Dark matter direct/indirect detection complementarity

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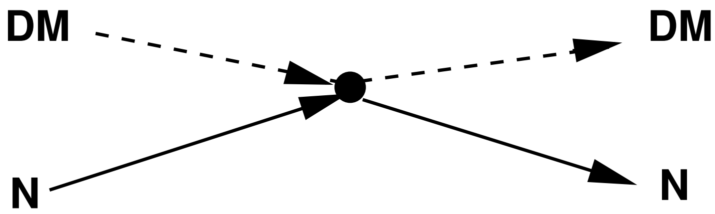
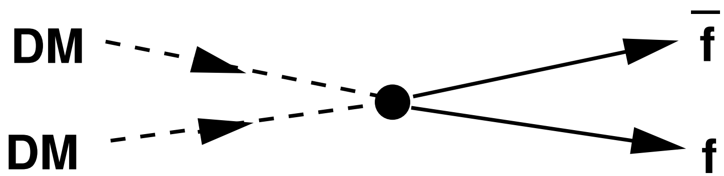
Canadian Multi-Messenger Astrophysics Workshop, 30 Jan. 2020

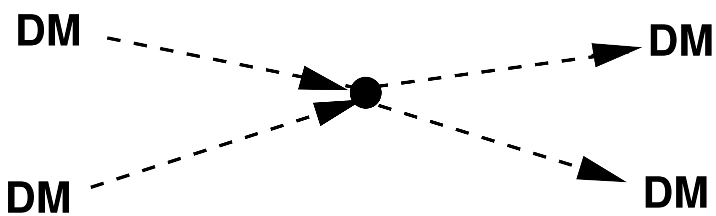
Messengers for dark matter



Direct detection: DM is its own messenger (PICO, DEAP-3600 at SNOLAB



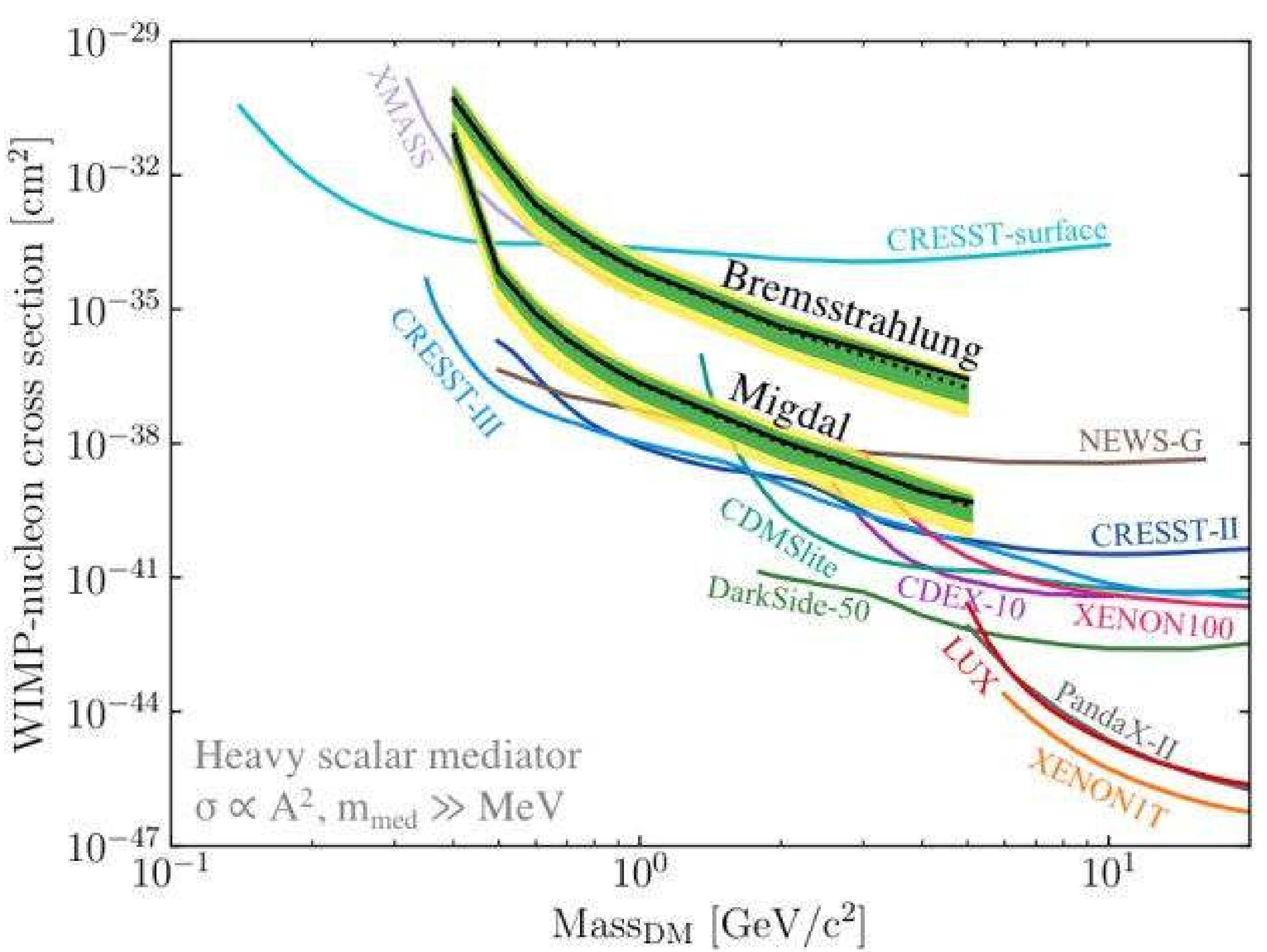
Indirect detection: DM annihilates in galaxy, we see decay products (gamma rays: VERITAS; X-rays: 21-cm surveys–CHIME)



Even more indirect: DM self-scatters, changes its halo properties in galaxies (optical, rotation curves, sky surveys)

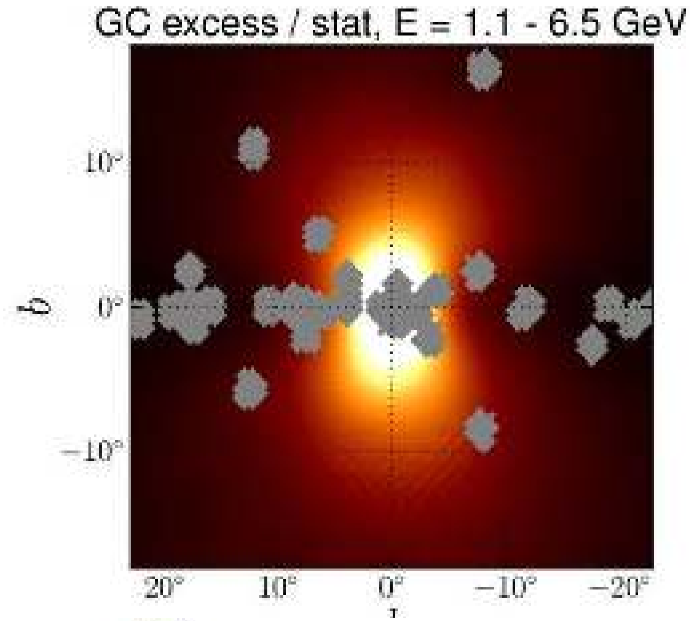
Direct detection limits

So far the message from direct searches is nothing yet!

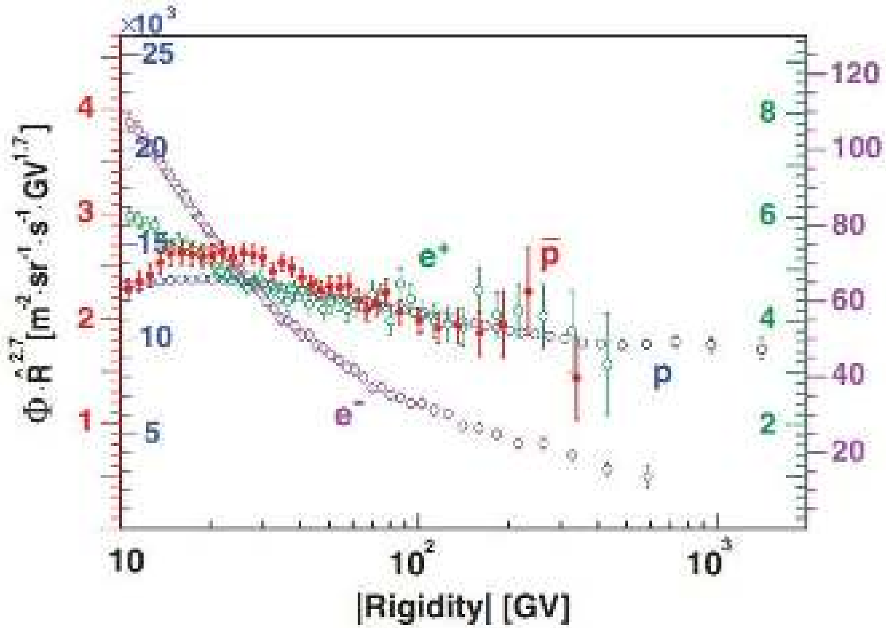


Cosmic ray anomalies

Indirect searches may be seeing something,



Fermi-LAT observes excess ~GeV γ-rays from the galactic center (1704.03910)

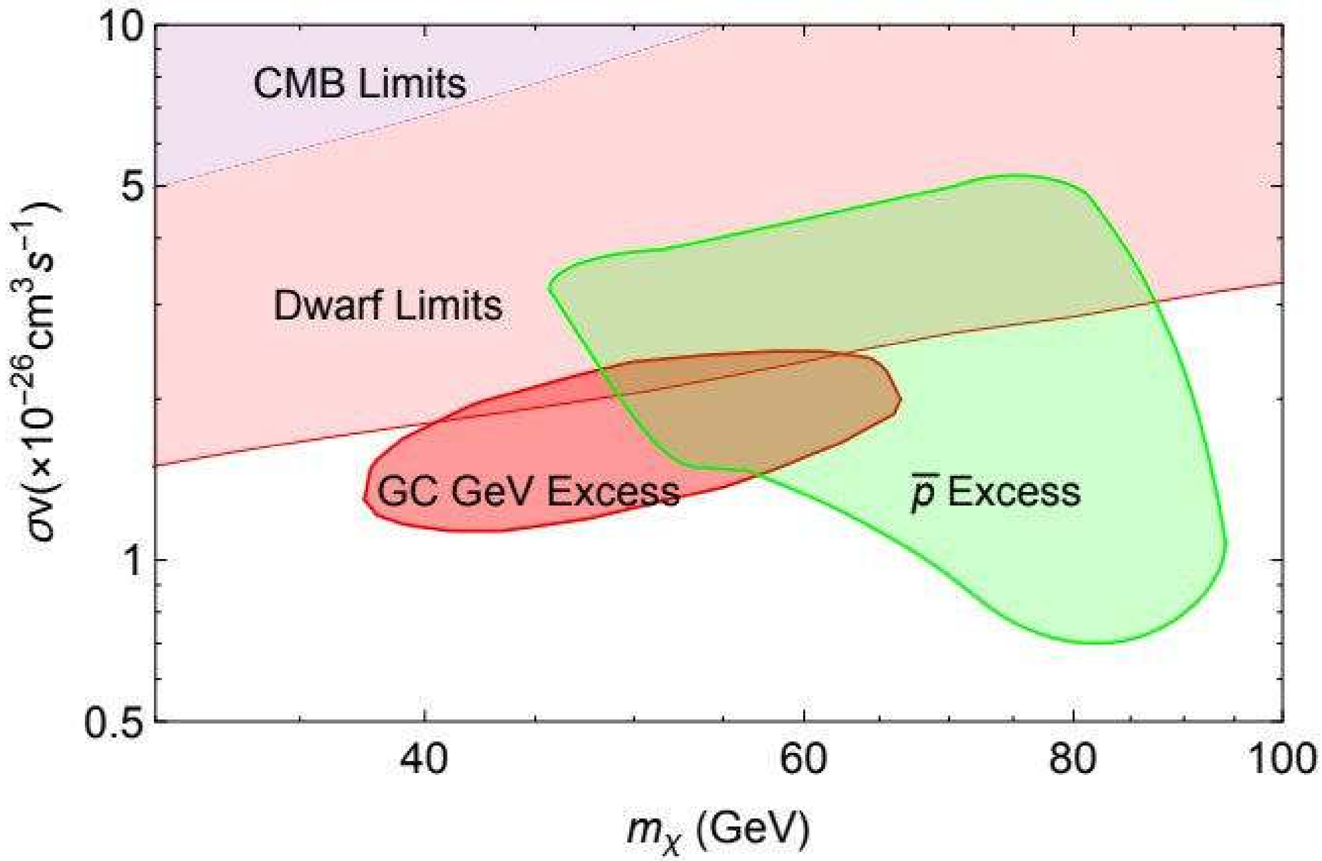


AMS detects antiprotons, determined by numerous theorists to exceed predicted flux (Phys.Rev.Lett. 2016)

Could they have a common dark matter origin?

DM annihilation to $b\bar{b}$

Cholis, Linden & Hooper find compatible parameters for both excesses from $\chi\chi \to b\bar{b}$ (1903.02549)



They also claim strong significance for the $\bar{p}$ excess, $4.7\,\sigma$.

Likelihood of other final states is less, $u\bar{u}$, $d\bar{d} \to 3.3\,\sigma$, $W^+W^- \to 3.6\,\sigma$.

The GC γ-ray excess and pulsars

Researchers vigorously debate DM versus millisecond pulsars (MSPs) as origin of the γ-ray excess.

Population of unresolved MSPs seemed a good astrophysical candidate.

pro-MSP:

Mirabal,1309.3428
Calore *et al.*, 1406.2706
O'Leary *et al.*, 504.02477
Bartels *et al.*, 1805.11097

anti-MSP:

Hooper *et al.*, 1305.0830
Cholis *et al.*, 1407.5625
Haggard *et al.*, 1701.02726

Statistics of γ-rays argued to favor MSPs over DM.

Bartels *et al.*, 1506.05104

Lee *et al.*, 1506.05124

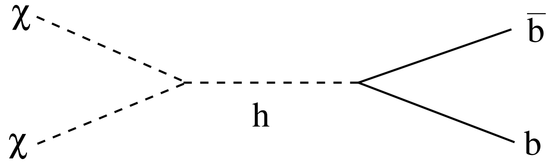
Recently Leane & Slatyer (1904.08430) dispute that claim, favoring DM. Encouragement to pursue DM explanations!

The Higgs portal

Scalar DM generically couples to Higgs,

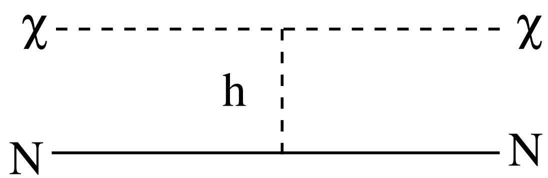
$$\tfrac{1}{4}\lambda_{hs}\chi^2 h^2 \to \tfrac{1}{2}\lambda_{hs} v\,\chi^2 h$$

A nice answer to the question "why $b\bar{b}$?" Higgs couples most strongly to b (assuming $m_\chi < m_t$).



$$\sigma v \sim \frac{\lambda_{hs}^2 m_b^2}{4\pi(4m_\chi^2 - m_h^2)^2}$$

There are strong constraints from direct detection,

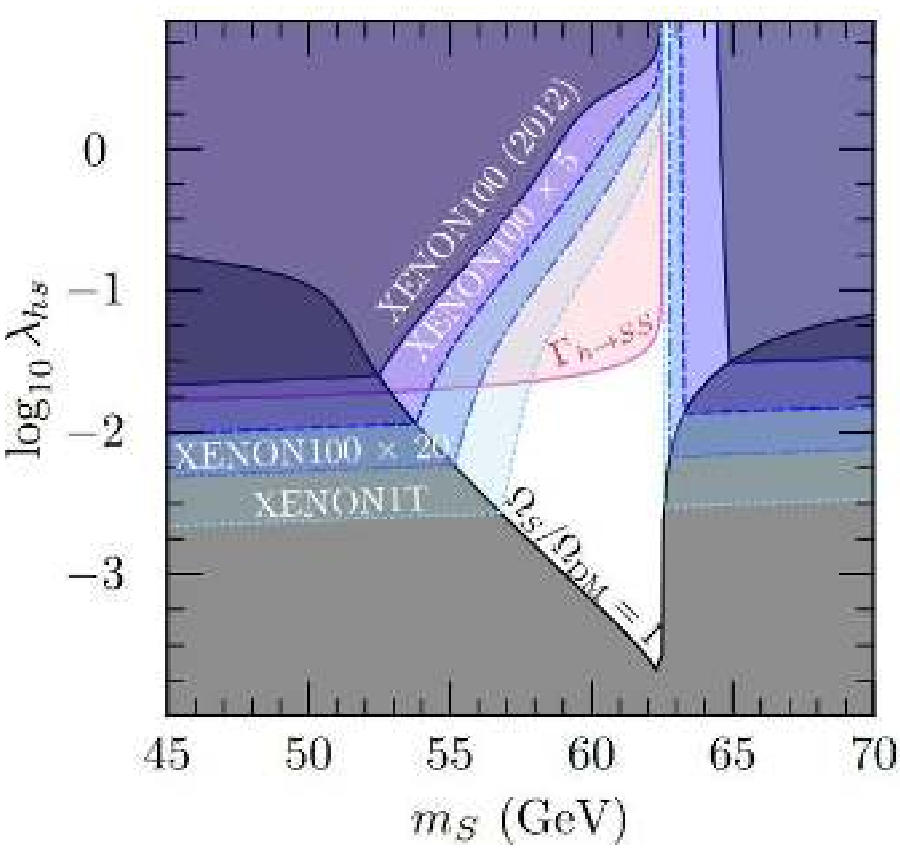


$$\sigma = \frac{\lambda_{hs}^2 f_N^2 m_n^4}{4\pi m_h^4 m_\chi^2}$$

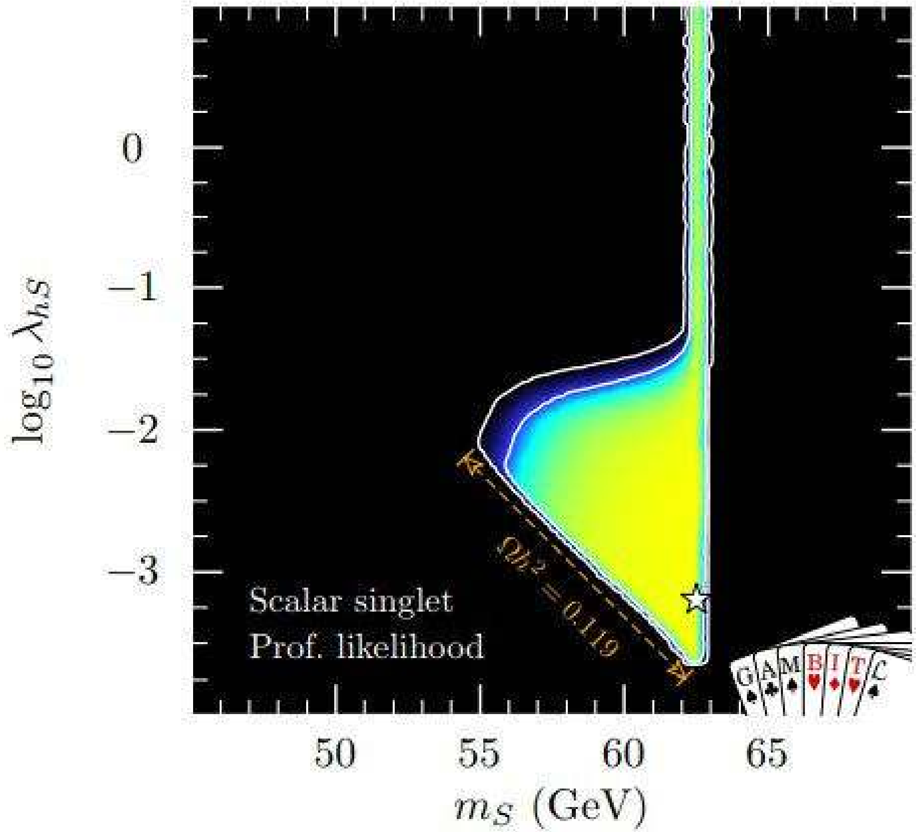
that can be evaded by being close to the Higgs resonance,

$$m_\chi \sim \frac{m_h}{2}$$

Singlet scalar DM global fits



JC, Kainulainen, Scott, Weniger 1306.4710



GAMBIT collaboration, 1705.07931

Region from 55 GeV to $m_h/2 = 62.5$ GeV is not ruled out.

But the indirect detection cross section is highly suppressed in this region!

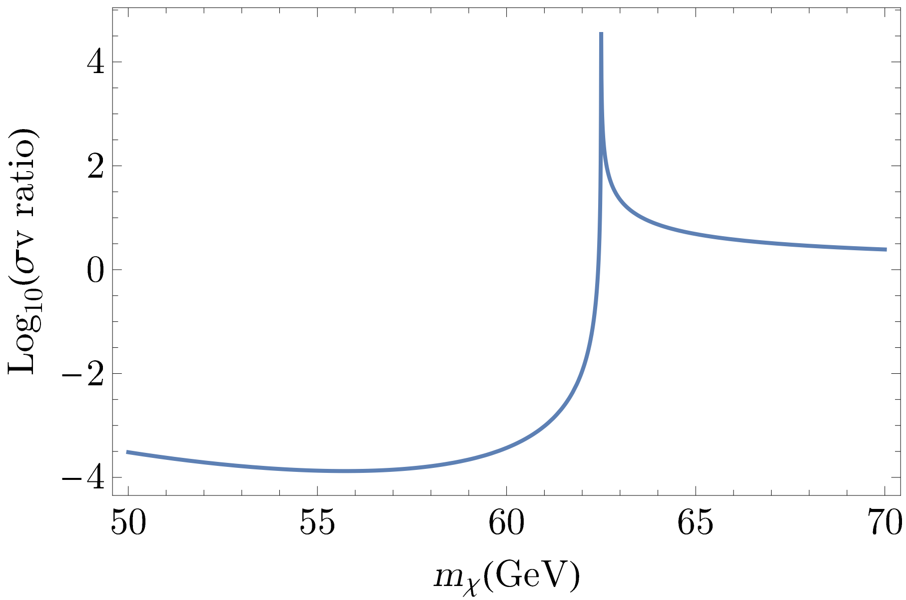
Suppression of σv in galaxy

Thermal average of σv for $\chi\chi \to b\bar{b}$ during freezeout of DM in early universe can probe resonance when $m_\chi < m_h/2$:

$$\langle \sigma v\rangle_{\rm f.o.} \sim N \int d^3p\, e^{-\beta E} \frac{\rm const.}{(4(m_\chi^2 + p^2) - m_h^2)^2 + (\Gamma_h m_h)^2}$$

Present-day annihilations in galaxy have $v \ll 1$,

$$\langle \sigma v\rangle_{\rm gal.} \sim \frac{\rm const.}{(4m_\chi^2 - m_h^2)^2 + (\Gamma_h m_h)^2}$$



The ratio $\langle \sigma v\rangle_{\rm gal.}/\langle \sigma v\rangle_{\rm f.o.}$ is highly suppressed for $m_\chi < m_h/2$.

We need it to be ~ 1 to explain the cosmic ray excesses.

Pseudo-Nambu-Goldstone Boson DM

JC & Takashi Toma, arxiv:1906.02175

pNGB DM can reconcile $m_\chi > m_h/2$ with direct detection constraints.

Let DM be imaginary part of a complex scalar field, $S = (s + i\chi)/\sqrt{2}$ with softly- (and spontaneously) broken global U(1) symmetry:

$$V = \frac{\lambda_S}{2}\left(|S|^2 - \frac{v_s^2}{2}\right)^2 + \frac{m_\chi^2}{4}\left(S^2 + S^{*2}\right) + \lambda_{HS}|H|^2|S|^2$$

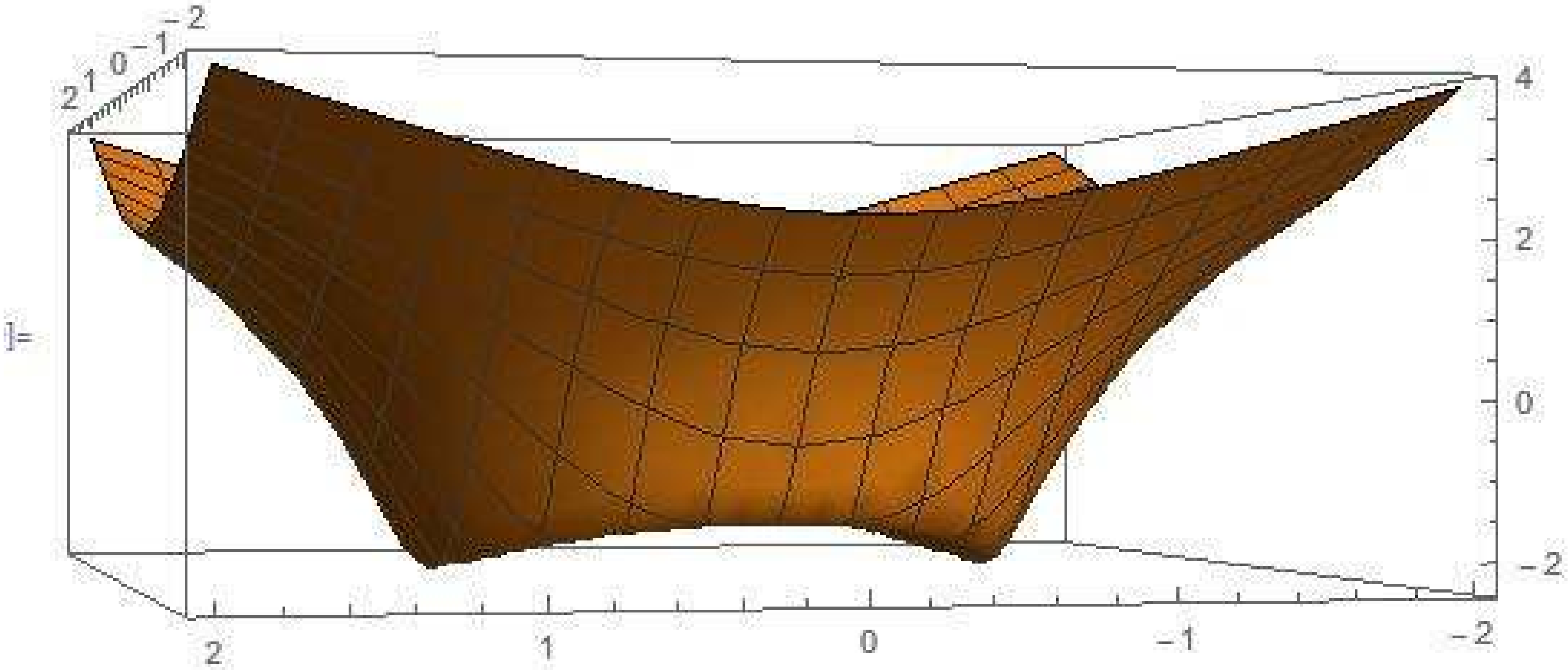
The pNGB gets mass m_χ, but its couplings to matter vanish as momentum transfer $\to 0$, no direct detection signal

We can take $m_\chi > m_h/2$ to get large enough $\chi\chi \to b\bar{b}$ annihilation cross section

Complex scalar potential

$$V = \frac{\lambda_S}{2}\left(|S|^2 - \frac{v_s^2}{2}\right)^2 + \frac{m_\chi^2}{4}\left(S^2 + S^{*2}\right)$$

looks qualitatively like



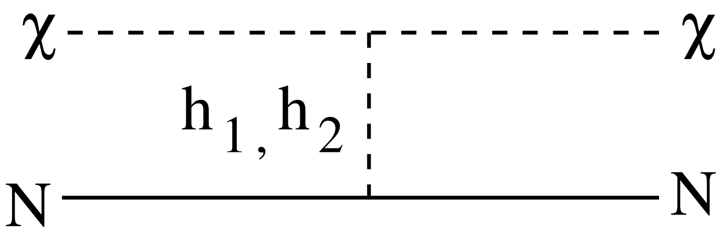
Bottom of potential is a distorted wine bottle

Suppression of direct detection signal

When S gets VEV, Higgs portal causes mixing between h and s,

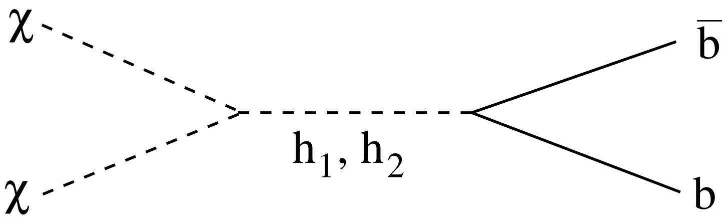
$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

The two diagrams interfere destructively, vanishing as $t \to 0$:



The two diagrams cancel to $O(q^2/m_h^2)$ for low momentum transfer q

Cancellation is ineffective in s-channel, leaving indirect signal,

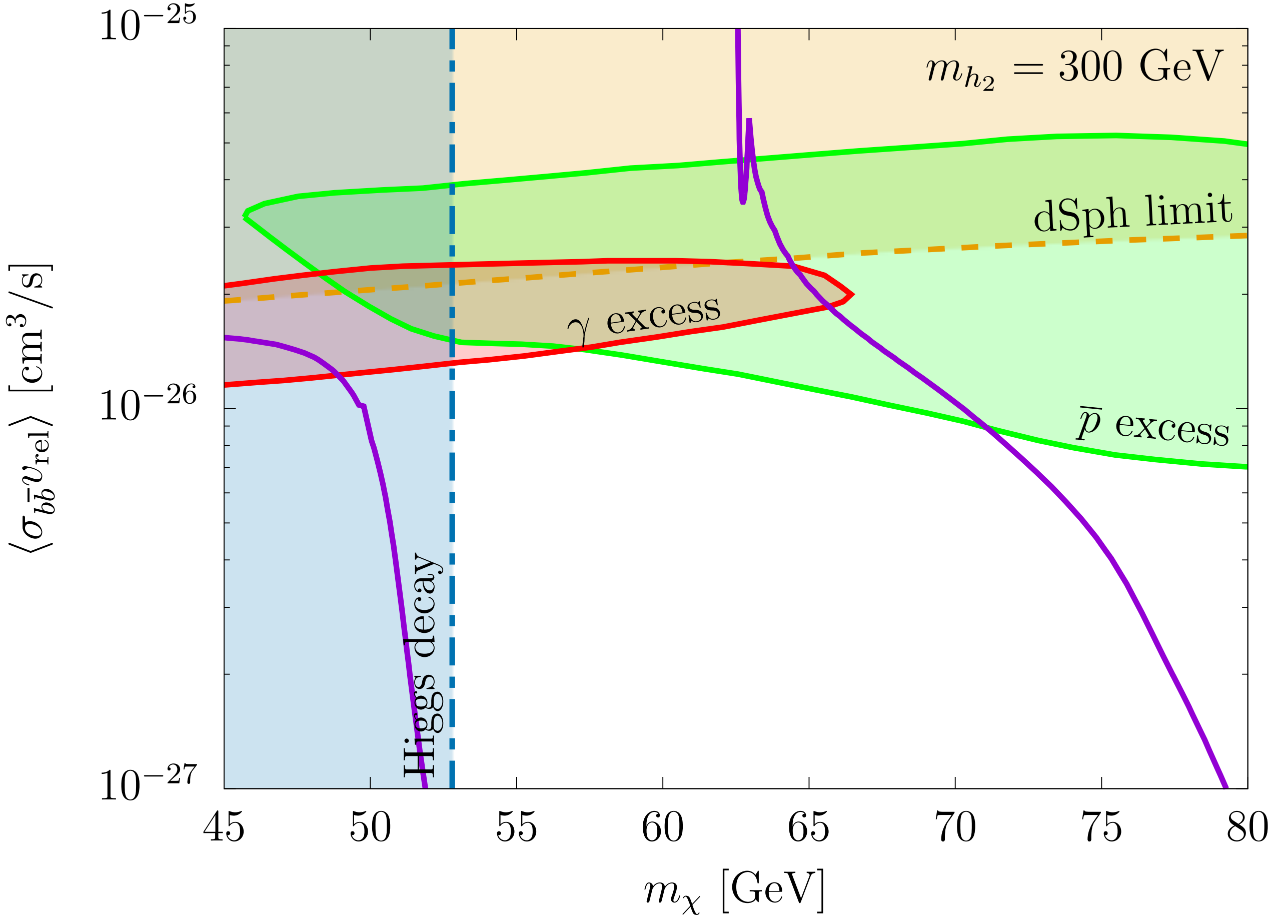


Momentum transfer is large, $q \sim m_\chi$, no cancellation

since $s \cong 4m_\chi^2$ is not small

Working models

Purple curve gets DM relic density right.

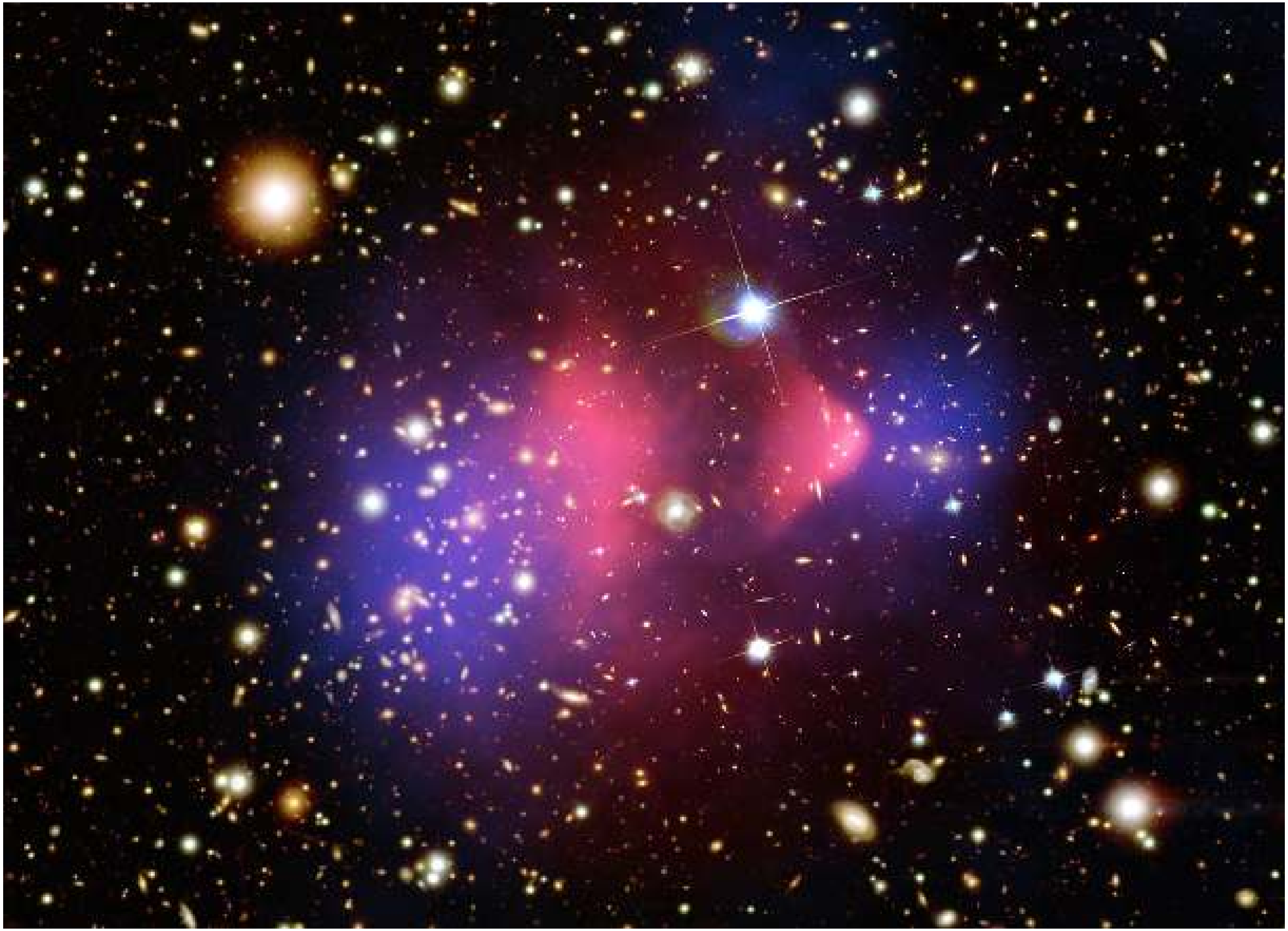


We can explain cosmic ray excesses for $m_\chi = (64 - 67)$ GeV.
Mass of extra Higgs boson m_{h_2} not strongly constrained.

Illustration of direct/indirect complementarity for guiding the search for models

DM self-interactions?

Bullet Cluster demonstrates noninteracting nature of DM,



Hints of DM self-interactions

Bullet cluster can tolerate a certain level of DM self-interactions, Randall *et al.*, (0704.0261),

$$\frac{\sigma}{m} \lesssim 0.7\ \mathrm{b/GeV}$$

(recall $1\ \mathrm{b} = 10^{-24}\ \mathrm{cm}^2$).

A similar limit arises from cosmological simulations of galaxy structure (Rocha *et al.*, 1208.3025 & 1208.3026)

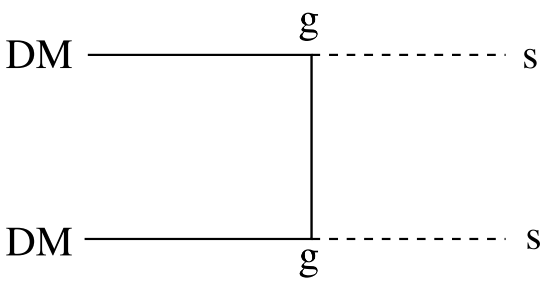
Saturating this limit could solve claimed problems for DM: cuspy versus cored halos, lack of large satelllite galaxies predicted by simulations (Weinberg *et al.*, 1306.0913)

Note that $1\ \mathrm{b} \gg 10^{-40}\mathrm{cm}^2$! (Direct detection limit)

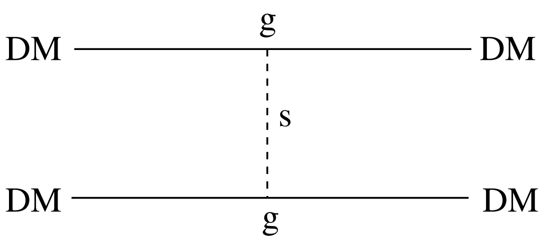
Self vs. nuclear interactions

DM self-interactions need not be related to interactions with nuclei, but sometimes they are.

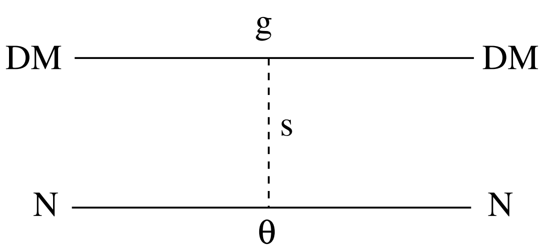
Example: (JC, M. Puel, T. Toma) $\sim 0.3\,\mathrm{GeV}$ mass sterile ν DM.



We need a light scalar s so DM can annihilate



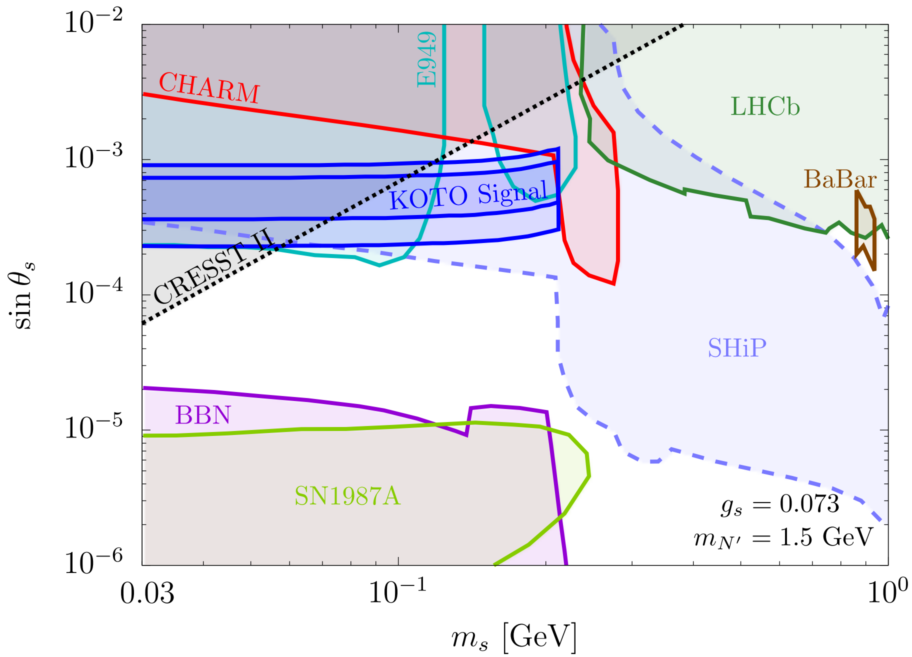
Then s exchange leads to self-interactions

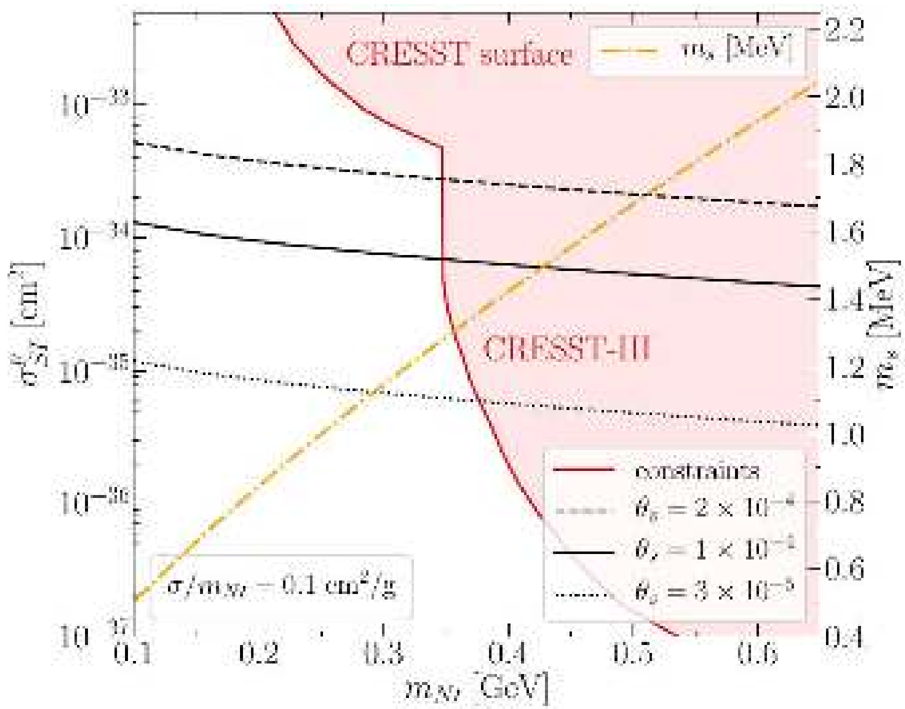


But s must mix with Higgs so it can decay: it mediates nuclear interactions. ($\theta =$ mixing angle)

Not simple to reconcile since θ cannot be too small . . .

Constraints on θ





Mixing θ is constrained by many experiments.

We can't reconcile large self-interactions with other constraints for DM mass $\gtrsim 1\,\mathrm{GeV}$.

But for DM mass $\lesssim 0.3\,\mathrm{GeV}$ and $m_s \sim 1\,\mathrm{MeV}$ we can reconcile self-interactions and other constraints

Conclusions

Dark matter is strongly constrained by direct and indirect searches

Indirect searches give hints of DM annihilation and DM self-interactions in the galaxy

Fitting everything together into an appealing model can be challenging

Perhaps we are close to a real direct detection, and not just improved limits!