Indirect Dark Matter Searches in JUNO

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IHEP

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JUNO中微子天文和天体物理学研讨会　南京大学

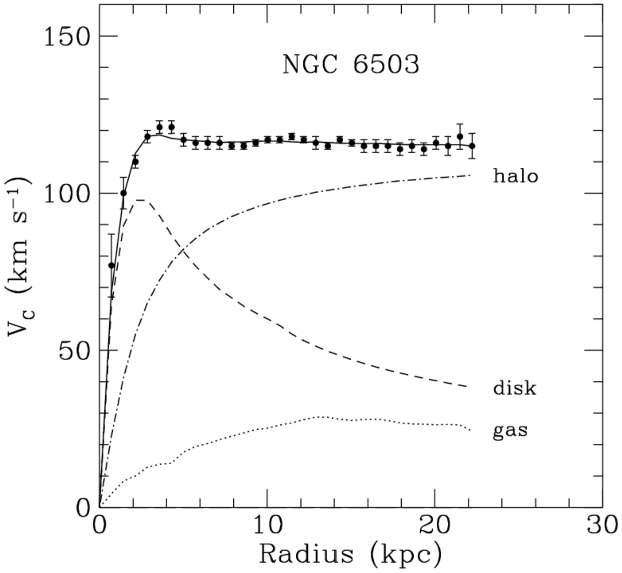
Outline

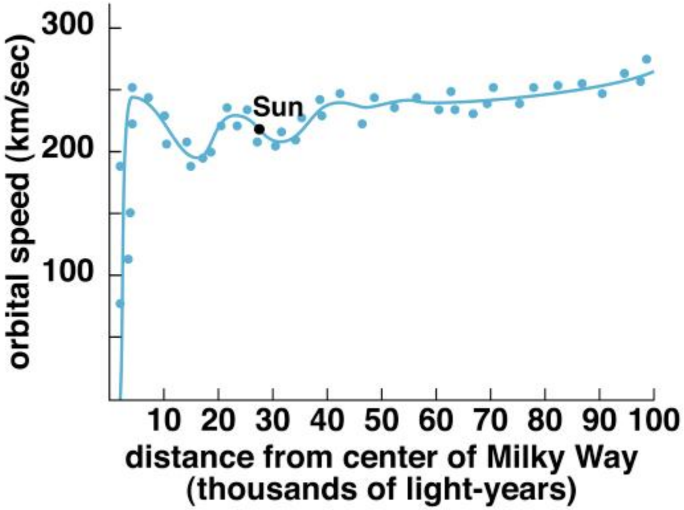
- **Evidences for dark matter**
- **Neutrinos from Solar dark matter annihilation**
- **JUNO performances**
  - ☐ **Detecting $\nu_e/\bar{\nu}_e$** **[W.L. Guo, JCAP 01 (2016) 039); 1511.04888]**
  - ☐ **Detecting $\nu_\mu/\bar{\nu}_\mu$** **[G.L. Lin *et al*, JUNO Yellow Book; 1507.05613]**
- **Summary**

(1) Evidence for Dark matter

Evidence 1： Galactic scale

Since 1975, Vera Rubin started to notice FLAT rotation curves in spiral galaxies.





(c)

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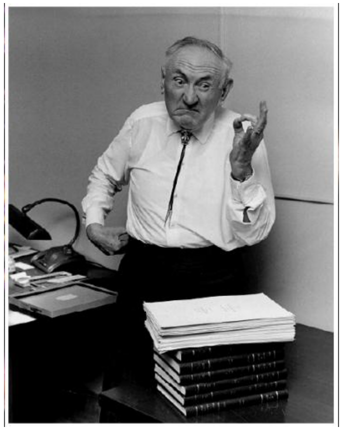
Newtonian dynamics:

$$v(r)=\sqrt{\frac{G\times M(r)}{r}} \Rightarrow v(r)\propto \frac{1}{\sqrt{r}}$$

$$M(r)\propto r$$

Evidence 2： Galaxy cluster scale

(1) : Measure the velocity of galaxies in clusters

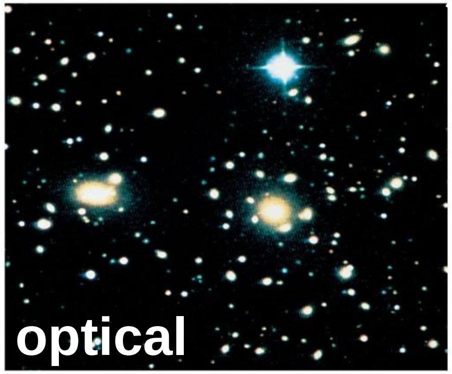


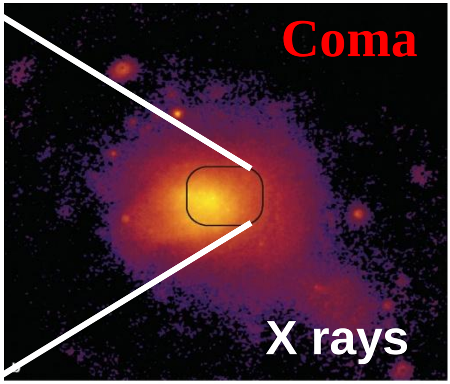
The first indication for dark matter is made by Fritz Zwicky in 1933.

(2) : The X–rays trace the hot gas

$$kT \approx (1.3 - 1.8)\,\mathrm{keV}\left(\frac{M_r}{10^{14}\,M_\odot}\right)\left(\frac{1\,\mathrm{Mpc}}{r}\right)$$

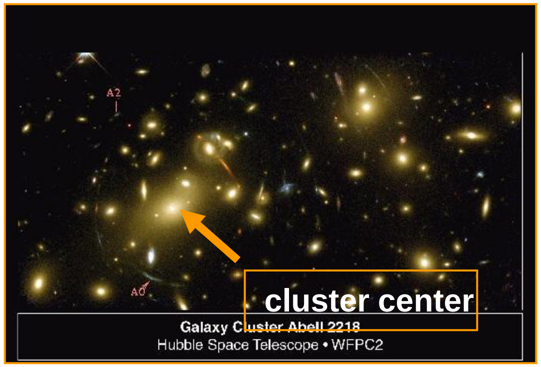
The observed temperature $T \approx 10$ keV



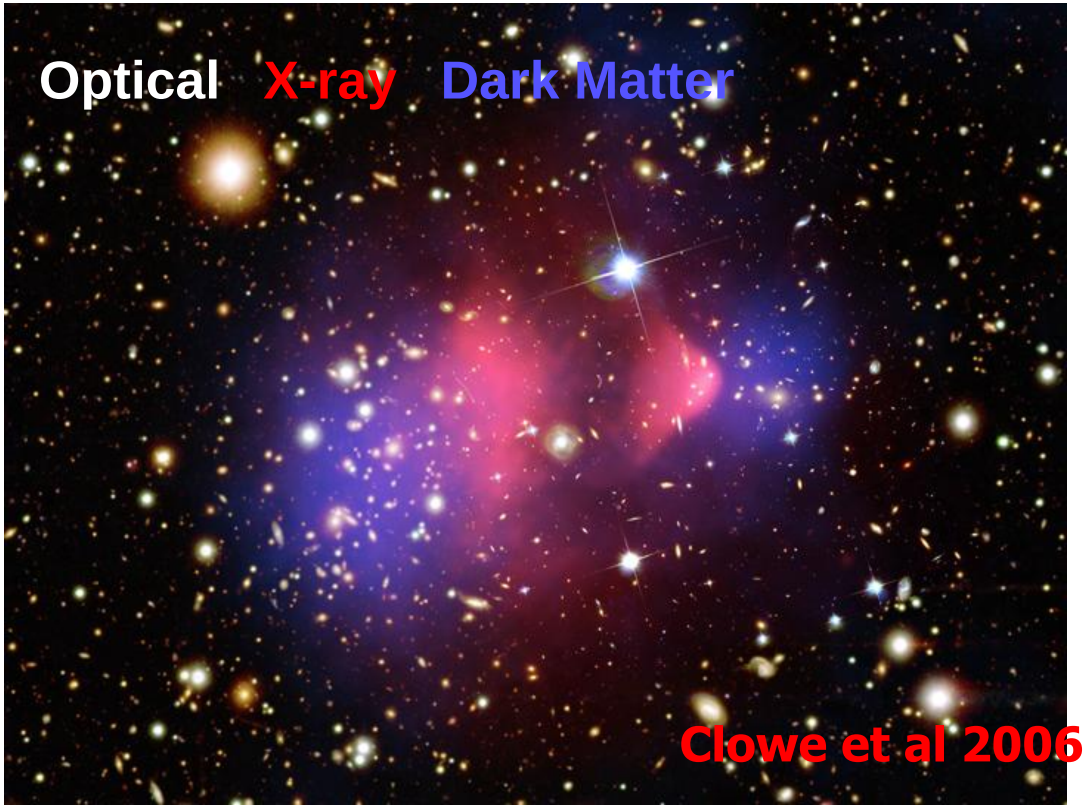


(3) : The gravitational lensing

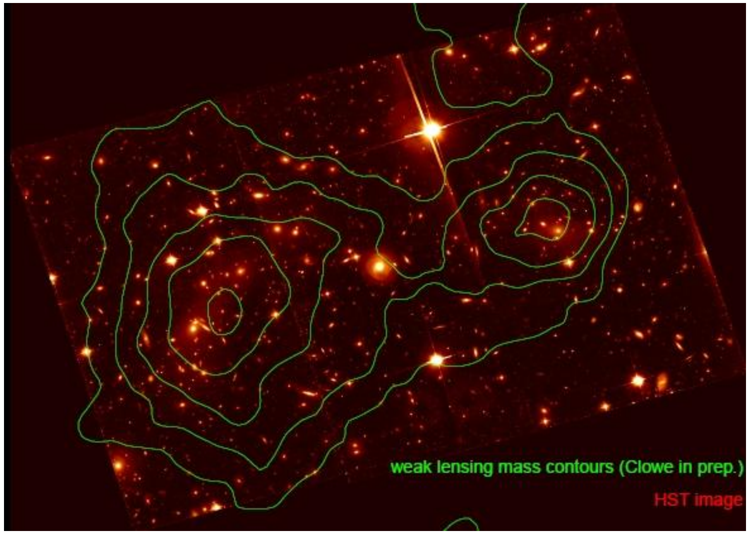
- **Strong lensing**
- **Weak lensing**
- **Microlensing**

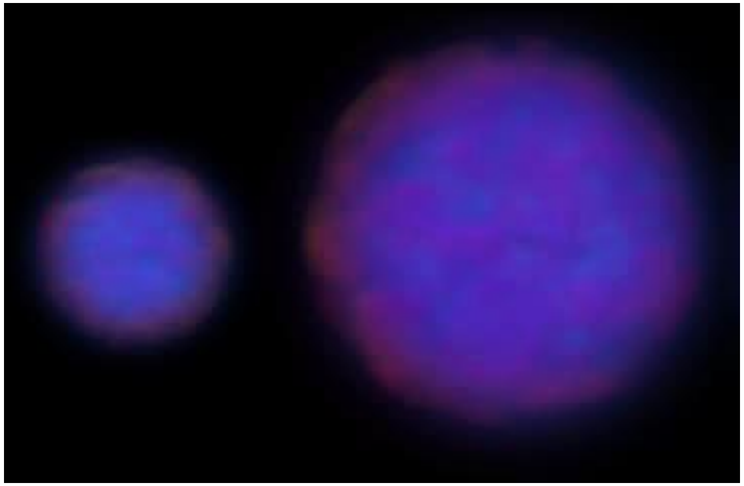


The Bullet Cluster



Clowe et al 2006





Dark Matter coincides with galaxies

Both (nearly) collisionless

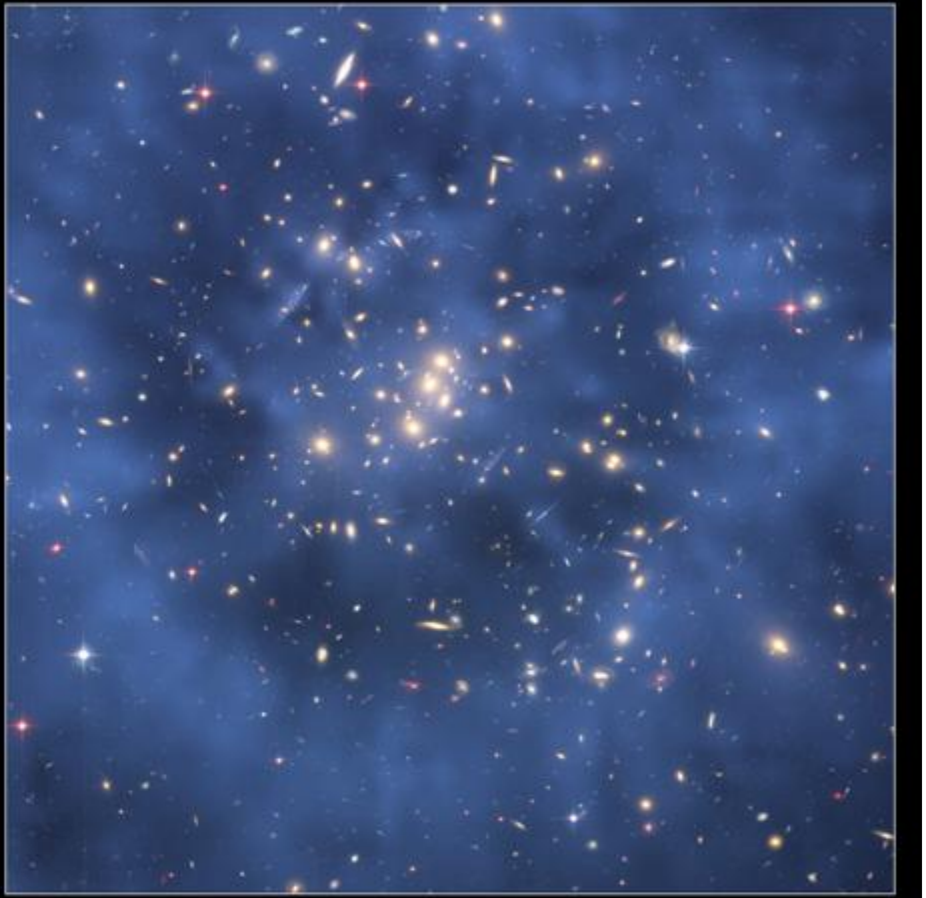
Gas separated from Dark Matter

Inelastic collision

Dark Matter Ring

Galaxy Cluster Cl 0024+17 (ZwCl 0024+1652)
Hubble Space Telescope • ACS/WFC

NASA, ESA, and M.J. Jee (Johns Hopkins University) STScI-PRC07-17b

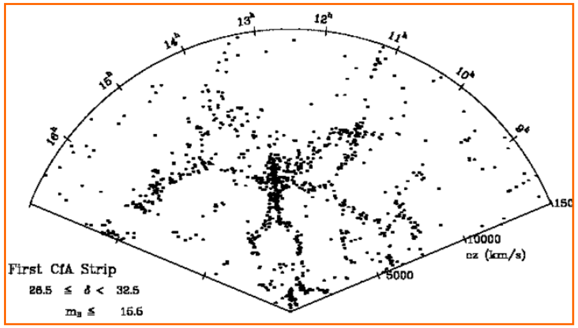


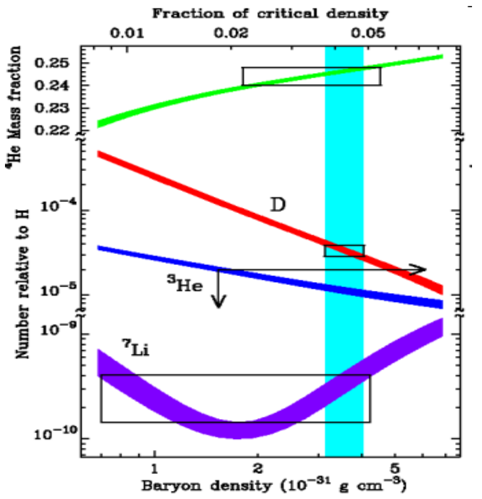
Dark Matter Ring in Galaxy Cluster Cl 0024+17 (ZwCl 0024+1652)
Hubble Space Telescope • ACS/WFC

NASA, ESA, and M.J. Jee (Johns Hopkins University) STScI-PRC07-17a

Evidence 3： Cosmological scale

(1) : Large scale structure





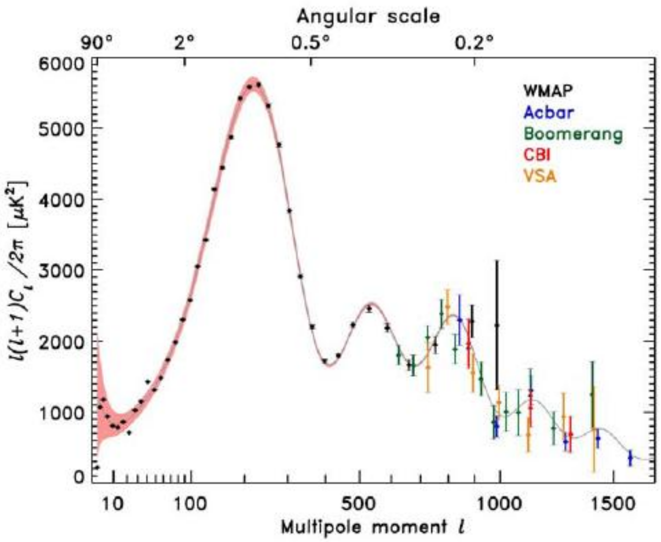
Density fluctutation about 10^{-3}

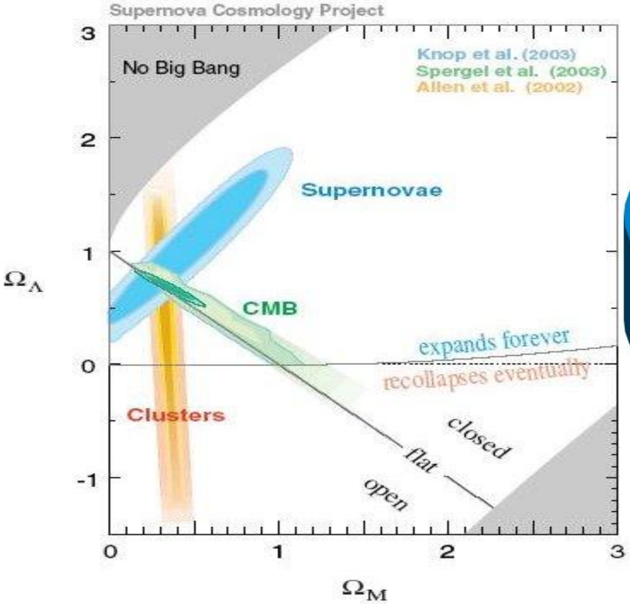
The observed value is about 10^{-5}

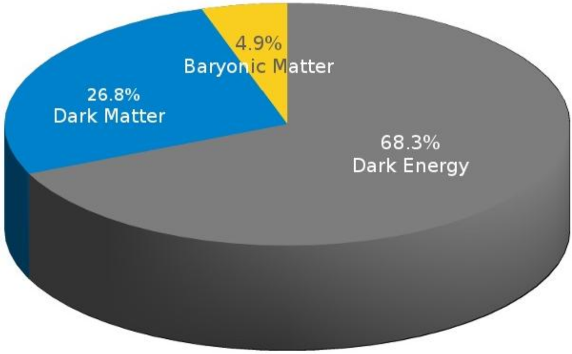
$$\Omega_M h^2 = 0.135^{+0.008}_{-0.009}, \Omega_b h^2 = 0.0224 \pm 0.0009$$

BBN indicates $0.018 < \Omega_b h^2 < 0.023$

(2) : CMB



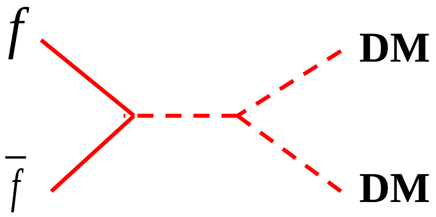




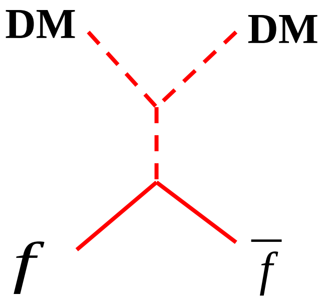
Current results: $\Omega_\Lambda h^2 = 0.3182(69.3\%); \Omega_{DM} h^2 = 0.1186(25.8\%); \Omega_b h^2 = 0.02226(4.9\%)$ **Planck**

Dark matter searches

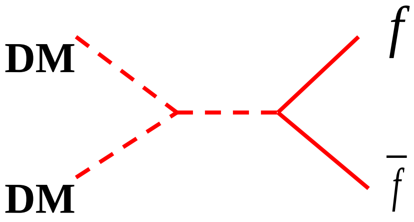
(1) Collider search:

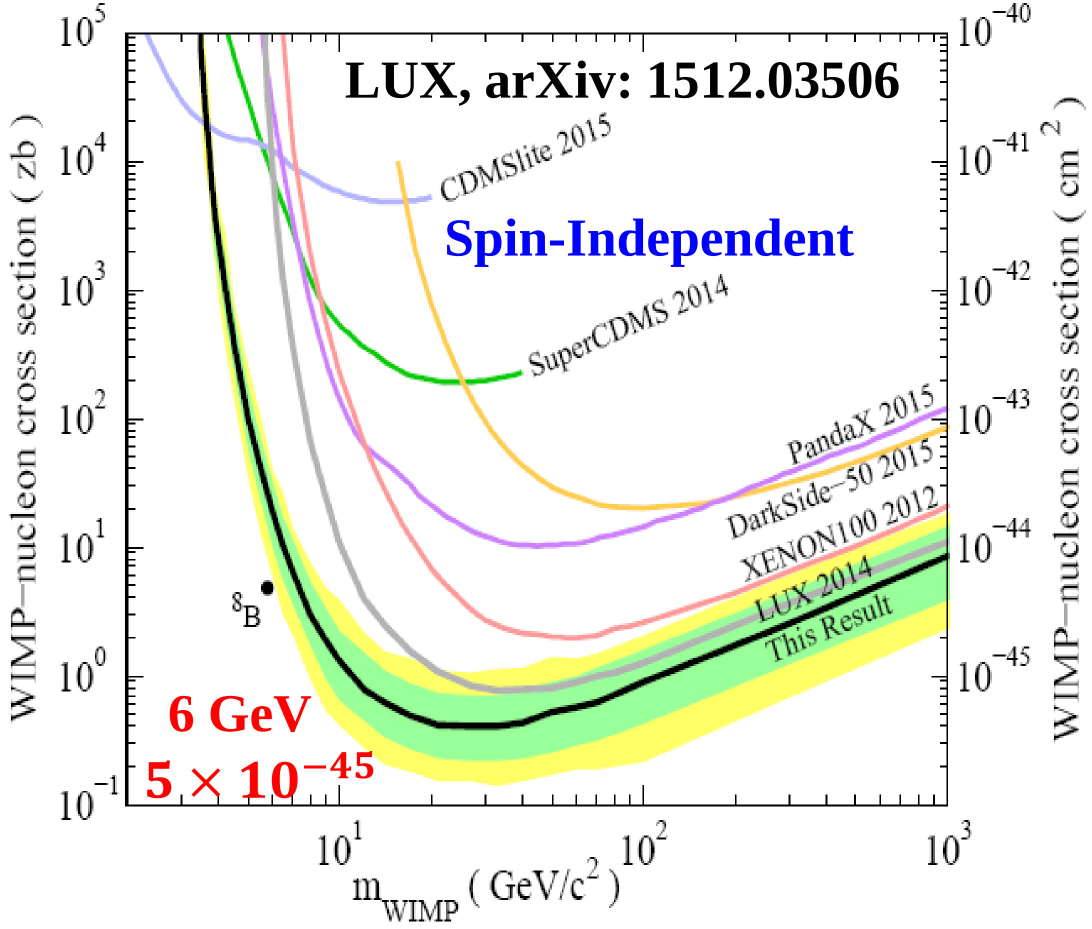


(2) Direct search:



(3) Indirect search:




LUX, arXiv: 1512.03506

Spin-Independent

6 GeV

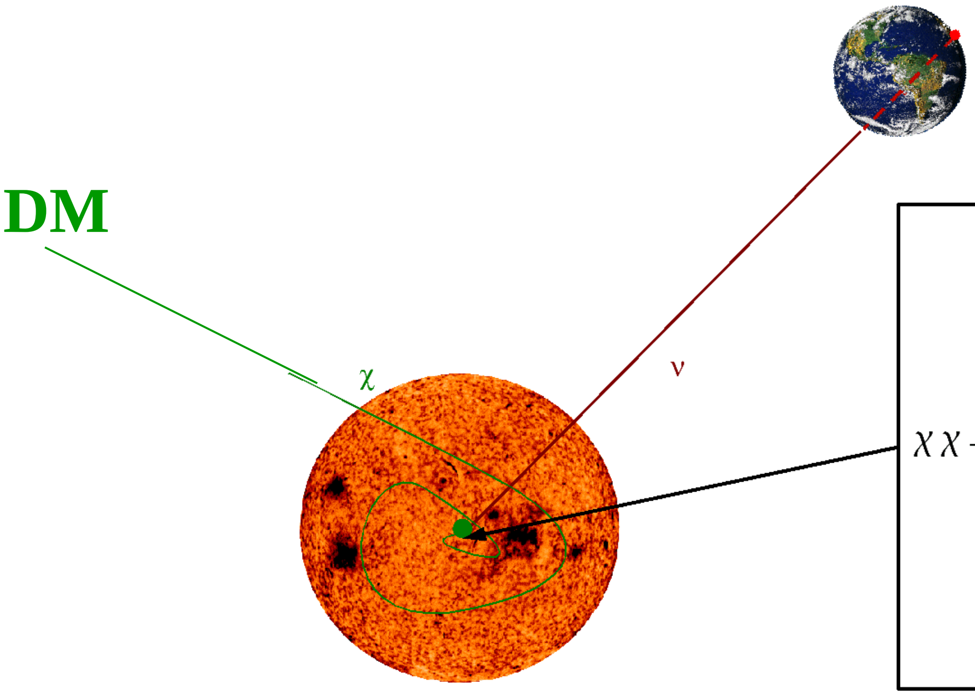
5×10^{-45}

Annihilation productions:

Gamma rays, Neutrinos, electrons, Positrons
Protons and antiprotons etc.

(2) Neutrinos from Solar dark matter annihilation

DM captured and annihilation in the Sun:



neutrino-

JUNO

$\nu_e/\overline{\nu}_e$

$\nu_\mu/\overline{\nu}_\mu$

$$\chi\chi \to \begin{bmatrix} \nu\bar{\nu} \\ b\bar{b} \\ t\bar{t} \\ \tau^-\tau^+ \\ W^-W^+ \\ Z^0Z^0 \\ Higgs + \text{other particles} \end{bmatrix} \to \nu + \bar{\nu} + \text{other particles}$$

DM elastic scattering $\propto \sigma_{Ni}$ ⇨ **DM is captured** $v_{DM} < v_{esc}$ ⇨ **Thermalization and Accumulated in core**

⇨ **Annihilation** $\propto N^2$

DM evolution in the Sun

Evolution function:

$$\boxed{\dot{N} = C_\odot - C_A N^2}$$

$$C_A = \frac{\enclose{circle}{\langle \sigma v \rangle}}{V_{\rm eff}} \, ,$$

$$V_{\rm eff} = 5.8 \times 10^{30}\ {\rm cm}^3 \left(\frac{1\,{\rm GeV}}{m_D} \right)^{3/2}$$

Annihilation rate:

$$\Gamma_A = \frac{1}{2} C_A N^2 = \enclose{ellipse}{\frac{1}{2} C_\odot} \tanh^2 \underline{\left(t_\odot \sqrt{C_\odot C_A} \right)}$$

> > 1 → Equilibrium

Capture rate:

$$C_\odot^{\rm SI} \approx 4.8 \times 10^{24} {\rm s}^{-1} \frac{\rho_0}{0.3\,{\rm GeV}/{\rm cm}^3} \frac{270\,{\rm km/s}}{\bar{v}} \frac{1\,{\rm GeV}}{m_D} \sum_i F_i(m_D) \frac{\enclose{circle}{\sigma_{N_i}^{\rm SI}}}{10^{-40}\,{\rm cm}^2} f_i \phi_i S \left(\frac{m_D}{m_{N_i}} \right) \frac{1\,{\rm GeV}}{m_{N_i}} \, , \tag{2.3}$$

$$C_\odot^{\rm SD} \approx 1.3 \times 10^{25} {\rm s}^{-1} \frac{\rho_0}{0.3\,{\rm GeV}/{\rm cm}^3} \frac{270\,{\rm km/s}}{\bar{v}} \frac{1\,{\rm GeV}}{m_D} \frac{\enclose{circle}{\sigma_p^{\rm SD}}}{10^{-40}\,{\rm cm}^2} S \left(\frac{m_D}{m_p} \right) \, , \tag{2.4}$$

G. Jungman, M. Kamionkowski, K. Griest, Phys. Rept. 267, 195 (1996)

DM capture and annihilation equilibrium

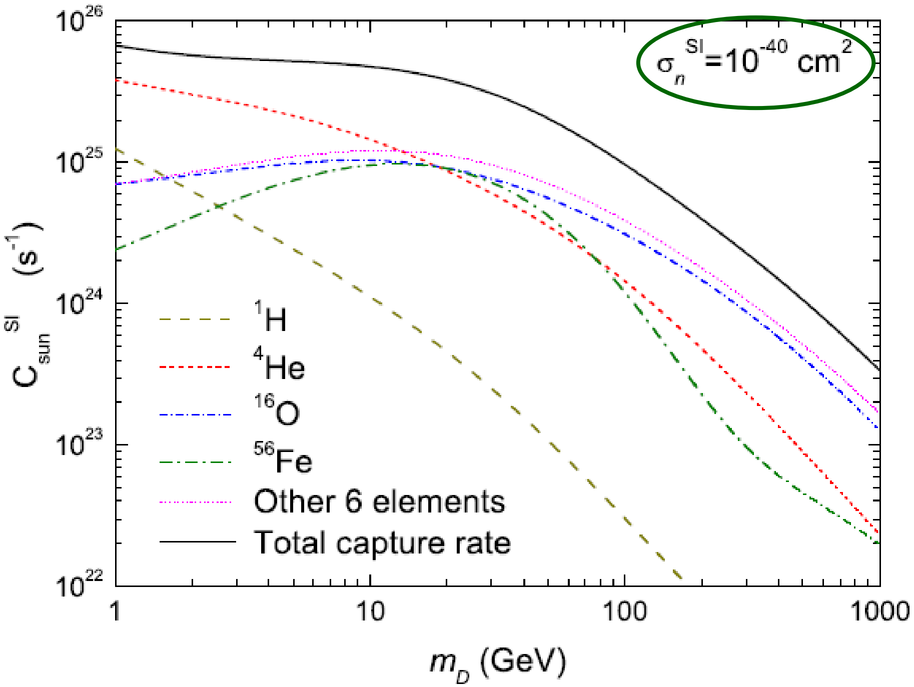
Equilibrium Condition:

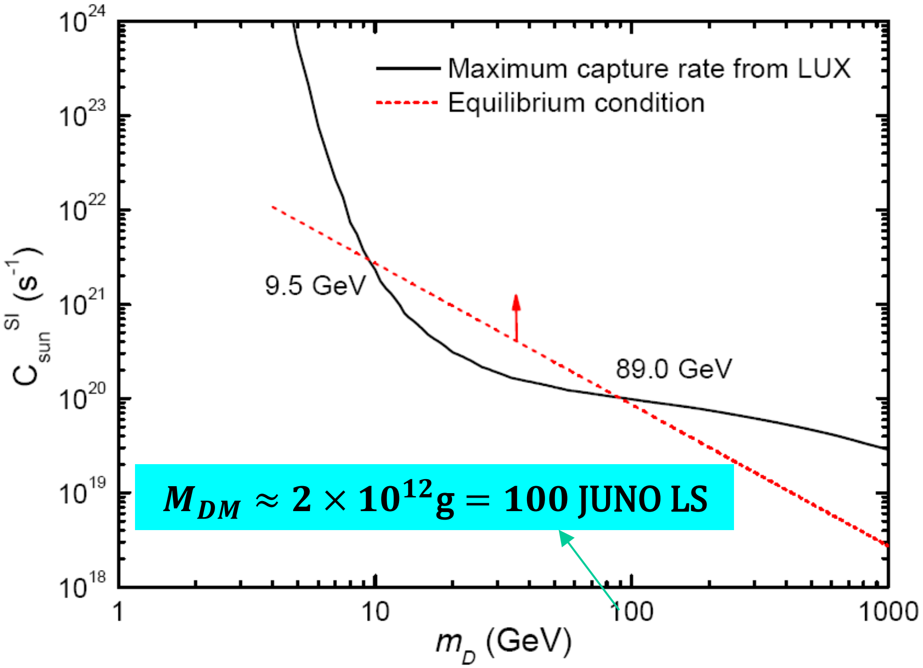
$$t_\odot\sqrt{C_\odot C_A} \geq 3.0 \;\Rightarrow\; \tanh^2\left[t_\odot\sqrt{C_\odot C_A}\right] \geq 0.99$$

$$\left.\begin{aligned}\langle\sigma v\rangle &\approx 3\times10^{-26}\,\mathrm{cm^3\,s^{-1}}\\ t_\odot &\simeq 4.5\ \mathrm{Gyr}\end{aligned}\right\} \quad \boxed{C_\odot \geq 8.6\times10^{22}/(m_D/1\mathrm{GeV})^{3/2}\mathrm{s}^{-1}}$$

Spin-Independent (SI) capture rates:

LUX, arXiv: 1512.03506





$M_{DM} \approx 2\times10^{12}\mathrm{g} = 100$ **JUNO LS**

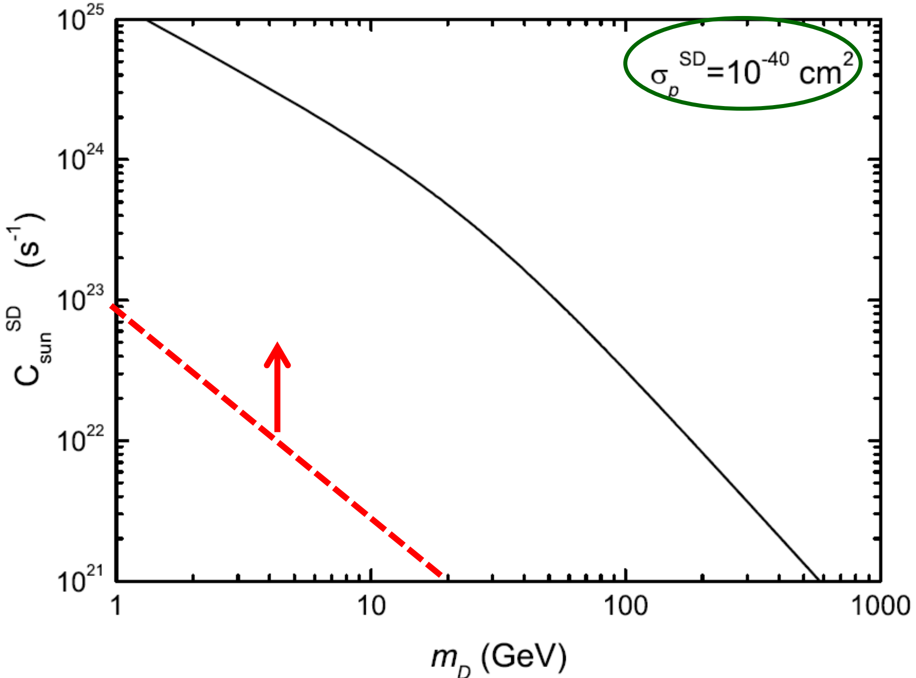
DM capture and annihilation equilibrium

Equilibrium Condition:

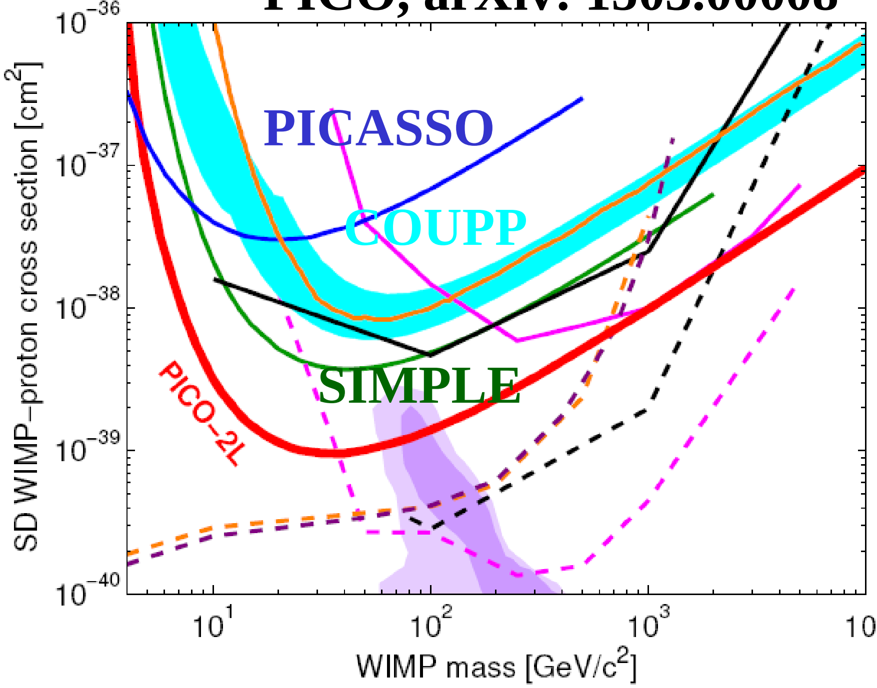
$$t_\odot \sqrt{C_\odot C_A} \geq 3.0 \quad \Rightarrow \quad \tanh^2[t_\odot \sqrt{C_\odot C_A}] \geq 0.99$$

$$\left.\begin{array}{l} \langle\sigma v\rangle \approx 3\times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1} \\ t_\odot \simeq 4.5\ \mathrm{Gyr} \end{array}\right\} \quad \boxed{C_\odot \geq 8.6\times 10^{22}/(m_D/1\mathrm{GeV})^{3/2}\mathrm{s}^{-1}}$$

Spin-Dependent (SD) capture rates:



PICO, arXiv: 1503.00008



Neutrino fluxes from solar DM annihilation

Neutrino Fluxes:

$$\boxed{\frac{d\Phi_{\nu_e}}{dE_\nu} = \frac{\Gamma_A}{4\pi R_{\mathrm{ES}}^2}\frac{dN_{\nu_e}}{dE_\nu} \simeq \frac{C_\odot}{8\pi R_{\mathrm{ES}}^2}\frac{dN_{\nu_e}}{dE_\nu}}$$

$R_{\mathrm{ES}} = 1.496 \times 10^{13}\ \mathrm{cm}$ is the Earth-Sun distance

Differential neutrino energy spectrum:

- **Final states interactions**
  Hadronization, interactions, decay
- **Neutrino interactions**
- **Neutrino oscillations**

WimpSim

Blennow, Edsjo, Ohlsson, arXiv: 0709.3898

Input parameters:

$\frac{1}{3}\nu_e, \frac{1}{3}\nu_\mu, \frac{1}{3}\nu_\tau$

Annihilation Channels: $\chi\chi \to \boxed{\nu\bar{\nu},} \tau^+\tau^-, b\bar{b}$

Monoenergetic

Continuous

Dark matter mass: $4\ \mathrm{GeV} \le m_D \le 20\ \mathrm{GeV}$

Oscillation parameters:

$\sin^2\theta_{12} = 0.308,\quad \sin^2\theta_{23} = 0.437,\quad \sin^2\theta_{13} = 0.0234,$

$\Delta m_{21}^2 = 7.54 \times 10^{-5}\mathrm{eV}^2,\quad \Delta m_{31}^2 = 2.47 \times 10^{-3}\mathrm{eV}^2,\quad \delta = 0^\circ.$

(3) Neutrino signals in JUNO

The expected $\nu_e/\bar{\nu}_e$ numbers:

W.L. Guo, JCAP 01 (2016) 039

arXiv:1511.04888

$$N_S = N_n\, t \int_{E_{th}}^{m_D} \left[\frac{d\Phi_{\nu_e}}{dE_\nu}\sigma_{\nu_e} + \frac{d\Phi_{\bar{\nu}_e}}{dE_\nu}\sigma_{\bar{\nu}_e}\right] \epsilon(E_\nu)\, dE_\nu$$

$N_n \simeq 20\,\mathrm{kton}/m_n$

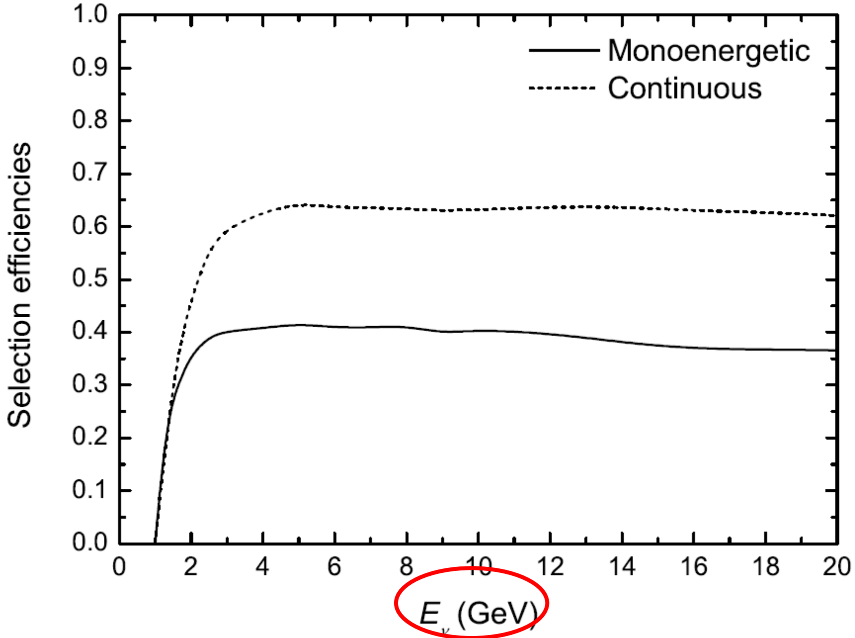
$t = 10$ years

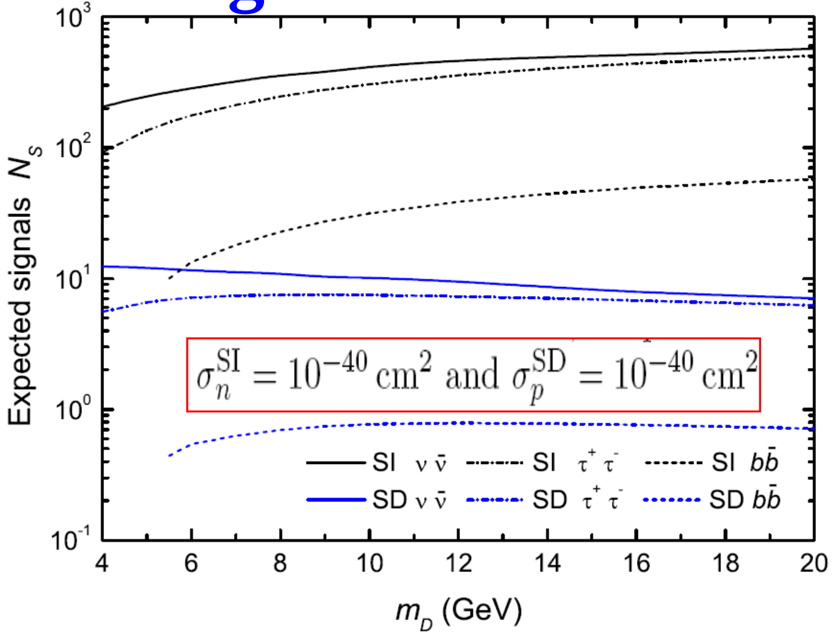
Selection conditions (MC and 10° $e^{\pm}$ angular resolution):

$\nu\bar{\nu}$: $Y_{vis} < 0.5$, $Ee_{vis} > 1$ GeV, $\theta < 20^{\circ}\sqrt{10/E_\nu}$, $E_{vis}/E_\nu > 0.9$, $E_{th} = 0.9E_\nu$

$b\bar{b}, \tau^+\tau^-$: $Y_{vis} < 0.5$, $Ee_{vis} > 1$ GeV, $\theta < 30^{\circ}$, $1 < E_{vis} < E_\nu$, $E_{th} = 1$GeV

Selection efficiencies and Expected signals:





Atmospheric neutrino background

CC backgrounds： All direction → Average → Cone

$\nu\bar{\nu}$: $Y_{vis} < 0.5$, $Ee_{vis} > 1$ GeV, $E_{vis}/m_D > 0.9$

$b\bar{b}, \tau^+\tau^-$: $Y_{vis} < 0.5$, $Ee_{vis} > 1$ GeV, $1 < E_{vis} < m_D$

NC backgrounds: Neglect!

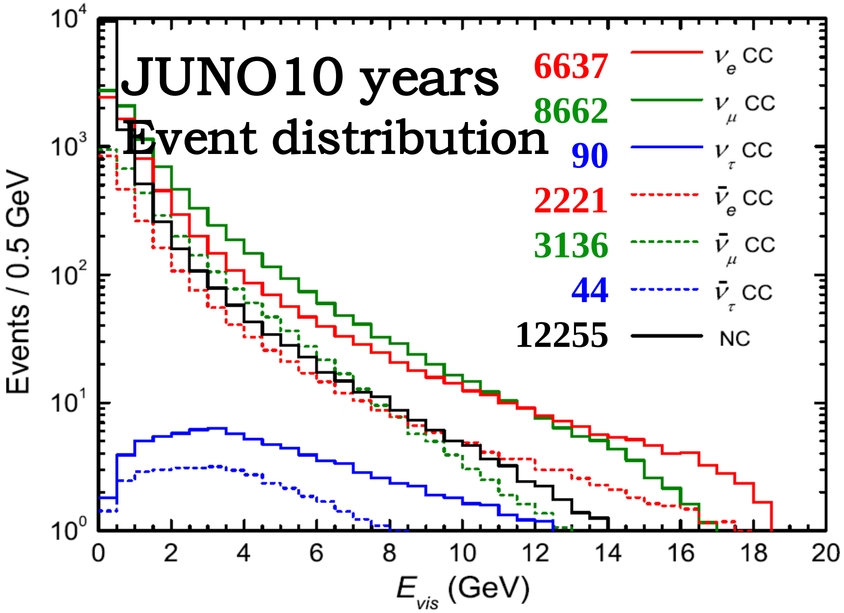
½ CC, Several hadrons, Misidentification rate

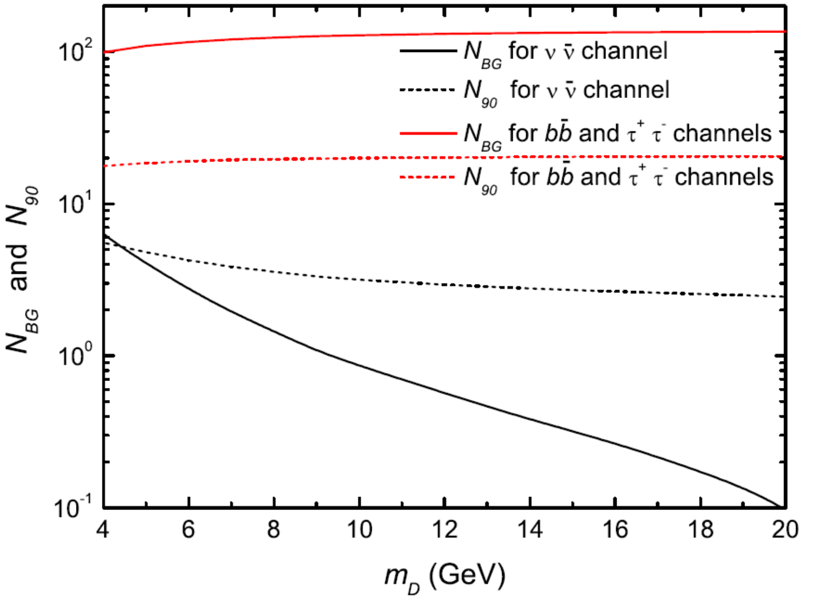
JUNO sensitivities:

$$\boxed{90\% = \frac{\int_{N_S=0}^{N_{90}} L(N_{\rm obs}|N_S)dN_S}{\int_{N_S=0}^{\infty} L(N_{\rm obs}|N_S)dN_S}}$$

$$L(N_{\rm obs}|N_S) = \frac{(N_S+N_{\rm BG})^{N_{\rm obs}}}{N_{\rm obs}!}e^{-(N_S+N_{\rm BG})}$$

$$N_{\rm obs} = N_{\rm BG}$$





$\nu_\mu/\bar{\nu}_\mu$ Neutrino signals in JUNO

The expected $\nu_\mu/\bar{\nu}_\mu$ event numbers:

**G.L. Lin *et al*,
JUNO Yellow Book;
1507.05613**

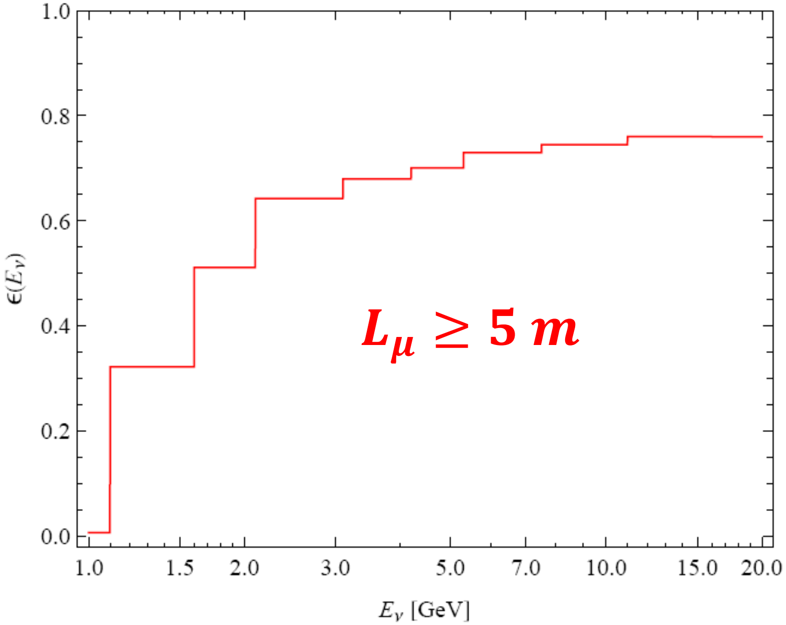
$$N_{\rm DM} = \int_{E_{\rm th}}^{m_\chi} \frac{{\rm d}\Phi_\nu^{\rm DM}}{{\rm d}E_\nu} A_\nu(E_\nu)\,{\rm d}E_\nu\,{\rm d}\Omega\,,$$

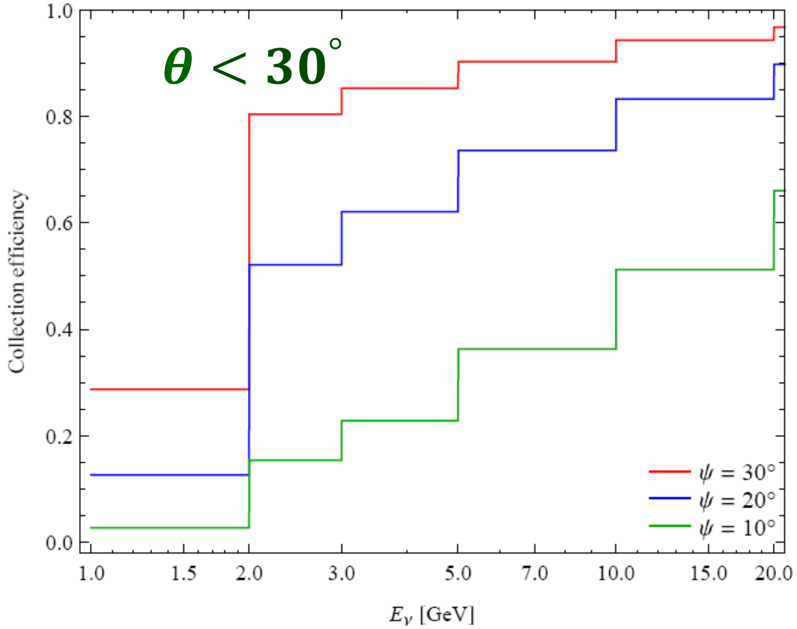
$$A_\nu(E_\nu) = M_{\rm LS}\left(\frac{N_A}{m}\right)[n_p\sigma_{\nu p}(E_\nu) + n_n\sigma_{\nu n}(E_\nu)]\epsilon(E_\nu)\,,$$

Selection conditions (MC and 1° $\mu^\pm$ angular resolution):

$\nu\,\bar{\nu}, \tau^+\tau^-$: $L_\mu \geq 5\,m$, $\theta < 30^\circ$, $E_{th} = 1\,\mathrm{GeV}$

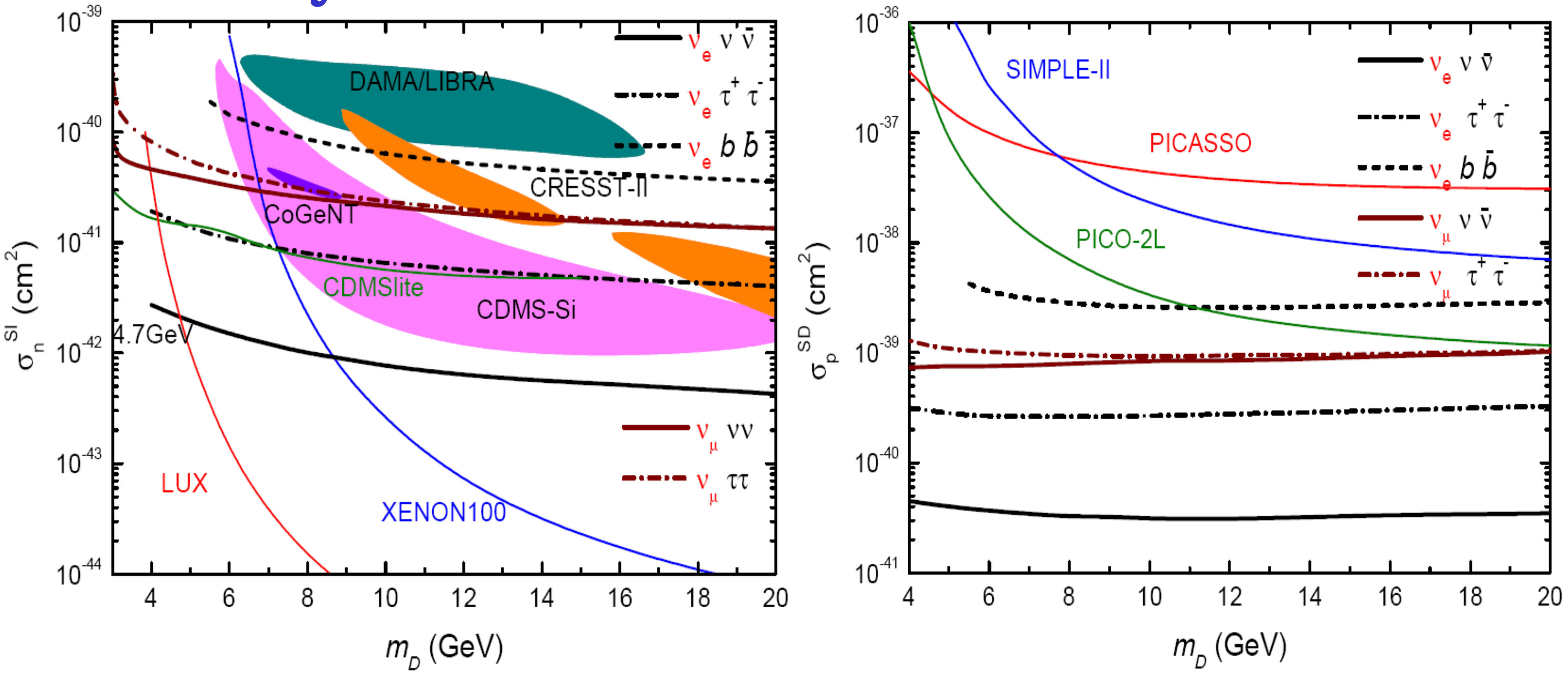
Selection efficiencies :





JUNO sensitivity from $\nu_e/\bar{\nu}_e$ and $\nu_\mu/\bar{\nu}_\mu$

JUNO 10 years sensitivities:



Summary:

- For the SD case, JUNO can give better limits than the DM direct searches
- For the SI case, a very narrow region in $\nu\,\bar{\nu}$ channel can give better limits

Thanks !