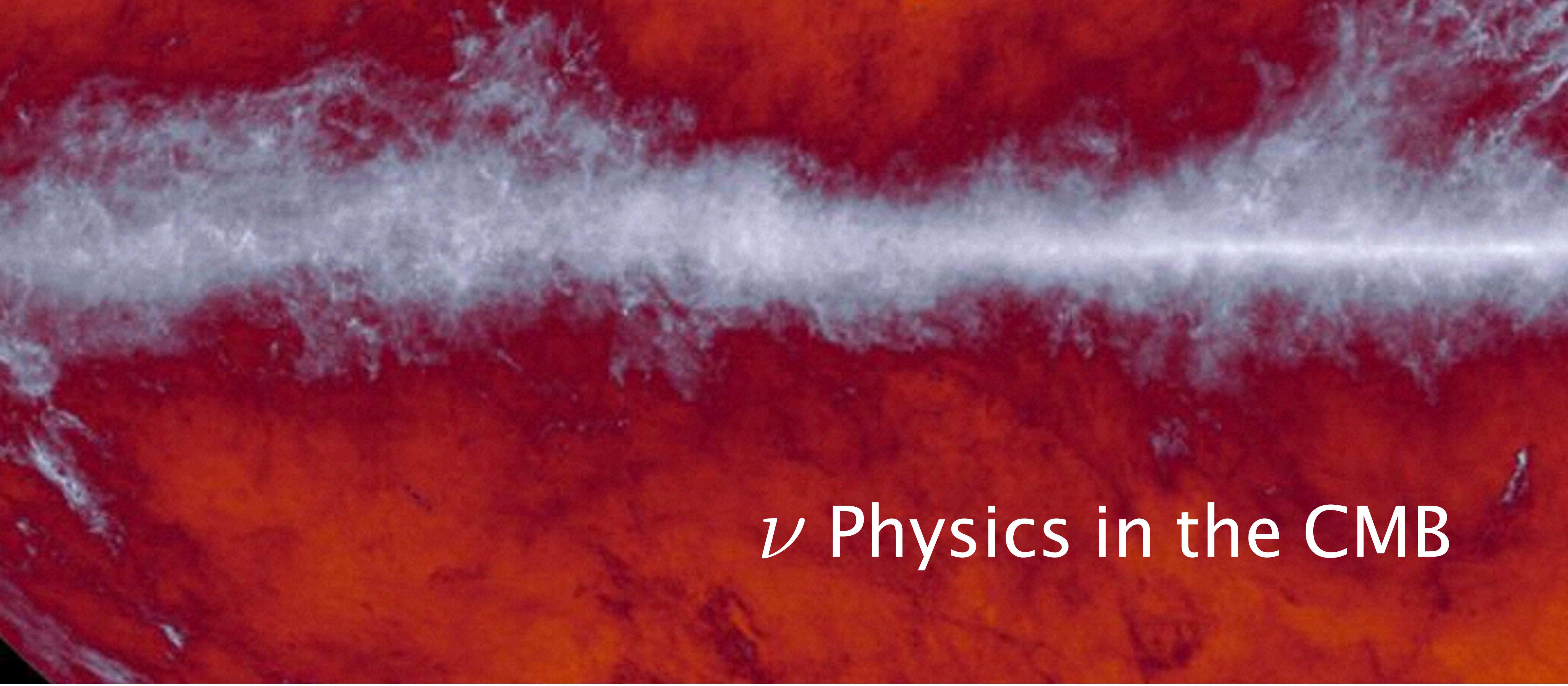


ν Physics in the CMB

Daniel Green

arXiv:1508.06342 with Baumann, Meyers and Wallisch

Outline

Cosmic History

Cosmic Neutrinos

Adiabatic fluctuations

Planck, CMB Stage IV and Neutrinos

Conventions

I will often use particle physics conventions

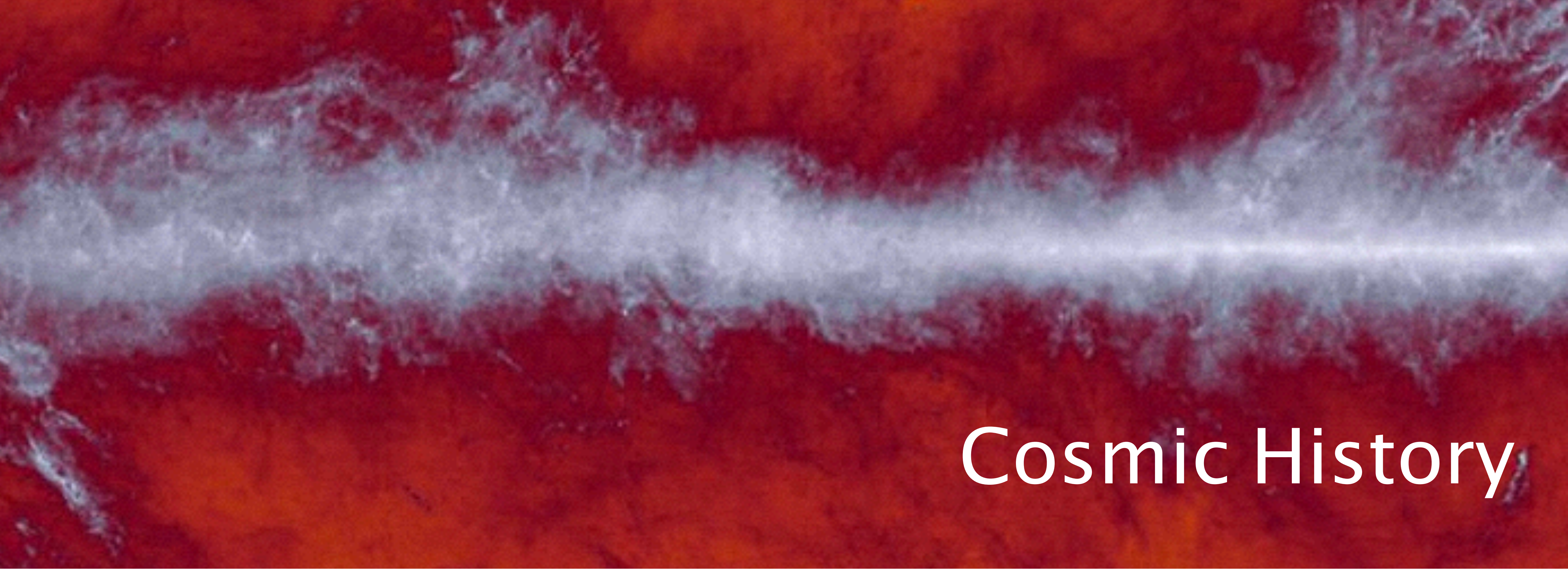
$$c = k_B = \hbar = 1$$

$$M_{\rm pl} = \sqrt{\frac{1}{8\pi G}} = 2.45 \times 10^{18}\,{\rm GeV}$$

$$G_F = \left(\frac{1}{292.8\,{\rm GeV}}\right)^2$$

$$1\,{\rm K} = 8.617 \times 10^{-5}\,{\rm eV}$$

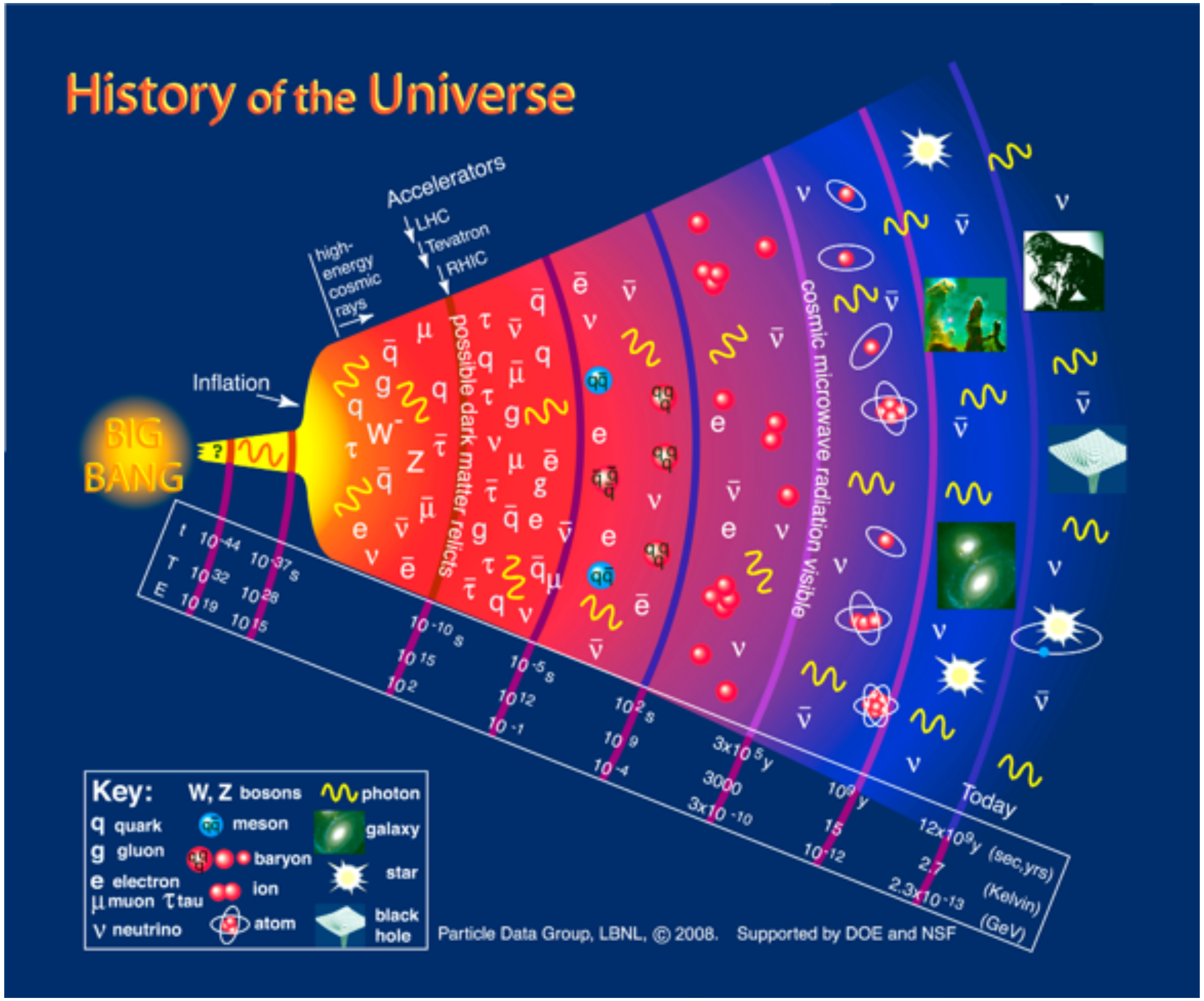
$$\tau \equiv \int \frac{dt}{a}$$



Cosmic History

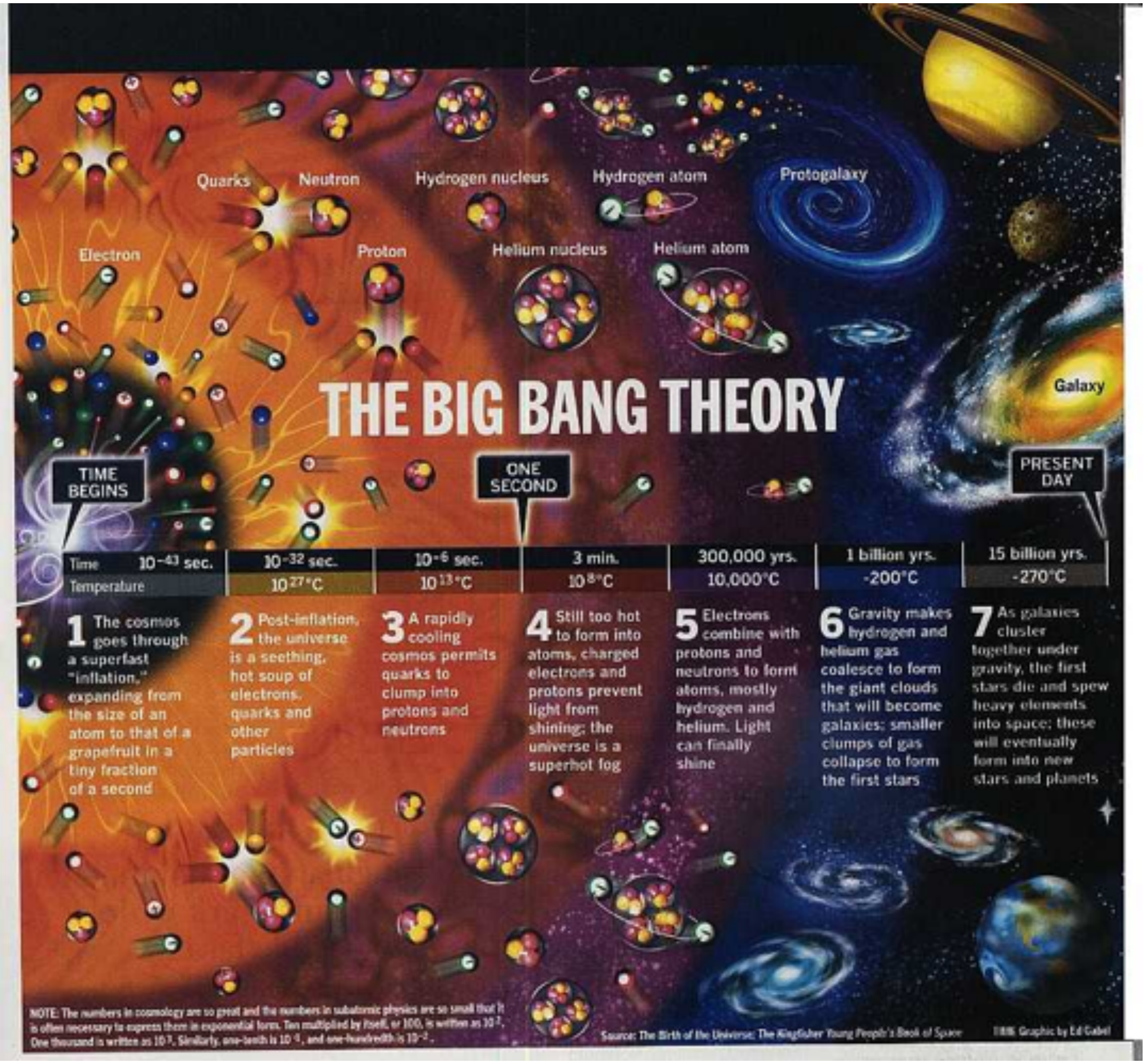
History of the Universe

A typical view of cosmology is something like this



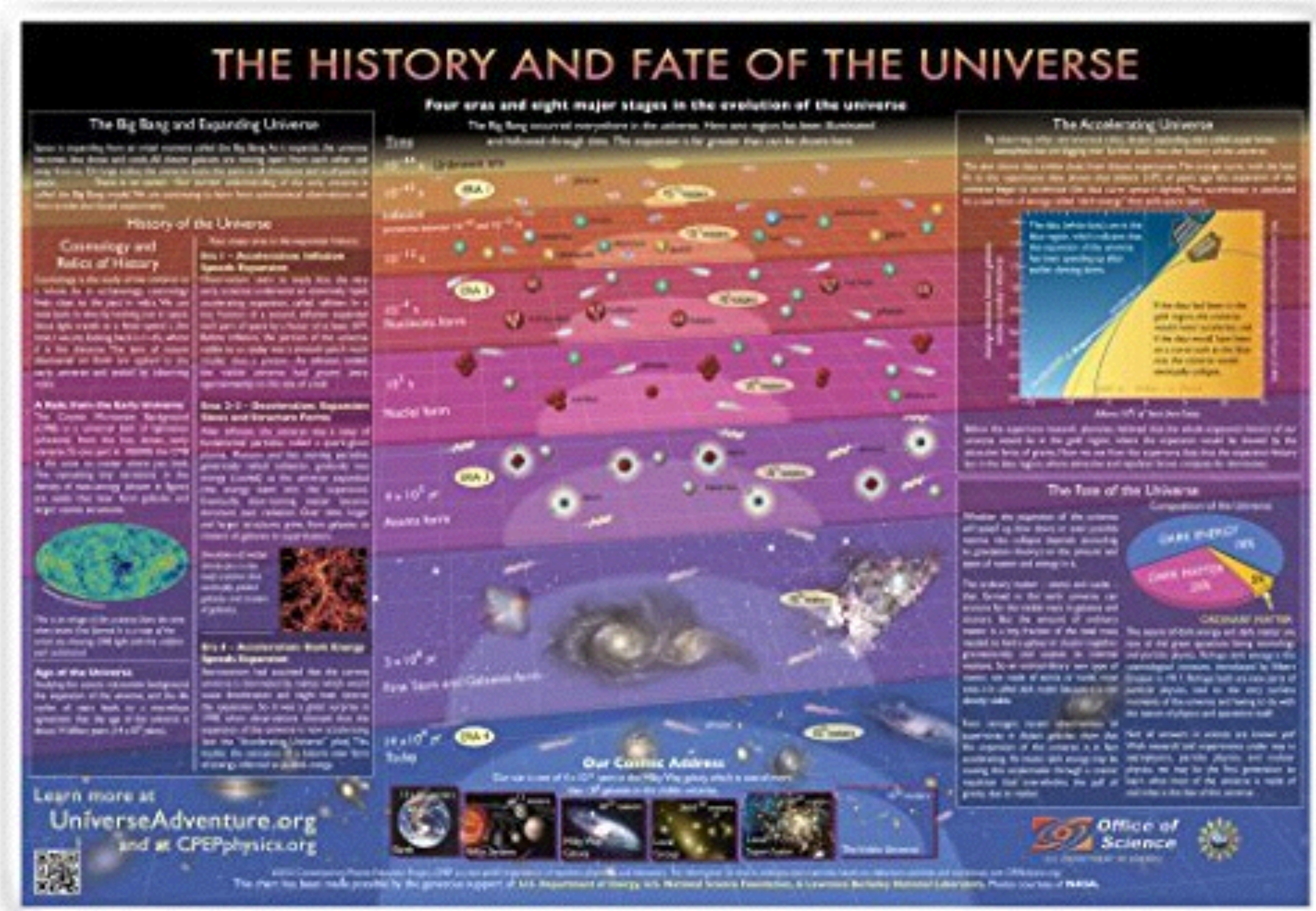
History of the Universe

A typical view of cosmology is something like this



History of the Universe

A typical view of cosmology is something like this



History of the Universe

A typical view of cosmology is something like this

‹ Back to search results for "history of the universe placemat"

Click to open expanded view

History and Fate of the Universe Laminated Placemat (1)

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- The perfect size for individual use. This placemat is laminated with heavy duty plastic - 10 mil.
- Illustrates major stages in the evolution of the Universe starting with the Big Bang.
- Describes the accelerating Universe, dark energy, dark matter, cosmological redshift and cosmic microwave background radiation.
- Up-to date resource guide.
- Attractive colorful educational poster. Perfect addition to any classroom, wall or dining table.

History of the Universe

They tell a remarkably consistent story

1. Early phase of inflation

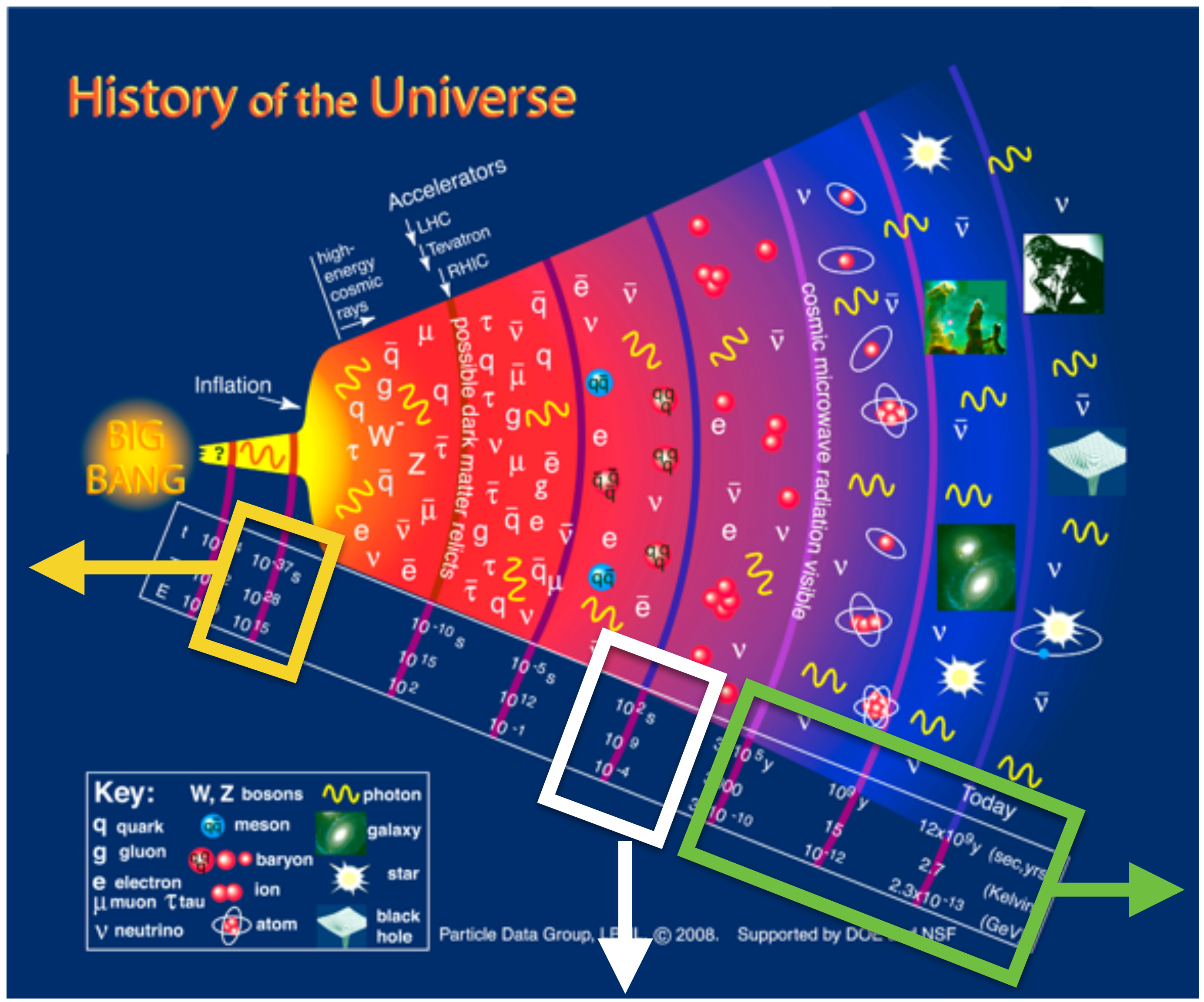
2. Reheating up to $T \gg 1\,\mathrm{TeV}$

3. Standard model cools through expansion

4. (Perhaps) WIMP Dark Matter freeze-out

History of the Universe

This story is plausible but hardly proven



Initial Conditions

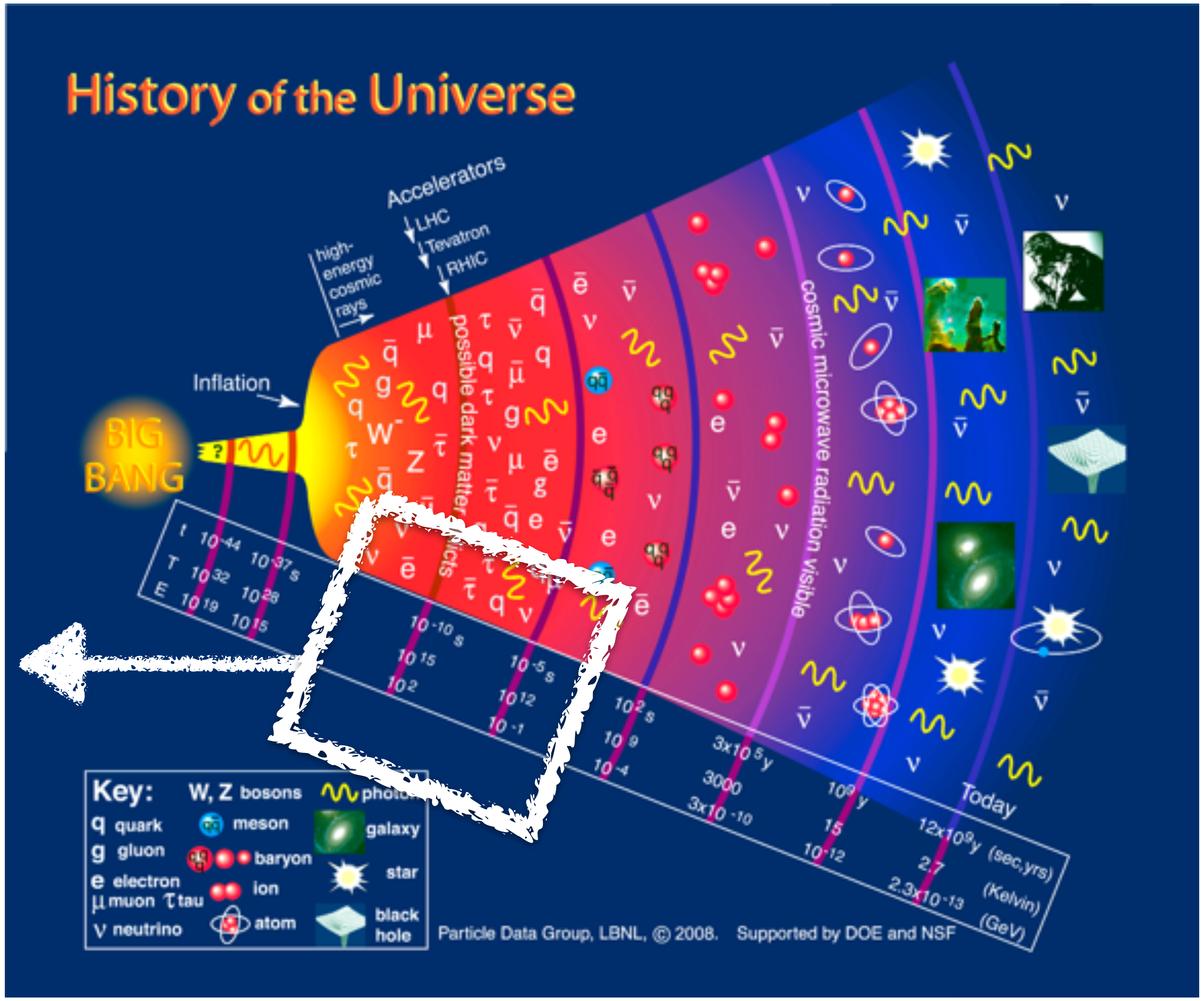
Direct Observation

Inferred from relics

History of the Universe

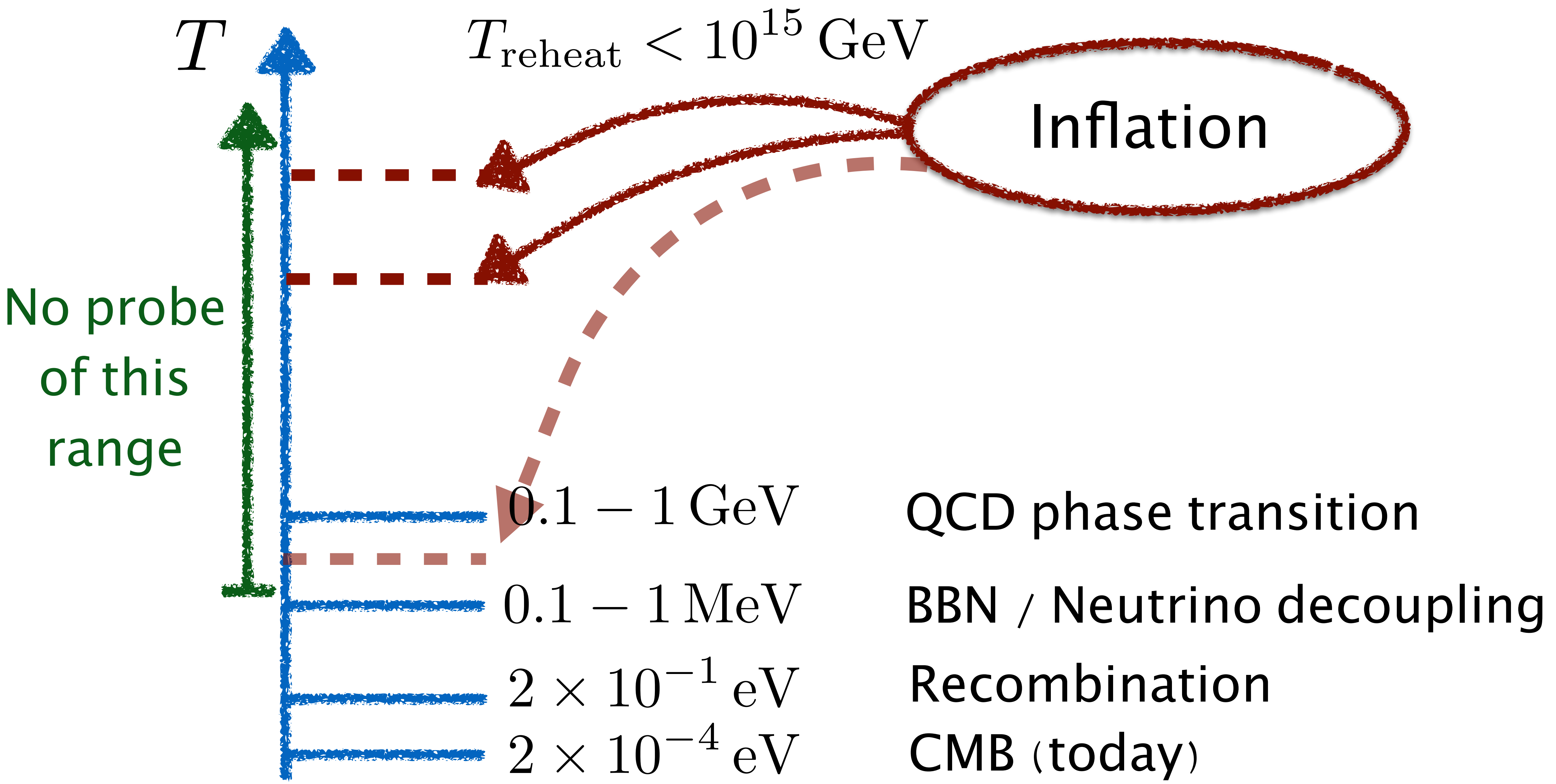
This story is plausible but hardly proven

Unproven(?)



History of the Universe

This is more dramatic in terms of scales



History of the Universe

The practical difficulty is thermal equilibrium

It erases memory from the system

Information is stored in relics:

- Long wavelength modes (inflation)
- Decoupling (photons, neutrinos, gravitons)
- Chemical potentials (leptons,baryons,nuclei)

History of the Universe

We can still exploit neutrinos and gravitons:

- Neutrinos have a direct view of $T \lesssim 1\,\mathrm{MeV}$
- Gravitons have unobstructed view
- (DM may also fit on this list one day)

Very difficult to measure either directly

Astrophysical methods are improving significantly

Neutrinos are now a realistic cosmic probe

History of the Universe

We want to use the relics to:

(1) Understand our cosmic history

(2) Test the laws of physics

These goals are not independent

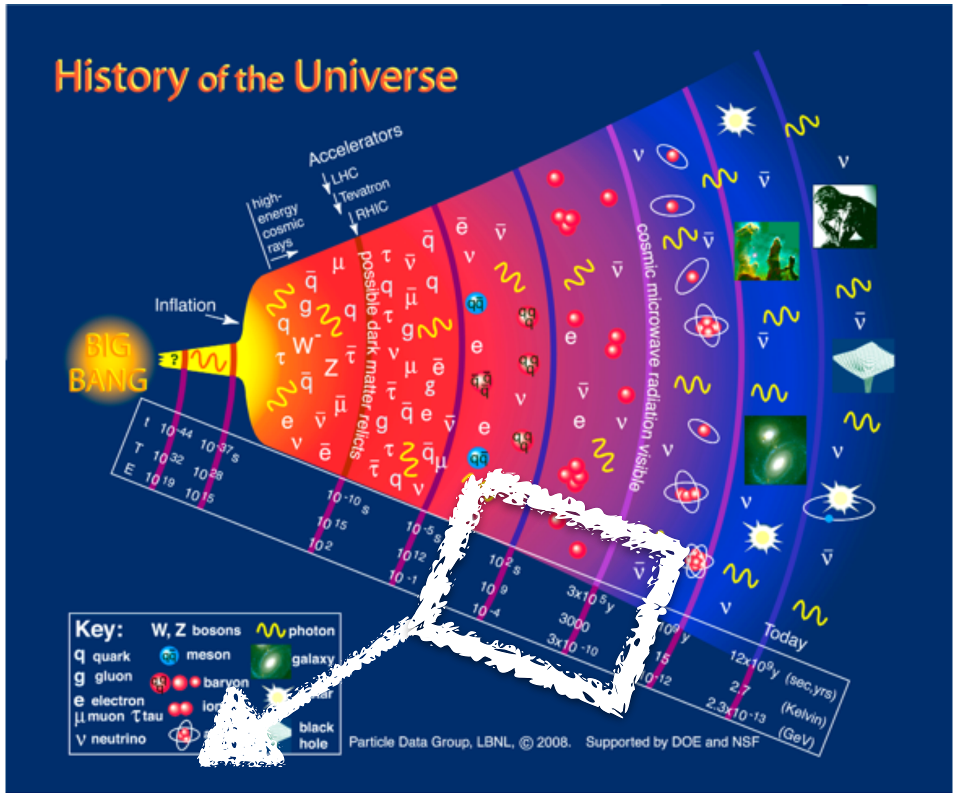
The challenge is how to interpret observations

Cosmology depends on the history & the laws

History of the Universe

I will focus on two related goals:

(1) The cosmic neutrino background

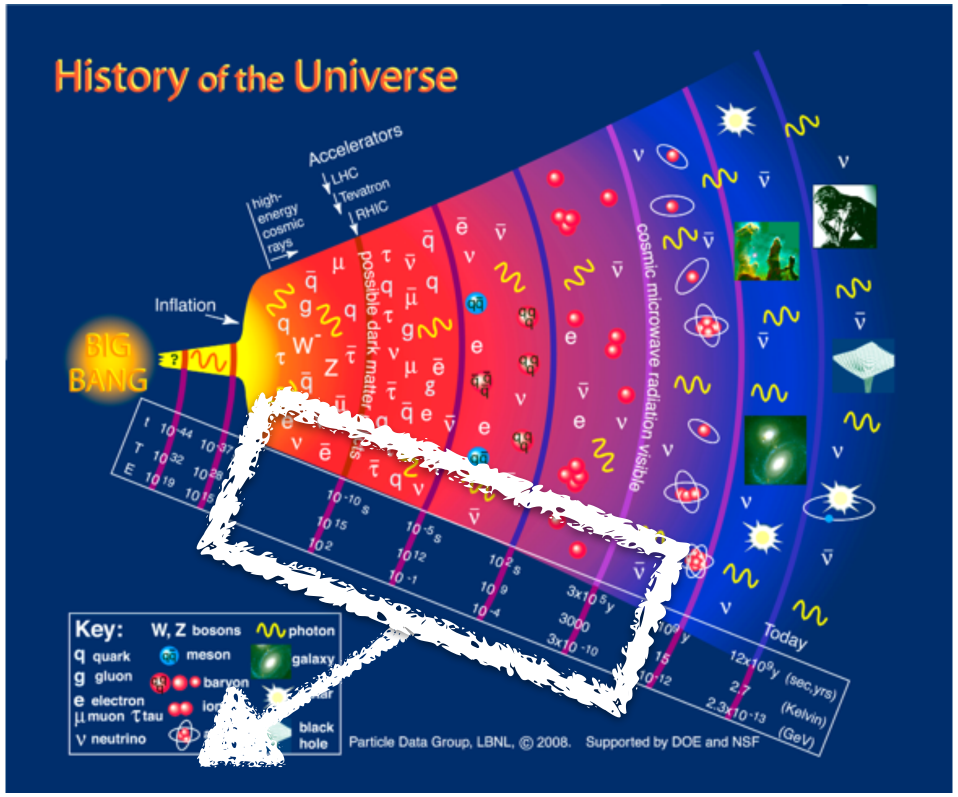


Direct probe of history at temperatures $T \lesssim 1\,\mathrm{MeV}$

History of the Universe

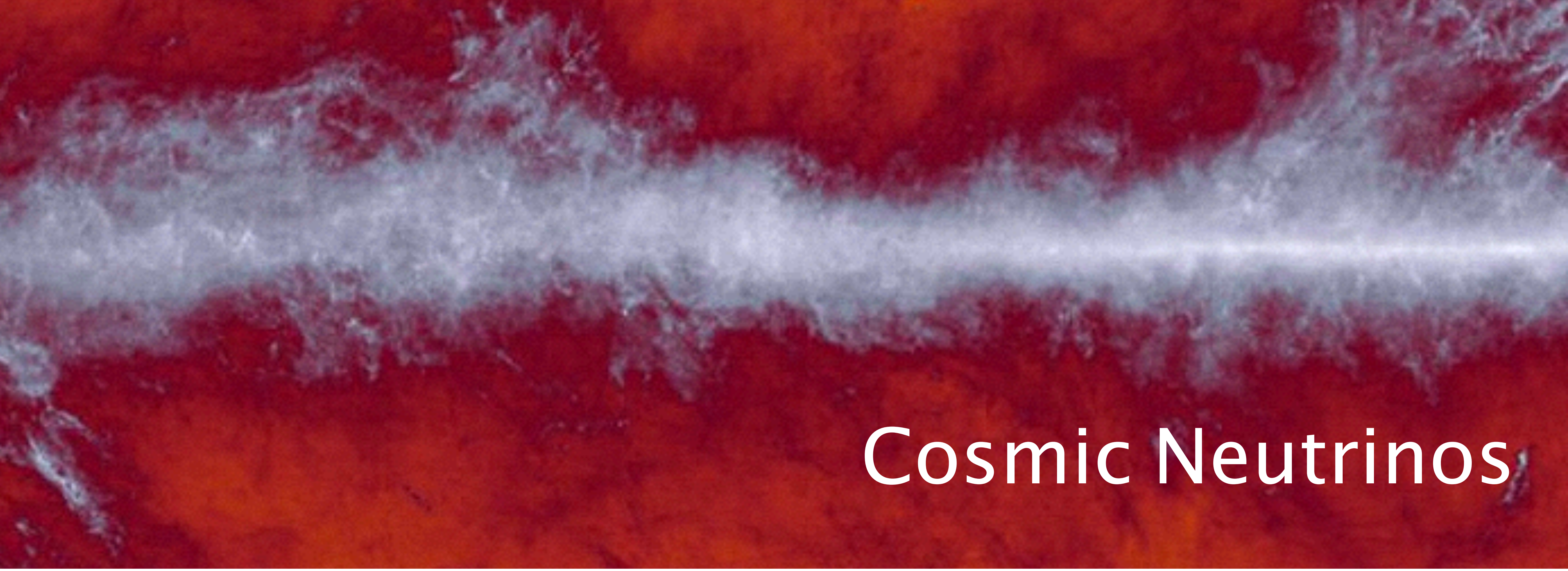
I will focus on two related goals:

(2) Search for new light particles and forces



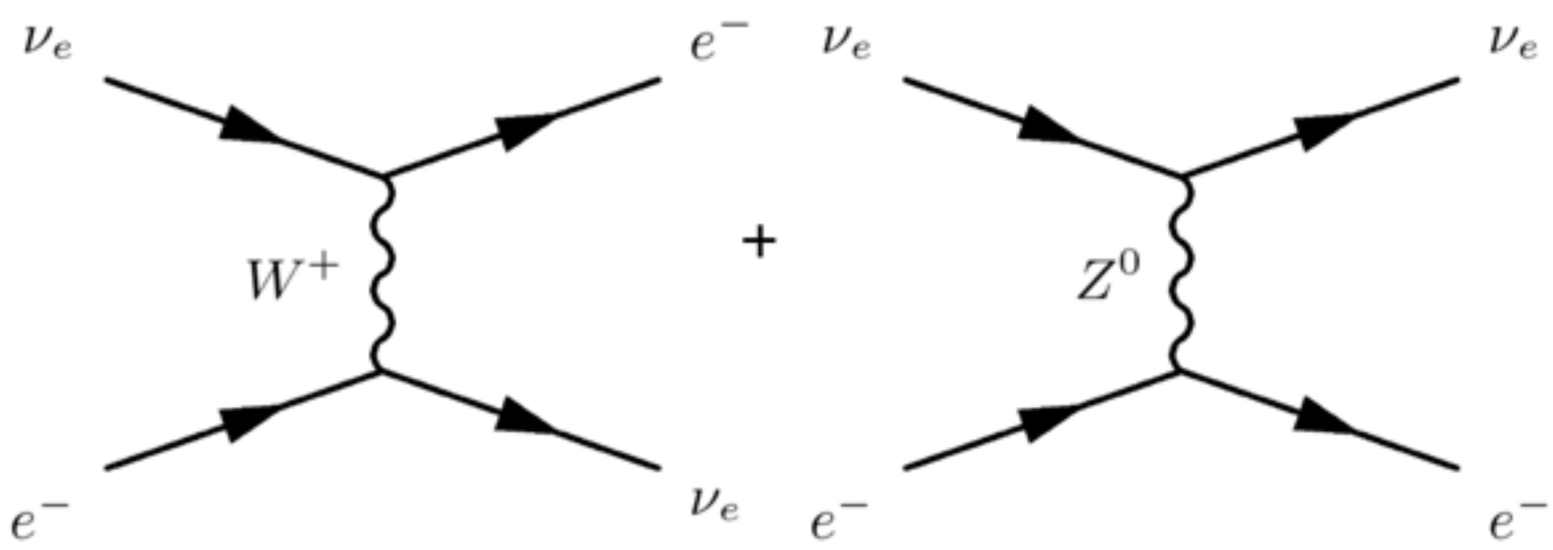
Probe of entire thermal history & very weak couplings

Cosmic Neutrinos



Cosmic Neutrinos

For $T \gg 1\,\mathrm{MeV}$, neutrinos were in equilibrium



This is a weak process $\Gamma \sim G_F^2 T^5$

This process is efficient if

$$\Gamma > H = \sqrt{\frac{\pi^2 g_\star}{90}} \frac{T^2}{M_{\rm pl}}$$

Cosmic Neutrinos

For $T \lesssim 1\,\mathrm{MeV}$, scattering becomes inefficient

But as long as $T_\gamma \propto a^{-1}$ we have $T_\nu = T_\gamma$

Electron-positron annihilation heats photons

$$T_\gamma < m_e = 511\,\mathrm{keV} \qquad e^+ e^- \to 2\gamma$$

If neutrinos are completely decoupled then

$$T_\nu^3 = \frac{4}{11} T_\gamma^3$$

Cosmic Neutrinos

The total energy density in neutrinos is then

$$\rho_\nu = 3 \times \left(2 \times \tfrac{7}{8}\right) \left(\tfrac{4}{11}\right)^{4/3} \tfrac{\pi^2}{30} T_\gamma^4 = 3 \times \tfrac{7}{8} \left(\tfrac{4}{11}\right)^{4/3} \rho_\gamma$$

Number of species of neutrinos

Conventional to measure density in terms of

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

Called the effective number of neutrino species

Cosmic Neutrinos

In limit of perfect decoupling : $N_{\text{eff}} = 3.$

e^+e^- annihilation is soon after “freeze-out”

Still a substantial rate for $e^+e^- \to \nu\bar{\nu}$

Imperfect decoupling : $N_{\text{eff}} = 3.035$

Imperfect decoupling + QED : $N_{\text{eff}} = 3.046$

Mangano et al. (2005)

(QED changes ρ_γ, p_γ for a given T)

Detecting Cosmic Neutrinos

Two basic approaches to "detecting" the CνB:

- Direct detection via collisions in the lab
- Detect the gravitational effects of neutrinos

Gravity has been surprisingly effective

e.g. Planck 2015 $$N_{\rm eff} = 3.04 \pm 0.18$$

The CνB has been detected with high significance(?)

Detecting Cosmic Neutrinos

After decoupling, gravity couples neutrinos to SM

Neutrinos carry a large fraction of energy

$$\frac{\rho_\nu}{\rho_{\text{total}}} \simeq 0.41 \qquad \text{for} \qquad T \gg T_{\text{eq.}}$$

This energy significantly affects expansion rate

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

Metric fluctuations also affected at the same level

Detecting "Cosmic Neutrinos"

Are we sure these are really neutrinos?

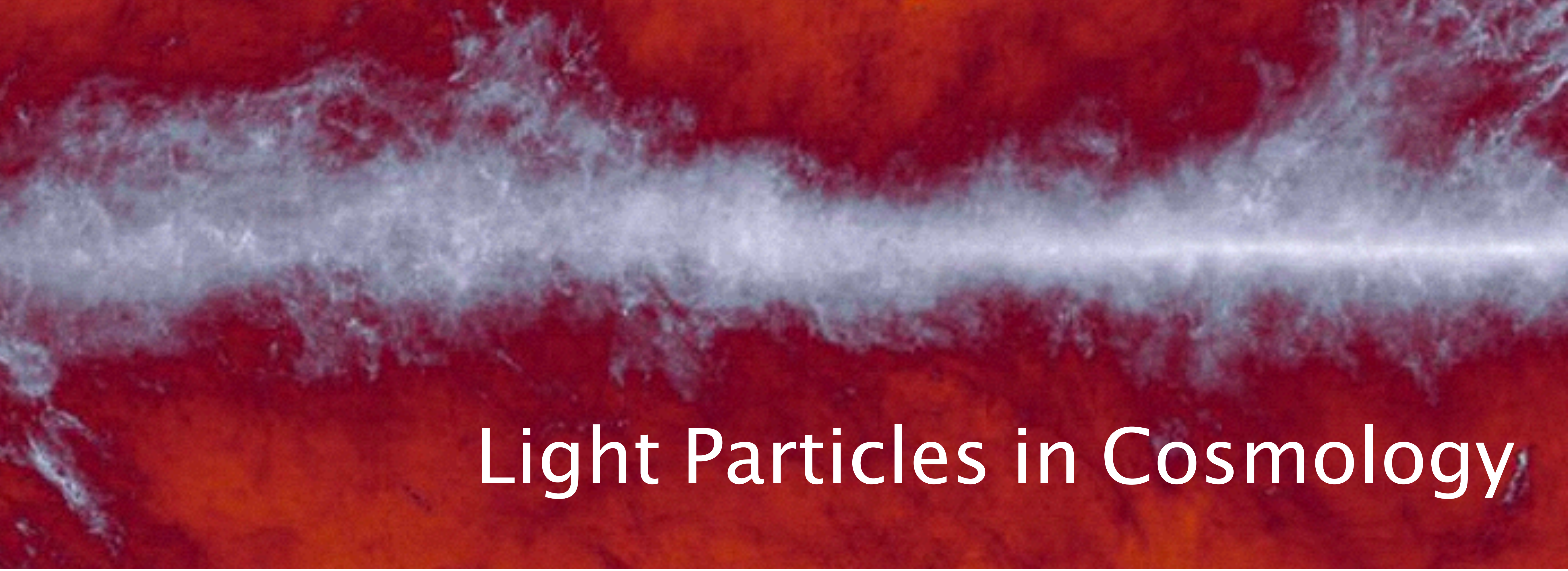
What, if anything, is this teaching us?

The virtues and weaknesses are the same

Gravity is indiscriminate:

- It can't tell us these are exactly neutrinos
- It is sensitive to everything neutrino-like

Punchline: $N_{\rm eff}$ is more than just neutrinos (not less)



Light Particles in Cosmology

Light Particles

From gravity's point of view, massless neutrinos are

- Radiation : $\bar{\rho}_\nu \propto a^{-4}$
- Free-streaming : $\frac{d}{dt} f(\mathbf{x}, t, \mathbf{p}) = 0$

We should group everything with these properties

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

$$N_{\text{fluid}} \equiv \frac{8}{7} \left(\frac{11}{4}\right)^{4/3} \frac{\rho_R^{\text{non-free-stream}}}{\rho_\gamma}$$

Bell et al. (2005); Friedland et al. (2007)

Light Particles

What we measure is totally different from the lab

E.g. Number of Neutrinos from Z-width

$$N_\nu = 2.9840 \pm 0.0082 \qquad N_\nu \neq N_{\rm eff}$$

Number of particles with SM couplings of neutrinos

$N_{\rm eff}$ measures gravitational not SM couplings

We need more information to compare to the lab

Light Particles

When is $N_{\text{eff}} \neq 3.046$

- Change to thermal history for $T < 1\,\text{MeV}$
- Non-standard neutrino couplings
- New massless particles

Massless fields are easy to parameterize

Also easy to map to other experimental constraints

Naturally Light Particles

We will require that $m = 0$ is protected by symmetry

E.g. $\mathcal{L} = F(\partial_\mu \phi \partial^\mu \phi)$ has symmetry $\phi \to \phi + c$

Determines minimal coupling to SM Brust et al. (2013)

$$\mathcal{L}_{\rm int} = \frac{1}{\Lambda^{n \geq 1}} \mathcal{O}_{\rm dark}^{(\mu ..)} \mathcal{O}_{(\mu ..){\rm SM}}$$

Structure depends on spin of particles

Coupling to photons $n \geq 1$, matter $n \geq 2$

Naturally Light Particles

Common feature is decoupling at low temperatures

$$\Gamma \propto \frac{1}{\Lambda^{2n}} T^{2n+1} \qquad\qquad H \propto T^2$$

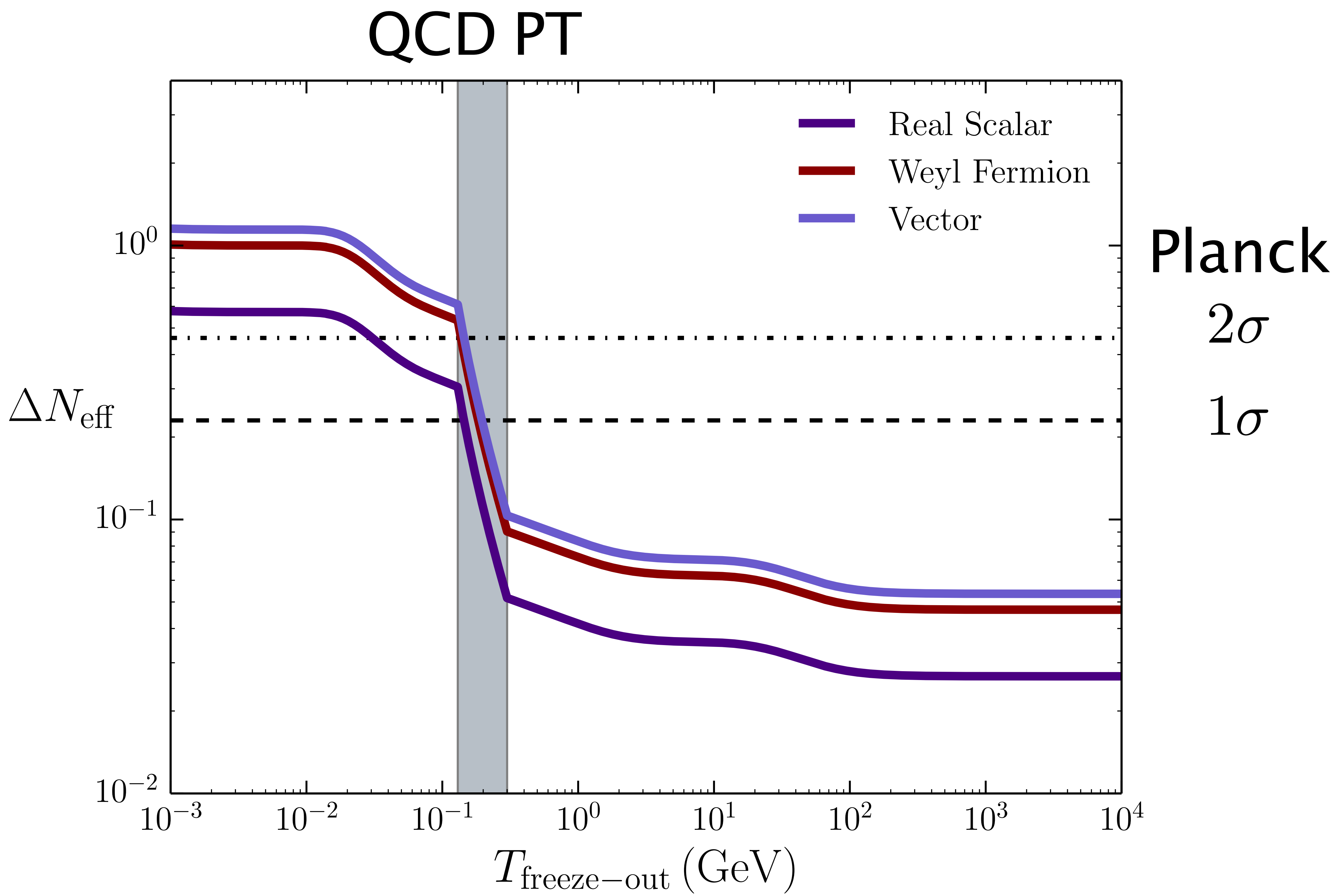
$$H \gg \Gamma \quad \text{for} \quad T < T_\star$$

If $T_{\text{Reheat}} > T_\star$ then $\Delta N_{\text{eff}} = f(T_\star)$

Observable predictions quite model independent

Depends on spin and freeze-out temperature

Naturally Light Particles



Naturally Light Particles

Irreducible contributions (SM + 1 massless particle)

Real Scalar: $\Delta N_{\mathrm{eff}} = 0.027$

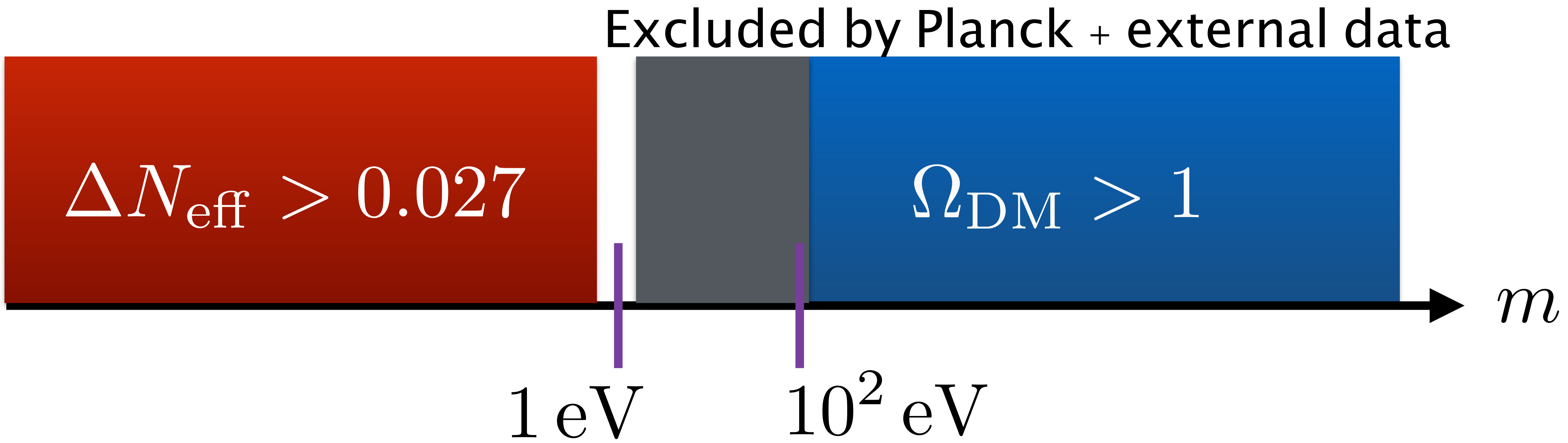
Weyl Fermion: $\Delta N_{\mathrm{eff}} = 0.047$

Vector boson: $\Delta N_{\mathrm{eff}} = 0.054$

Precision at this level is sensitive to $T \to T_{\mathrm{Reheat}}$

Naturally Light Particles

Adding a non-zero mass has little impact



Even decaying scenarios produce similar $\Delta N_{\rm eff}$

Axions

Axions are a concrete example

Many possible coupling to the SM

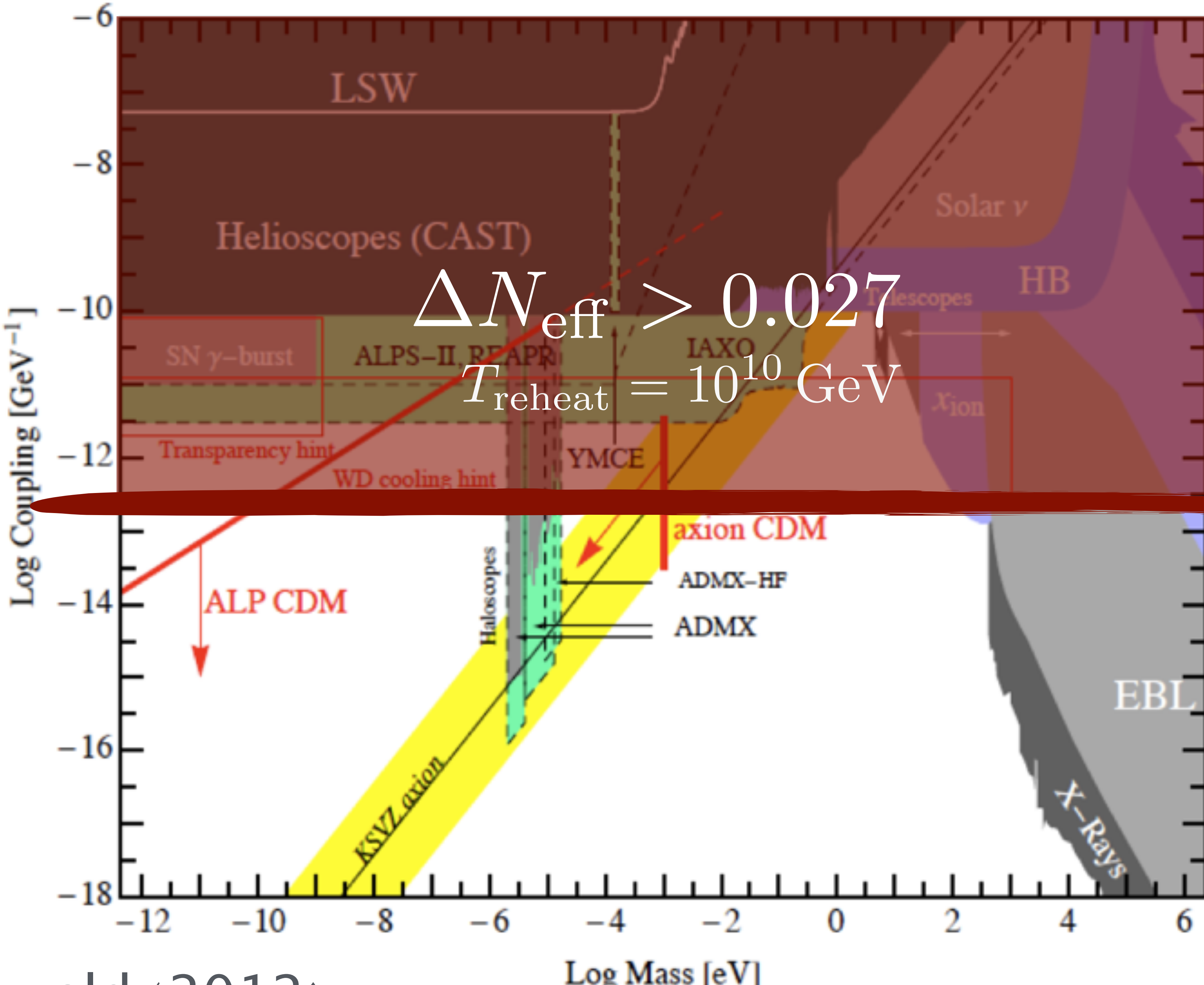
Coupling to photons $$\mathcal{L}_{a\gamma\gamma} = \frac{1}{4} g_{a\gamma\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu}$$

Coupling to gluons $$\mathcal{L}_{agg} = \frac{1}{4} g_{agg} a \tilde{G}^a_{\mu\nu} G^{a\,\mu\nu}$$

Axion production rate $$g \propto \frac{1}{\Lambda} \to \Gamma \propto g^2 T^3$$

Axions

$g_{a\gamma\gamma}$



$$\Delta N_{\rm eff} > 0.027$$
$$T_{\rm reheat} = 10^{10}\ {\rm GeV}$$

figure: Ringwald (2012)

Axions

$$g_d \sim \frac{10^{-4}}{\text{GeV}} g_{agg}$$

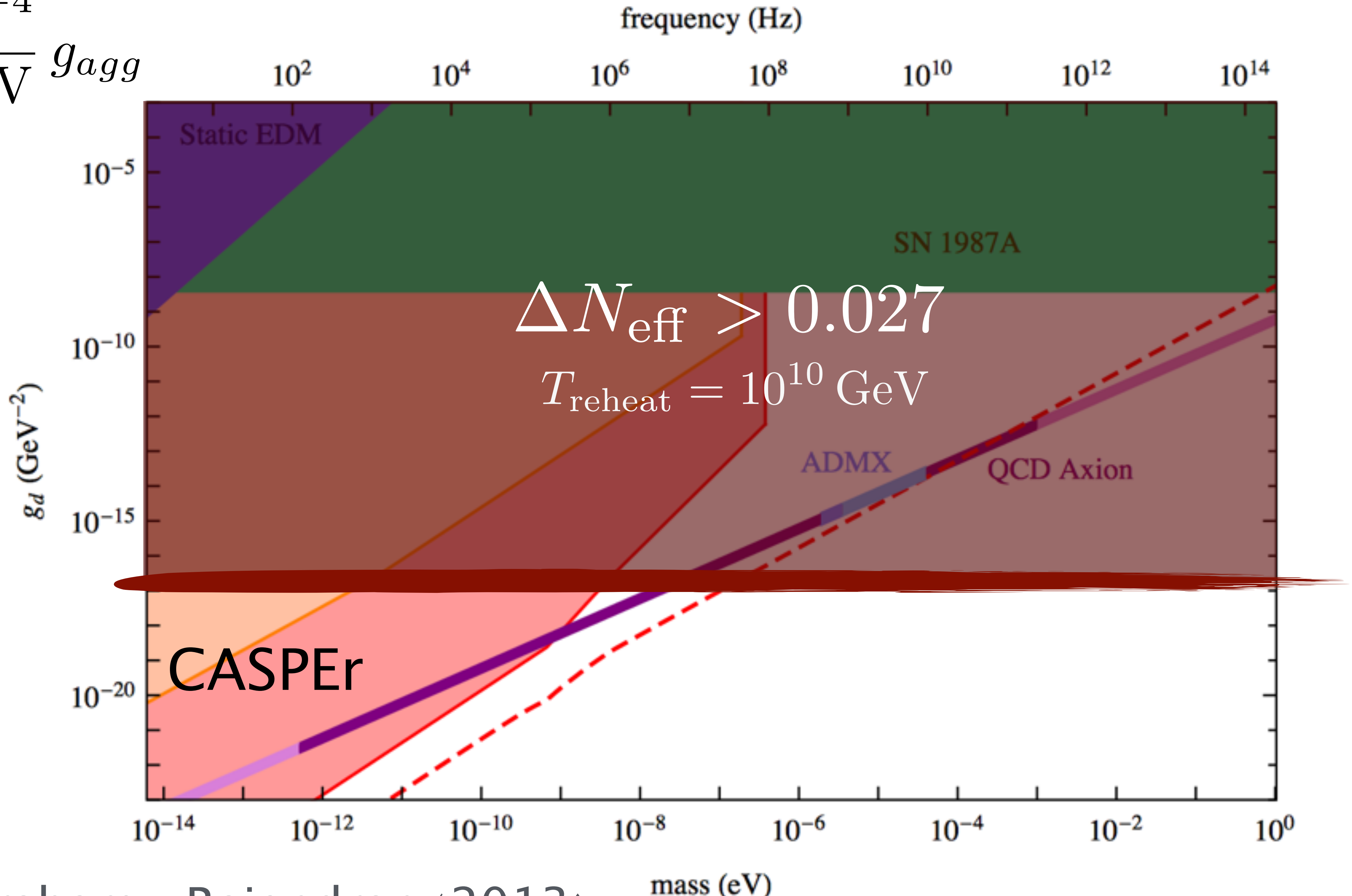


figure: Graham & Rajendran (2013)

Adiabatic Fluctuations

Challenge

What observables give a clean channel for discovery?

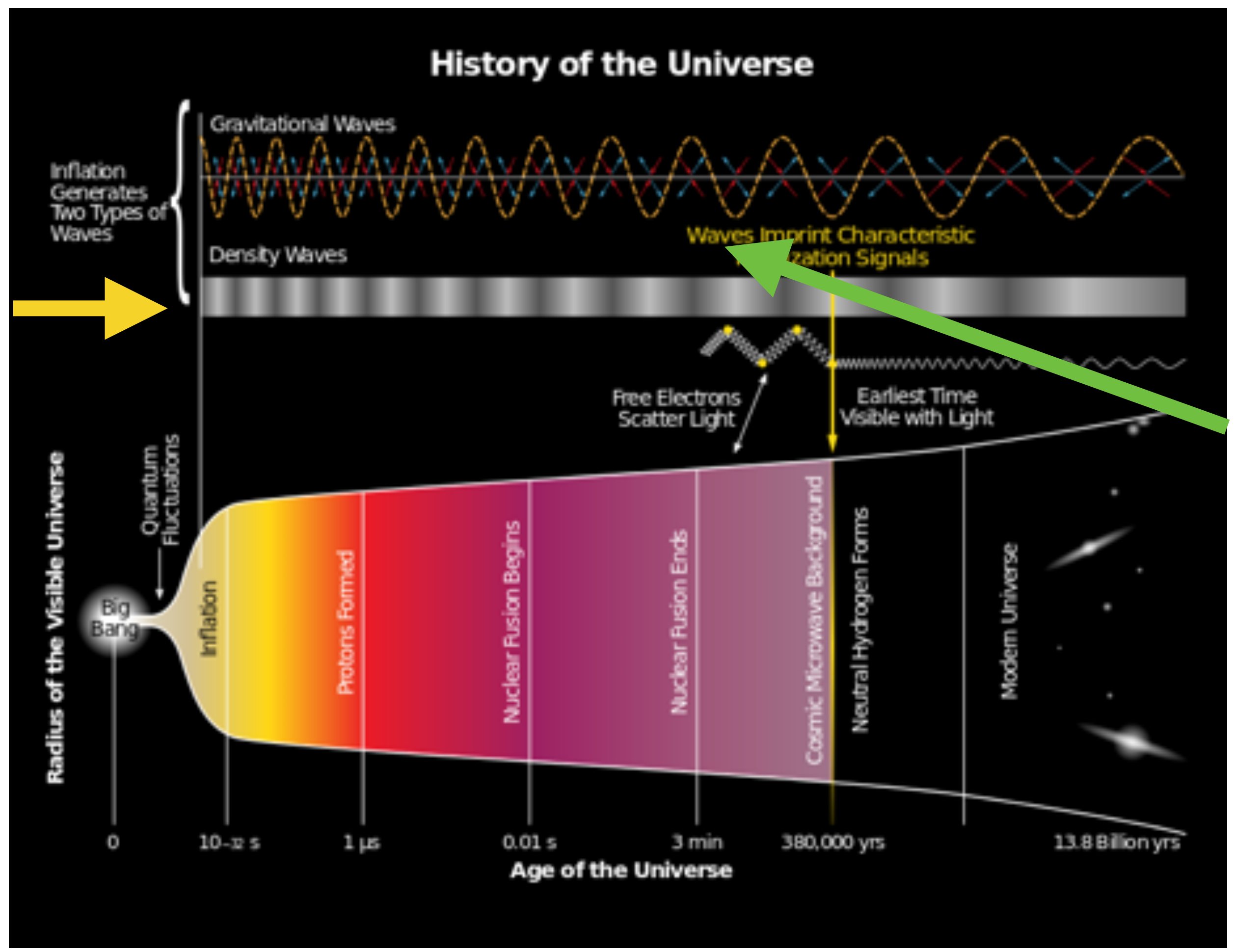
I.e. Would you believe a detection ?

- Many cosmological parameters are degenerate
- Must be distinguishable from astrophysics
- Must be free of major systematics

Adiabatic modes

Naively – degeneracy might seem like the problem

Fluctuations created during inflation



Live through entire thermal history

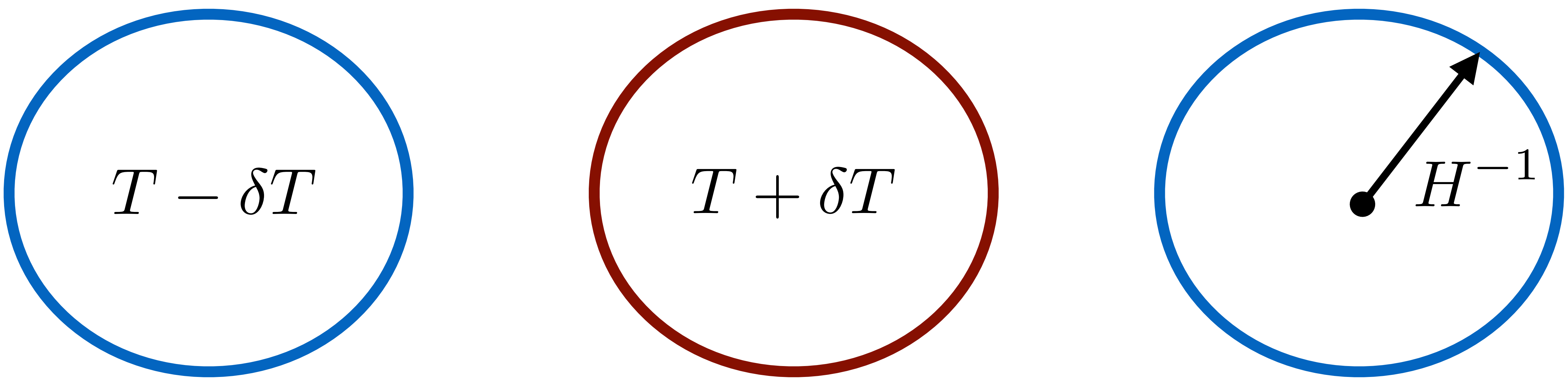
Why aren't we sensitive to everything?

Adiabatic modes

Primary reason : Conservation of adiabatic mode

Bardeen et al (1983); Salopek & Bond (1990); Wands et al. (2000); Weinberg (2003)

Physical intuition – locally changes temperature



Since $T \propto a^{-1}$, locally it just a redefinition of a

Long wavelength mode has no local effects

Adiabatic modes

Primary reason : Conservation of adiabatic mode

Technical Explanation - choice of metric / gauge

$$ds^2 = -dt^2 + a^2(t)e^{2\zeta(x,t)}d\vec{x}^2$$

This metric was residue gauge transformation

$$x \to e^{\lambda}x \qquad \zeta \to \zeta - \lambda$$

Constant mode is pure-gauge

Adiabatic modes

This "symmetry" is surprisingly powerful

Consider a long-wavelength fluctuation $\zeta_{\vec{k}\to 0}$

Implies all-order conservation

$$\dot{\zeta}_{\vec{k}\to 0} = b\,\frac{k^2}{a^2}\zeta + \ldots \to 0$$

Assassi, Baumann, DG (2012)

Fluctuations frozen – independent of local physics

Adiabatic modes

This "symmetry" is surprisingly powerful

Consider a long-wavelength fluctuation $\zeta_{\vec{k}\to 0}$

Single-field Consistency Conditions Maldacena (2002)

$$\lim_{k\to 0}\langle\zeta_k \ldots\rangle \to x\cdot\nabla\langle\ldots\rangle P_\zeta(k)$$

Violations are a clean channel for BSM physics

Creminelli & Zaldarriaga (2003) + ... ;
Chen & Wang (2009) ; Baumann & DG (2011) ;

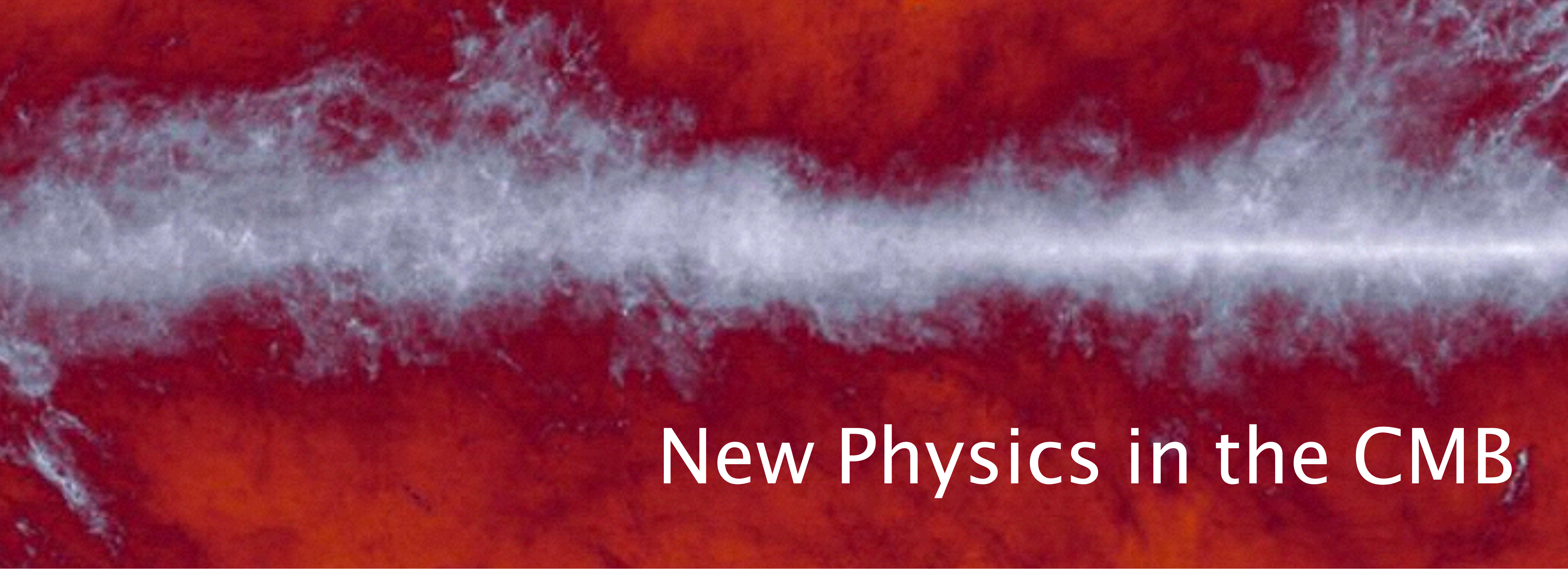
Adiabatic modes

Power of adiabatic modes is not limited to inflation

Origin of many clean cosmological probes

Allows clean detection of cosmic neutrinos via CMB

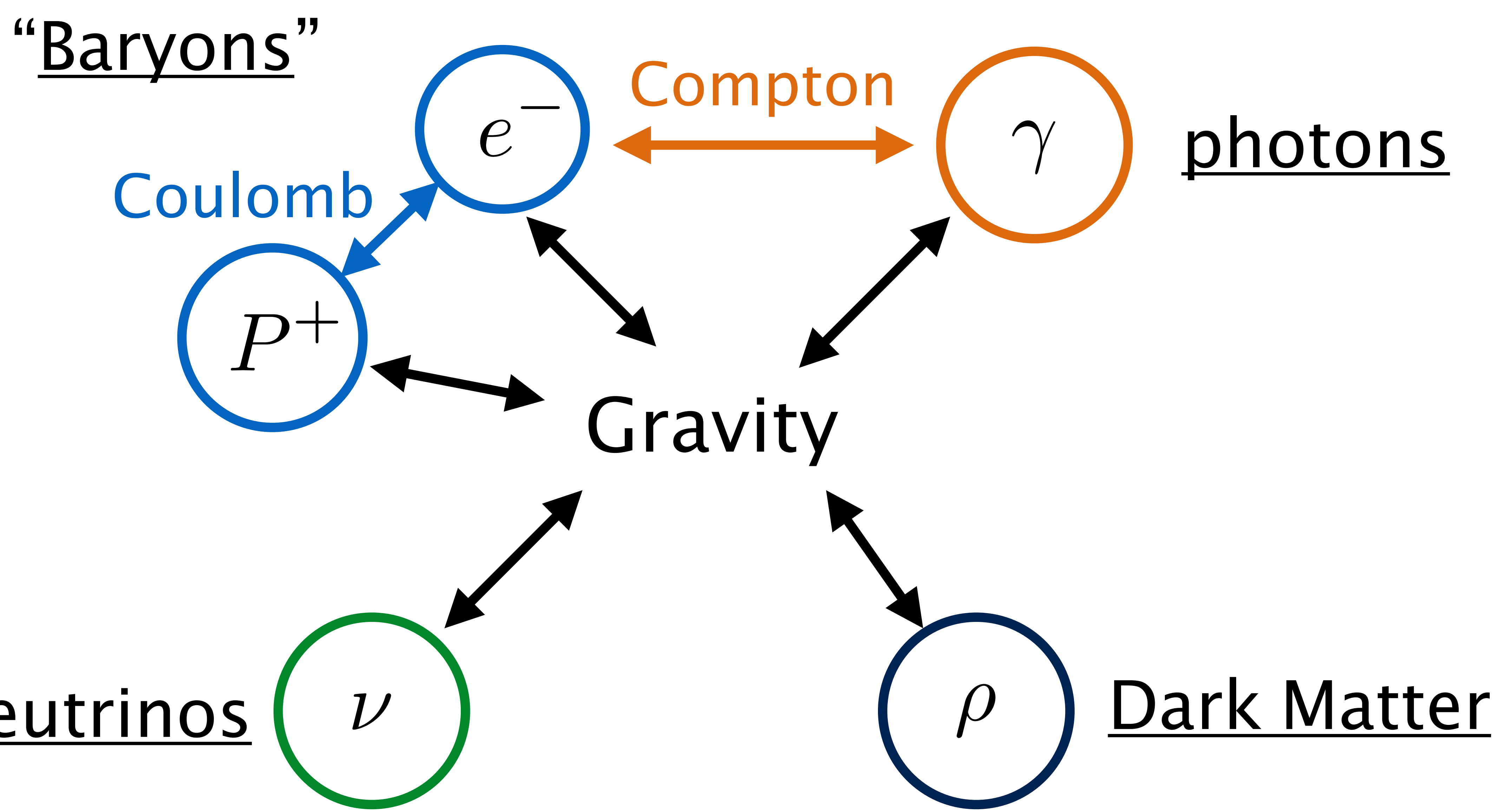
Channel to search for additional light particles



New Physics in the CMB

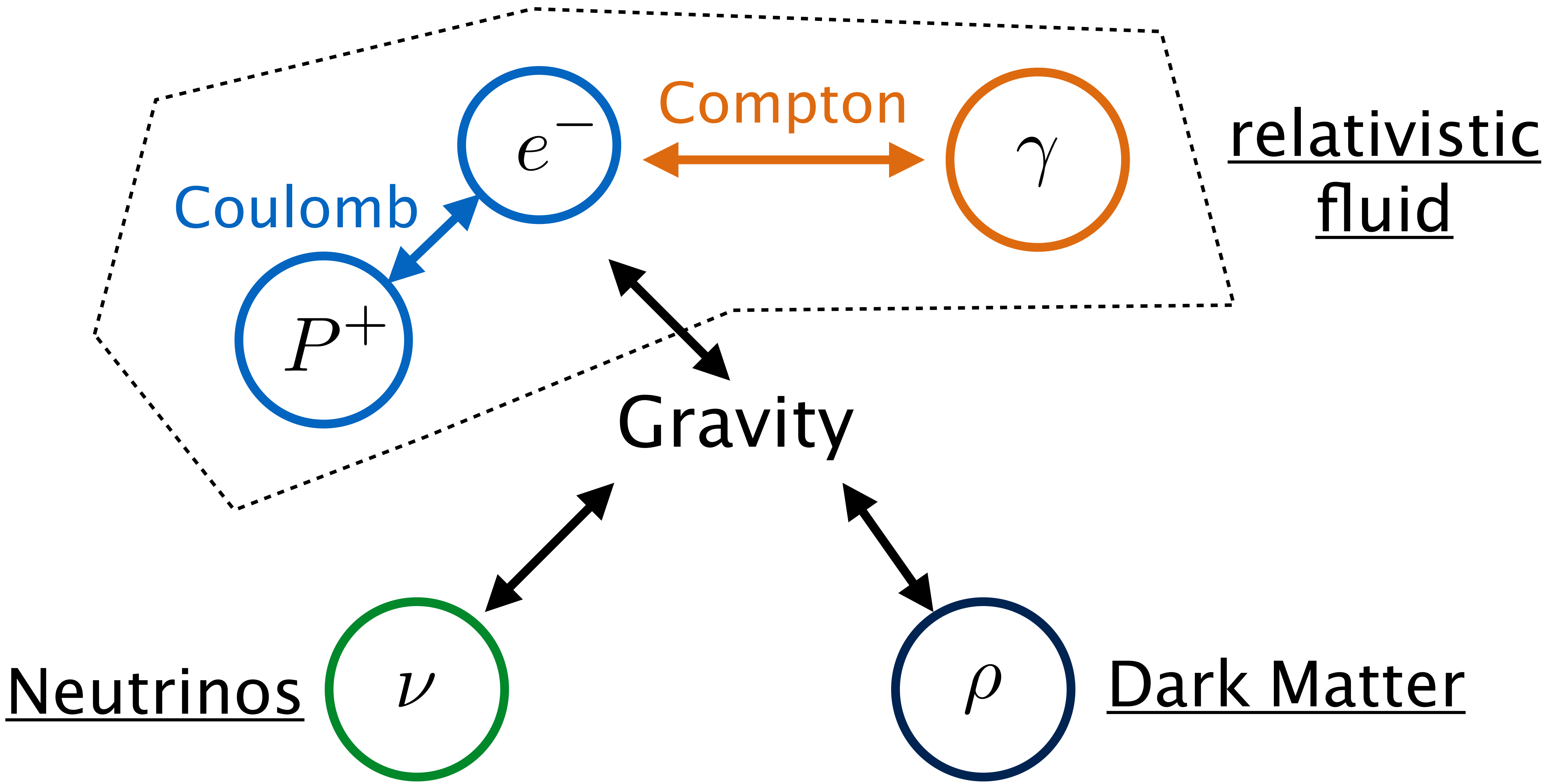
Gravity and Sound

The physics of the CMB is determine by 4 things



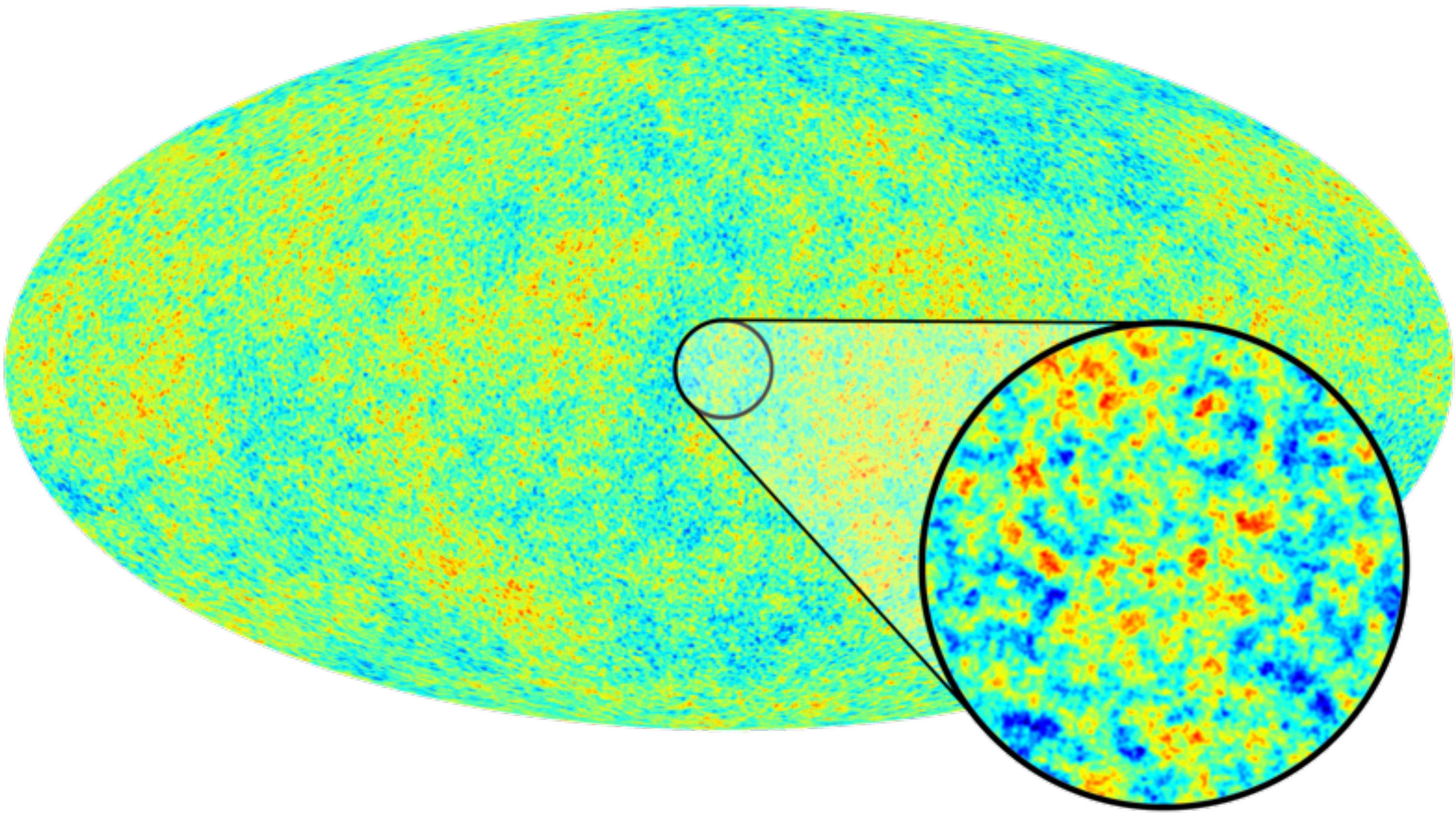
Gravity and Sound

Before CMB, photons-baryons effectively one fluid



Gravity and Sound

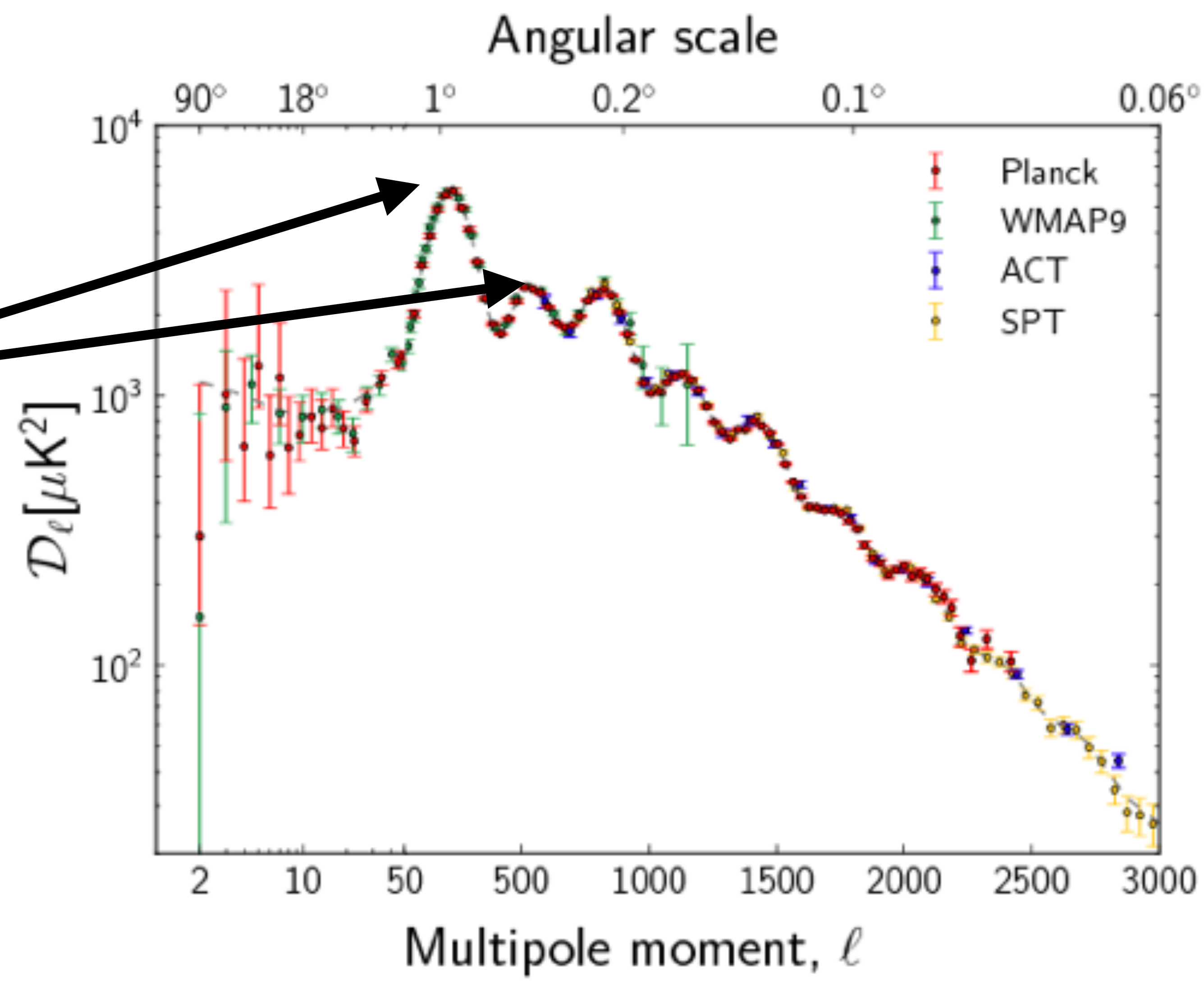
What we see is a snap-shot of the sound waves



Gravity and Sound

What we see is a snap-shot of the sound waves

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

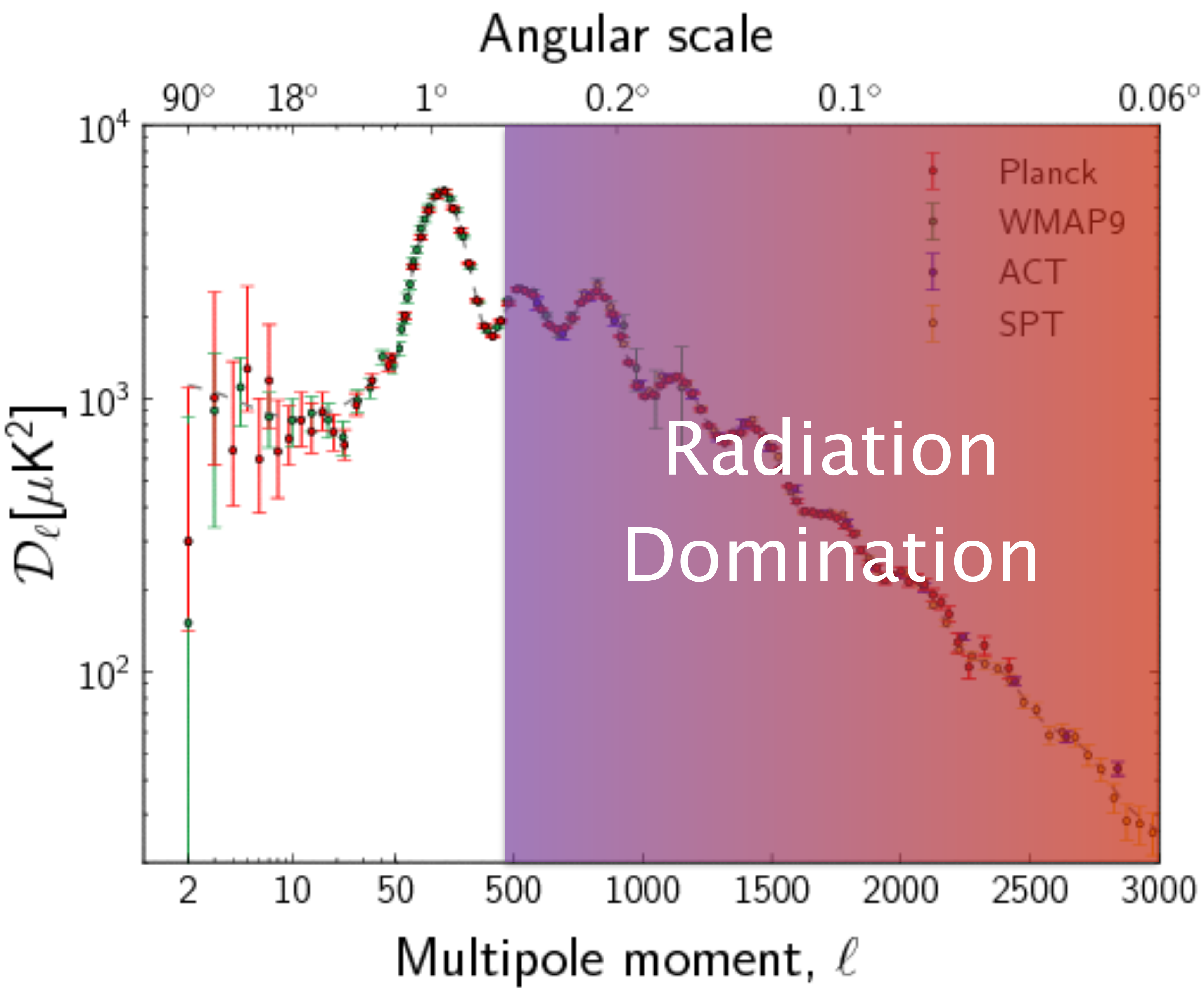


$$r_s = \int^{a_\star} \frac{da}{a^2 H} \frac{1}{\sqrt{3(1 + R_b(a))}}$$

Relates scale $\ell \sim k\tau_0$ and time $k\, r_s(\tau_\star) = n\pi$

Gravity and Sound

Smaller scale mostly live in radiation domination



Gravity and Sound

Dynamics of baryon-photon fluid simplifies

$$ds^2 = a^2 \left[(-1 - 2\Phi) d\tau^2 + (1 - 2\Psi) \delta_{ij} dx^i dx^j \right]$$

$$\Phi_\pm \equiv \Phi \pm \Psi$$

$$\ddot{d}_\gamma - c_\gamma^2 \nabla^2 d_\gamma = \nabla^2 \Phi_+ \qquad c_\gamma^2 \simeq \tfrac{1}{3}$$

Sound waves in the photon-baryon fluid

Gravity and Sound

Dynamics of baryon-photon fluid simplifies

$$ds^2 = a^2 \left[(-1 - 2\Phi) d\tau^2 + (1 - 2\Psi) \delta_{ij} dx^i dx^j \right]$$

$$\Phi_\pm \equiv \Phi \pm \Psi$$

$$\ddot{d}_\gamma - c_\gamma^2 \nabla^2 d_\gamma = \nabla^2 \Phi_+ \qquad c_\gamma^2 \simeq \frac{1}{3}$$

Interactions with all other matter

Gravity and Sound

Formal solution in terms of $y = c_\gamma k\tau$

$$d_\gamma = (d_{\gamma,0} + c_\gamma^{-2} A(y)) \cos(y) + c_\gamma^{-2} B(y) \sin(y)$$

$$A(y) \equiv \int_0^y dy' \Phi_+(y') \sin(y')$$

$$B(y) \equiv \int_0^y dy' \Phi_+(y') \cos(y')$$

Phase Shift

High-ℓ is well approximated by $y \to \infty$

$$\delta_\gamma = \Delta \cos(y + \varphi) + \mathcal{O}(y^{-1})$$

Phase shift: $\varphi \neq 0 \leftrightarrow B(y \to \infty) \neq 0$

Bashinsky & Seljak (2003)

We can learn a lot from a very simple trick

$$B + iA = \int_0^\infty e^{iy} \Phi_+(y)$$

$$B = \frac{1}{2} \int_{-\infty}^\infty e^{iy} \Phi_+^{(S)}(y)$$

Phase Shift

Phase shift determined Cauchy's integral formula

$$\frac{1}{2}\oint dz\, \Phi_+^{(S)}(z)e^{iz} = B + \{\mathrm{coutour\,at\,}\infty\} = \pi i \sum \mathrm{Res}\Phi_+^{(S)}(z)e^{iz}$$

Non-zero phase shift means that

- $\Phi_+^{(S)}(z)$ is non-analytic → non-adiabatic
- Growth at $z = \pm i\infty$ → waves with $c > c_\gamma$

Analyticity = conservation $\zeta_{k\to 0} \propto c_0 + c_1 k^2\tau^2 + \dots$

Phase Shift

Phase shift determined Cauchy's integral formula

$$\frac{1}{2}\oint dz\,\Phi_+^{(S)}(z)e^{iz} = B + \{\text{coutour at}\,\infty\} = \pi i \sum \text{Res}\Phi_+^{(S)}(z)e^{iz}$$

Non-zero phase shift means that

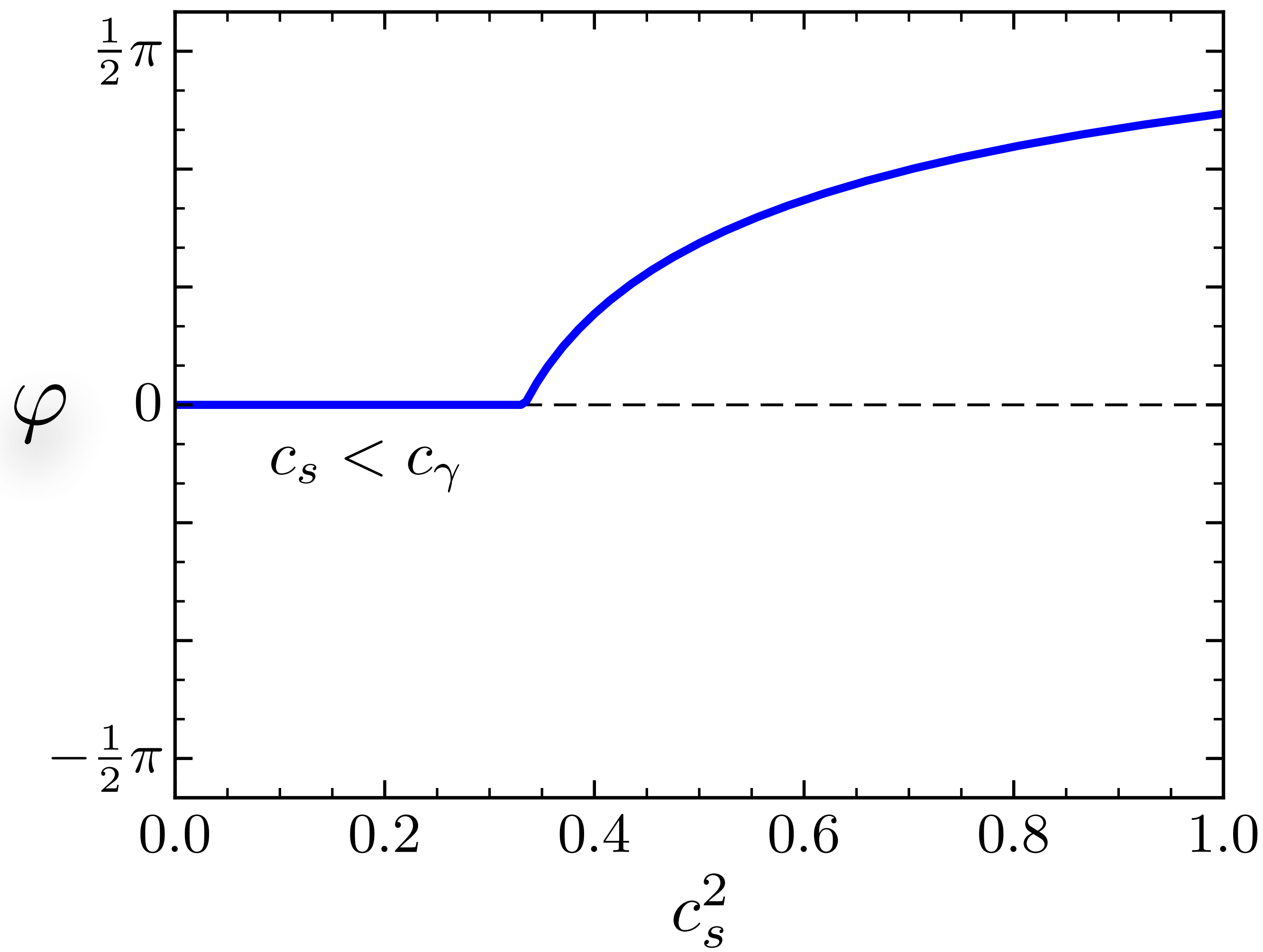
- $\Phi_+^{(S)}(z)$ is non-analytic → non-adiabatic
- Growth at $z = \pm i\infty$ → waves with $c > c_\gamma$

Free streaming radiation is effectively $c = 1 > c_\gamma$

Phase Shift

E.g. dark fluid with some EofS and sound speed

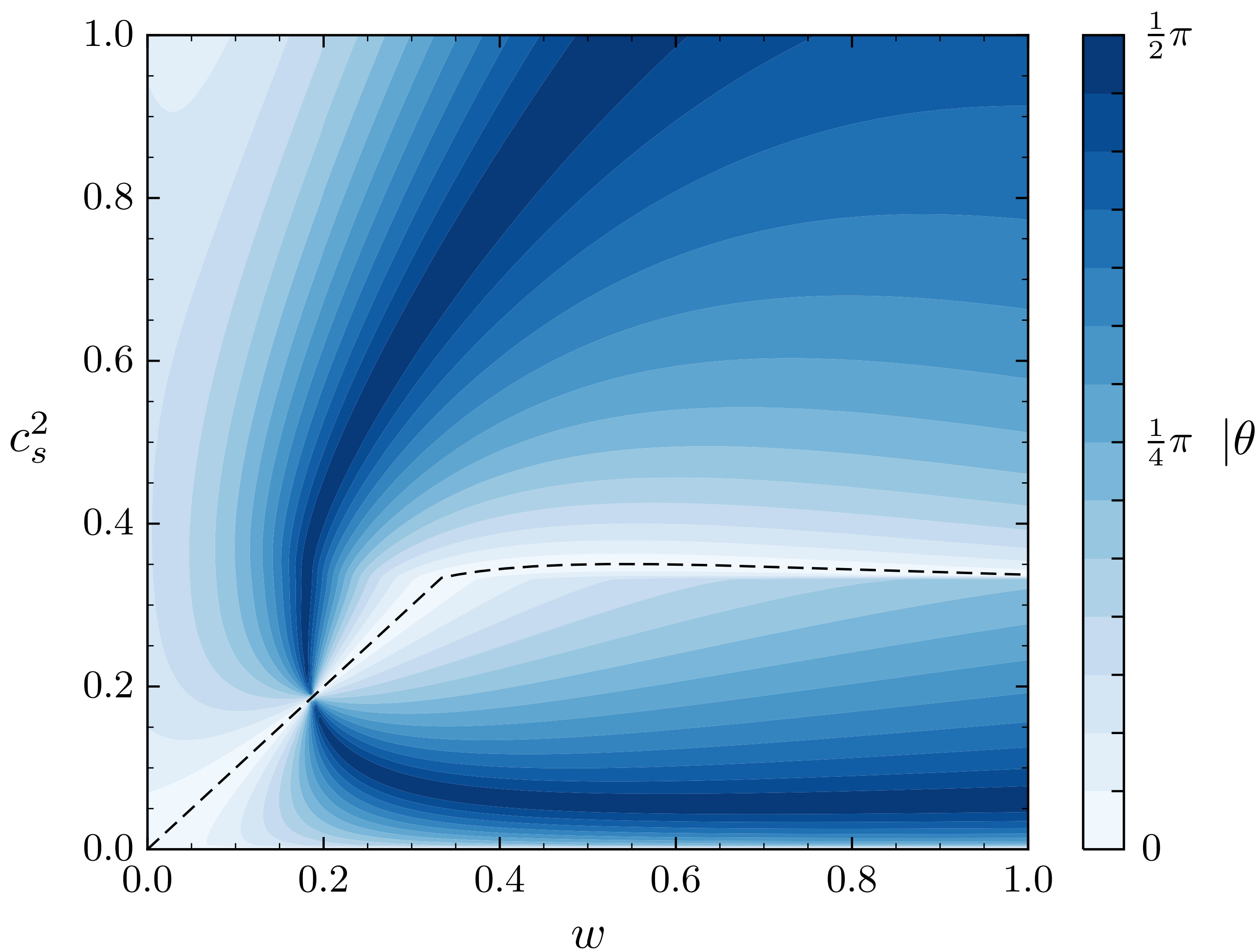
Adiabatic modes require $\omega = c_s^2$



Phase Shift

E.g. dark fluid with some EofS and sound speed

non-adiabatic allows $\omega \neq c_s^2$



Phase Shift

General lessons:

- Phase shift is clean measure of $N_{\rm eff}$
- Not degenerate with $N_{\rm fluid}$, etc.
- Non-zero anisotropic stress is a red-herring

Conservation of ζ makes it difficult to fake

Damping Tail

Mean-free path of photon important on small scales

Effective viscosity: damping $d_\gamma \propto e^{-k^2/2k_d^2}$

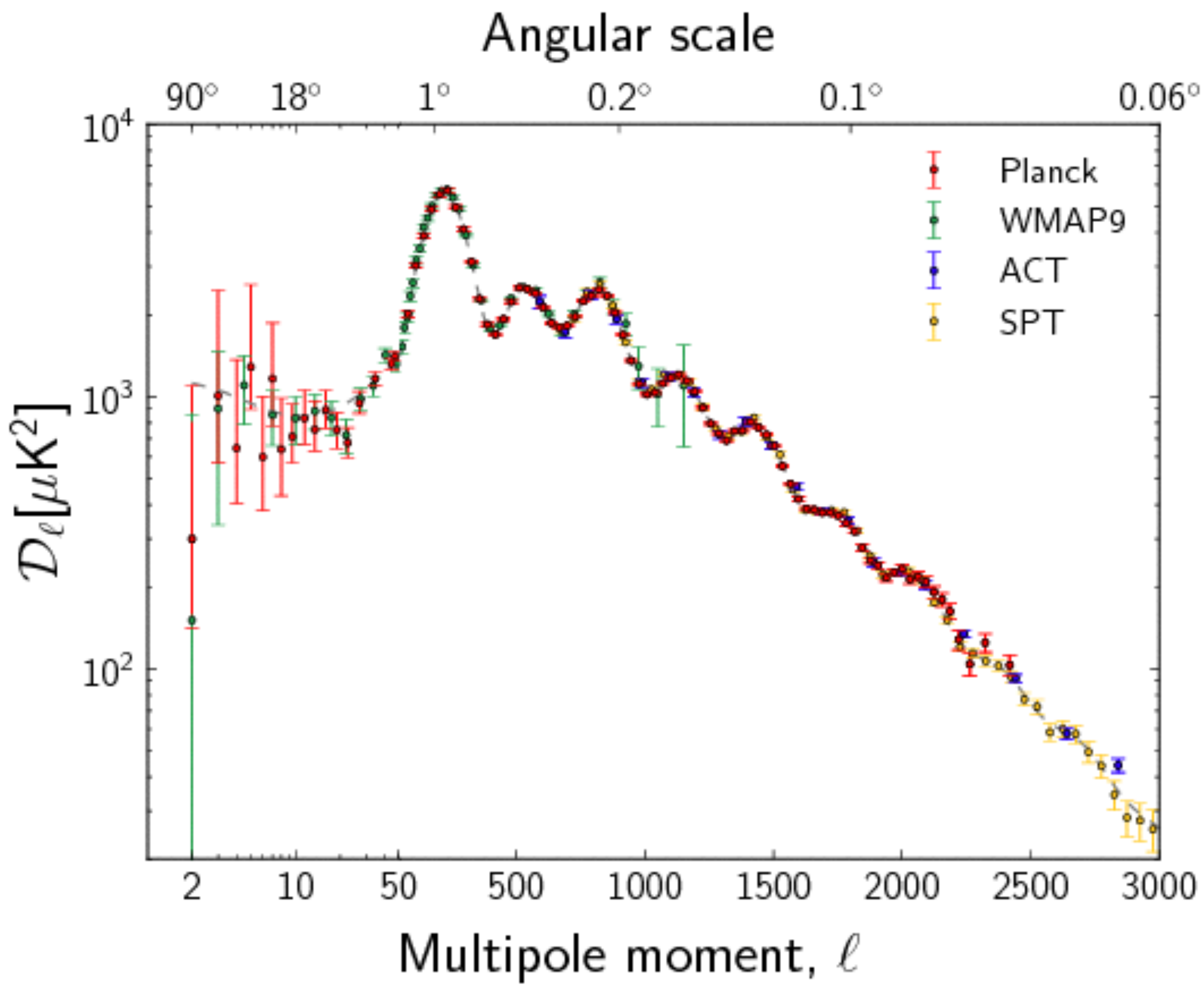
$$R \equiv \frac{\rho_b}{\rho_\gamma}$$

$$k_d^{-2} \equiv \int_0^{a_\star} \frac{da}{a^2 \sigma_T n_e H} \frac{R^2 + \frac{16}{15}(1+R)}{6(1+R)^2}$$

$$n_e \propto (1 - Y_p) \qquad H^2 \propto (\rho_\gamma + \rho_R^{\mathrm{F.S.}} + \rho_R^{\mathrm{non-F.S.}})$$

Damping Tail

Damping tail is not difficult to see



Damping Tail

Damping tail is highly degenerate

- Obviously degenerate with $N_{\rm fluid} + N_{\rm eff}, Y_p$

  Bashinsky & Seljak (2003)

- We must also be careful to keep first peak fixed

  Hou et al. (2011)

Polarization helps break degeneracy with Y_p

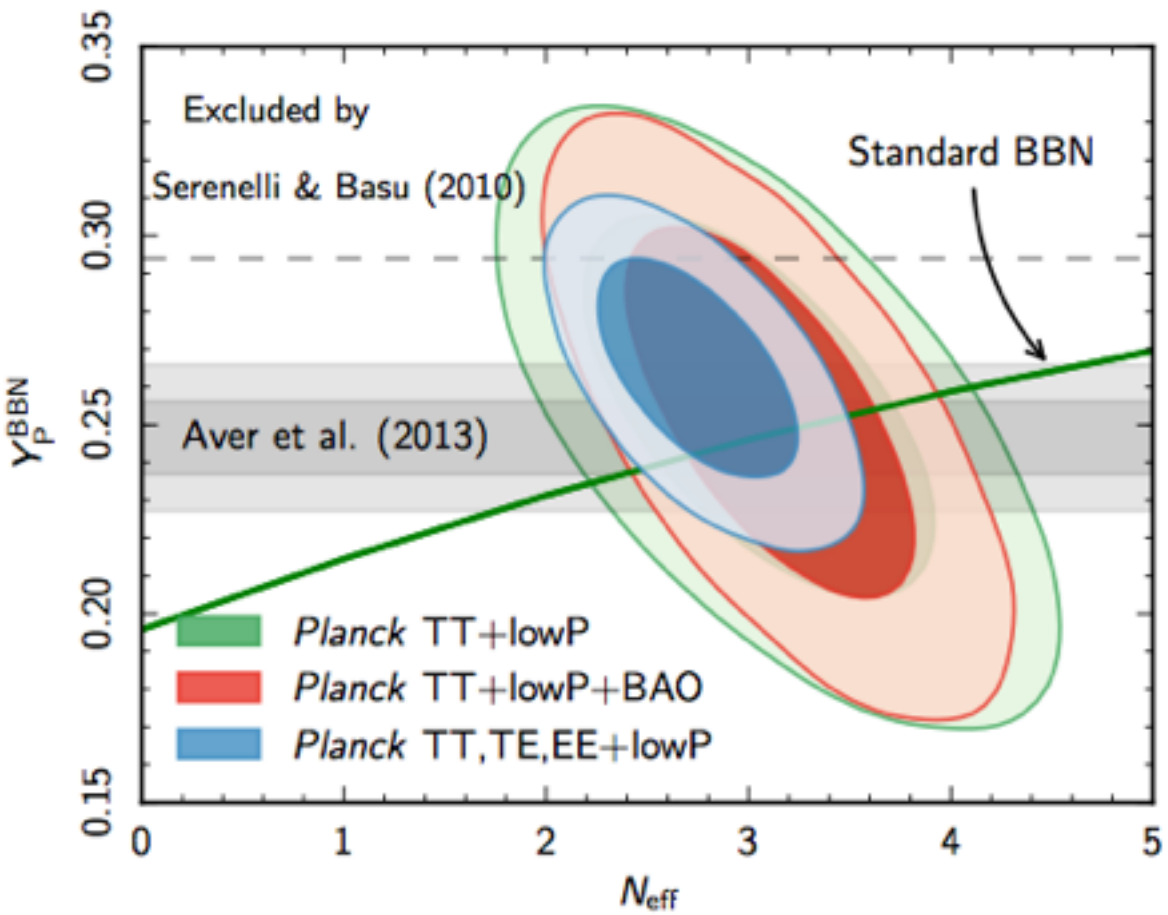
Y_p is sensitive to $N_{\rm eff}^{\rm BBN}$

Planck, CMB Stage IV and Neutrinos

Planck

Current constraints from Planck 2015

$$N_{\rm eff} = 3.04 \pm 0.18$$

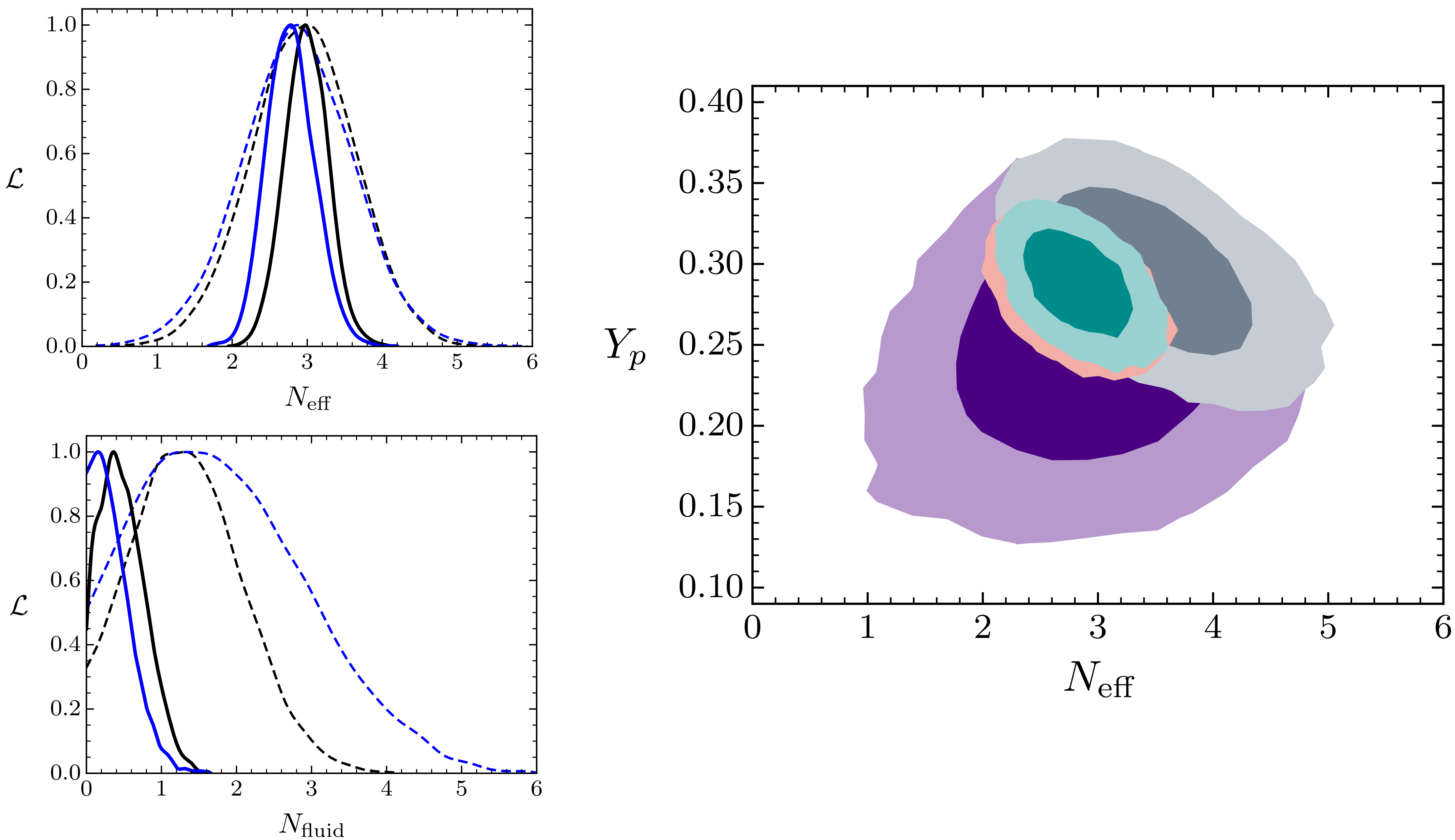


Consistent with standard neutrinos

Degeneracy with Y_p is under control

Planck

We can further isolate the origin of the constraints



Planck

Appears that phase shift breaks the degeneracies

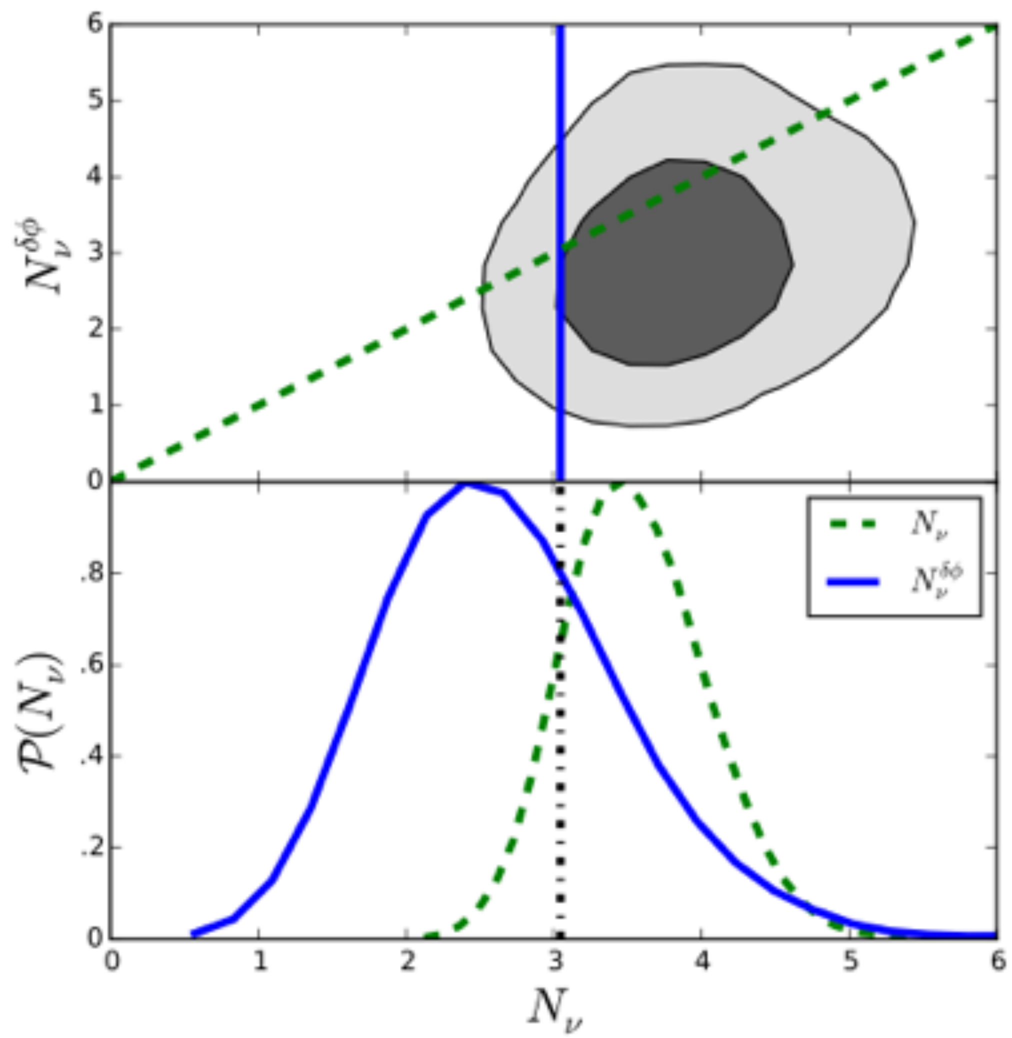
	TT, TE, EE		TT-only	
	varying Y_p	fixed Y_p	varying Y_p	fixed Y_p
$N_{\rm eff}$	$2.78^{+0.30}_{-0.35}$	$2.99^{+0.30}_{-0.29}$	$2.87^{+0.76}_{-0.74}$	$2.94^{+0.71}_{-0.69}$
$N_{\rm fluid}$	< 0.88	< 1.06	< 3.93	< 2.65

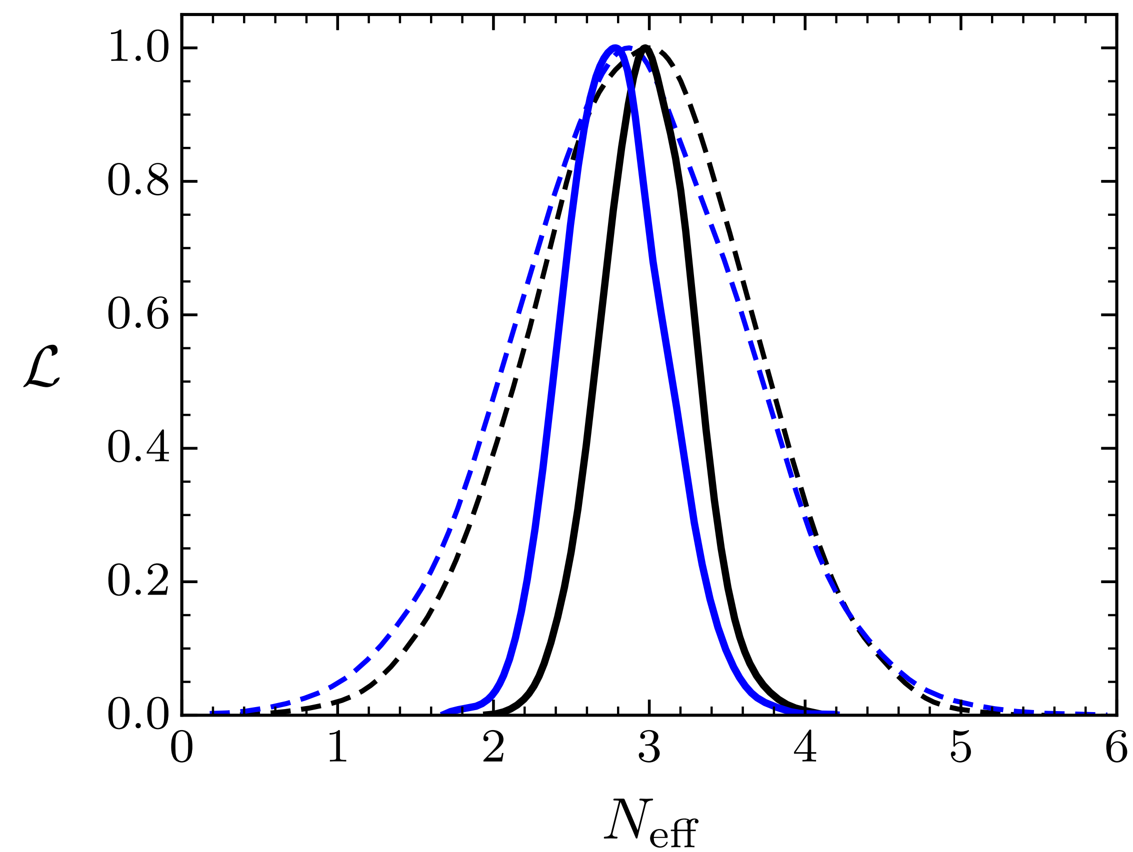
Without damping tail $\sigma(N_{\rm eff}) \simeq 0.3$

With damping tail $\sigma(N_{\rm eff}) \simeq 0.2$

Phase shift directly detected in TT data

Follin et al. (2015)





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

$$N_{\rm eff} = 2.87^{+0.76}_{-0.74}$$

Planck

Constraints correspond to shift $\delta\ell \simeq 1$

Compatible with Planck measurements of peaks

***TT* power spectrum**

Peak 1	220.0 ± 0.5	5717 ± 35
Trough 1	415.5 ± 0.8	1696 ± 13
Peak 2	537.5 ± 0.7	2582 ± 11
Trough 2	676.1 ± 0.8	1787 ± 12
Peak 3	810.8 ± 0.7	2523 ± 10
Trough 3	997.7 ± 1.4	1061 ± 5
Peak 4	1120.9 ± 1.0	1237 ± 4
Trough 4	1288.8 ± 1.6	737 ± 4
Peak 5	1444.2 ± 1.1	797.1 ± 3.1
Trough 5	1621.2 ± 2.3	400 ± 4
Peak 6	1776 ± 5	377.4 ± 2.9
Trough 6	1918 ± 7	245 ± 4
Peak 7	2081 ± 25	214 ± 4
Trough 7	2251 ± 8	119.5 ± 3.5
Peak 8	2395 ± 24	105 ± 4

***TE* power spectrum**

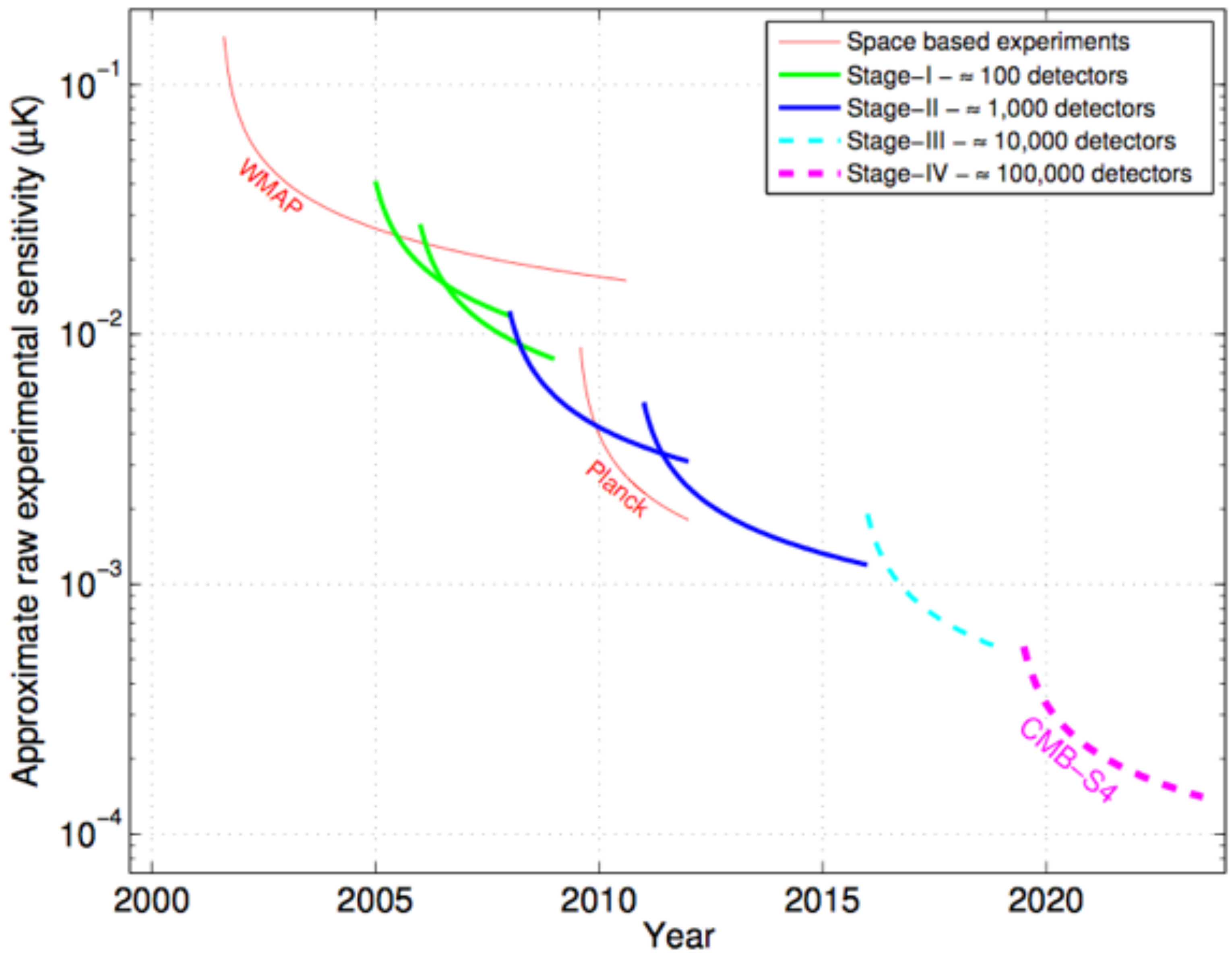
Trough 1	150.0 ± 0.8	−48.0 ± 0.8
Peak 1	308.5 ± 0.4	115.9 ± 1.1
Trough 2	471.2 ± 0.4	−74.4 ± 0.8
Peak 2	595.3 ± 0.7	28.6 ± 1.1
Trough 3	746.7 ± 0.6	−126.9 ± 1.1
Peak 3	916.9 ± 0.5	58.4 ± 1.0
Trough 4	1070.4 ± 1.0	−78.0 ± 1.1
Peak 4	1224 ± 1.0	0.7 ± 0.5
Trough 5	1371.7 ± 1.2	−60.9 ± 1.1
Peak 5	1536 ± 2.8	5.6 ± 1.3
Trough 6	1693.0 ± 3.3	−27.6 ± 1.3
Peak 6	1861 ± 4	1.2 ± 1.0

***EE* power spectrum**

Peak 1	137 ± 6	1.15 ± 0.07
Trough 1	197 ± 8	0.848 ± 0.034
Peak 2	397.2 ± 0.5	22.04 ± 0.14
Trough 2	525 ± 0.7	6.86 ± 0.16
Peak 3	690.8 ± 0.6	37.35 ± 0.25
Trough 3	832.8 ± 1.1	12.5 ± 0.4
Peak 4	992.1 ± 1.3	41.8 ± 0.5
Trough 4	1153.9 ± 2.7	12.3 ± 0.9
Peak 5	1296 ± 4	31.6 ± 1.0

CMB Stage IV

CMB Stage IV will be ground based CMB mission



CMB Stage IV

Nothing has been firmly established about it

An overly optimistic version would be

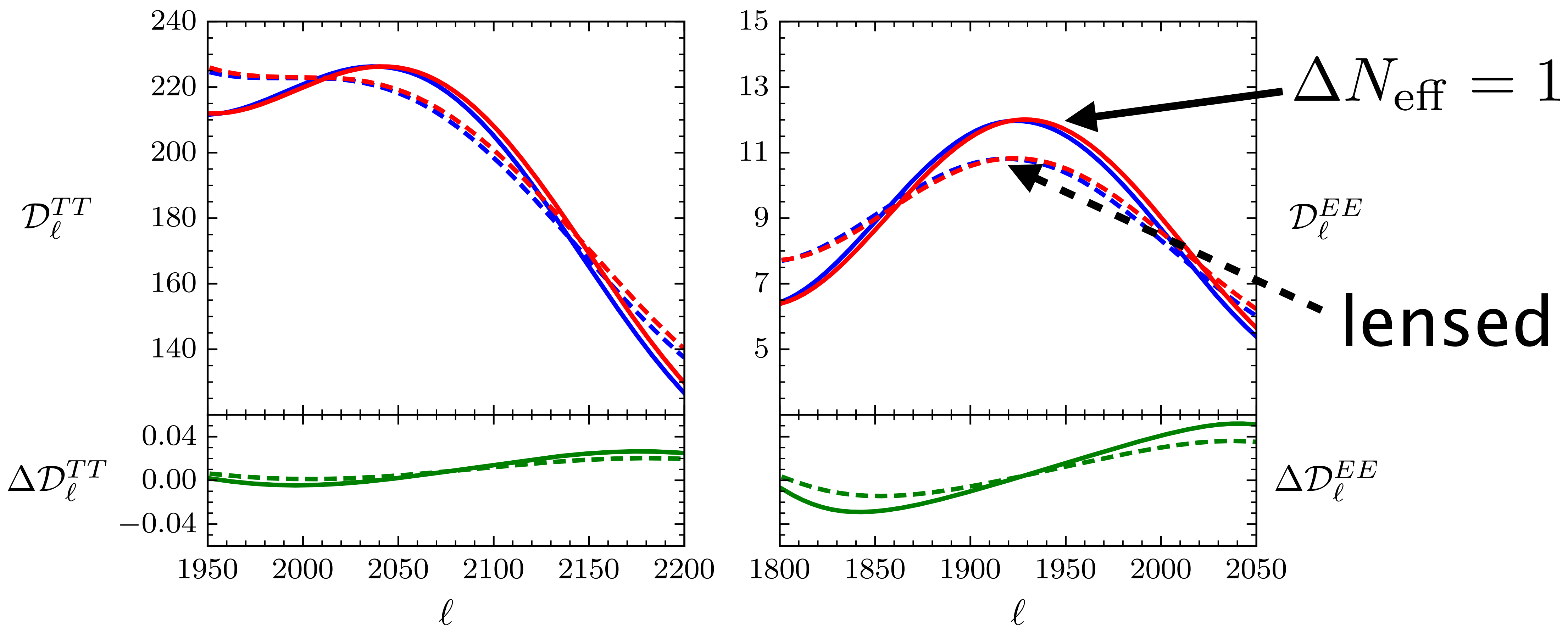
$$N_{\rm detectors} = 10^6 \qquad f_{\rm sky} = 0.75$$

To get a sense of raw capabilities

Parameter	$1'$	$2'$	$3'$	$\ell_{\rm max} = 3000$	$\ell_{\rm max} = 4000$
$\sigma(N_{\rm eff})$ (Y_p fixed, $N_{\rm fluid} = 0$)	0.013	0.015	0.016	0.023	0.015
$\sigma(N_{\rm eff})$ (Y_p fixed, $N_{\rm fluid} \neq 0$)	0.026	0.027	0.029	0.034	0.028
$\sigma(N_{\rm eff})$ (Y_p varying, $N_{\rm fluid} = 0$)	0.048	0.051	0.055	0.058	0.052
$\sigma(N_{\rm eff})$ (Y_p varying, $N_{\rm fluid} \neq 0$)	0.050	0.052	0.055	0.061	0.051
$N_{\rm fluid}$ (Y_p varying)	< 0.16	< 0.17	< 0.18	< 0.20	< 0.17
$N_{\rm fluid}$ (Y_p fixed)	< 0.068	< 0.072	< 0.076	< 0.090	< 0.072

CMB Stage IV

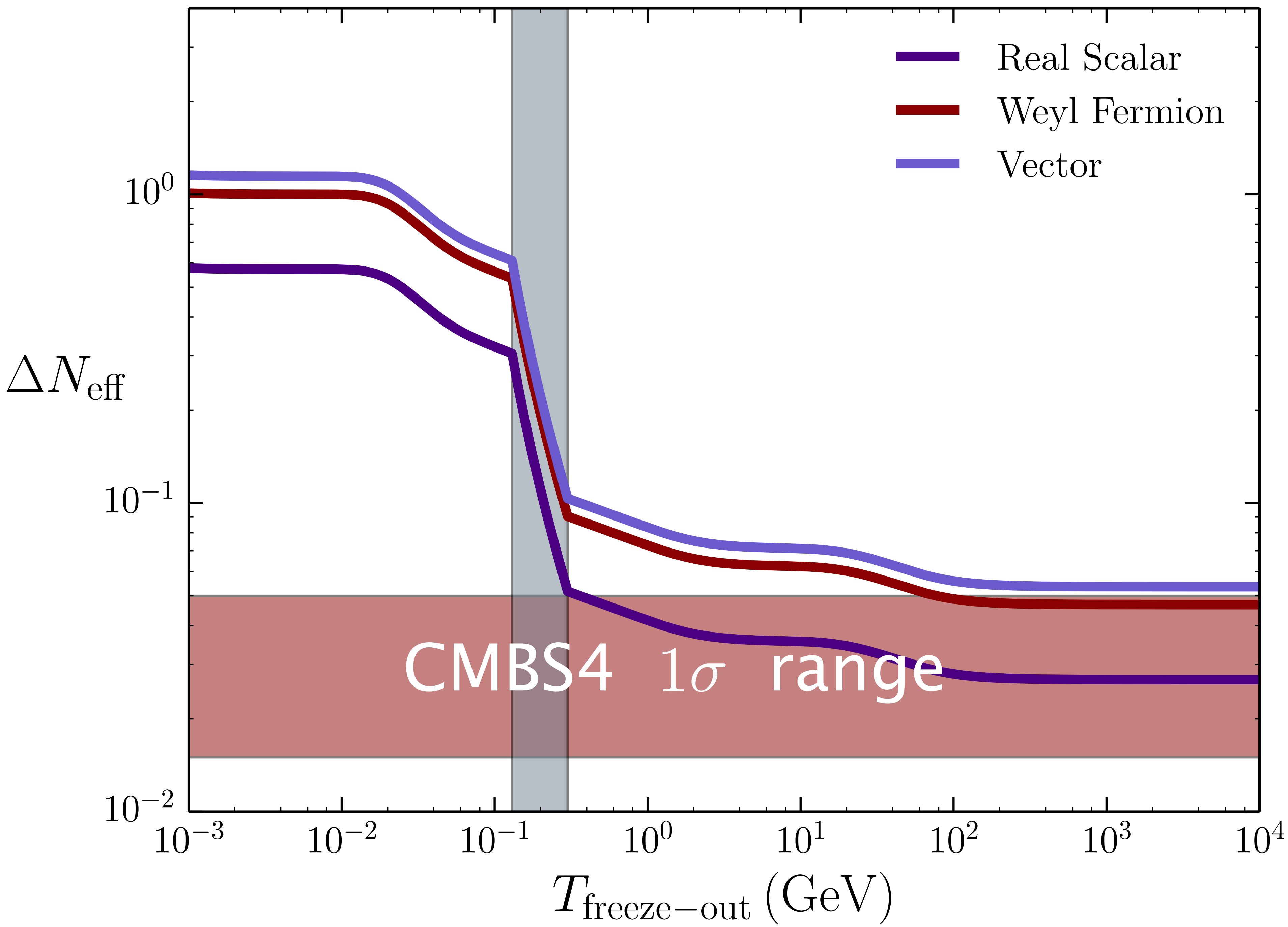
Most of this improvement is driven by E-modes



De-lensing helps reduce the error bars (like BAO)

Forecasts correspond to $\delta\ell \sim 0.1$

CMB Stage IV



Real Scalar
Weyl Fermion
Vector
10^0
10^{-1}
10^{-2}
$\Delta N_{\rm eff}$
CMBS4 1σ range
10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2 10^3 10^4
$T_{\rm freeze-out}$ (GeV)

CMB Stage IV

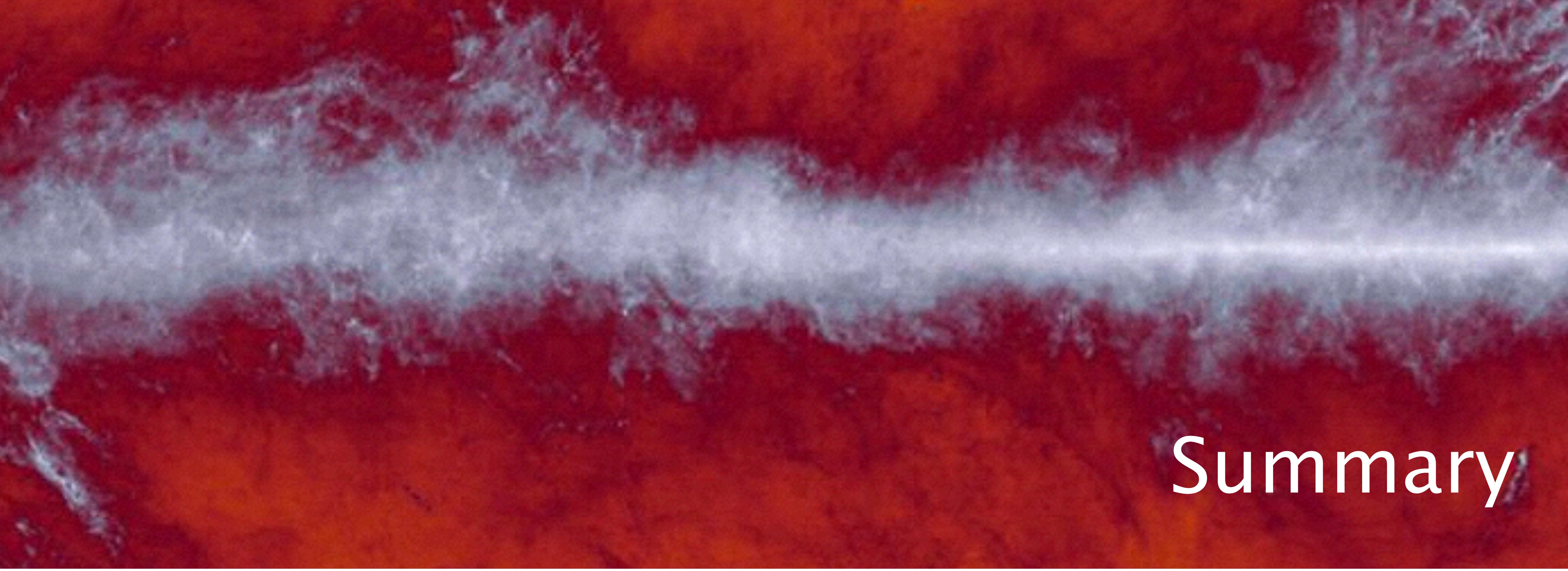
These forecasts are at a very interesting level

$\sigma(N_{\mathrm{eff}}) \sim 0.01$ sensitive back to reheating

A null detection would still be very interesting

Sensitivity to phase shift breaks most degeneracies

Can measure $N_{\mathrm{eff}}, Y_p, N_{\mathrm{fluid}}$ simultaneously



Summary

Summary

Much about our thermal history is uncertain

Large improvements expected from the CMB

Cosmic neutrinos are a direct window to $T \sim 1\,\mathrm{MeV}$

New light particles detectable back to reheating

Sensitive to many changes to “standard” picture

Summary

Phase shift of the acoustic peaks is robust signature

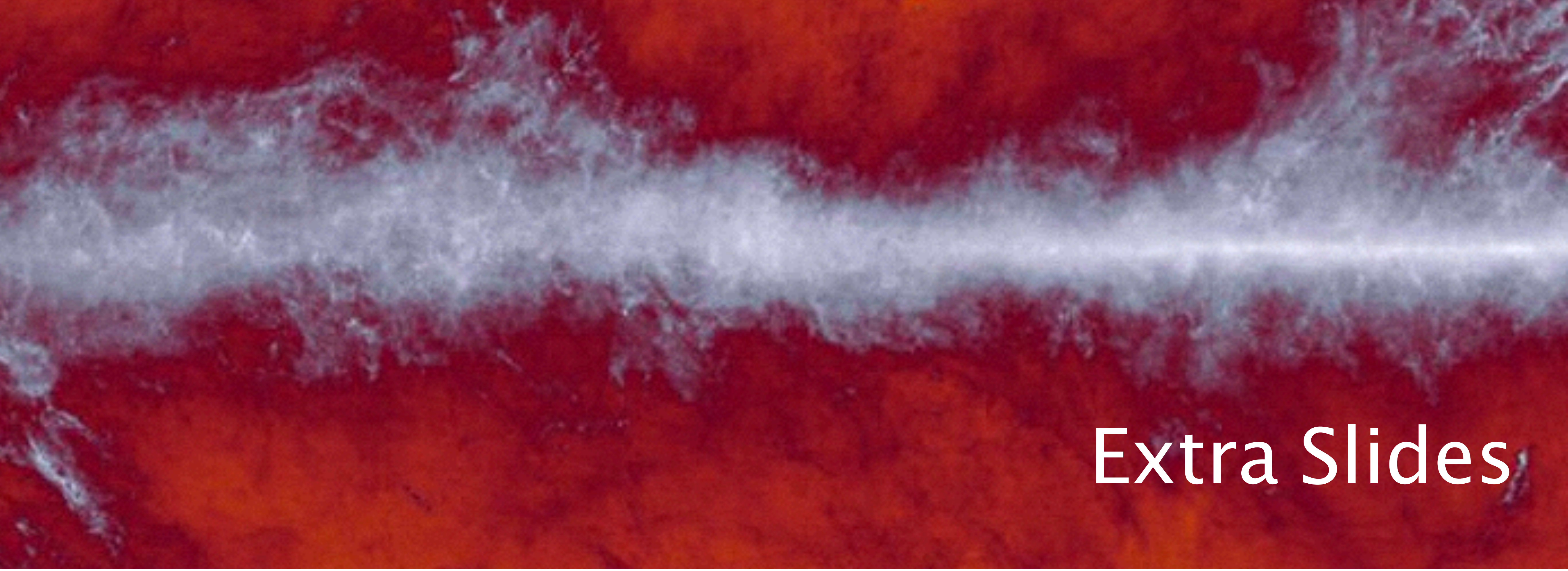
Distinguishes free and non-free streaming radiation

CMB stage IV can in principle reach $\sigma(N_{\rm eff}) \sim 0.01$

$\Delta N_{\rm eff} > 0.027$ is an achievable threshold

1σ

Many more opportunities to explore



Extra Slides

Relation to Experiments

New massless particles a highly constrained

Stellar cooling : $\Lambda_{\phi e,\gamma} \gtrsim 10^9\,\mathrm{GeV}$

Supernova 1987a : $\Lambda_{\phi\mu} \gtrsim 10^6\,\mathrm{GeV}$

Collider (LEP,LHC): $\Lambda_{X^2\Psi^2} \gtrsim 10^3\,\mathrm{GeV}$

Implied freeze-out temperature model dependent

$$T_{\text{freeze-out}} \gtrsim 10\,\mathrm{MeV} - 10\,\mathrm{TeV}$$

Relation to BBN

BBN is primarily sensitive to $H(T \sim .1\,\mathrm{MeV})$

Abundances are sensitive to timing / expansion

E.g. $Y_p \approx 0.247 + 0.014\,(N_{\rm eff}^{\rm BBN} + N_{\rm fluid}^{\rm BBN} - 3.046)$

Current limit from BBN-only $N_{\rm eff}^{\rm BBN} = 2.85 \pm 0.28$

Cyburt et al (2015)

Measures radiation density at a few minutes

Also sensitive to late decays / energy injection