Large Scale Structure Signals of Neutrino Decay

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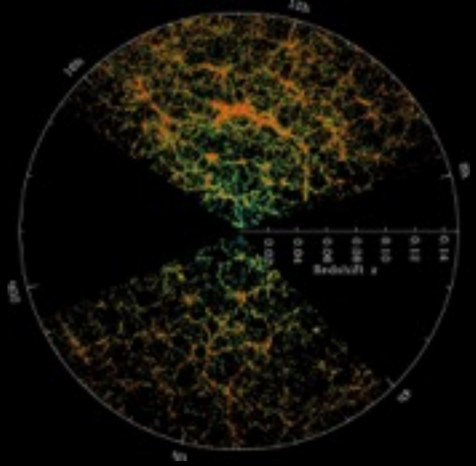
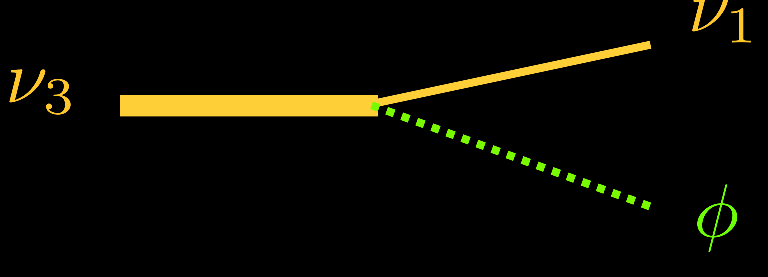
1909.05275, 19XX….

Topics in Cosmic-Nu Phys

10/10/2019





What is the mass & lifetime of a neutrino?

The best bound on neutrino mass comes from cosmology

From Planck 2018 data

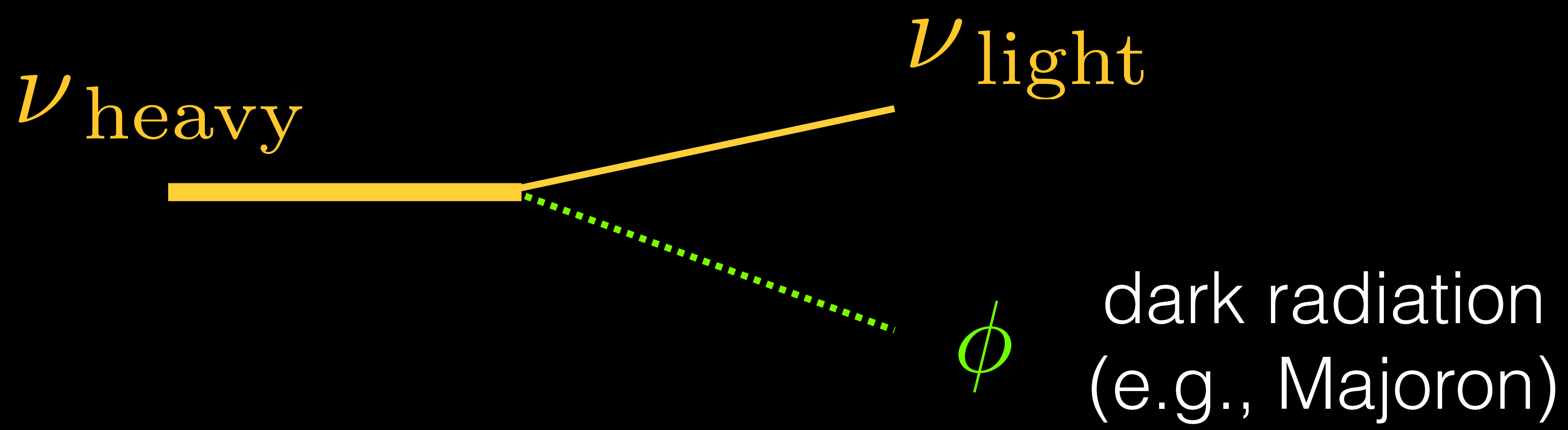
$$\sum m_\nu < 0.24\,\mathrm{eV}$$

(~0.12 eV if including BAO)

This assumes neutrinos are stable particles

Neutrinos may not be as stable as predicted in the SM

e.g., models explain the tiny neutrino mass



Can we measure the **lifetime of neutrinos**?

How stable are SM neutrinos?

Existing bounds on neutrino lifetime are very weak
(for decay into invisible particles)

ν

- long-based line experiments $\tau > 10^{-14}\,\mathrm{sec}$
- supernovae $\tau > 8\,\mathrm{hrs}$ e.g., Frieman et al (1988)
- $\tau > 13\,\mathrm{yrs}$ CMB (neutrinos need to free stream)

e.g., Archidiacono and Hannestad (2014)
Escudero and Fairbairn (2019)

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neutrino mass / lifetime are very hard to measure

- can we improve the bounds?
- can we probe neutrino decay?

How stable are SM neutrinos?

Existing bounds on neutrino lifetime are very weak
(for decay into invisible particles)

ν

long-based line experiments $\tau > 10^{-14}\,\mathrm{sec}$

supernovae $\tau > 8\,\mathrm{hrs}$

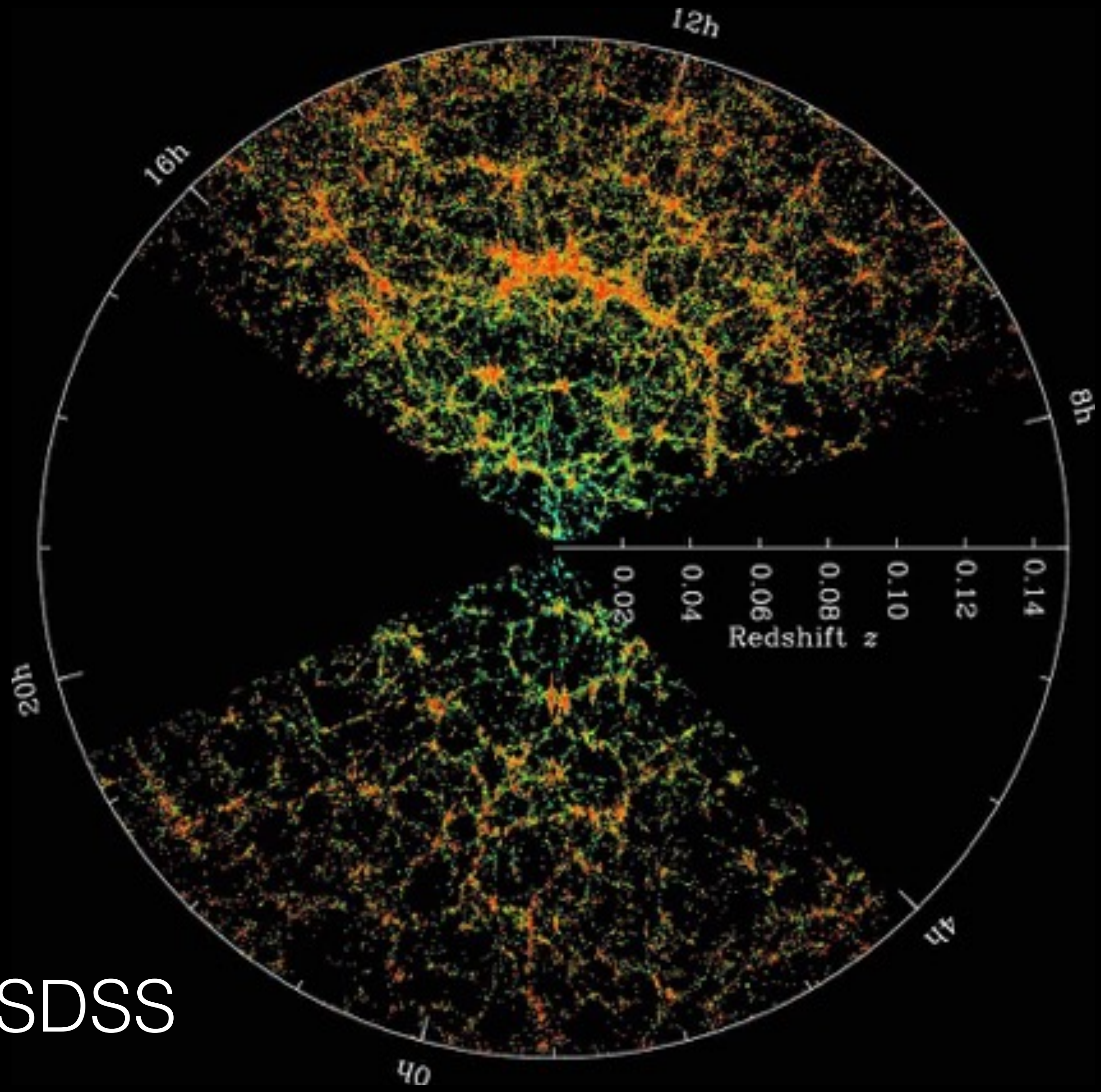
$\tau > 13\,\mathrm{yrs}$ CMB (neutrinos need to free stream)

~ 10 billion yrs

near future data
(e.g., Euclid, CMB-S4)

see also Serpico (2007)

Data: Large Scale Structure



SDSS

galaxy distribution is determined by cold dark matter distribution

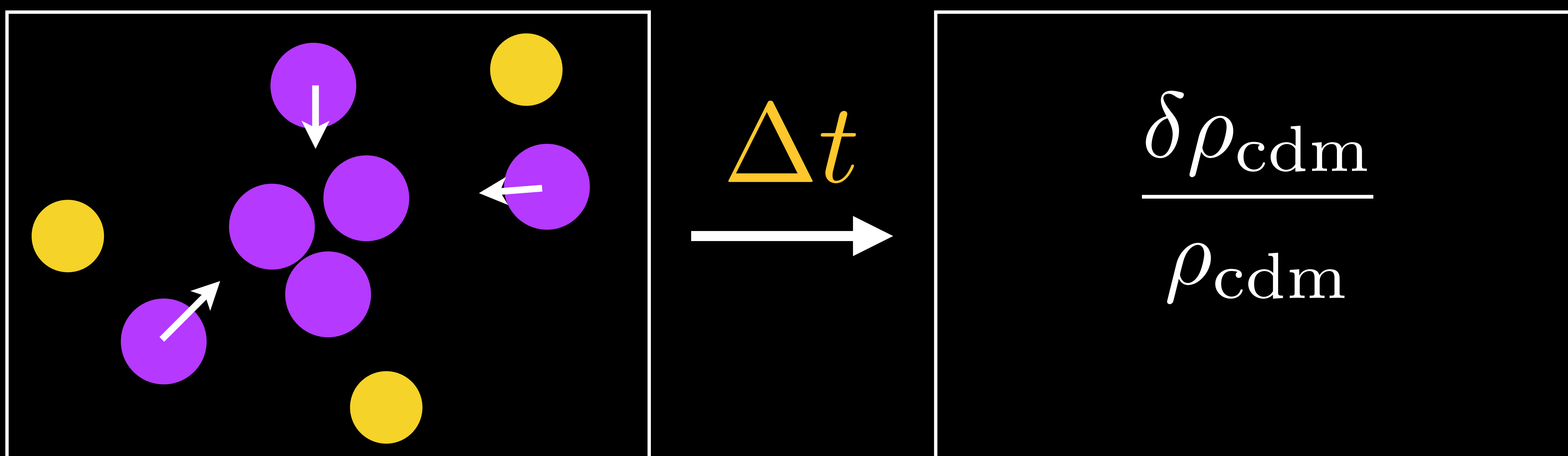
$$\frac{\delta N_{\rm galaxy}}{N_{\rm galaxy}} \propto \frac{\delta \rho_{\rm cdm}}{\rho_{\rm cdm}} \gg 10^{-5}$$

density fluctuation is larger than CMB fluctuation

Structure formation

matter radiation equilibrium

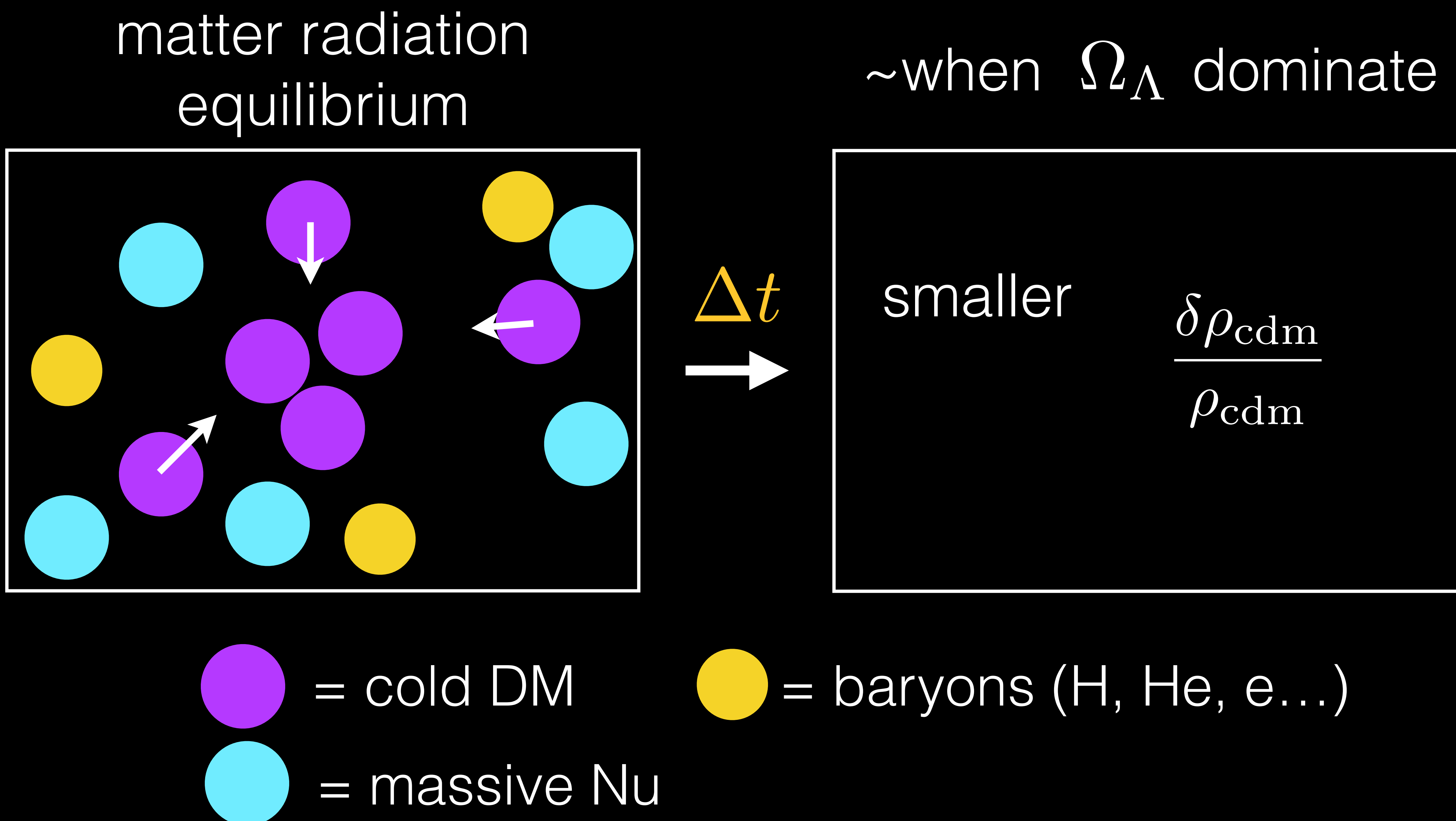
~when Ω_Λ dominate



= cold DM   = baryons (H, He, e…)

Adding massive neutrinos

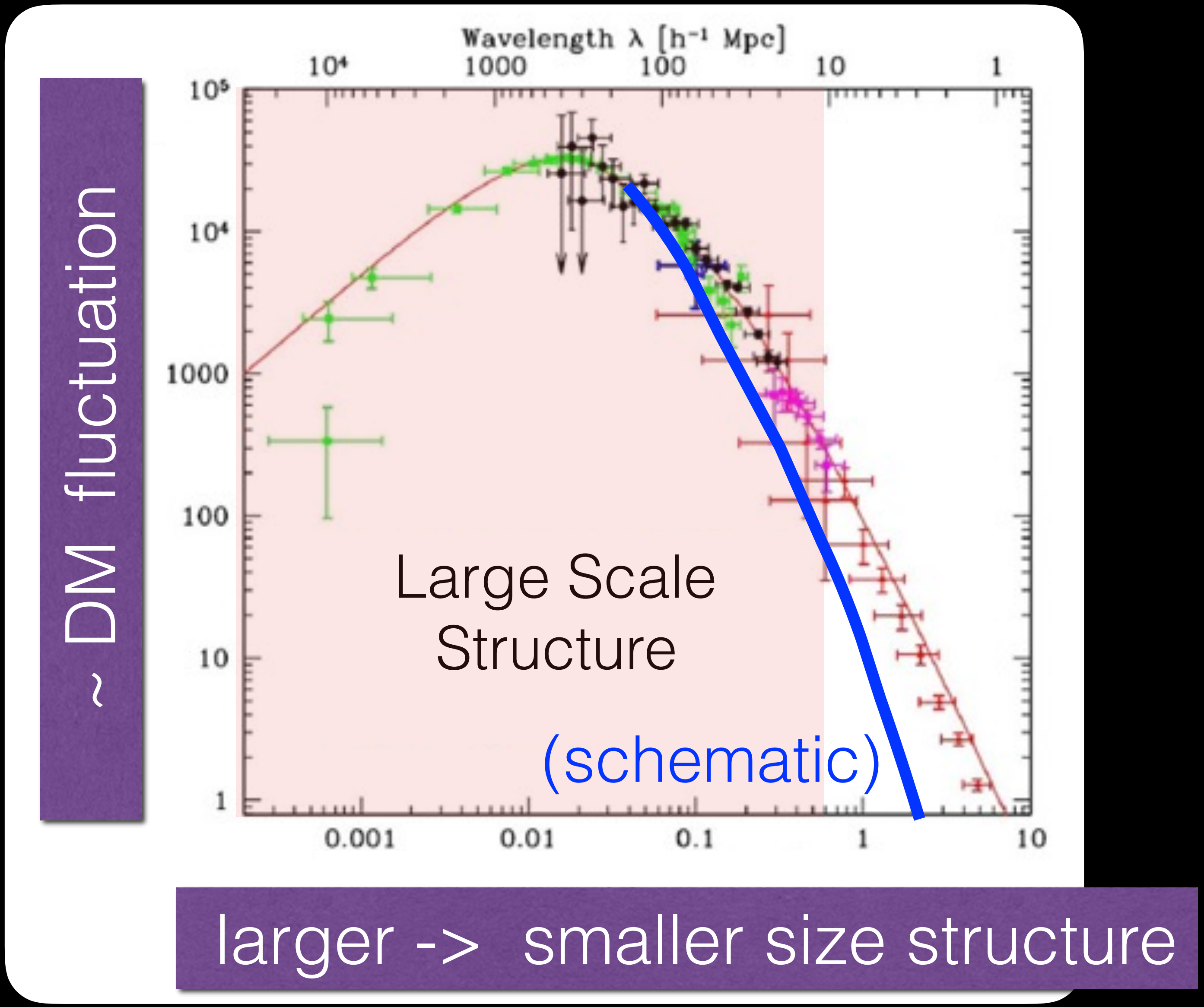
=> increase Hubble expansion => shorten Δt



larger m_ν => smaller density perturbation

Large Scale Structure data is sensitive to the sum of neutrino mass

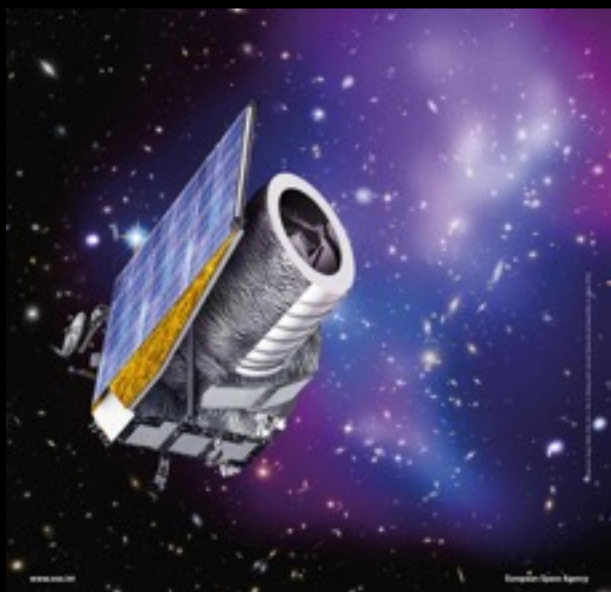
$$P(k) \sim k^{-3} \delta_m(k)^2$$



Tegmark et al. (2004)

current measurements have about 10% level precision

Much better data will come within a decade!



Euclid (~2021)

LSST (~2023)

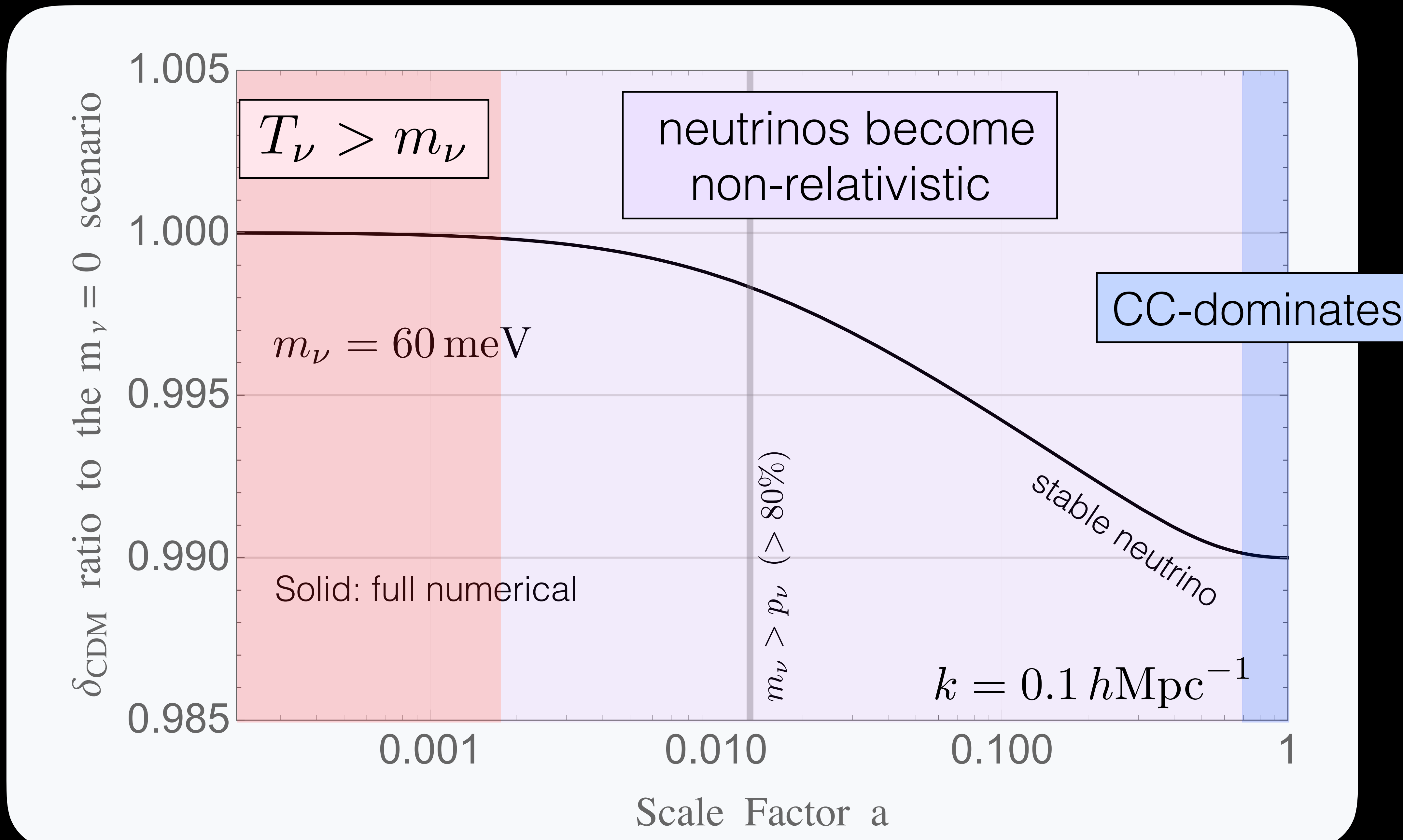
DESI (~2020)

will be sensitive to ~ 0.1 - 1%
change in matter power spectrum

CMB-S4 (202?)

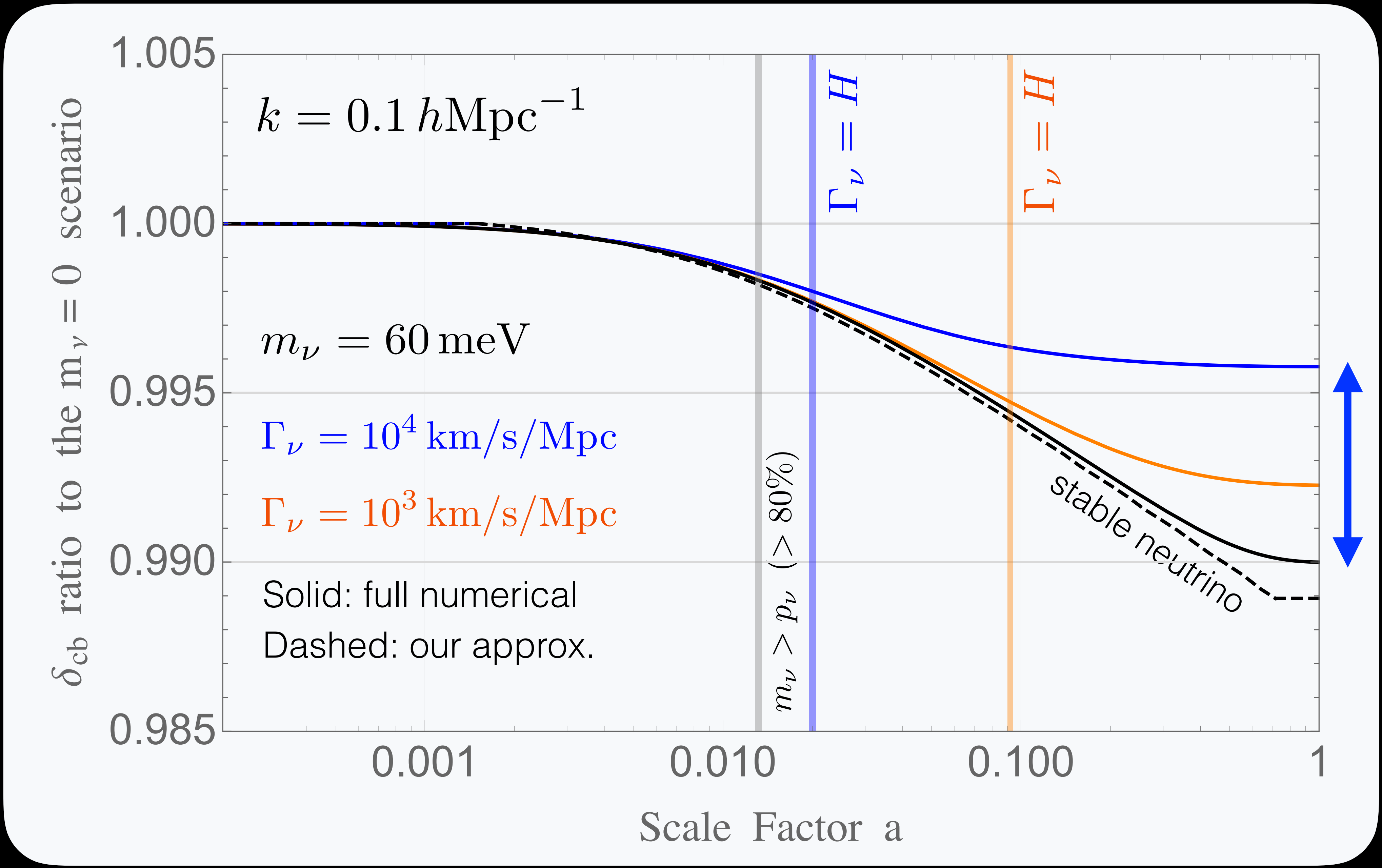
Ratio of perturbation $\delta_{\rm cdm} = \dfrac{\delta\rho_{\rm cdm}}{\rho_{\rm cdm}}$ in redshift

$$\left(\frac{\delta_{\rm cdm}^{m_\nu}}{\delta_{\rm cdm}^{\not m_\nu}}\right)$$



What if neutrino decays into dark radiation?

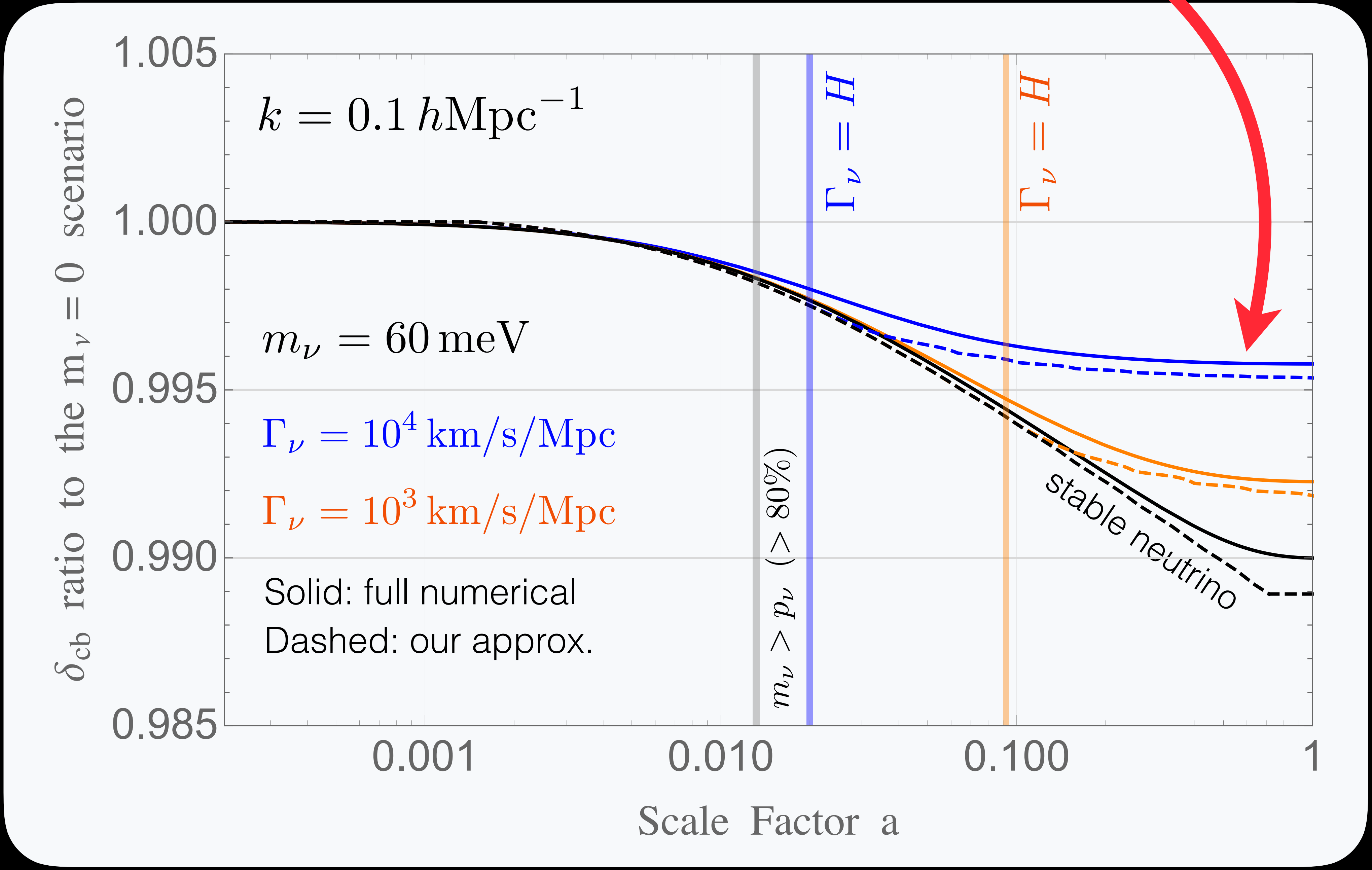
Ratio of perturbation $\delta_{\rm cdm} = \dfrac{\delta\rho_{\rm cdm}}{\rho_{\rm cdm}}$ in redshift



$$\mathrm{km/s/Mpc} \approx (10^3\ \mathrm{Gyrs})^{-1}$$

Analytical approximation

including redshift change from Nu to daughter radiation

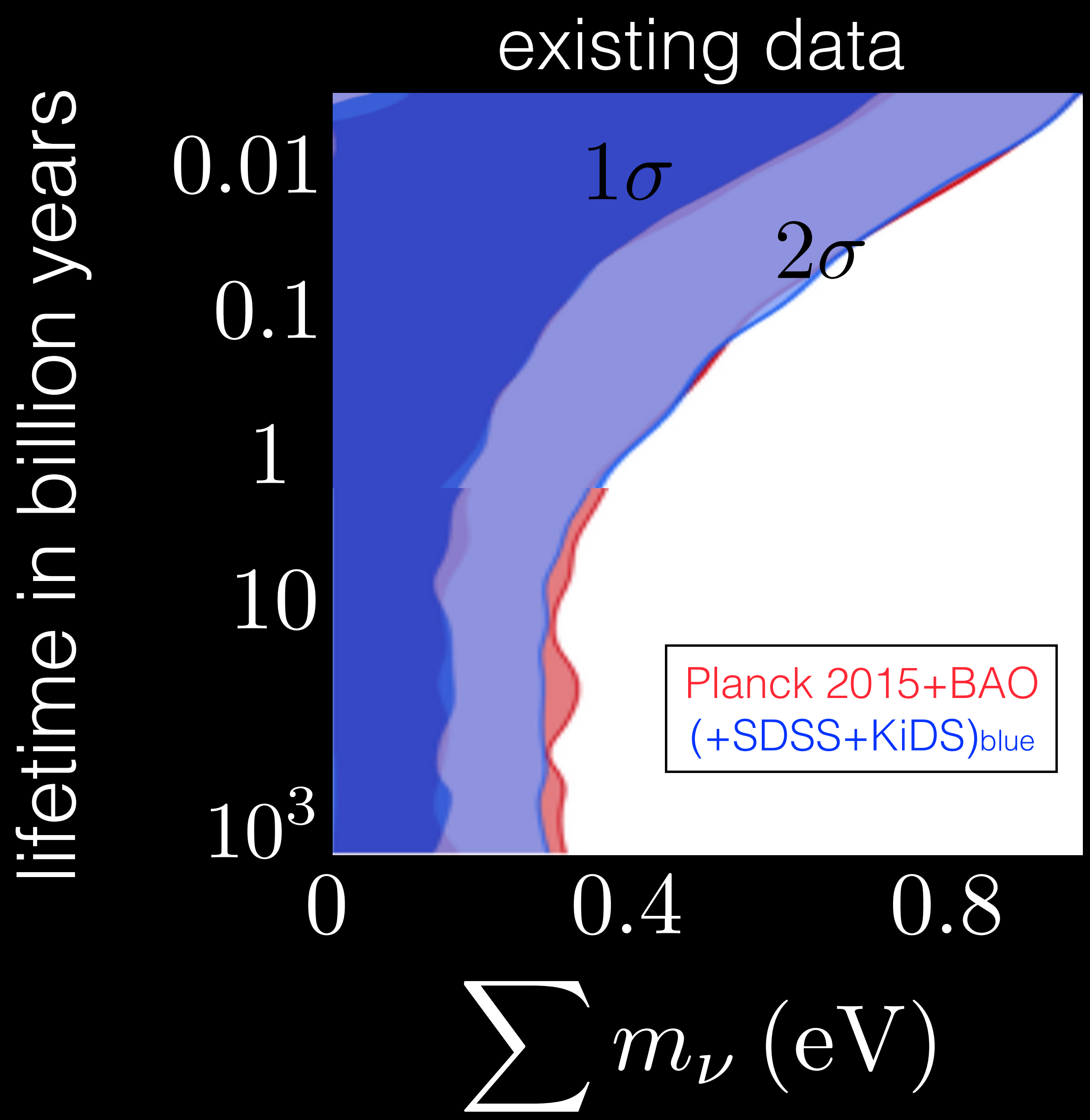


$$\mathrm{km/s/Mpc} \approx (10^3\ \mathrm{Gyrs})^{-1}$$

neutrino decay => larger density perturbation
than the stable Nu case

Current Large Scale Structure & Planck 2015

(see the original plots in 1909.05275)



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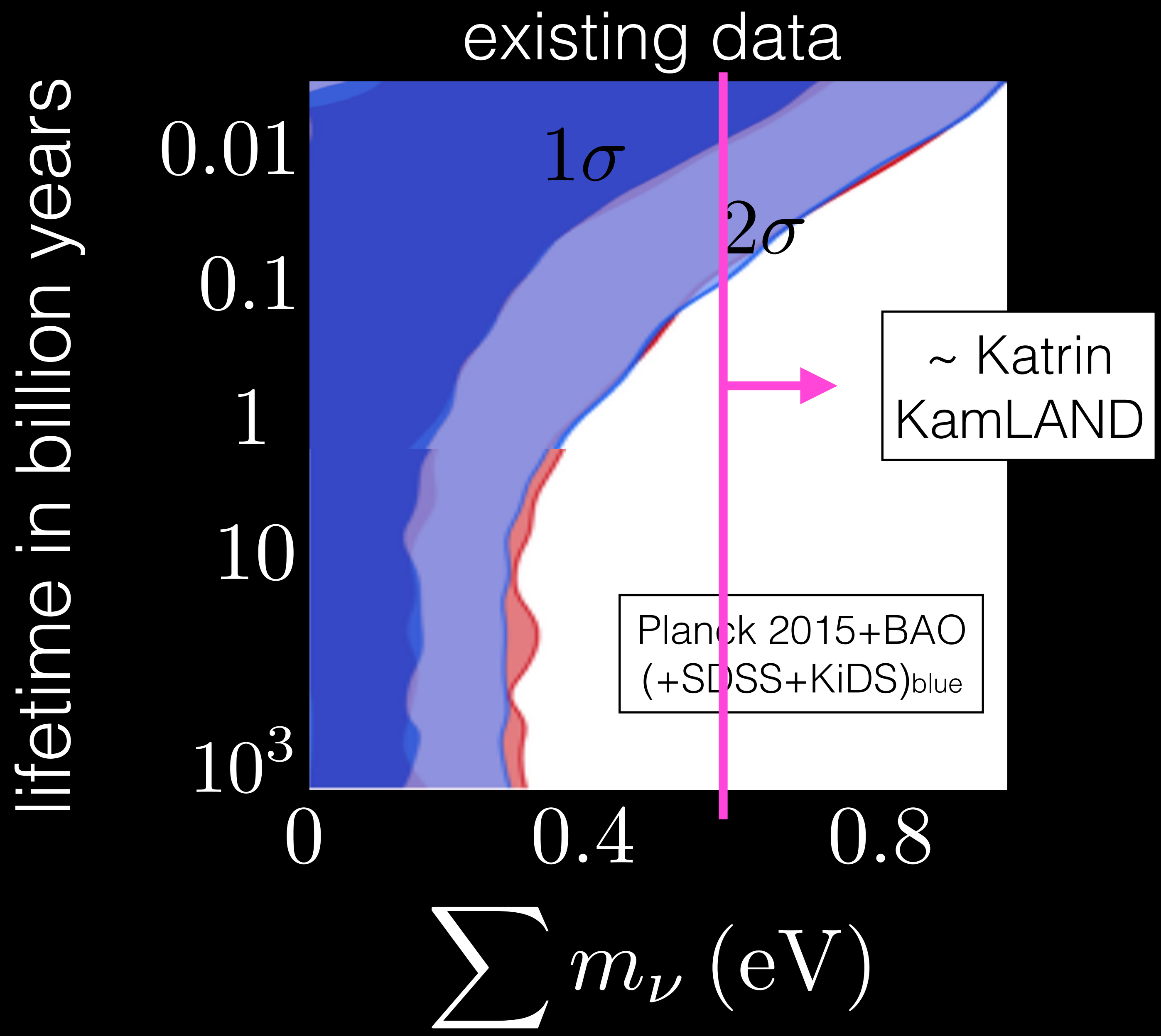


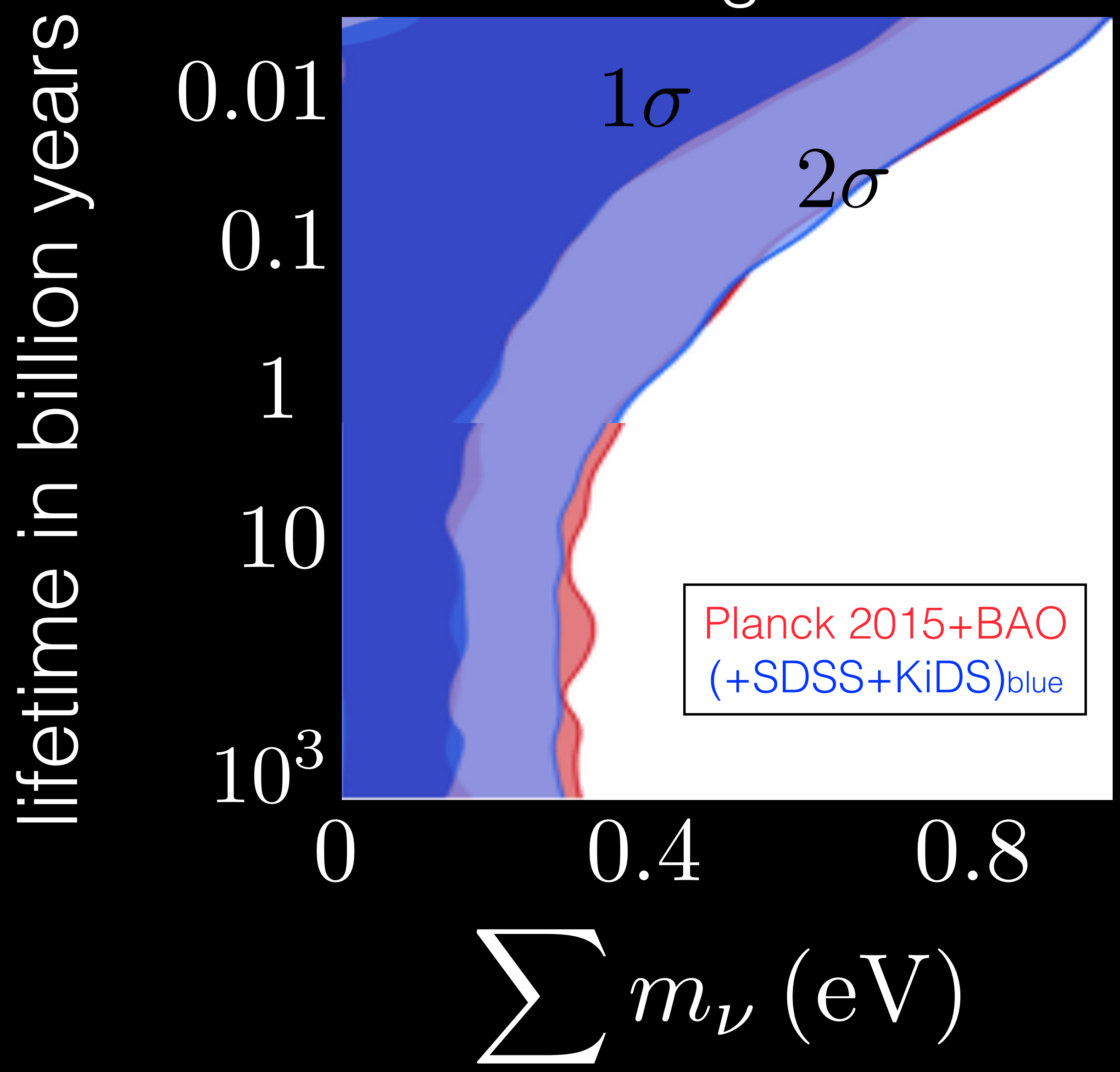
sensitivity from other lab experiments

Cosmic-Nu Telescope?

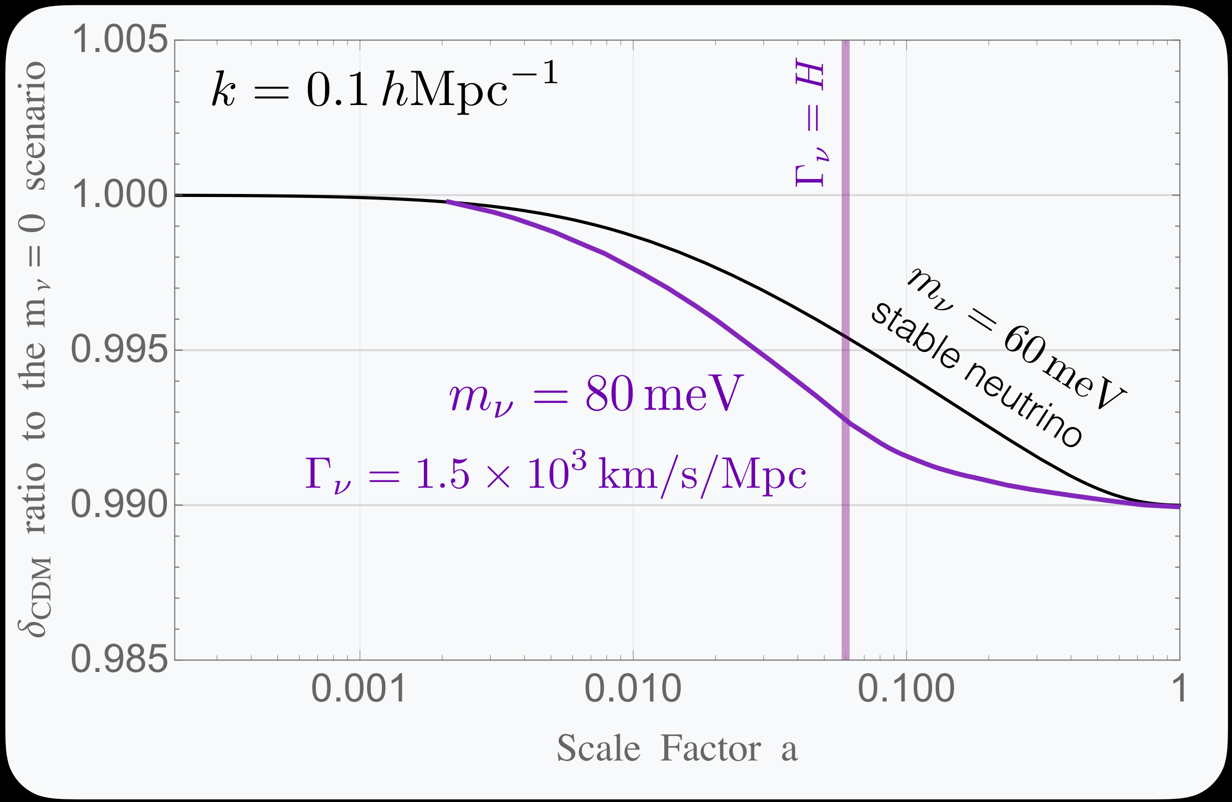
Current Large Scale Structure & Planck 2015

(see the original plots in 1909.05275)

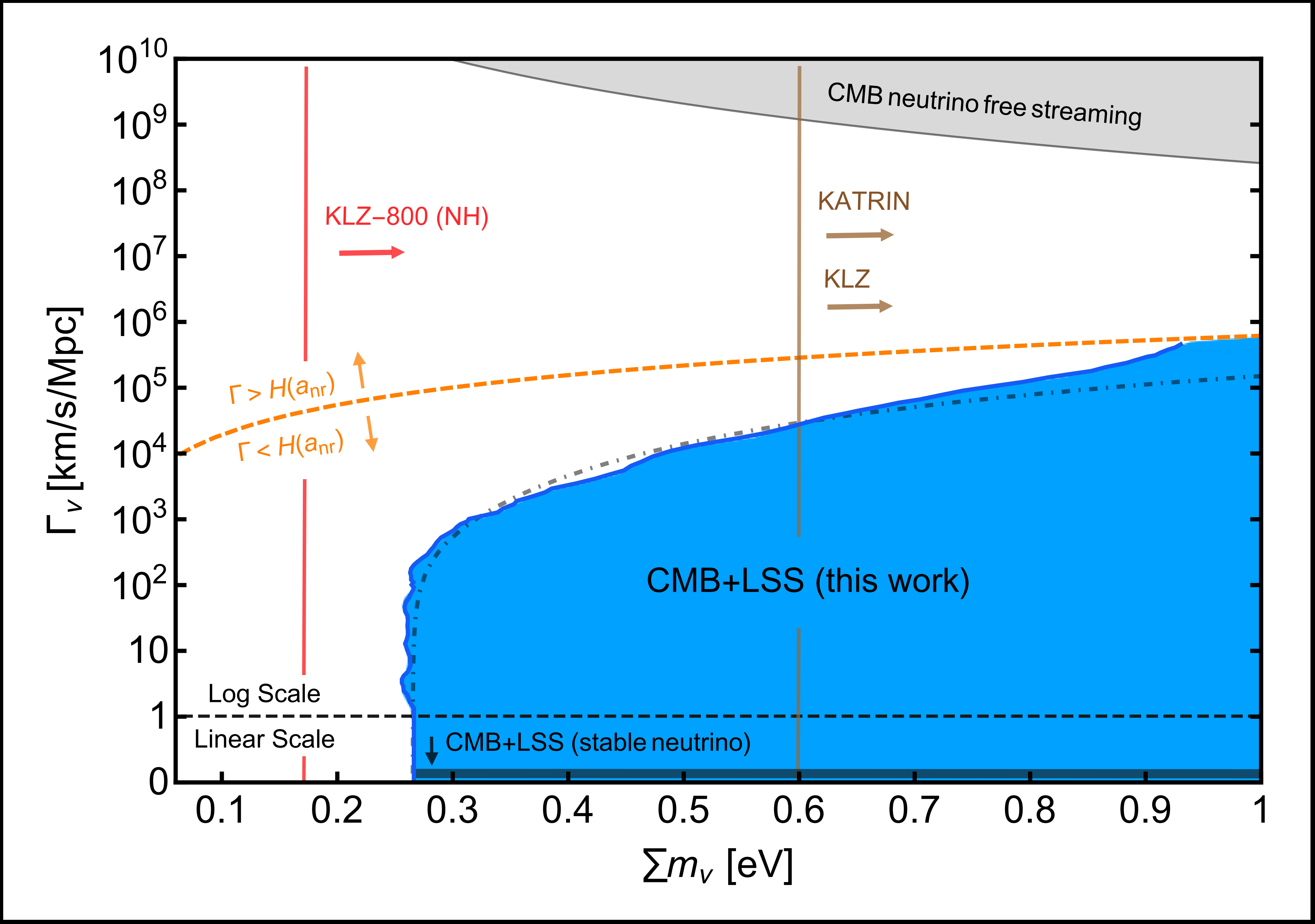
existing data



a mass / lifetime degeneracy



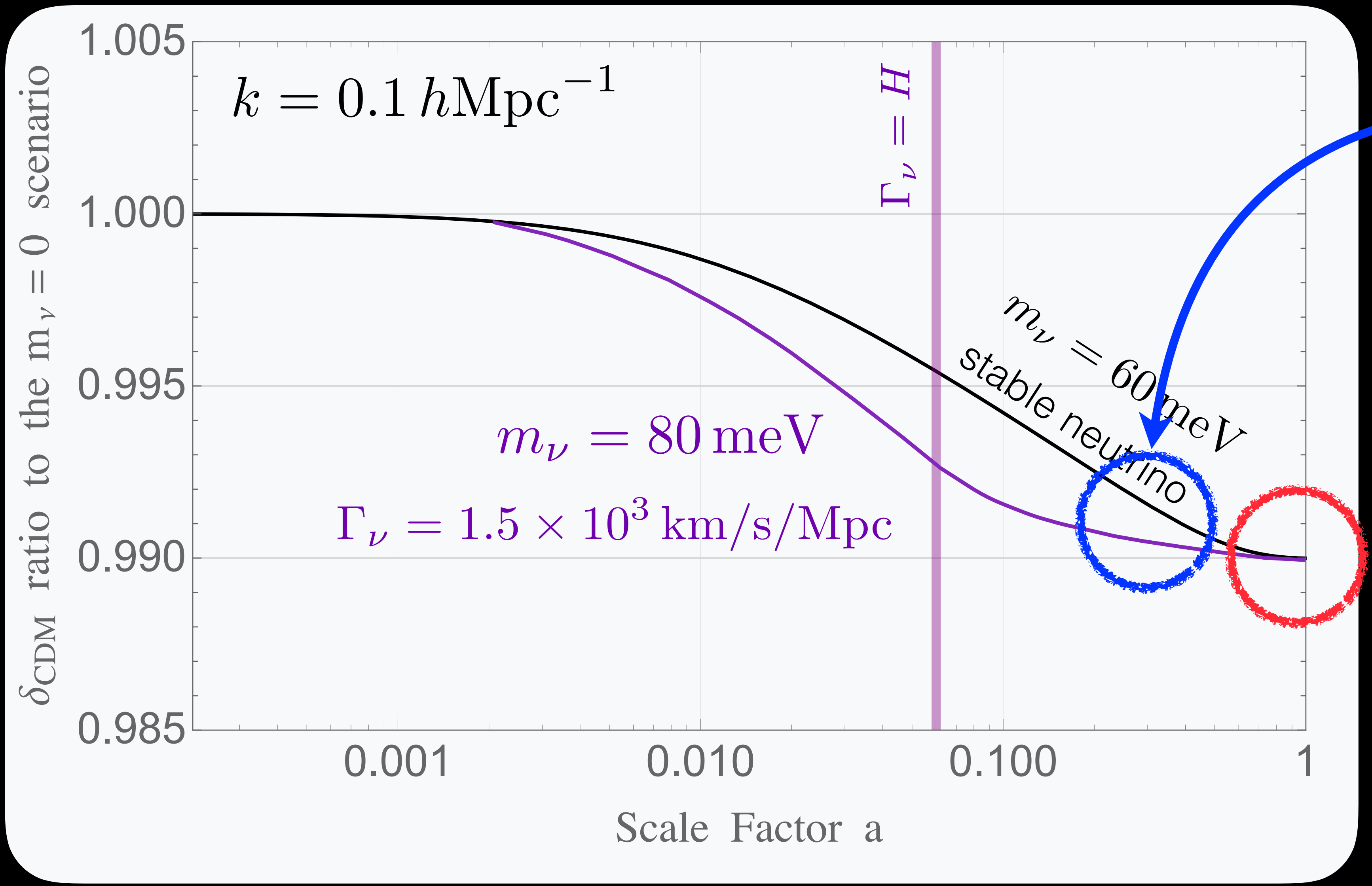
Current Large Scale Structure & Planck 2015



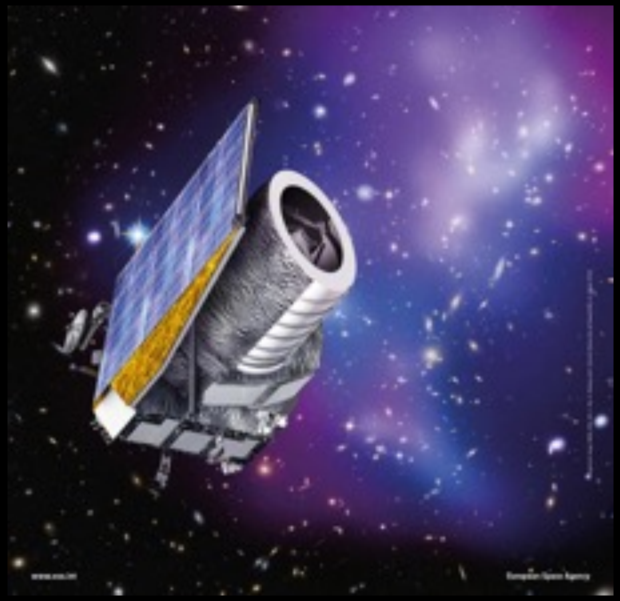
This is not satisfying…

- set independent constraints on mass / lifetime?
- make mass / lifetime measurements?

Break lifetime / mass degeneracy by higher redshift measurements



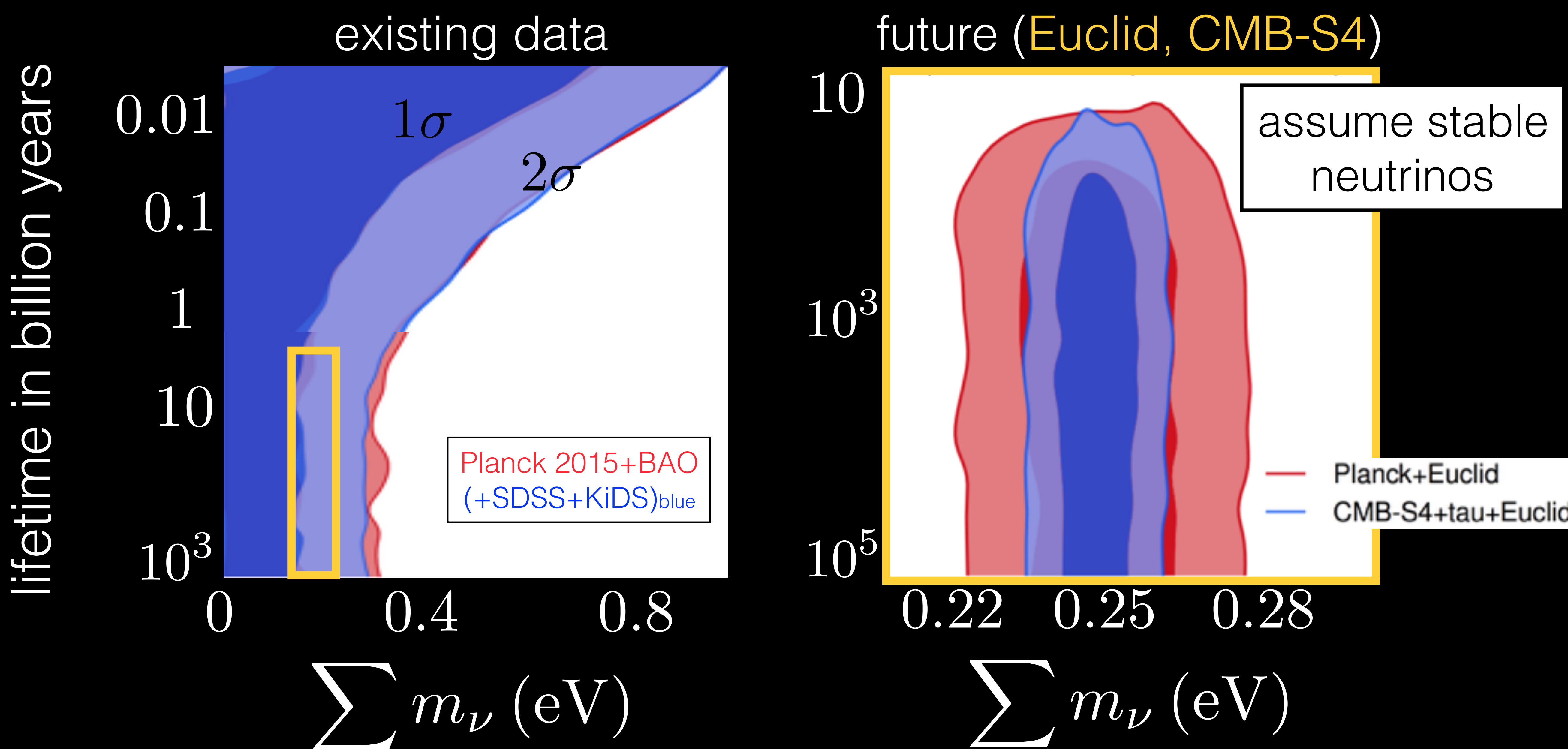
use the observation at higher redshift



e.g., Euclid (~2021)
0.4 ~< z ~< 2

Constrain neutrino mass & lifetime

Chacko, Dev, Du, Poulin, **YT** (in preparation, preliminary)



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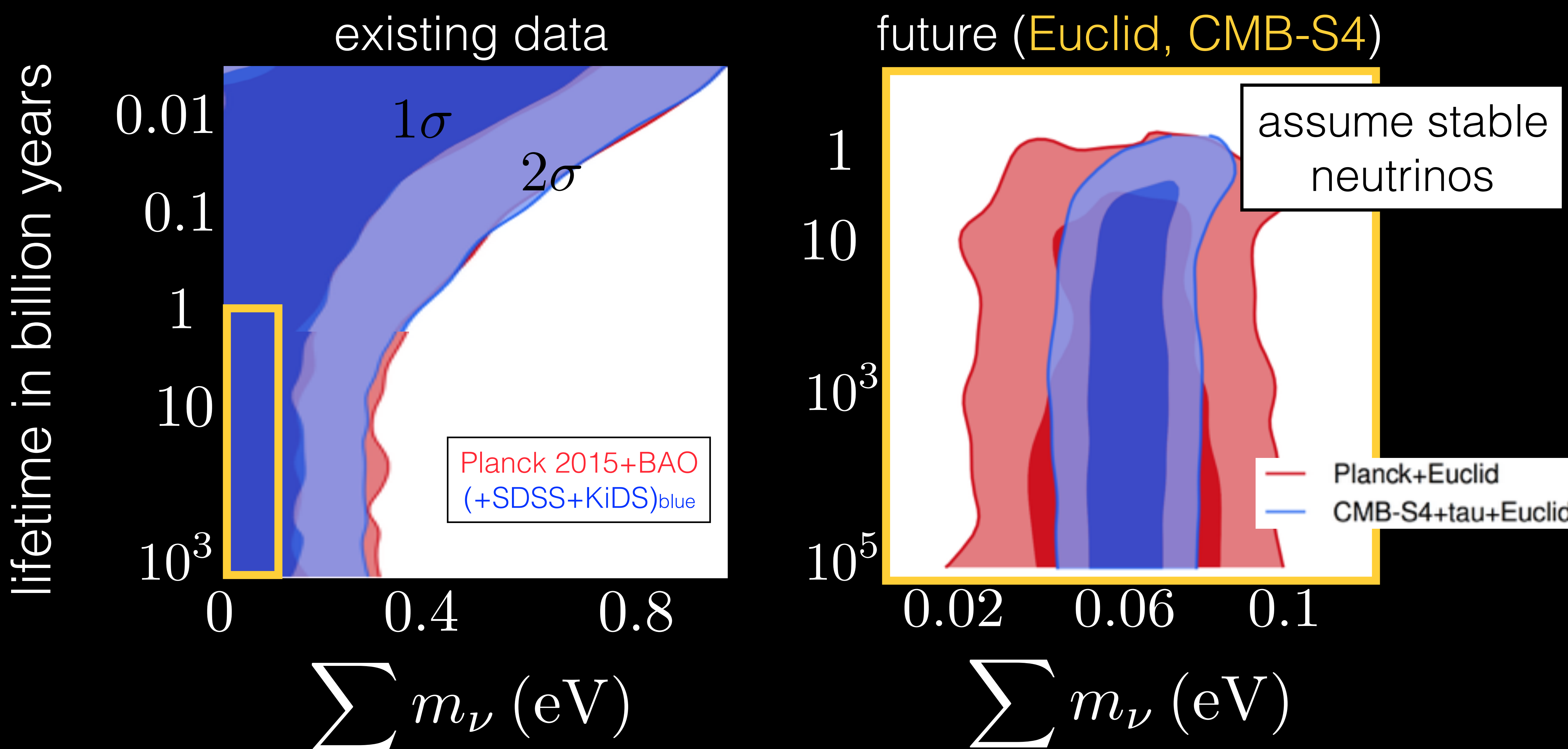
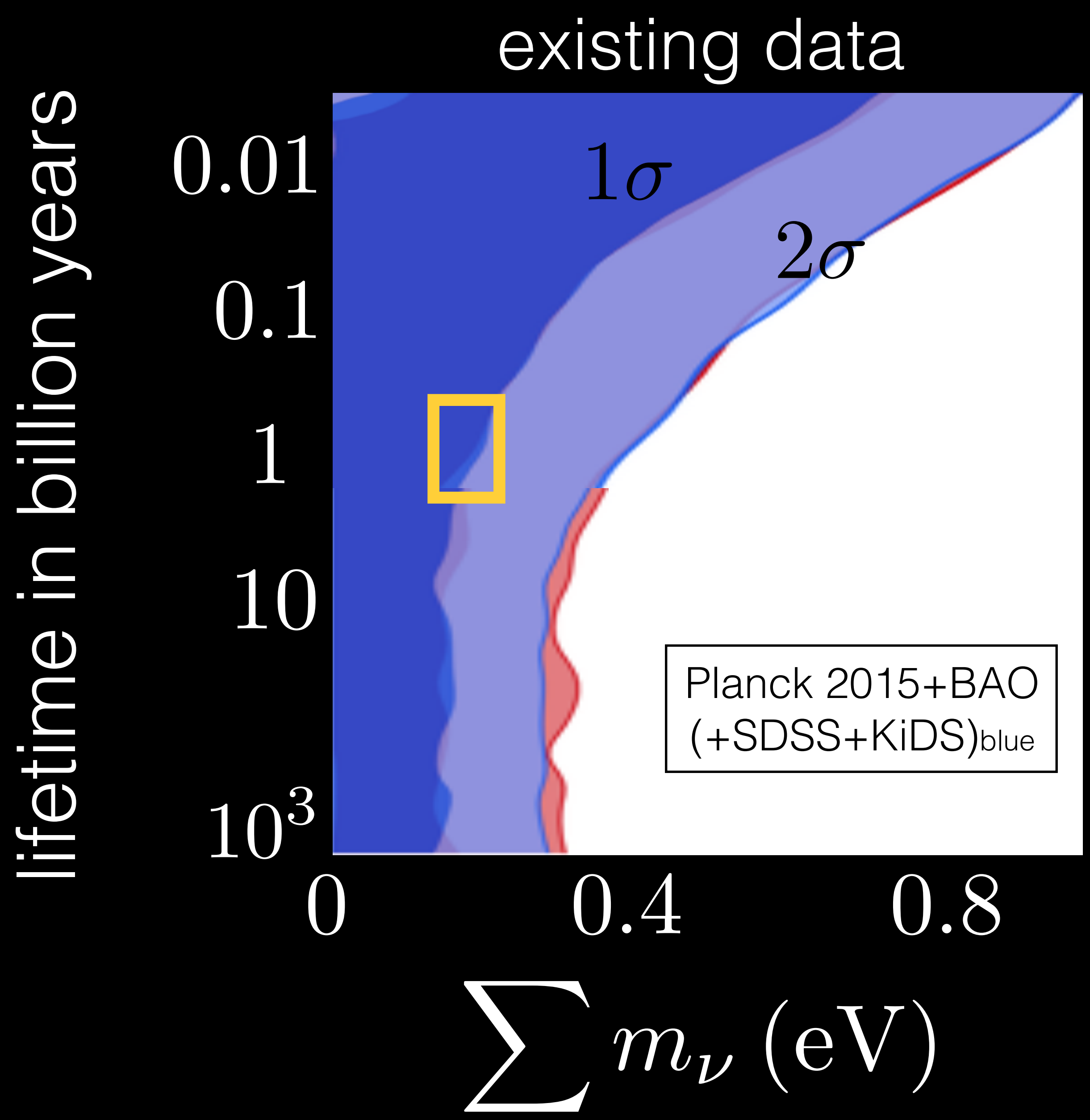
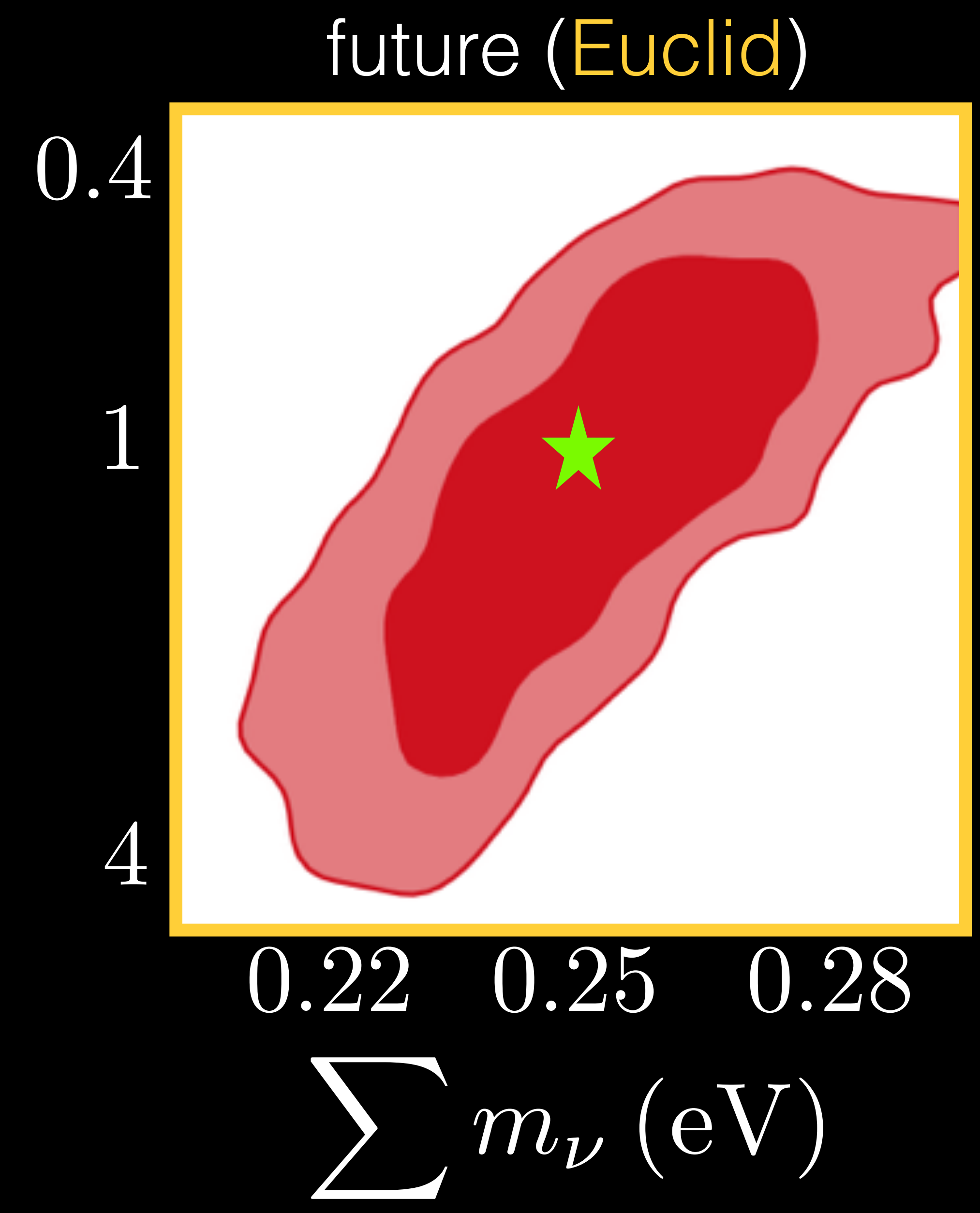


Measure neutrino mass & lifetime

Chacko, Dev, Du, Poulin, **YT** (in preparation, preliminary)





Conclusion

New physics that interacts very weakly to visible particles,
or only has invisible decays
may be studied using precision cosmological data

Near future Large Scale Structure and CMB lensing
measurements can constrain or even measure
neutrino lifetime that has a cosmological time scale

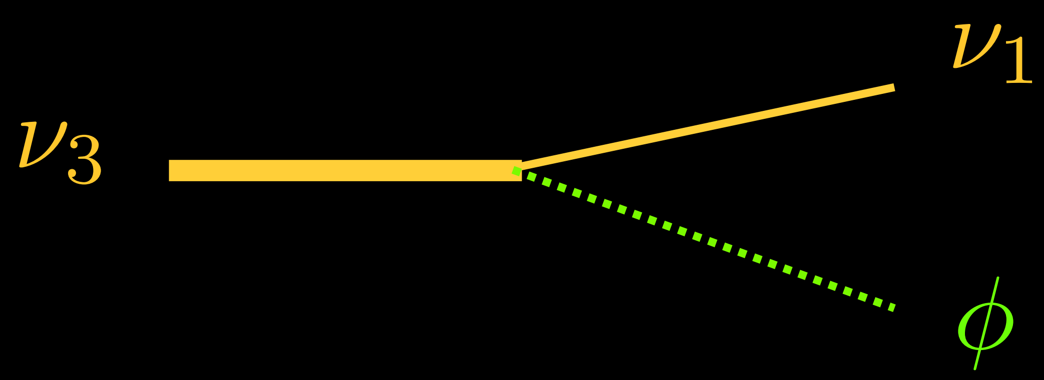
Backup

Example: Nu decay in a Majoron model

An explanation of the small neutrino mass

$$\frac{\Phi_\alpha \Phi_\beta}{\Lambda^3}\left(\bar{L}^c_\alpha \sigma_2 H\right)\left(H\sigma_2 L_\beta\right) \qquad \alpha,\ \beta = e,\ \mu,\ \tau$$

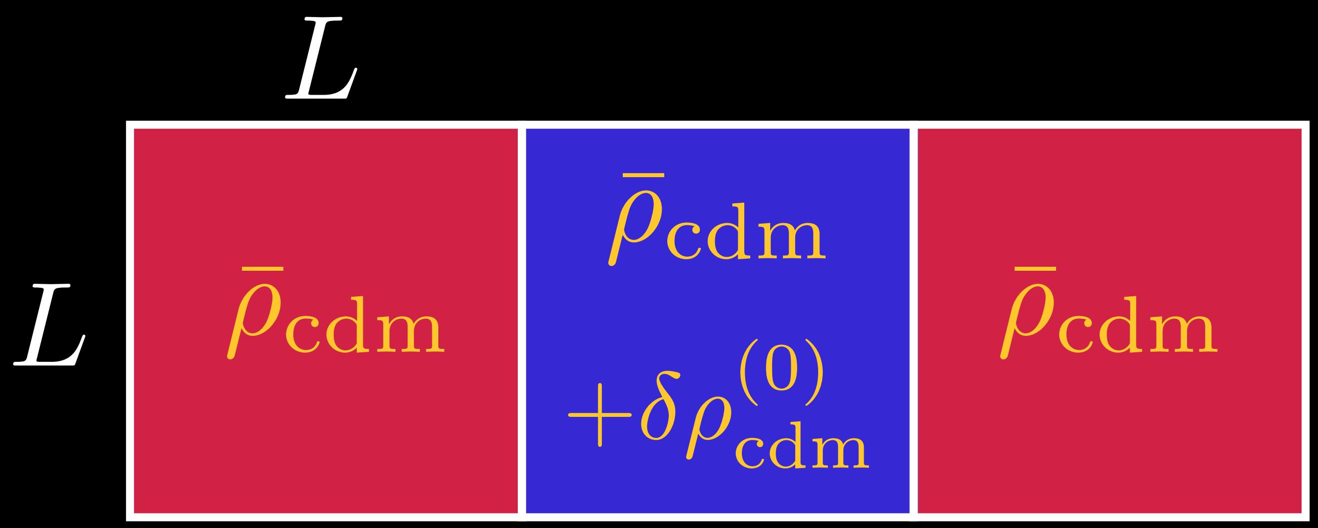
$$\Phi_\alpha = \frac{f_\alpha}{\sqrt{2}} e^{i\frac{\phi_\alpha}{f_\alpha}}$$



$$c\tau_{\nu_3} \sim \frac{1}{8\pi}\frac{m_\nu^3}{f_\alpha^2} = 5\,\mathrm{Gyrs}\left(\frac{0.1\,\mathrm{eV}}{\Delta m_\nu}\right)^3\left(\frac{\langle\Phi\rangle}{100\,\mathrm{TeV}}\right)^2.$$

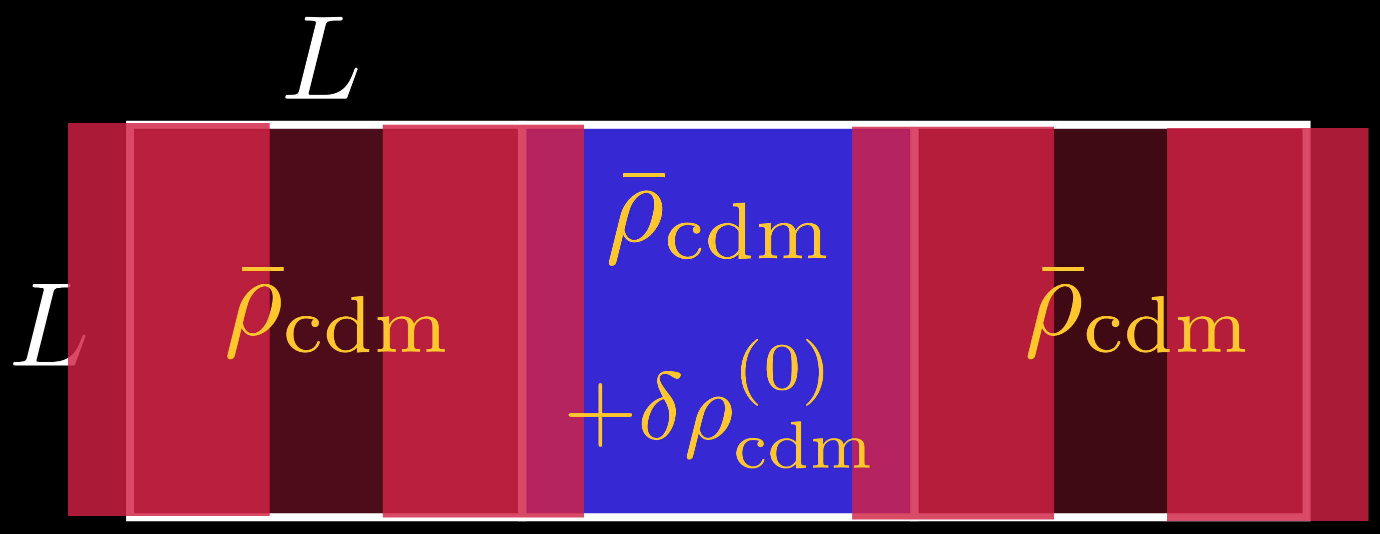
also see the example in 1909.05275

t_{eq}



~ primordial fluctuation

$t_{eq} + \Delta t$



matter falls into deeper gravitational well

$$\frac{\mathrm{d}^2 x}{\mathrm{d}\,t^2} \sim \frac{G\,\delta m_{\rm cdm}}{L^2}$$

$$\frac{\Delta x}{L} \sim \frac{\delta\rho_{\rm cdm}}{\bar{\rho}_{\rm cdm}} = \delta_{\rm cdm}$$

$$\frac{\mathrm{d}^2 \delta_{\rm cdm}}{\mathrm{d}\,t^2} \sim G\,\bar{\rho}_{\rm cdm}\,\delta_{\rm cdm}$$

$$t \to a$$

We ***don't quite know the physical time*** of structure formation, but we know it mainly begins at matter-radiation equilibrium

$$\rho_m(a_{eq}) = \rho_r(a_{eq})$$

and the physical time depends on energy density

$$\mathrm{d}\,t = \frac{\mathrm{d}\,a}{a\,H(a,\bar{\rho}_{\mathrm{tot}})} \approx H_0^{-1}\left(\frac{\rho_c}{\bar{\rho}_{\mathrm{tot}}}\right)^{\frac{1}{2}}\sqrt{a}\,\mathrm{d}a$$

Larger total energy, shorter physical time for structure formation

$$\frac{\mathrm{d}^2\delta_{\mathrm{cdm}}}{\mathrm{d}\,t^2} \sim G\,\bar{\rho}_{\mathrm{cdm}}\,\delta_{\mathrm{cdm}}$$

$$\mathrm{d}\,t \to \mathrm{d}\,a$$

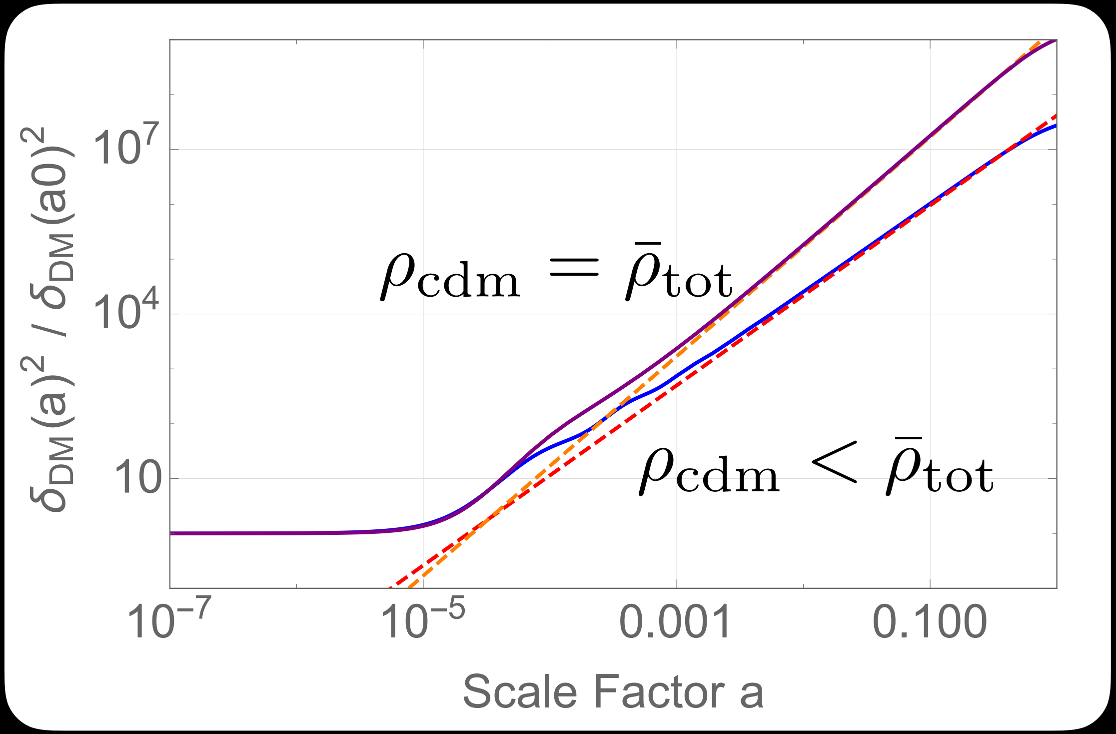
$$\left[\frac{\mathrm{d}^2}{\mathrm{d}a^2} - \frac{3}{2a}\frac{\mathrm{d}}{\mathrm{d}a} - \frac{1}{2a^2}\right]\delta_{\mathrm{cdm}}(a) \sim \frac{1}{a^2}\left(\frac{\bar{\rho}_{\mathrm{cdm}}}{\bar{\rho}_{\mathrm{tot}}}\right)\delta_{\mathrm{cdm}}$$

$$\delta_{\mathrm{cdm}}(a_f) = \delta_{\mathrm{cdm}}(a_i)\left(\frac{a_f}{a_i}\right)^{1-\frac{3}{5}\left(1-\frac{\bar{\rho}_{\mathrm{cdm}}}{\bar{\rho}_{\mathrm{tot}}}\right)}$$

``fluffy" matter reduces structure

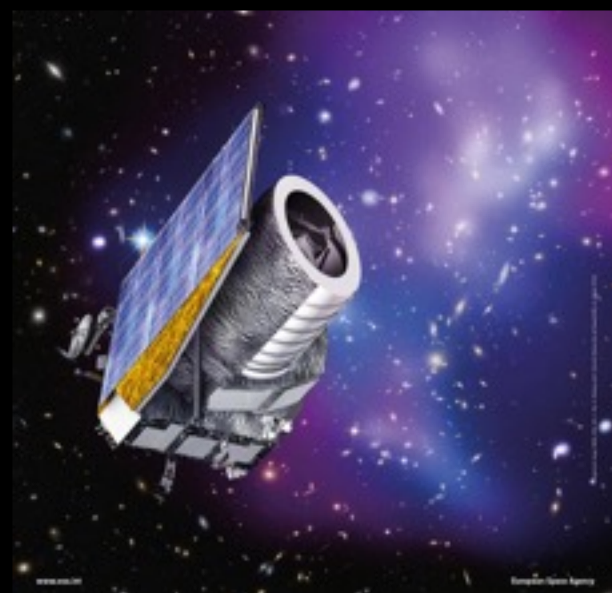
$$\bar{\rho}_{\rm tot} \approx \bar{\rho}_{\rm cdm} + \bar{\rho}_{\rm fluffy} \quad (\bar{\rho}_{\rm fluffy} \ll \bar{\rho}_{\rm cdm})$$

$$\delta_{\rm cdm}(a_f) = \delta_{\rm cdm}(a_i) \left(\frac{a_f}{a_i}\right)^{1 - \frac{3}{5}\frac{\bar{\rho}_{\rm fluffy}}{\bar{\rho}_{\rm cdm}}}$$

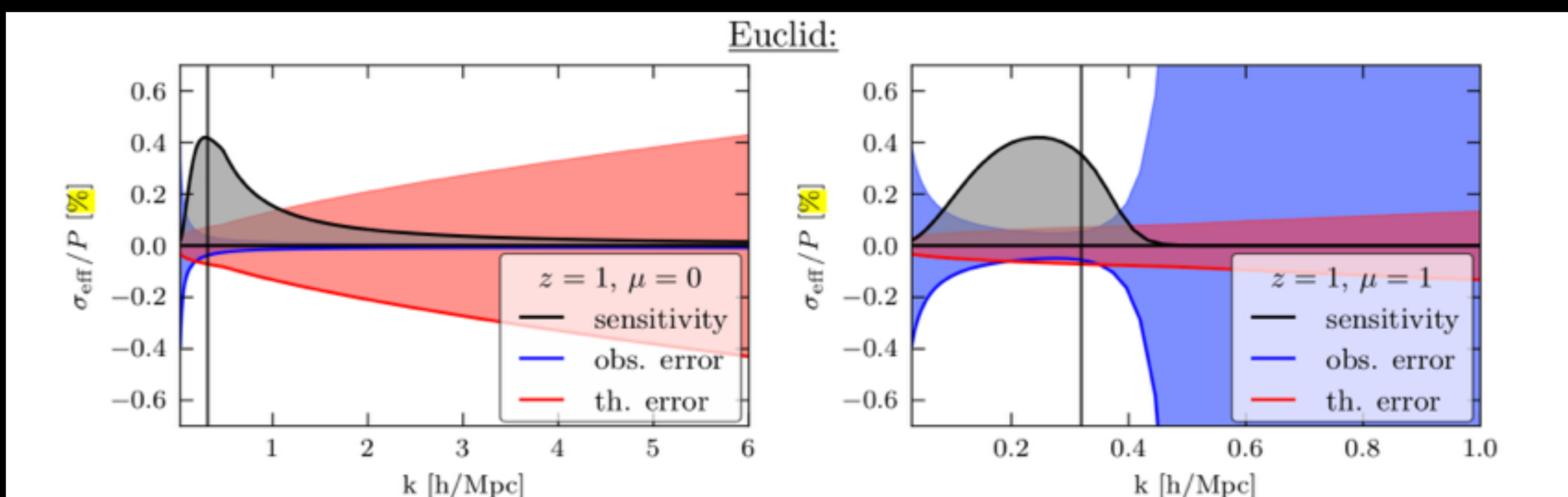


shortens the physical time for structure formation, but doesn't help to form structure

Expected sensitivity of Euclid experiment

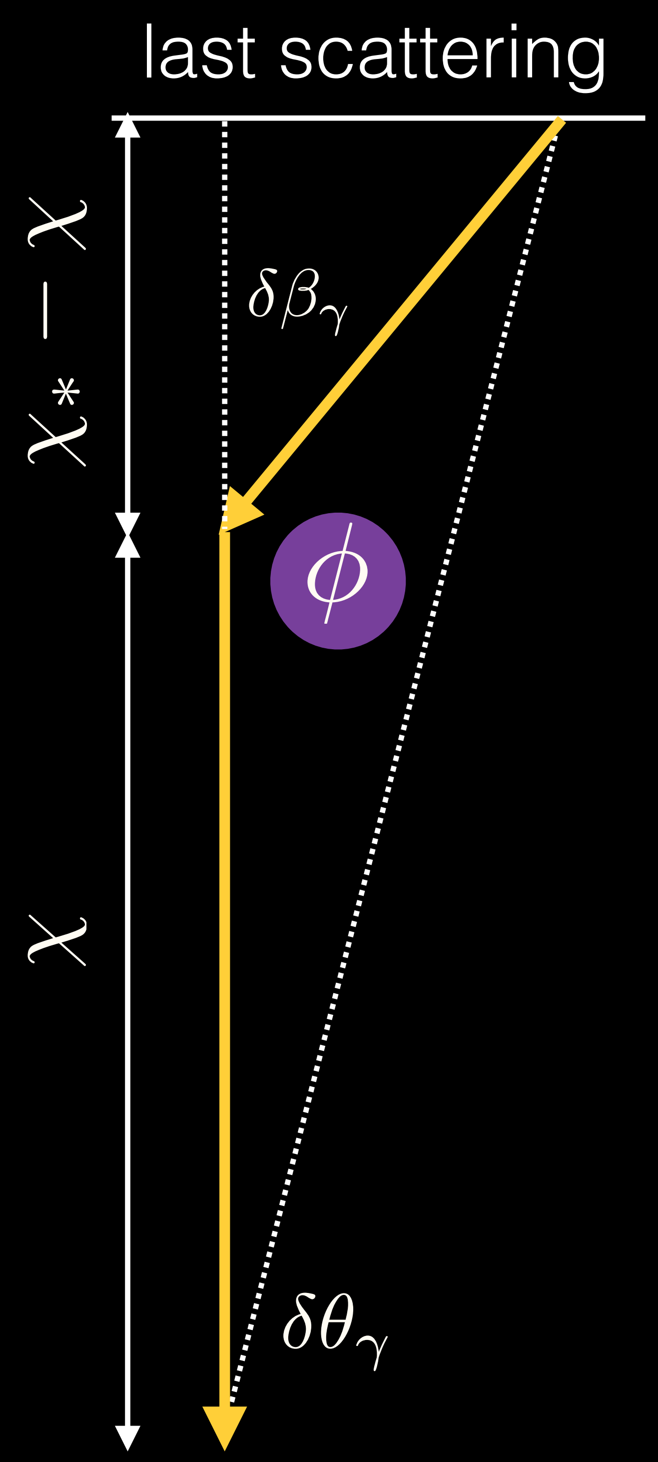


Euclid (launch 2021)
0.45 ~< z ~< 2.05



Sprenger, Archidiacono, Clesse, Lesgourgues (2018)

CMB measurement: lensing of CMB photon



$$\delta\beta_\gamma \sim \phi \propto \delta\rho_{\rm cdm}$$ (very roughly)

$$C_\ell^{\phi\phi} \sim \int \mathrm{d}\chi \langle \phi\phi \rangle \propto \int \mathrm{d}\chi \langle \delta_{\rm cdm}\delta_{\rm cdm} \rangle$$