phoeniX 2023

SIDM & GRB221009A

Based on: Phys. Rev. D **108**, 083038

[arXiv: 2308.06172]

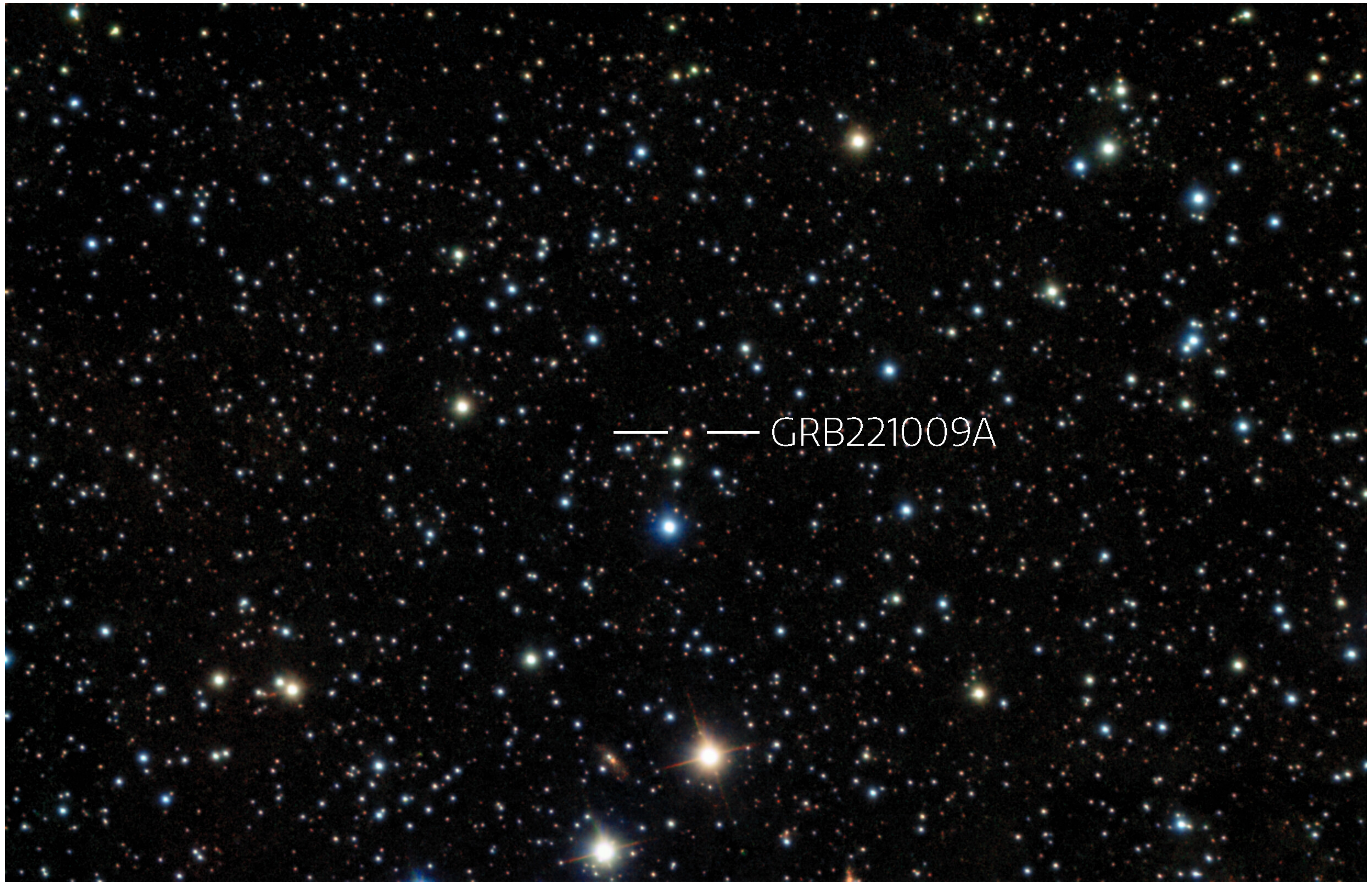
भारतीय प्रौद्योगिकी संस्थान हैदराबाद

Indian Institute of Technology Hyderabad

Vicky Singh Thounaojam

October 9, 2022

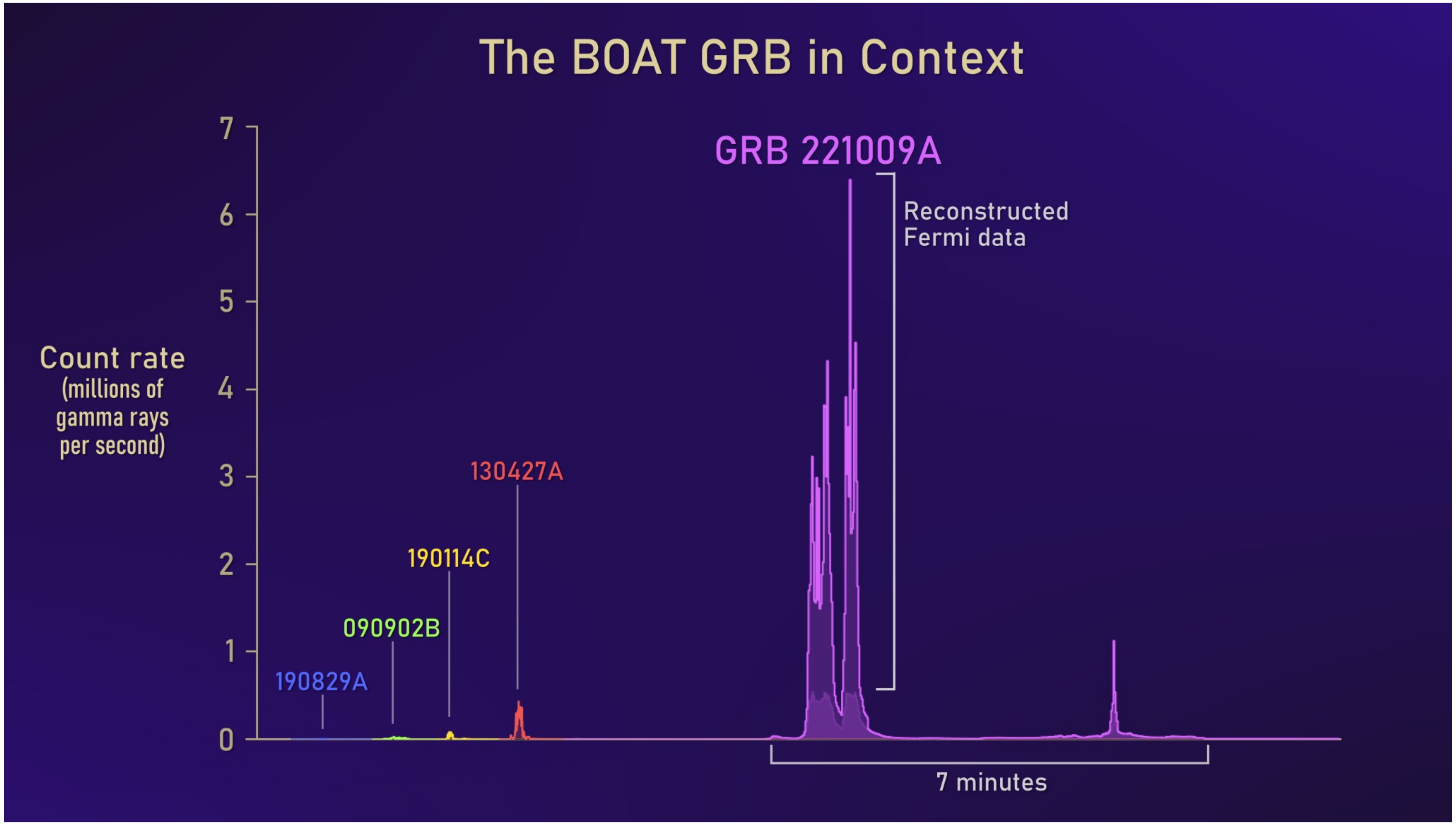
- Fermi Gamma Ray space telescope and Neil Gehrels Swift Observatory detected unusually bright gamma-ray bursts, nicknamed BOAT (*brightest of all time*).
- The source is 2.4 billion light years away from Earth. The corresponding redshift is $z \approx 0.151, d \approx 645\ Mpc$
- "*It's a once in a century event, maybe once in 1,000 years*," Brendan O'Connor, an astronomer at the University of Maryland and George Washington University



Near-simultaneous observations were made of GRB221009A from Gemini South in Chile. The image is a combination of 4 exposures in I, J, H, K with two instruments taken in the morning of Friday, October 14, 2022

A cosmic conundrum

Large High Altitude Air Shower Observatory



NASA's Goddard Space Flight Center and Adam Goldstein (USRA)

- In particular, LHAASO's WCDA and K2MA detected $\mathcal{O}(5000)$ events of GRB with energies ranging from **0.5 TeV to 18 TeV** within 2000s after the initial burst.
- Observation of such highly energetic photon is highly unlikely as such highly energetic γ rays should be severely attenuated in the inter-galactic medium by e pair production on background photons.
- Various attempts were put forth in the literature by invoking Lorentz Invariance Violation, Axion like particles, Sterile Neutrinos, Light scalar, external inverse Compton mechanism, etc.

Beyond Standard Model (BSM)

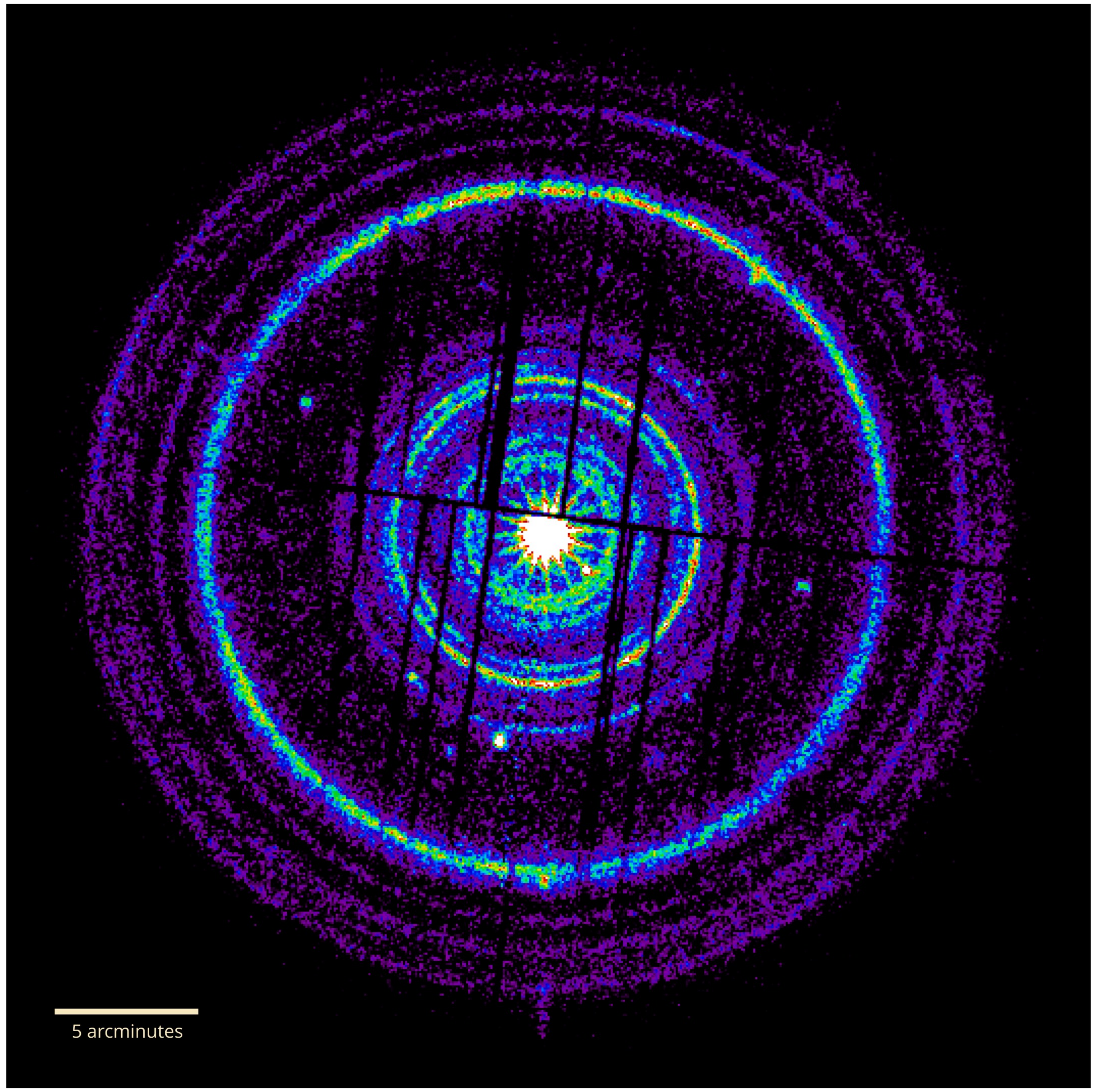
Sterile Neutrinos and Light Scalar

- **Standard Propagation:** *Flux produced by γ rays goes as $\Phi_\gamma^d \sim e^{-\tau}$ where $\tau \sim 5(15)$ for a photon of energy $10(18)$ TeV, thereby suffered much attenuation when propagating and interacting with the EBL.*

Need for BSM Physics

- **Propagation scenario:** *The probability that an individual species X particle decay in the distance interval [x+dx] and the produced photon reaches Earth is* $B_\gamma e^{-x/\lambda_X} \dfrac{dx}{\lambda_X} e^{(d-x)/\lambda_\gamma}$

Multiplying the above by the initial flux of X and integrating over x, gives the X induced gamma ray flux on Earth.



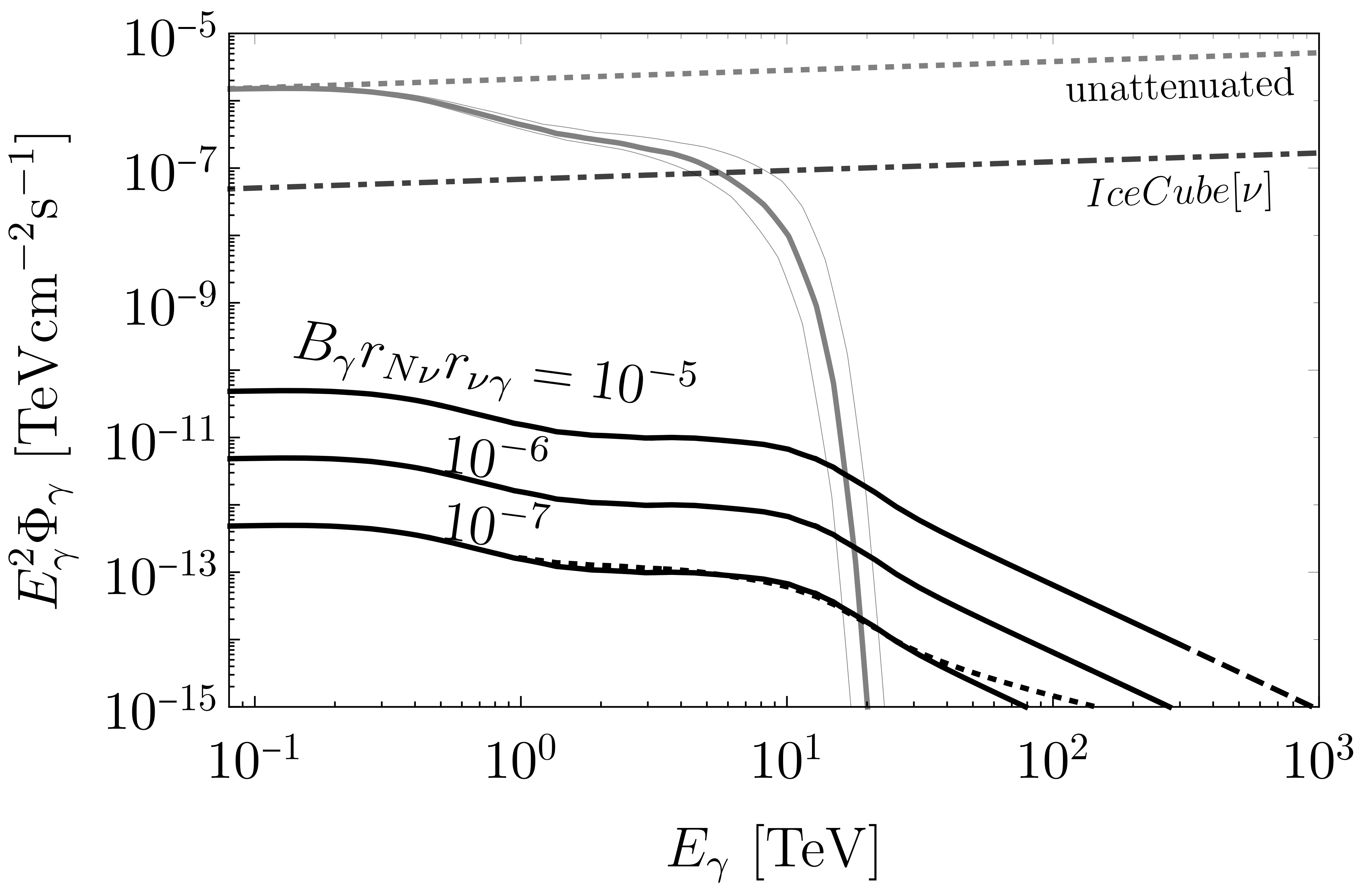
Credit: ESA/XMM-Newton/M. Rigoselli (INAF)

Propagation Scenario

Sterile Neutrino, $N \to \nu\gamma$

$$\Phi_\gamma^{(N)} = \Phi_N B_\gamma \frac{1}{\lambda_N/\lambda_\gamma - 1}\left[\mathrm{e}^{-d/\lambda_N} - \mathrm{e}^{-d/\lambda_\gamma}\right]$$

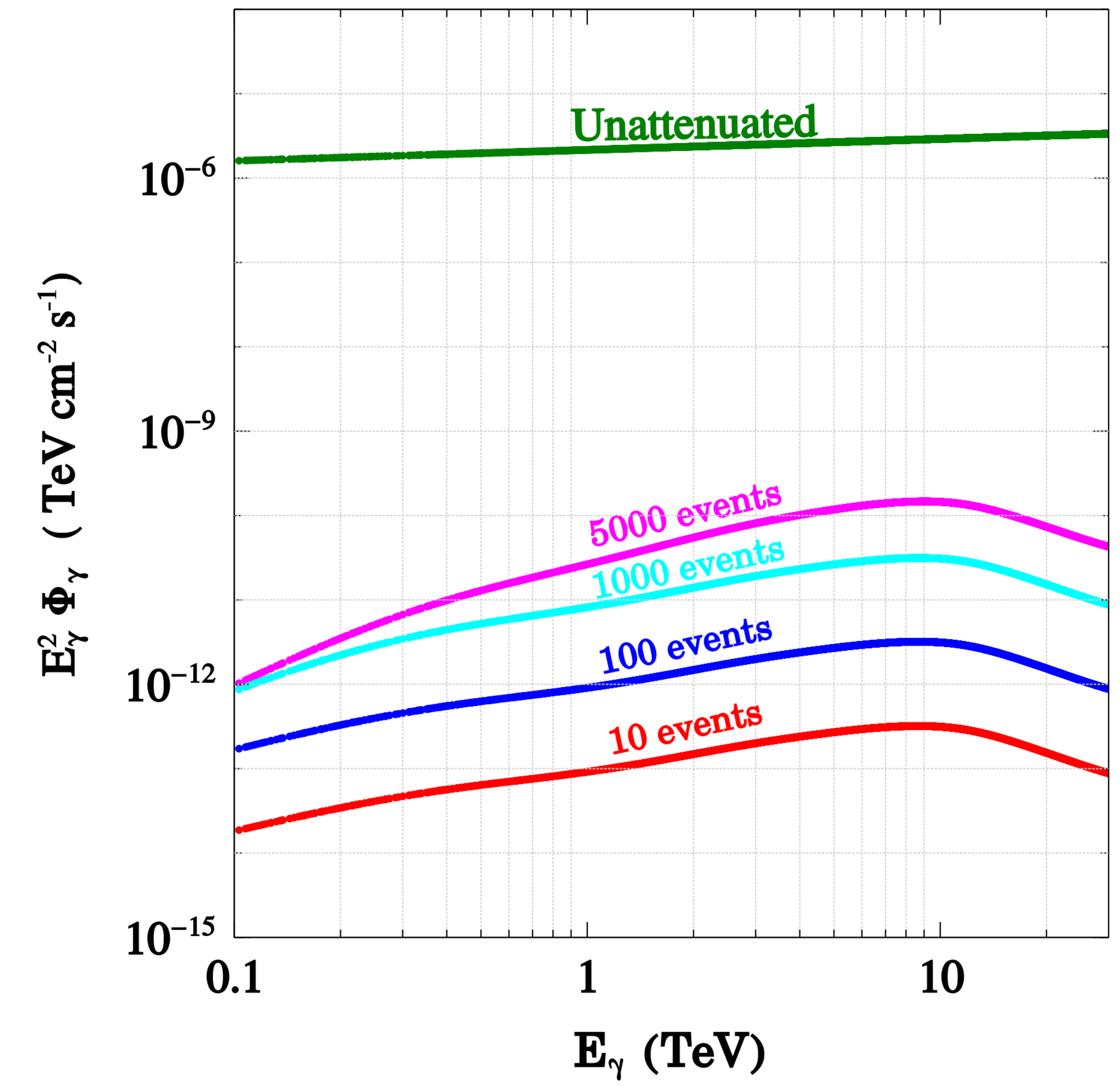
2211.00634



Scalar, $S \to \gamma\gamma$

$$\Phi_\gamma = \frac{2\Phi_S B_\gamma}{\tau\lambda_S/d - 1}\left(e^{-d/\lambda_S} - e^{-\tau}\right)$$

arXiv:2301.02258v3



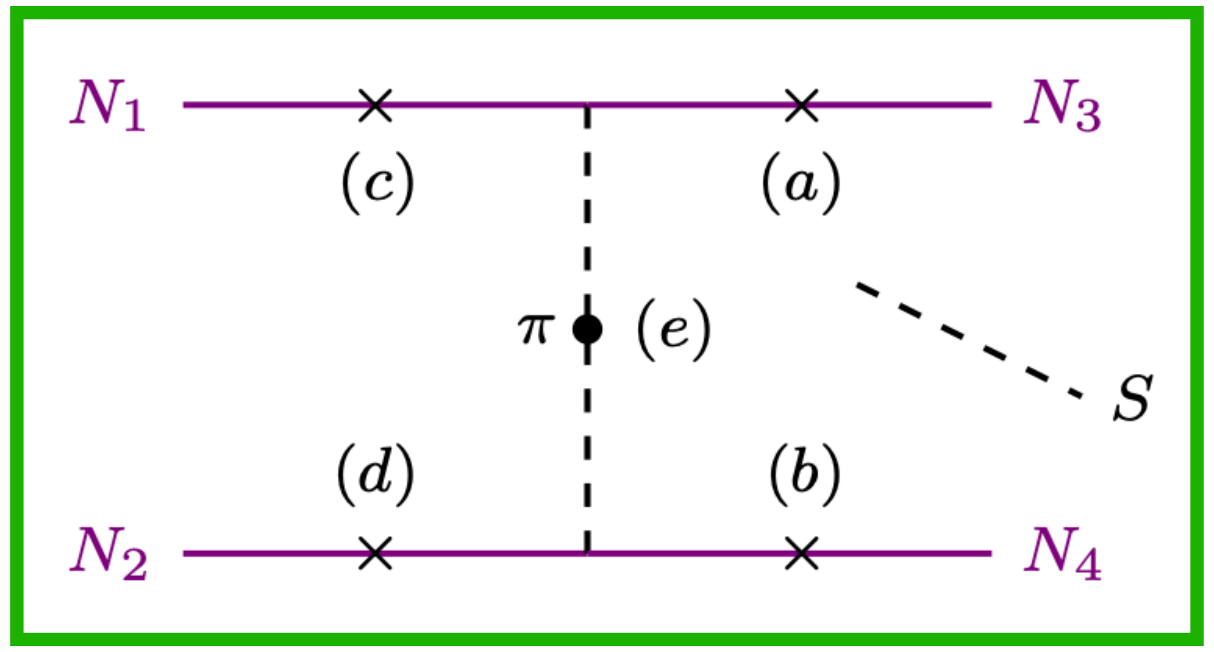
Light Scalar Explanation

S production at GRB site: nucleon-nucleon Bremsstrahlung via pion exchange

$$\boxed{\mathcal{L} \supset -\sin\theta_{SH}\left[A_\pi(\pi^0\pi^0 + \pi^+\pi^-) + y_H \overline{N}N + \frac{m_l}{v_{EW}}\bar{l}l\right]S}$$

$$\boxed{\Gamma_{S\gamma\gamma} = \frac{121}{9}\frac{\alpha^2 m_S^3 \sin^2\theta}{512\pi^3 v^2}}$$

N is nucleon



S can be connected to either the blob or the cross: 2005.00490

- The light scalar S mixes with the SM Higgs H.
- This scalar is produced at the GRB site, and undergoes significant boosting, remaining unattenuated by the EBL.
- Upon reaching Earth, the light scalar decays remotely, yielding two energetic photons via radiative processes.

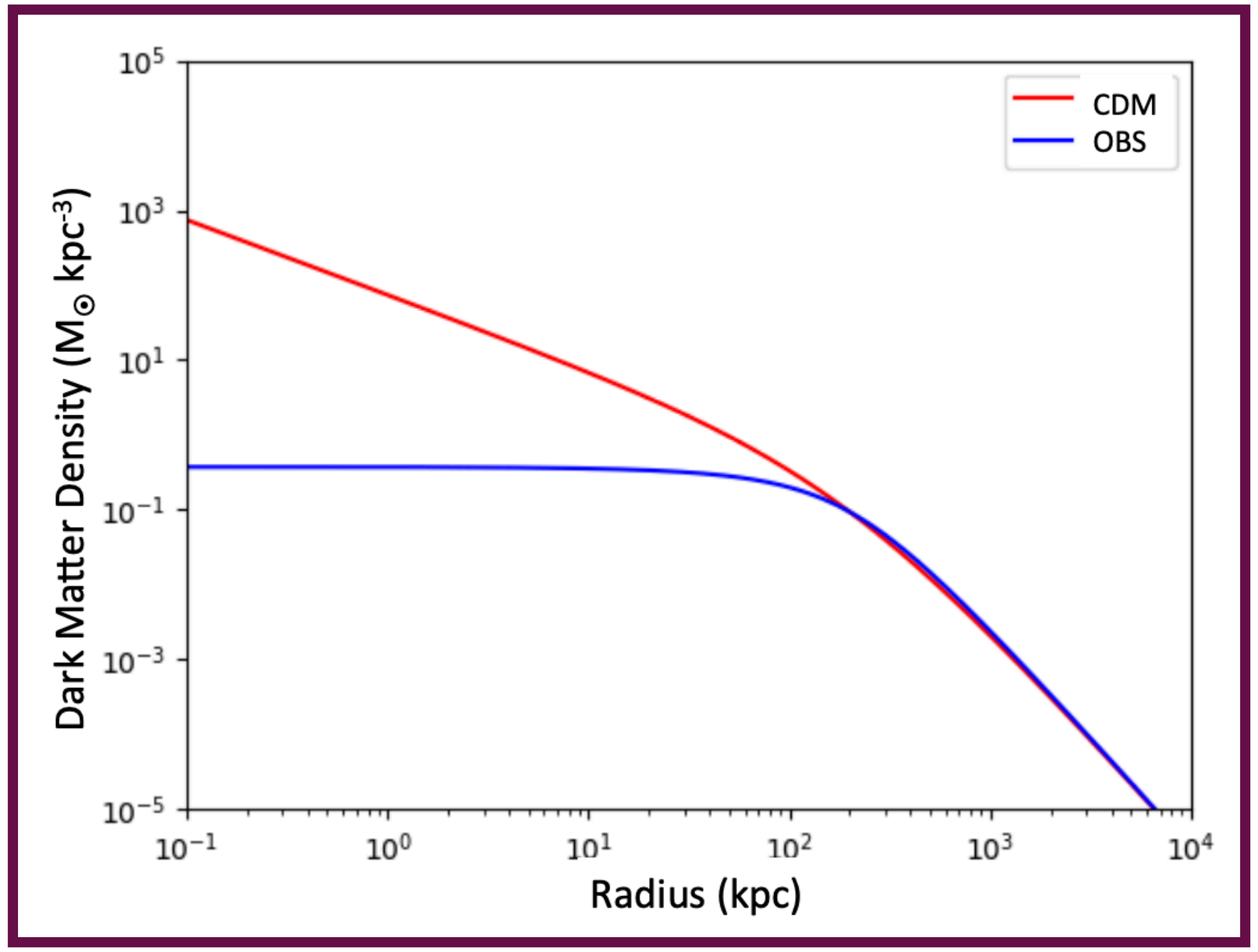
M_S has to be smaller so that the di-photon decay could be made responsible for the GRB221009A

$\theta_{HS} \sim 10^{-8}$

Problems with ΛCDM

To name a few

- **Core-Cusp Problem:** *the density profile of dark matter haloes in galaxies [W. De Blok et al., Advances in Astronomy, 2010]*
- **Missing Satellite Problem:** *over prediction of small satellite galaxies in simulation [1707.04256, astro-ph/9907411, astro-ph/9901240]*
- **Too big to fail:** *absence of the most luminous satellite galaxies in the most massive sub-haloes [1705.02358, 1707.04256]*



Self-Interacting Dark Matter

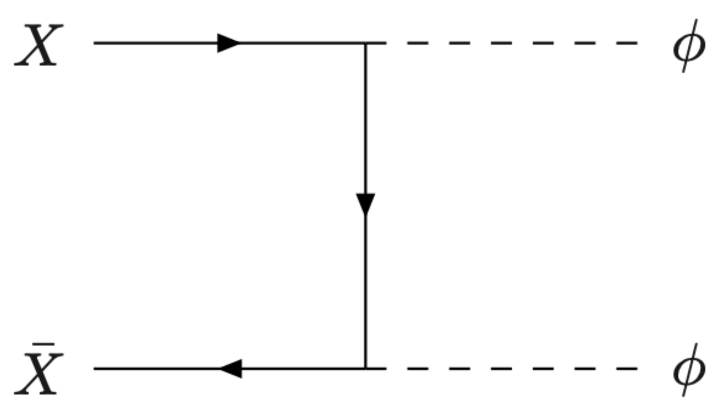
VOLUME 84, NUMBER 17 PHYSICAL REVIEW LETTERS 24 APRIL 2000

Observational Evidence for Self-Interacting Cold Dark Matter

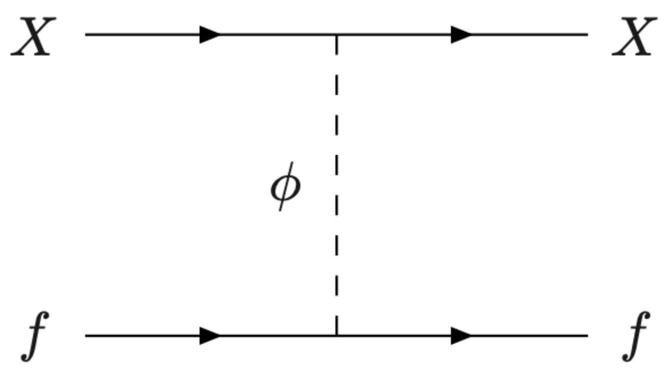
David N. Spergel and Paul J. Steinhardt
Princeton University, Princeton, New Jersey 08544
(Received 20 September 1999)

Cosmological models with cold dark matter composed of weakly interacting particles predict overly dense cores in the centers of galaxies and clusters and an overly large number of halos within the Local Group compared to actual observations. We propose that the conflict can be resolved if the cold dark matter particles are self-interacting with a large scattering cross section but negligible annihilation or dissipation. In this scenario, astronomical observations may enable us to study dark matter properties that are inaccessible in the laboratory.

PACS numbers: 95.35.+d, 98.35.Gi, 98.62.Ai, 98.62.Gq

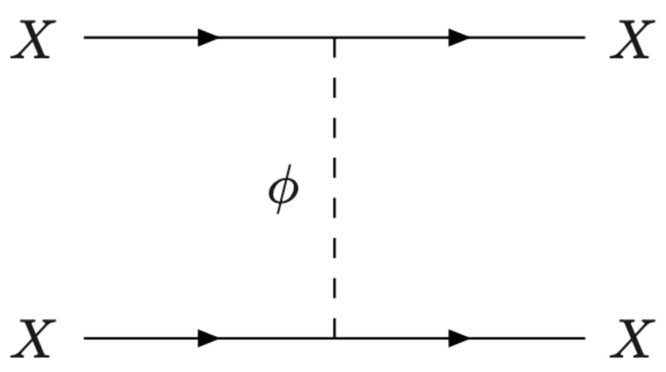


DM annihilation



Direct detection

$$\boxed{\mathcal{L}_{\rm int} = \begin{cases} g_\chi \bar{\chi}\gamma^\mu \chi \phi_\mu & \text{(vector mediator)} \\ g_\chi \bar{\chi}\chi\phi & \text{(scalar mediator)} \end{cases}}$$



DM self-interactions

In the perturbative limit, $(\alpha_\chi m_\chi)/m_\phi \ll 1$

$$\boxed{\frac{d\sigma}{d\Omega} = \frac{\alpha_\chi^2 m_\chi^2}{\left[m_\chi^2 v_{\rm rel}^2 (1-\cos\theta)/2 + m_\phi^2\right]^2}}$$

If $m_\phi \gg m_\chi v_{rel}$ contact interaction, no v dependence

If $m_\phi \ll m_\chi v_{rel}$ Rutherford scattering, $\sim v_{rel}^{-4}$

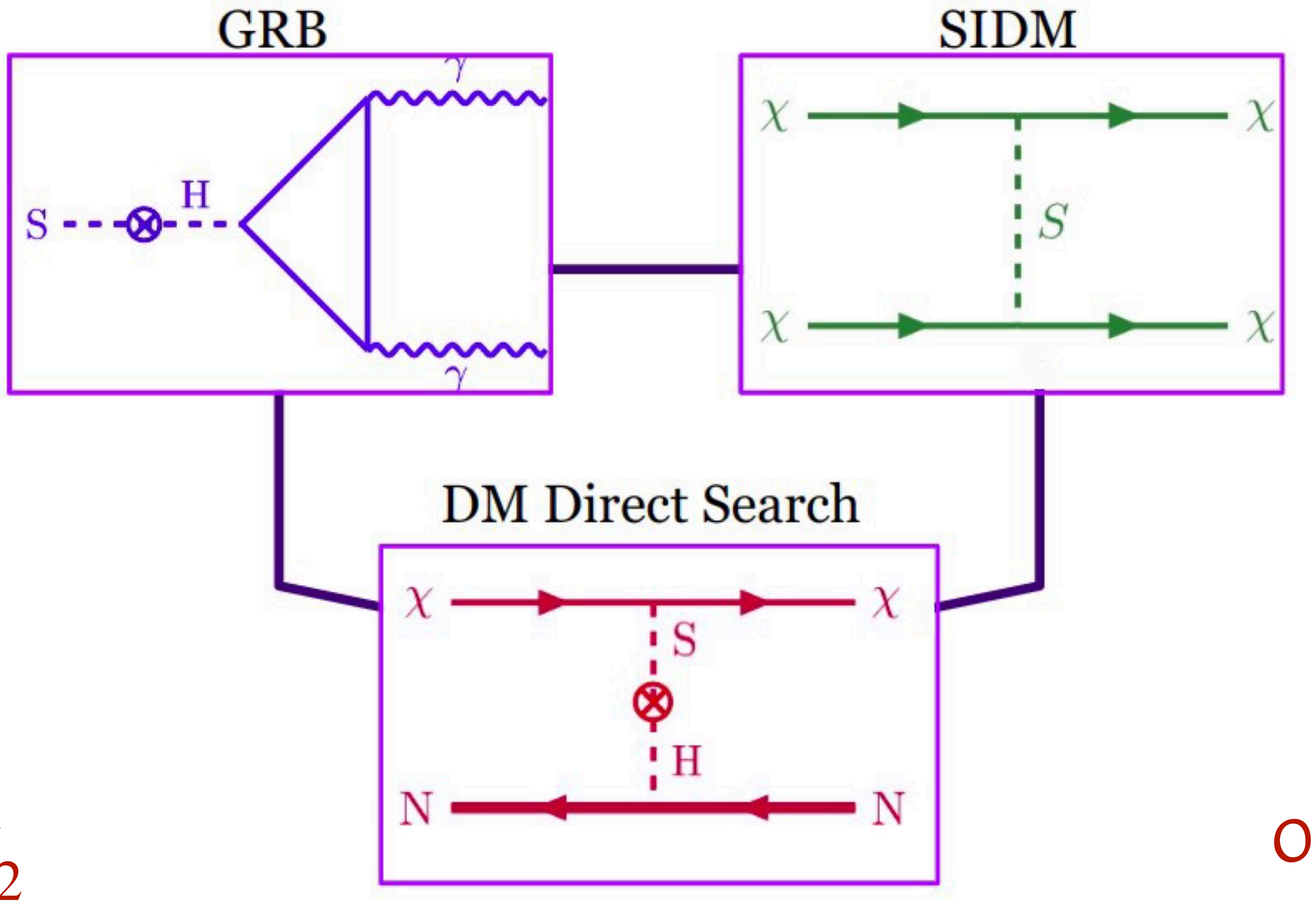
Neither limit provides the mildly velocity-dependent cross-section favoured by observations

Yukawa Potential $\rightarrow$ $\boxed{V(r) = \pm \frac{\alpha_\chi}{r} e^{-m_\phi r}}$

However, a small but finite mass can provide the right velocity dependence

Motivation

Weakly Interacting Particle, propagating most of the distance between the GRB source and the Earth



S

EVEN UNDER Z_2

χ

ODD UNDER Z_2

Relevant Terms and Thermal Freeze-Out

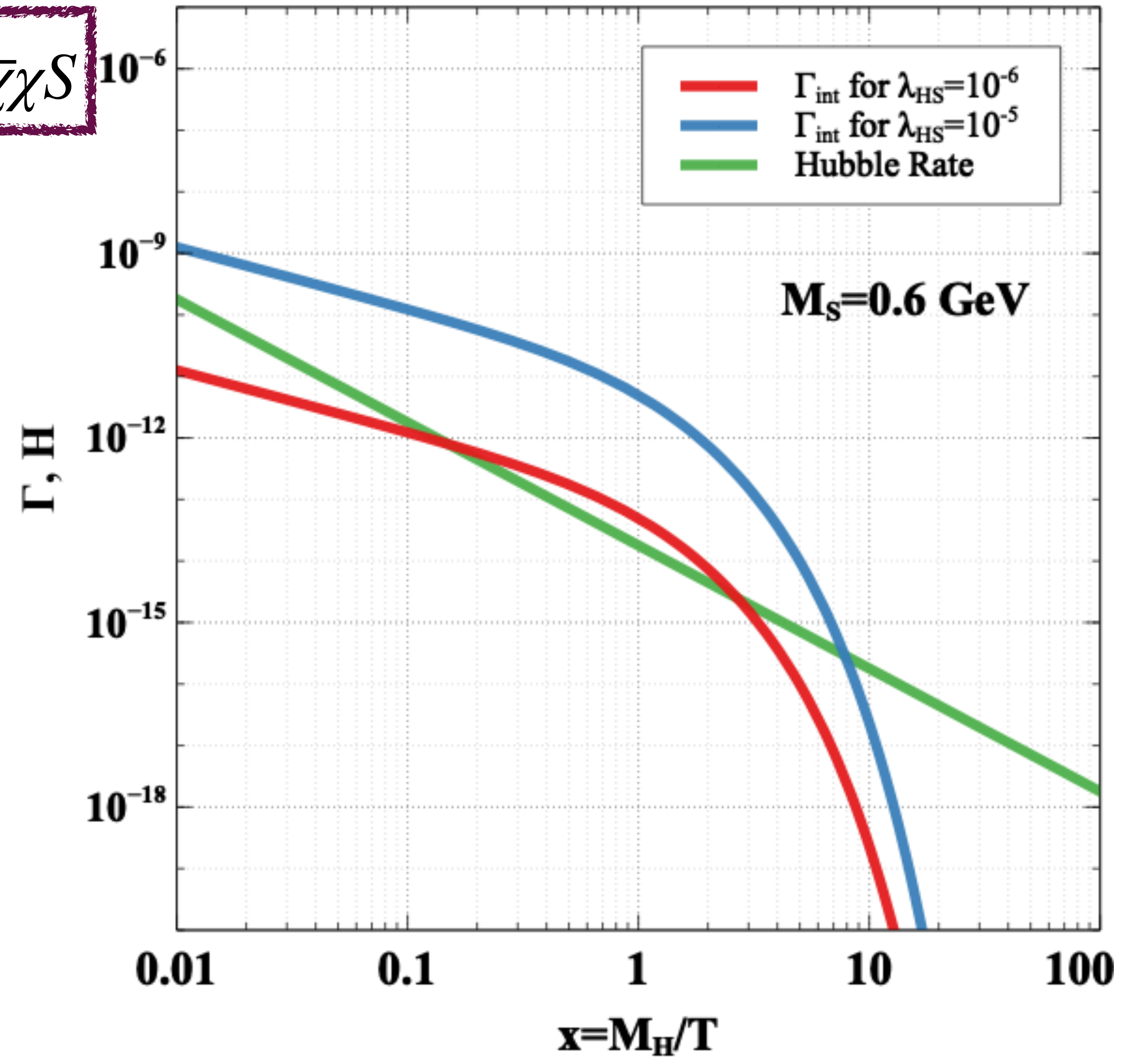
$$\boxed{\mathscr{L} \supset \lambda_{HS}(H^\dagger H)(S^\dagger S) + \mu_{HS} S(H^\dagger H) + y_S \bar{\chi}\chi S}$$

$$\boxed{tan(2\theta_{SH}) = \frac{uv\lambda_{HS} + \sqrt{2}v\mu_{HS}}{M_H^2 - M_S^2}}$$

$$\theta_{SH} = 10^{-8}$$

$$\boxed{\begin{array}{c}\{\lambda_{HS}, \mu_{HS}\} = \{10^{-5}, -6.6\times10^{-6}\} \\ \{10^{-6}, -2.6\times10^{-7}\}\end{array}}$$

Note: $\alpha_\chi = y_S^2/4\pi$



$HH \leftrightarrow SS$ interaction rate against Hubble rate

Small mixing angles imply the DM annihilation to SMSM is suppressed.

The dominant annihilation cross-section is due to

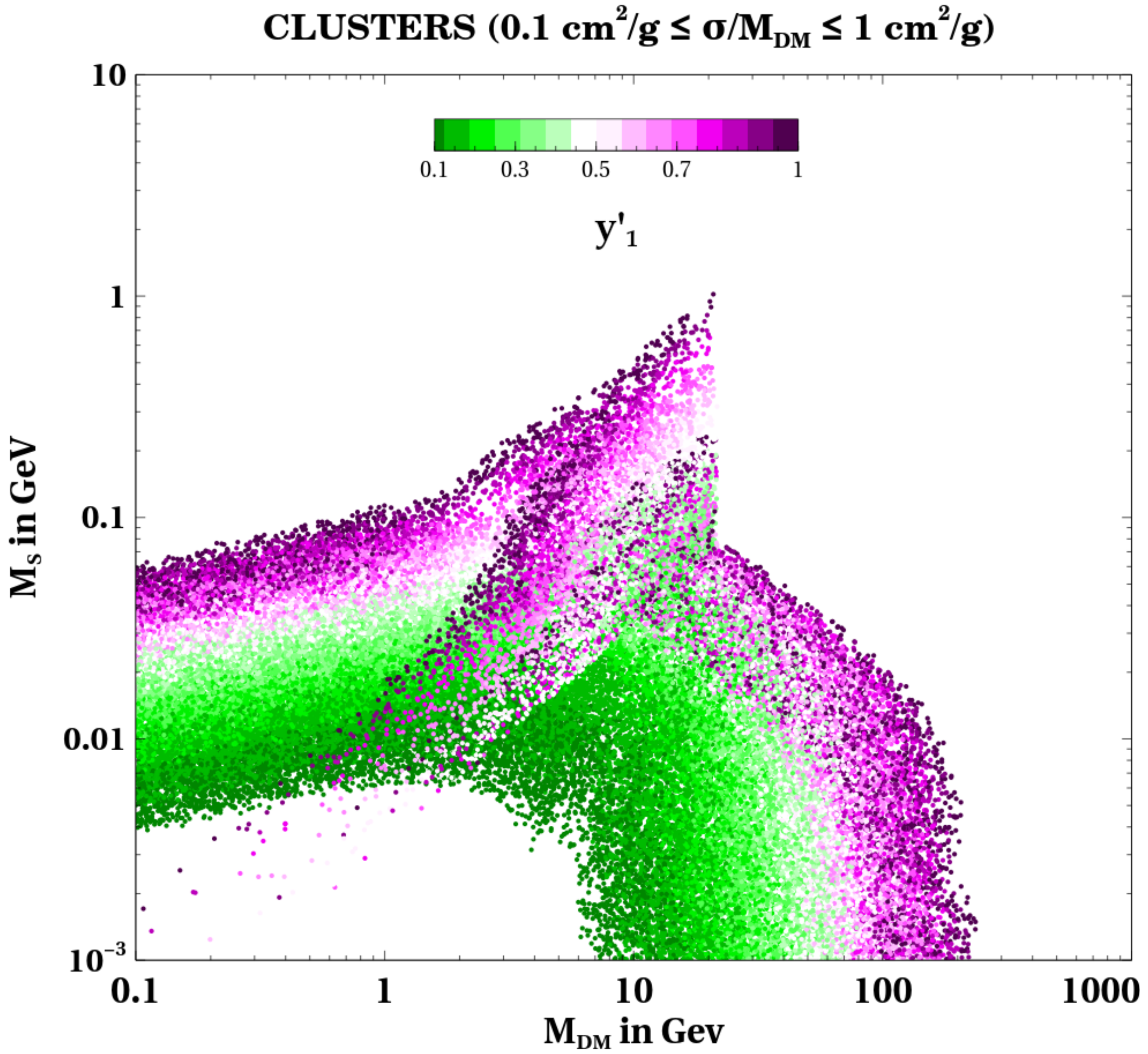
$$SS \to \chi\chi$$

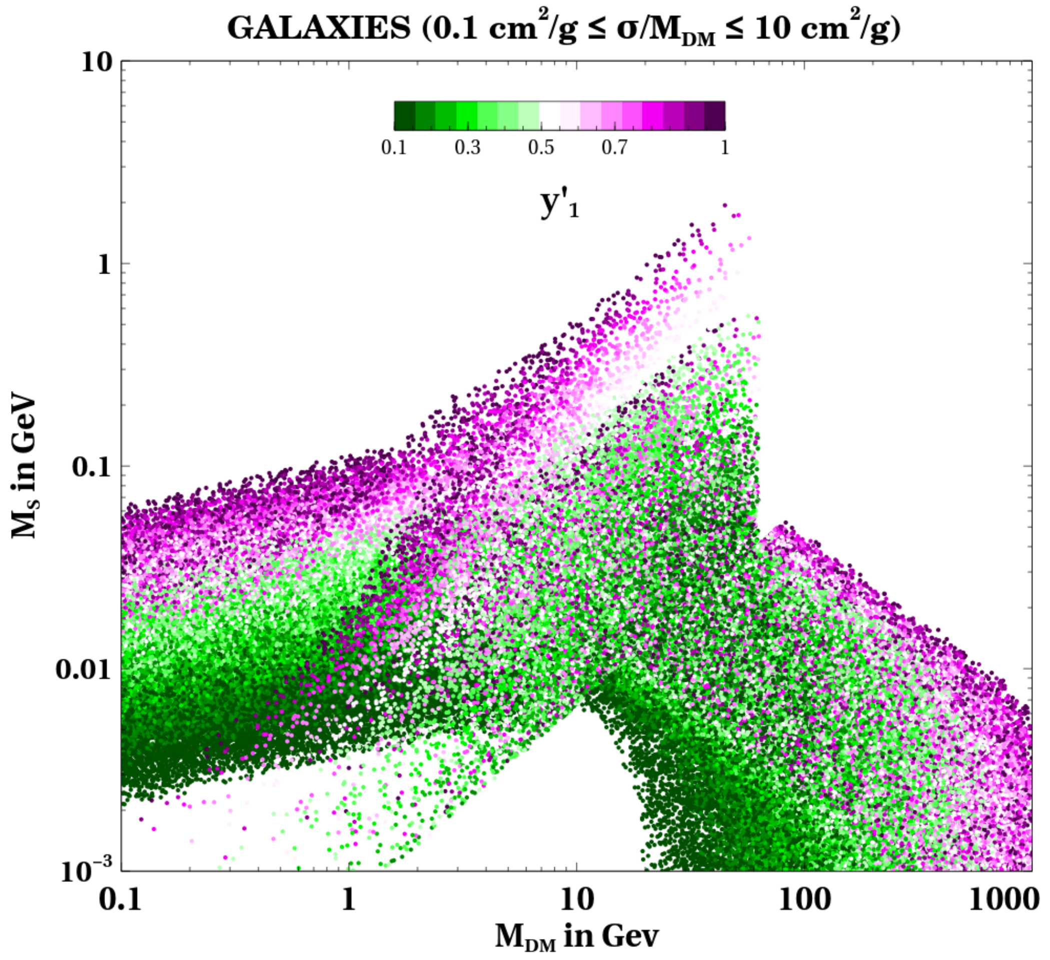
$$\boxed{\langle\sigma v\rangle = \frac{3}{4}\frac{y_S^2}{16\pi M_\chi^2}v^2\left(1 - \frac{(M_S^i)^2}{M_\chi^2}\right)^{1/2}}$$

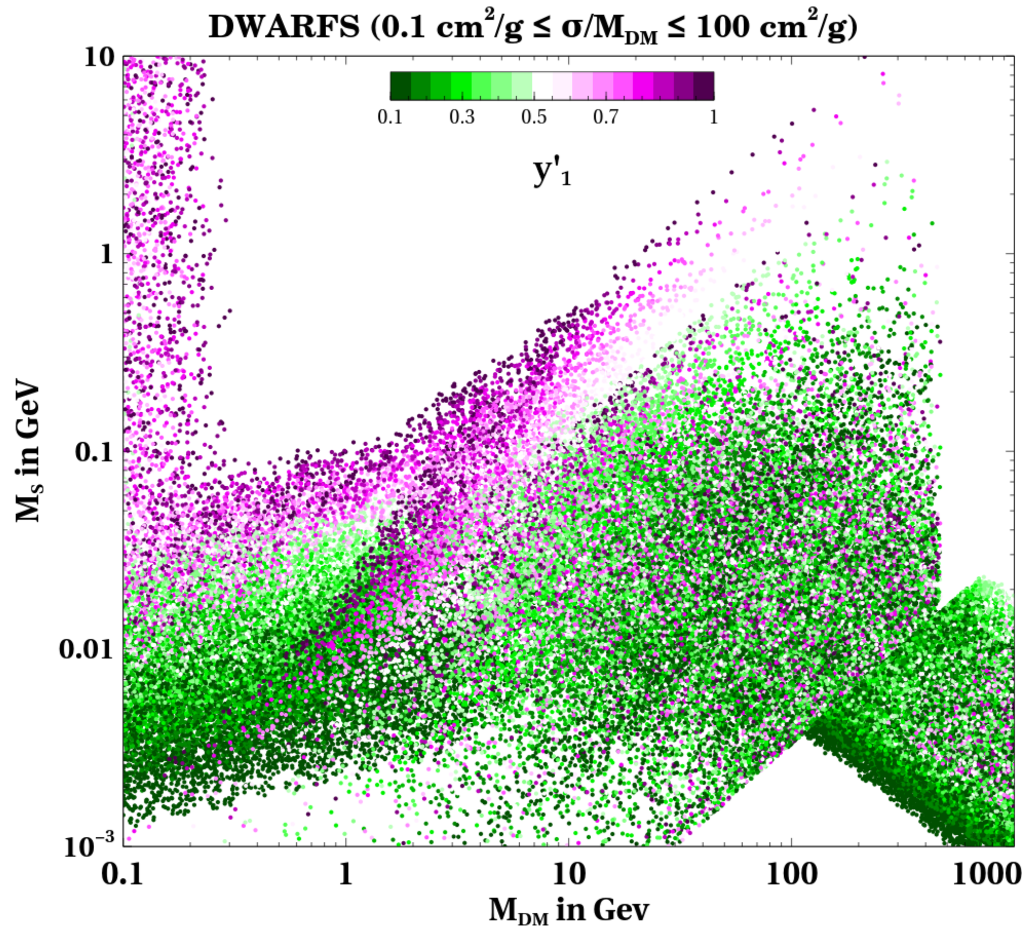
Under-abundant for light SIDM

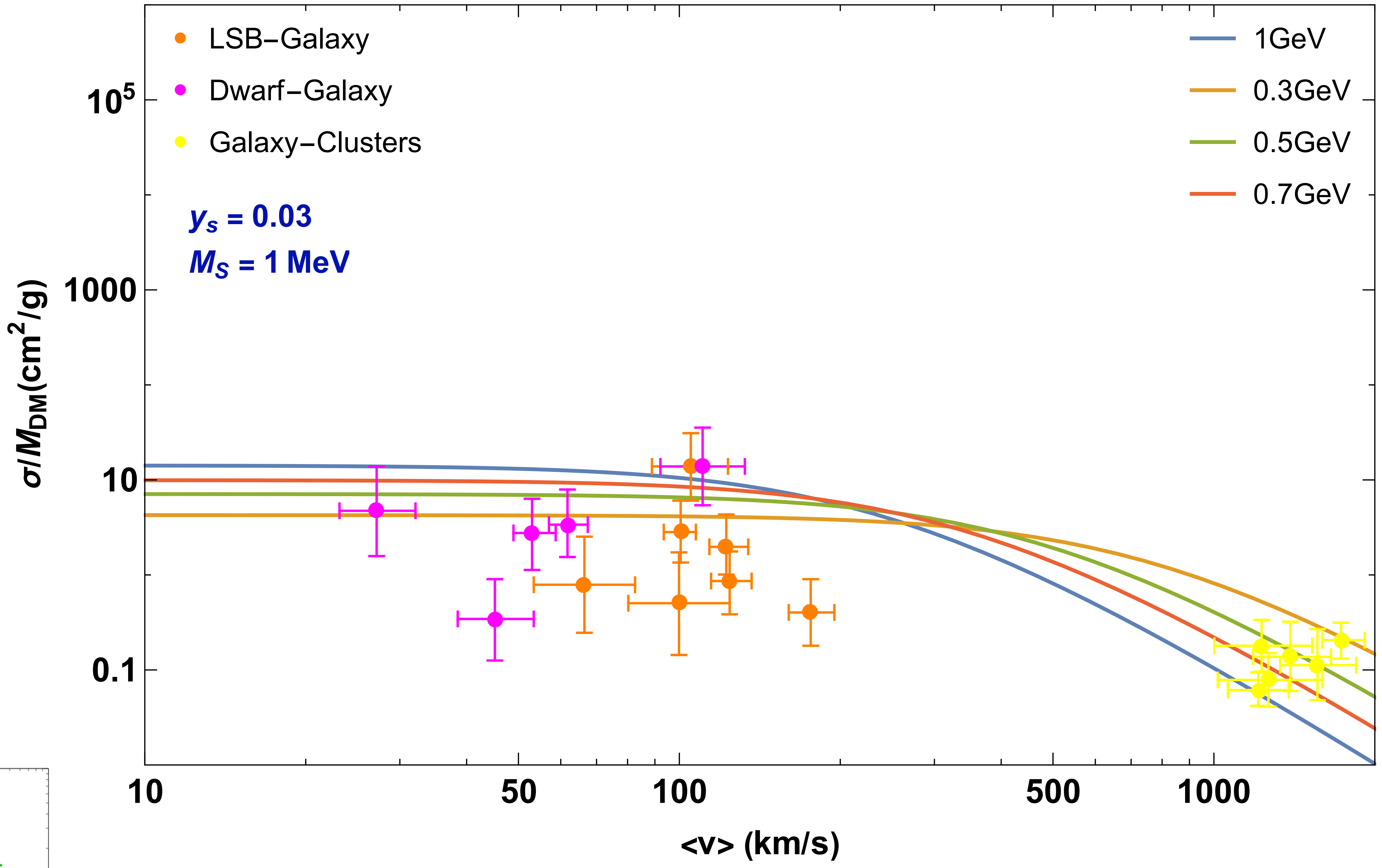
WHY LARGER M_S?

Astrophysical Constraints









A dark matter of mass 0.7 GeV, whose self-interactions is mediated by a light scalar of mass 1 MeV

Source: arXiv:2112.06847

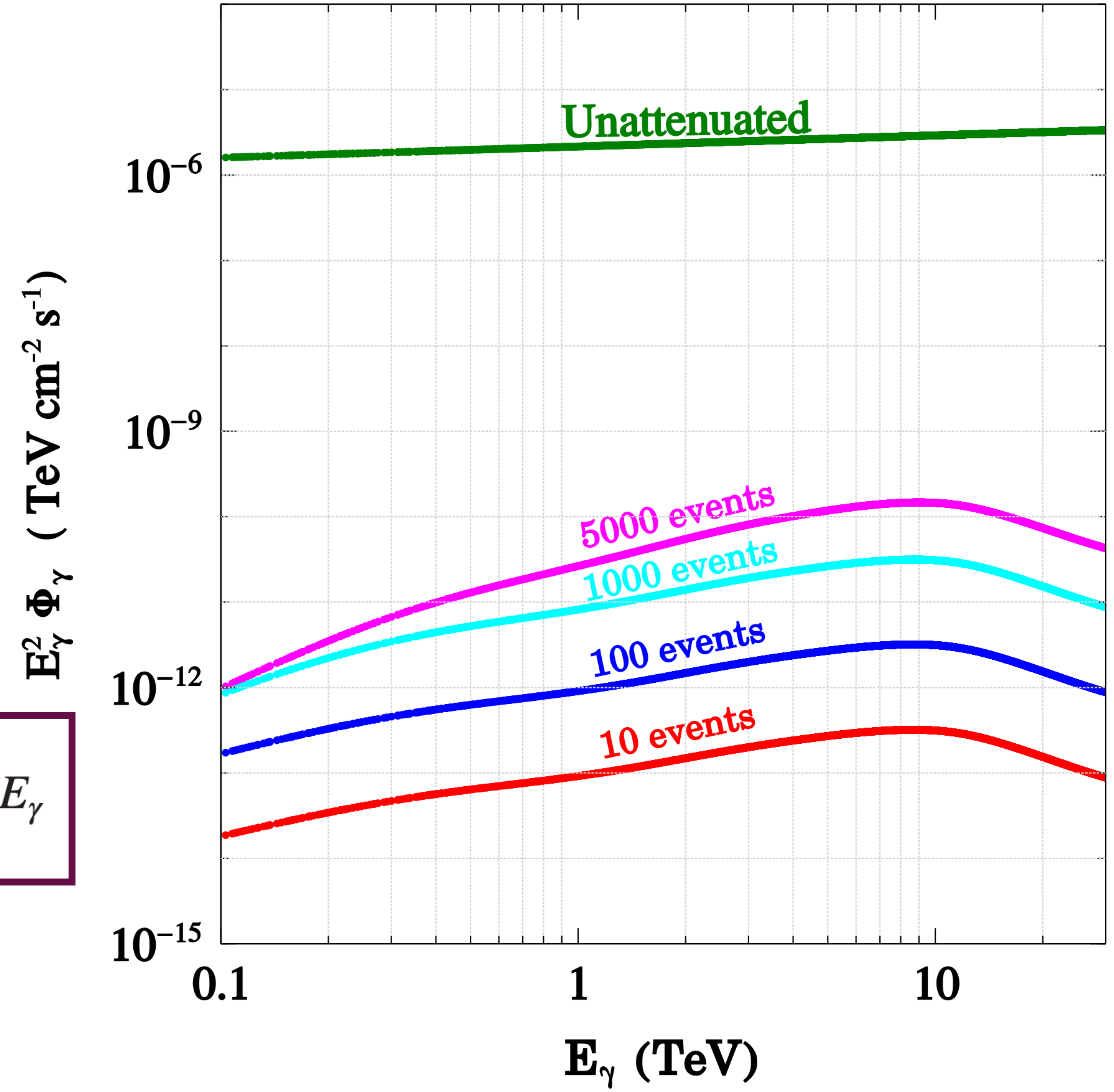
S-induced Gamma ray flux

Unattenuated Gamma ray flux, extrapolating the data measured by Fermi-LAT

$$\Phi^0_\gamma(E_\gamma) = \frac{2.1\times10^{-6}}{\mathrm{cm^2\,s\,TeV}}\left(\frac{E_\gamma}{\mathrm{TeV}}\right)^{-1.87\pm0.04}$$

arXiv:2210.07172v3

$$N_\gamma = \Delta t\int_{0.5}^{18\ \mathrm{TeV}} \mathrm{Area}\times\Phi^S_\gamma(E_\gamma)dE_\gamma$$



S-induce gamma ray flux, assuming $E_S = 2E_\gamma$ over a detector area of $1km^2$ in a time window of $\Delta t = 2000\ s$

Upper limit of mass S:

$M_S < 2m_e$

Else, it will dominantly decay to e^-e^+ pairs.

&

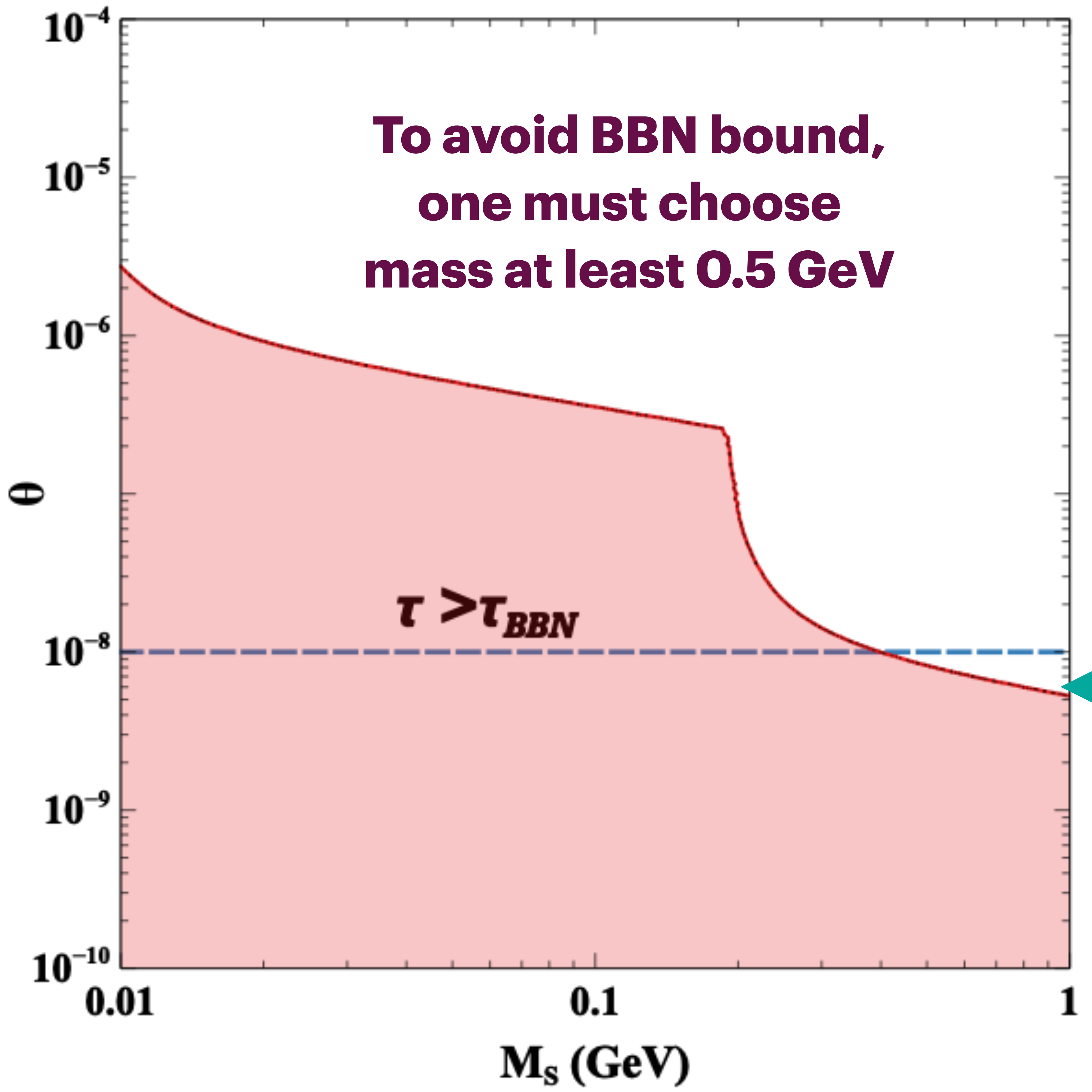
Di-photon decay will be suppressed.

Cannot explain LHAASO's data

Cosmological constraints

$$\Gamma_{S\to e^-e^+} = \frac{M_S m_e^2 \sin^2\theta_{SH}}{8\pi v_{\rm EW}^2}\left(1-\frac{4m_e^2}{M_S^2}\right)^{3/2}$$

$$\frac{dY_{\rm DM}}{dx} = -\frac{s(M_{\rm DM})\langle\sigma v\rangle_{\rm total}}{x^2 H(M_{\rm DM})}\left(Y_{\rm DM}^2 - (Y_{\rm DM}^{\rm eq})^2\right)$$

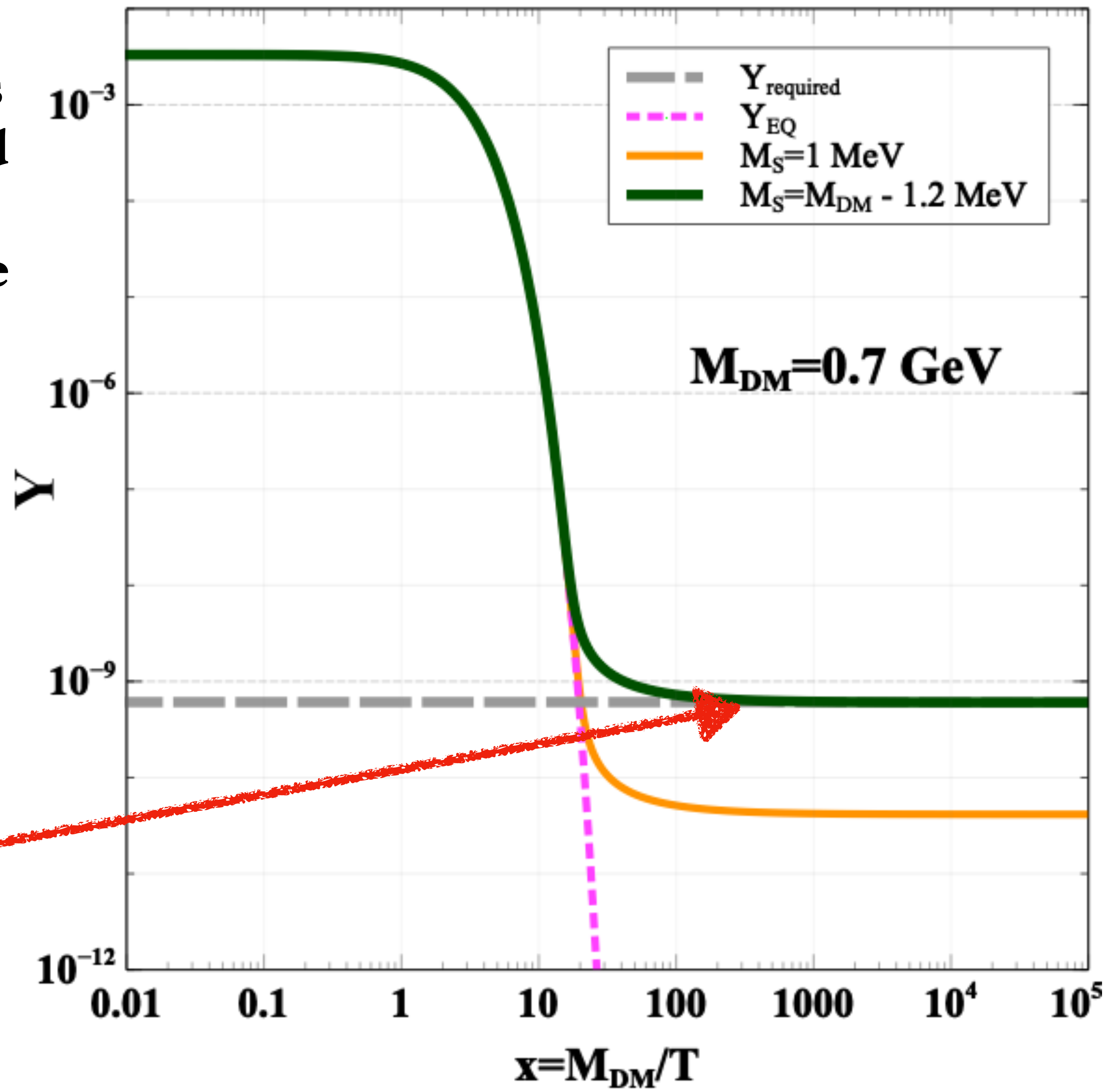


To avoid BBN bound, one must choose mass at least 0.5 GeV

So, 0.6 GeV

If $M_S \lesssim M_\chi$, then the dark matter annihilation rate is further suppressed

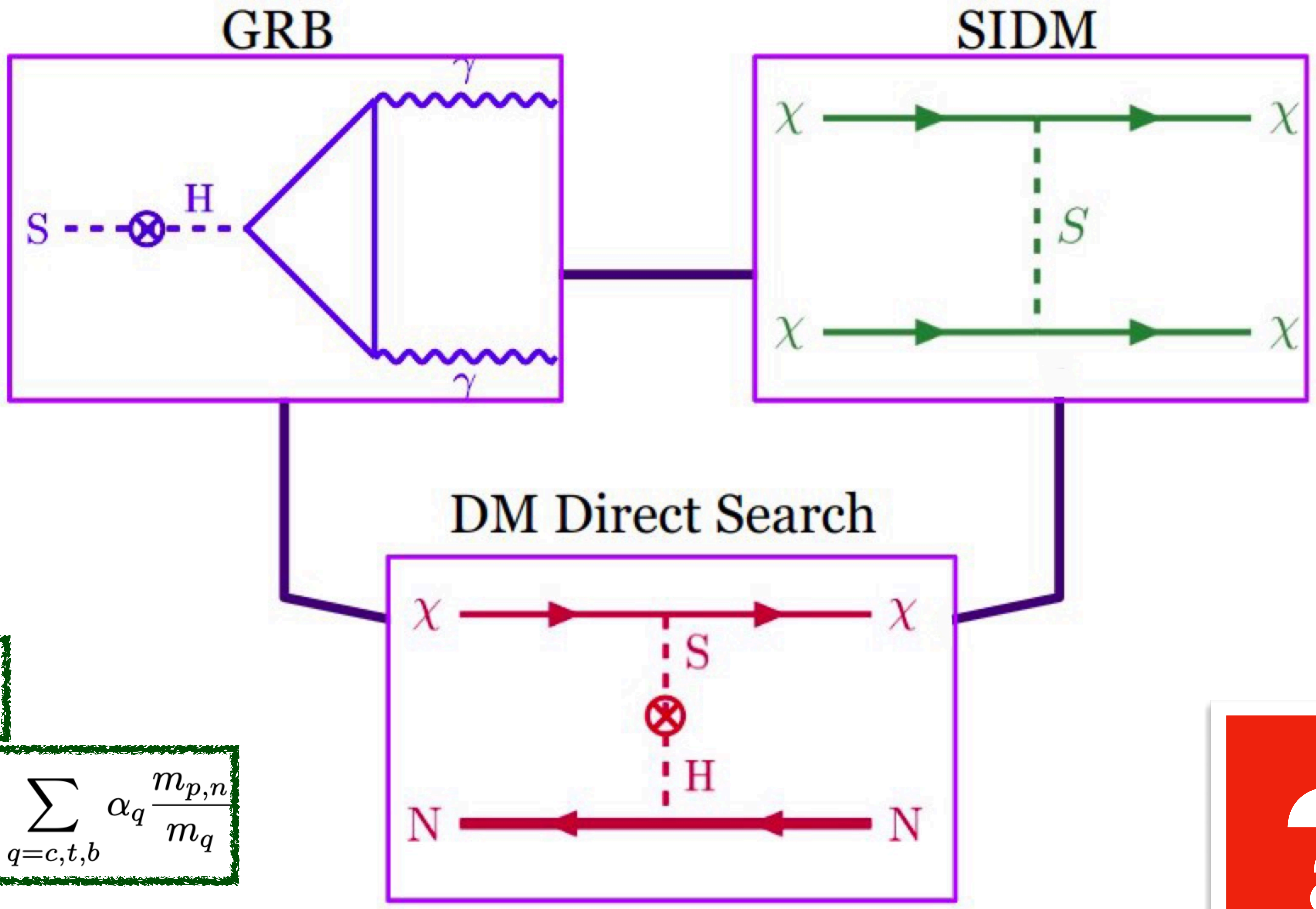
thanks to the phase space suppression



The correct relic can be achieved in a minimal scenario

Problem❗

$M_S \approx 1\ MeV$
$\theta_{HS} \sim 10^{-8}$



$\theta_{HS} \sim 10^{-8}$
Implies
$M_S > 0.5 GeV$
&
$M_S \lesssim M_\chi$

Spin-Independent elastic scattering of DM is possible

$$\sigma_{SI}^{S-H} = \frac{\mu_r^2}{4\pi A^2}\left[Z f_p + (A-Z) f_n\right]^2$$

$$f_{p,n} = \sum_{q=u,d,s} f_{T_q}^{p,n} \alpha_q \frac{m_{p,n}}{m_q} + \frac{2}{27} f_{TG}^{p,n} \sum_{q=c,t,b} \alpha_q \frac{m_{p,n}}{m_q}$$

$$\alpha_q = y_S^2 \theta_{HS} \frac{m_q}{v} \left| \frac{1}{M_S^2} - \frac{1}{M_H^2} \right.$$

$M_S \approx 1\ MeV$
$\theta_{HS} \sim 10^{-8}$

?

Way-Out: FOPT

- Assuming that S was heavy in the early Universe, with an initial mass denoted by M_S^i
- If this S couples to another scalar η driving a first-order phase transition (FOPT) with a coupling of the type $\mu S^\dagger S \eta$, then below the nucleation temperature of the FOPT, the physical mass of S changes as $(M_S^f)^2 = (M_S^i)^2 - u_\eta \mu$ where u_η is the vev of η
- Suitable fine-tuning can bring the mass of S down to its desired value, the detail of which depend upon the model under consideration
- Lastly, if this FOPT occurs well after establishing the correct relic abundance of DM, then the relic may or may not get affected due to the release of latent heat from the FOPT, which again can be avoided depending upon the model.

PHYSICAL REVIEW LETTERS **130,** 031803 (2023)

Maximizing Direct Detection with Highly Interactive Particle Relic Dark Matter

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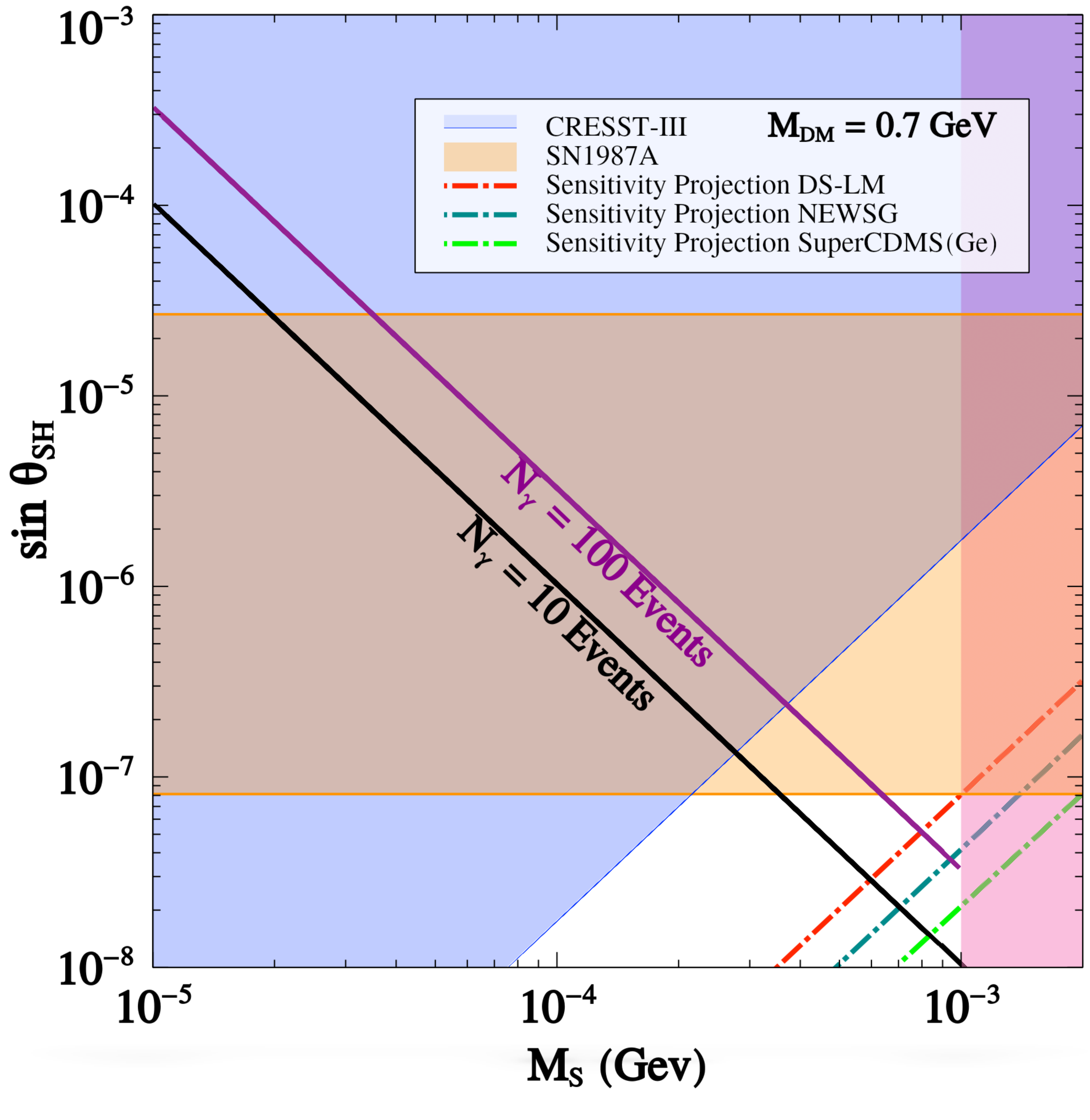
(Received 3 January 2022; revised 25 August 2022; accepted 20 December 2022; published 20 January 2023)

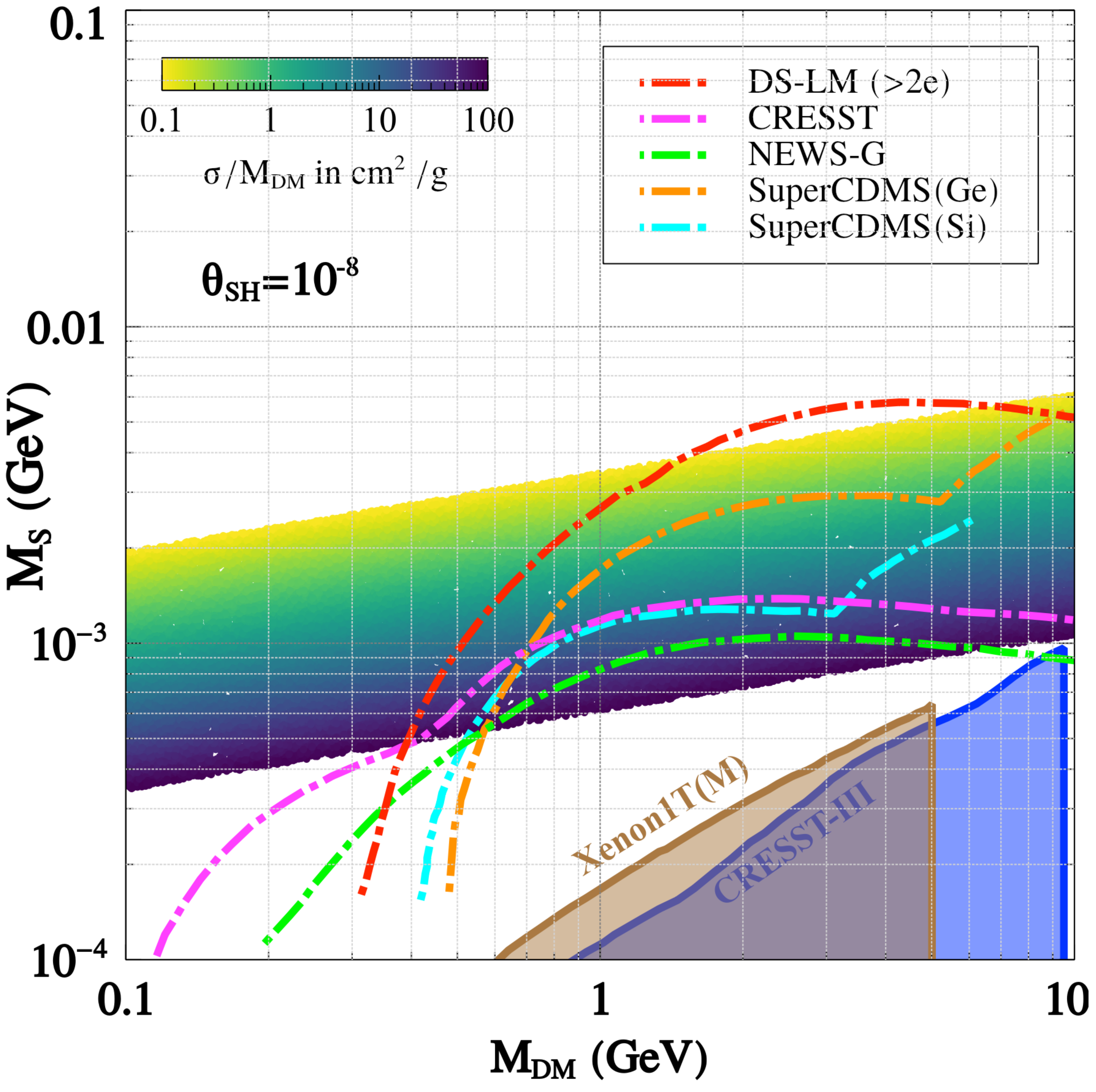
We estimate the maximum direct detection cross section for sub-GeV dark matter (DM) scattering off nucleons. For DM masses in the range 10 keV–100 MeV, cross sections greater than $10^{-36} - 10^{-30}$ cm^2 seem implausible. We present a DM candidate which realizes this maximum cross section: highly interactive particle relics (HYPERs). After HYPERs freeze-in, a dark sector phase transition decreases the mediator's mass. This increases the HYPER's direct detection cross section without impacting its abundance or measurements of big bang nucleosynthesis and the cosmic microwave background.

DOI: 10.1103/PhysRevLett.130.031803

$$M_S^i \xrightarrow{\text{FOPT}} M_S^f = M_S \ll M_S^i$$

Results


CRESST-III
SN1987A
Sensitivity Projection DS-LM
Sensitivity Projection NEWSG
Sensitivity Projection SuperCDMS(Ge)
M_{DM} = 0.7 GeV
N_γ = 100 Events
N_γ = 10 Events
$\sin\theta_{SH}$
M_S (Gev)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}


0.1
1
10
100
σ/M_{DM} in cm^2 /g
DS-LM (>2e)
CRESST
NEWS-G
SuperCDMS(Ge)
SuperCDMS(Si)
$\theta_{SH}=10^{-8}$
Xenon1T(M)
CRESST-III
M_S (GeV)
M_{DM} (GeV)
0.01
10^{-3}
10^{-4}

Summary

- Minimal scenario involves a light scalar mediator, simultaneously enabling DMself-interaction and explaining the observed VHE photons from GRB221009A
- The scalar's mixing with the SM Higgs boson allows for its production at the GRB site, which then propagates escaping attenuation by the EBL
- The same mixing also facilitates DM-nucleon or DM-electron scatterings at terrestrial detectors, linking SIDM phenomenology to the GRB221009A events
- Correct relic density of light SIDM can be achieved without invoking any new particle if the mediator had a heavier mass in the early Universe

THANK YOU