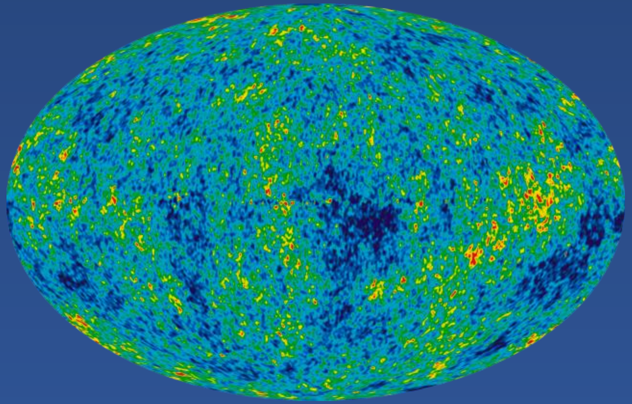
Constraining Dark First-Order PTs with CMB and Structure Formation Observations



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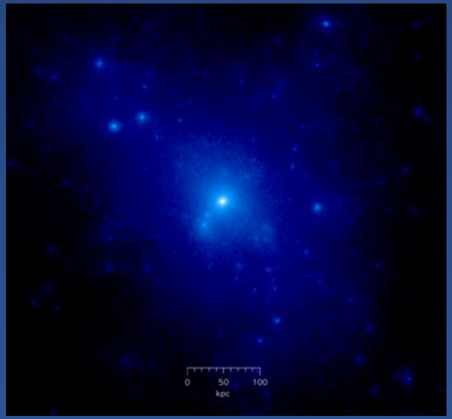

arXiv: 2603.00272

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PHENO 2026, University of Pittsburgh

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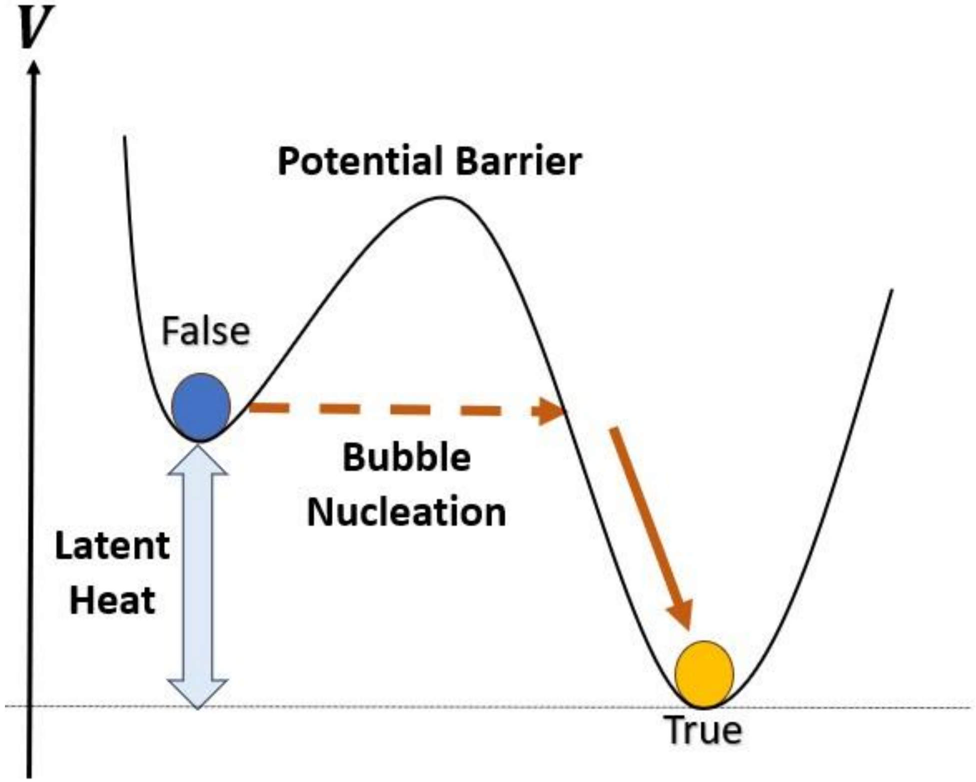
Dark Phase Transition

First-Order Phase Transition (PT):

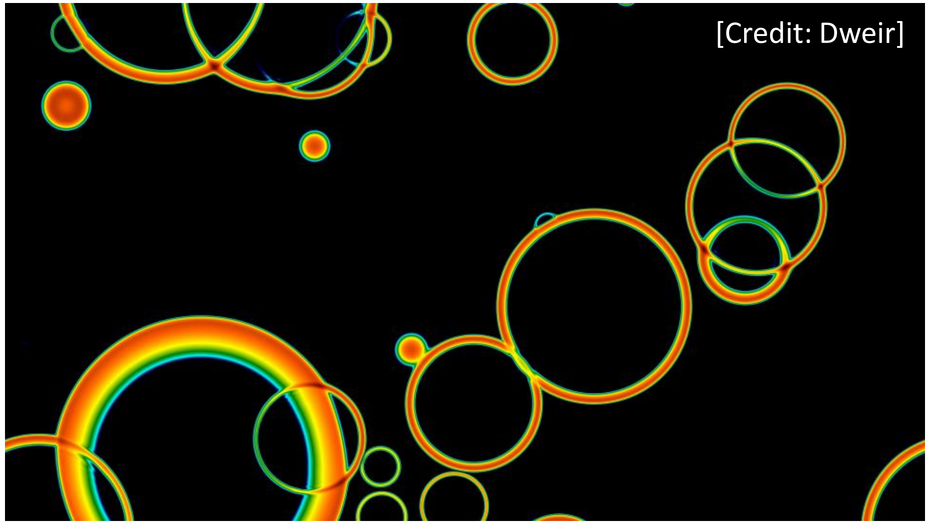
- Transition from false to true vacuum separated by ***potential barrier***
- Proceeds by random ***bubble nucleation***
- Potential difference released as ***latent heat***



Consider ***dark*** cosmological first-order PT that occurs at ***"late times"*****:**

1. **Dark:** occurs in ***secluded*** dark sector that interacts with SM only ***gravitationally*** (***"nightmare scenario"***)
2. **Late:** occurs during radiation era at $T_{PT} \lesssim$ **MeV** (***between BBN and recombination***)

Relevance? E.g. ***Dark PT models*** proposed to ***solve*** H_0 ***tension*** [Niedermann and Sloth (2020)]



[Credit: Dweir]

PT Parameters

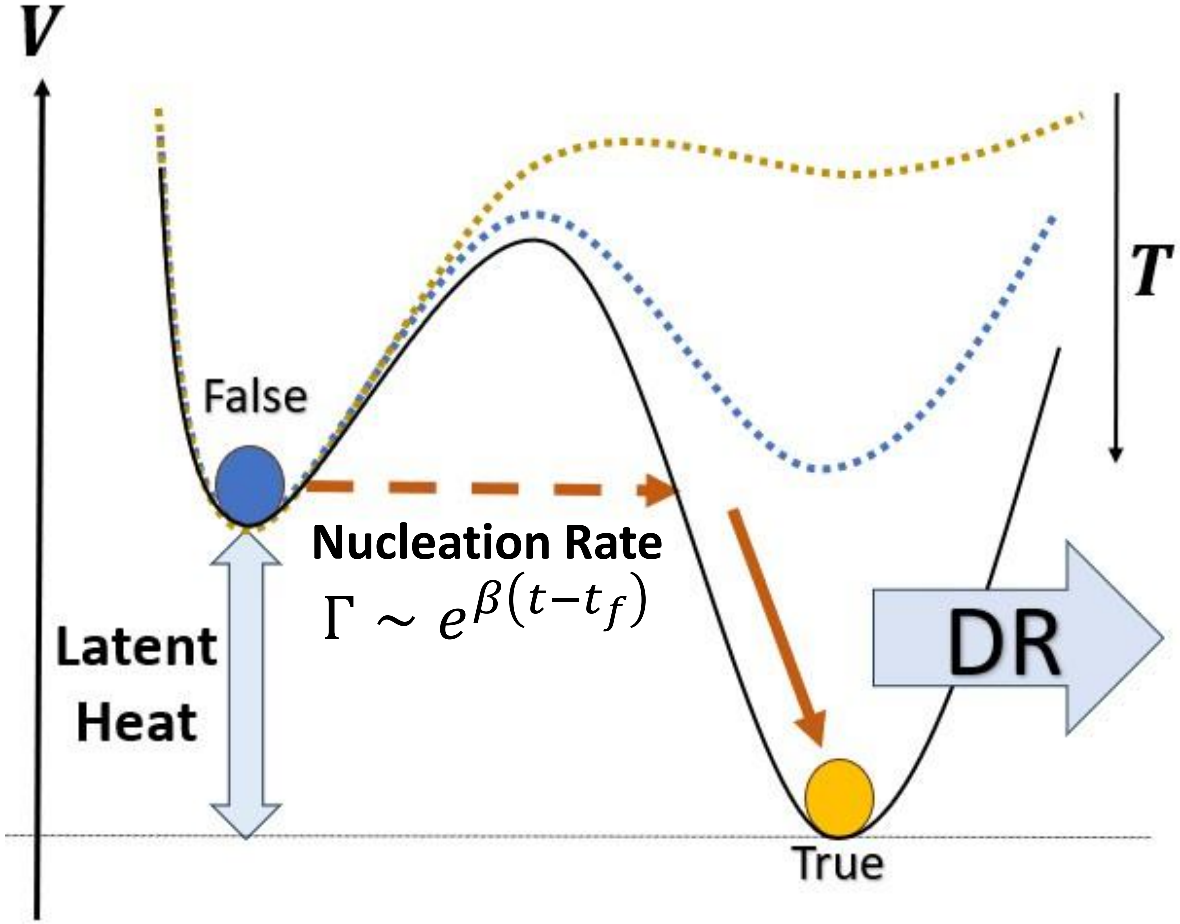
Assumptions:

- All latent heat released as ***dark radiation (DR)***
- ***Bubble wall velocity*** $v_w = 1$ (can rescale results)

For ***phenomenological study***, describe first-order PT with three generic parameters:

1. **When PT happens:** PT redshift $\boldsymbol{z_{PT}}$, directly related to SM photon temperature $\boldsymbol{T_{PT}}$
2. **How fast PT happens:** PT rate normalized to Hubble expansion rate $\boldsymbol{\beta/H_{PT}}$
3. **How much energy is released**: ratio of latent heat released (into DR) to total radiation energy at PT

$$\boldsymbol{f_{DR} \equiv \frac{\rho_{DR}}{\rho_{DR} + \rho_\nu + \rho_\gamma}}$$



PT Parameter Space

Aim: constrain dark PT parameters with ***gravitational probes!***

- Given β/H_{PT}, what is *2σ **exclusion bound*** on f_{DR} for each T_{PT}?
- ***Apply to dark PT models:*** e.g. how large must β/H_{PT} *be* to escape bounds?

Homogeneous CMB bound:

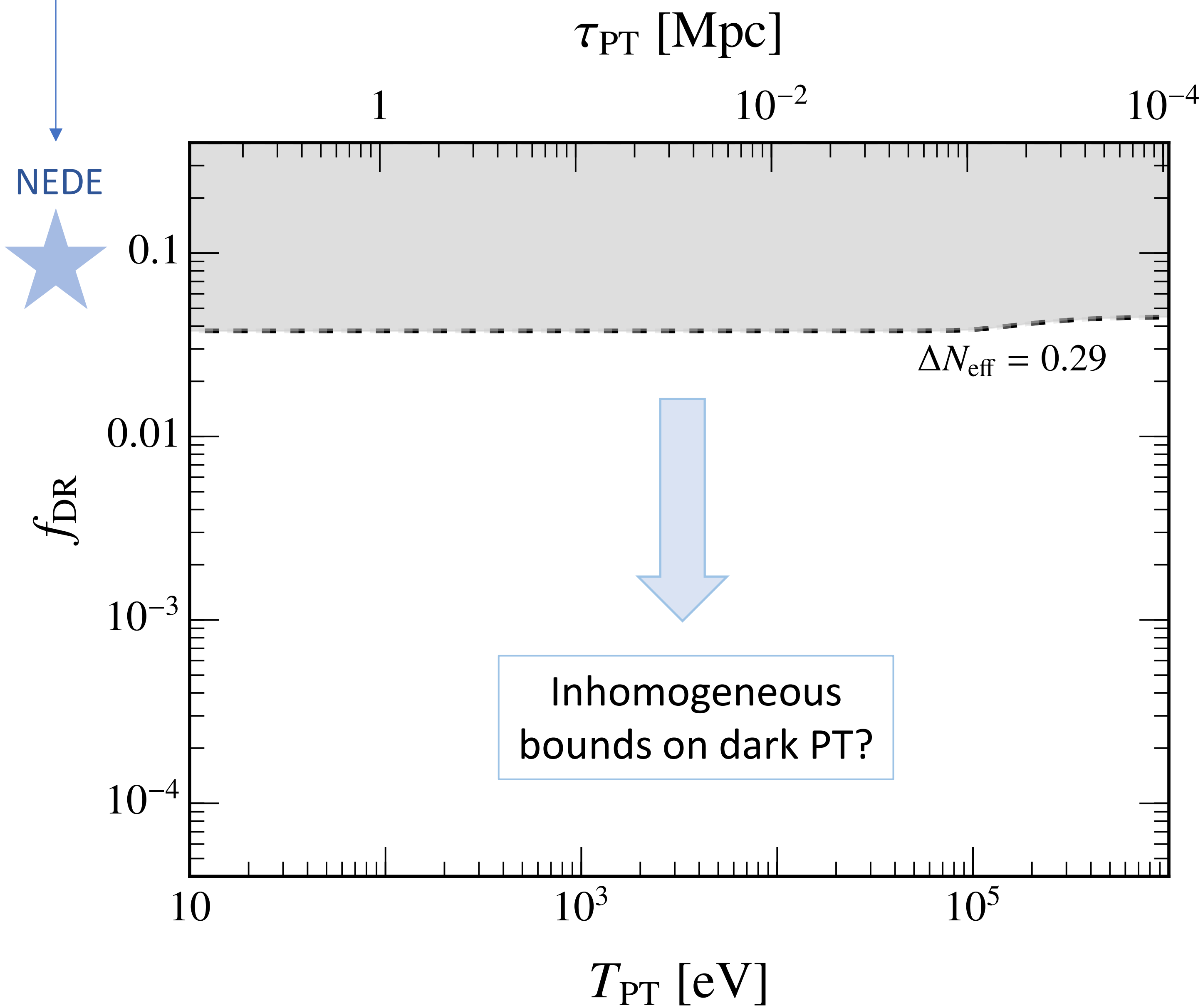
$$\Delta N_{\rm eff} < 0.29$$

(Planck TTTEEE + lowE + lensing + BAO)

Inhomogeneous bound can be stronger

➢ Constrain ***scalar curvature perturbations*** generated by PT

New early dark energy (NEDE): H_0 model with prompt first-order PT achieved via trigger field. [Niedermann and Sloth (2020)]



Inhomogeneous bounds on dark PT?

Curvature Perturbations

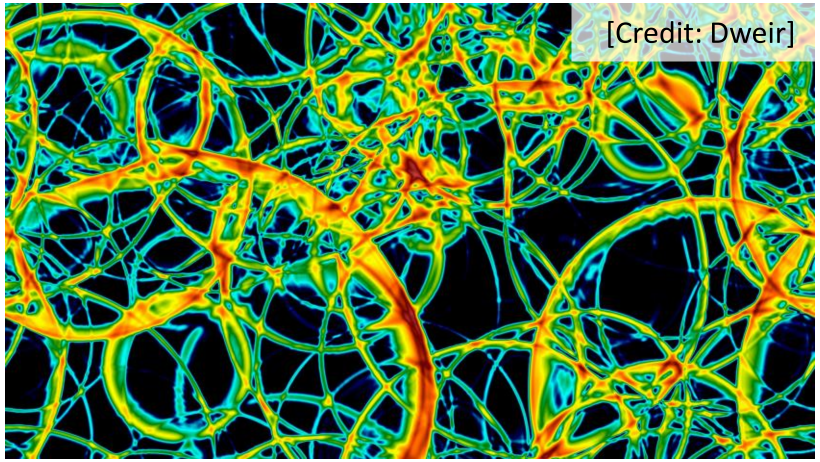
Stochastic bubble nucleation generates ***scalar curvature perturbations*** with power spectrum
[Elor, Jinno, Kumar, McGehee, Tsai (2024)]

$$P_{\zeta,\mathrm{PT}}(k) = f_{DR}^2\left(\frac{H_{PT}}{\beta}\right)^2 \frac{k^3}{2\pi^2}\int d^3r\, e^{i\vec{k}\cdot\vec{r}}\beta^2\langle\delta t_c(\vec{x})\delta t_c(\vec{y})\rangle$$

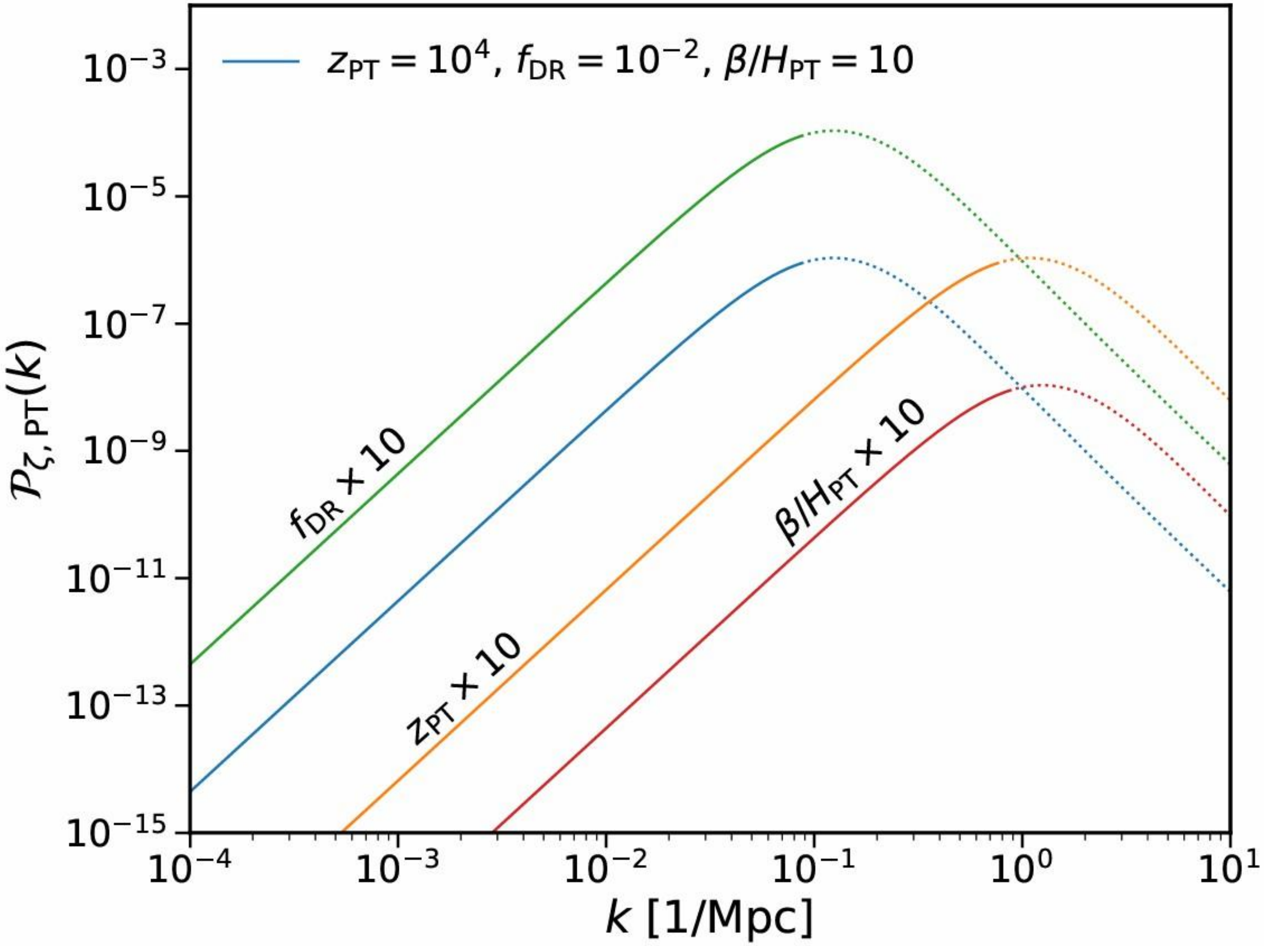
- **<u>Average bubble size</u>** reached at PT completion ($v_w = 1$, rescale β for $v_w < 1$):

$$d_b \approx (8\pi)^{1/3} v_w/\beta$$

- Consider scales $k < a_{PT}/d_b$ ***large compared to bubble size***:
  - Exhibits ***universal*** $\sim k^3$ slope due to finite bubble statistics
  - ***Scales with PT parameters*** $(z_{PT}, f_{DR}, \beta/H_{PT})$
    - ➢ ***Consider $\beta/H_{PT} = 10$ for this talk***



[Credit: Dweir]

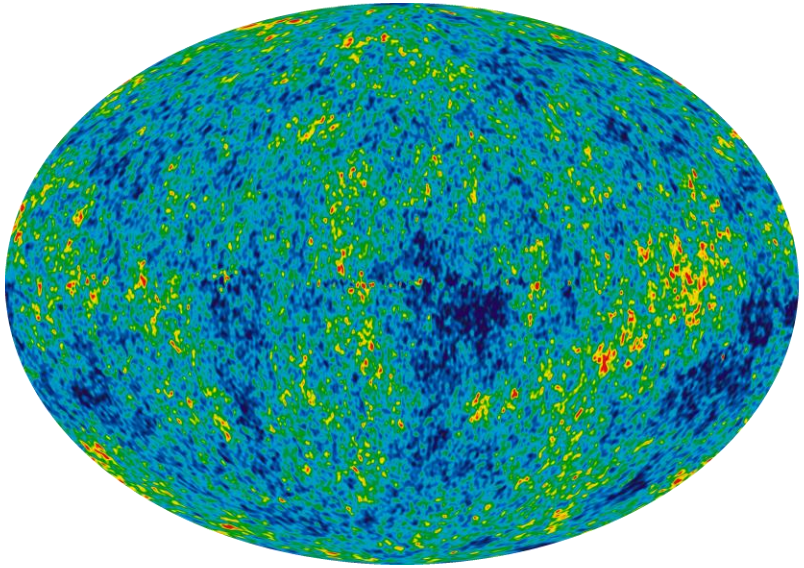


CMB Measurements

Additional curvature perturbation from PT ***modifies perturbations in photon-baryon plasma*** before recombination

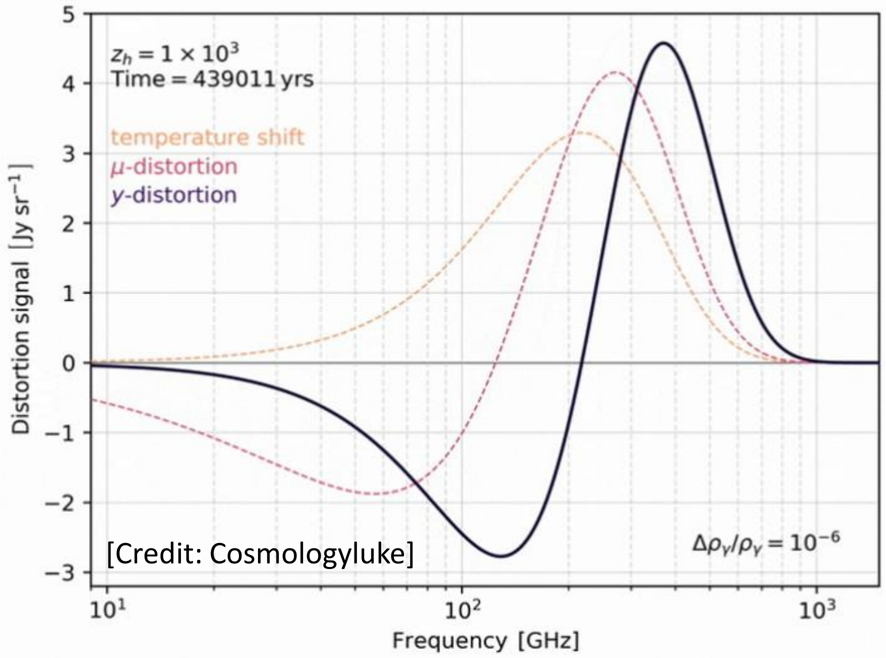
- ➢ Probe with CMB measurements of ***anisotropies*** and ***spectral distortions***

CMB Anisotropies



Last scattering surface $z \ \sim 1090$

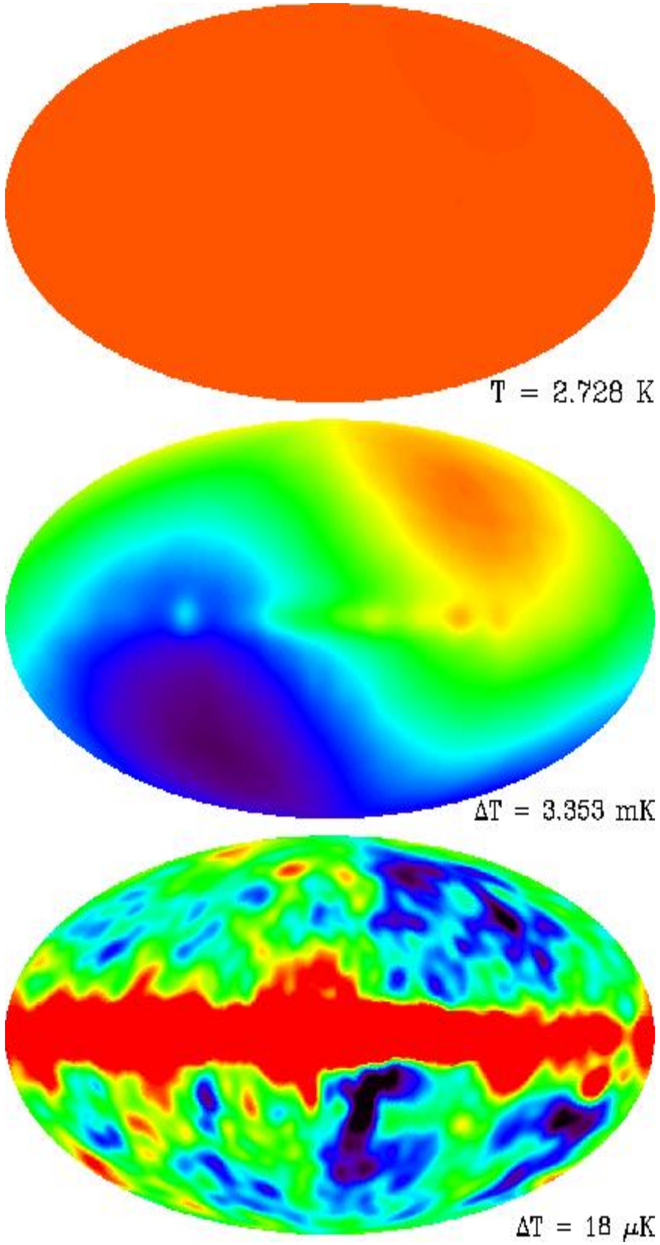
Spectral Distortions



[Credit: Cosmologyluke]

Inefficient thermalization $z \lesssim 2 \times 10^6$

[Credit: NASA / COBE Science Team]

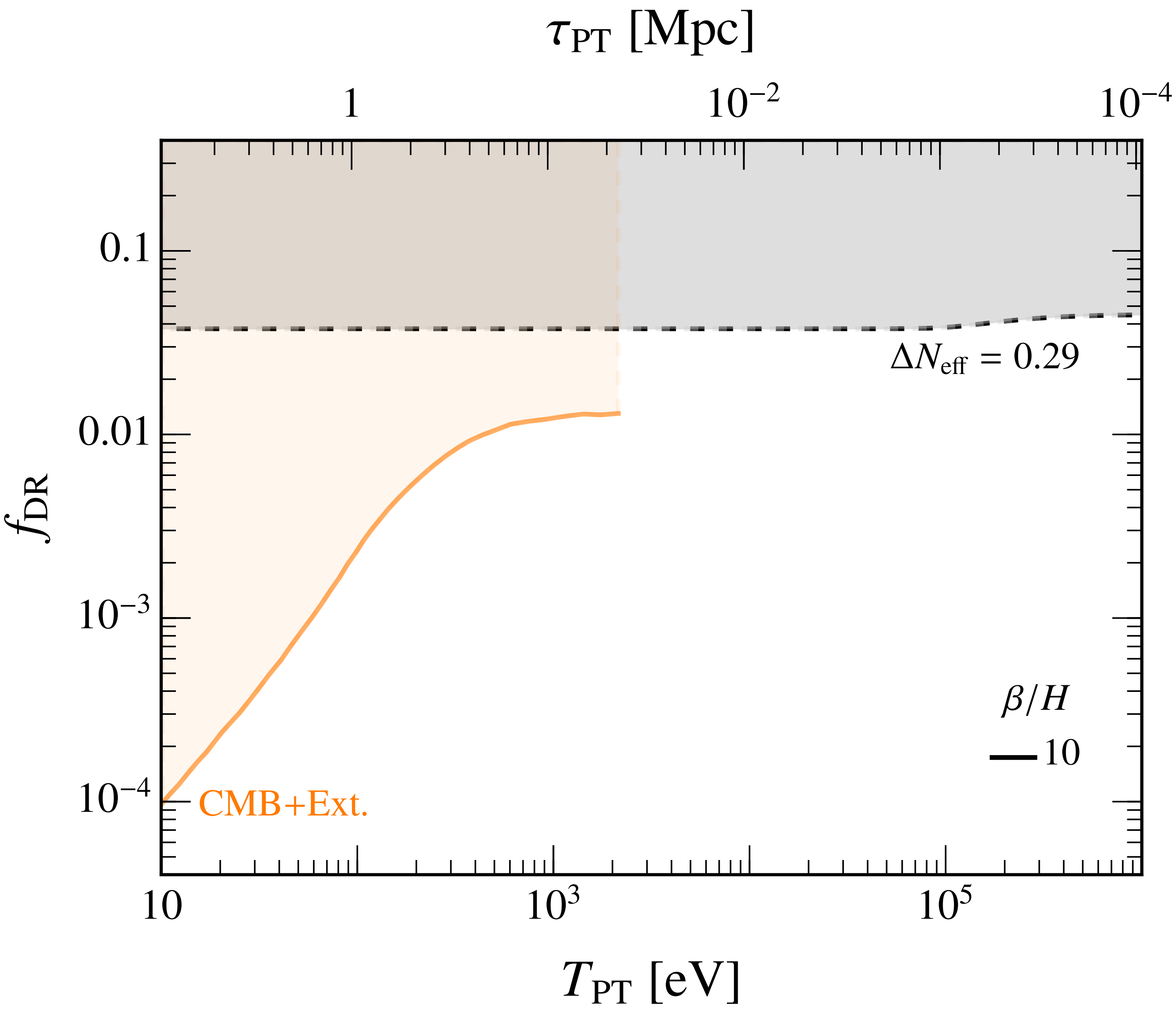


CMB Anisotropies

<u>CMB anisotropy measurements:</u> constrain modifications to ***spatial fluctuations*** in metric and photon density

- Implement in CLASS:
  - Use external_Pk module for curvature power spectrum
  - Include ΔN_{eff} contribution to free-streaming neutrino species (Ω_{ur})
- **<u>MCMC scan:</u>** fit to ***Planck data*** (sensitive up to $k = 0.1/\text{Mpc}$), including ***BAO*** and ***cosmic shear*** data (KV450)

<u>Datasets:</u> Planck2018 + lensing + Ext.
where Ext. = BAO + KV450



CMB Distortions

CMB spectral distortions: constrain energy released into photon-baryon plasma from additional curvature perturbations

- Small scale perturbations ***dissipate energy*** into plasma by Silk damping
- Produces ***μ- and y-type distortions*** to CMB black-body spectrum

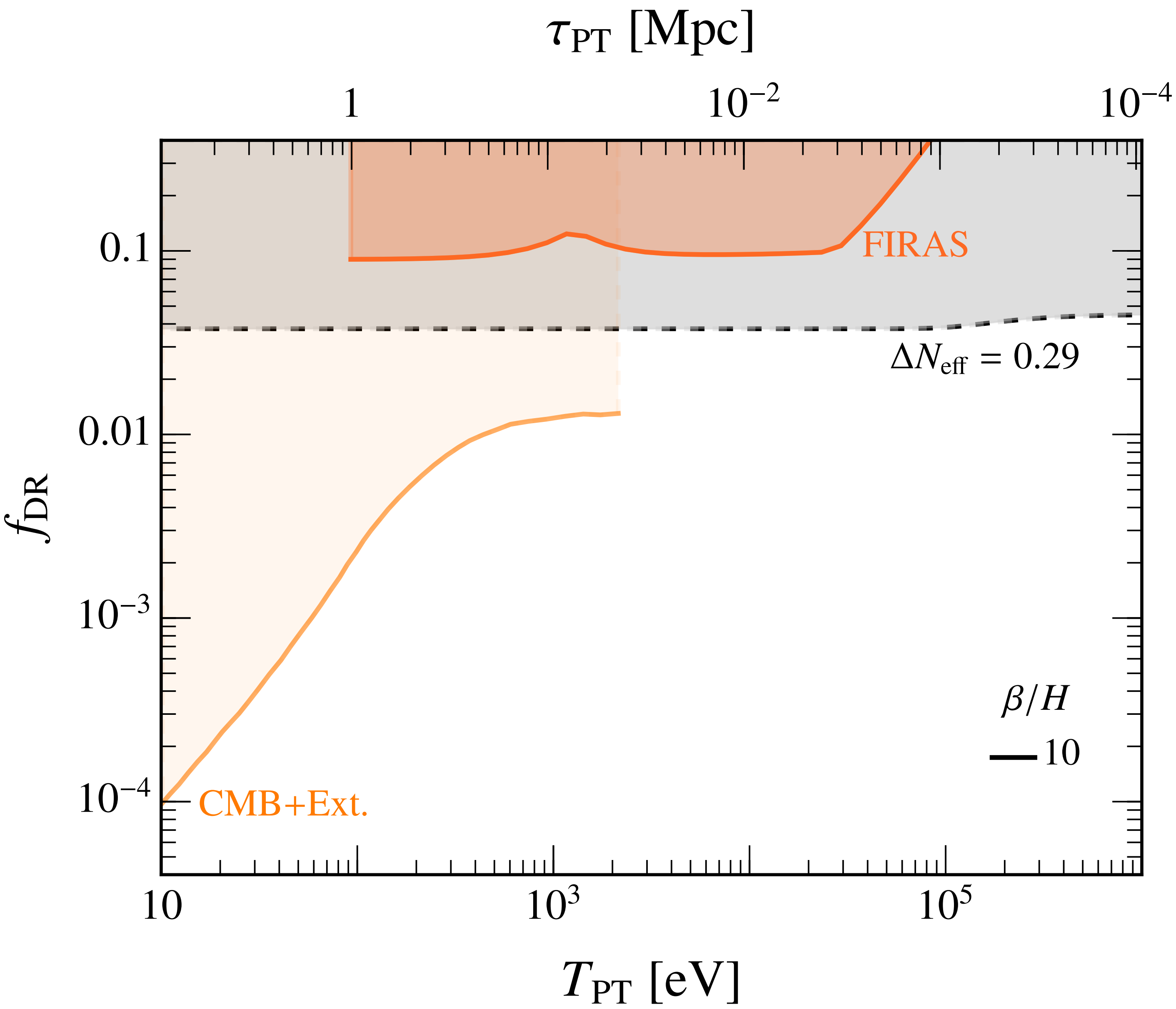
- Approximate $|\mu|$ or $|y|$ in ***tight-coupling limit*** of photon-baryon plasma $\mathrm{k} \gtrsim 1/\mathrm{Mpc}$
  [Chluba, Erickcek, Ben-Dayan (2012) [1203.2681]]

➢ ***Compare with FIRAS bounds***

Dataset: COBE FIRAS instrument

$$|\mu| < 9.0 \times 10^{-5}, |y| < 1.5 \times 10^{-5}$$

[Fixsen, Cheng, Gales, Mather, Shafer, Wright (1996)
[astro-ph/9605054]]

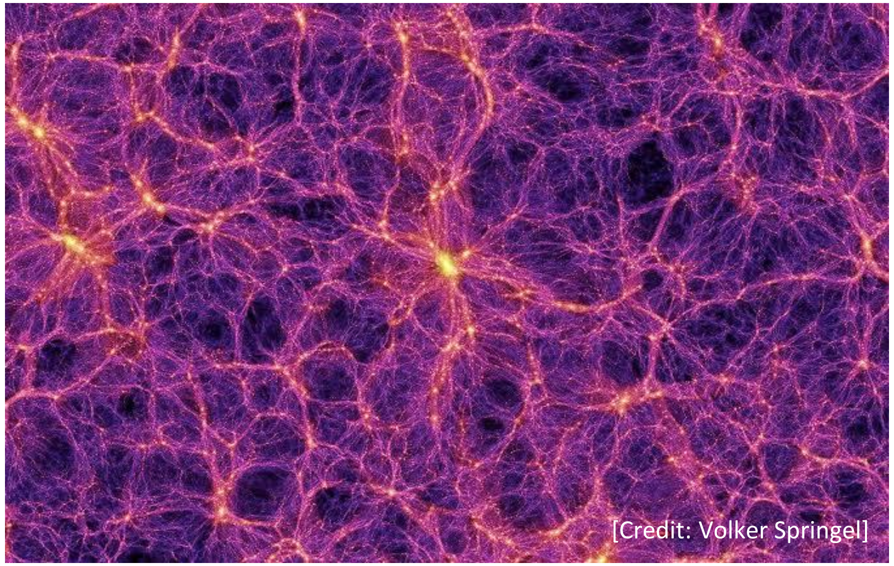


Structure Formation Probes

Additional curvature perturbation from PT ***enhances matter perturbations and structure formation***

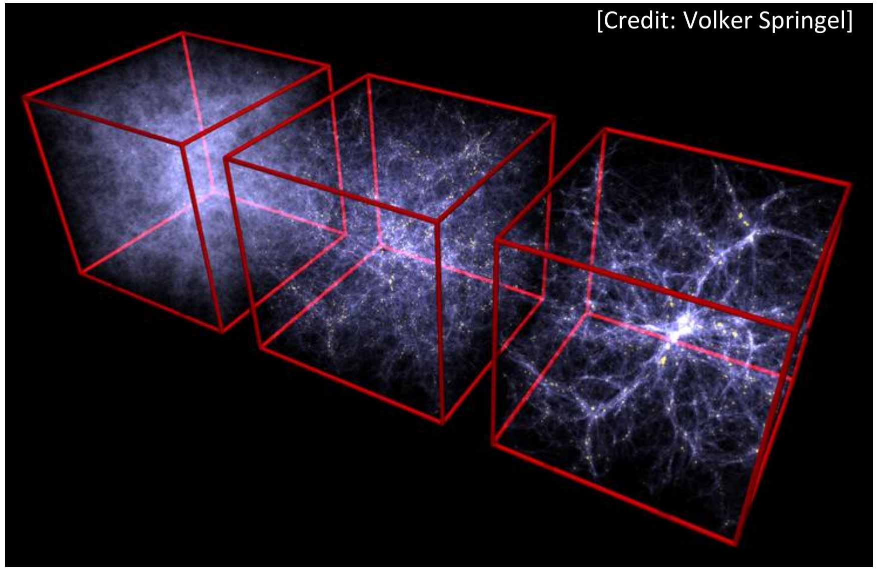
- Consider probes of structure formation on ***different scales to probe different T_{PT}***

Large-Scale Structure



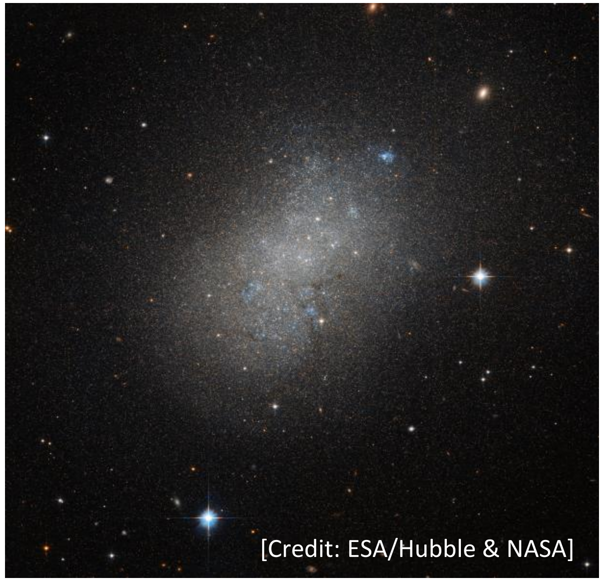
[Credit: Volker Springel]

Halo Formation



[Credit: Volker Springel]

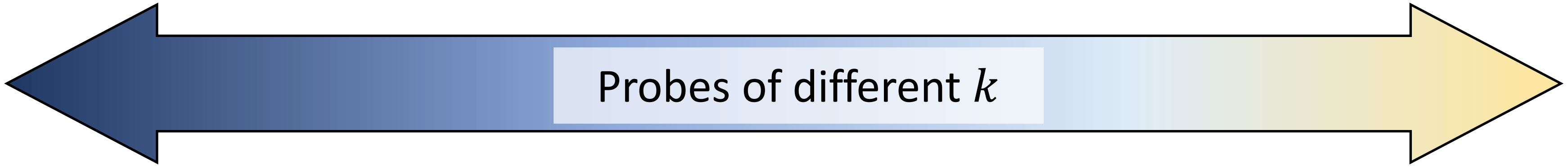
Dwarf Galaxies



[Credit: ESA/Hubble & NASA]

Inter-galactic

$\tau_{PT} \gtrsim 1\ \mathrm{Mpc}$

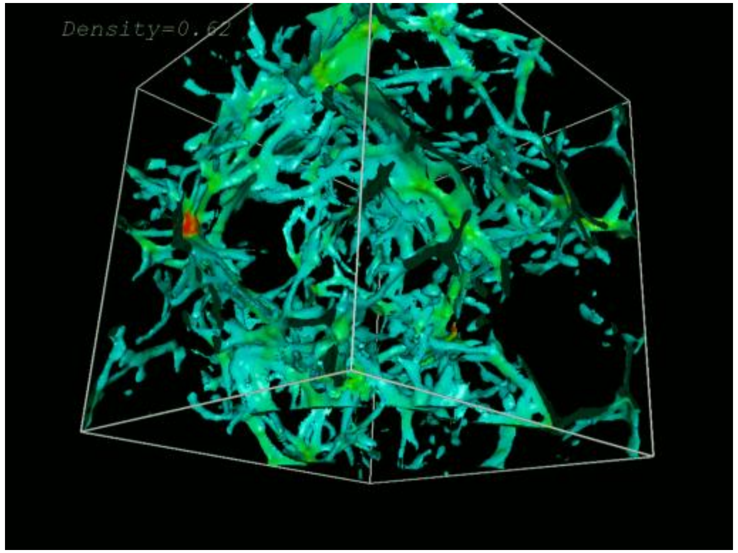


Probes of different k

Sub-galactic

$\tau_{PT} \lesssim 10\ \mathrm{kpc}$

Lyman-α Forest



Lyman-α forest: measurements of ***Lyman-α absorption lines*** (redshifted) in photon flux from distant quasars

- Distribution of ***neutral hydrogen*** in the ***intergalactic medium***
- Probe structure on ***intergalactic scales***

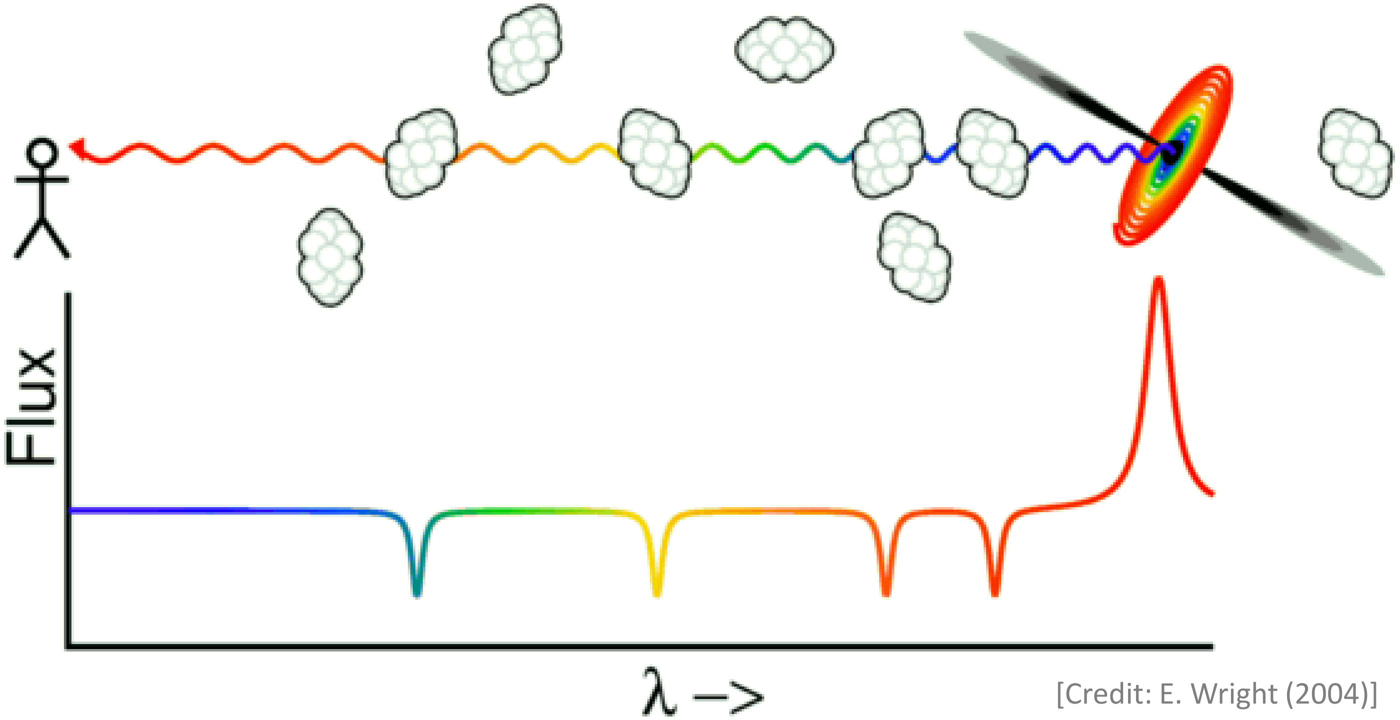
Data can be **compressed** into amplitude and slope of **linear** matter power spectrum $\mathrm{P_{lin}}$ at pivot redshift $z_p = 3$ and scale $k_p = 1.03$ h/Mpc

Compressed Lyman-α Likelihood

$$\Delta_{\text{lin}}^2 \equiv \frac{k_p^3}{2\pi^2}\mathrm{P_{lin}}(k_p, z_p)$$

$$n_{\text{lin}} \equiv \frac{\mathrm{d}\ln \mathrm{P_{lin}}(k,z)}{\mathrm{d}\ln k}\bigg|_{k_p, z_p}$$

$(z_p = 3,\ k_p = 1.03$ h/Mpc)



[Credit: E. Wright (2004)]

Lyman-α: Compressed Likelihood

Compressed Lyman-α likelihood: Perform parameter scan with ***linear*** calculations to ***estimate*** bound

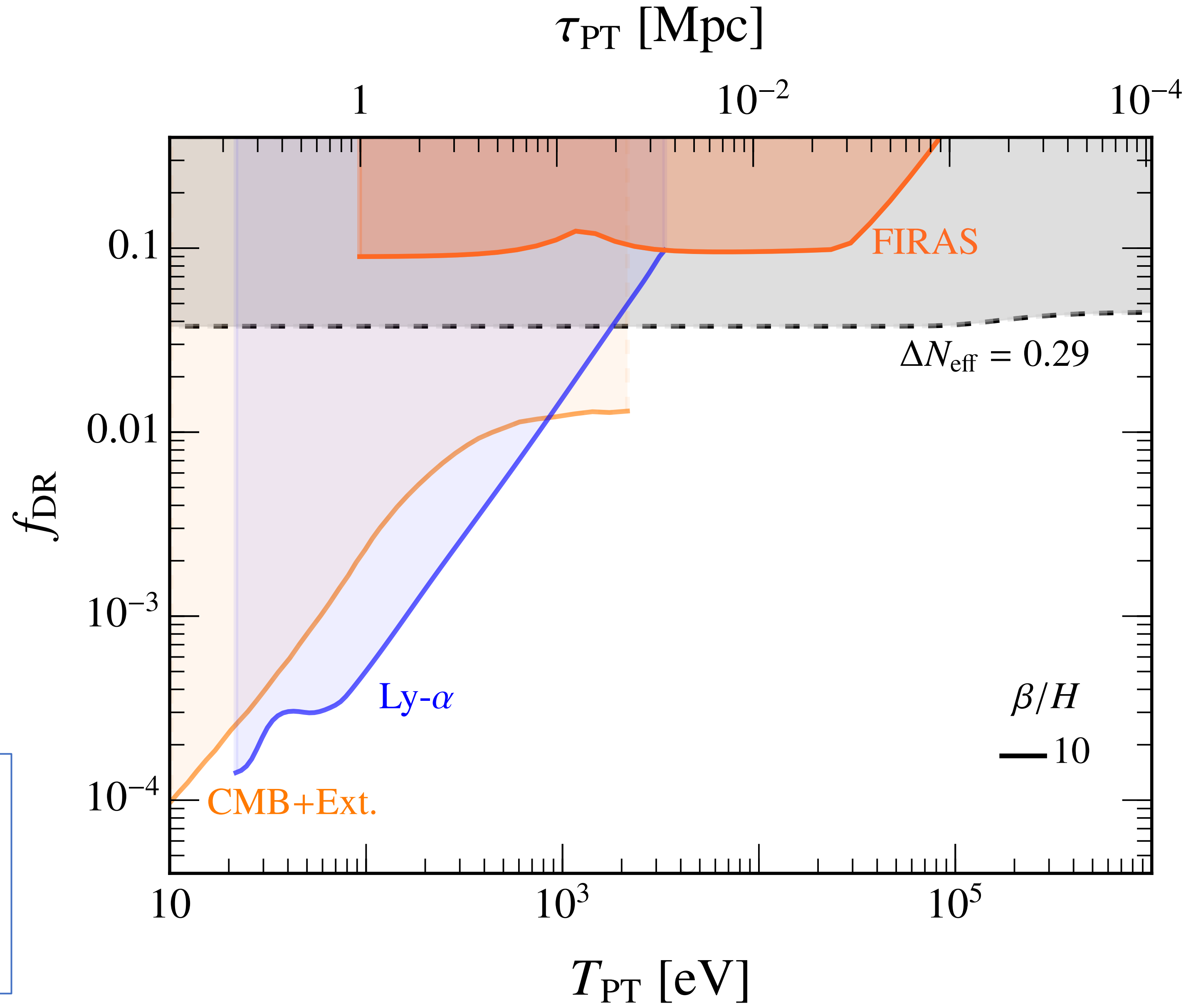
- Probes ***single scale*** $k_p = 1.03$ h/Mpc
- Calculate $\mathrm{P_{lin}}(k, z_p)$ from CLASS:
  - Fit amplitude $\Delta^2{}_{lin}$ and slope n_{lin} with ***PRIYA data***
  - Calculate $\Delta\chi^2$ relative to ΛCDM for 2σ bound

Dataset: PRIYA

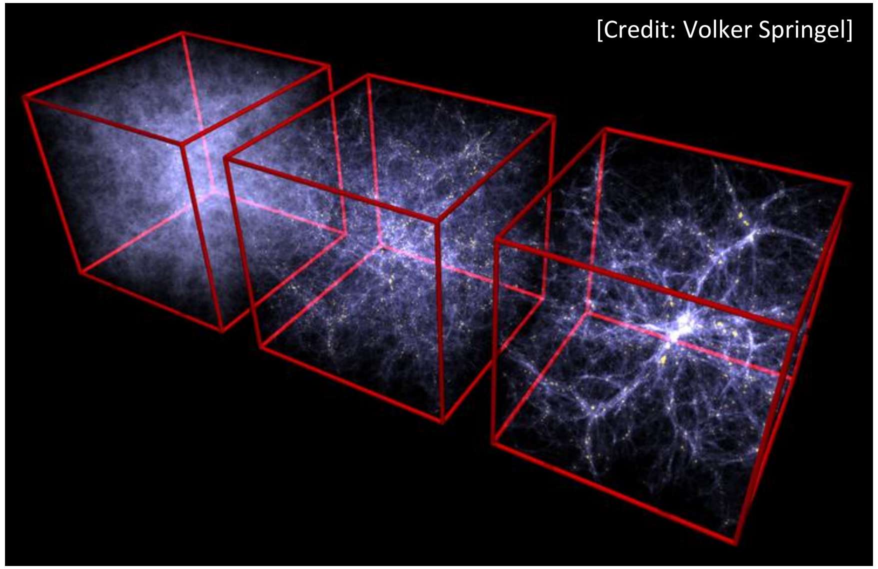
$\Delta^2_{\mathrm{lin}} = 0.267 \ \pm 0.022$, $n_{\mathrm{lin}} = \ -2.288 \ \pm 0.024$

Correlation coefficient 0.4

[He, Ivanov, Bird, An, Gluscevic (2025) [2503.15592]]



Early Reionization


[Credit: Volker Springel]

Halo Formation: dark matter (DM) perturbations undergo ***non-linear*** gravitational collapse into bound ***DM halos***

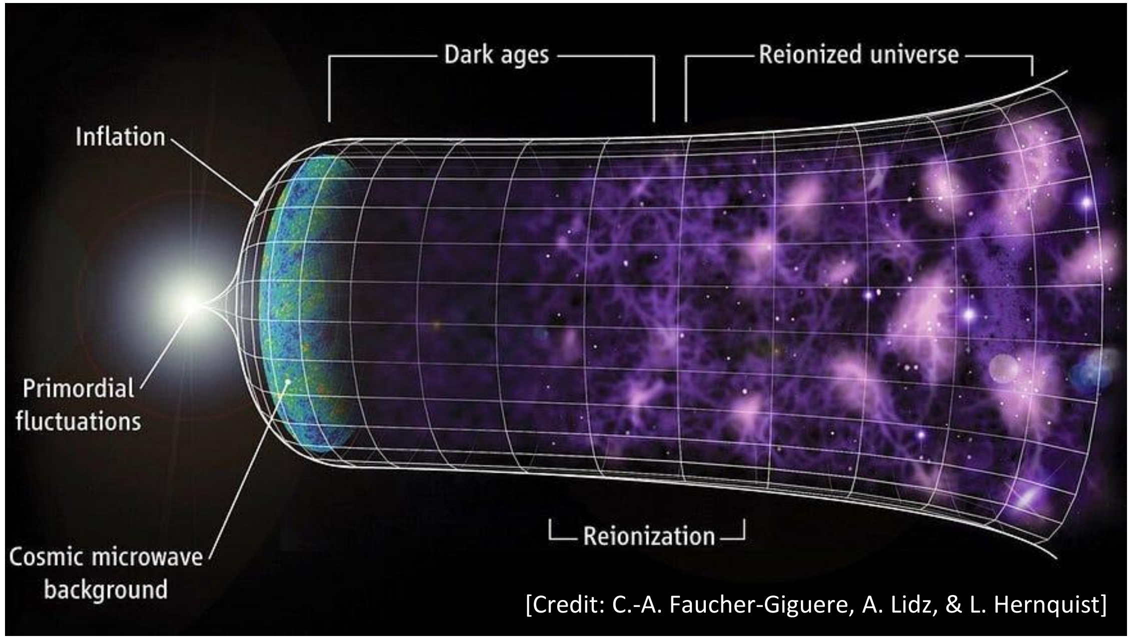
- ***Press-Schechter formalism*** estimates mass distribution of collapsed halos given initial ***linear*** perturbations

$$P_\zeta \longrightarrow \delta_{DM} \longrightarrow \frac{\mathrm{d}n}{\mathrm{d}M}$$

- ***Curvature perturbations*** from PT enhances ***matter perturbations***, which enhances ***halo formation***
- Use this process to probe PT on ***galactic scales***

Early Reionization [Qin, Kumar, Natarajan, Weiner (2025)]:

- ***Excessive star/galaxy formation*** occurring ***too early*** can lead to earlier reionization of universe than inferred from CMB and Ly-α data
  - ➢ Constrains DM perturbation enhancements



[Credit: C.-A. Faucher-Giguere, A. Lidz, & L. Hernquist]

Early Reionization

Qin, Kumar, Natarajan, Weiner (2025) [2506.13858]

Use ***Press-Schechter*** to determine collapse fraction of halos with mass $M > M_{\min}$

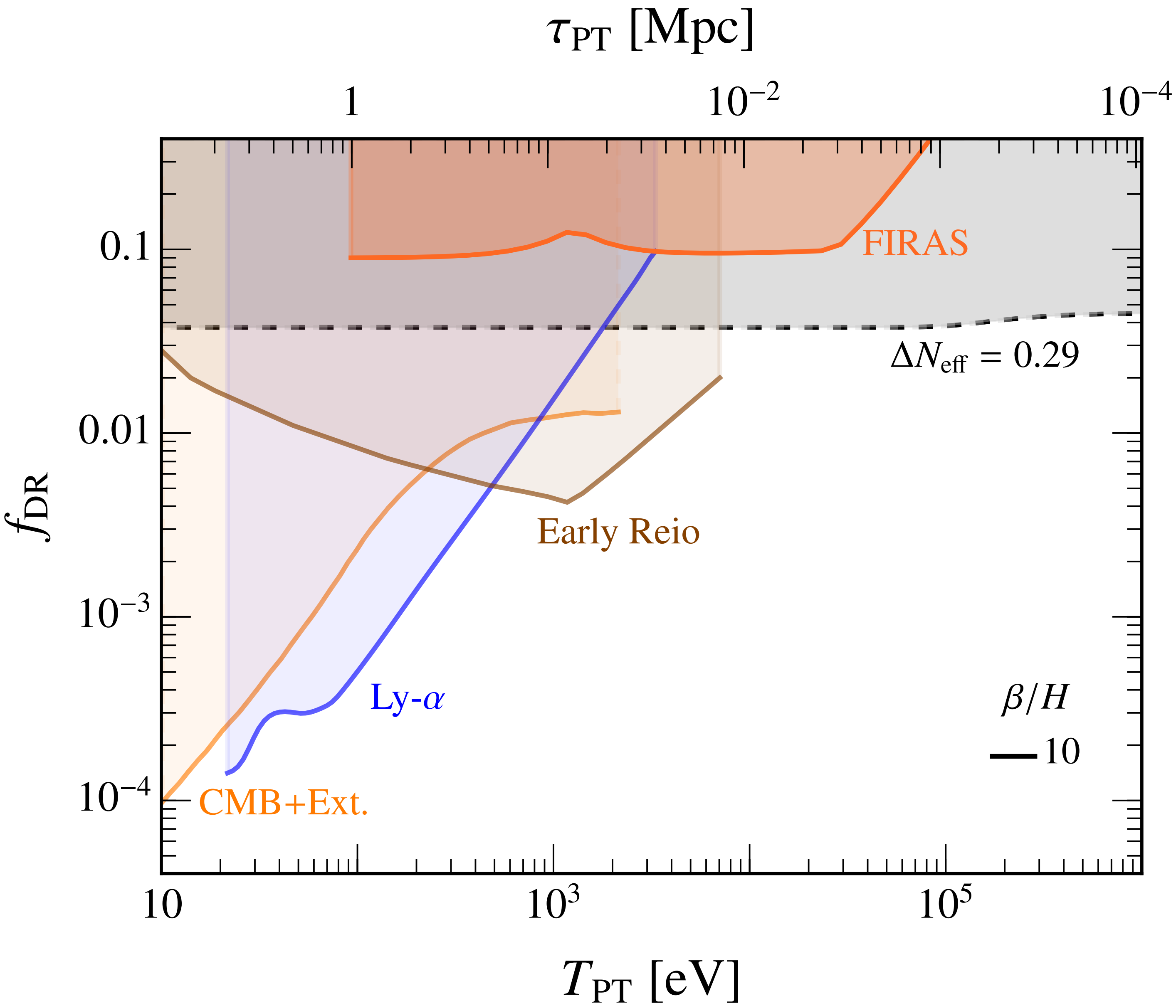
$$f_{\mathrm{coll}}(z, M_{\min}) = \frac{1}{\rho_m} \int_{M_{\min}}^{\infty} dM\, M \frac{dn}{dM}(z)$$

- Consider ***reionization to be early*** if it ***completes*** at redshift $1 + z_{\mathrm{early}} = 20$
- Only consider ***massive DM halos*** that enable ***efficient atomic cooling*** ($T_{\mathrm{vir}} \gtrsim 10^4$ K) for ***star formation*** at z_{early}: $M_{\min} = 2 \times 10^7 M_{\odot}$

<u>**Exclude early reionization**</u> scenario by requiring (ionization efficiency 10):

$$f_{\mathrm{coll}}\left(z_{\mathrm{early}}, 2 \times 10^7 M_{\odot}\right) < 0.1$$

to set bound on PT



UFD Heating

Ultra-faint Dwarf Galaxies (UFDs)

- ***DM-dominated***: high mass-to-luminosity ratios
- Large ***core DM densities***
- ***Very old*** with few metal poor stars
- Small stellar scale radius $R_{*,0}$, ***stars tightly clustered*** in core

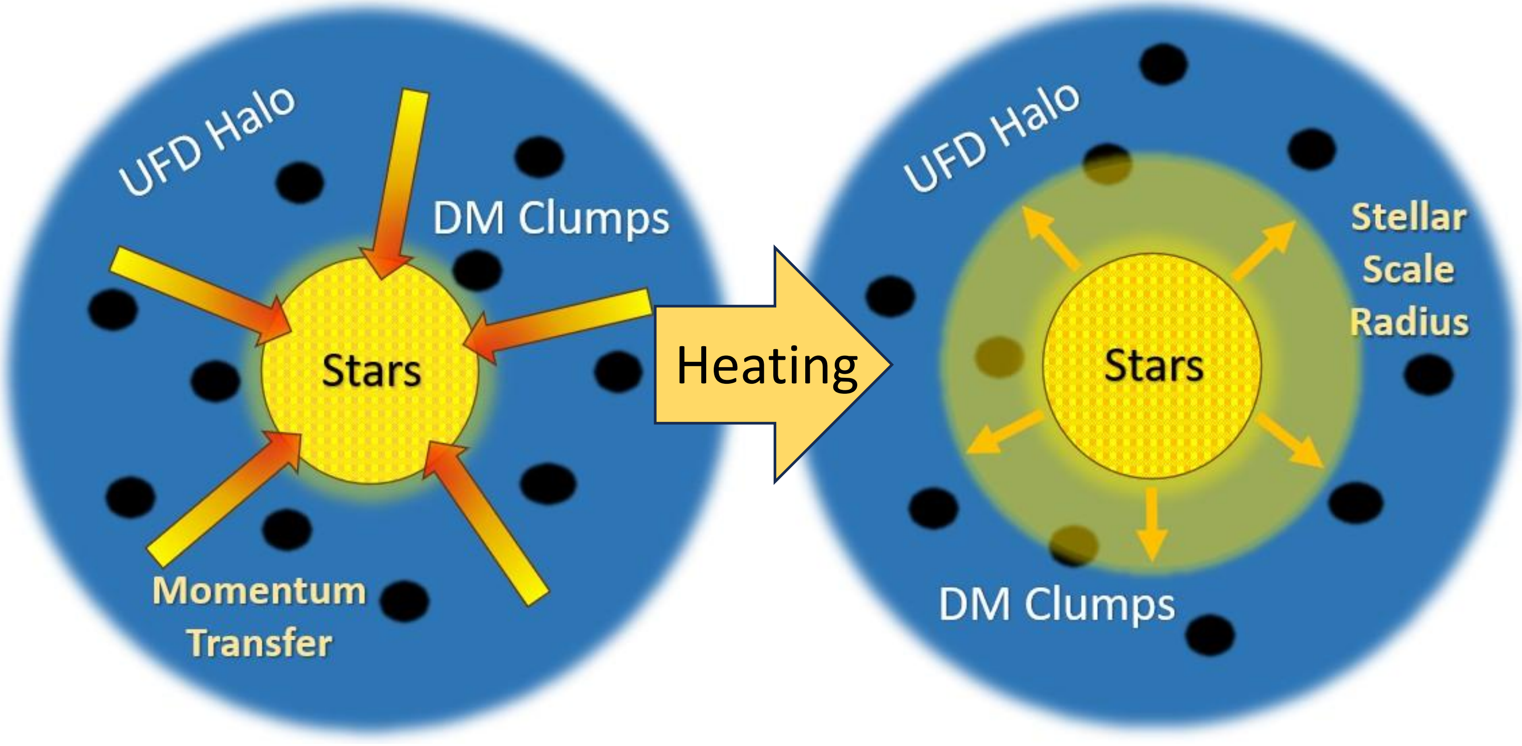
Enhancements to matter perturbations on small scales can lead to ***significant “clumping” of DM*** before galaxy formation

- Clumps make up ***internal structure*** of larger host halos following ***hierarchical structure formation***
- Probe internal structure with ***ultra-faint dwarf galaxies (UFDs)***

UFD Heating [Graham and Ramani (2024)]:

- DM clumps reside in host UFD halo
  - Low density clumps destroyed by ***tidal forces***
  - Surviving clumps ***transfer momentum*** to stars gravitationally
  - Stellar scale radius $R_{*,0}$ ***expands***

➢ ***Large number density of DM clumps*** can lead to ***excessive heating*** of stars!



UFD Heating

Graham and Ramani (2024) [2404.01378]

Constrain ***excessive DM clumping*** due to PT with ***UFD heating effect:***

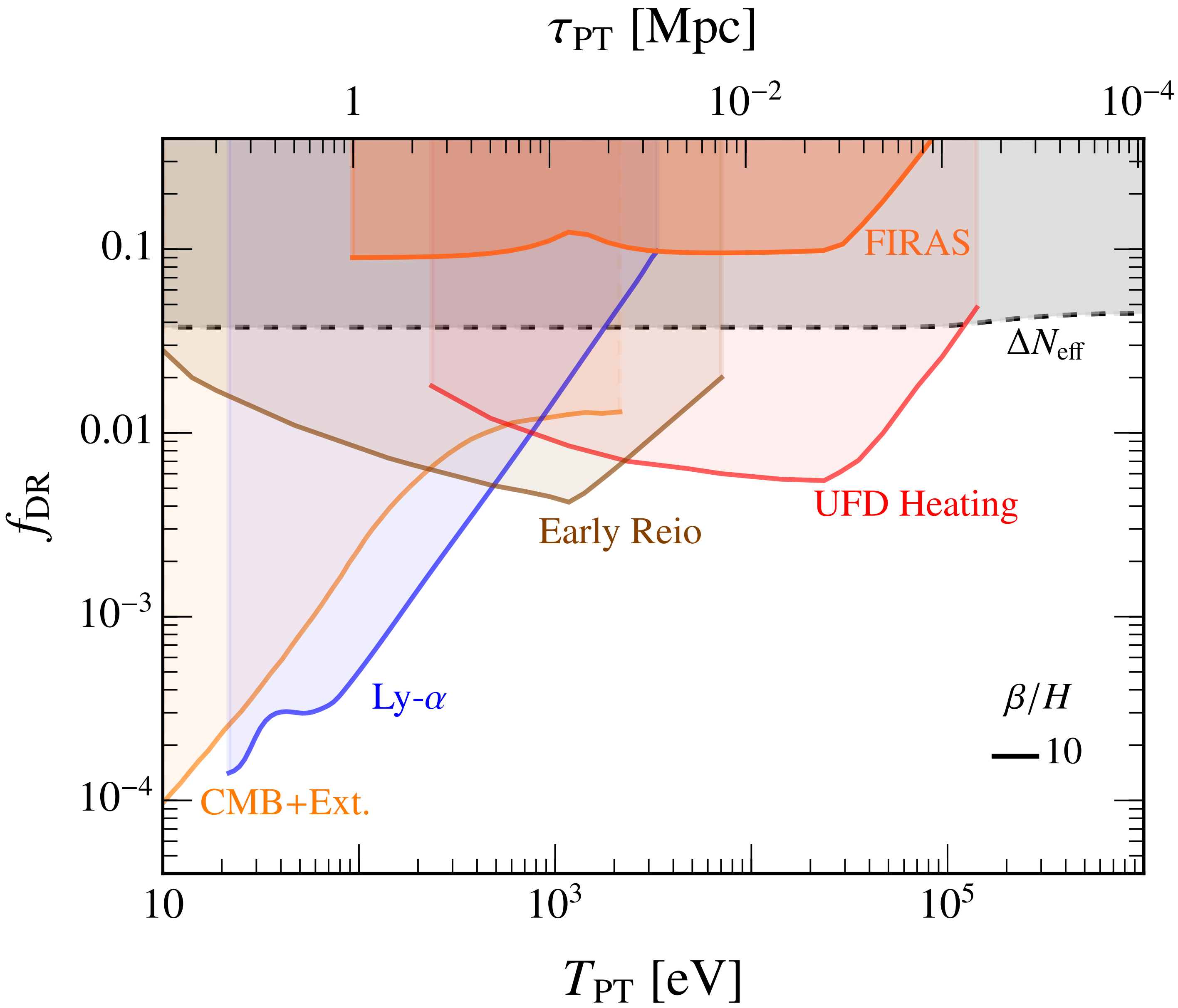
- **Candidate UFD: Segue 1** *(Milky Way satellite) with* stellar scale radius ***today***

$$R_{0,*} = 24.7 \pm 2.9 \text{ pc}$$

- ***Excessive heating*** if stars must *initially* be in tight cluster ≤ 2 pc (high stellar density) to reproduce observed $R_{0,*}$

Use ***Press-Schechter*** to estimate ***predicted*** collapse fraction of DM into clumps $f_{\text{clump}}(z, M)$ *(i.e. mini-halos with masses within decade of M)*

Excluding excessive heating scenario sets bound on $f_{\text{clump}}(z, M)$ and hence on PT



Conclusion

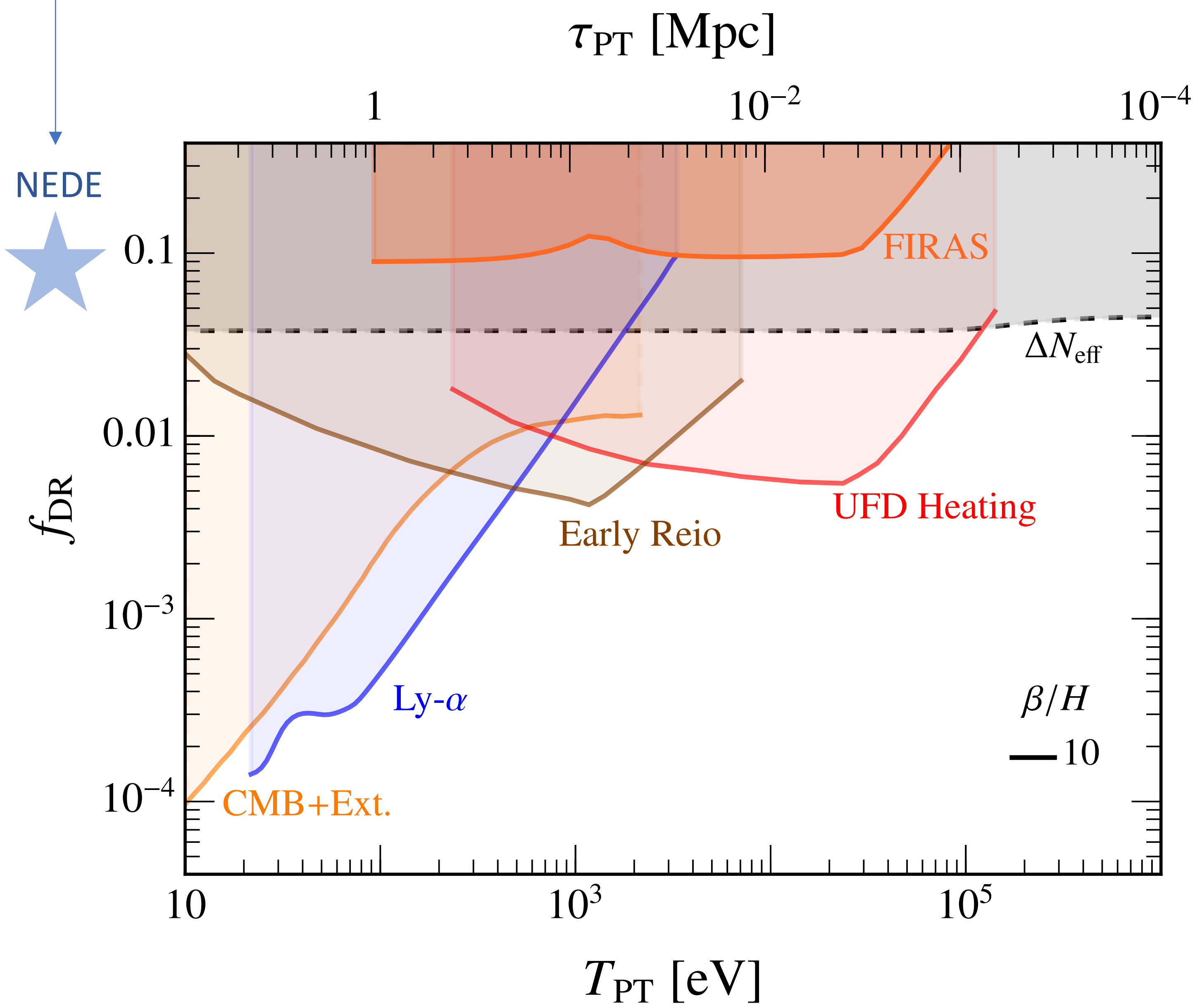
Dark and "Late" First-Order PT:

1. Generates ***curvature perturbations*** with observable effects on ***CMB*** and ***structure formation***
2. Can be ***more sensitive*** to f_{DR} than homogeneous ΔN_{eff} (if β/H_{PT} not too large)

Going forward:

- ***Observables:*** Other gravitational probes to constrain different T_{PT}?
- ***Models:*** Applicable to dark sector models featuring late first-order PT
- ***Improve bounds:*** future experiments like Simons Observatory, SuperPIXIE etc.

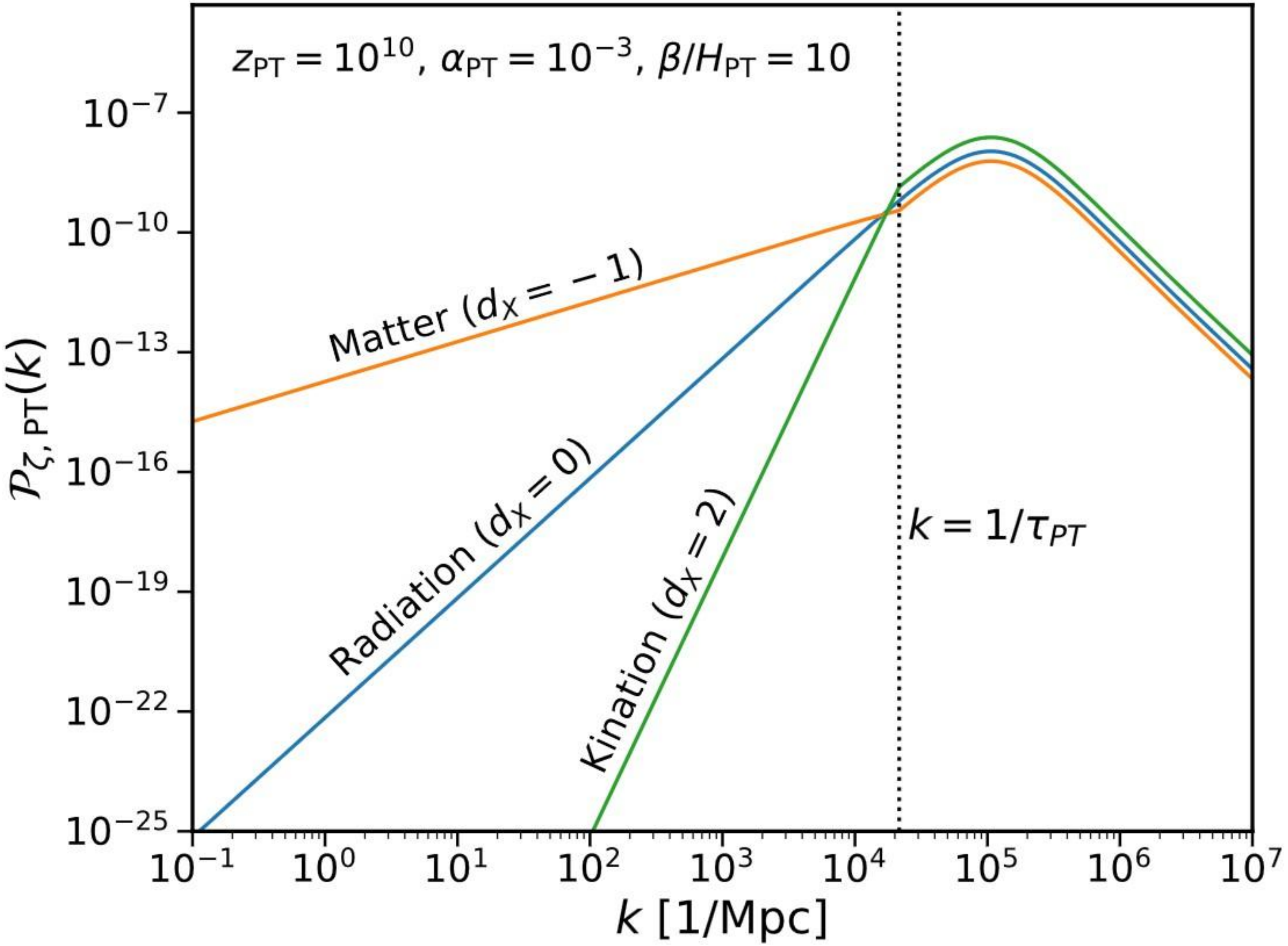
New early dark energy (NEDE): H_0 model with prompt first-order PT achieved via trigger field. [Niedermann and Sloth (2020)]



Backup Slides

Curvature PT: Different Redshifts

- Latent heat can also be released into other dark fluids with different redshifts
- In radiation era, the super-horizon slope of the spectrum is modified with a different power law as shown



CMB Distortion Details

Energy stored in curvature perturbations with $k \lesssim 5400\ \mathrm{Mpc}^{-1}$is dissipated by Silk damping, producing μ- and y-type distortions of the CMB.

For modes with $k_{\mathrm{min}} \gtrsim 1\ \mathrm{Mpc}^{-1}$, the photon-baryon fluid is tightly coupled and baryon loading can be neglected.

In this regime, the resulting spectral distortions can be approximated as [Chluba, Erickcek, Ben-Dayan (2012) [1203.2681]]:

$$|\mu| \text{ or } |y| \simeq A \int_{k_{min}}^{\infty} \frac{dk}{k} P_{\zeta}(k)[Be^{-k/\left(5400\ \mathrm{Mpc}^{-1}\right)} - Ce^{-\left(k/\left(31.6\ \mathrm{Mpc}^{-1}\right)\right)^2}]$$

with $(A, B, C)_{\mu} = (2.2,1,1)$ and $(A, B, C)_{y} = (0.4,0,-1)$.

Set lower integration limit to $k = 1\ \mathrm{Mpc}^{-1}$, below which the tightly coupled photon–baryon approximation starts to break down and a more careful treatment of photon–baryon perturbations is required.

Growth Factor Corrections

Matter perturbations grow by $\Delta_{\rm DM}(\tau_i, \tau)$ factor when inside horizon. When treating $P_\zeta(k)$ as primordial, we correct modes generated by PT that were sub-horizon ***before PT occurs*** to avoid overestimation

For Lyman-α compressed likelihood, we only probe a single mode k_p. For PT occurring after k_p enters horizon, we correct PT-induced component of $\mathrm{P}_{lin}(k)$ with **CLASS** matter transfer function $T_{DM}(k, \tau)$

$$\mathrm{P}_{\rm lin}(k, z_p) = \mathrm{P}_{\rm lin,ad}(k, z_p) + \left(\frac{T_{\rm DM}(k, 1/k_p)}{T_{\rm DM}(k, \tau_{\rm PT})}\right)^2 \mathrm{P}_{\rm lin,PT}(k, z_p) \qquad (k_p > \tau_{\rm PT}^{-1})$$

This is related to the growth factor $\Delta_{\rm DM}(\tau_i, \tau)$ by

$$\Delta_{\rm DM}(\tau_i, \tau) = \frac{T_{\rm DM}(k, \tau)}{T_{\rm DM}(k, \tau_i)}$$

So we are undoing the growth in k_p that occurred between $\tau = 1/k_p$ and $\tau_{\rm PT}$

For Early Reionization and UFD heating, we use the analytical form:

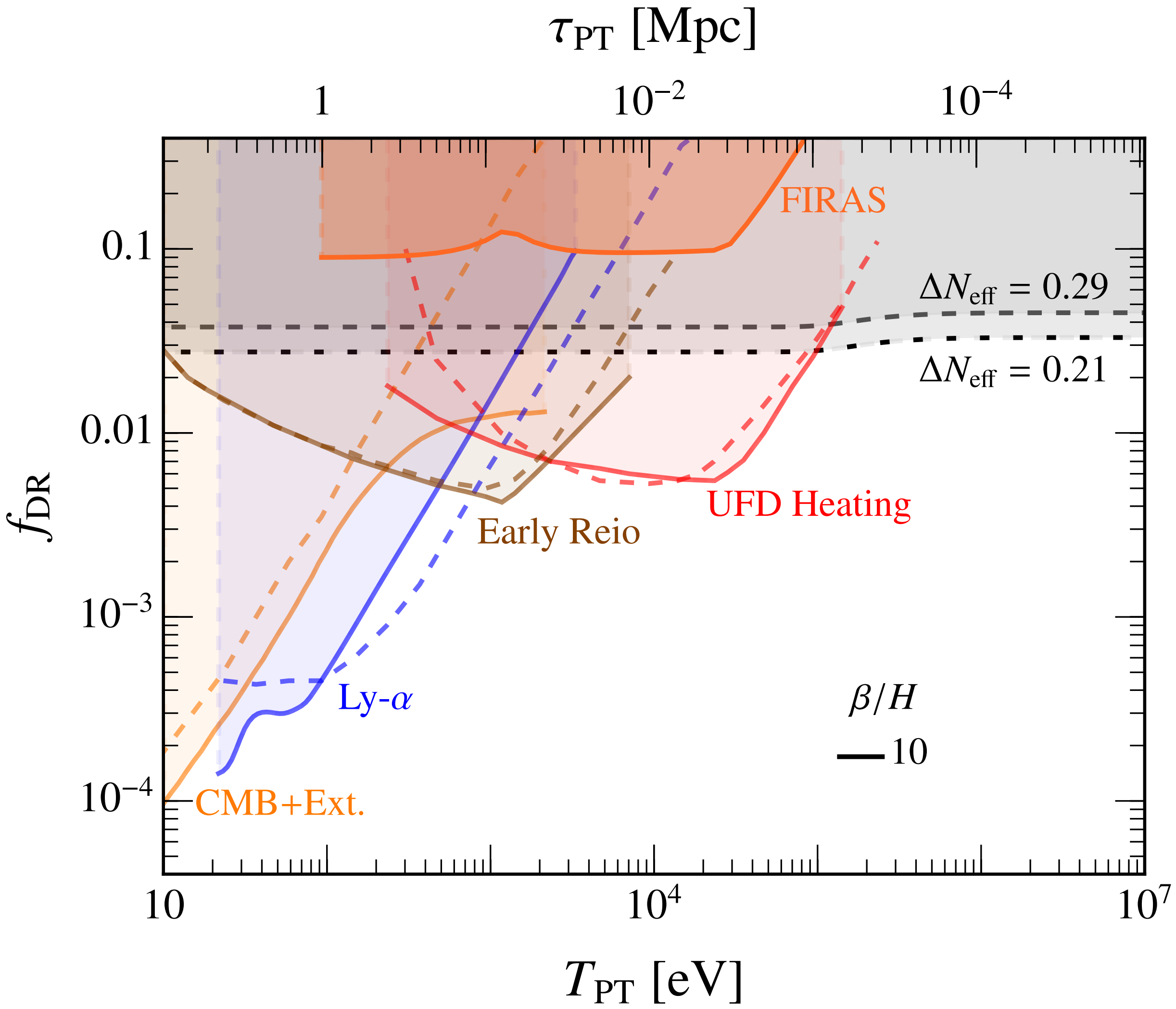
$$\Delta_{\rm DM}(\tau_i, \tau_{\rm eq}) \simeq 6.4\ \ln\left(0.44\, \tau_{\rm eq}/\tau_i\right)$$

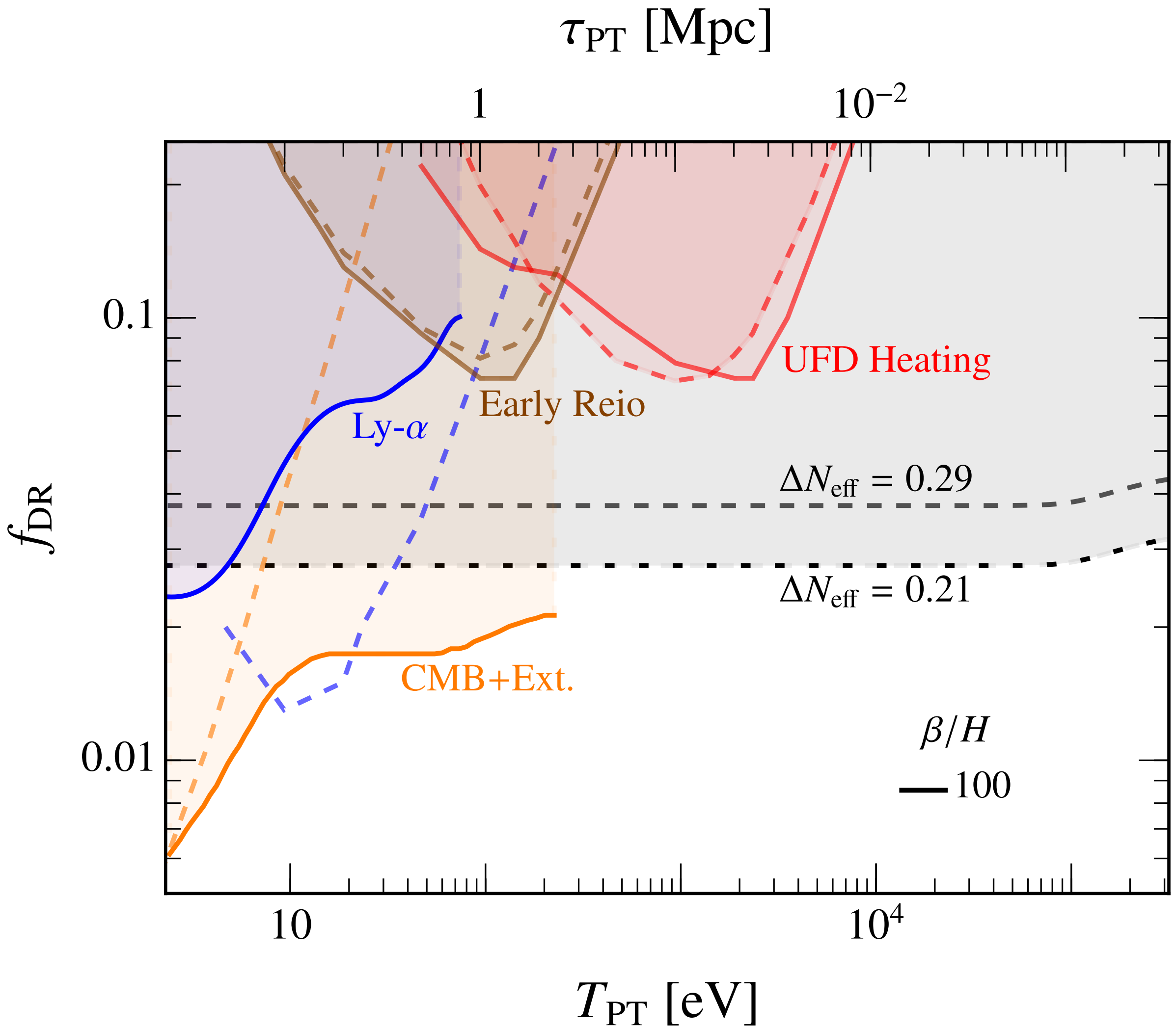
For log growth in radiation era, and apply

$$P_{\zeta,\rm PT}(k) \longrightarrow P_{\zeta,\rm PT}(k) \times \left(\frac{\Delta_{\rm DM}(\tau_{\rm PT}, \tau)}{\Delta_{\rm DM}(1/k, \tau)}\right)^2 \qquad (\text{for } k > 1/\tau_{\rm PT})$$

Bounds for different β / H_{PT}

arXiv: 2603.00272





Cosmological Constraints

- *Taken from: Elor et. al. Phys. Rev. Lett. 133, 211003*
- Current (filled) and projected bounds on primordial curvature perturbation ***directly translated from literature***
- Future experiments projected to improve bounds for ΔN_{eff} (SO) and CMB distortions (SuperPIXIE)