Supernova Cooling from Neutrino-devouring Dark Matter

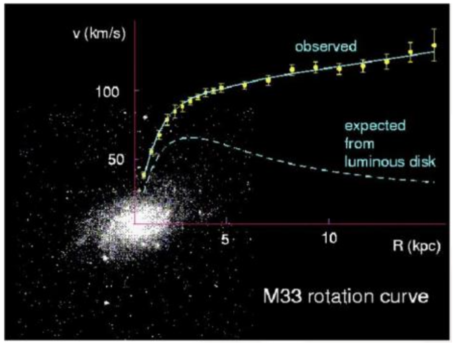
Yugen Lin
（林宇根）
Institute of Theoretical Physics, Chinese Academy of Sciences

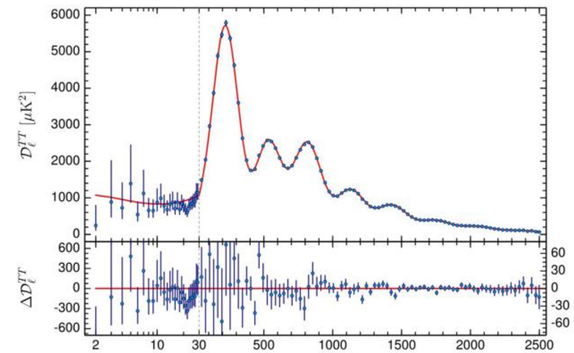
2025.10.26

Collaboration with Chih-Ting Lu and Ningqiang Song

arXiv: 2507.22124

Evidence for Dark Matter

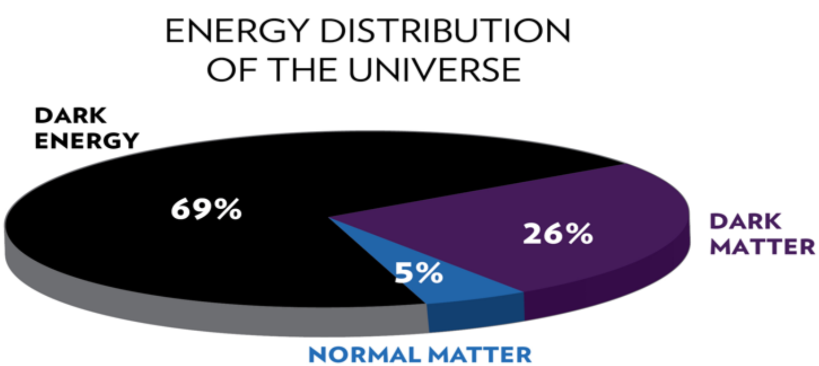




Galaxy Rotation Curve

Bullet Cluster

CMB

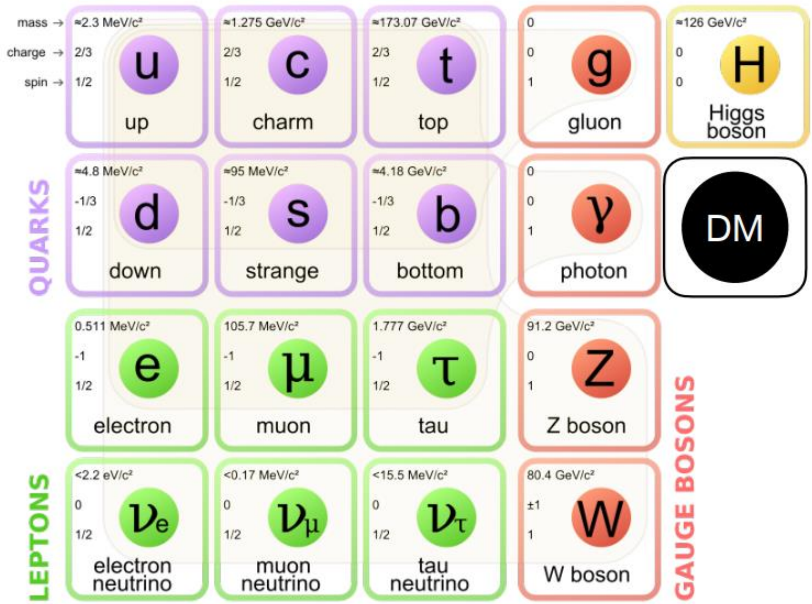


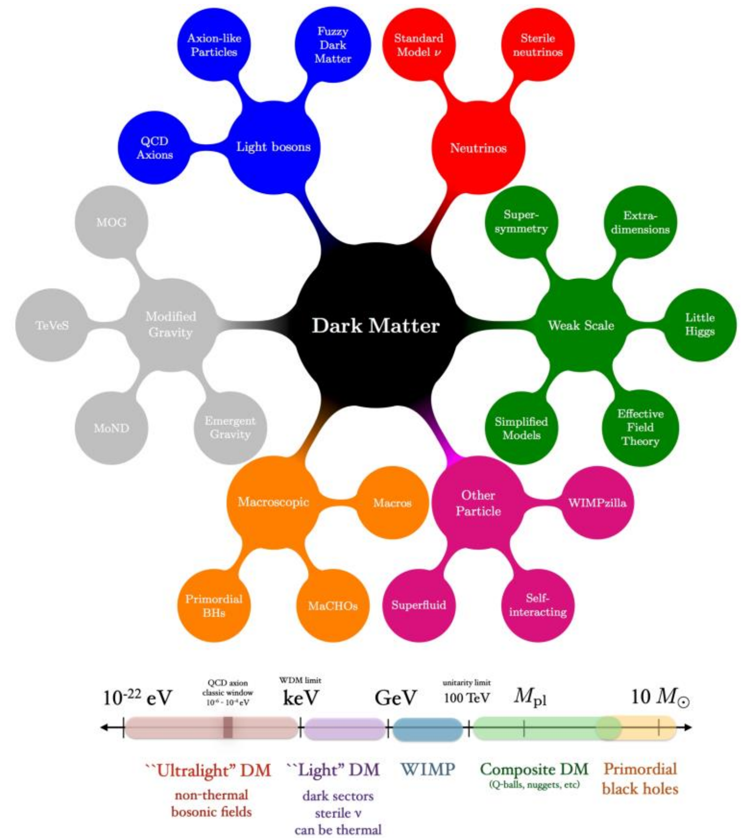
DM: $\Omega_c h^2 = 0.11933 \pm 0.00091$

NM: $\Omega_b h^2 = 0.022242 \pm 0.00014$

DE: $\Omega_\Lambda = 0.6889 \pm 0.0056$

What is Dark Matter ?

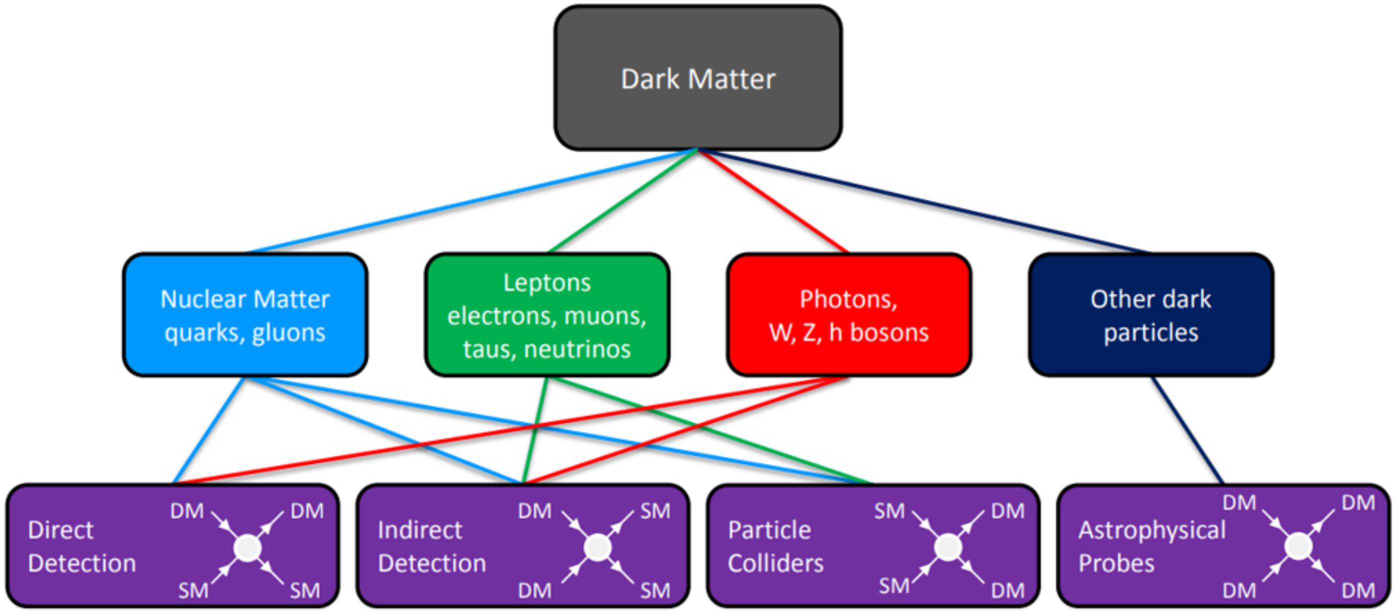


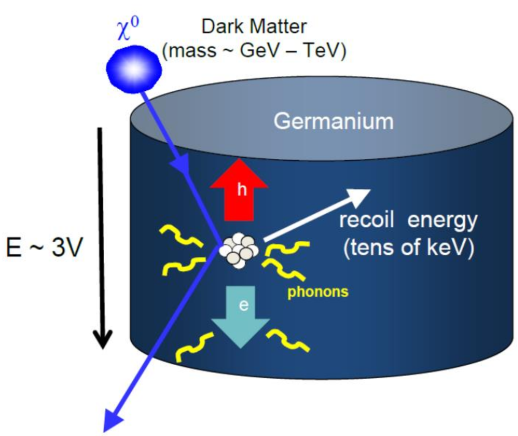


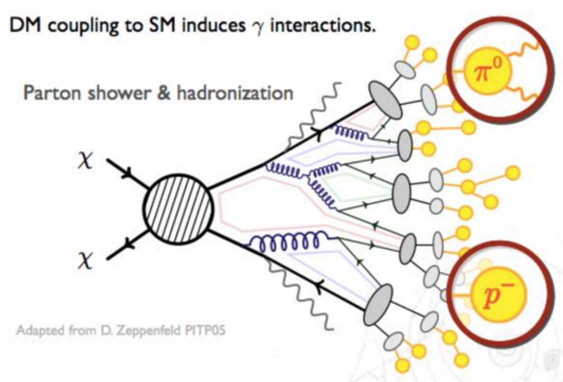
- What do we know about DM at present?
  1. Neutral 2. Non-baryonic 3. Stable 4. Relative-cold

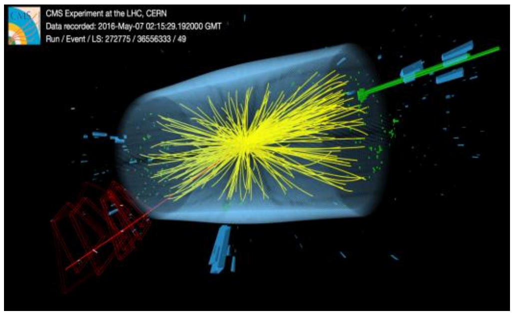
- What do we not know about DM at present?
  1. Mass? 2. Spin? 3. Interaction? …

Ways of Probing DM

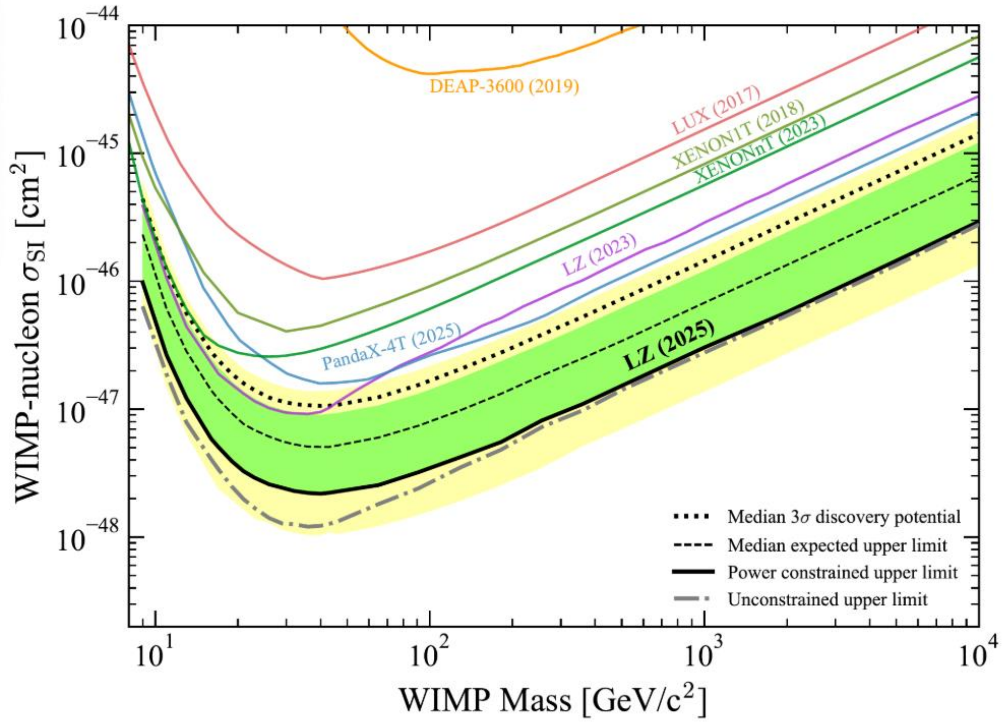








Direct Detection Status



- DM in the GeV-TeV mass scale has been under extensive searches in multi-tonne scale experiments underground by investigating the recoil signals of nucleus down to the energy of *O*(keV) range.

✓ DM searches have pushed the limit on the WIMP-nucleon cross-section near the neutrino floor. The null results of direct detection experiments have sparked the search for lighter DM below the GeV mass scale.

Fermionic Dark Matter

- Particle DM detection strategy

  1. Scattering: depositing kinetic energy, it is difficult to probe light DM.

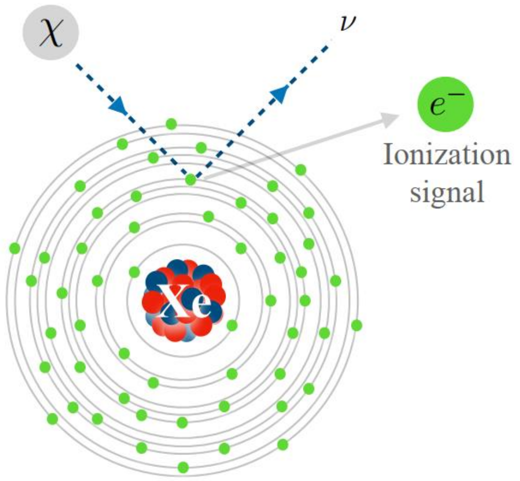
  2. Absorption: depositing mass energy, it is easy to overcome the threshold.

- Fermionic DM model

  1. Scalar-type: $O_S = \frac{1}{\Lambda^2}(\bar{\chi} P_L \nu)(\bar{e} e)$

  2. Vector-type: $O_V = \frac{1}{\Lambda^2}(\bar{\chi} \gamma^\mu P_L \nu)(\bar{e} \gamma_\mu e)$

  3. Tensor-type: $O_T = \frac{1}{\Lambda^2}(\bar{\chi} \sigma^{\mu\nu} P_L \nu)(\bar{e} \sigma_{\mu\nu} e)$



- Direct detection signal

  1.Ionized electron, it can be searched in photoelectron signatures.

  2.Neutrino, missing energy.

UV Completion

- Scalar interaction:

$$\mathcal{L} \supset y_{ee}\varphi\bar{e}e + y_{\chi\nu}\varphi\bar{\chi}P_L\nu + \text{h.c.}$$

ϕ is a heavy scalar field.

Integrating out the scalar field, we can obtain

$$O_S = \frac{1}{\Lambda^2}(\bar{\chi}P_L\nu)(\bar{e}e)\,, \quad \frac{1}{\Lambda^2} \equiv \frac{y_{\chi\nu}y_{ee}}{m_\varphi^2}\,.$$

- Vector interaction:

$$\mathcal{L} \supset g_e\bar{e}\gamma_\mu eA'^\mu + g_\chi\bar{\chi}\gamma_\mu\chi A'^\mu\,,$$

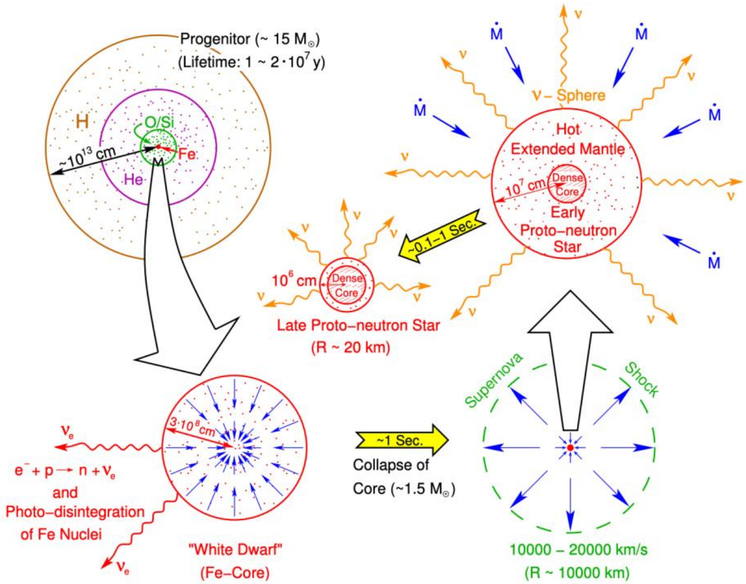
A' is a new gauge boson.

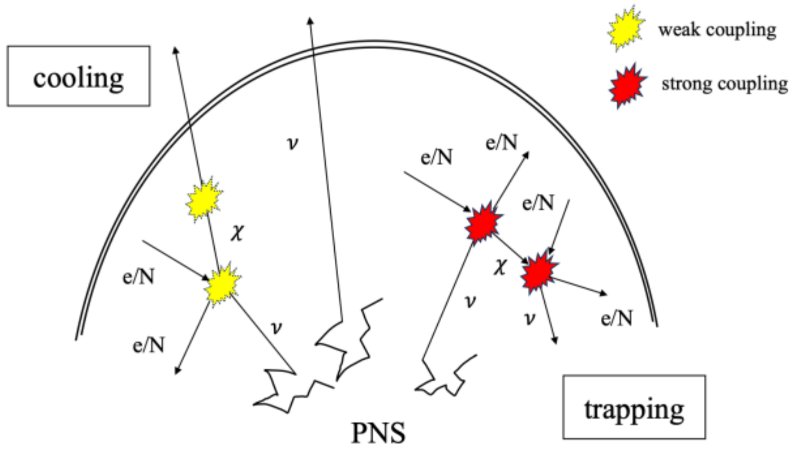
Integrating out A', $\mathcal{L} \supset \frac{g_e g_\chi}{m_{A'}^2}\bar{e}\gamma^\mu e\bar{\chi}\gamma_\mu\chi.$

$$\mathcal{L}_{\text{mass}} \supset m_\chi\bar{\chi}\chi + (y\phi\bar{\chi}P_L\nu + \text{h.c.}) = \begin{pmatrix}\bar{\nu} & \bar{\chi}\end{pmatrix}\begin{pmatrix}0 & 0 \\ y\langle\phi\rangle & m_\chi\end{pmatrix}P_L\begin{pmatrix}\nu \\ \chi\end{pmatrix} + \text{ h.c.}$$

$$O_V = \frac{1}{\Lambda^2}(\bar{\chi}\gamma^\mu P_L\nu)(\bar{e}\gamma_\mu e)\,, \quad 1/\Lambda^2 \equiv g_e g_\chi s_\theta c_\theta/m_{A'}^2, \quad s_\theta = y\langle\phi\rangle/\sqrt{y^2\langle\phi\rangle^2 + m_\chi^2}$$

Supernova Explosion





✓ Core-collapse SN can reach core temperatures in excess of 30 MeV, which makes them an ideal astrophysical source for sub-GeV dark matter.

✓ Raffelt criterion: The luminosity carried by the new particles must be smaller than the luminosity carried by neutrinos.

DM Production

- ✓ Considering the supernova core temperature, the process $\nu e^- \rightarrow \chi e^-$ can effectively produce dark matter $M_\chi \lesssim 100$ MeV.

- ✓ The differential number of fermionic DM particle produced via the effective DM-neutrino interaction per unit time *t* at position *r* is

$$\frac{1}{4\pi r^2}\frac{\partial^2}{\partial r \partial t}\left(\frac{d\mathcal{N}_\chi}{dE_\chi}\right) = \sigma_{\nu e} n_e \frac{dn_\nu}{dE_\nu}$$

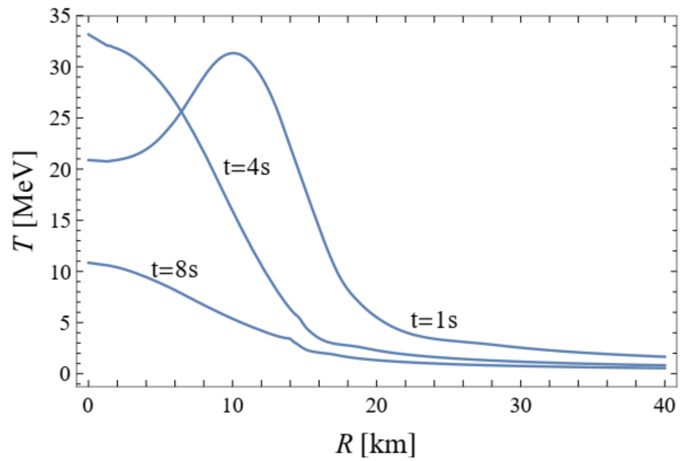
$$dn_\nu/dE_\nu = n_\nu f_\nu(E_\nu)/\bar{E}_\nu \qquad f_\nu = \frac{(1+\alpha)^{(1+\alpha)}}{\Gamma(1+\alpha)}\left(\frac{E_\nu}{\bar{E}_\nu}\right)^\alpha \mathrm{Exp}\left[-(1+\alpha)\frac{E_\nu}{\bar{E}_\nu}\right]$$

$$\frac{d\mathcal{N}_\chi}{dE_\chi} = \int_0^R 4\pi R'^2 dR' \int_0^t dt' \frac{(1+\alpha(t',R'))^{(1+\alpha(t',R'))}}{\Gamma(1+\alpha(t',R'))\,\bar{E}(t',R')} \left[\frac{E}{\bar{E}(t',R')}\right]^{\alpha(t',R')} \mathrm{Exp}\left[-(1+\alpha(t',R'))\frac{E}{\bar{E}(t',R')}\right] n_\nu(t',R')\,\sigma(\Lambda, M_\chi, T(t',R'), E)\, n_e(t',R').$$

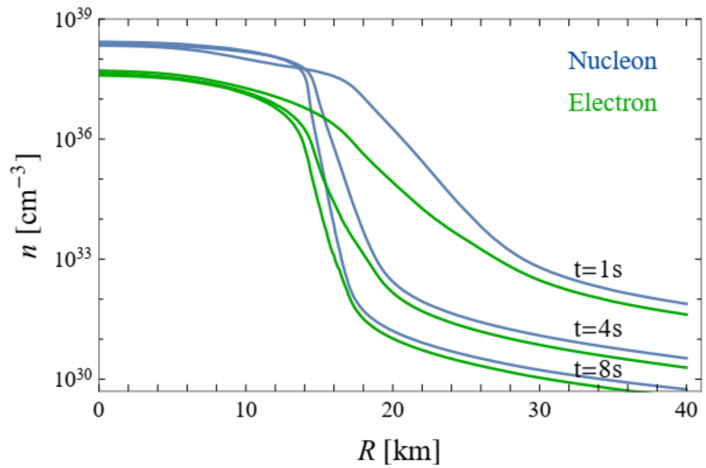
- ✓ Solving the above equation using data associated to the simulation performed by the Garching group of an $8.8 M_\odot$ progenitor star.

Supernova Simulation Data

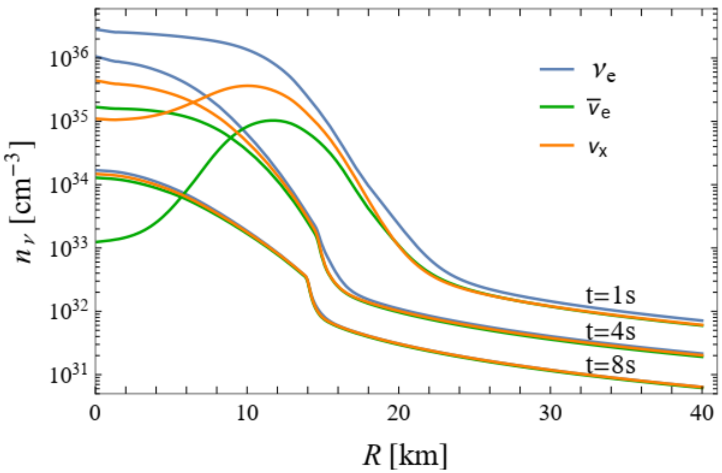
SN temperature



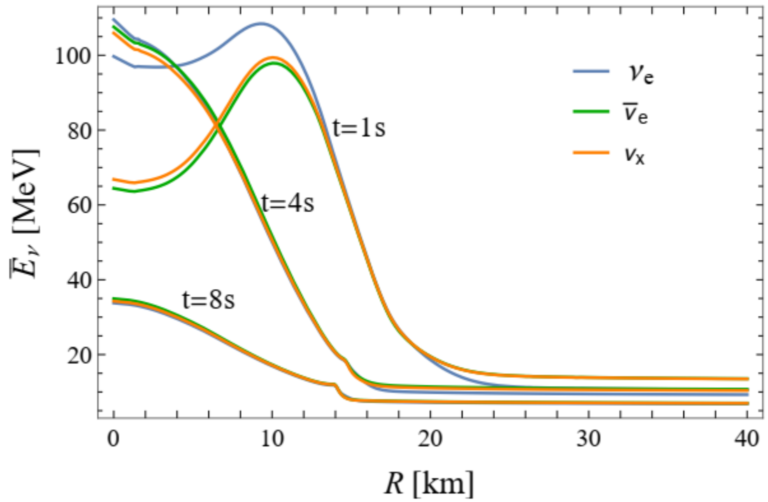
e/N number density



Neutrino number density

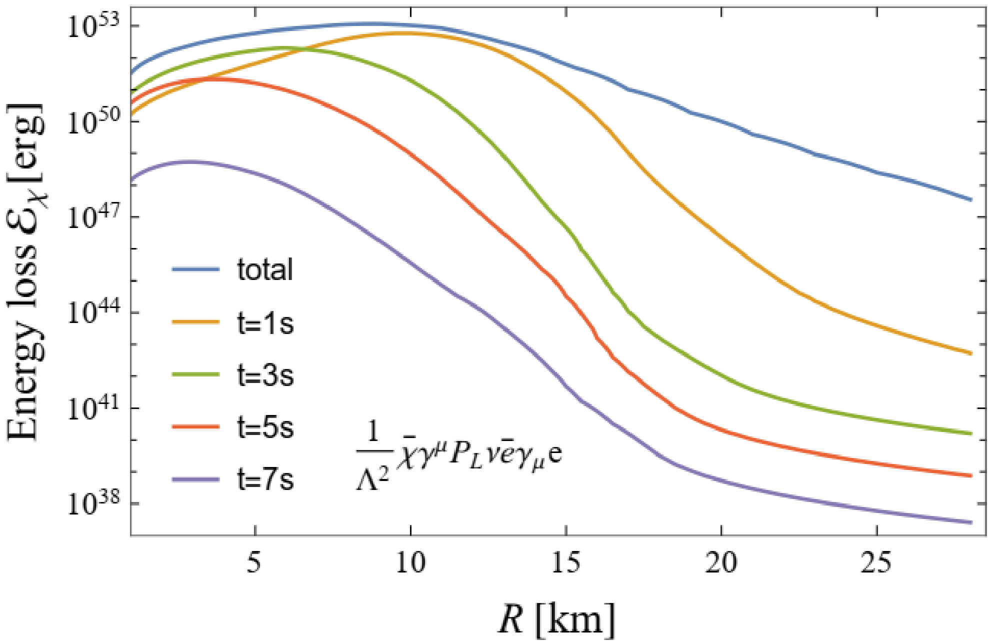


Neutrino mean energy



Supernova Energy Loss

$$\frac{d\mathcal{N}_\chi}{dE_\chi} = \int_0^R 4\pi R'^2 dR' \int_0^t dt' \frac{dn_\nu(t',R')}{dE_\nu} \times \sigma_{\nu e}\left(\Lambda, M_\chi, T\left(t',R'\right), E_\nu\right) n_e\left(t',R'\right)$$



- Parameter choice: M_χ= 1 MeV, $\Lambda^{-1} = 10^{-7}\mathrm{MeV}^{-1}$.
- The position of maximum energy loss: $R \sim 10$ km.

Supernova energy loss from DM production in 1 km wide spherical shells and 1 s time slides as a function of radius.

DM Propagation

- ✓ If $1/\Lambda^2$ is too large, the produced DM particle may further scatter with the electron or nucleon to convert back to a neutrino.

- ✓ The survival probability of DM from back-conversion

$$P(t,r) = \mathrm{Exp}\left(-\int_r^{\infty} \frac{\mathrm{d}r'}{\lambda(t,r')}\right)$$

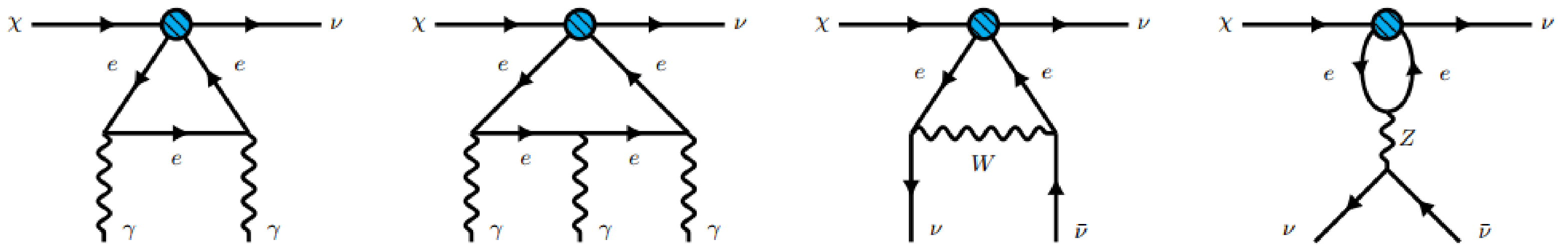
  - $\lambda(t,r)$ is the mean free path of DM, $\lambda_{\chi e}(r) = (n_e \sigma_{\chi e \to \nu e})^{-1}$
  - The energy of DM produced at (*t*, *R*): $\bar{E}_\chi = \int \frac{d\mathcal{N}_\chi}{dE_\chi} E_\chi dE_\chi / \int \frac{d\mathcal{N}_\chi}{dE_\chi} dE_\chi$

- ✓ The two approximation for the calculation of the free path $\lambda(t,r)$

  - In the first approach, we fix the time variable and evaluate λ at $t = 1$ s.
  - In the second approach, we fix the radius and evaluate λ at $r = 10$ km.

Fermionic DM Decay

$$O_S = \frac{1}{\Lambda^2}(\bar{\chi}P_L\nu)(\bar{e}e) \qquad O_V = \frac{1}{\Lambda^2}(\bar{\chi}\gamma^\mu P_L\nu)(\bar{e}\gamma_\mu e)$$



- Scalar-type: the leading decay is $\chi \to \nu\gamma\gamma$

$$\Gamma_{\nu\gamma\gamma} \simeq 10^{-26}\mathrm{sec}^{-1}\left(\frac{m_\chi}{20\ \mathrm{keV}}\right)^7\left(\frac{\mathrm{TeV}}{\Lambda}\right)^4$$

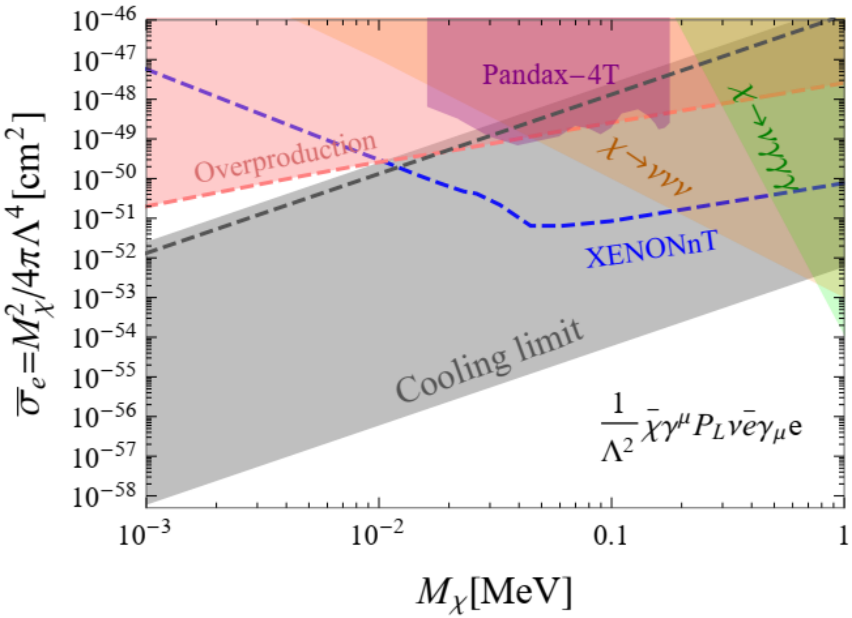
- Vector-type: the leading decay is $\chi \to \nu\gamma\gamma\gamma$ and $\chi \to \nu\nu\nu$

$$\Gamma_{\nu\gamma\gamma\gamma} \simeq 10^{-26}\mathrm{sec}^{-1}\left(\frac{m_\chi}{320\ \mathrm{keV}}\right)^{13}\left(\frac{\mathrm{TeV}}{\Lambda}\right)^4$$

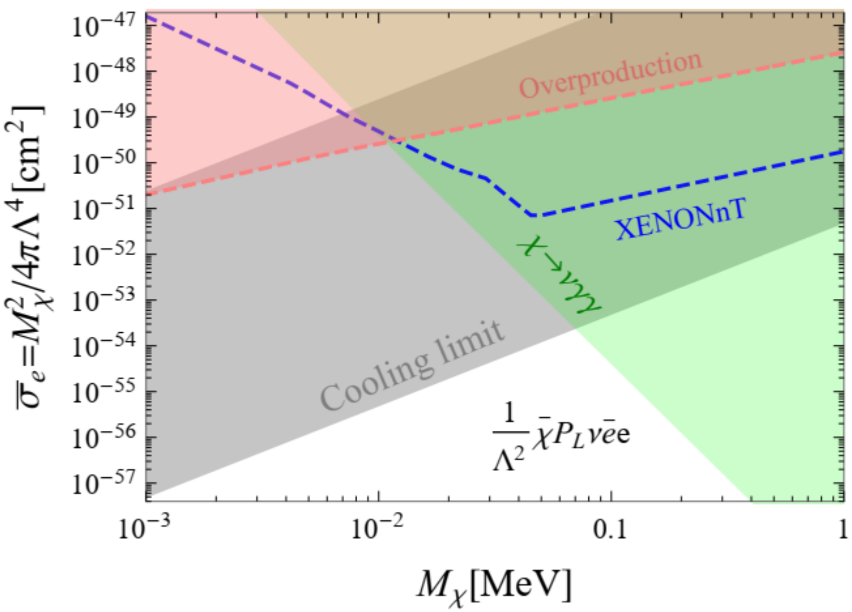
$$\Gamma_{\nu\nu\nu} \simeq 10^{-17}\mathrm{sec}^{-1}\left(\frac{m_\chi}{200\ \mathrm{keV}}\right)^5\left(\frac{\mathrm{TeV}}{\Lambda}\right)^4$$

Cooling Limits

Vector-type operator



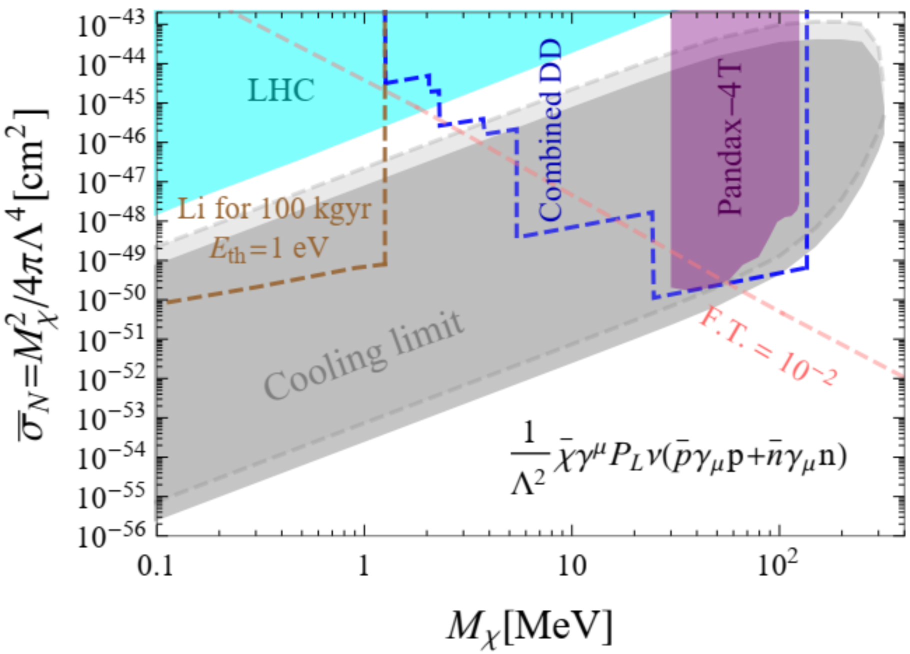
Scalar-type operator



- ✓ The cooling limits have strong complementarity with constraints from DM decay, cosmology, astrophysics, and direct detection experiments.
- ✓ Supernova cooling sets stringent constraints on FDM, which span by about seven orders of magnitude in the cross section. It rules out the cross sections as low as $10^{-51} - 10^{-58}\ \mathrm{cm}^2$ in the keV–MeV mass range.

Cooling Limits

$\nu N \to \chi N$



- ✓ We also do the similar analysis for neutrino-nucleon scattering process.
- ✓ For DM coupling to nucleons, supernova cooling rules out $10^{-49} - 10^{-56}$ cm^2 in the 0.1 – 100 MeV mass range.
- ✓ The supernova limits do not require the new particles to be cosmological DM, which can be extended to arbitrarily small masses of new particles.

Summary

- The direct detection null results have sparked the search of lighter DM with masses below the GeV scale.
- Core-collapse SN is an ideal astrophysical source for sub-GeV particles, which can set unique constraints on the existence of new, low-mass particles that are weakly-coupled to the SM.
- We exclude the cross sections down to $10^{-51} - 10^{-58}\ \mathrm{cm}^2$ in the keV-MeV mass range for DM-electron scattering, and $10^{-49} - 10^{-56}\ \mathrm{cm}^2$ in the 0.1-100 MeV mass range for DM-nucleon scattering.
- SN cooling limits are complementary with the constraints from cosmology, astrophysics, LHC and direct detection experiments, which can also be scaled and extended to arbitrarily small masses of new particles.