A Step in Understanding the Hubble Tension

Melissa Joseph

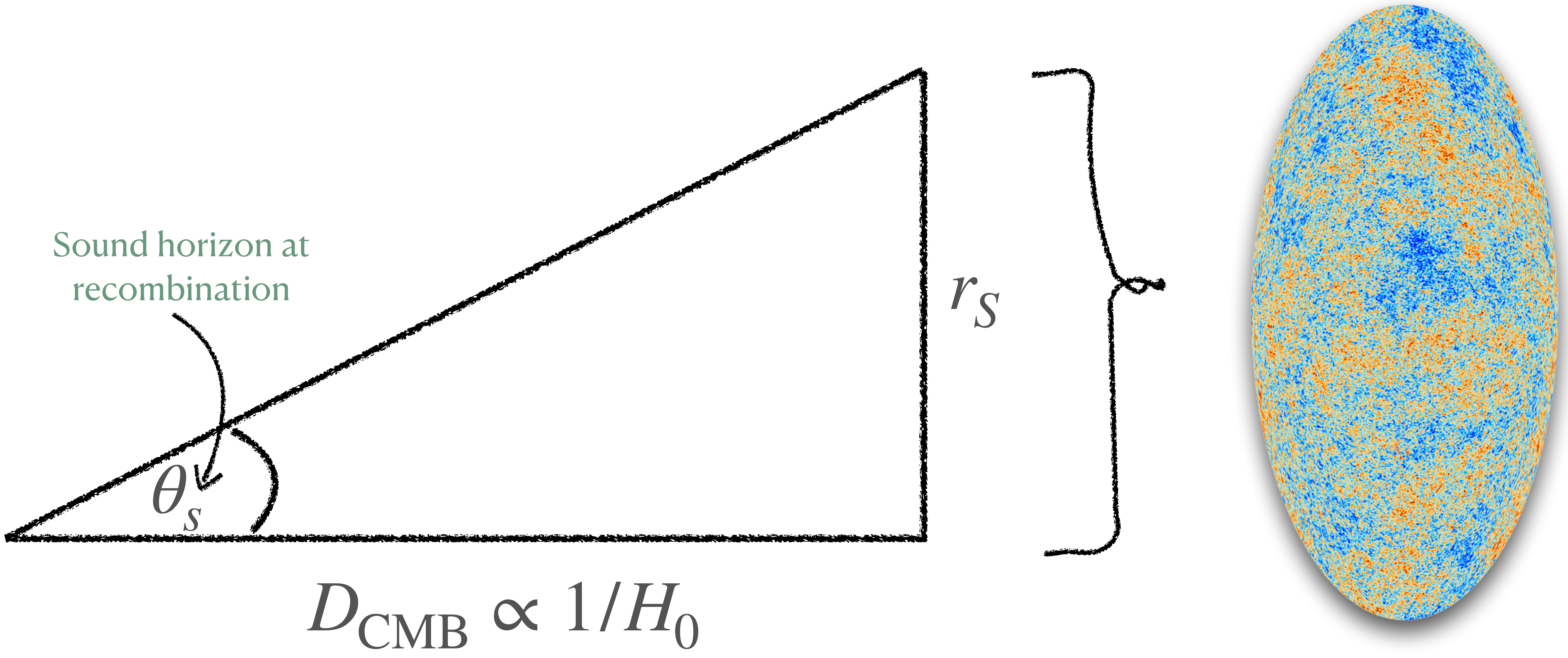
Daniel Aloni, Asher Berlin, Martin Schmaltz, Neal Weiner
arXiv: 2111.00014

H_0 Tension

- Local measurement: 73.2 ± 1.3 km/s/Mpc (Riess et al 2021)
  - Distance ladder w/ Type 1a SN & Cepheids

- Value from ΛCDM (fit to CMB): 67.4 ± 0.5 km/s/Mpc (Planck 2018)

~ 4σ tension



$$r_s = \int_{z_{rec}}^{\infty} dz \frac{c_s^2}{H(z)}$$

$$H(z) \propto \sqrt{\rho}$$

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Simplest extension of ΛCDM - add extra radiation

$$\Delta N_{\rm eff} = \frac{\rho_{DR}}{\rho_{1\nu}}$$

$\Lambda\text{CDM}: \; N_{\rm eff} = 3.044$

Radiation is dark

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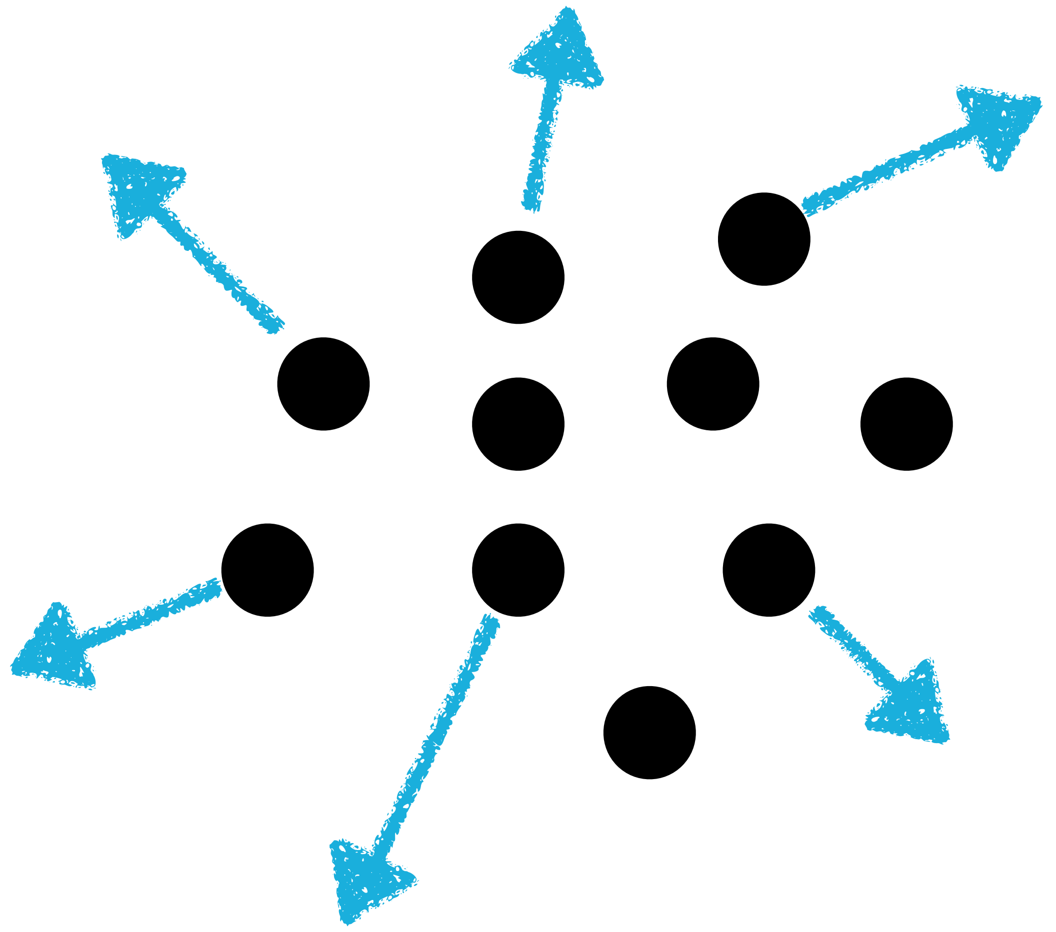
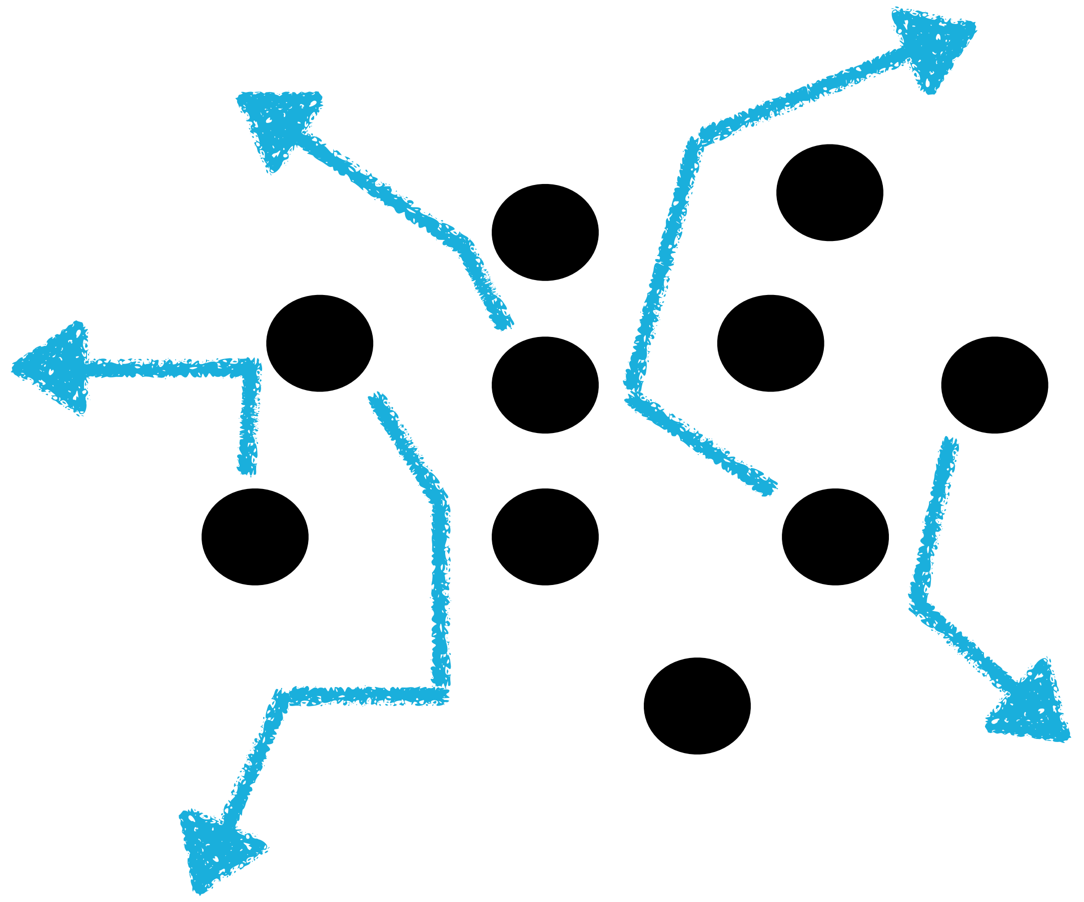
Free-streaming (no interactions) radiation

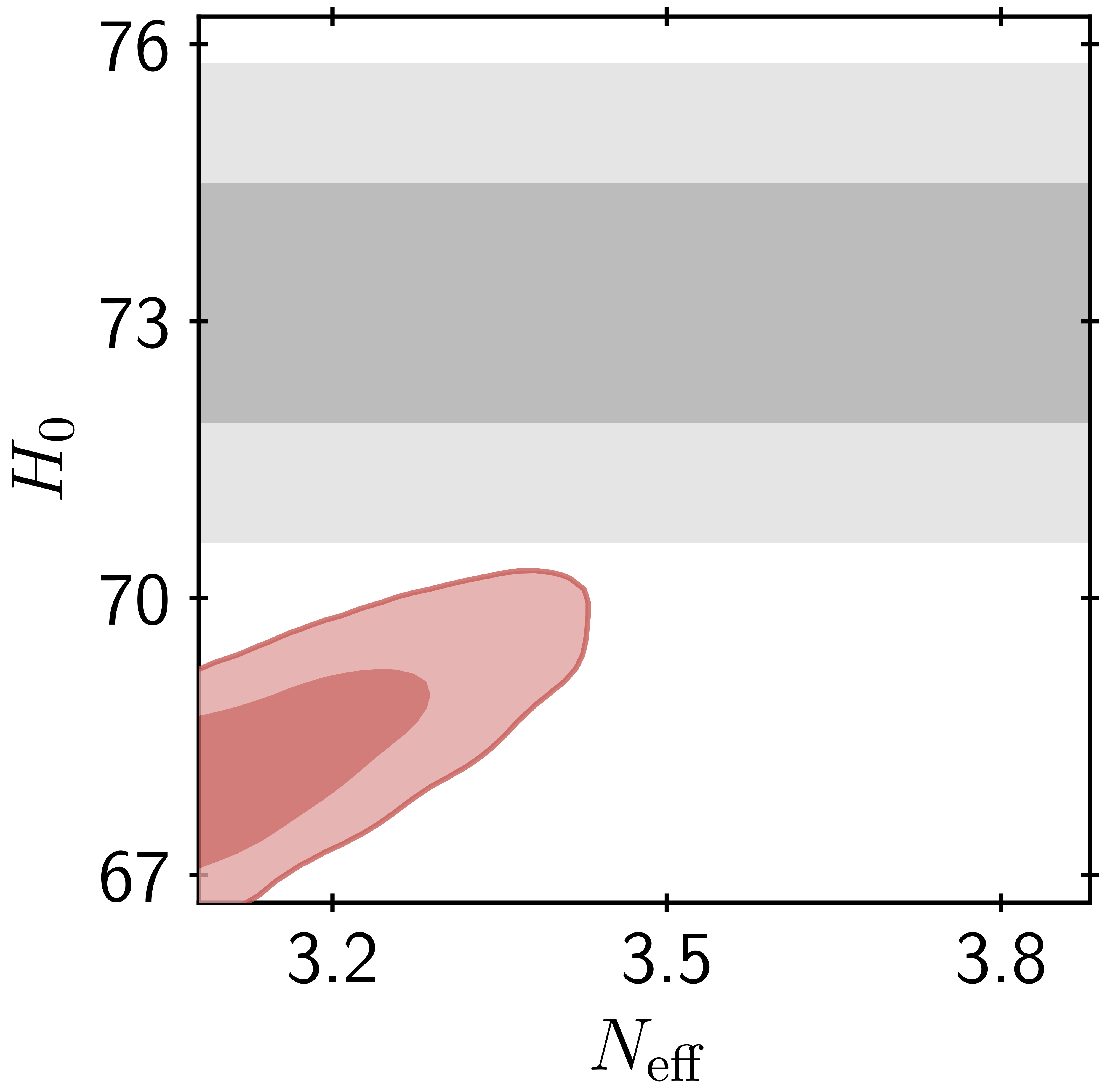


$$'c_s^2 = 1'$$

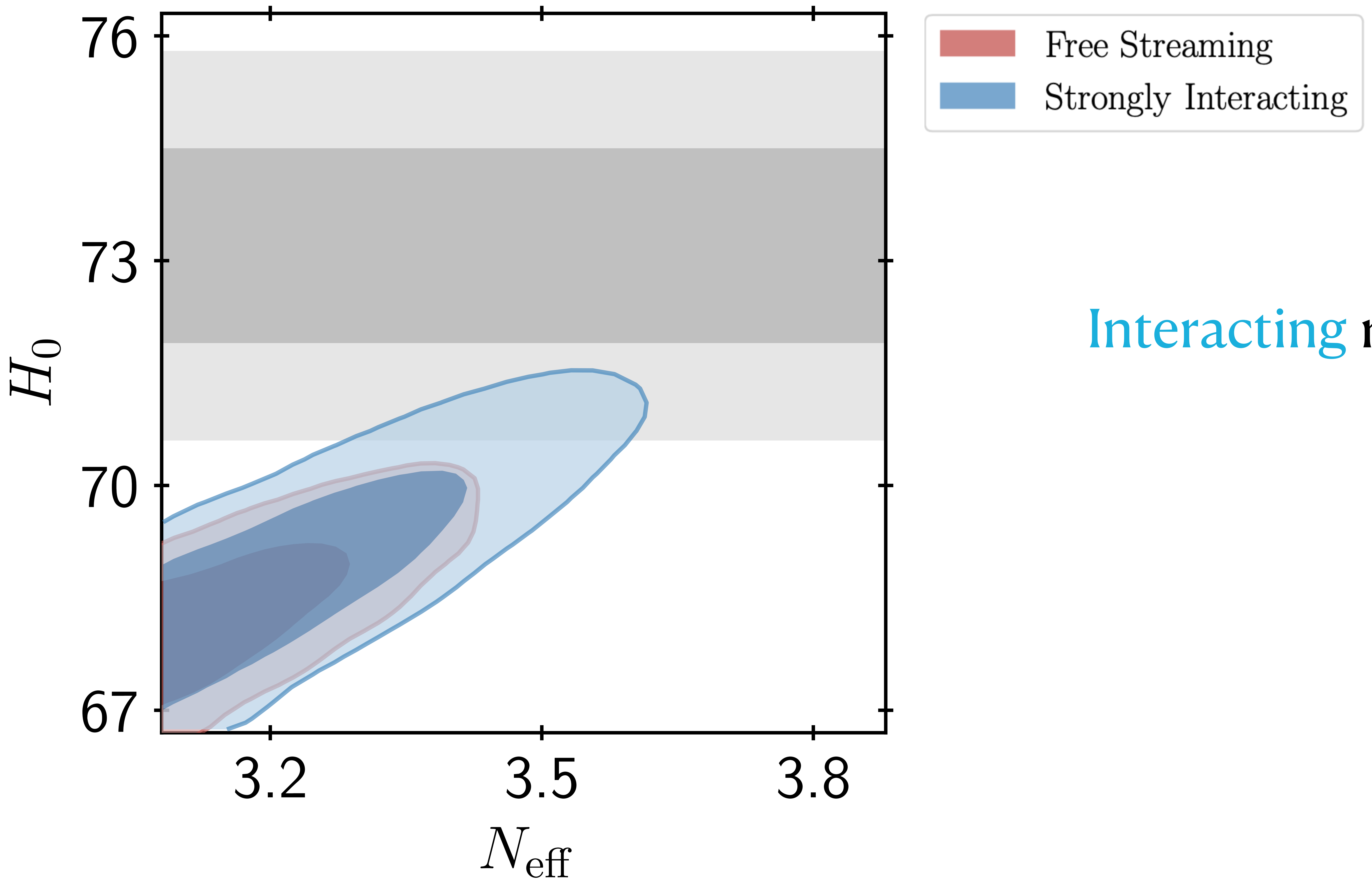
Strongly interacting radiation



$$c_s^2 = 1/3$$



Free-streaming radiation model is too constrained



Interacting radiation (SIDR) is better

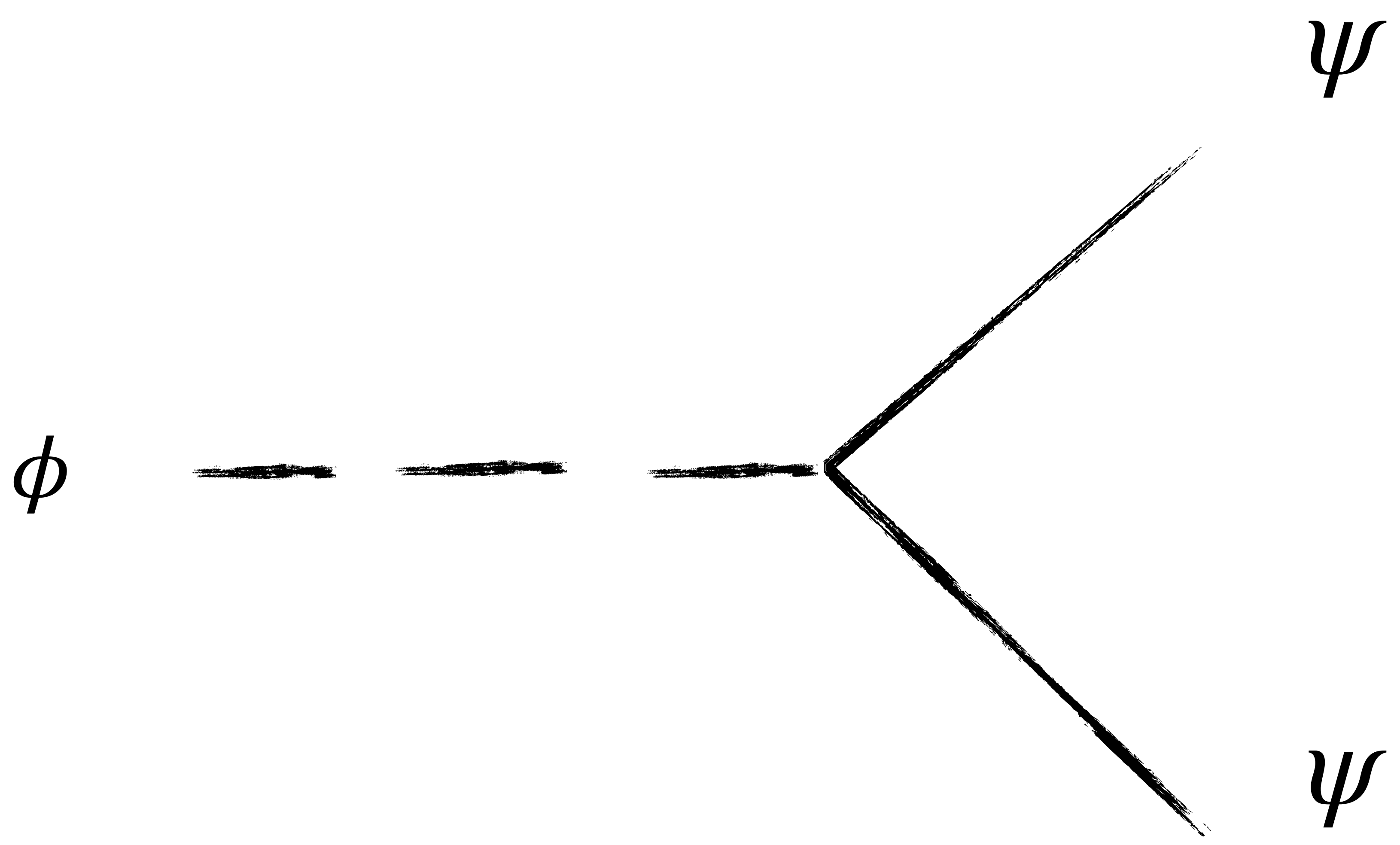
but still $> 3\sigma$

Consider a simple model with two particle species

Wess-Zumino Dark Radiation (WZDR)

Massive scalar - ϕ (~eV)

Massless fermion - ψ



What happens at the mass threshold?

Massive particles
become non-relativistic
and decay

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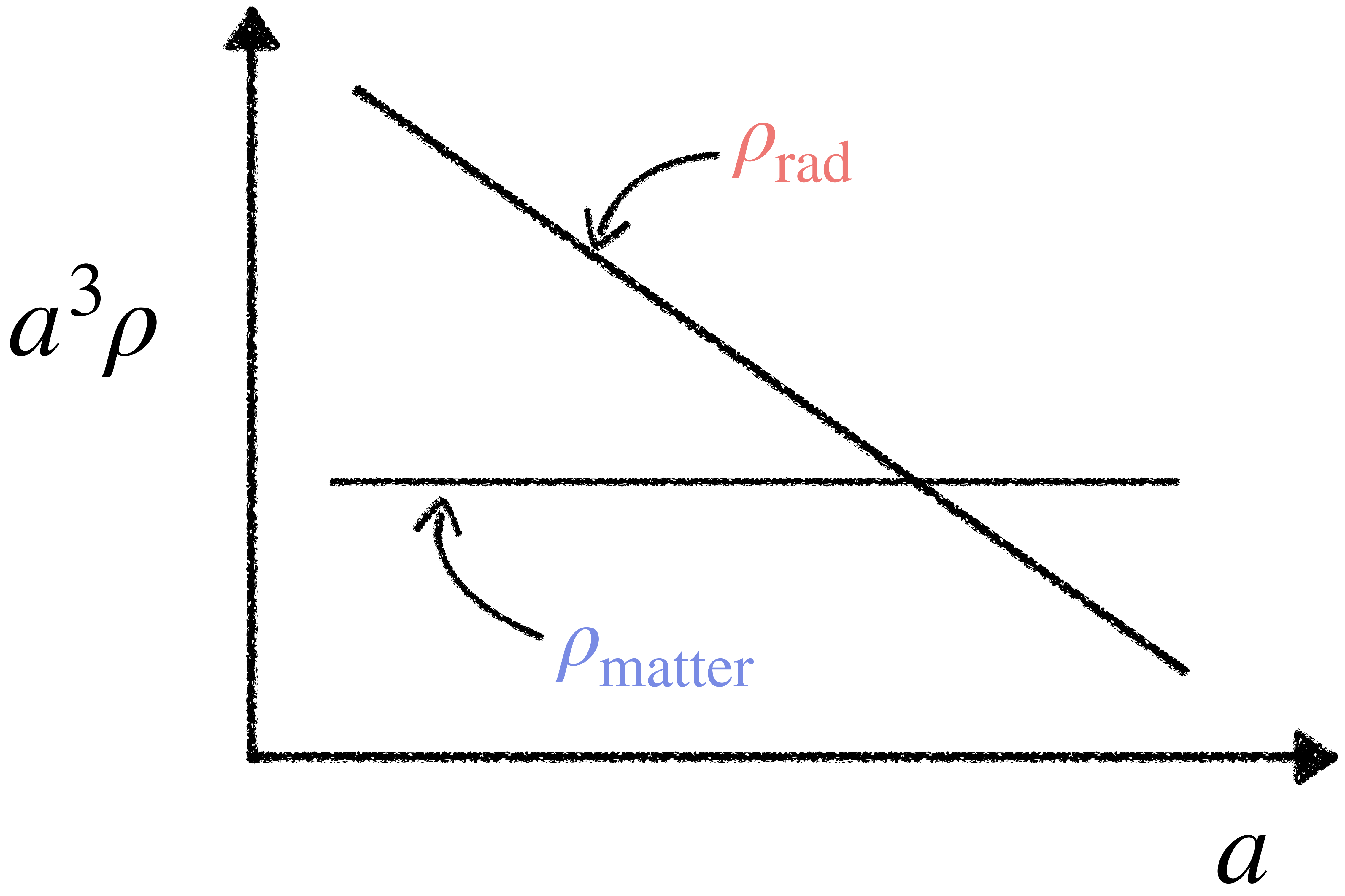
Massive particles become non-relativistic and decay

A mix of relativistic $\sim a^{-4}$ and non-relativistic $\sim a^{-3}$ particles



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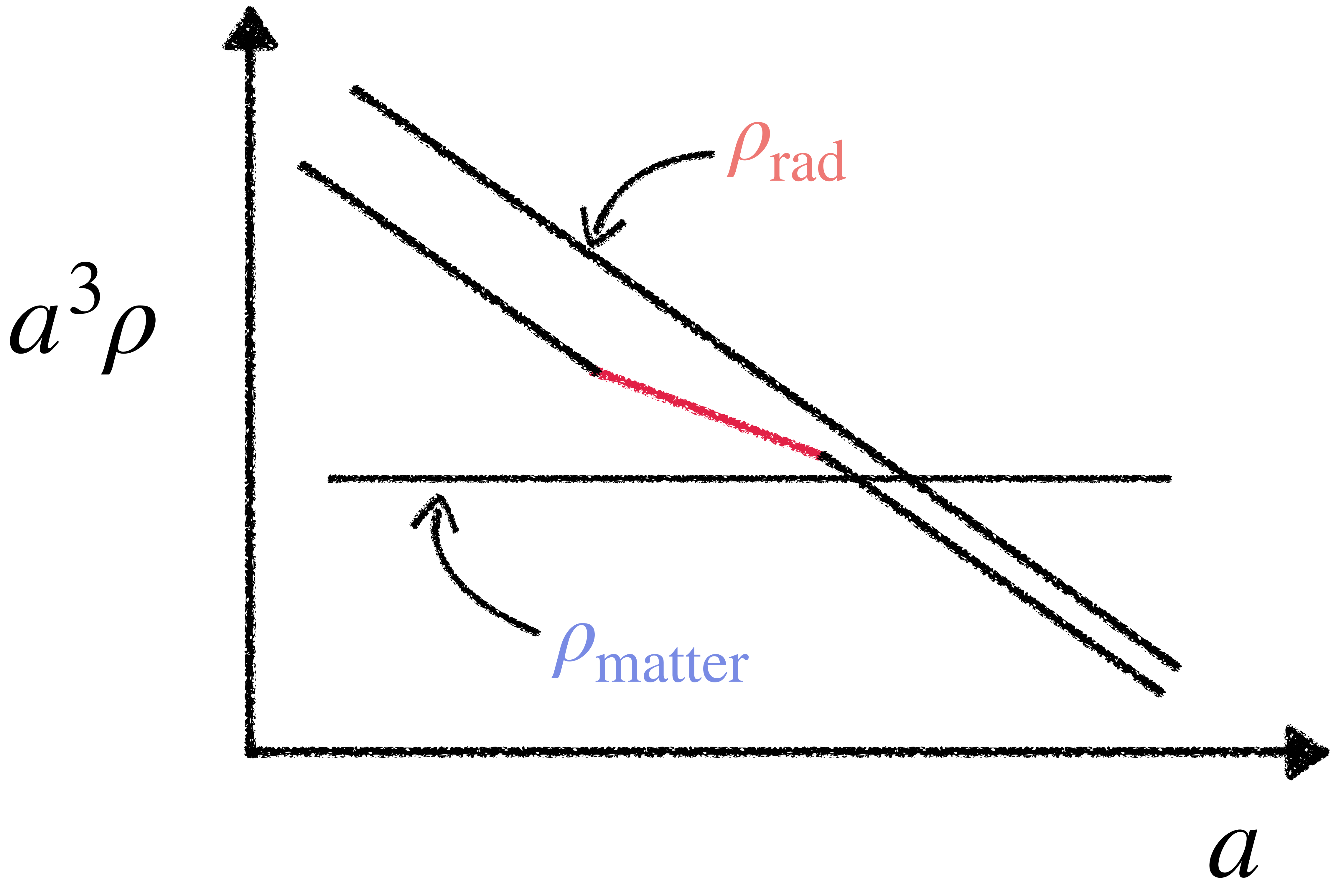

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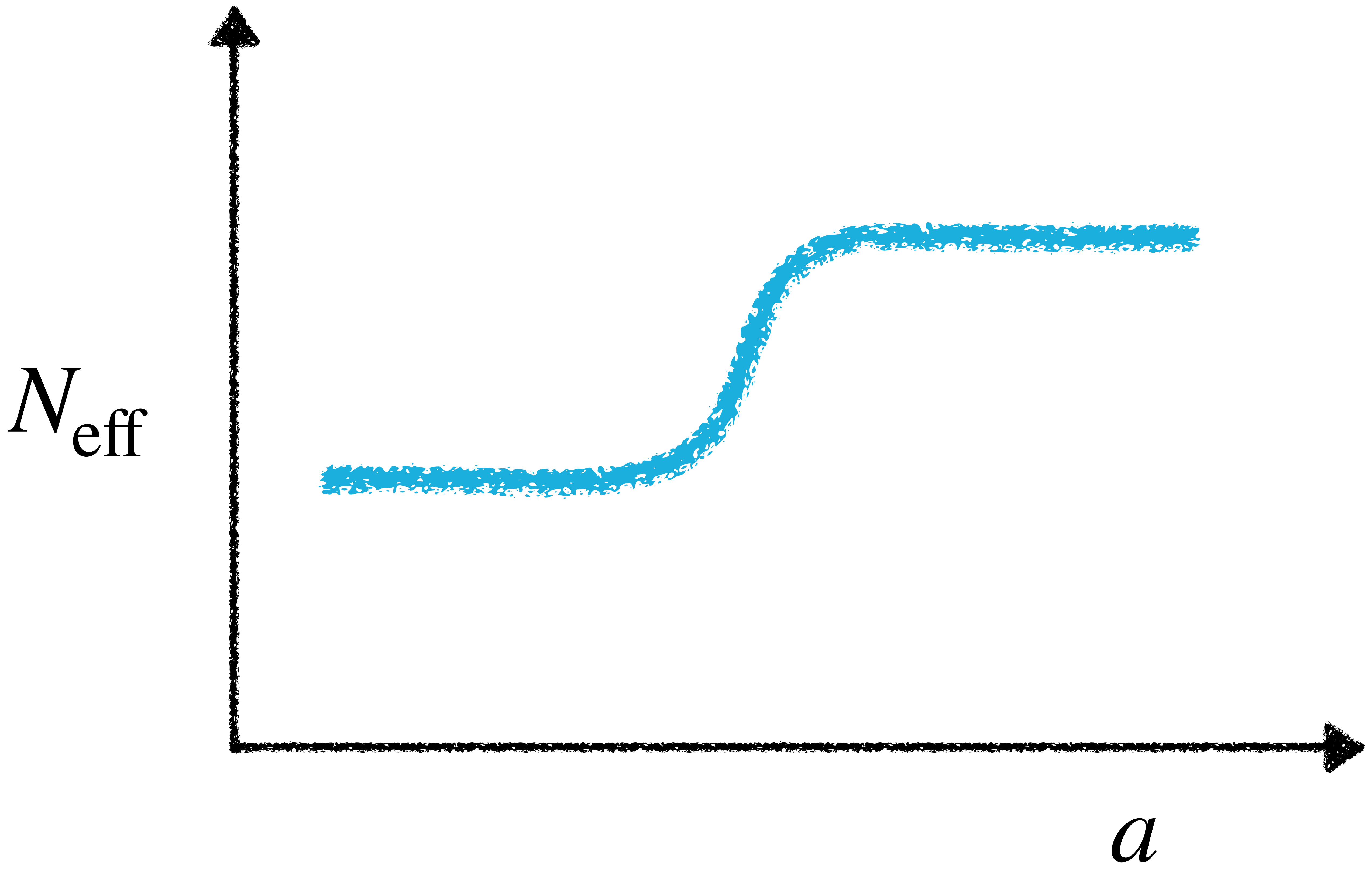

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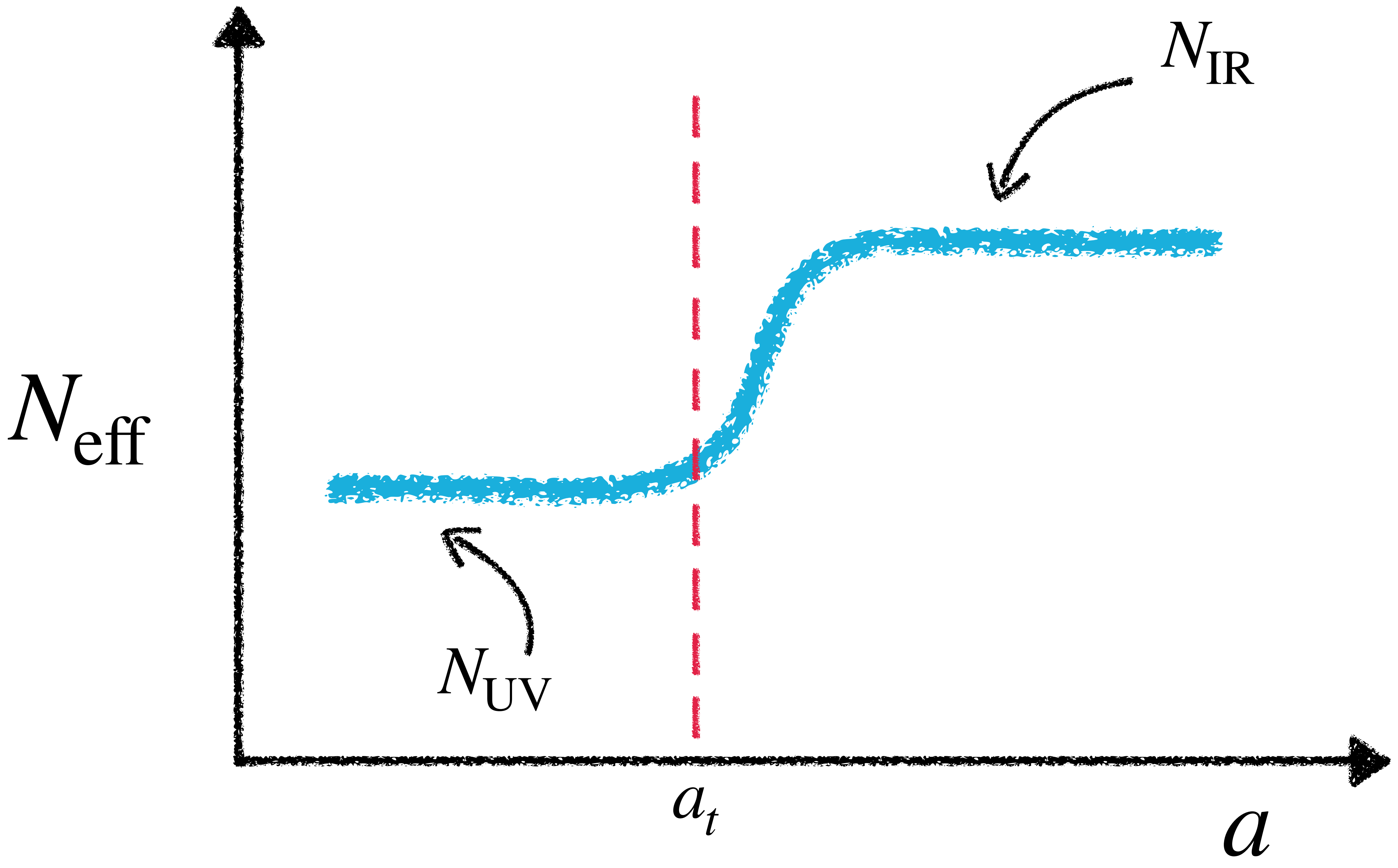

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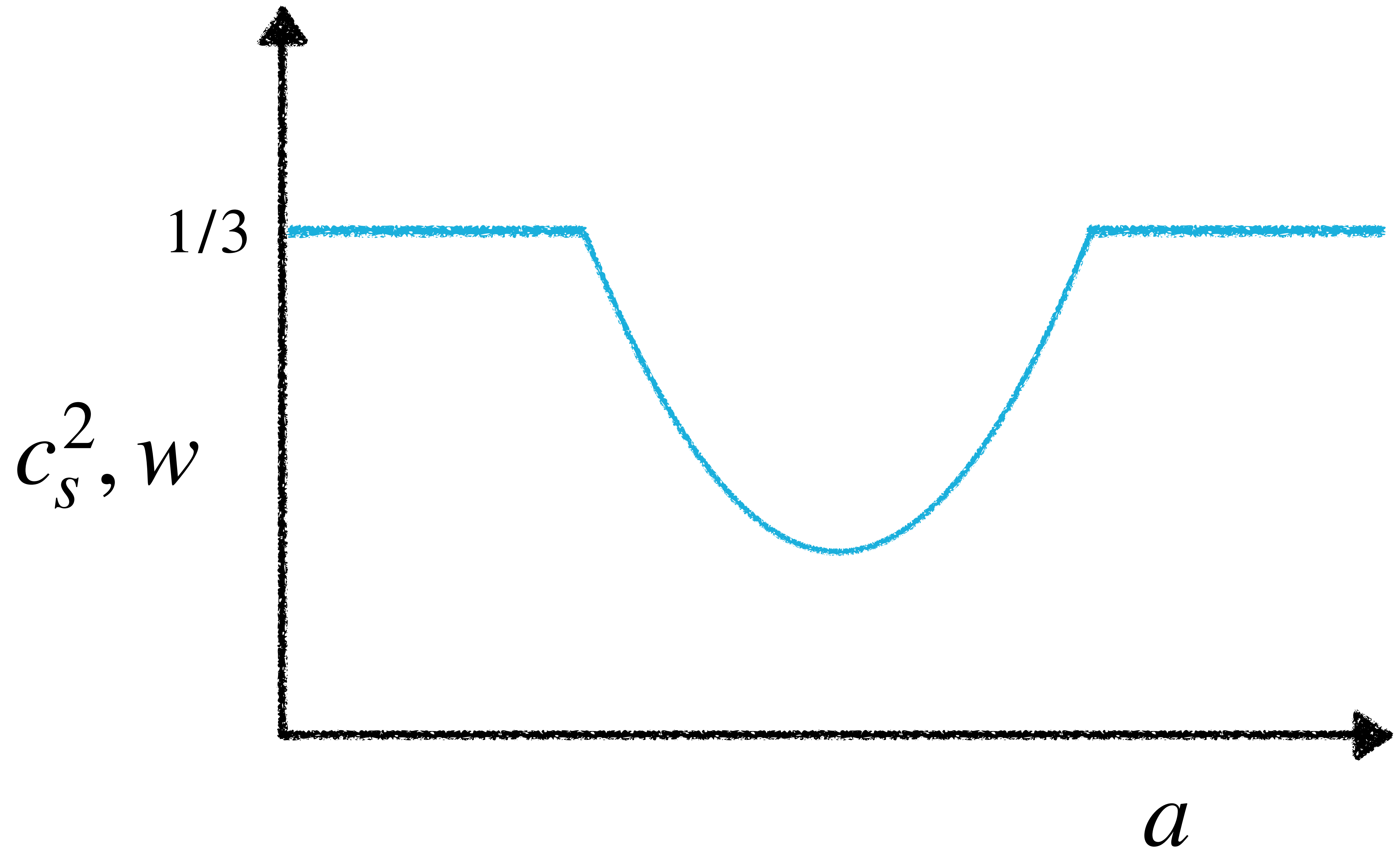

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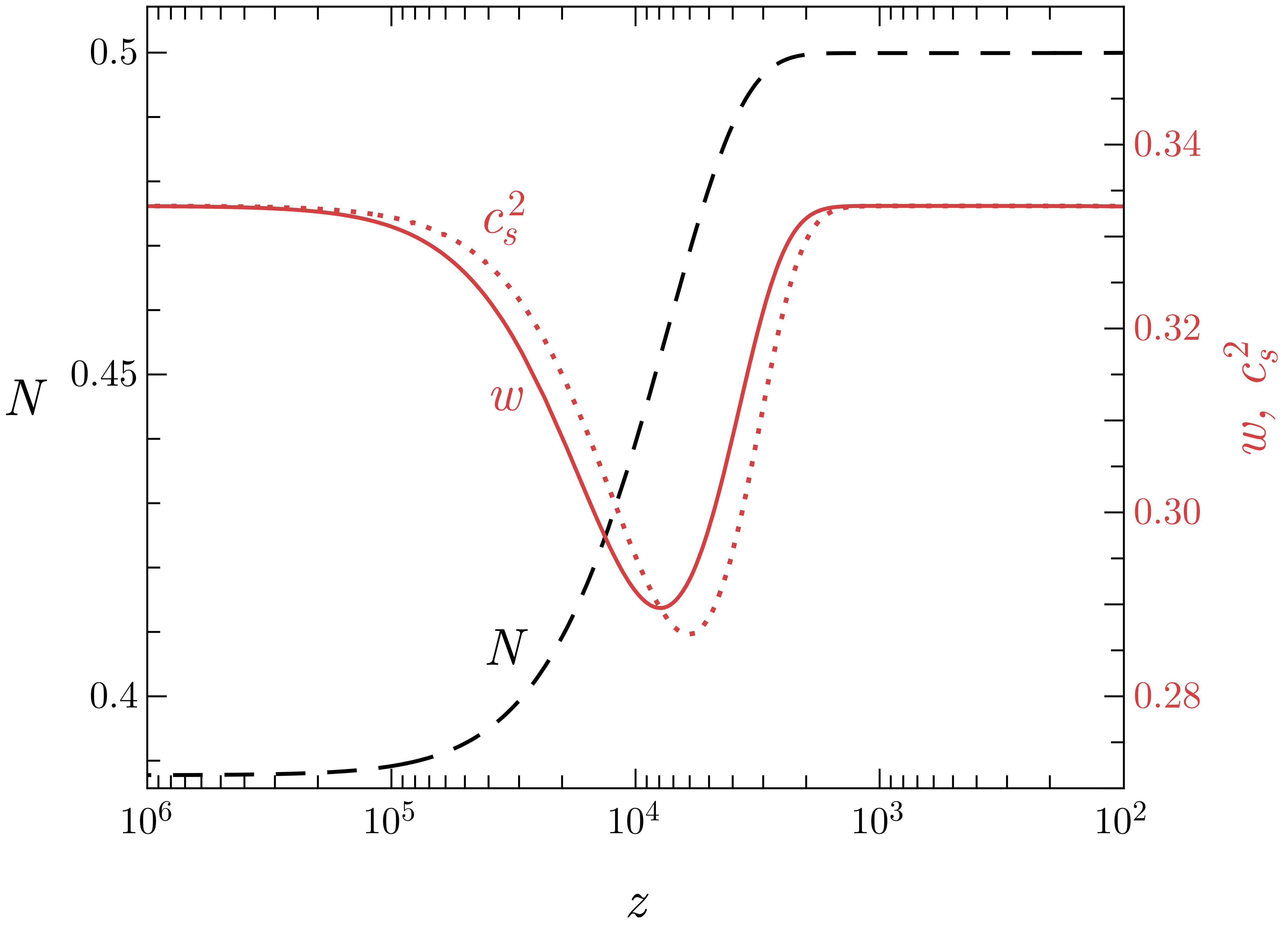
Entropy Conservation:

$$S = a^3 \frac{\rho(T) + P(T)}{T} = \text{constant}$$



Data

$\mathscr{D}$ - Planck 2018 TT, EE, TE and Lensing, BAO(6dF, MGS, BOSS DR12), Pantheon

$\mathscr{D}+$ - Planck 2018 TT, EE, TE and Lensing, BAO(6dF, MGS, BOSS DR12), Pantheon, SH0ES

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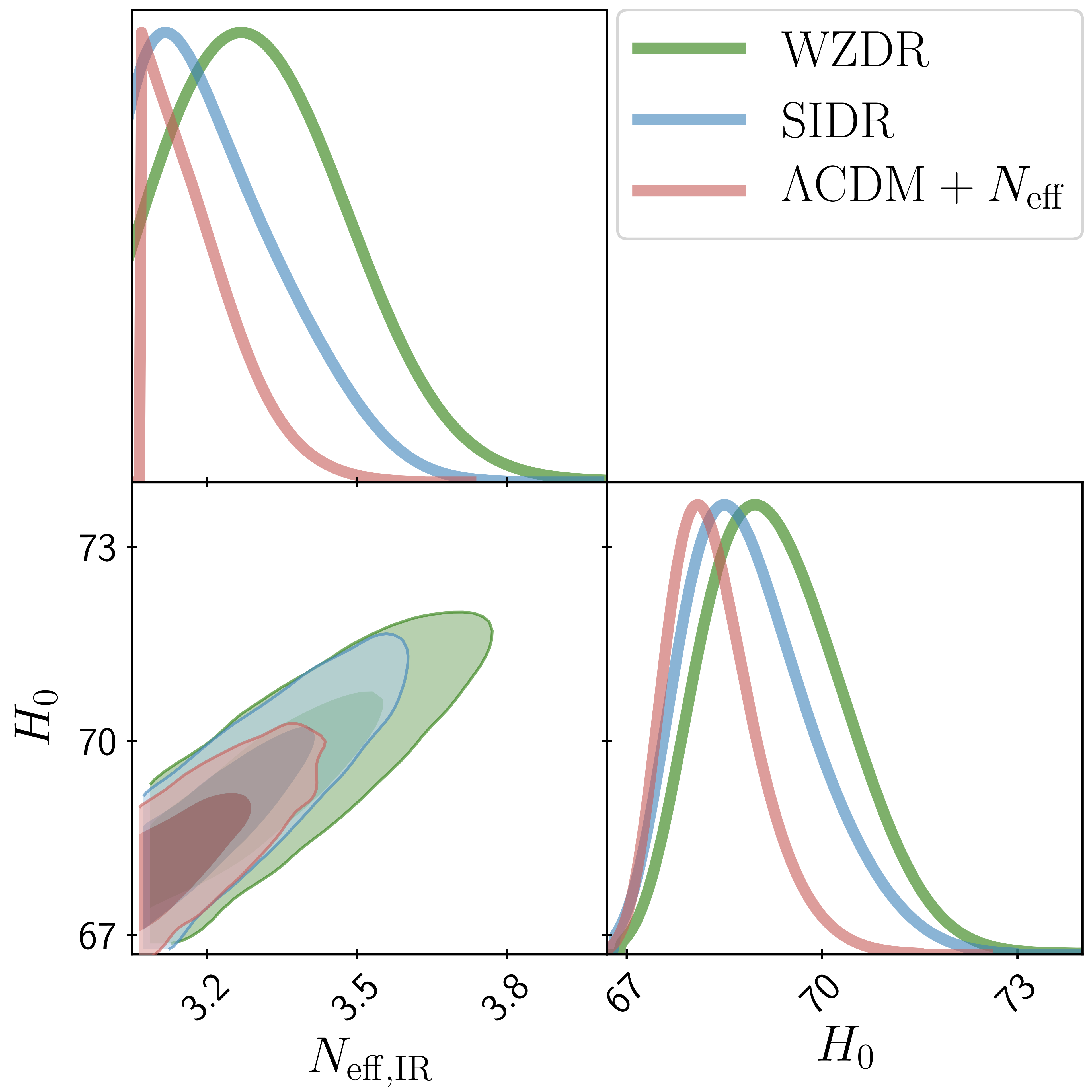
Results



Model	Tension	$\Delta\chi^2$
ΛCDM + $N_{\rm eff}$	3.7 σ	-5.7
SIDR	3.1 σ	-10.6
WZDR	2.7 σ	-15.1

The H_0 Olympics: A fair ranking of proposed models [Schöneberg *et.al.* 2107.10291]

Summary

- Simplest extensions of ΛCDM include adding extra radiation

- If the radiation is interacting: a simple model includes a massive particle (WZDR)

- WZDR does well in external metrics comparing solutions to the Hubble tension

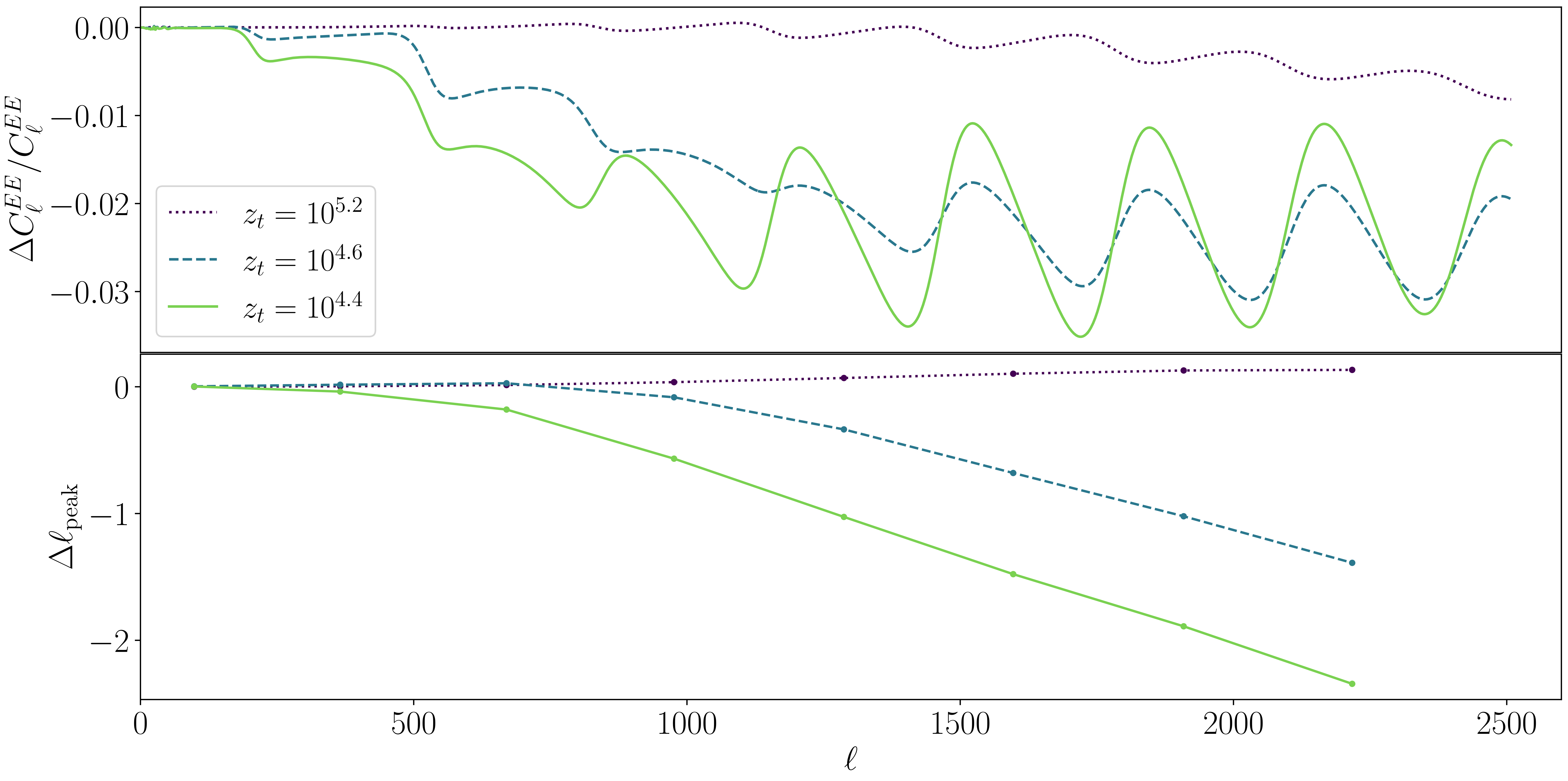
- Next: Natural extensions include interactions with the dark matter

A More General Model

A more general model allows arbitrary number of massless and massive species

We can vary the N_{eff} in the UV and IR independently

We find the WZDR case is still the preferred region


$\Delta C_\ell^{EE}/C_\ell^{EE}$
0.00
−0.01
−0.02
−0.03
$z_t = 10^{5.2}$
$z_t = 10^{4.6}$
$z_t = 10^{4.4}$
$\Delta \ell_{\rm peak}$
0
−1
−2
0
500
1000
1500
2000
2500
ℓ

$$\dot{d}_\gamma + k^2 c_s^2 d_\gamma \simeq 0$$

$$d_\gamma \simeq C_1 \cos(kc_s\tau) + C_2 \sin(kc_s\tau)$$

Superhorizon equations

$$d_\gamma = -3\zeta \qquad \dot{d}_\gamma \propto H^{-1}$$

$$\mathscr{H}^{-1}(z) = \begin{cases} \tau(z) & z \ll z_t \\ \tau(z) + \Delta\tau & z \gg z_t \end{cases}$$

$$\Delta\tau \simeq \int_{z_t}^{\infty} dz \left(\frac{1}{H_{\mathrm{WZDR}}(z)} - \frac{1}{H_{\mathrm{SIDR}}(z)} \right) ,$$

$$d_\gamma(z) \propto \begin{cases} \cos[c_\gamma\, k\, \tau(z)] & (k \ll k_t) \\ \cos[c_\gamma\, k\, (\tau(z) + \Delta\tau)] & (k \gg k_t) \end{cases} ,$$