GRB221009A events and Self-Interacting Dark Matter

Satyabrata Mahapatra

SUNGKYUNKWAN UNIVERSITY 1398 성균관대학교

3rd International Joint Workshop on the Standard Model and Beyond
And
11th KIAS Workshop on Particle Physics and Cosmology

With D. Borah, N. Sahu and V. Thounaojam
Phys.Rev.D 108 (2023) 8, 083038 [arXiv: 2308.06172]

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

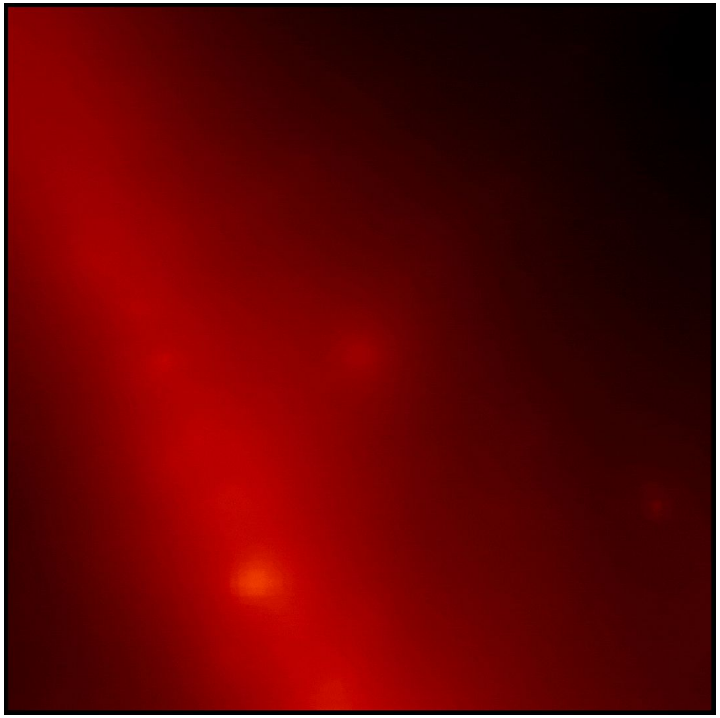
GRB221009A:
BOAT – the brightest of all time.

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).

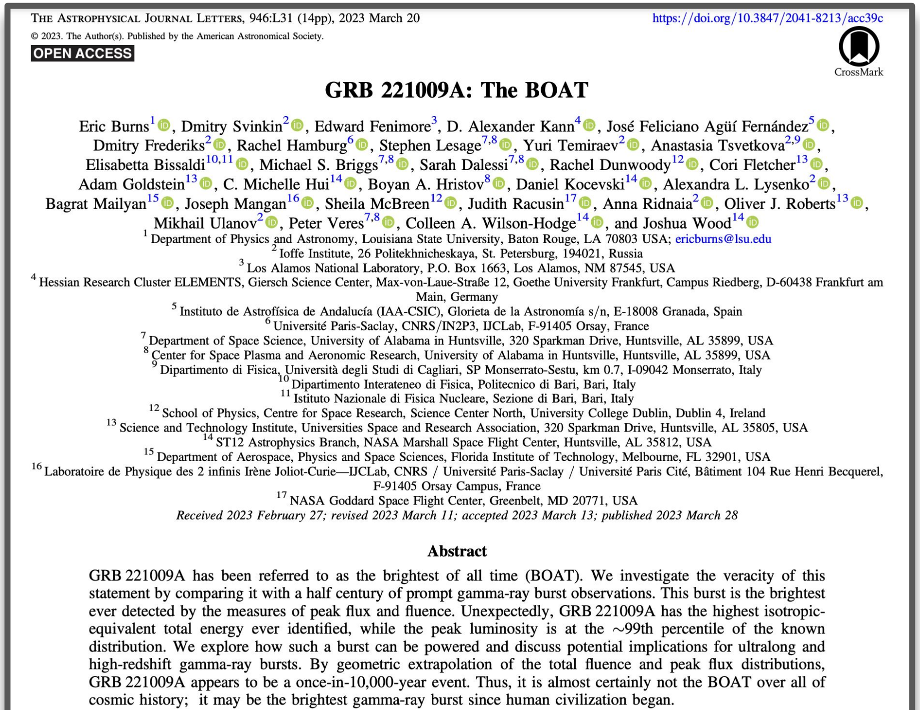
- The photon energies reconstructed by LHAASO extend up to 18 TeV.



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

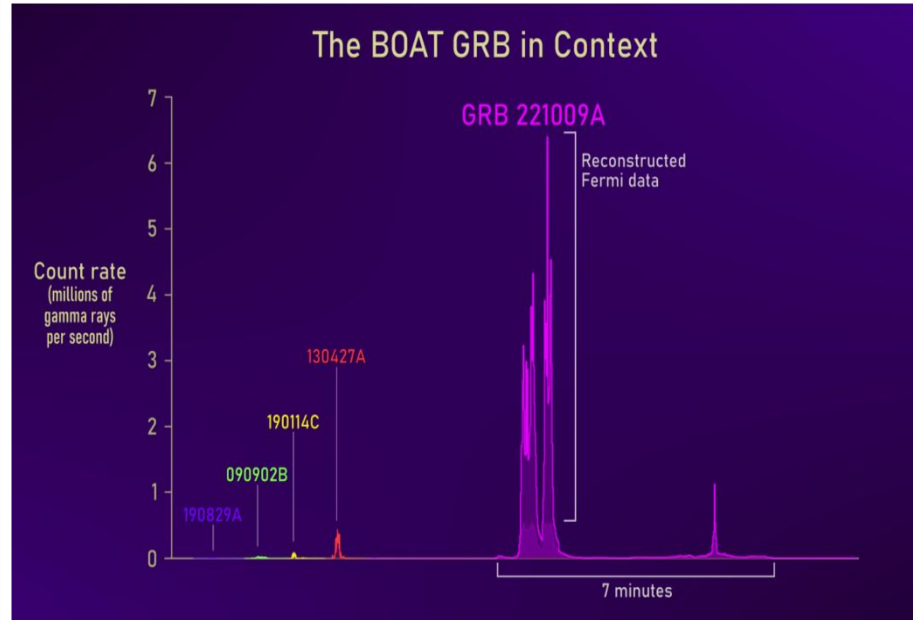
GRB 221009A: The BOAT

Eric Burns[1], Dmitry Svinkin[2], Edward Fenimore[3], D. Alexander Kann[4], José Feliciano Agüí Fernández[5], Dmitry Frederiks[2], Rachel Hamburg[6], Stephen Lesage[7,8], Yuri Temiraev[2], Anastasia Tsvetkova[2,9], Elisabetta Bissaldi[10,11], Michael S. Briggs[7,8], Sarah Dalessi[7,8], Rachel Dunwoody[12], Cori Fletcher[13], Adam Goldstein[13], C. Michelle Hui[14], Boyan A. Hristov[8], Daniel Kocevski[14], Alexandra L. Lysenko[2], Bagrat Mailyan[15], Joseph Mangan[16], Sheila McBreen[12], Judith Racusin[17], Anna Ridnaia[2], Oliver J. Roberts[13], Mikhail Ulanov[2], Peter Veres[7,8], Colleen A. Wilson-Hodge[14], and Joshua Wood[14]

[1] Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803 USA; ericburns@lsu.edu
[2] Ioffe Institute, 26 Politekhnicheskaya, St. Petersburg, 194021, Russia
[3] Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545, USA
[4] Hessian Research Cluster ELEMENTS, Giersch Science Center, Max-von-Laue-Straße 12, Goethe University Frankfurt, Campus Riedberg, D-60438 Frankfurt am Main, Germany
[5] Instituto de Astrofísica de Andalucía (IAA-CSIC), Glorieta de la Astronomía s/n, E-18008 Granada, Spain
[6] Université Paris-Saclay, CNRS/IN2P3, IJCLab, F-91405 Orsay, France
[7] Department of Space Science, University of Alabama in Huntsville, 320 Sparkman Drive, Huntsville, AL 35899, USA
[8] Center for Space Plasma and Aeronomic Research, University of Alabama in Huntsville, Huntsville, AL 35899, USA
[9] Dipartimento di Fisica, Università degli Studi di Cagliari, SP Monserrato-Sestu, km 0.7, I-09042 Monserrato, Italy
[10] Dipartimento Interateneo di Fisica, Politecnico di Bari, Bari, Italy
[11] Istituto Nazionale di Fisica Nucleare, Sezione di Bari, Bari, Italy
[12] School of Physics, Centre for Space Research, Science Center North, University College Dublin, Dublin 4, Ireland
[13] Science and Technology Institute, Universities Space and Research Association, 320 Sparkman Drive, Huntsville, AL 35805, USA
[14] ST12 Astrophysics Branch, NASA Marshall Space Flight Center, Huntsville, AL 35812, USA
[15] Department of Aerospace, Physics and Space Sciences, Florida Institute of Technology, Melbourne, FL 32901, USA
[16] Laboratoire de Physique des 2 infinis Irène Joliot-Curie—IJCLab, CNRS / Université Paris-Saclay / Université Paris Cité, Bâtiment 104 Rue Henri Becquerel, F-91405 Orsay Campus, France
[17] NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
Received 2023 February 27; revised 2023 March 11; accepted 2023 March 13; published 2023 March 28

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.

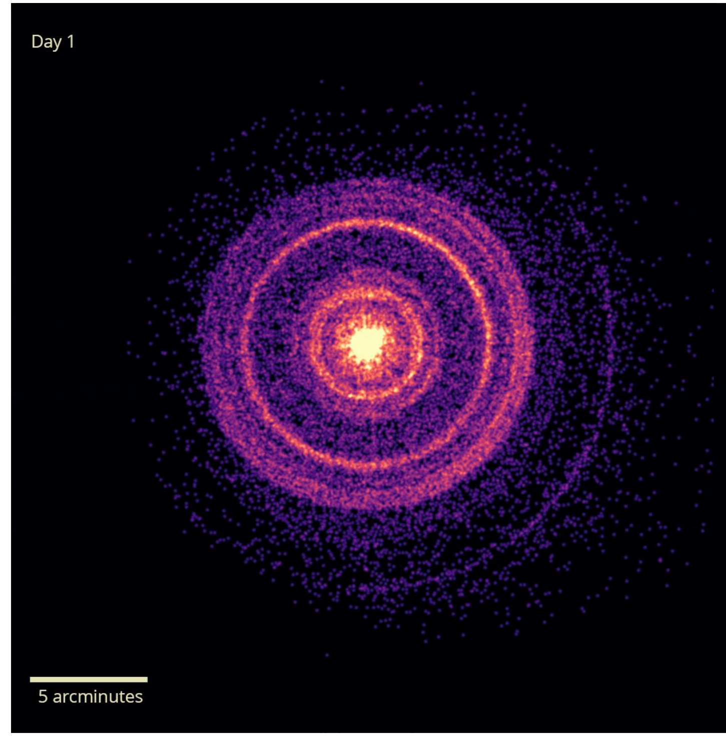


NASA's Goddard Space Flight Center and Adam Goldstein (USRA)

- **GRB 221009A was likely the brightest burst at X-ray and gamma-ray energies 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. This composite merges observations made two and five days after GRB221009A erupted.
- GRB221009A is only the seventh gamma-ray burst to display X-ray rings.



Credit: NASA/Swift/A. Beardmore (University of Leicester)

The Radio to GeV Afterglow of GRB 221009A

Tanmoy Laskar,[1,2] Kate D. Alexander,[3] Raffaella Margutti,[4] Tarraneh Eftekhari,[5,6,*] 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 is around $e^{-15} \sim 10^{-7}$.

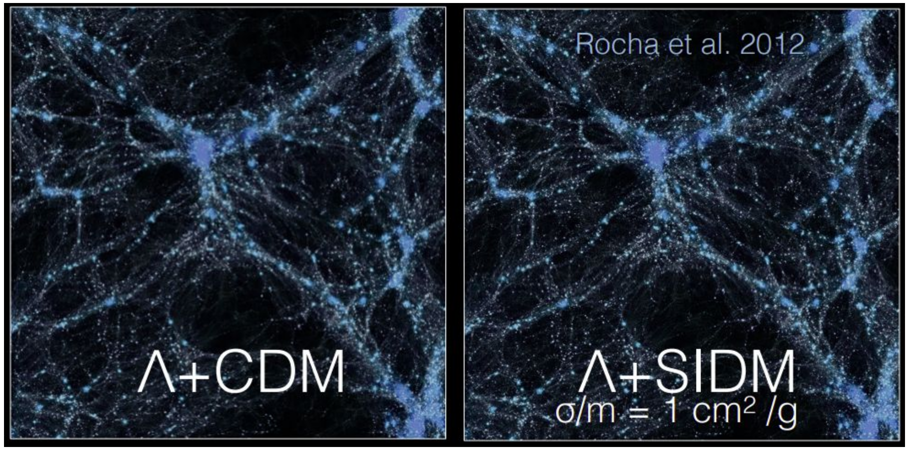
Need for BSM Physics!!!

ALPs, Sterile Neutrinos, Scalars and Lorentz Invariance Violation.

For E.g. Yanagida et. al., Takahashi et.al., Smirnov et. al, Vedran et. al. , 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 ($\rho \sim r^{-1}$)

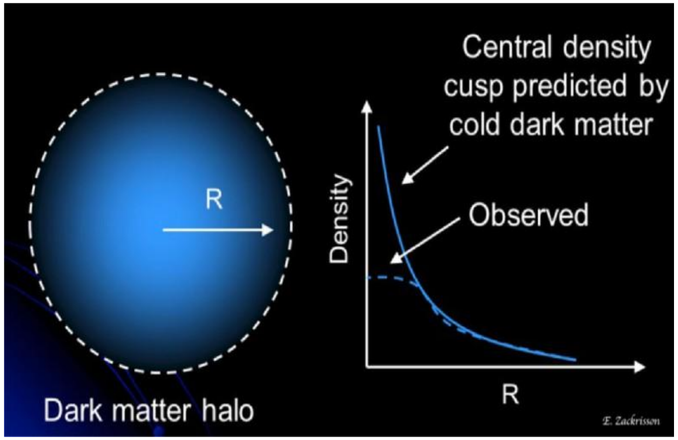
  Observation: Central densities of halos→ Cored ($\rho \sim r^{0}$).

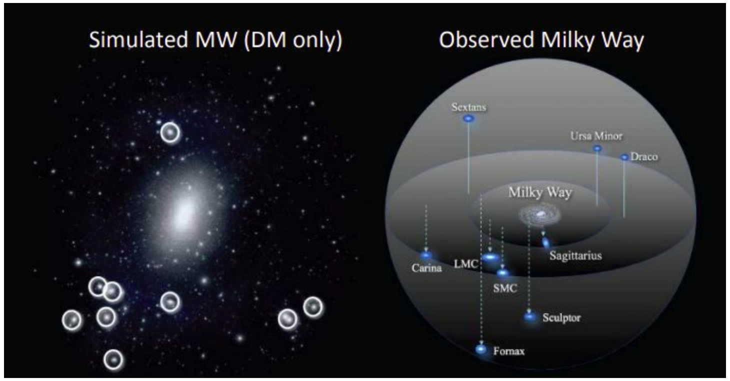
- **<u>The missing satellite Problem:</u>**

  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:

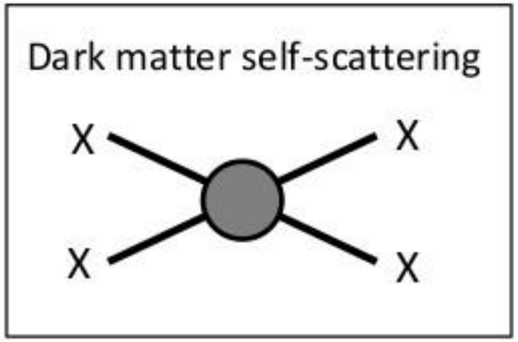
Warm DM :

- 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.

Tulin and Yu

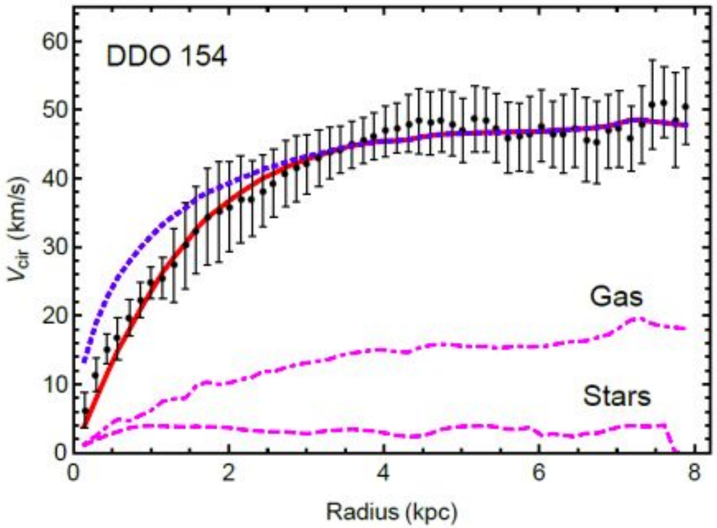


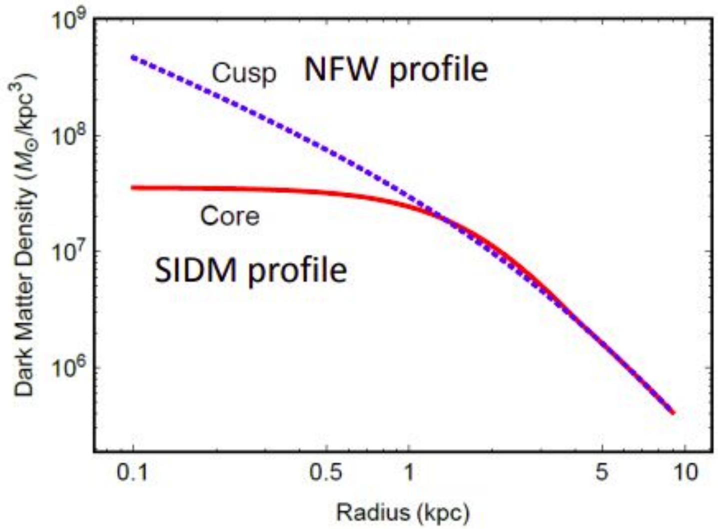
CDM structure problems can be resolved introducing dark matter self-interaction .

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

Spergel and Steinhardt.

Issues with CDM $\longrightarrow$ Solution in SIDM





What value of scattering cross-section is needed?

Collision rate:

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

Thus

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

Velocity Dependent Self-interaction

Low energies (v/c ~ 10^{-4})

Medium energies (v/c ~ 10^{-3})

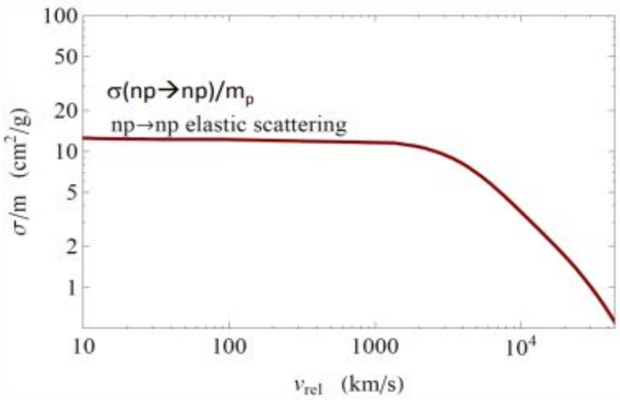
High energies (v/c ~ 10^{-2})

Stronger self-scattering needed for (dwarf-sized) halos. $\sigma/m \sim 0.5 - 10 cm^2/g$ at dwarf-scale velocity $v \sim 10 km/s$.

Weaker self-scattering favoured by cluster merging/halo profiles. $\sigma/m \sim 0.1 - 1 cm^2/g$ at cluster-scale velocity $v \sim 1000 km/s$.

A velocity-dependent DM self-scattering.

Popular choice: a light mediator ($m_{mediator} << m_{DM}$) with mass 1-100 MeV.



Light Mediator Models for SIDM

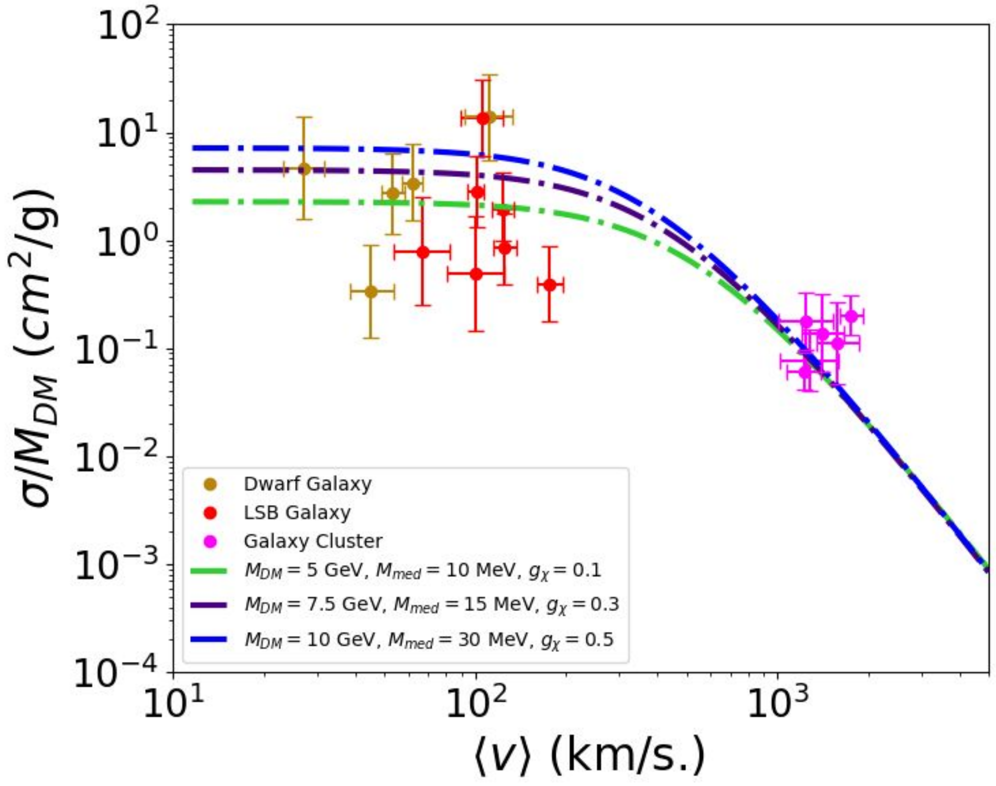
$$\mathcal{L}_{\text{int}} = \begin{cases} g_\chi \bar{\chi} \gamma^\mu \chi \phi_\mu & \text{(vector mediator)} \\ g_\chi \bar{\chi} \chi \phi & \text{(scalar mediator)} \end{cases} \qquad V(r) = \pm \frac{\alpha_\chi}{r} e^{-m_\phi r}$$

The Differential cross-section:

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

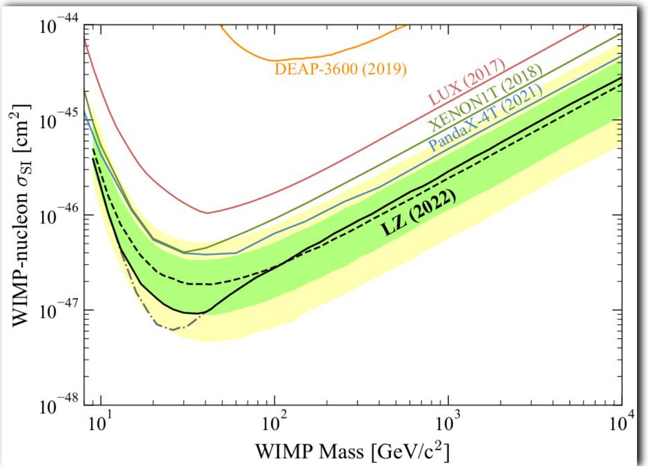
- In the limit of $m_\phi >> m_\chi v_{\text{rel}} \implies$ contact interaction (v_{rel}^0)
- In the limit $m_\phi << m_\chi v_{\text{rel}} \implies$ Rutherford scattering (v_{rel}^{-4})
- Neither limit provides the mildly velocity-dependent cross section favoured by observations.
- A small but finite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

Light Mediator Models for SIDM



Borah,SM, Sahu

GeV/ Sub-GeV Scale DM

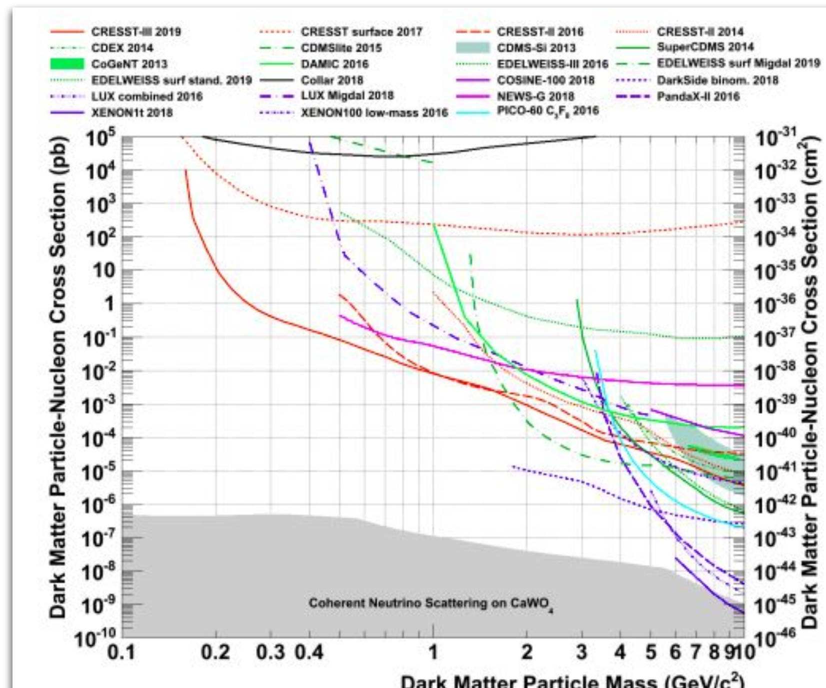


- No observation yet at Direct search experiments.

Motivation: To look for several viable alternatives to WIMP

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

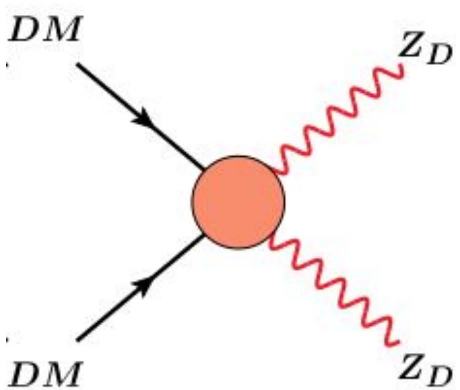
Many Experiments looking for Light DM: XENON1T, CRESST-III, EDELWEISS, Super-CDMS, SENSEI, DAMIC, DarkSide-50.

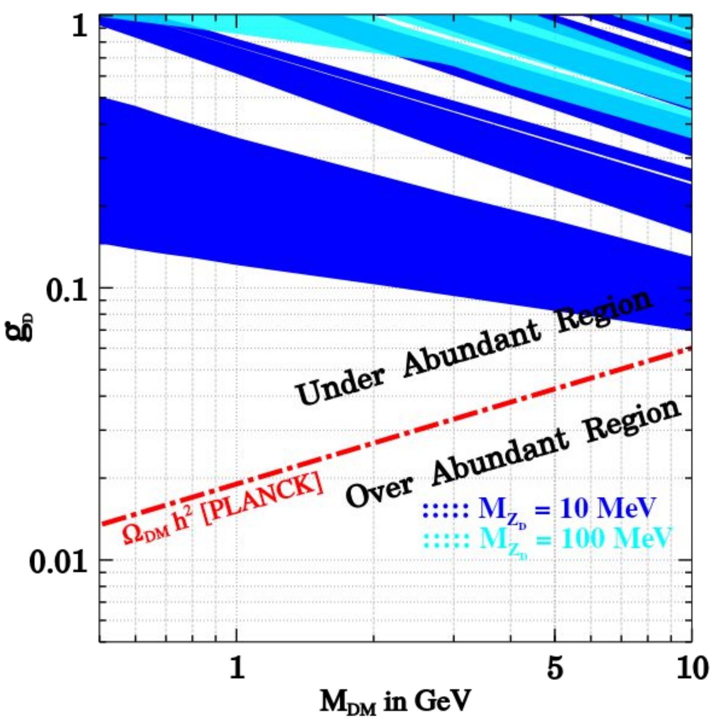


Challenge for Light SIDM

Challenge for SIDM: Achieving Correct Relic Density

Self-Interaction $\Longrightarrow$ Under Abundant Relic

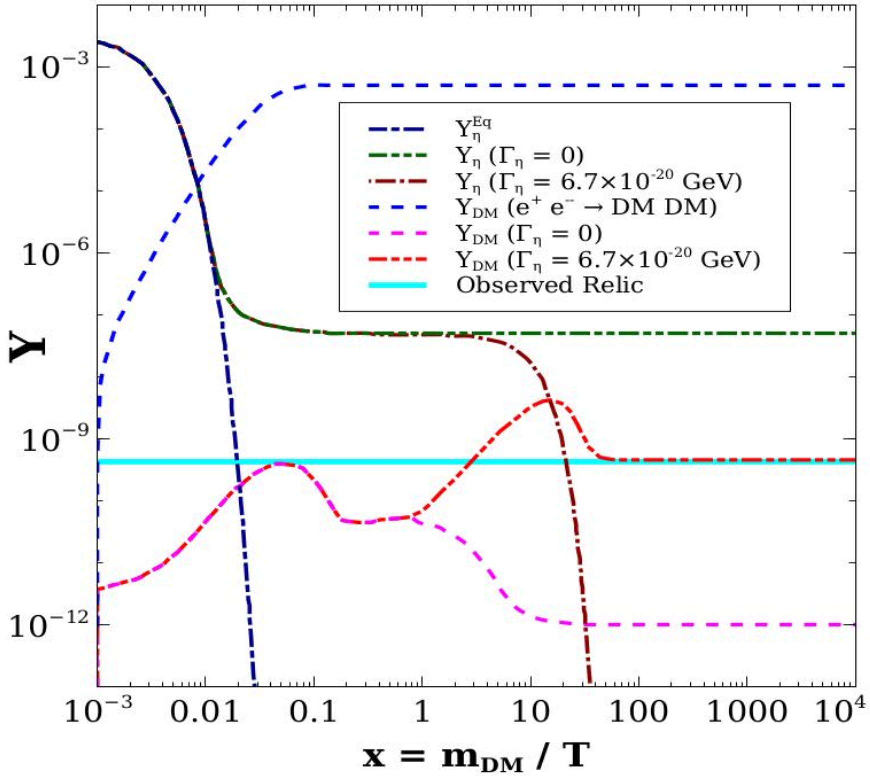


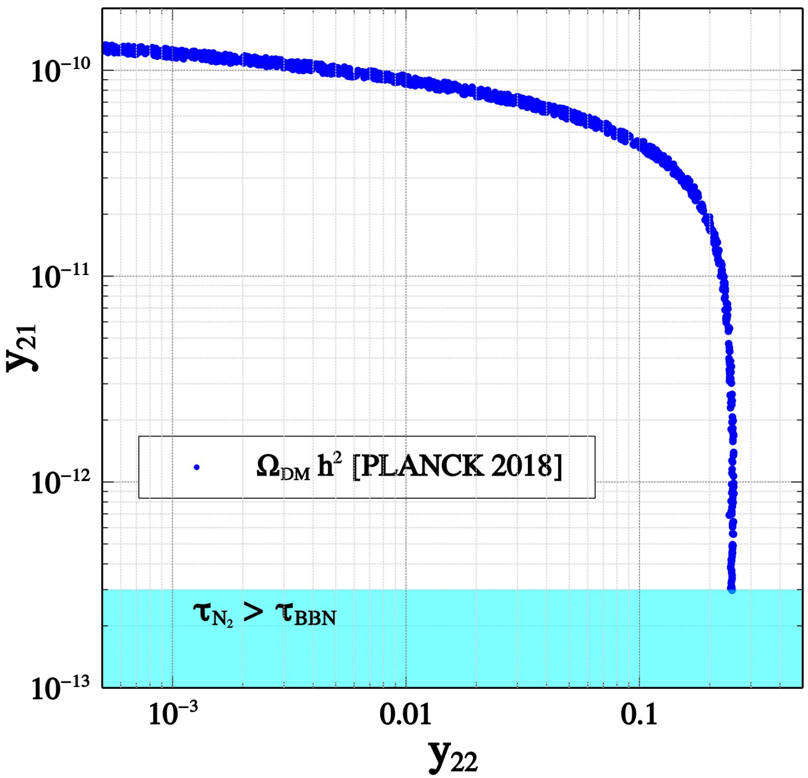


Borah,SM, Sahu

Challenge for Light SIDM

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



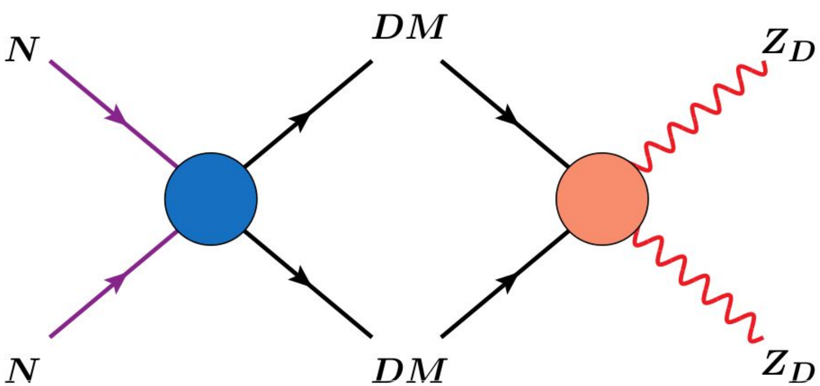


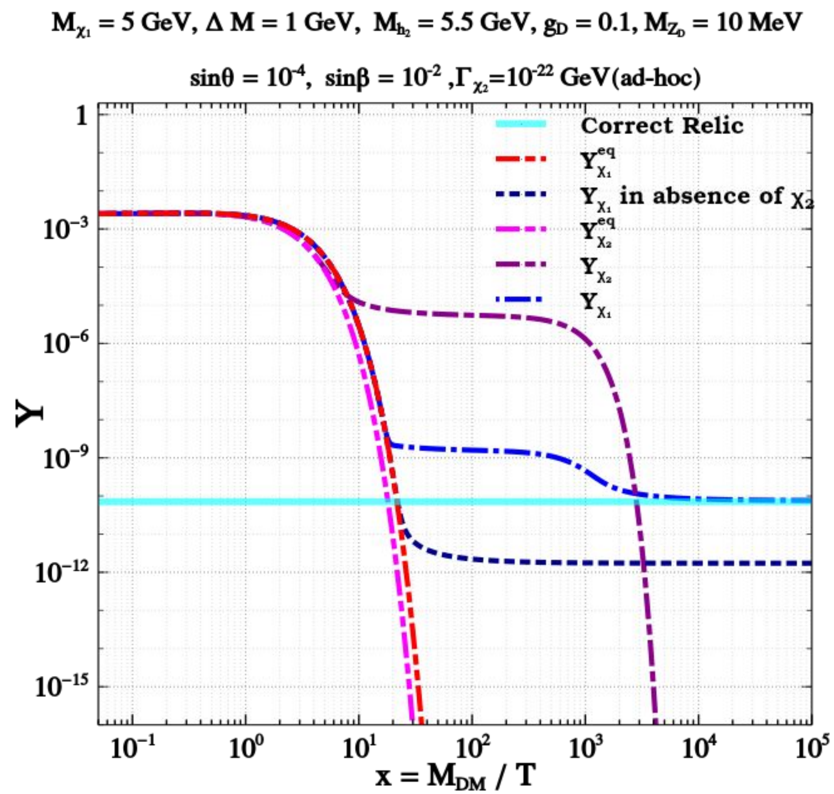
Borah,SM, Sahu,Dutta

Requires Additional particles in the spectrum !!!

Challenge for Light SIDM

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



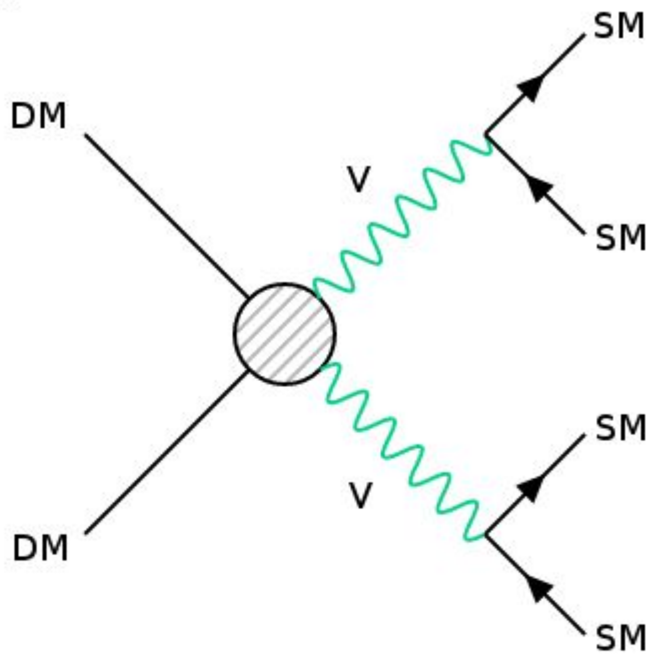


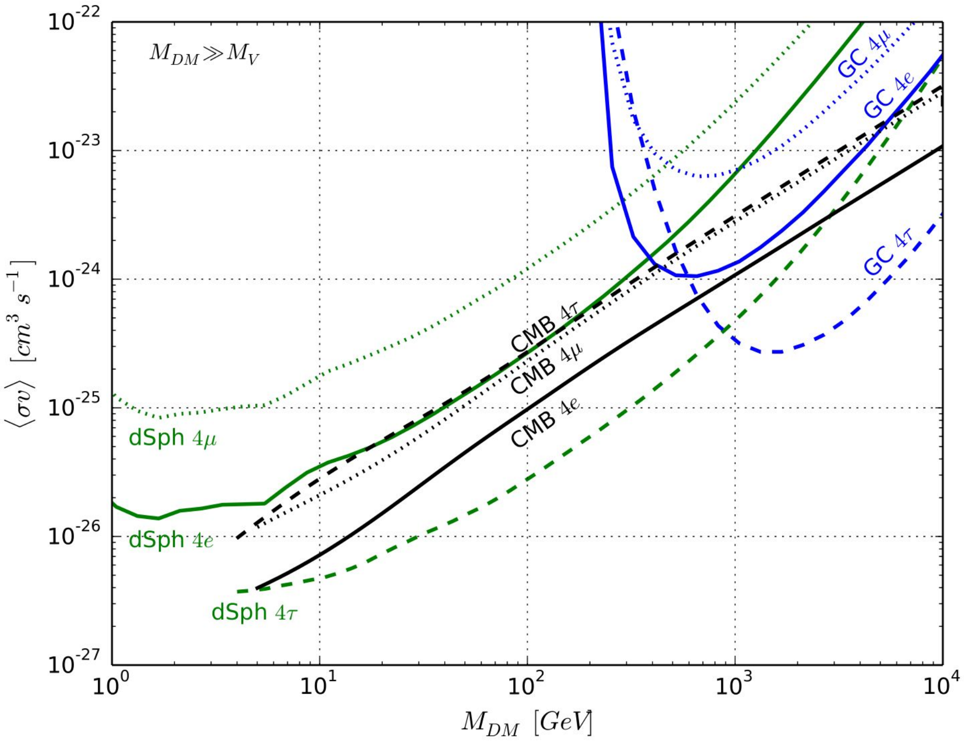
Borah,SM, Sahu

Requires Additional particles in the spectrum !!!

Challenge for Light SIDM

Stringent Constraints from CMB and Indirect Detection





Profumo et. al

SIDM framework and GRB221009A

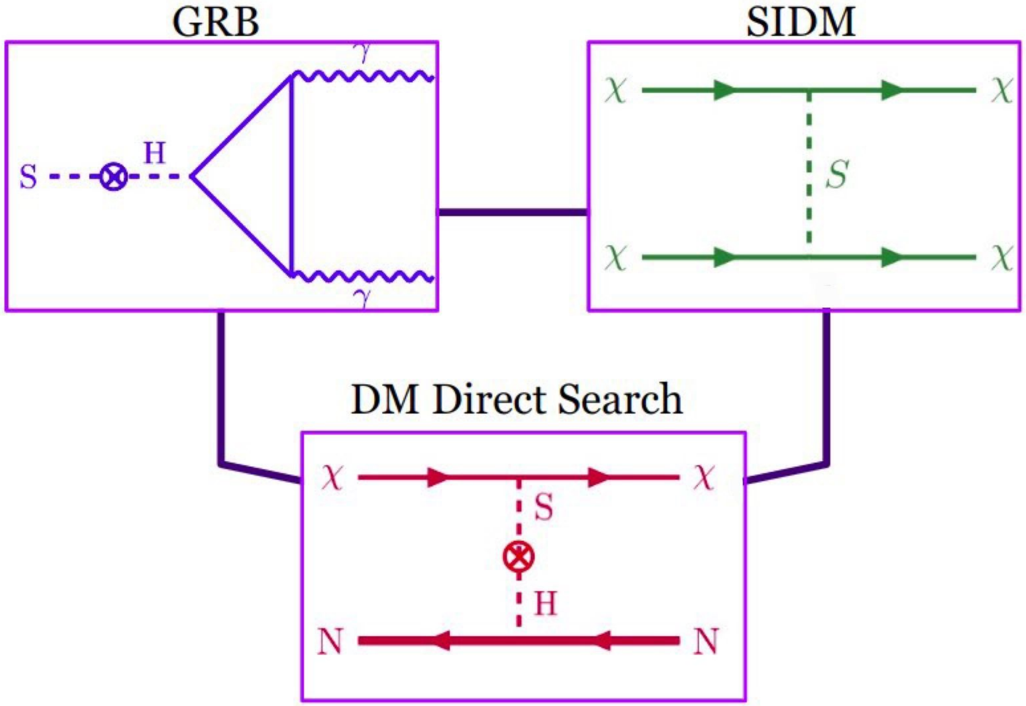
- The idea is to have a weakly interacting particle propagating most of the distance between the GRB source and Earth.
- And that particle need to have certain interactions with photons.

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.

$$\boxed{N + N \to N + N + S}$$

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

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:

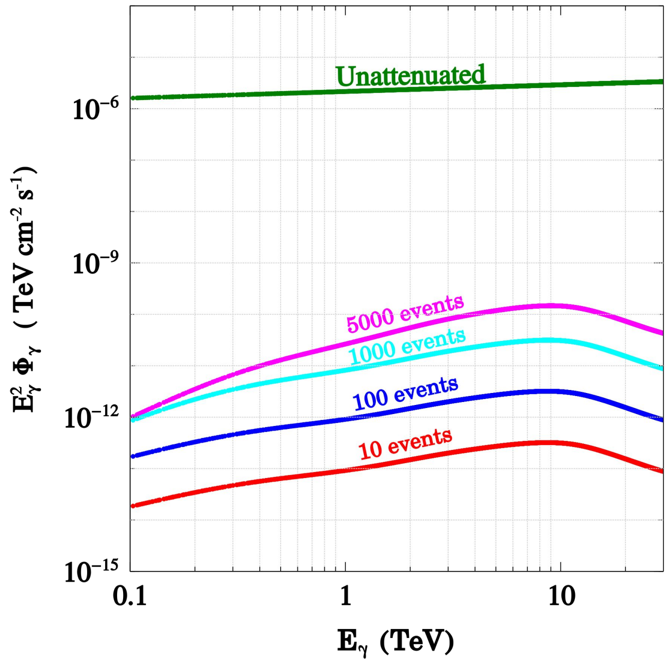
$$N_\gamma = \Delta t \int_{0.5}^{18\ \text{TeV}} Area \times \Phi_\gamma^S(E_\gamma) dE_\gamma$$

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

$$\Phi_\gamma^0(E_\gamma) = \frac{2.1 \times 10^{-6}}{\text{cm}^2\ \text{s TeV}} \left(\frac{E_\gamma}{\text{TeV}}\right)^{-1.87 \pm 0.04}$$

Baktash et. al.

GRB221009A



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

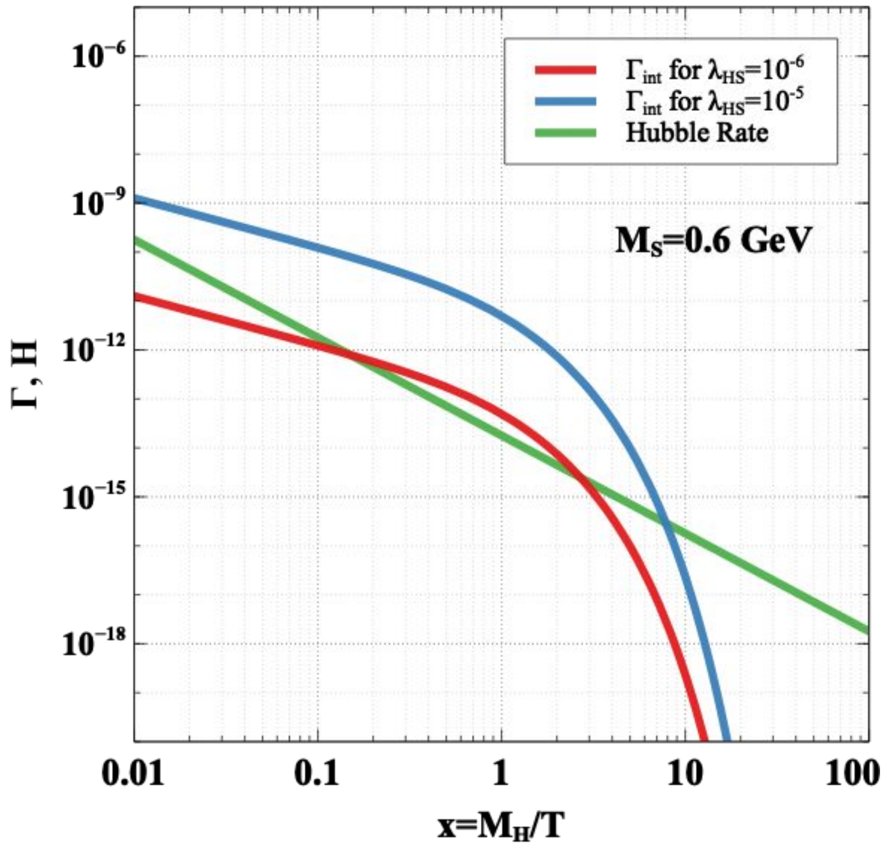
Upper limit on mass of S :$M_S < 2m_e$
(Else it will dominantly decay to $e^- e^+$ pairs.)
If $\Gamma_{S\to e^- e^+}/\Gamma_{S\to\gamma\gamma}$ becomes large, di-photon decay is suppressed
$\Longrightarrow$ can not explain the LHAASO's data.

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.



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

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

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

Production of SIDM

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

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

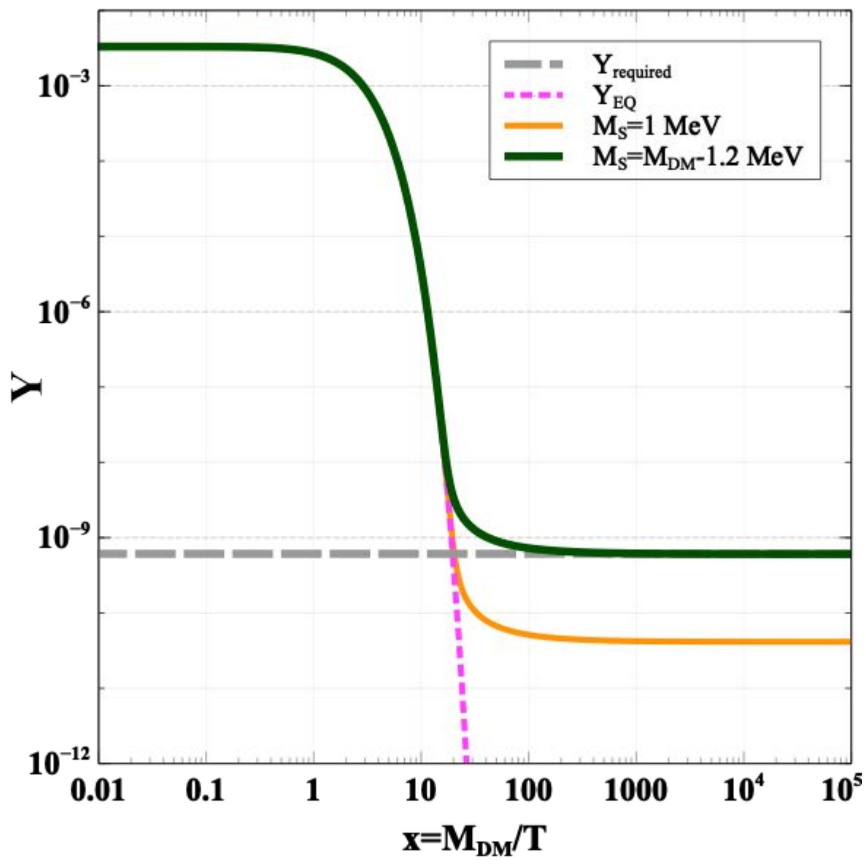
$$\langle\sigma v\rangle_{total} = \langle\sigma v\rangle_{\chi\chi\to SS} + \langle\sigma v\rangle_{\chi\chi\to SMSM}$$

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

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

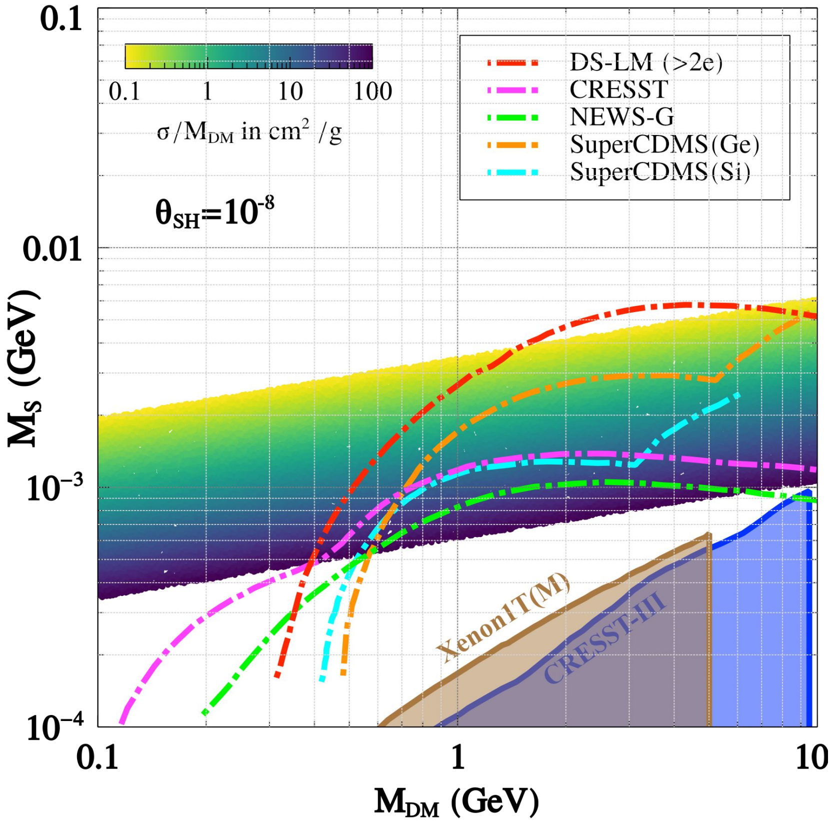


Direct Detection of SIDM

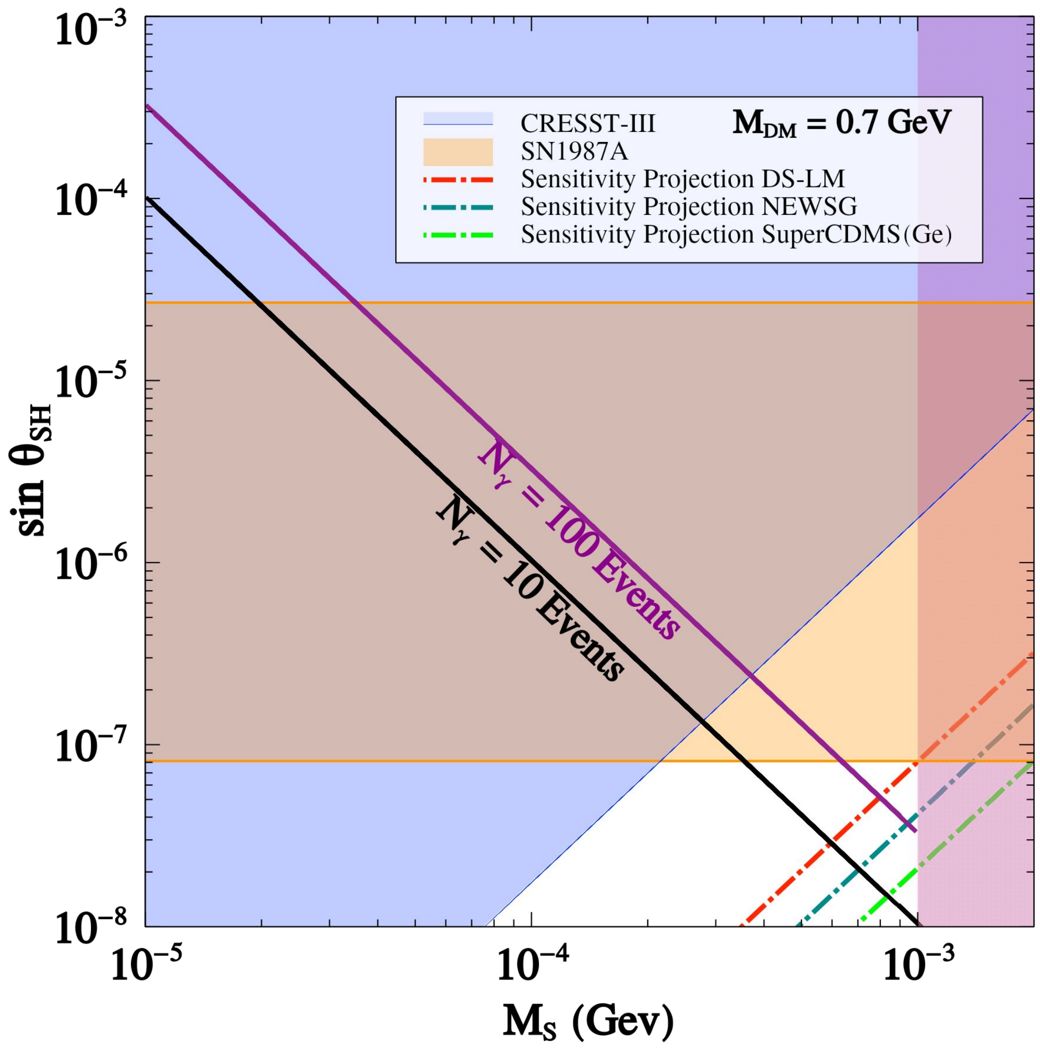
$$\boxed{\sigma_{\rm SI} = \frac{\mu_r^2}{4\pi A^2}[Zf_p + (A-Z)f_n]^2}$$

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

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



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 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.
- Also helps in evading the CMB and indirect search constraints.

Thank You...!!!