

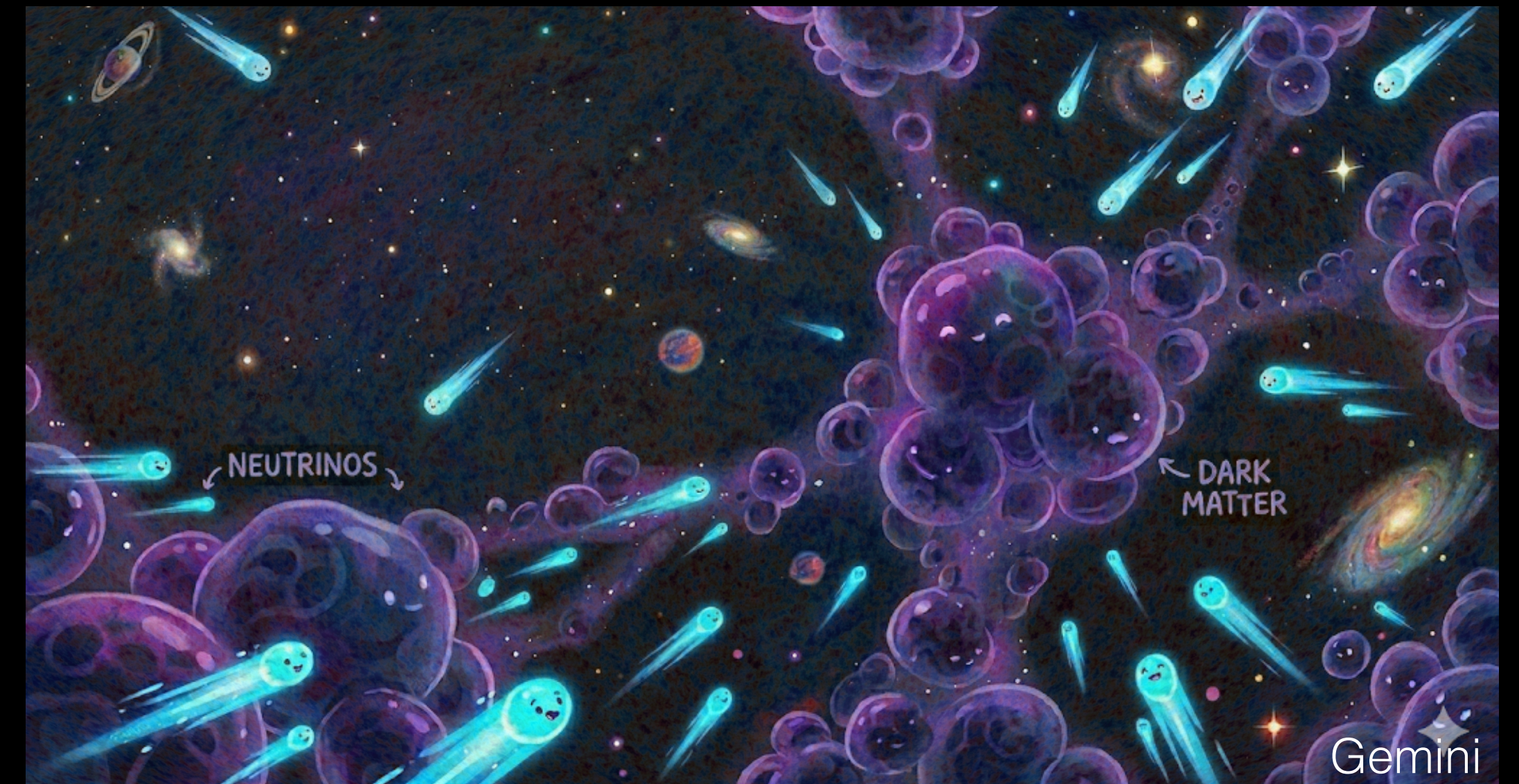
Particle Physics at Cosmic Frontier



Yuhsin Tsai

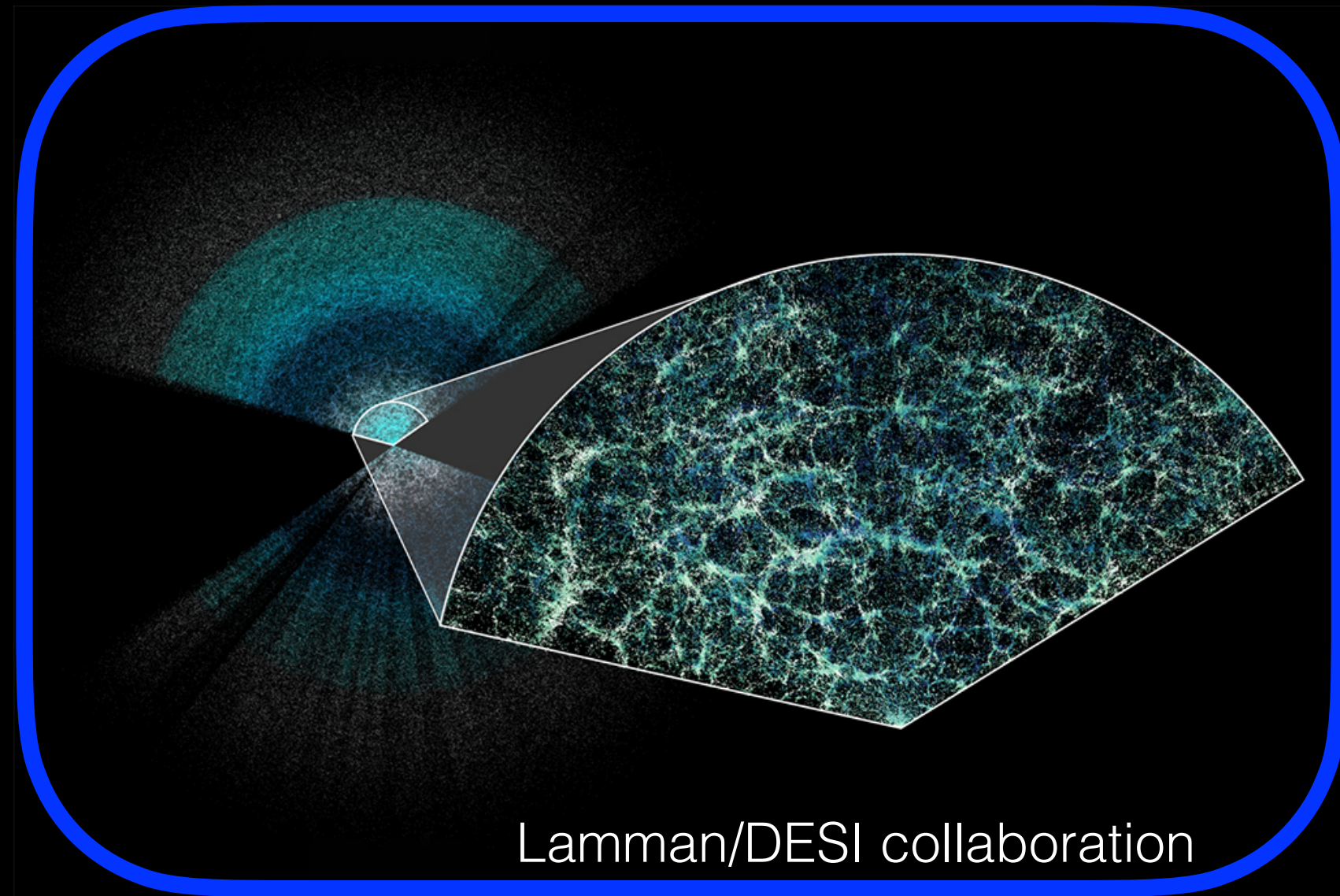
University of Notre Dame

PHENO, May 11, 2026

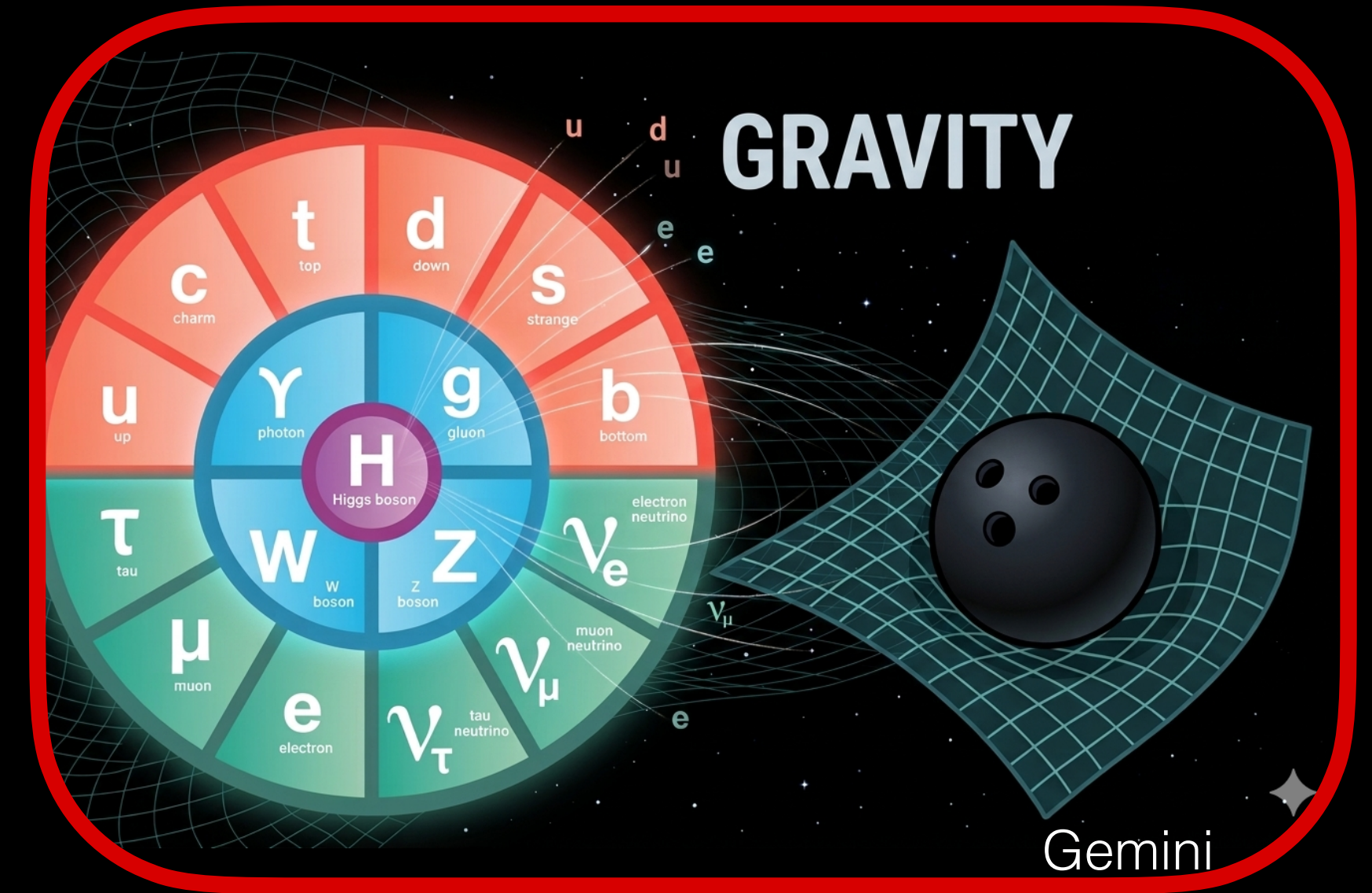


Particle physics & Cosmology are deeply interconnected

Macroscopic structure

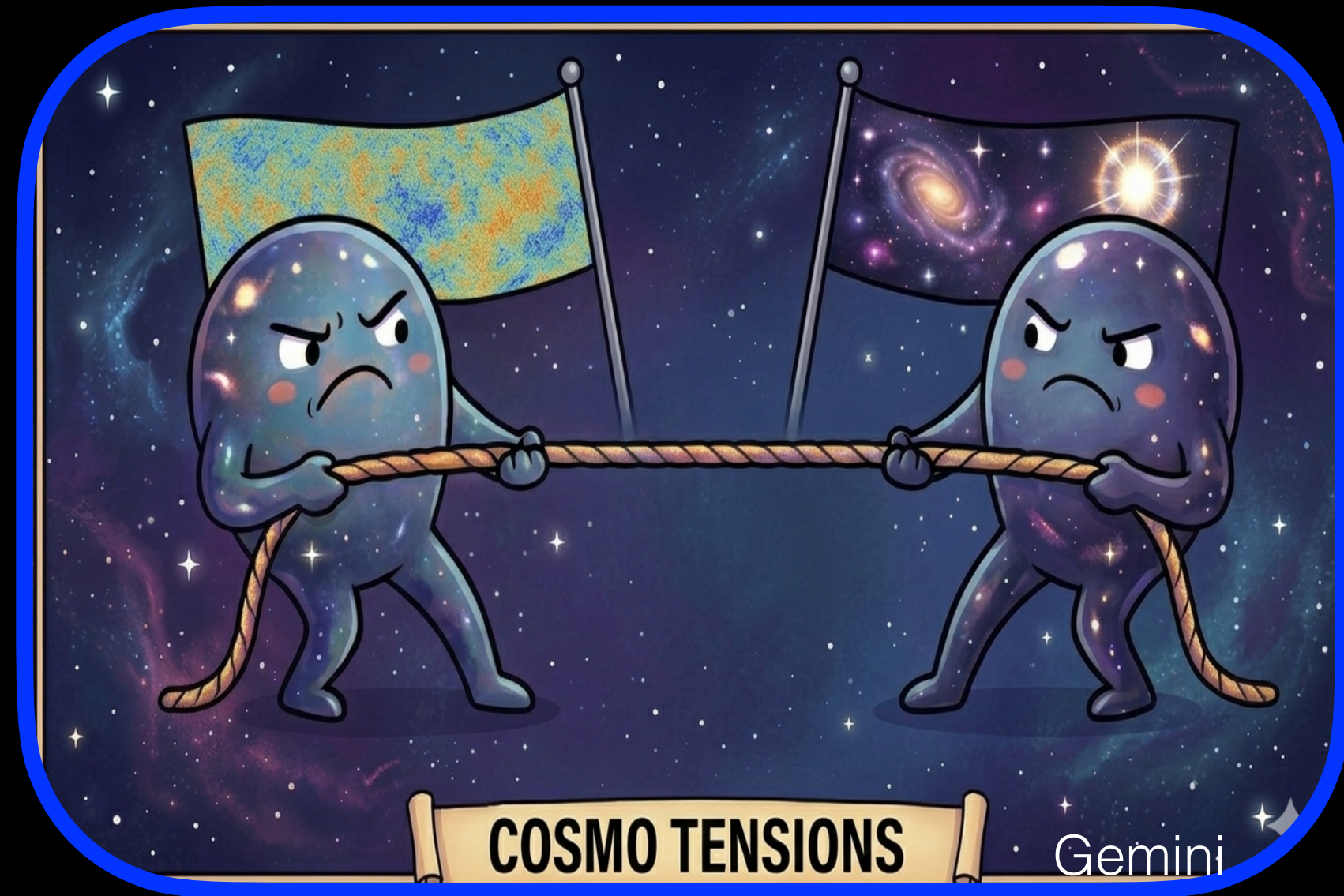


Subatomic physics



Interplay between the two fields

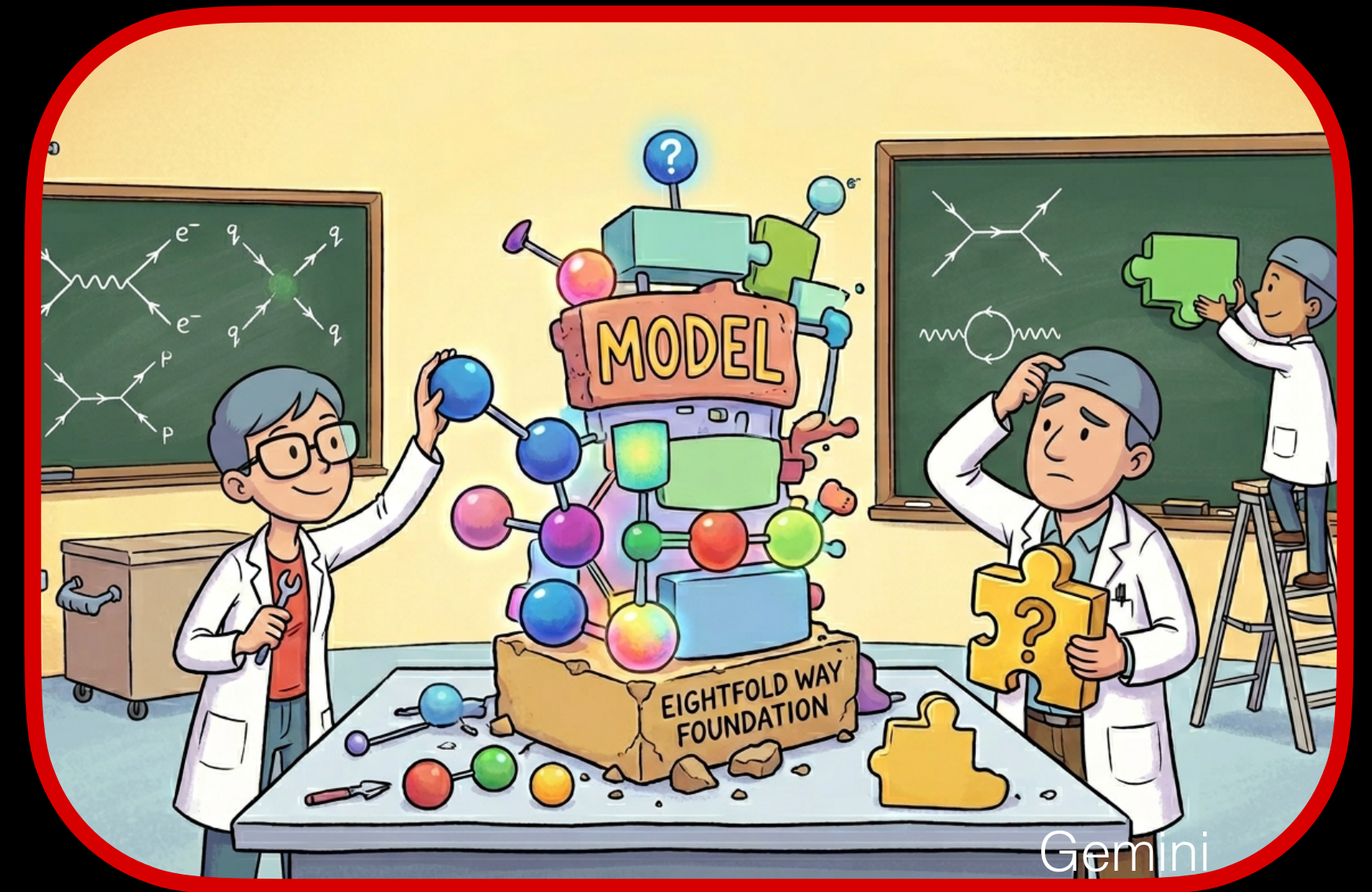
Cosmological tensions



explain

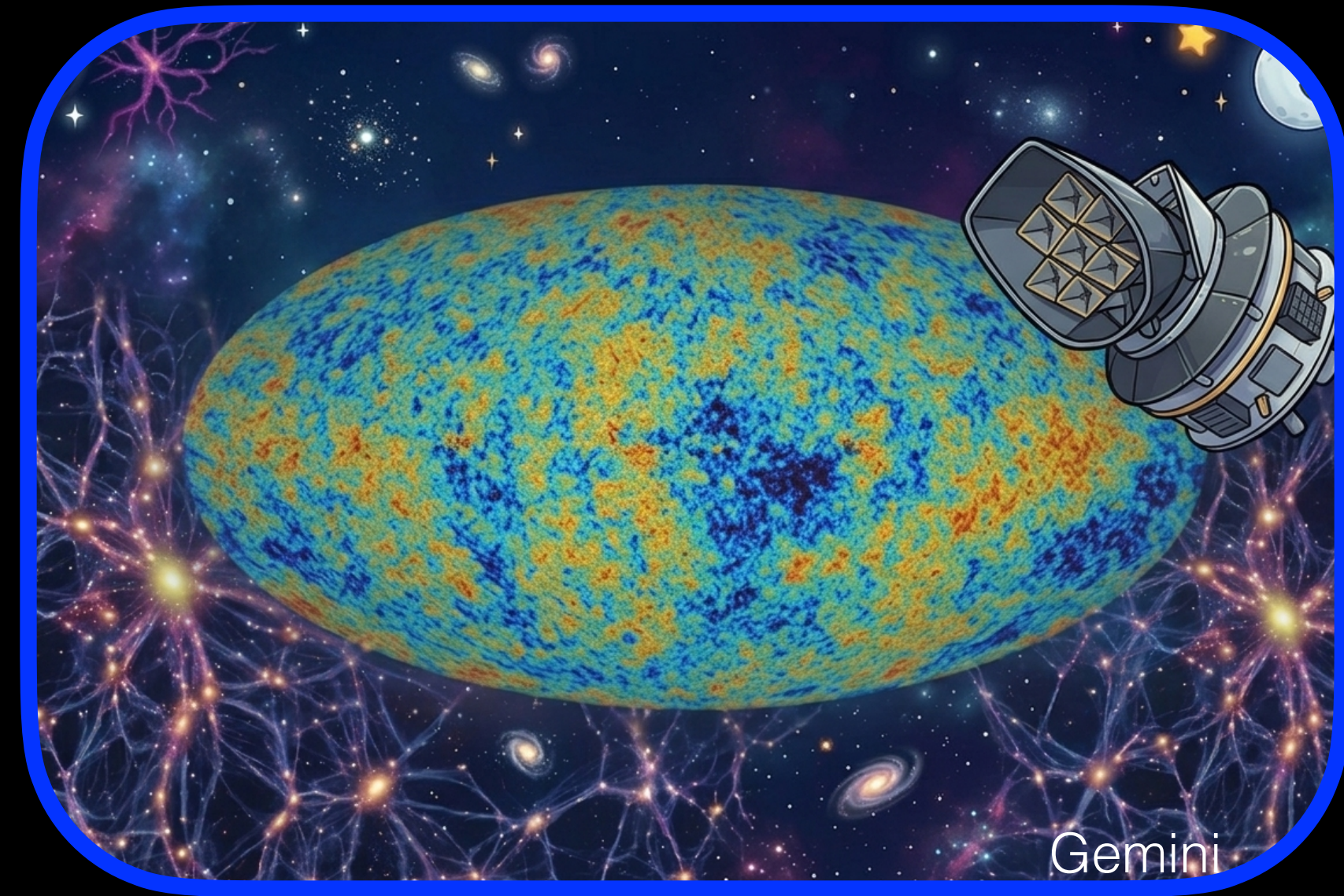


New physics models



Interplay between the two fields

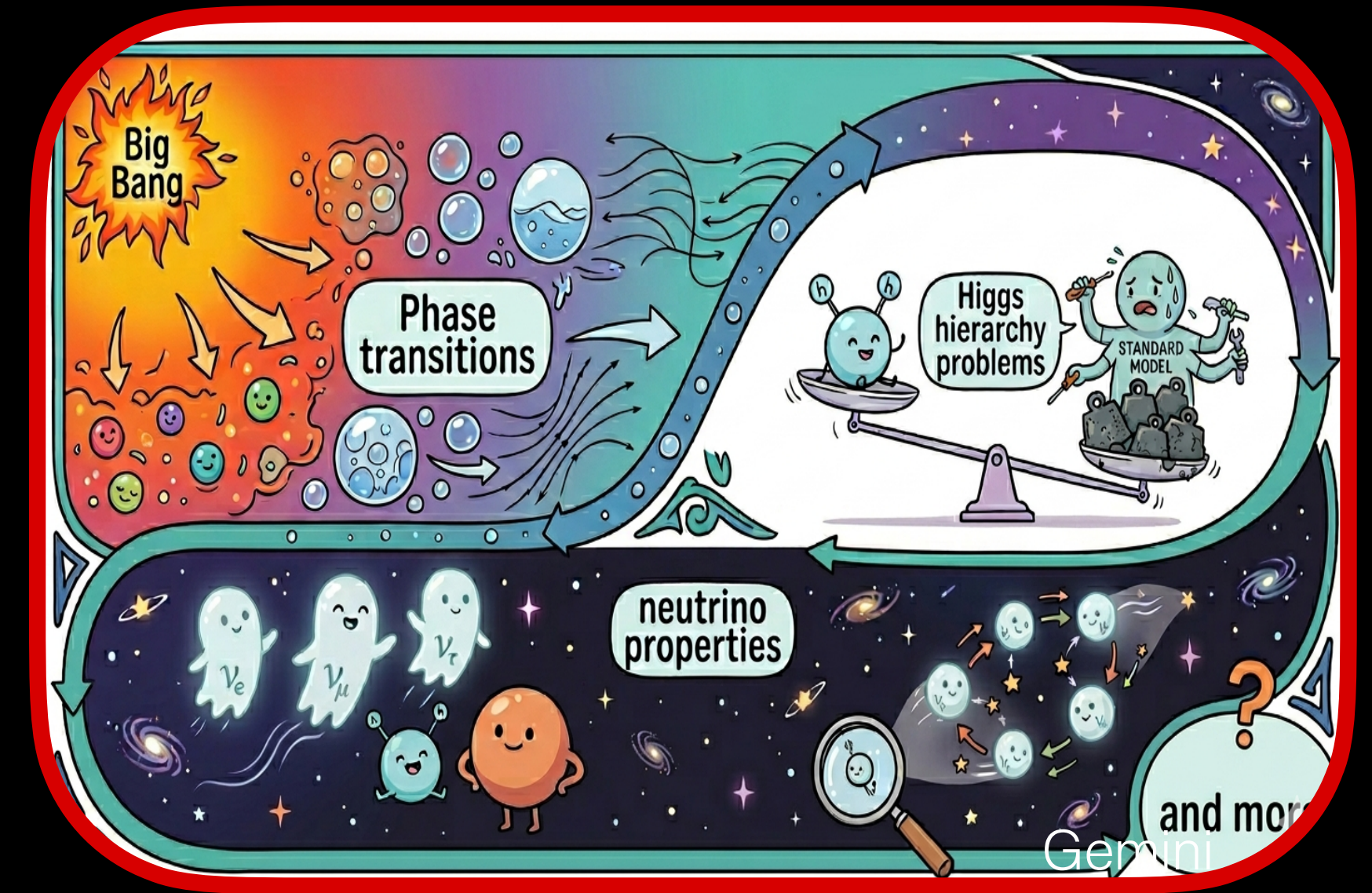
Cosmological measurements



probe
constrain

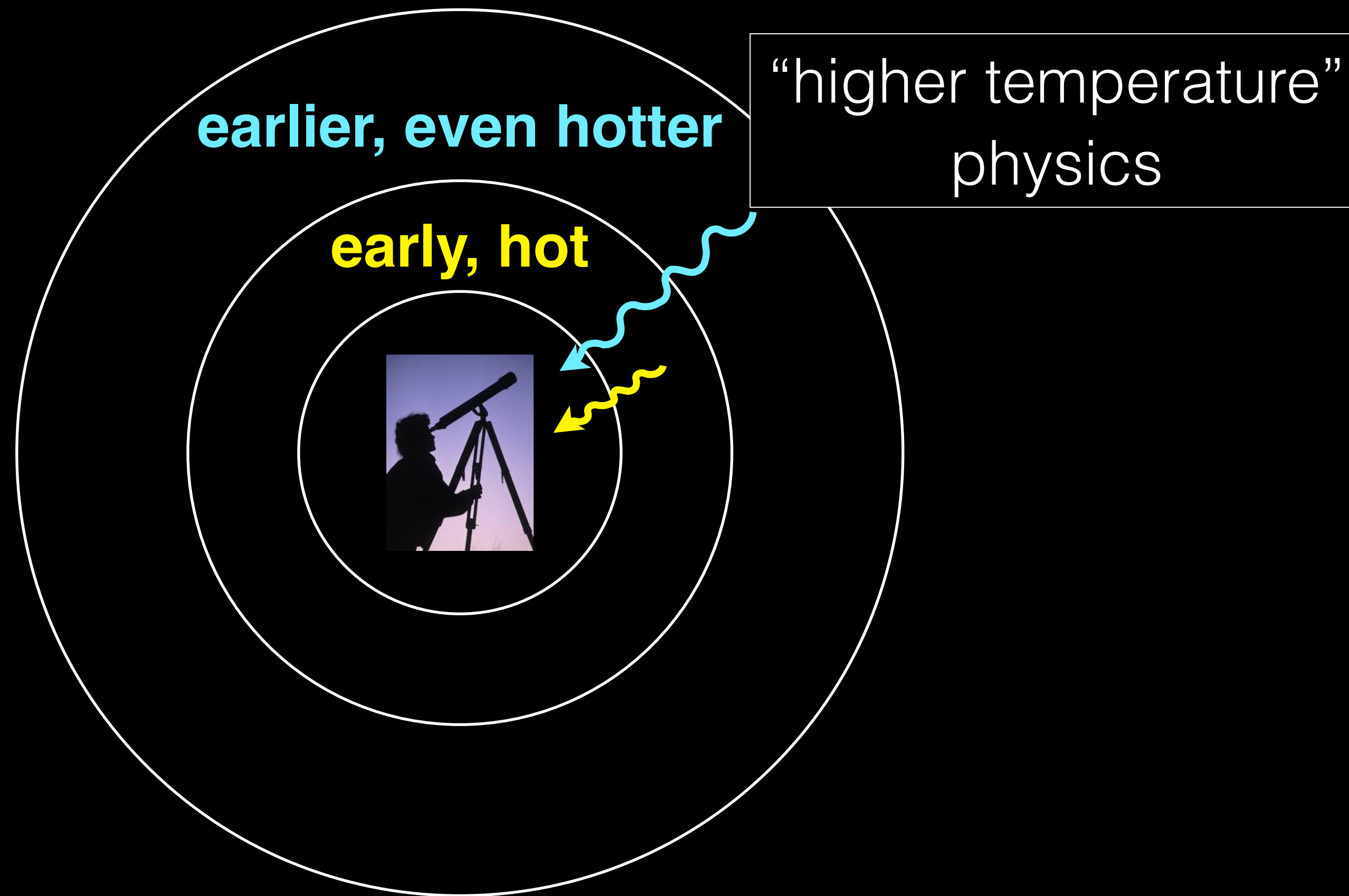


Plausible particle
physics scenarios

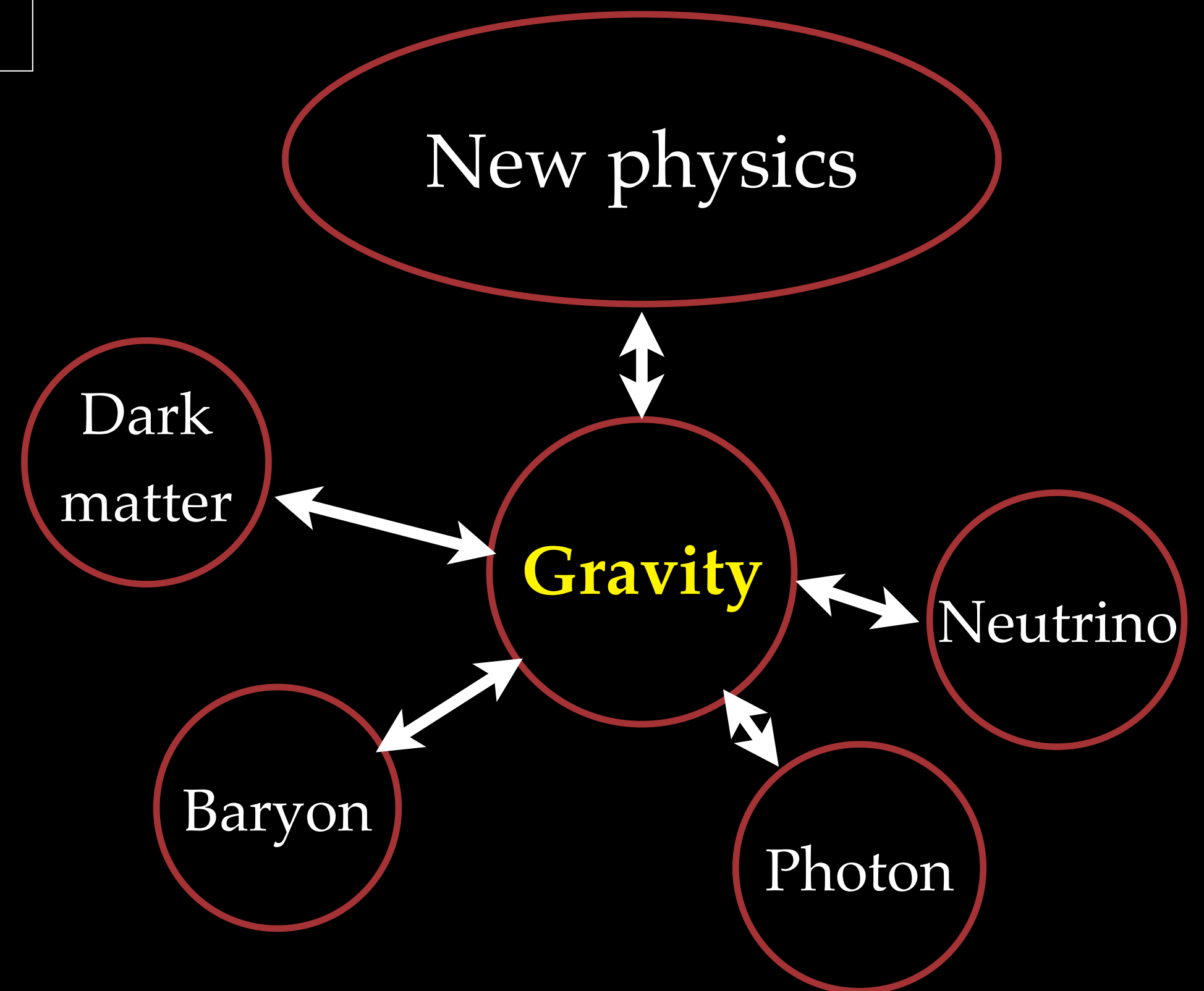


I'll focus more on this direction

Probing the “invisible” physics: **looking into the sky!** WHY?

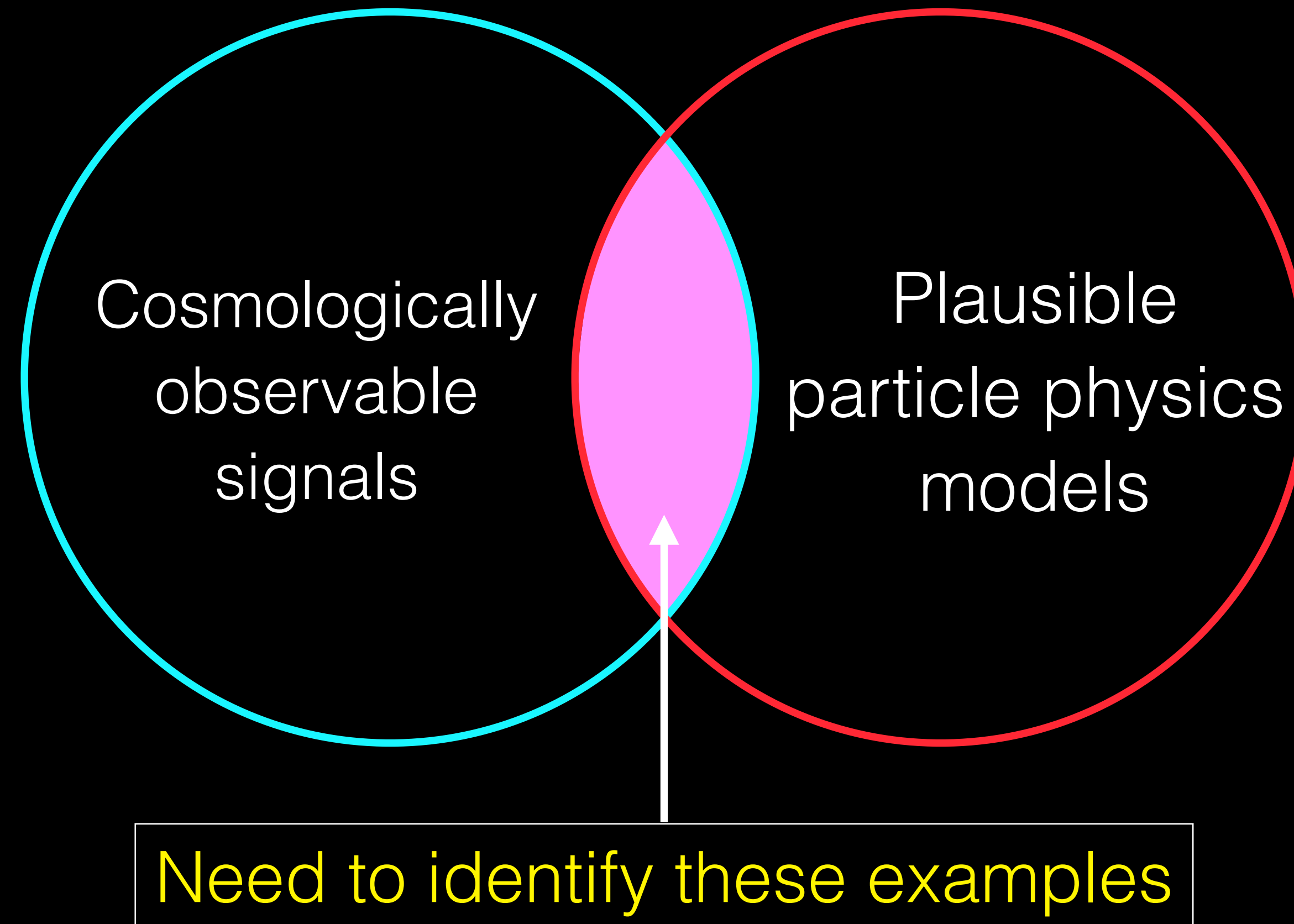


Can probe new physics “gravitationally”



However, life is never so easy...

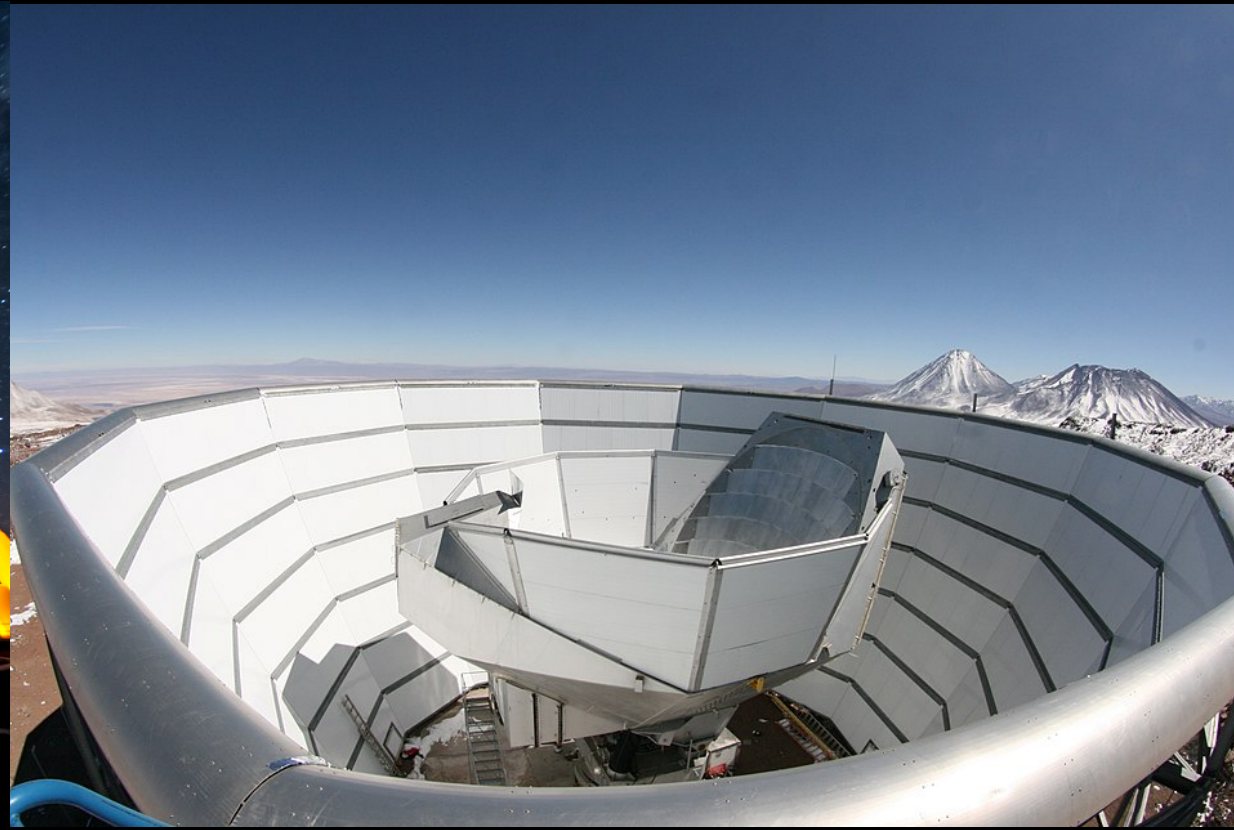
Obvious signals are usually **destroyed at early times**



Data Is Coming—Find More Particle Physics to Test!



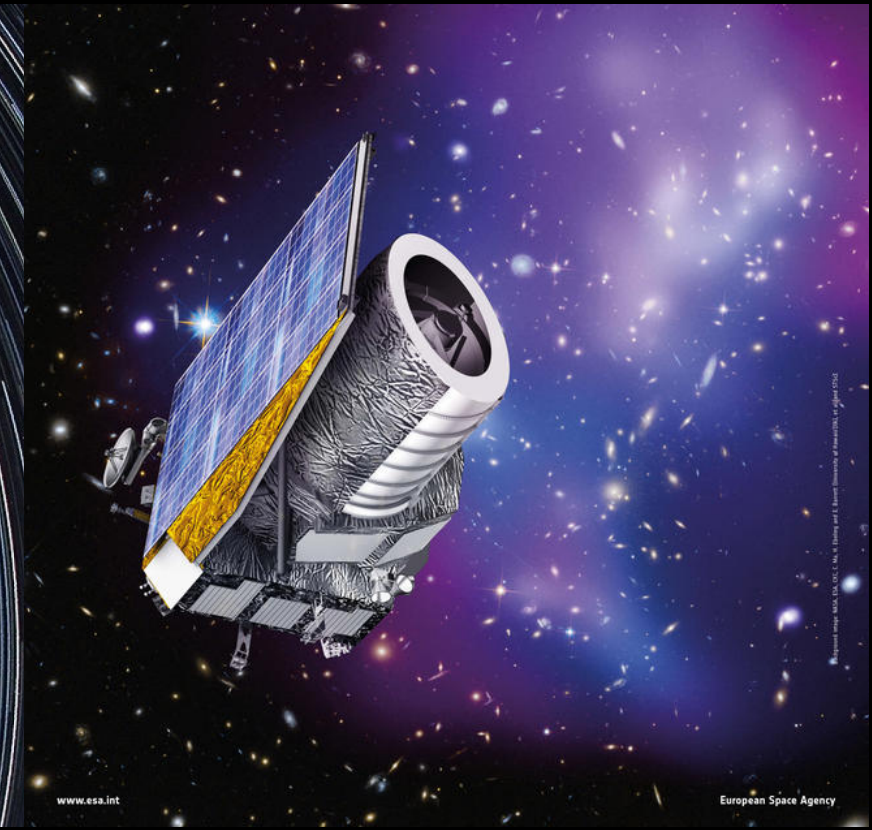
DES (-2019)



ACT (-2021)



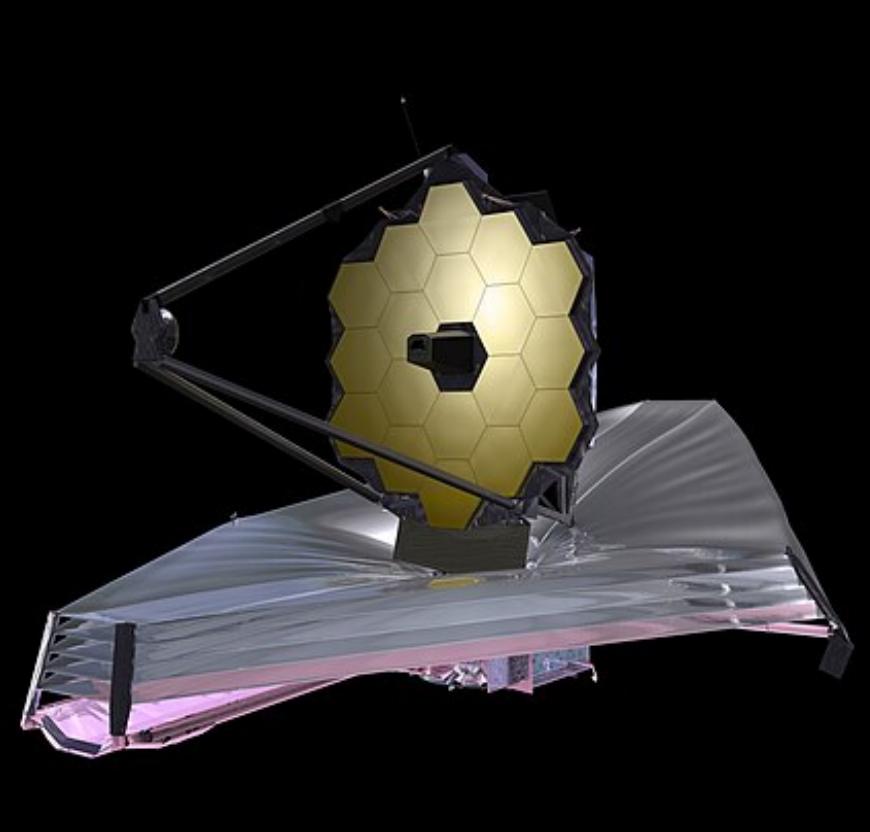
DESI (2020-)



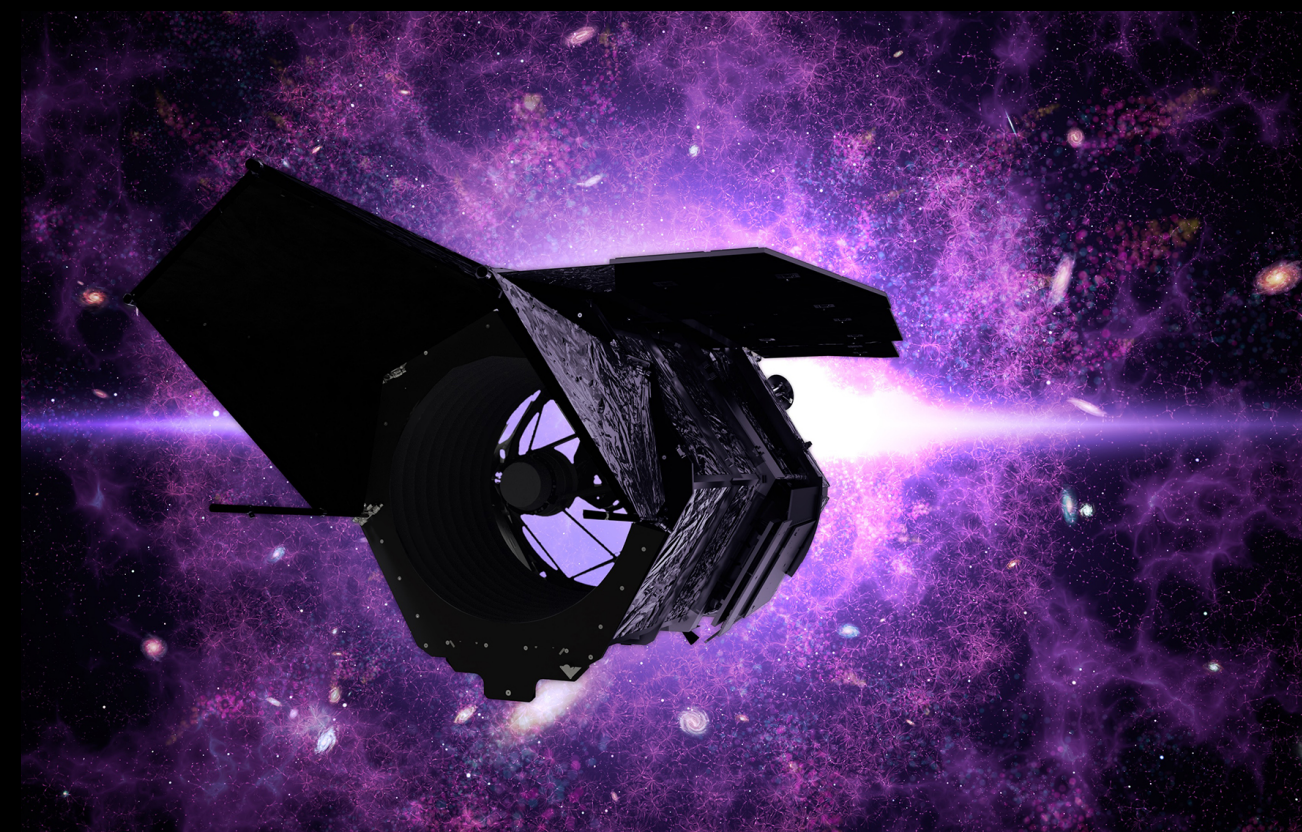
Euclid (2023-)



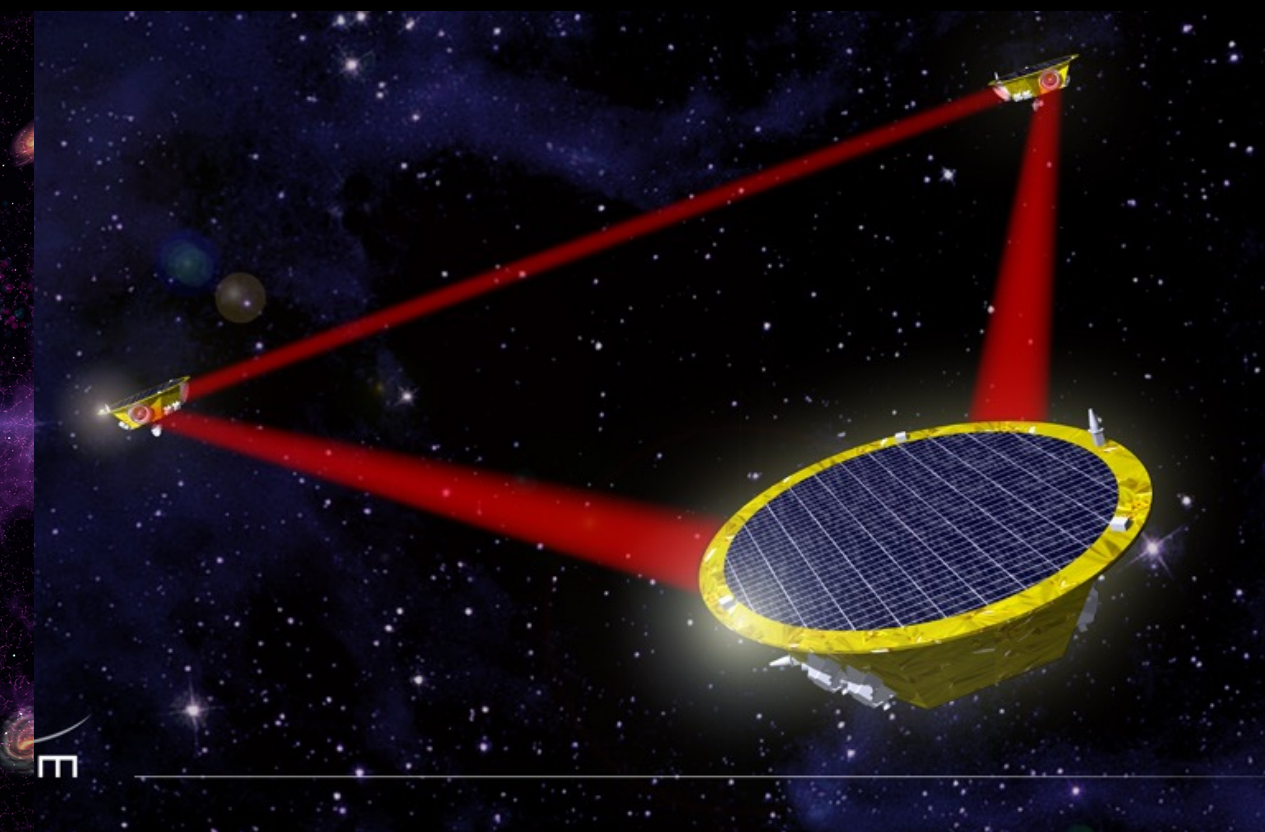
Vera C. Rubin
Observatory (2025-)



JWST (2022-)



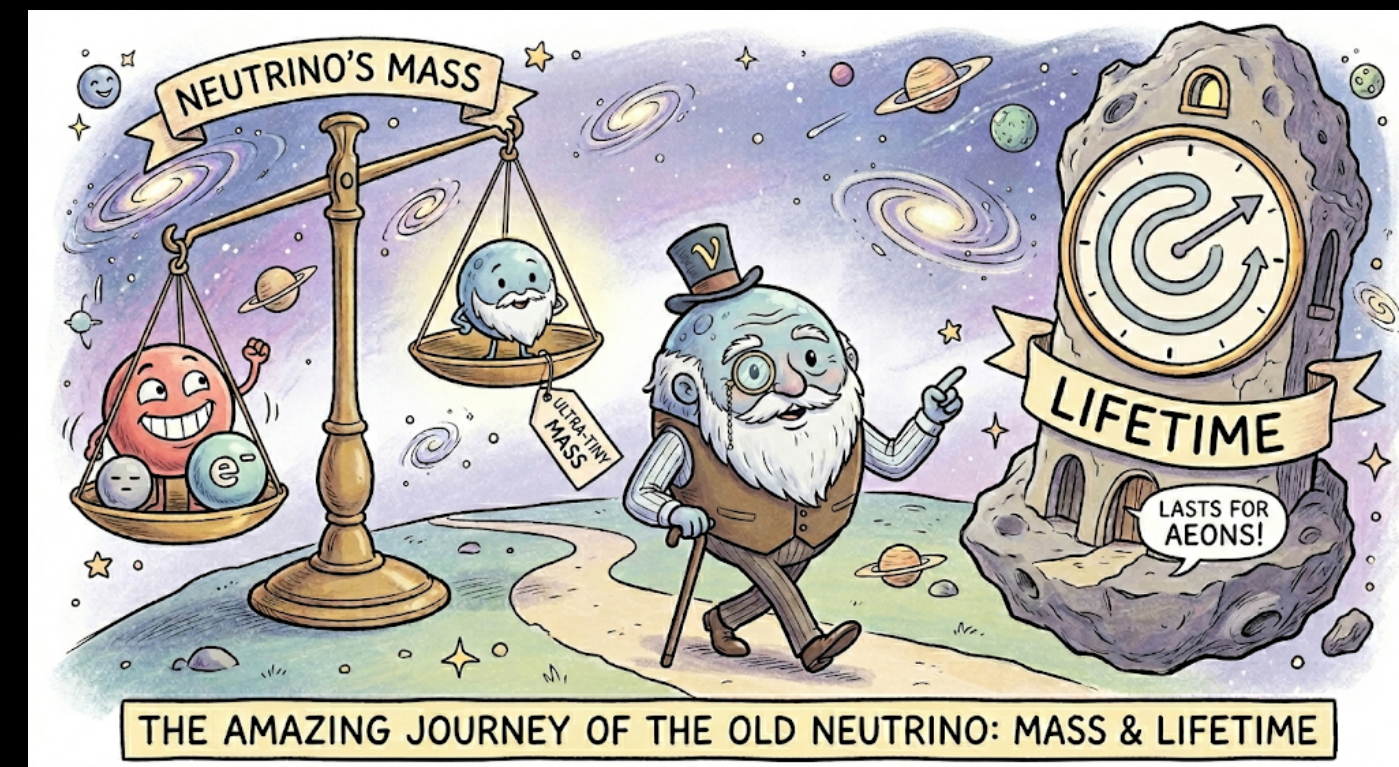
Roman (2026-)



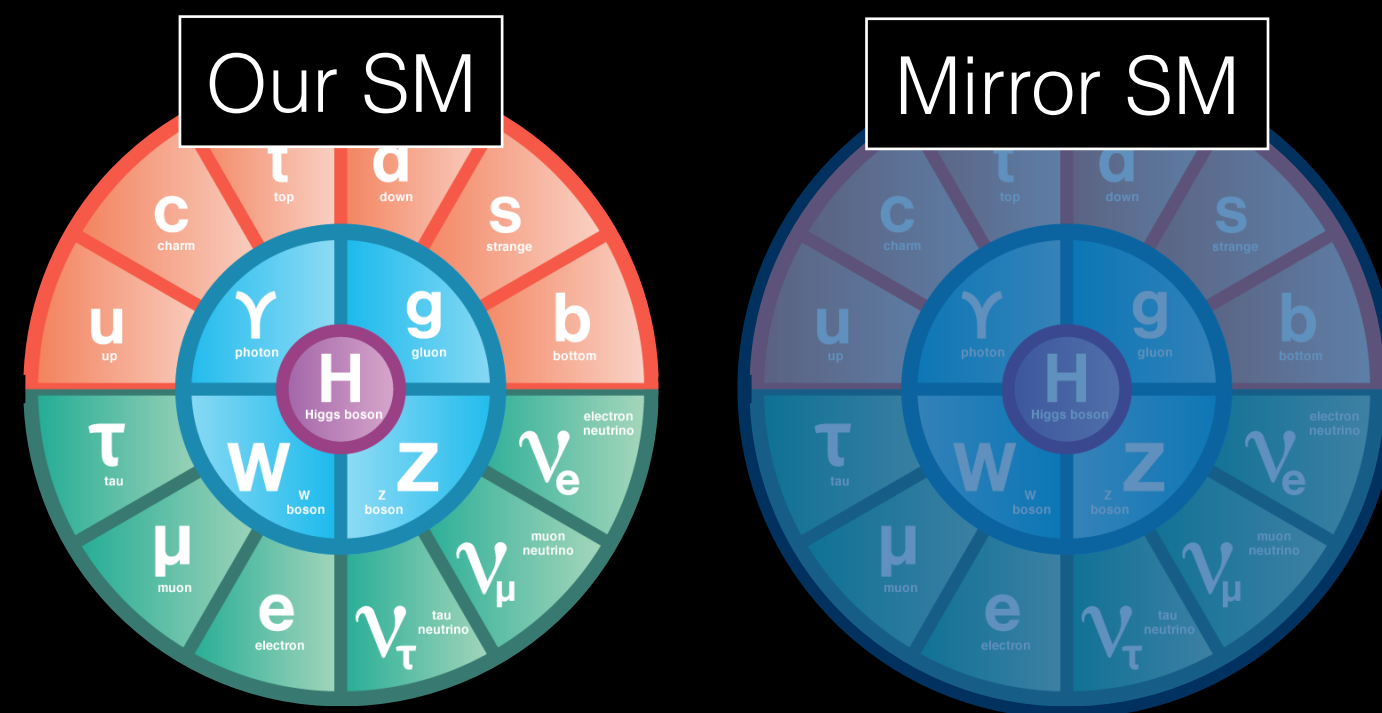
LISA (~203?)?

Let's discuss examples of cosmological probes of "invisible" physics

- Neutrino mass and lifetime

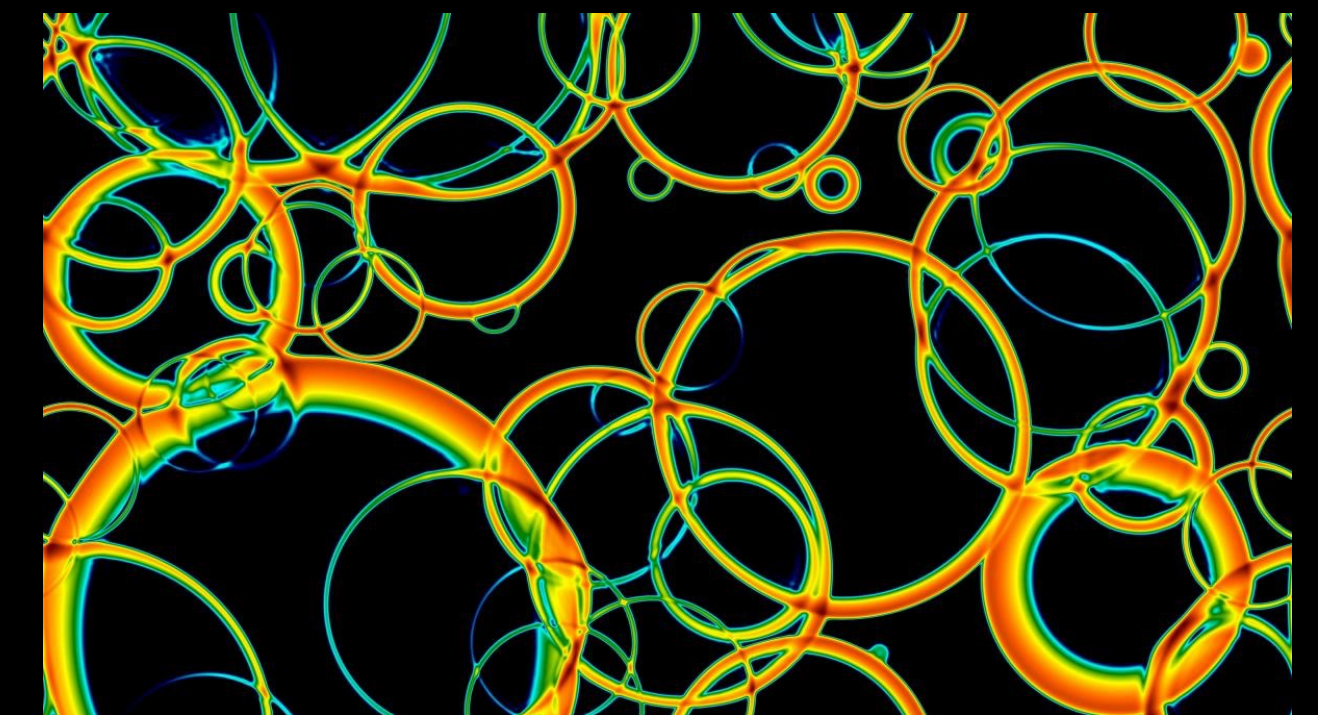


Gemini



- Dark sector & Higgs hierarchy problem

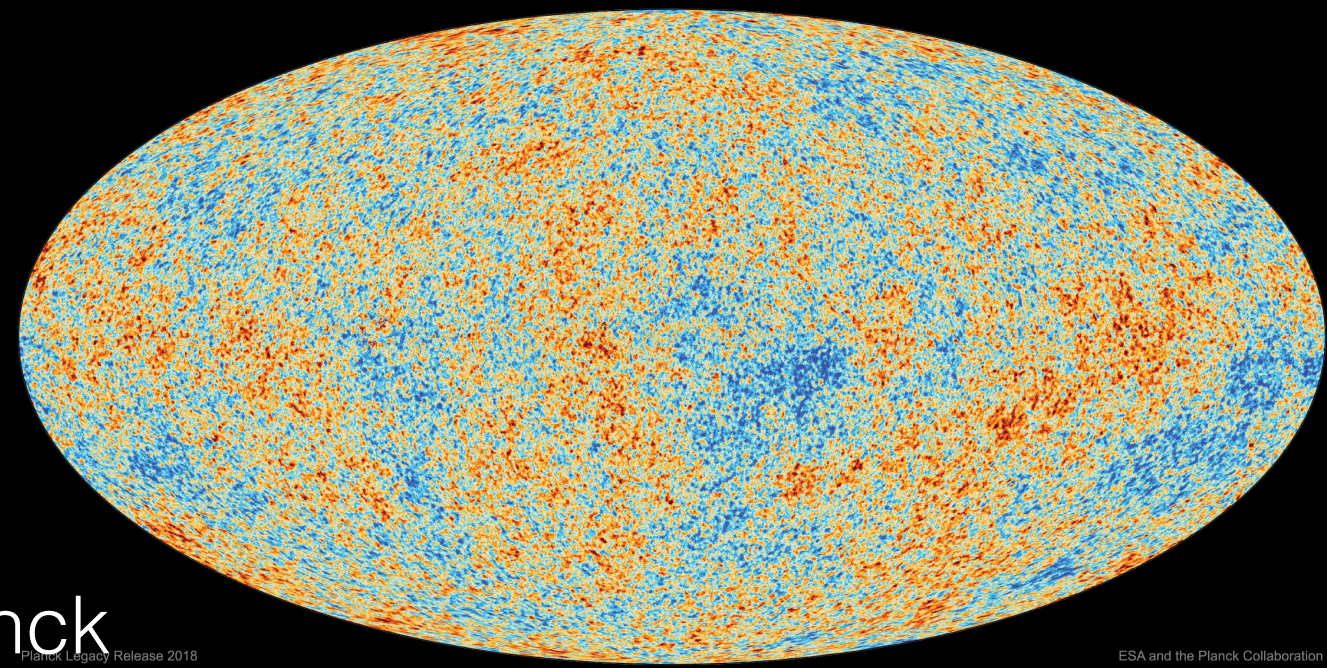
- Extended dark objects in the early Universe



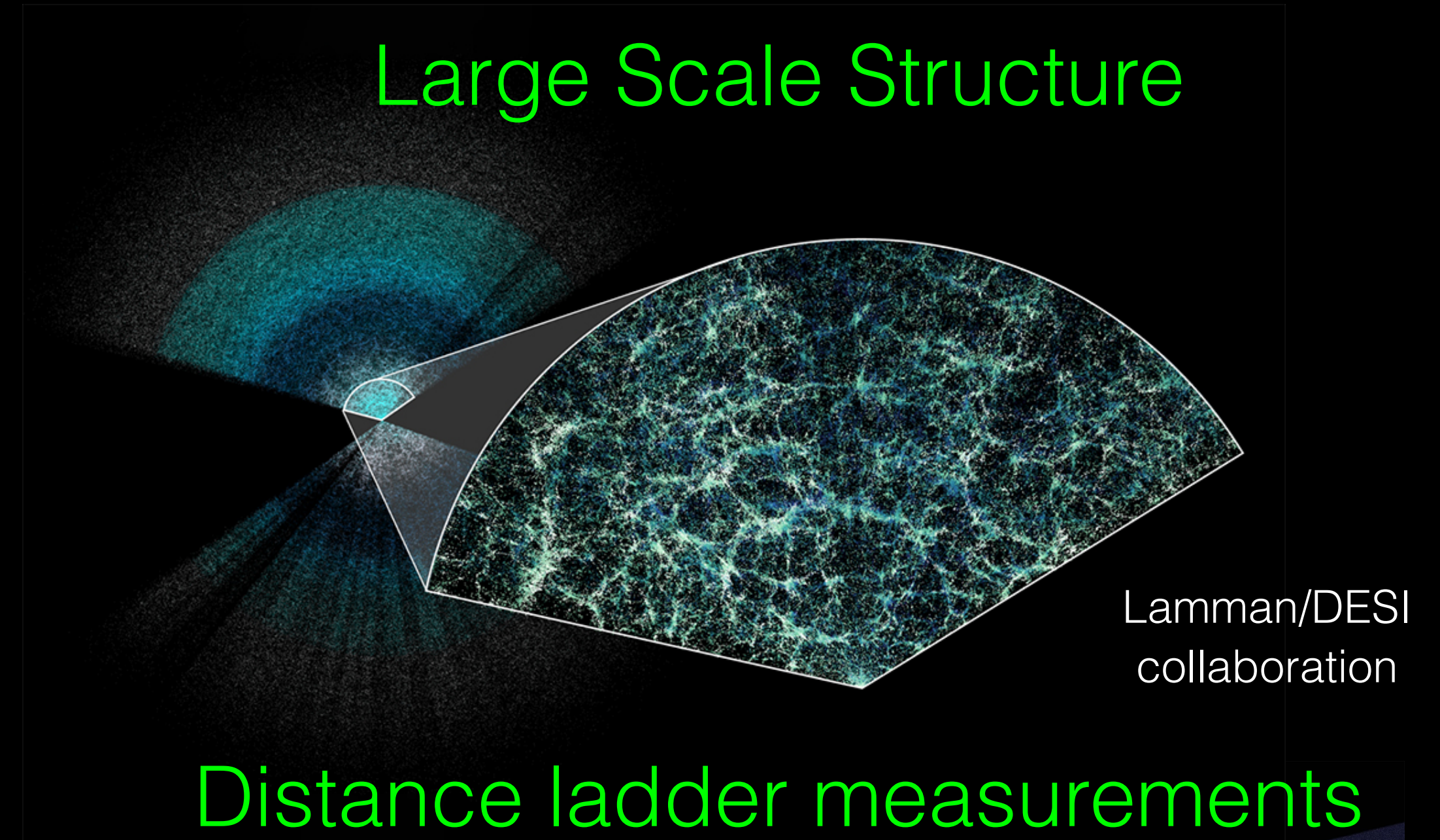
What's the data?

Let's only focus on **large scale** (> million light years) measurements here

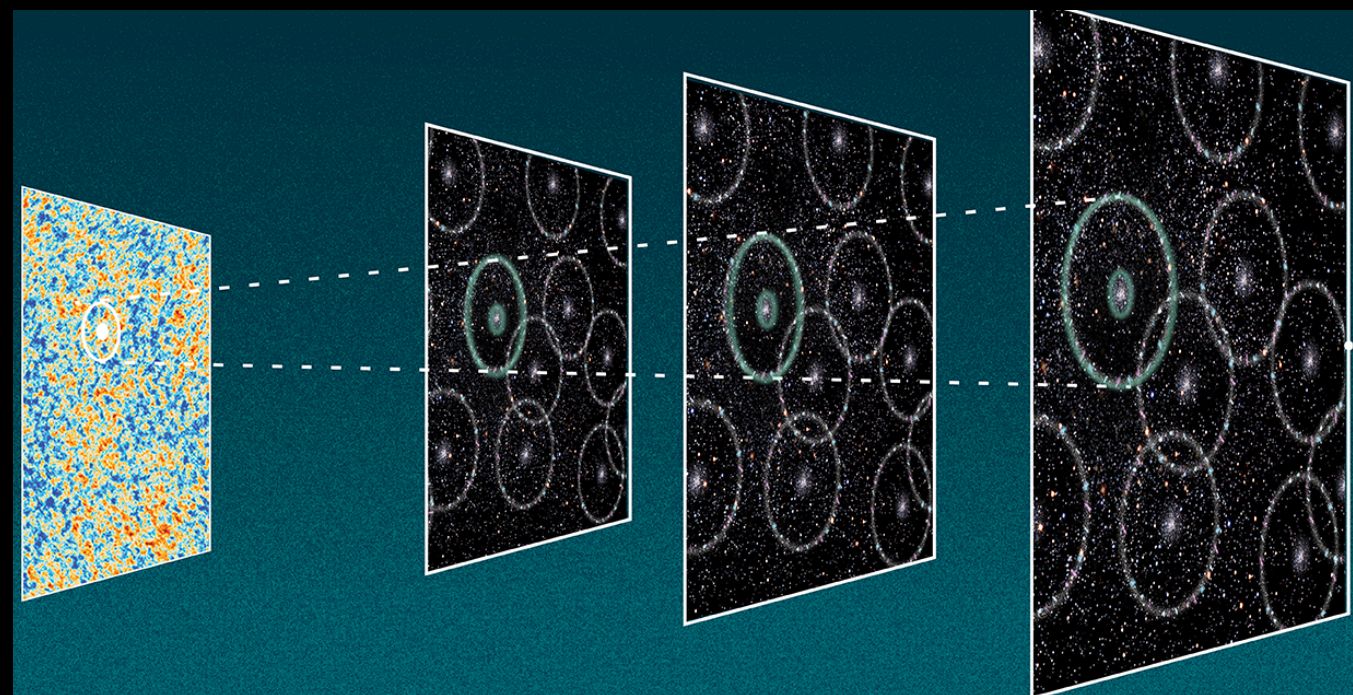
Cosmic Microwave Background



Large Scale Structure

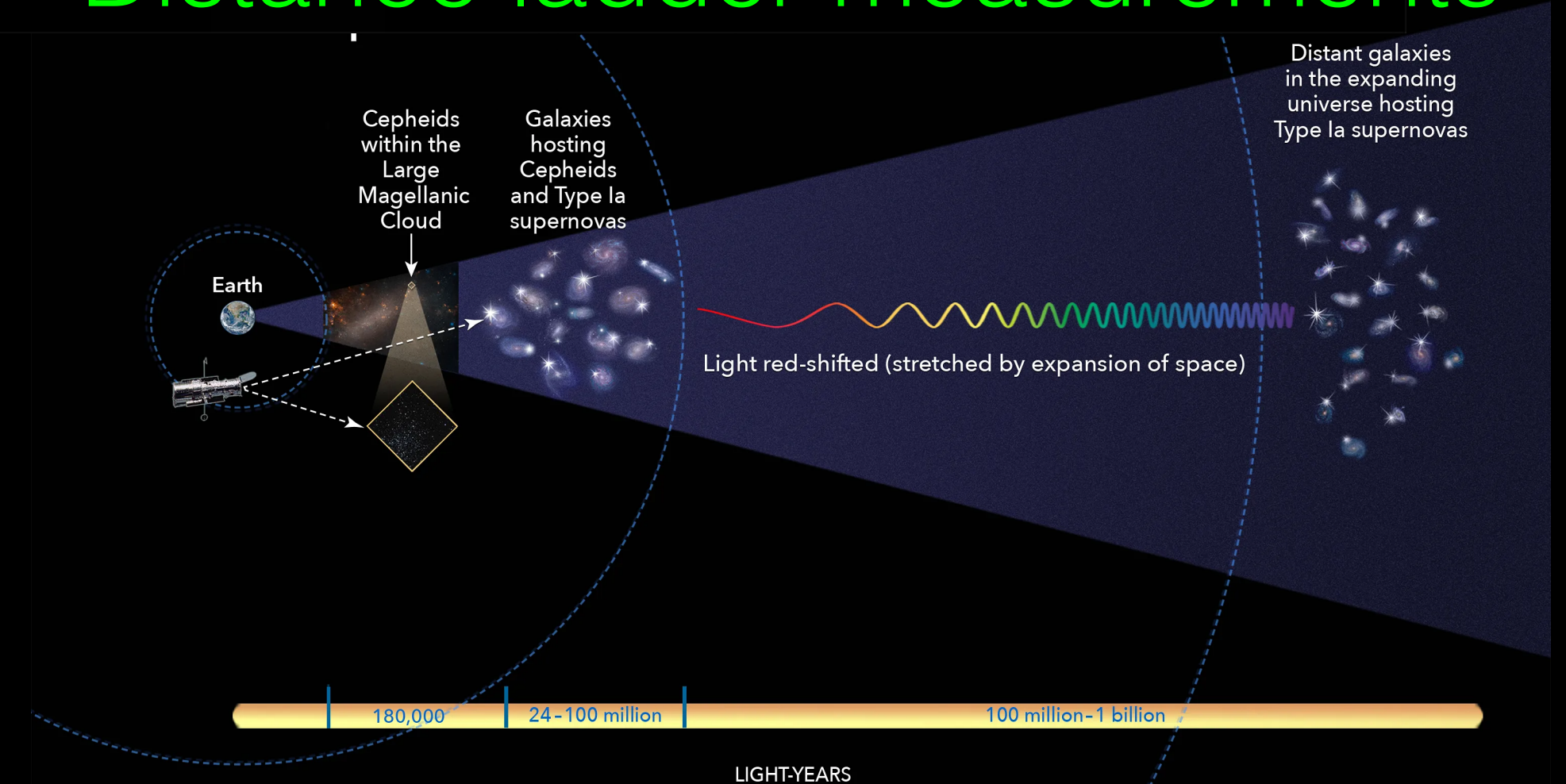


Baryon acoustic oscillation (BAO)



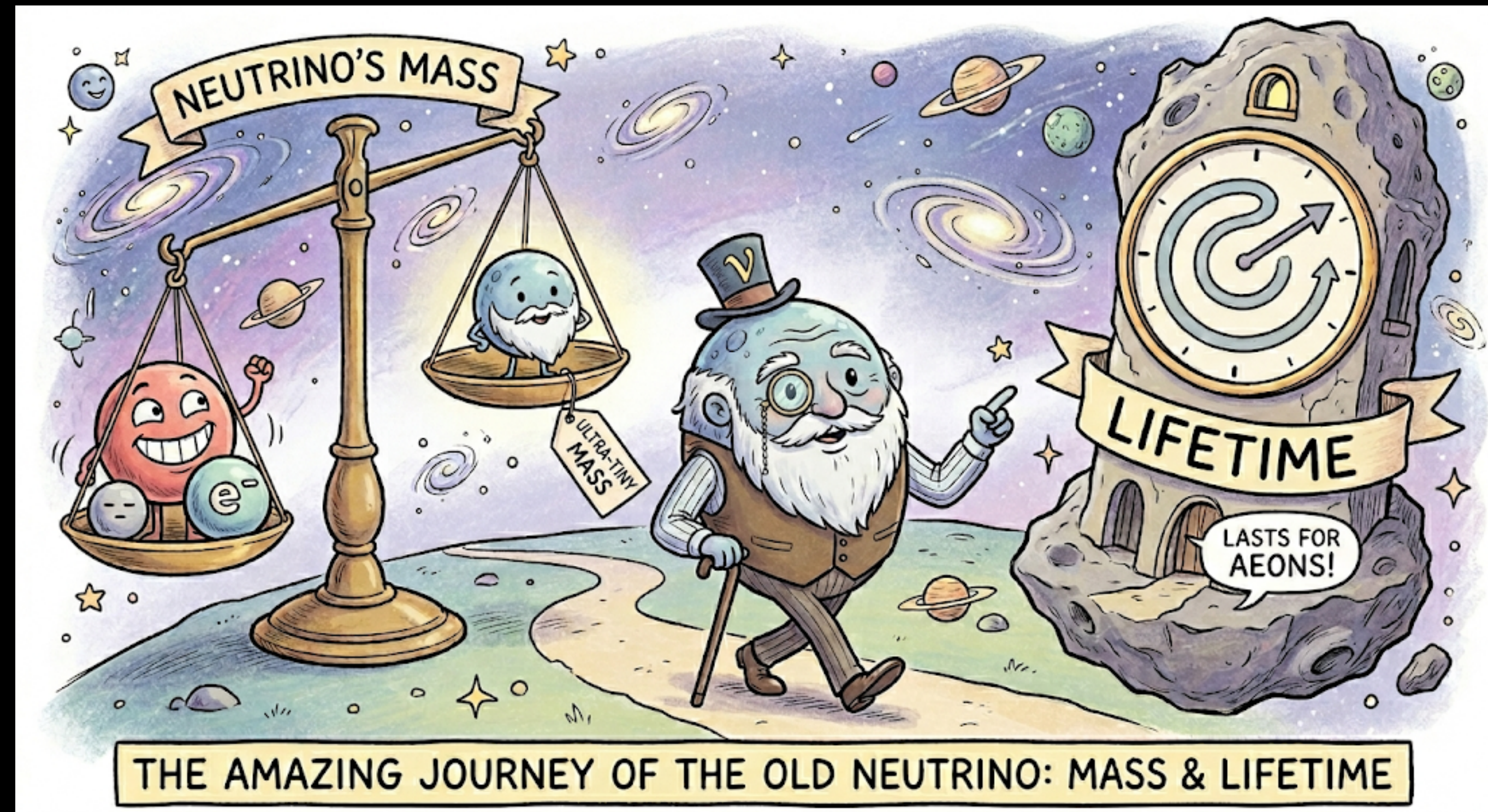
Artist representation: (ESA/Planck) Secara

Distance ladder measurements



Example I

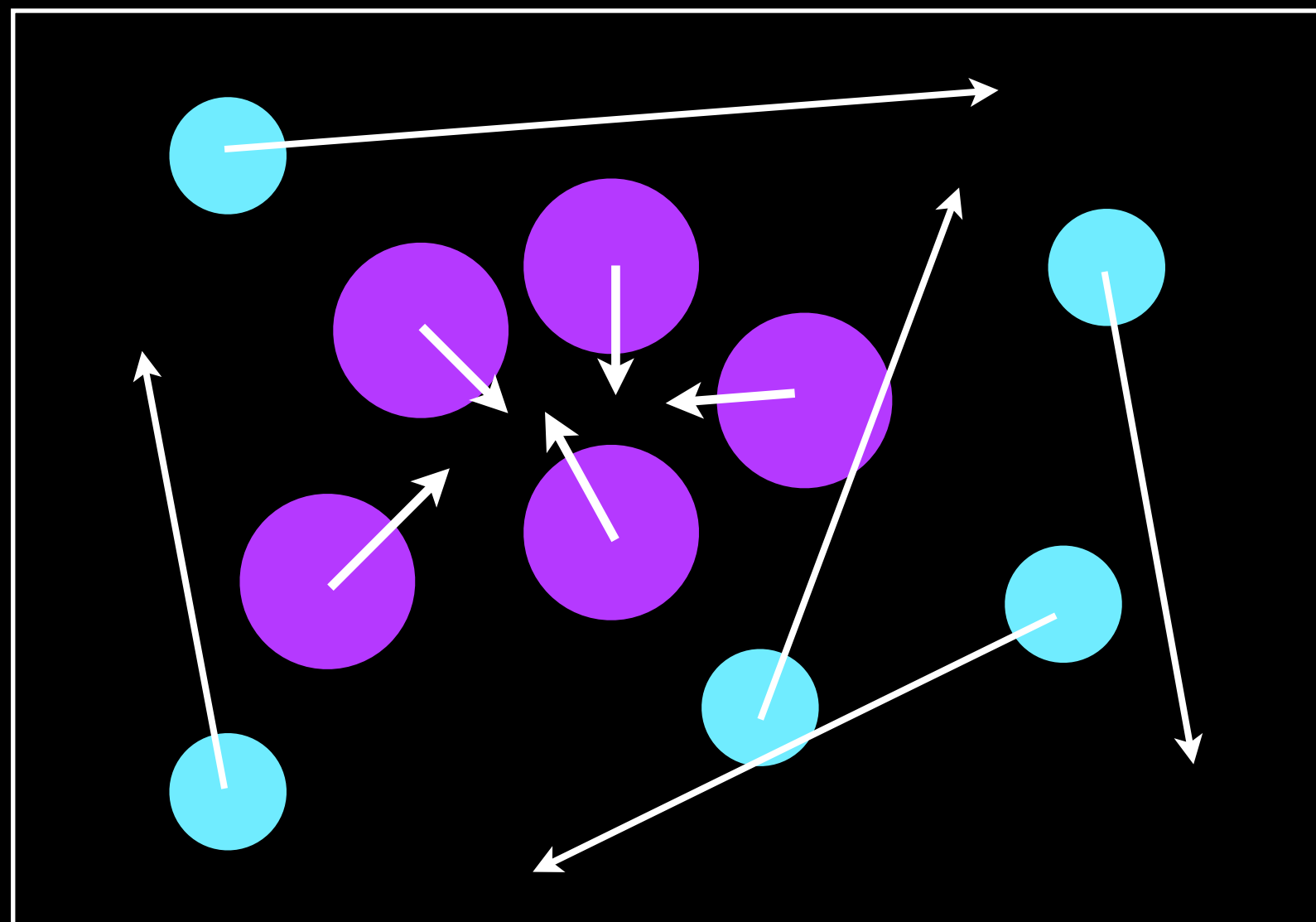
Neutrino **mass** & lifetime



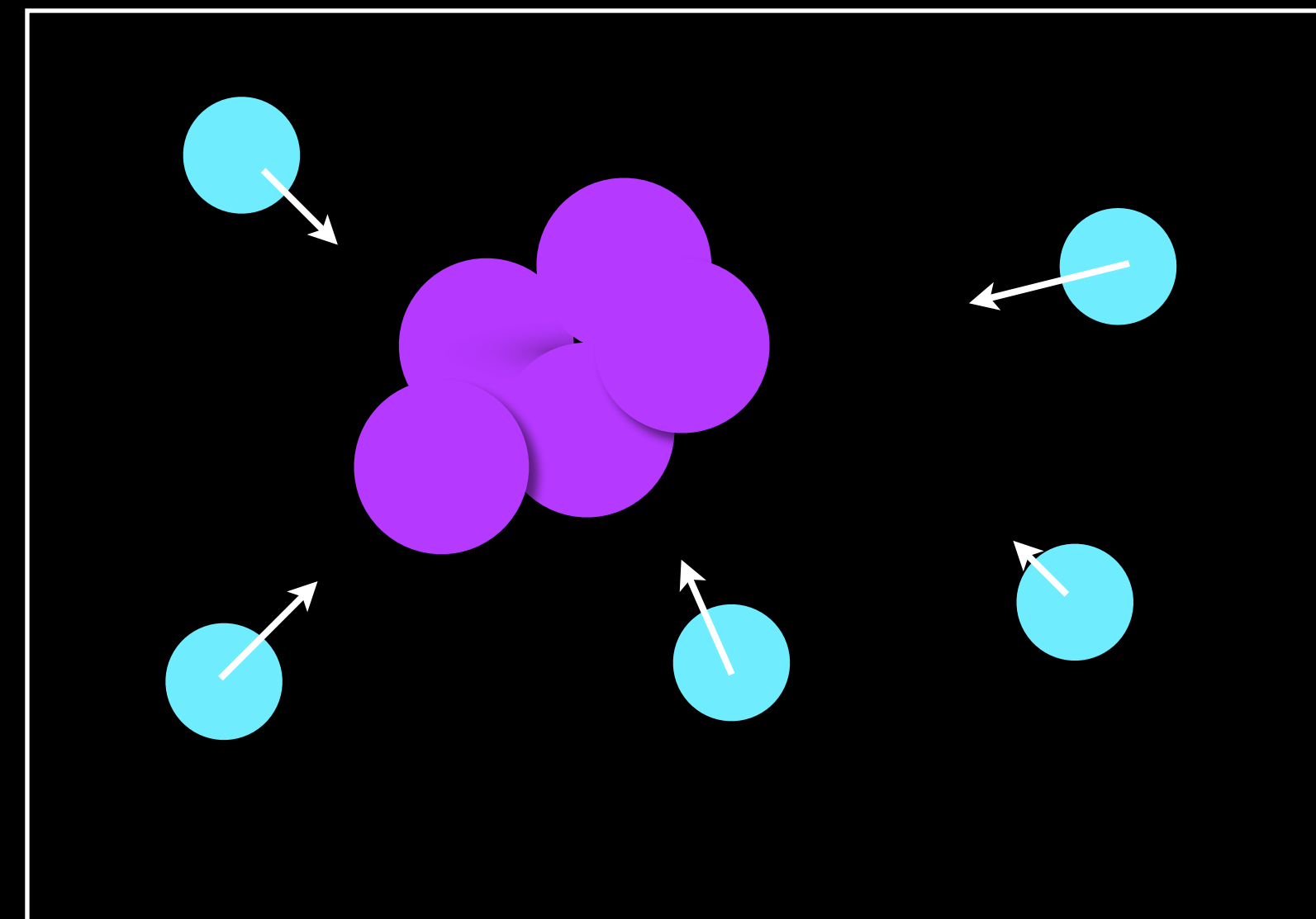
Gemini

Neutrinos are as abundant as photons in the early universe.
They **resist clustering**, but their mass increases the Hubble expansion rate
and **reduces structure formation time**

neutrinos look massless when
dark matter begins to clump



neutrinos finally slow down
dark matter already forms structure

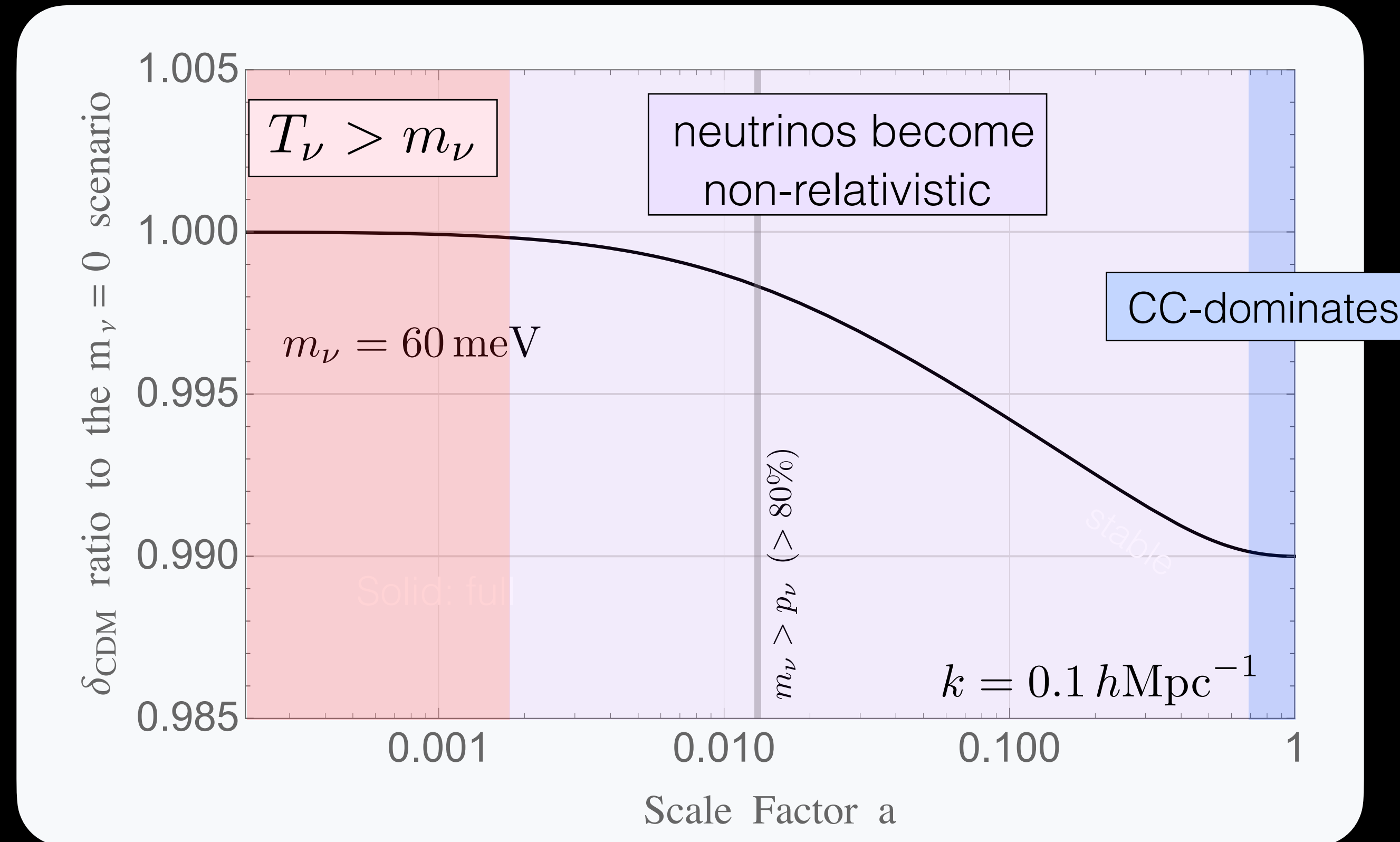


As a result: massive neutrinos suppress matter perturbations

Ratio of dark matter density perturbation

$$\frac{\Lambda\text{CDM} + m_\nu}{\Lambda\text{CDM} + m_\nu = 0}$$

(fixing the total matter abundance and LCDM parameters)



Cosmic expansion, later time =>

The effect decreases the matter perturbation and CMB-lensing signal

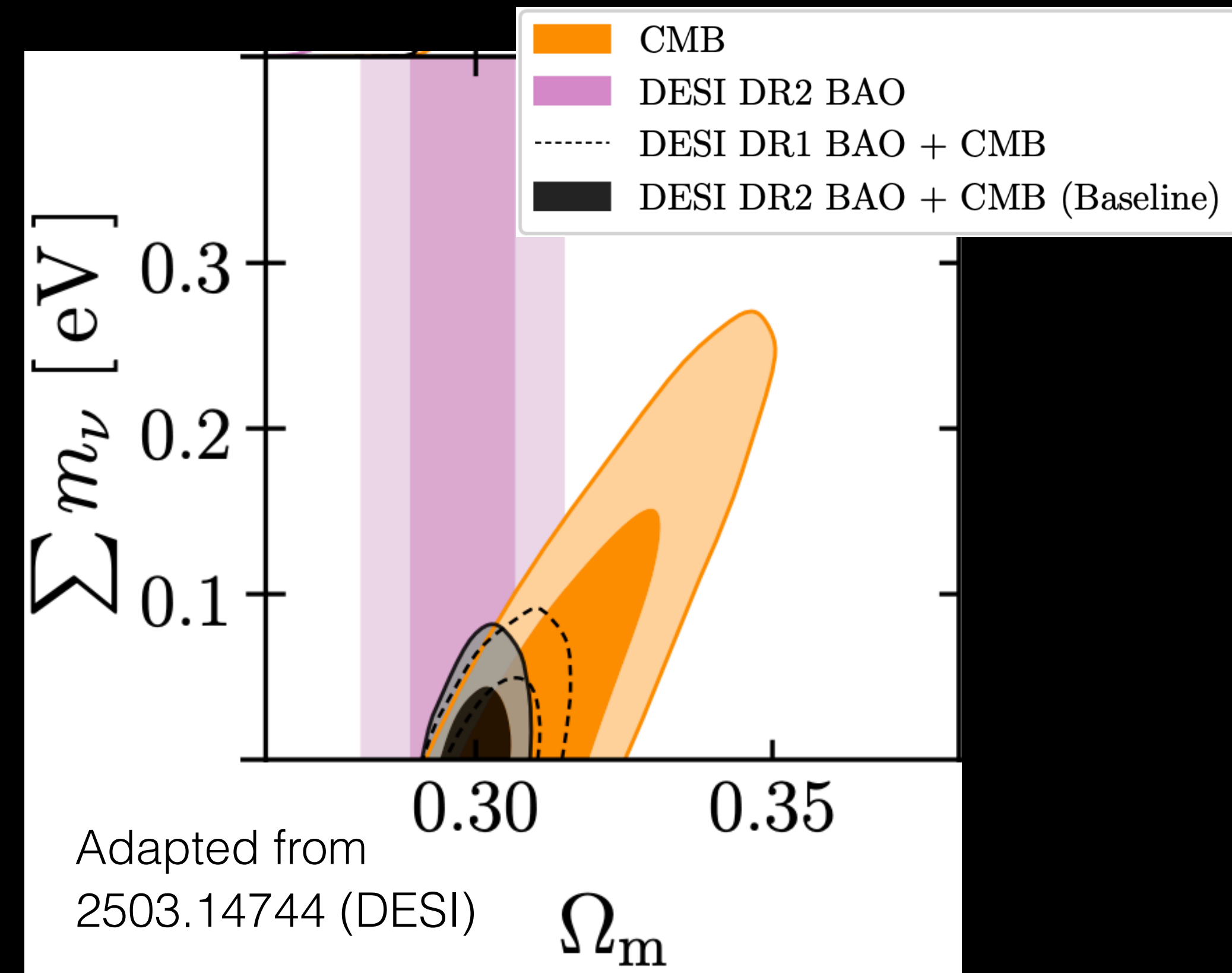
With both the structure and expansion-history measurements, set upper bounds on $\sum m_\nu$, may eventually determine their masses

Planck (PR3) $\sum m_\nu < 0.12 \text{ eV} \text{ (95 \% CL)}$

DESI+Planck (PR4) $\sum m_\nu < 0.064 \text{ eV}$

Normal order $\sum m_\nu > 0.059 \text{ eV}$

Inverted order $\sum m_\nu > 0.098 \text{ eV}$



Possible tension between the minimum neutrino mass (ν -oscillations) and the cosmological bound (see, e.g. Loverde&Weiner(2024) for impact of different cosmo data on m_ν)

The possible mass tension motivates new physics explanations

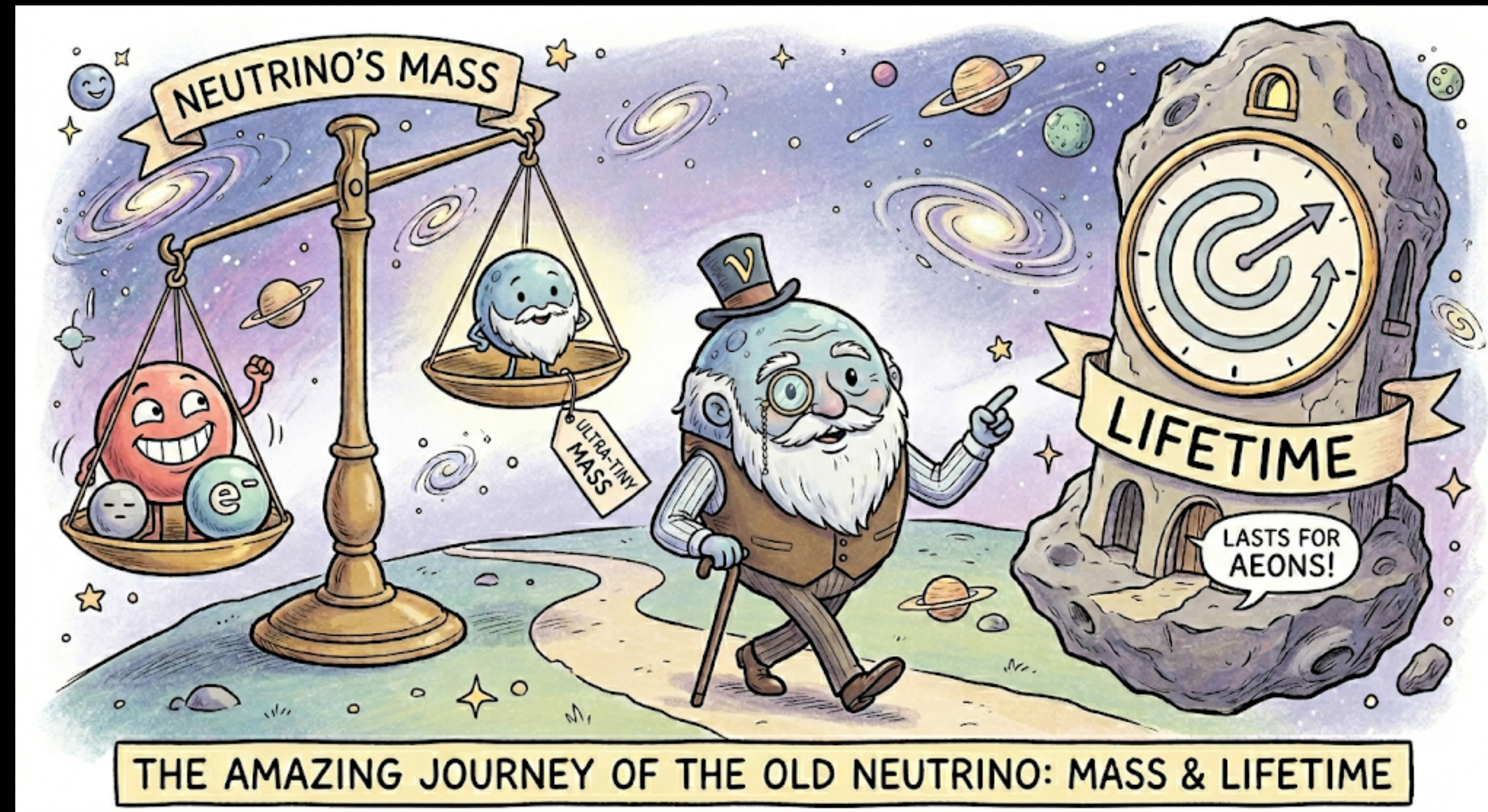
- **Negative neutrino mass problem?**
(e.g., Craig, Green, Meyers, Rajendran (2024), Green, Meyers (2024))
- Physics provides extra modification of the structure
(e.g., Costa, Creque-Sarbinowski, Simon, Weiner (2025), Graham, Green, Meyers (2026))
- Time-varying neutrino mass
(e.g., Lorenz, Funcke, Calabrese, Hannestad (2019))
- Neutrino decays
(e.g., Escudero, Lopez-Pavon, Rius, Sandner (2020), Abellán (2026))
- Non-standard neutrino interactions
(e.g., Escudero, Schwetz, Terol-Calvo (2022), Das, Dev, Gao, Ghosh, Kim (2026))
- Large τ_{reio}
(e.g., Jhaveri, Karwal, Hu (2025))
- (and many more...)

See talk by Subhajit Ghosh

It's an active area of research!

Example II

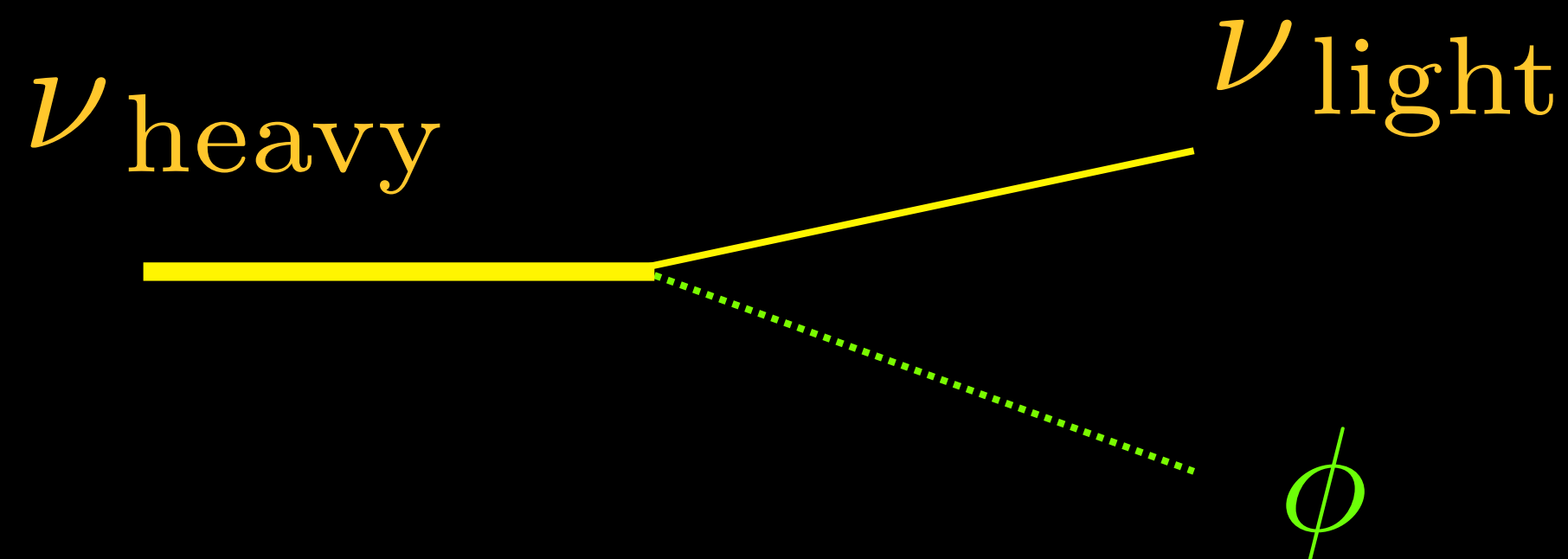
Neutrino's mass & lifetime



Gemini

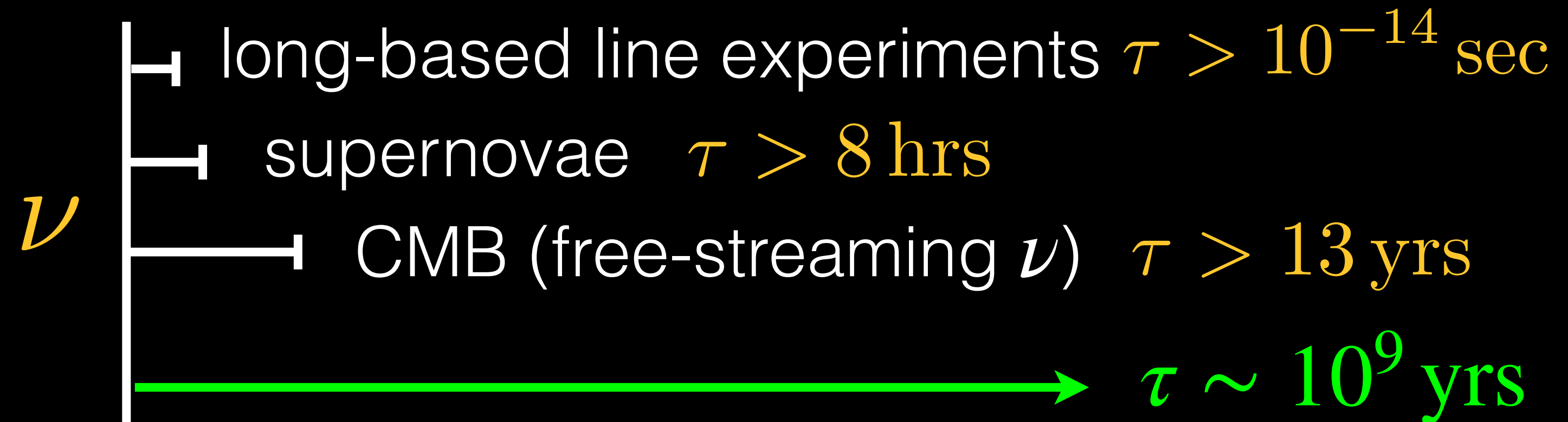
In BSM scenarios, **neutrinos may decay** into invisible particles

e.g., for Majoron model that generate neutrino masses



dark radiation
(e.g., Majoron)

Lifetime bounds on invisible neutrino decays



Observing minimum neutrino mass impacts on cosmic evolution will **extend neutrino lifetime limits** to the age of the universe

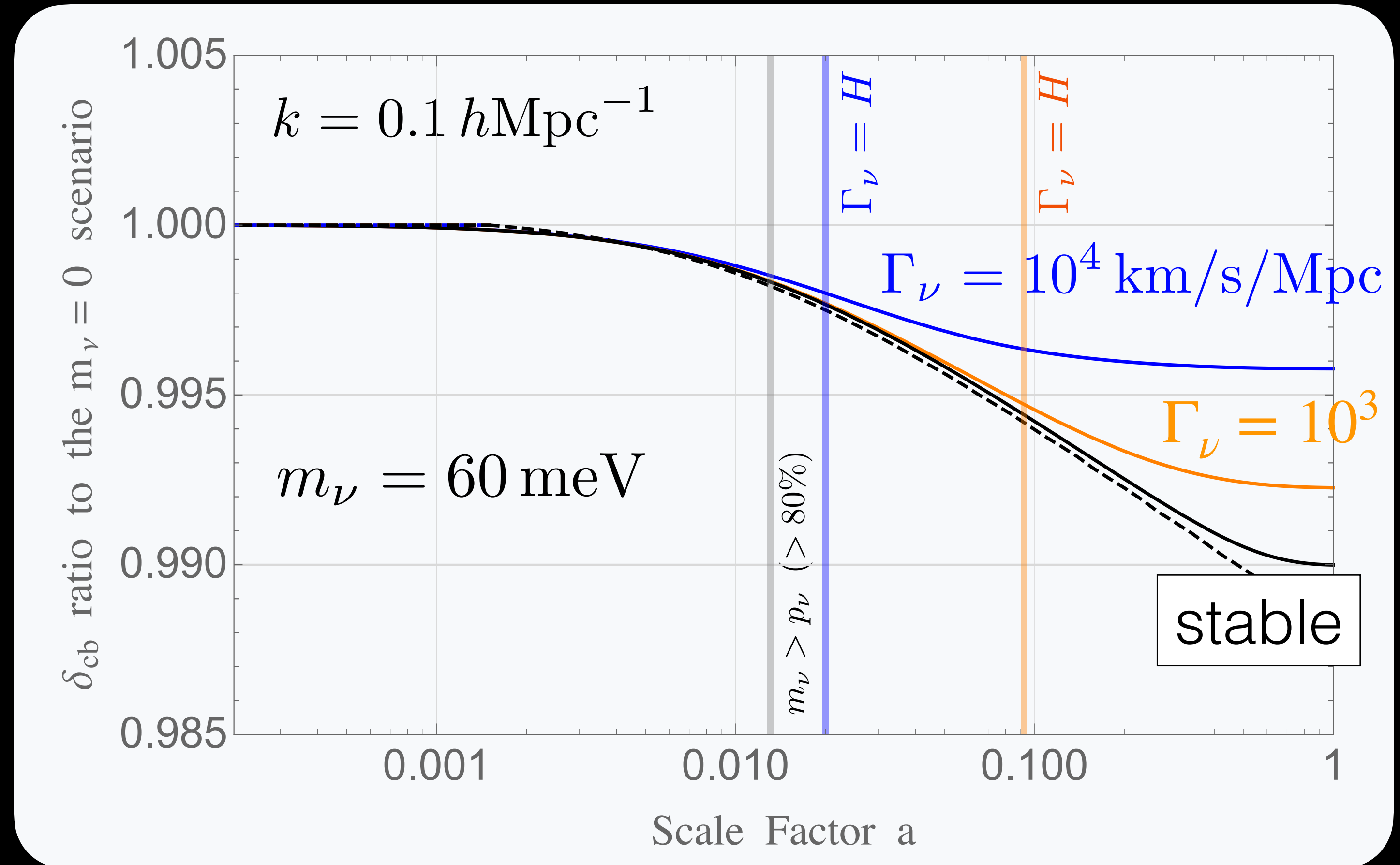
Serpico (2007)(2009)

Neutrino decay reduces the suppression of matter perturbation

Ratio of matter density perturbation

$$\frac{\Lambda\text{CDM} + m_\nu}{\Lambda\text{CDM} + m_\nu = 0}$$

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



Chacko, Dev, Du, Poulin, **YT** (2019)

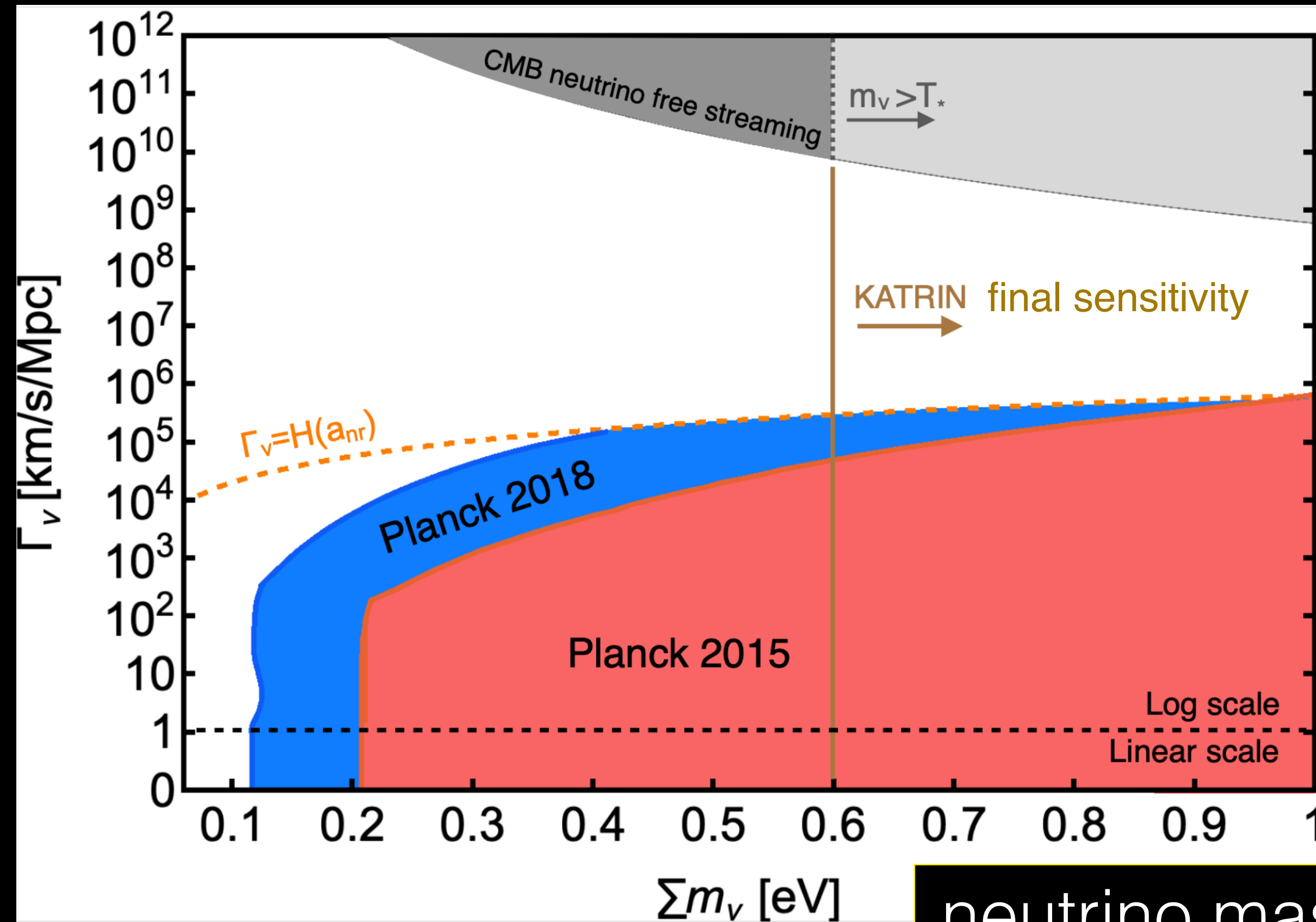
Cosmic expansion, later time =>

Heavier neutrinos are fine, if they decay earlier

Rate of
invisible neutrino decay

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

Abellán, Chacko, Dev,
Du, Poulin, **YT** (2022)



neutrino mass

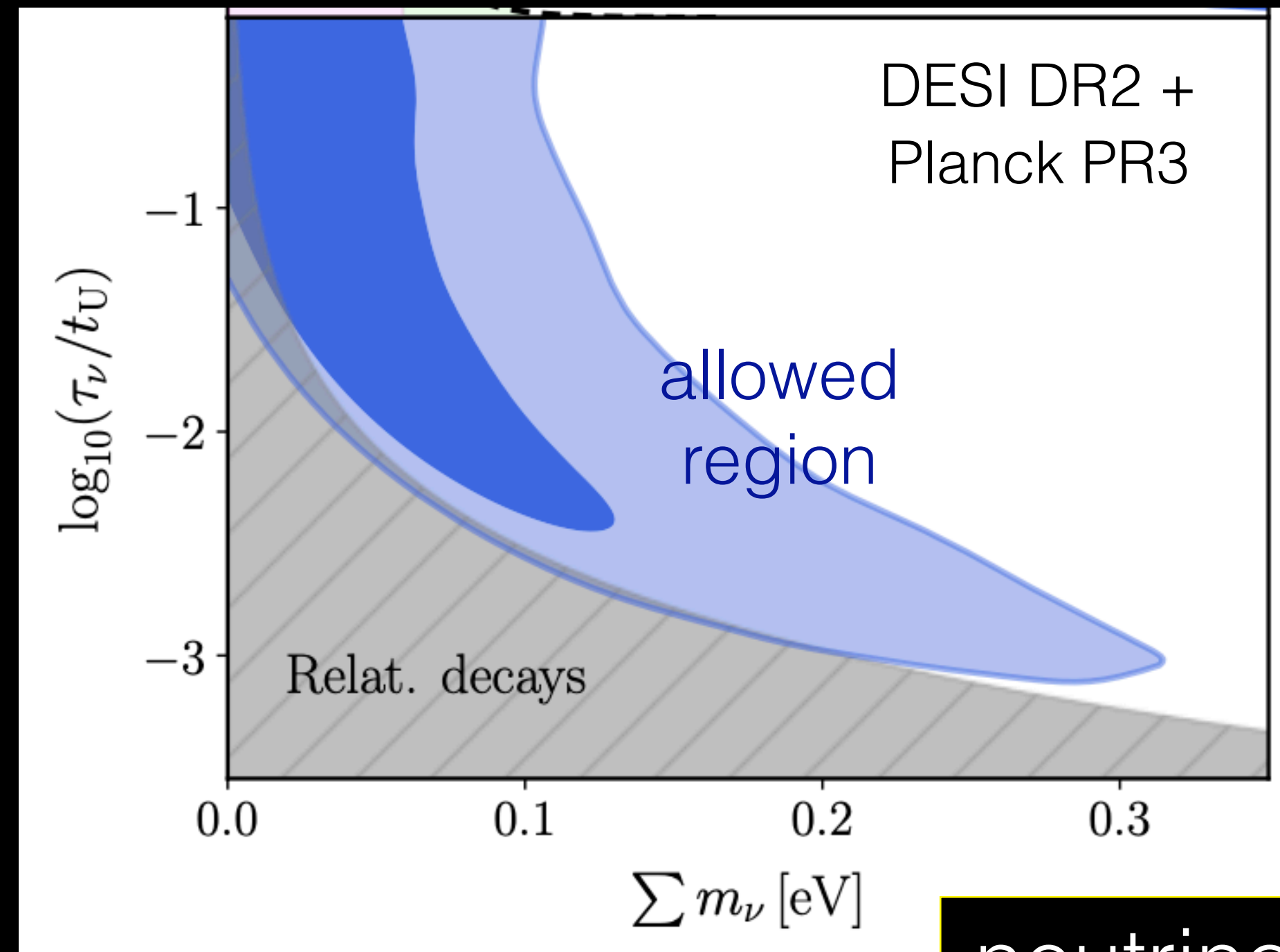
Recently updated constraint: Abellán (2026)

See also: Basboll, Bjaelde, Hannestad, Raffelt (2008)

Barenboim, Chen, Hannestad, Oldengott, Tram, Wong (2011)

Neutrino decay can relax the mass tension

Abellán (2026)



Lifetime of invisible neutrino decay

neutrino mass

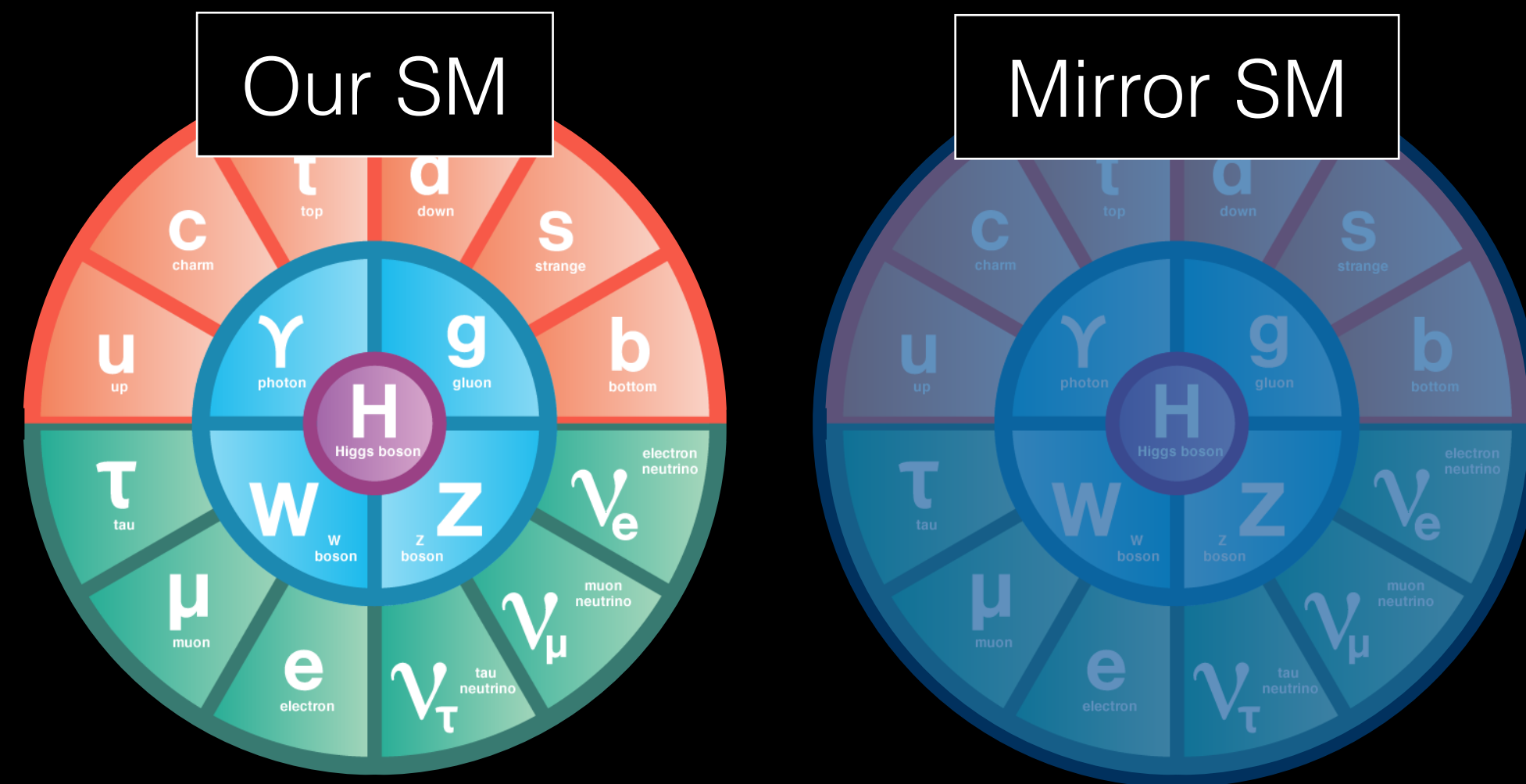
for decay into massless radiation

$$\sum m_\nu < 0.23 \text{ eV}$$

Chance to **measure** neutrino mass & lifetime: Chacko, Dev, Du, Poulin, **YT** (2020)

Example III

Dark sector physics &
solution to the Higgs hierarchy problem

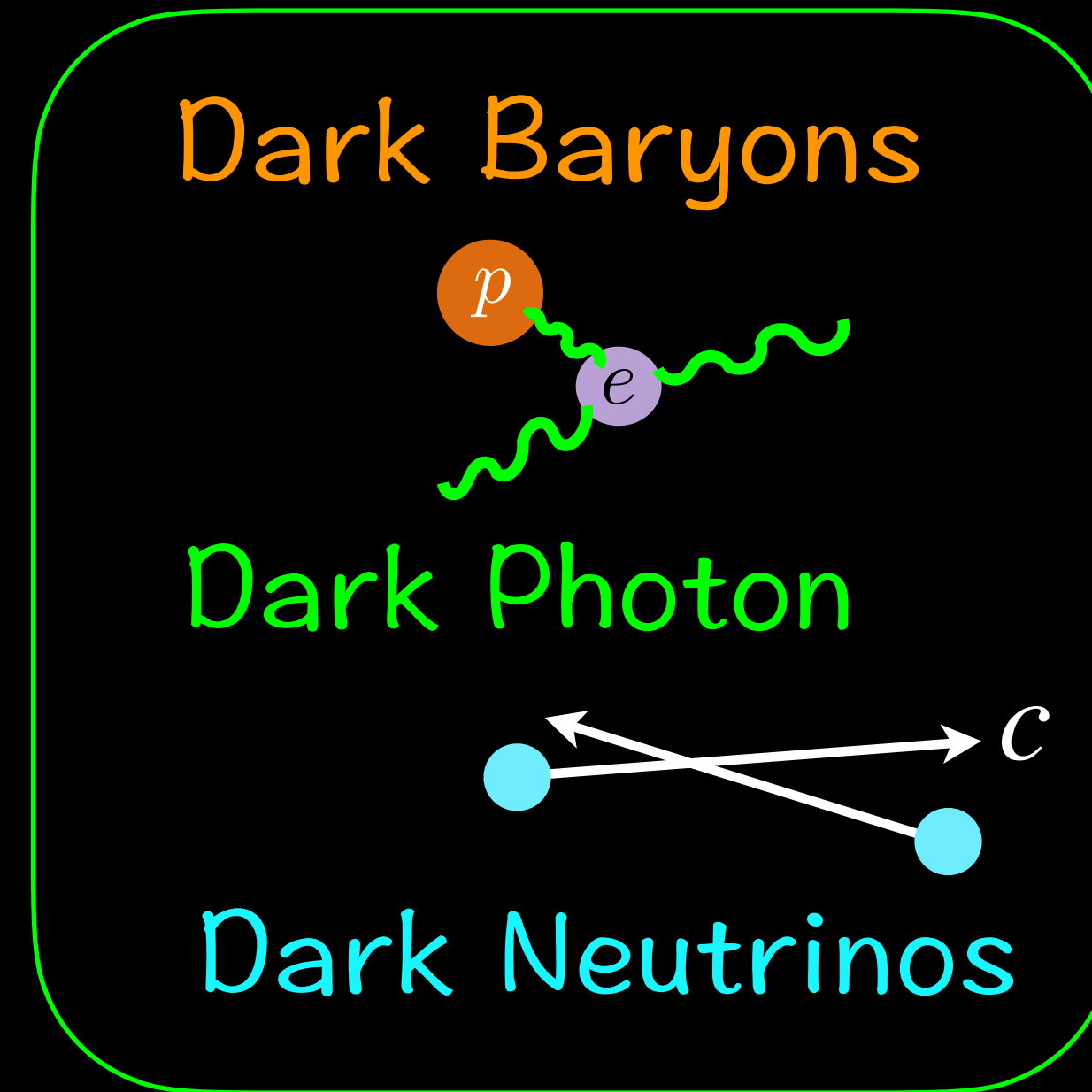


Dark matter, about **5 times** more abundant than visible matter, could be a whole **dark sector** world



Visible particle soup

Gravity
↔



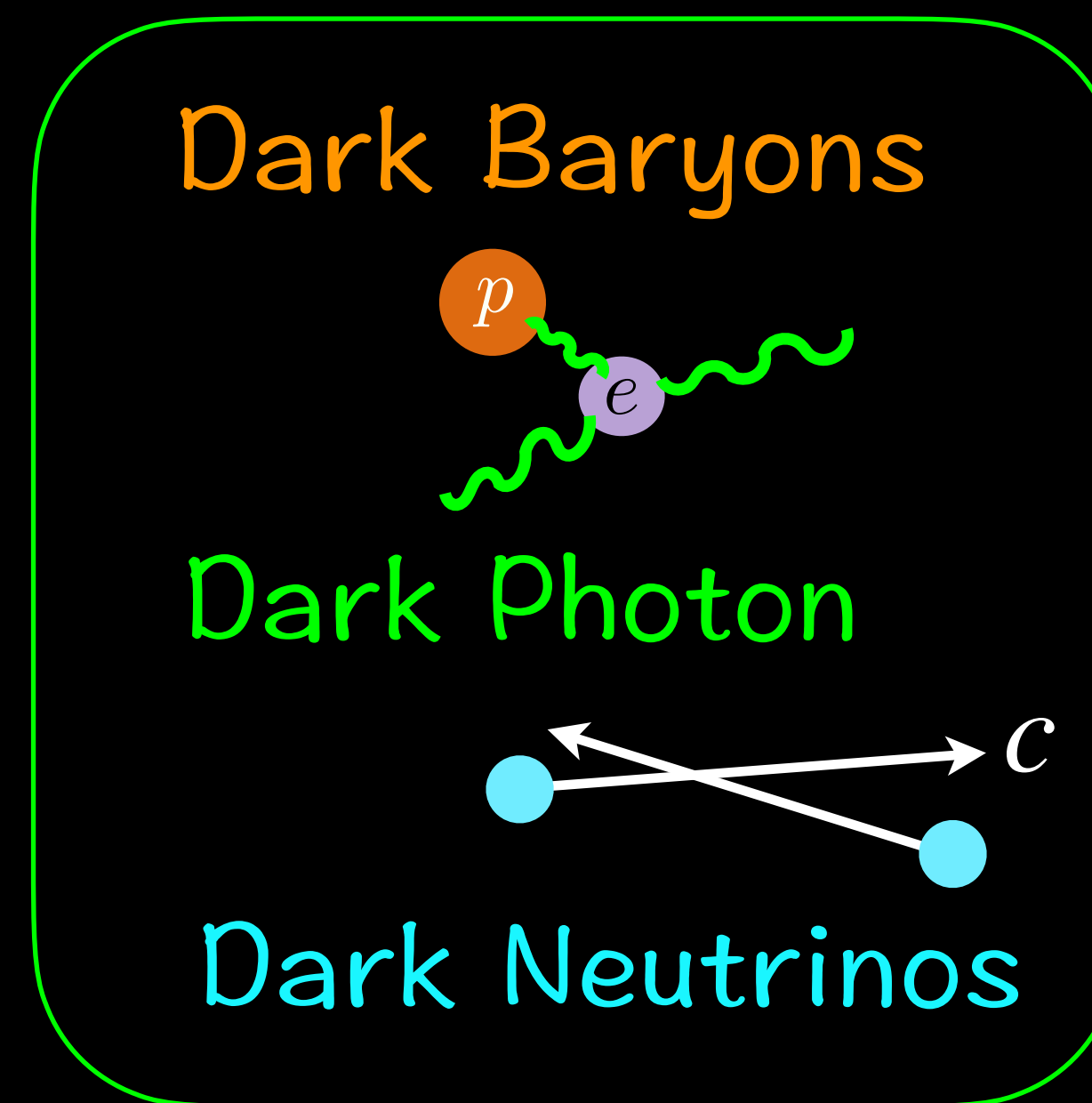
Dark sector soup

The **dark sector** could help address long-standing puzzles, including the Higgs hierarchy problem



Visible particle soup

Gravity
↔

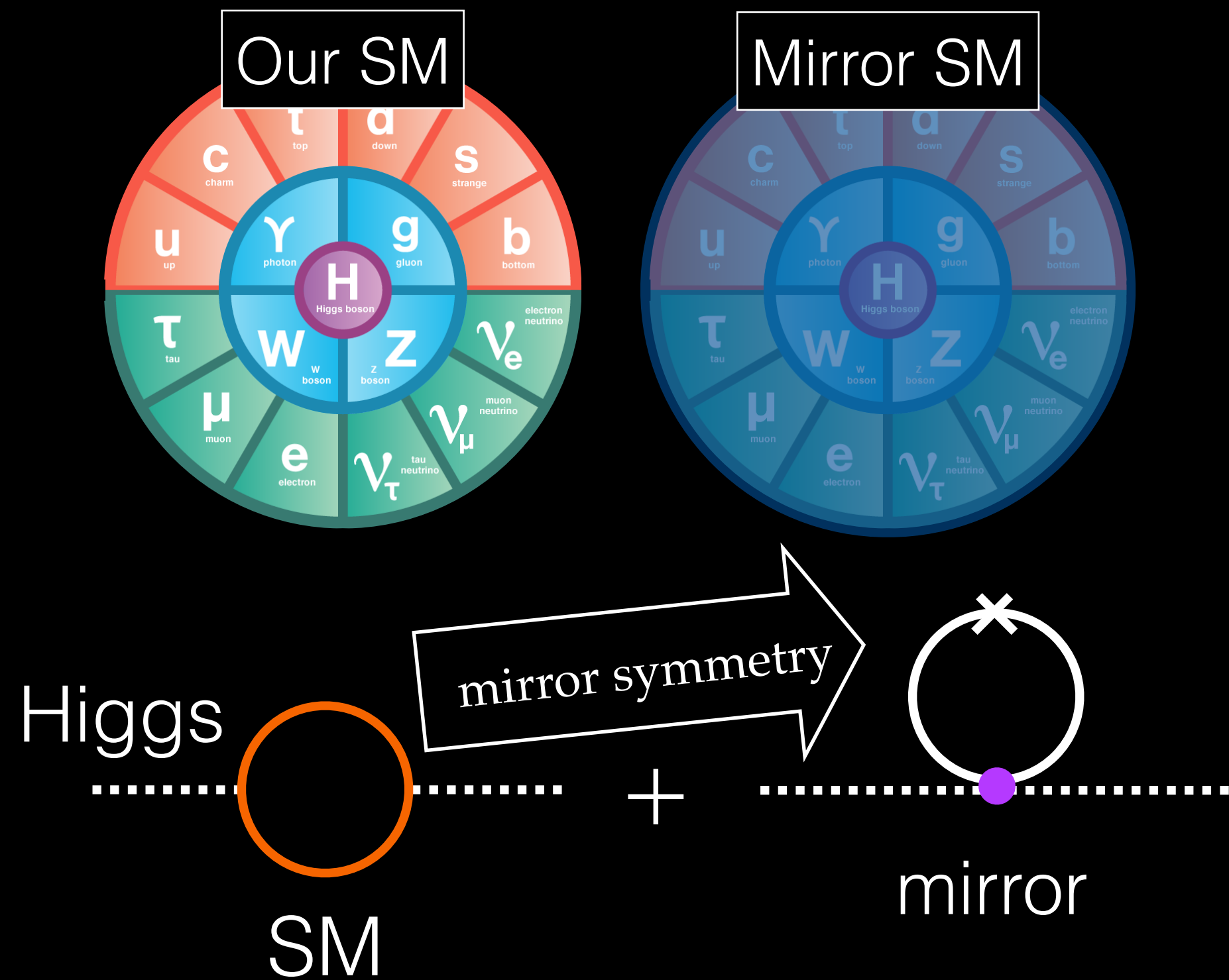


Dark sector soup

Dark sector particles can address the Higgs hierarchy problem

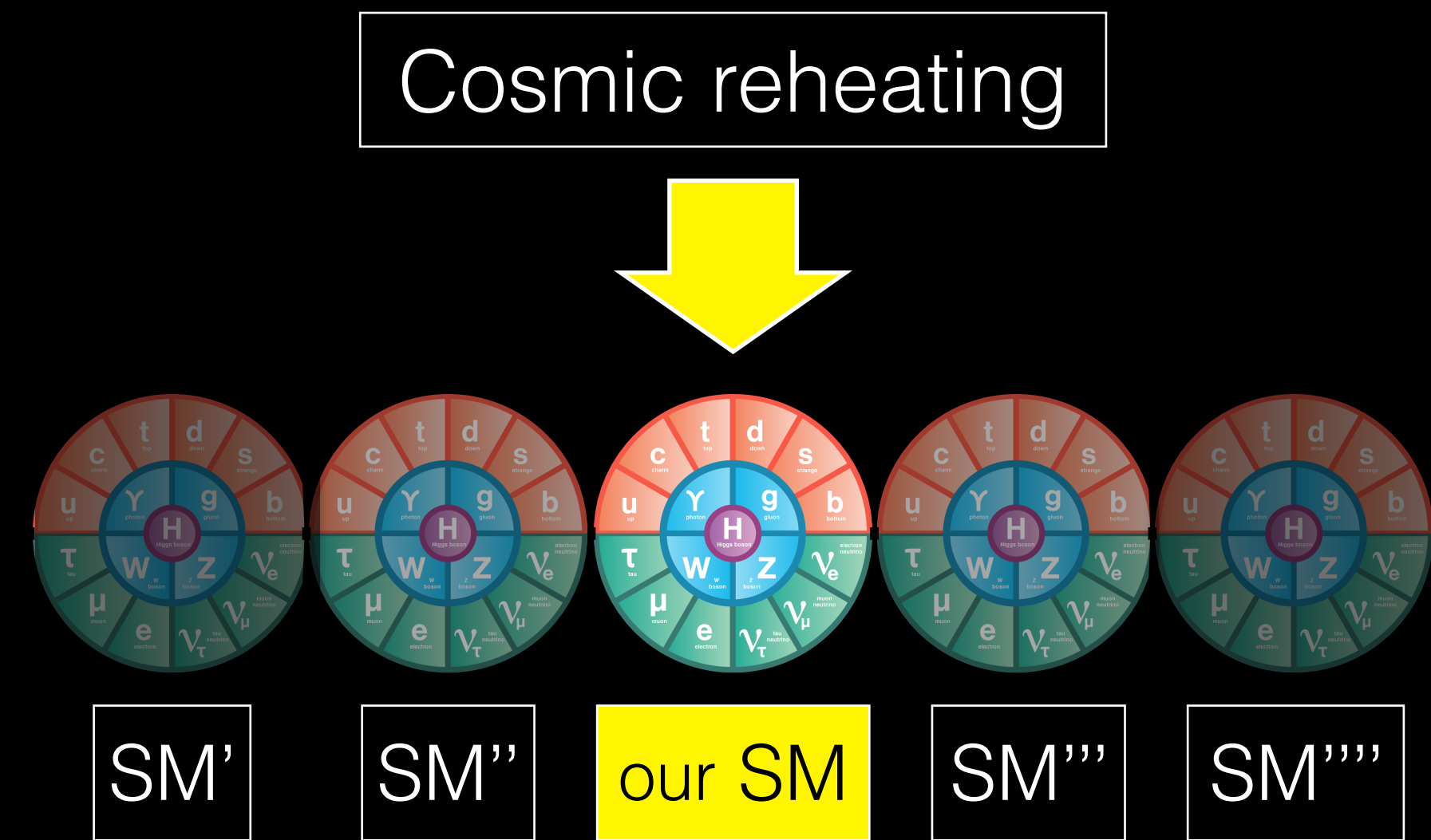
One mirror sector

(Mirror Twin Higgs: Chacko, Goh, Harnik)



Multiple-SM sectors

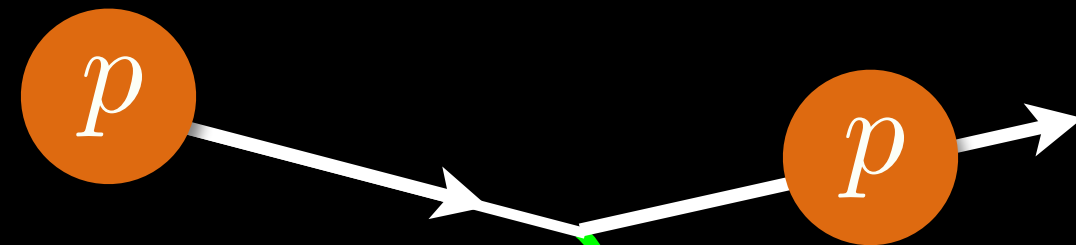
(N-naturalness: Arkani-Hamed, Cohen, D'Agnolo, Hook, Kim, Pinner (2016))



Both leave interacting dark sector particles

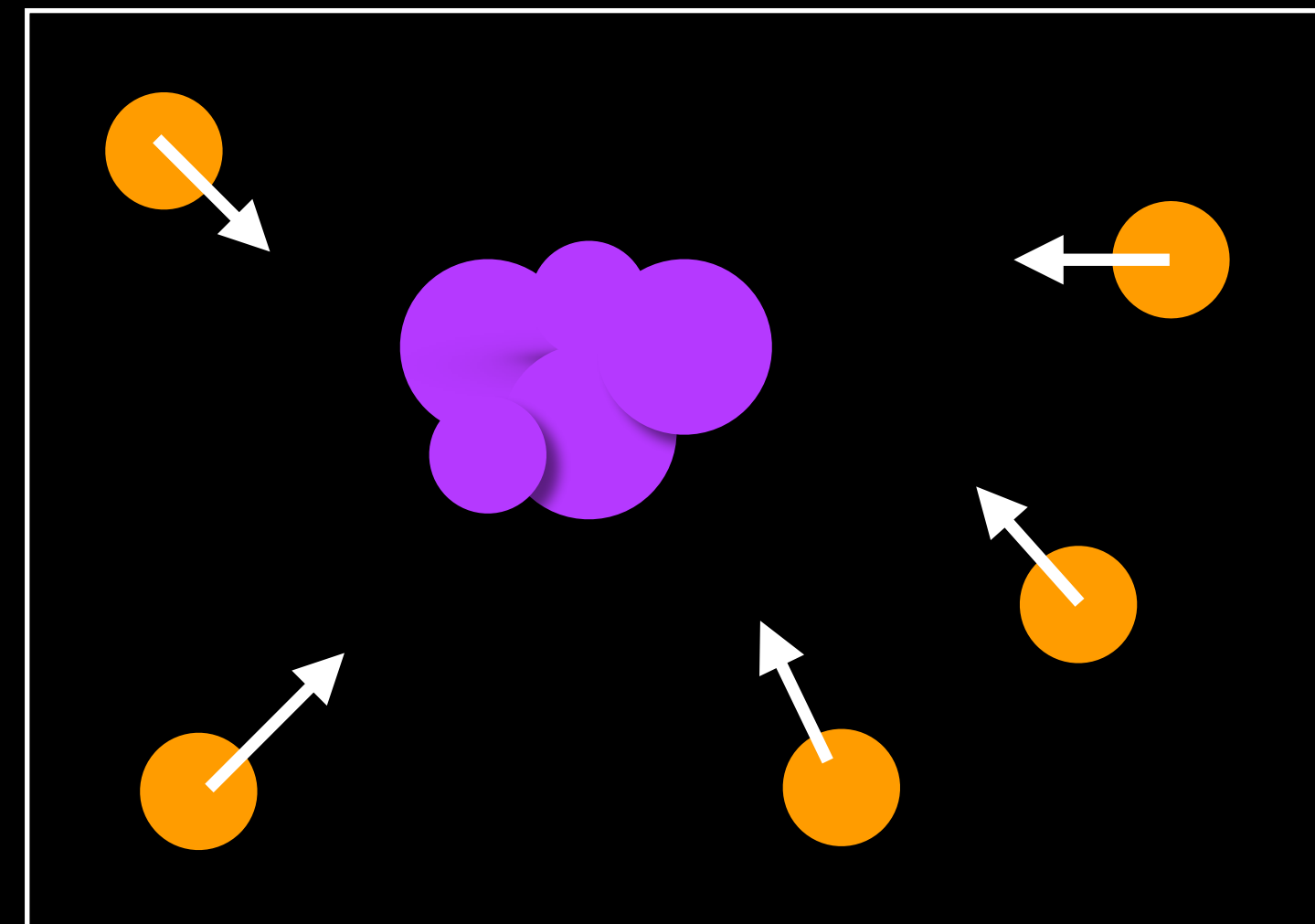
The **dark baryon-photon** scattering slows down the structure formation

Dark proton



Dark photon

Dark protons fall into gravitational potential

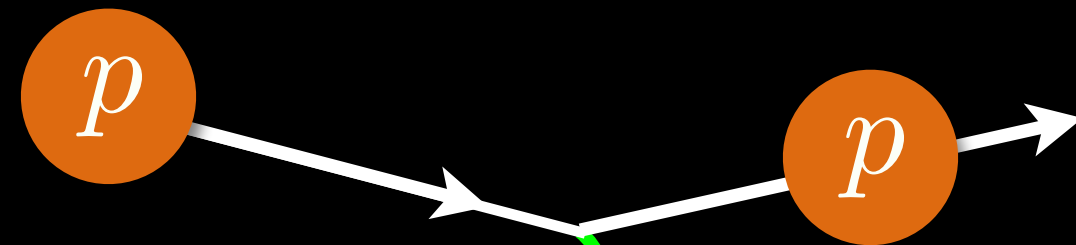


γ = dark photon
 e = dark electron

p = dark proton
● = cold DM

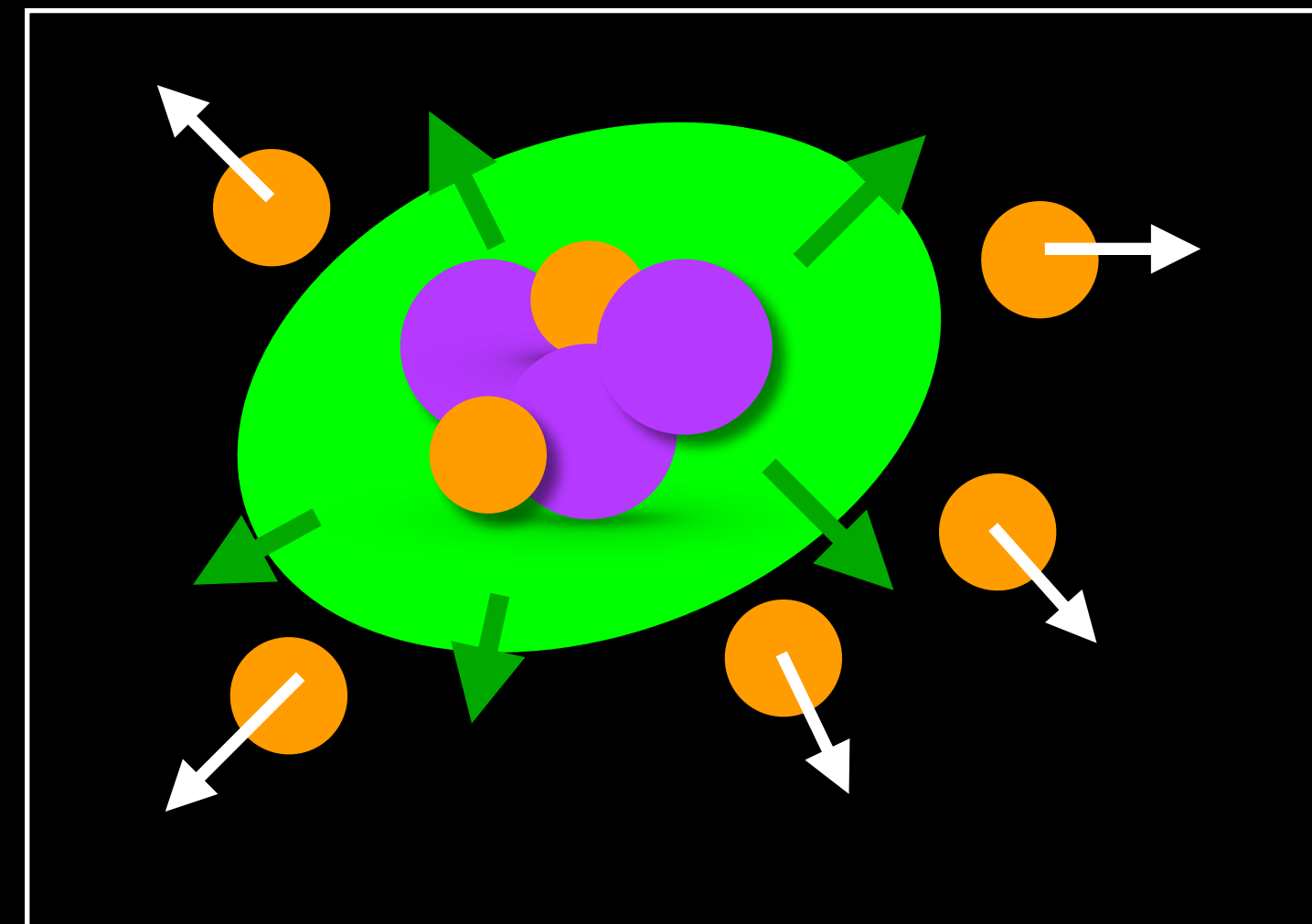
The **dark baryon-photon** scattering slows down the structure formation

Dark proton



Dark photon

Pushed back by **radiation pressure**

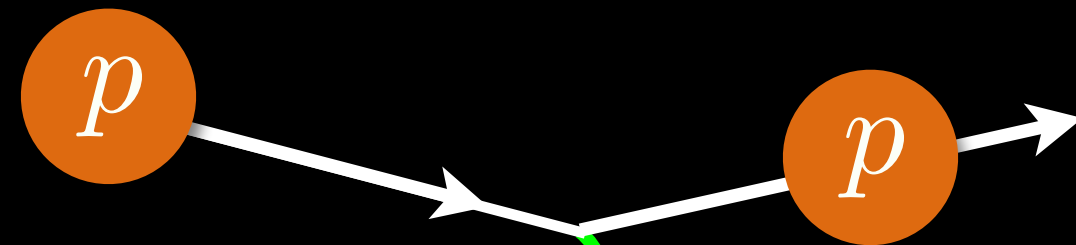


γ = dark photon
 e = dark electron

p = dark proton
 \bullet = cold DM

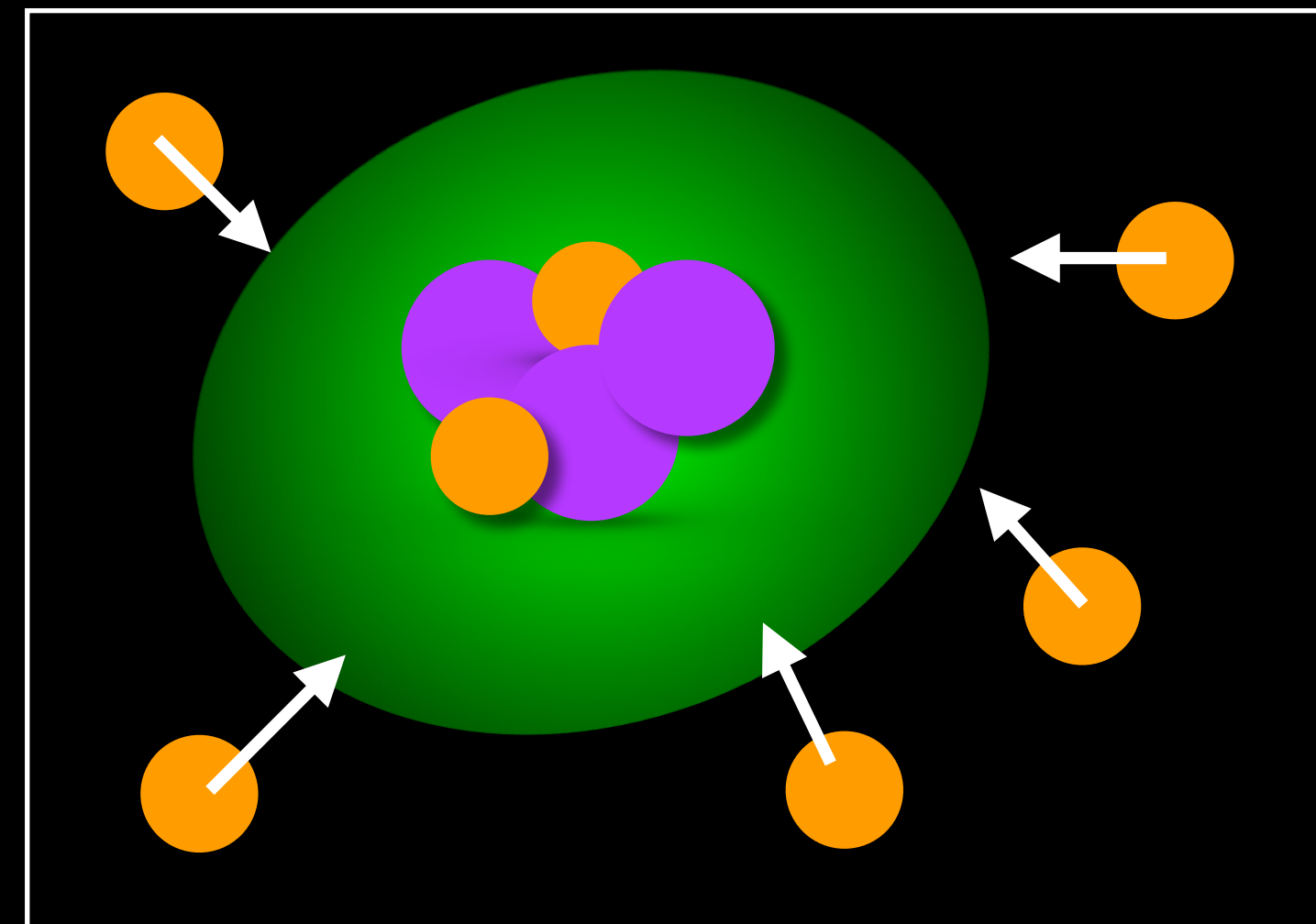
The **dark baryon-photon** scattering slows down the structure formation

Dark proton



Dark photon

Suppressed **dark proton** perturbations



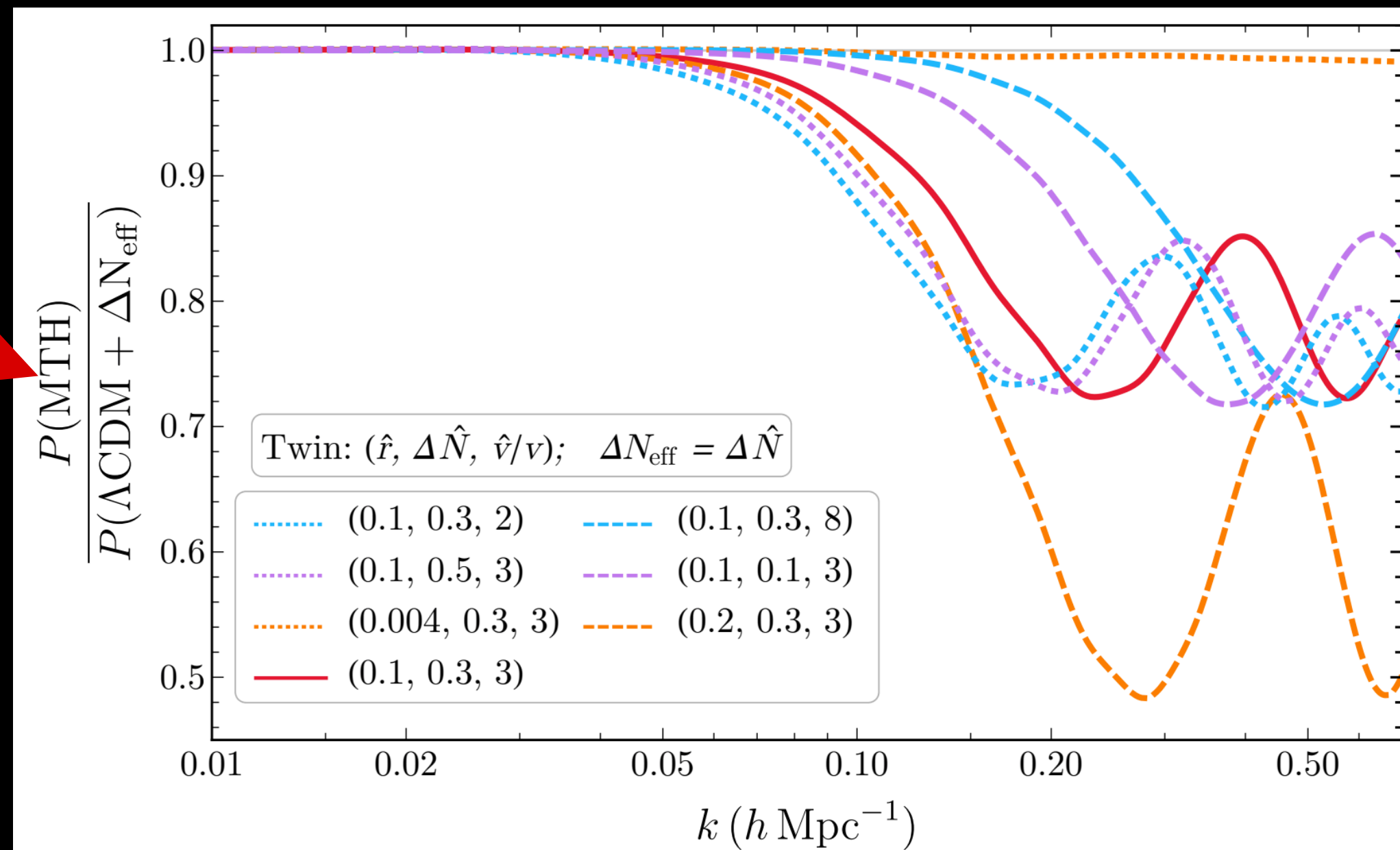
Dark photon density oscillates differently from the SM radiation

γ = dark photon
 e = dark electron

p = dark proton
 \bullet = cold DM

Dark Acoustic Oscillations (DAO) suppress matter fluctuations

Ratio of matter density perturbation

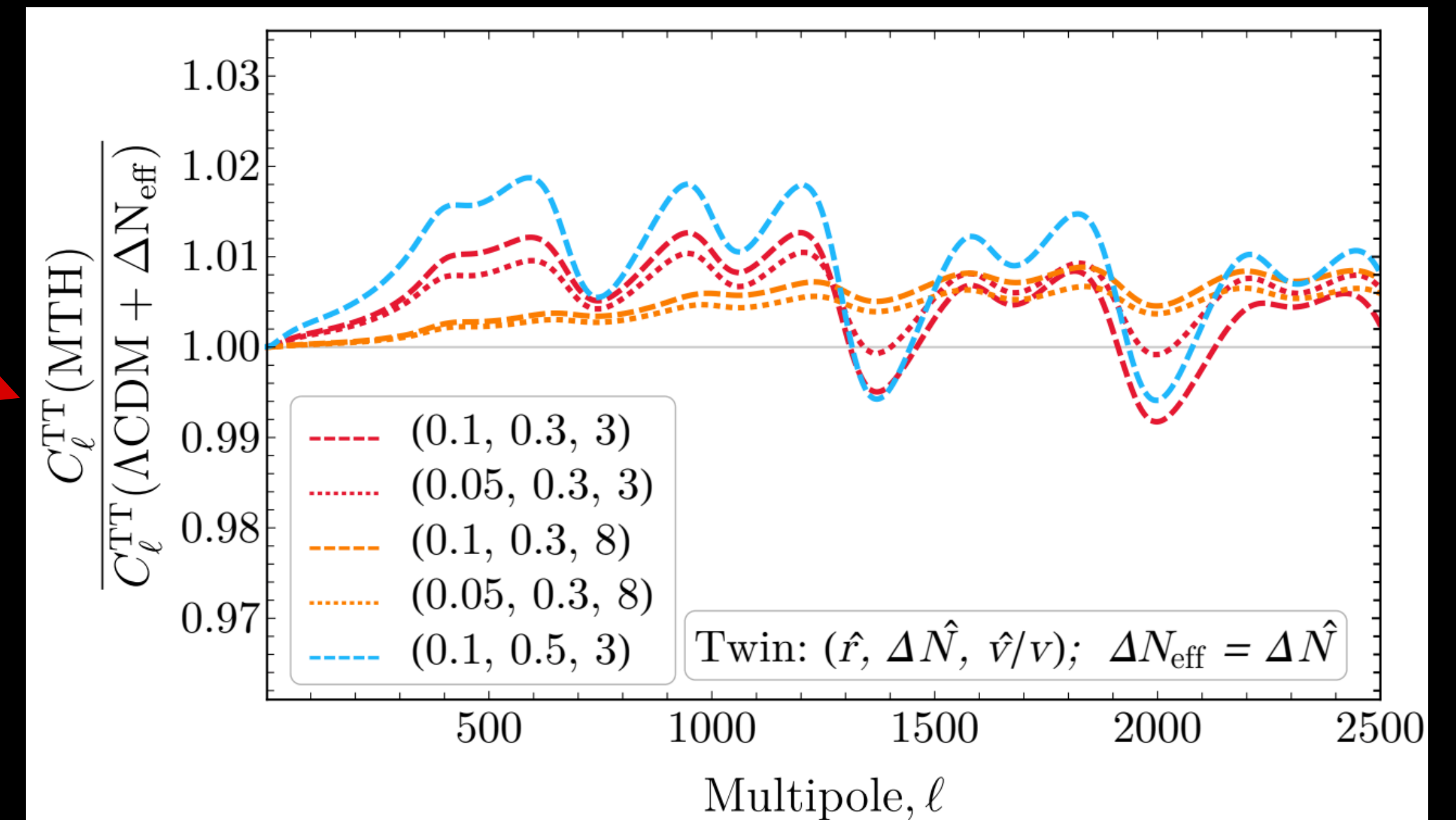


larger => smaller scale structure

Bansal, Kim, Kolda, Low, **YT** (2022)

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

Ratio of CMB temperature fluctuations

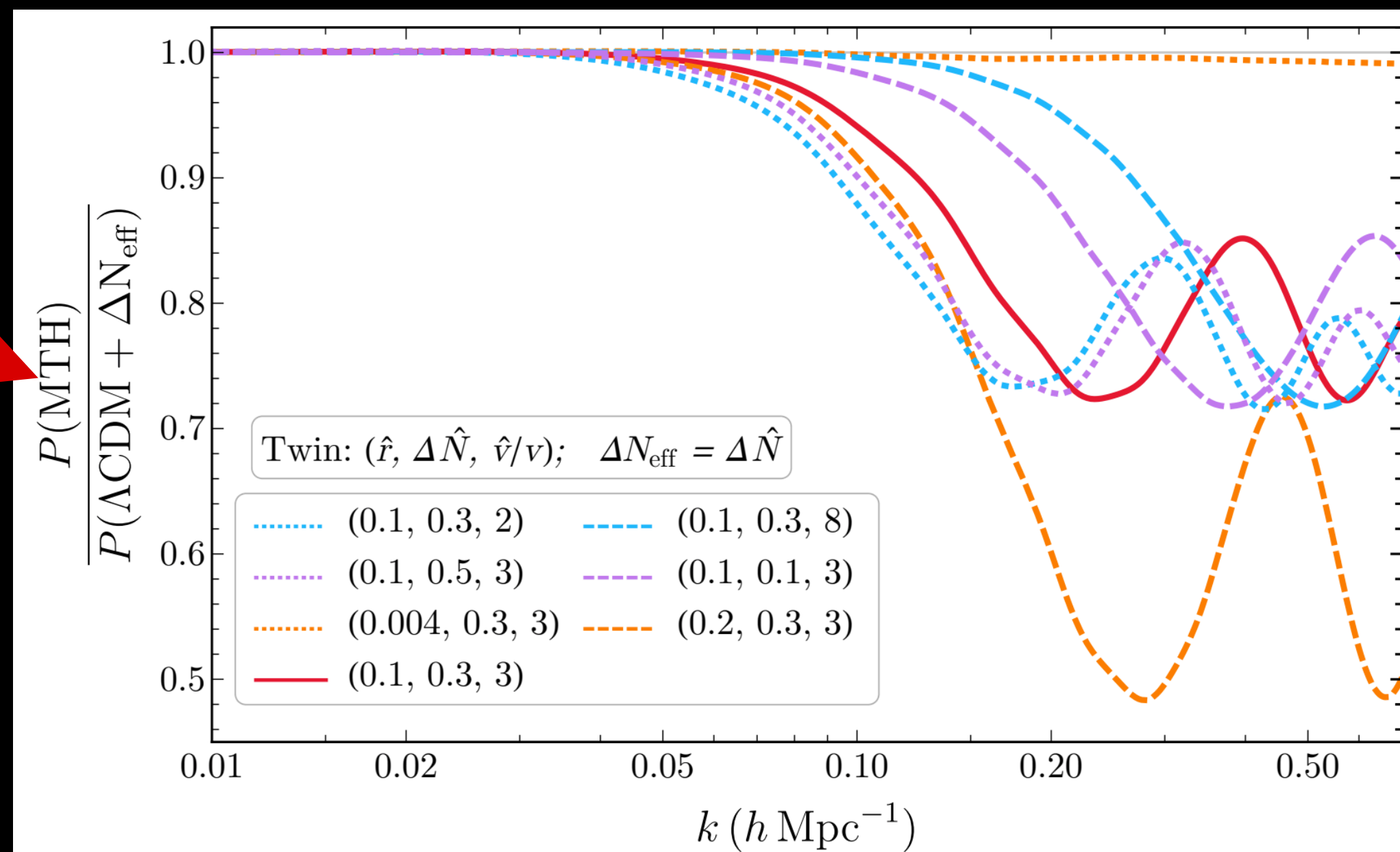


larger => smaller scale structure

Cir-Racine, Sigurdson (2012), Cir-Racine, Putter, Raccanelli, Sigurdson (2012), Buen-Abad, Marques-Tavares, Schmaltz (2015), Bansal, Barron, Curtin, **YT** (2022), Ghosh, Ho, **YT** (2024), Buen-Abad, Chacko, Flood, Kilic, Marques-Tavares, Youn (2025), and many many more...

Interacting DM (like the dark proton) can have up to $\sim O(1-10)\%$ of total DM density

Ratio of matter density perturbation

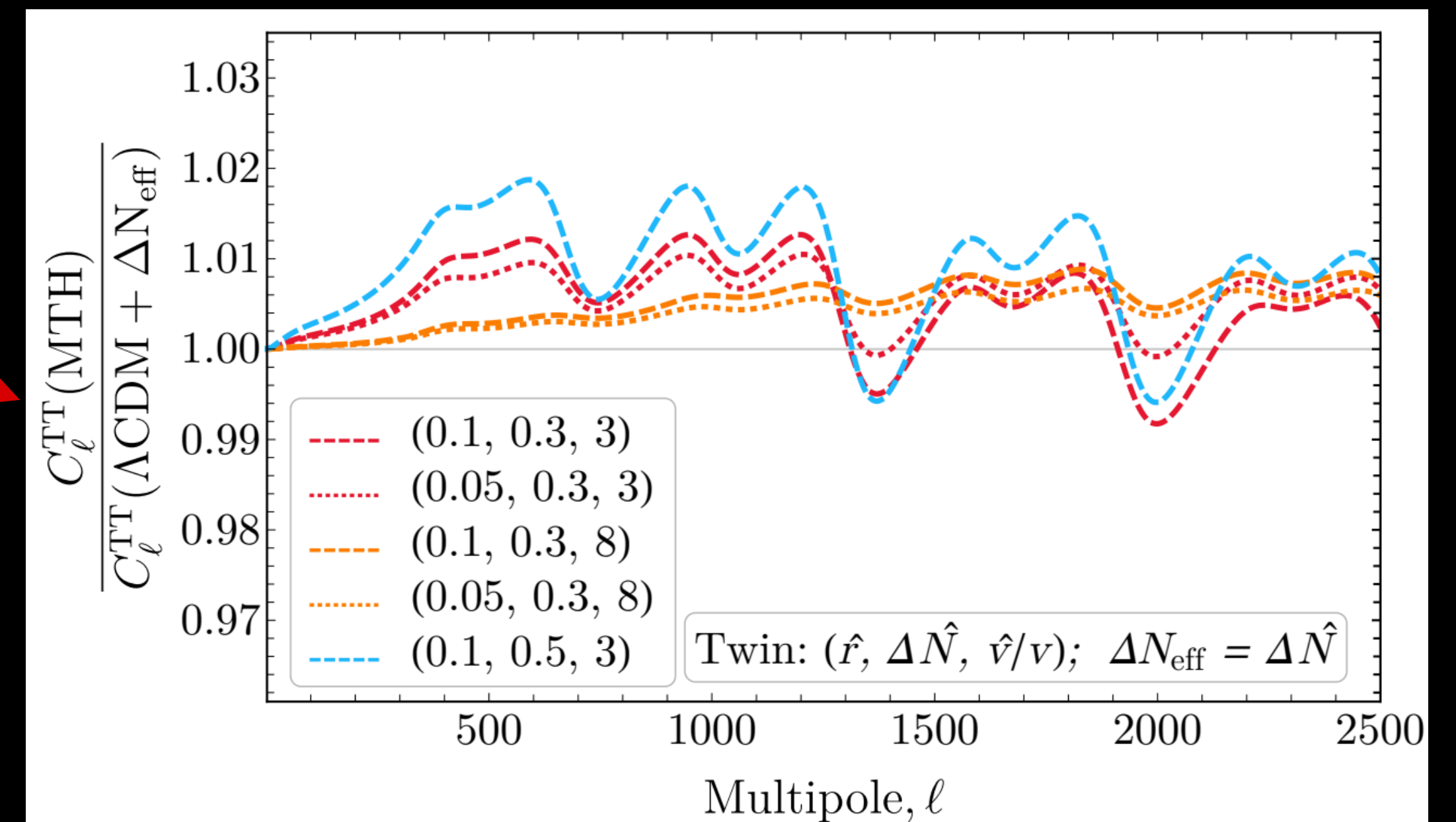


larger \Rightarrow smaller scale structure

Bansal, Kim, Kolda, Low, **YT** (2022)

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

Ratio of CMB temperature fluctuations



larger \Rightarrow smaller scale structure

Cir-Racine, Sigurdson (2012), Cir-Racine, Putter, Raccanelli, Sigurdson (2012), Buen-Abad, Marques-Tavares, Schmaltz (2015), Bansal, Barron, Curtin, **YT** (2022), Ghosh, Ho, **YT** (2024), Buen-Abad, Chacko, Flood, Kilic, Marques-Tavares, Youn (2025), and many many more...

Assessing the Higgs hierarchy solution: Mirror Twin Higgs model with dark photon & baryon



more tuning

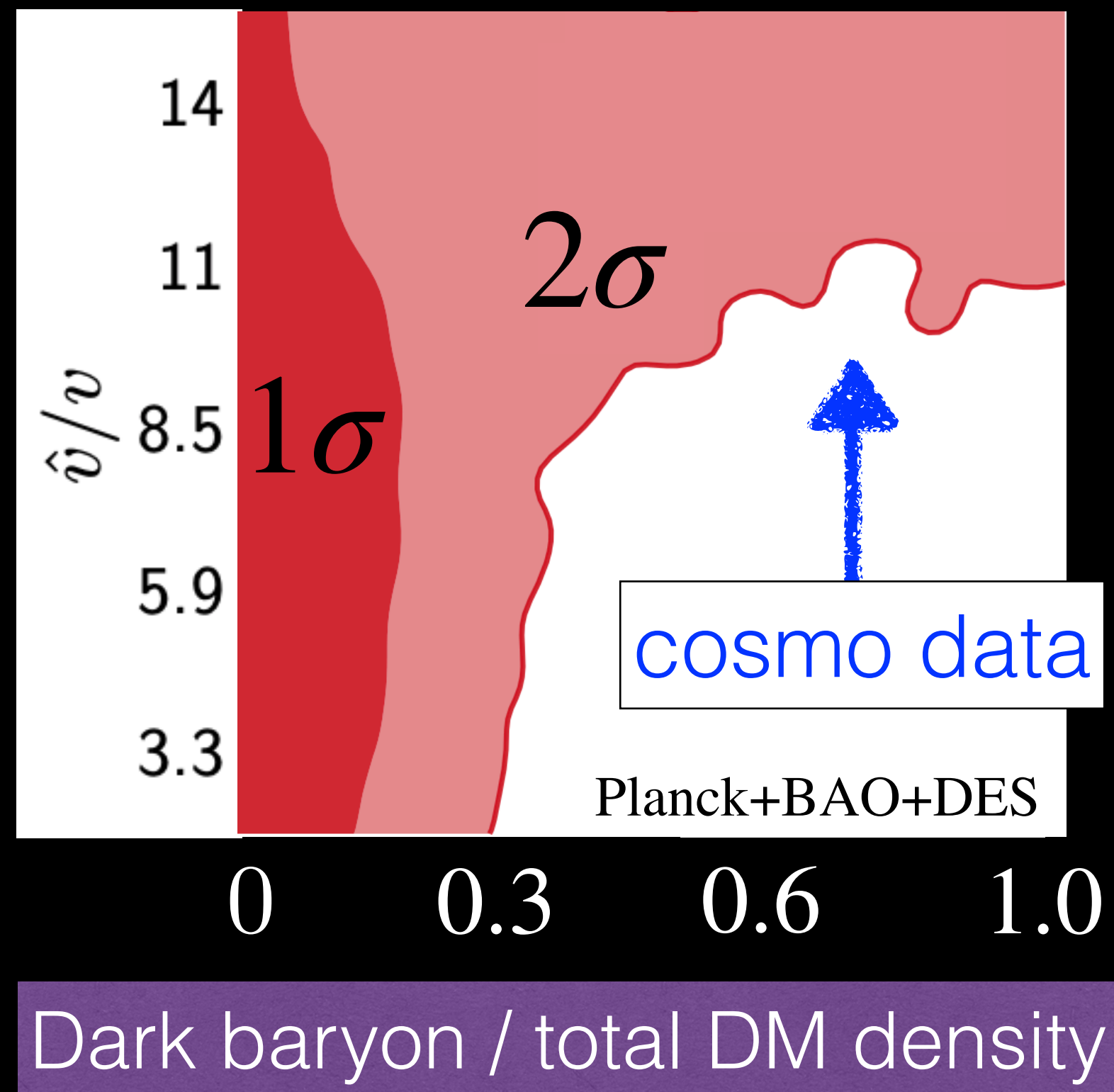
1 %



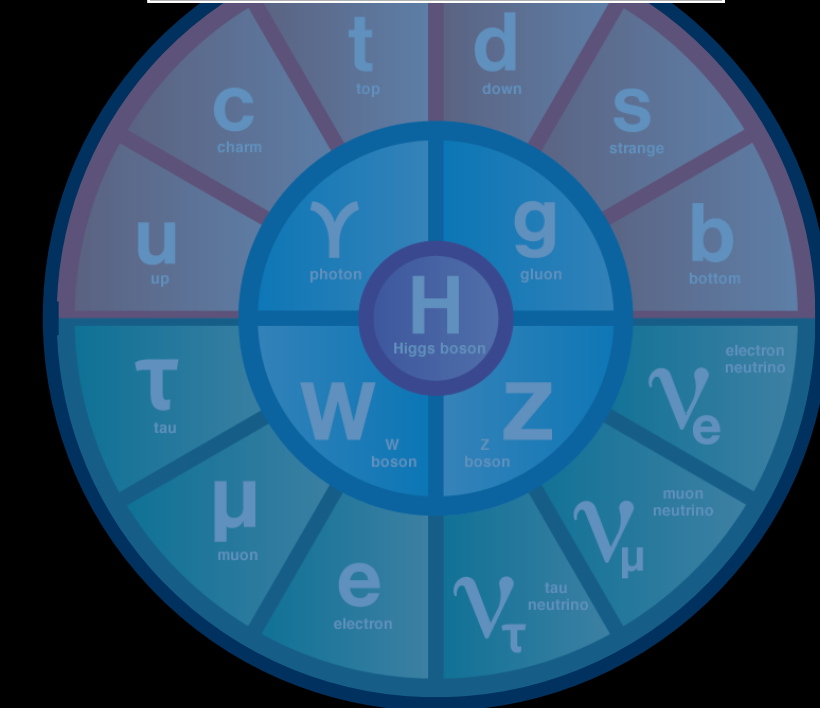
less tuning

10 %

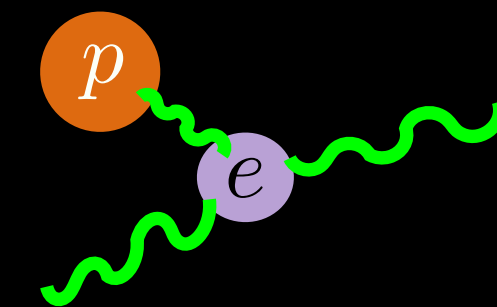
Mirror Twin Higgs model



Mirror SM



Dark protons



Dark Photon

Zu, Zhang, Tsai, YT+ (2023)

Assessing the Higgs hierarchy solution:

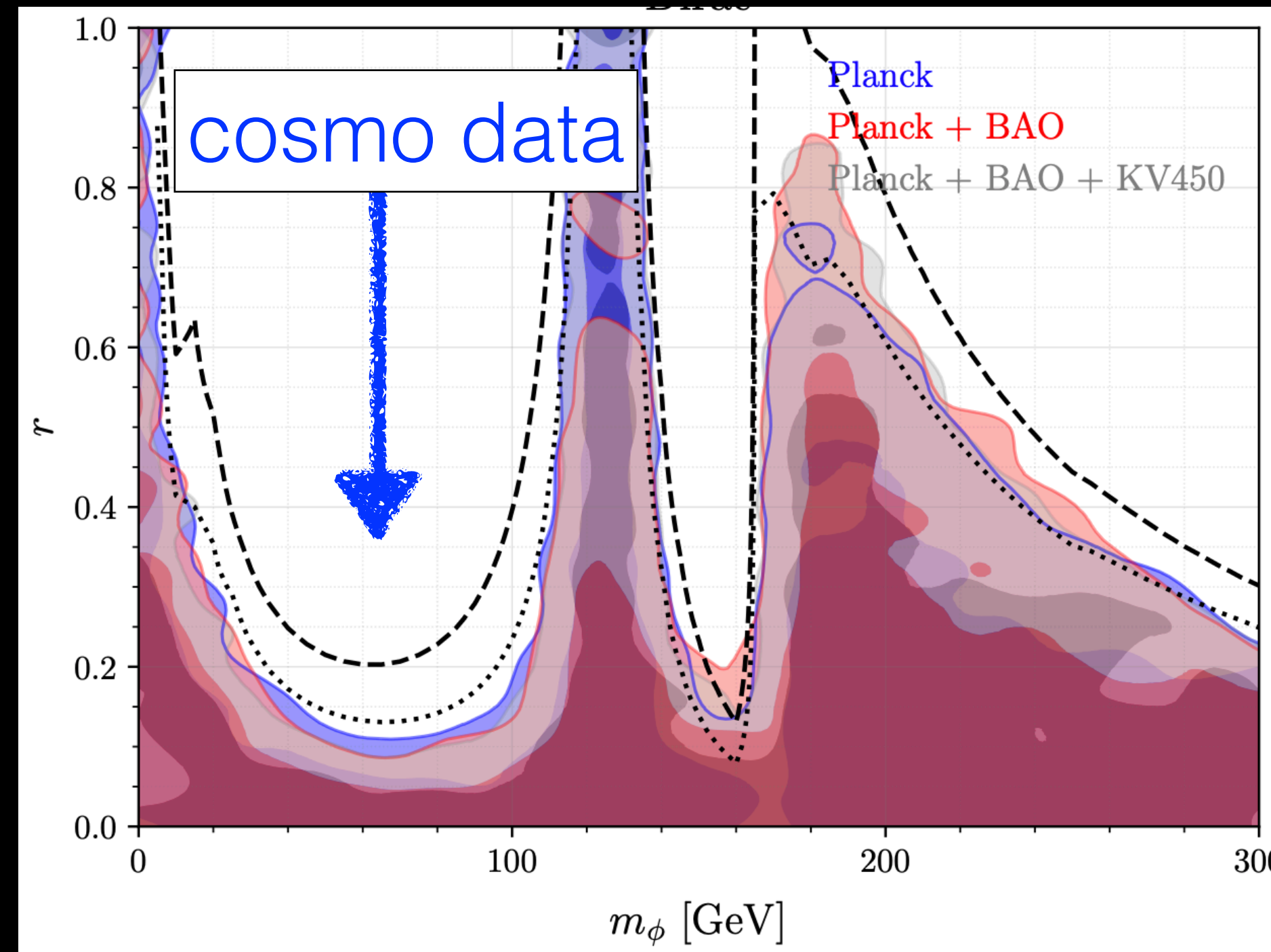
N-naturalness model with a tower of massive neutrinos



less tuning

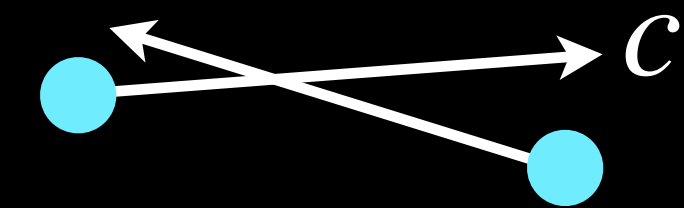
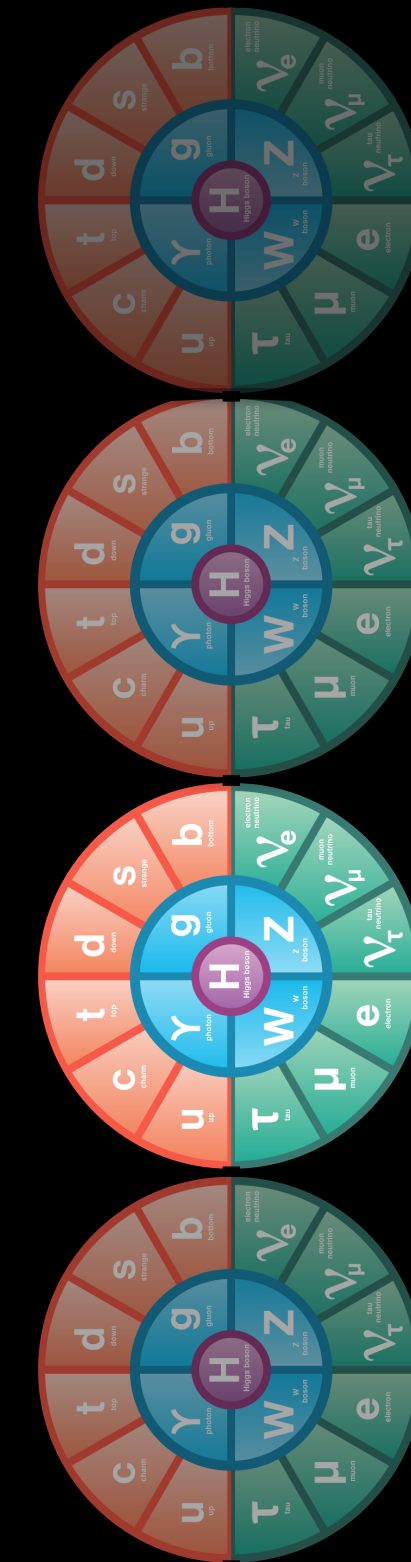


more tuning



Reheaton mass

Bansal, Ghosh, Low, YT (2025)



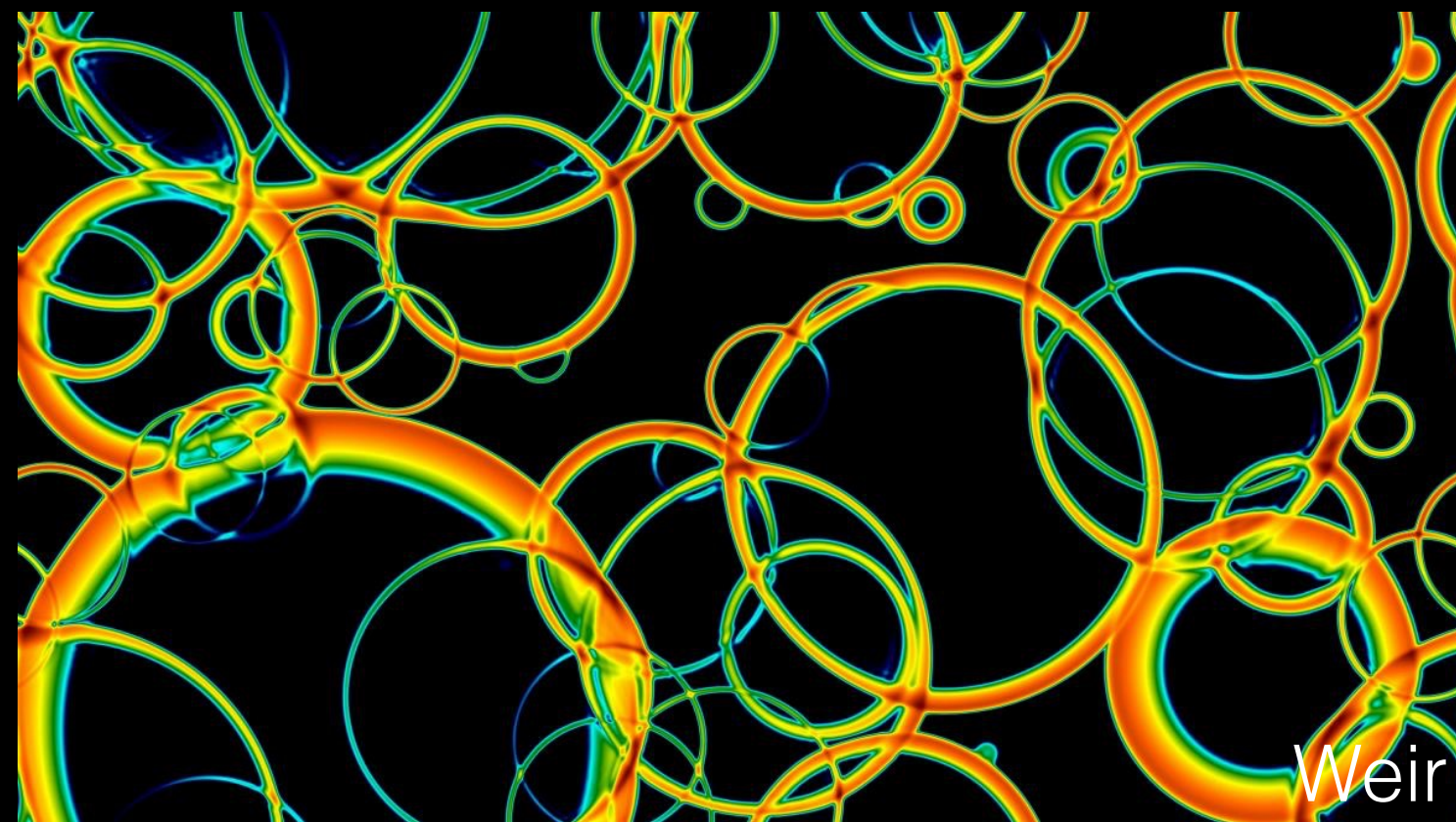
Dark Neutrinos

Example IV

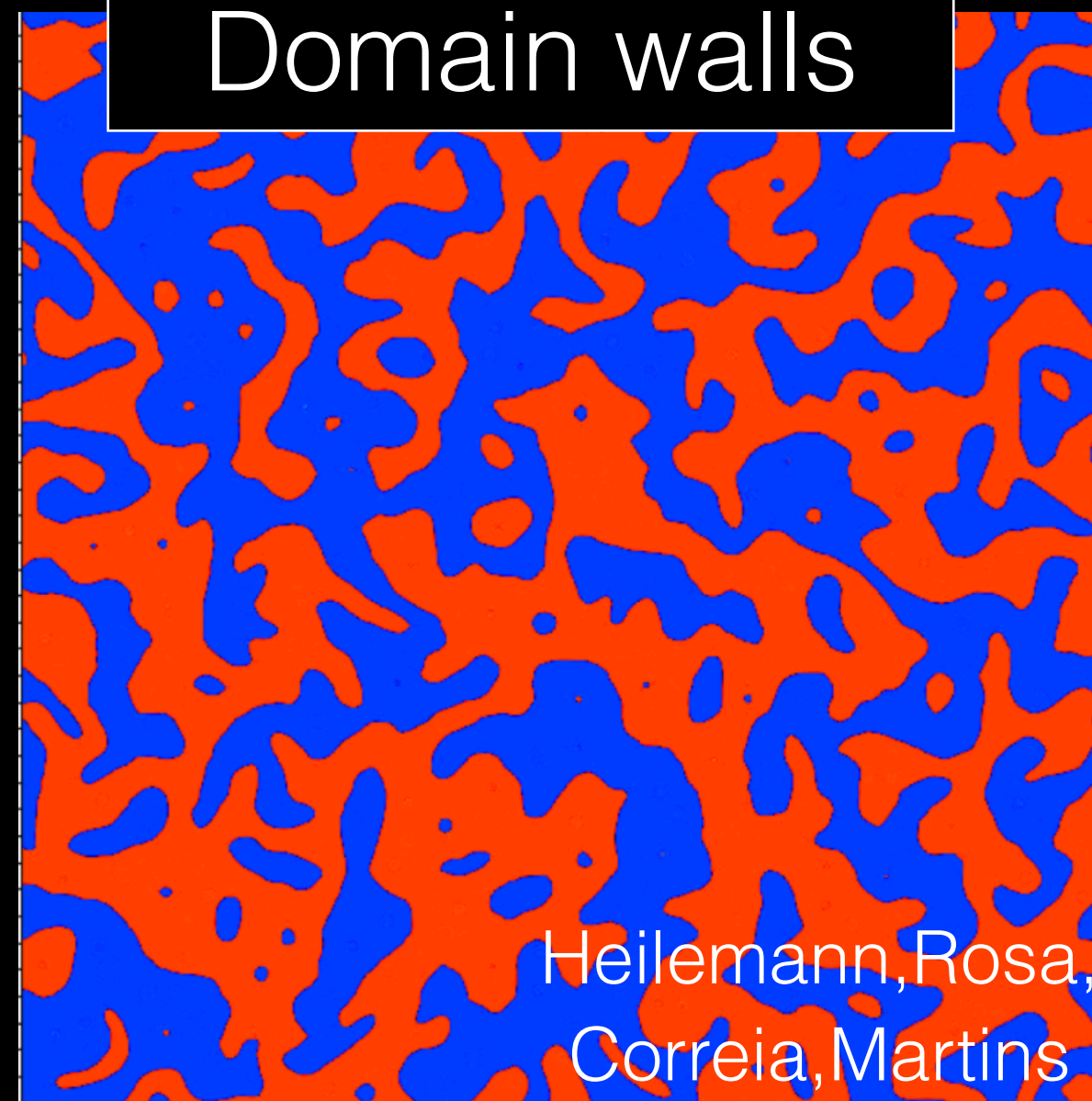
Extended objects in the early universe:

e.g., phase transition **bubbles**, **domain walls**, and **ultralight DM**

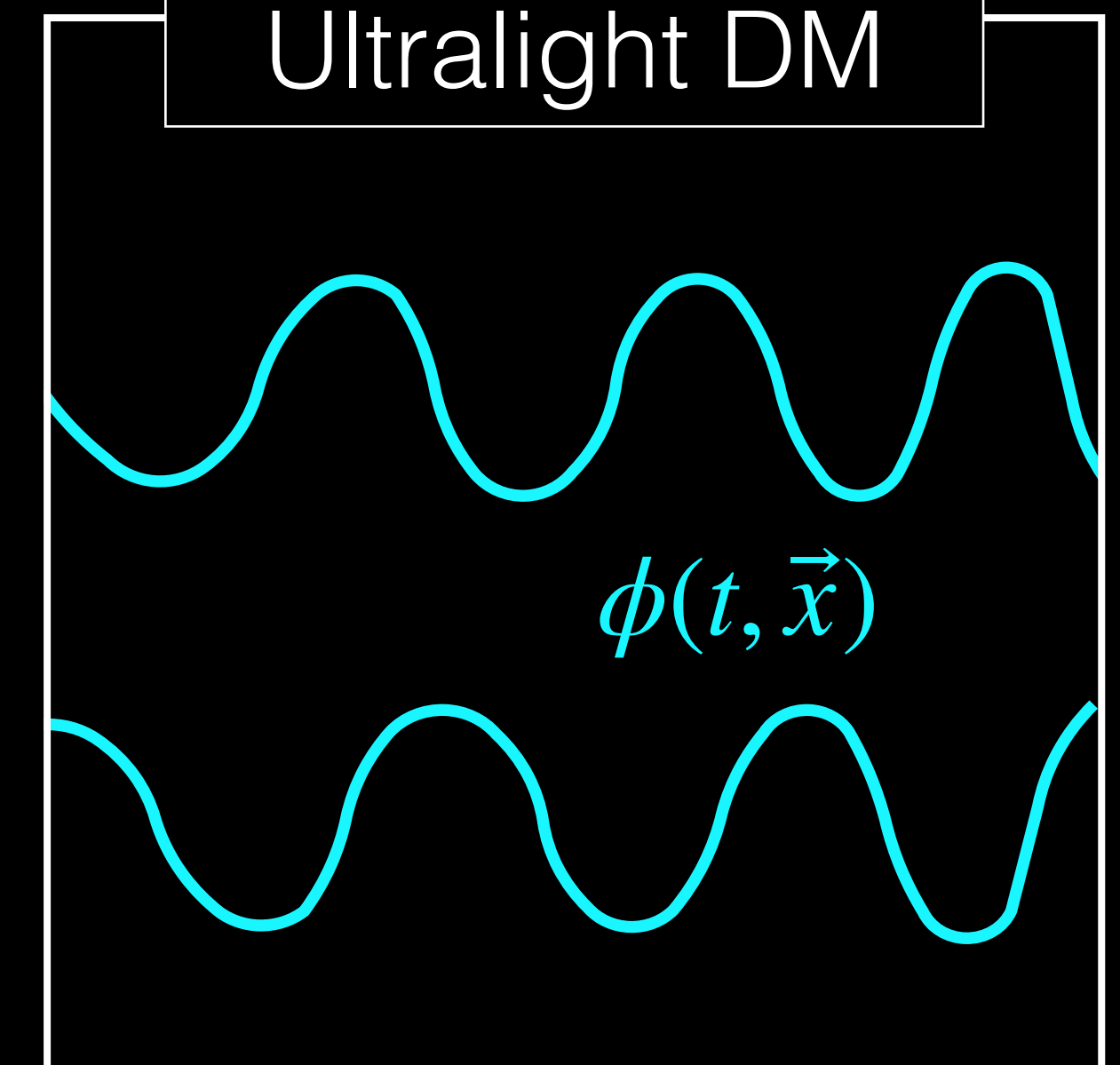
PT Bubbles



Domain walls



Ultralight DM



Signals of cosmological perturbations arise from both
“initial perturbations” and their “time evolution”

$$\delta(k, z) = \delta_{\text{ini}}(k) \times D(z) T(k)$$

energy density
or metric
perturbation

Initial
perturbation

Scale-dependent
evolution in time

All the new physics I've discussed so far
modifies the “time evolution”

$$\delta(k, z) = \delta_{\text{ini}}(k) \times D(z) T(k)$$

energy density
or metric
perturbation

Initial
perturbation

Scale-dependent
evolution in time

Extended objects with large-scale energy fluctuations can modify “initial perturbations” post-inflation

$$\delta(k, z) = \delta_{\text{ini}}(k) \times D(z) T(k)$$

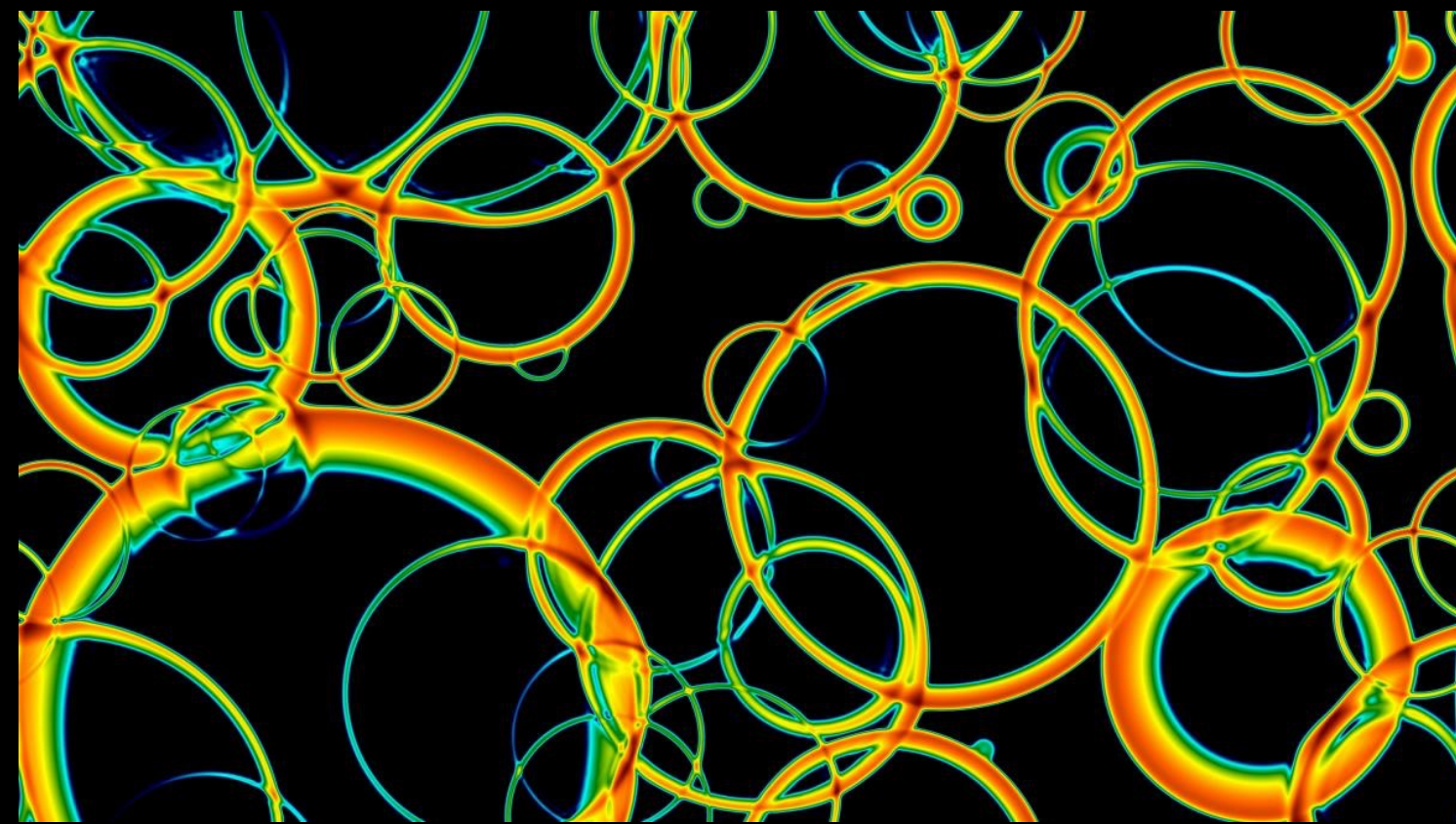
energy density
or metric
perturbation

Initial
perturbation

Scale-dependent
evolution in time

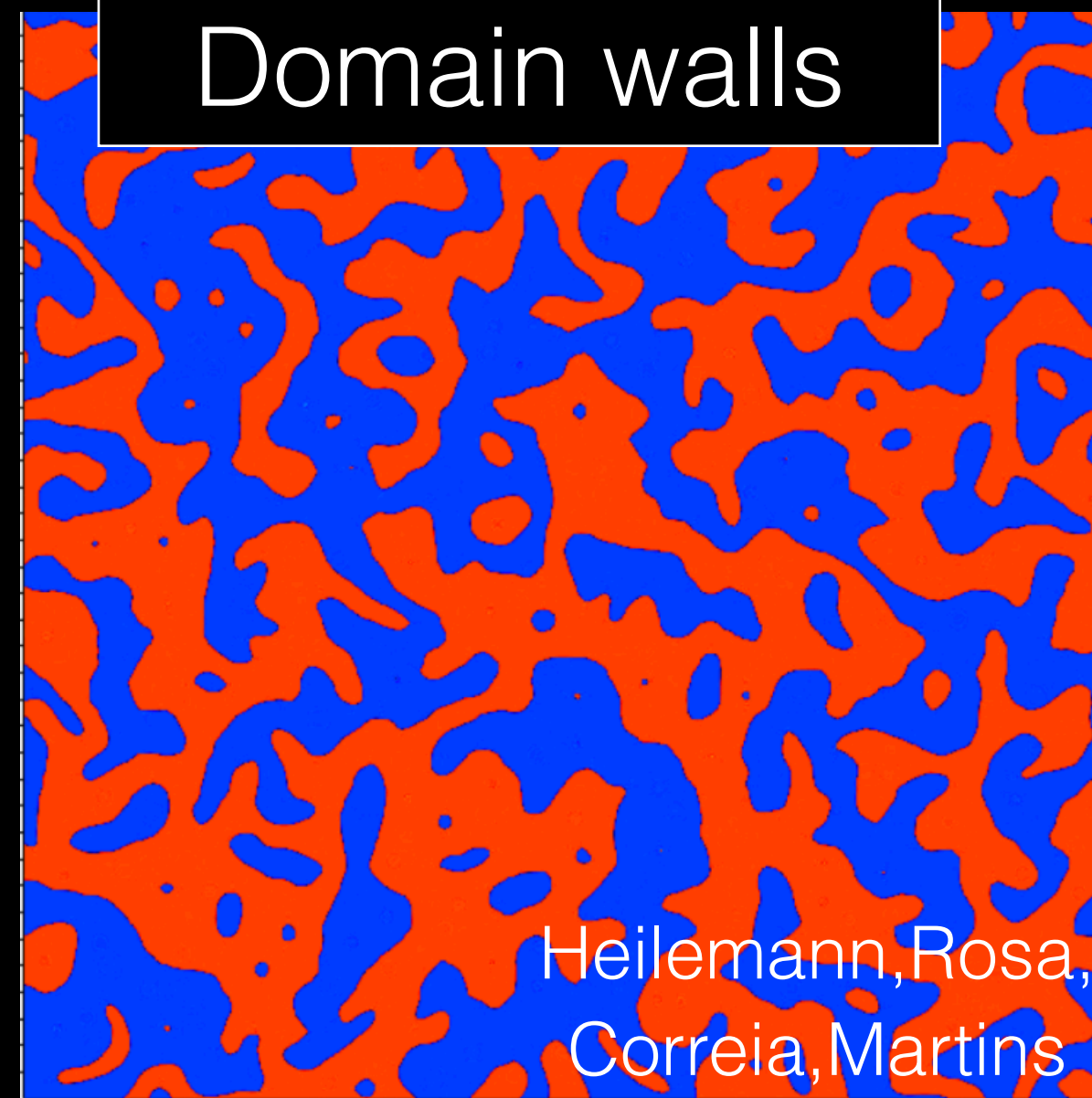
These objects produce both **scalar** and **tensor** mode perturbations

PT Bubbles



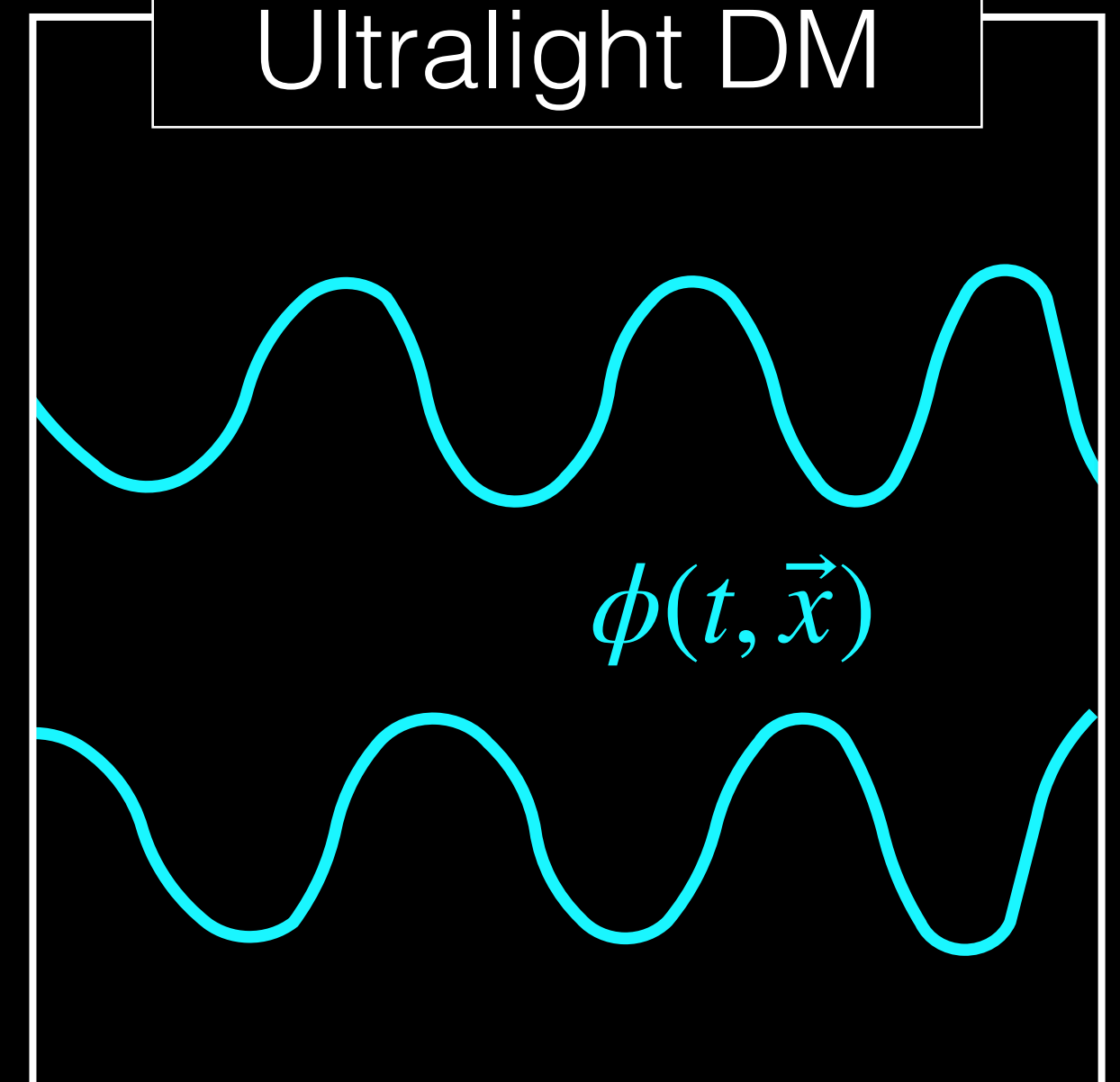
Weir

Domain walls



Heilemann, Rosa,
Correia, Martins

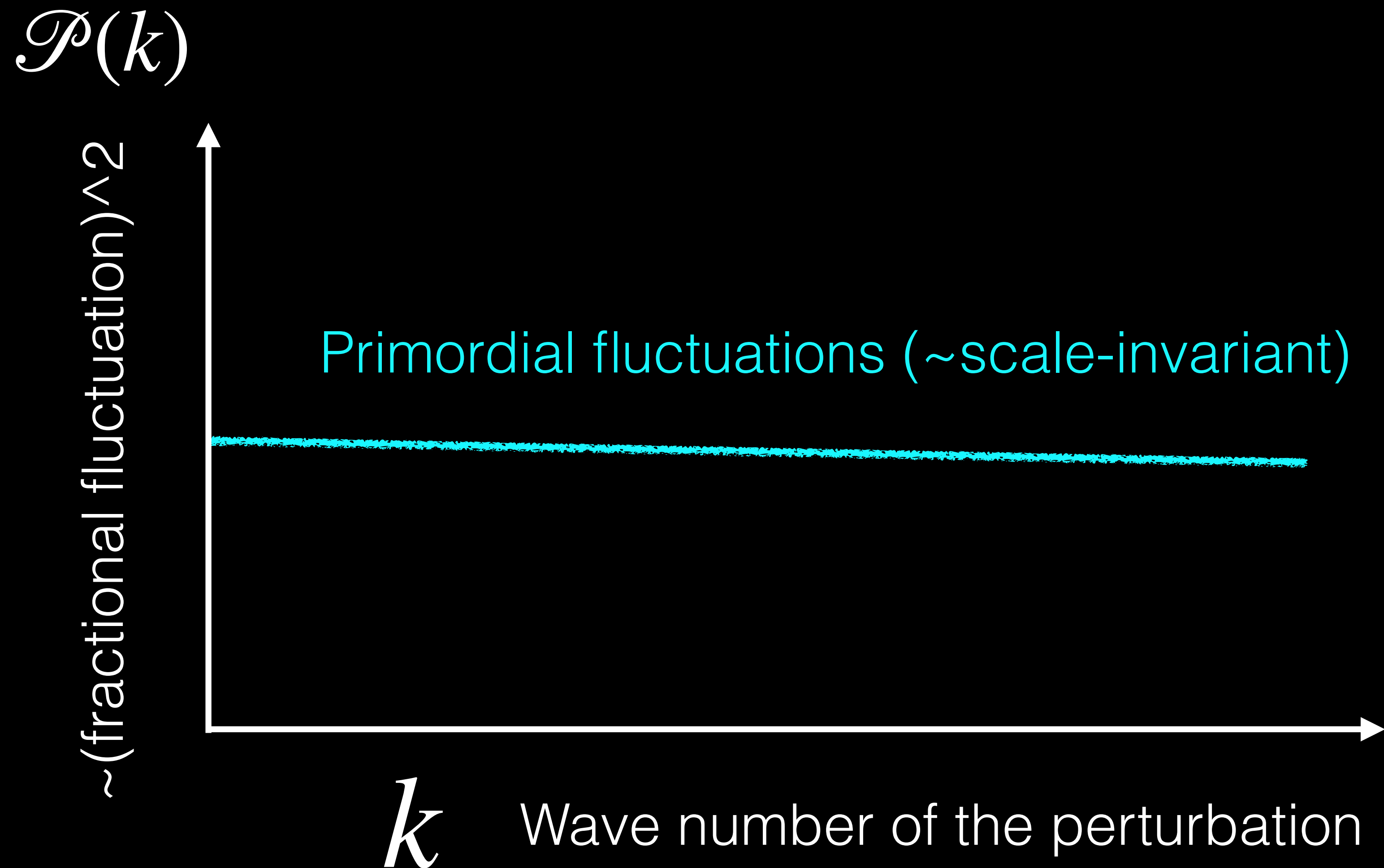
Ultralight DM



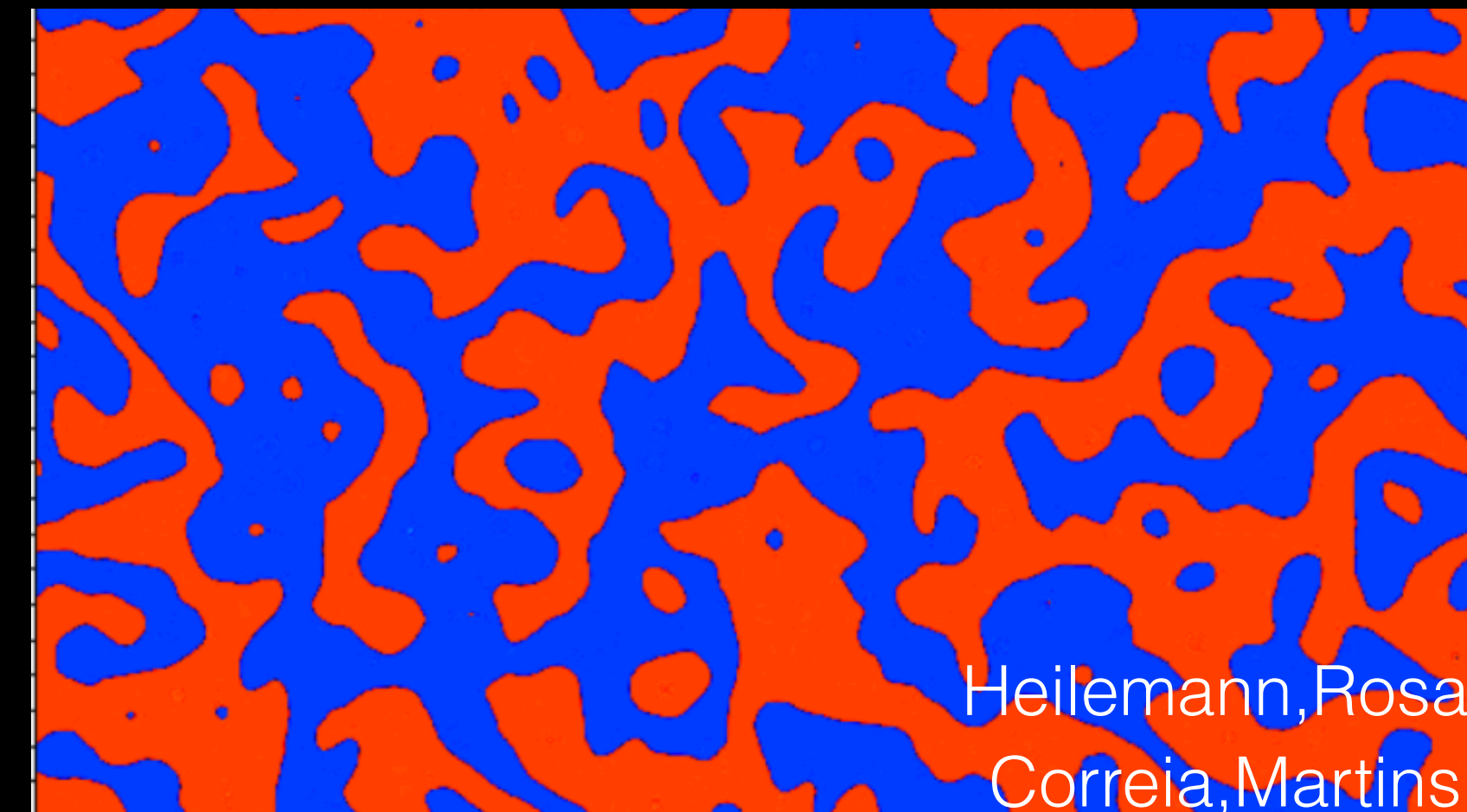
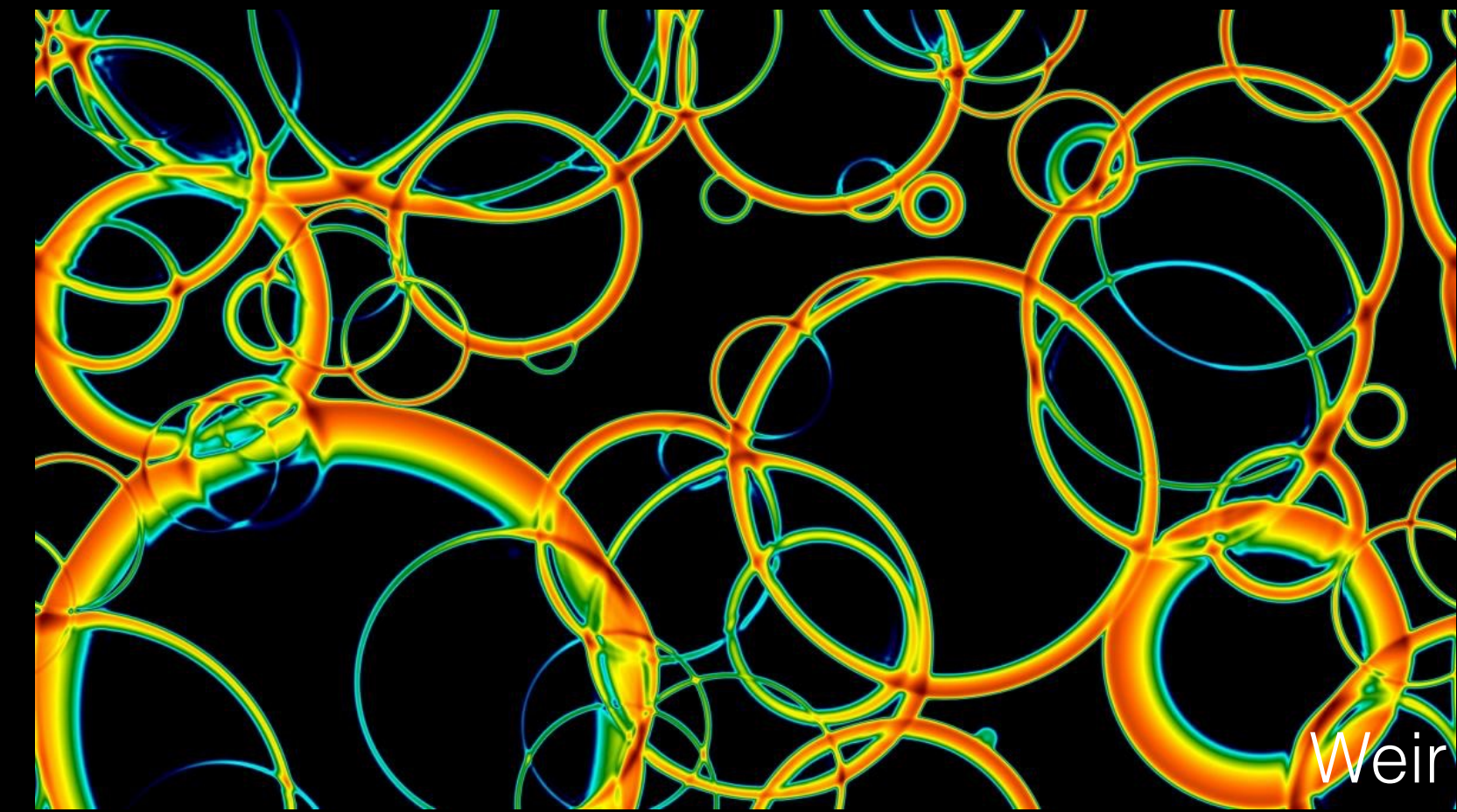
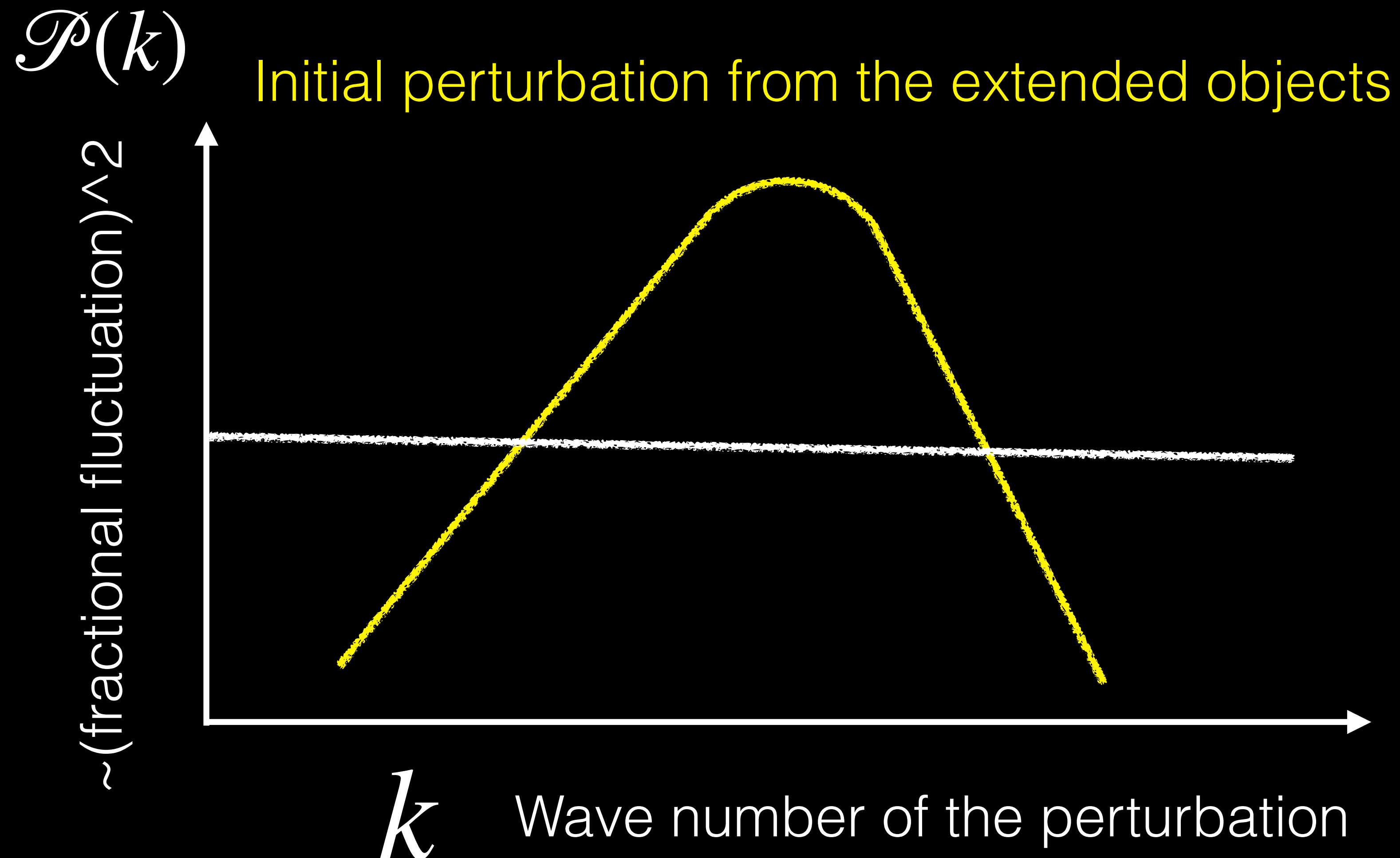
$$\phi(t, \vec{x})$$

modify the cosmological structures and source gravitational waves

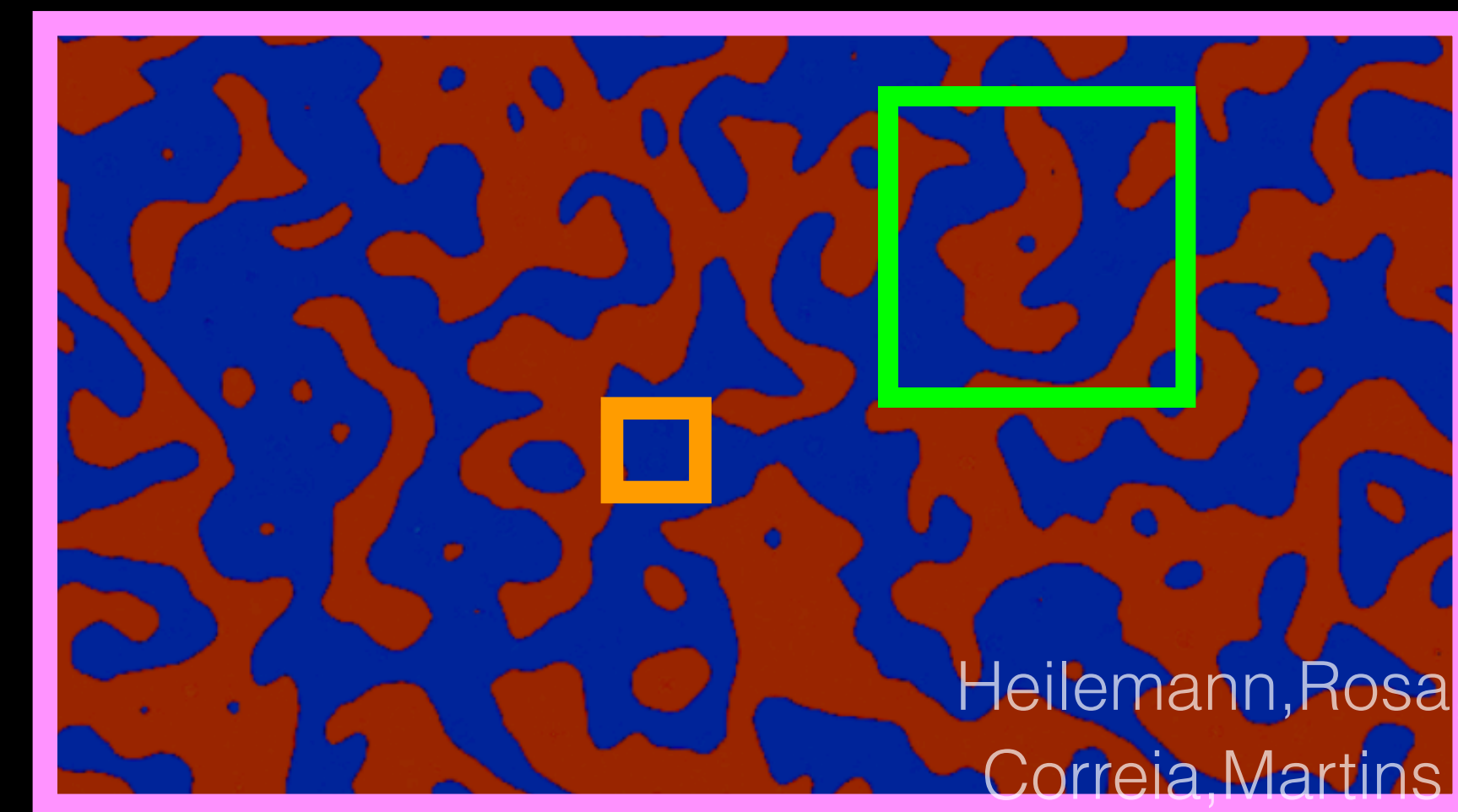
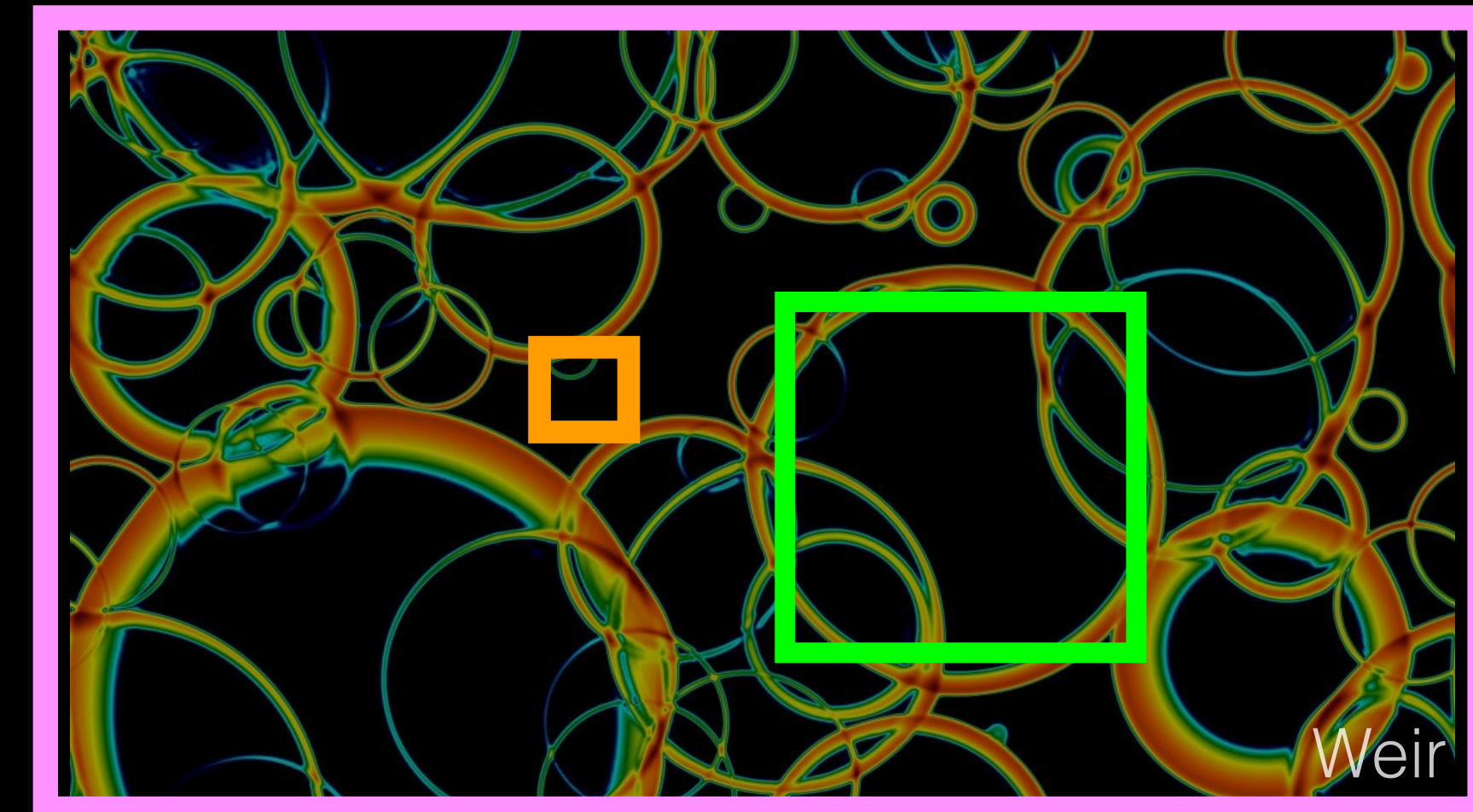
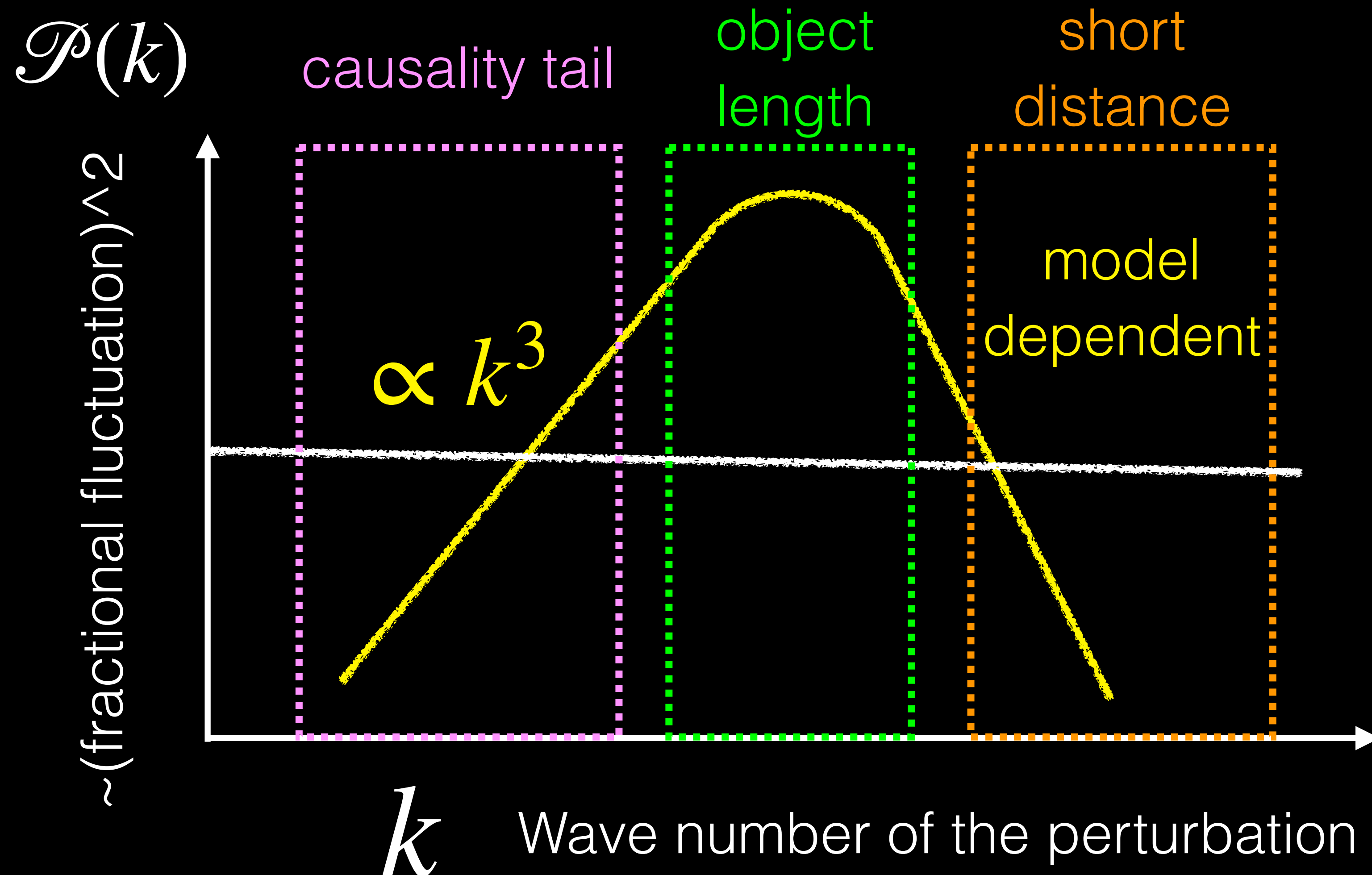
The “standard” (adiabatic) primordial fluctuations
are nearly scale-invariant



Extended objects inject uncorrelated (iso)curvature perturbations, creating a distinct peaked structure

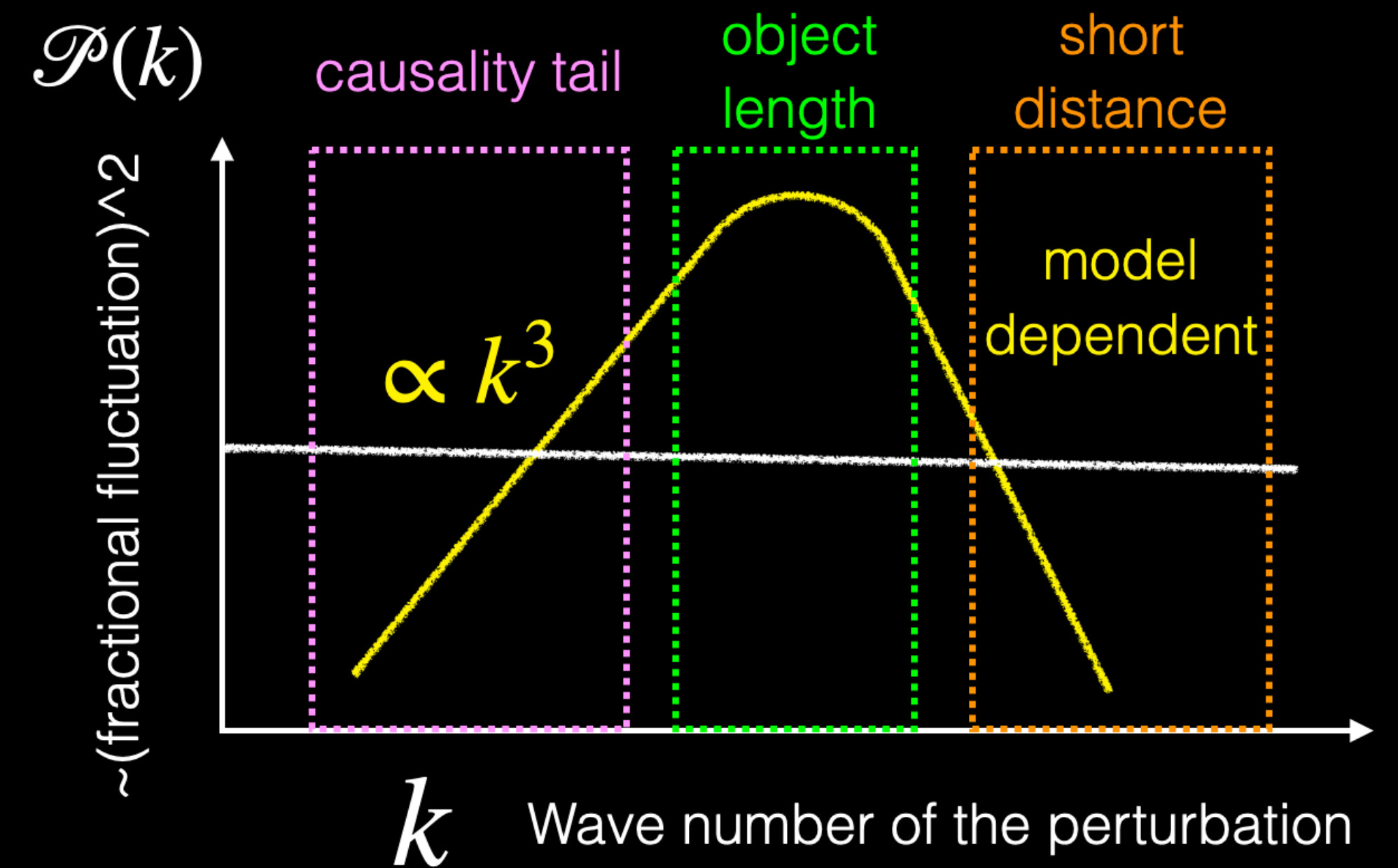


The length scale of the **peak** corresponds to the **correlation length** of the objects; **height** $\sim O(0.1)$ fluctuation scaled by energy density ratio



These new physics fluctuations modify a wide range of cosmological signals

- CMB fluctuations
- Matter perturbation spectrum
- CMB blackbody energy spectrum
- Sub-halo mass function
- Re-ionization physics
- Ultra-violet luminosity function (UVLF)
- ...

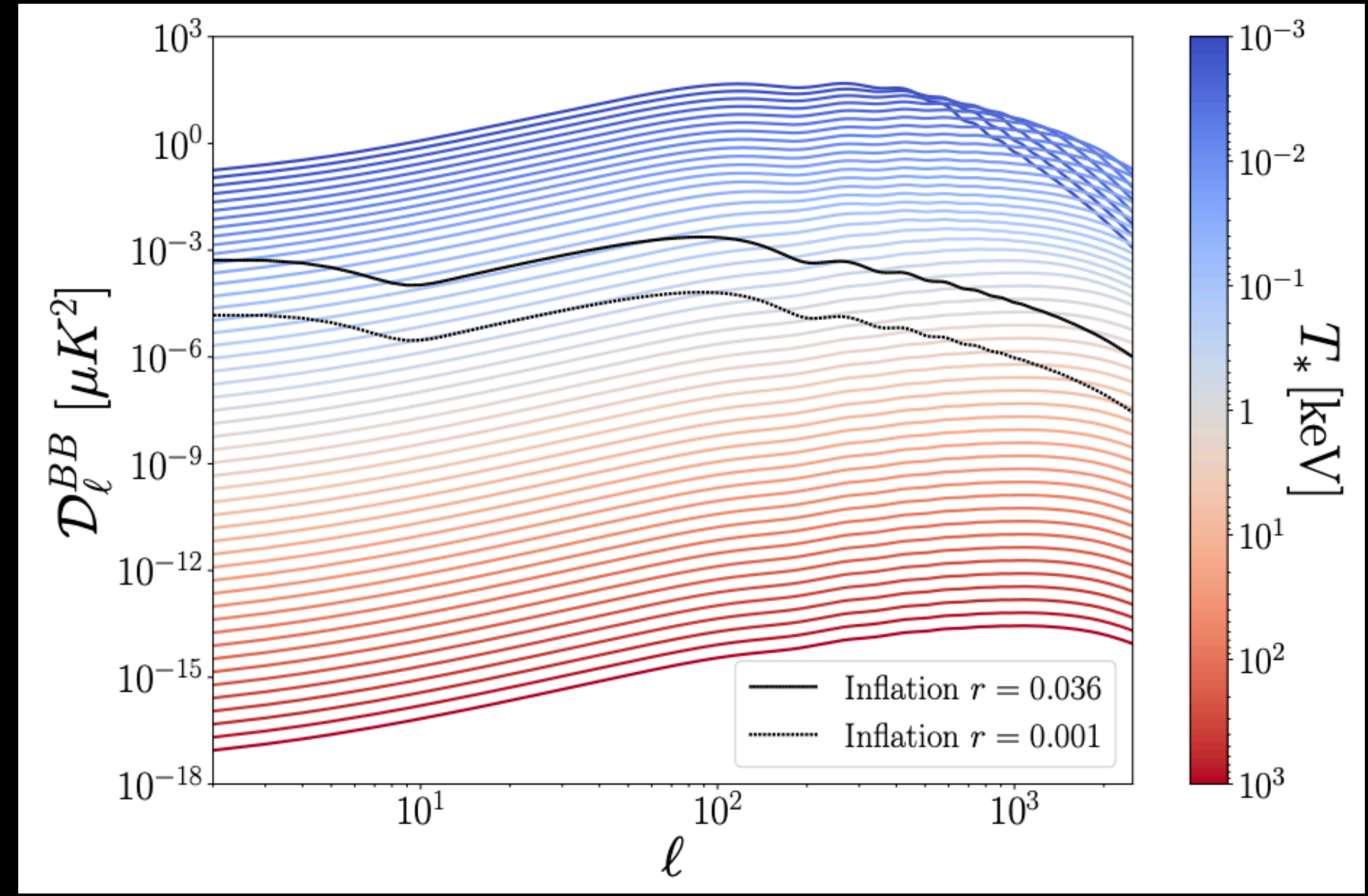
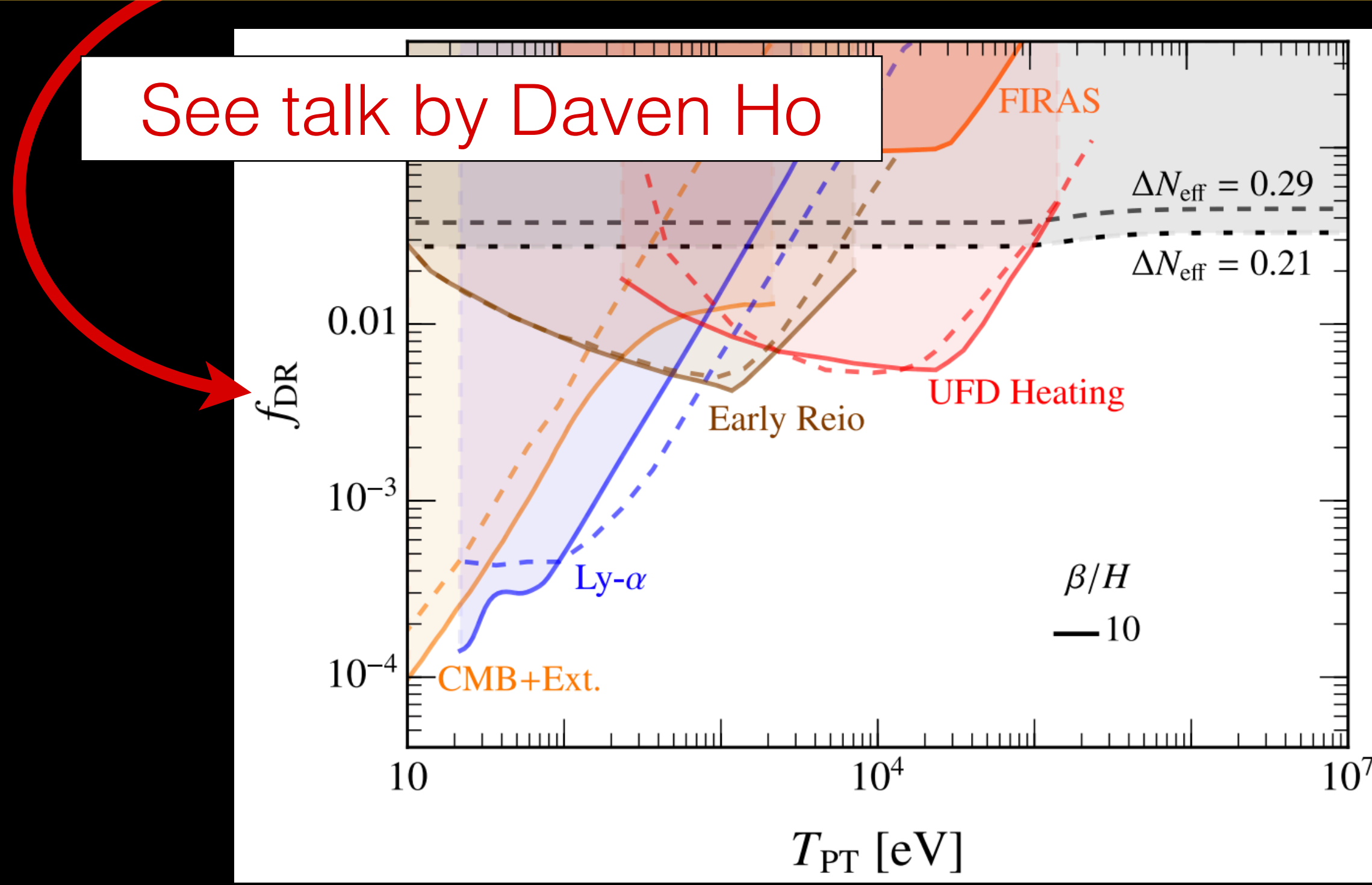


Can set stringent upper bounds on the energy injected into these extended objects

Even in a **dark sector**, cosmology can gravitationally probe **late-time phase transitions** down to **0.01%** of the photon energy

The allowed phase transition energy / radiation energy

CMB B-mode signal



Temperature of the universe at phase transition

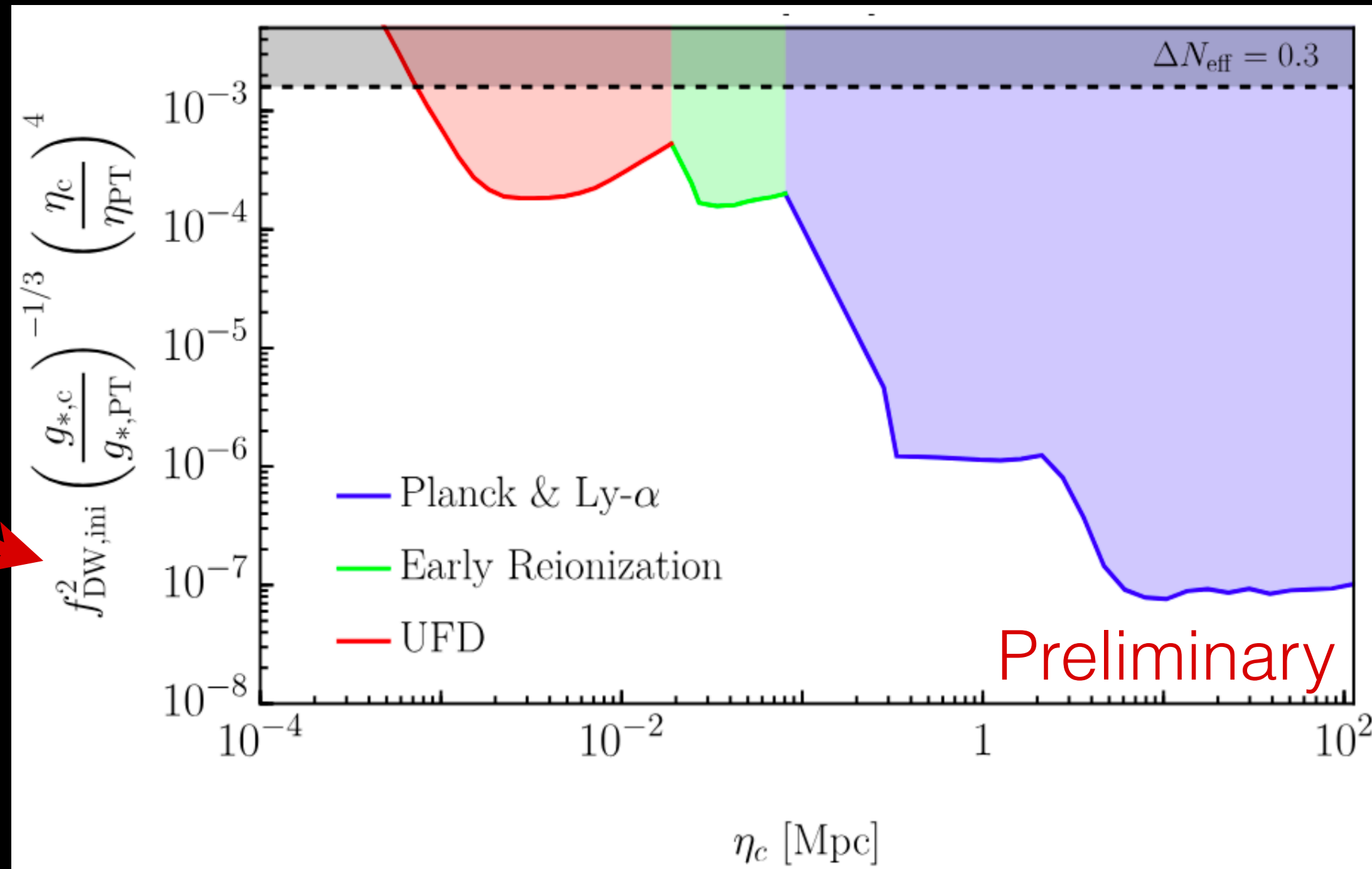
Greene, Ireland, Krnjaic, **YT** (2025) (2026)

Zebrowski, Ireland, Greene, Reichardt, Krnjaic, **YT** (2025)

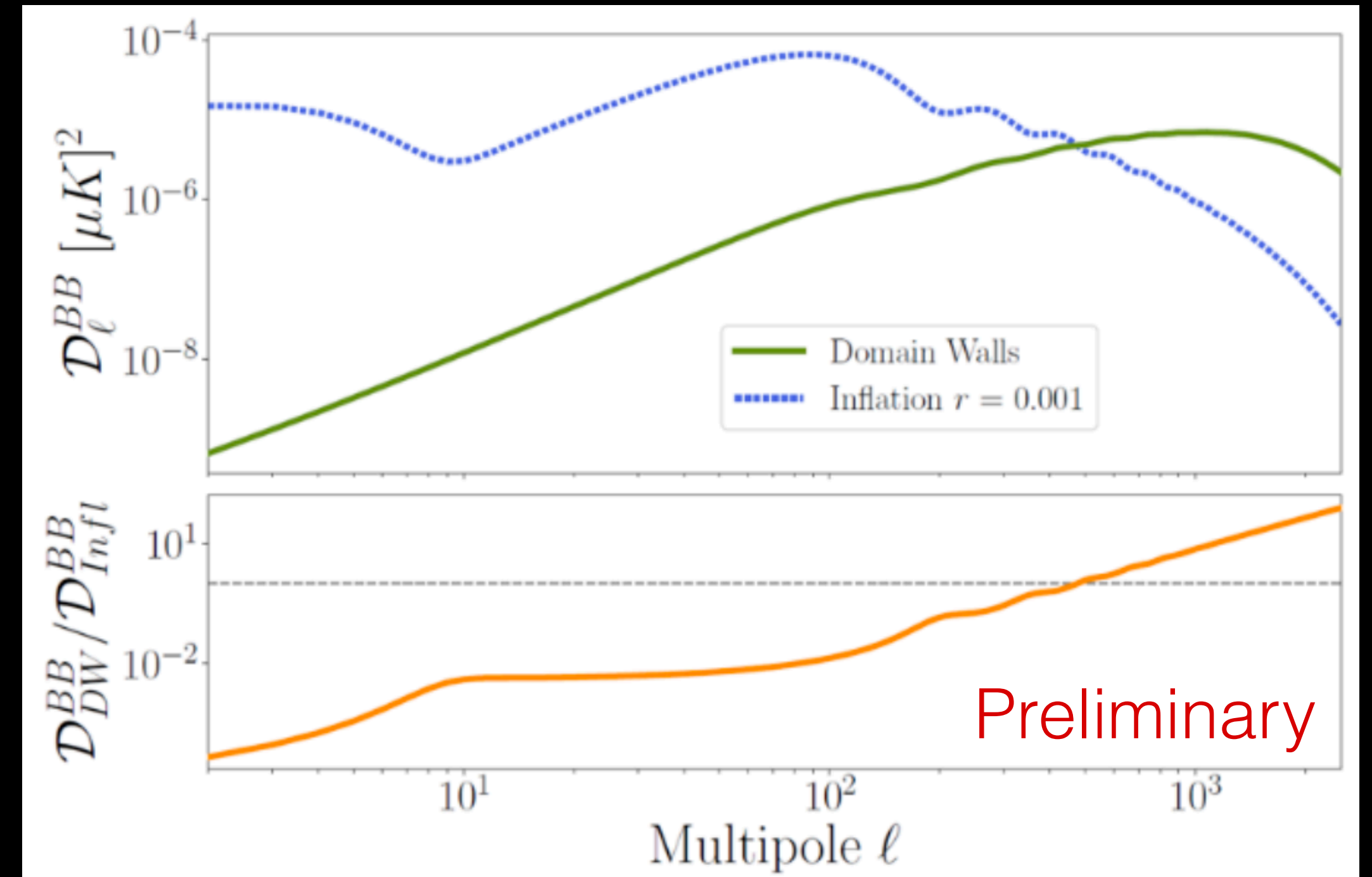
Elore, Jinno, Kumar, McGehee, **YT** (2023); Greene, Ho, Kumar, **YT** (2026); Koren, **YT**, Wang (2025)

A similar analysis applies to **unstable domain walls**: redshift differently and with length grows over time, leading to distinct initial perturbations

The allowed phase transition energy / radiation energy



CMB B-mode signal



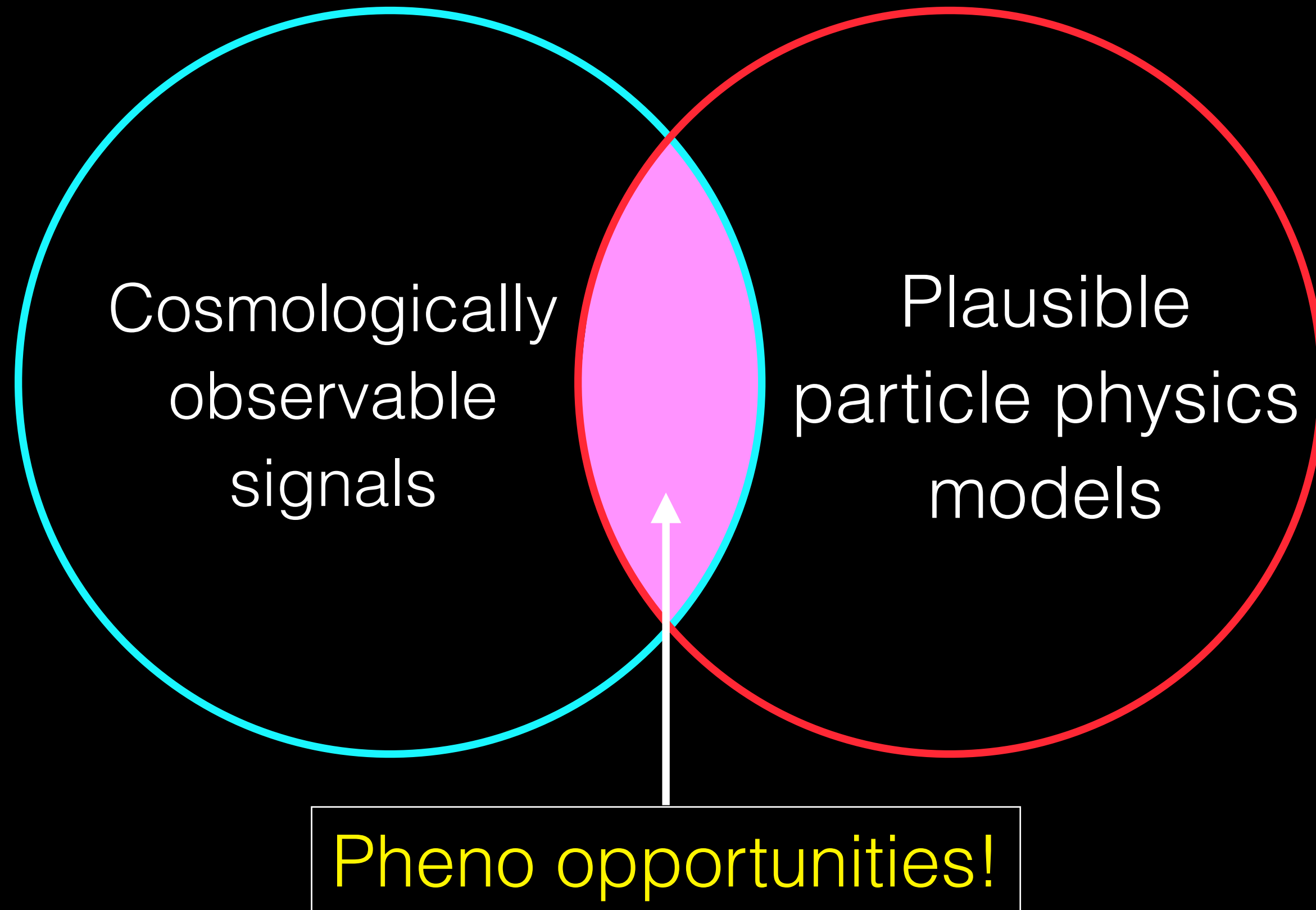
Temperature of the universe at phase transition

Greene, Ireland, Krnjaic, **YT**, Yang (in progress)

See talk by Fengwei Yang

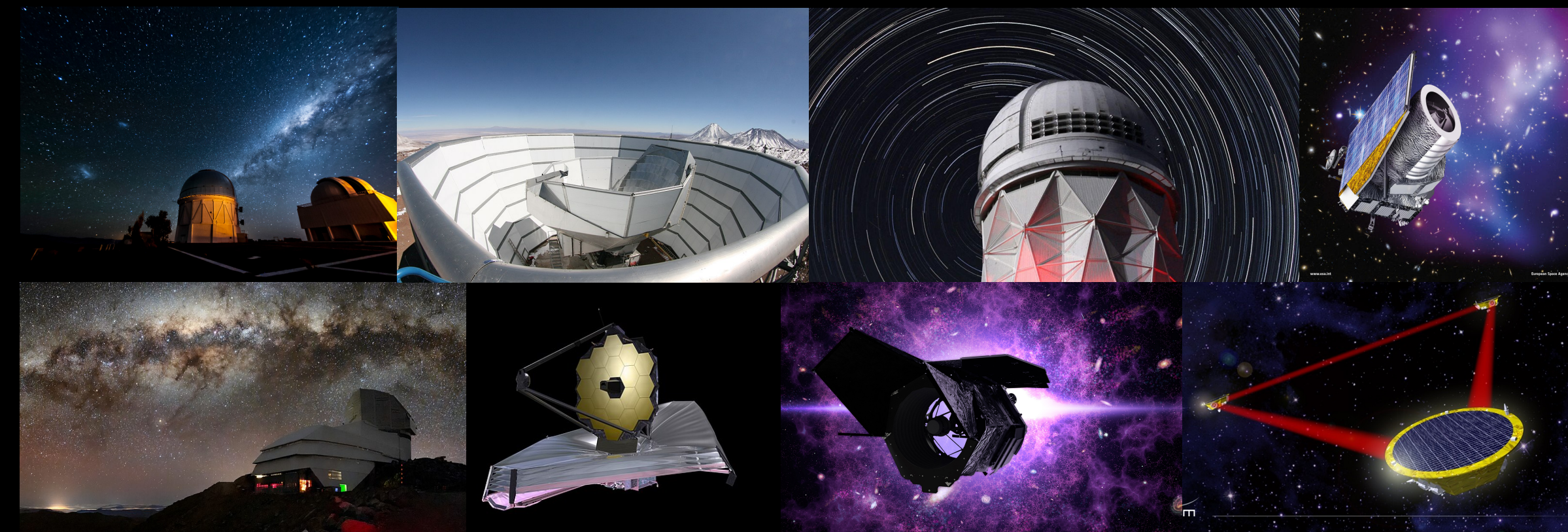
Summary

Cosmology allows us to probe particle physics that is difficult, or even impossible, to observe directly



Data Is Coming—

Find More Particle Physics to Test!



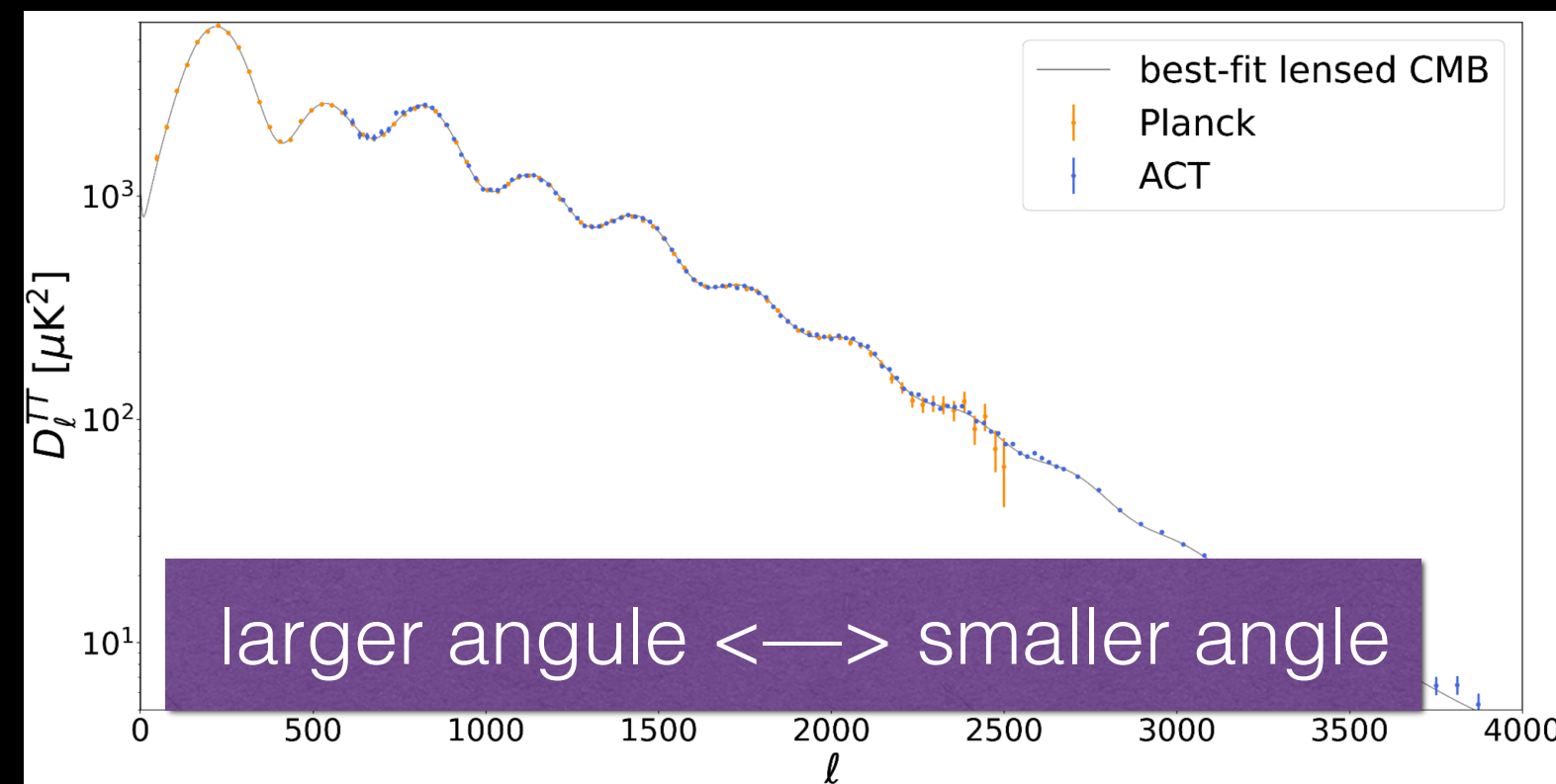
Backup Slides

What's the data?

Let's only focus on **large scale** (> million light years) measurements here

Cosmic Microwave Background

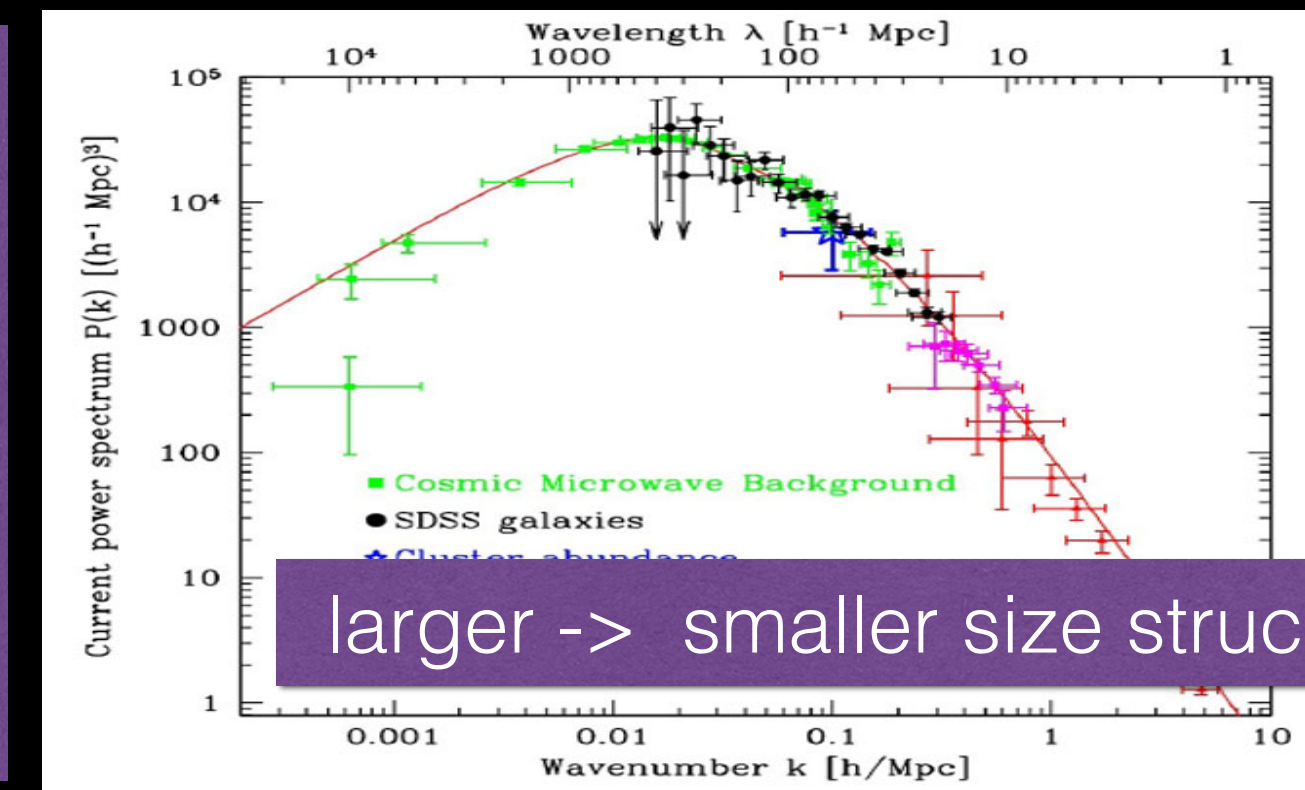
CMB photon
Fluctuations



ACT

Large Scale Structure

DM fluctuations



Baryon acoustic oscillation (BAO)

$H(z)$ Hubble expansion history

$D_A(z)$ Distance to objects at a redshift

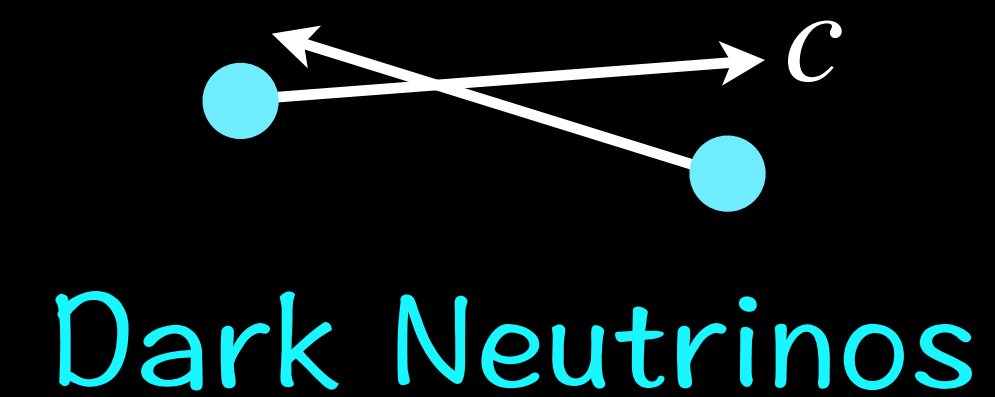
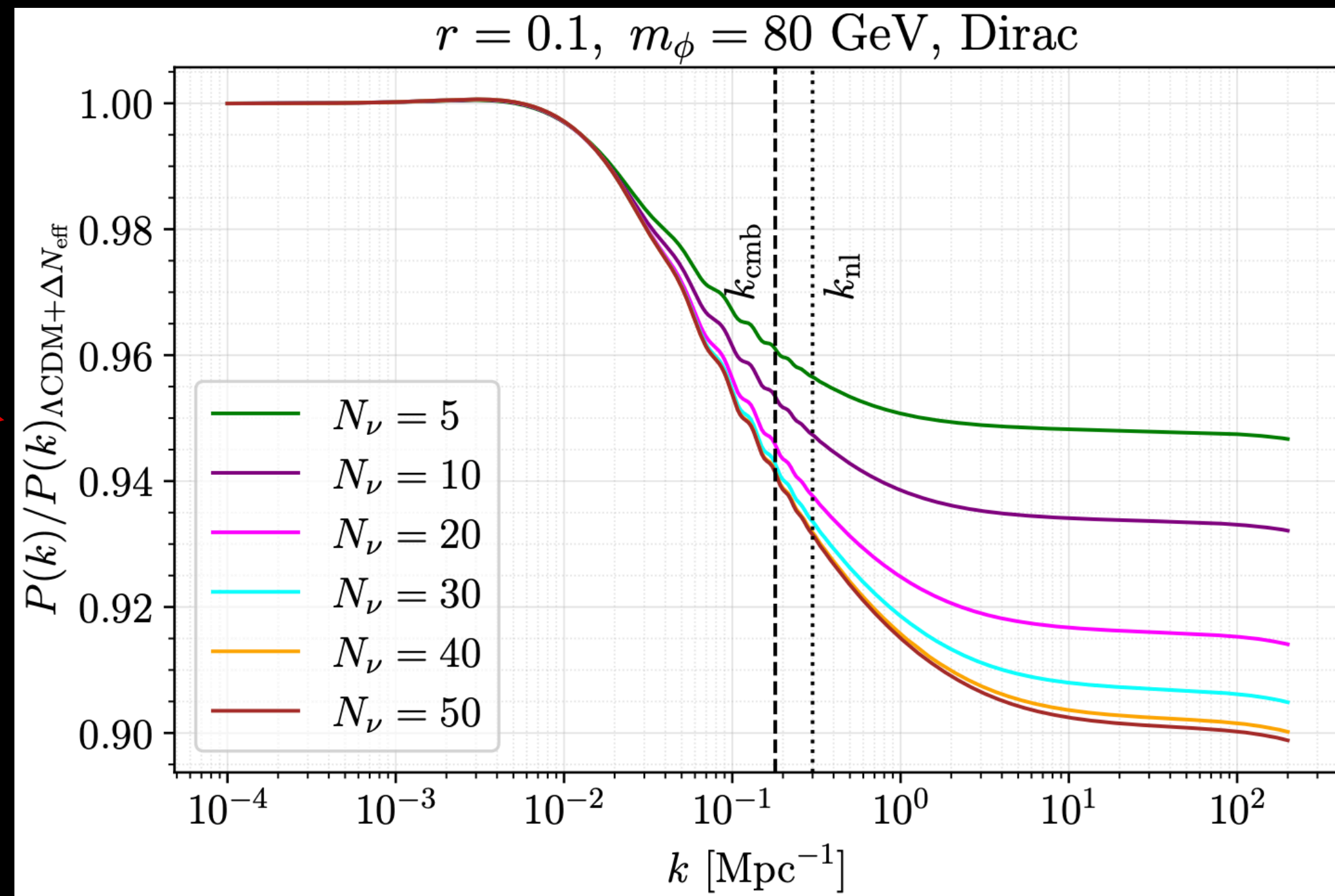
Ω_m Matter density (and more...)

Distance ladder measurements

H_0 Hubble expansion rate near today

Presence of the warm dark matter (like dark neutrinos) also suppress matter perturbation

Ratio of matter density perturbation



larger \rightarrow smaller size structure

Bansal, Ghosh, Low, YT (2025)

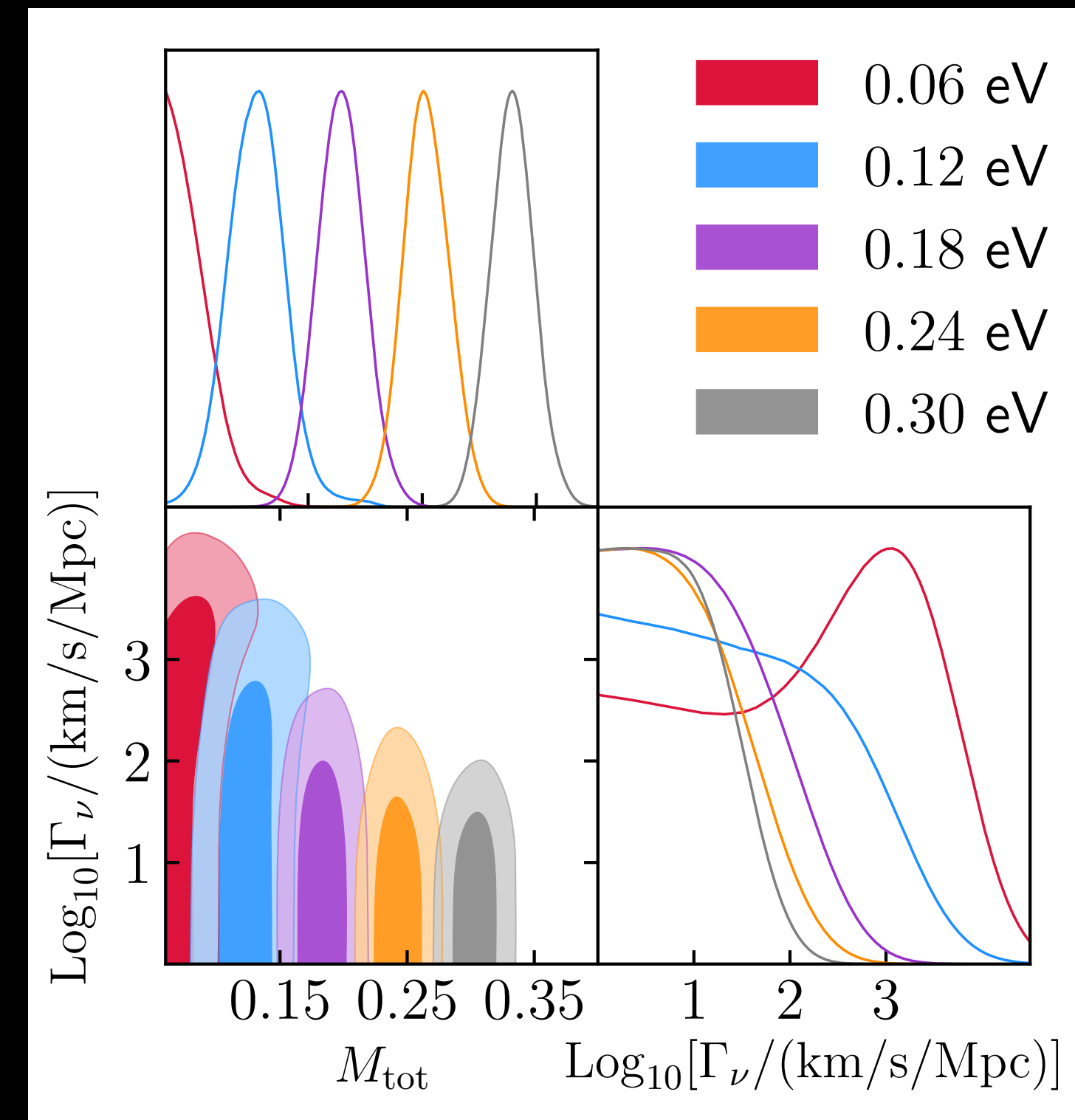
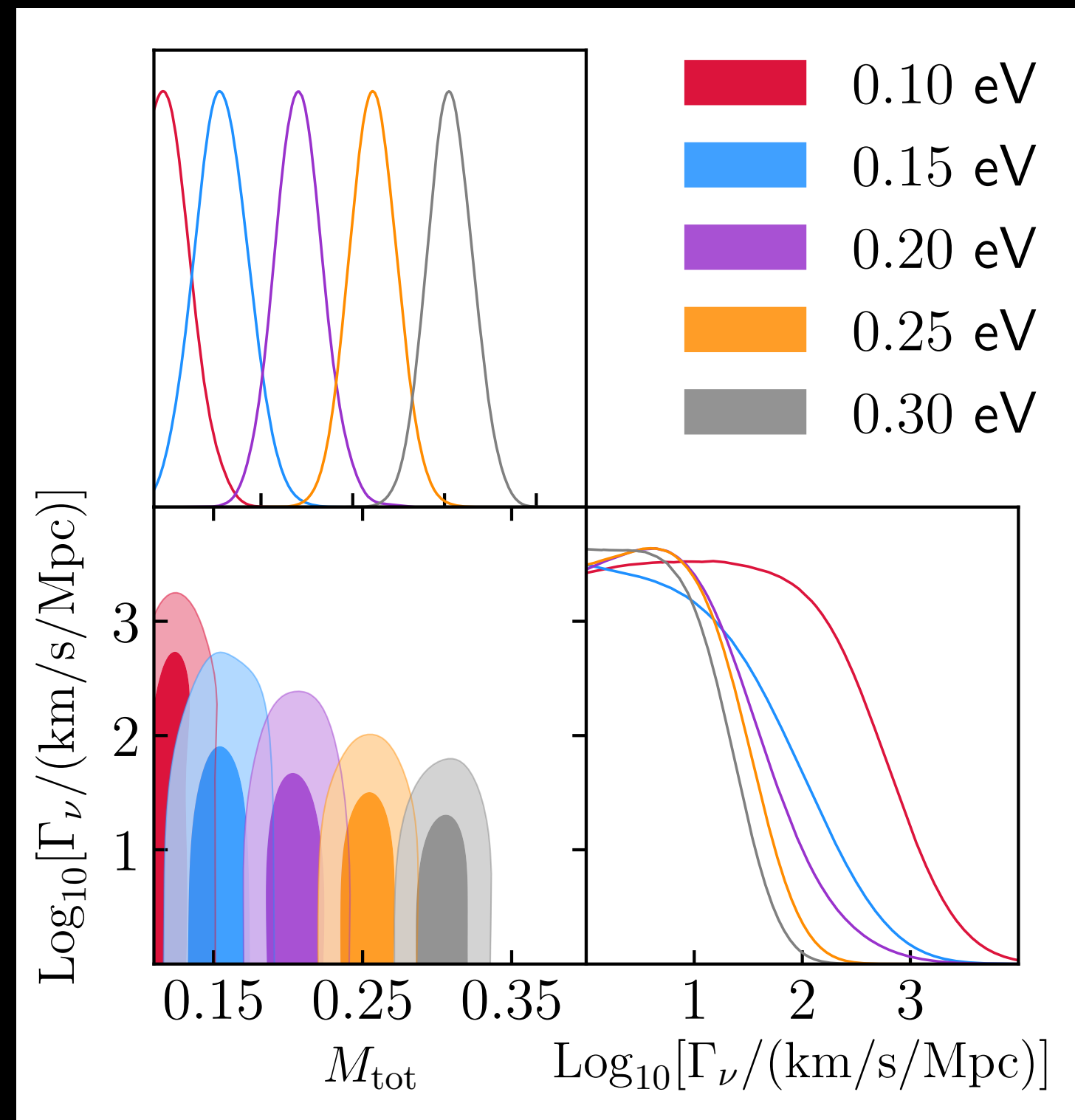
Constrain neutrino mass & lifetime

Planck + Euclid P(k) + Euclid Lensing

(see 2002.08401 for more details)

Normal hierarchy

Inverted hierarchy



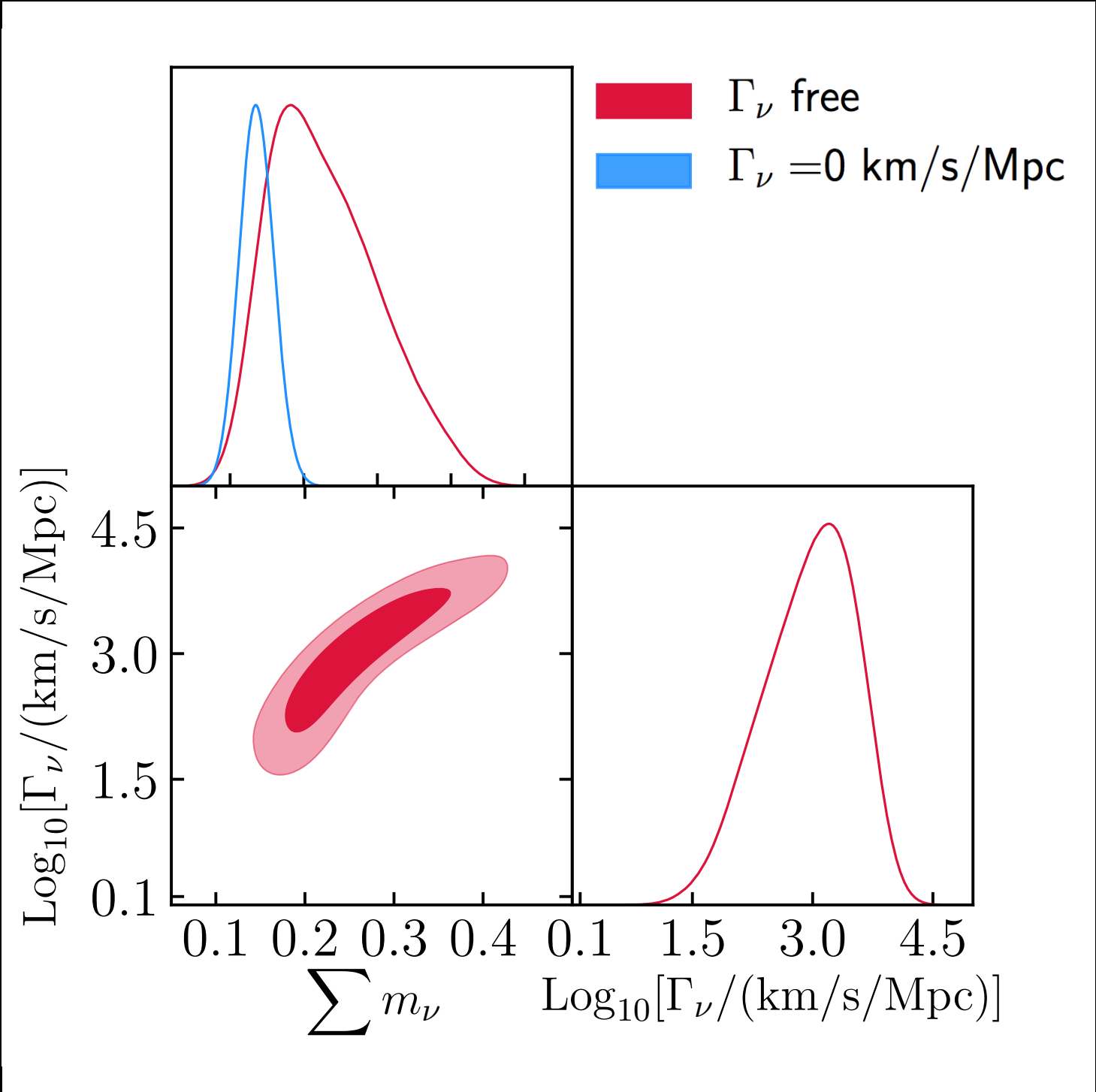
set lower bounds on neutrino lifetime with O(1-10) billion years

If neutrinos do decay, there's a chance to measure neutrino mass & lifetime

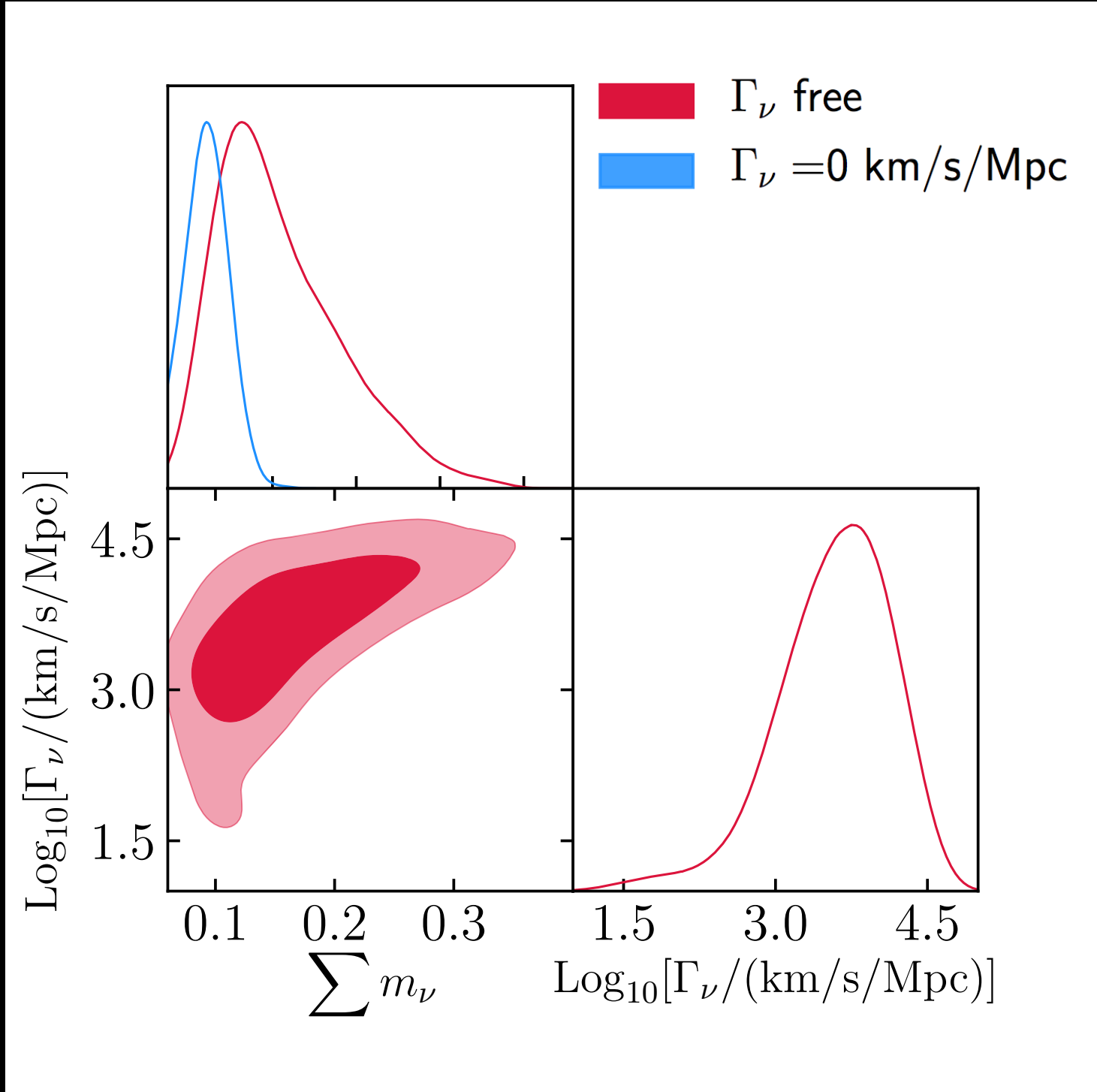
Planck + Euclid P(k) + Euclid Lensing

(see 2002.08401 for more details)

Normal hierarchy



Inverted hierarchy



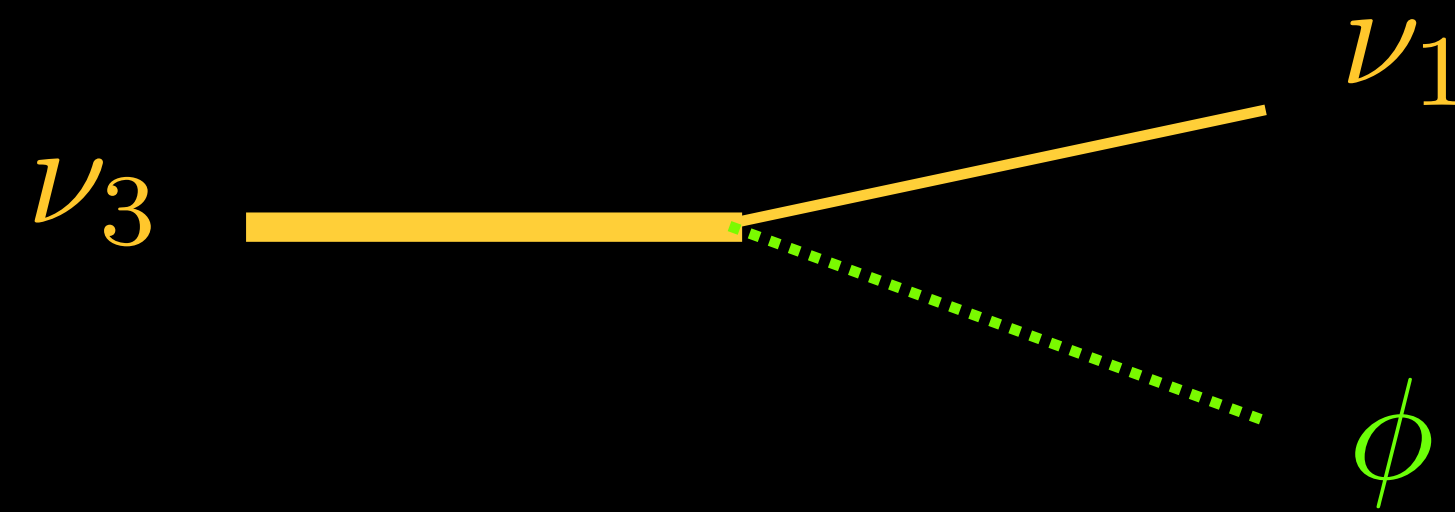
possible mass/lifetime measurement if lifetime is O(1) Gyrs

Example: Nu decay in the Majoron model

An explanation of the small neutrino mass

$$\frac{\Phi_\alpha \Phi_\beta}{\Lambda^3} (\bar{L}_\alpha^c \sigma_2 H) (H \sigma_2 L_\beta) \quad \alpha, \beta = e, \mu, \tau$$

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



Chacko, Dev,
Du, Poulin, **YT** (2019)

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