Neutrinos in the early universe

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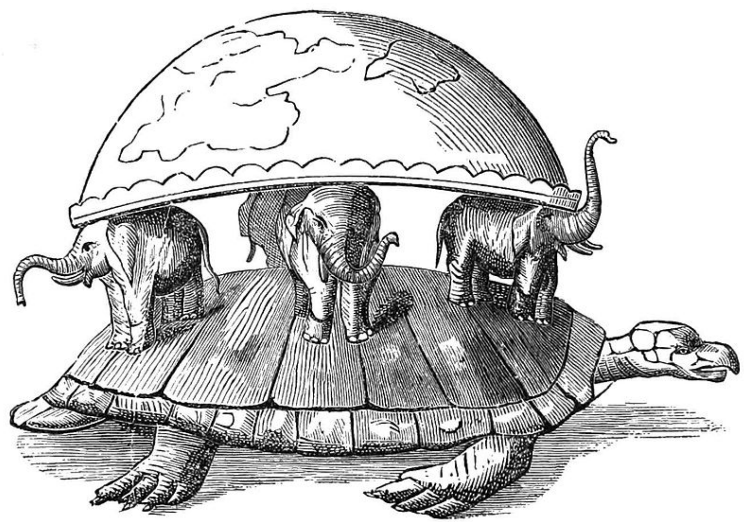


International Neutrino Summer School, Schloss Waldthausen, May 20 – June 1 , 2018

The grand lecture plan...

Lecture 1: Cosmology 101

Lecture 2: Neutrinos in homogeneous cosmology

Lecture 3: Neutrinos in inhomogeneous cosmology

1. Neutrinos and structure formation
2. Signatures of neutrino dark matter and neutrino mass constraints
3. Future prospects

Lecture 3: Neutrinos in inhomogeneous cosmology

1. Neutrinos and structure formation

2. Signatures of neutrino dark matter and neutrino mass constraints

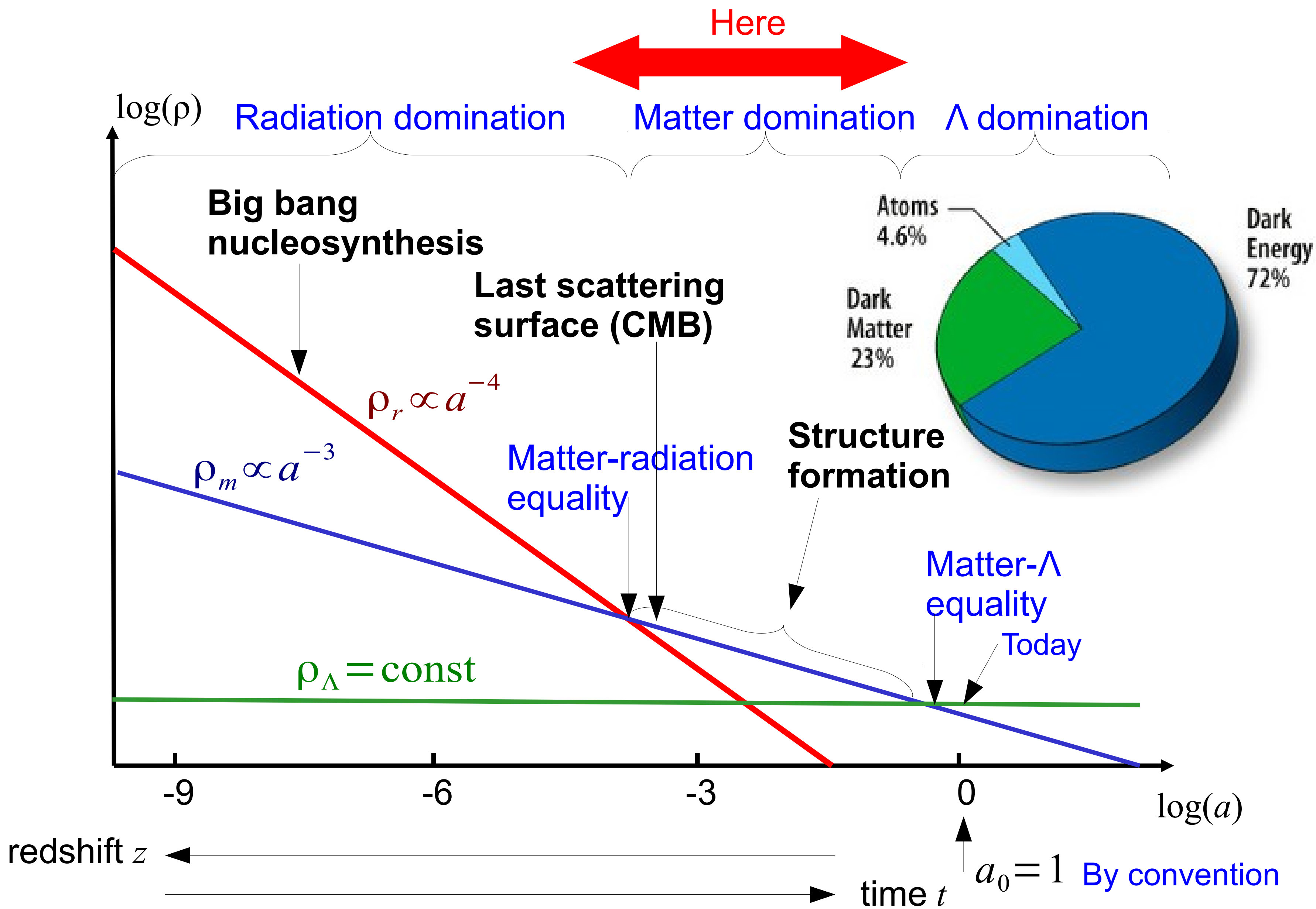
3. Future prospects

Useful references...

- **Lecture notes**
  - E. Bertschinger, *Cosmological dynamics*, astro-ph/9503125.

- **Reviews**
  - J. Lesgourgues & S. Pastor, *Massive neutrinos and cosmology*, Phys. Rep. **429** (2006) 307 [astro-ph/0603494].
  - Y. Y. Y. Wong, *Neutrino mass in cosmology: status and prospects*, Ann. Rev. Nucl. Part. Sci. **61** (2011) 69 [arXiv:1111.1436].

- **Textbooks**
  - J. Lesgourgues, G. Mangano, G. Miele & S. Pastor, *Neutrino cosmology*


Here
log(ρ)
Radiation domination
Matter domination
Λ domination
Big bang nucleosynthesis
Last scattering surface (CMB)
Atoms 4.6%
Dark Energy 72%
Dark Matter 23%
$\rho_r \propto a^{-4}$
$\rho_m \propto a^{-3}$
Matter-radiation equality
Structure formation
Matter-Λ equality
Today
$\rho_\Lambda = \mathrm{const}$
-9
-6
-3
0
log(a)
redshift z
time t
$a_0 = 1$
By convention

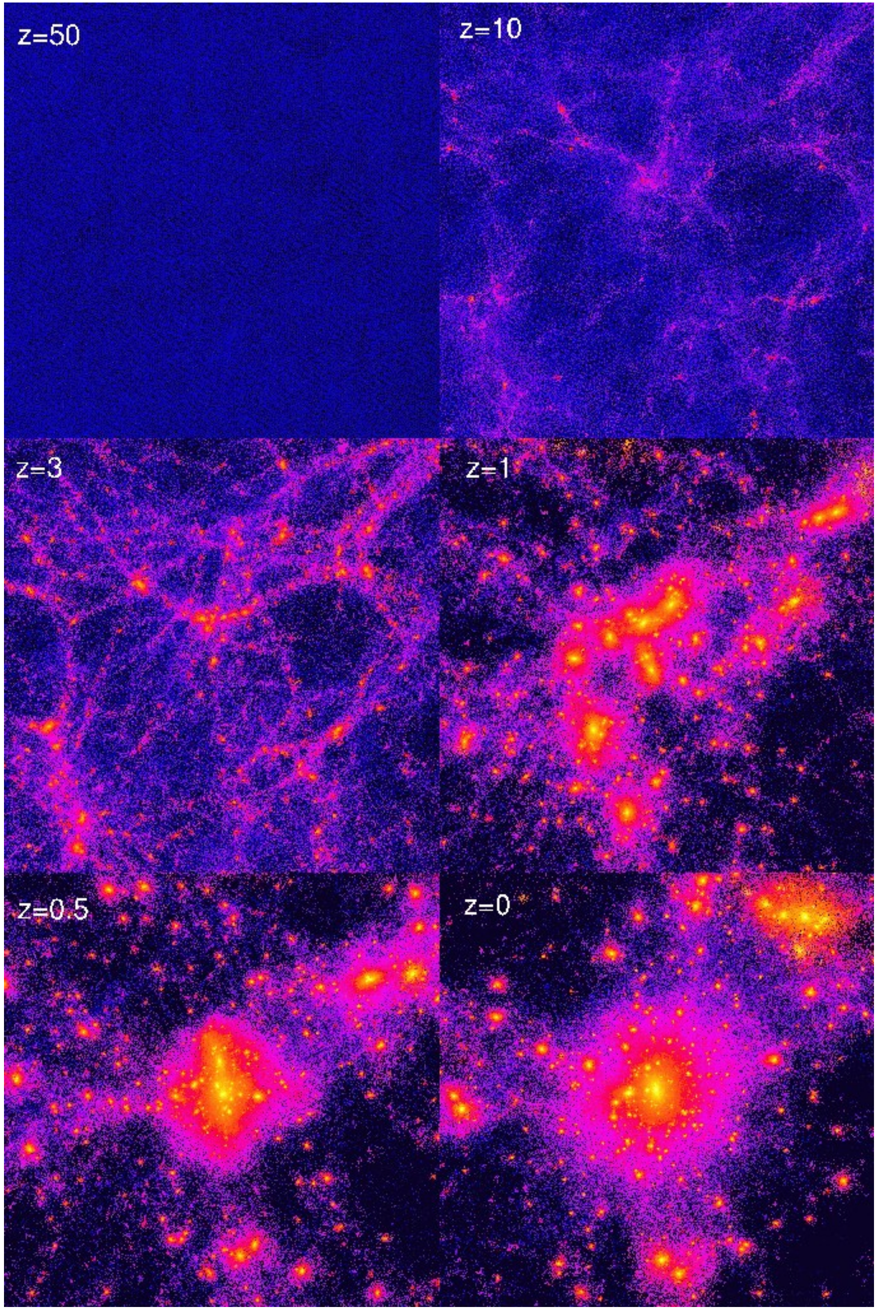
1. Neutrinos and structure formation...

How structures form...

- The early universe is filled with an almost homogeneous matter density field with tiny **random fluctuations**:

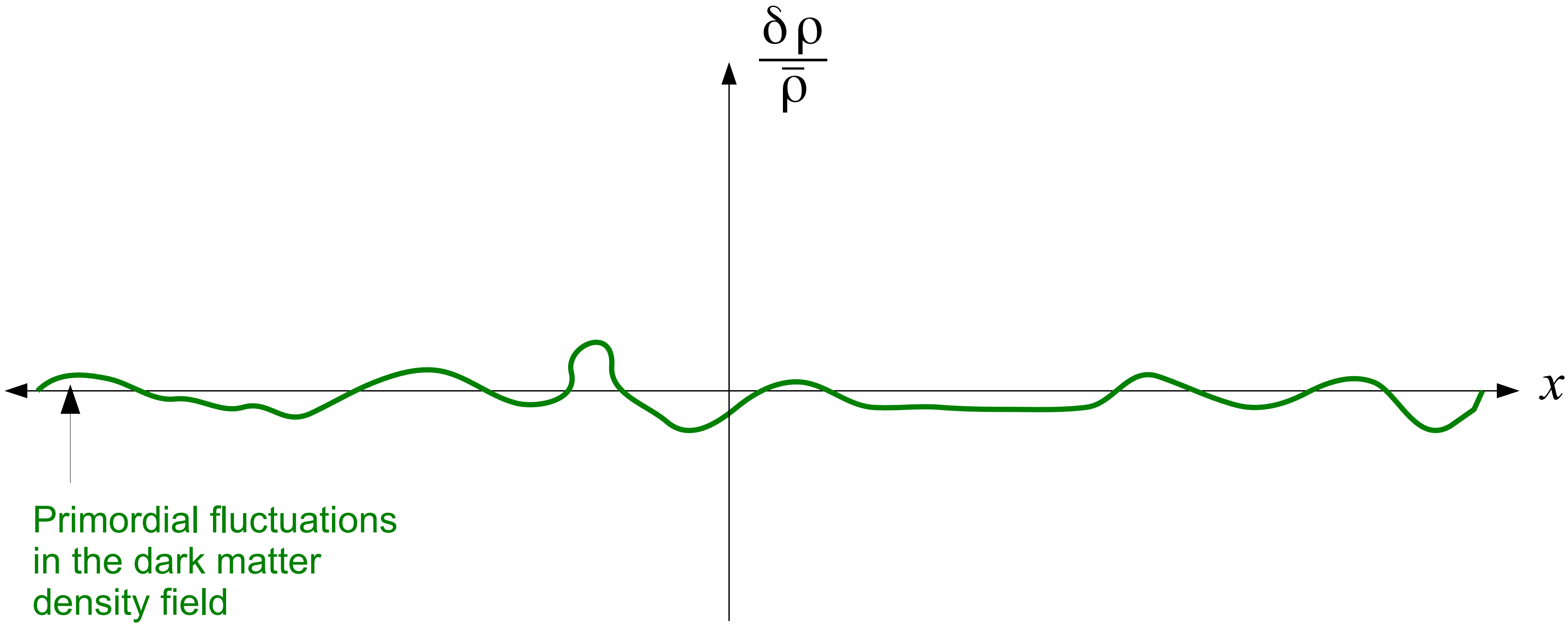
$$\delta \equiv \frac{\delta \rho}{\bar{\rho}}$$

- Perturbations “grow” via **gravitational instability**, and eventually form galaxies and galaxy clusters, etc.
- Leading theory for the origin of small fluctuations is inflation. (Quantum fluctuations on the inflaton field.)

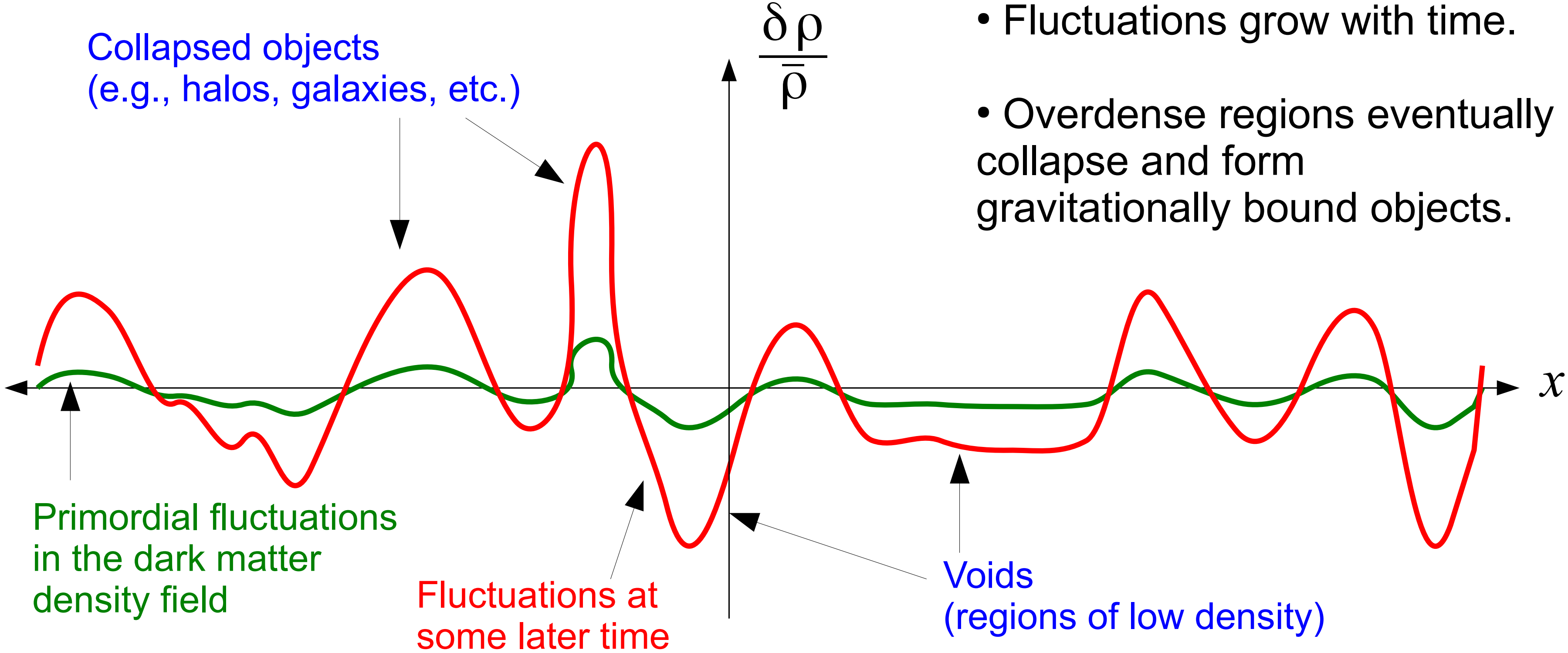


How structures form...

• Primordial fluctuations seeded by, e.g., inflation.



How structures form...



- Initial fluctuations seeded by, e.g., inflation.
- Fluctuations grow with time.
- Overdense regions eventually collapse and form gravitationally bound objects.

Neutrino dark matter...

- Standard hot big bang predicts a relic neutrino background:
  - **Temperature**:

$$T_{\nu,0} = \left(\frac{4}{11}\right)^{1/3} T_{\mathrm{CMB},0} = 1.95\,\mathrm{K}$$

  - **Number density** (per flavour):

$$n_{\nu,0} = \frac{6}{4}\frac{\zeta(3)}{\pi^2} T^3_{\nu,0} = 112\ \mathrm{cm}^{-3}$$

  - **Energy density** (per flavour):

If the relic neutrinos are nonrelativistic today (i.e., $m_\nu > 0.1\ \mathrm{meV}$)

$$\Omega_{\nu,0} = \frac{m_\nu}{94\,h^2\,\mathrm{eV}}$$

Observations indicate

$$\Omega_{\mathrm{DM}} \sim 0.25$$

Can it be explained by neutrino dark matter?

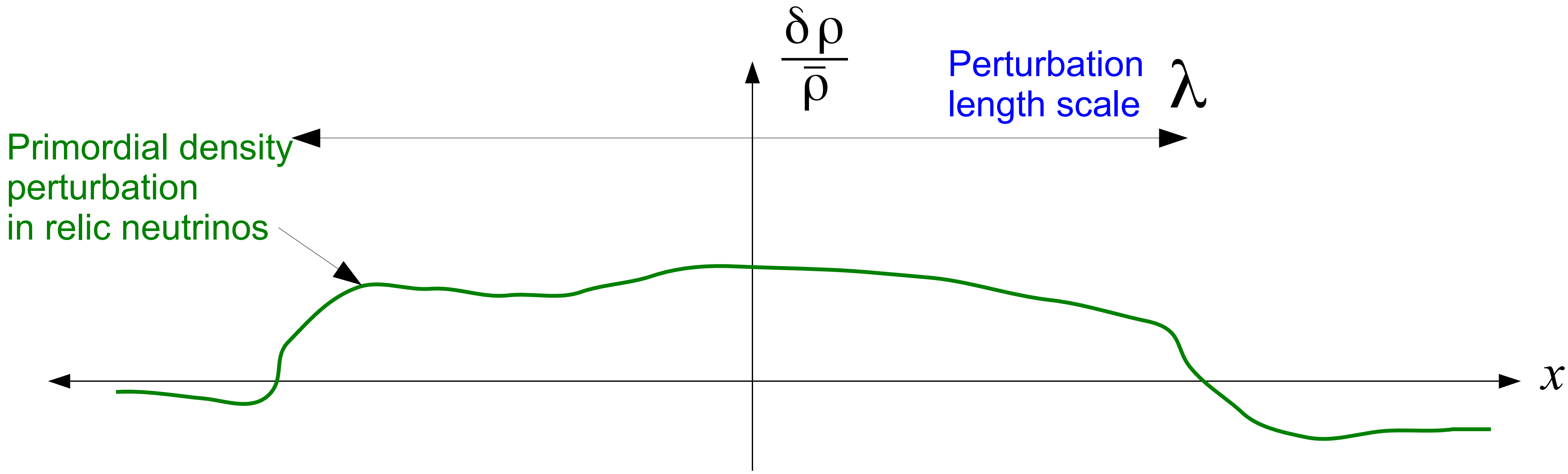
Neutrino dark matter...

- **Answer**: No
- **Reason**:
  - The obvious one: a neutrino mass of ~ 10 eV is needed (not allowed by current tritium β-decay experiments).
  - The deeper one: relic neutrinos come with large thermal motion, with a characteristic **thermal speed**

$$v_{\text{thermal}} = \frac{T_\nu}{m_\nu} \simeq 50.4(1+z)\left(\frac{\text{eV}}{m_\nu}\right) \text{ km s}^{-1}$$

→ Thermal motion counters the effect of gravitational instability.
→ Neutrino gas **does not collapse** because neutrinos fly away!

Suppose relic neutrinos make up **all** of the dark matter...



- **Collapse time scale**:

$$\Delta t_{\text{collapse}} \equiv \left(4\pi G \bar{\rho} a\right)^{-1/2}$$

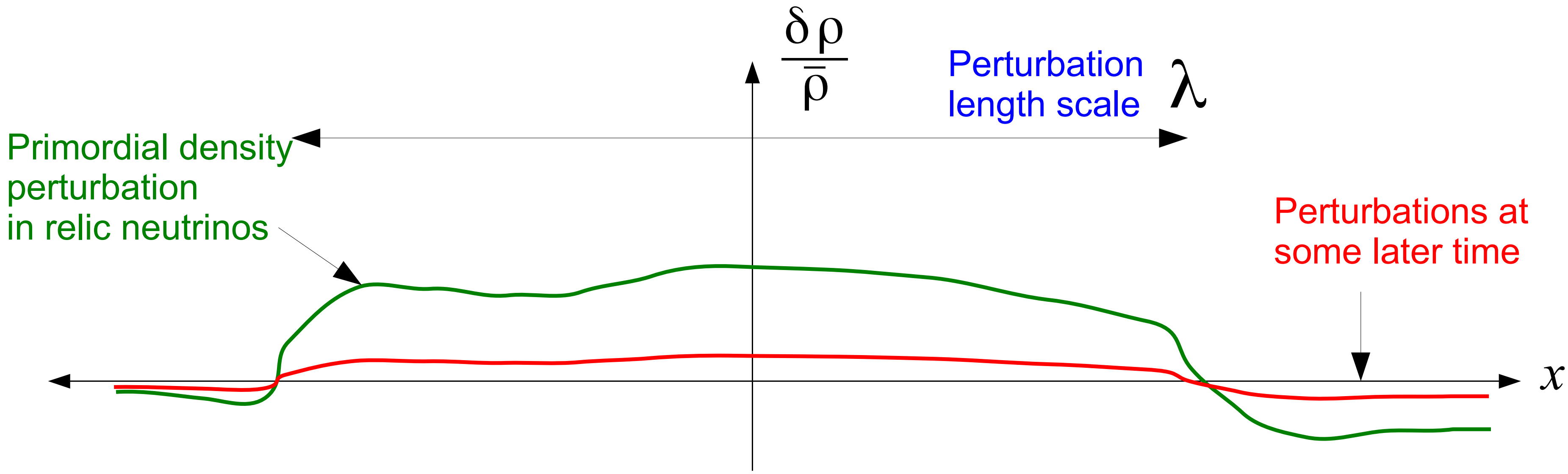
How long does it take for the overdense region to collapse to a point

Escape time scale:

$$\Delta t_{\text{escape}} \equiv \frac{\lambda}{v_{\text{thermal}}}$$

How long does it take for the neutrinos to fly out of the region

Suppose relic neutrinos make up **all** of the dark matter...



- **Collapse time scale**:

$$\Delta t_{\text{collapse}} \equiv (4\pi G \bar{\rho} a)^{-1/2}$$

Escape time scale:

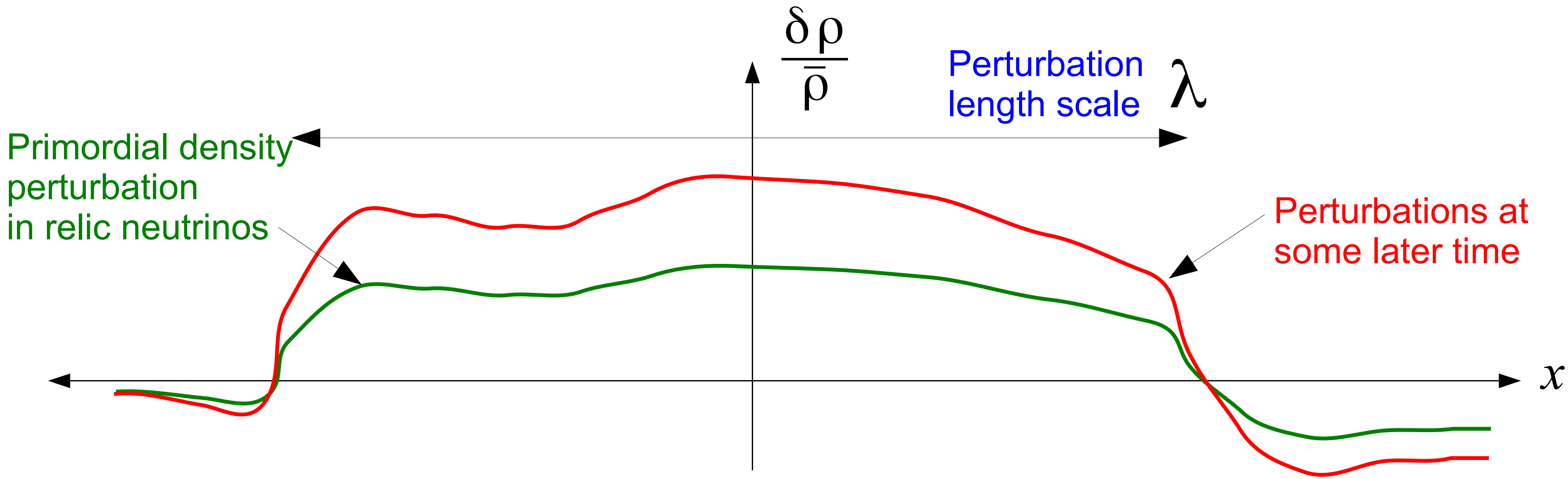
$$\Delta t_{\text{escape}} \equiv \frac{\lambda}{v_{\text{thermal}}}$$

Limit 1: Erasure
Collapse happens **slower** than escape

$$\Delta t_{\text{collapse}} \gg \Delta t_{\text{escape}}$$

→ Neutrinos fly away before gravity can capture them.
→ Perturbation is erased.

Suppose relic neutrinos make up **all** of the dark matter...



- **Collapse time scale**:

$$\Delta t_{\text{collapse}} \equiv (4\pi G \bar{\rho} a)^{-1/2}$$

Escape time scale:

$$\Delta t_{\text{escape}} \equiv \frac{\lambda}{v_{\text{thermal}}}$$

Limit 2: Growth
Collapse happens **faster** than escape

$$\Delta t_{\text{collapse}} \ll \Delta t_{\text{escape}}$$

→ Density perturbation collapses before neutrinos can fly away.
→ Perturbation grows.

Suppose relic neutrinos make up **all** of the dark matter...

- **Growth or erasure**? Define the free-streaming scale at redshift z:

$$\boxed{\begin{aligned}\lambda_{\mathrm{FS}}(z) &\equiv v_{\mathrm{thermal}}\,\Delta t_{\mathrm{collapse}}\\ &= 0.41\,\Omega_{m,0}^{-1/2}(1+z)^{1/2}\left(\frac{\mathrm{eV}}{m_\nu}\right)h^{-1}\,\mathrm{Mpc}\end{aligned}}$$

Equivalent to

$$\Delta t_{\mathrm{collapse}} = \Delta t_{\mathrm{escape}}$$

$\rightarrow$ Unless density perturbations are regenerated by other means, at any redshift z, structures of length scale $\lambda < \lambda_{\mathrm{FS}}(z)$ **cannot be formed** out of relic neutrinos.

Suppose relic neutrinos make up **all** of the dark matter...

- The maximum free-streaming scale is that at the time when neutrinos become nonrelativistic:

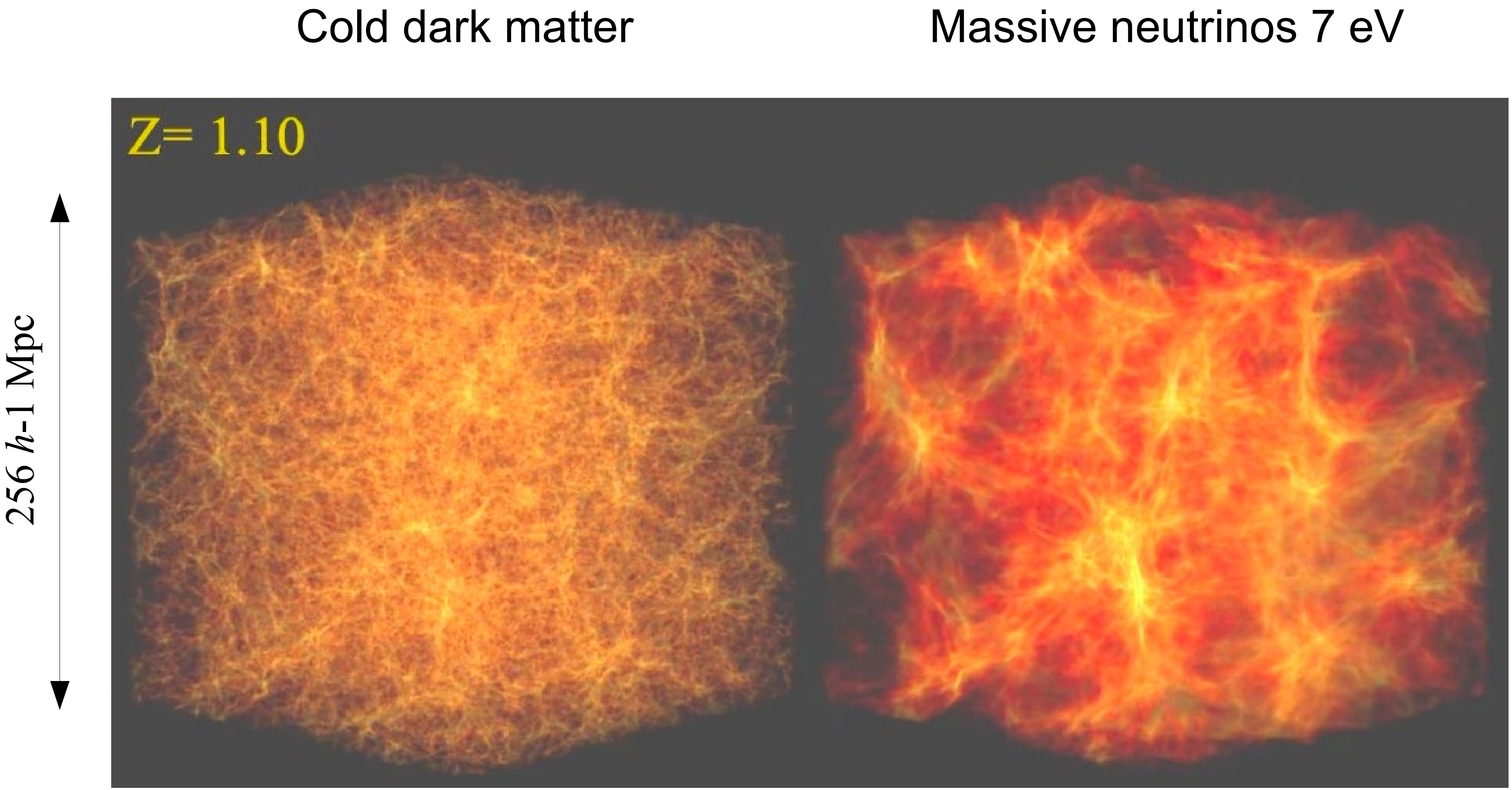
$$\boxed{\lambda_{\mathrm{FS,max}} \equiv \lambda_{\mathrm{FS}}(z_{\mathrm{nr}}) = 31.8\, \Omega_{m,0}^{-1/2} \left(\frac{\mathrm{eV}}{m_\nu} \right)^{1/2} h^{-1}\, \mathrm{Mpc}}$$

Using

$$1 + z_{\mathrm{nr}} \simeq \frac{m_\nu}{T_{\nu,0}}$$

$\rightarrow$ $\lambda_{\mathrm{FS,max}}$ corresponds to the maximum size of objects that **could not have been formed** in a neutrino dark matter-only universe.

$\rightarrow$ If a 10 eV-mass neutrino was the dark matter, $\lambda_{\mathrm{FS,max}} \sim 25$ Mpc, we would not have galaxies ($\lambda \sim 10$ kpc) and galaxies clusters ($\lambda \sim 1$ Mpc)!



Simulations by Troels Haugbølle

Why study neutrino dark matter then?

- **Because it must be there.**

- Neutrino oscillations indicate that at least one neutrino mass eigenstate has a **mass of > 0.05 eV**.

→ Predictions for cosmology:

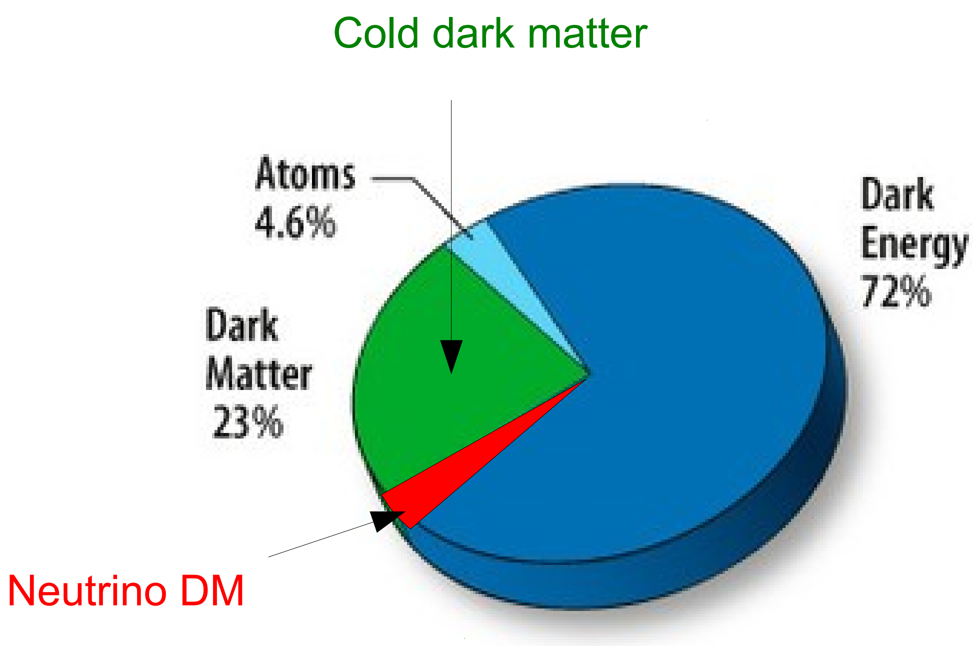
$$\Omega_\nu = \sum \frac{m_\nu}{94\, h^2 \mathrm{eV}} > 0.1\%$$

→ Although only a subdominant DM component, the free-streaming behaviour of neutrino DM still leaves an **imprint** on large-scale structures.

→ Can be used to establish Ω_ν and hence the neutrino mass.

The concordance framework...

- We work within the **ΛCDM framework** extended with a subdominant component of massive neutrino dark matter.
  - Flat geometry.
  - Initial conditions from standard single-field slow-roll inflation.



2. Signatures of subdominant neutrino DM and neutrino mass constraints...

Subdominant neutrino DM and large-scale structure...

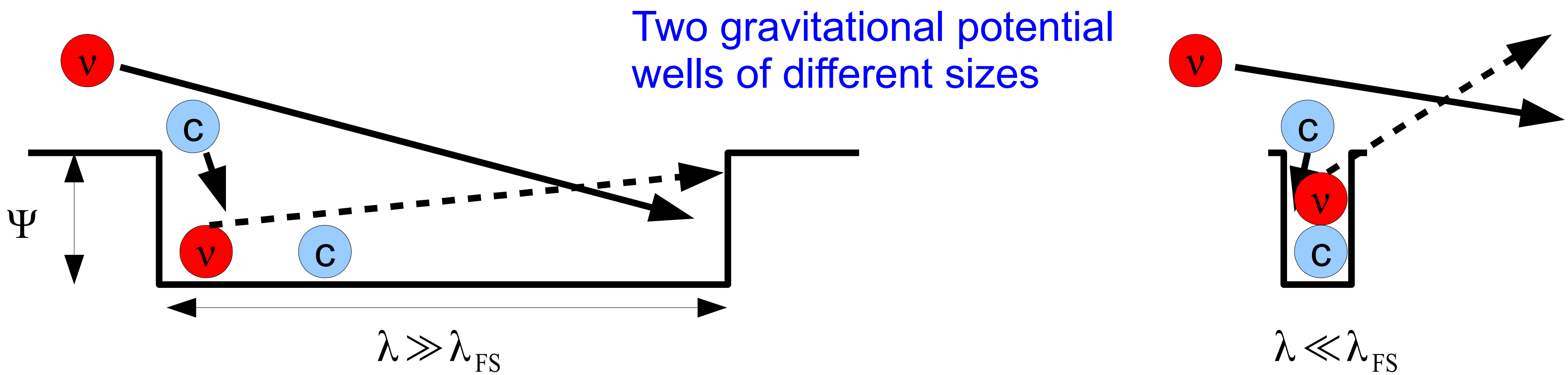
- The presence of CDM acts as a source of density perturbations.

  → Density perturbations on length scales smaller than the neutrino free-streaming scale λ_{FS} are **not completely erased**.

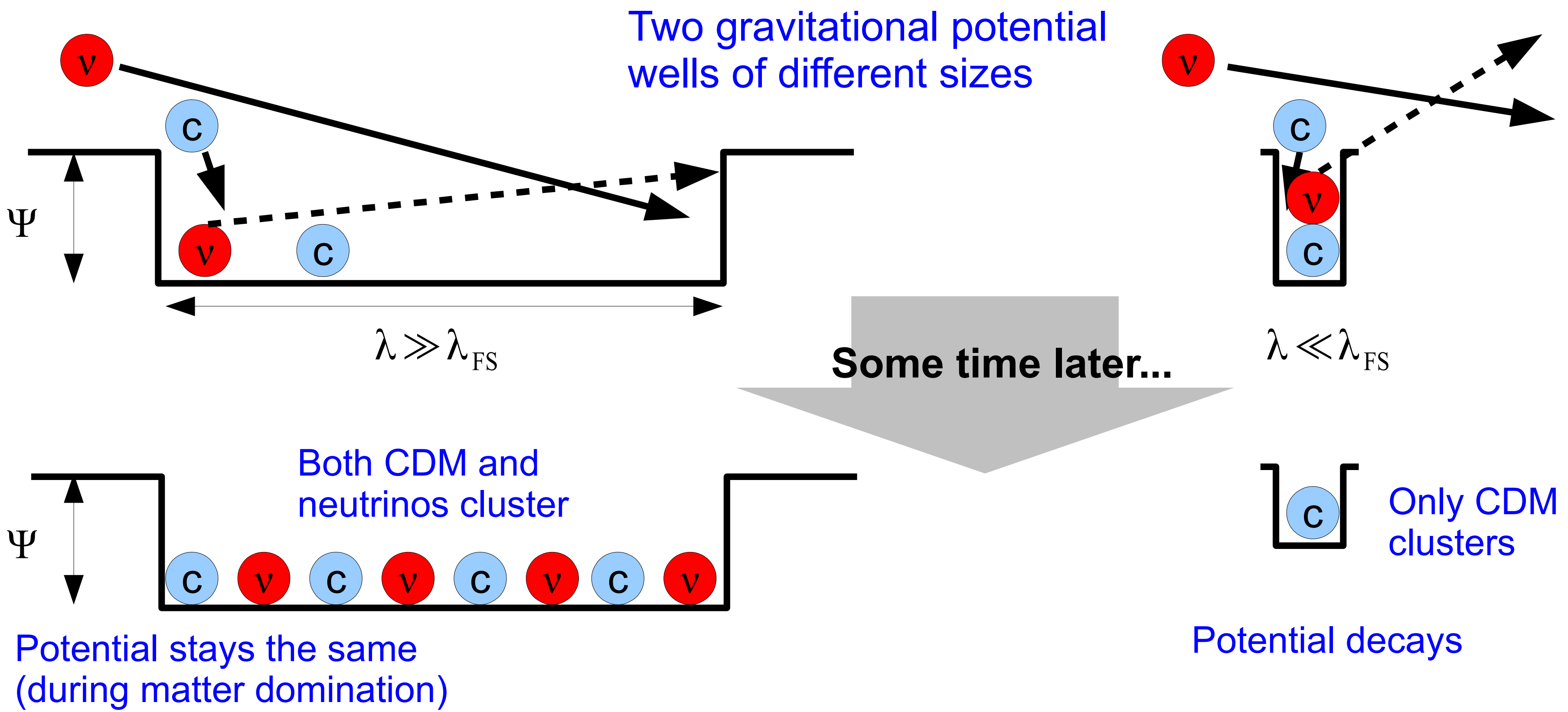
- However, thermal motion of the relic neutrinos still makes neutrino clustering difficult.

  → Expect a suppression in the abundance of structures on scales below λ_{FS} through free-streaming-induced potential decay.

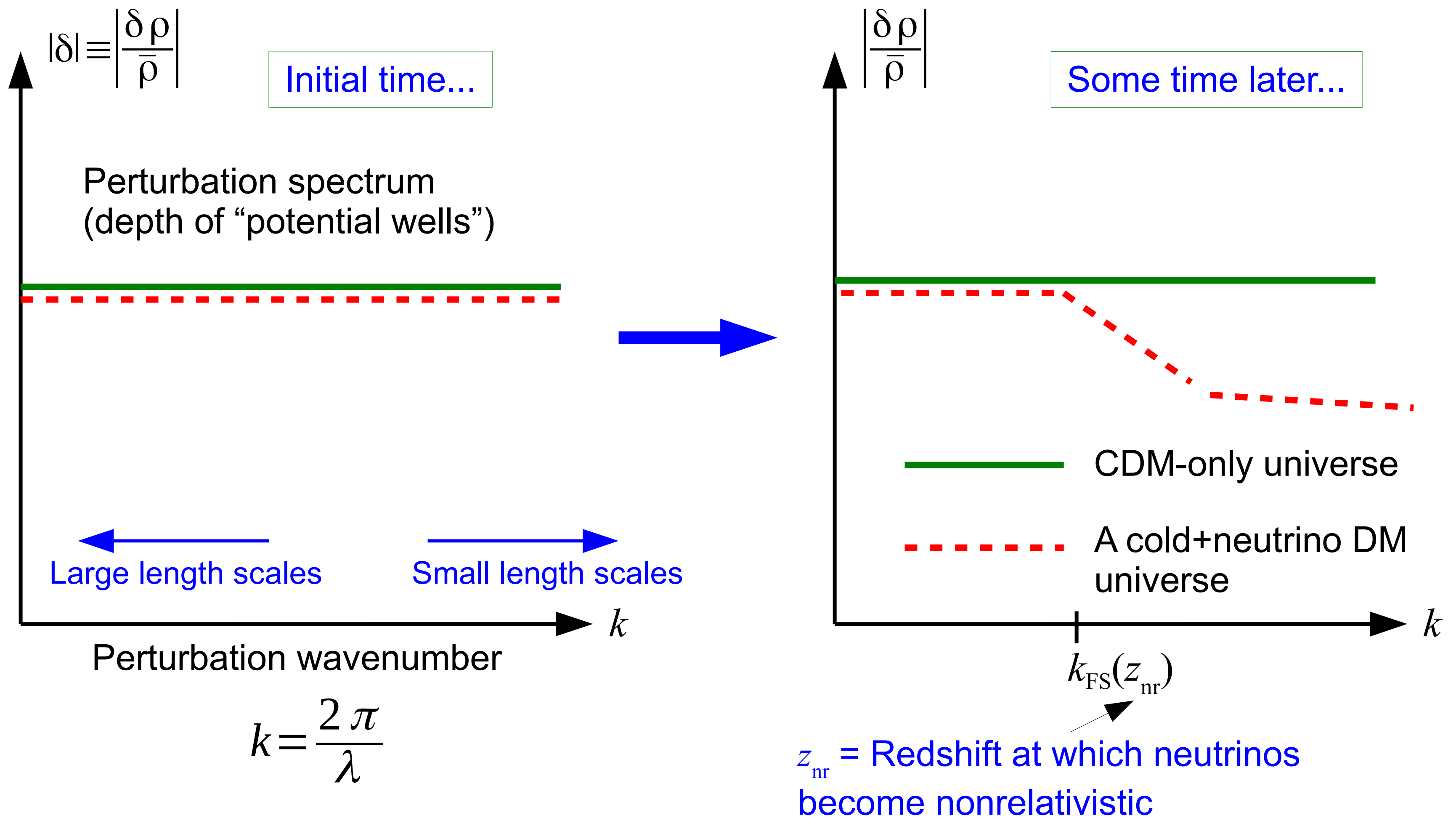
Free-streaming-induced potential decay...



Free-streaming-induced potential decay...

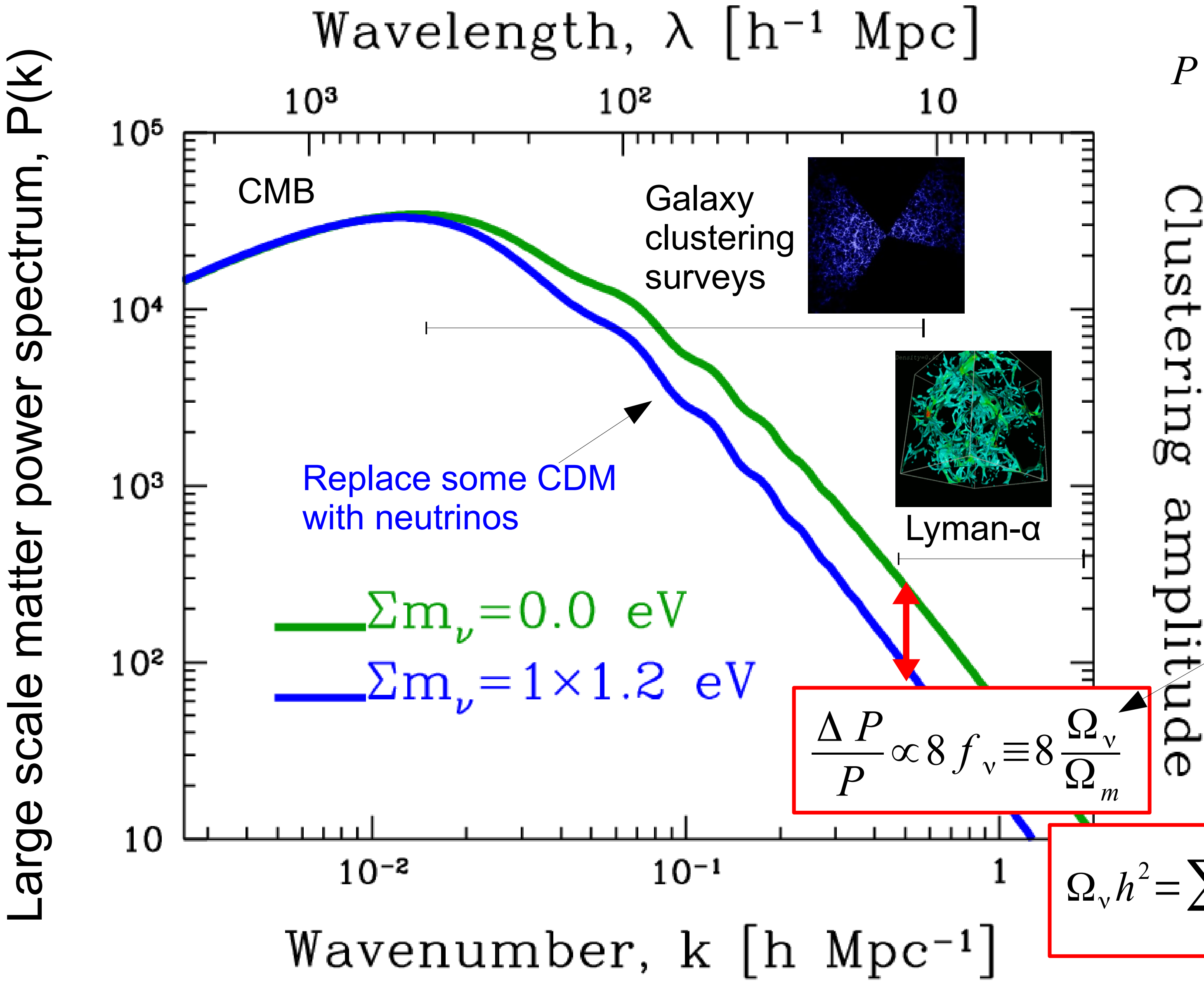


→ **Cosmological neutrino mass measurement** is based on observing this free-streaming induced potential decay at $\lambda << \lambda_{FS}$.



The presence of neutrino dark matter induces a step-like feature in the **spectrum** of gravitational potential wells

$$P(k) = \langle |\delta(k)|^2 \rangle$$

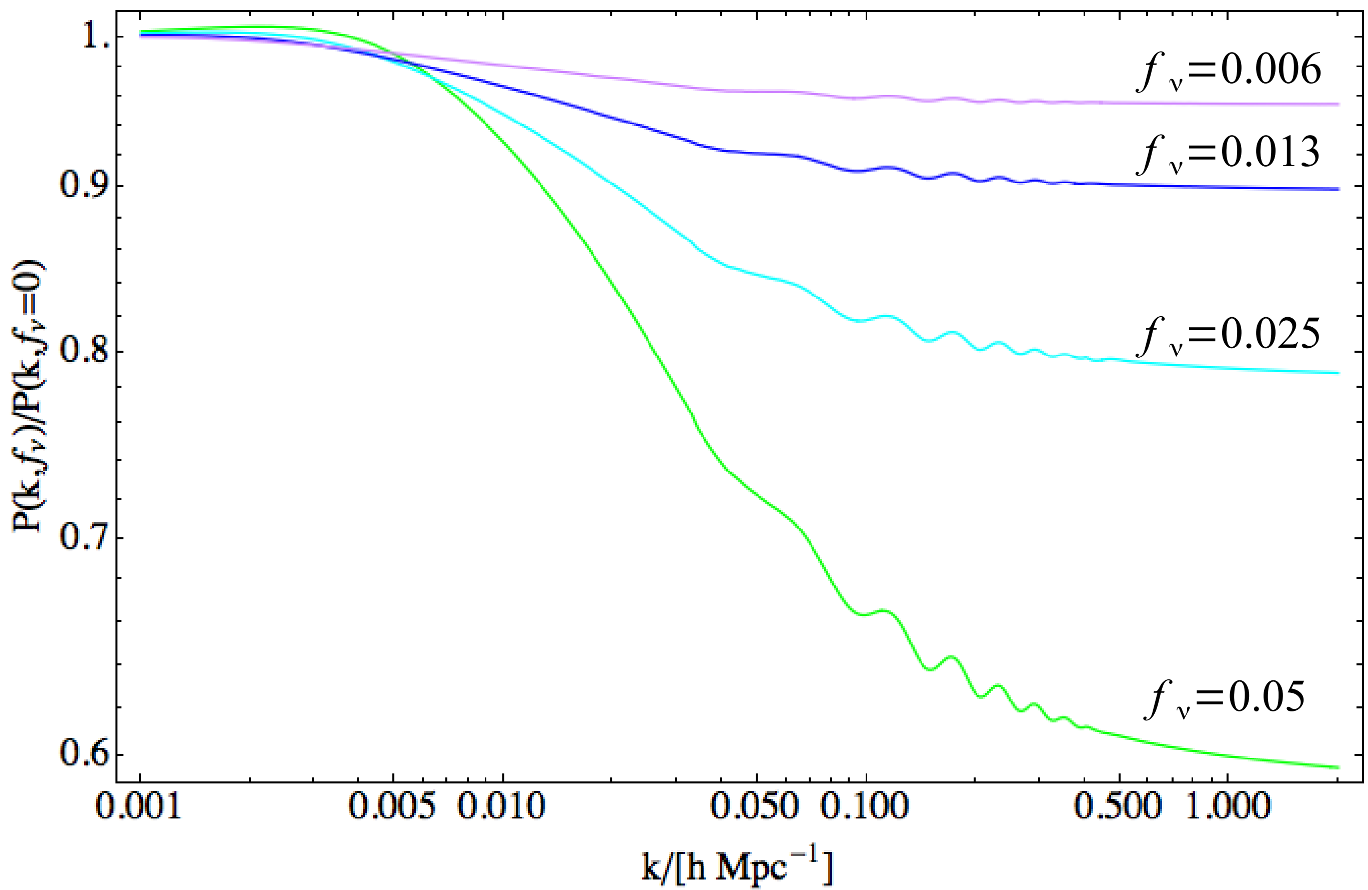


f_ν = Neutrino fraction

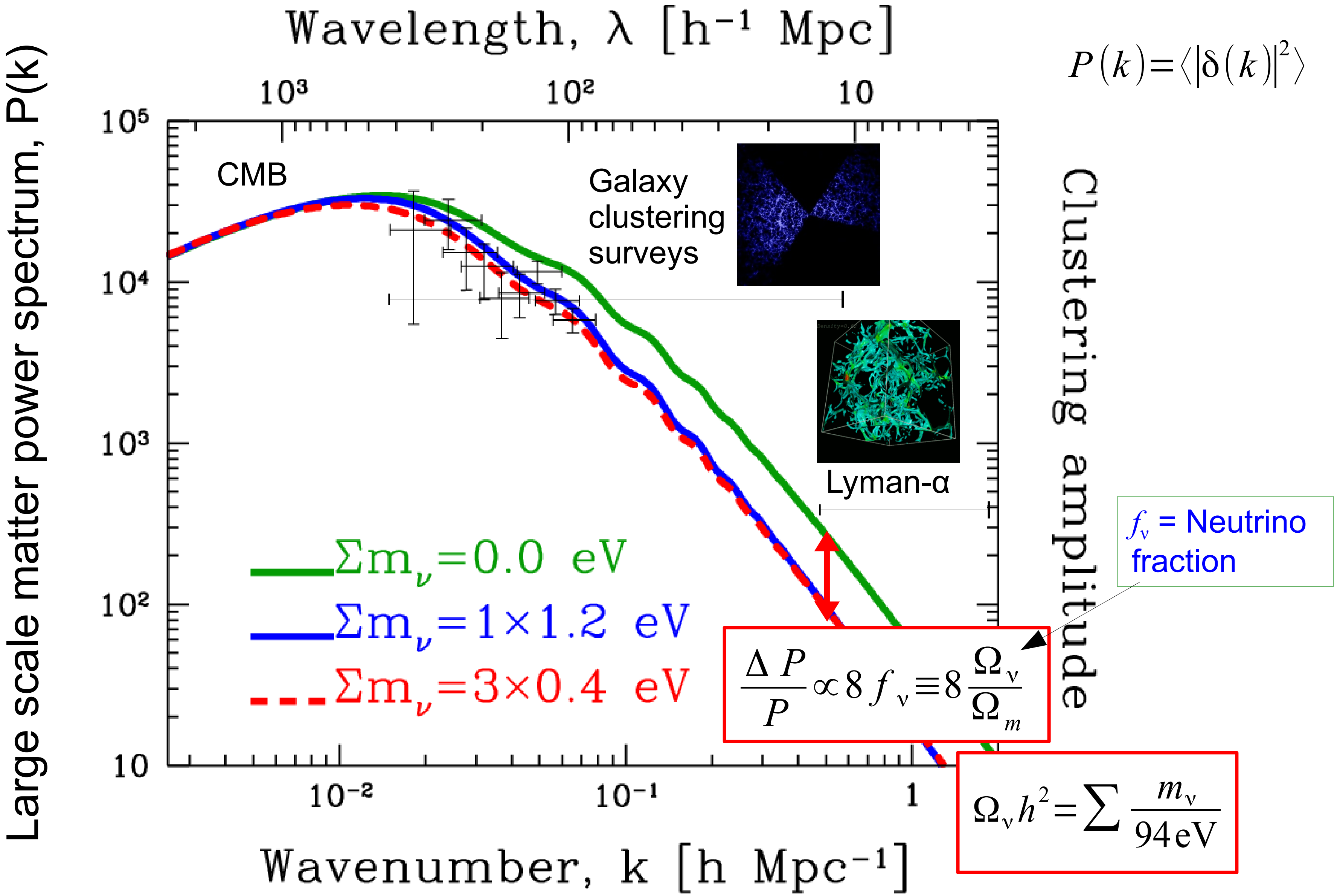
$$\boxed{\frac{\Delta P}{P} \propto 8 f_\nu \equiv 8 \frac{\Omega_\nu}{\Omega_m}}$$

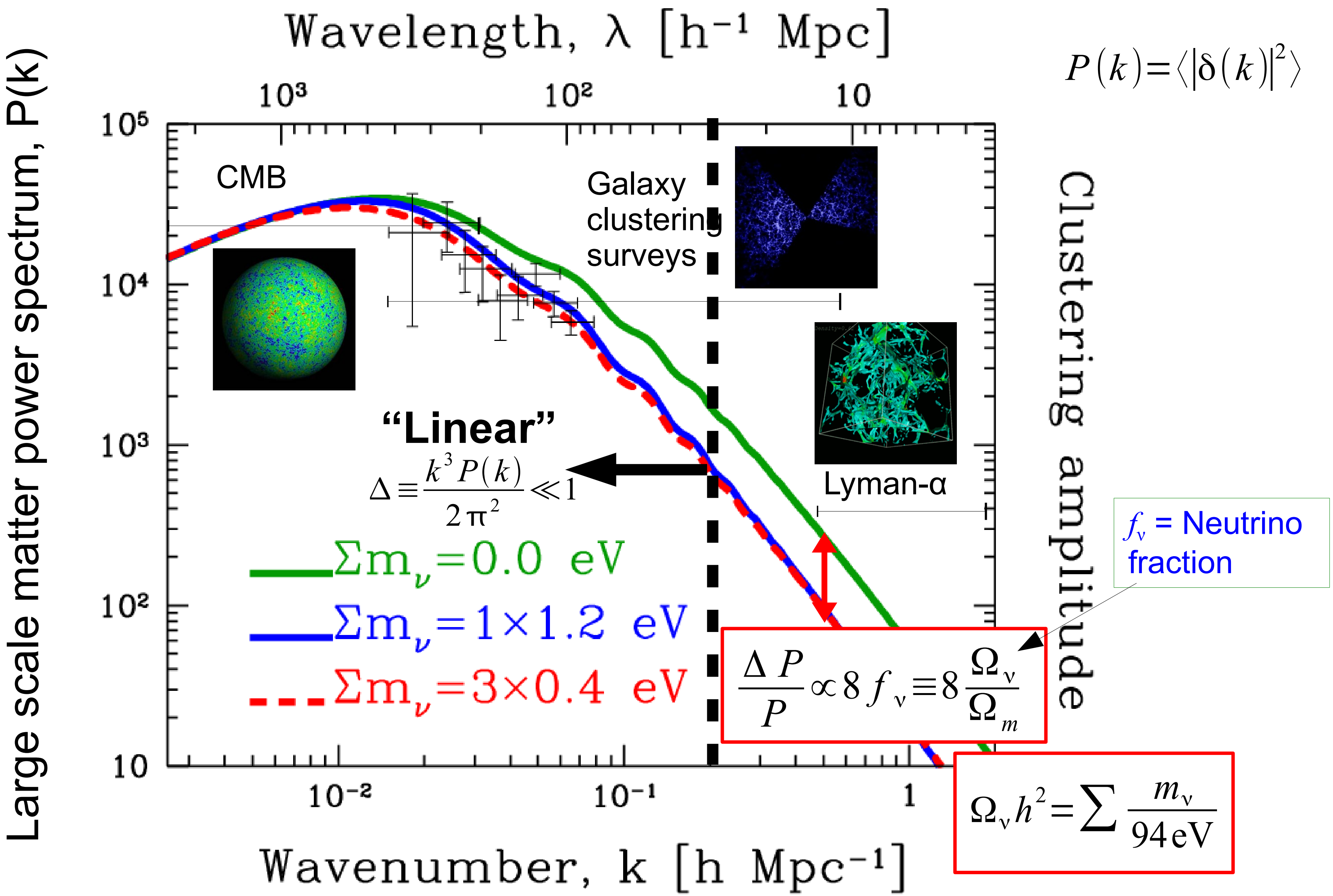
$$\boxed{\Omega_\nu h^2 = \sum \frac{m_\nu}{94\,\mathrm{eV}}}$$

Power spectra normalised
to $f_\nu = 0$ power spectrum



$$P(k) = \langle |\delta(k)|^2 \rangle$$

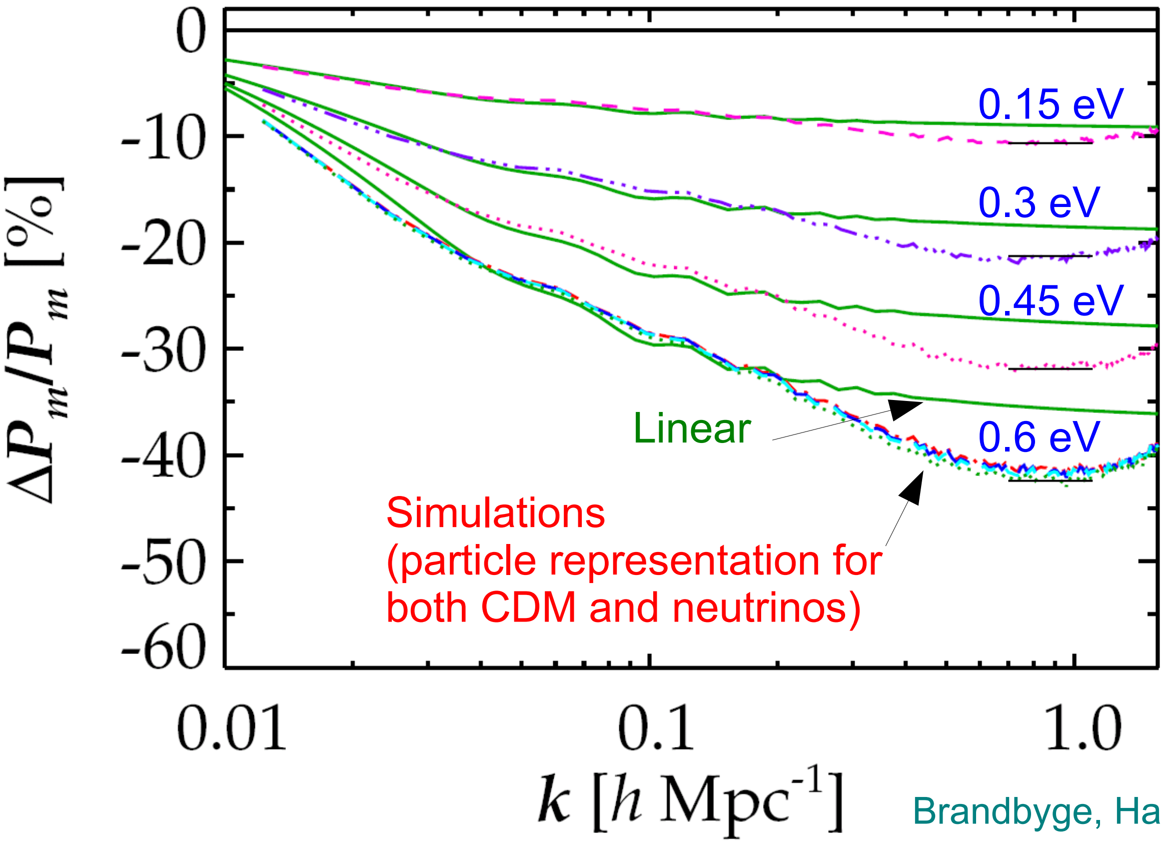




Wavelength, λ [h⁻¹ Mpc]
$P(k)=\langle|\delta(k)|^2\rangle$
10³
10²
10
10⁵
10⁴
10³
10²
10
CMB
Galaxy clustering surveys
Lyman-α
Large scale matter power spectrum, P(k)
Clustering amplitude
"Linear"
$\Delta\equiv\frac{k^3P(k)}{2\pi^2}\ll 1$
$\Sigma m_\nu=0.0$ eV
$\Sigma m_\nu=1\times1.2$ eV
$\Sigma m_\nu=3\times0.4$ eV
f_ν = Neutrino fraction
$\frac{\Delta P}{P}\propto 8f_\nu\equiv 8\frac{\Omega_\nu}{\Omega_m}$
$\Omega_\nu h^2=\sum\frac{m_\nu}{94\,\mathrm{eV}}$
10⁻²
10⁻¹
1
Wavenumber, k [h Mpc⁻¹]

Change in the total matter power spectrum relative to the massless case:

$$\frac{\Delta P_m}{P_m} \equiv \frac{P_{f_\nu \neq 0}(k) - P_{f_\nu = 0}(k)}{P_{f_\nu = 0}(k)}$$



Linear perturbation theory:

$$\frac{\Delta P_m}{P_m} \sim 8 \frac{\Omega_\nu}{\Omega_m}$$

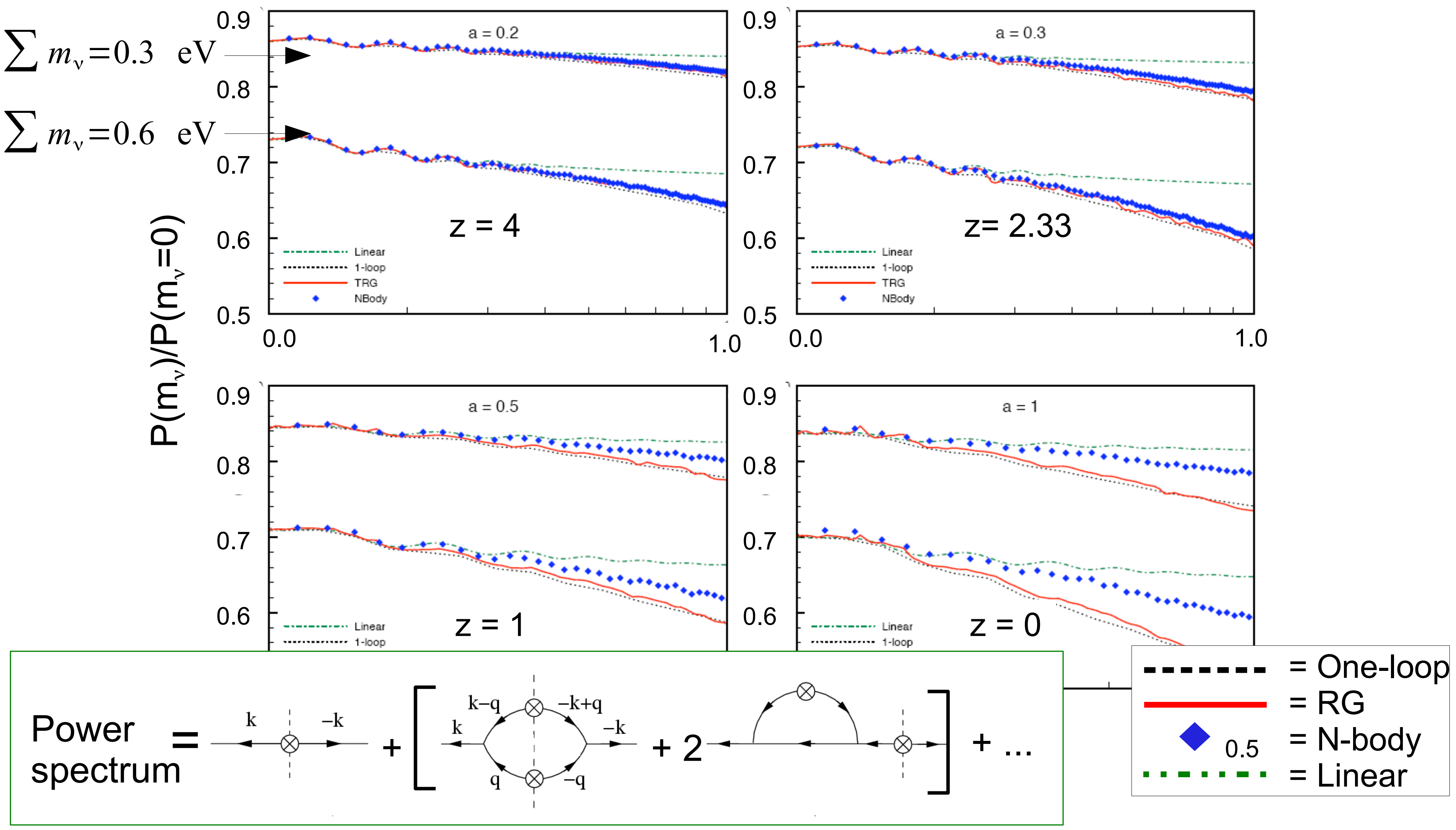
With nonlinear corrections:

$$\frac{\Delta P_m}{P_m} \sim \underline{9.8} \frac{\Omega_\nu}{\Omega_m}$$

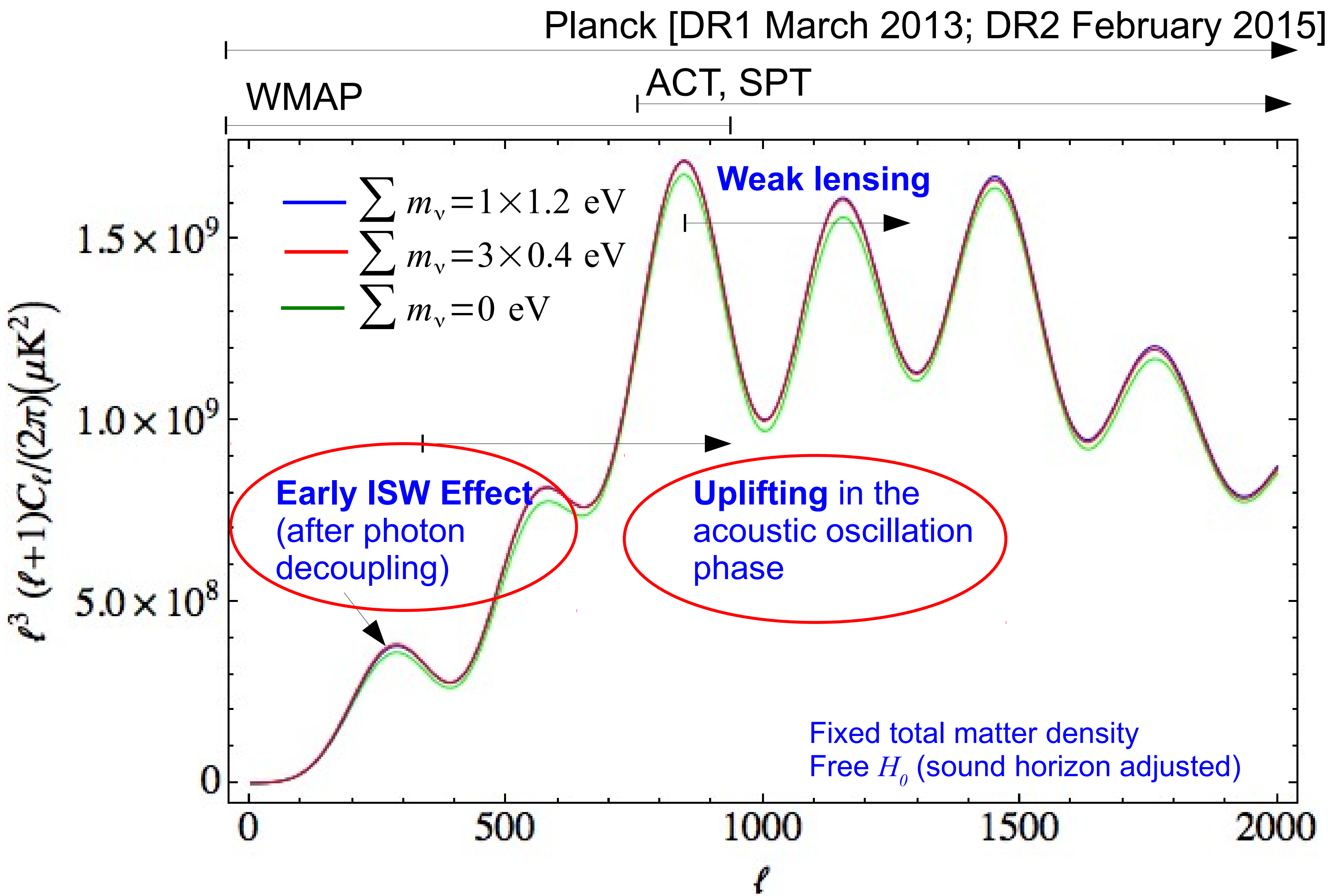
Brandbyge, Hannestad, Haugbolle & Thomsen 2008

Semi-analytical: Loops and beyond...

Saito et al. 2008; Y[3]W 2008; Shoji & Komatsu 2009
Lesgourgues, Matarrese, Pietroni & Riotto 2009



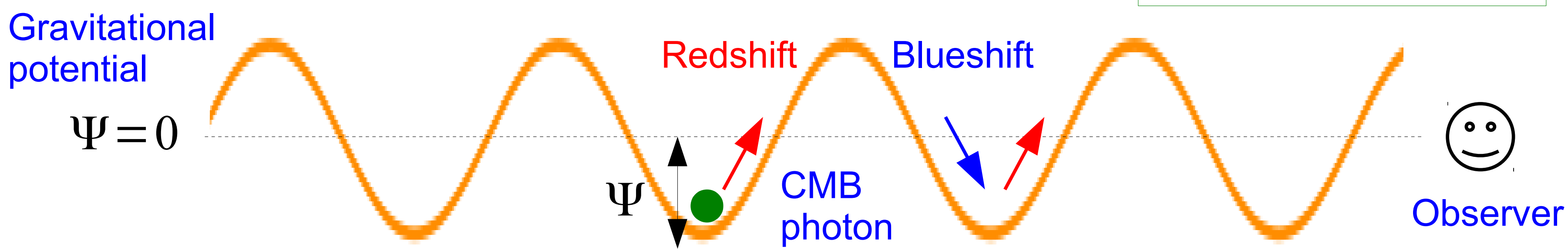
The CMB contains information on m_ν too...



Sachs-Wolfe effect:

Observed CMB temperature fluctuation

$$\left.\frac{\Delta T}{T}\right|_{\text{observed}} = \left.\frac{\Delta T}{T}\right|_{\text{intrinsic}} + \Psi$$



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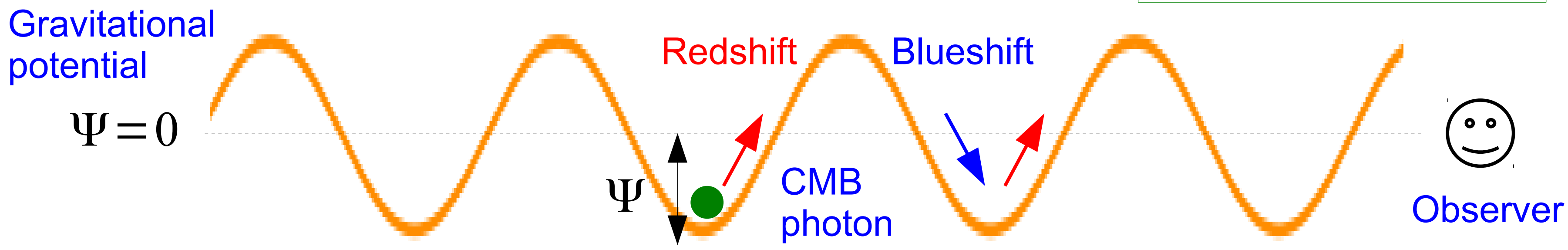
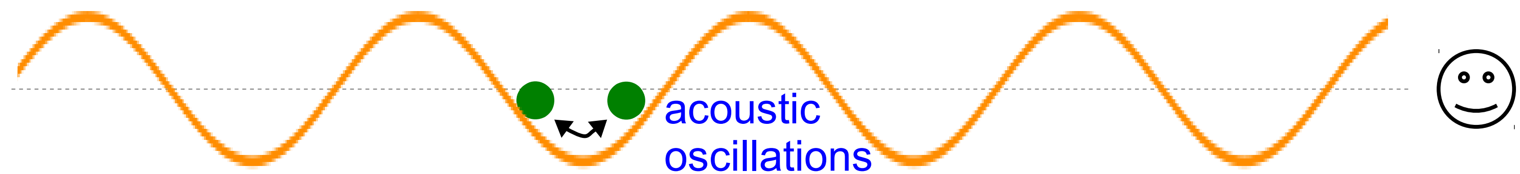


Uplifting (potential decay before γ decoupling): $\left.\frac{\Delta T}{T}\right|_{\text{intrinsic}} \uparrow \quad |\Psi| \downarrow \longrightarrow \left.\frac{\Delta T}{T}\right|_{\text{observed}} \uparrow$



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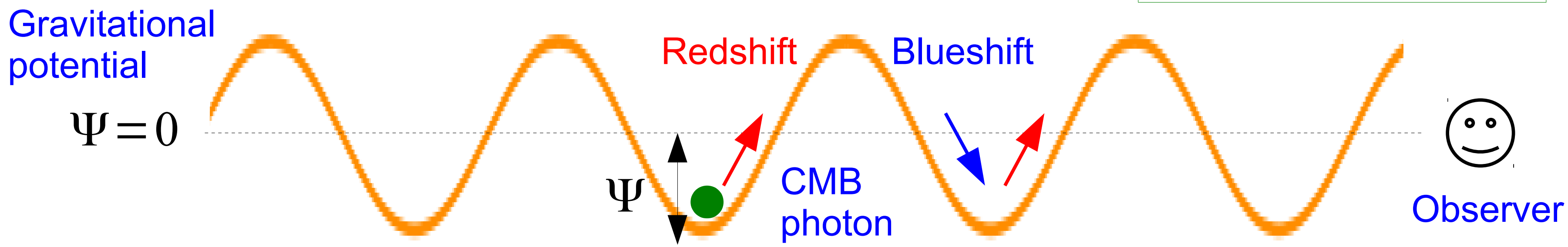
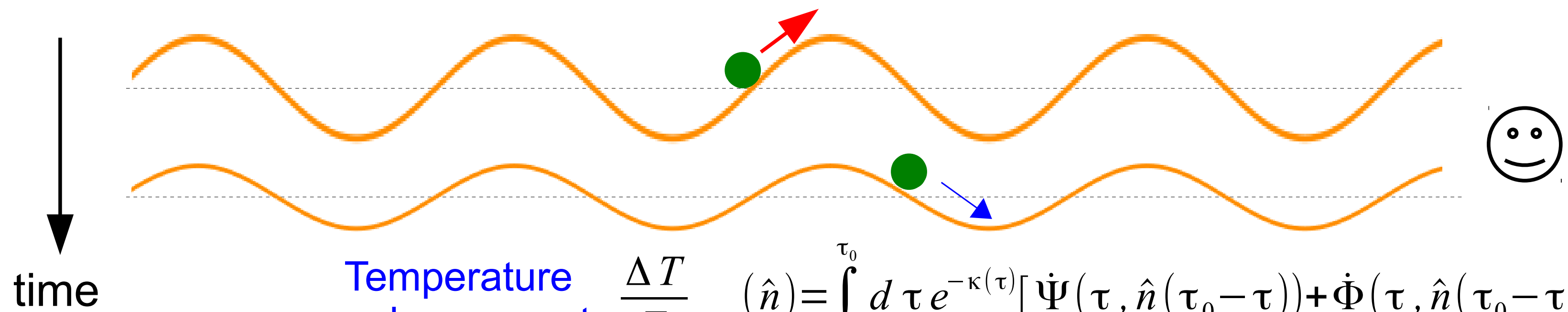


Uplifting (potential decay before γ decoupling): $\left.\frac{\Delta T}{T}\right|_{\text{intrinsic}} \uparrow \quad |\Psi| \downarrow \rightarrow \left.\frac{\Delta T}{T}\right|_{\text{observed}} \uparrow$

Integrated Sachs-Wolfe effect (potential decay after γ decoupling):



Temperature enhancement $\left.\frac{\Delta T}{T}\right|_{\text{ISW}}(\hat{n}) = \int_0^{\tau_0} d\tau\, e^{-\kappa(\tau)} [\dot{\Psi}(\tau, \hat{n}(\tau_0 - \tau)) + \dot{\Phi}(\tau, \hat{n}(\tau_0 - \tau))]$

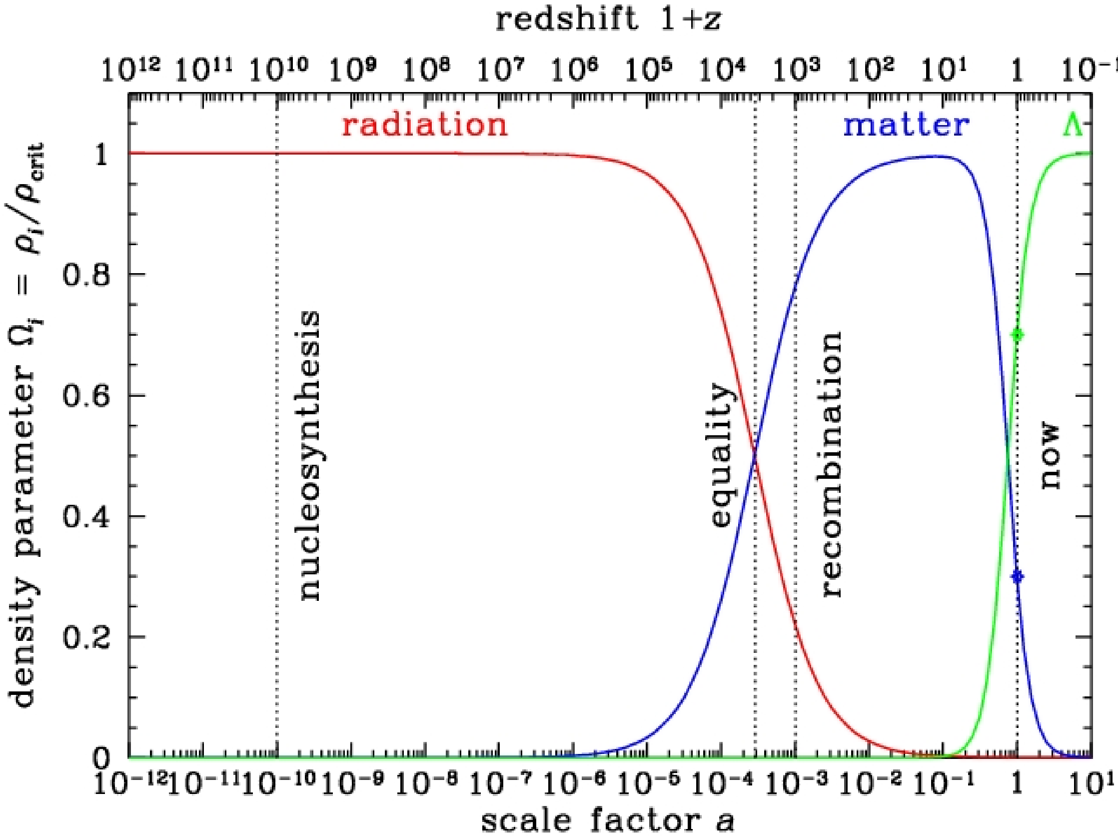
Potential decay happens anyway, even in ΛCDM, whenever the universe is not completely by nonrelativistic matter.

- It is good for probing neutrino masses because **O(0.1–1) eV-mass neutrinos** become nonrelativistic around recombination.

  → Changes the “matter” content, and hence the scale and time dependence of the potential decay.

O(0.1–1) eV mass neutrino

Relativistic → Nonrelativistic



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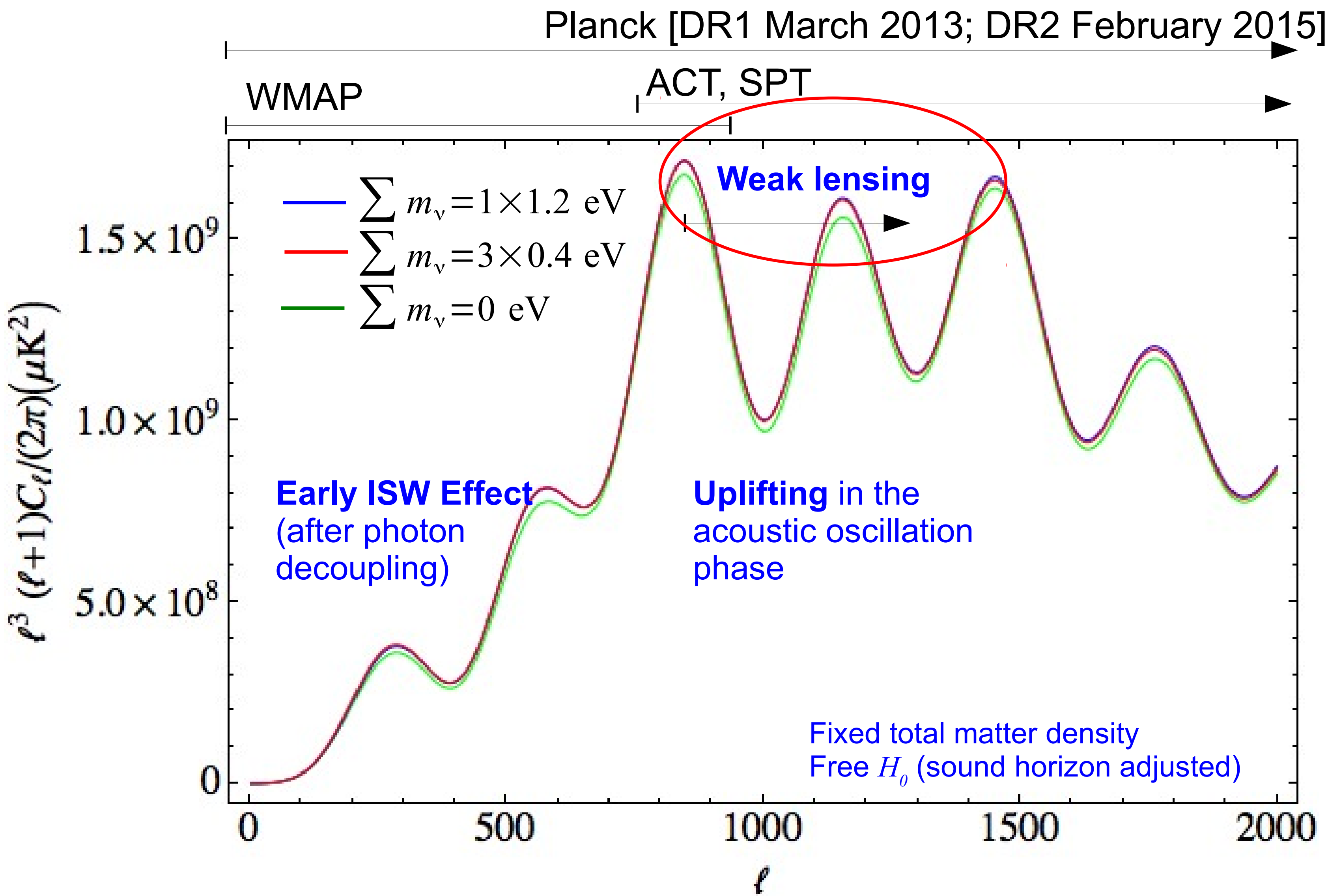
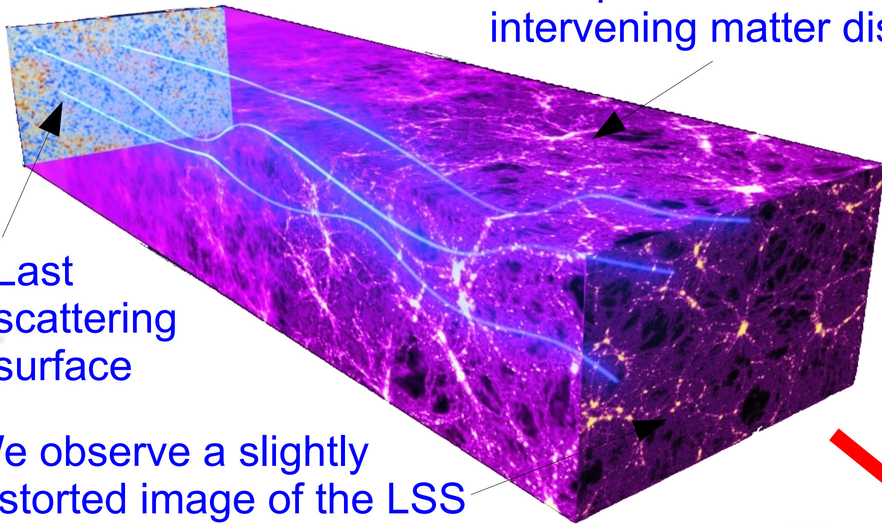


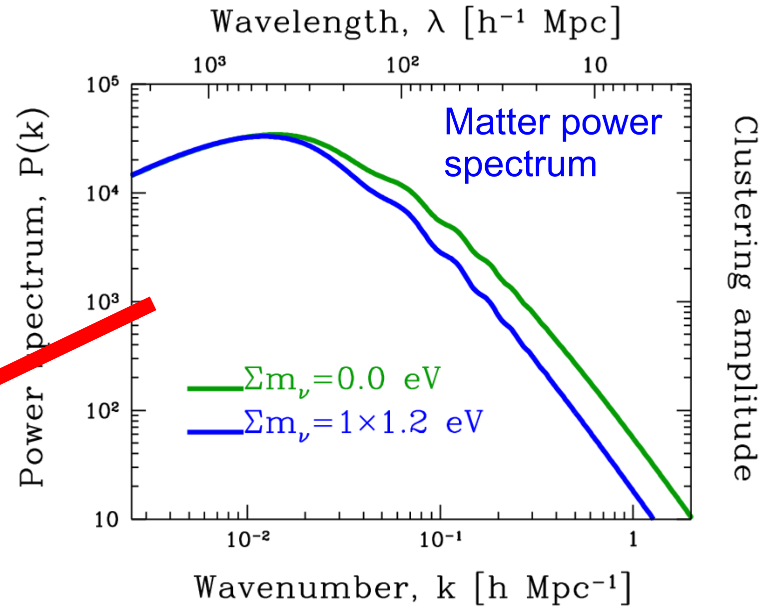
Weak gravitational lensing...

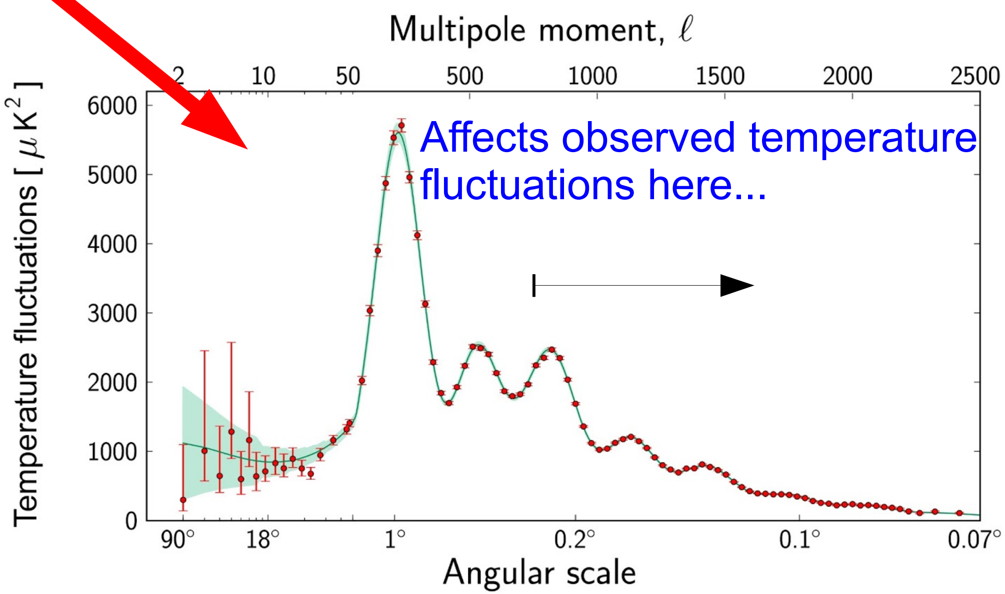
CMB photons **deflected** by intervening matter distribution



Last scattering surface

We observe a slightly distorted image of the LSS





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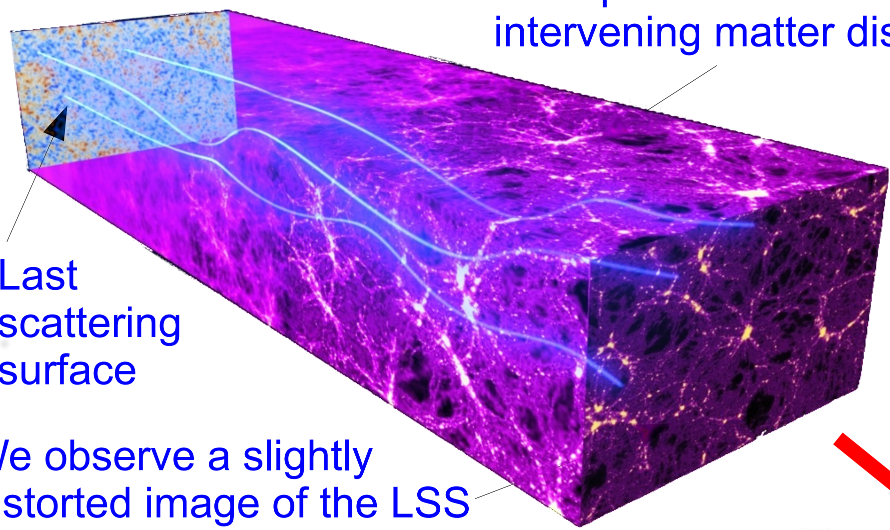

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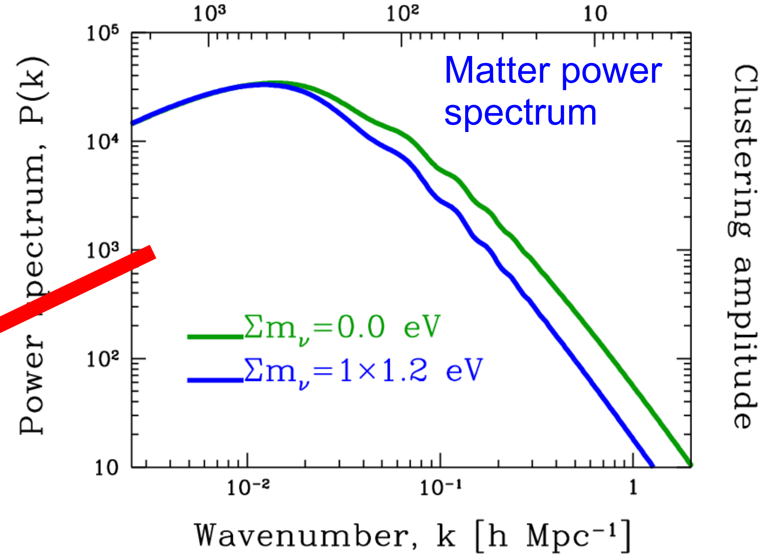
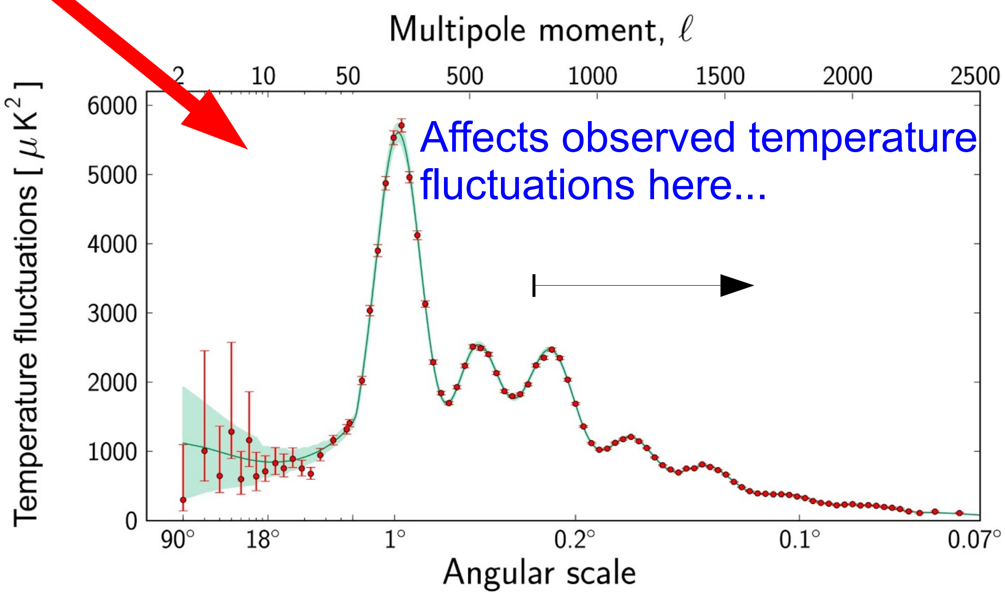




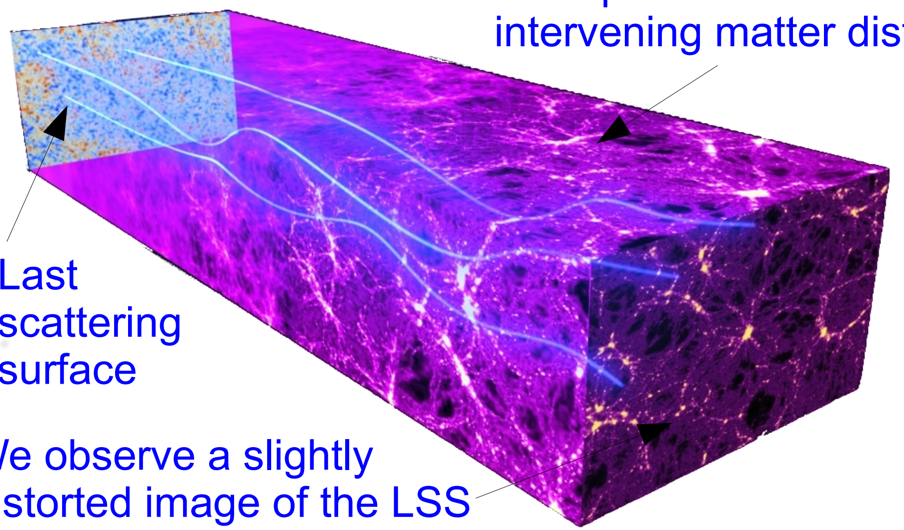
Planck TT+TE+EE+lowP

$$\sum m_\nu < 0.49 \text{ eV} \quad (95\% \text{C.L.})$$

... largely because of this lensed TT signal.

Ade et al. 1502.01589

Weak lensing: lensing potential power spectrum...



Can also try to **reconstruct the intervening matter distribution**.

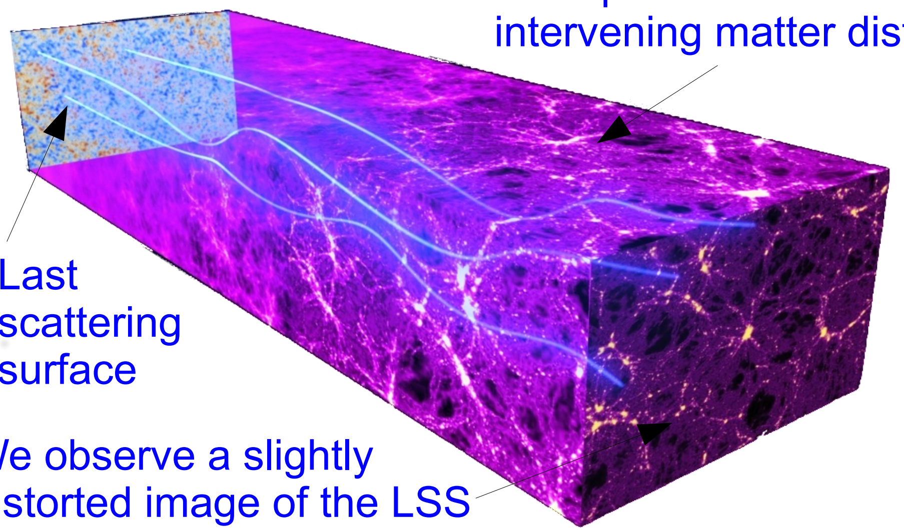
Use **4-point correlation** of observed map to infer the unlensed image.

→ Reconstruct deflection angle

→ Construct lensing potential map

Weak lensing: lensing potential power spectrum...

CMB photons **deflected** by intervening matter distribution



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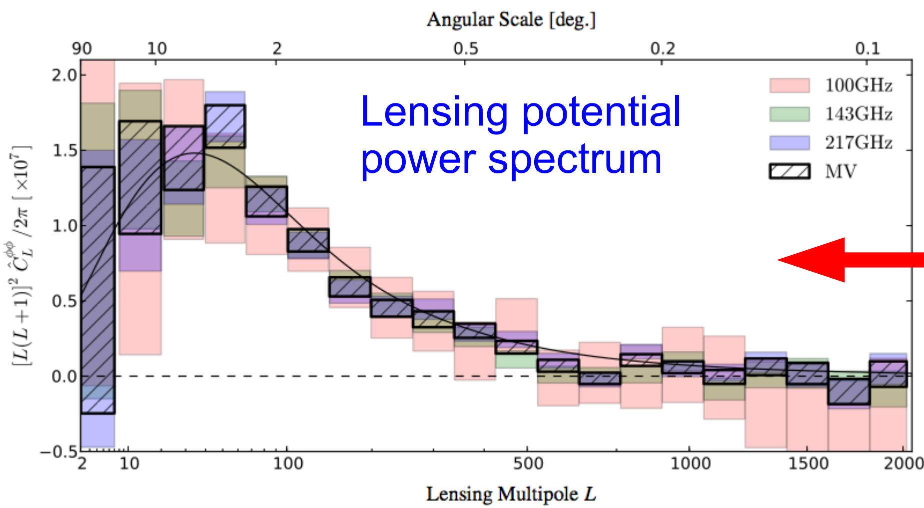

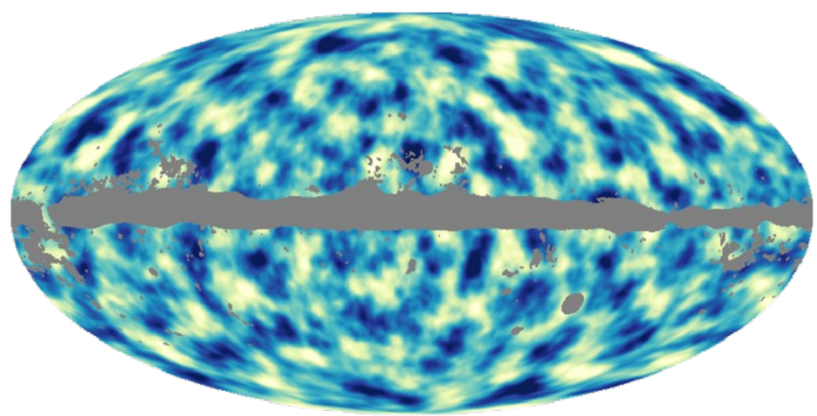

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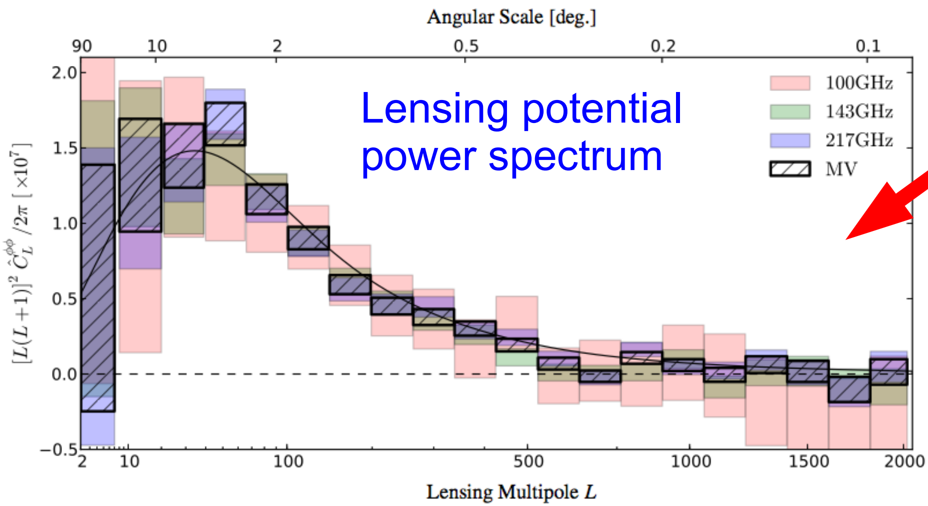
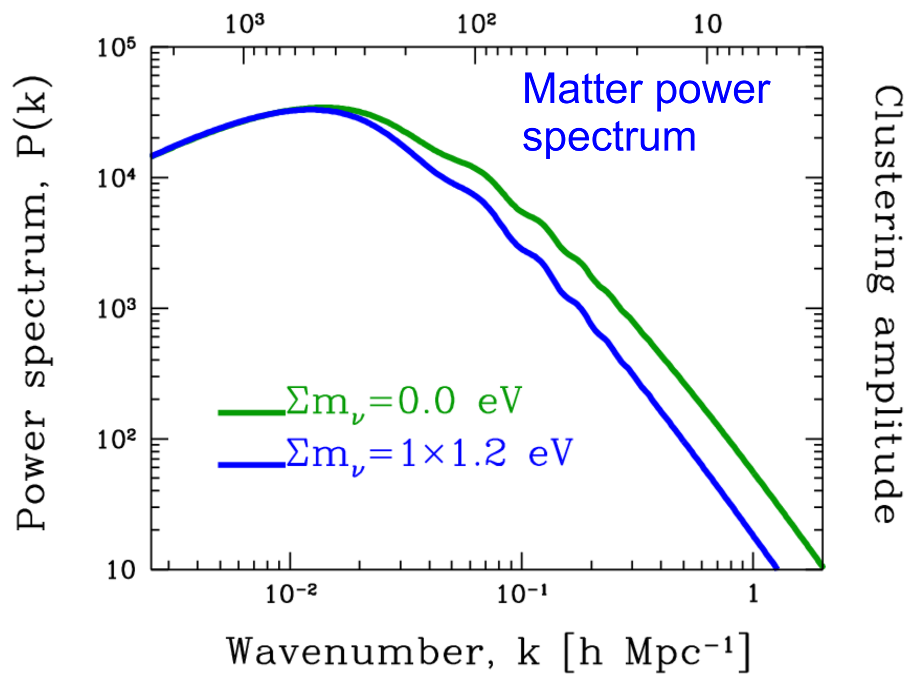
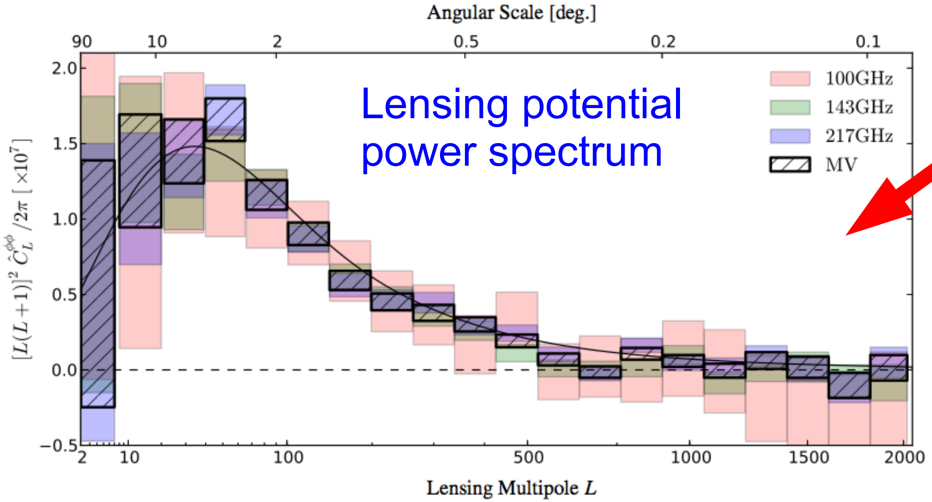


This is essentially this integrated along the line-of-sight (with some geometric factors folded in).



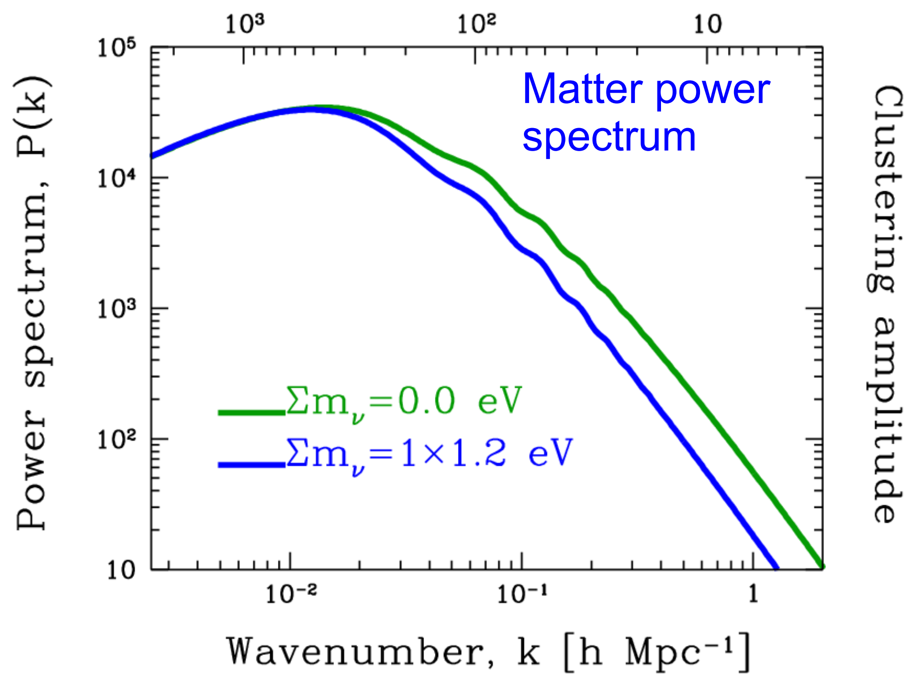
Weak lensing: lensing potential power spectrum...



This is essentially this integrated along the line-of-sight (with some geometric factors folded in).

Planck TT+TE+EE+lowP+lensing

$$\sum m_\nu < 0.59\ \mathrm{eV}\ \ (95\%\,\mathrm{C.L.})$$



Not as good as the no-lensing bound, because of “slight” incompatibility of the lensing amplitude inferred from lensed TT and the lensing potential power spectrum.

Current neutrino mass constraints...

Lattanzi & Gerbino, arXiv:1712.07109

7-parameter fits

Dataset	Σm_ν[eV]	
Planck TT+lowP	< 0.72	Ade et al. [Planck] 2016
Planck TT+lowP+lensing	< 0.59	Ade et al. [Planck] 2016
Planck TT,TE,EE+lowP	< 0.49	Ade et al. [Planck] 2016
Planck TT+SimLow	< 0.59	Aghanim et al. [Planck] 2016
Planck TT,TE,EE+lowP+BAO+FS	< 0.16	Alam et al. [BOSS] 2017
Planck TT+lowP+BAO	< 0.19	Vagnozzi et al. 2017
Planck TT,TE,EE+lowP+BAO	< 0.15	Vagnozzi et al. 2017
Planck TT+lowP+FS	< 0.30	Vagnozzi et al. 2017
Planck TT+lowP+BAO+JLA	< 0.25	Abbott et al. [DES] 2017
Planck TT+lowP+BAO+JLA+WL	< 0.29	Abbott et al. [DES] 2017
Planck TT,TE,EE+BAO+SZ	< 0.20	Ade et al. [Planck] 2016
Planck TT+lowP+Lyα-FS	< 0.13	Palanque-Delabrouille et al. 2015

Current neutrino mass constraints...

Lattanzi & Gerbino, arXiv:1712.07109

7-parameter fits

Dataset	Σm_ν[eV]		
Planck TT+lowP	< 0.72	Ade et al. [Planck] 2016	CMB only
Planck TT+lowP+lensing	< 0.59	Ade et al. [Planck] 2016	
Planck TT,TE,EE+lowP	< 0.49	Ade et al. [Planck] 2016	
Planck TT+SimLow	< 0.59	Aghanim et al. [Planck] 2016	
Planck TT,TE,EE+lowP+BAO+FS	< 0.16	Alam et al. [BOSS] 2017	+(quasi-)linear LSS
Planck TT+lowP+BAO	< 0.19	Vagnozzi et al. 2017	
Planck TT,TE,EE+lowP+BAO	< 0.15	Vagnozzi et al. 2017	
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Planck TT,TE,EE+BAO+SZ	< 0.20	Ade et al. [Planck] 2016	+nonlinear LSS
Planck TT+lowP+Lyα-FS	< 0.13	Palanque-Delabrouille et al. 2015	+baryonic physics

Current neutrino mass constraints...

Lattanzi & Gerbino, arXiv:1712.07109

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Planck TT,TE,EE+BAO+SZ	< 0[illegible]9	Ade et al. [Planck] 2016	→ +nonlinear LSS
Planck TT+lowP+Lyα-FS	< 0.13	Palanque-Delabrouille et al. 2015	→ +baryonic physics

Caution: Spectral index!
2.3σ discrepancy between Lya and Planck:

$n_s = 0.939 \pm 0.010$ Lya

$n_s = 0.9645 \pm 0.0049$ Planck

Current neutrino mass constraints...

Lattanzi & Gerbino, arXiv:1712.07109

7-parameter fits

Dataset	Σm_ν[eV]		
Planck TT+lowP	< 0.72	Ade et al. [Planck] 2016	
Planck TT+lowP+lensing			MB only
Planck TT,TE,EE+lowP			
Planck TT+SimLow			
Planck TT,TE,EE+lowP+BAO+			
Planck TT+lowP+BAO	< 0.19	Vagnozzi et al. 2017	
Planck TT,TE,EE+lowP+BAO	< 0.15	Vagnozzi et al. 2017	+(quasi-)linear LSS
Planck TT+lowP+FS	< 0.30	Vagnozzi et al. 2017	
Planck TT+lowP+BAO+JLA	< 0.25	Abbott et al. [DES] 2017	
Planck TT+lowP+BAO+JLA+WL	< 0.29	Abbott et al. [DES] 2017	
Planck TT,TE,EE+BAO+SZ	< 0.20	Ade et al. [Planck] 2016	+nonlinear LSS
Planck TT+lowP+Lyα-FS	< 0.13	Palanque-Delabrouille et al. 2015	+baryonic physics

+ Local Hubble rate $H_0 = 73.02 \pm 1.79$

Riess et al. 2016

$$\sum m_\nu < 0.113 \text{ eV}$$

(Planck only $H_0 = 67.5 \pm 0.64$; 3σ discrepancy)

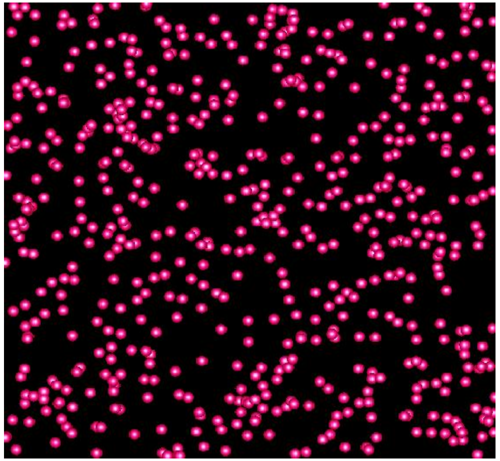
Moral of the story here...

- Treat aggressive cosmological neutrino mass bounds from **combining multiple data sets** with extreme caution.

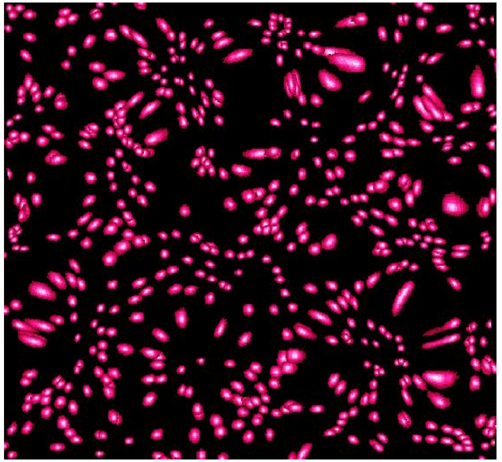
  – Significant discrepancies in the estimates of **other cosmological parameters** likely mean that the analysis (theory, data, etc.) is not as well understood as the proponents would like to think.

3. Future prospects…

Weak lensing of galaxies/Cosmic shear...



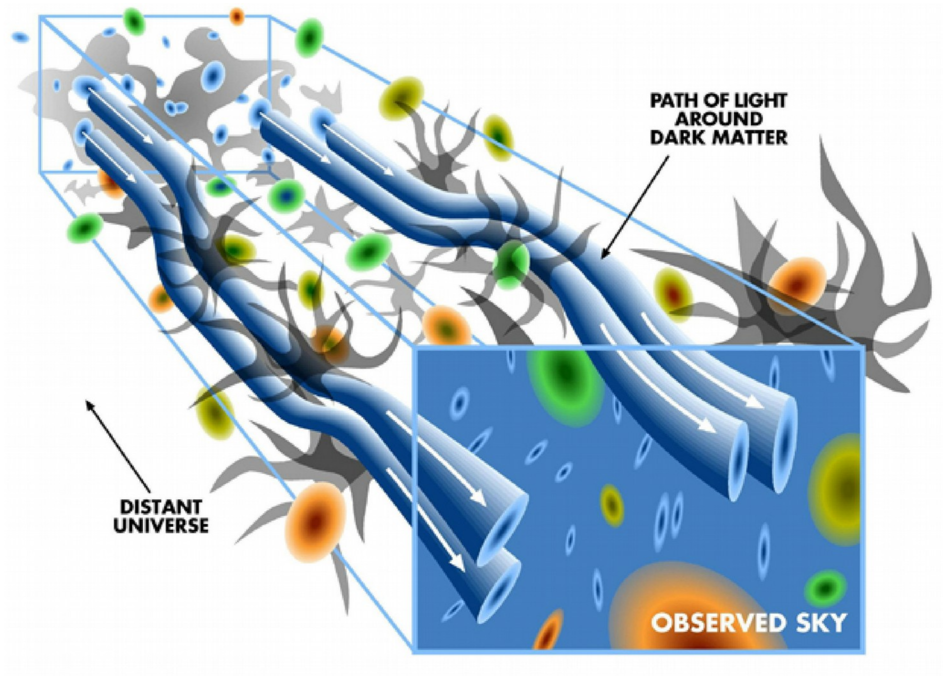
Unlensed

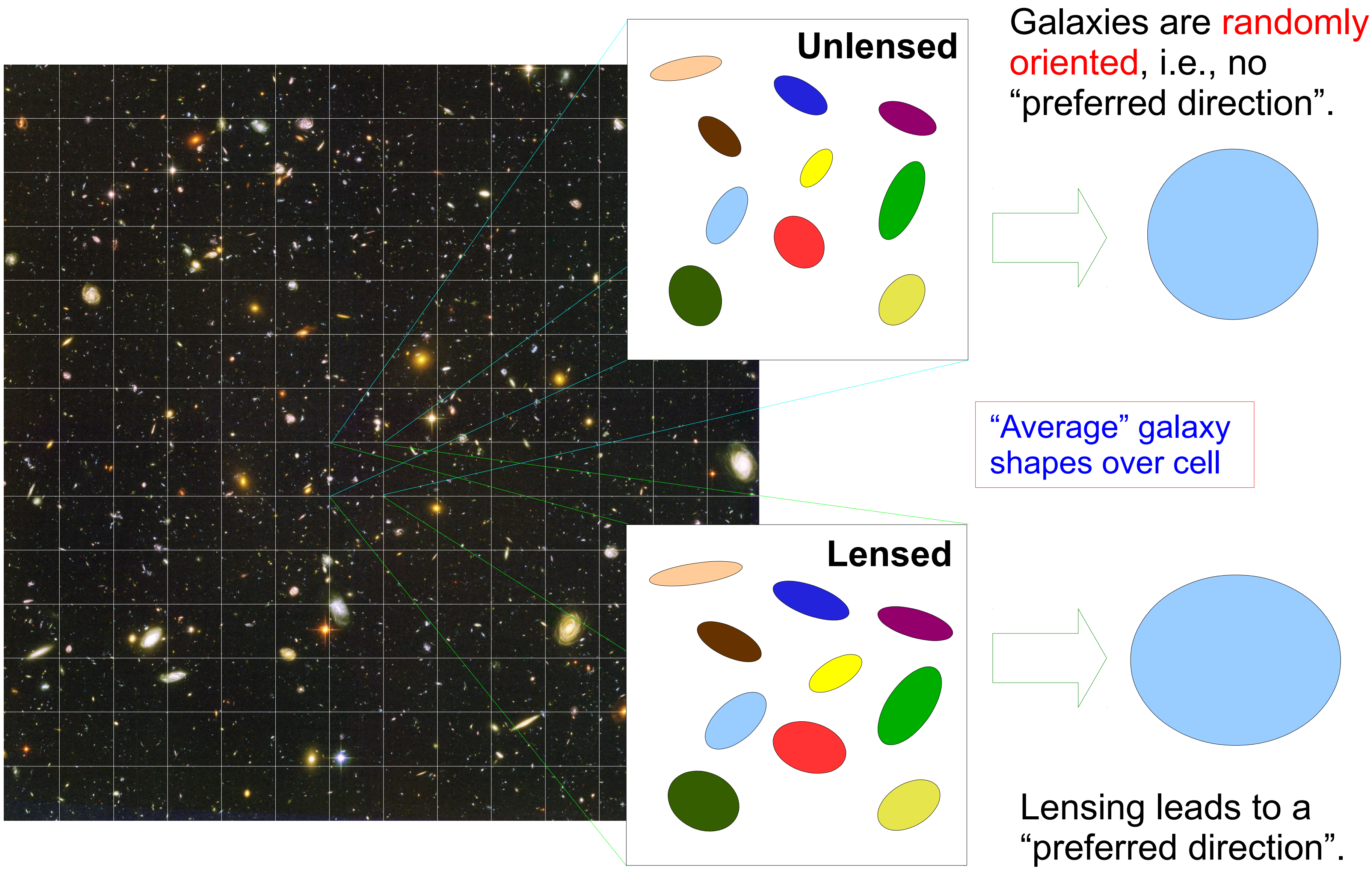


Lensed

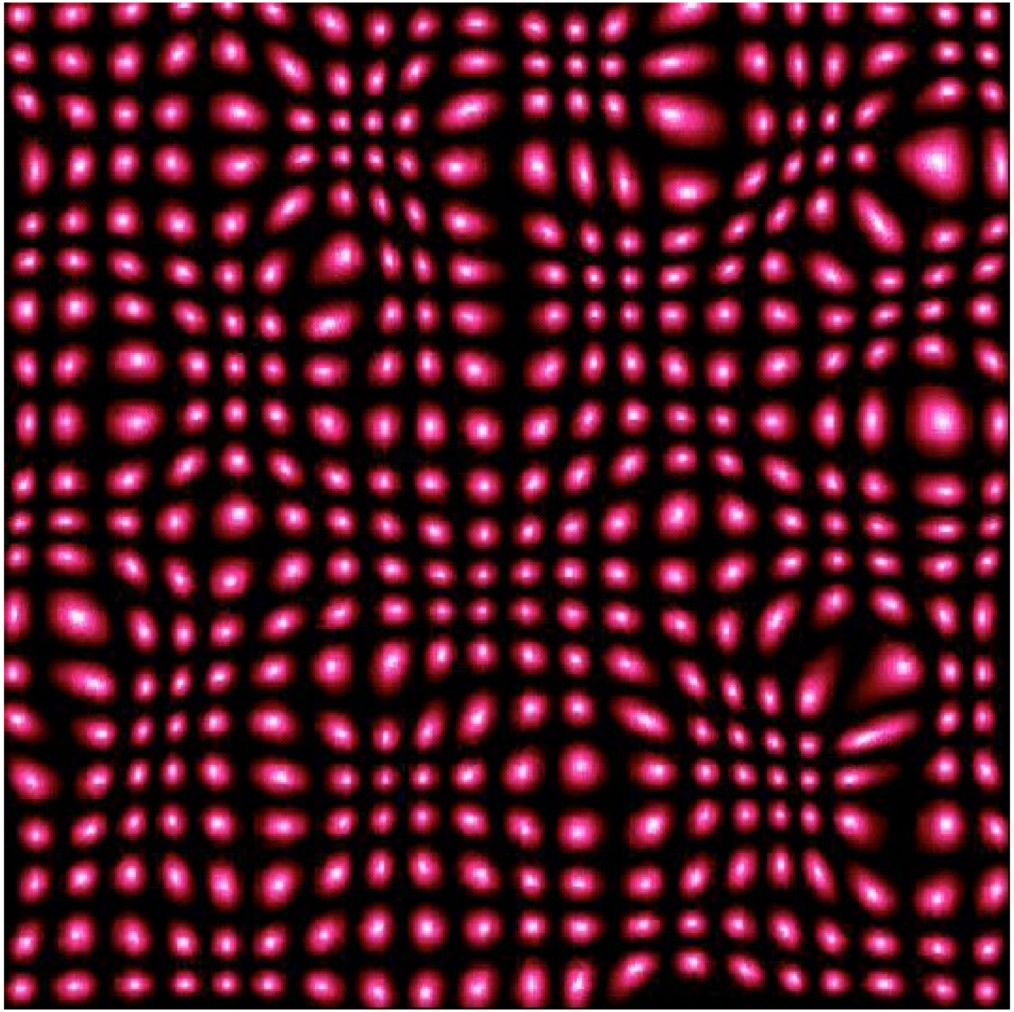
Distortion (magnification or stretching) of distant galaxy images by **foreground matter**.

- Sensitive to both luminous and dark matter (no bias problem).

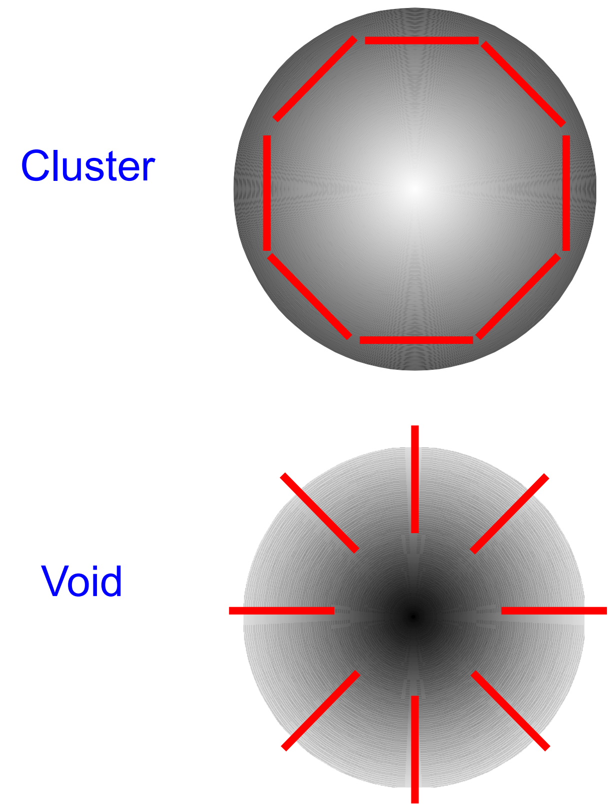



Unlensed
Galaxies are randomly oriented, i.e., no "preferred direction".
"Average" galaxy shapes over cell
Lensed
Lensing leads to a "preferred direction".

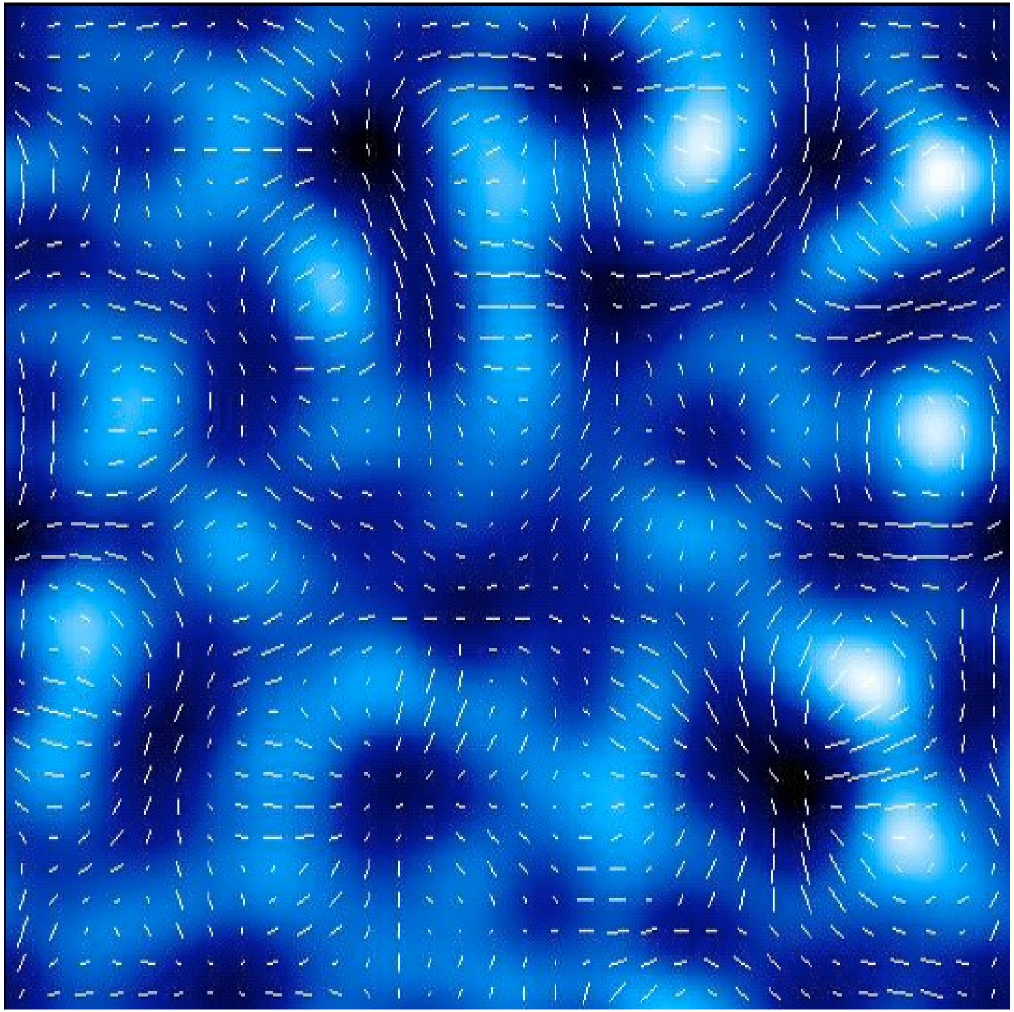
Shear map



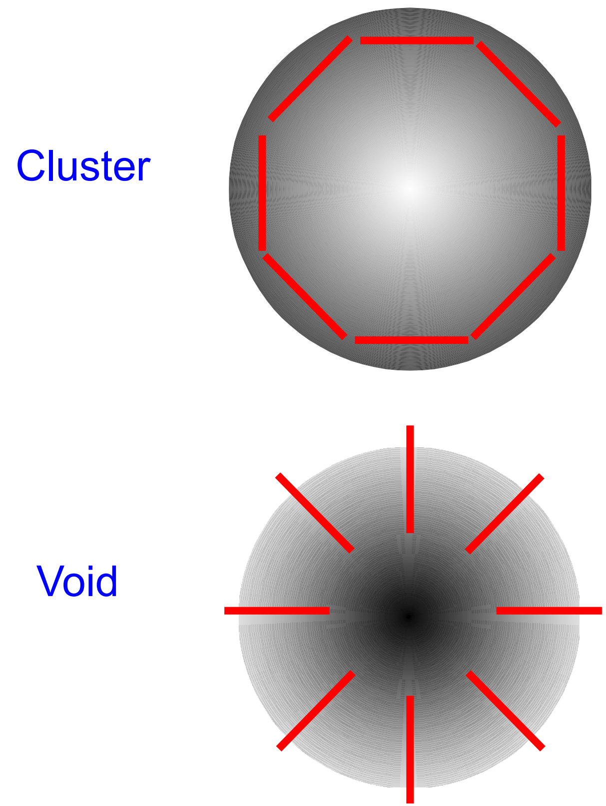
Weak lensing theory predicts:



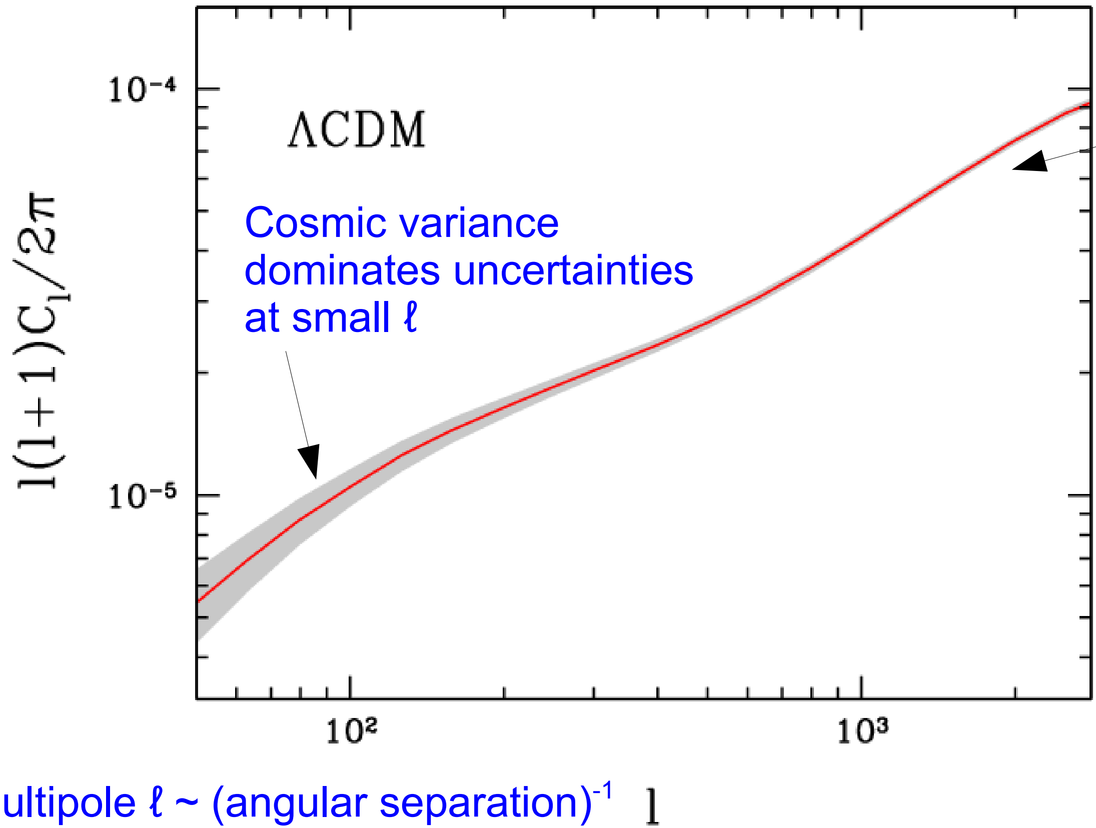
Shear map → Convergence map (projected mass)



Weak lensing theory predicts:



Convergence (or shear) power spectrum:



Cosmic variance dominates uncertainties at small ℓ

Shot noise dominates at large ℓ

$$\Delta C_\ell = \frac{\langle \gamma^2 \rangle}{n^2}$$

γ = Intrinsic ellipticity
n = source galaxy surface density

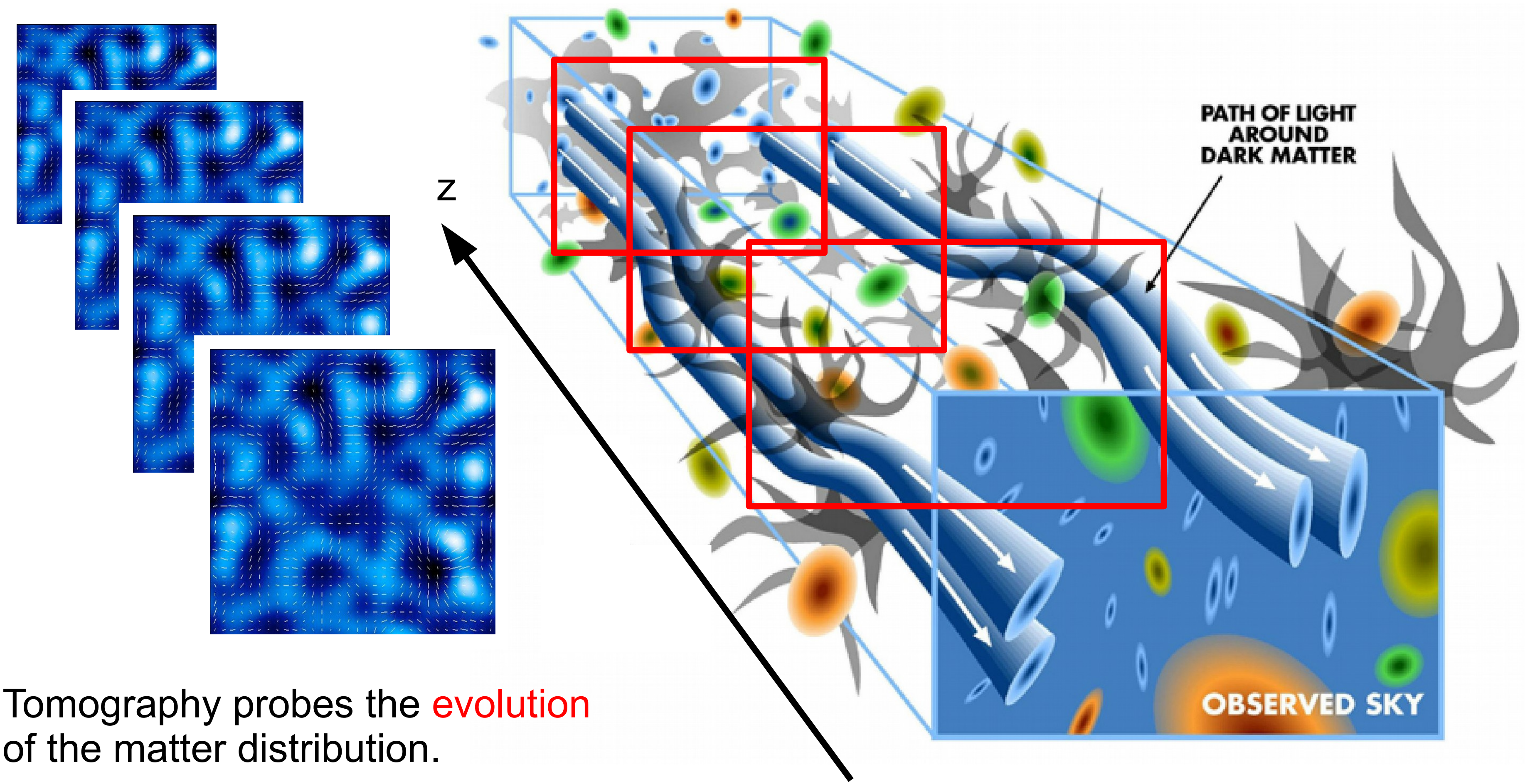
multipole ℓ ~ (angular separation)$^{-1}$

$$C_l \propto \int_0^\infty d\chi\, a^{-2} \left[\int_\chi^\infty d\chi'\, n_{\rm gal}(\chi') \frac{D(\chi'-\chi)}{D(\chi')} \right]^2 P_{\rm matter}(k = l/D(\chi))$$

(Limber limit)

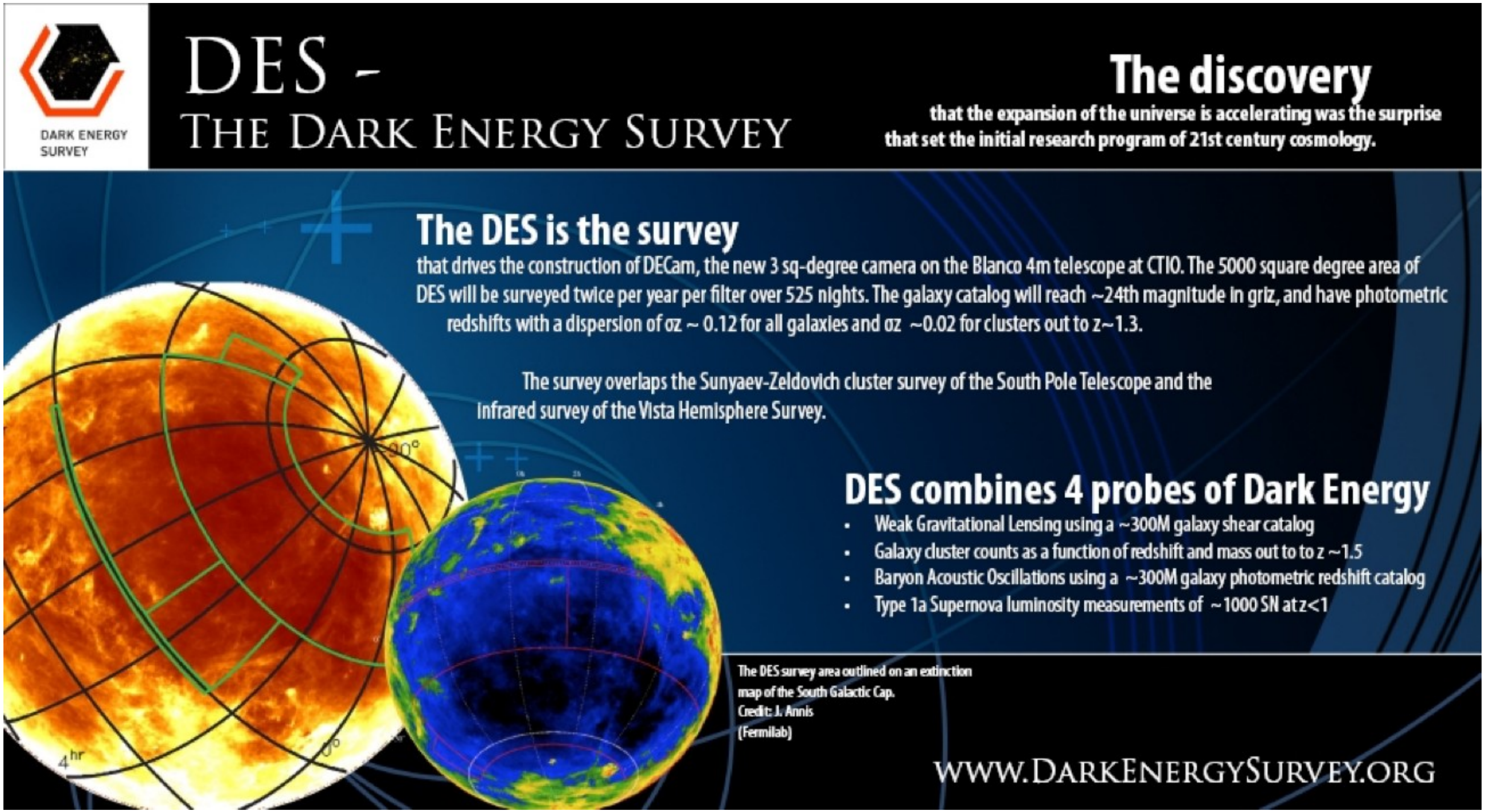
Tomography = bin galaxy images by redshift

- Photometric redshifts for ~ 1 billion galaxies in Euclid survey.



Tomography probes the evolution
of the matter distribution.

DES is happening right now...



ESA Euclid mission selected for implementation...

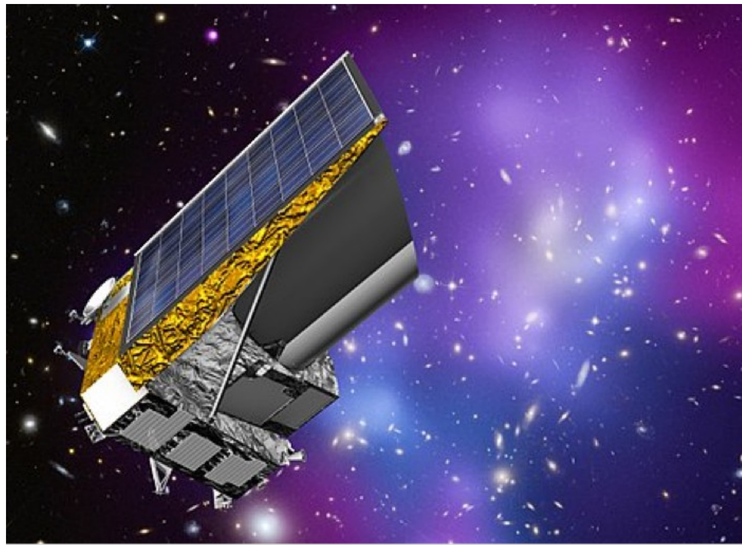
Launch planned for 2020.

- 6-year lifetime
- 15000 deg^2 (>1/3 of the sky)
- Galaxies and clusters out to z~2
  - Photo-z for 1 billion galaxies
  - Spectro-z for 50 million galaxies
- Optimised for weak gravitational lensing (cosmic shear)

ESA Euclid mission selected for implementation...

Type Ia supernovae

Galaxy clusters
(cluster mass function)



Baryon acoustic oscillations (BAO)

Galaxy distribution
(photo-z and spectro-z)

<u>Cosmic shear</u>
(weak gravitational lensing of galaxies)

Cosmic shear with Euclid...

A **7-parameter forecast**:

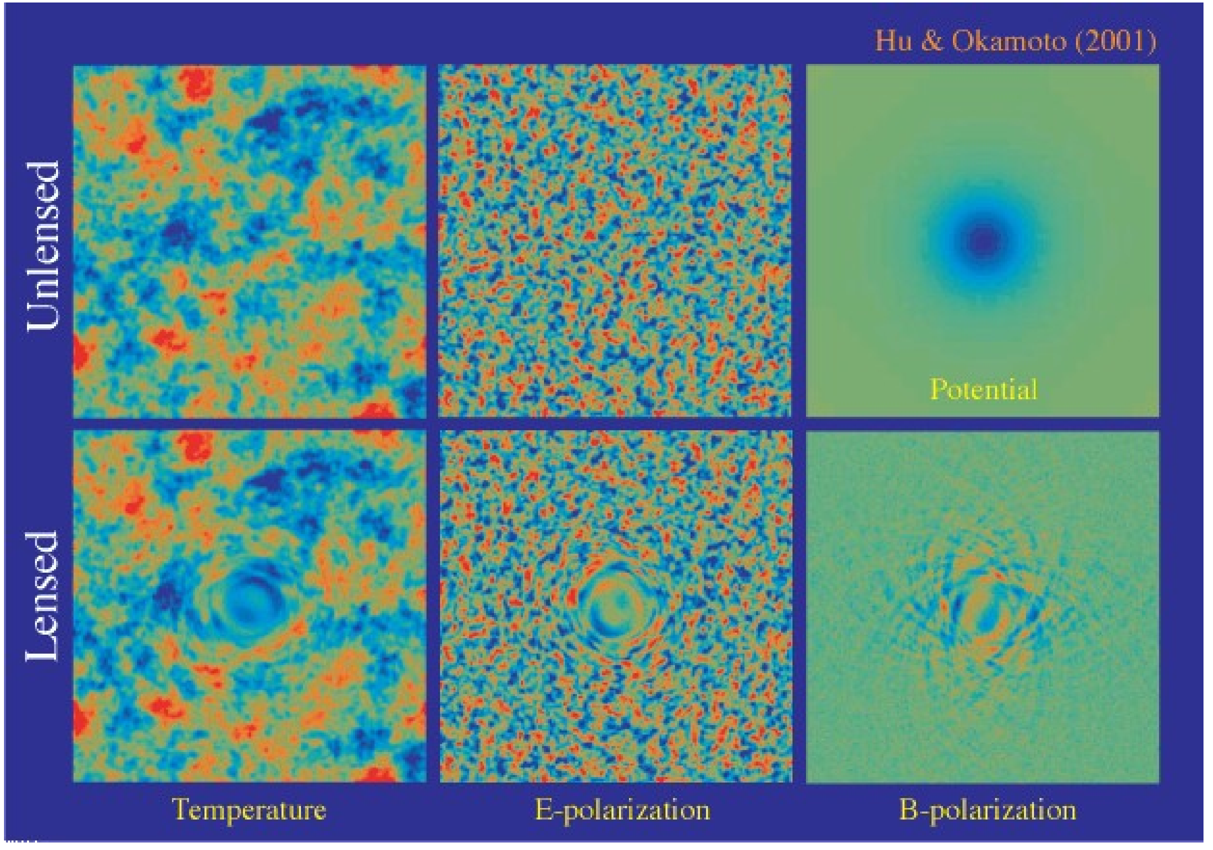
Data	$10^3 \times \sigma(\omega_{\mathrm{dm}})$	$100 \times \sigma(h)$	$\sigma(\sum m_\nu)/\mathrm{eV}$
c	2.02	1.427	0.143
cs	0.423	0.295	0.025
cg	0.583	0.317	0.016
$\mathrm{cg_l}$	0.828	0.448	0.019
$\mathrm{cg_b}$	0.723	0.488	0.039
$\mathrm{cg_{bl}}$	1.165	0.780	0.059
csg	0.201	0.083	0.011
csgx	0.181	0.071	0.011
$\mathrm{csg_b}$	0.385	0.268	0.023
$\mathrm{csg_bx}$	0.354	0.244	0.022

Hamann, Hannestad & Y^{3}W 2012

c = CMB (Planck); g = galaxy clustering
s = cosmic shear; x = shear-galaxy cross

Lensing of the CMB polarisation...

Weak gravitational lensing leads to a small **transfer of power** from the E-mode polarisation to the B-mode.

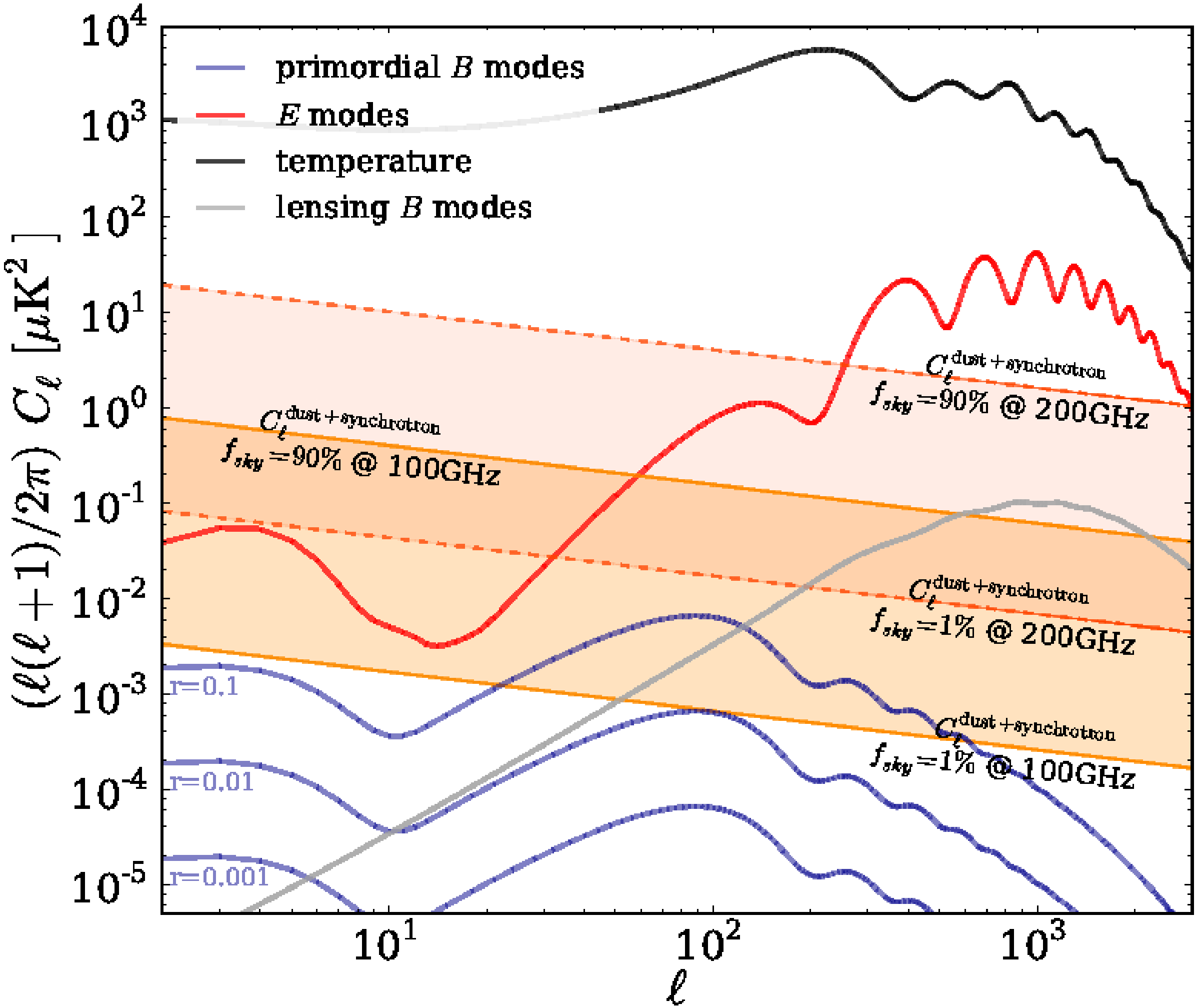


A hugely exaggerated example

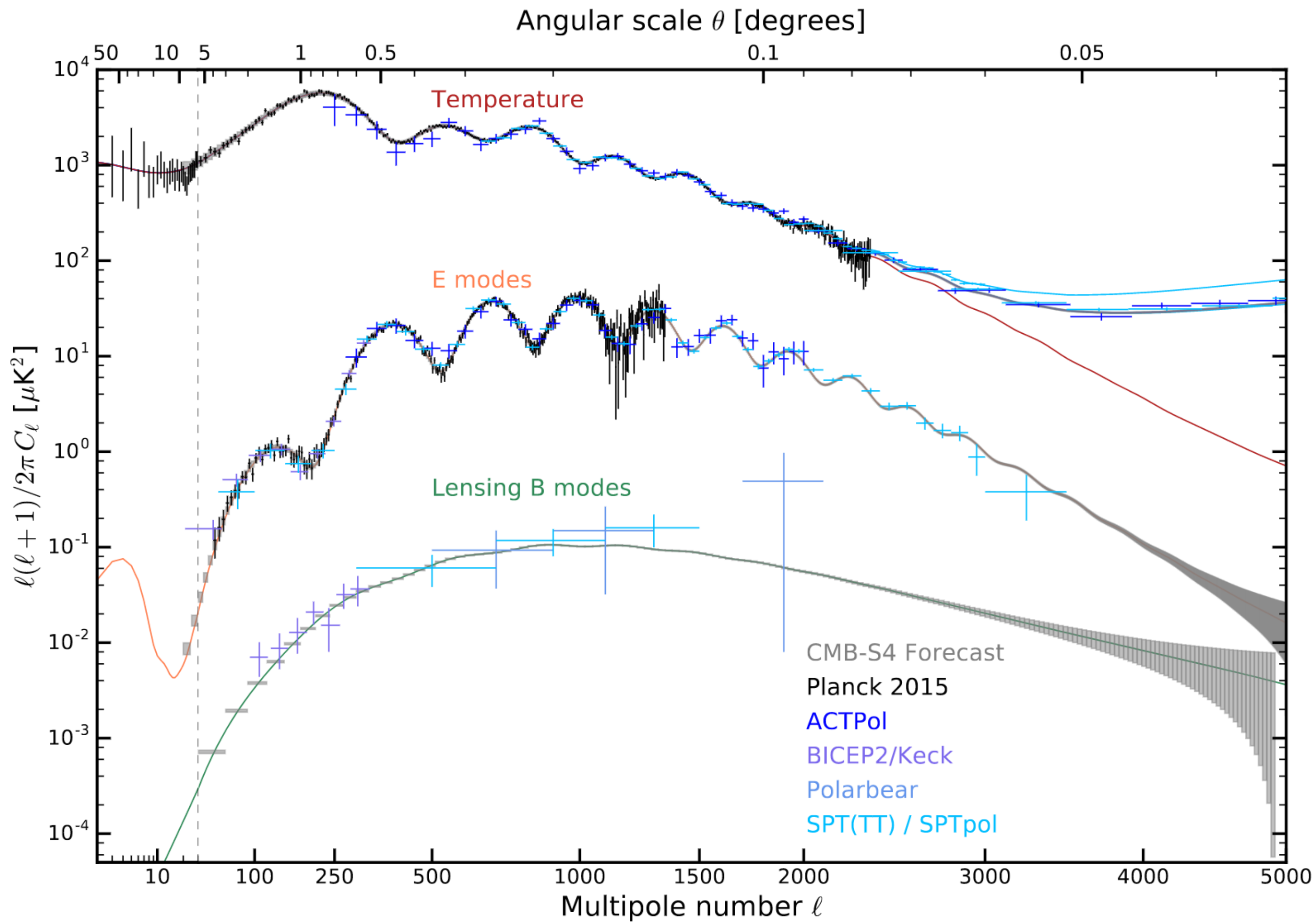
Lensing of the CMB polarisation...

Lensing signal = dominant B-mode signal at large multipoles especially in the absence of primordial gravitational waves

- Noise for primordial gravitational wave detection
- Great for neutrino cosmology



Lensing of the CMB polarisation...



CMB S4 science book

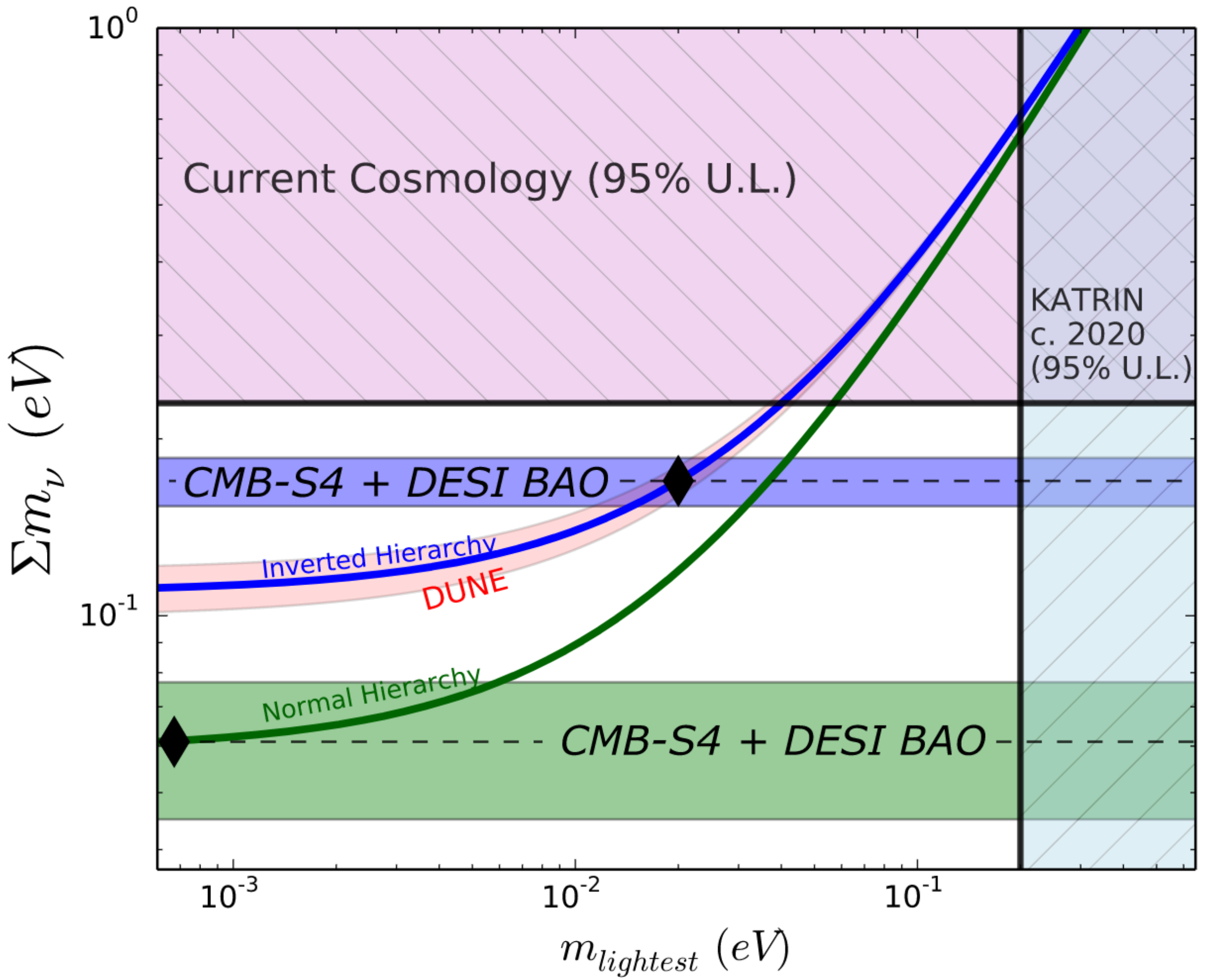
Lensing of the CMB polarisation with CMB-S4...

- Ground-based CMB probe planned for the 2020s.

- Potential **1σ sensitivity** to neutrino masses:

$$\sigma\left(\sum m_\nu\right) = 0.015 \text{ eV}$$

CMB S4 science book



Take-home message...

- The cosmic microwave background anisotropies and the large-scale structure distribution can be used to probe neutrino physics.

- **Existing data** already place strong constraints on the neutrino mass.

- **Future probes** exploiting weak gravitational lensing of CMB polarisation (e.g., CMB S4) and cosmic shear (e.g., Euclid) can potentially tighter the bound 10-fold.