Title: TBA

Speakers: Suroor Gandhi

Series: Cosmology & Gravitation

Date: December 14, 2023 - 11:00 AM

URL: https://pirsa.org/23120050

Abstract: Abstract TBA

Zoom link https://pitp.zoom.us/j/95952209469?pwd=TERqVlZsMVhvbzJqU1hsalhiUVYxdz09

Scattering Interactions between Dark Matter & Standard Model Particles in Cosmology

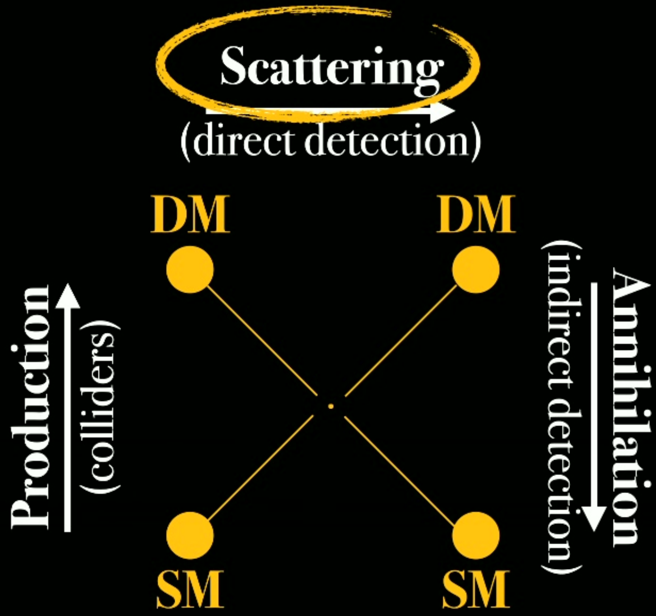
Suroor Seher Gandhi

New York University | AAUW American Fellow | James Arthur Graduate Associate

Perimeter Institute for Theoretical Physics | December 14, 2023

Image: ESA, Planck Collaboration

Dark Matter (DM)—Standard Model (SM) Interactions



Schematic inspired by *Understanding DM throughout Cosmic History*, Colloquium by K. K. Boddy at Aspen Center for Physics (2020)

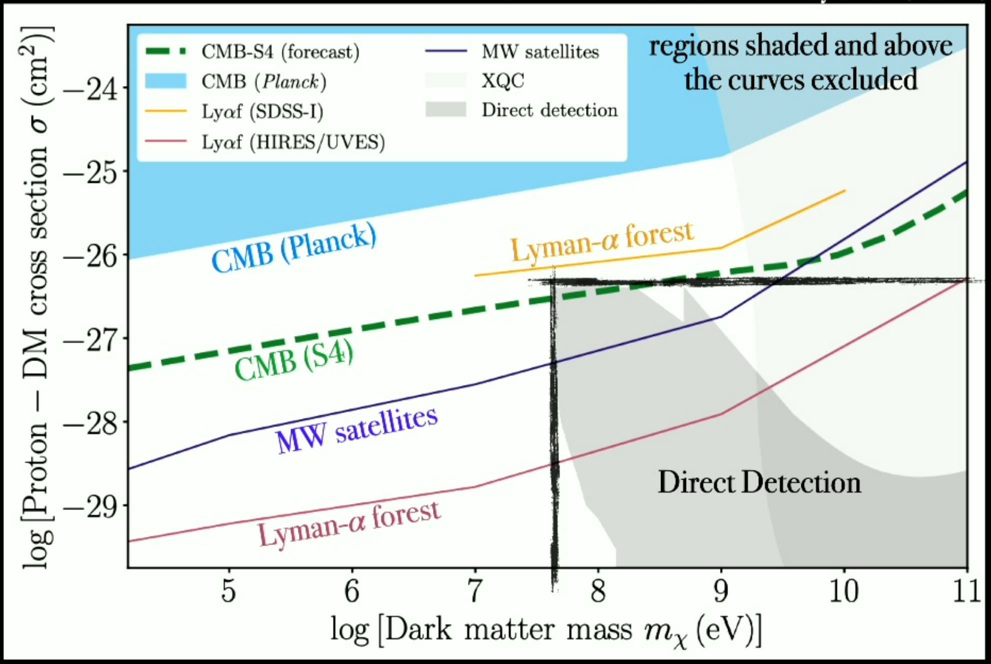
- **Classic example: the WIMP paradigm– theoretically well-motivated**
  - **Simple extension of SM**
  - **"WIMP miracle"**
- **Inconclusive results have motivated the search for DM beyond the WIMP**
- **Inspired scientific programs**
- **My focus: signatures of DM from scattering**

Suroor Seher Gandhi | Perimeter Institute | December 14, 2023

Multiple Cosmic Probes of DM-SM Scattering

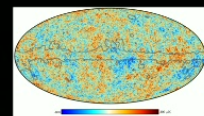
- E.g., terrestrial direct detection experiments look for scattering
- Sensitive to DM mass $\sim$ GeV – TeV
- Underground shielding imposes a cross-section "ceiling" barrier
- **Rich diversity** of cosmic probes available

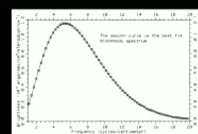
Dvorkin, Hlozek, An, Boddy et. al (2022)

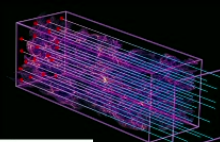


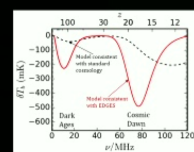
Era of Precision Cosmology

And for each of these probes, we have multiple experiments collecting data…









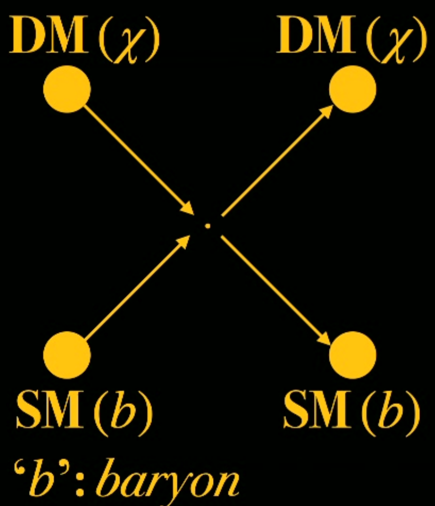
- **Cosmologists are observing the universe with increasing precision.**
- **My goal as a theorist:**

  Theoretical accuracy must remain commensurate with high-precision observations.

SIMONS OBSERVATORY · VERA C. RUBIN OBSERVATORY · WEBB SPACE TELESCOPE · esa euclid · SDSS · chime · ALMA · CMB-S4 Next Generation CMB Experiment

*a grossly non-exhaustive list

DM-SM (χ-b) Scattering in the Cosmological Framework



- **Cosmological observables are sensitive to energy and momentum exchanged among species**
- **$\Rightarrow$ DM-SM (χ-b) scattering alters the heat and momentum injected into the baryon fluid**
  - $\dot{Q}_\chi\Big|_{\rm scat} \propto \frac{d}{dt}\int d^3\mathbf{v}_\chi\,(\vec{\mathbf{v}}_\chi - \vec{\mathbf{V}})^2\, f_\chi(\vec{\mathbf{v}}_\chi)$ **(affects T_χ, T_b)**
  - $\dot{\vec{\mathbf{V}}}_\chi\Big|_{\rm scat} = \frac{d}{dt}\int d^3\mathbf{v}_\chi\,\vec{\mathbf{v}}_\chi\, f_\chi(\vec{\mathbf{v}}_\chi)$ **(affects b eq. of motion→CMB)**
- **Involves solving the Collisional Boltzmann equation**

$$\frac{d}{dt} f_\chi(\vec{\mathbf{v}}_\chi) = C[f_\chi](\vec{\mathbf{v}}_\chi)$$

Issues in the Theoretical Framework

Issue 1: Blanket Assumption of Thermalized Dark Matter Velocities

- Almost *all* constraints on DM-SM scattering assume that $f_\chi(\vec{\mathbf{v}}_\chi) = f_\chi^{\mathrm{MB}}(\vec{\mathbf{v}}_\chi)$
- Irrespective of whether the DM model involves efficient interactions

S. Seher Gandhi & Y. Ali-Haïmoud (2022)

Issue 2: The Intrinsic Nonlinearity of DM-SM Scattering

- DM-SM scattering rate depends non-linearly on perturbations
- The standard framework of ΛCDM cosmology can only handle eq.s that are linear in perturbations

Y. Ali-Haïmoud, **S. Seher Gandhi,** & T. L. Smith (arXiv:2312.xxxxx)

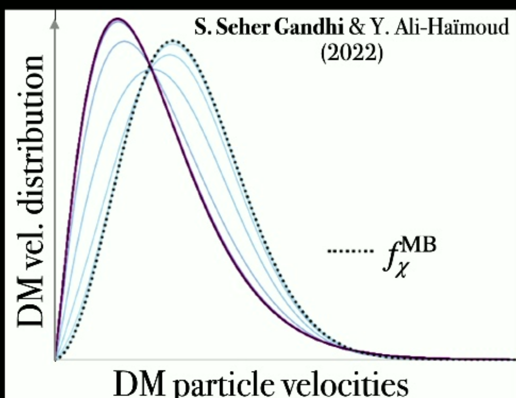
Issue 1: Blanket Assumption of Thermalized DM Velocities

Thermalized ⇔ Maxwell-Boltzmann (MB) Distributed

Why is the MB assumption used for DM-SM scattering?

- $\dot{Q}_\chi$, $\dot{\vec{V}}_\chi$ have analytical forms
- No need to implement the collision operator (a tremendous simplification!)

$$C_{\chi b}[f_\chi](\vec{v}) = \int d^3v' \Big(\underbrace{\Gamma_{\chi b}(\vec{v}' \to \vec{v}) f_\chi(\vec{v}')}_{\text{scat. rate from } \vec{v}' \to \vec{v}} - \underbrace{\Gamma_{\chi b}(\vec{v} \to \vec{v}') f_\chi(\vec{v})}_{\text{scat. rate from } \vec{v} \to \vec{v}'} \Big)$$



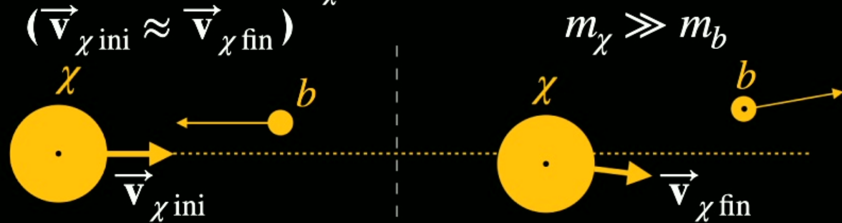
So why is the MB assumption a problem?

- $f_\chi = f_\chi^{\rm MB}$ assumes perfect χb or $\chi\chi$ scattering efficiency at all times– even if not self-consistent.
- Excludes study of models with non-trivial DM self-scattering by forcing $C_{\chi\chi}[f_\chi^{\rm MB}] = 0$.

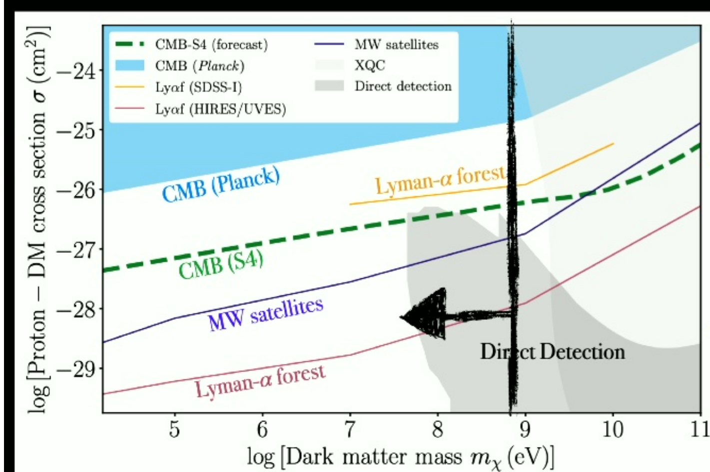
A Less Stringent Approximation— Diffusion

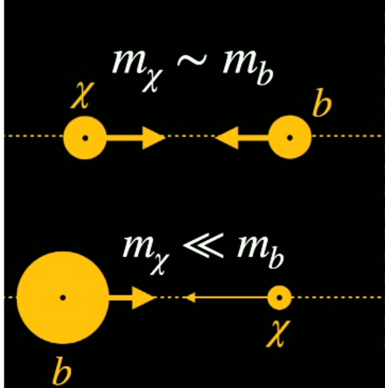
Diffusion or Fokker-Planck (FP) Formalism (Y. Ali-Haïmoud 2019)

diffusive χ-b scattering:
small change in $\vec{\mathbf{v}}_\chi$
($\vec{\mathbf{v}}_{\chi\,\mathrm{ini}} \approx \vec{\mathbf{v}}_{\chi\,\mathrm{fin}}$)



- ❖ **Fokker-Planck (FP ⇔ diffusion) formalism sets $C[f_\chi](\vec{\mathbf{v}}_\chi) \approx C^{\mathrm{FP}}[f_\chi](\vec{\mathbf{v}}_\chi)$** **[Ali-Haïmoud 2019]**
- ❖ **$\dot{Q}_\chi$, $\dot{\vec{\mathbf{V}}}_\chi$ computed more self-consistently: exact for a *given* f_χ**
- ❖ **Diffusion is valid for $m_\chi \gg m_b$**
- ❖ **But, how accurate is $C^{\mathrm{FP}}[f_\chi]$ outside this mass limit?**
- ❖ **E.g., DM-proton scattering when $m_\chi \lesssim m_p$ (1 GeV)**

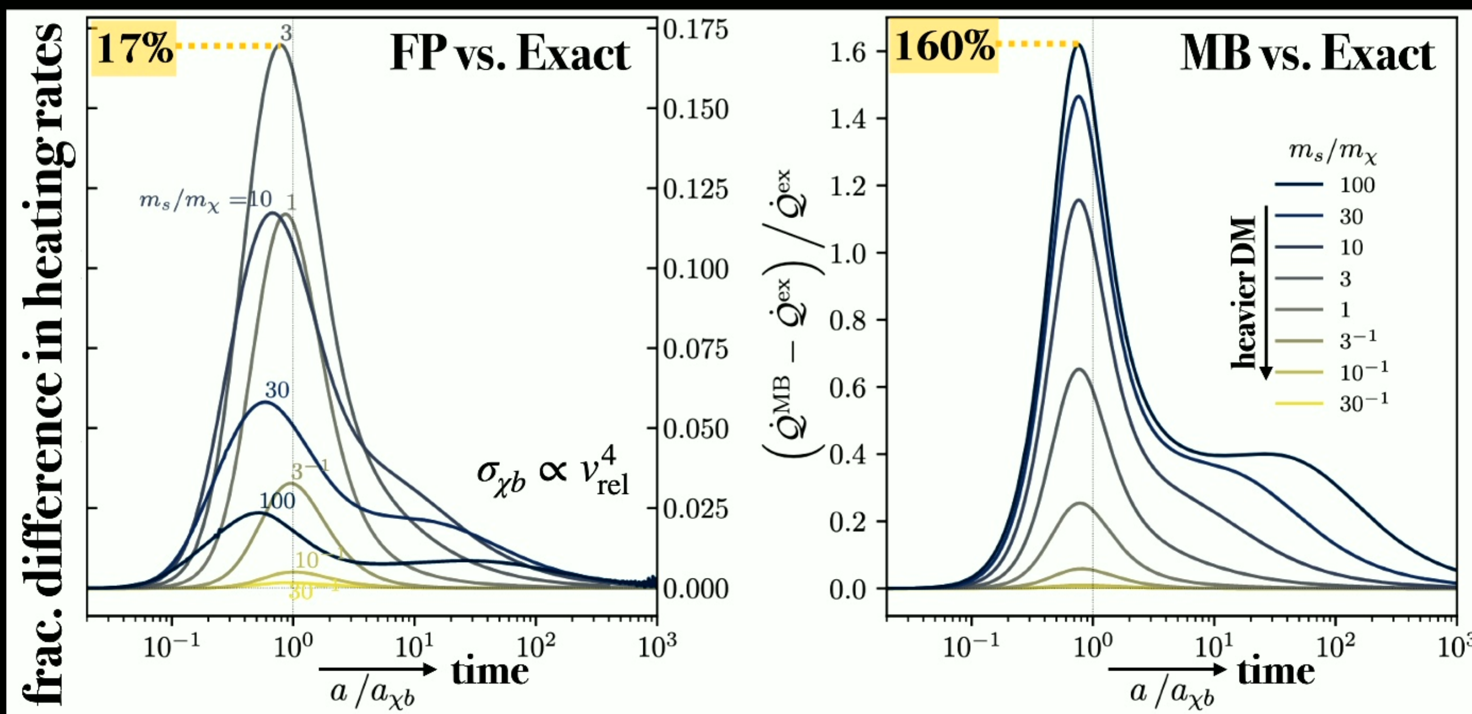




An Exact Method

to determine the accuracy of Diffusion

- My work: **evolved $f_\chi(\vec{\mathbf{v}}_\chi)$ exactly** for a smooth-universe or **background**– simpler ($C^{1D}_{\chi b}[\bar{f}_\chi]$) but still nontrivial
- Used the **background heat-exchange rate $\dot{Q}_\chi$** to compare the FP and exact methods

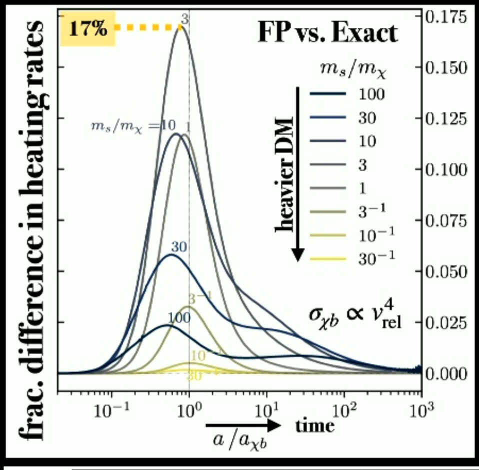


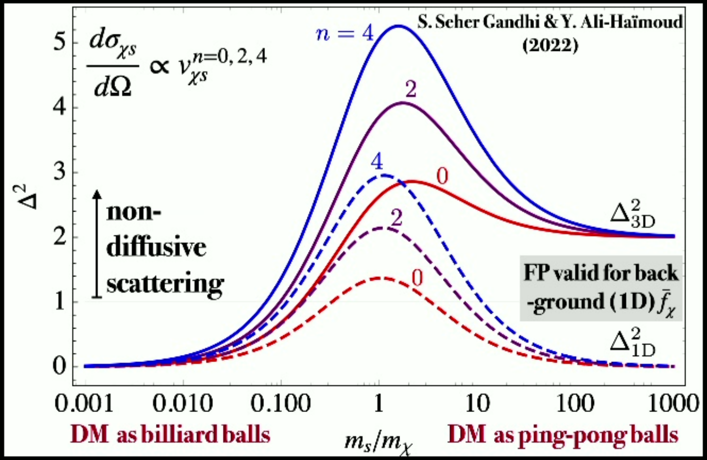
- Max FP error ~17% **across all mass regimes**
- Max MB error ~160%
- **Motivates assuming diffusion** in lieu of MB beyond the background (**with aniotropies**)

S. Seher Gandhi & Y. Ali-Haïmoud (2022)

Is FP accurate for $m_\chi \ll m_s$?— 3D vs. 1D diffusion

- **3D diffusion** requires small change in DM vel. **vector** $\vec{v}$
- **1D diffusion** only requires small change in DM vel. **magnitude** v
- Showing coefficients that quantify diffusivity of 3D & 1D scattering for given m_s/m_χ
- Scattering is **non-diffusive** for $m_s \sim m_\chi$ in 3D **as well as** 1D, but FP still accurate to $\lesssim 20\%$
- **Bodes well for 3D** (relevant for cosmology)





Issues in the Theoretical Framework

Issue 1: Blanket Assumption of Thermalized Dark Matter Velocities

- Almost *all* constraints on DM-SM scattering assume that $f_\chi(\vec{\mathbf{v}}_\chi) = f_\chi^{\mathrm{MB}}(\vec{\mathbf{v}}_\chi)$
- Irrespective of whether the DM model involves efficient interactions

S. Seher Gandhi & Y. Ali-Haïmoud (2022)

Issue 2: The Intrinsic Nonlinearity of DM-SM Scattering

- DM-SM scattering rate depends non-linearly on perturbations
- Our standard framework of ΛCDM cosmology can only handle eq.s that are linear in perturbations

Y. Ali-Haïmoud, **S. Seher Gandhi,** & T. L. Smith (arXiv:2312.xxxxx)

Issue 2: The Intrinsic Nonlinearity of DM-SM Scattering

And its Incorporation into Linear Cosmology (e.g. CMB Power Spectra)

- **Eq. of motion:** $\dot{\vec{\mathbf{V}}}_\chi = \dot{\vec{\mathbf{V}}}_\chi\Big|_{\rm std} + \Gamma_V\left[V_{\chi b}\,; (T_\chi/m_\chi + T_b/m_b)\right]\left(\vec{\mathbf{V}}_b - \vec{\mathbf{V}}_\chi\right)$

  $V_{\chi b} \equiv |\vec{\mathbf{V}}_\chi - \vec{\mathbf{V}}_b|$: relative bulk vel., $(T_\chi/m_\chi + T_b/m_b)$: relative thermal vel. $\equiv (T/m)_{\chi b}$

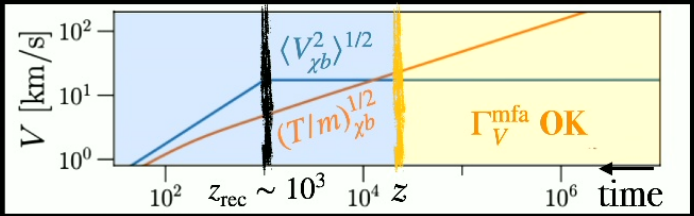
- **Current methods evade this issue with a "mean-field" ansatz (mfa)** — C. Dvorkin et. al (2013)

  $$\Gamma_V\left[V_{\chi b}\,; (T/m)_{\chi b}\right] \longrightarrow \Gamma_V^{\rm mfa} \equiv \Gamma_V\left[0\,; (T/m)_{\chi b} + \langle V_{\chi b}^2\rangle^{\rm std}\right]$$

- **Not derived, but** $\Gamma_V\left[V_{\chi b}\,; (T/m)_{\chi b}\right] = \Gamma_V^{\rm mfa}$ **if** $V_{\chi b} \ll (T/m)_{\chi b}^{1/2}$

- $\Gamma_V^{\rm mfa}$ **is used even when it has unknown accuracy**

  ... at epochs directly affecting the CMB ($z_{\rm rec} \sim 10^3$)

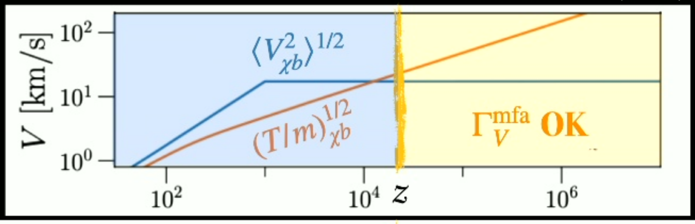


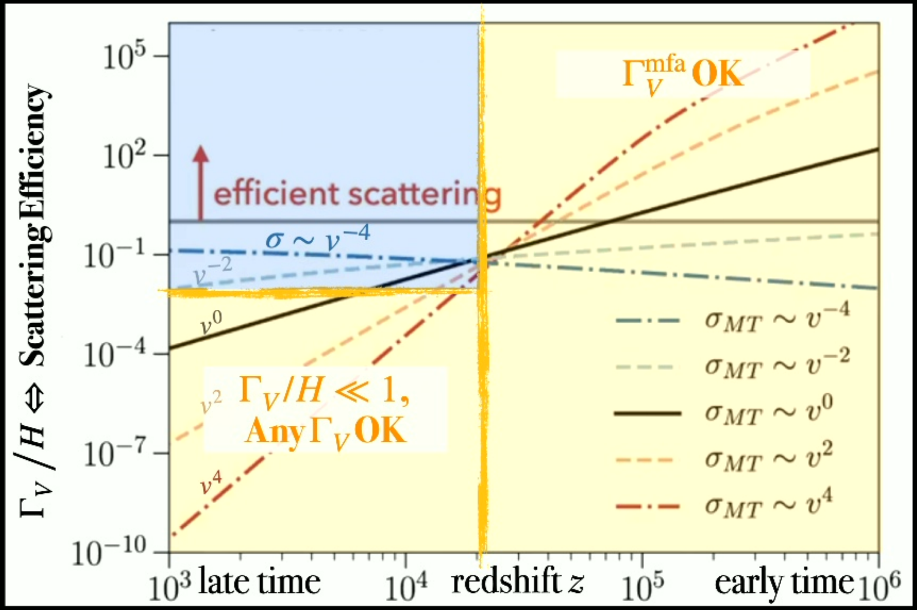
T. Driskell et. al (2022)

Regimes Most Affected by the Non-Linearity

- $\Gamma_V \to \Gamma_V^{\rm mfa}$ is OK if $\langle V_{\chi b}^2 \rangle \ll (T/m)_{\chi b}$
- **Any Γ_V is OK** if scattering is inefficient (as $\Gamma_V / H \ll 1$ does not matter)
- The CMB is most sensitive to $\chi\, b$ scattering in $\sigma_{\chi b} \propto v_{\chi b}^{-4}$ (**Coulomb-like DM**)
- **CMB** places some of the **strongest constraints** on $\sigma_{\chi b} \propto v_{\chi b}^{-4}$

T. Driskell et. al (2022)





K. K. Boddy, Aspen Center for Physics Colloquium (2020)

The Search for a more Rigorous Approach

An Approximation for the Fundamental Nonlinearity From First Principles

- We propose a **new expansion parameter**– the scattering cross-section $\sigma_{\chi b}$

such that CMB anisotropies $\Theta \approx \Theta^{(0)} + \Theta^{(1)}$

$$\langle \Theta\, \Theta \rangle \sim C_\ell = C_\ell^{\rm std} + \Delta C_\ell\,, \qquad \Delta C_\ell^{(01)} \sim \langle \Theta^{(0)}\, \Theta^{(1)} \rangle$$

- We distill how $\langle \Theta^{(0)}\, \Theta^{(1)} \rangle$ **ultimately** depends on $\Gamma_V(V_{\chi b})$
- We find $\langle \Theta^{(0)}\, \Theta^{(1)} \rangle$ **is invariant** under

$$\Gamma_V(V_{\chi b}) \rightarrow \frac{\langle V_{\chi b}^2\, \Gamma_V \rangle}{\langle V_{\chi b}^2 \rangle} \equiv \widetilde{\Gamma}_V$$

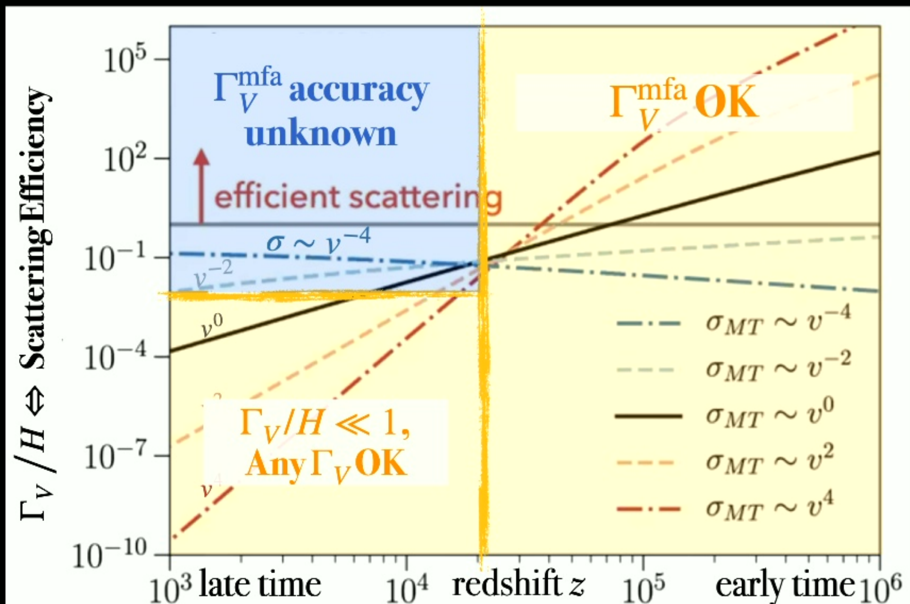
- **A serendipitous finding:** $\widetilde{\Gamma}_V$ is precisely... $= \Gamma_V^{\rm mfa}$

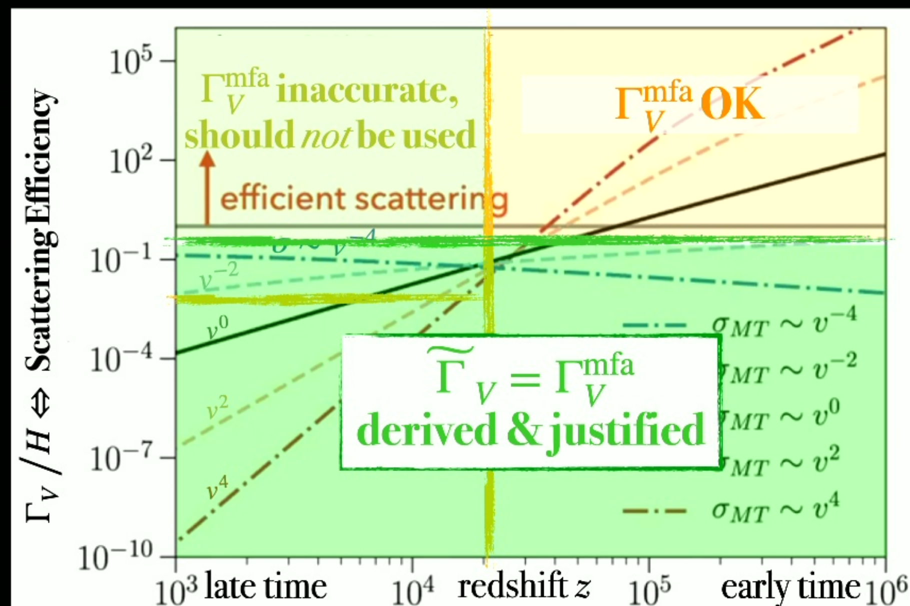
from C. Dvorkin et. al (2013)

Current Methods on Firmer Footing

For Sufficiently Weak Interactions

- Before, regime of applicability of $\Gamma_V^{\rm mfa}$ was uncertain.
- Now, we know $\Gamma_V^{\rm mfa}$ is exact for weak enough interactions: check that ΔC_ℓ linear in $\sigma_{\chi b}$

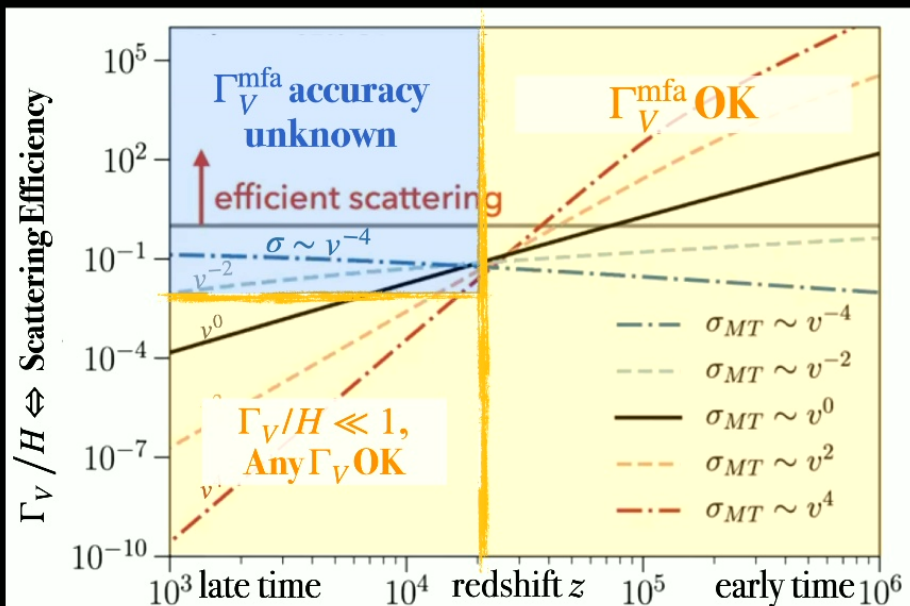


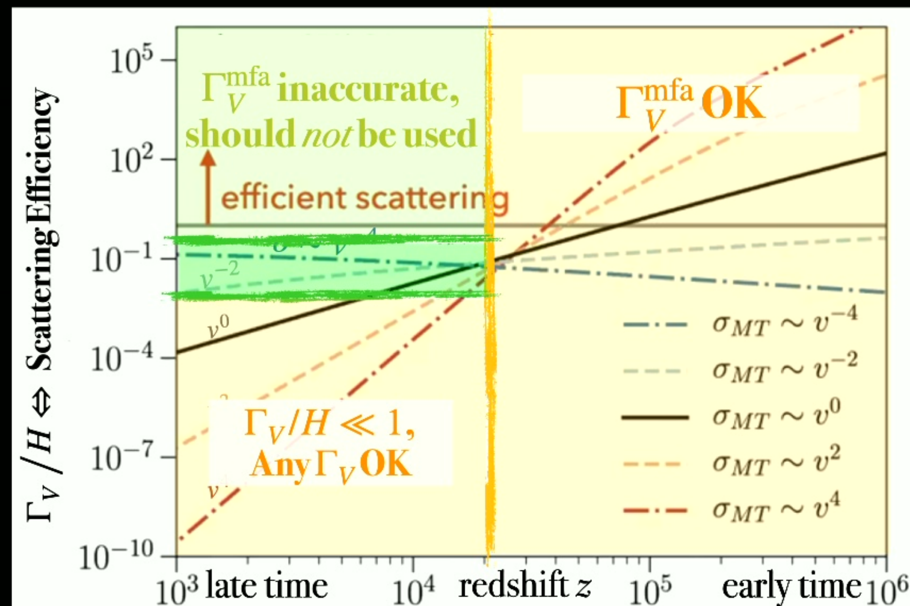


Underlying plot: K. K. Boddy;
Overplotted results: Y. Ali-Haïmoud, **S. Seher Gandhi**, & T. Smith (2312.xxxxx)

Current Methods on Firmer Footing
For Sufficiently Weak Interactions

- ❖ The regions we've added to are the **most interesting** for the CMB

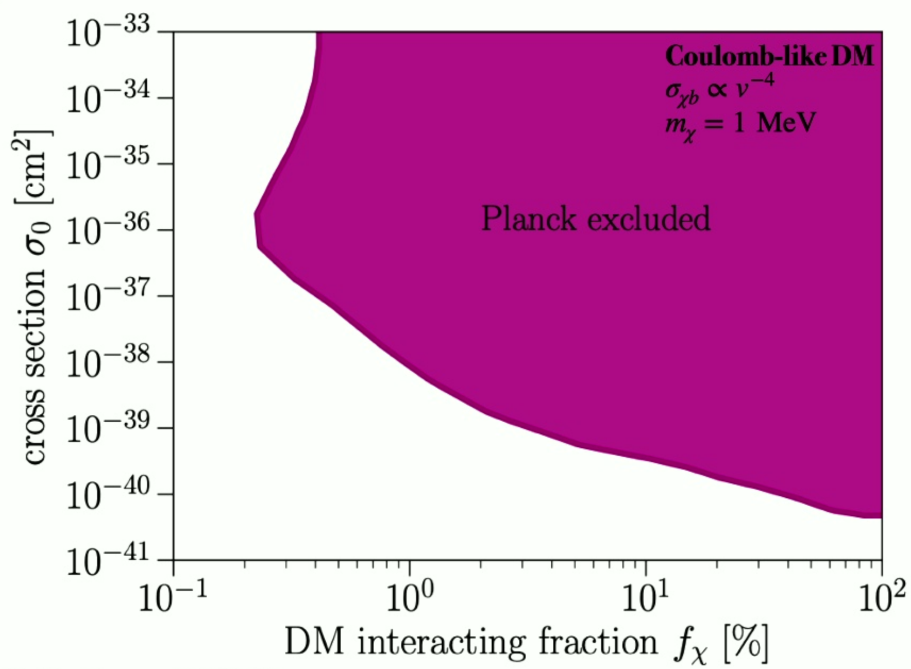




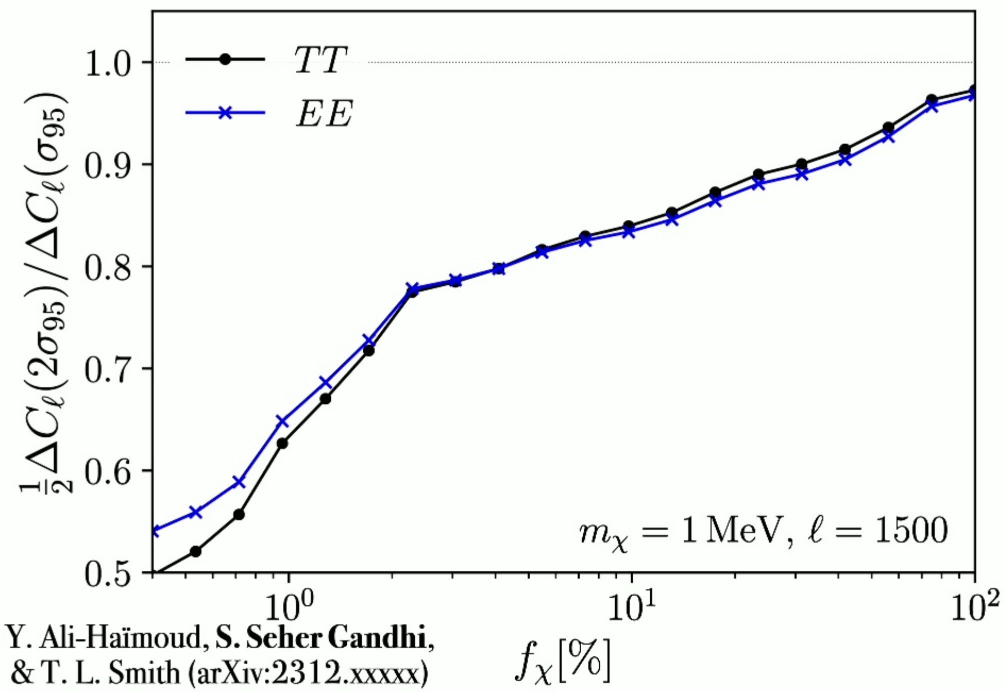
Underlying plot: K. K. Boddy;
Overplotted results: Y. Ali-Haïmoud, **S. Seher Gandhi**, & T. Smith (2312.xxxxx)

Regime of Inapplicability of Current Methods

Strongly Interacting Dark Matter



K. Boddy et. al (2018)



Y. Ali-Haïmoud, **S. Seher Gandhi**, & T. L. Smith (arXiv:2312.xxxxx)

Ideas for Further Exploration

Non-Gaussian Signatures and B-Mode Polarization

- $\Gamma_V \to \widetilde{\Gamma}_V$ does **not** give the **exact** Θ, but only the **exact** $\langle \Theta^{(0)}\,\Theta^{(1)} \rangle$
- $\Theta \propto \Gamma_V(V_{\chi b})\vec{\mathbf{V}}_{\chi b}$ – nonlinear in initial curvature perturbations, ζ
  $\Rightarrow$ non-Gaussianities: e.g. CMB **trispectrum** or connected **4 pt. function**
  - *Planck* sensitivity to primordial 4 pt. function $\mathrm{T}_{\mathrm{prim}} \sim 10^{-4}\langle\zeta^2\rangle^2$
  - $\mathrm{T}^{(0001)} \sim \langle \Theta^{(0)}\,\Theta^{(0)}\,\Theta^{(0)}\,\Theta^{(1)} \rangle \sim 10^{-2}\langle\zeta^2\rangle^2$ for $\sigma_{\chi b}$ at 95% C.L. from *Planck* C_ℓ's
  - $\mathrm{T}^{(0001)}/\mathrm{T}^{\mathrm{prim}} \sim 10^2$ if $\sigma_{\chi b}$ saturates *Planck* C_ℓ bounds $\Rightarrow$ DM-SM scattering **trispectrum** could have much **higher constraining power**
- **Curl** of $\Gamma_V(V_{\chi b})\vec{\mathbf{V}}_{\chi b}$ can be **non-zero** $\Rightarrow$ source ***B*-mode polarization**

Key Takeaways

Theoretical Accuracy in Cosmological DM-SM Scattering

- **There are assumptions in the cosmological framework which we should reassess and adjust**
  - MB (assumption) vs. FP (approximation)
  - mean-field $\Gamma_V^{\rm mfa}$ assumption vs. $\widetilde{\Gamma}_V = \Gamma_V^{\rm mfa}$ approximation at $\mathcal{O}(\sigma_{\chi b})$
- **The assumptions made are not necessarily unique choices**
  - If not for the mathematical simplicity of MB, one could have assumed FP instead
  - Instead of $\Gamma_V^{\rm mfa} = \Gamma_V(\langle V_{\chi b}^2\rangle)$, one could have reasonably assumed $\Gamma_V^{\rm mfa} = \left\langle \Gamma_V(V_{\chi b}^2)\right\rangle_{V_{\chi b}}$
- **Developing improved, self-consistent approximations can clarify future directions**
  - DM self-scattering concurrently with DM-SM scattering using FP formalism
  - A better framework for <100% fraction of interacting DM is needed (maybe expand in f_χ?)
  - Higher-order statistics (e.g. trispectrum) from DM-SM scattering

THANK YOU

- Other topics I have worked on include galactic dynamics and stellar chemistry
- I'm also interested in learning more about and working on:
  - Mapping the "dark" baryonic distribution with the CMB
  - Cosmological inference using BH binaries x-correlated with quasars
  - Astro- and cosmological statistics