Reconciling Cosmological Tensions with Inelastic Dark Matter and Dark Radiation in $U(1)_D$ Framework

JCAP 09 (2024) 065

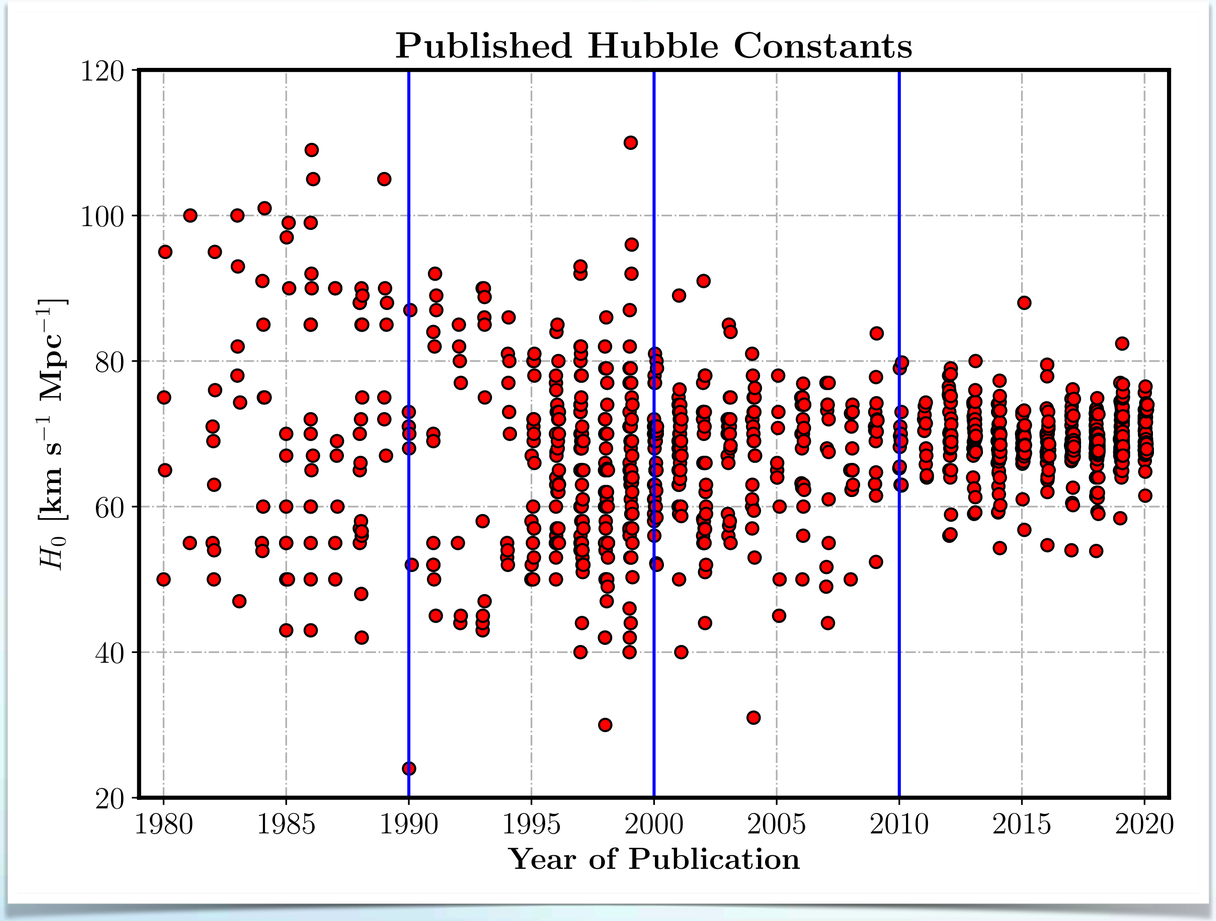
Satyabrata Mahapatra

With Ki-Young Choi & Wonsub Cho

The International Joint Workshop on the Standard Model and Beyond 2024
3rd Gordon Godfrey Workshop on Astroparticle Physics

December 9-13 @ UNSW, Sydney

Motivation: H_0 - tension



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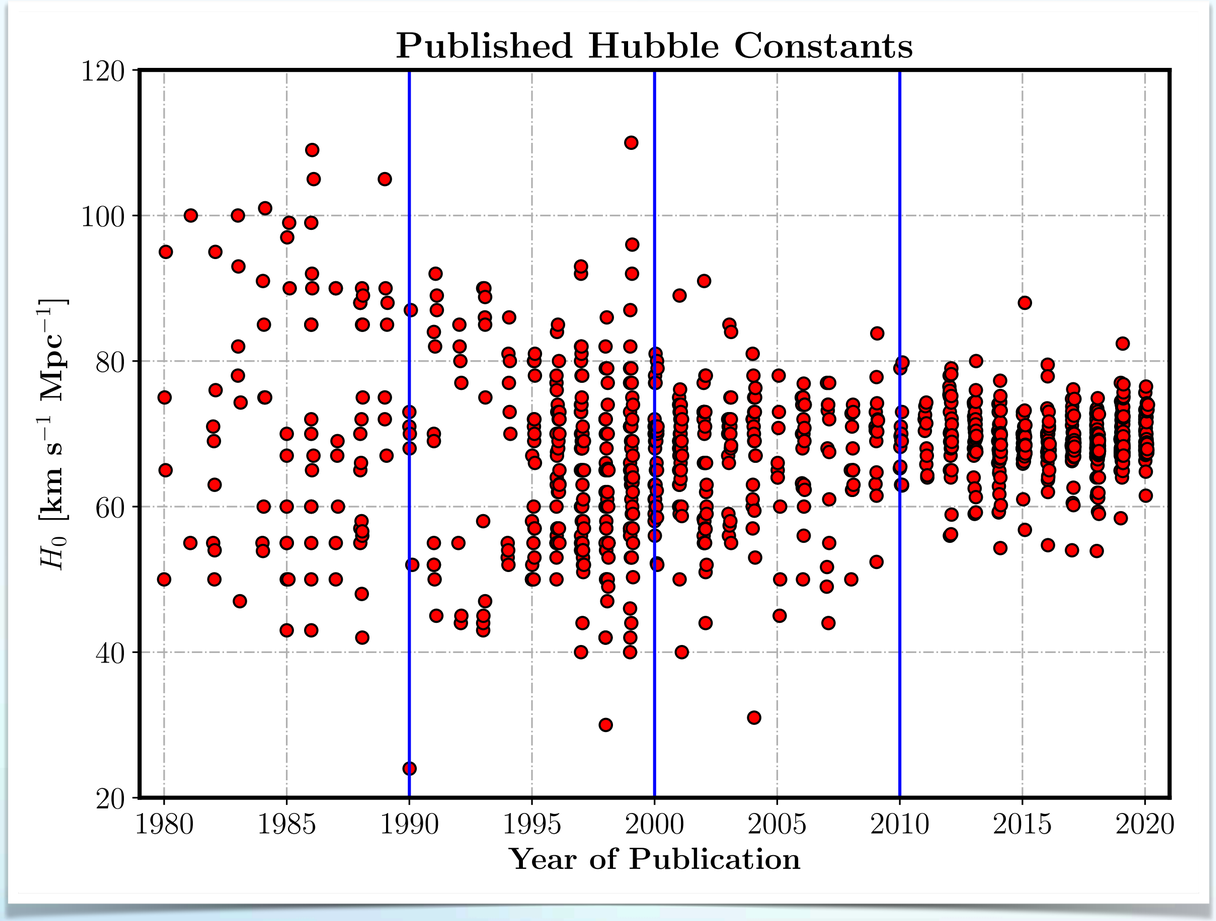

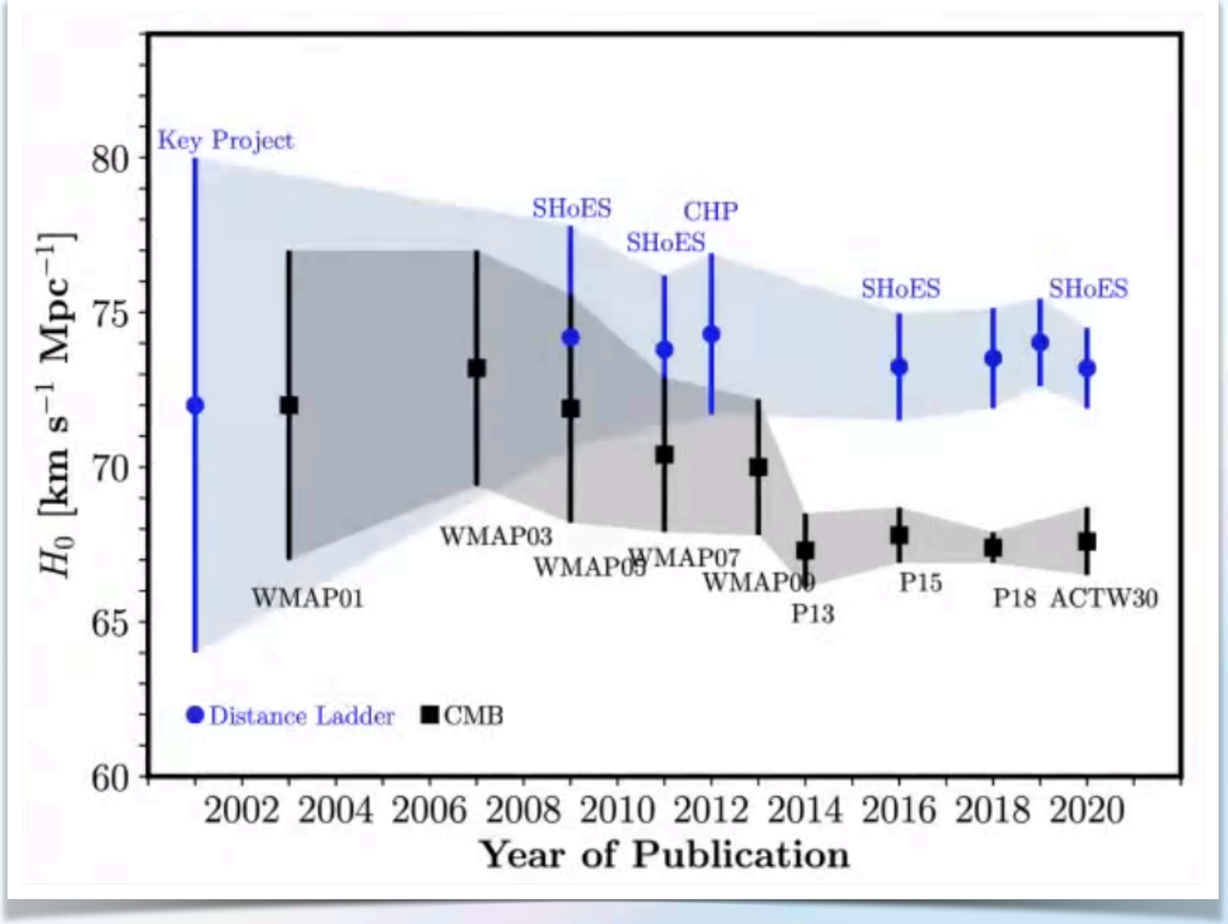

2106.15656

Our Universe is expanding $\sim 8\,\%$ faster than predicted by ΛCDM

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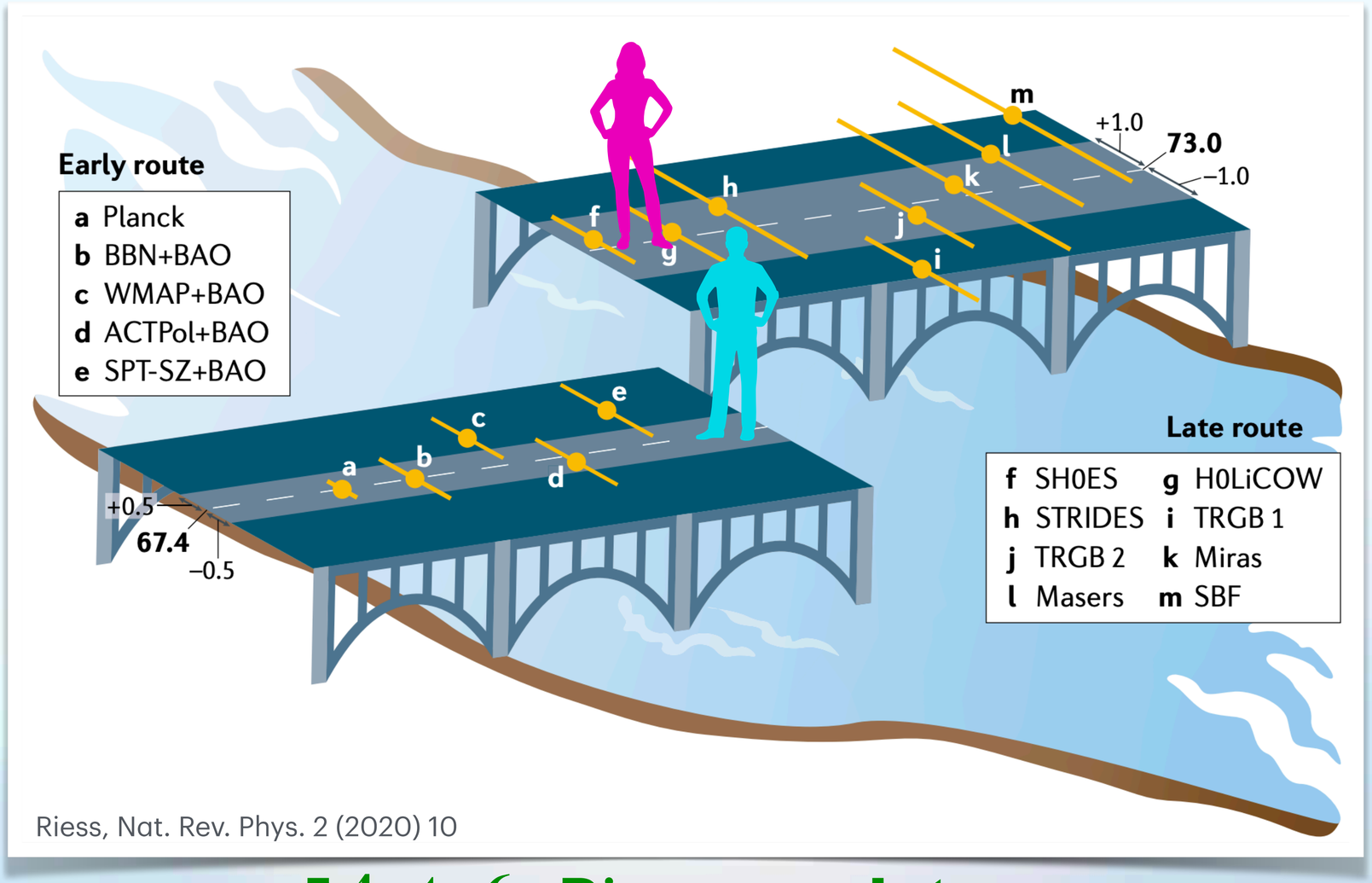
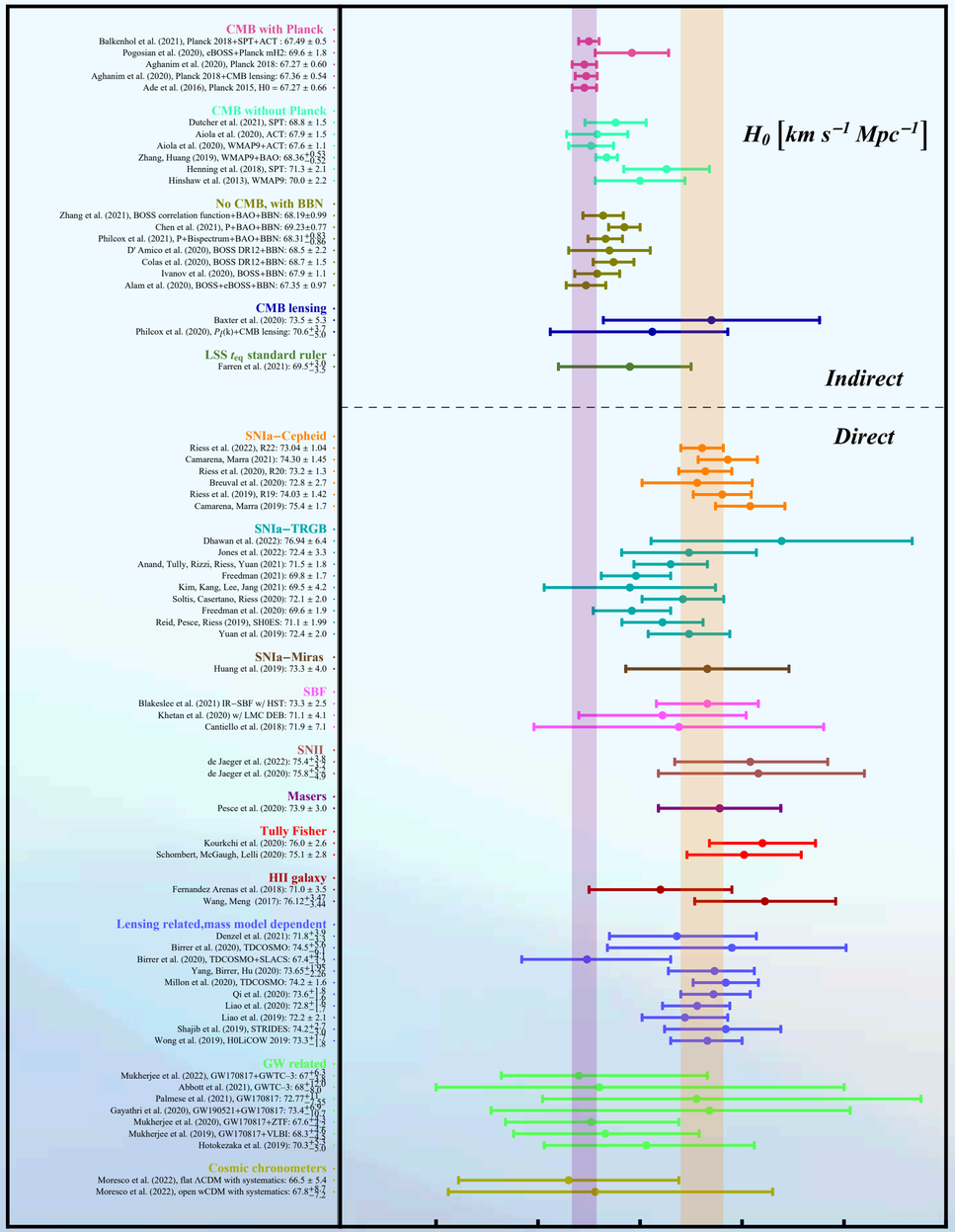
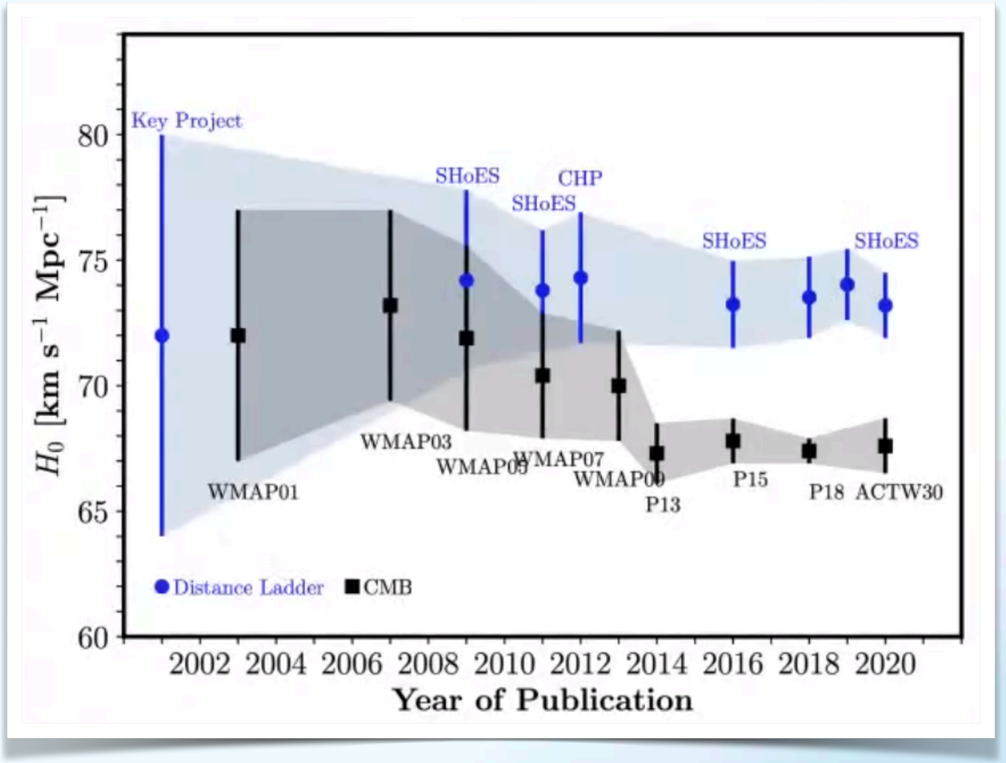


Riess, Nat. Rev. Phys. 2 (2020) 10

A 4σ to 6σ Discrepancy between
the indirect model dependent estimates at early times
and
the direct late time measurements

Motivation: H_0 - tension



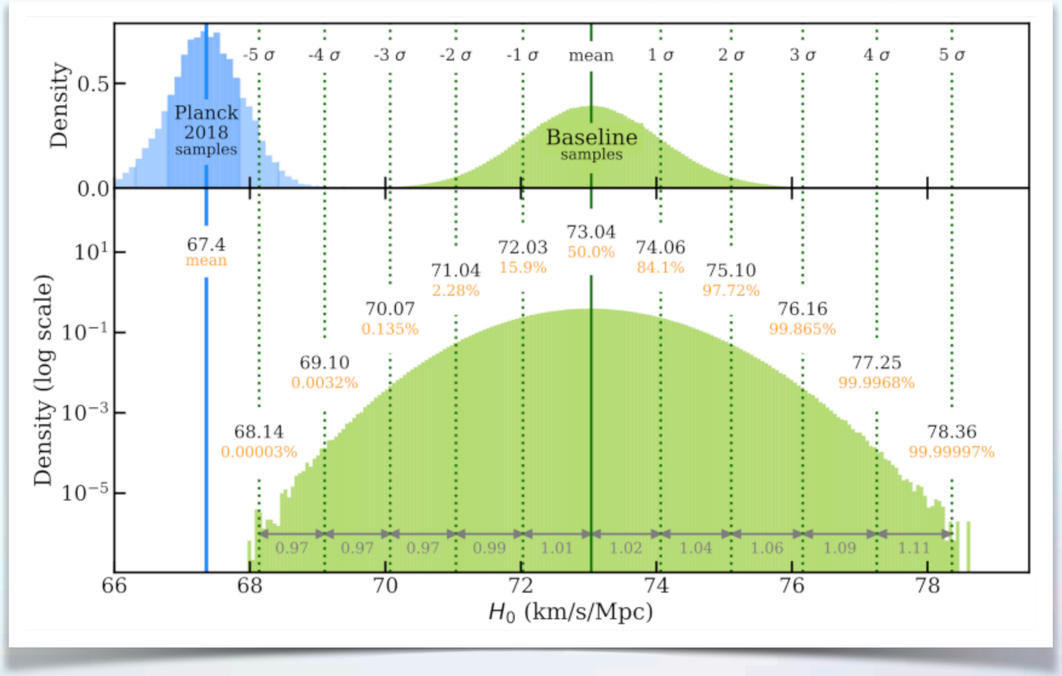


All the indirect, model-dependent early estimates, such as those from the CMB and BAO agree among themselves

All the direct, late-time ΛCDM-independent measurements, such as those from distance ladders and strong lensing, also agree among themselves

2203.06142

Motivation: H_0 - tension



2112.04510

Most Statistically significant, Long standing and widely persisting tension

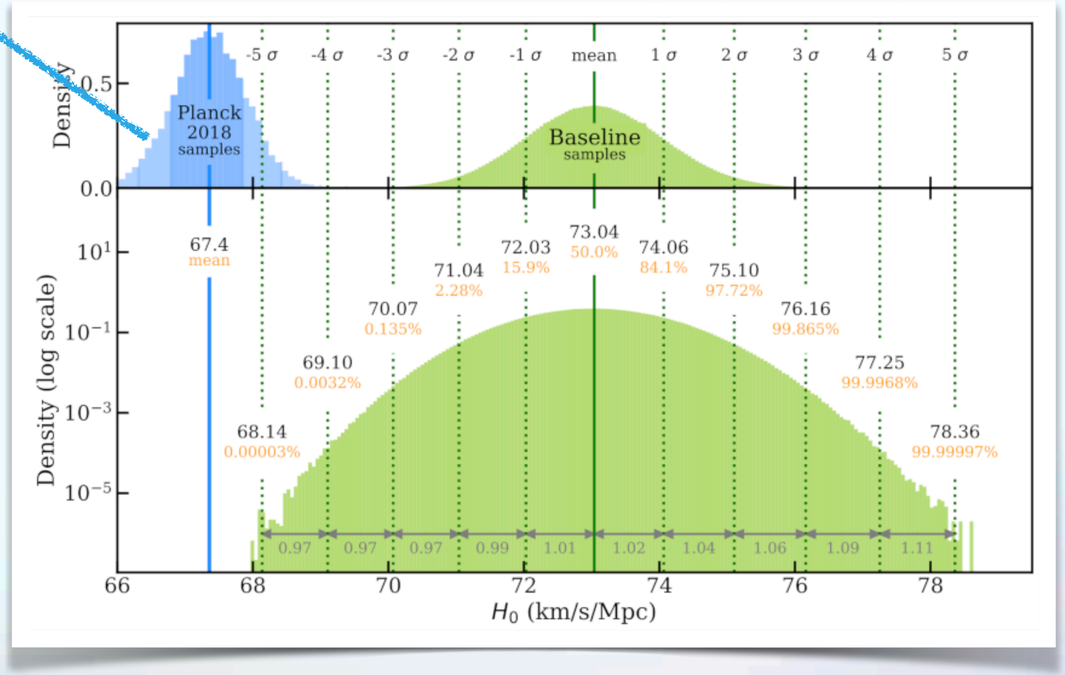
Motivation: H_0 - tension

Planck CMB:

$$H_0 = 67.27 \pm 0.6 \text{ km/s/Mpc}$$

Estimates assuming vanilla ΛCDM model

$$\theta_S \sim H_0 \times r_s$$



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SH0ES collaboration:

$H_0 = 73.04 \pm 1.04$ km/s/Mpc

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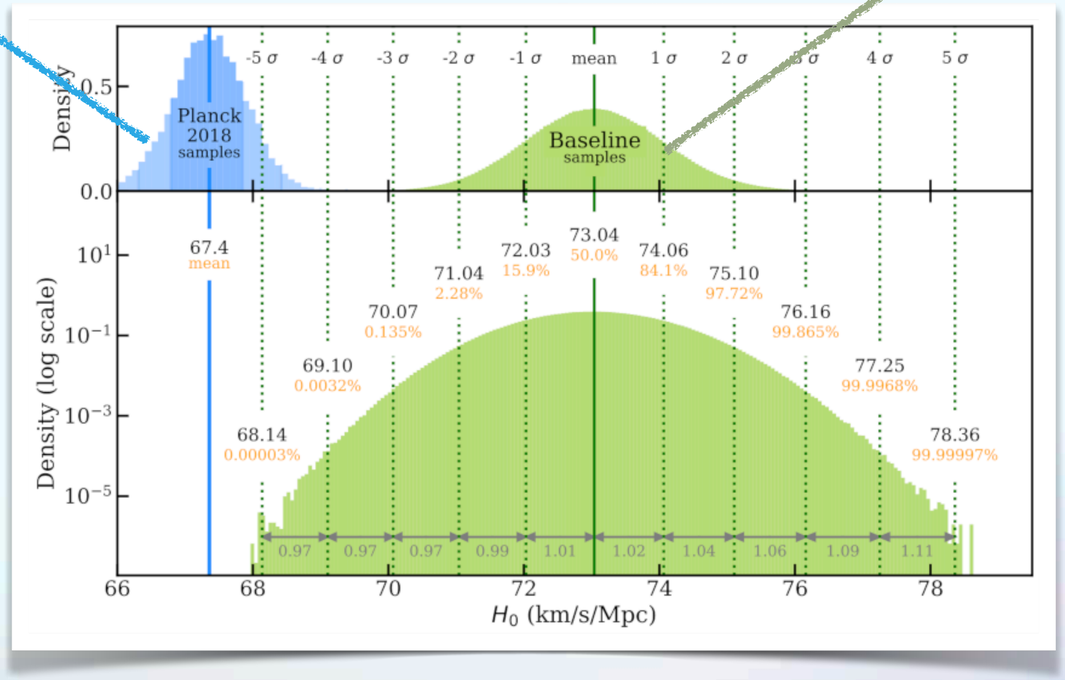


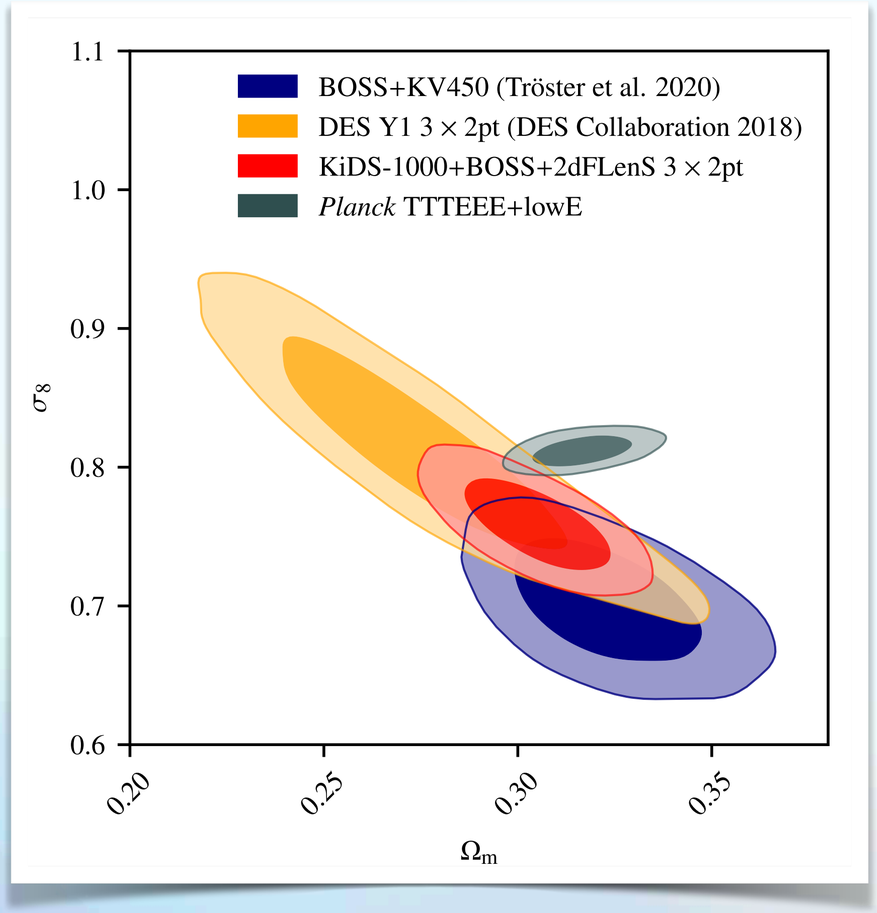
2112.04510

Direct measurements in the local Universe using cosmic distance ladders.

$v = H_0 \times d$

Most Statistically significant, Long standing and widely persisting tension

Motivation: S_8 - tension

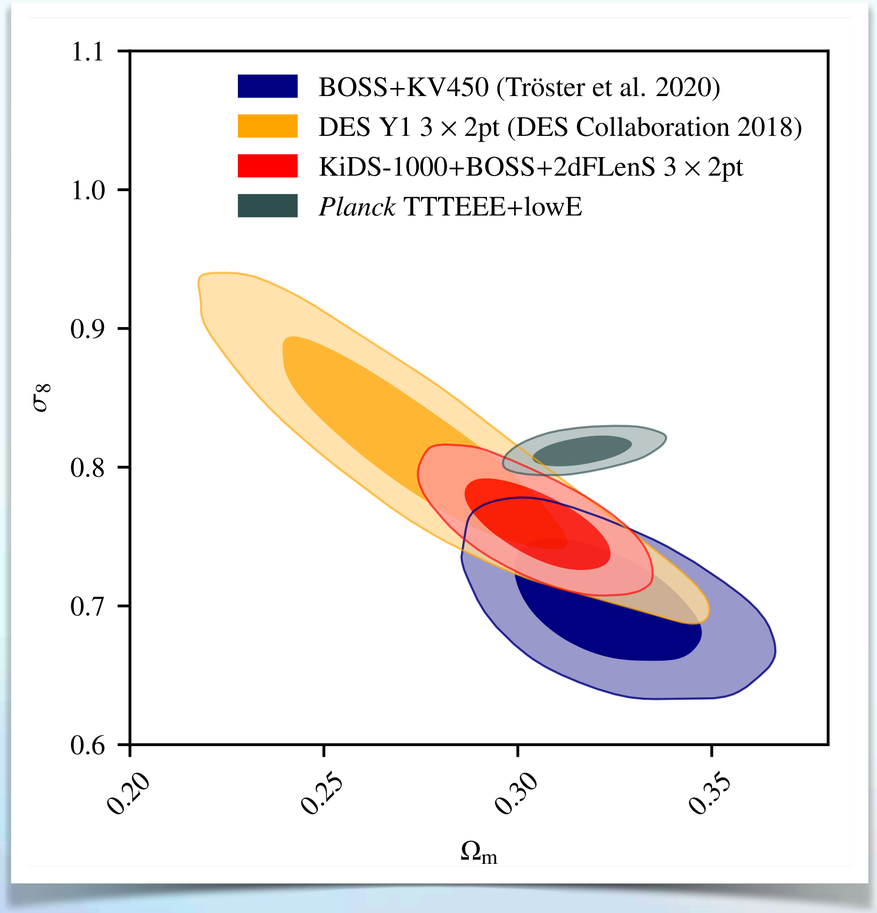


2007.15632

Discrepancy between the amplitude of matter fluctuations inferred from LSS surveys and the CMB data

$$S_8 = \sigma_8 \left(\frac{\Omega_m}{0.3} \right)^{1/2}$$

Motivation: S_8 - tension



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3.4σ between Planck and KV450 + BOSS

3.1σ between Planck and KiDS-1000

2.6σ between Planck and CFHTLenS survey and KiDS-450

3.2σ between Planck and KV-450 + DES Y1

2.5σ between Planck and DES Y3

2203.06142

Motivation: S_8 - tension

$$\textit{Planck}: \; S_8 = 0.834 \pm 0.016$$

$$\text{DES Y3}: \; S_8 = 0.776 \pm 0.017$$

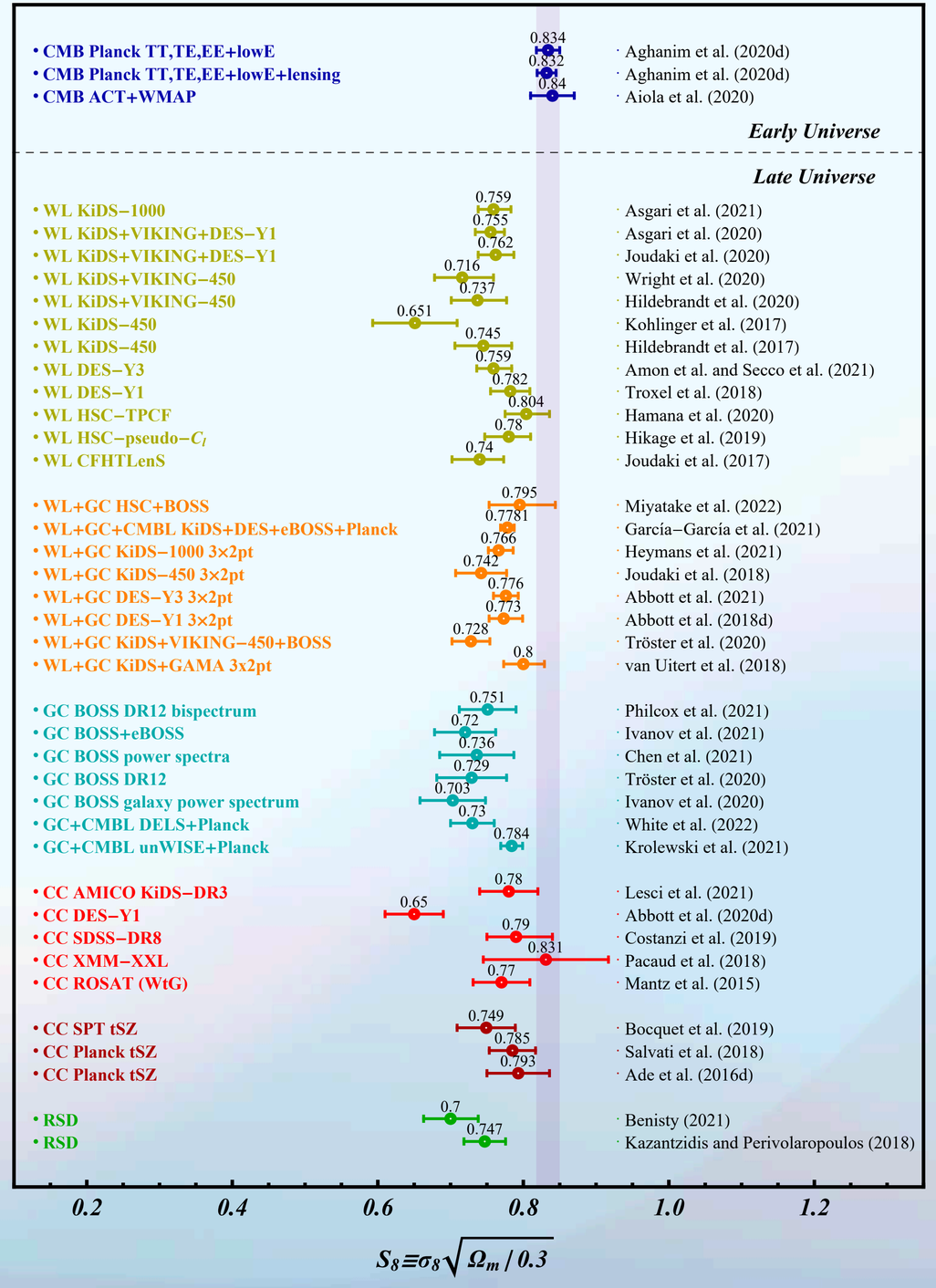
$$\text{KiDS 1000}: \; S_8 = 0.759 \pm 0.024$$

CMB experiments typically yield higher values

weak lensing and galaxy clustering data infer a lower value

Universe is less "clumpy" than predicted by ΛCDM

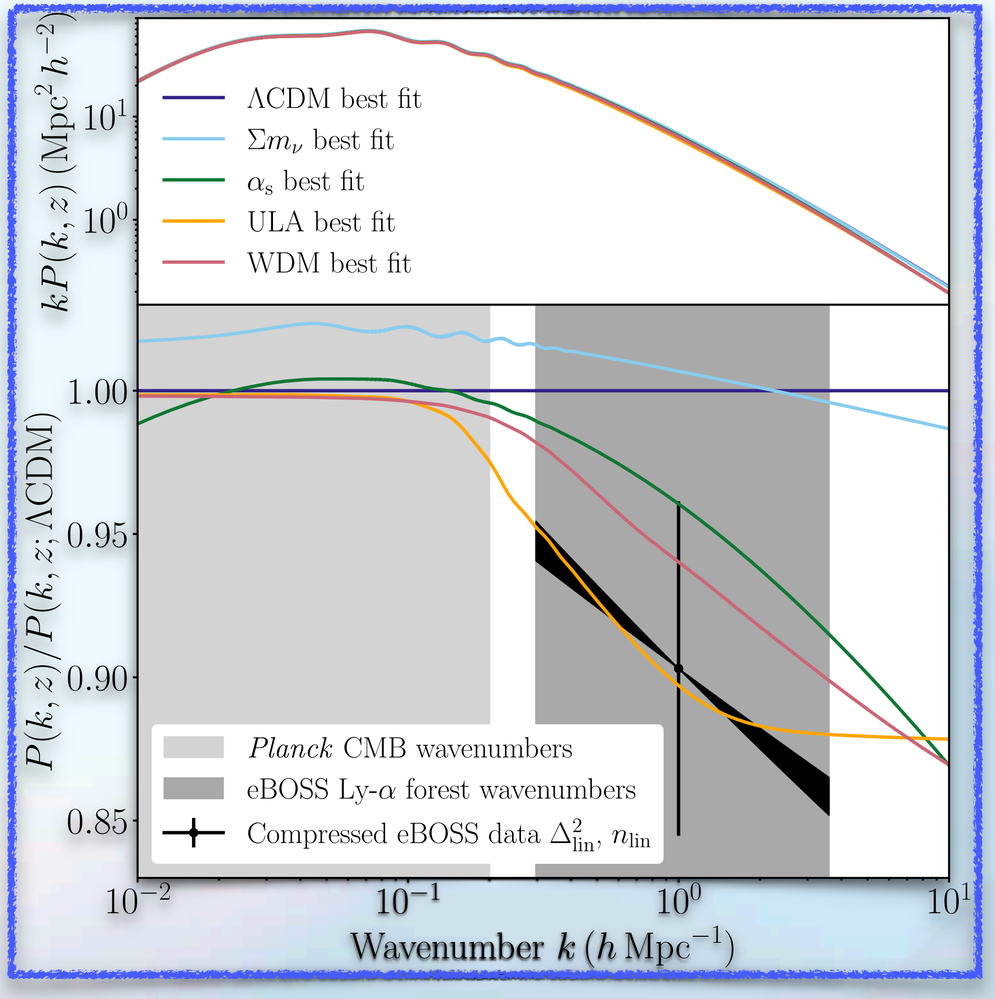
2203.06142



Motivation: Ly-α discrepancy

4.9σ tension between
Planck CMB, BAO and SNe data with ΛCDM
and
eBOSS Ly-α forest

in inference of the linear matter power spectrum at wavenumber $\sim 1h\,\mathrm{Mpc}^{-1}$ and redshift = 3.



2311.16377

Amplitude: $\Delta^2_{\rm lin} \equiv \dfrac{k_{\rm p}^3 P_{\rm lin}(k_{\rm p}, z_{\rm p})}{2\pi^2}$ **Tilt:** $n_{\rm lin} \equiv \dfrac{\mathrm{d}\ln P_{\rm lin}(k,z)}{\mathrm{d}\ln k}\Big|_{k_{\rm p},z_{\rm p}}$

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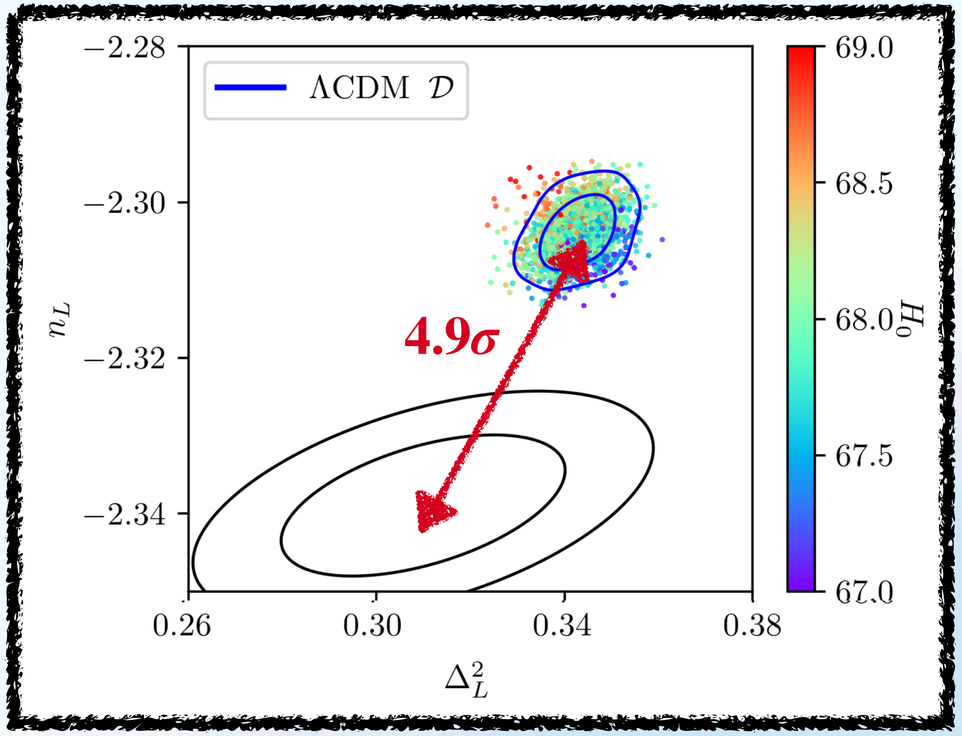

2405.17554

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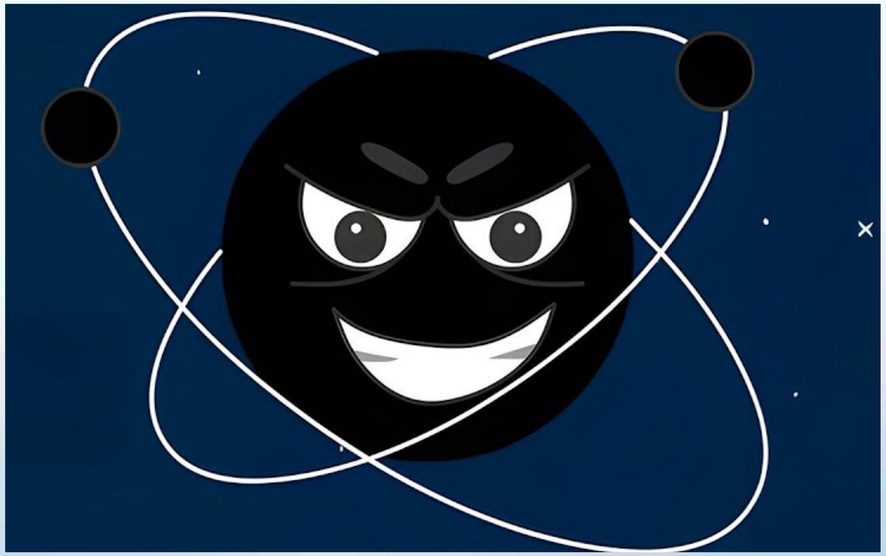
Significance of addressing these tensions

These tensions are unlikely to be mere statistical anomalies

They highlight potential gaps in our understanding

Requires us to extend beyond the standard ΛCDM paradigm and explore new physics.

Novel properties and interactions of dark matter..??



Proposed solutions for H_0-tension

Early Time Soln.

Late Time Soln.

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Modify Physics of CMB

$$\theta_S \sim H_0 \times r_s$$

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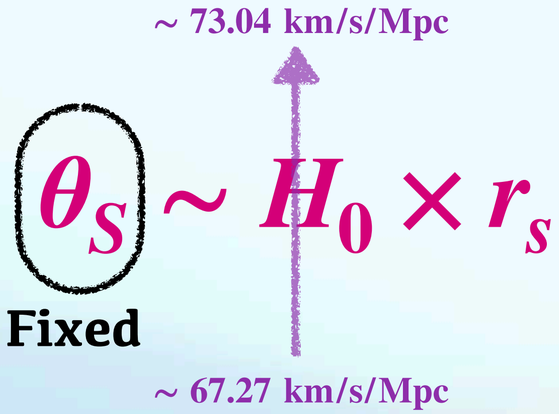

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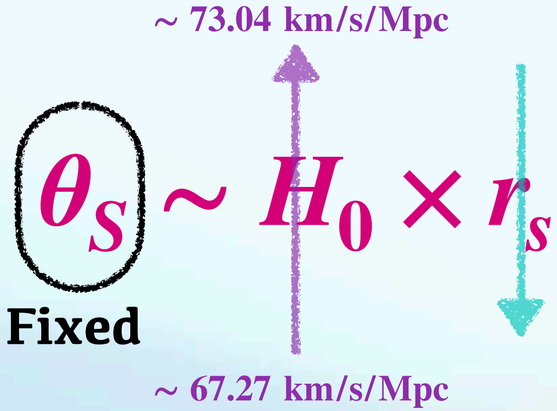

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~ 73.04 km/s/Mpc

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~ 67.27 km/s/Mpc

$$r_s = \int_0^{\tau_{\text{rec}}} c_s d\tau = \int_0^{\tau_{\text{rec}}} c_s \frac{da}{\left[\frac{8\pi G}{3}(\rho_{\text{Total}})\right]^{1/2}}$$

Additional energy around MRE

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Add Dark Radiation !!!

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$$\Delta N_{\rm eff} = \frac{\rho_{\rm DR}}{\rho_{\nu_L}} = \frac{8}{7}\left(\frac{T_\nu}{T_\gamma}\right)^{-4}\frac{\rho_{\rm DR}}{\rho_\gamma} \simeq \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_{\rm DR}}{\rho_\gamma}$$

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Add Dark Radiation (After BBN) !!!

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Simplest Implementation: ΛCDM + $\Delta N_{\rm eff}$ (Free Streaming)

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Adverse effects:

- **Worsens S8 tension**

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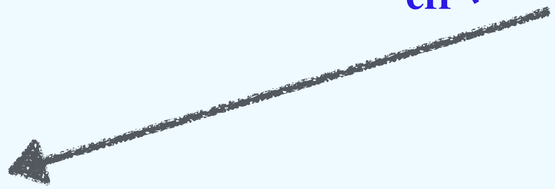

Adverse effects:

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- **Significant challenges in fitting CMB polarization data**

  Modification of Silk damping tail

  Phase-shift in CMB high ℓ

Proposed solutions for H_0-tension

Simplest Implementation: ΛCDM + $\Delta N_{\rm eff}$ (Free Streaming)

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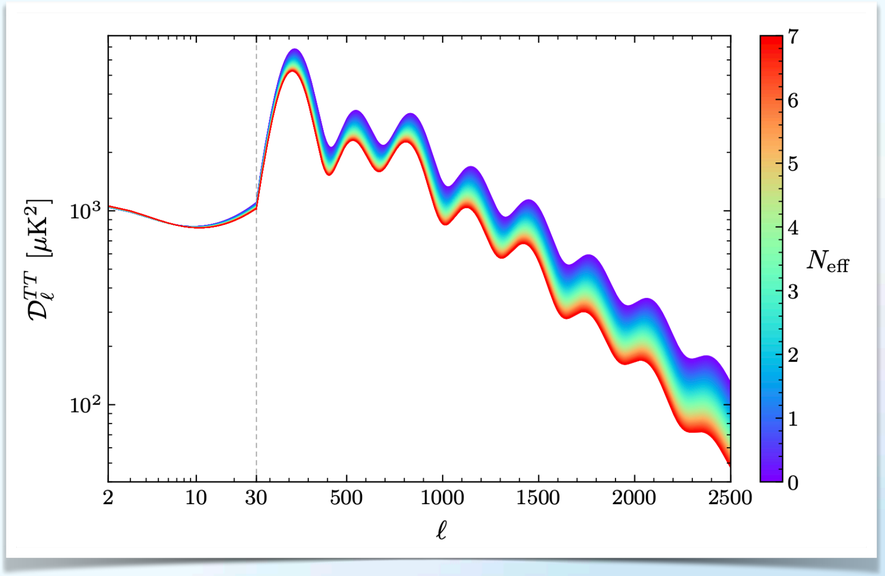

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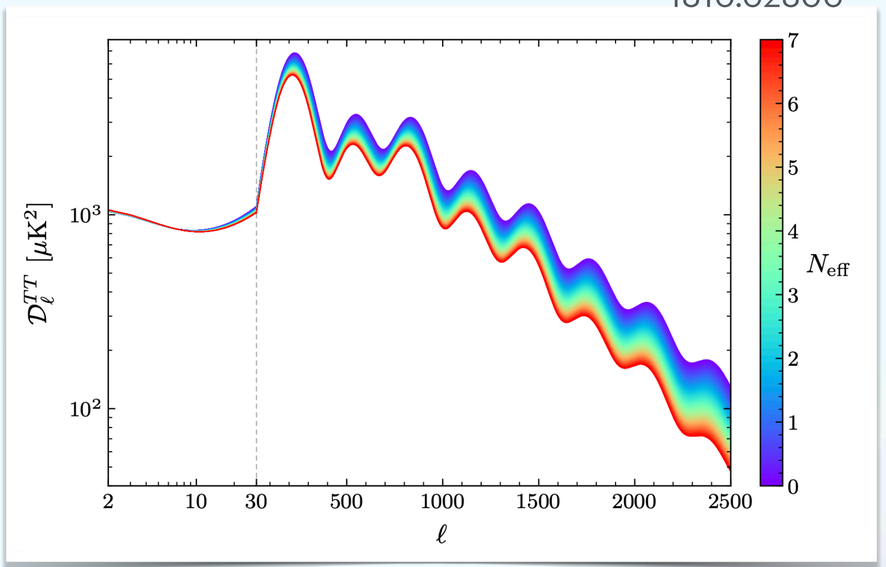

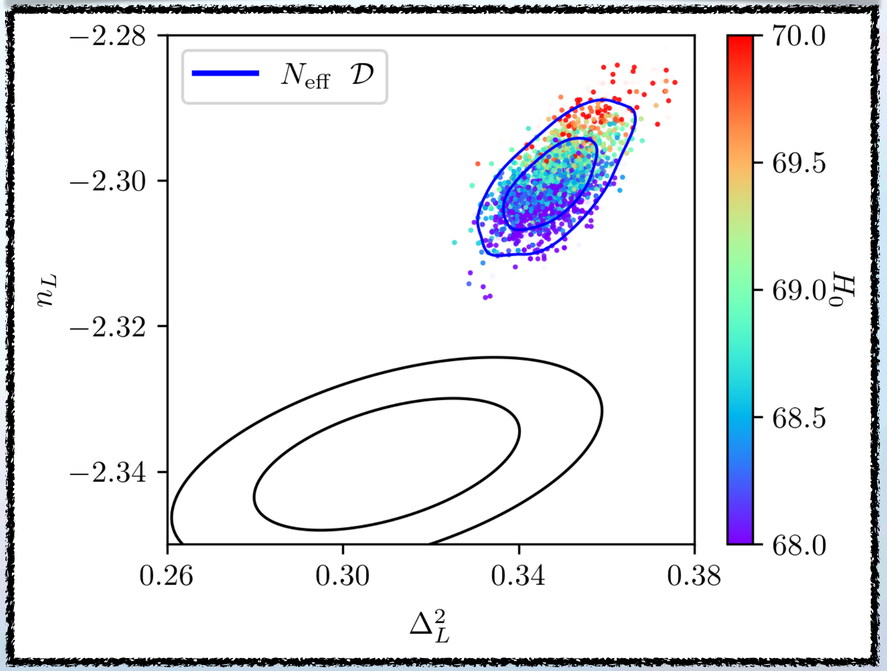

2405.17554

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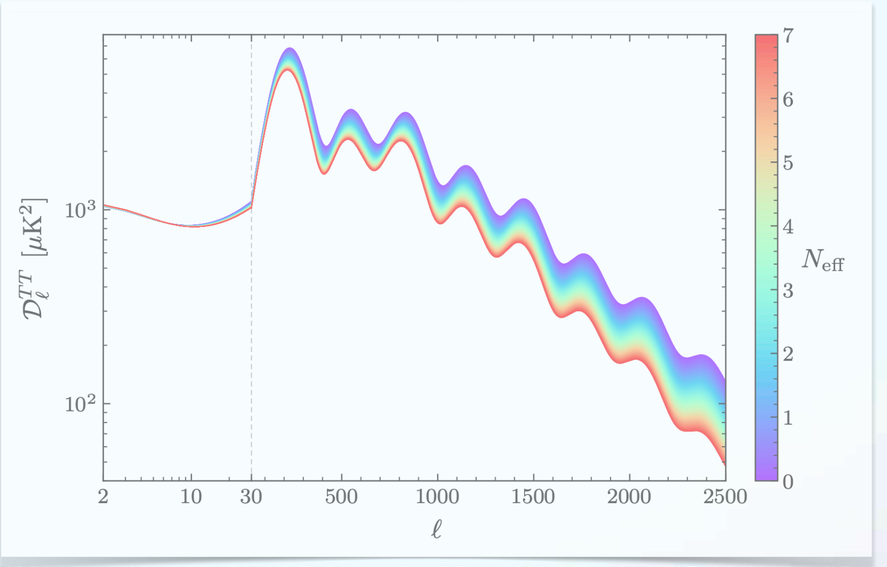
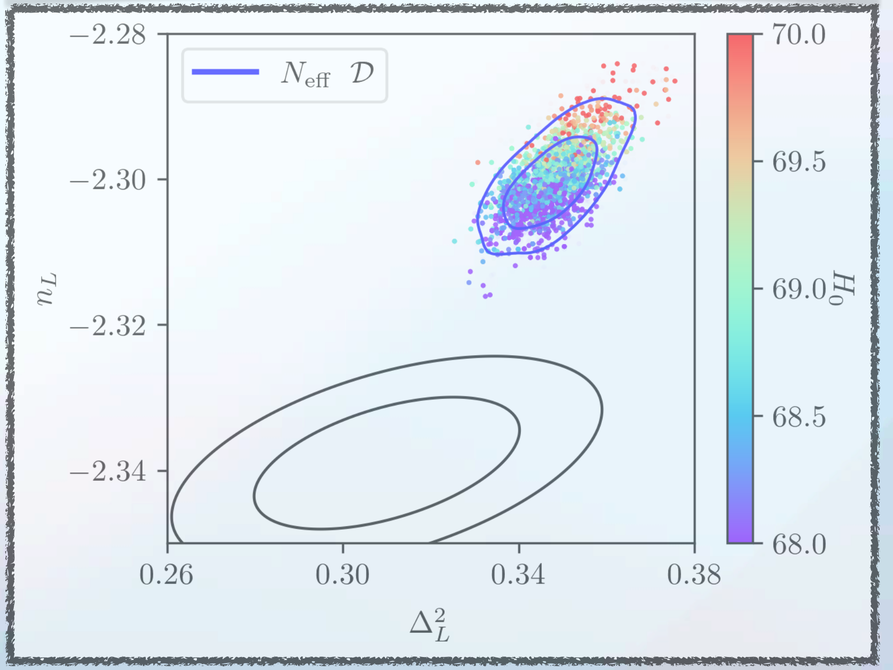
Free Streaming DR is Insufficient !!!





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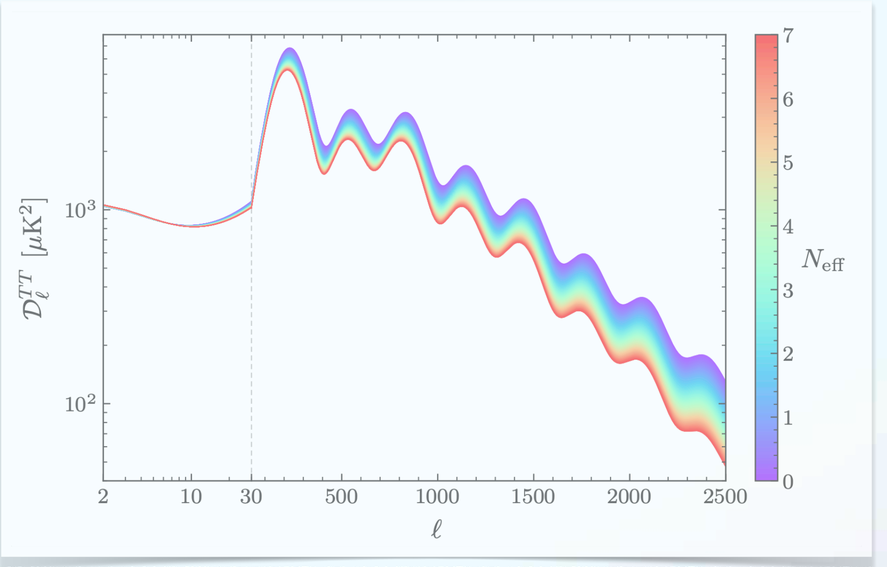

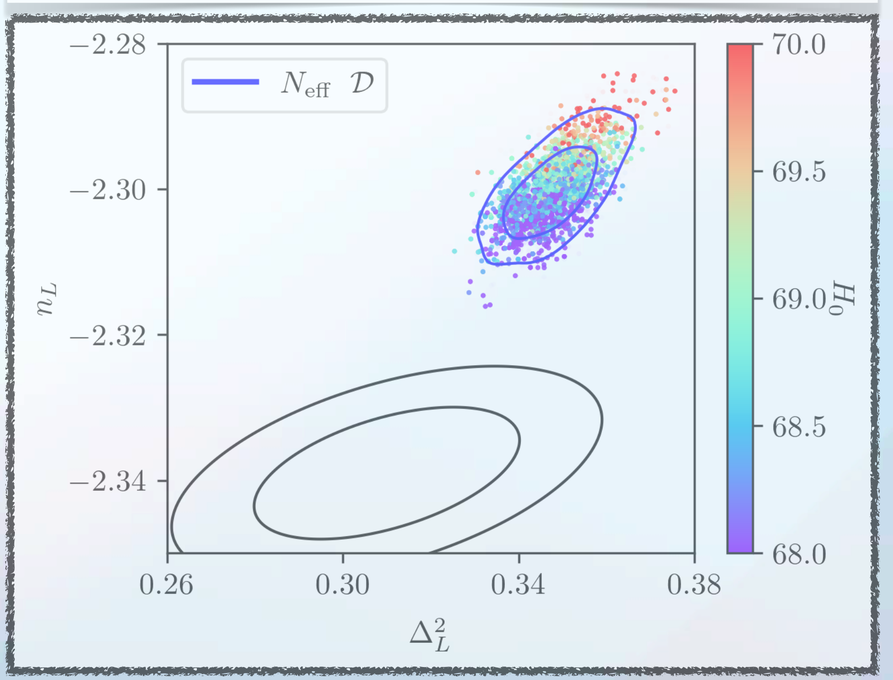

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Extremely Constrained

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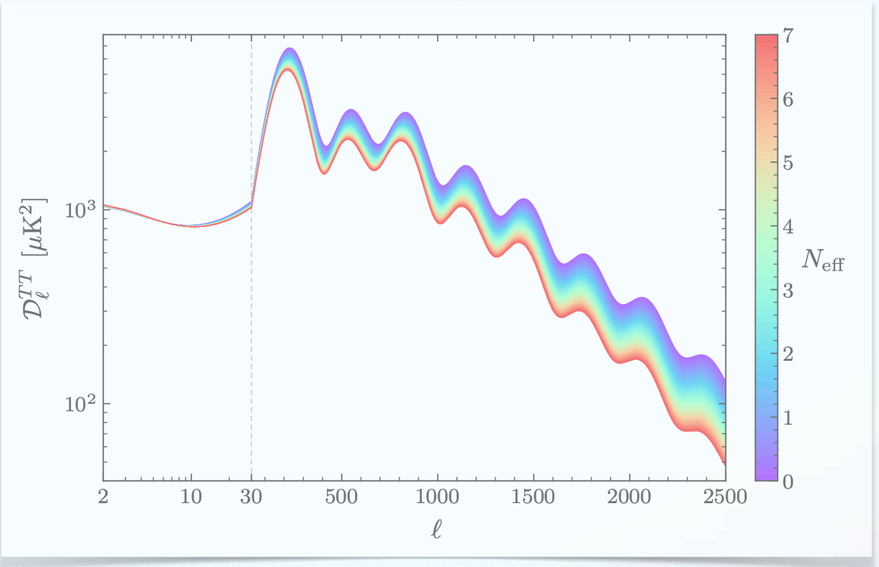
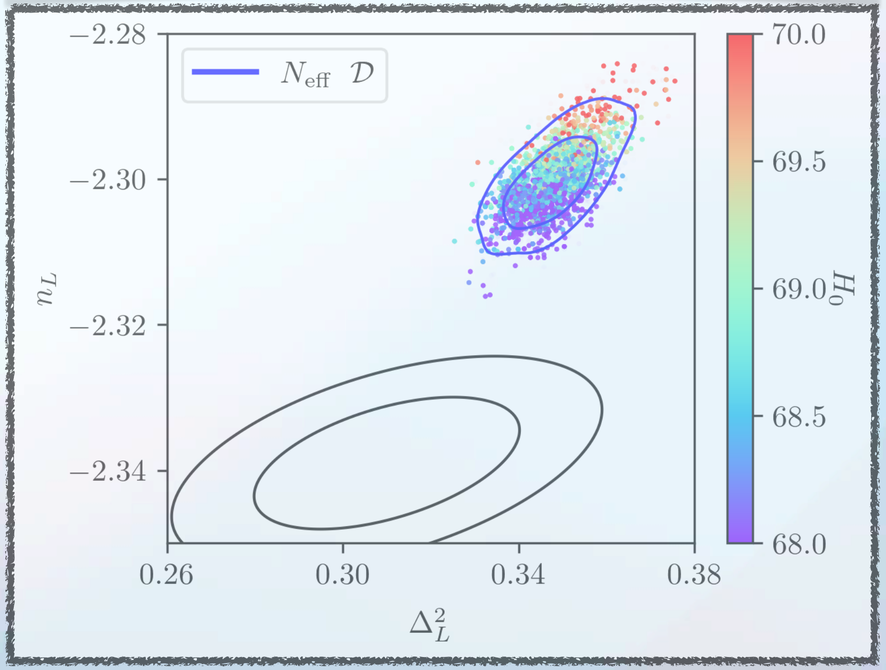
Alternatives: Interacting DR (IDR) or

DR Interacting with DM





Interacting DR models

Less efficient at erasing small-scale structure → **Less constrained by CMB fits**

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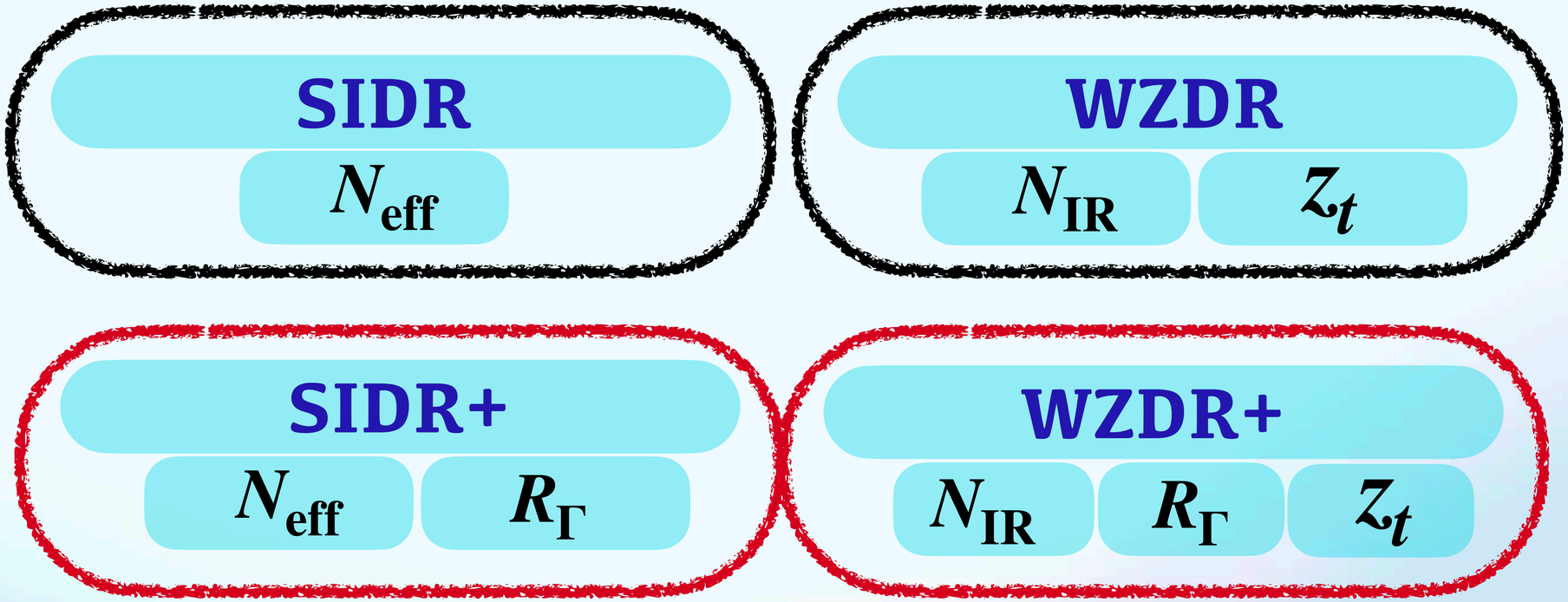

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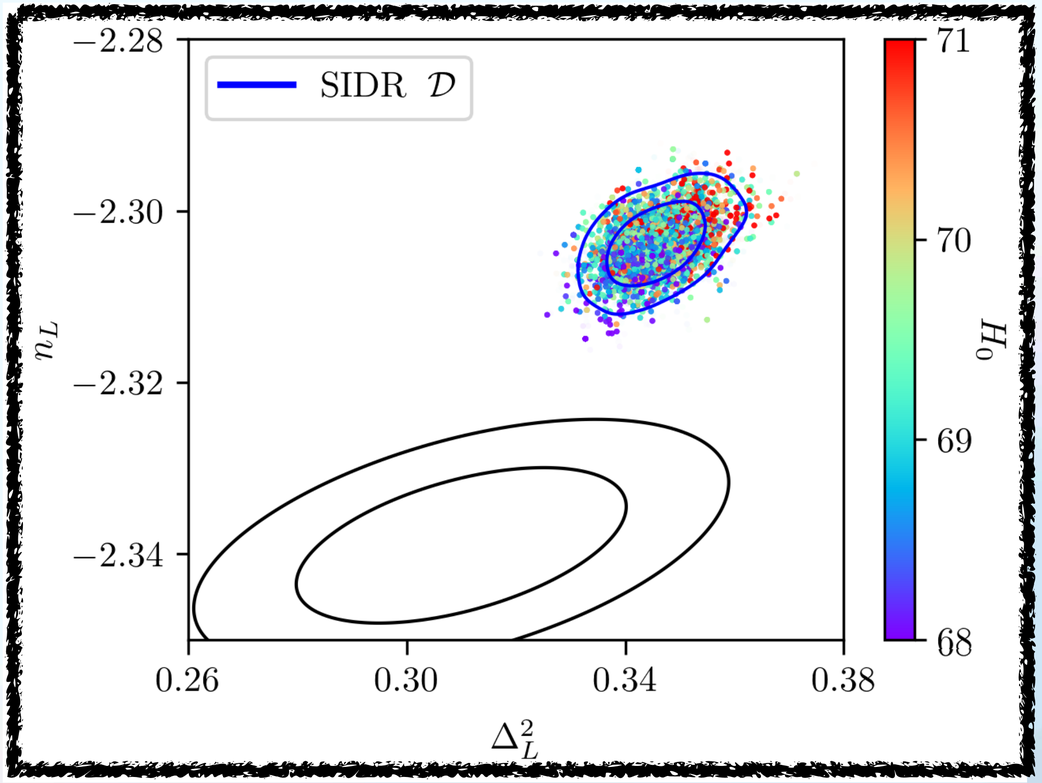
Interacting DR models

SIDR

$N_{\rm eff}$

- **Acts as a perfect fluid.**
- **Overcomes limitations of FSDR.**
- **Allows for more $\Delta N_{\rm eff}$ for a better H_0 fit while still fitting CMB data well.**

- **No help with the tension in Ly-α**



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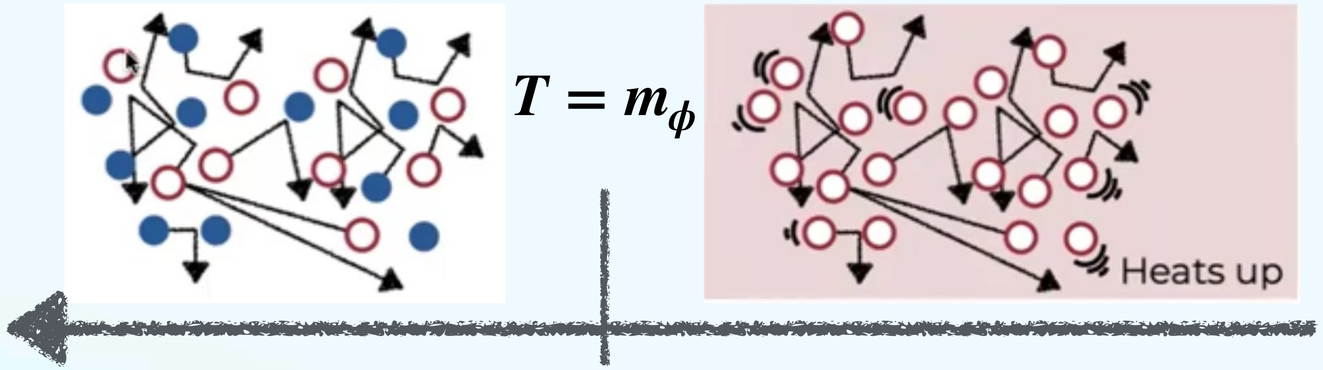
Interacting DR models

$$\mathcal{L}_{\mathrm{WZDR}} = \lambda\phi\bar{\psi}\psi + \lambda^2(\phi^*\phi)^2$$

$$m_\phi \neq 0$$



WZDR

N_{IR} z_t

2111.00014

- **IDR fluid with 2 components.**
- **Model of "Stepped DR".**
- **Enhances the fit to CMB.**

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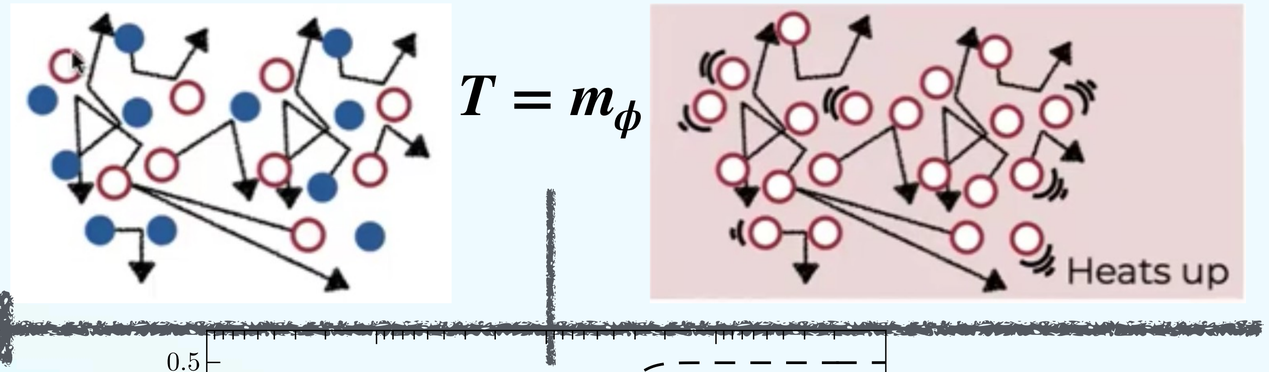

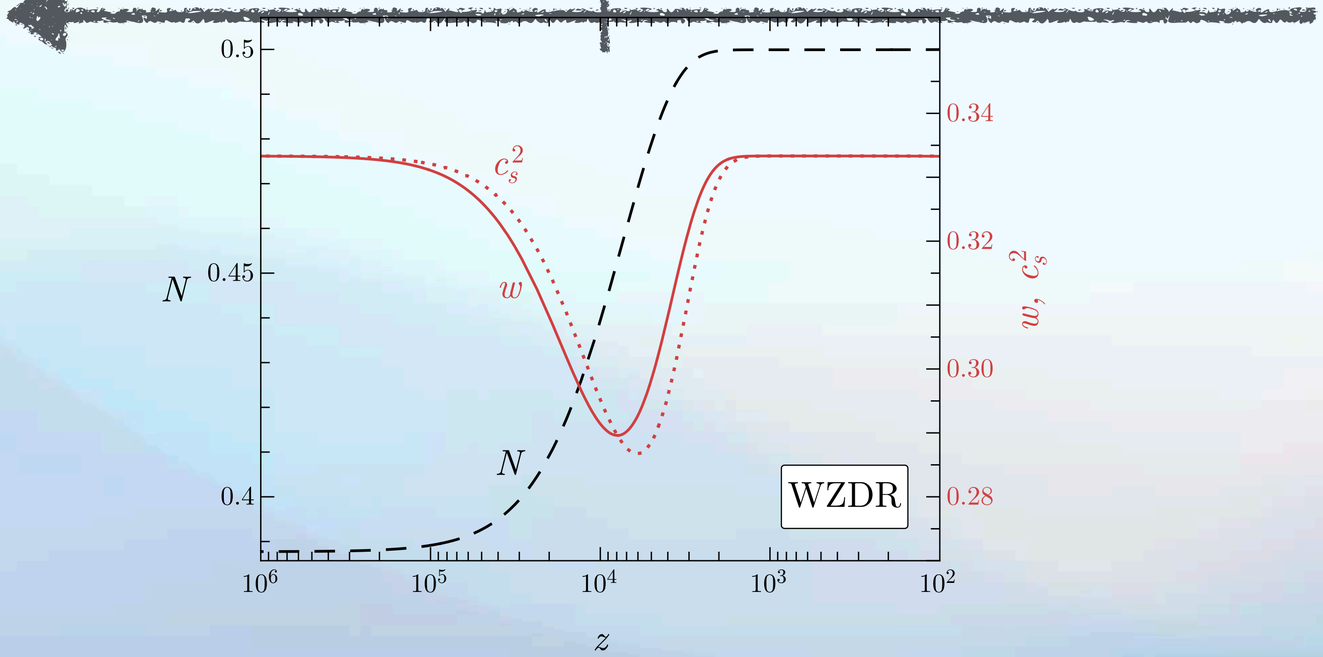

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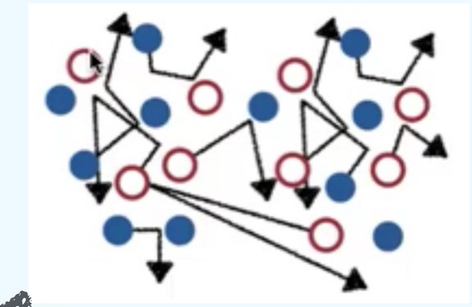
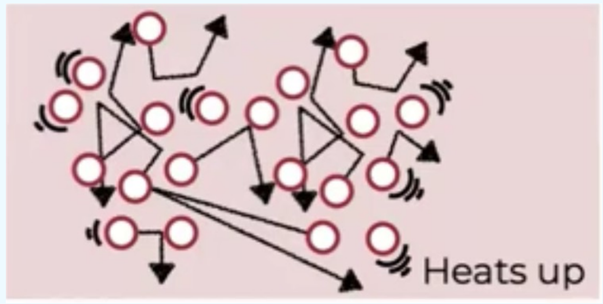
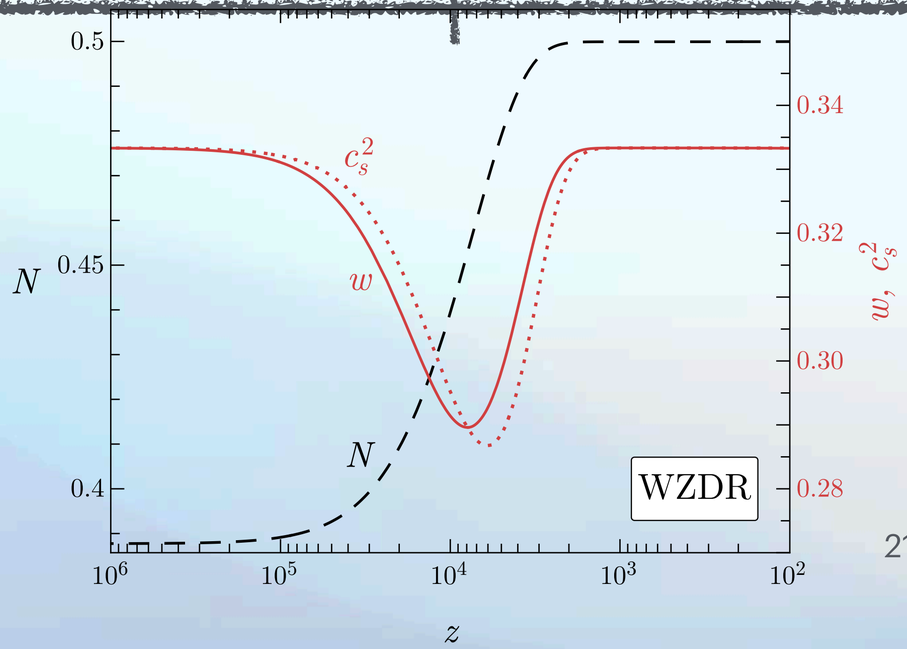
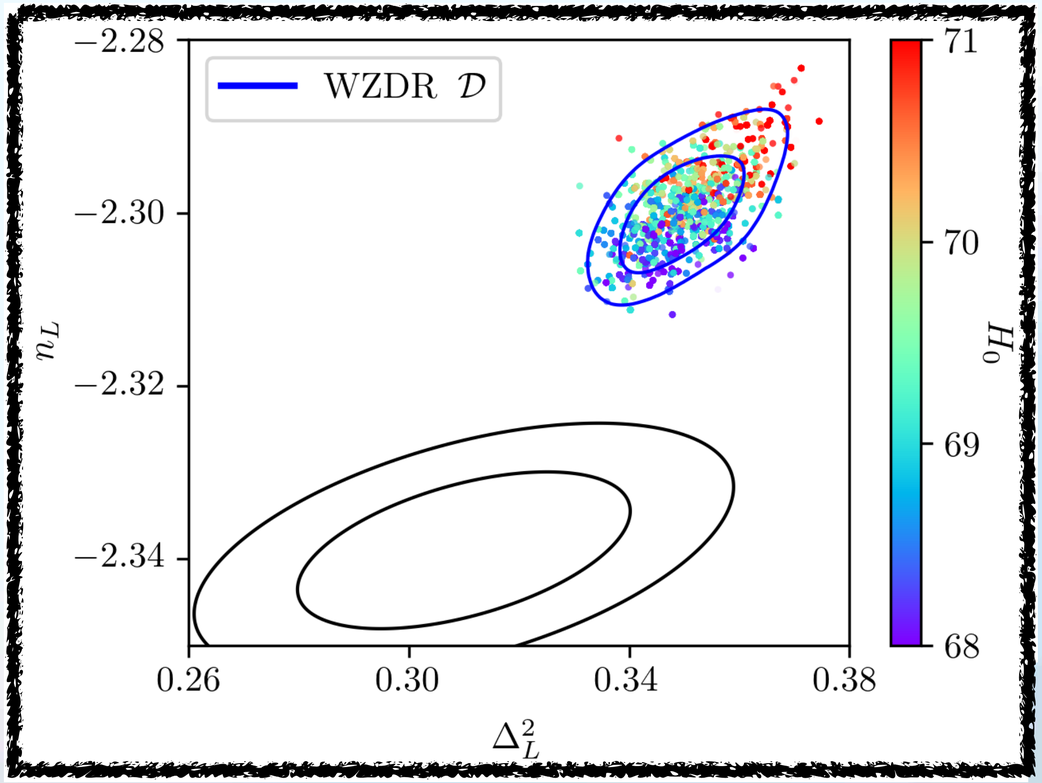


$T = m_\phi$





2111.00014



2405.17554

- **No help with the tension in Ly-α**

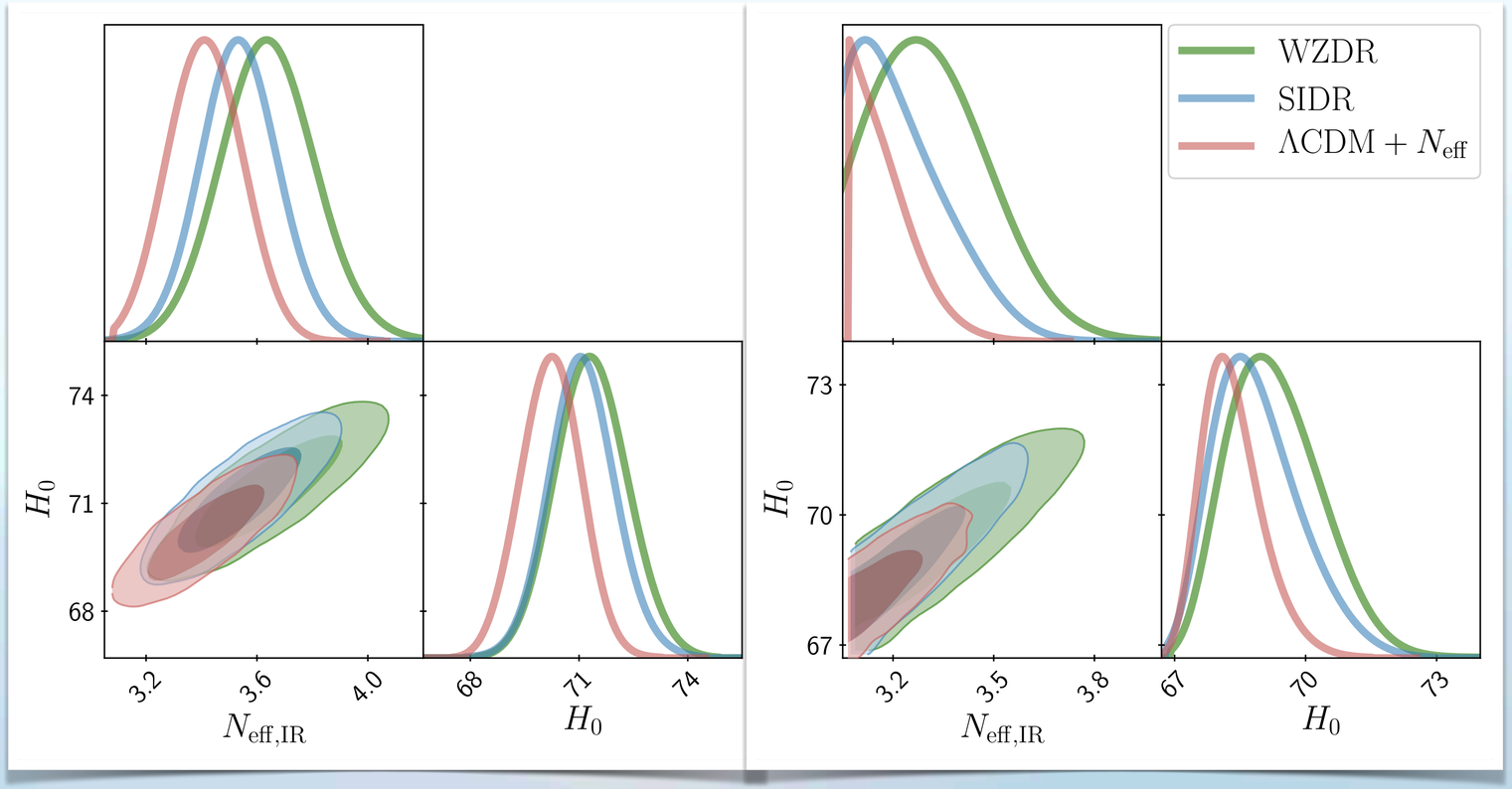
Interacting DR models

SIDR

$N_{\rm eff}$

WZDR

$N_{\rm IR}$ z_t



2111.00014

Interacting DM-DR models

Models where IDR couples to DM show consistency with all LSS data, including Ly-α, while still significantly alleviating H_0 tension.

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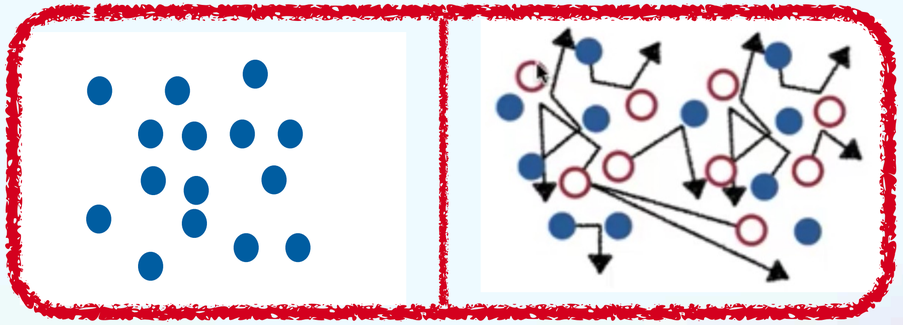

2405.17554

- **Interaction with DR** → **Transfers momentum to DM**

$$\dot{\vec{p}}_{\rm DM} = -a\Gamma\,\vec{p}_{\rm DM}$$

- **Additional Pressure** → **Suppresses Structure Formation**

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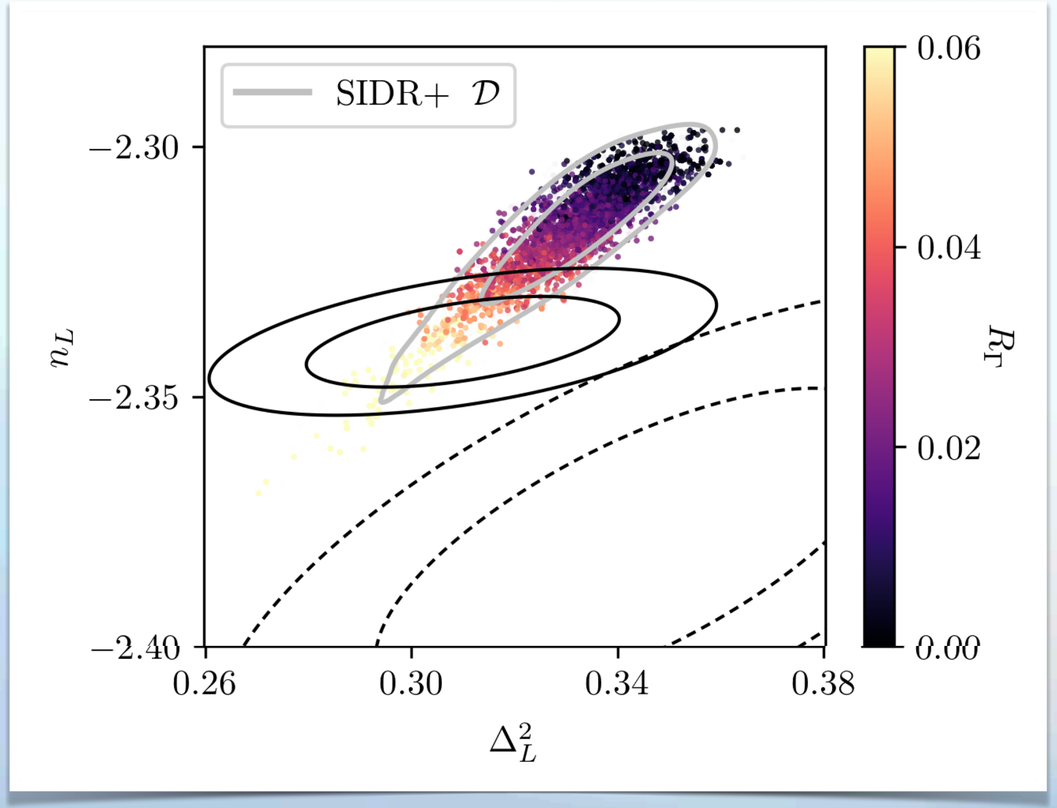
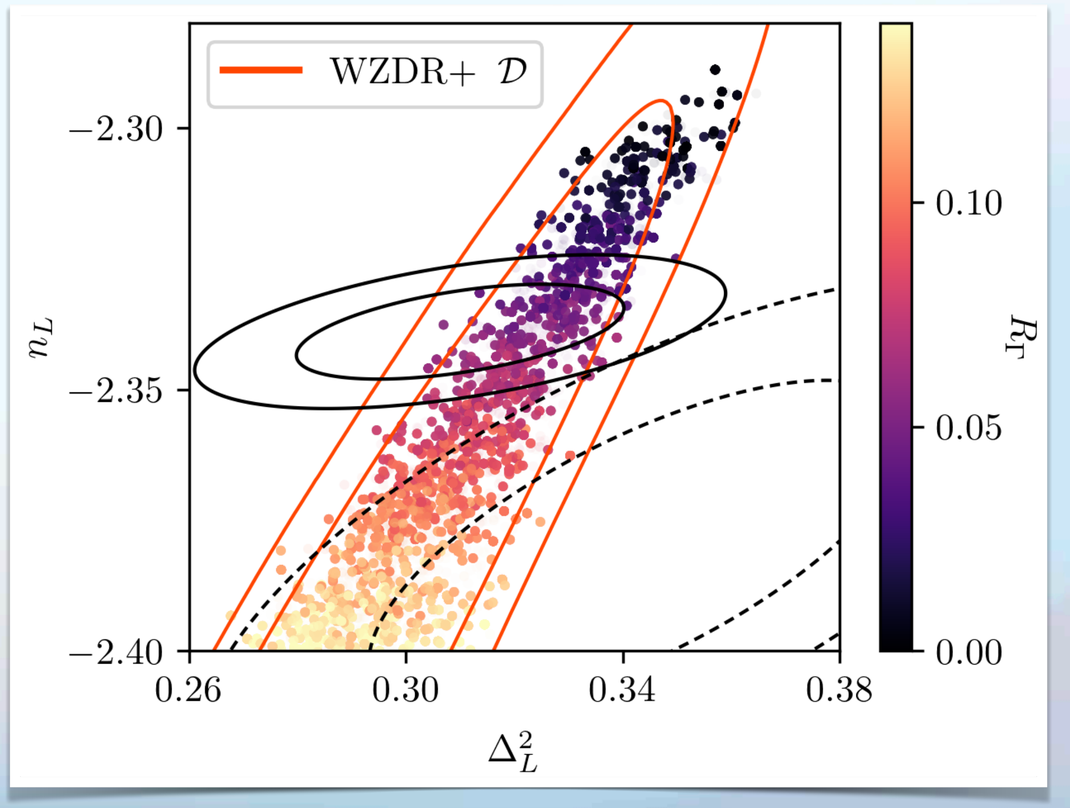
2405.17554





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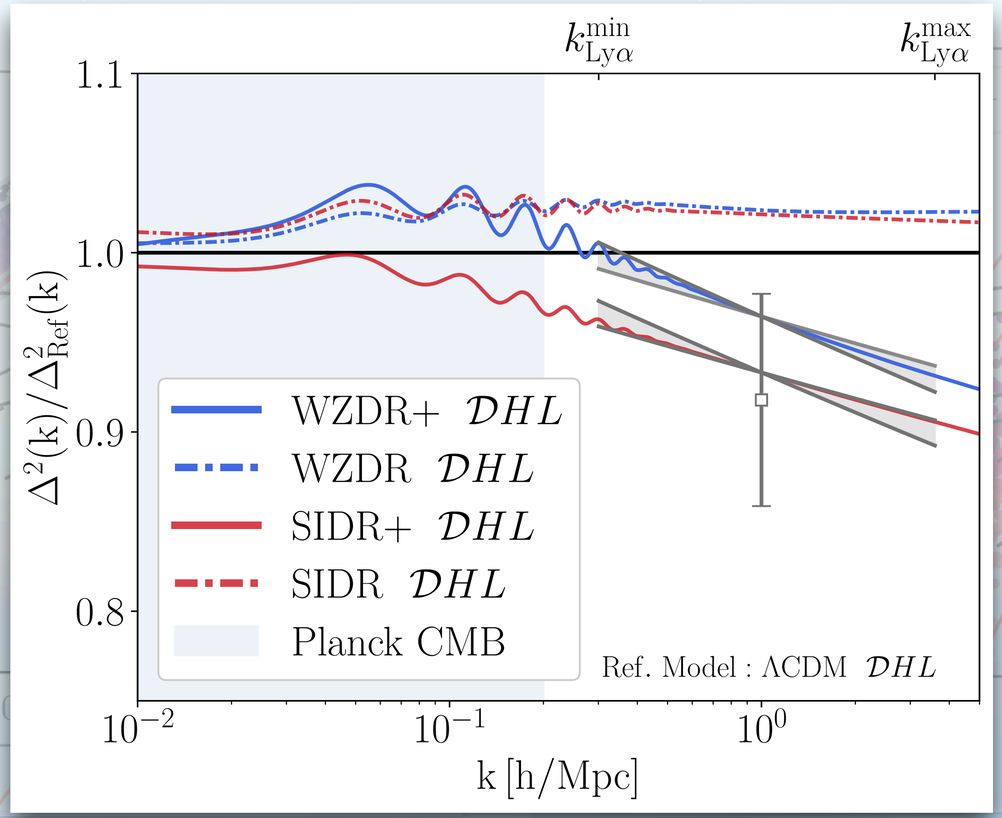
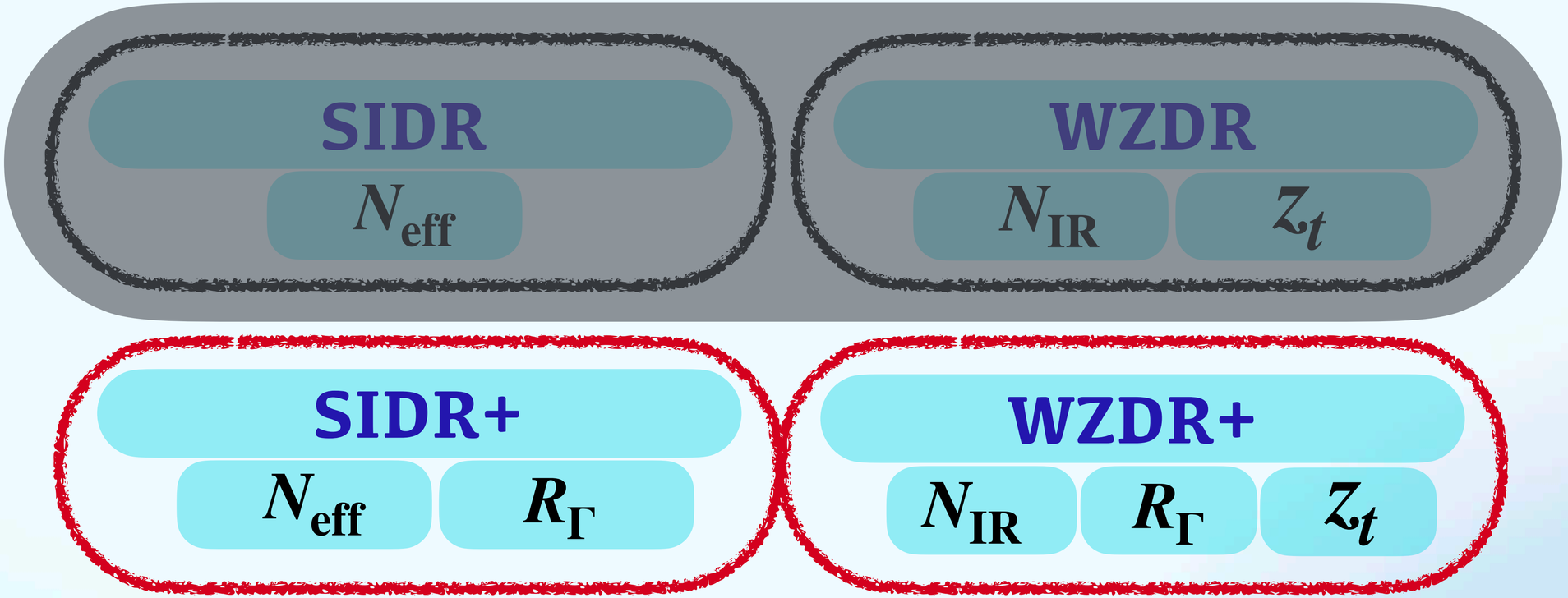
2405.17554



SIDR+ z_t Model :



$\Delta N_{\rm eff} \sim 0.6$

$R_\Gamma \sim 0.07$

$\log_{10}(z_t) \sim 4.25$

2405.17554

Our Proposal : SIDR+ z_t

Overview of the Model

$$\mathcal{G} \equiv \mathcal{G}_{\mathrm{SM}} \otimes U(1)_D$$

2408.03004

- **inelastic dark matter (iDM) scenario coupled with DR.**

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$$\mathcal{L} \supset i\bar{\psi}\gamma^\mu D_\mu \psi - M_\psi \bar{\psi}\psi + i\bar{\chi}\gamma^\mu D_\mu \chi - M_\chi \bar{\chi}\chi$$

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$$\mathcal{L} \supset i g_D (Z_D)_\mu \left[c_\beta^2\ \ \overline{\xi}_1 \gamma^\mu \xi_1 + s_\beta^2\ \ \overline{\xi}_2 \gamma^\mu \xi_2 + c_\beta s_\beta\ (\overline{\xi}_1 \gamma^\mu \xi_2 + \overline{\xi}_2 \gamma^\mu \xi_1) \right] - y(\cos\gamma\ h_2 + \sin\gamma\ h_1) \left[c_{2\beta} (\overline{\xi}_1 \xi_2 + \overline{\xi}_2 \xi_1) + s_{2\beta}\ (\overline{\xi}_2 \xi_2 - \overline{\xi}_1 \xi_1) \right]$$

$$\mathcal{L} \supset \epsilon g (Z_D)_\mu \bar{f} \gamma^\mu f + \epsilon g_X \frac{s_{\theta_W}}{c_{\theta_W}} Z_\mu \left[c_\beta^2\ \ \overline{\xi}_1 \gamma^\mu \xi_1 + s_\beta^2\ \ \overline{\xi}_2 \gamma^\mu \xi_2 + c_\beta s_\beta\ (\overline{\xi}_1 \gamma^\mu \xi_2 + \overline{\xi}_2 \gamma^\mu \xi_1) \right]$$

Possible features of the Model

- Decay of S produces DM and DR, yielding $\Omega_{\rm DM}h^2$ and $\Delta N_{\rm eff}$ after BBN
- DR has self-interactions, facilitated by $\lambda_\phi \left(\Phi^\dagger \Phi\right)^2$
- DM-DR interactions leading to momentum transfer
- Suppression of DM-DR interactions at z_t determined by δ
- Two "Step" increase in DR energy density

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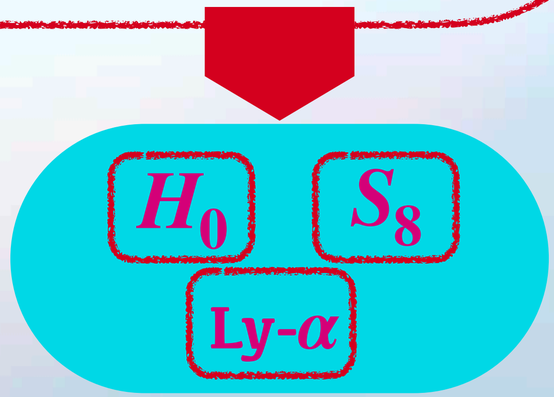
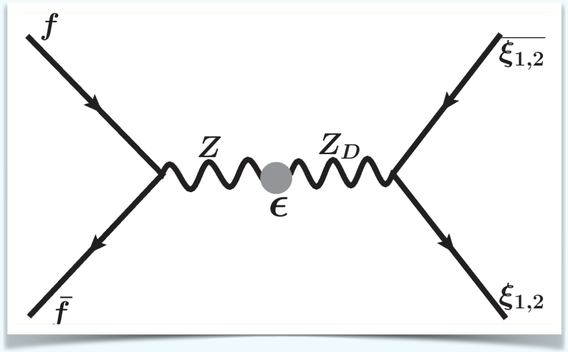
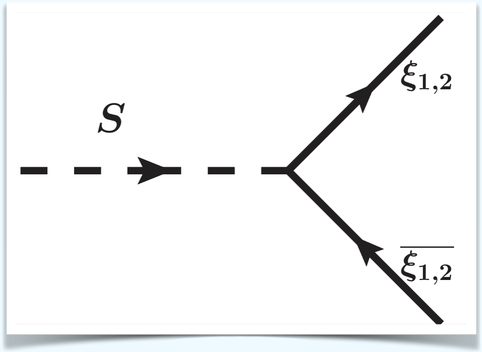
2408.03004



Production of DM and DR





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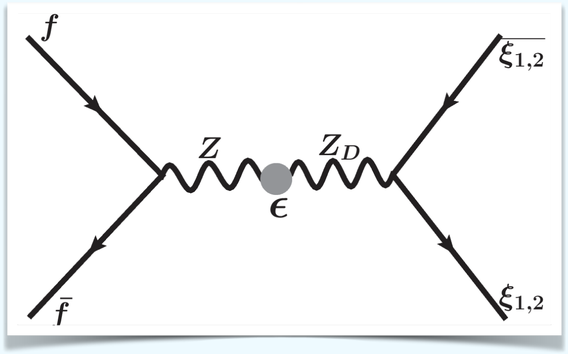

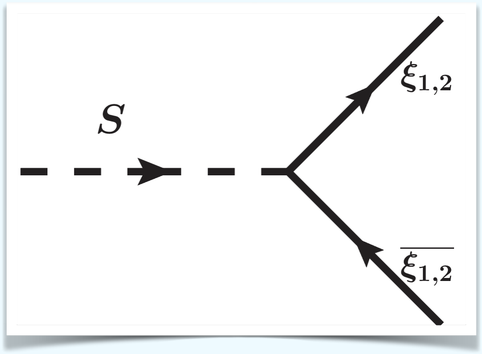

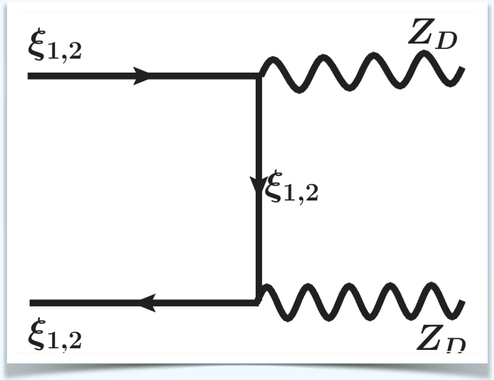

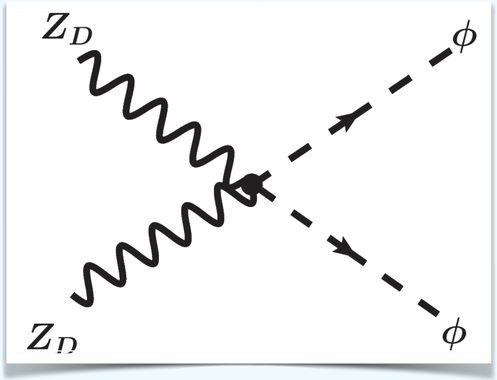

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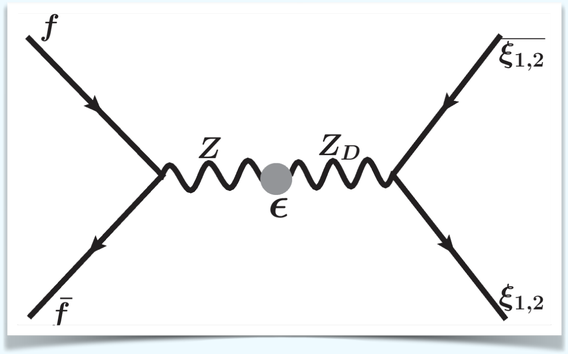

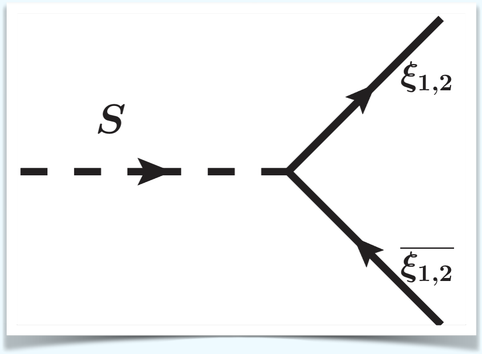

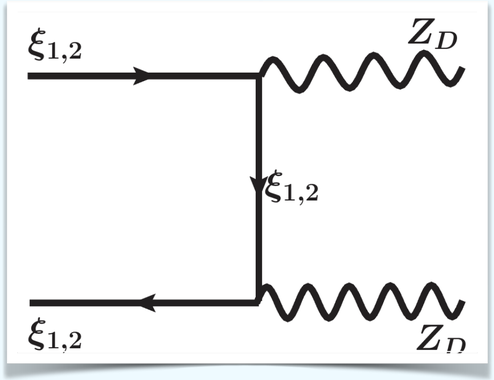

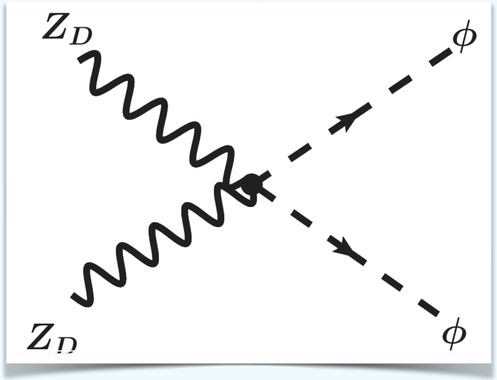

$$\rho_S|_{\text{decay}} = \rho_\xi + \rho_{Z_D} + \rho_\phi$$

2408.03004

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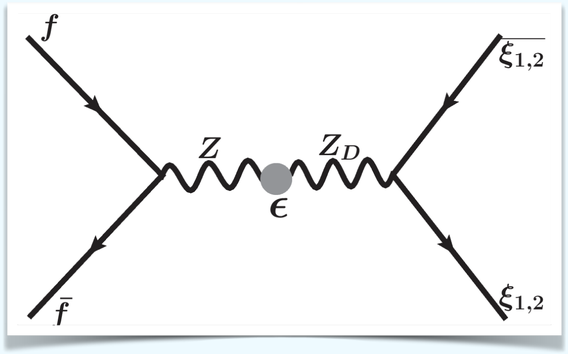

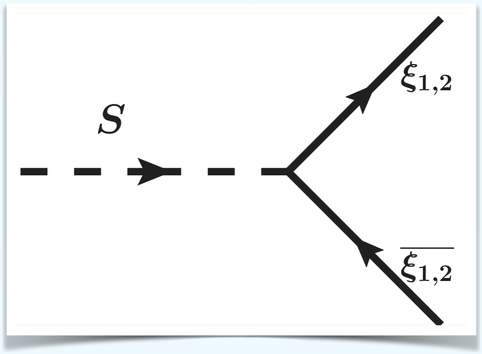

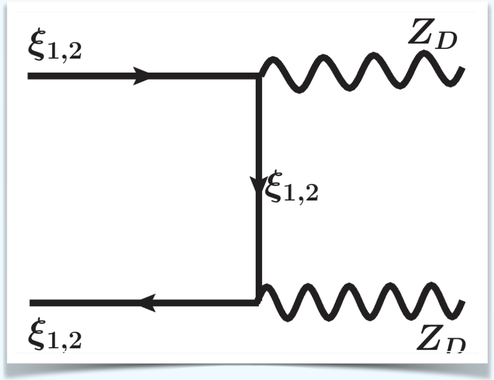

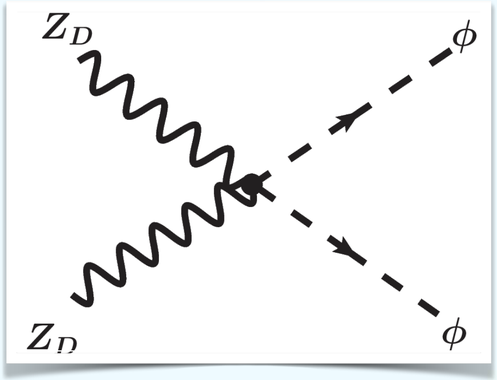

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2408.03004

Annihilation of DM into Z_D

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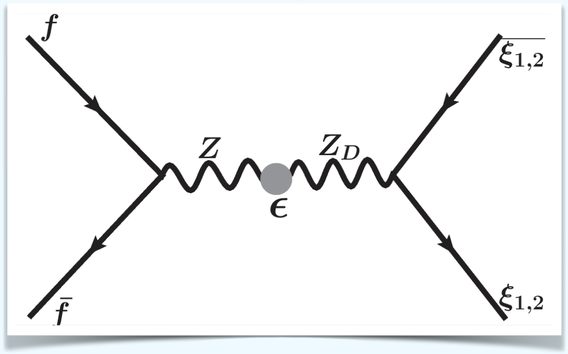
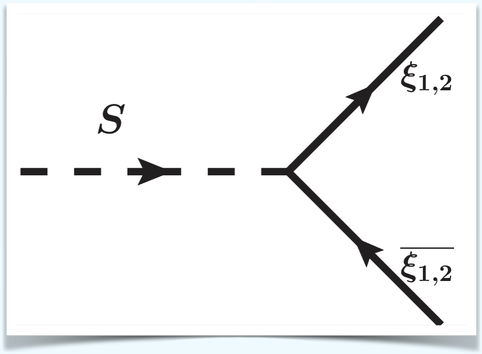
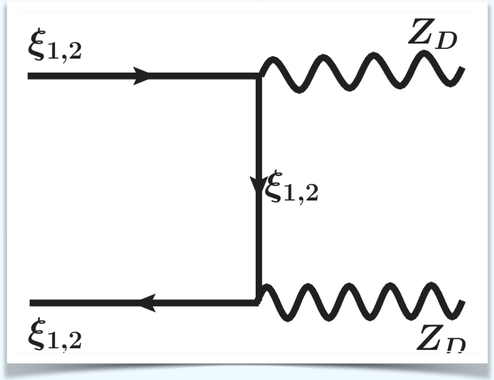
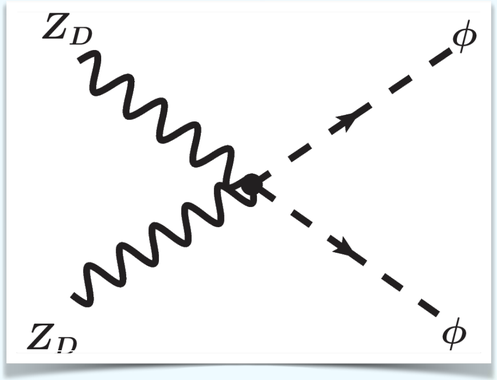
Production of DM and DR









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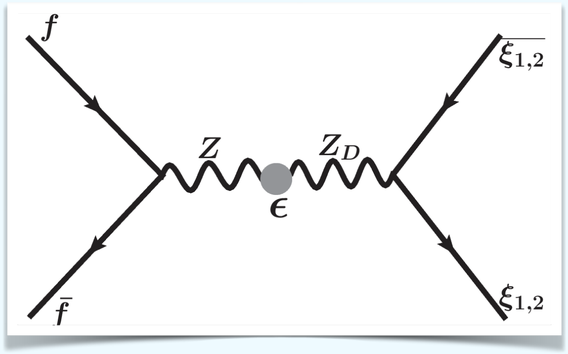
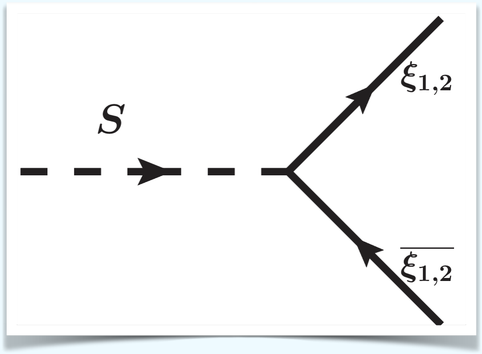
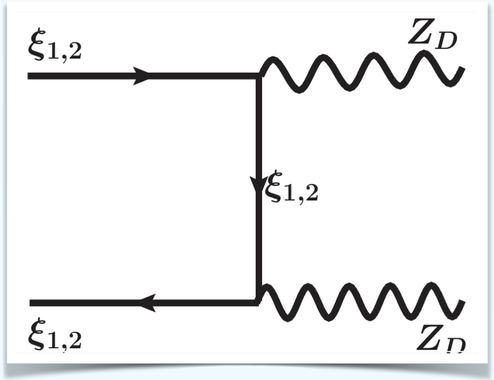
Annihilation of Z_D into DR

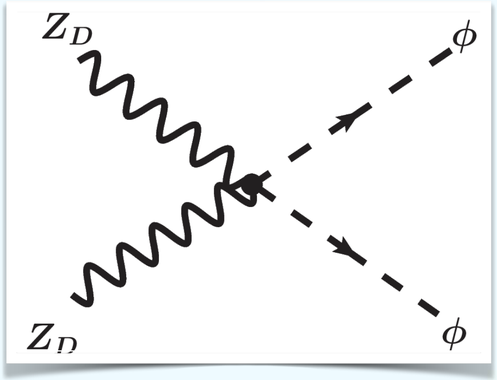
$$\frac{\Delta N_{\text{eff}}|_{\text{after}}}{\Delta N_{\text{eff}}|_{\text{before}}} = \left(\frac{g_*^{Z_D} + g_*^{\phi}}{g_*^{\phi}}\right)^{1/3} \simeq 1.58.$$

Production of DM and DR









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2408.03004

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Annihilation of Z_D into DR

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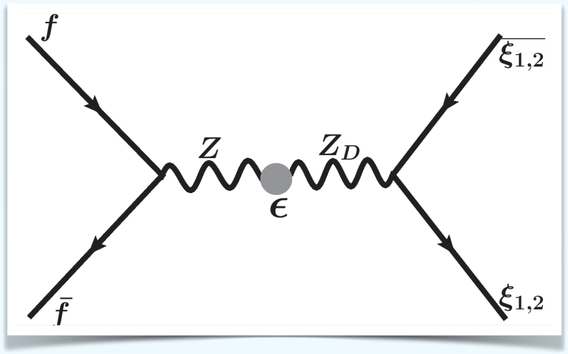
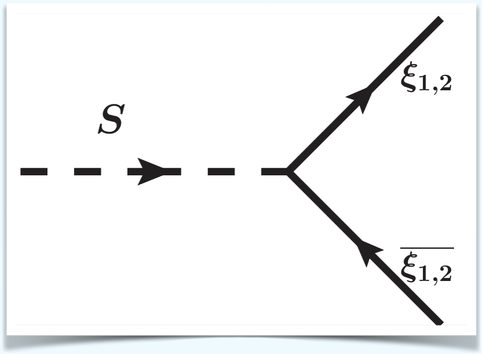
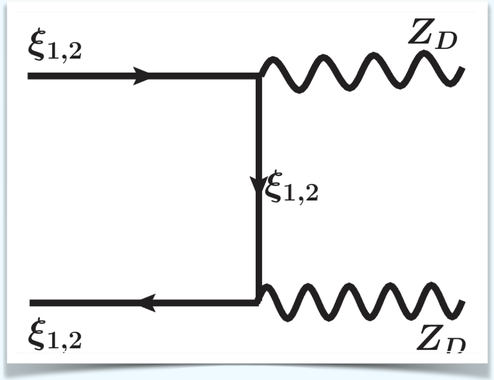
2 stepwise increase in ΔN_{eff}

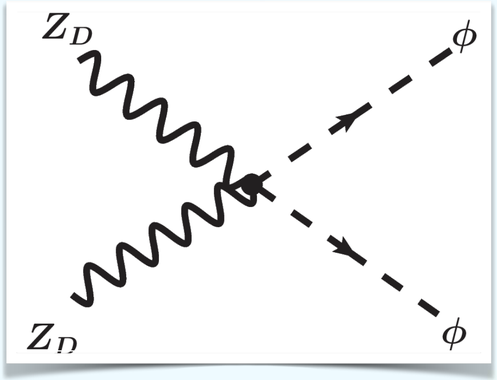
cascading energy transfer from heavier to lighter species in the dark sector, ultimately augments the DR component.

Production of DM and DR









$$\rho_S|_{\text{decay}} = \rho_\xi + \rho_{Z_D} + \rho_\phi$$

Annihilation of DM into Z_D

$$\frac{\Delta N_{\text{eff}}|_{\text{after}}}{\Delta N_{\text{eff}}|_{\text{before}}} = \left(\frac{\frac{7}{8}g_*^{\xi_1} + g_*^{Z_D} + g_*^{\phi}}{g_*^{Z_D} + g_*^{\phi}}\right)^{1/3} \simeq 1.23.$$

Annihilation of Z_D into DR

$$\frac{\Delta N_{\text{eff}}|_{\text{after}}}{\Delta N_{\text{eff}}|_{\text{before}}} = \left(\frac{g_*^{Z_D} + g_*^{\phi}}{g_*^{\phi}}\right)^{1/3} \simeq 1.58.$$

2 stepwise increase in ΔN_{eff}

$$\Delta N_{\text{eff}} \simeq \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_{\text{DR}}}{\rho_\gamma}$$

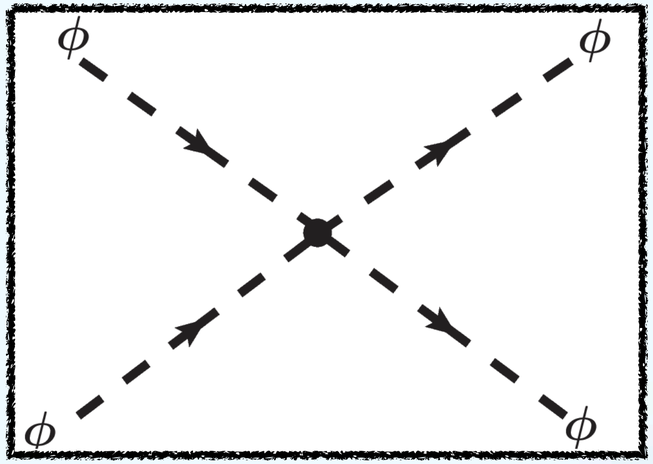
To achieve $\Delta N_{\text{eff}} \simeq 0.6 \implies T_h = 0.77\ T_v$

VS T_v ..... DS T_h

2408.03004

Self-Interacting DR

Self-interactions prevent the dark radiation from free-streaming, causing it to behave as an ideal relativistic fluid.



$$\Gamma_{\phi\phi\leftrightarrow\phi\phi}/H = \frac{\frac{9\zeta(3)}{8\pi^3}\lambda_\phi^2\zeta T_v}{\frac{\pi}{3\sqrt{10}}(g_* + \zeta^4)^{1/2}T_v^2} = 0.13 M_{Pl}\lambda_\phi^2\frac{\zeta}{(g_* + \zeta^4)^{1/2}T_v} \gtrsim 1$$

$$\lambda_\phi \gtrsim 10^{-13}.$$

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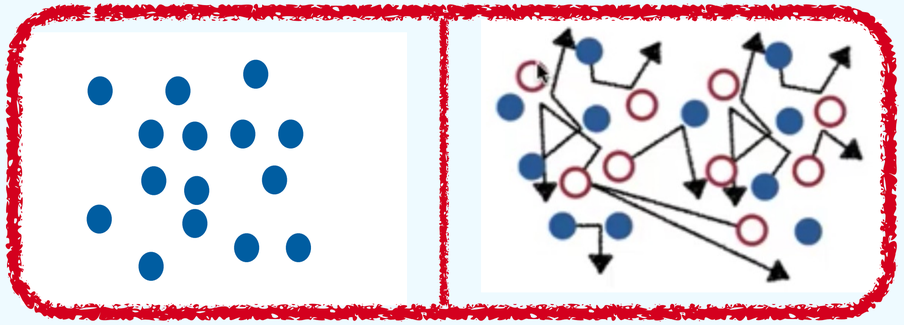
DM-DR Interaction

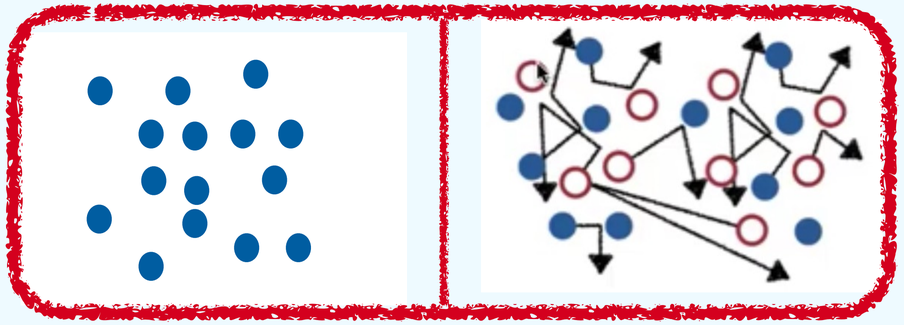


- Interaction with DR → Transfers momentum to DM

$$\dot{\vec{p}}_{\mathrm{DM}} = -a\Gamma\,\vec{p}_{\mathrm{DM}}$$

- Additional Pressure → Suppresses Structure Formation

DM-DR Interaction



- Interaction with DR → Transfers momentum to DM

$$\dot{\vec{p}}_{\rm DM} = -\,a\Gamma\,\vec{p}_{\rm DM}$$

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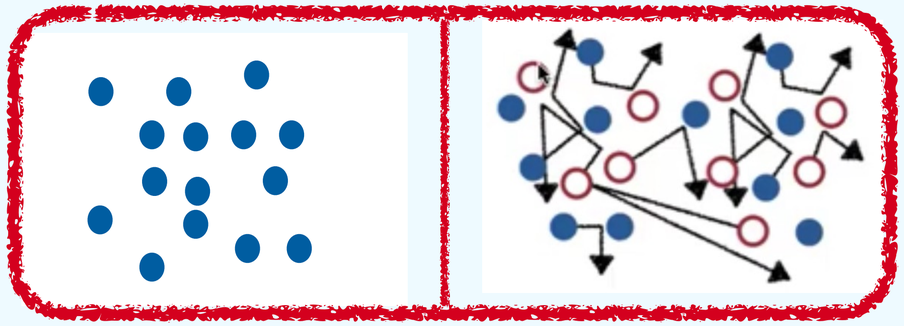
$$\dot{\vec{p}}_{\rm DM} = \frac{a}{2E_p}\int \frac{d^3k}{(2\pi)^3 2E_k} f(k;T) \int \frac{d^3k'}{(2\pi)^3 2E_{k'}} \frac{d^3p'_{\rm DM}}{(2\pi)^3 2E_{P'_{\rm DM}}} (2\pi)^4 \delta^{(4)}(p_{\rm DM} + k - p'_{\rm DM} - k') \mid \mathscr{M} \mid^2 (\vec{p'}_{\rm DM} - \vec{p}_{\rm DM})$$

$$\Gamma \simeq \frac{1}{8(2\pi)^3 M_{\rm DM}^3} \int k^3 f(k;T) dk \int d\cos\theta \mid \mathscr{M} \mid^2 (1 - \cos\theta)$$

DM-DR Interaction



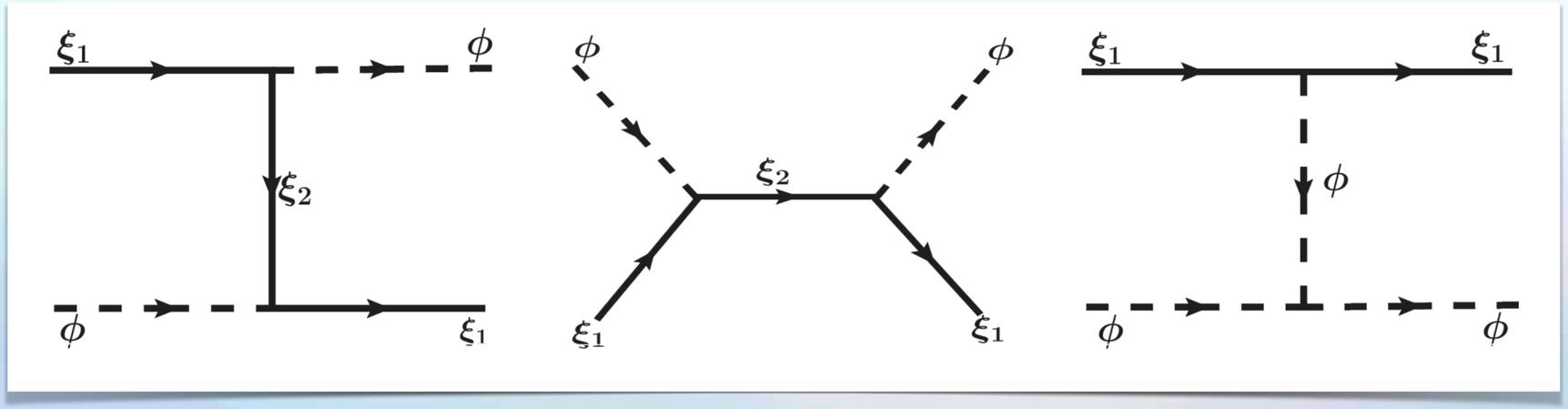
- Interaction with DR → Transfers momentum to DM

$$\dot{\vec{p}}_{\rm DM} = -a\Gamma\,\vec{p}_{\rm DM}$$

$\xi_{1,2}$

ϕ DS Z_D

T_h



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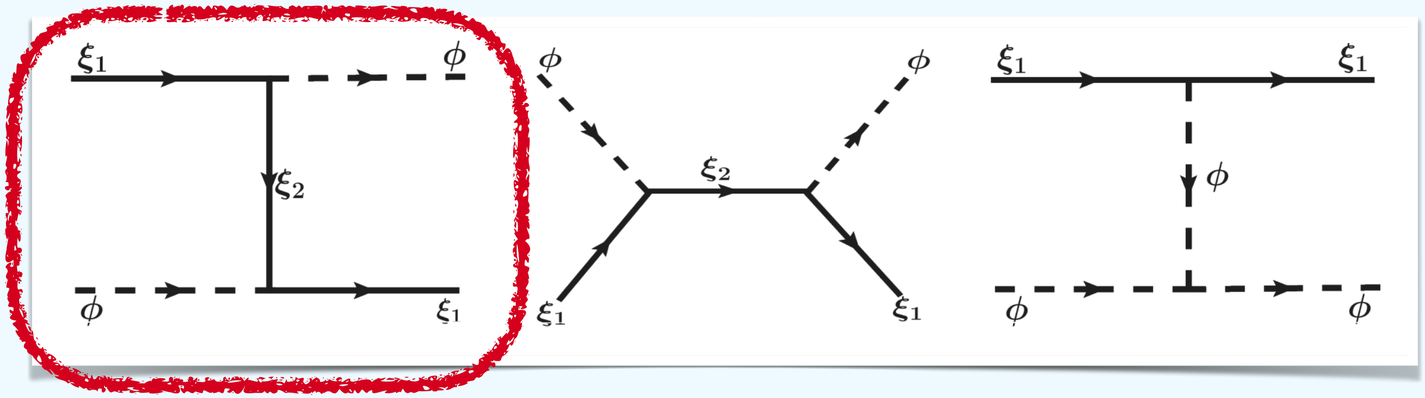
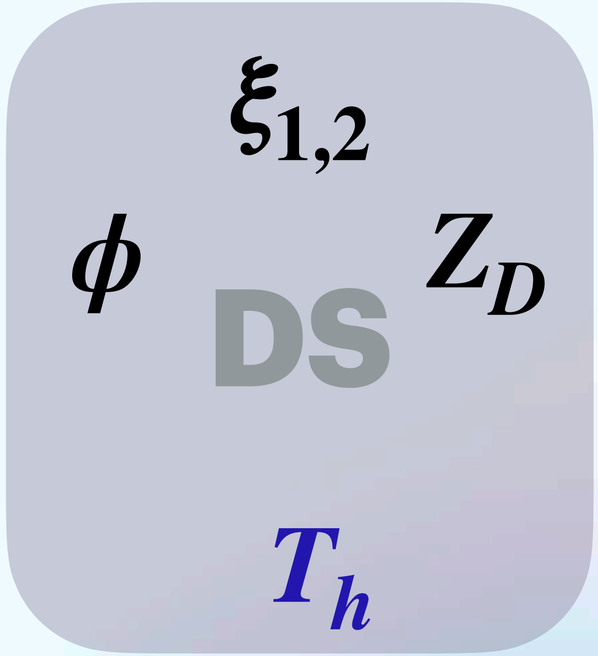
DM-DR Interaction

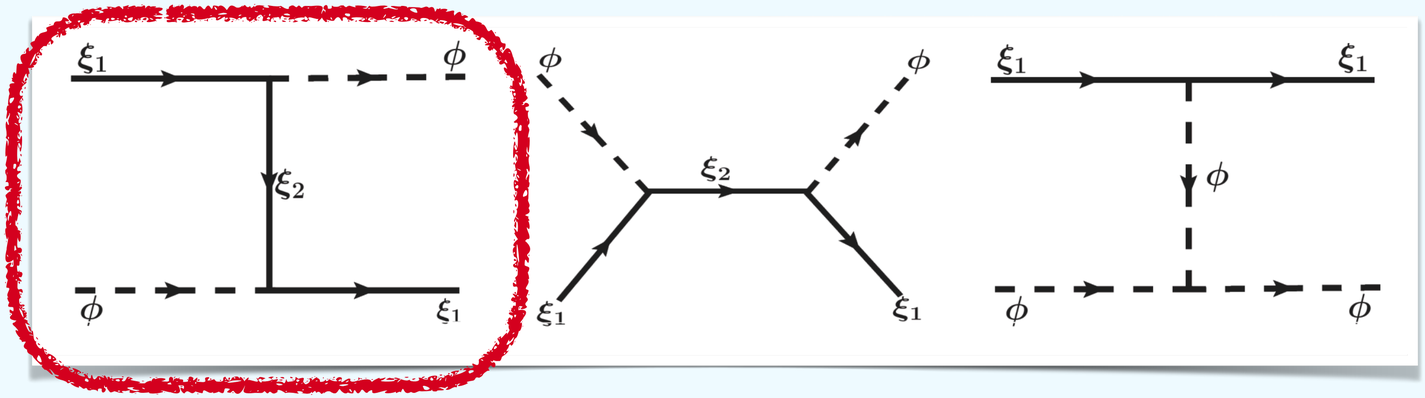


$$\overline{|\mathscr{M}|^2} \simeq \frac{y^4(1-2\sin^2\beta)^4 M_{\xi_1}^2}{(k+\delta)^2}$$

2408.03004



DM-DR Interaction



$$\overline{|\mathscr{M}|^2} \simeq \frac{y^4(1-2\sin^2\beta)^4 M_{\xi_1}^2}{(k+\delta)^2}$$

2408.03004

$$\Gamma \simeq \frac{y^4(1-2\sin^2\beta)^4 T_h^2}{32\pi^3 M_{\xi_1}} f(x)$$

$$\simeq 2.43\times10^{-34}\,\mathrm{GeV}\left(\frac{T_h}{100\,\mathrm{eV}}\right)^2\left(\frac{y(1-2\sin^2\beta)}{4.1\times10^{-6}}\right)^4\left(\frac{0.01\,\mathrm{MeV}}{M_{\xi_1}}\right), \quad \text{for} \quad T_h \gg \delta,$$

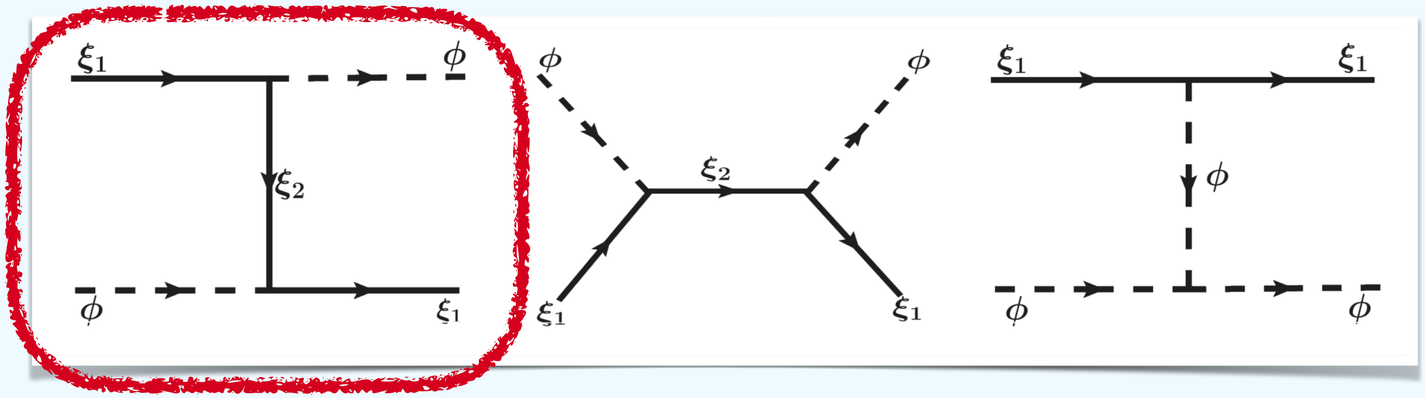
$$\simeq 1.46\times10^{-43}\,\mathrm{GeV}\left(\frac{T_h}{0.1\,\mathrm{eV}}\right)^4\left(\frac{y(1-2\sin^2\beta)}{4.1\times10^{-6}}\right)^4\left(\frac{0.01\,\mathrm{MeV}}{M_{\xi_1}}\right)\left(\frac{10\,\mathrm{eV}}{\delta}\right)^2, \quad \text{for} \quad T_h \ll \delta,$$

$\xi_{1,2}$

ϕ DS Z_D

T_h

DM-DR Interaction



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2408.03004

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$$R_\Gamma \equiv \frac{\Gamma}{H} \simeq 0.07\left(\frac{y(1-2\sin^2\beta)}{4.1\times10^{-6}}\right)^4\left(\frac{0.01\,\mathrm{MeV}}{M_{\xi_1}}\right), \quad \text{for} \quad T \gg \delta,$$

$\xi_{1,2}$

ϕ DS Z_D

T_h

$$1+z_t = \delta/T_{h_0}$$

SIDR+ z_t Model :

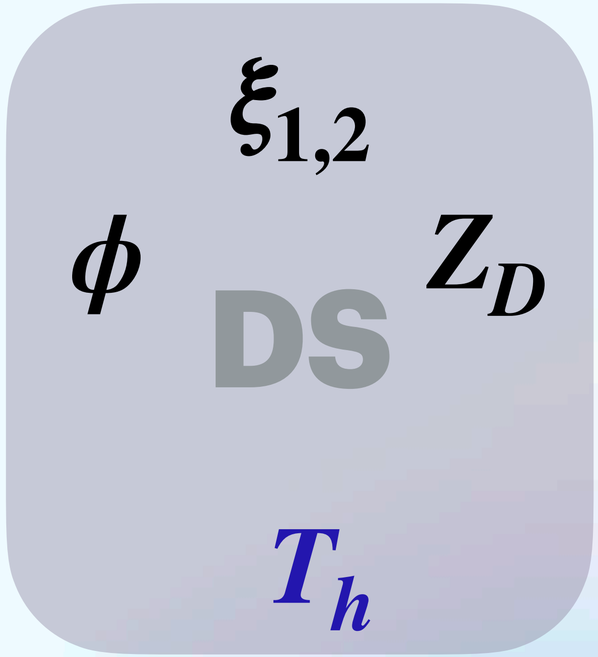
$\Delta N_{\rm eff} \sim 0.6$

$R_\Gamma \sim 0.07$

$\log_{10}(z_t) \sim 4.25$

$\Omega_{\rm DM} h^2 = 0.12$

And other consistency checks…



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$$M_\xi = 0.01 \text{ MeV}, \quad \delta = 3.2 \text{ eV}, \quad M_{Z_D} = 5 \text{ eV}, \quad \alpha_D = 2.8 \times 10^{-10}, \quad y = 4.1 \times 10^{-6}$$

$$v_\phi = 8.4 \times 10^{-5} \text{ GeV}, \quad \lambda_\phi = 1.4 \times 10^{-12}, \quad \sin 2\beta = 0.153$$

Boltzmann Equations and Numerical Results

DS never thermalizes with SM.

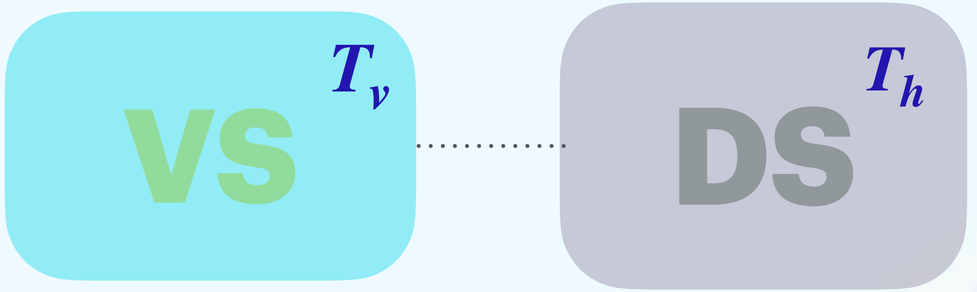
How to produce DM?

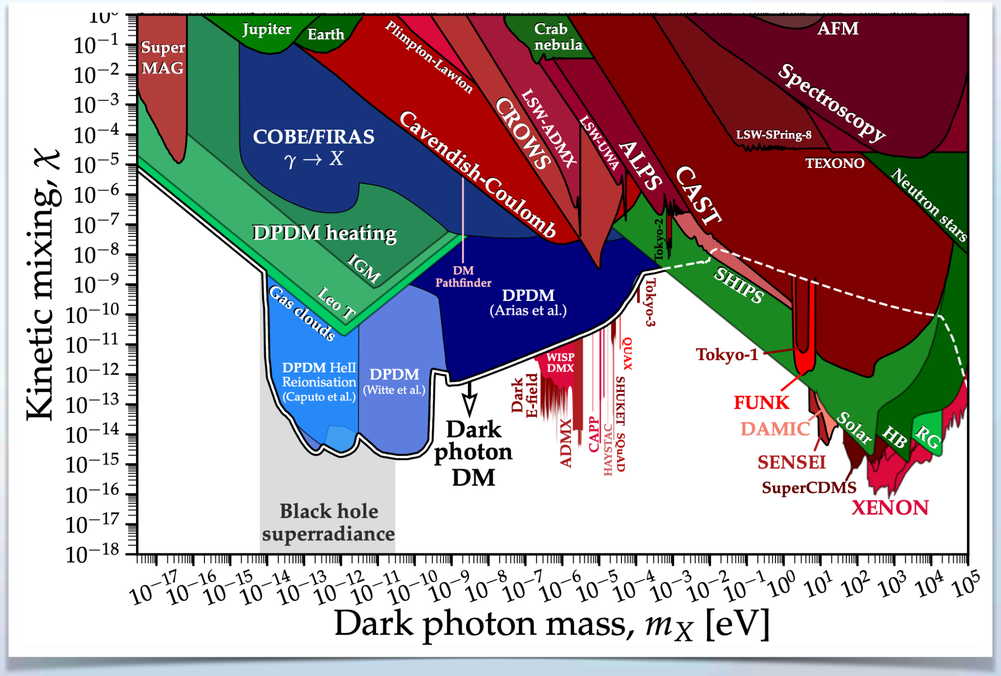
Freeze-in?

Insufficient to produce the required DR

Soln: Non-thermal production

Source: Decay of S





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Boltzmann Equations and Numerical Results

$$\frac{d\rho_v}{dt} + 3H(\rho_v + p_v) = -j_h,$$
$$\frac{d\rho_h}{dt} + 3H(\rho_h + p_h) = j_h,$$

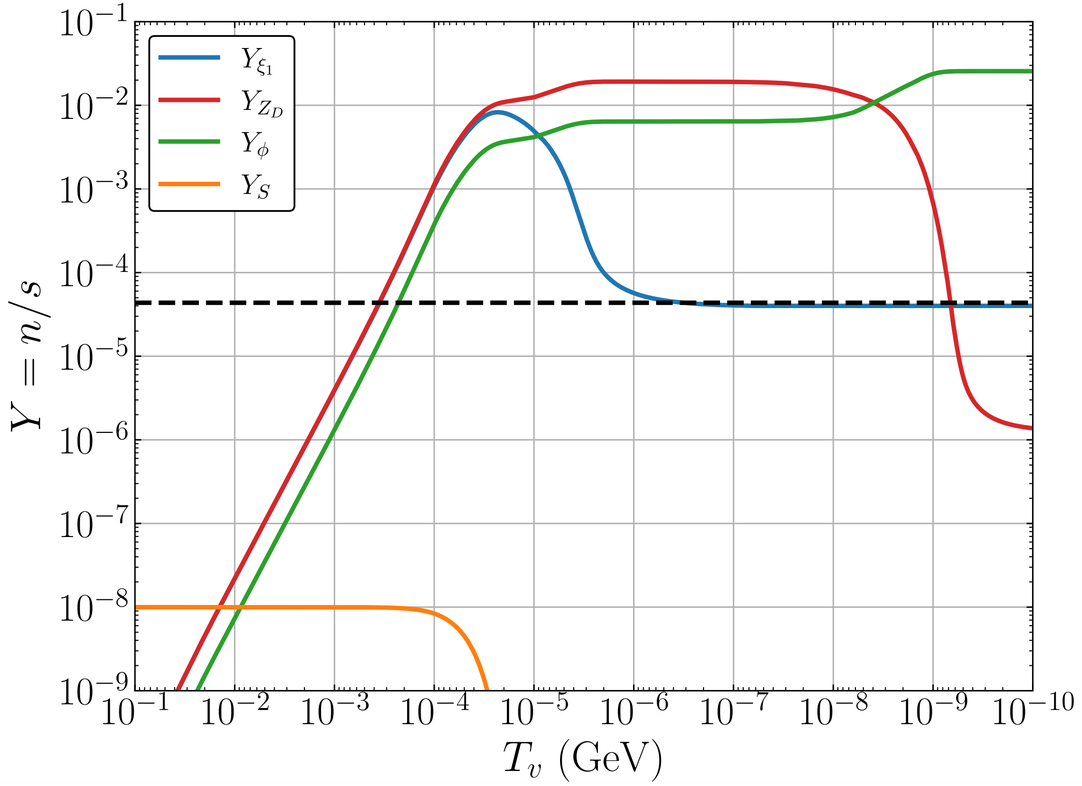
VS T_v ..... DS T_h

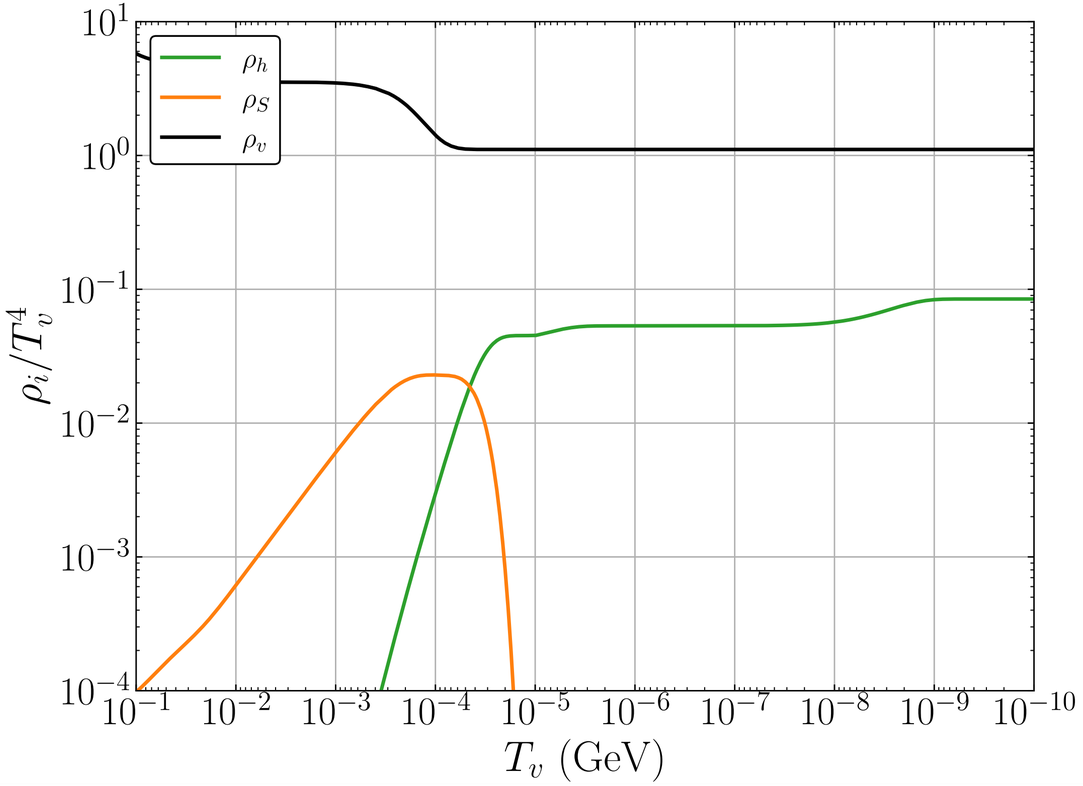
$$\frac{dT_v}{dt} = -\frac{3H(\rho_v + p_v) + j_h}{d\rho_v/dT_v}$$

$$\frac{d\rho_h}{dT_v} = \frac{3H(1+\omega_h)\rho_h - j_h}{3H(1+\omega_v)\rho_v + j_h}\frac{d\rho_v}{dT_v}$$

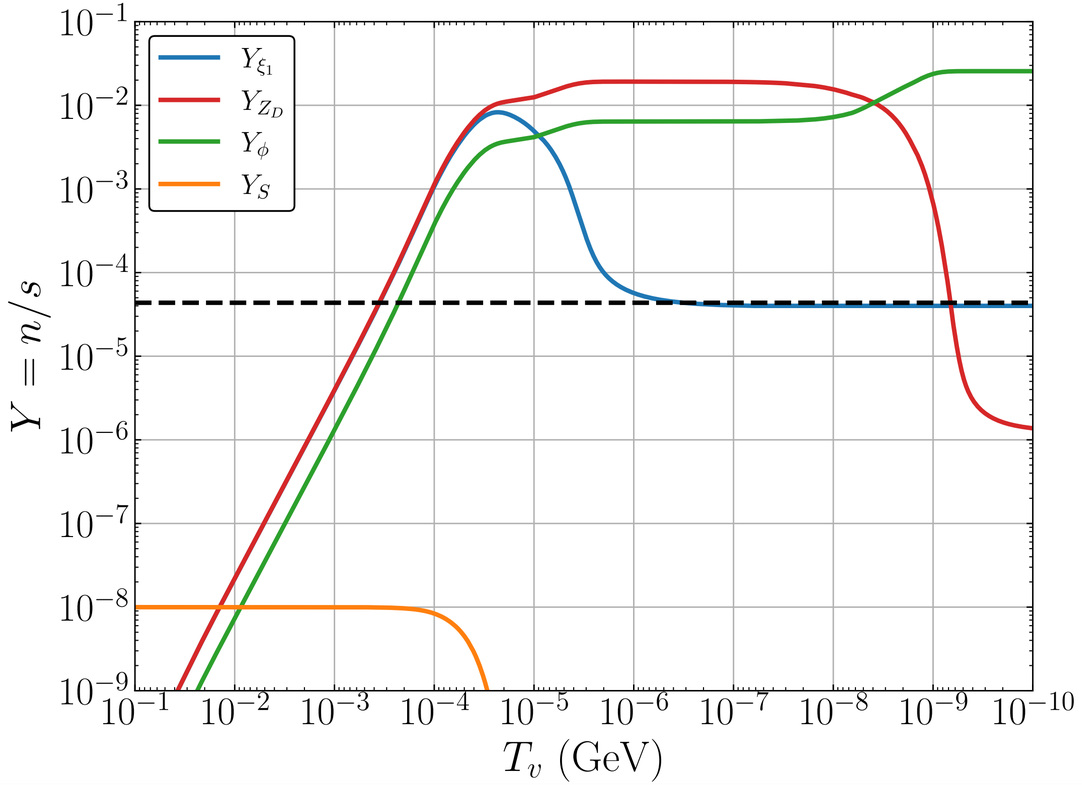
$$j_h = n_S m_S \Gamma_S + \sum_f j(f\bar{f} \to \xi_i\bar{\xi}_j)(T_v) + j(f\bar{f} \to Z_D\gamma)(T_v) + j(f\gamma \to fZ_D)(T_v)\,.$$

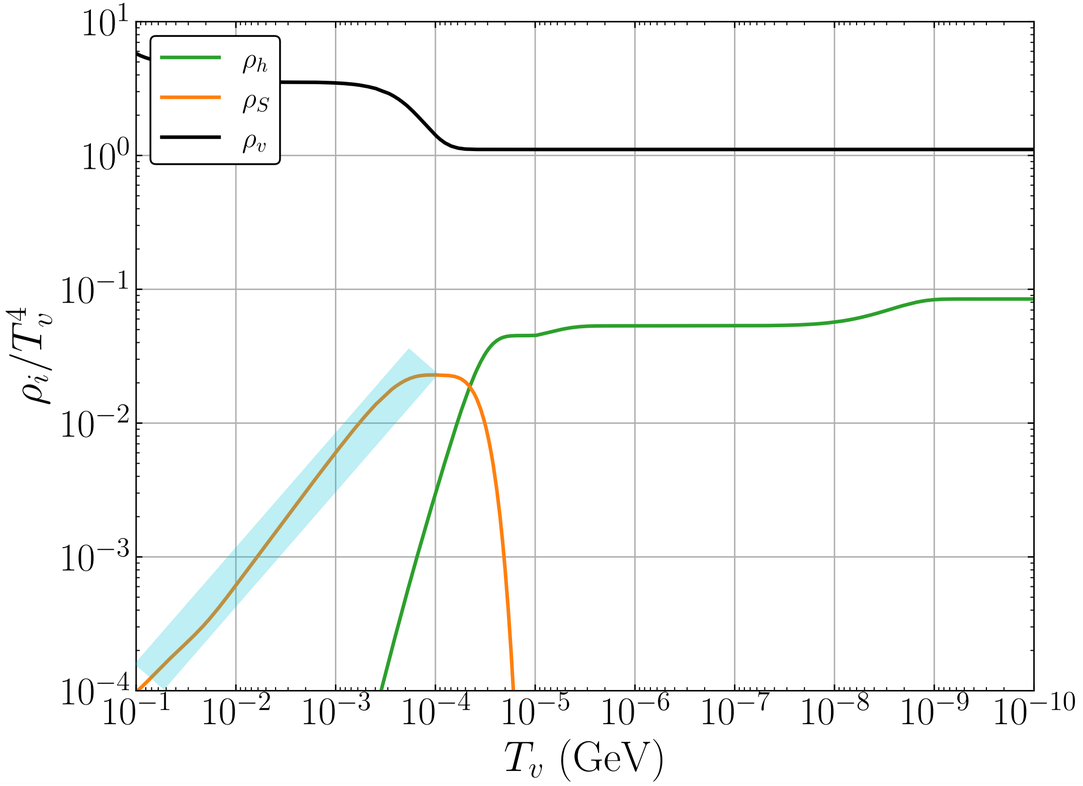
Boltzmann Equations and Numerical Results



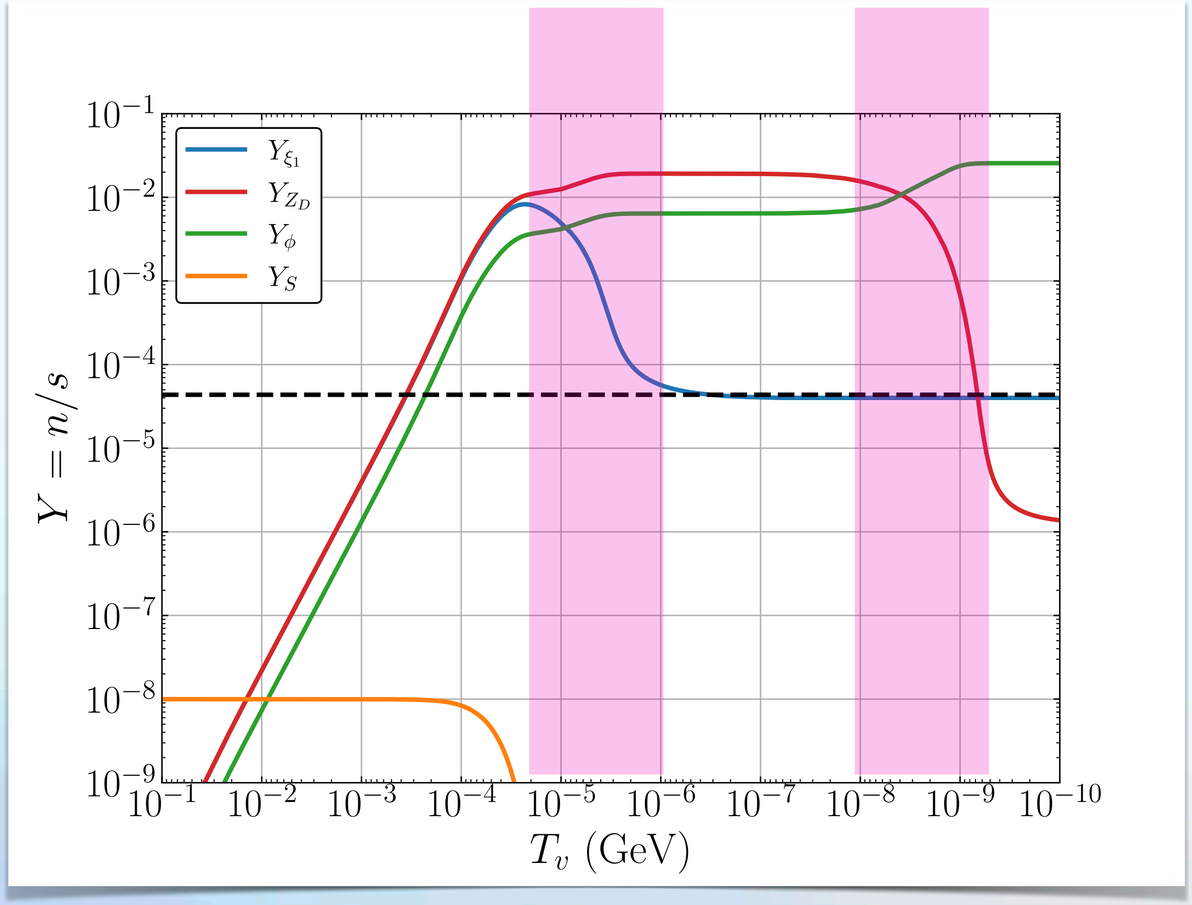


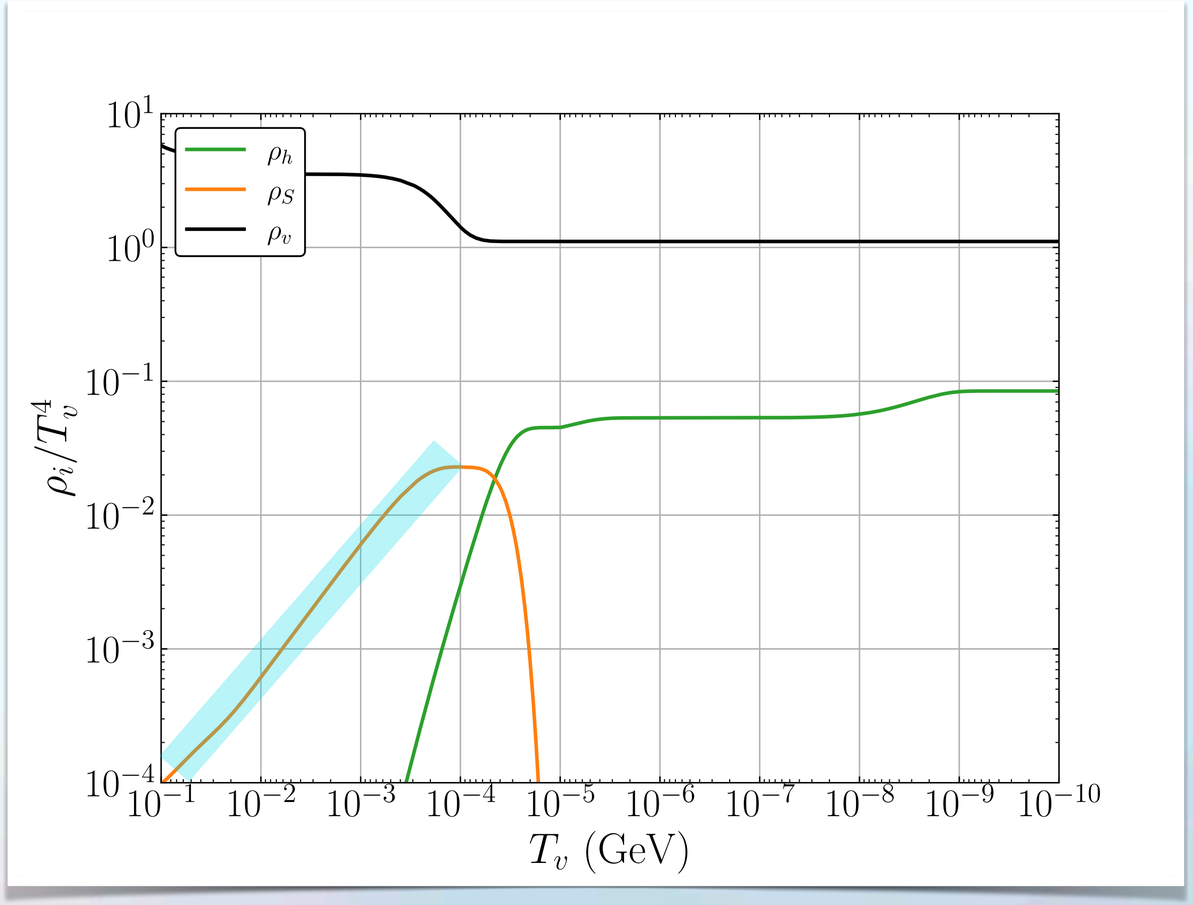
Boltzmann Equations and Numerical Results



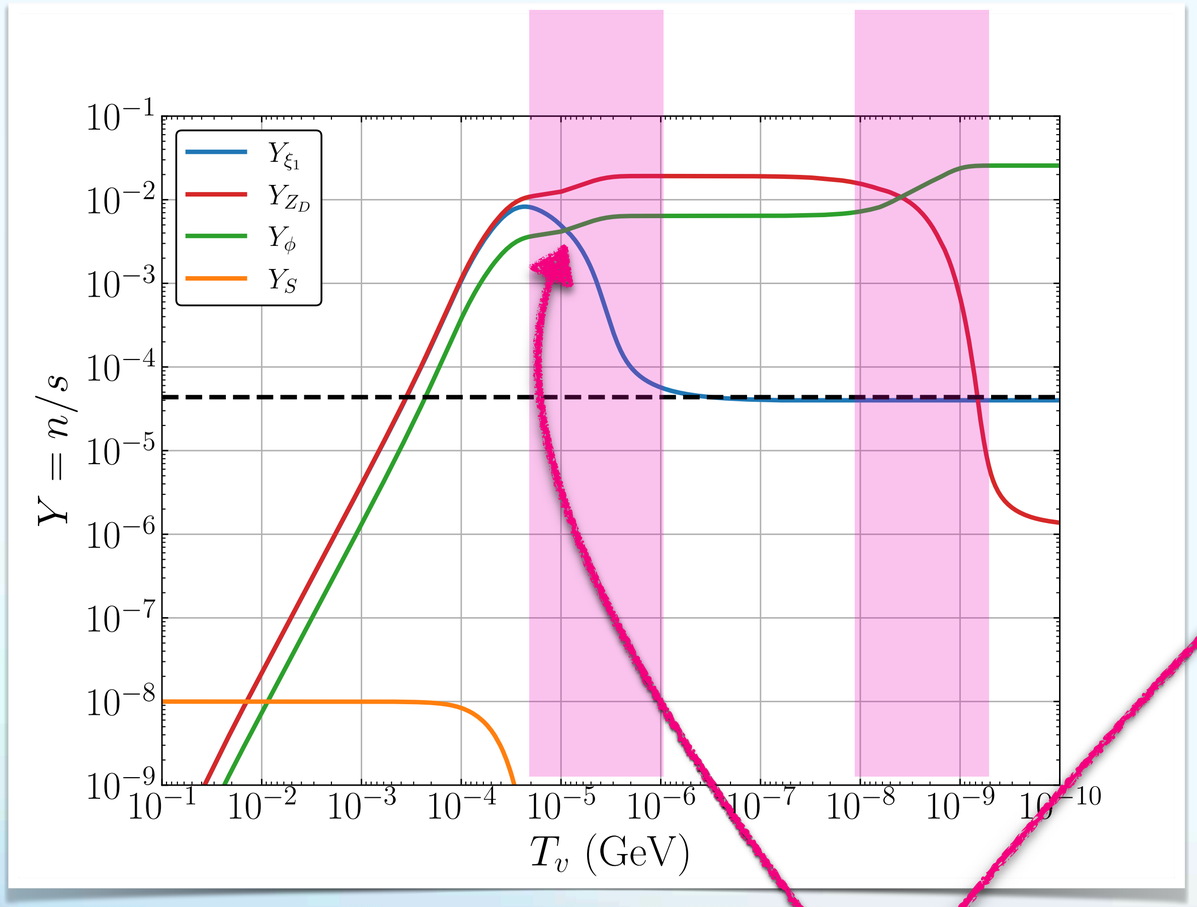


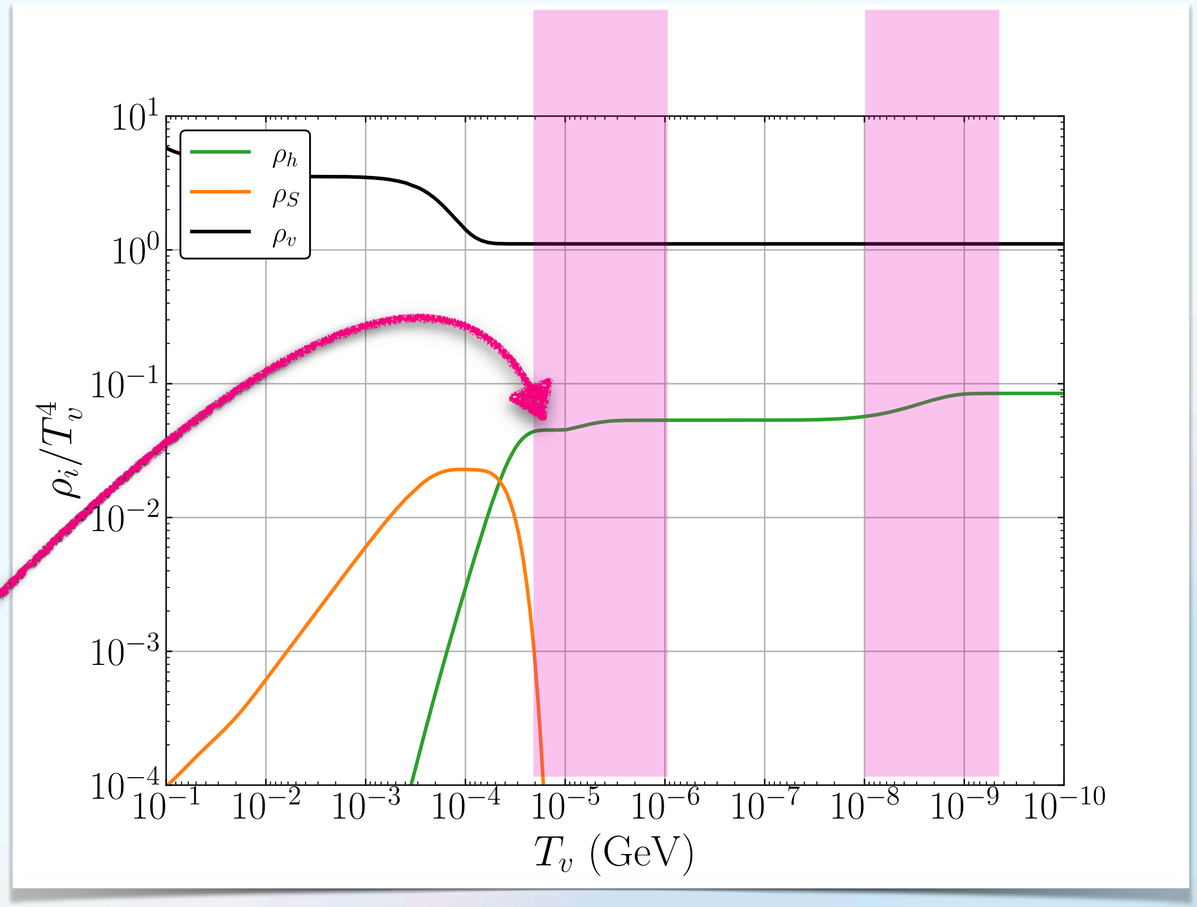
Boltzmann Equations and Numerical Results





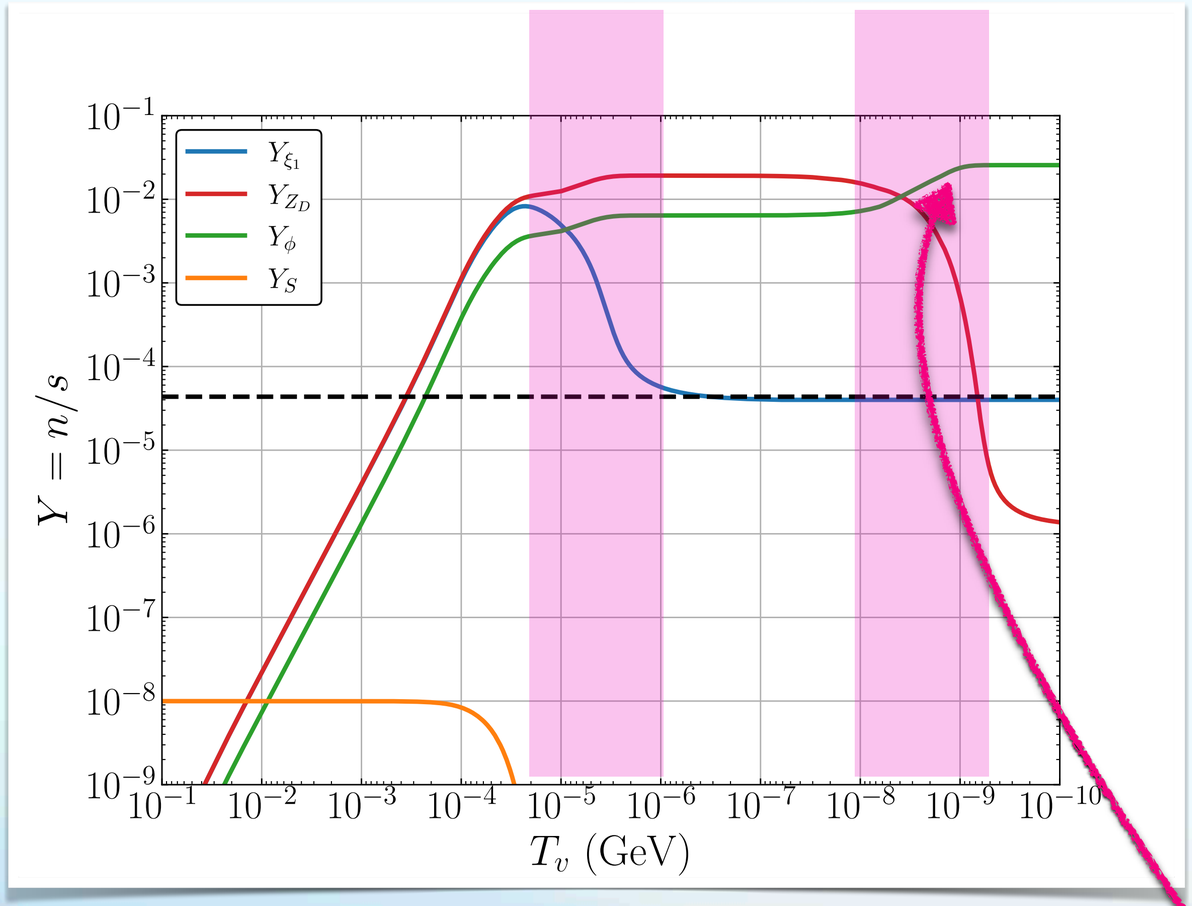
Boltzmann Equations and Numerical Results

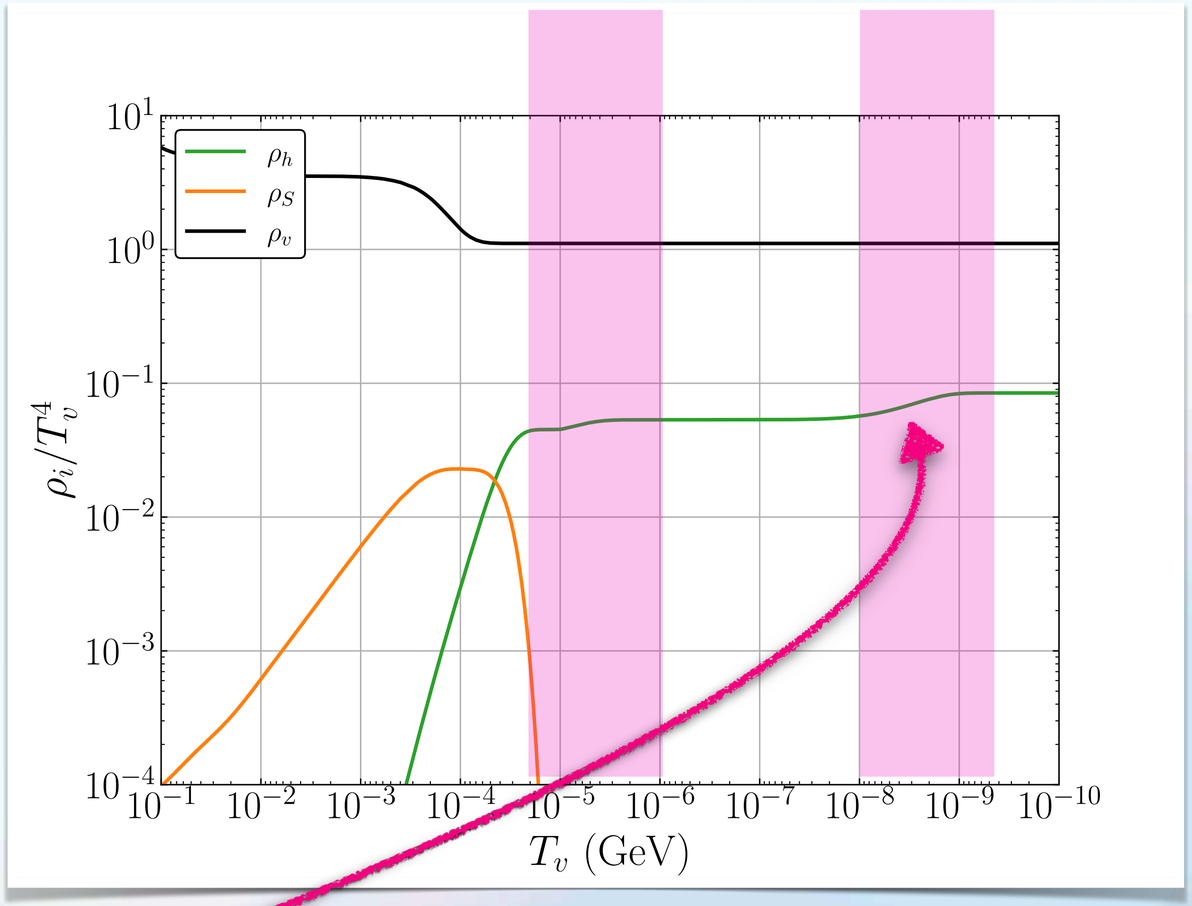




1st Step

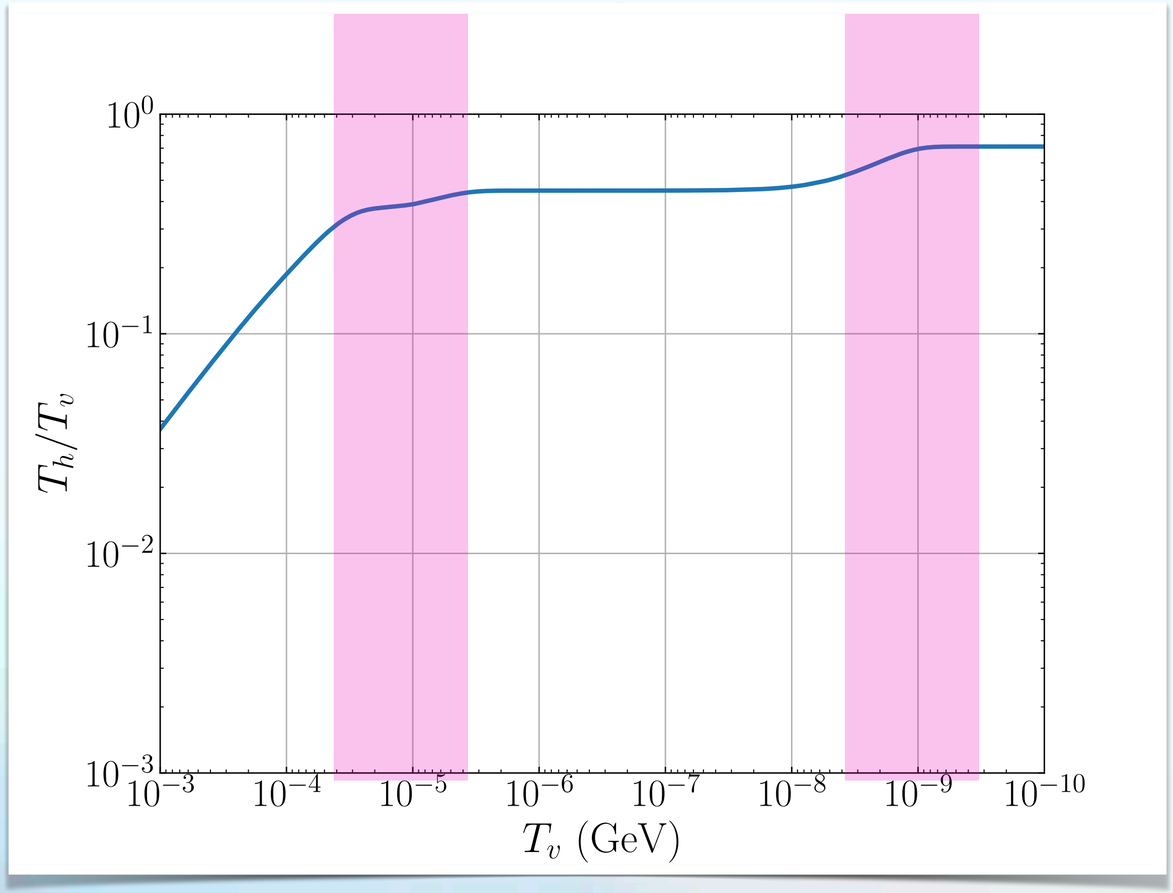
Boltzmann Equations and Numerical Results

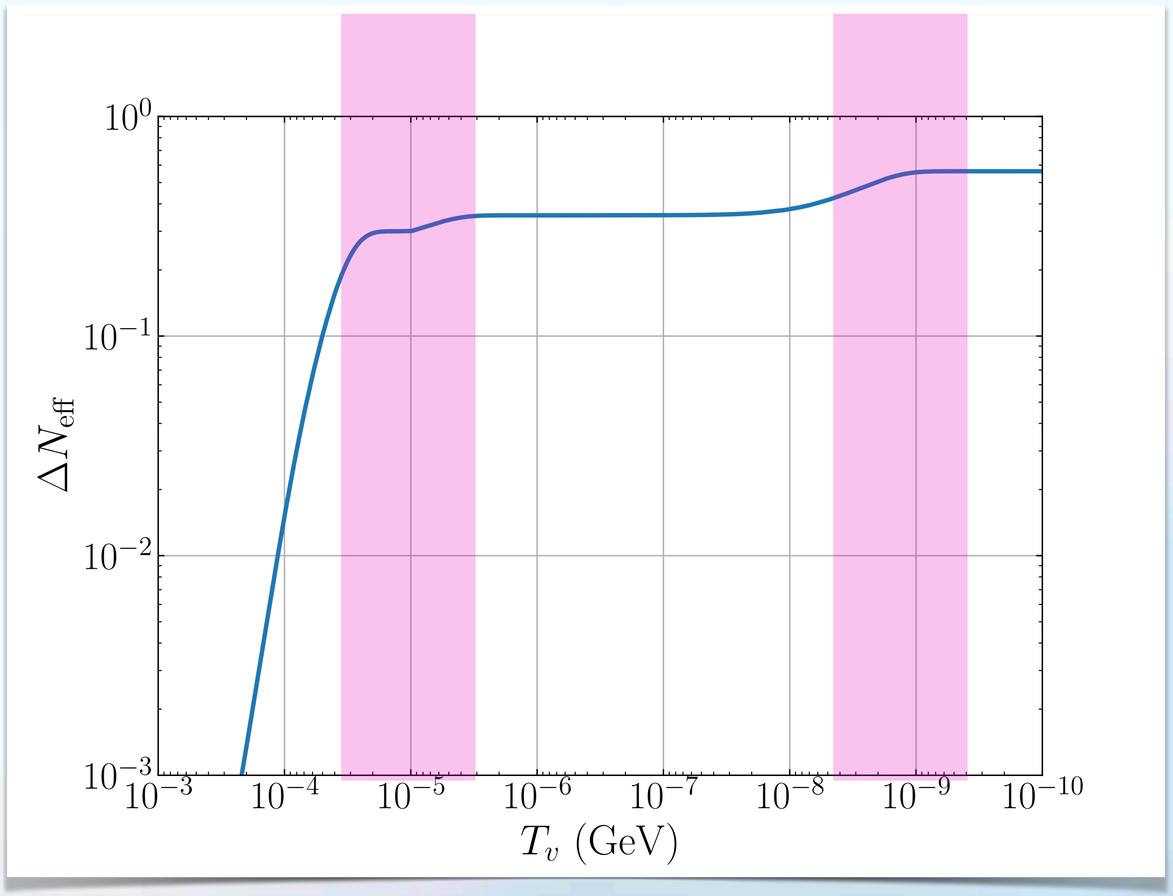




2nd Step

Boltzmann Equations and Numerical Results





Conclusion

- **A novel particle physics framework ‘SIDR+ z_t', which offers a comprehensive approach to address multiple cosmological tensions.**
- **Inelastic DM interacting with DR: suppress the MPS at small scales, potentially reconciling Lyman-α observations.**
- **A distinct temperature dependence for DM-DR interaction rate: a cut-off at the transition redshift z_t determined by the mass-splitting between inelastic dark fermions**
- **The energy scales of the steps for increase in energy density of the two “stepped" DR fluids, being independent of the MPS suppression scale, provides enhanced flexibility in addressing the cosmological tensions.**
- **The production mechanism for dark sector particles via freeze-in and non-thermal contributions, allows for significant $N_{\rm eff}$ from SIDR without violating BBN constraints, while simultaneously achieving the correct DM relic abundance.**

Conclusion

In the H_0 Olympics

2107.10291

Thank You.