Possible Realizations of Light Thermal Self-interacting Dark Matter & GRB221009A events

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BSM in Particle Physics and Cosmology: 50 Years Later

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With D. Borah, N. Sahu and V. Thounaojam

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Overview

- GRB221009A
- Issues with CDM and Need for SIDM
  - Challenges for light SIDM
- SIDM Framework to explain GRB221009A
  - GRB221009A events
  - Self-Interacting DM and GRB221009A connection
  - Relic Density of DM
  - Direct Detection of DM
  - Other relevant constraints
  - Summary
- Conclusion

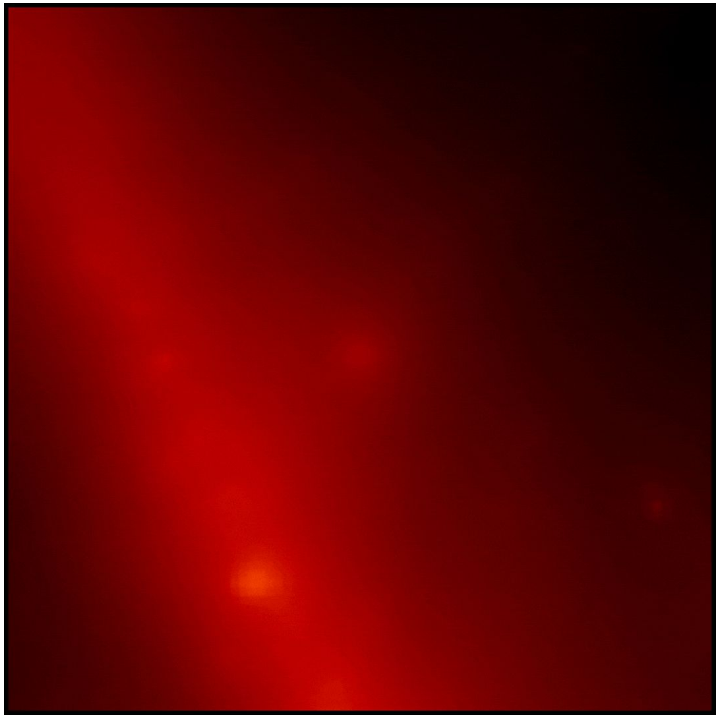
GRB221009A:
BOAT – the brightest of all time.

Burns et.al.

- The initial detection was by BAT, XRT, UVOT on **Swift** **(Swift J1913.1+1946)**, as well as GBM and LAT on **Fermi** satellite.

- **LHAASO**'s WCDA as well as KM2A instrument detected O(5000) photons with $E\gamma >$ 500 GeV from GRB221009A within 2000 s after the initial outburst (GCN 32677).

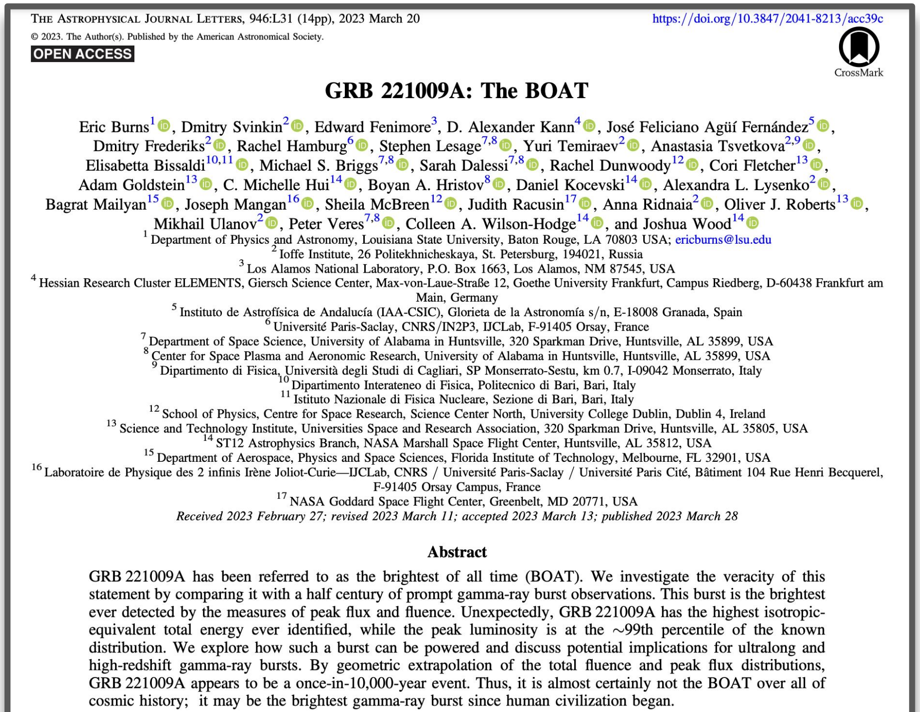
- The photon energies reconstructed by LHAASO extend up to 18 TeV.



Ten-hour timelapse of GRB 221009A,

Credit: NASA/DOE/Fermi LAT Collaboration

GRB221009A


The Astrophysical Journal Letters, 946:L31 (14pp), 2023 March 20 https://doi.org/10.3847/2041-8213/acc39c

CrossMark

GRB 221009A: The BOAT

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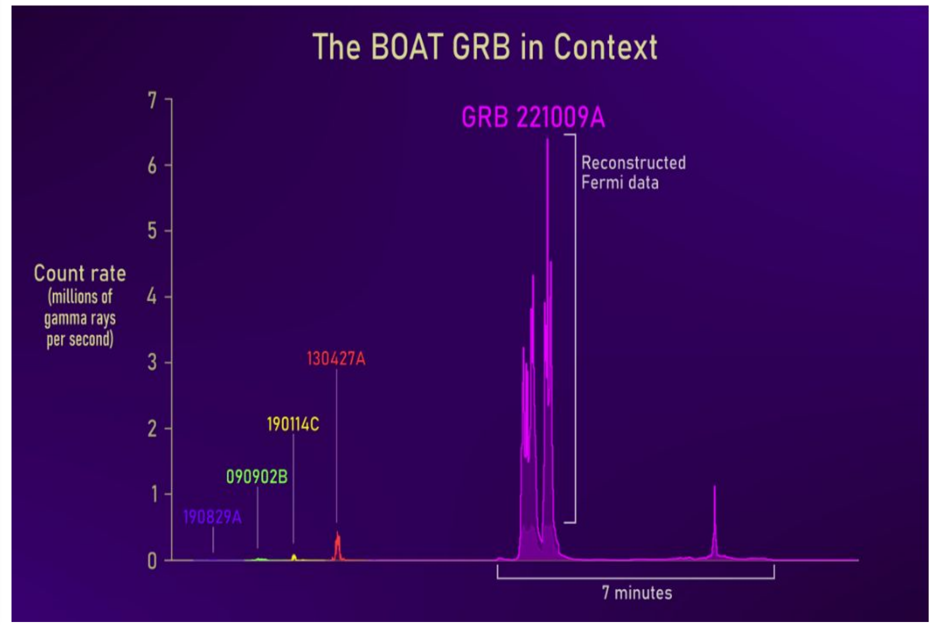
Abstract

GRB 221009A has been referred to as the brightest of all time (BOAT). We investigate the veracity of this statement by comparing it with a half century of prompt gamma-ray burst observations. This burst is the brightest ever detected by the measures of peak flux and fluence. Unexpectedly, GRB 221009A has the highest isotropic-equivalent total energy ever identified, while the peak luminosity is at the ∼99th percentile of the known distribution. We explore how such a burst can be powered and discuss potential implications for ultralong and high-redshift gamma-ray bursts. By geometric extrapolation of the total fluence and peak flux distributions, GRB 221009A appears to be a once-in-10,000-year event. Thus, it is almost certainly not the BOAT over all of cosmic history; it may be the brightest gamma-ray burst since human civilization began.



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

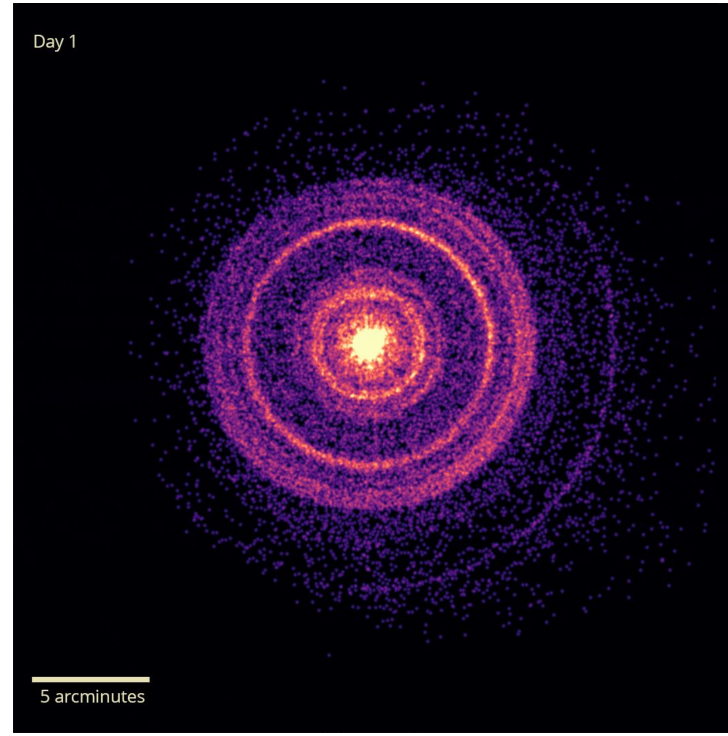
- **GRB 221009A was likely the brightest burst to occur since human civilization began. [Once in 10,000 years]**

GRB221009A

- X-rays from the initial flash of GRB 221009A could be detected for weeks.

- XMM-Newton images recorded 20 dust rings, shown here in arbitrary colors.

- likely remain detectable with radio telescopes for years



Credit: NASA/Swift/A.

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The Radio to GeV Afterglow of GRB 221009A

Tanmoy Laskar[1,2], Kate D. Alexander[3], Raffaella Margutti[4], Tarraneh Eftekhari[5,6,31], Ryan Chornock[7], Edo Berger[8], Yvette Cendes[8], Anne Duerr[1], Daniel A. Perley[9], Maria Edvige Ravasio[2,10], Ryo Yamazaki[11,12], Eliot H. Ayache[13], Thomas Barclay[14,15], Rodolfo Barniol Duran[16], Shivani Bhandari[17,18,19,20], Daniel Brethauer[7], Collin T. Christy[3], Deanne L. Coppejans[21], Paul Duffell[22], Wen-fai Fong[5,6], Andreja Gomboc[23], Cristiano Guidorzi[24,25,26], Jamie A. Kennea[27], Shiho Kobayashi[9], Andrew Levan[2], Andrei P. Lobanov[28], Brian D. Metzger[29,30], Eduardo Ros[28], Genevieve Schroeder[5,6], and P. K. G. Williams[8]

GRB221009A: The Puzzle

- GRB221009A events are reported to have occurred at a redshift of **$z \approx 0.15$ d = 645 Mpc**.
- However, observing such energetic photons is ***extremely unlikely*** since the ***flux is expected to be rapidly attenuated*** when propagating and interacting with ***EBL.***
- The likelihood for propagation of 18 TeV photon from z ~ 0.15 to Earth without scattering : $e^{-15} \sim 10^{-7}$.

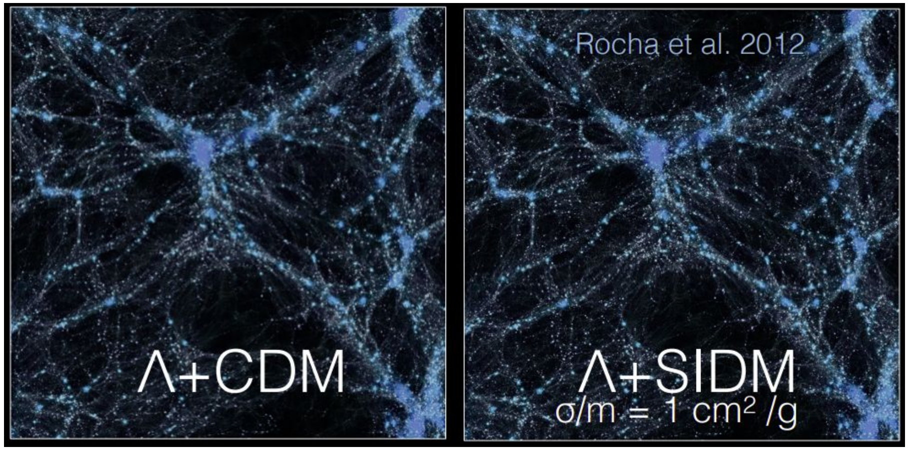
Need for BSM Physics!!!

ALPs, Sterile Neutrinos, Scalars and Lorentz Invariance Violation.

For E.g. Yanagida et. al., Takahashi et.al., Smirnov et. al, Brdar & Li. , Silk et.al.

Self-Interacting Dark Matter

- DM Beyond the collisionless paradigm : SIDM.
- Motivation: Potential to explain long standing small-scale structure
- observations that are in tension with CDM predictions.
- On smaller scales, cosmological DM only simulations & astrophysical observations are facing discrepancies since 1990's.
- At large scale, SIDM leaves intact the success of ΛCDM.



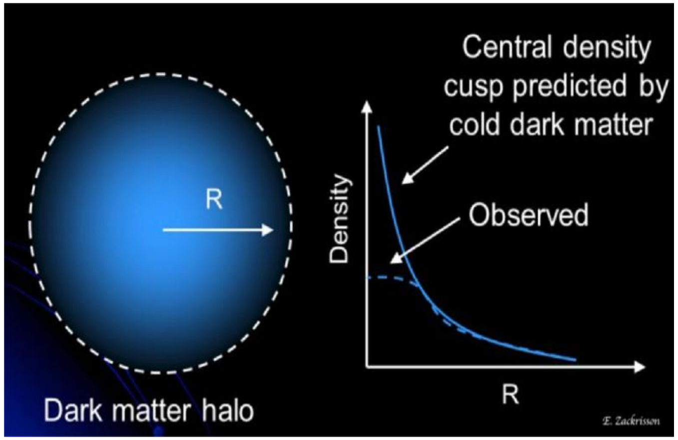
Rocah et. al.

Issues with CDM

- **<u>The cusp-core problem:</u>**

  ΛCDM: Central densities of halos→ Cuspy ($\rho \sim r^{-1}$)

  Observation: Central densities of halos→ Cored ($\rho \sim r^{0}$).

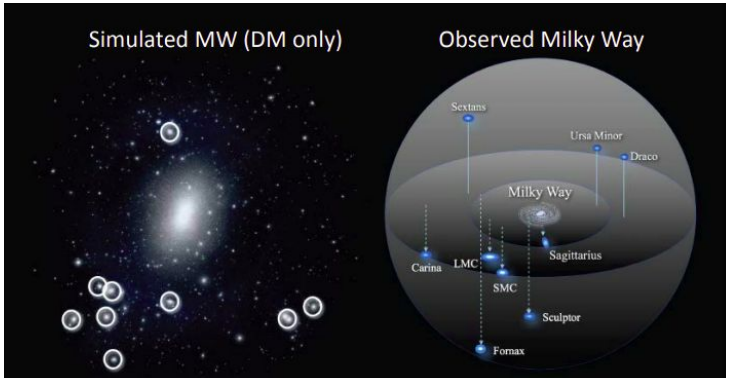


- **<u>The missing satellite Problem:</u>**

  ΛCDM Simulations predict more satellites than those observed.

- **<u>Too big to fail Problem:</u>**

  Observed satellites of the MW are not massive enough to be consistent with predictions of ΛCDM.

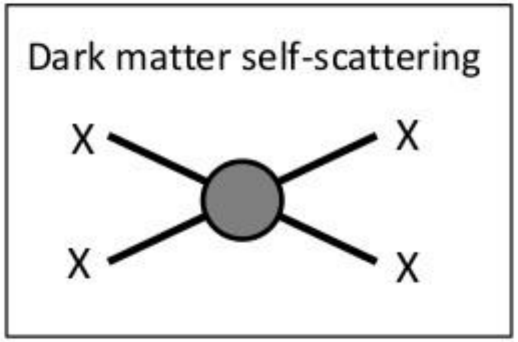


Issues with CDM ⟶ Solution in SIDM

Possible Solutions:

Warm DM :

- May solve missing satellite and TBTF problems.
- Can't solve core-cusp problem
- In strong tension with Lyman-α.



Baryonic Feedback:

- Unclear to what degree baryon dynamics affect halo properties.
- Quite different conclusions with different feedback prescriptions
- Can be regarded as a systematic uncertainty.

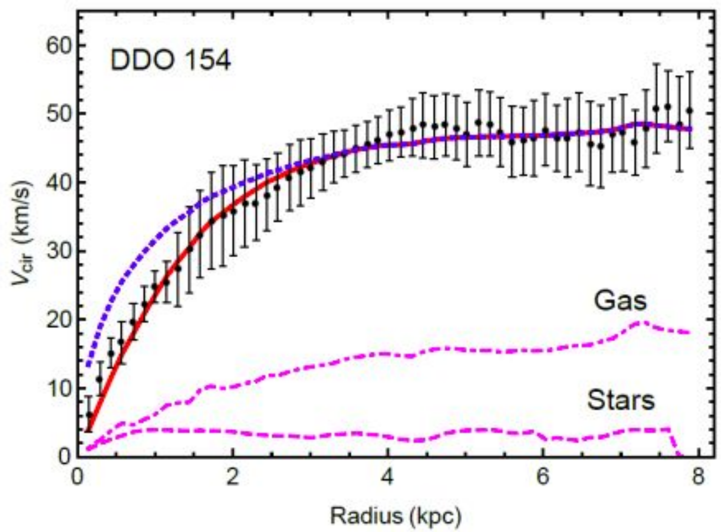
CDM structure problems can be resolved introducing dark matter self-interaction .

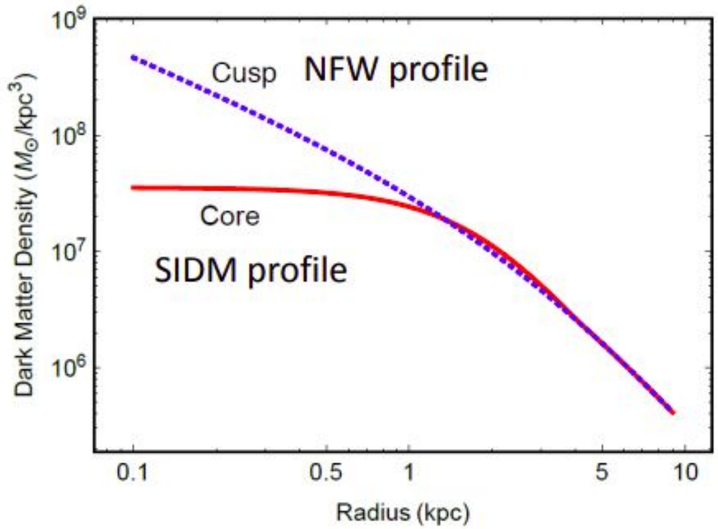
Dark matter particles in halos elastically scatter with other dark matter particles.

Tulin and Yu

Spergel and Steinhardt.

Issues with CDM ⟶ Solution in SIDM





What value of scattering cross-section is needed?

Collision rate:

$$R_{\mathrm{Scatt.}} = \frac{\sigma v_{rel}\ \rho_{DM}}{m} = 0.1\ \mathrm{Gyr}^{-1}\ \left(\frac{\rho_{DM}}{0.1 M_\odot/pc^3}\right)\left(\frac{v_{rel.}}{50\mathrm{km/s}}\right)\left(\frac{\sigma/m}{1\mathrm{cm}^2/\mathrm{g}}\right)$$

Thus

$$\frac{\sigma}{m_{\mathrm{DM}}} \sim 1\mathrm{cm}^2/g \sim 2\ \mathrm{barns/GeV}$$

Light Mediator Models for SIDM

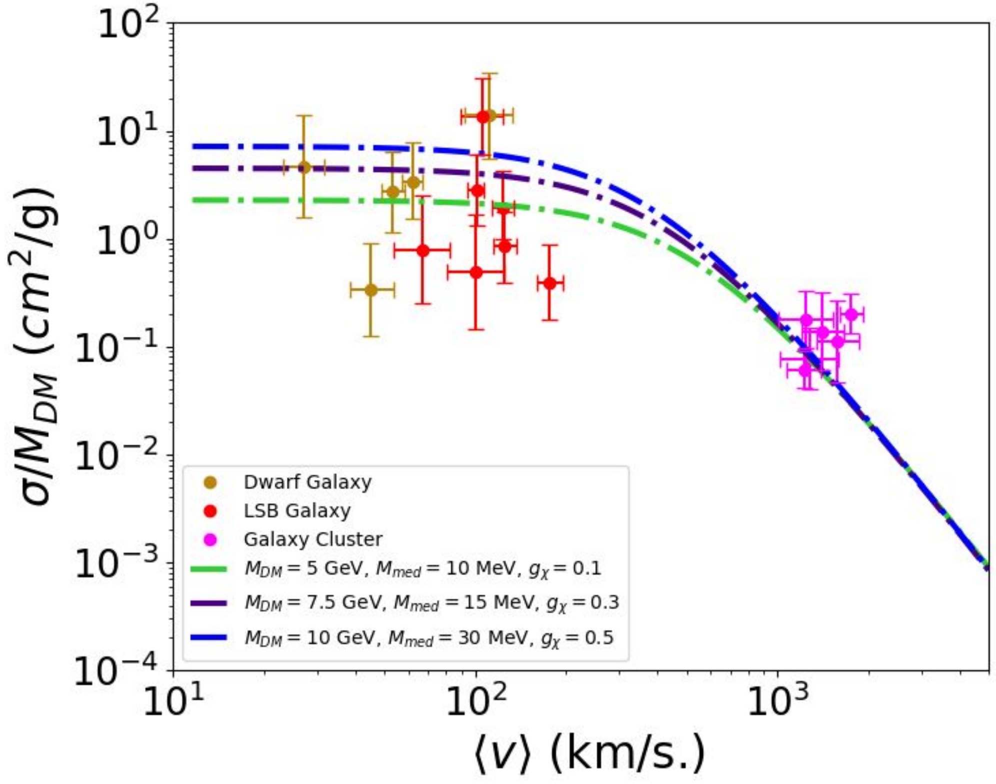
$$\mathcal{L}_{\rm int} = \begin{cases} g_\chi \bar{\chi}\gamma^\mu \chi \phi_\mu & \text{(vector mediator)} \\ g_\chi \bar{\chi}\chi\phi & \text{(scalar mediator)} \end{cases} \qquad V(r) = \pm \frac{\alpha_\chi}{r} e^{-m_\phi r}$$

The Differential cross-section:

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

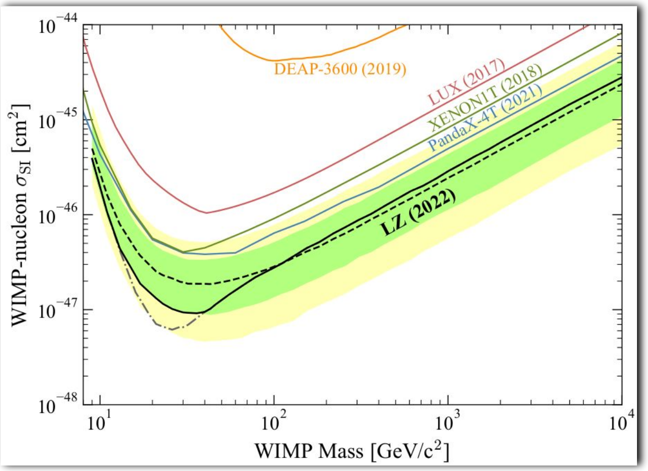
- In the limit of $m_\phi >> m_\chi v_{\rm rel}$ $\Longrightarrow$ contact interaction ($v_{\rm rel}^0$)
- In the limit $m_\phi << m_\chi v_{\rm rel}$ $\Longrightarrow$ Rutherford scattering ($v_{\rm rel}^{-4}$)
- Neither limit provides the mildly velocity-dependent cross section favoured by observations.
- A small but finite mediator mass can provide the right velocity dependence.

Light Mediator Models for SIDM



Borah,SM, Sahu

GeV/ Sub-GeV Scale DM

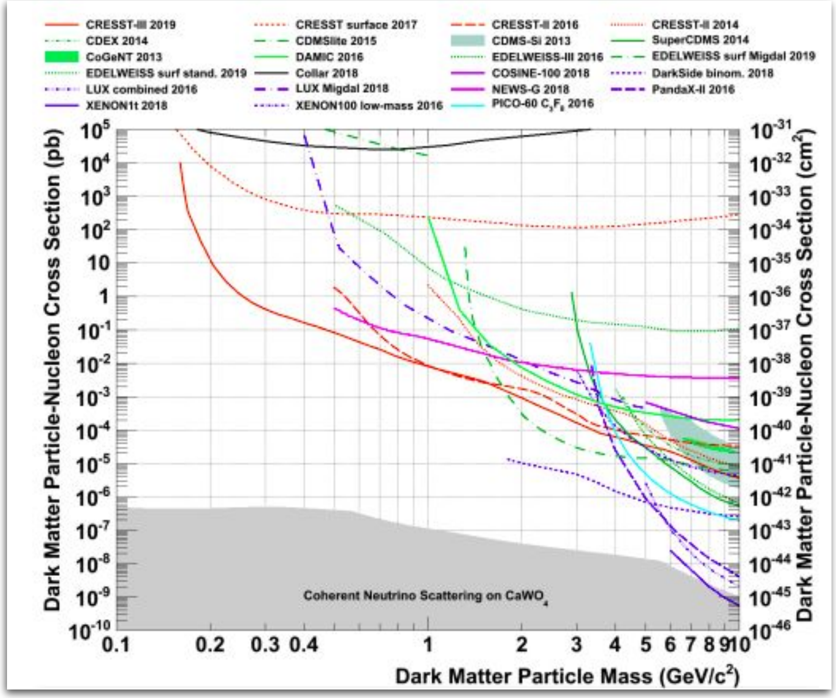


- No observation yet at Direct search experiments.

Motivation: To look for several viable alternatives to WIMP

Exciting possibility: light DM around GeV or sub-GeV scale.

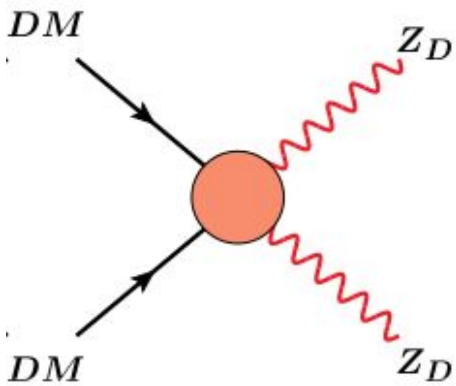
Many Experiments looking for Light DM: XENON1T, CRESST-III, EDELWEISS, Super-CDMS, SENSEI, DAMIC, DarkSide-50.

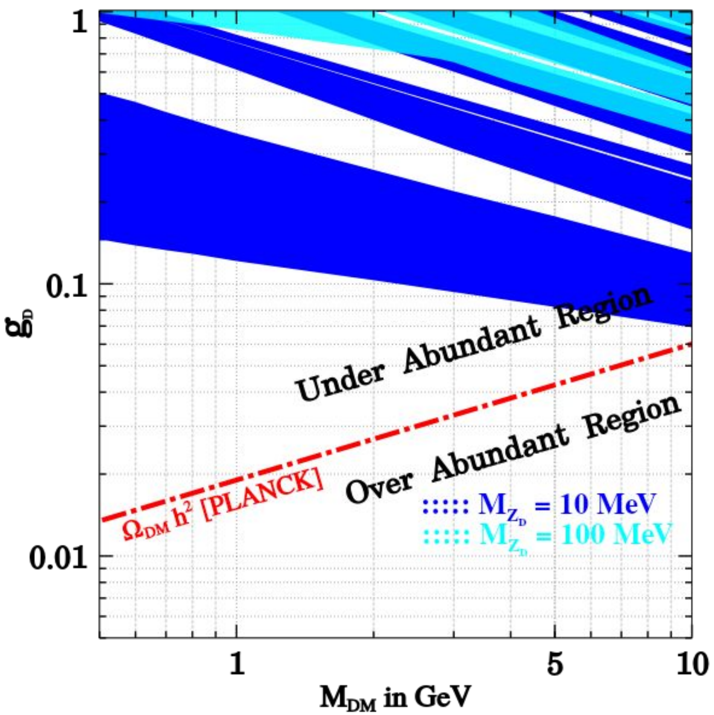


Challenge for Light SIDM

Challenge for SIDM: Achieving Correct Relic Density

Self-Interaction $\Longrightarrow$ Under Abundant Relic





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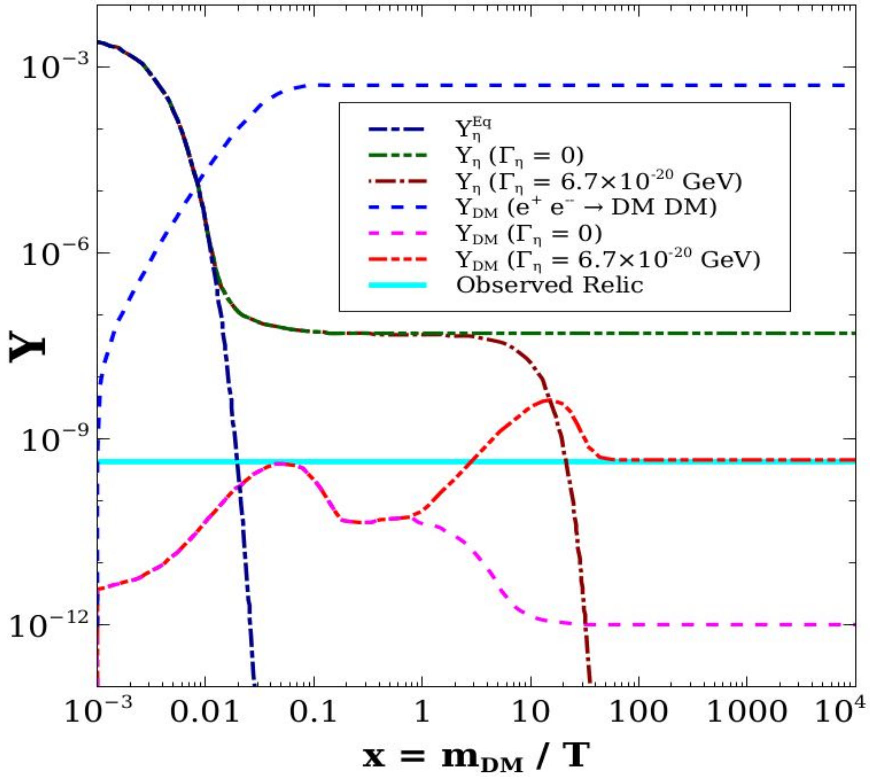
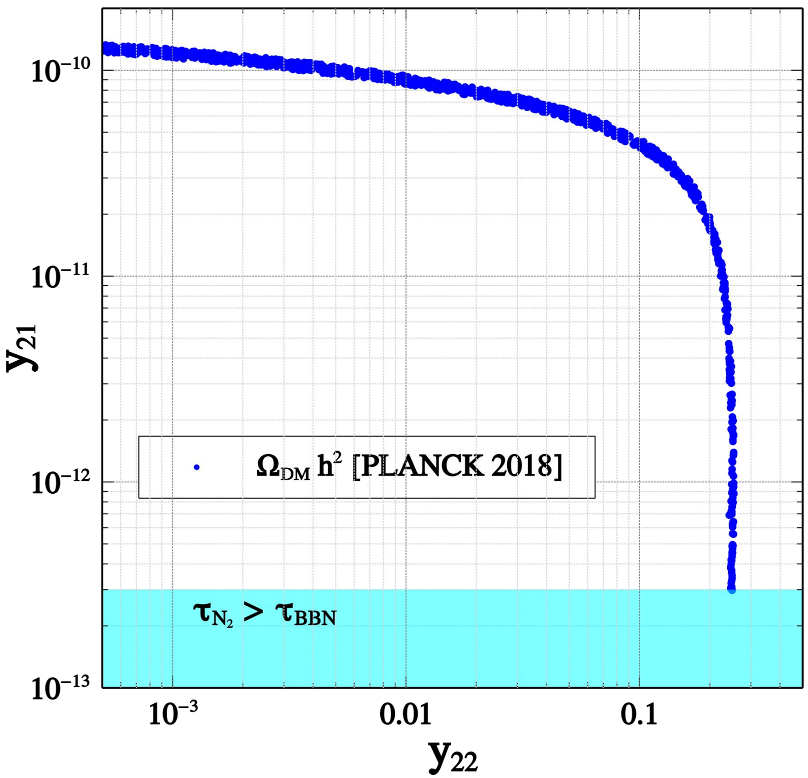
Challenge for Light SIDM

Solutions for achieving Correct Relic Density
$\Longrightarrow$ Non-thermal / Hybrid Setups





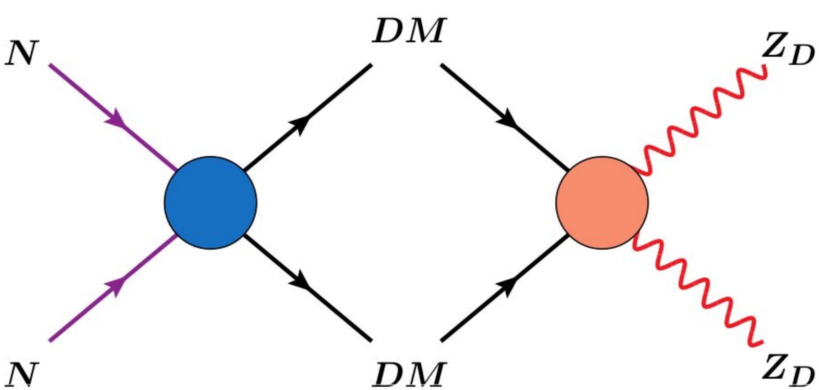
Borah, SM, Sahu

Requires Additional particles in the spectrum !!!

Challenge for Light SIDM

Solutions for achieving Correct Relic Density
$\Longrightarrow$ **Novel Thermal Production mechanism**

$$\mathcal{L} \supset i\overline{\psi}\gamma^{\mu}D_{\mu}\psi - M_{\psi}\overline{\psi}\psi - M_N\overline{N}N - \{Y_{\psi N}\overline{\psi}\Phi N + \text{h.c.}\} + \frac{\epsilon}{2}B^{\alpha\beta}Y_{\alpha\beta}$$



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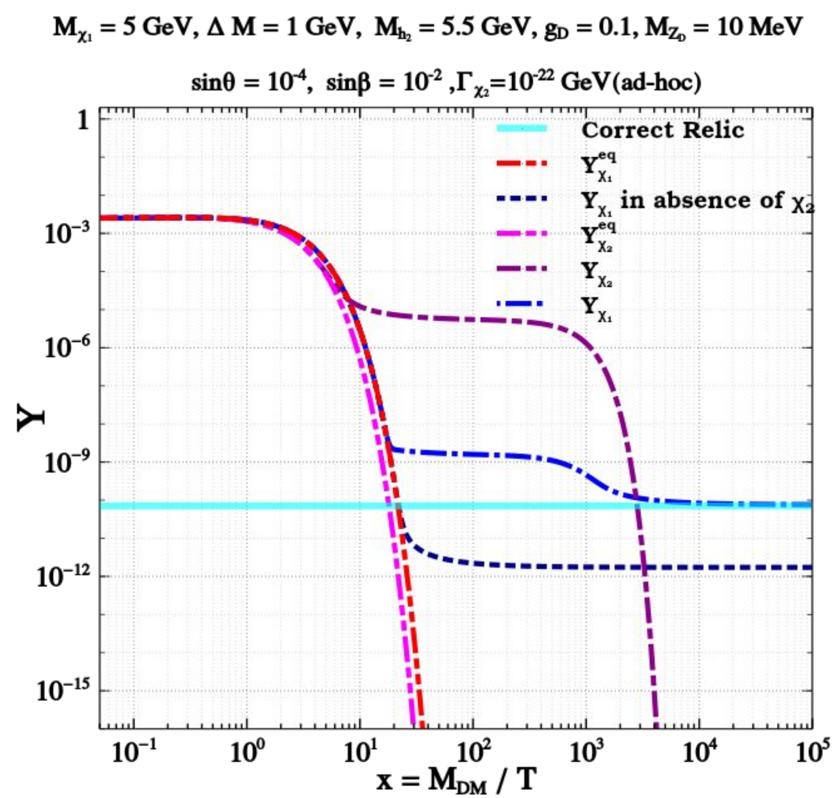
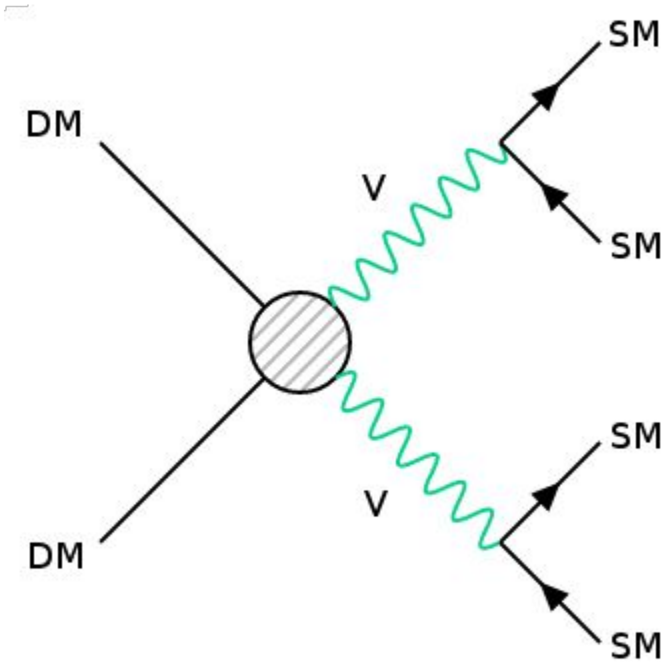
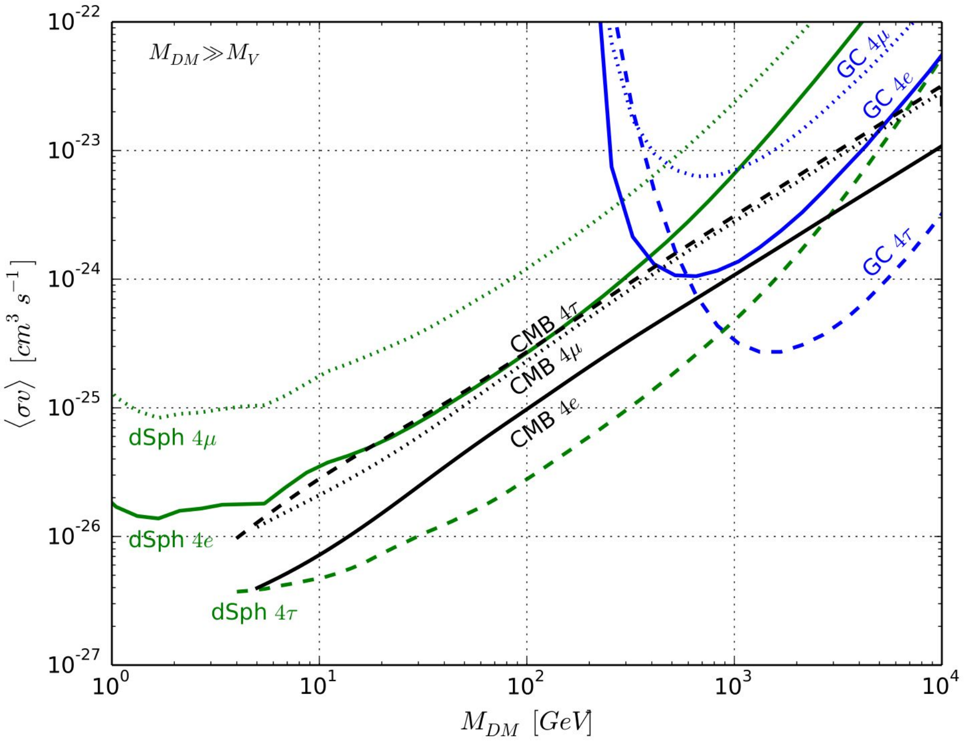


Requires Additional particles in the spectrum !!!

Challenge for Light SIDM

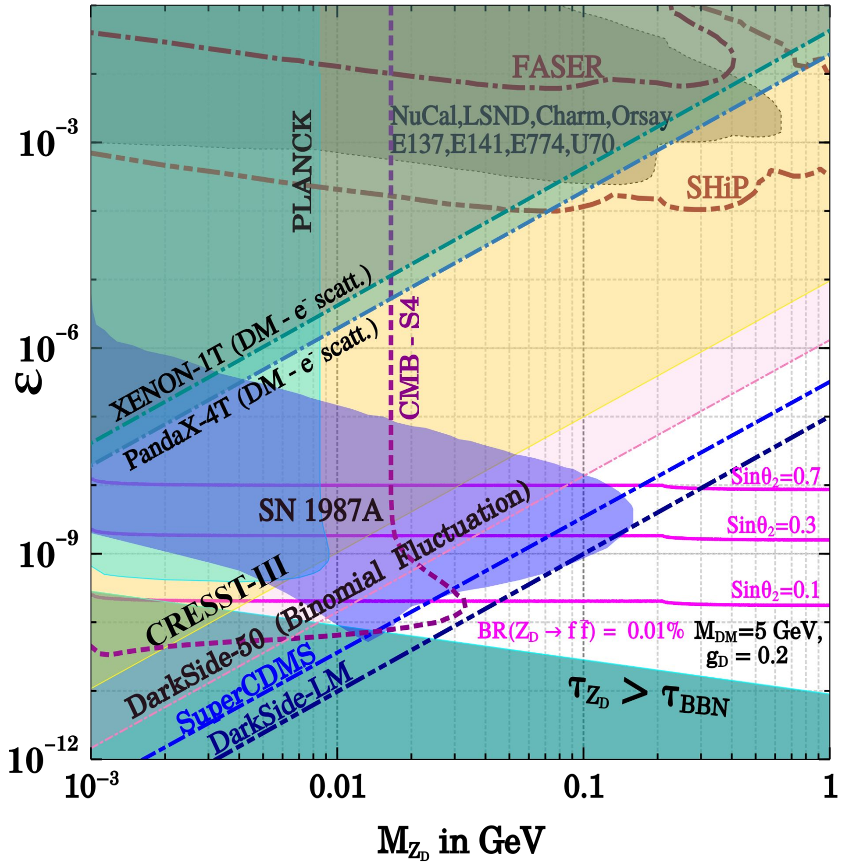
Stringent Constraints from CMB and Indirect Detection

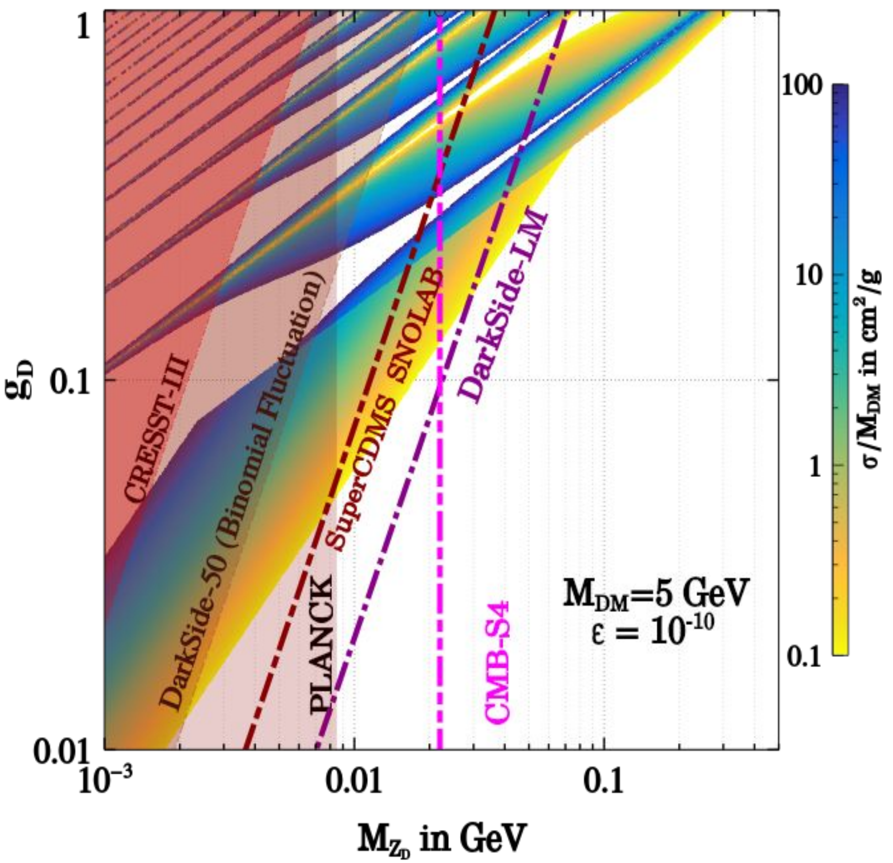




Profumo et. al

Summary :





CMB and indirect search bounds can be evaded if the mediator dominantly decays into neutrinos or some dark radiations.

SIDM framework and GRB221009A

- The idea is to have a weakly interacting particle propagating most of the distance between the GRB source and Earth.

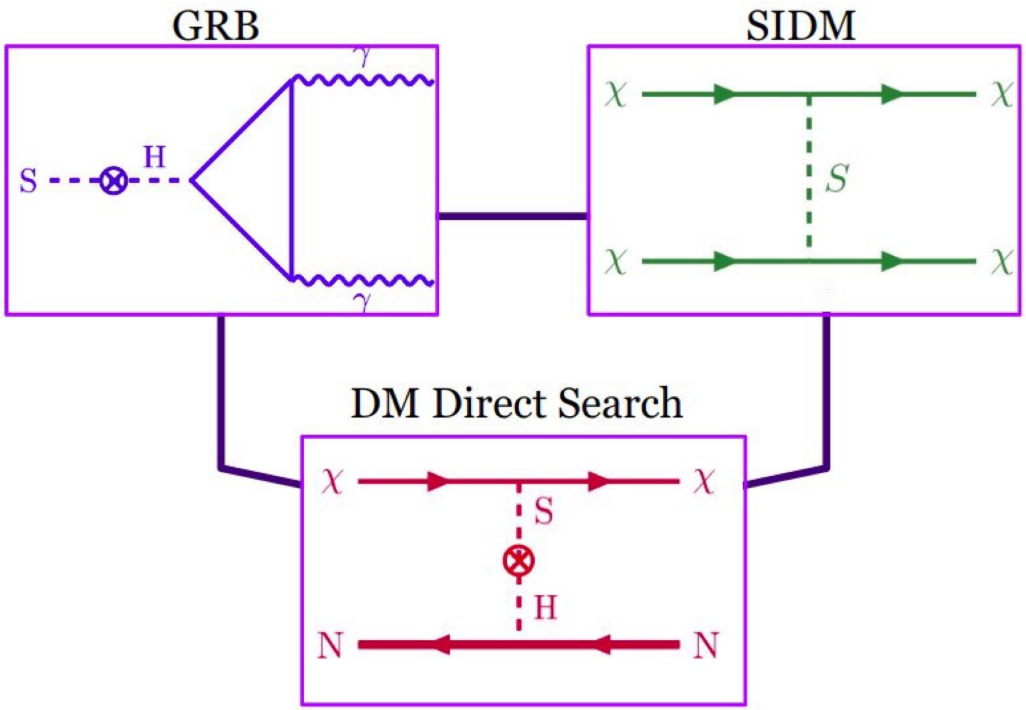
- And that particle need to have certain interactions with photons.

χ: **Singlet Dirac Fermion, Odd under $\mathcal{Z}_2$.**
S: **Singlet Scalar, Even under $\mathcal{Z}_2$.**

$$\mathcal{L} \supset -M_\chi \overline{\chi}\chi - y_S \bar{\chi}\chi S + h.c. - V(H,S)$$

$$\begin{aligned} V(H,S) \;\supset\; & \mu_S^2 S^\dagger S + \lambda_S (S^\dagger S)^2 + \lambda_{SH}(H^\dagger H)(S^\dagger S) \\ + \; & \mu_{SH} S(H^\dagger H) \end{aligned}$$

SIDM framework and GRB221009A



Interesting Connection between SIDM and GRB221009A

GRB221009A

S production at the GRB: nucleon-nucleon bremsstrahlung via pion exchange.

$$N + N \to N + N + S$$

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

Once produced, the scalar can decay into leptons or pions at tree-level or to photons at one loop level via mixing with the SM Higgs boson.

$$\Gamma_{S\to\gamma\gamma} = \frac{121}{9}\frac{\alpha^2 M_S^3 \sin^2\theta_{SH}}{512\pi^3 v_{EW}^2}$$

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

S particles provide an effective means for the survival of the photons to Earth.

GRB221009A

If the S scalar decay occurs at a distance interval of [x, x + dx], the decay-production probability

$$P_{\text{decay}} = B_\gamma e^{-x/\lambda_S} \times \frac{dx}{\lambda_S} e^{-(d-x)/\lambda_\gamma}.$$

Gamma-ray flux from S decay:

$$\Phi_\gamma^S = \frac{2\Phi_S Br_\gamma}{\tau\lambda_S/d - 1}\left(e^{-d/\lambda_S} - e^{-\tau}\right) \qquad \lambda_S = \frac{E_S}{M_S\Gamma_S}$$

With the S-induced γ flux, the number of events:

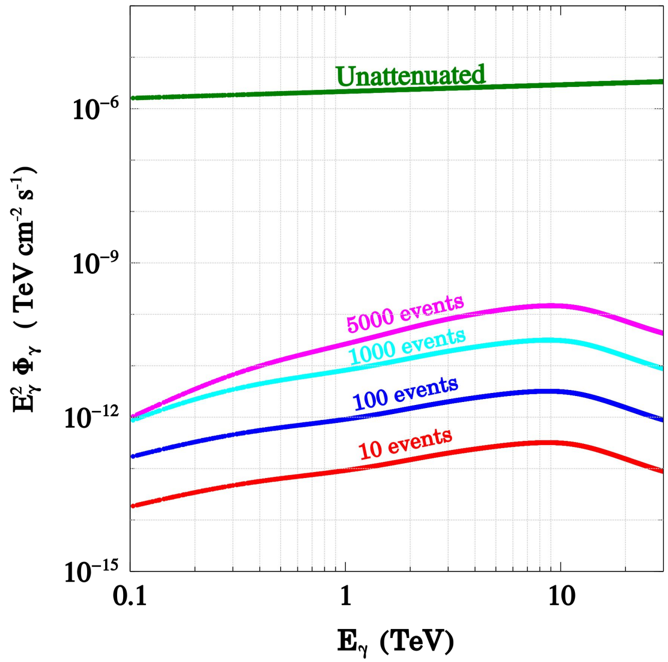
$$N_\gamma = \Delta t \int_{0.5}^{18\ \text{TeV}} Area \times \Phi_\gamma^S(E_\gamma) dE_\gamma$$

Un-attenuated gamma flux is obtained by extrapolating the flux measured by Fermi-LAT:

$$\Phi_\gamma^0(E_\gamma) = \frac{2.1 \times 10^{-6}}{\text{cm}^2\ \text{s TeV}}\left(\frac{E_\gamma}{\text{TeV}}\right)^{-1.87\pm0.04}$$

Baktash et. al.

GRB221009A



$\theta_{SH} = \mathcal{O}(10^{-8})$

Upper limit on mass of S :$M_S < 2m_e$
(Else it will dominantly decay to e^-e^+ pairs.)
If $\Gamma_{S\to e^-e^+}/\Gamma_{S\to\gamma\gamma}$ becomes large, di-photon decay is suppressed
$\Longrightarrow$ can not explain the LHAASO's data.

Flux of γ-rays originated from the decay of S is calculated assuming the scalar energy $E_S = 2\ E_\gamma$; over a detector area of 1 km^2 and time window of 2000 s which is typical of LHASSO's KM2A detector.

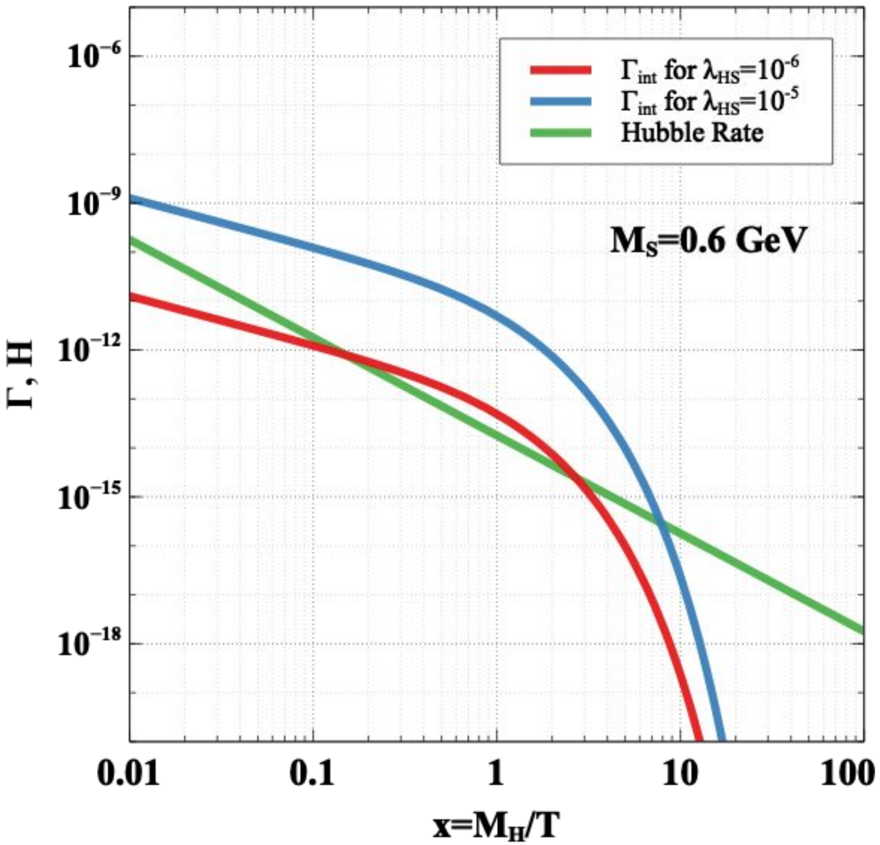
Production of SIDM

Goal: Achieving correct relic density in the minimal setup.

- S is in thermal equilibrium with the SM bath through its scalar portal interactions.
- This also brings DM χ to thermal equilibrium because of its significant coupling with *S*.

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

$$\theta_{SH} = \mathcal{O}(10^{-8})$$



$$\{\lambda_{SH}, \mu_{SH}\} \equiv \{10^{-5}, -6.6\times 10^{-6}\} \text{ and } \{10^{-6}, -2.6\times 10^{-7}\}$$

Production of SIDM

Goal: Achieving correct relic density in the minimal setup.
Possible if S goes through a phase transition in the early Universe.

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

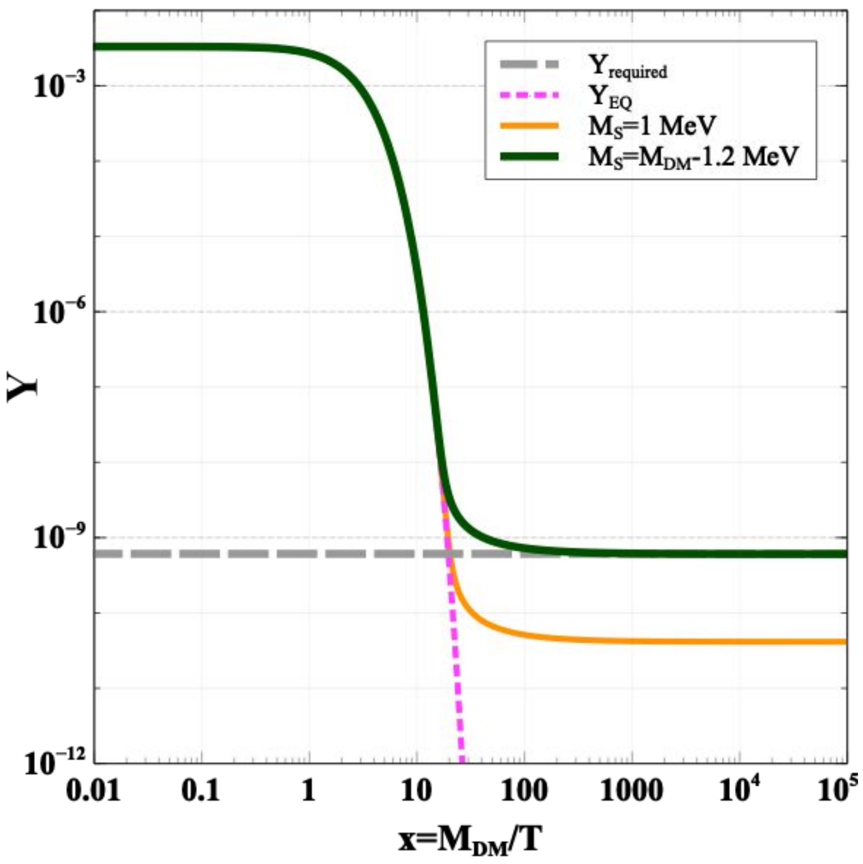
$$\langle\sigma v\rangle_{total} = \langle\sigma v\rangle_{\chi\chi\to SS} + \langle\sigma v\rangle_{\chi\chi\to SMSM}$$

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

S has a heavier mass in the very early Universe.

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

Helps evading CMB constraints

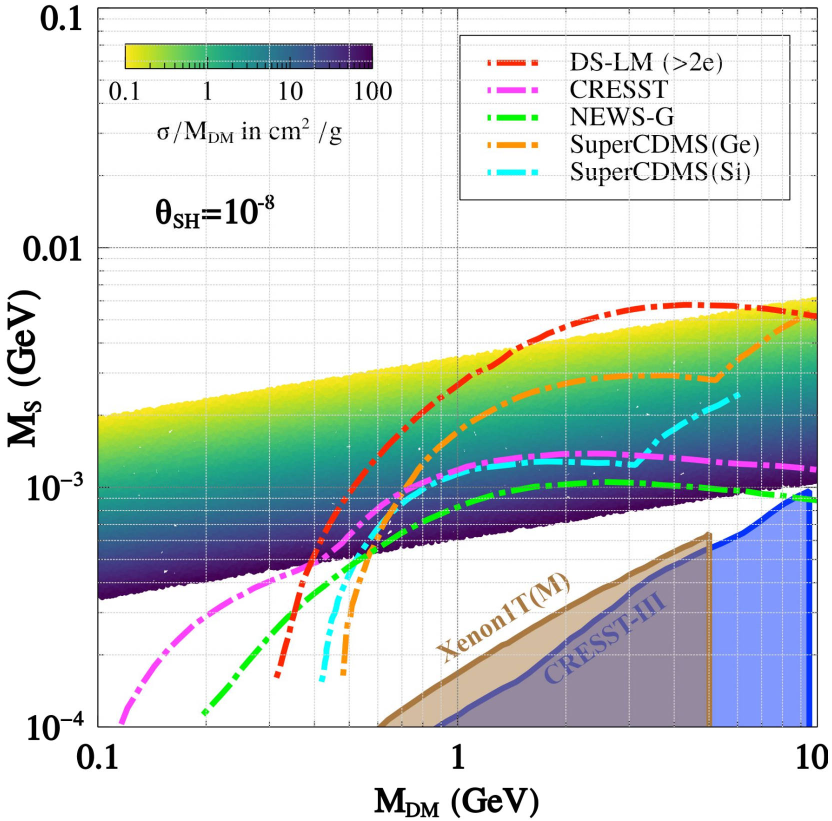


Direct Detection of SIDM

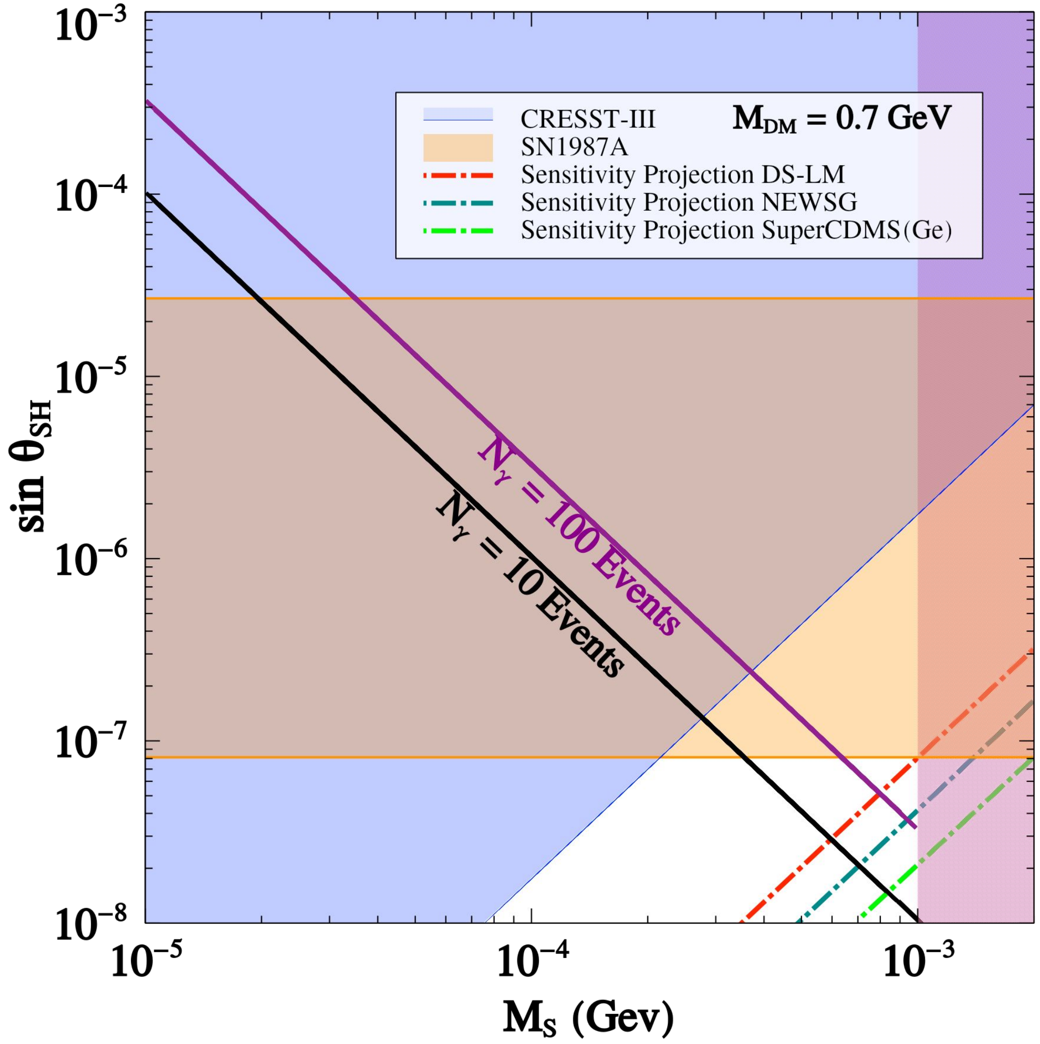
$$\sigma_{\rm SI} = \frac{\mu_r^2}{4\pi A^2}\left[Z f_p + (A - Z) f_n\right]^2$$

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

$$\alpha_q = y_s \sin\theta_{SH} \frac{m_q}{v_{EW}} \left[\frac{1}{M_S^2} - \frac{1}{M_H^2}\right]$$



Summary



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}
10^{-5}
10^{-4}
10^{-3}

Conclusion

- Minimal scenario involves a light scalar mediator, simultaneously enabling DM self-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.
- Also helps in evading the CMB and indirect search constraints.

Thank You...!!!