Probing Light Particles Beyond the Standard Model with Supernovae and Cosmic Rays

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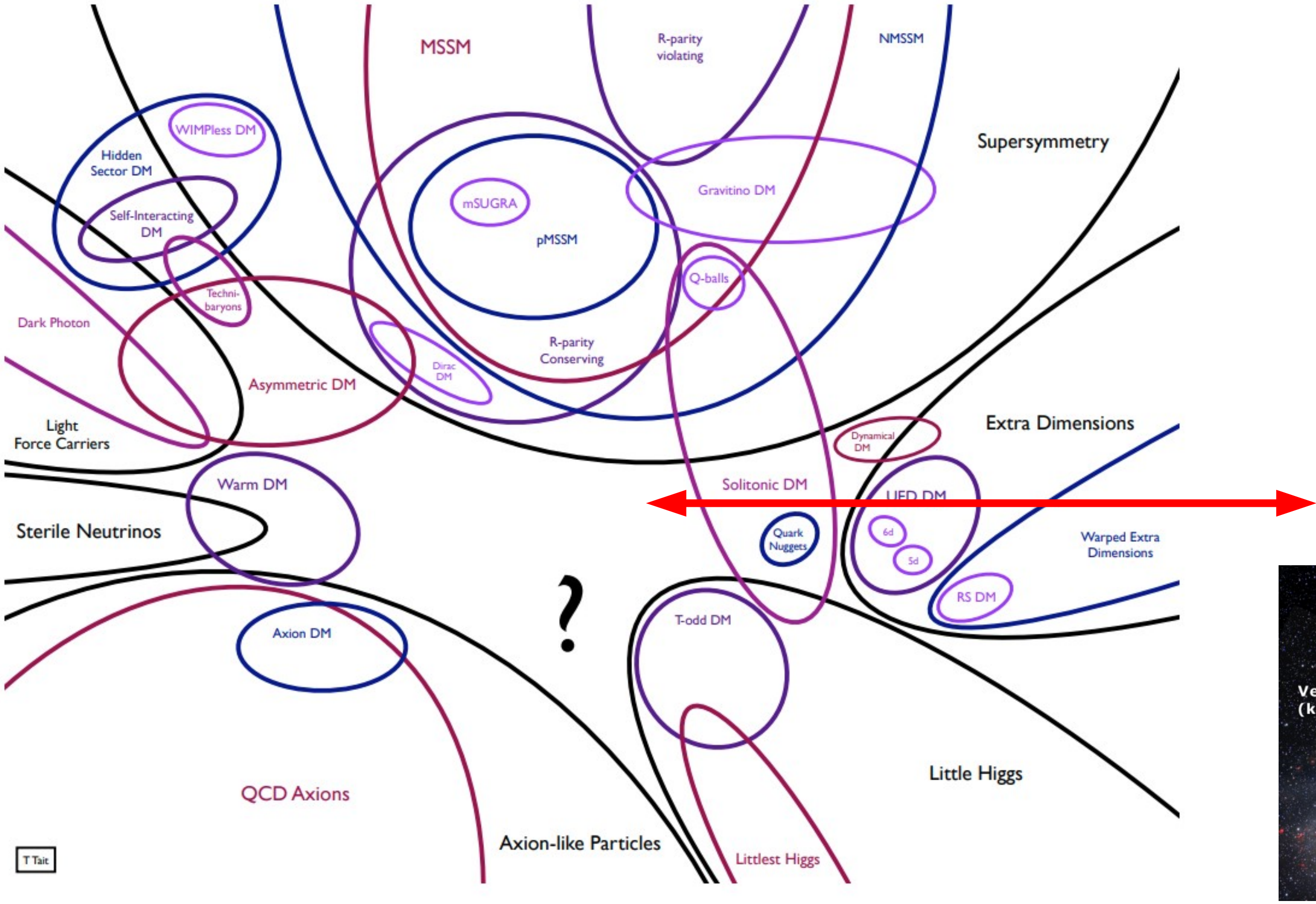
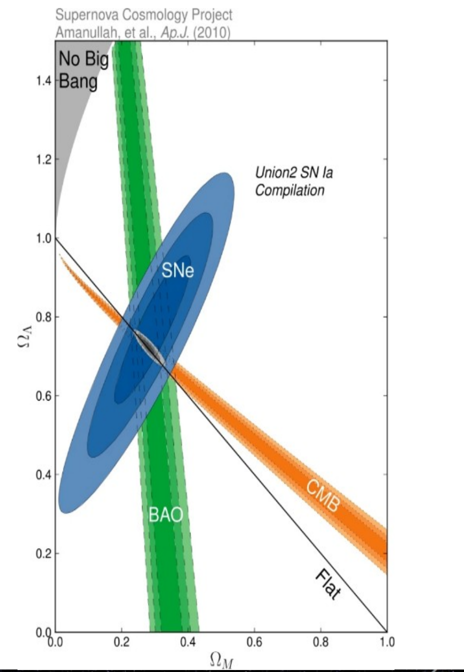
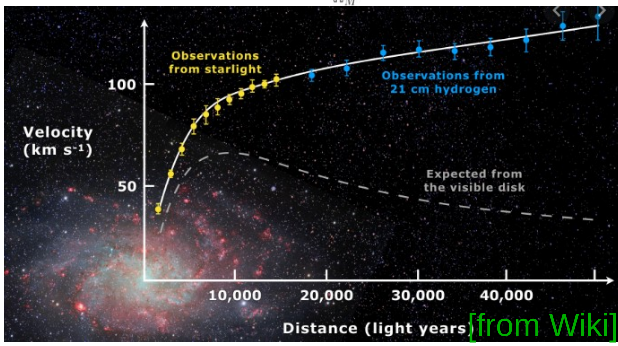
Introduction & outline



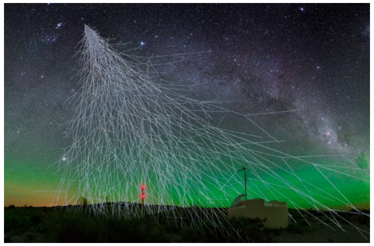




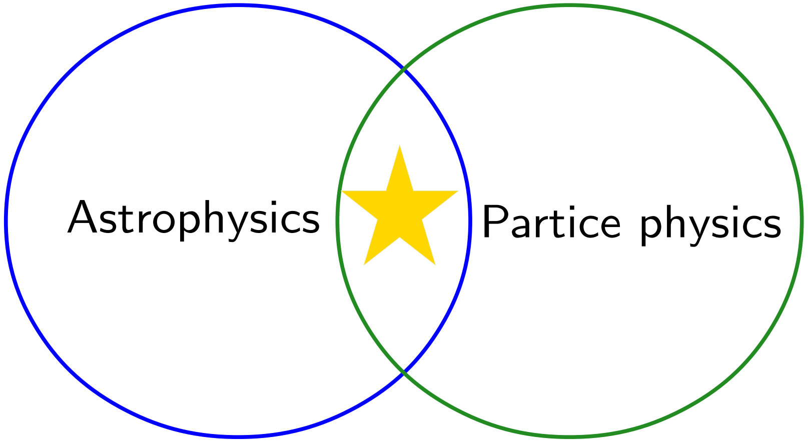
How can we help to hunt for dark matter particles with astrophysical objects or phenomena?

Introduction & outline

- Constraining bSM particles with core-collapse supernovae
  - cooling constraints on ∼keV sterile neutrinos
  - supernova bounds on dark photon portal dark sector
  - ∼ eV sterile neutrinos with next Galactic SN



- Probing sub-GeV, cosmic-ray upscattered dark matter
  - elastically upscattered DM at IceCube
  - inelastic effects
- Summary



Constraining particles beyond-the-Standard-Model with core-collapse supernovae

Core-collapse supernovae

SN1987a

– the death of massive stars $\gtrsim 8\ M_\odot$

– progenitor of neutron stars (and maybe some black holes)

– luminosity $\simeq 10^9 L_\odot$ for $\sim \mathcal{O}(100)$ days

$(E_\gamma \sim 10^{49}$ erg)

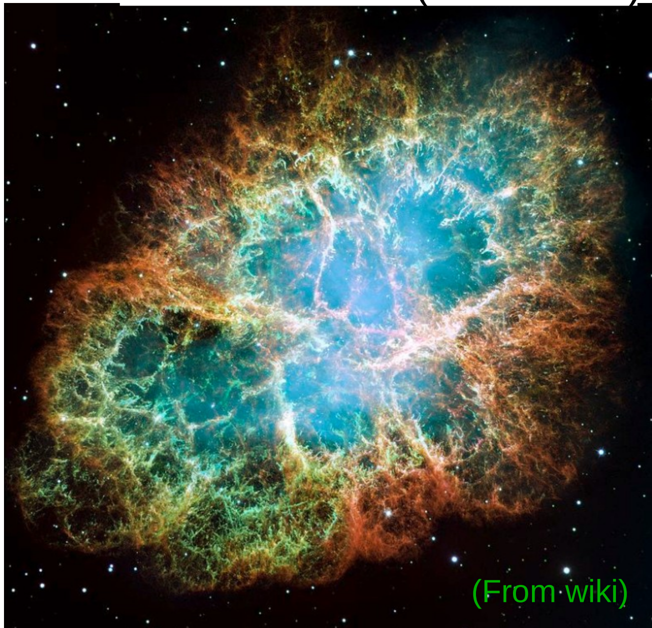
– explosion energy $\sim 10^{51}$ erg $\equiv 1$ B(ethe)

– nature's strongest neutrino emitter $\sim 10^{53}$ erg

– occurs $\sim$ every second in the universe

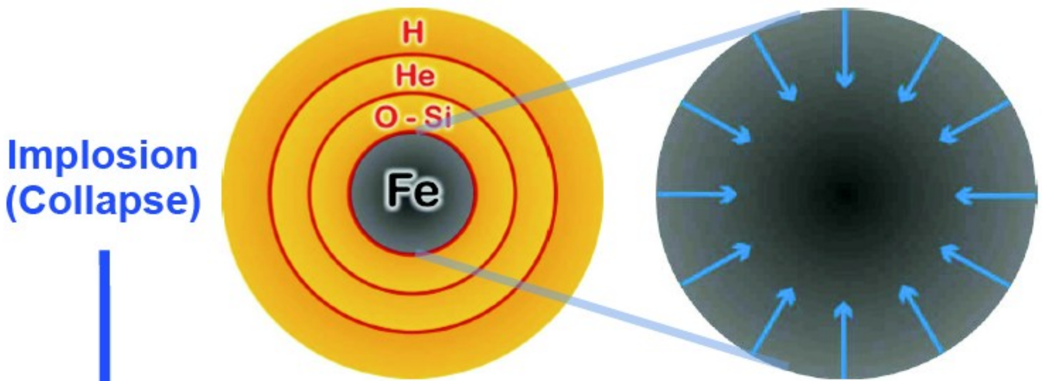
– rate in the Milky Way $\sim 0.5 - 2$ per century

Crab Nebula (SN 1054)



Core-collapse supernovae

progenitor star



$M_{\rm Fe,core} \approx 1.4 M_\odot$

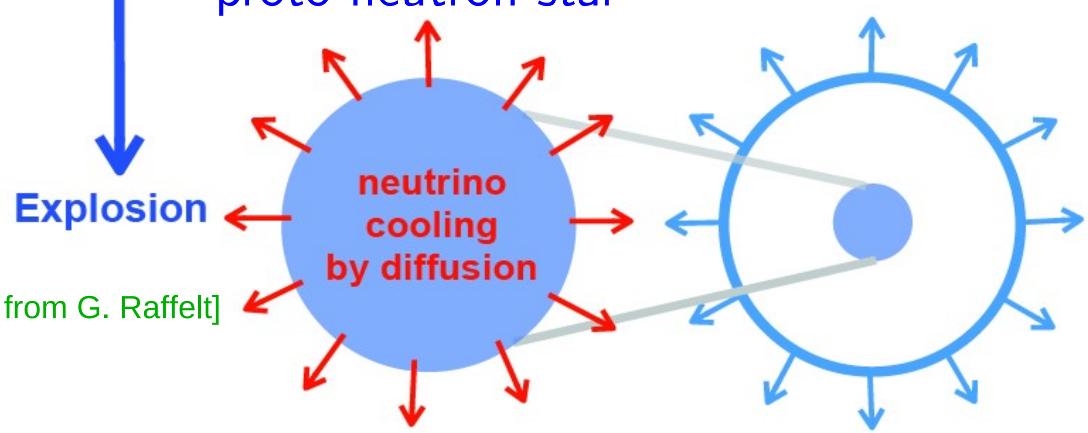
$R_{\rm Fe,core} \approx 3000$ km

$\rho_c \approx 10^9$ g cm^{-3}

$T_c \approx 10^{10}$ K~ 1 MeV

$E_{\rm grav} \sim \frac{G M_{\rm PNS}^2}{R_{\rm PNS}} \sim 10^{53}$ erg

proto-neutron star



[Figure from G. Raffelt]

$M_{\rm PNS} \approx 1.4 M_\odot$

$R_{\rm PNS} \approx 15$–50 km

$\rho_c \approx 3 \times 10^{14}$ g cm^{-3}

$T_c \approx 30$ MeV

$\sim 10^{58}$ ν's released in $\sim$ 10 seconds

$$e^- + p^+ \to n + \nu_e, \quad e^- + e^+ \to \nu_i + \bar{\nu}_i$$
$$e^+ + n^+ \to p + \bar{\nu}_e, \quad N + N \to N + N + \nu_i + \bar{\nu}_i$$

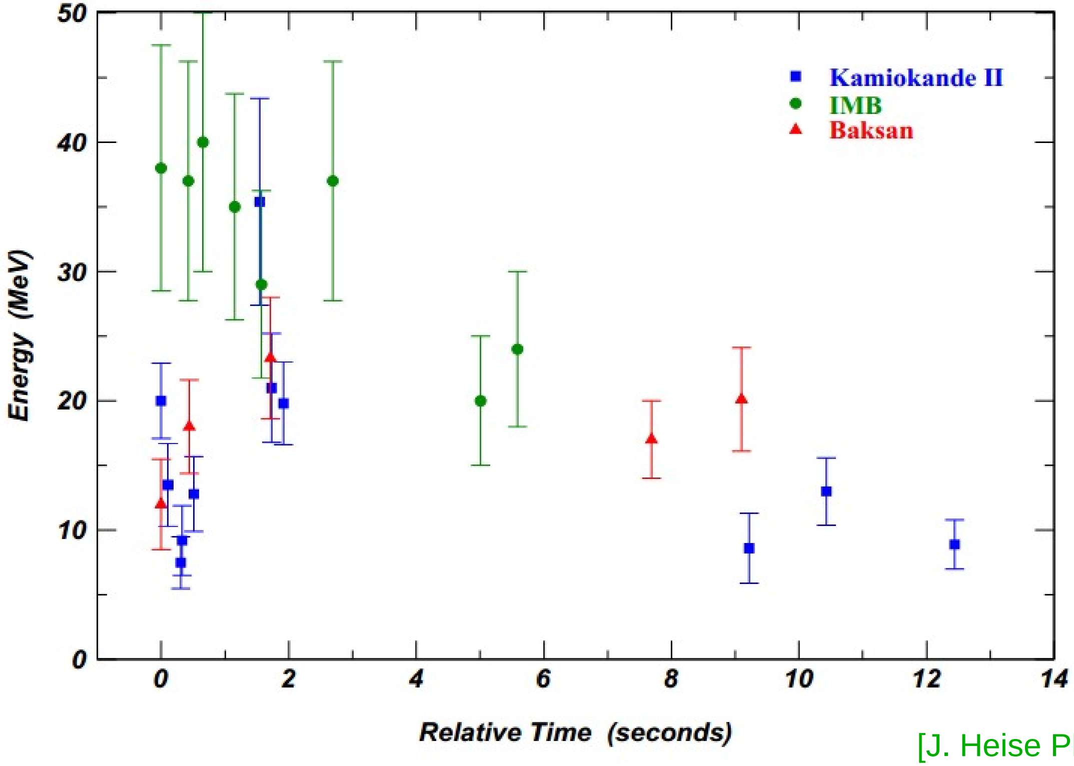
Supernova neutrinos

~ 20 SN $\bar{\nu}_e$ detected from SN1987a in ~ 10 s

$L_{\bar{\nu}_e} \sim 5 \times 10^{52}$ erg, $\langle E_{\bar{\nu}_e} \rangle \sim 15$ MeV

The Tarantula Nebula
and supernova 1987a
in the LMC (~50 kpc)

(From AAO website)

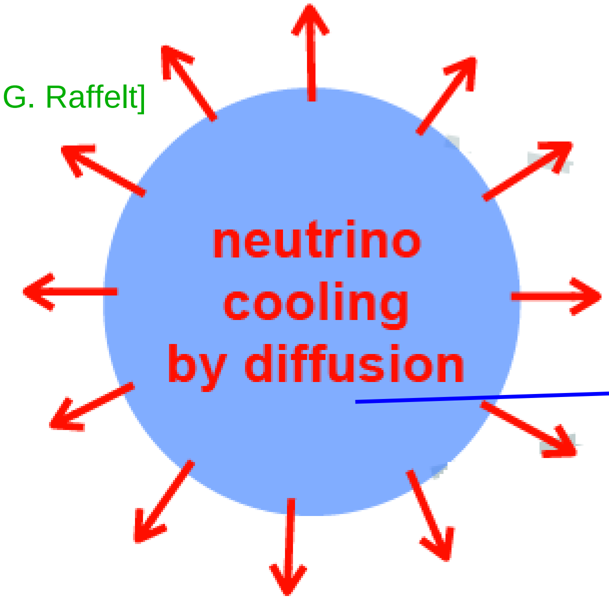


[J. Heise PhD Thesis (2002)]

a next Galactic supernova will allow us to see $\sim 10^3$–10^4 neutrinos, in all flavors!

Proto-neutron star cooling constraining bSM physics

[Figure from G. Raffelt]



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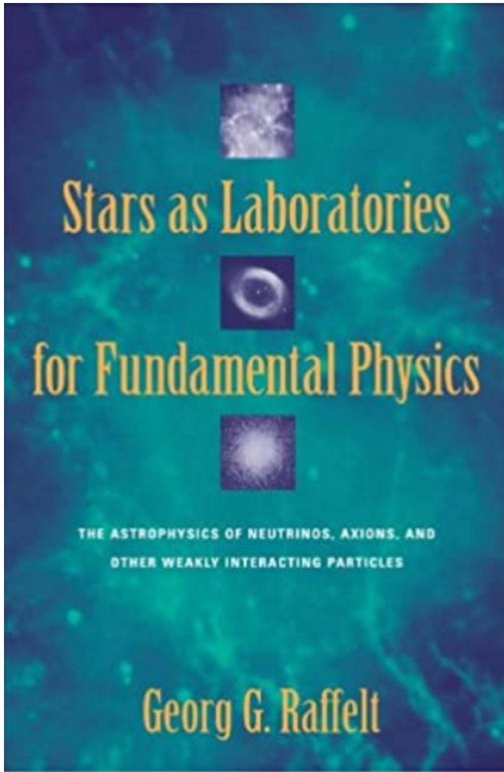
weakly-interacting particles?

If the energy carried away by any bSM particles is larger than that by neutrinos predicted with the Standard Model, the cooling timescale of the proto-neutron star becomes shorter than ~ 10 s

Raffelt's criteria: $L_{\mathrm{new\ particle}} < L_\nu \sim 3 \times 10^{52}$ erg/s

axions, keV sterile neutrinos, dark photons,...



(I) cooling bounds on keV sterile neutrinos

– hypothetically "flavor" beyond the known 3 kinds of active neutrinos

– if slightly mixed with active neutrinos, may be warm dark matter candidates
[Dodelson+1993, Shi & Fuller 1999, Abazajian+ 2001...]

– potentially produce x-ray lines via radiative decay process
[Boyarsky+ 2014, BulBul+ 2014, Abazajian+ 2017, Dessart+2020...]

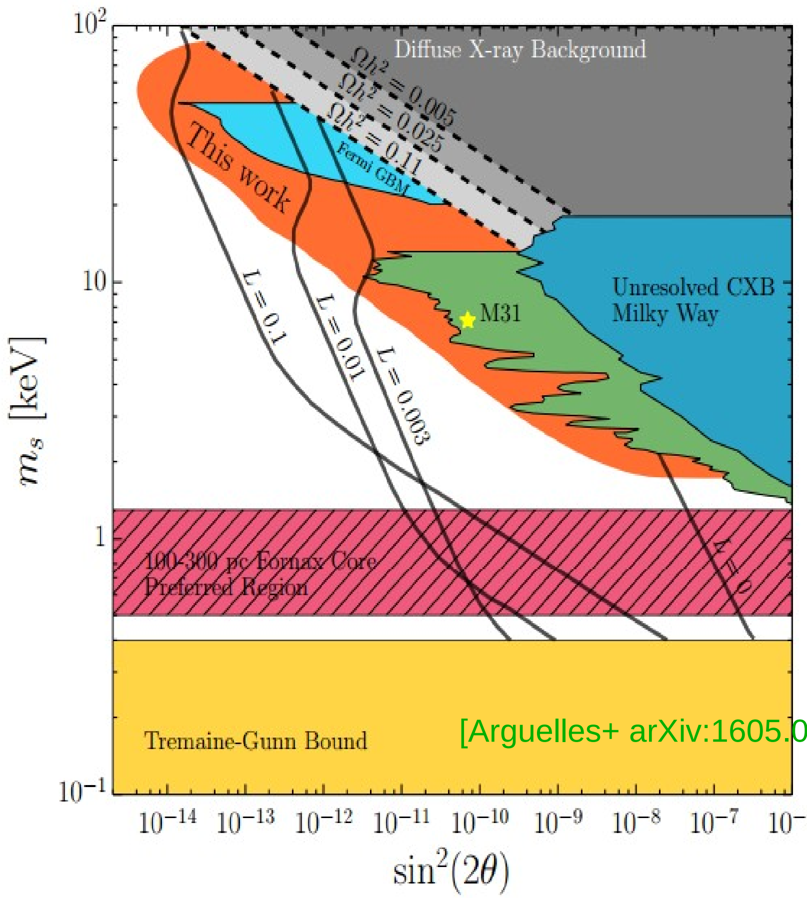
Inside a PNS, they can be produced via:

(i) adiabatic flavor conversion through MSW-like resonance:

$$\Delta m^2_{41} \sim G_F n_{b,\mathrm{PNS}} T_{\mathrm{PNS}}$$

(ii) scattering production

$$\Gamma_{\nu_s} \sim \Gamma_{\nu_a} \sin^2 2\theta_M$$

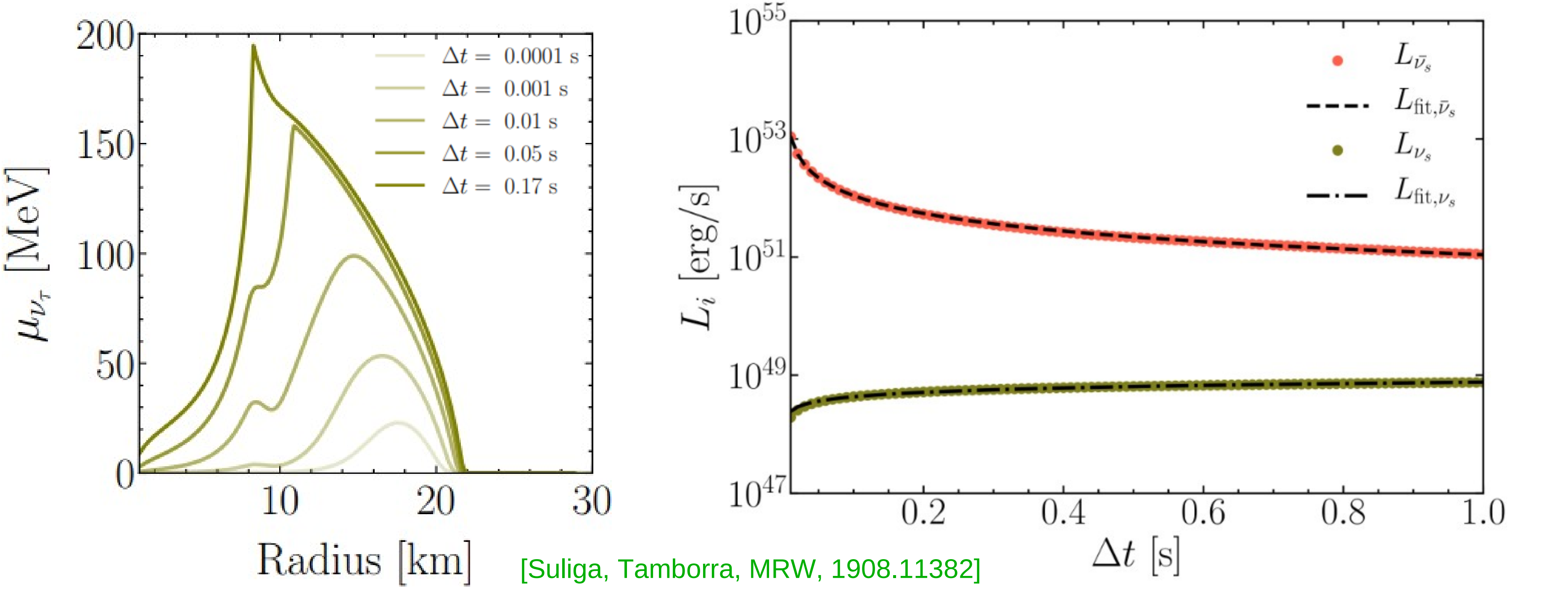


[Arguelles+ arXiv:1605.00654]

(I) cooling bounds on keV sterile neutrinos

In a series of work (1908.11382 & 2004.11389), we show that it is necessary to include the feedback effects of sterile neutrino production on the PNS interior, which in turn, suppress their production

basic idea: ν_s and $\bar{\nu}_s$ production are asymmetric
- $\rightarrow$ larger asymmetry (more degenerate) in the active sector
- $\rightarrow$ less phase space for flavor conversion to occur



[Suliga, Tamborra, MRW, 1908.11382]

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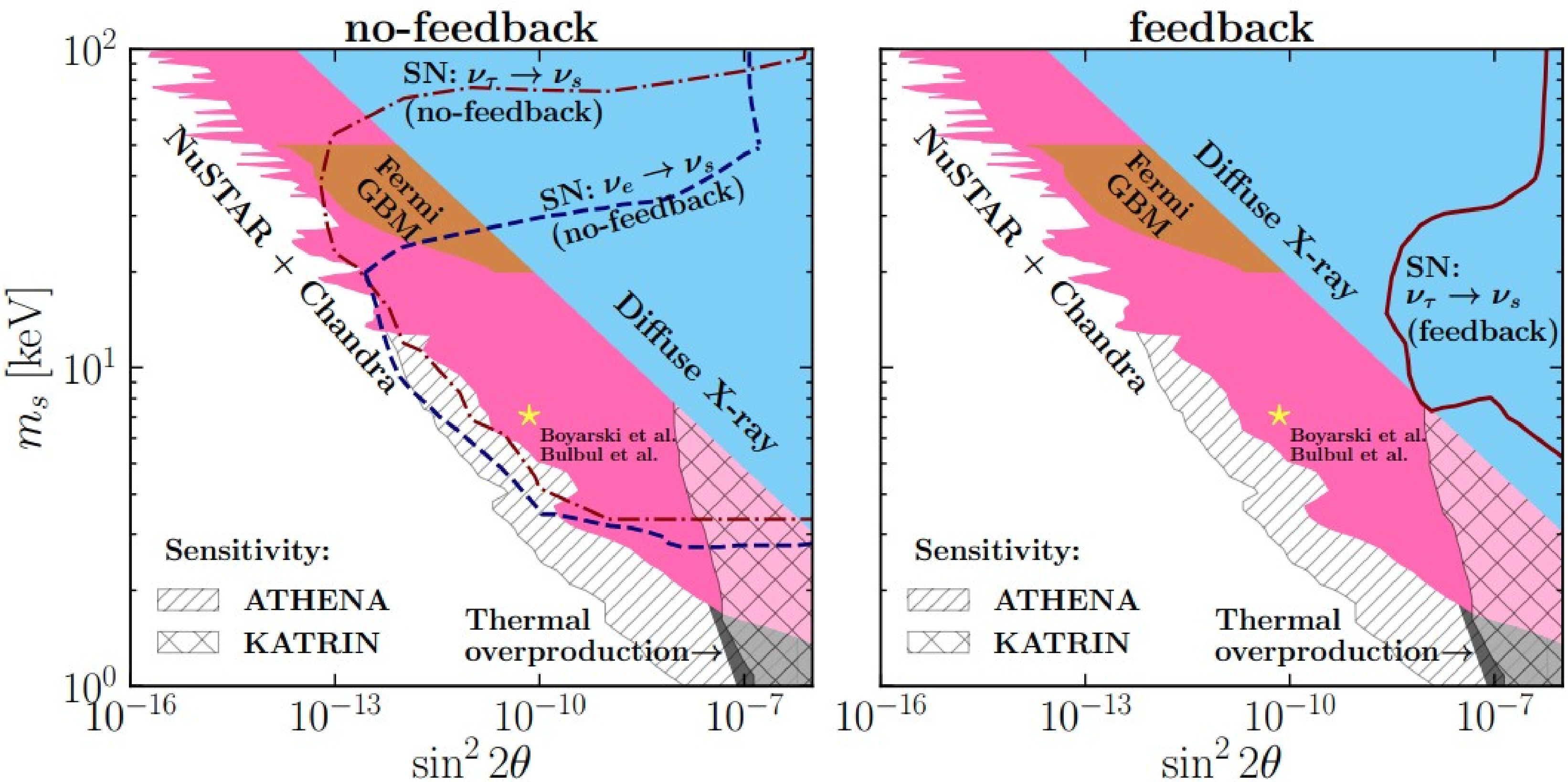


largely lifts the SN constraint on keV sterile neutrinos

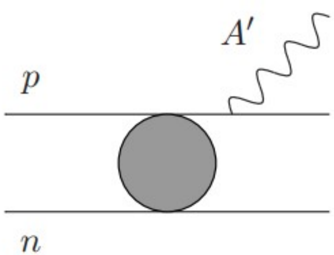
(II) cooling constraint on dark sector (dark photon portal)

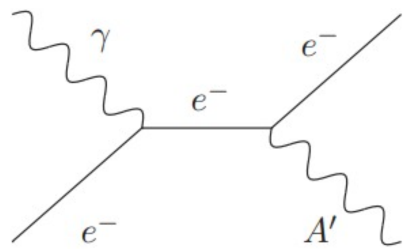
Another bSM model being actively examined in recent years is to involve dark fermions portal by dark photon, which mixes with the SM photon

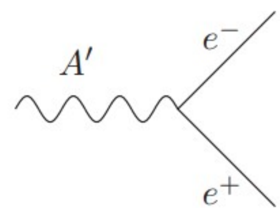
[Holdom 1986, Okun 1982, and many others]

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu + \bar{\chi}\left(i\partial - m_\chi\right)\chi + g_D\bar{\chi}\chi$$

They can be produced in PNS via a number of processes, e.g.,

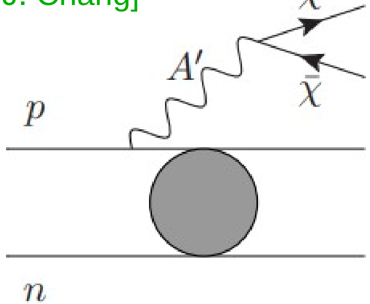


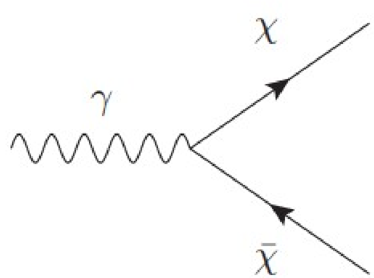


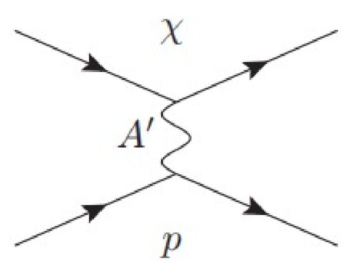


$+ \ldots$

[Adapted from J. Chang]







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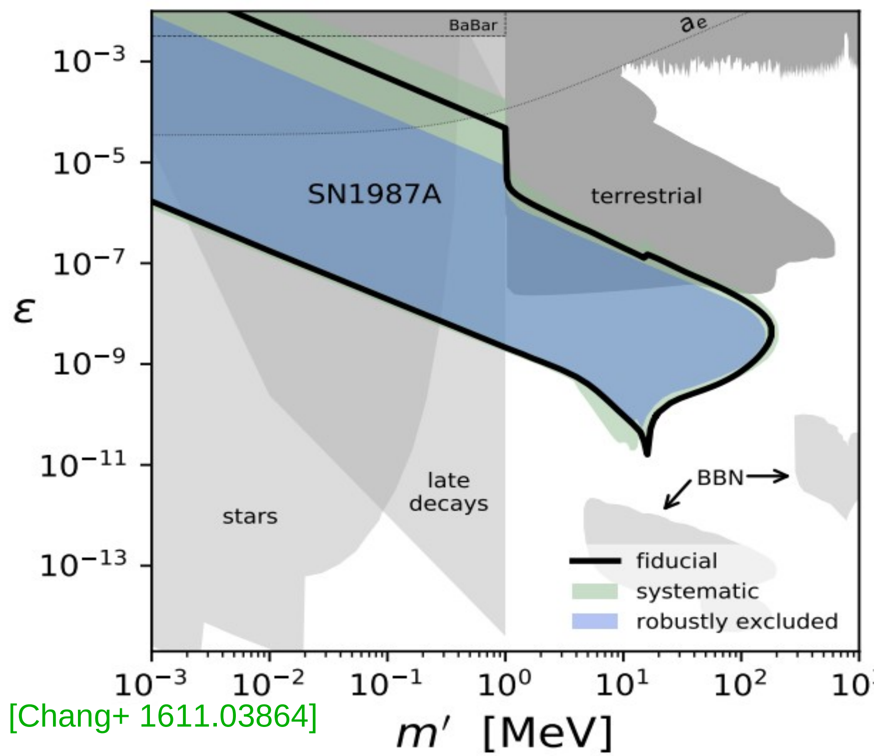
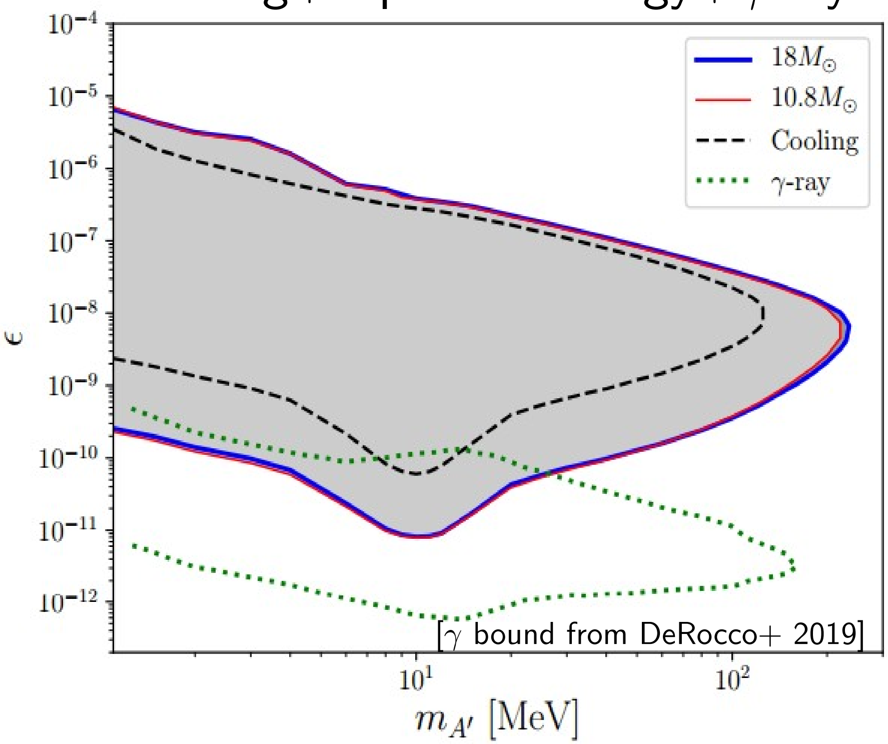
Considering the degree of freedom of dark photon only:

cooling constraint



[Chang+ 1611.03864]

cooling+explosion energy+γ-ray



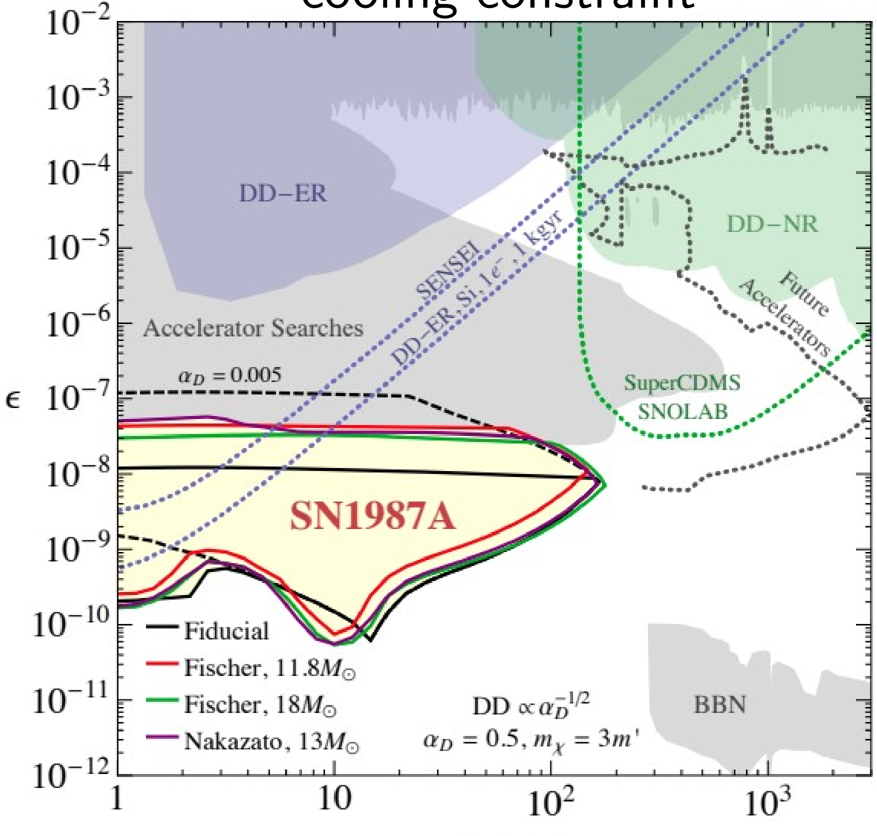
[Sung, Tu, MRW 1903.07923]

[See also Dent+, Rrapaj+, Hardy+,...]

(II) cooling constraint on dark sector (dark photon portal)

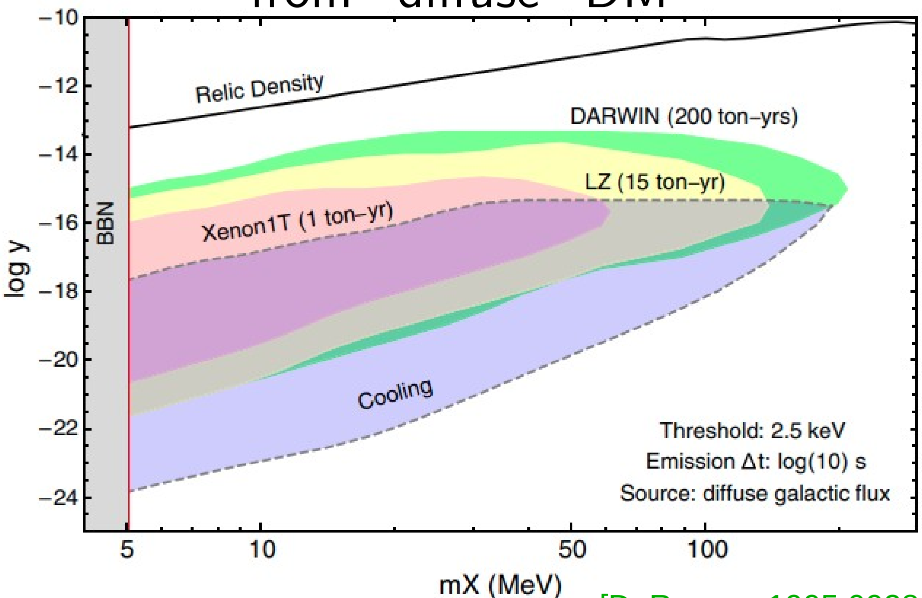
A couple work examine the constraints/signals of sub-GeV light dark fermions

cooling constraint



[Chang+ 1803.00933]

from "diffuse" DM

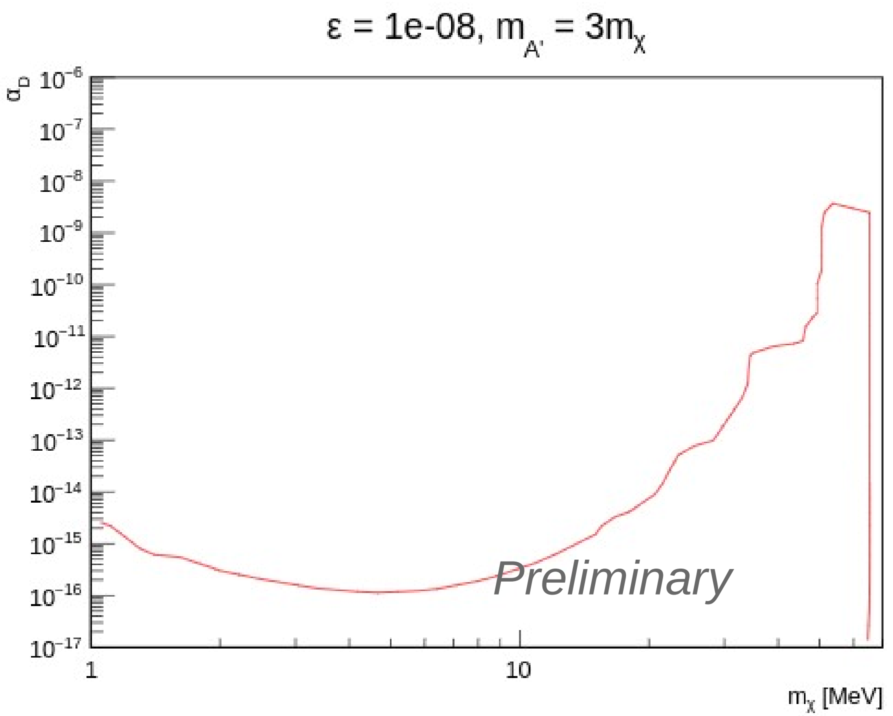


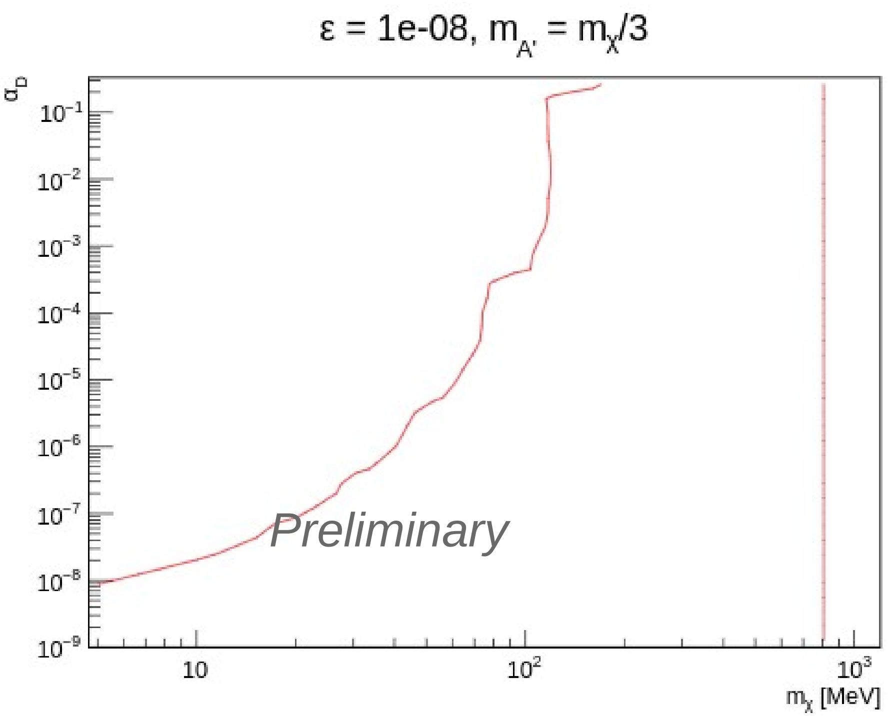
[DeRocco+ 1905.09284]

However, self-trapping of dark sector particles were completely ignored

(II) cooling constraint on dark sector (dark photon portal)

The self-trapping of dark sector particles can work very efficient to keep dark sector particles inside the PNS

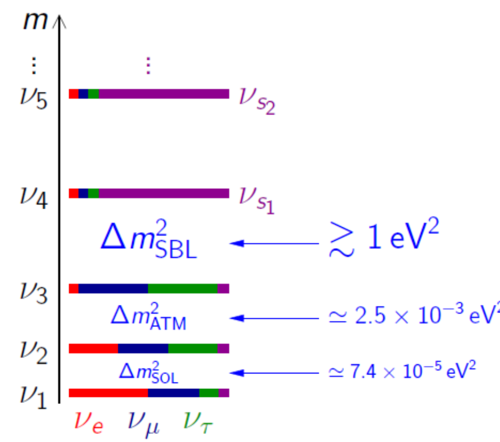




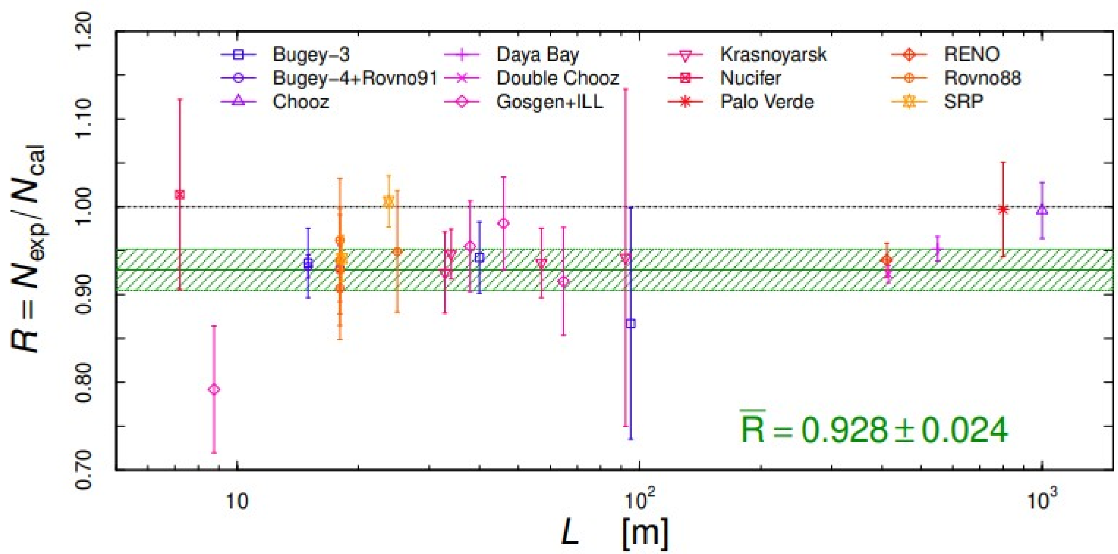
[Sung, Guo, MRW, in preparation (21xx.xxxx)]

May have interesting implications on other stellar bounds or generation of dark matter inside a neutron star

(III) eV sterile neutrinos with next galactic SN



A few accelerator neutrino experiments (LSND, MiniBooNE) and short-baseline reactor experiments showed anamolies ($\sim 2-3\sigma$) that may be reconciled if light ($\sim$ eV) sterile neutrino exists



[Giunti+ 1906.01739]

Unlike keV sterile neutrinos, eV sterile neutrinos are produced outside the PNS and not constrained by cooling bounds

However, active neutrinos emitted from the PNS surface can still be converted to sterile ones and affect SN shock revival and nucleosynthesis

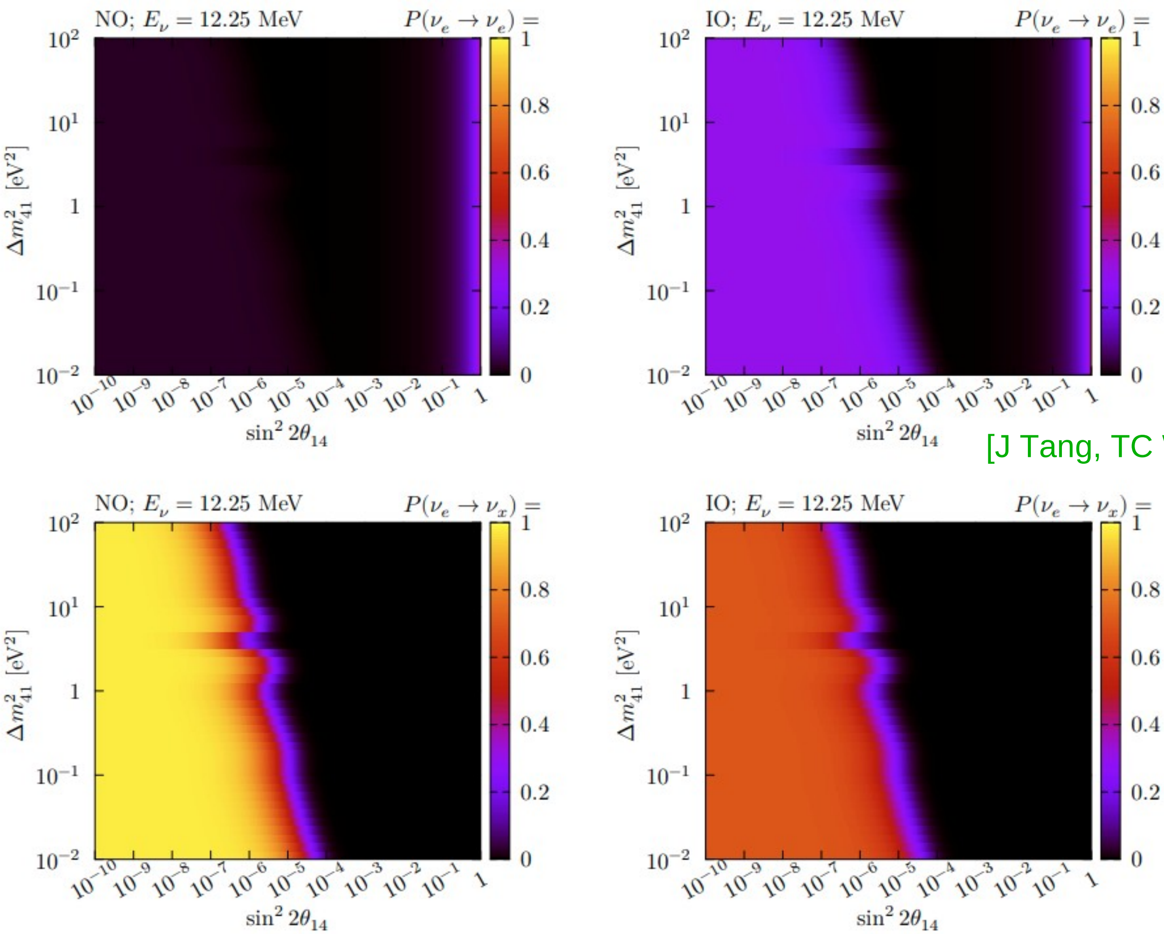
[Fetter+, McLaughlin+, Qian+, Tamborra+, MRW+...]

(III) eV sterile neutrinos with next galactic SN

Question: can we rule them out with SN1987a data?

→ difficult, because only $\bar{\nu}_e$ were detected + we do not know how collective oscillations operate in most period of neutrino emission

the next question: can we rule them out when the next galactic SN occurs?



[J Tang, TC Wang, MRW, 2005.09168]

(III) eV sterile neutrinos with next galactic SN

We focus on the $\sim O(10)$ ms window of the neutronization neutrino burst phase, for which we have good theory understanding of neutrino emission & oscillations

Table 3. Total event numbers for the normal ordering. The mixing angles θ_{12}, θ_{13}, and θ_{23} used are $33.48°$, $8.5°$, and $45°$, respectively. The active-sterile mixing angles θ_{24} and θ_{34} are fixed at 0.

ν_e; @10 kpc (NO)	DUNE ArCC	Hyper K eES	JUNO eES	JUNO pES
3-ν mixing	12.8	36.5	2.2	9.1
$\sin^2 2\theta_{14} = 10^{-9}$, $\Delta m^2_{41} = 10^2$ eV^2	12.8	36.2	2.2	9
$\sin^2 2\theta_{14} = 10^{-7}$, $\Delta m^2_{41} = 10^2$ eV^2	12.1	27.2	1.7	7.7
$\sin^2 2\theta_{14} = 10^{-5}$, $\Delta m^2_{41} = 10^2$ eV^2	10.2	11.3	0.7	3.3
$\sin^2 2\theta_{14} = 10^{-3}$, $\Delta m^2_{41} = 10^2$ eV^2	10.3	11.3	0.7	3.3
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$\sin^2 2\theta_{14} = 10^{-5}$, $\Delta m^2_{41} = 10^{-2}$ eV^2	12.4	31.3	1.9	8.4
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[J Tang, TC Wang, MRW, 2005.09168]

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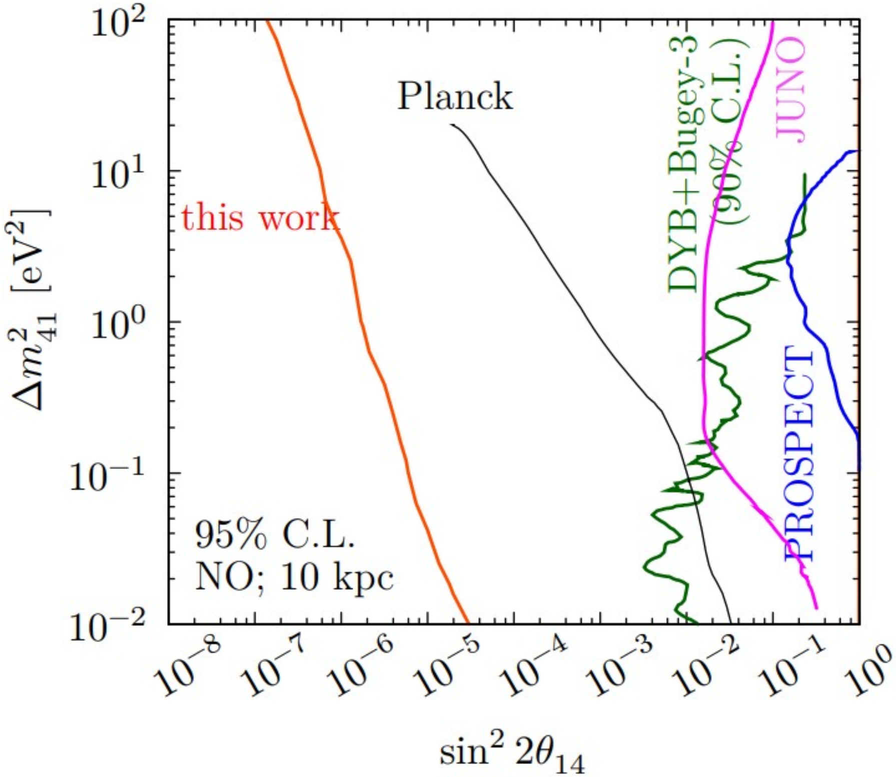

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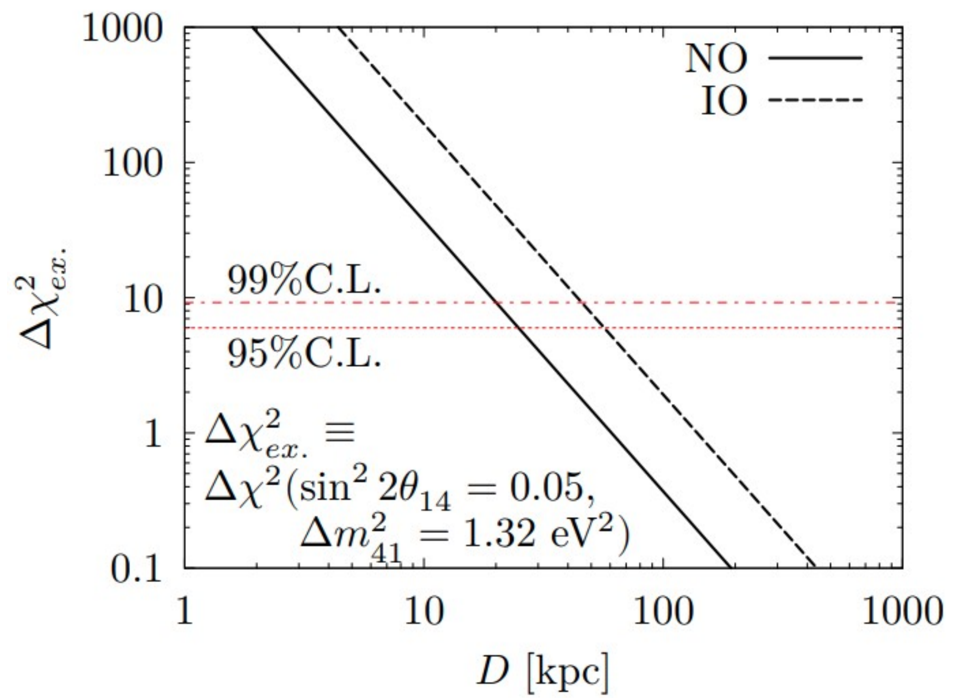
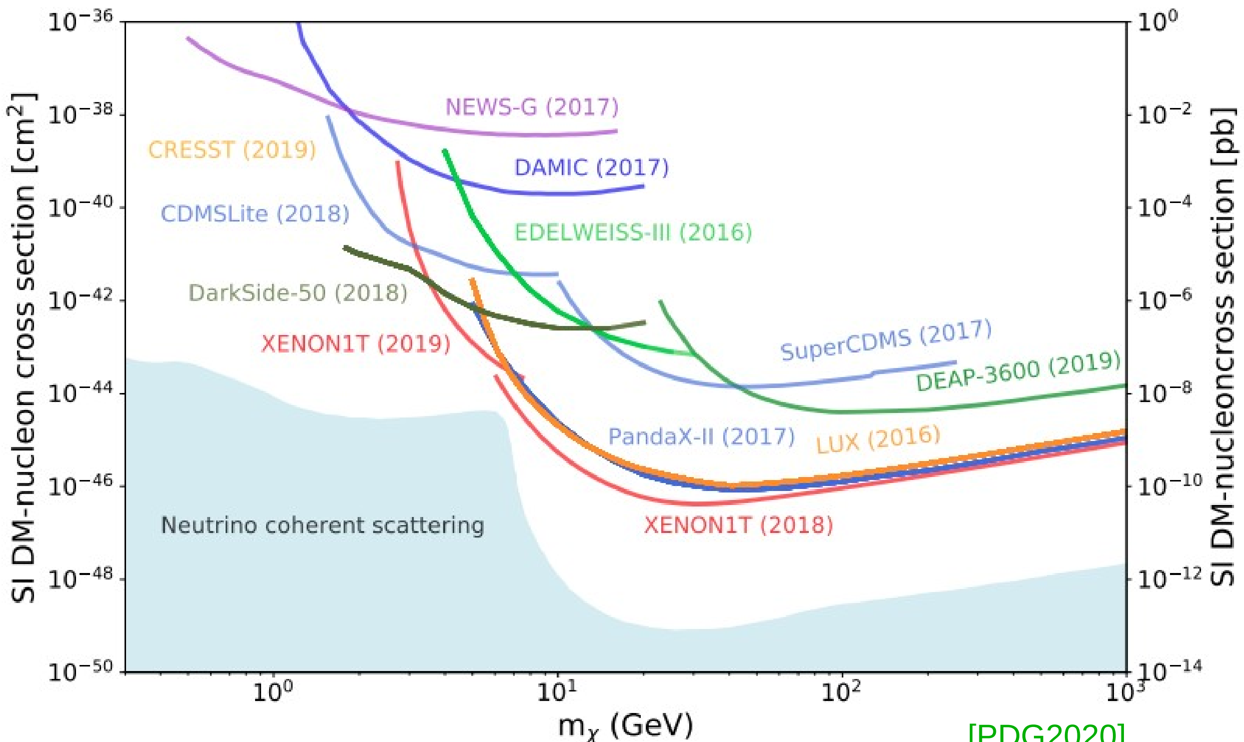


A next galactic SN will be able to place strong bounds on $\sim$ eV sterile neutrinos

Probing sub-GeV, cosmic-ray upscattered dark matter

Dark Matter

Searches for DM heavier than $\gtrsim$ few GeV –TeV thus far have yet found evidence of DM–nucleon (χN) interaction and will eventually reach the neutrino floor



[PDG2020]

→ (partly) "motivates" the consideration of other candidates with different masses and/or interactions

Dark Matter with high velocities/energies?

Experiments relying on nuclear recoils to probe the DM–nucleon cross-section quickly lose sensitivities for m_χ going below a few GeV, assuming local DM velocity distribution is $\sim$ virialized, i.e., $\langle v_\chi \rangle \sim 10^{-3}\, c$

However, just like the existence of non-thermal components of SM particles, there can possibly be a "non-thermal" component of DM whose velocities far exceed $\langle v_\chi \rangle$

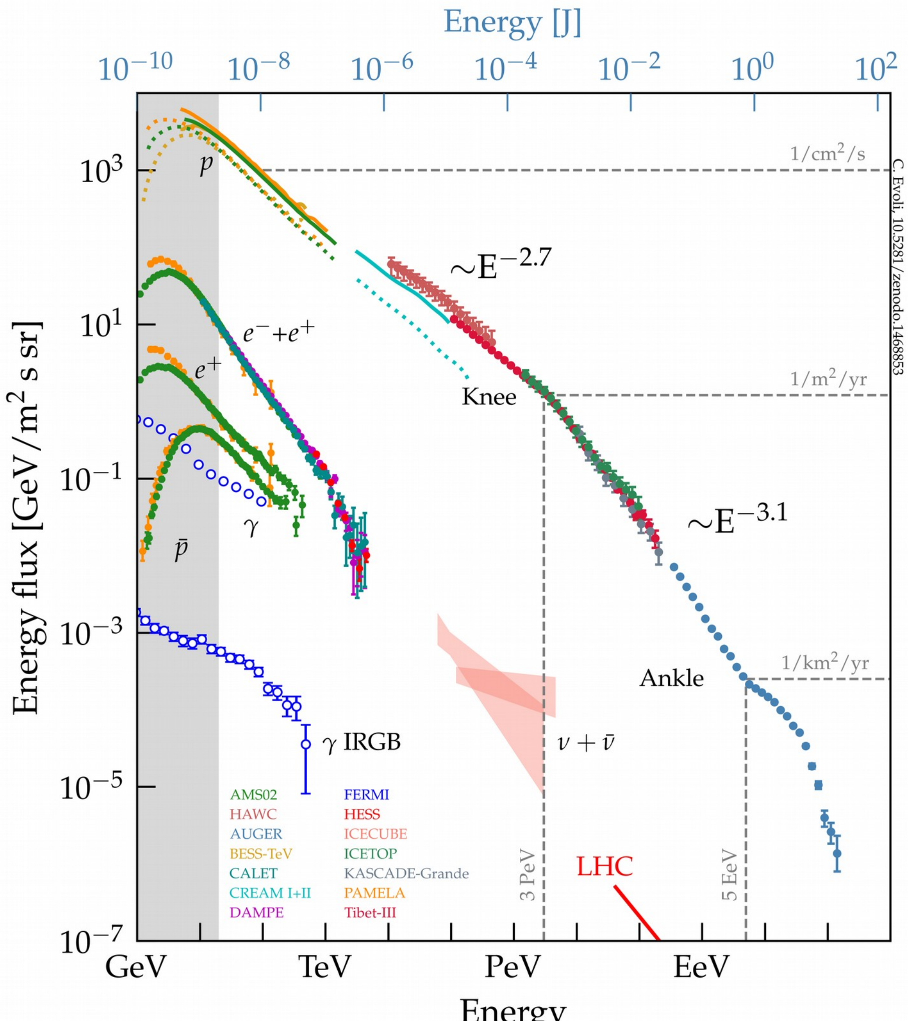
– boosted (light) DM from the annhilation or decay of (heavy) DM

[Agashe+ 2014, Bhattacharya+ 2016,...]

– upscattered DM by cosmic rays

[Bringmann+ 2018, Ema+ 2018, Cappiello+ 2019, Guo+, Ge+, Zhang+, Dent+, Wang+, Cho+, Cao+ 2020,...]

– many other theoretical possibilities...



How many up-scattered DM?

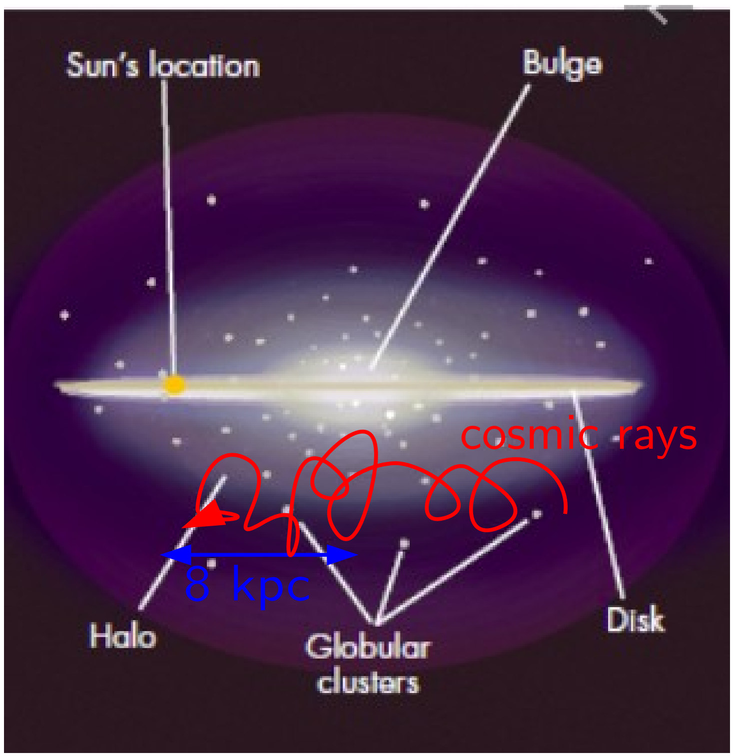
The differential DM flux upscattered by cosmic rays in Milky Way:

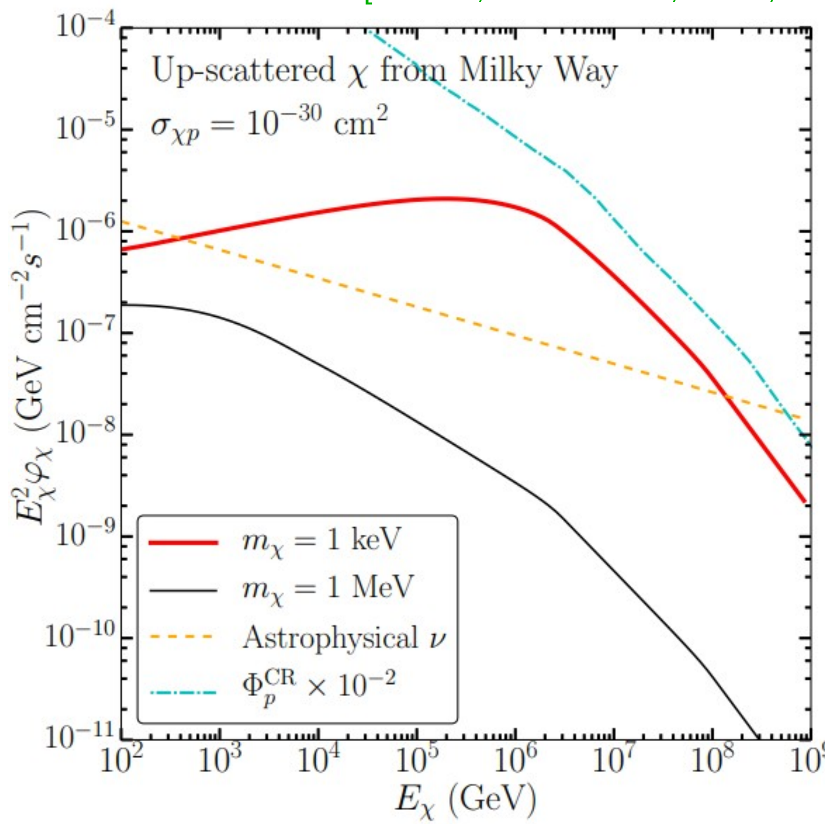
$$\Phi_\chi^{\rm MW}(E_\chi,\Omega) \equiv \frac{d^2N_\chi}{dE_\chi d\Omega}(E_\chi,\Omega) = \int_{\rm l.o.s.} d\ell \int dE_p \underbrace{\frac{\rho_\chi(r)}{m_\chi}}_{\text{DM number density}} \underbrace{\Phi_p(E_p)}_{\text{cosmic rays spectrum}} D_{p\chi}(E_p,E_\chi)\sigma_{p\chi},$$

DM number density
NFW profile

cosmic rays spectrum

[G. Guo, Y.-L. S. Tsai, MRW, 2004.03161]

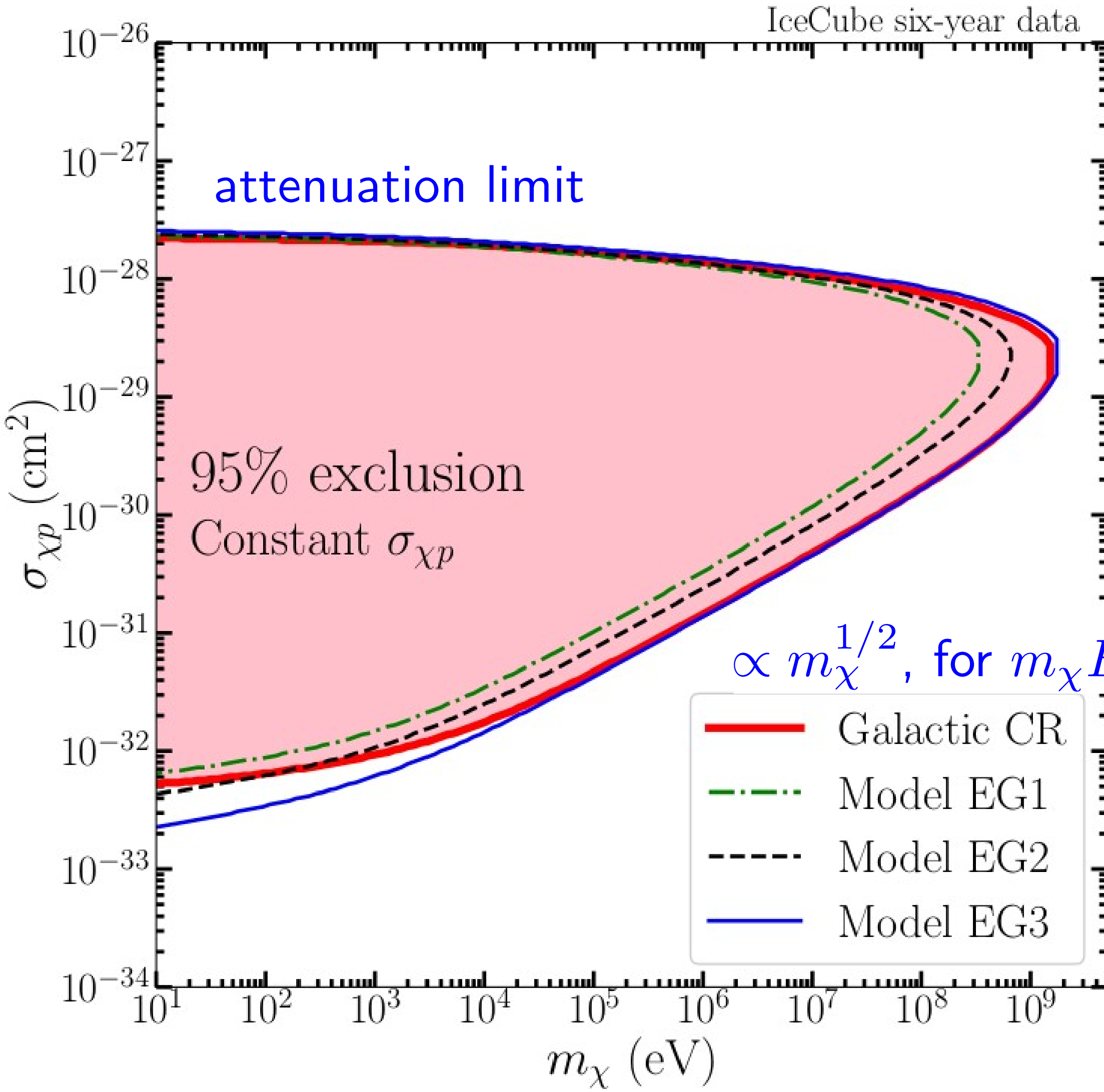




$\rightarrow$ possible to probe $\sigma_{\chi p} \gtrsim \sigma_{\nu p}$!

Constraining DM–nucleon cross section with IceCube

$N_{\text{event}} \propto m_\chi^{-1} \sigma^2 \exp(-\sigma n L)$ → exclusion ranges between two $\sigma_{\chi p}$ for a given m_χ



attenuation limit

$\propto m_\chi^{1/2}$, for $m_\chi E_\chi \gtrsim m_p^2$

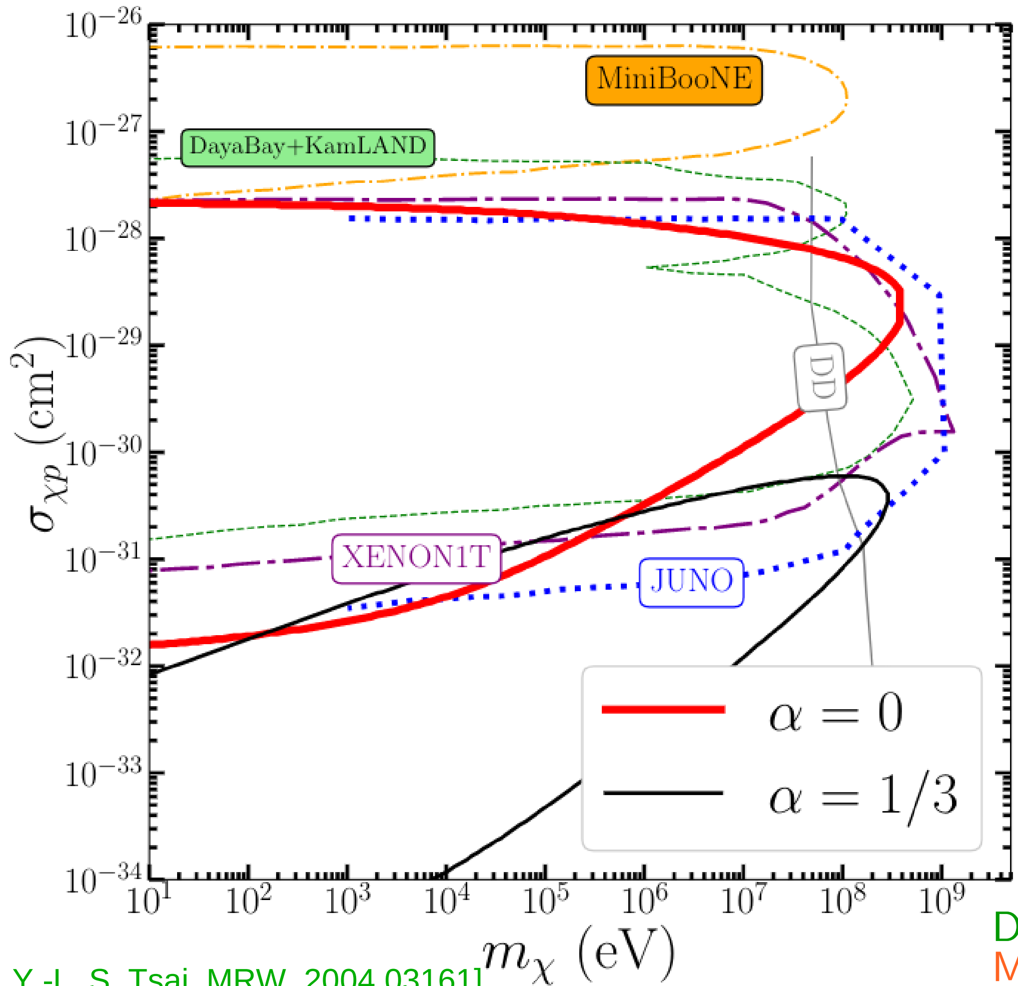
IceCube can test interesting range of $\sigma_{\chi p} \gtrsim \sigma_{\nu p}$ at the energy scale of $\sim$ PeV in the rest-frame of a nucleon

[G. Guo, Y.-L. S. Tsai, MRW, 2004.03161]

Constraining DM–nucleon cross section with IceCube

The comparison of this new constraint with the existing ones requires a particle physics model

A naive extrapolation of $\sigma_{\chi p} \propto E^{\alpha}$ all the way down to $E_\chi \simeq m_\chi$:



[G. Guo, Y.-L. S. Tsai, MRW, 2004.03161]

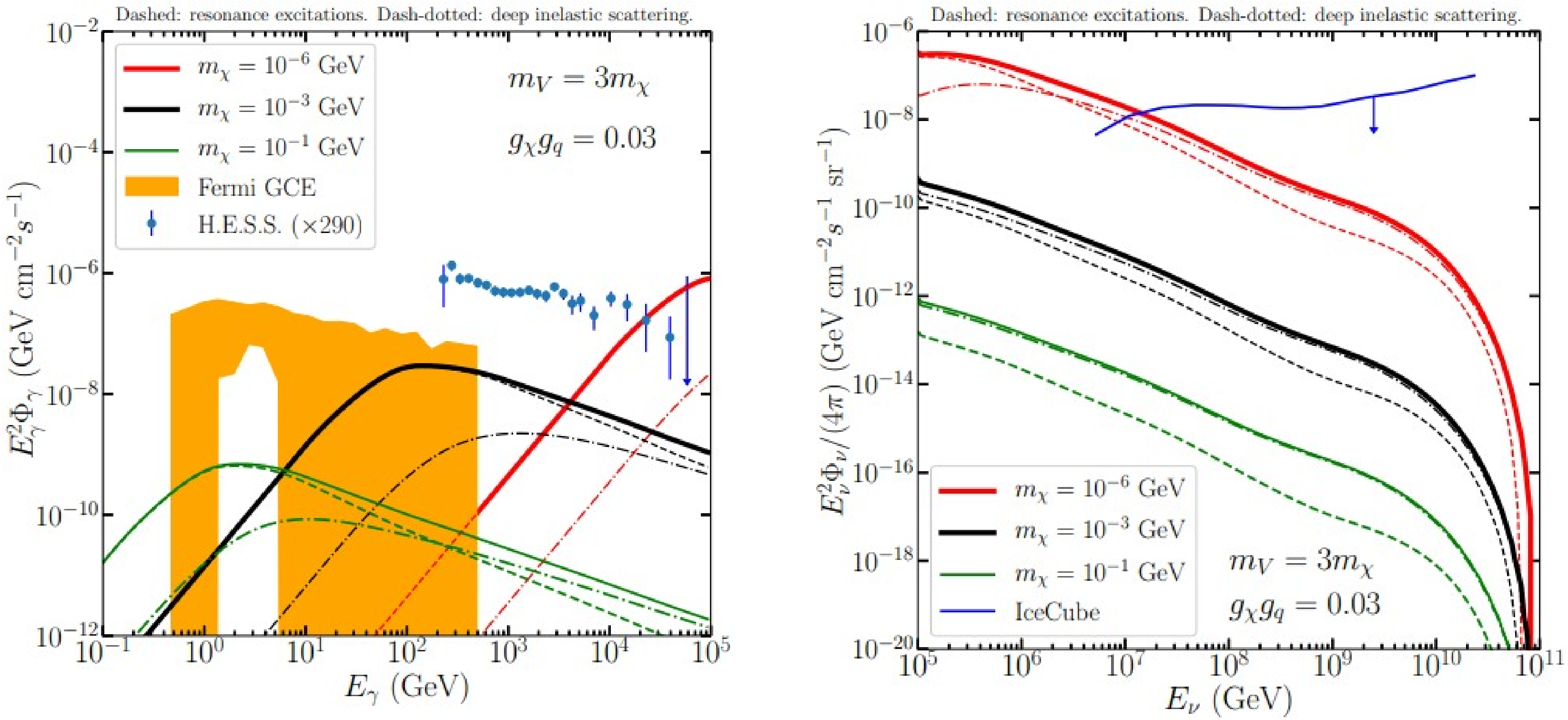
DYB+KamLAND & JUNO: Cappiello+2019
MiniBooNE & Xenon1T: Bringmann+2018

Effects due to inelastic scatterings

The center-of-mass energy of cosmic-ray – DM collision $\simeq m_\chi E_{\rm CR}$ can be much larger than ~ 1 GeV^2

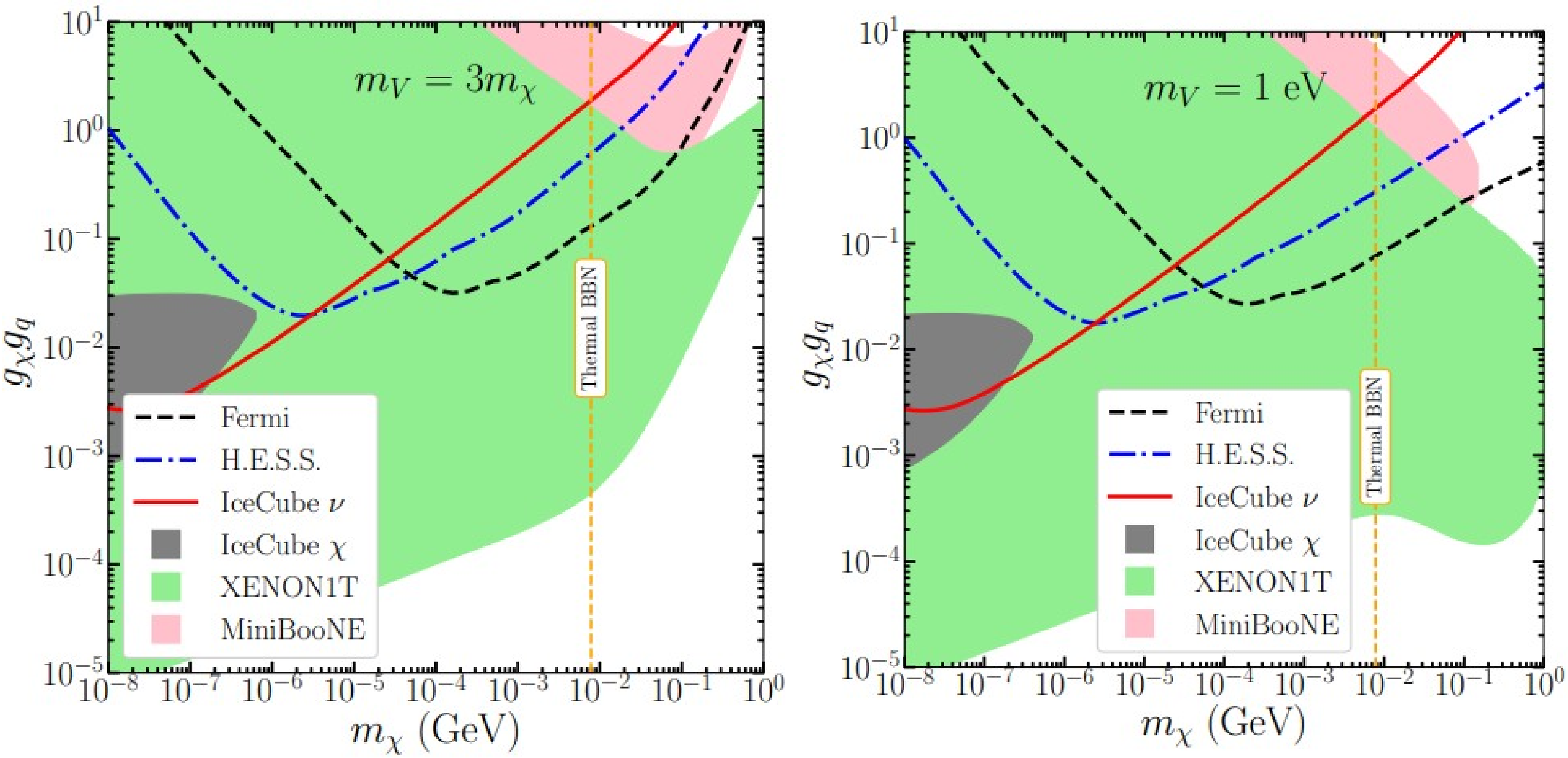
$\rightarrow$ excite nucleons (e.g.,Δ-resonance) or deep-inelastic scatterings to produce secondary γ-rays and neutrinos

For vector portal to baryons: $\mathcal{L} \supset \overline{\chi}(i\partial_\mu\gamma^\mu - m_\chi)\chi + g_\chi\overline{\chi}\gamma^\mu\chi V_\mu + \sum_{f=u,d,s,\ldots} g_{q_f}\overline{q}_f\gamma^\mu q_f V_\mu + \frac{1}{2}m_V^2 V_\mu V^\mu$



[G. Guo, Y.-L. S. Tsai, MRW, Q. Yuan, 2008.12137]

Effects due to inelastic scatterings



[G. Guo, Y.-L. S. Tsai, MRW, Q. Yuan, 2008.12137]

Although cannot compete with bounds set by e.g., XENON1T for most of the parameter space, might still be interesting for other specific type of models

Summary

Take-home message: astrophysics can be used to infer/constrain particle physics properties that complement with terrestial experiments.
Extra cares need to be taken to draw robust conclusions.

– supernova bounds on keV sterile neutrinos are lifted when considering their feedback effect

– bounds on dark photon portal dark matter depends greatly on the self-interacting nature of the dark sector

– detection of the next galactic SN may place strong bounds to eV sterile neutrinos

– the direct and indirect probes of dark matter upscattered by high-energy cosmic-rays with IceCube, Fermi, and H.E.S.S. can provide bounds in addition to low-energy experiments