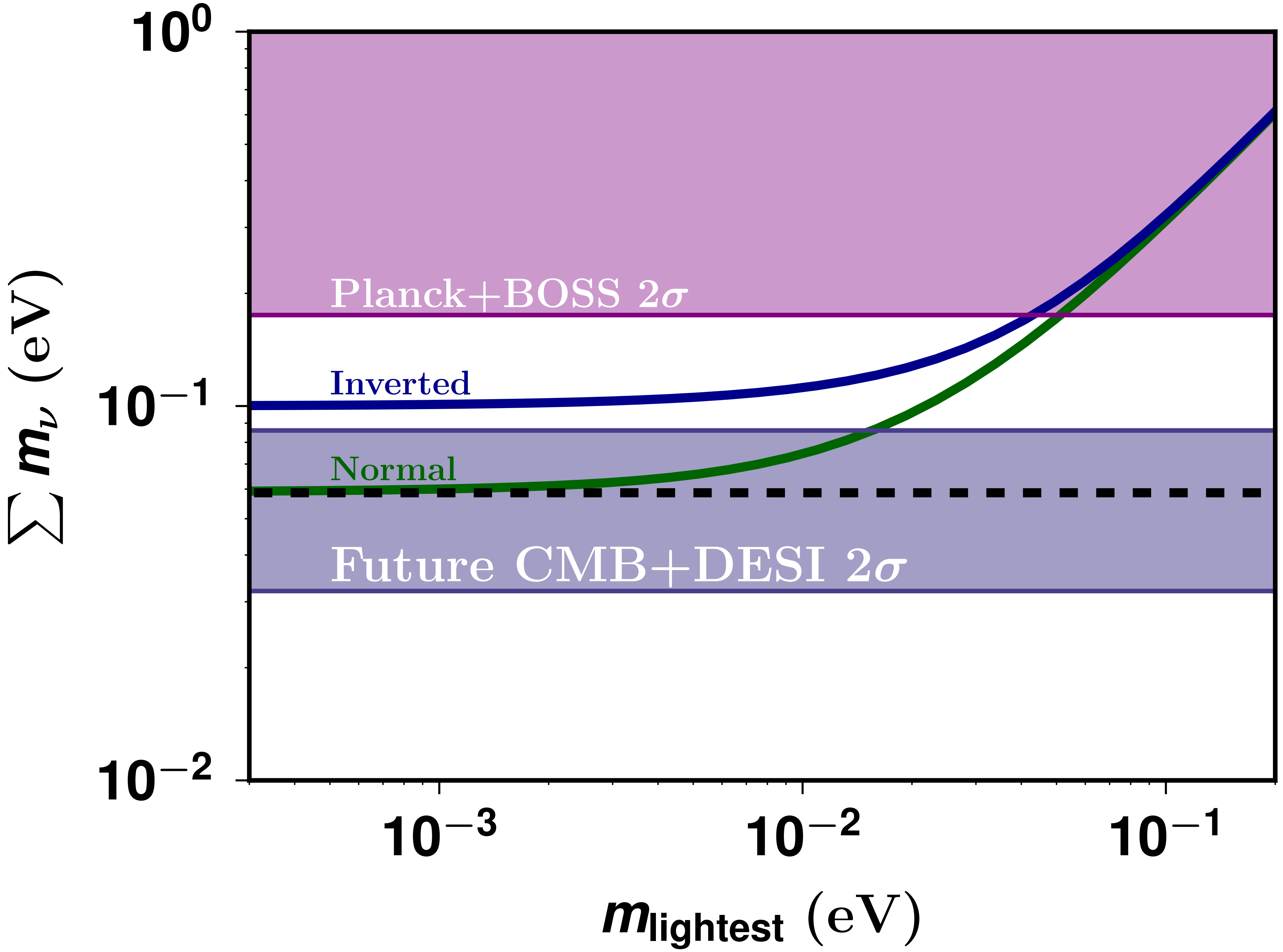
95% exclusion of $\sum m_\nu = 0$ for minimum mass

With improved measurements of reionization:

$$\sigma(\sum m_\nu) < 15\,\mathrm{meV}$$

Best bet is a satellite, possible from ground/balloon

Realistic Goals



$$\sum m_\nu \geq 58\,\mathrm{meV}$$

Beyond neutrinos

$N_{\rm eff}$ and $\sum m_\nu$ are gravitational measurements

Sensitive probes of dark / hidden sectors

From current constraints on $\sum m_\nu$

$$\Omega_\nu h^2 < 1.2 \times 10^{-3}\,(95\%)$$

Implies the fraction of hot dark matter is

$$f_\chi < 0.0045\,(95\%)$$

Summary

Summary

Cosmic neutrinos background exists

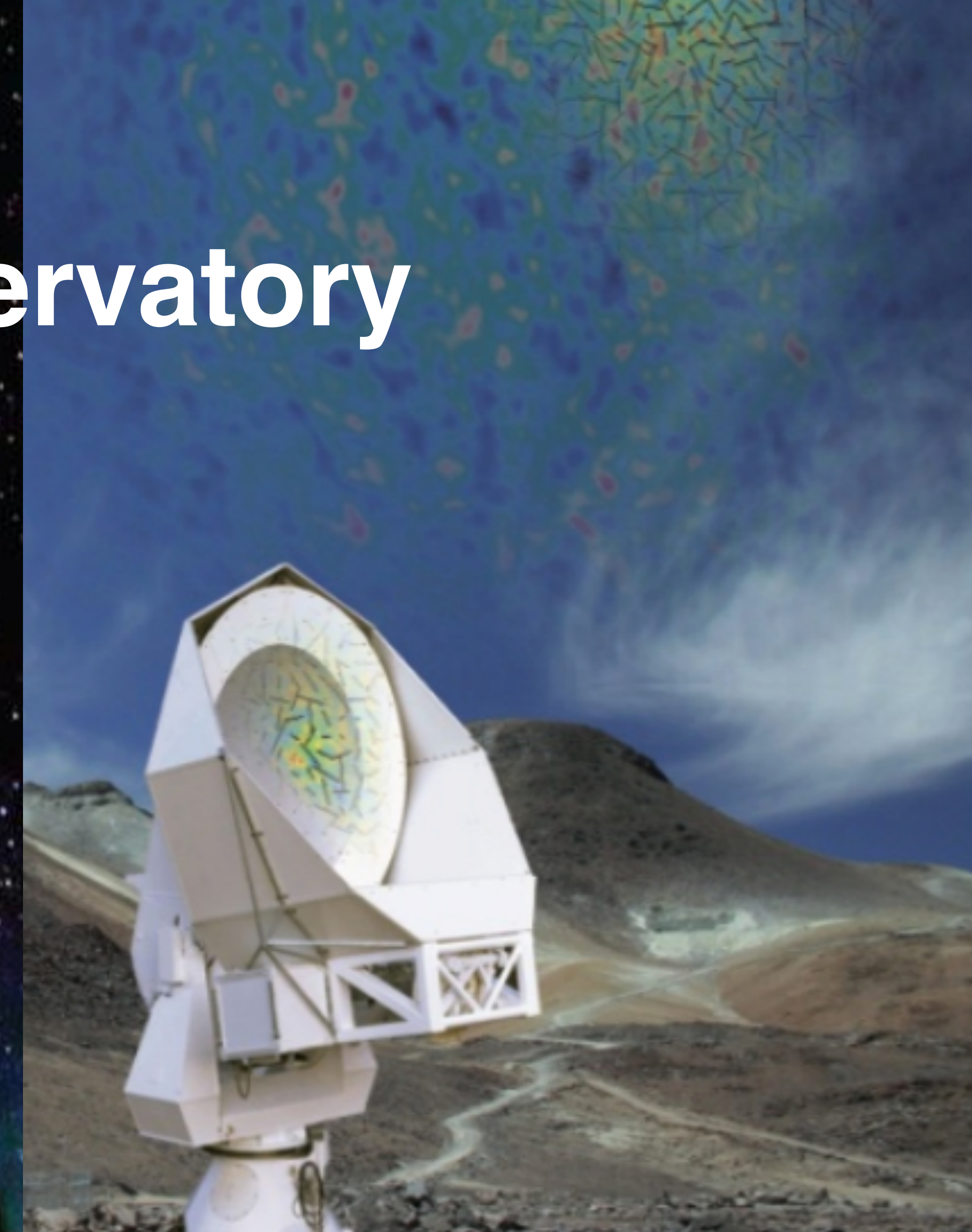
- CMB detects change to expansion rate at 30σ
- CMB detects phase shift at 10σ
- Galaxy clustering sees phase shift at 99.5%
- Detection of neutrino expected in 2020s

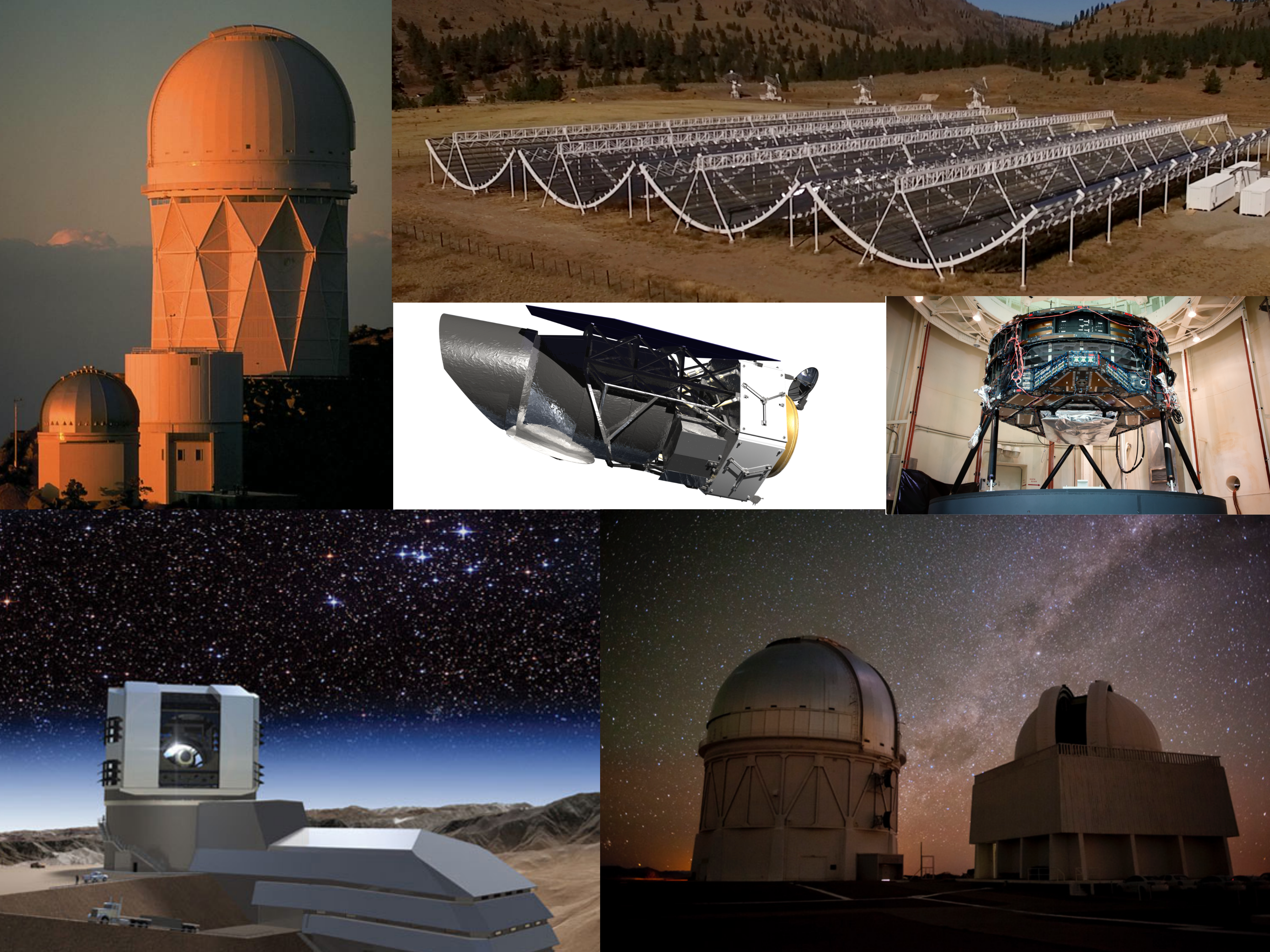
All detections are gravitational

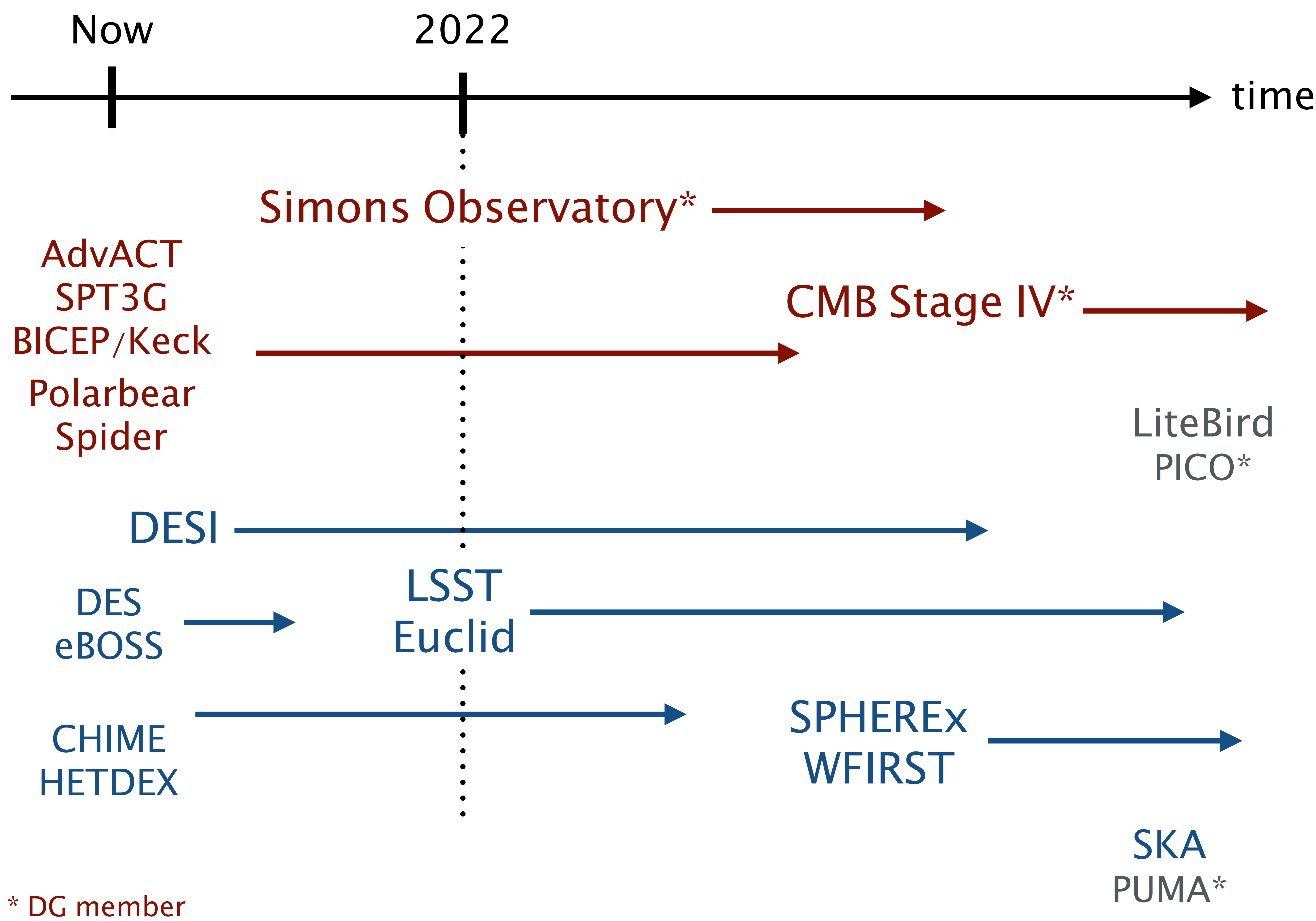
Provides a very sensitive window into new particles

The Simons Observatory

22°57'31"SOUTH, 67°47'15"WEST • ELEVATION: 17,027.6'
SIMONS OBSERVATORY






Now
2022
time
Simons Observatory*
AdvACT
SPT3G
BICEP/Keck
Polarbear
Spider
CMB Stage IV*
LiteBird
PICO*
DESI
DES
eBOSS
LSST
Euclid
CHIME
HETDEX
SPHEREx
WFIRST
SKA
PUMA*
* DG member

Summary

Coming generations will make a lot of progress

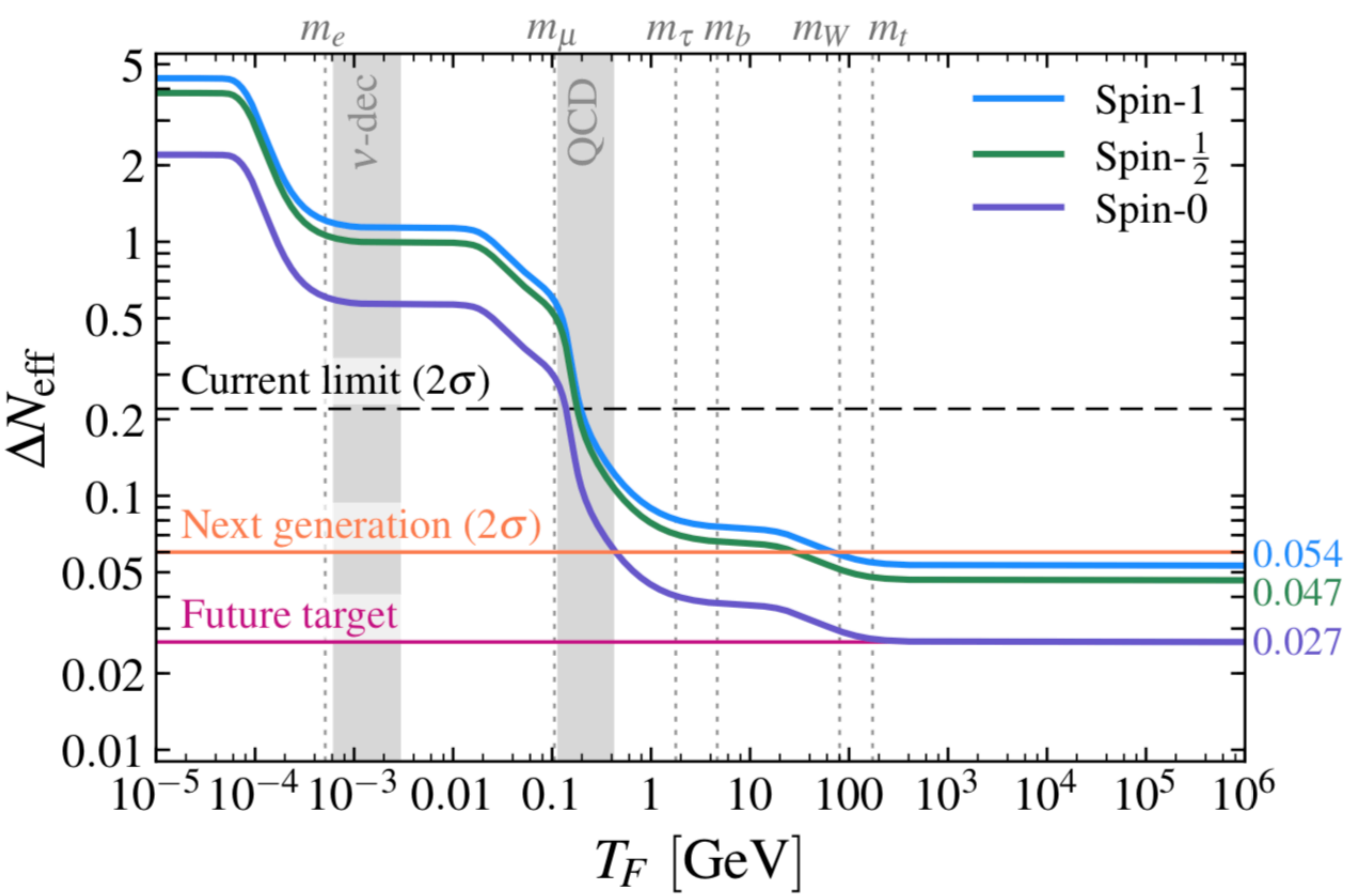
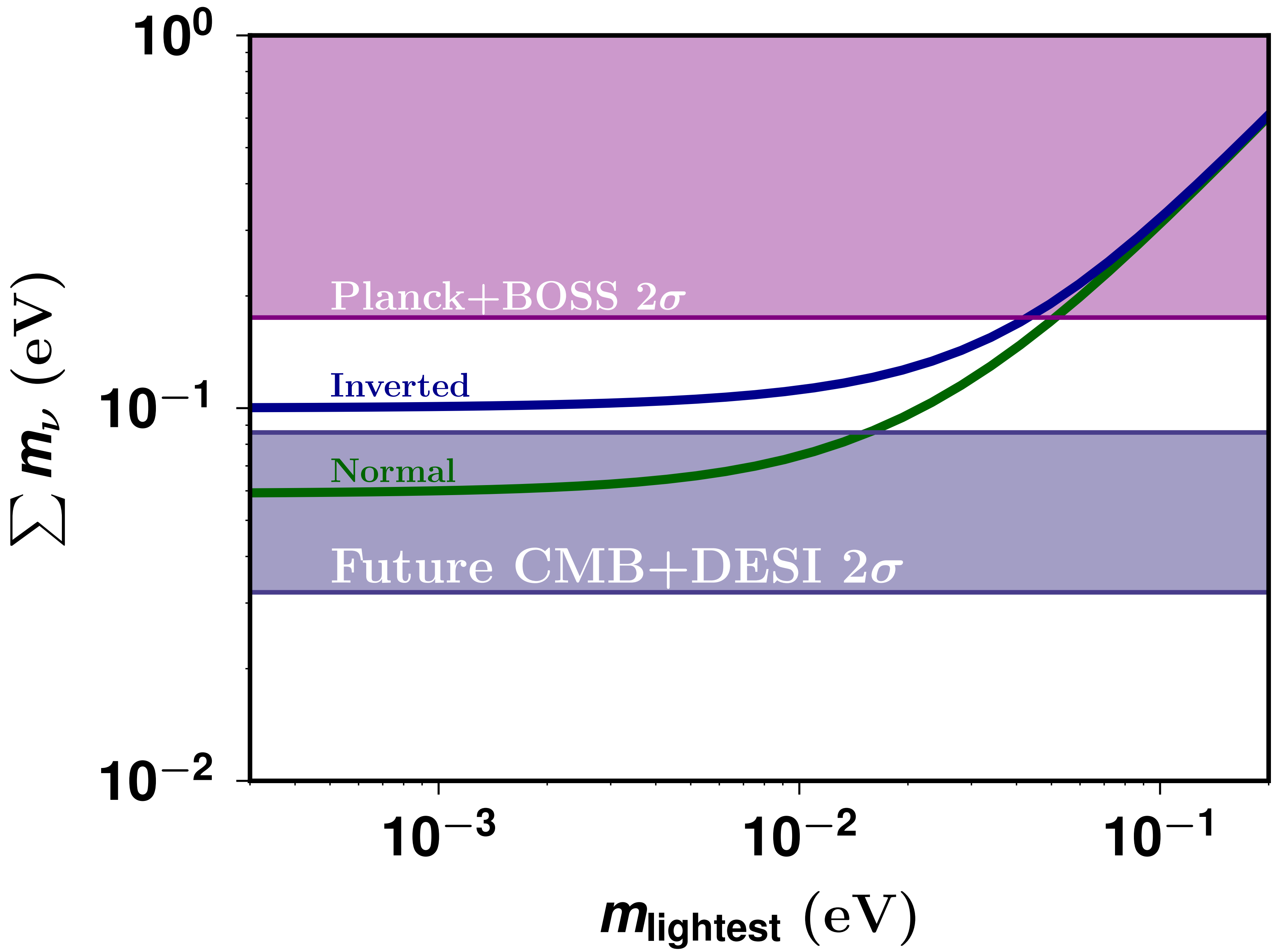


Image from DG et al. 2019

Summary

Coming generations will make a lot of progress




Thank you