Signals of New Physics in the Large Scale Structure Data

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U. Maryland / U. Notre Dame

Particle Physics in Computing Frontier
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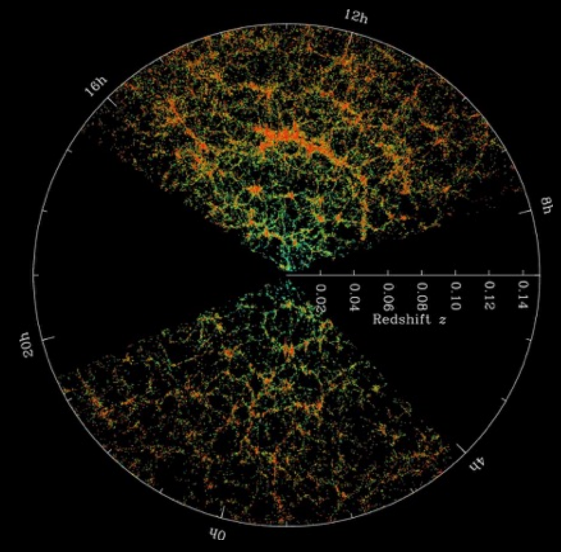


There’s no machine learning in this talk

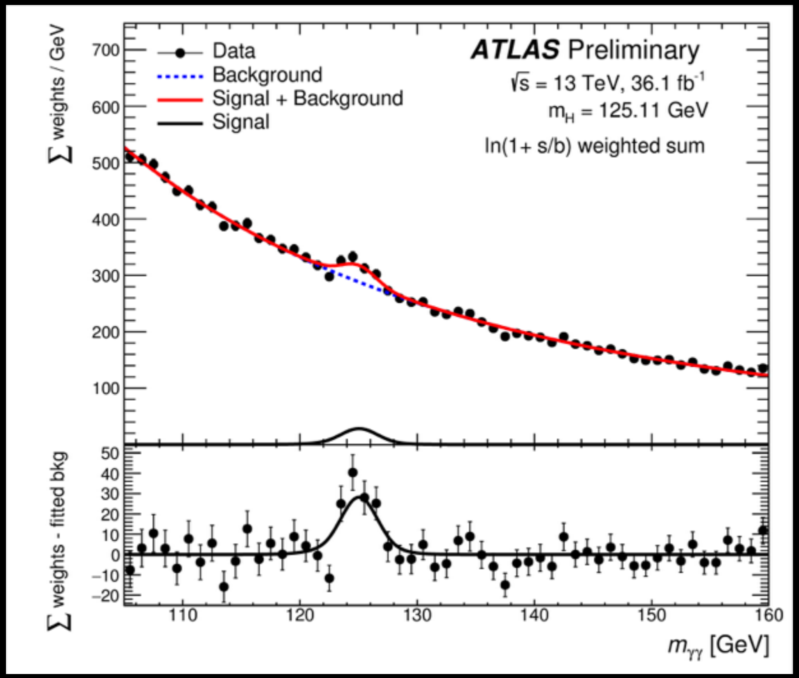
But I will explain:

What is the Large Scale Structure (LSS) of the universe?

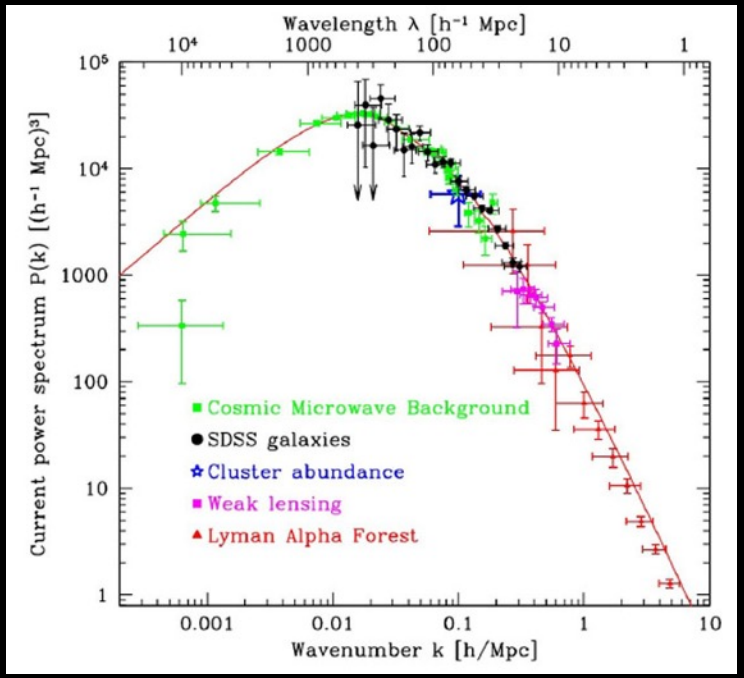
How can BSM physics show up?

What can BSM signals look like?

collider data



matter power spectrum



The plan:

Large Scale Structure (LSS) of the universe

LSS signal from “homogeneously-distributed” matter

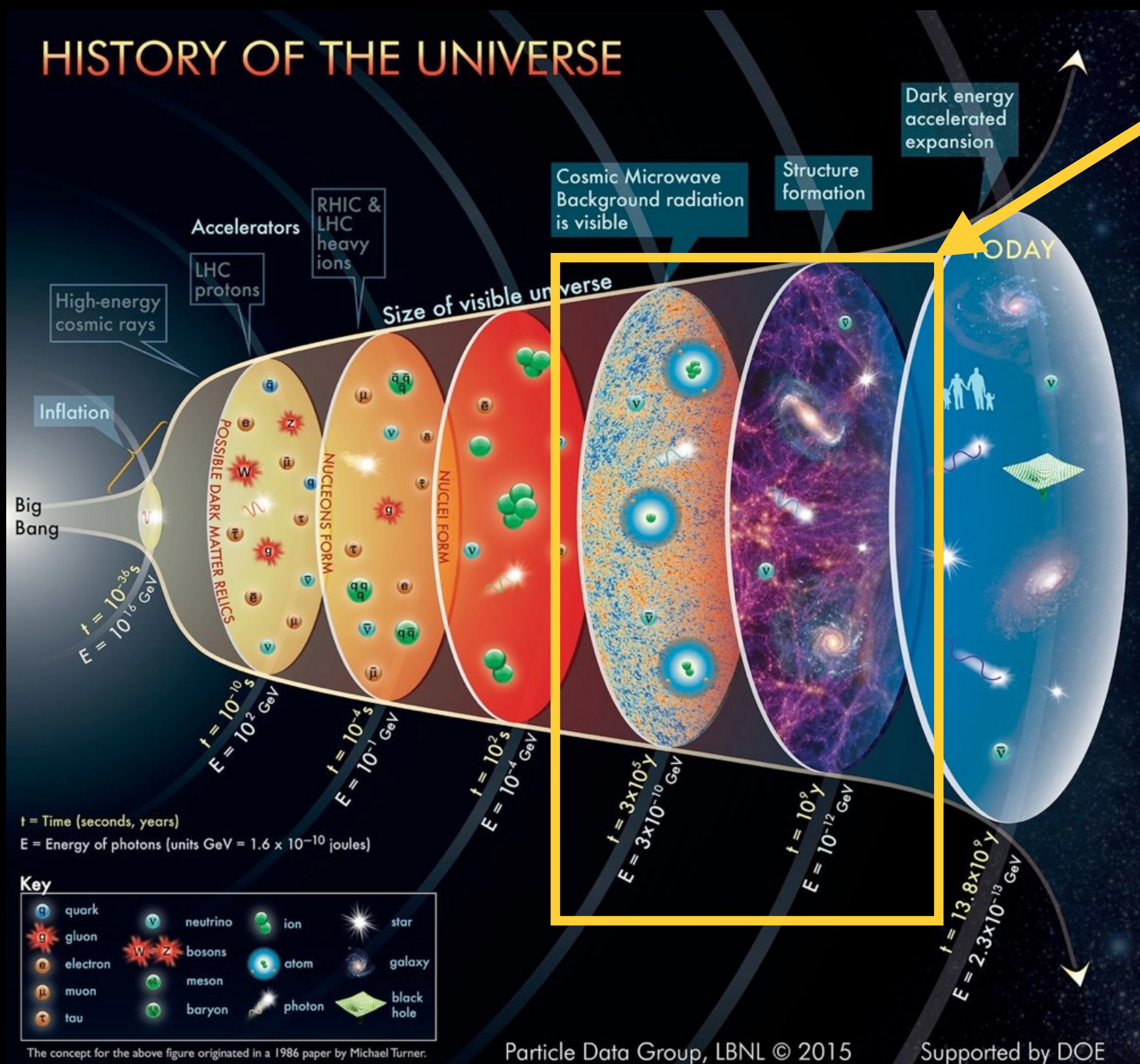
- example 1: Neutral Naturalness models
- example 2: signals of neutrino decay

Discussion:

- defects in CMB, LSS and the DM thermal distribution
  anisotropy in gravitational wave background…

Large Scale Structure of the universe

Time scale of the structure formation

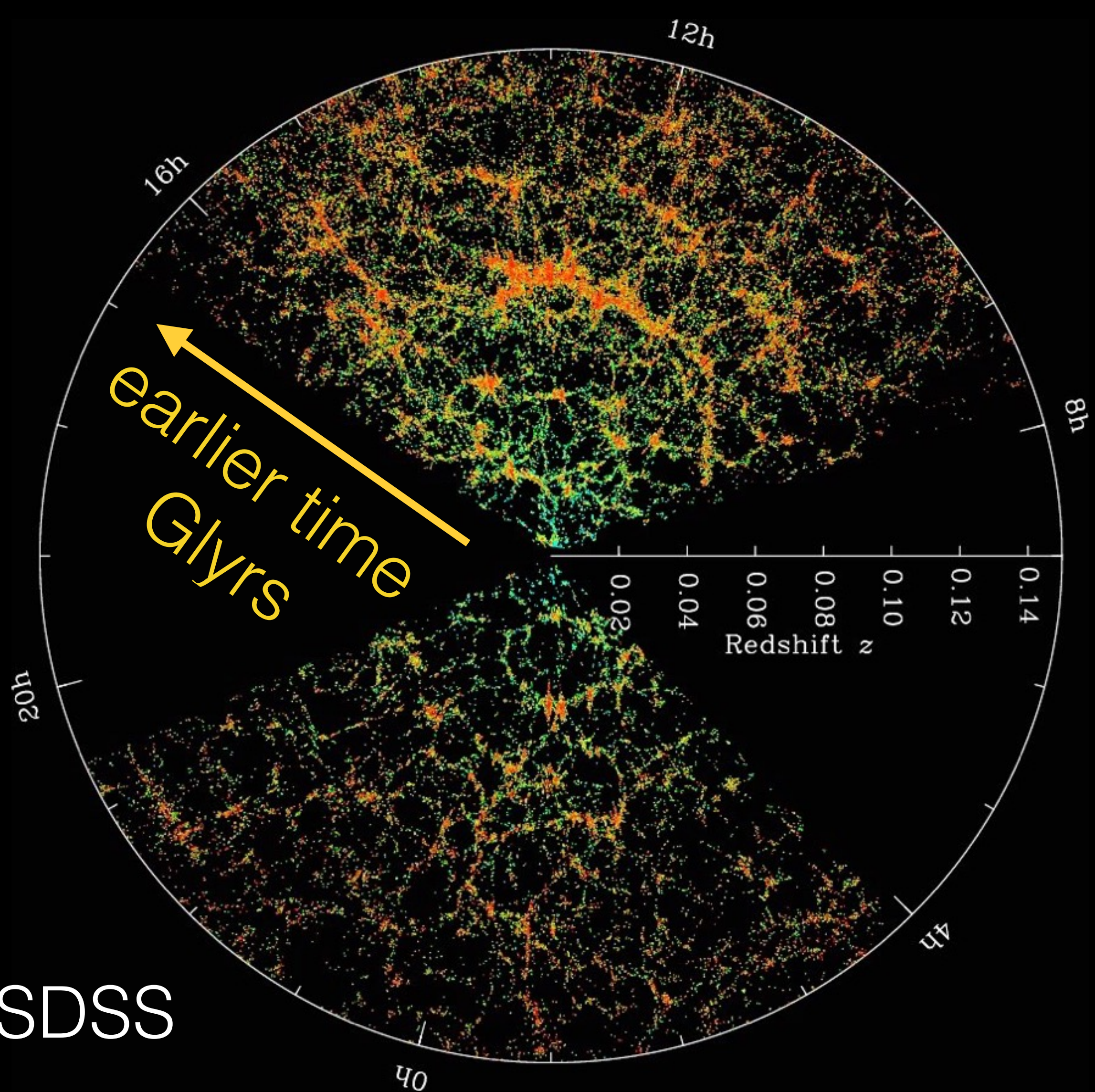


Cold DM clumps since matter-radiation equilibrium (T ~ eV, z ~ 3000)
and the structure formation continues until CC dominates (T ~ 10^-4 eV, z ~ 1)

New physics can modify LSS by

- change initial condition
- change expansion history
- change DM clumping

Several ways to see LSS, e.g., galaxy survey



SDSS

it's a 3D map

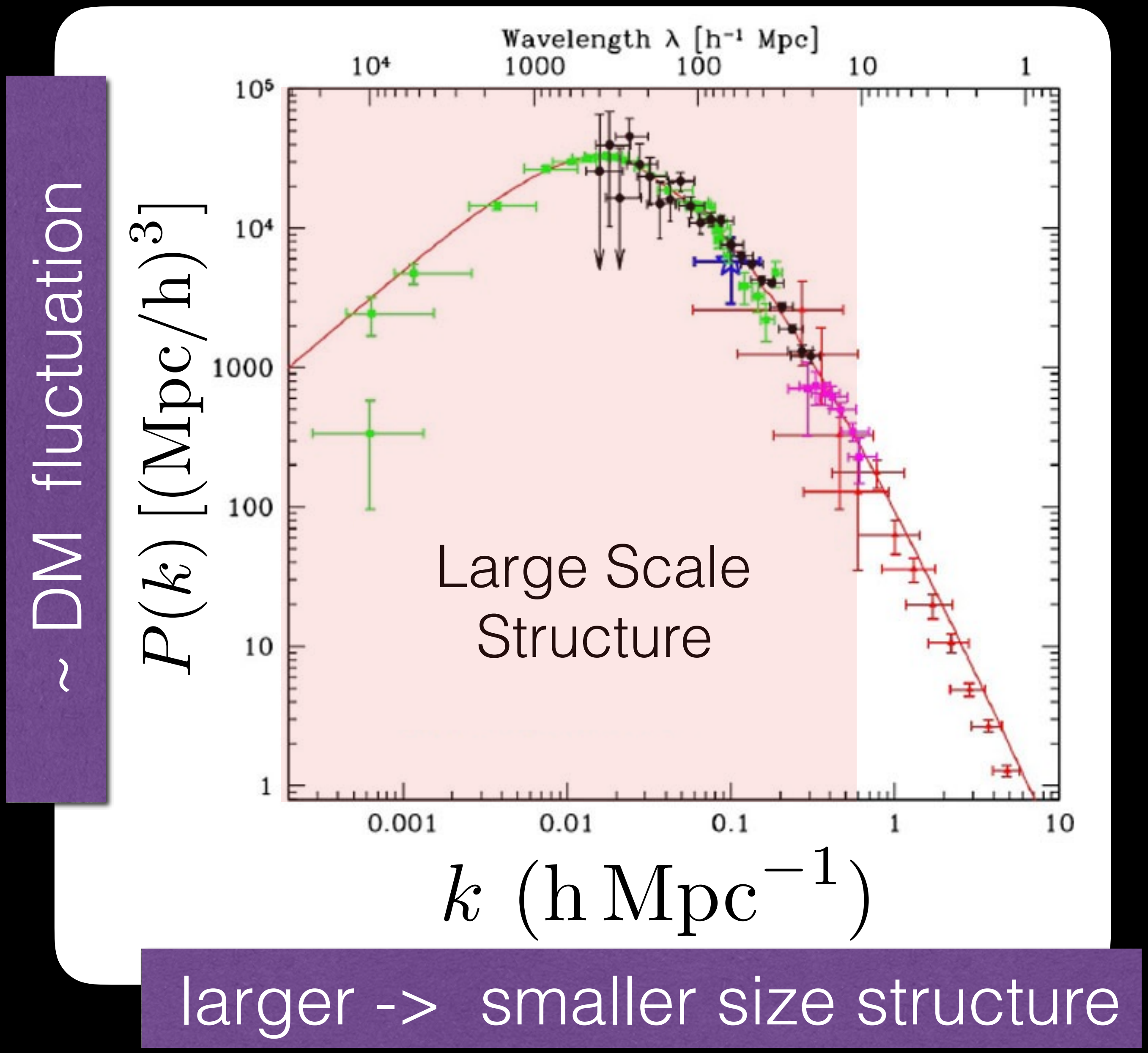
galaxy distribution is determined by cold dark matter distribution

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

density fluctuation is larger than CMB fluctuation due to structure formation

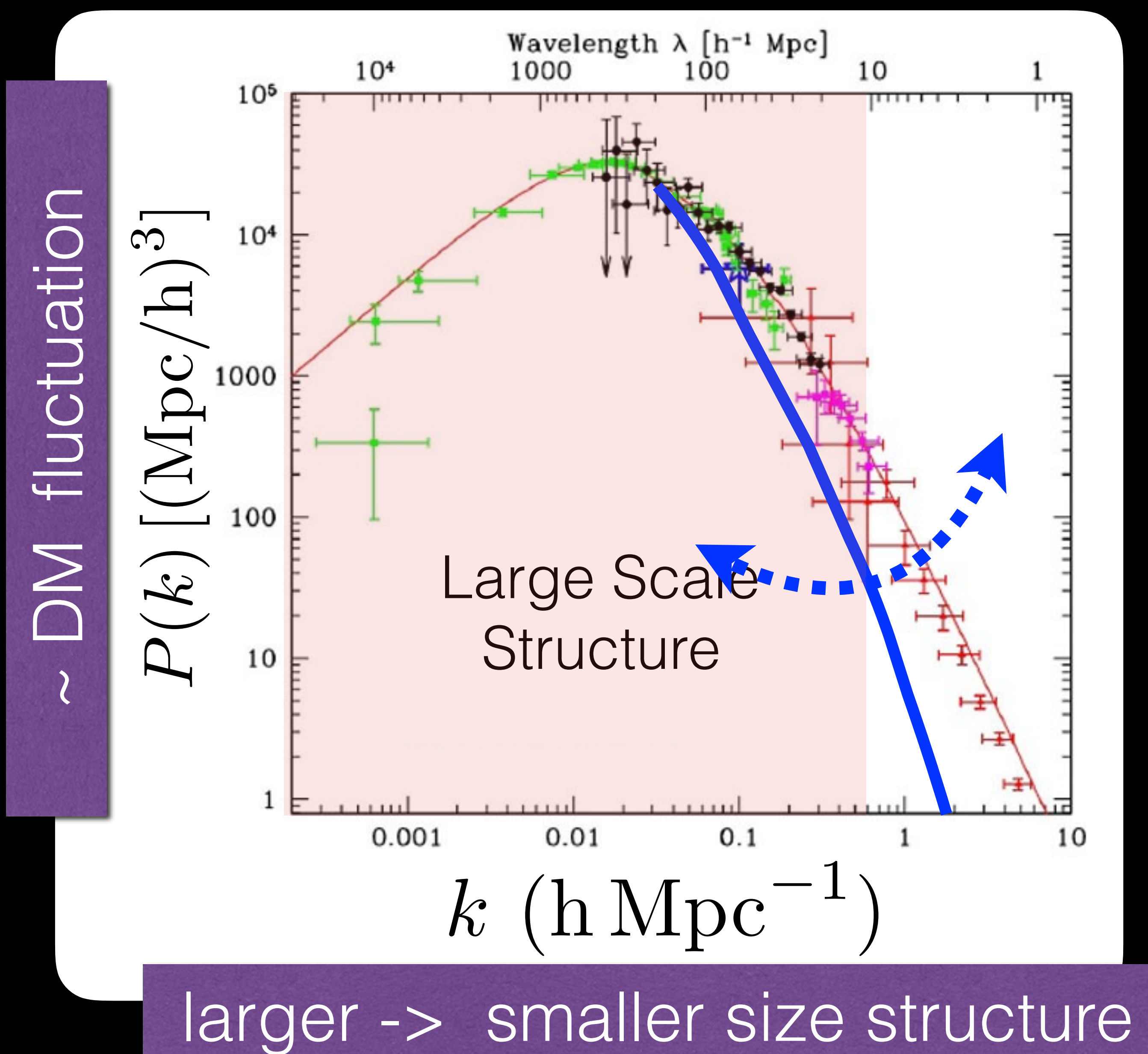
Matter power spectrum

$$P(k) \sim k^{-3}\delta_m(k)^2 \qquad k \sim L^{-1}$$



Matter power spectrum

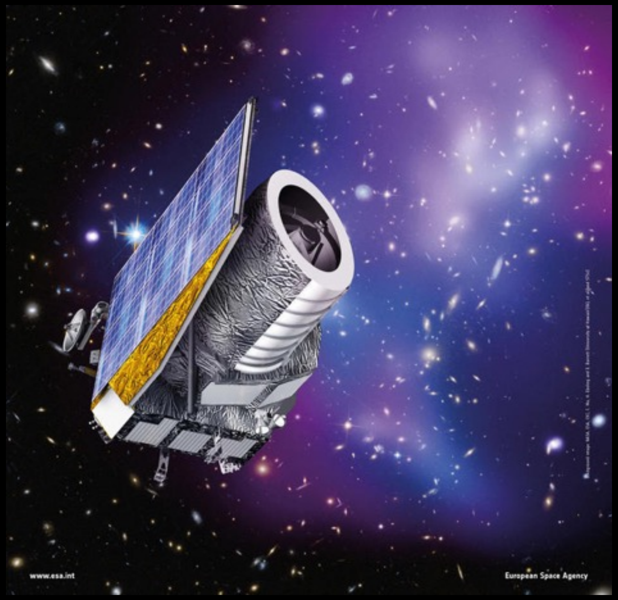
$$P(k) \sim k^{-3}\delta_m(k)^2 \qquad k \sim L^{-1}$$



New physics can change the structure ***everywhere*** in the universe

current measurements have about **10%** level precision

Higher precision measurements will come soon



Euclid (2022)

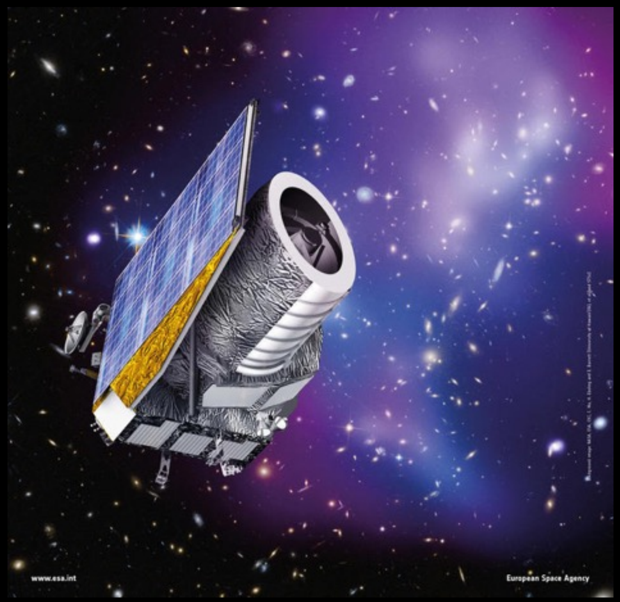
LSST (2023)

DESI (2019)

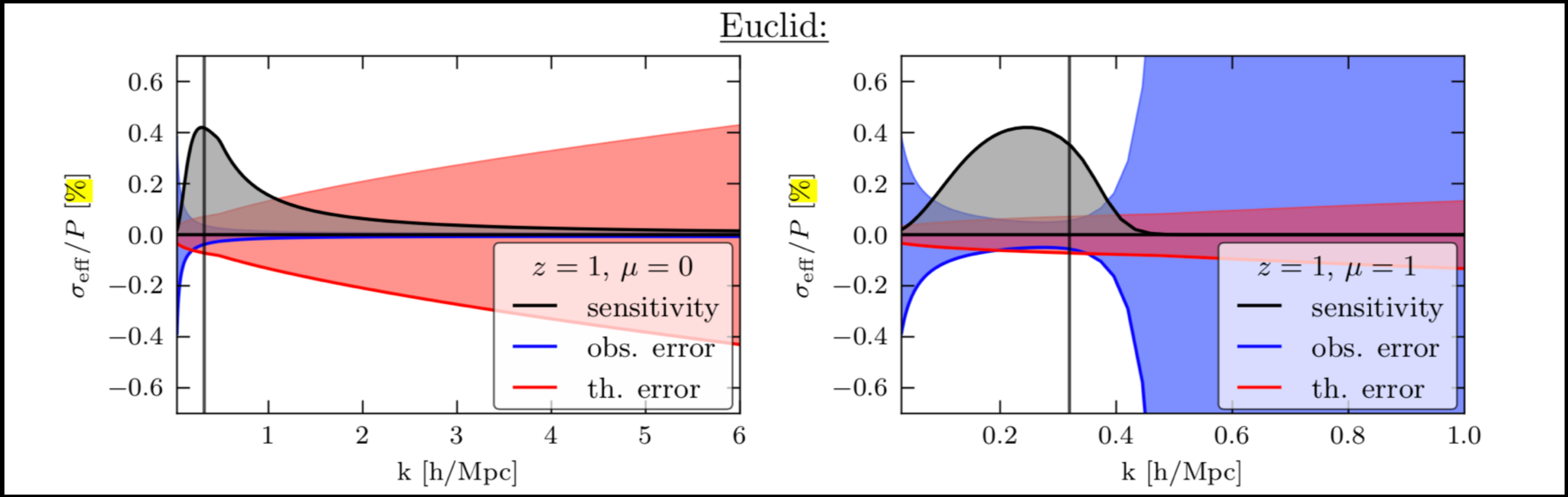
will be sensitive to ~ 0.1 - 1% change in matter power spectrum (mainly by increasing statistics)

CMB-S4 (202?)

E.g., Euclid experiment

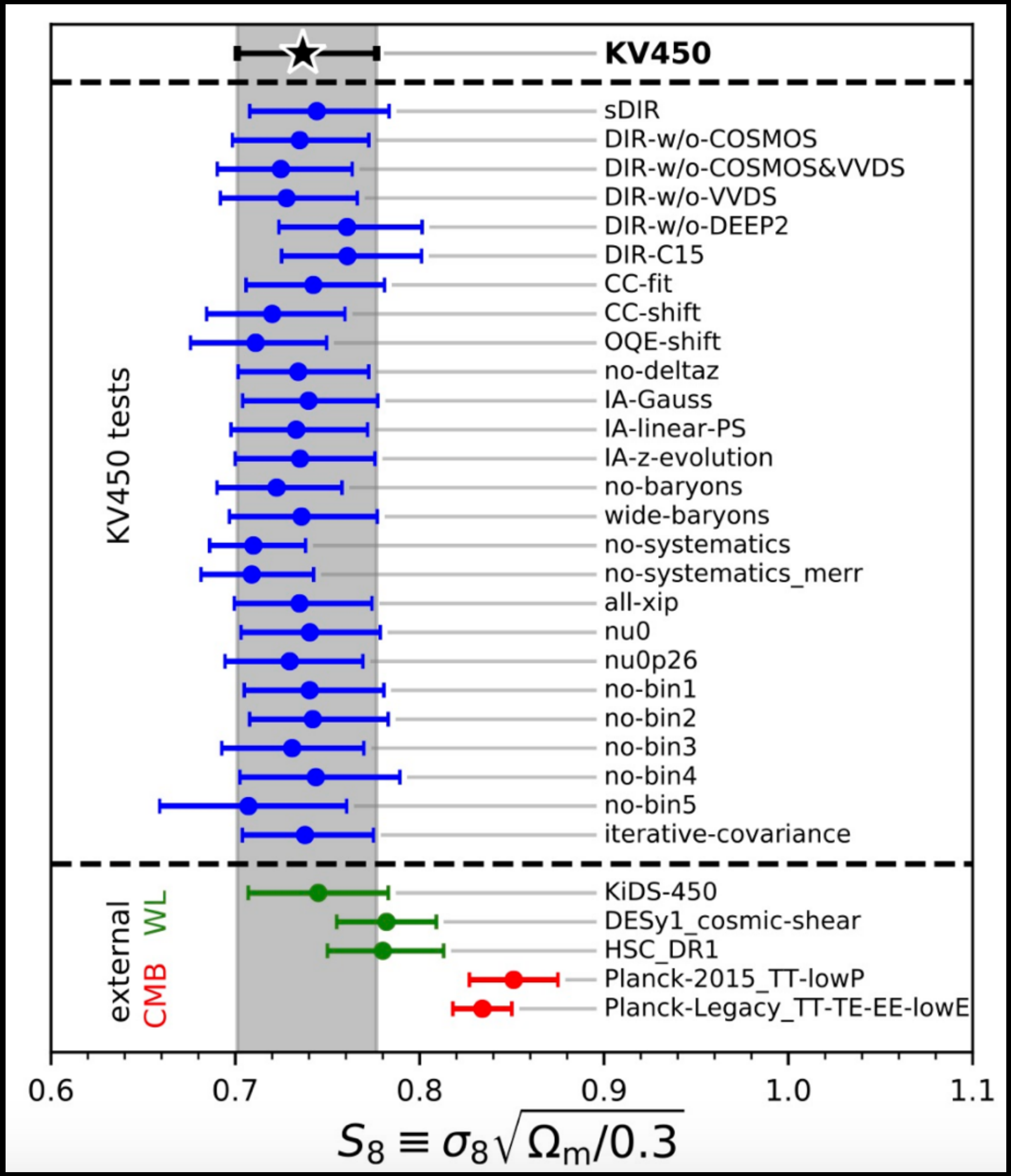


Euclid (plan to launch at 2022)
0.45 ~< z ~< 2.05



Sprenger, Archidiacono, Clesse, Lesgourgues (2018)

sigma 8 (S8) anomaly?



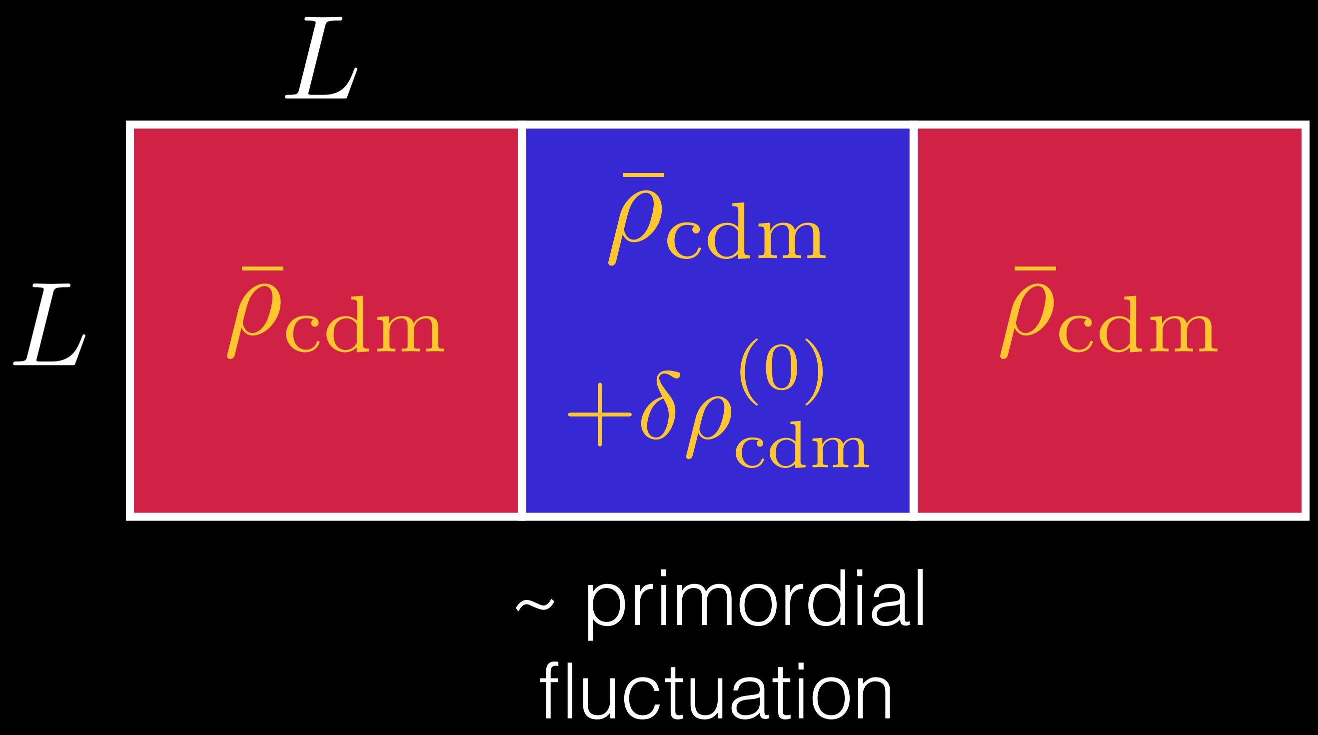
KV450

all the late time density contrast measurements get smaller results than Planck fit by assuming LCDM (2~3 sigma level)

LSS signals from

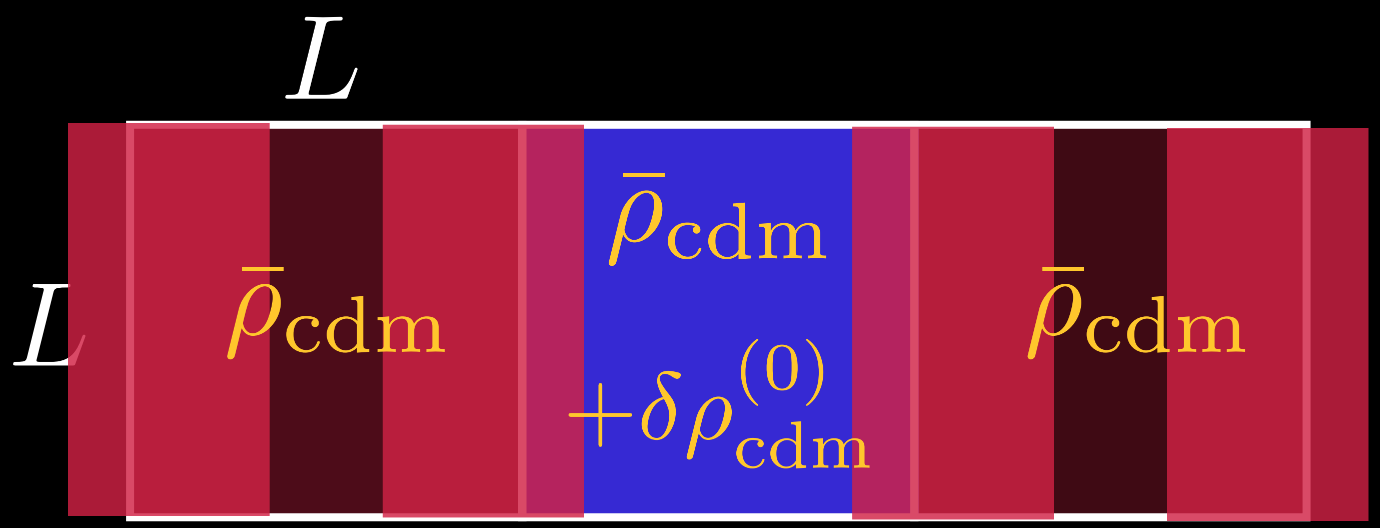
homogeneously distributed matter

t_{eq}



L
L
$\bar{\rho}_{\rm cdm}$
$\bar{\rho}_{\rm cdm}$
$+\delta\rho^{(0)}_{\rm cdm}$
$\bar{\rho}_{\rm cdm}$
~ primordial
fluctuation

$t_{eq} + \Delta t$



matter falls into deeper gravitational well

Newtonian physics

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

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

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

$$t \to a$$

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

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

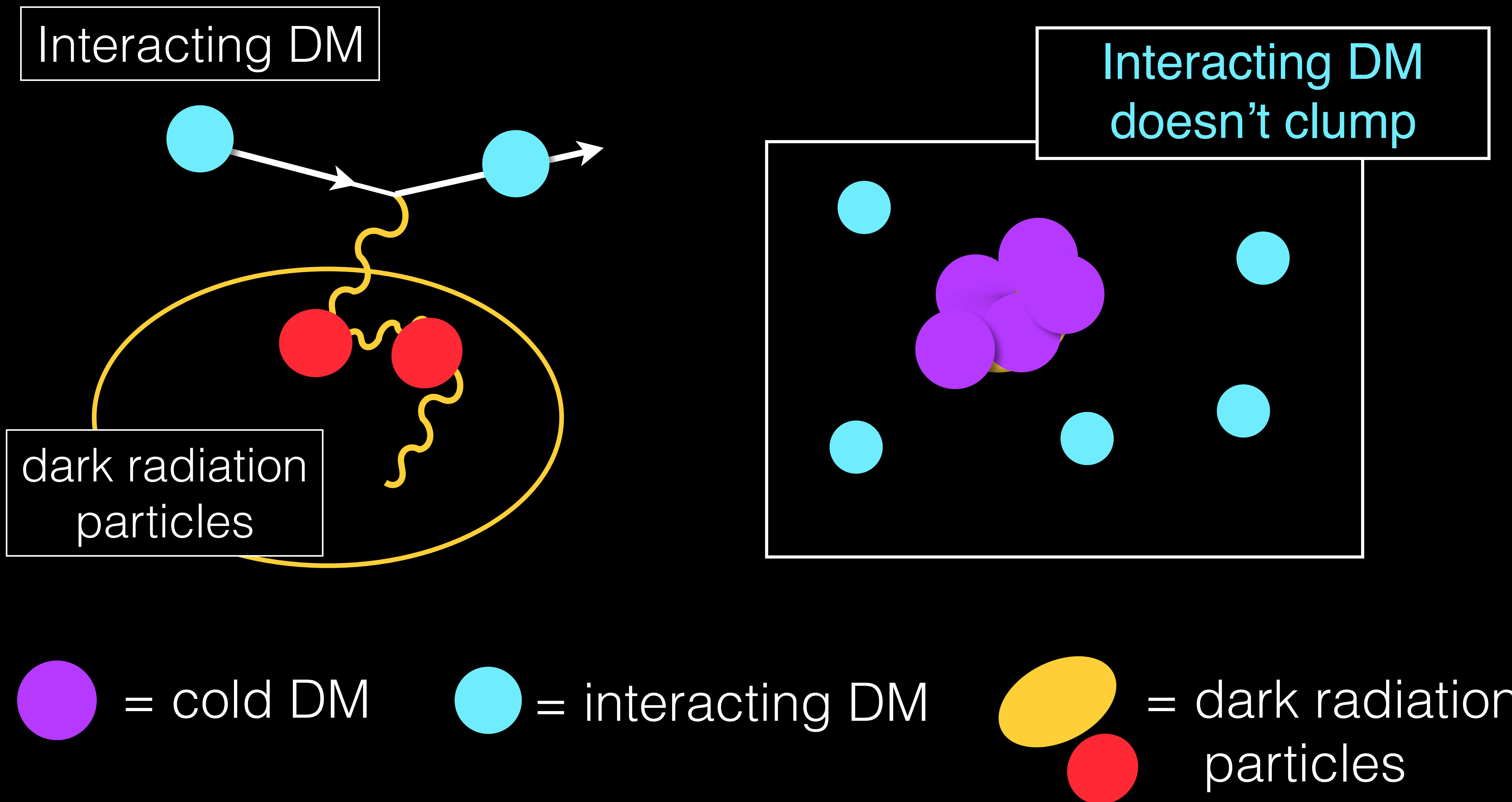
$$\mathrm{d}\,t \to \mathrm{d}\,a$$

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

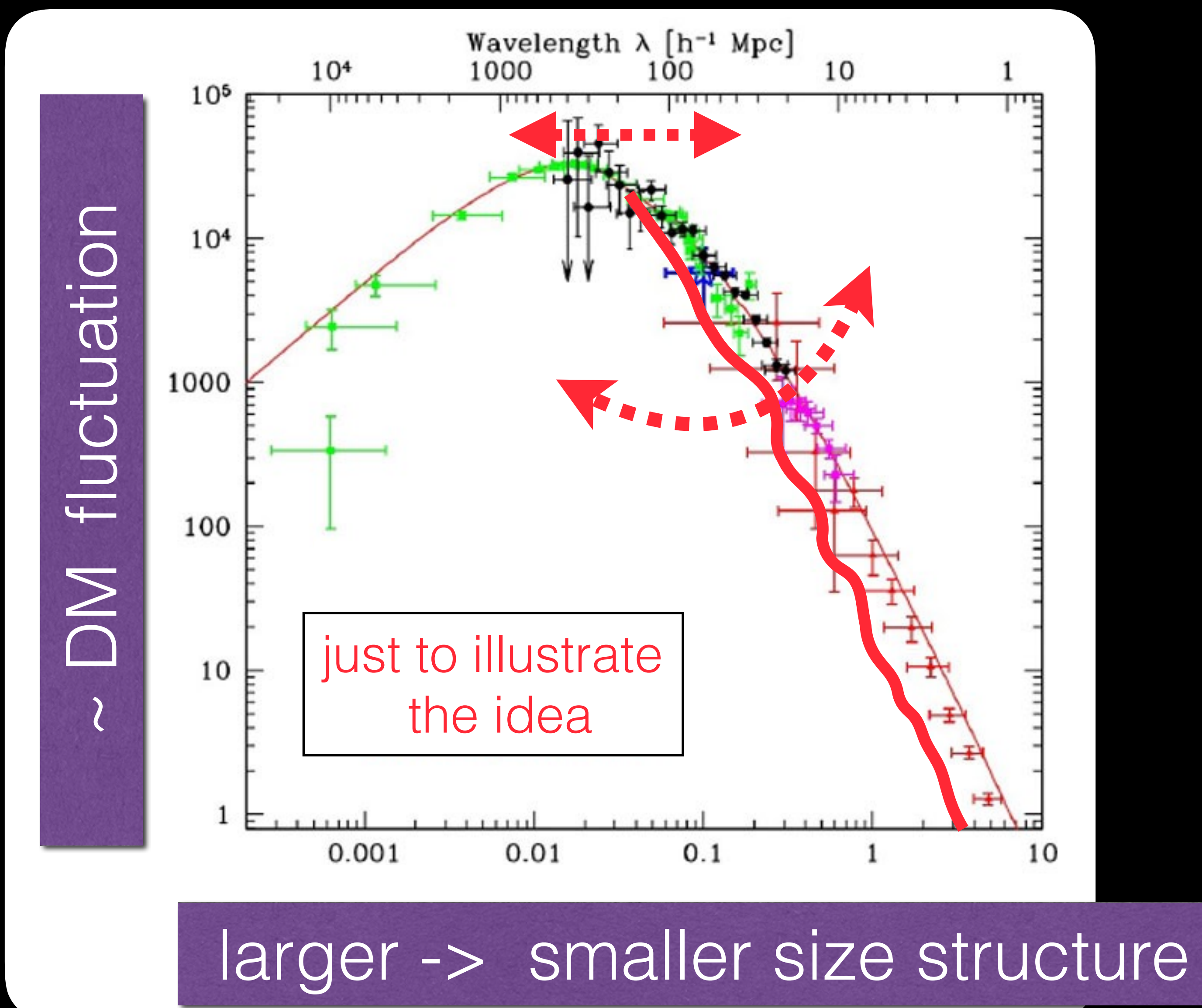
$$\delta_{\mathrm{cdm}}(a_f) = \delta_{\mathrm{cdm}}(a_i)\left(\frac{a_f}{a_i}\right)^{1-\frac{3}{5}\left(1-\frac{\bar{\rho}_{\mathrm{cdm}}}{\bar{\rho}_{\mathrm{tot}}}\right)}$$

If having matter that doesn’t clump => slow down the growth!

Matter-radiation interaction can suppress LSS



Matter-radiation interaction can suppress LSS



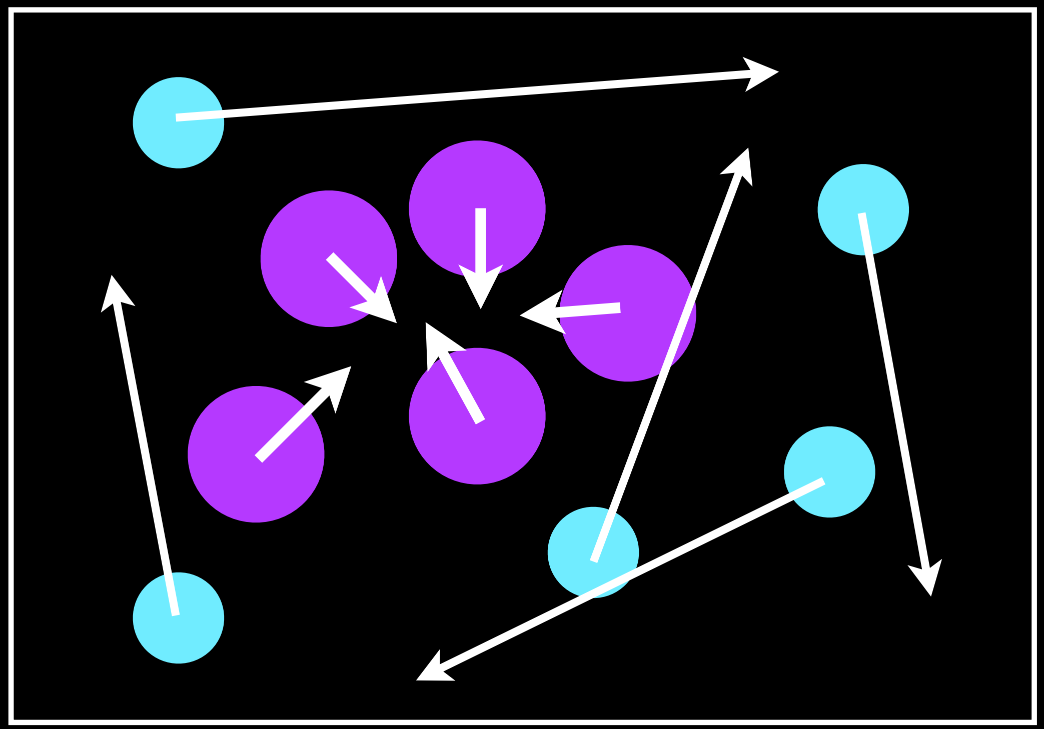
a scale-dependent suppression

Dark Acoustic Oscillations (Cyr-Racine el al (2013))

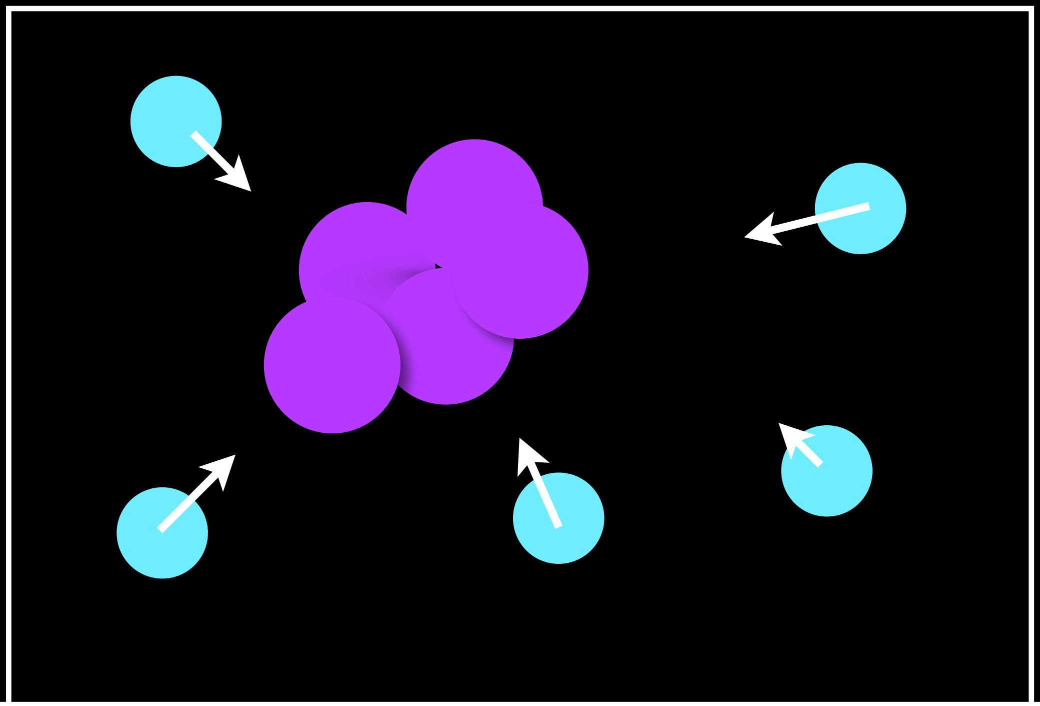
see e.g., Chacko, Cui, Hong, Okui, **YT** (2016), Prilepina, **YT** (2017), Chacko, Curtin, Geller, **YT** (2018), Dessert, Kilic, Trendafilova (2018)

Warm DM (or massive neutrinos) suppress LSS

neutrinos look massless when
dark matter begins to clump

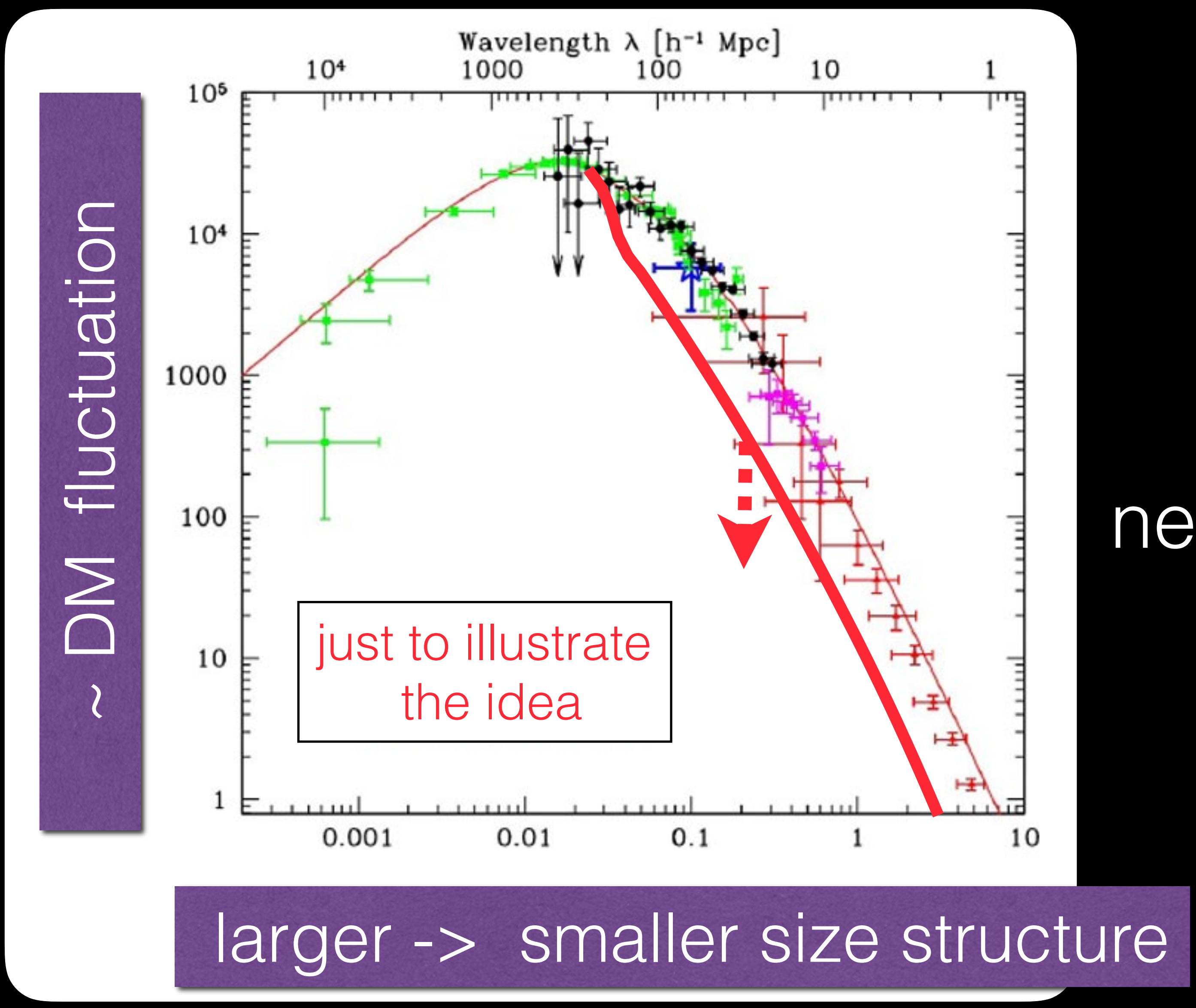


neutrinos finally slow down
dark matter already forms structure



they don't help structure formation

Warm DM (or massive neutrinos) suppress LSS



reduce structure before neutrinos become non-relativistic

see e.g., Chacko, Dev, Du, Poulin, **YT** (2019) and the reference therein

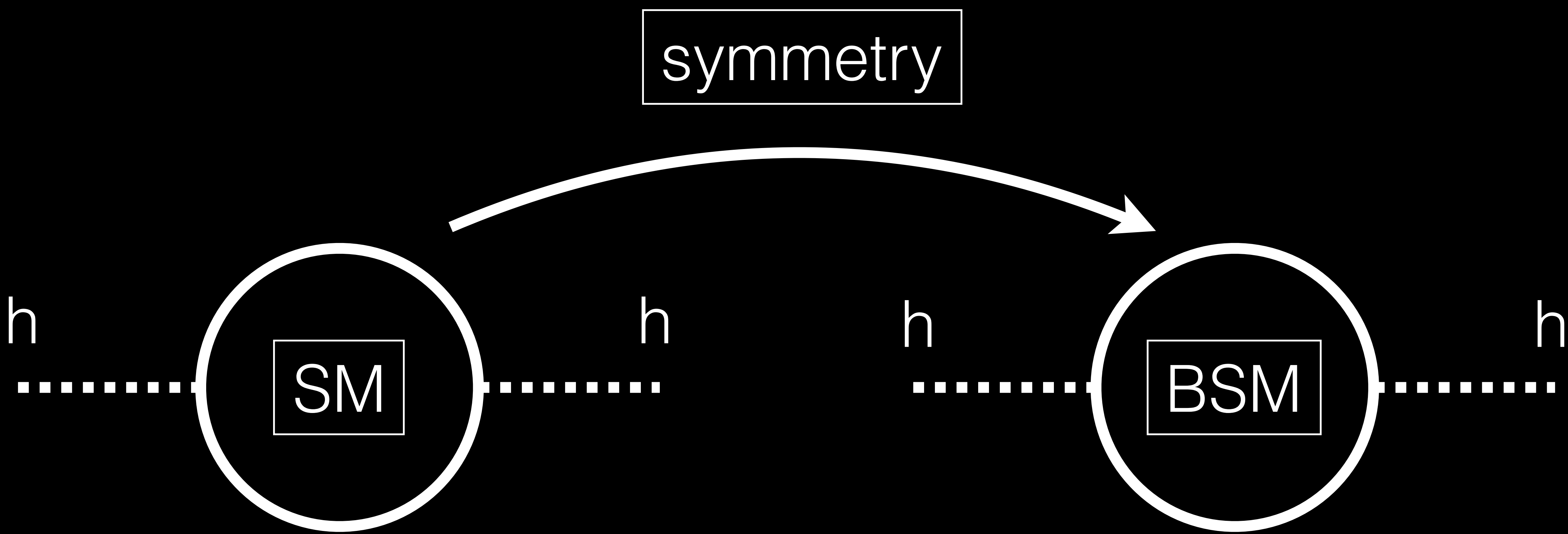
Eg.1: LSS signals of Hidden Naturalness model

— an example of Mirror Twin Higgs model

(other examples: *N*naturalness model, …)

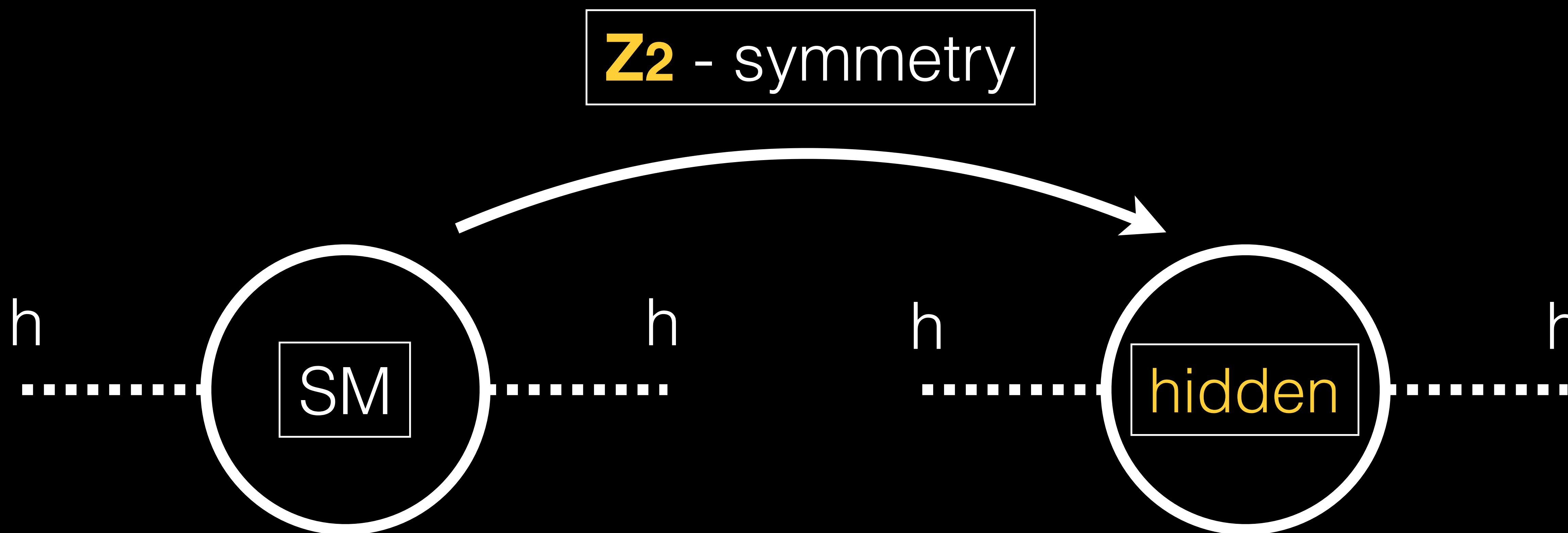
Common feature: (almost) no collider signatures

=> have to study them in cosmology


symmetry
h
SM
h
h
BSM
h

The Mirror Twin Higgs model (MTH)

Chacko, Goh, Harnik (2005)



contain SM-like particles in the “twin”-sector

BUT with lower-T and slightly larger VEV ($3<f/v<5$)

A long time ago, when T ~ eV

Mirror Twin Sector

GARDIANS OF THE
ELECTROWEAK FORCE

A long time ago, in a hidden
universe that is so close to us

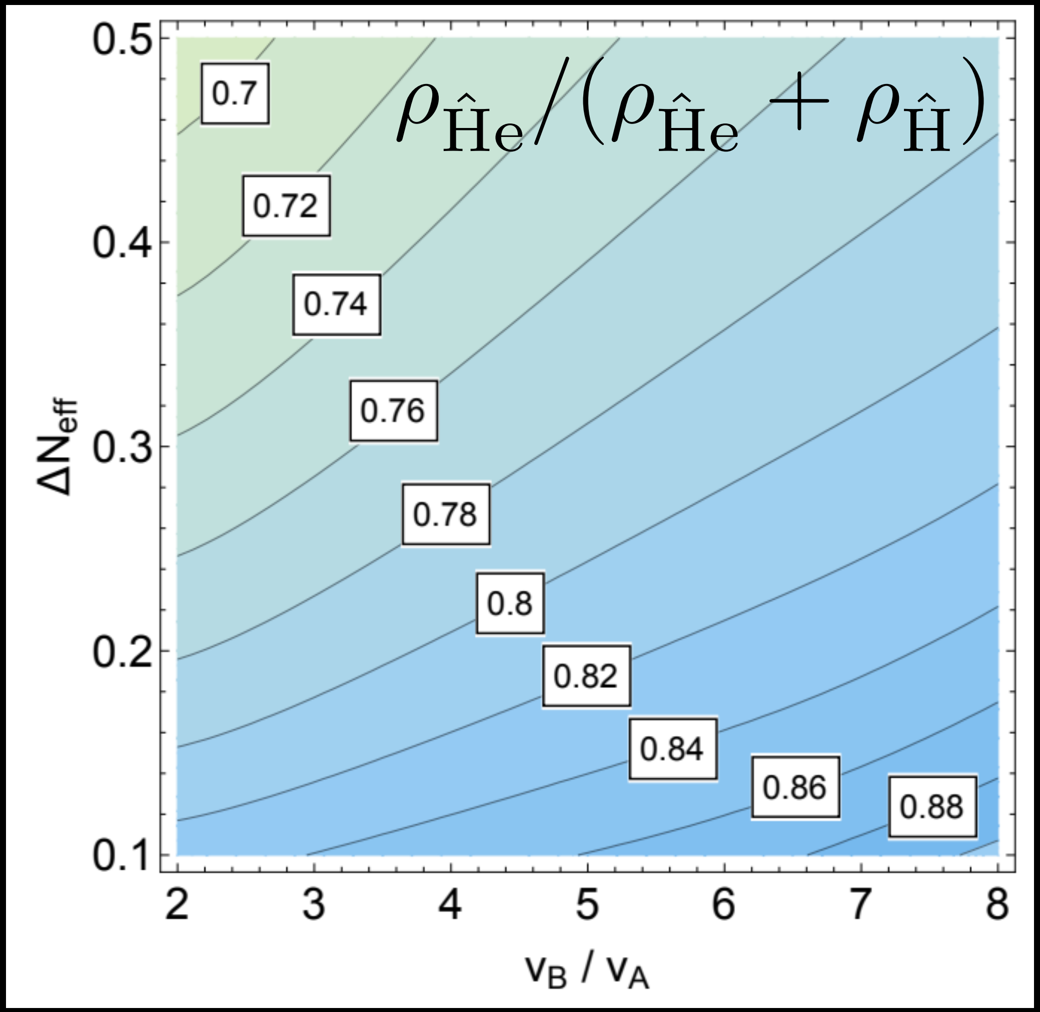
There are twin particles
maintaining the stability of the
Universe

mirror baryons (p/n/e)

dark radiation (photon/neutrinos)

We know the twin helium/hydrogen composition

Chacko, Curtin, Geller, **YT** (2018)

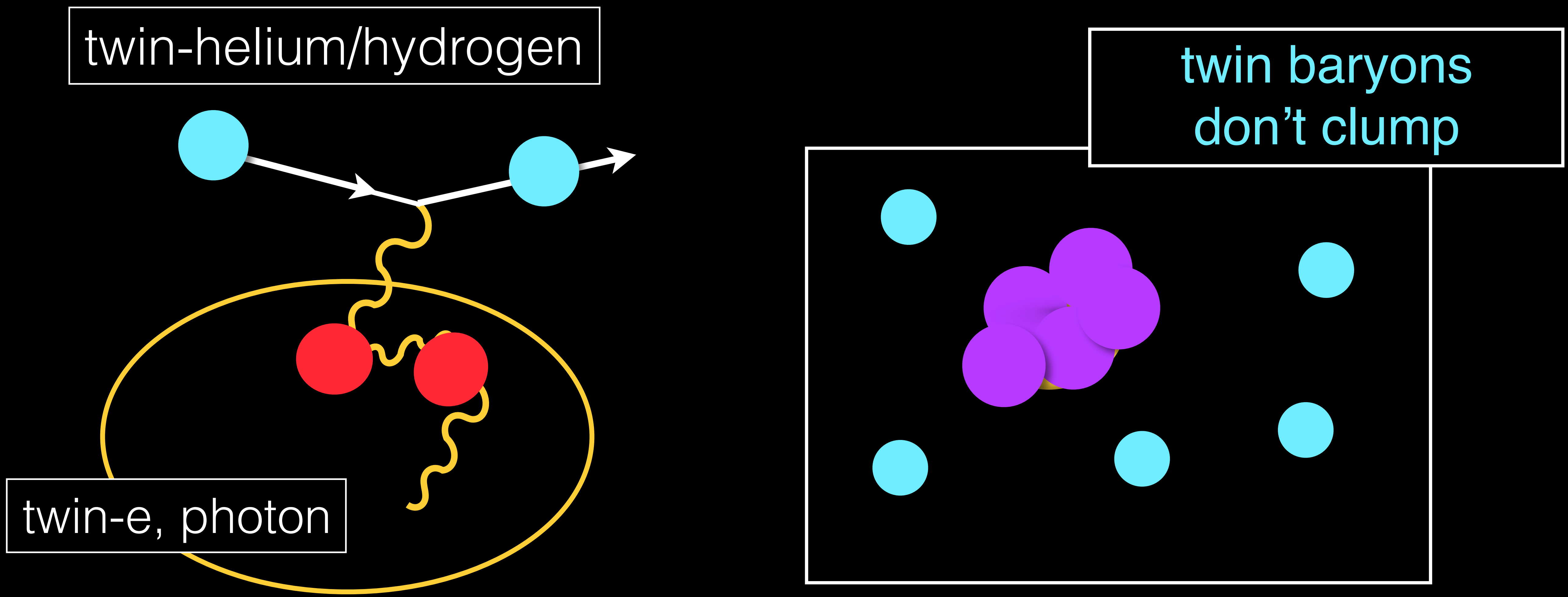


Mirror: ~ 75% mass is in **mirror He**

SM: ~ 75% mass is in **Hydrogen**

twin helium dominates the
twin baryon acoustic oscillations

Twin Acoustic Oscillations



= cold DM

= twin baryons

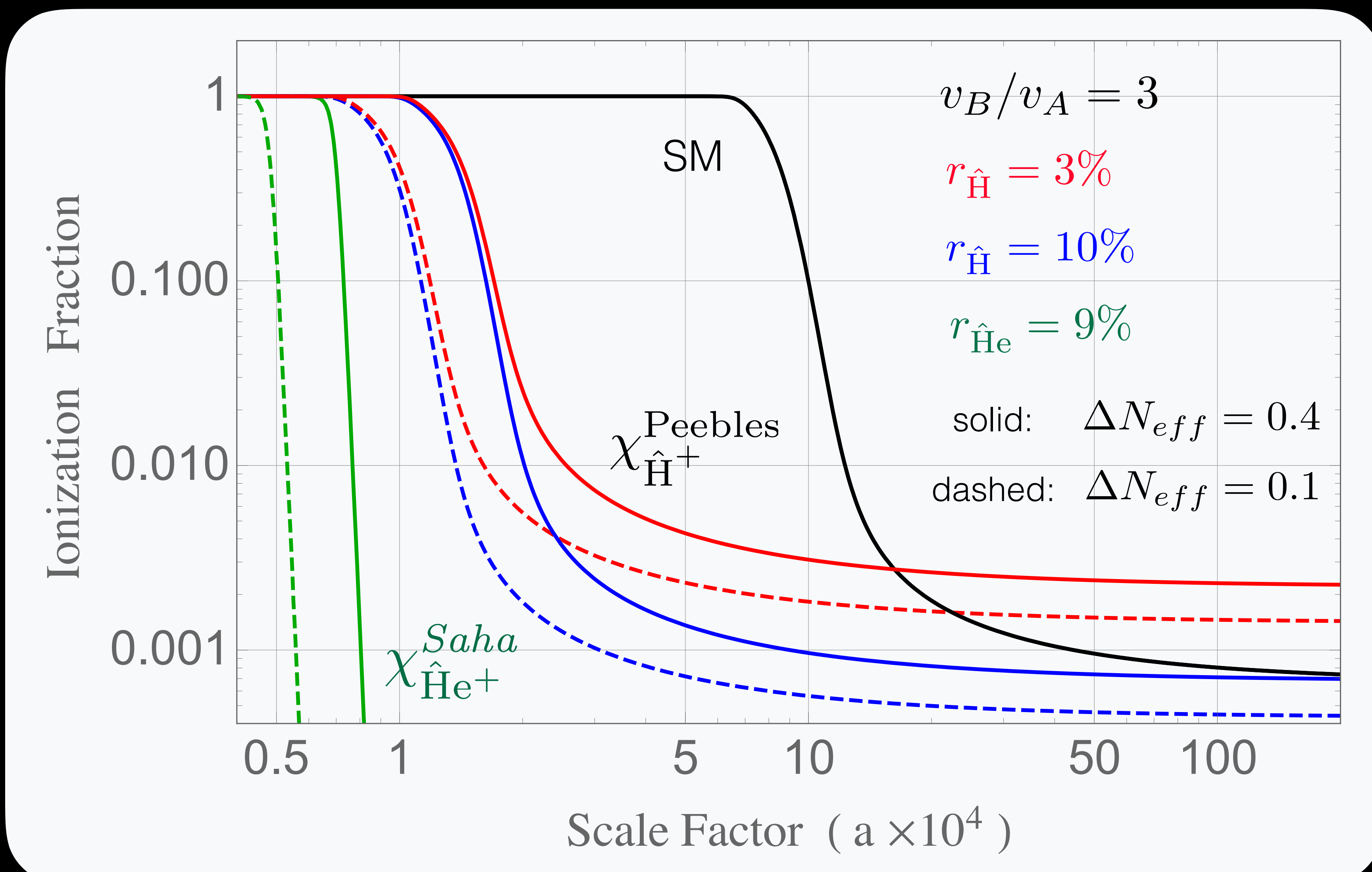
= twin electron & photon

Twin-recombination process

$$\mathrm{H}^{+} + e^{-} \to \mathrm{H}^{0} + \gamma + (\gamma)$$

$$\frac{n_{\mathrm{H}^{+}} n_{e^{-}}}{n_{\mathrm{H}^{0}}} \sim \left(\frac{m_e T}{2\pi}\right)^{3/2} e^{-\frac{13.6\,\mathrm{eV}}{T}}$$

Saha's eq

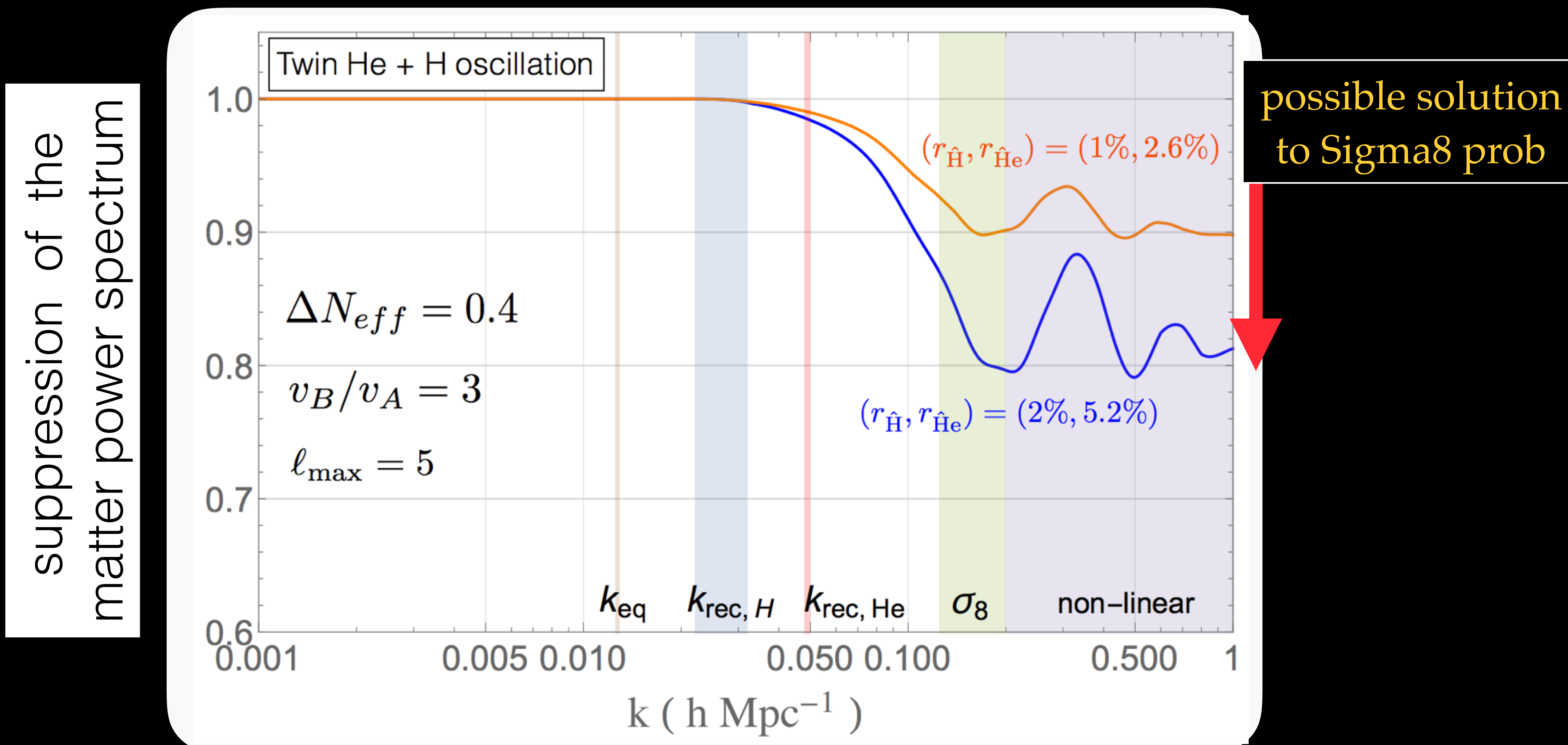


taking more precise energy transitions into account (Peebles)

Chacko, Curtin, Geller, **YT** (2018)

Suppression of the Large Scale Structure

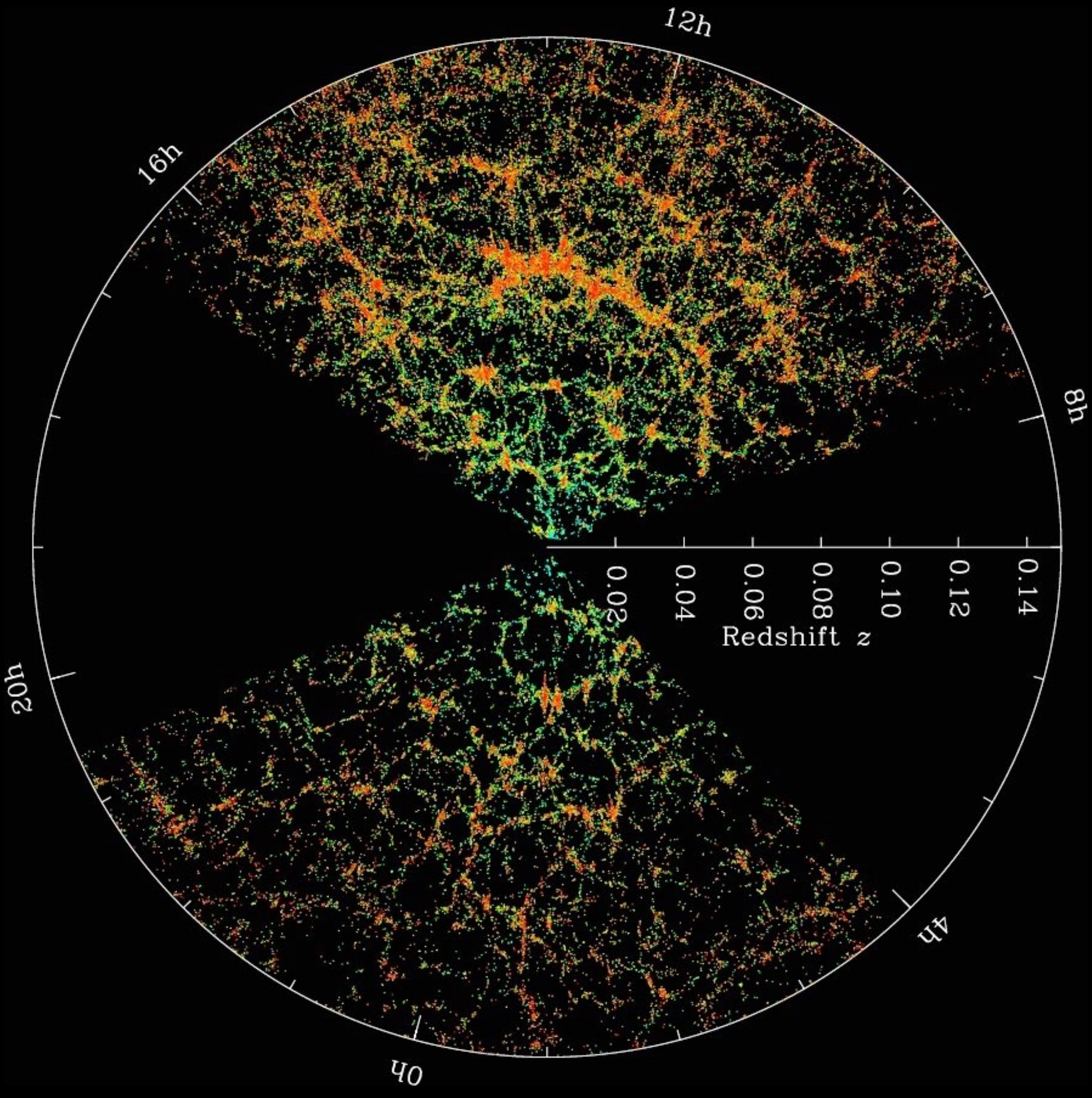
(with some fraction of DM being mirror baryons)



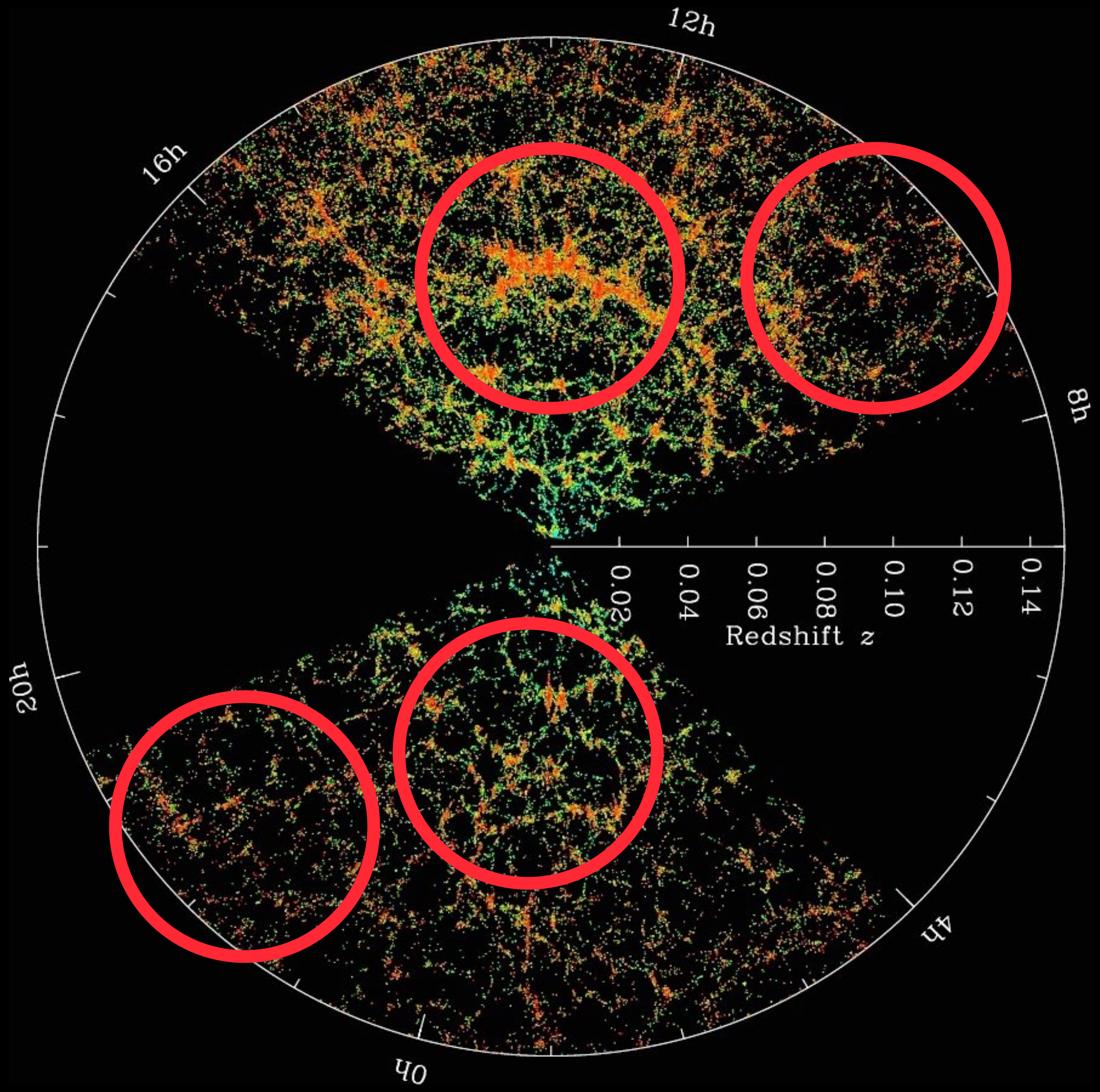
later ⟷ earlier

Horizon Entry

A cartoon picture of the Dark Acoustic Oscillation signal

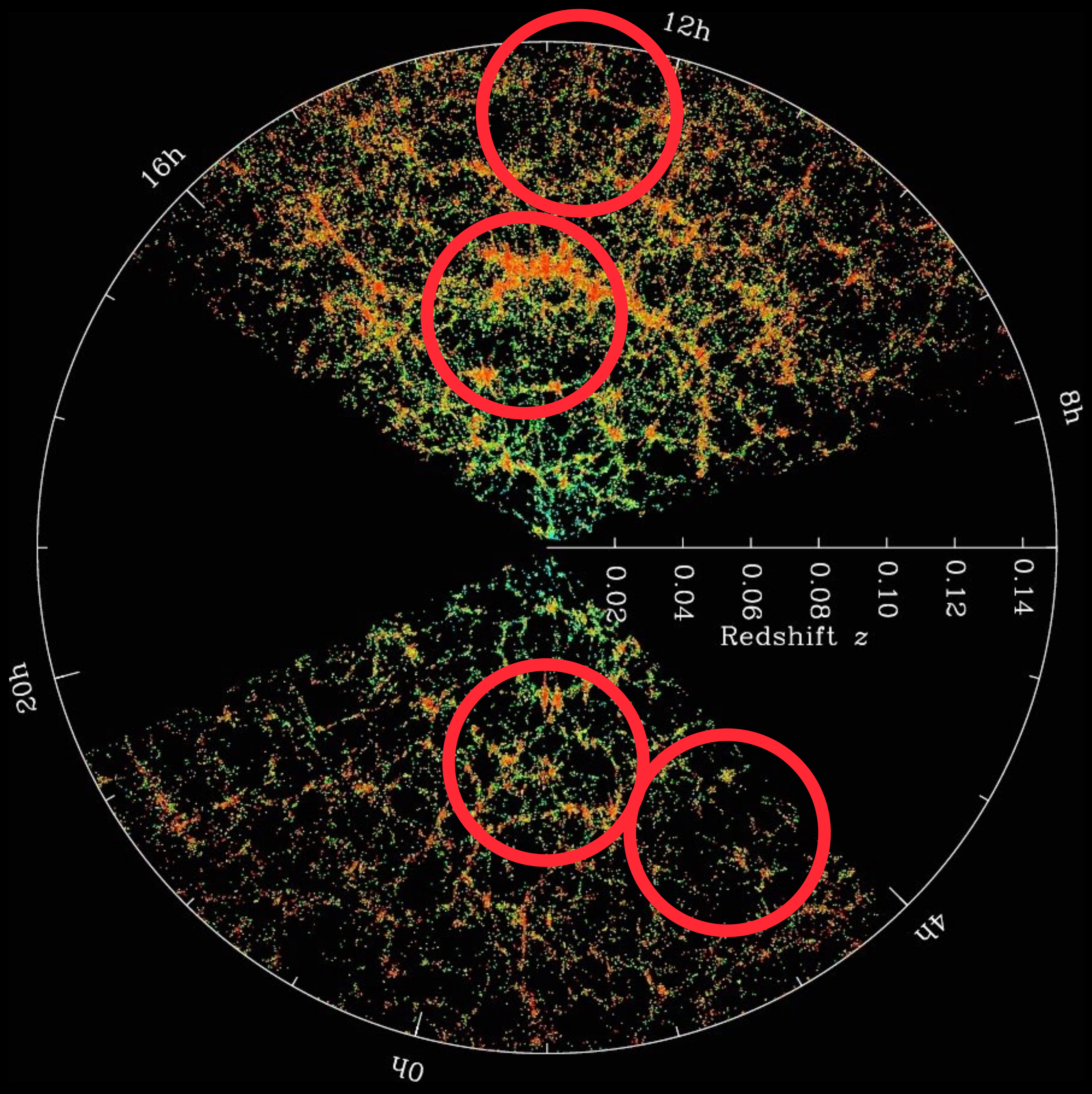


A cartoon picture of the Dark Acoustic Oscillation signal



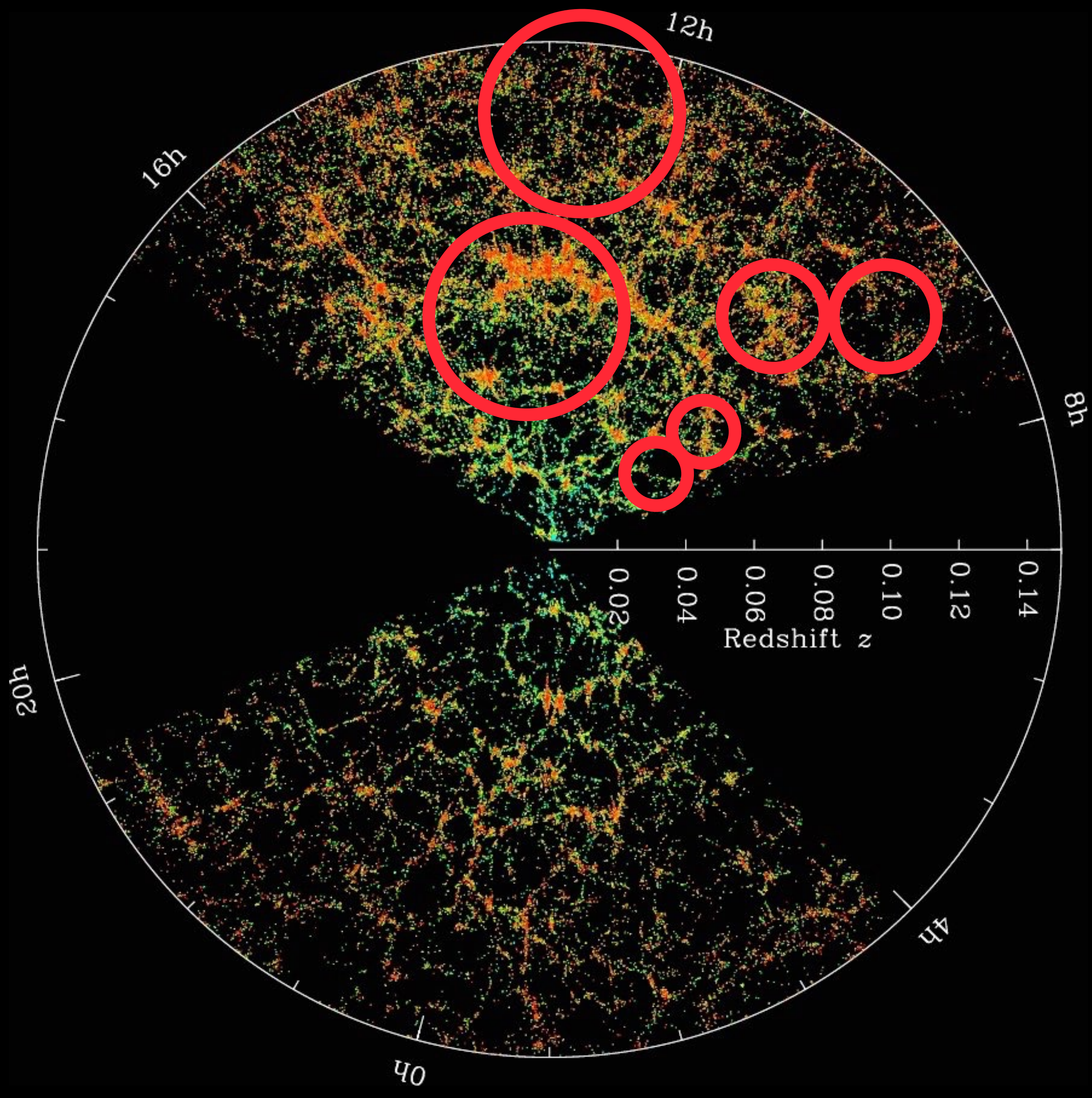
bigger structure (before recomb)
density contrast as expected

A cartoon picture of the Dark Acoustic Oscillation signal



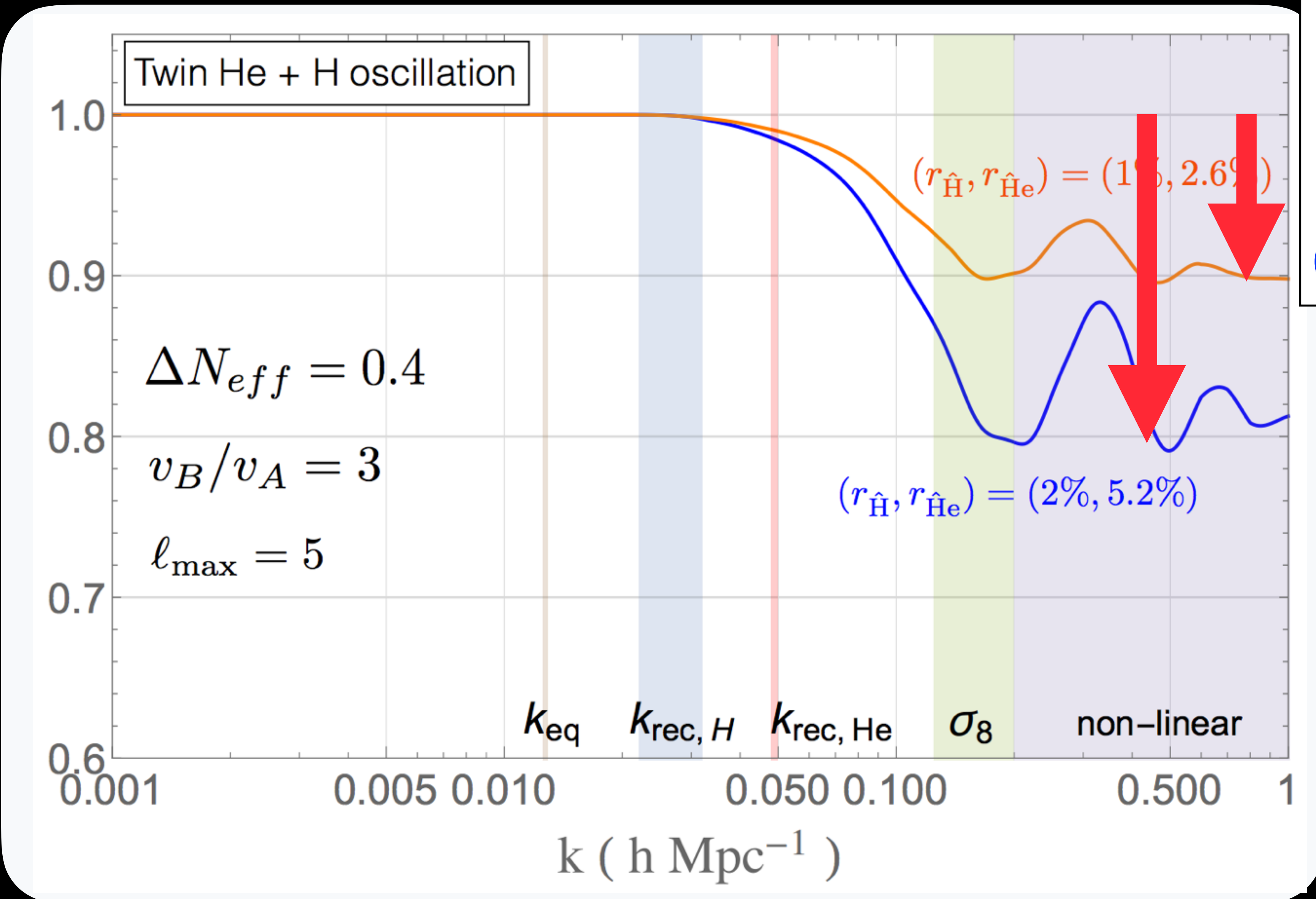
smaller structure (after recomb)
density contrast is smaller
than expected

A cartoon picture of the Dark Acoustic Oscillation signal



smaller structure (after recomb) density constrast oscillates when looking at smaller and smaller size of the structure

I. measure the mirror matter density



suppression of the matter power spectrum

suppression due to mirror oscillations (mass fraction)

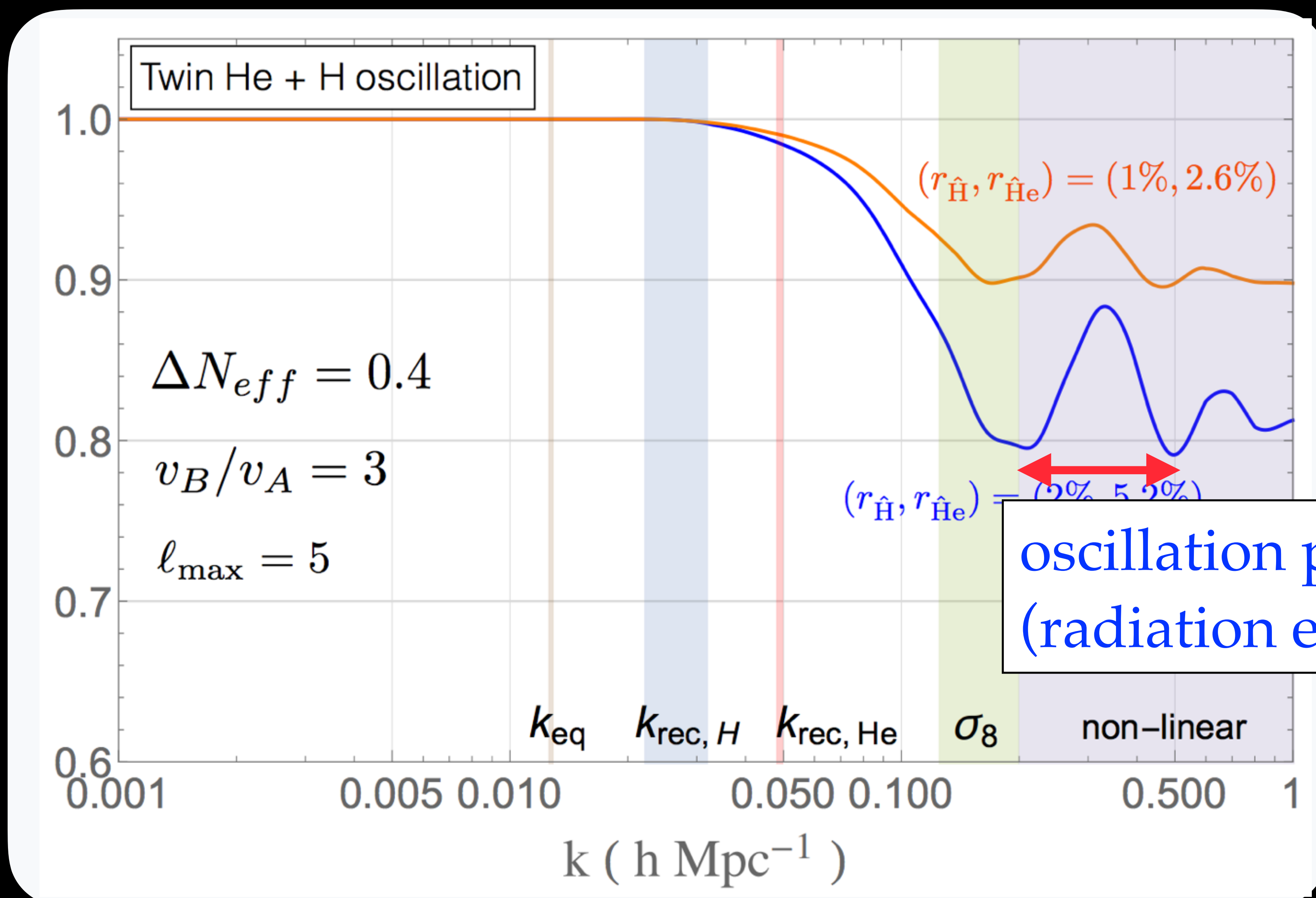
$$\left(\frac{v_B}{v_A}, \rho_{\hat{b}}, \hat{T}\right)$$

later ⟷ earlier

Horizon Entry

II. measure mirror photon energy

suppression of the matter power spectrum



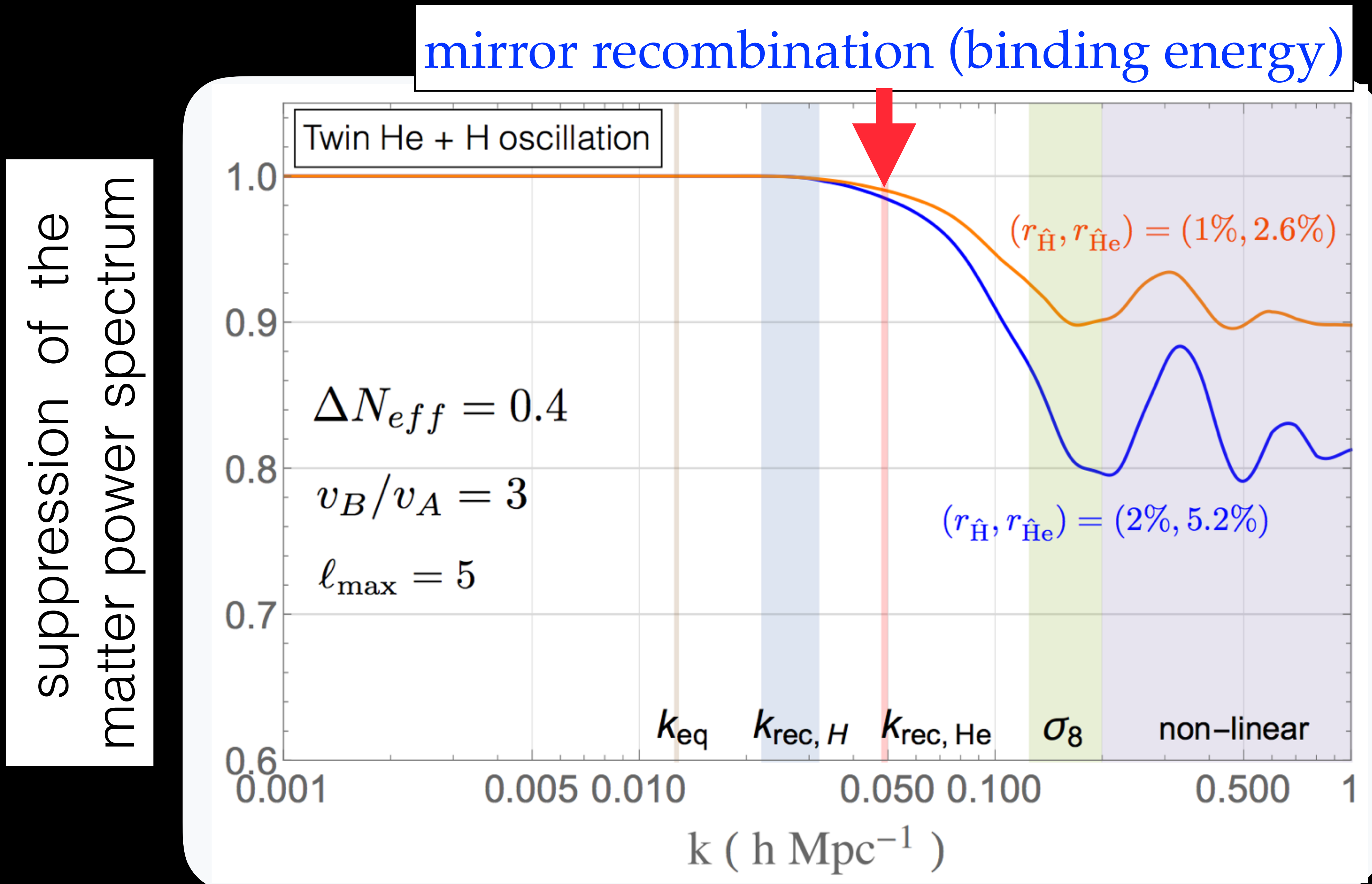
$$\left(\frac{v_B}{v_A}, \rho_{\hat{b}}, \hat{T}\right)$$

oscillation pattern
(radiation energy)

later ⟷ earlier

Horizon Entry

III. measure binding energy of mirror atoms

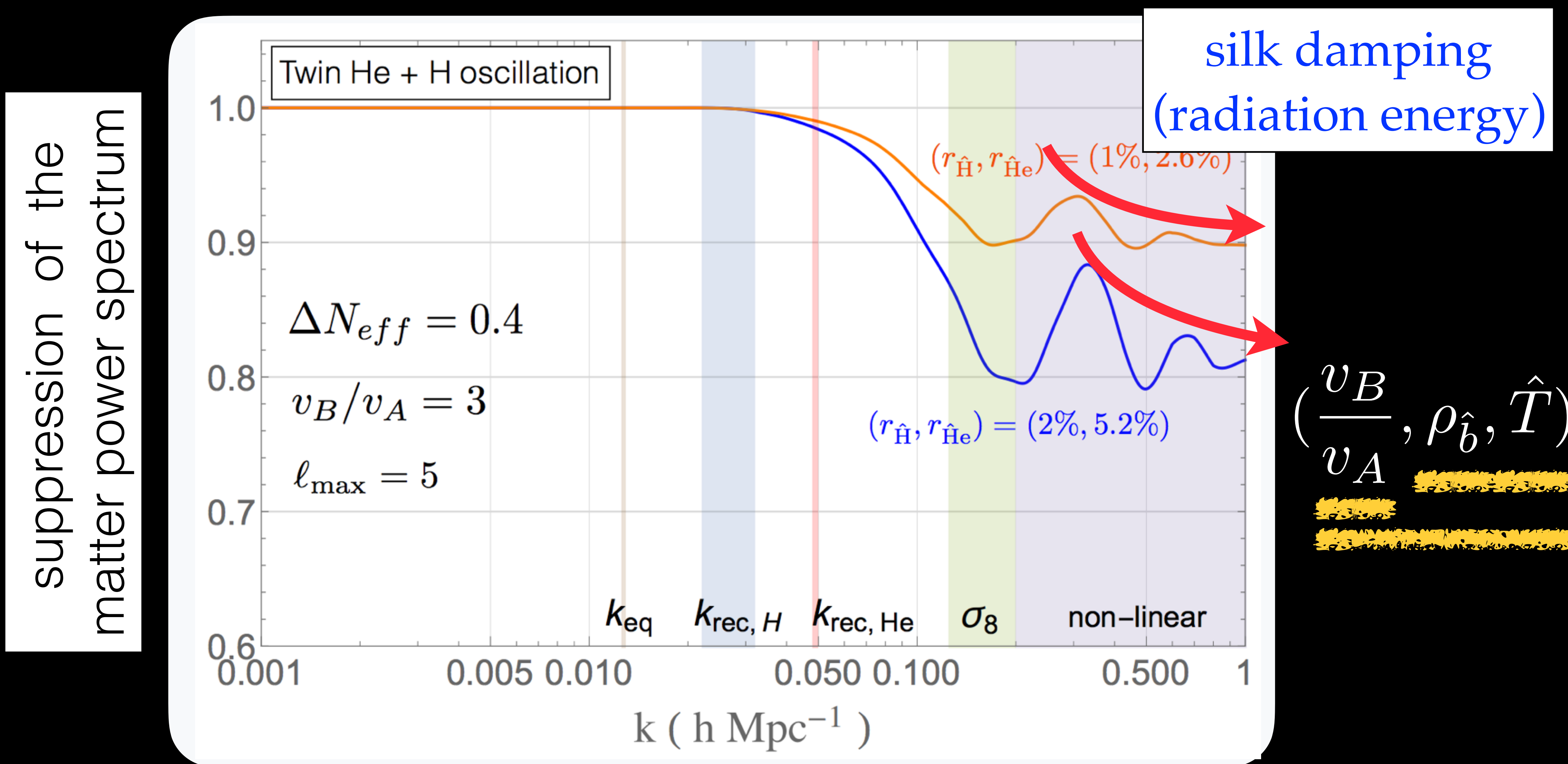


$$\left(\frac{v_B}{v_A}, \rho_{\hat{b}}, \hat{T}\right)$$

later ⟷ earlier

Horizon Entry

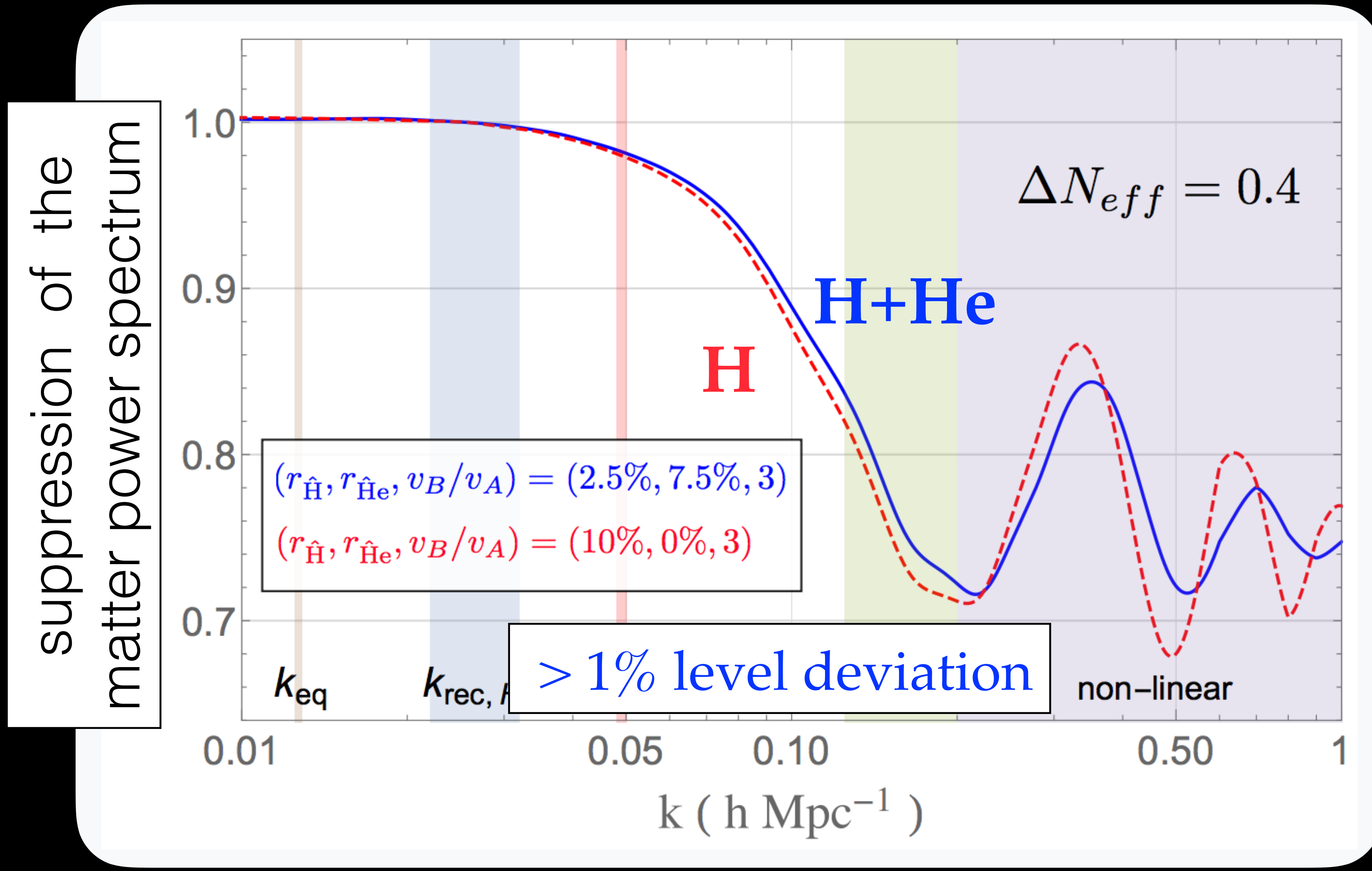
IV. dark photon - dark electron coupling



later ⟷ earlier

Horizon Entry

IV. identify the composition of mirror atoms



Here we choose the hydrogen abundance to match
the average suppression at large k-modes

Short summary:

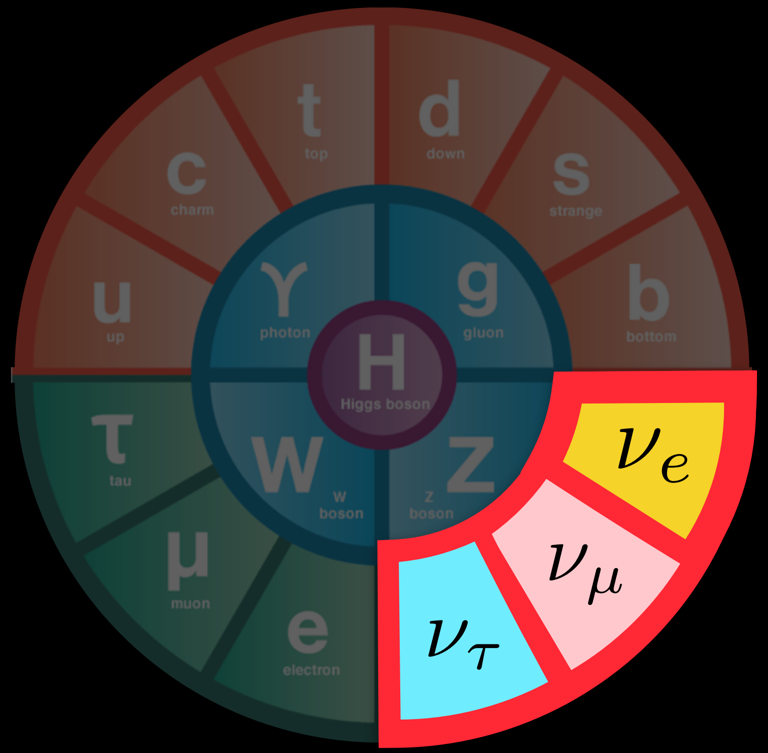
Even only couple to SM gravitationally,
MTH particles generate LSS signals in the form of
dark acoustic oscillations that stops after twin-recombination

Current bound requires ~< 10% of DM being MTH-baryons

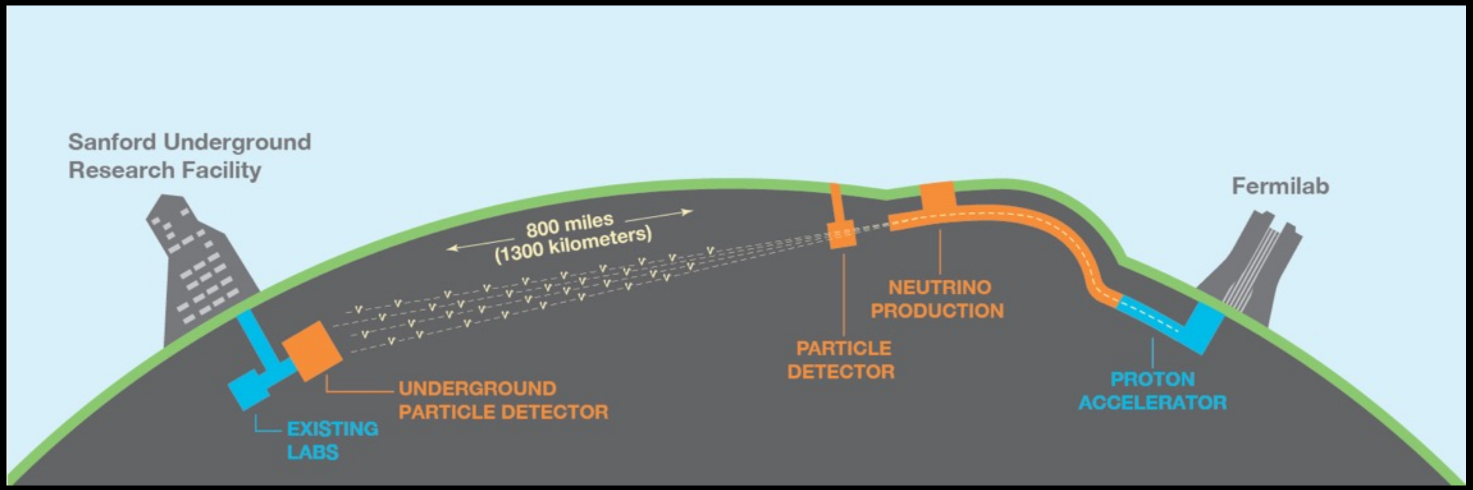
Can identify various details of the model

Example 2 : **neutrino mass / lifetime**

We have very successful neutrino experiments
to measure the **difference** between neutrino masses



Neutrino oscillation experiment



but what's the **absolute value** of their masses?

The best bound on neutrino mass comes from cosmology

From Planck 2018 data

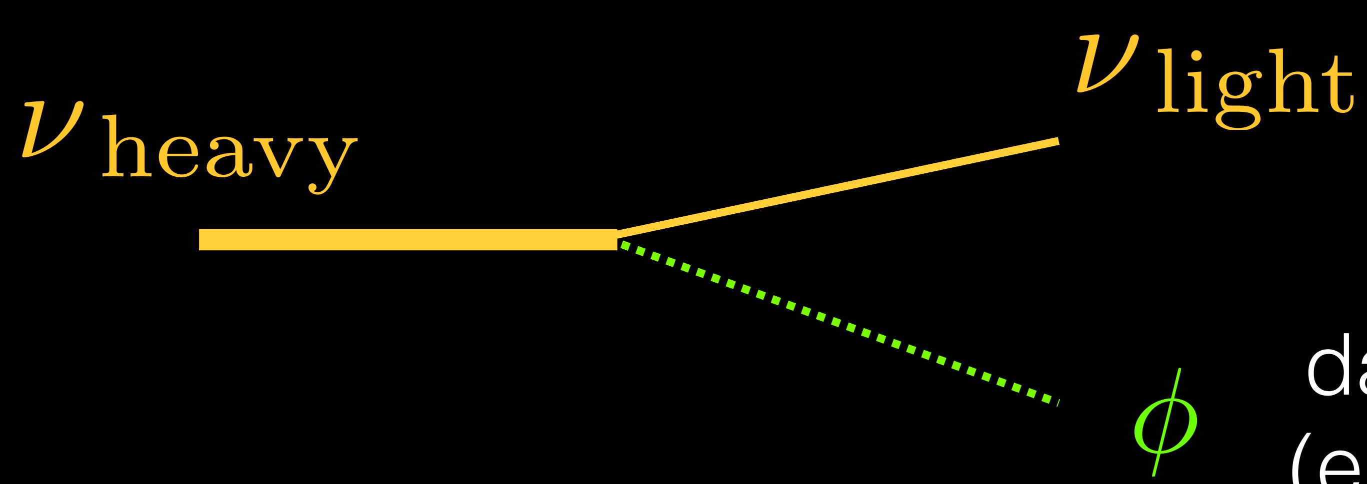
$$\sum m_\nu < 0.24\,\mathrm{eV}$$

(~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



dark radiation
(e.g., Majoron)

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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ν

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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)

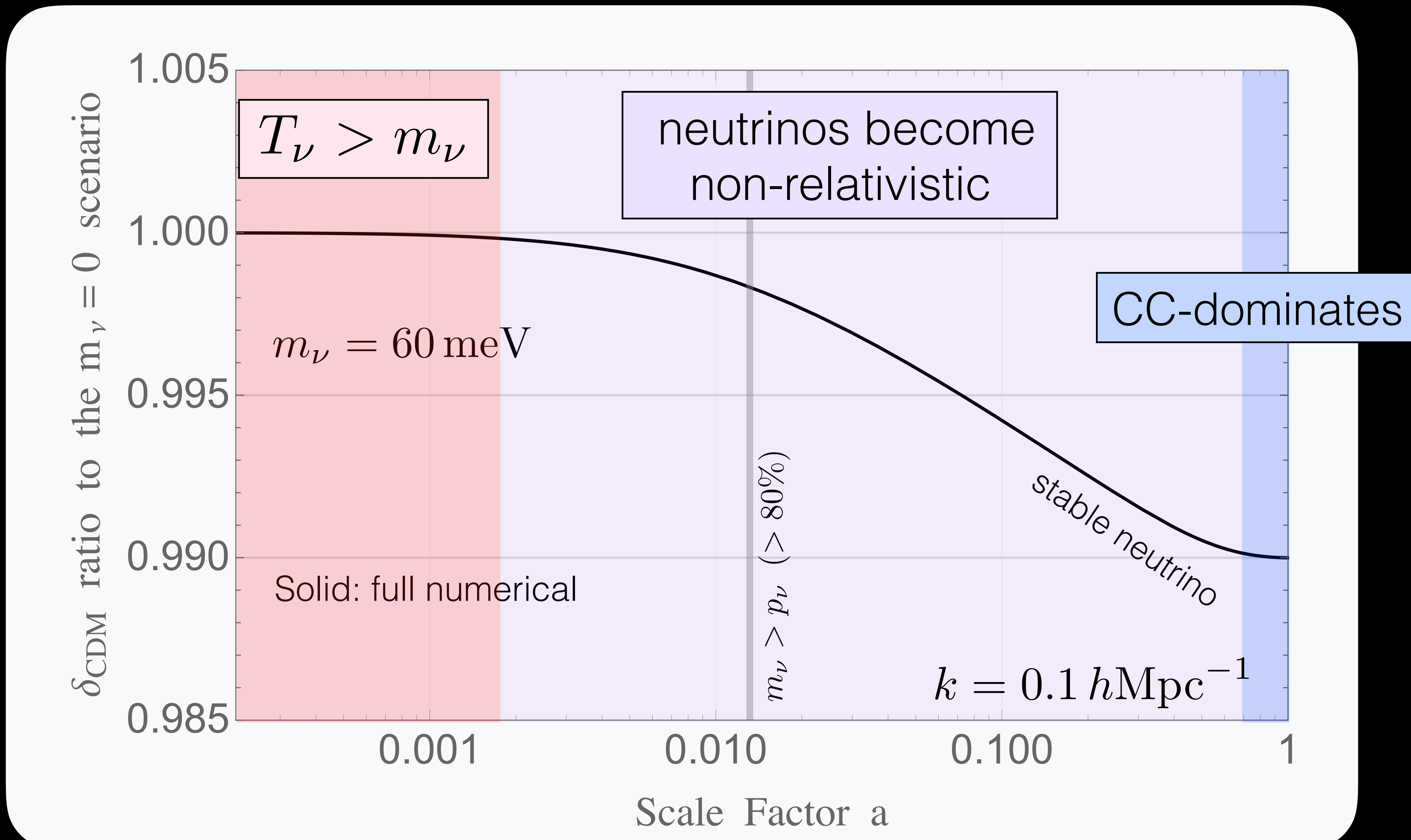
near future data
(e.g., Euclid, CMB-S4)

~ 10 billion yrs

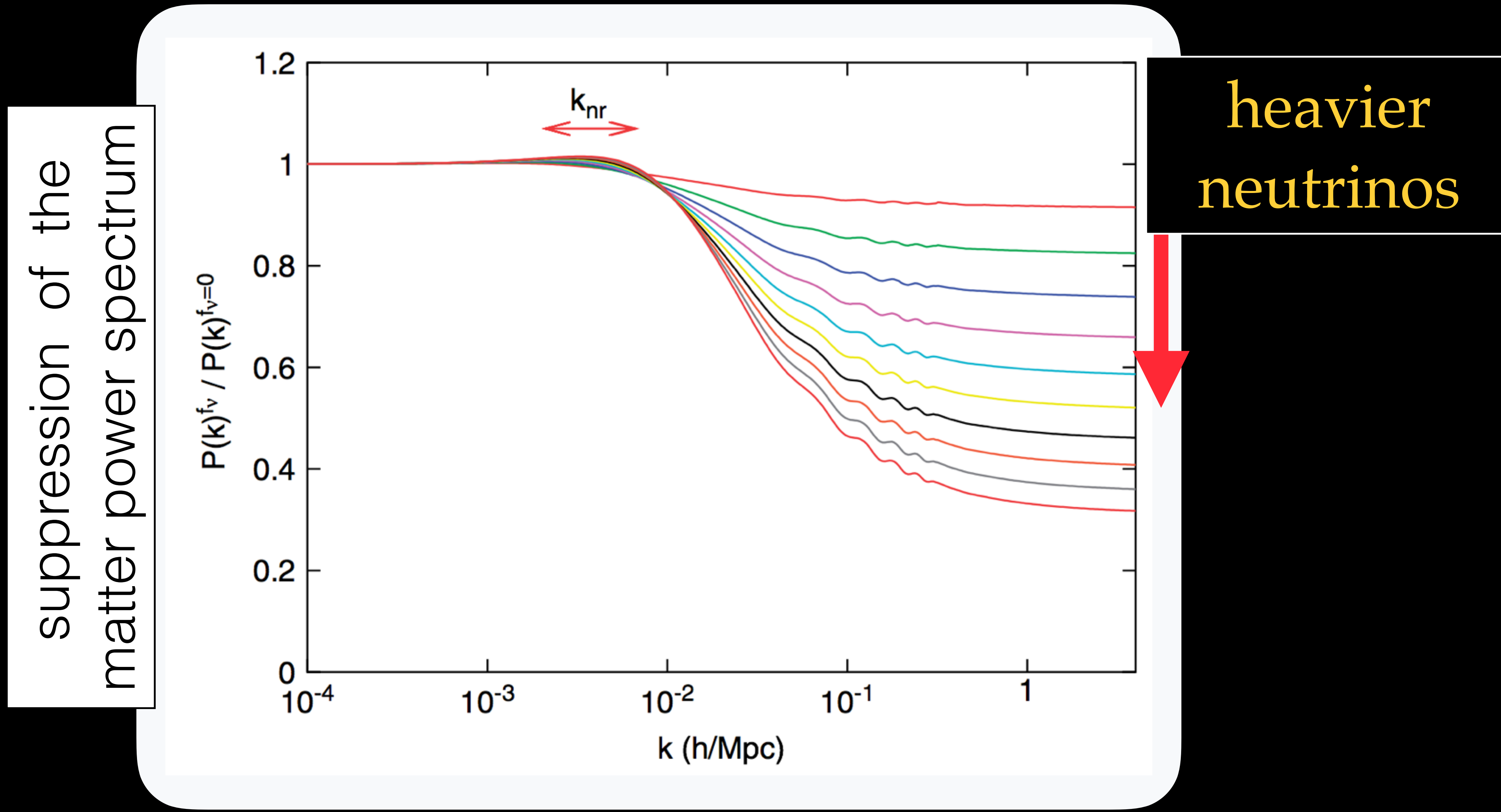
Chacko, Dev, Du, Poulin, **YT** (2019 one more soon), also Serpico (2007) stable neutrinos with mass

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

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



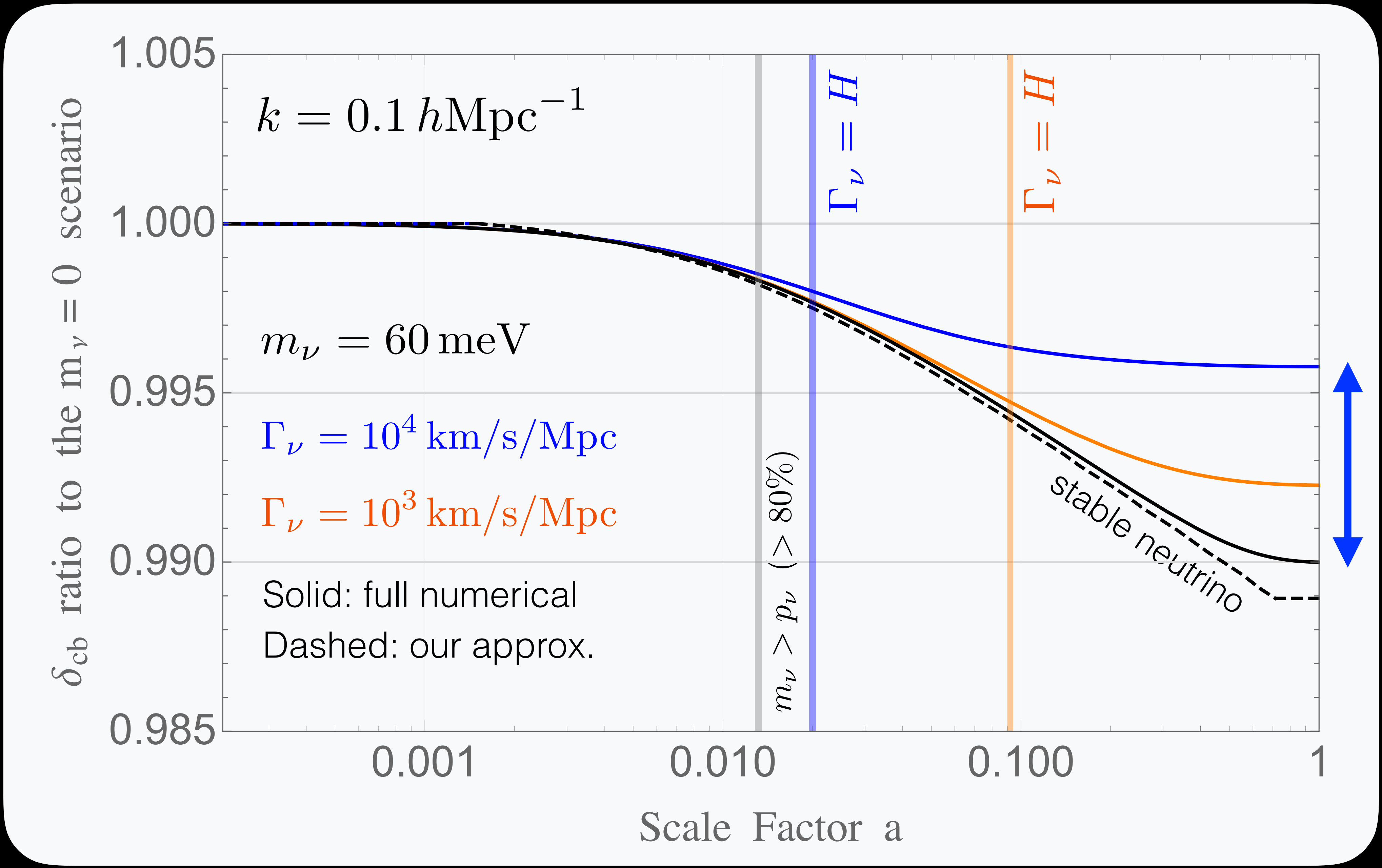
Suppression of the matter power spectrum



Lesgourgues and Pastor (2006)

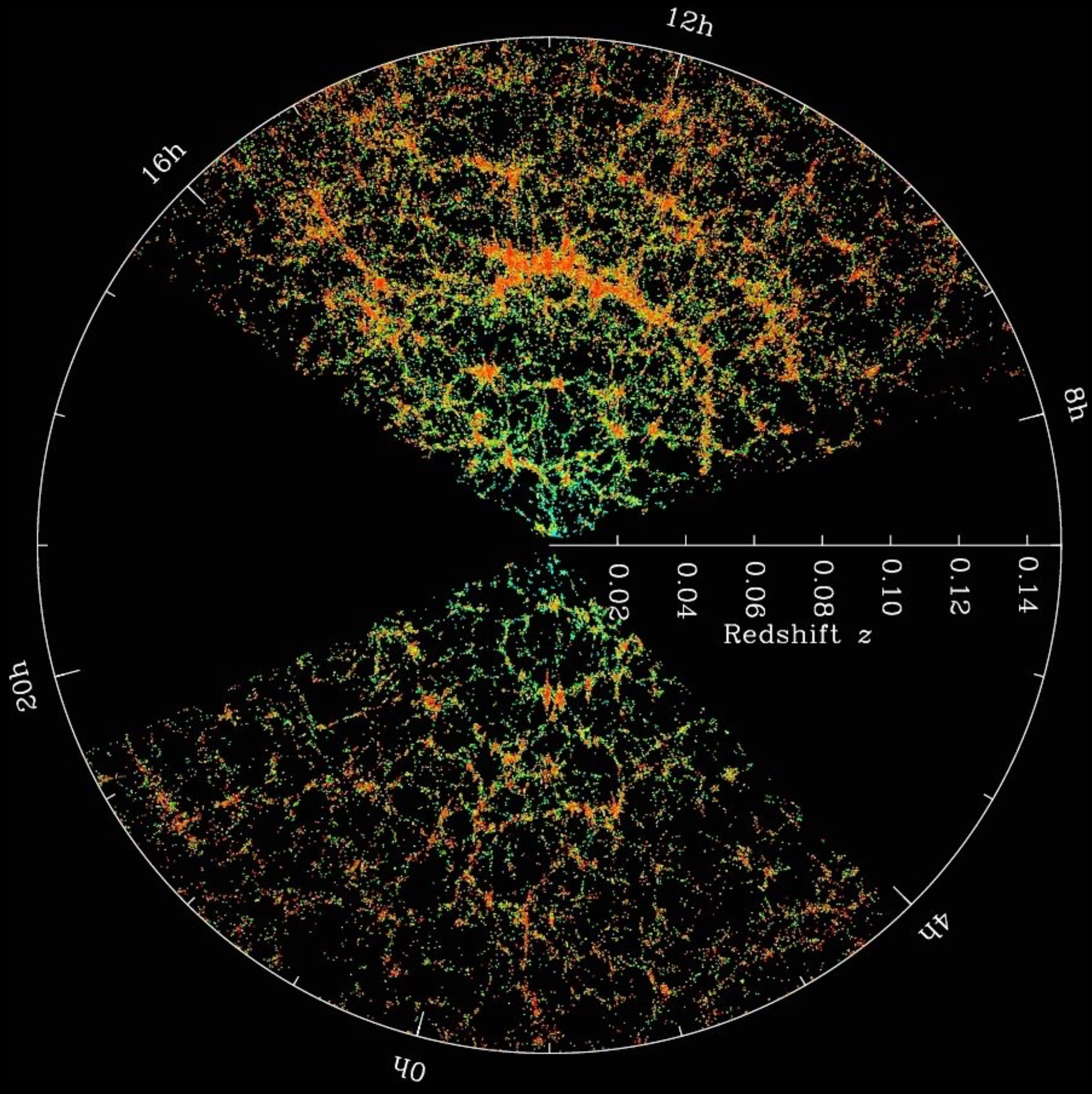
What if neutrinos decay?

``Larger" density contrast than expected



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

A cartoon picture of signal from stable massive neutrino



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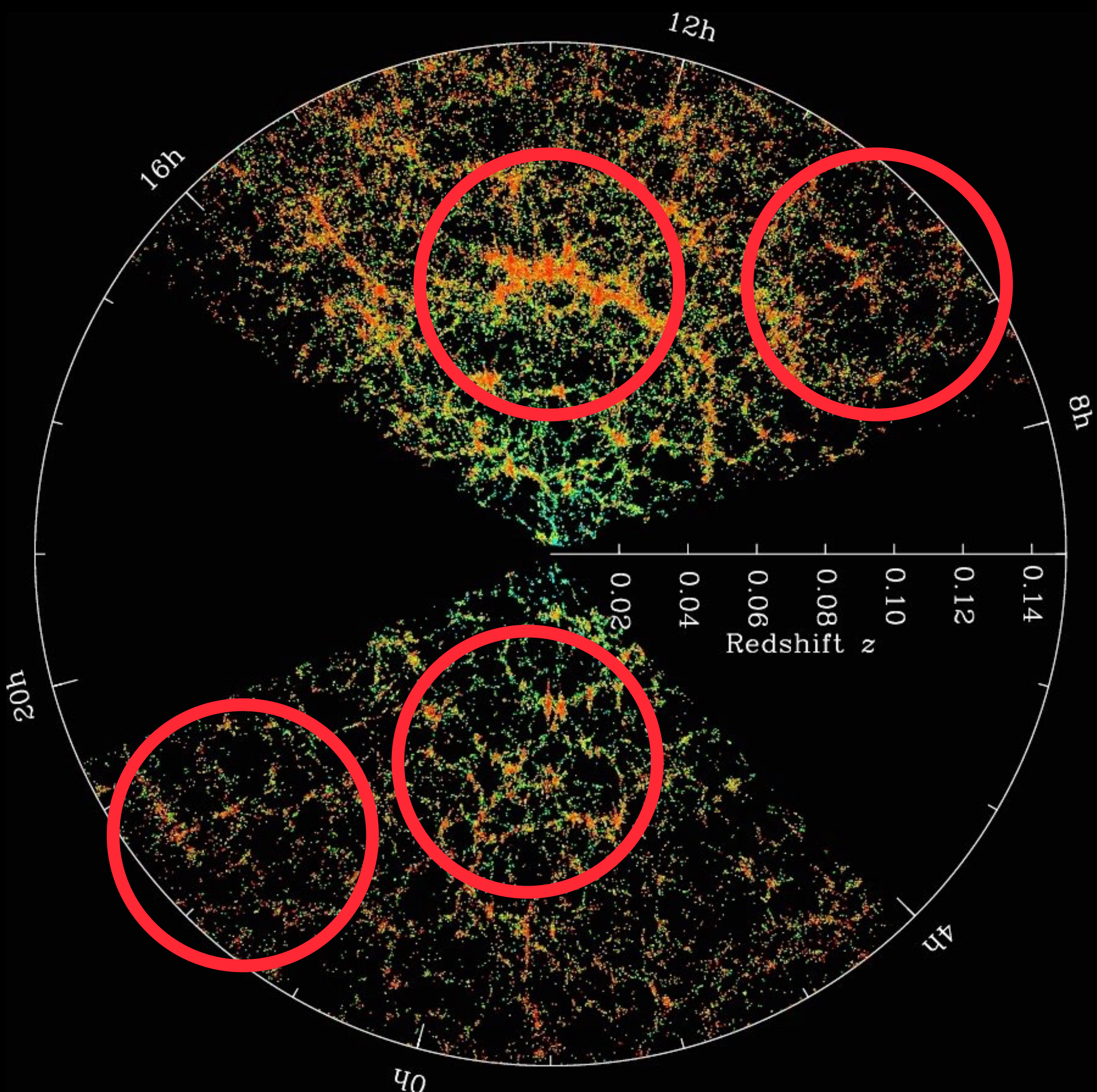
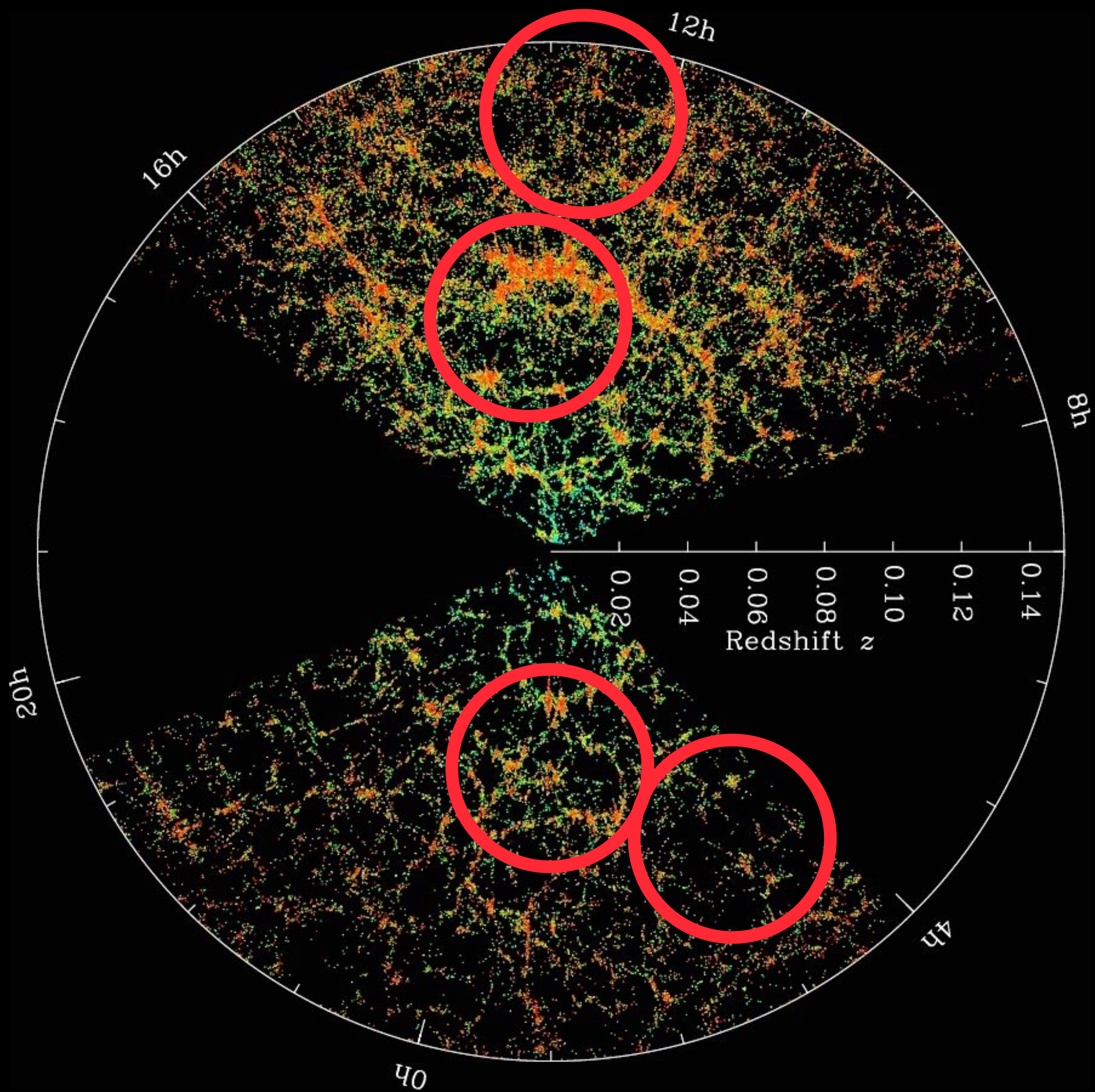


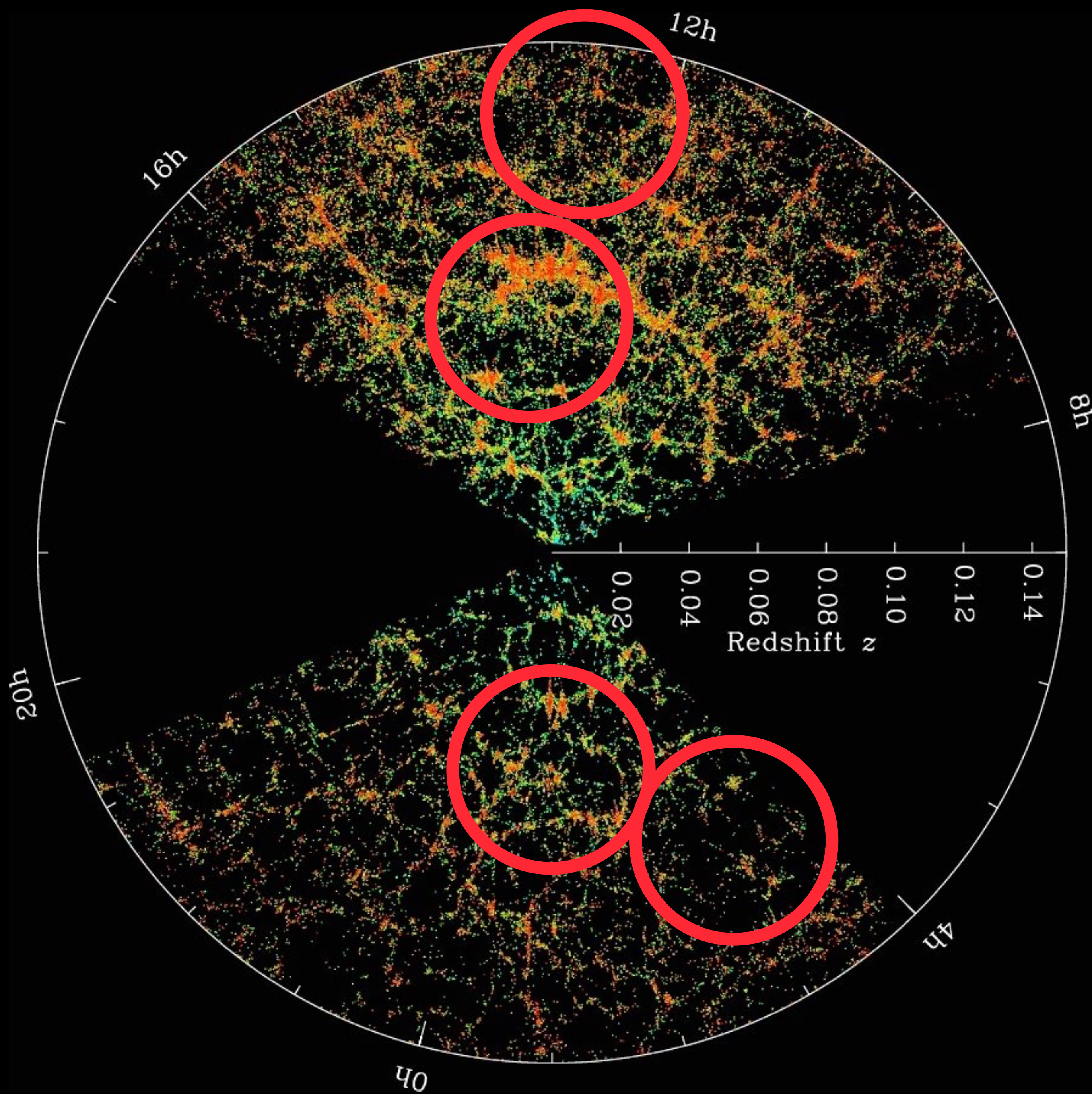
bigger structure
(after Nu is non-relativistic)
density contrast as expected

A cartoon picture of signal from stable massive neutrino



smaller structure
(since Nu was still relativistic)
density contrast is smaller than expected

But if neutrinos decay!



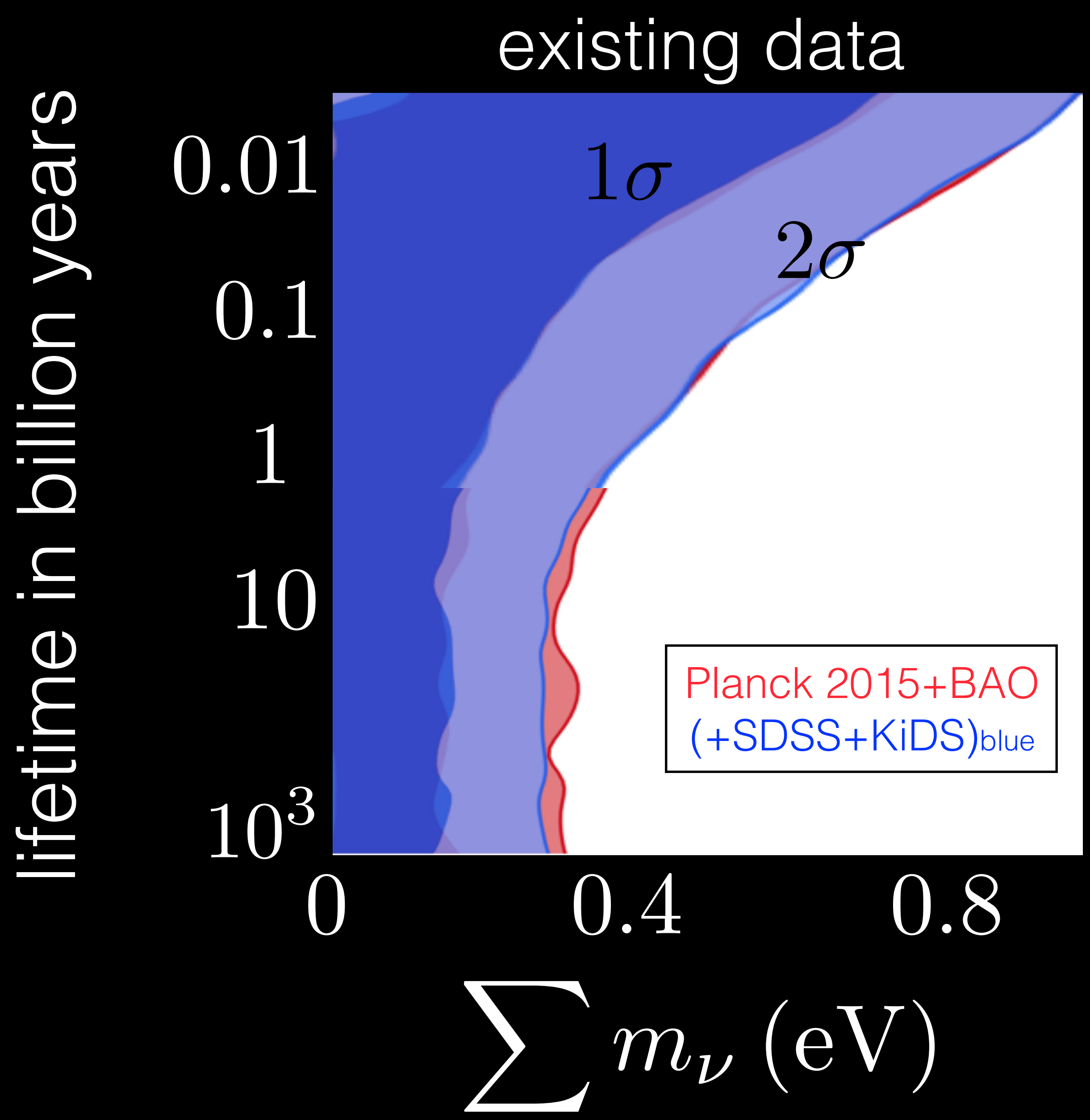
smaller structure
(since Nu was still relativistic)
density contrast is larger than
expected for massive neutrino

neutrino decay gives larger density perturbation

compare to the stable Nu case

Current Large Scale Structure & Planck 2015

Chacko, Dev, Du, Poulin, **YT** (1909.05275)



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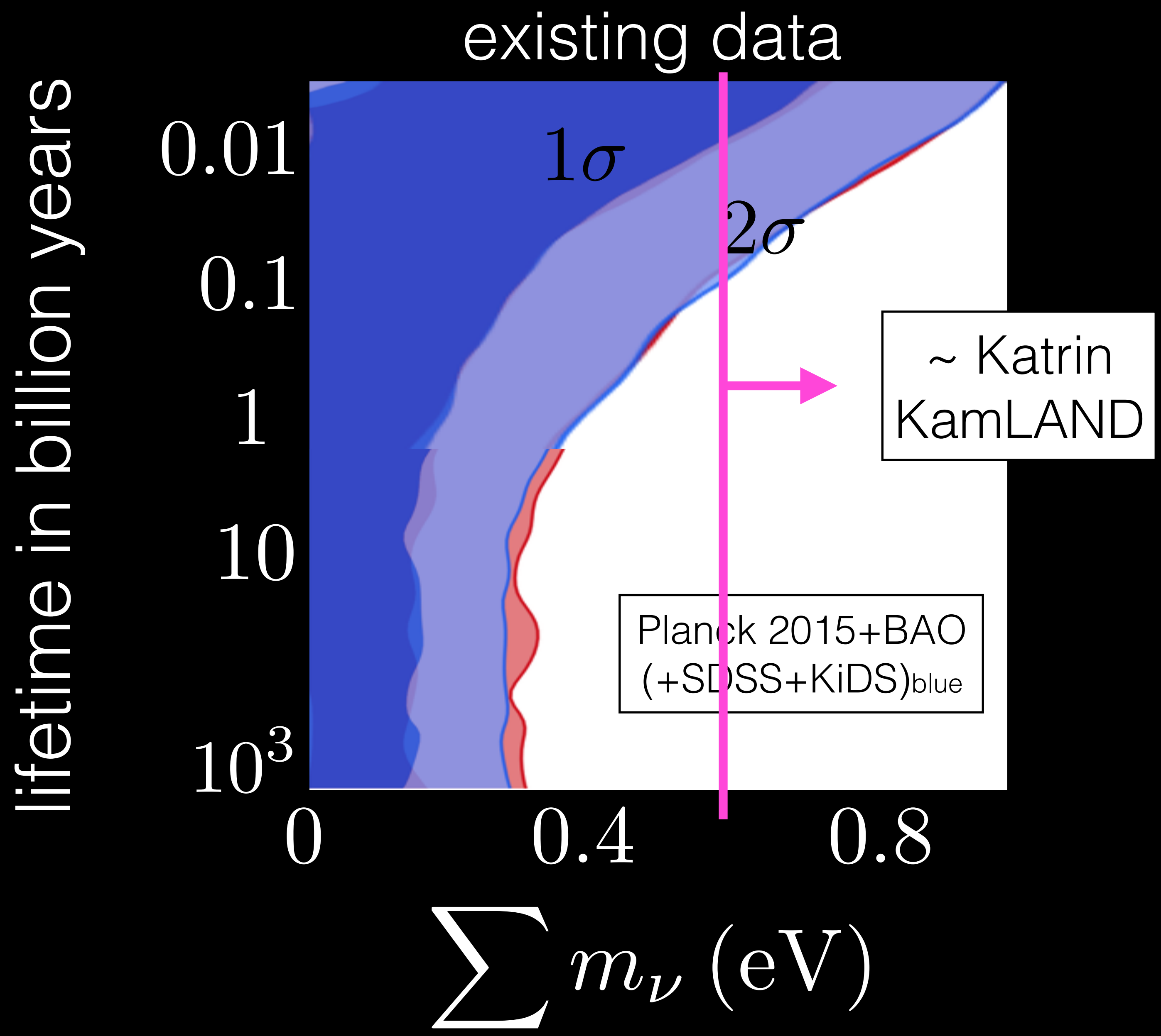

sensitivity from other lab experiments

Cosmic-Nu Telescope?

Current Large Scale Structure & Planck 2015

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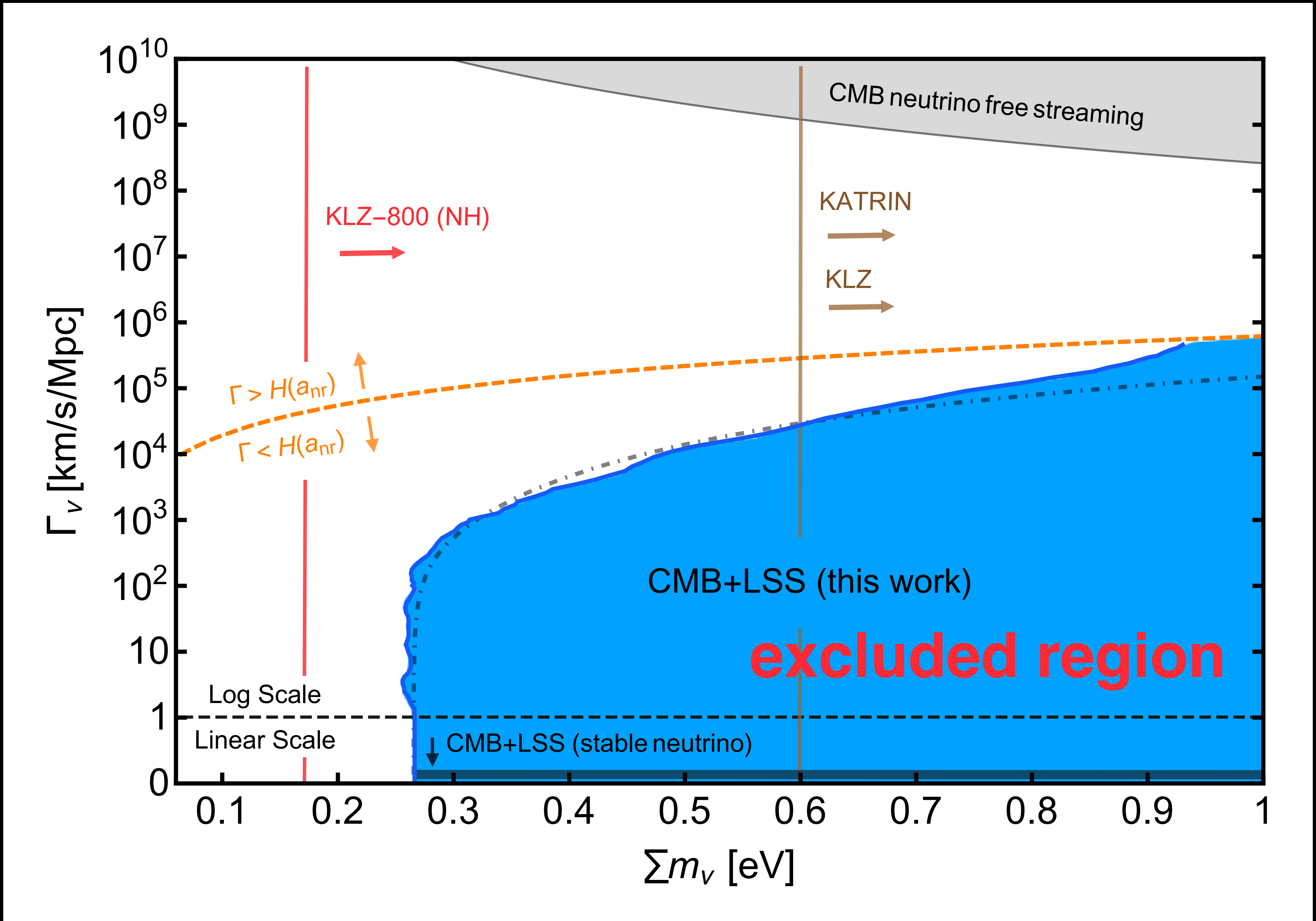
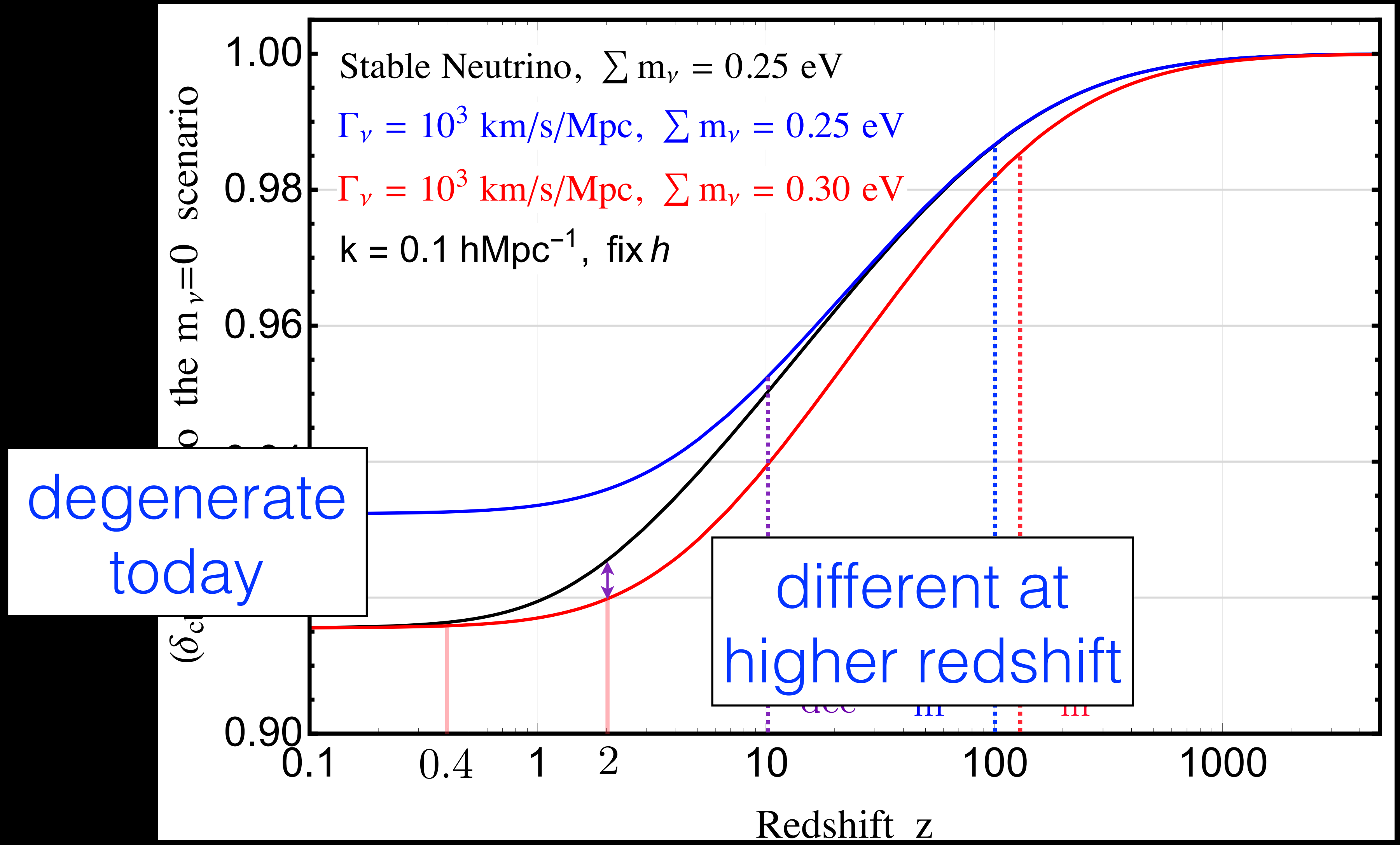


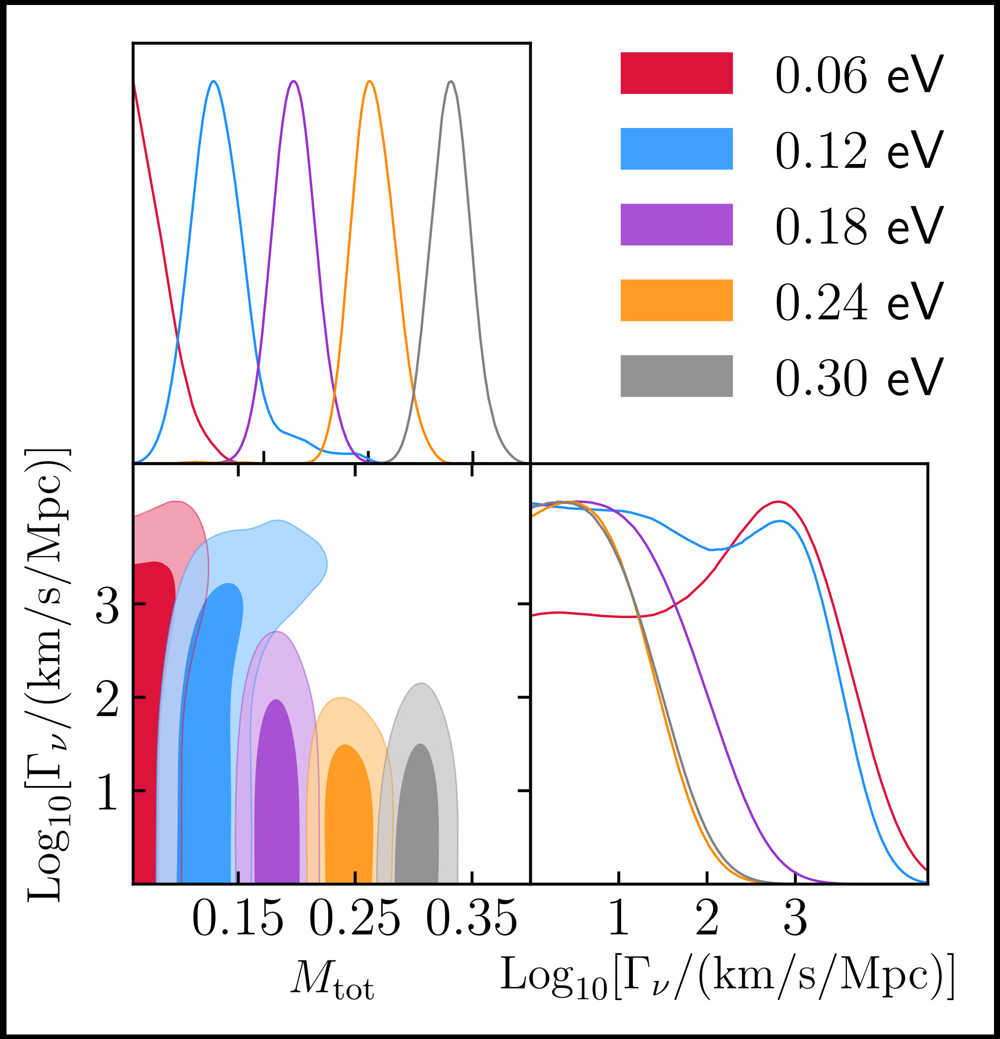
A degeneracy between mass & lifetime

Heavier neutrino decays can fake lighter neutrino signal

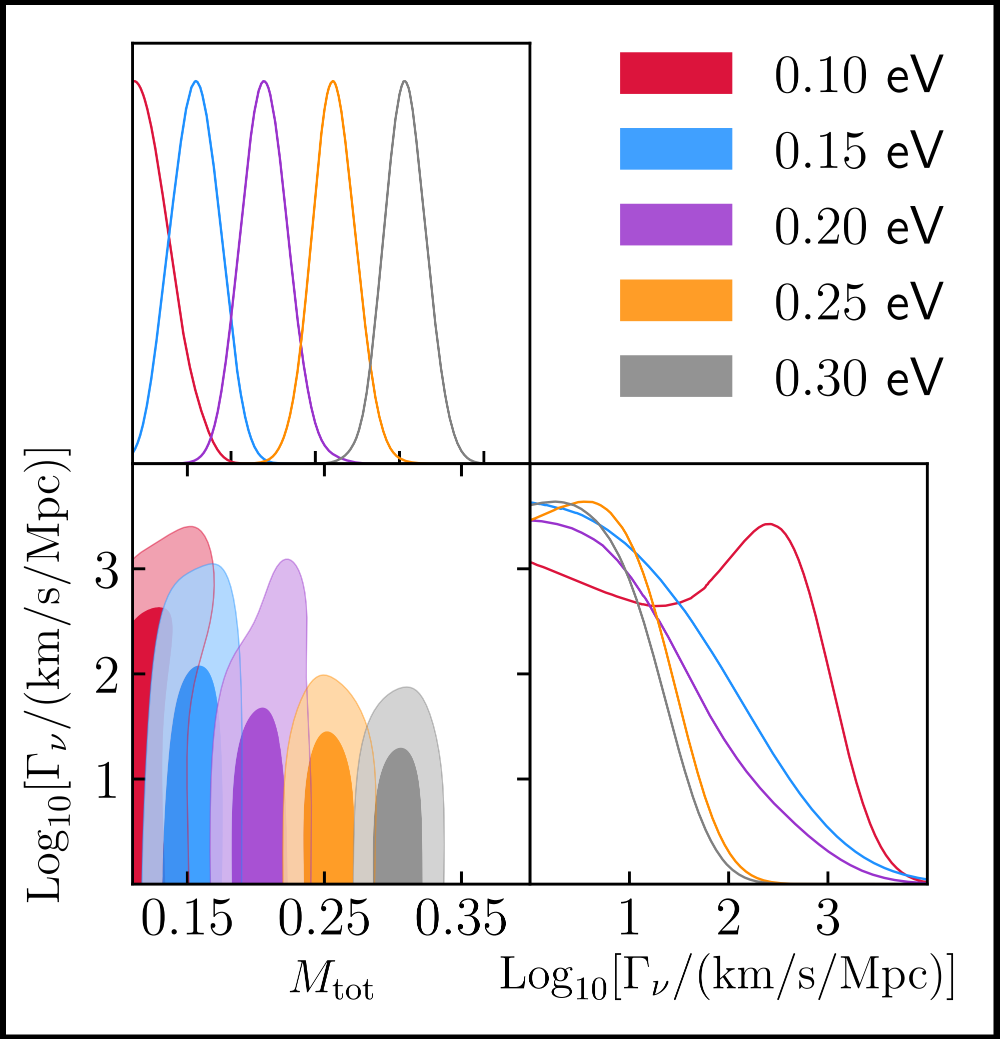


This is where the “time” (redshift) dependent measurement helps

e.g., near future Euclid data can break the degeneracy and set robust lifetime bound



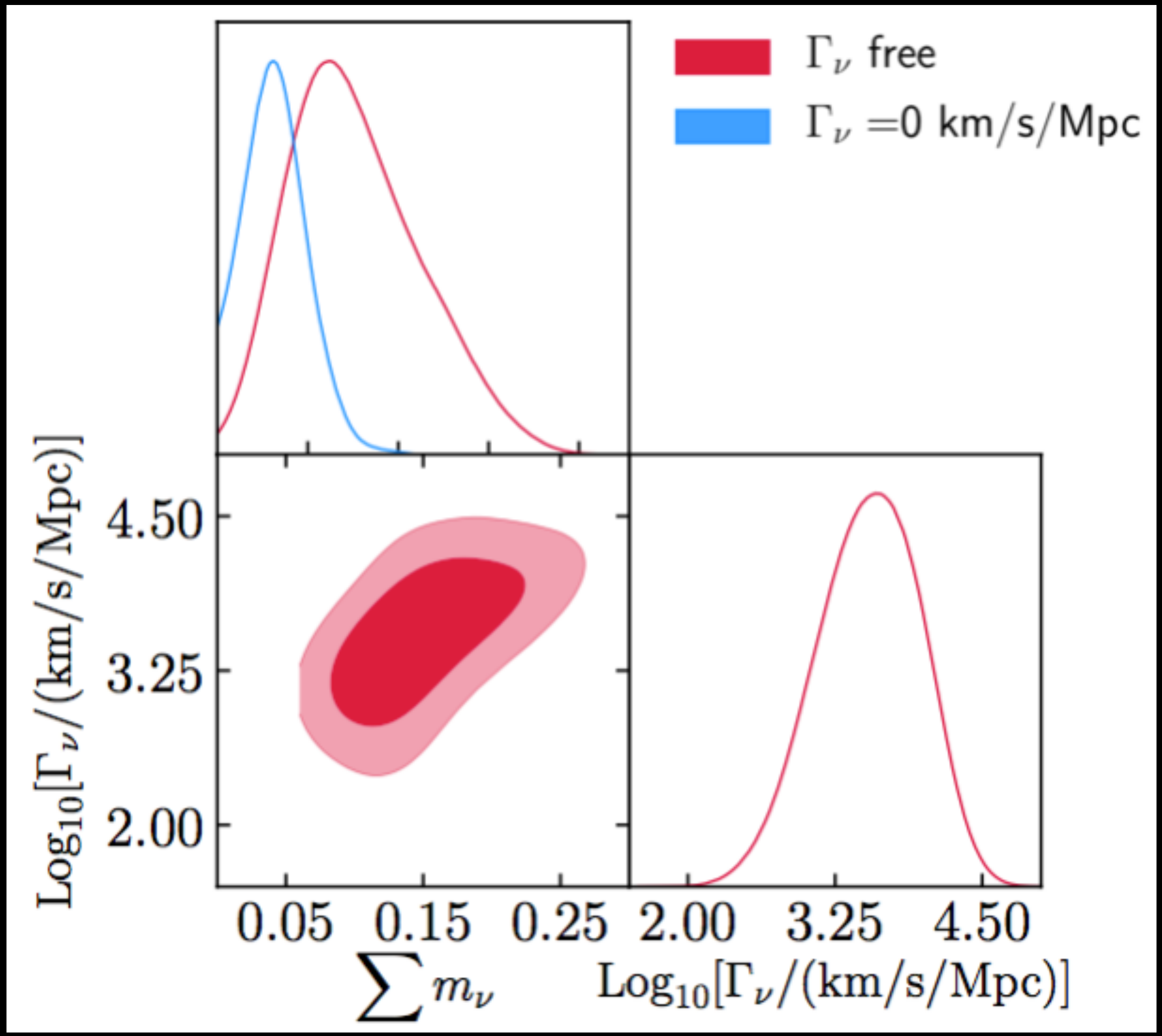
normal hierarchy

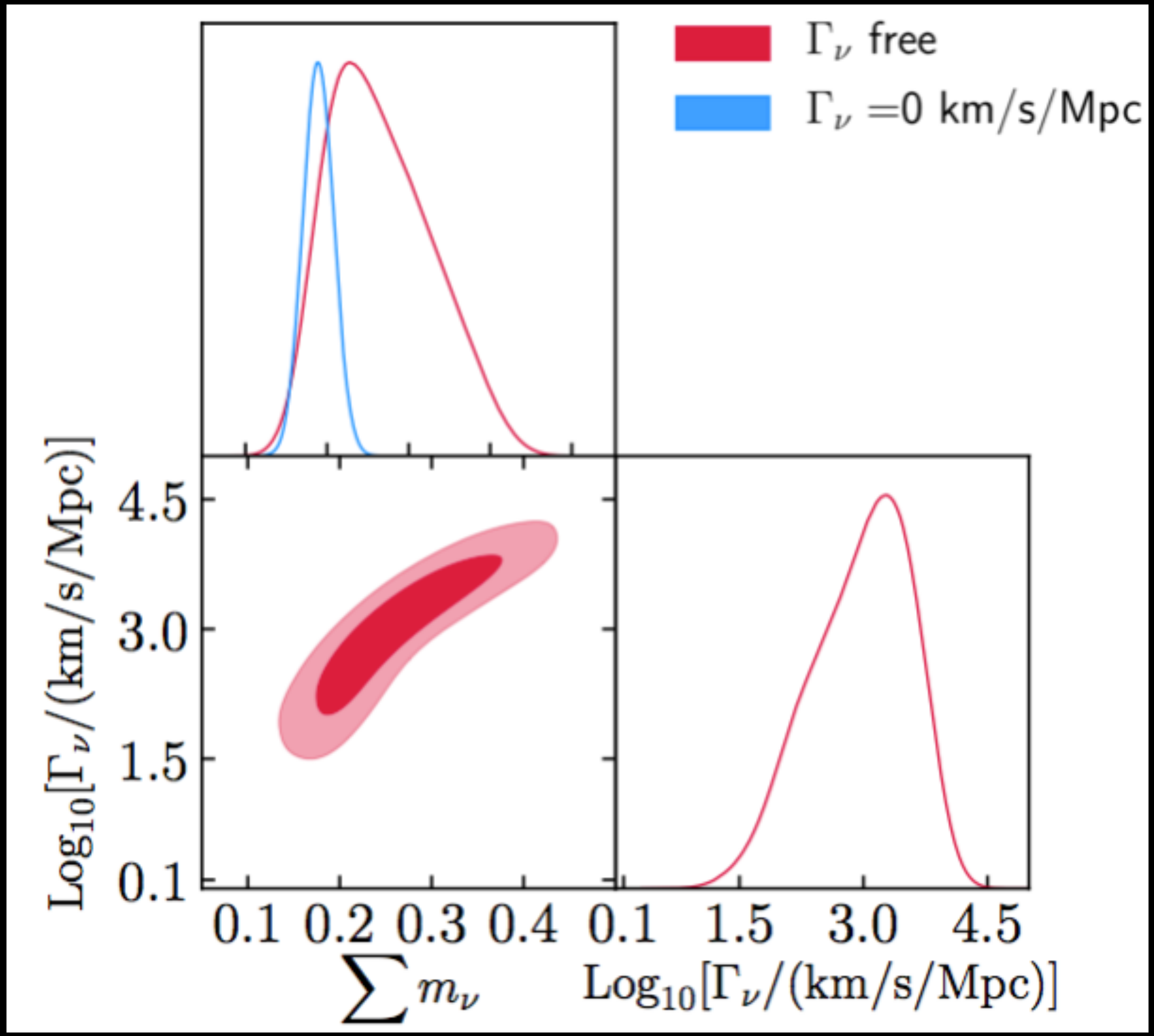


inverted hierarchy

Chacko, Dev, Du, Poulin, **YT** (preliminary result, to appear)

can even “measure” the decay rate if Nu decay





Chacko, Dev, Du, Poulin, **YT** (preliminary result, to appear)

Short summary:

massive neutrinos suppress the structure

LSS measurement can constrain/measure nu-mass

neutrino decay “increases” the structure

will be able to measure/constrain neutrino lifetime
to the age of the universe time scale

Conclusion

New physics that interacts very weakly,
or even only gravitationally, to visible particles
may be studied using precision cosmological data

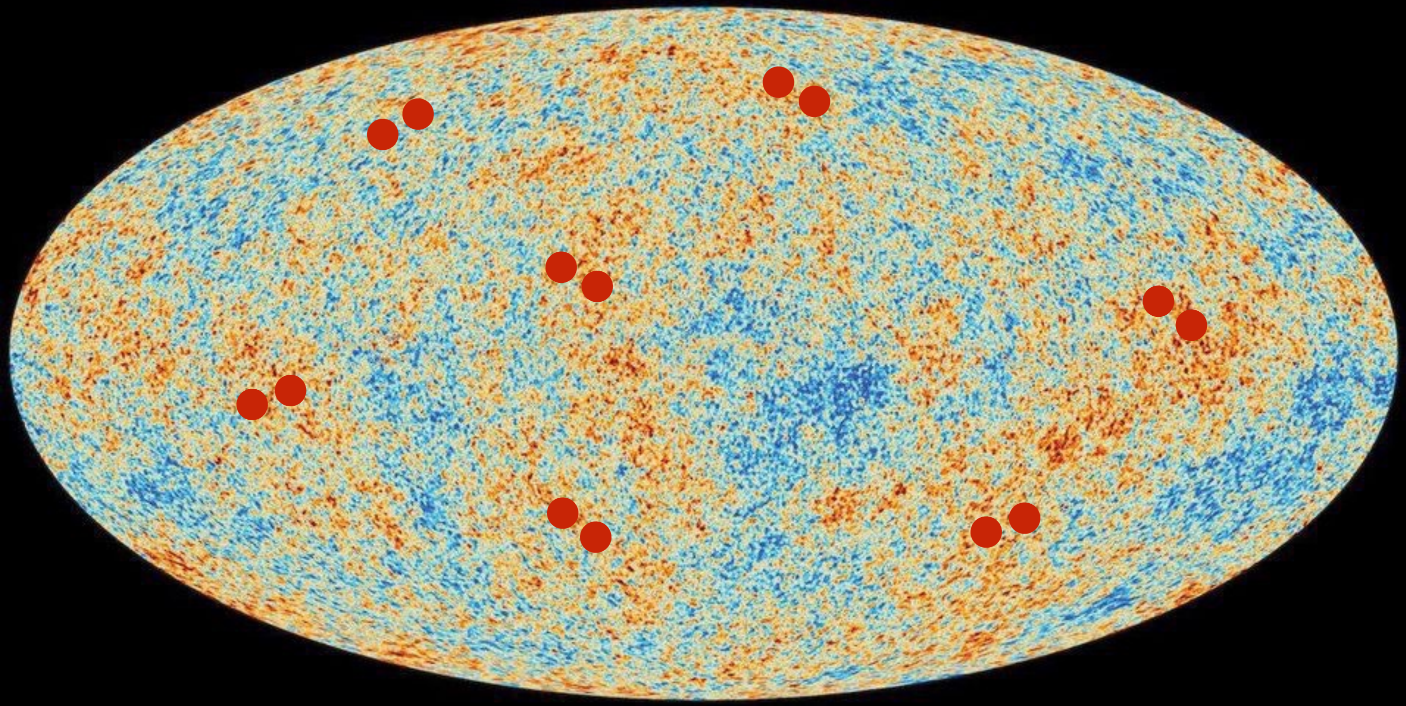
As the much better quality data is coming to us,
we need to get prepared and know what to look at

Discussion

Non-trivial defects in CMB

(super preliminary! just an idea)

e.g., pair-produced hot/cold spots



see also Maldacena (2015)

Non-trivial defects in CMB

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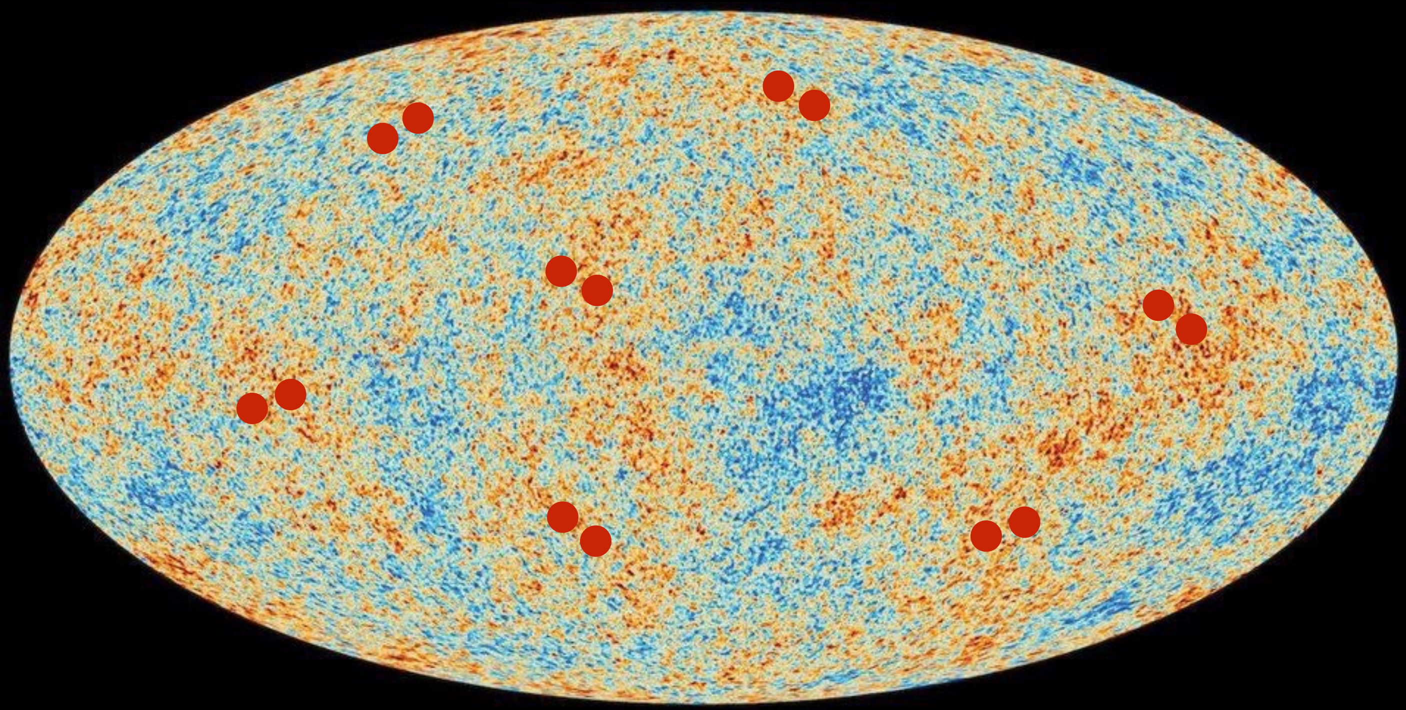


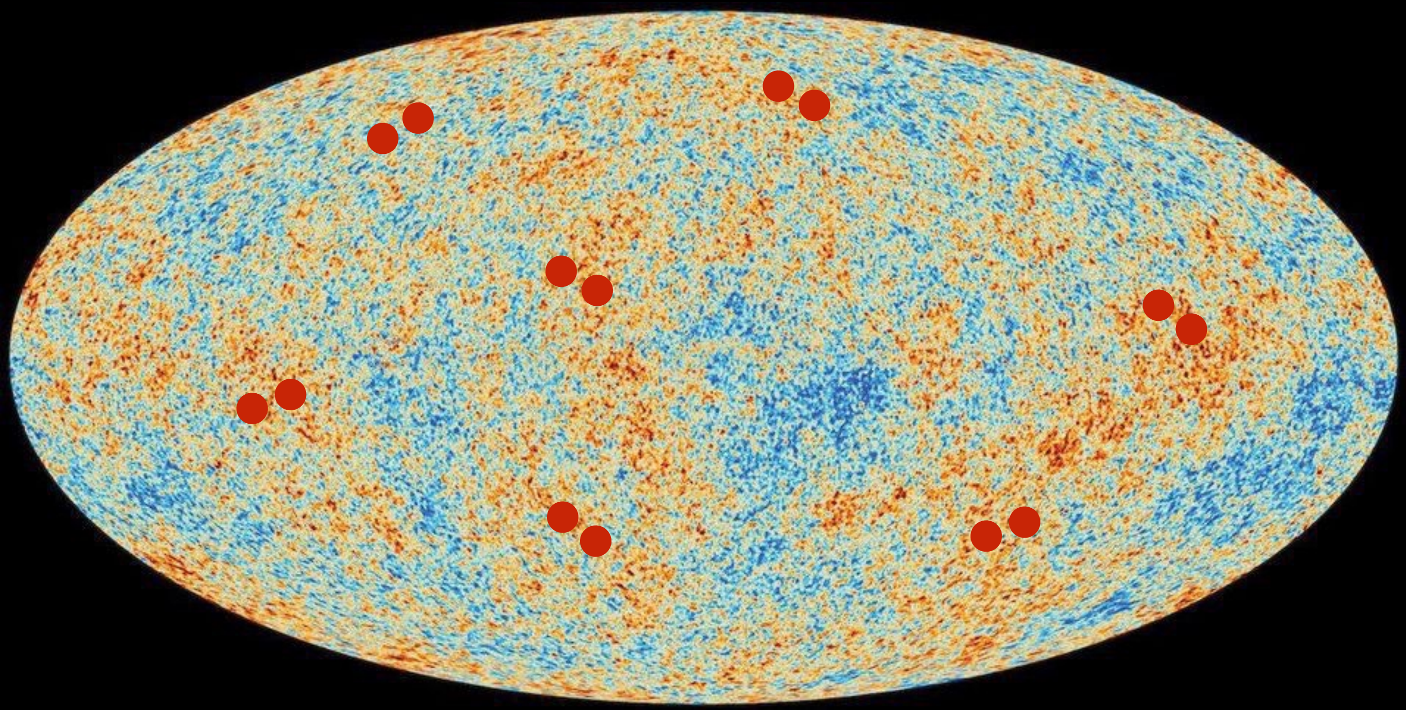
cannot see this in
power spectrum (Cl^TT)
maybe machine learning?

see also Maldacena (2015)

Non-trivial defects in CMB

(super preliminary! just an idea)

e.g., pair-produced hot/cold spots



need time-dependent mass

m >> H => m ~ H => m ~ Mpl >> H

How to make this?

- heavy particle production during inflation
- mass sources larger perturbation

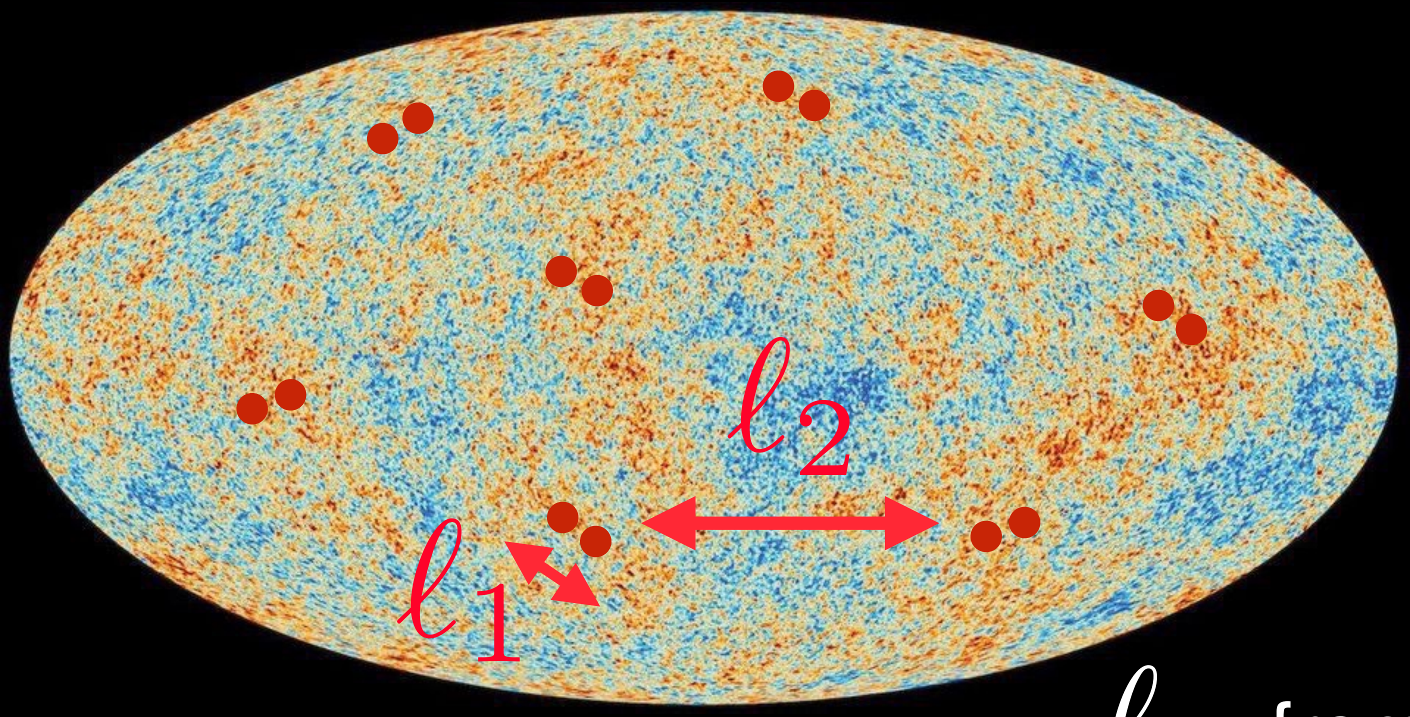
$$\mathcal{L} \subset \int \frac{d\eta}{H} m(\eta) \partial_\eta \xi$$

$$\langle \xi \rangle \sim \left(\frac{m(\eta = x)}{\sqrt{\epsilon} M_{pl}} \right) \left(\frac{H}{\sqrt{\epsilon} M_{pl}} \right)$$

Non-trivial defects in CMB

(super preliminary! just an idea)

e.g., pair-produced hot/cold spots



How to make this?

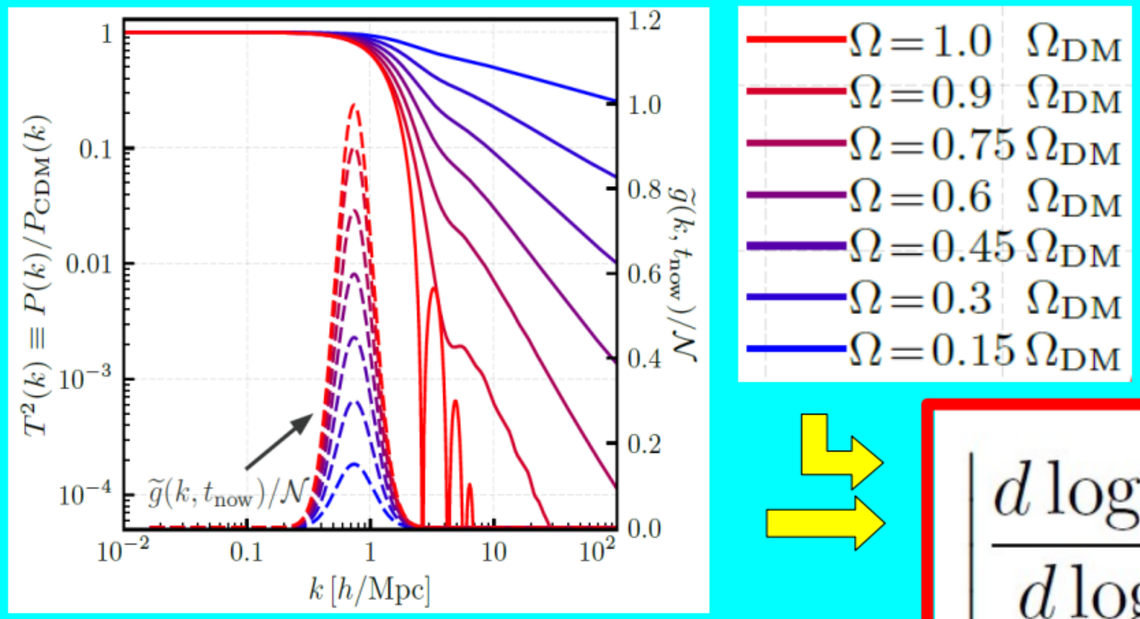
- heavy particle production during inflation
- mass sources larger perturbation

ℓ_1 from horizon size at particle production

ℓ_2 determined by the production probability

Transfer function => DM phase space distribution

Pushing this further,
we can even conjecture a specific function η !



$$\left|\frac{d\log T^2}{d\log k}\right| \approx [F(k)]^2 + \frac{3}{2}F(k)$$

approximate relation holds to very high precision!

Our conjecture then takes the non-trivial form

$$\frac{\tilde{g}(k)}{\mathcal{N}} \approx \frac{1}{2}\left(\frac{9}{16} + \left|\frac{d\log T^2}{d\log k}\right|\right)^{-1/2}\left|\frac{d^2\log T^2}{(d\log k)^2}\right|$$

This would allow us to "resurrect" *g(k)* from the transfer function *T²(k)*!

slide credit: Keith Dienes

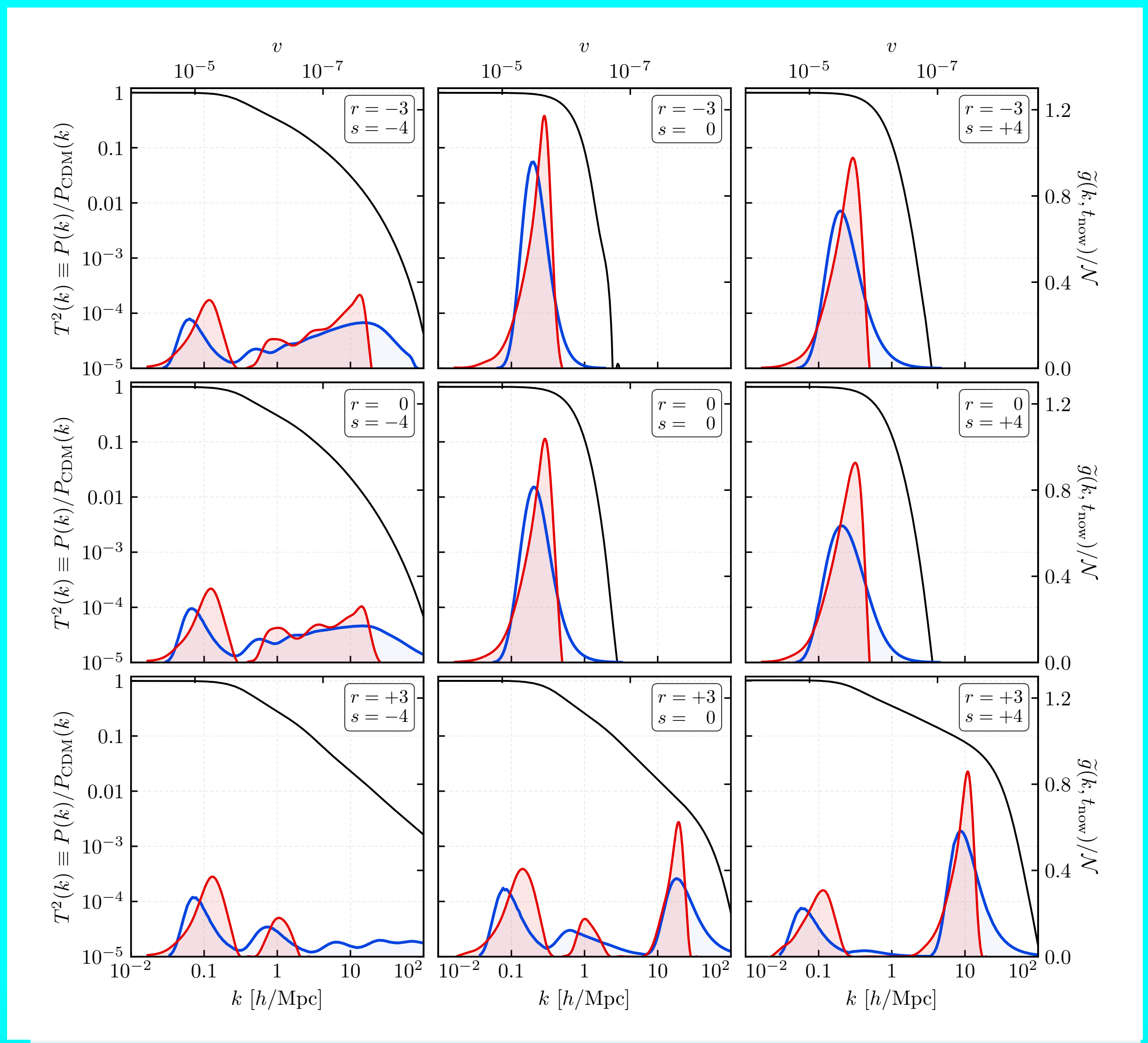
Dienes, Huang, Kost, Su, Thomas

Transfer function => DM phase space distribution

Finally, to what extent can we "resurrect" the dark-matter phase-space distribution from the transfer function?

Recall our conjecture....

$$\frac{\widetilde{g}(k)}{\mathcal{N}} \approx \frac{1}{2}\left(\frac{9}{16}+\left|\frac{d\log T^2}{d\log k}\right|\right)^{-1/2}\left|\frac{d^2\log T^2}{(d\log k)^2}\right|$$



Blue outline = original k-space DM distribution

Pink shaded = reconstruction directly from transfer function

slide credit: Keith Dienes

Dienes, Huang, Kost, Su, Thomas