Probing neutrino-DM interactions at neutrino detectors

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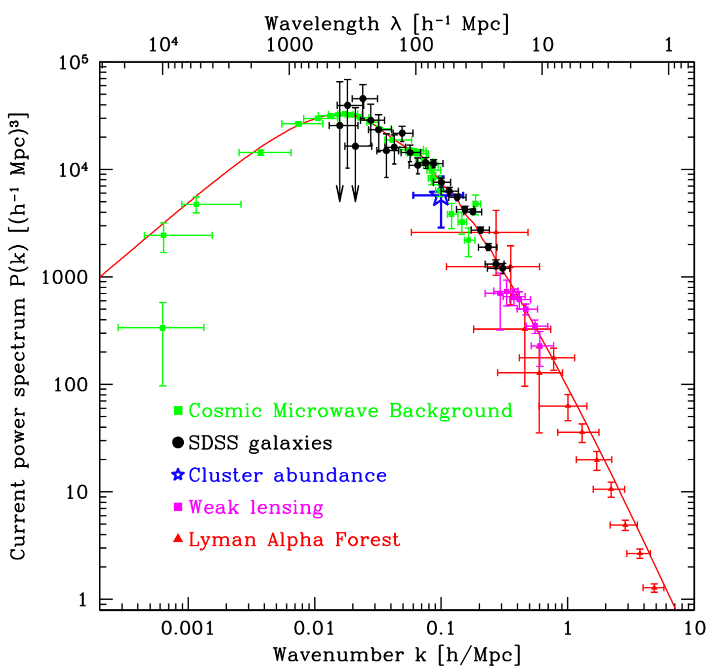
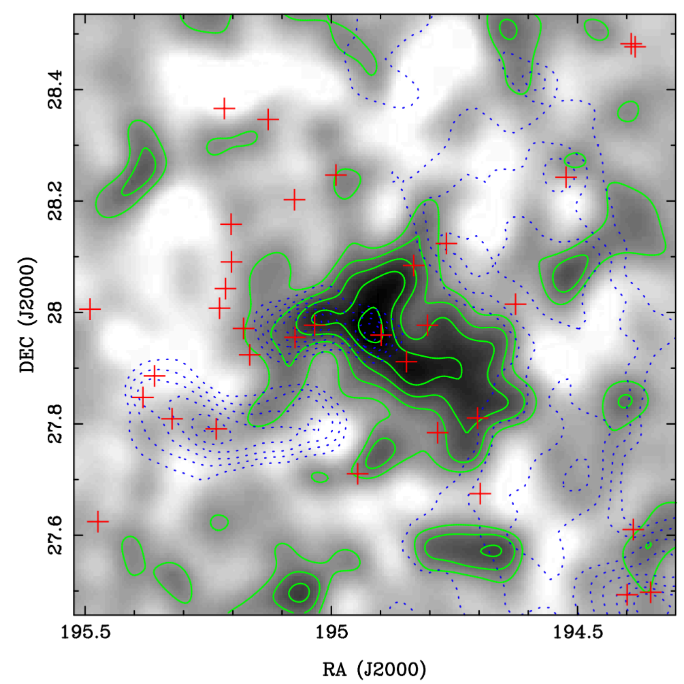
PASCOS 2026, 22-26 June - Sheffield

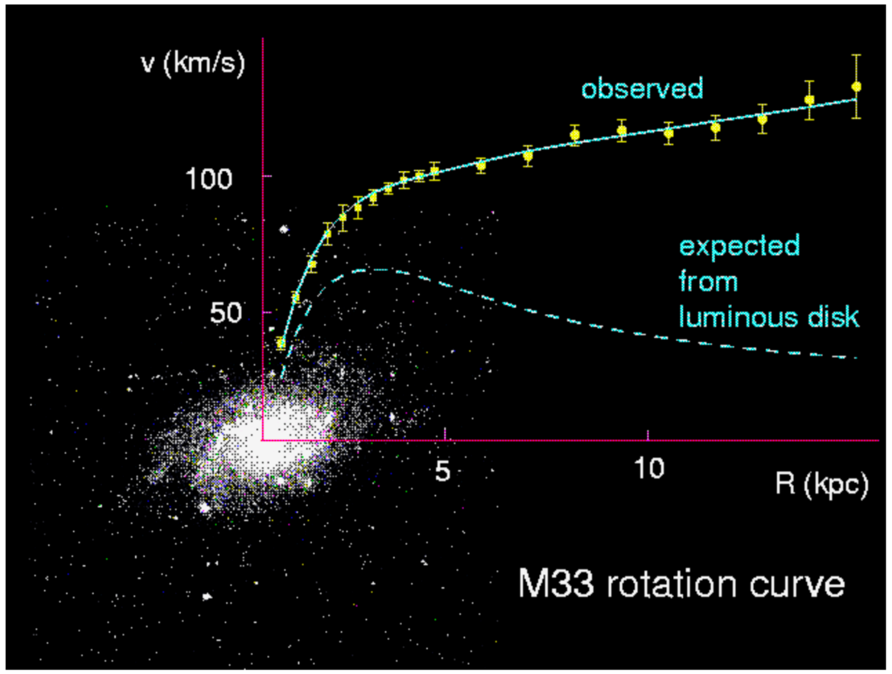
Introduction

Dark matter

R. Gavazzi *et al*, arXiv:astro-ph/0904.0220







M. Tegmark *et al*, arXiv:0310725

D. P. Roy, arXiv:physics/0007025

$$\boxed{\Omega_{\rm DM}^{\rm obs} h^2 = 0.1193 \pm 0.0009}$$

Planck Colllaboration, arXiv:1807.06209

Only probed gravitationally

Introduction

Dark matter production

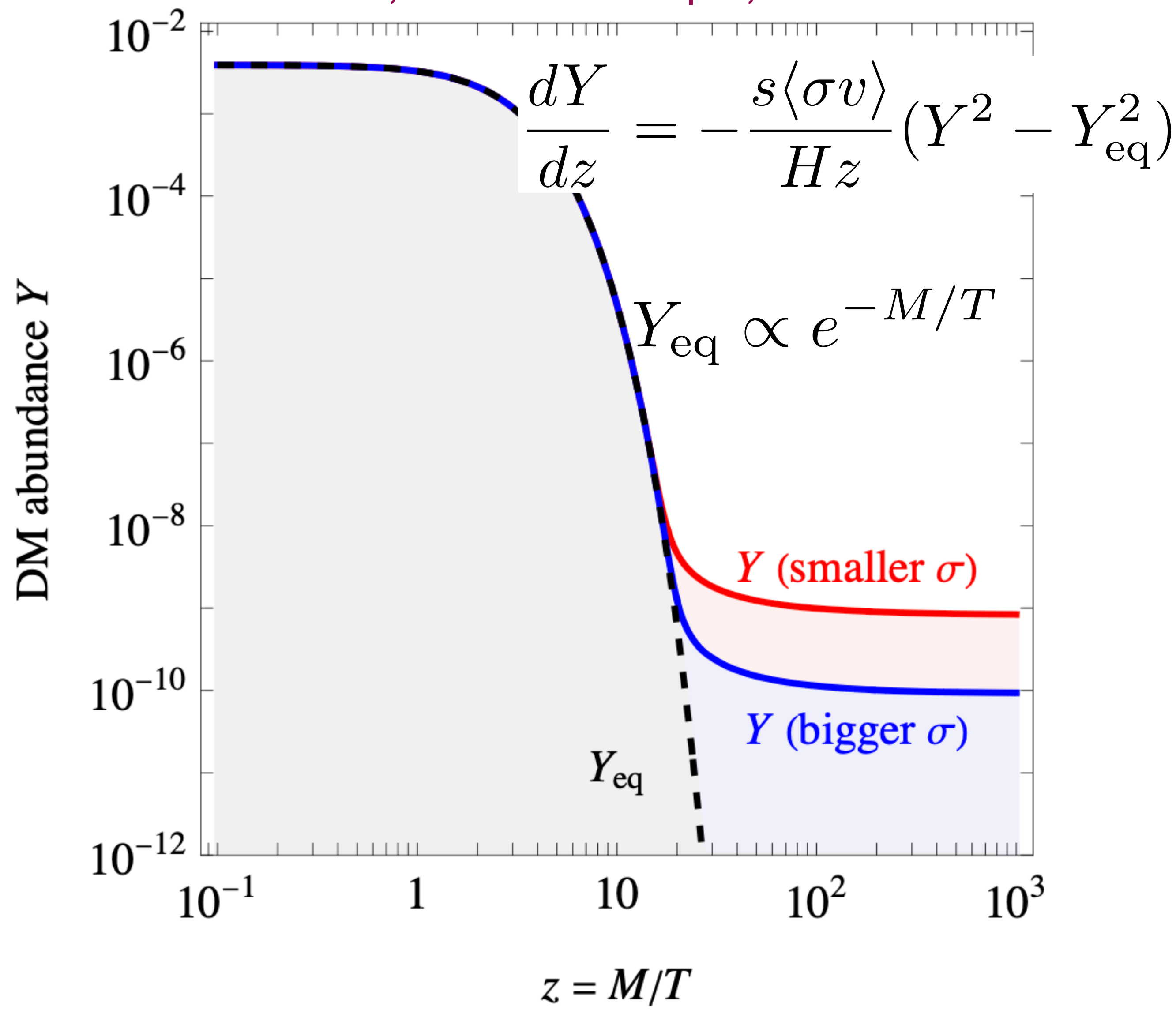
Thermal freeze-out

Independent of initial conditions

$$\langle \sigma v \rangle \simeq 3 - 4 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$$

Weak scale cross-section values

M. Cirelli, A. Strumia & J. Zupan, arXiv:2406.01705



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Dark matter production

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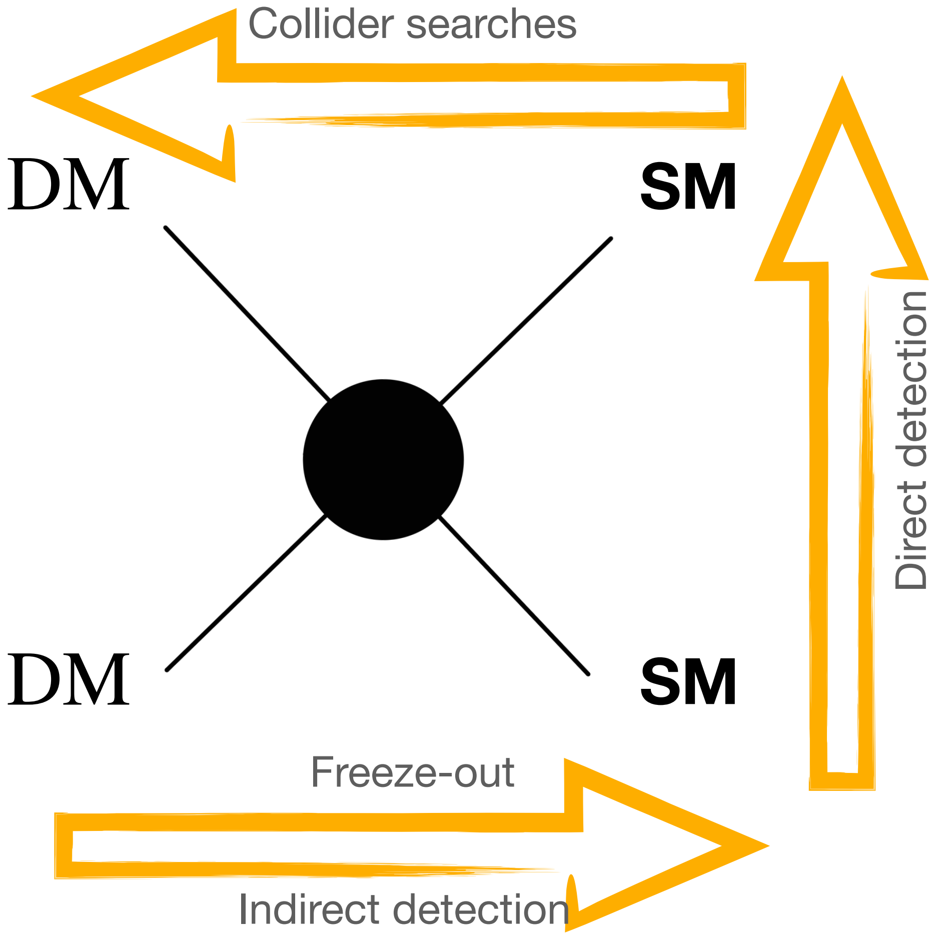
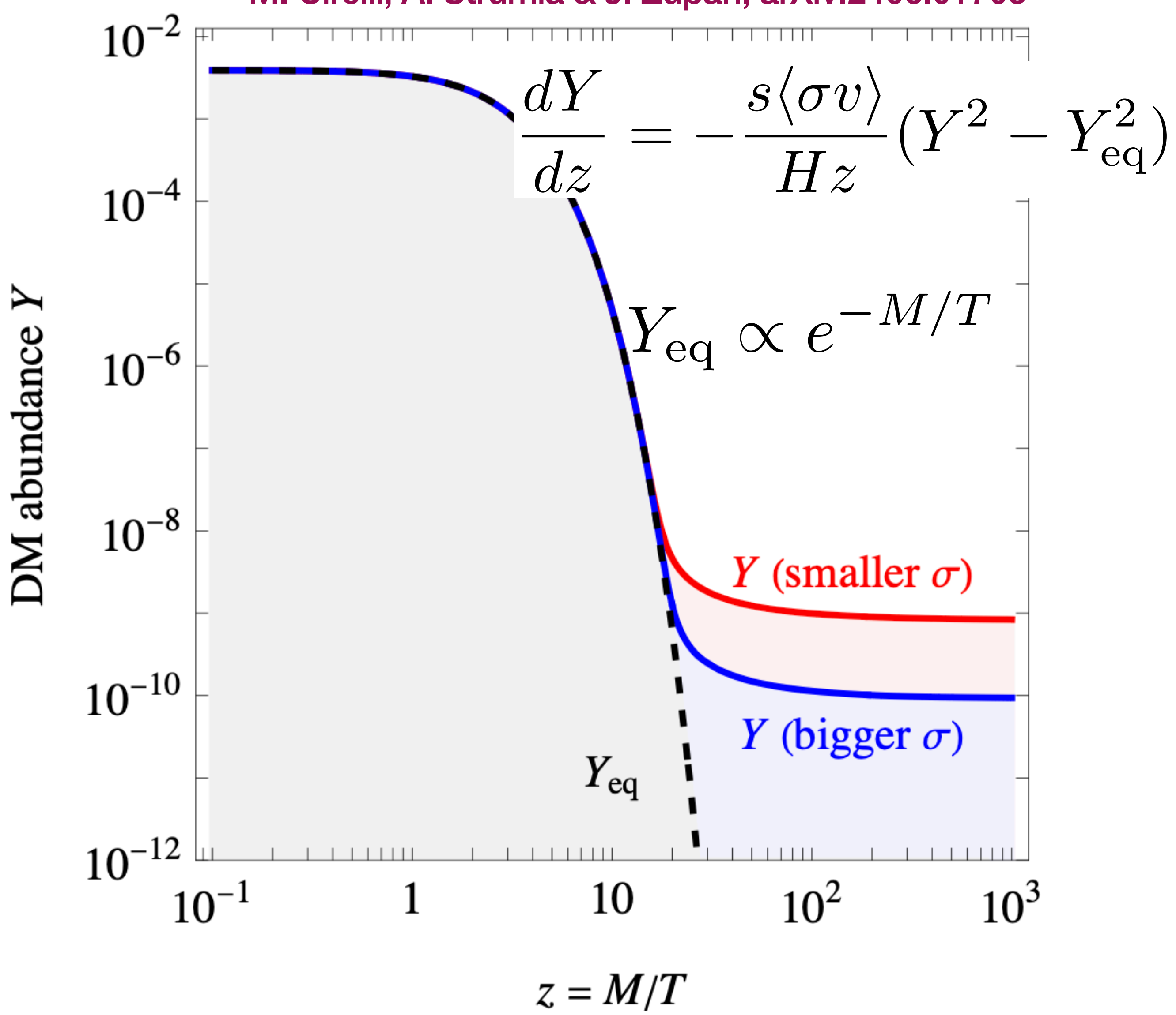


Rich experimental prospects

M. Cirelli, A. Strumia & J. Zupan, arXiv:2406.01705

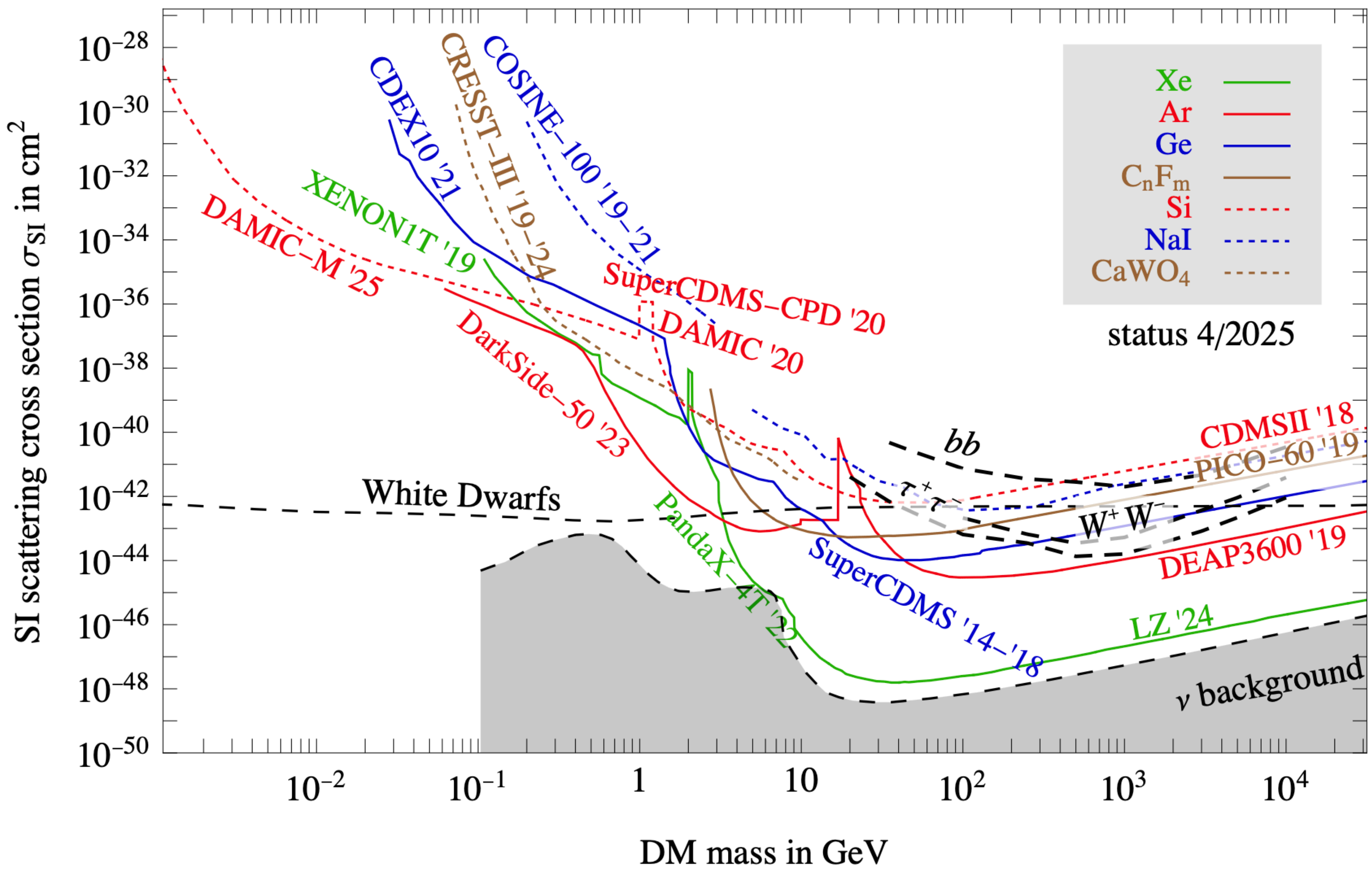


Introduction

Dark matter - Searches

- **Direct detection**

M. Cirelli, A. Strumia & J. Zupan, arXiv:2406.01705



Introduction

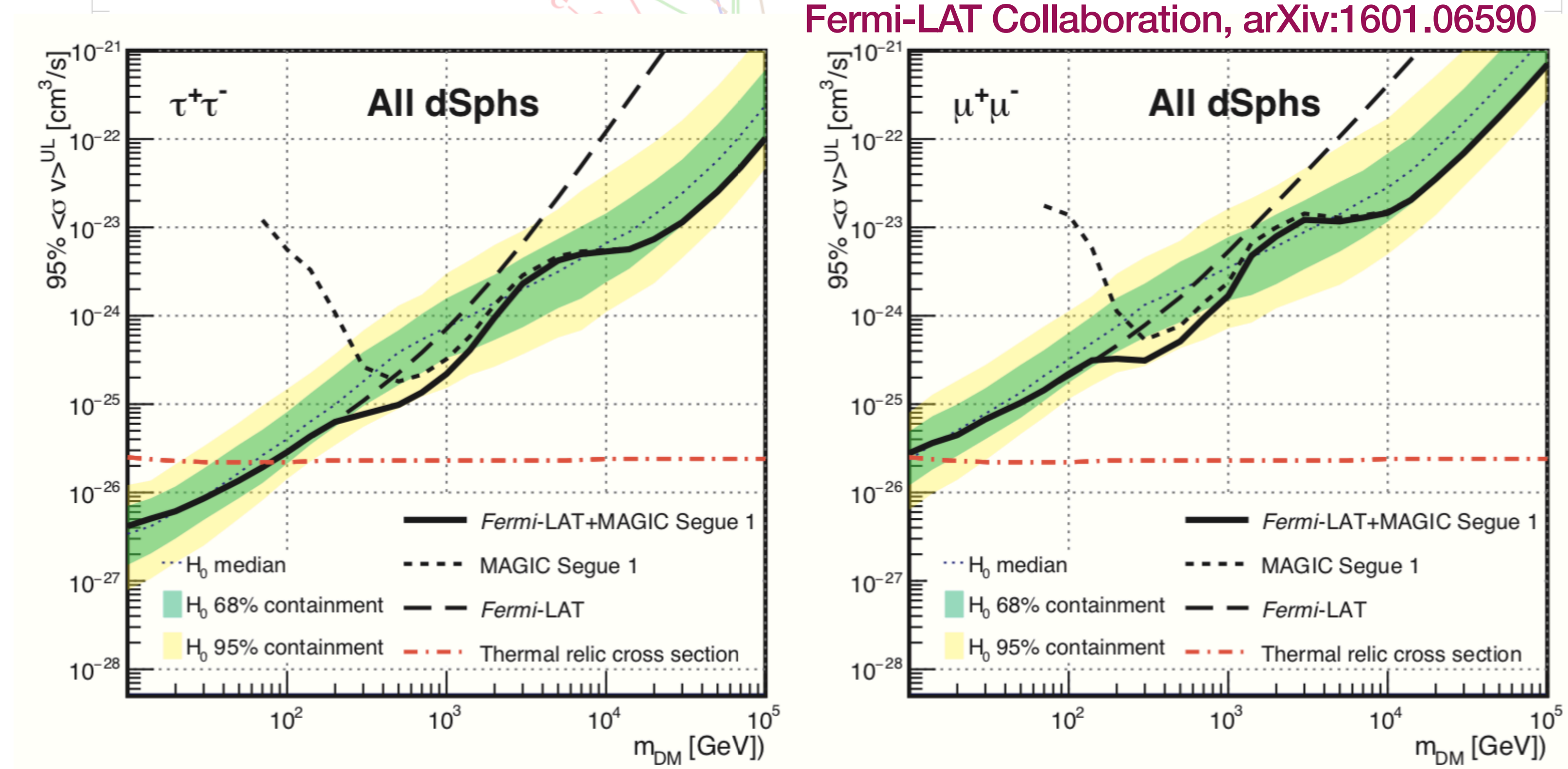
Dark matter - Searches

- Direct detection

- **Indirect detection**

M. Cirelli, A. Strumia & J. Zupan, arXiv:2406.01705

Fermi-LAT Collaboration, arXiv:1601.06590



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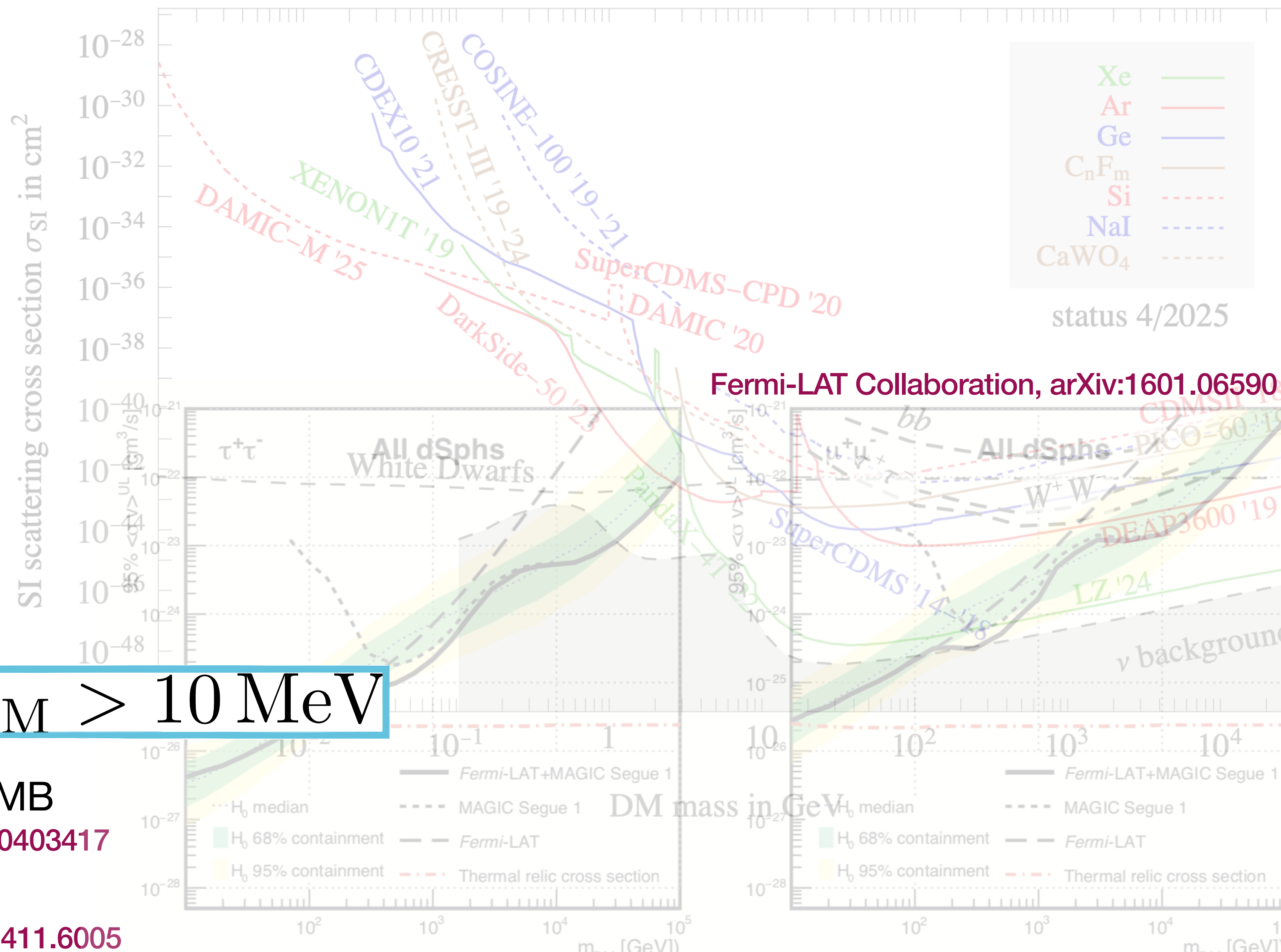
Dark matter - Searches

M. Cirelli, A. Strumia & J. Zupan, arXiv:2406.01705

- Direct detection
- Indirect detection
- **Cosmology**



Fermi-LAT Collaboration, arXiv:1601.06590

$$\boxed{\Delta N_{\rm eff} \to m_{\rm DM} > 10\,\mathrm{MeV}}$$

Energy injection into CMB

P. D. Serpico & G. G. Raffelt, arXiv:0403417
F. Iocco et al., arXiv:0809.0631
C. Bohem et al., arXiv:1303.6270
K. M. Nollet & G. Steigman, arXiv:1411.6005
P. Brax *et al*, arXiv:2303.16895
S. Kanemura *et al*, arXiv:2506.04568

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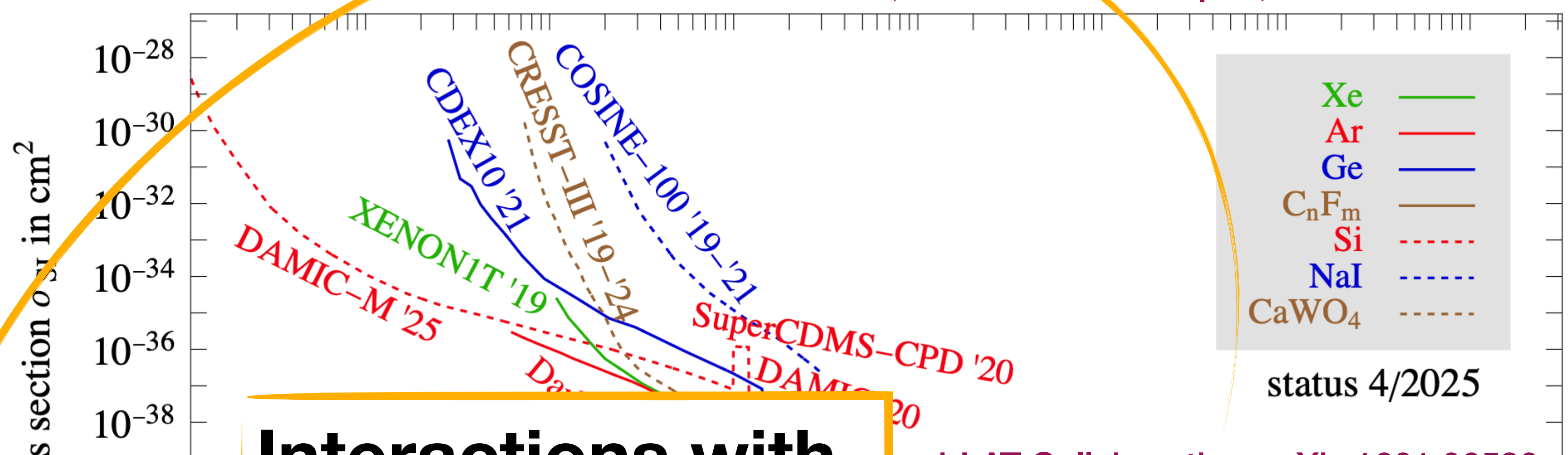
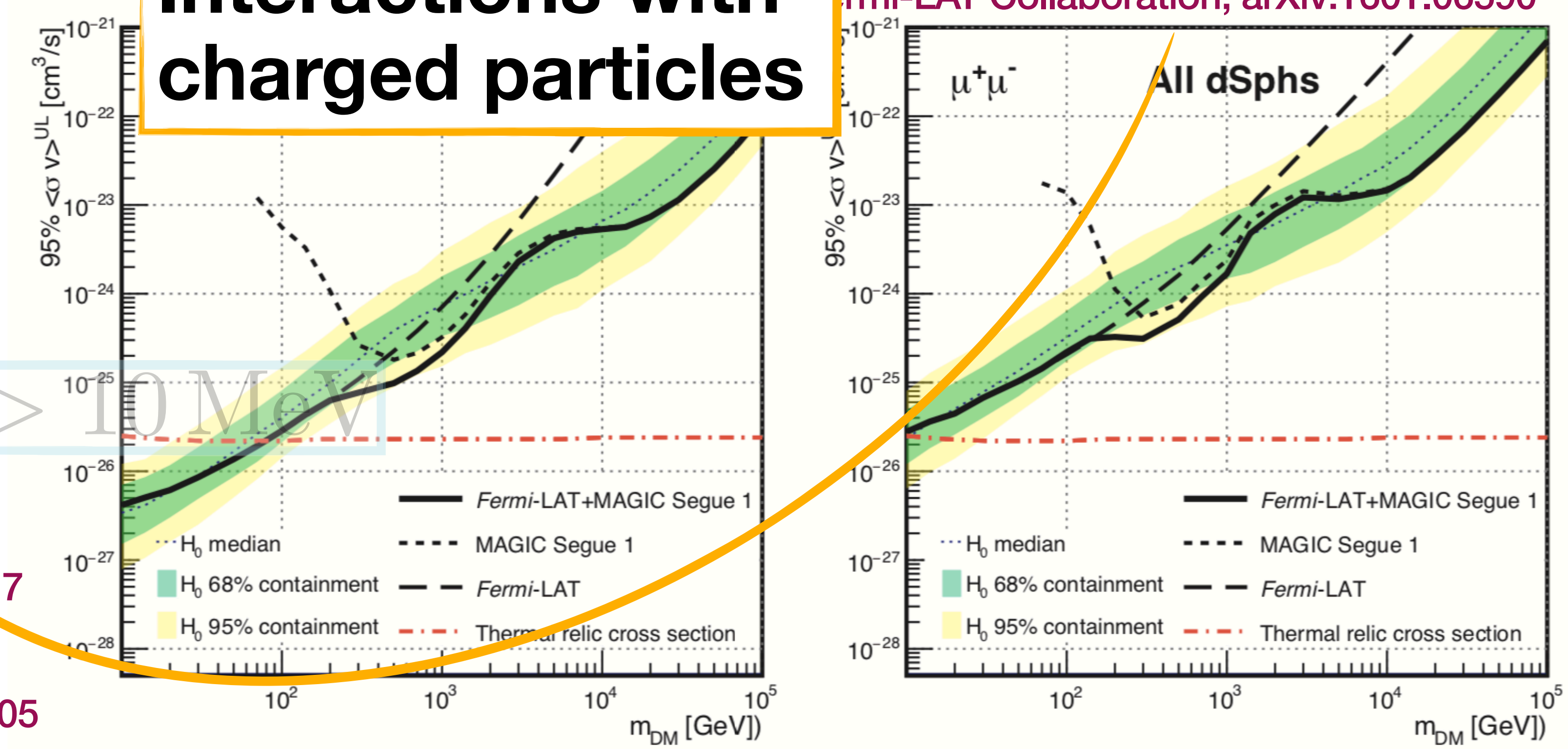


- **Direct detection**
- **Indirect detection**
- **Cosmology**

Interactions with charged particles

Fermi-LAT Collaboration, arXiv:1601.06590



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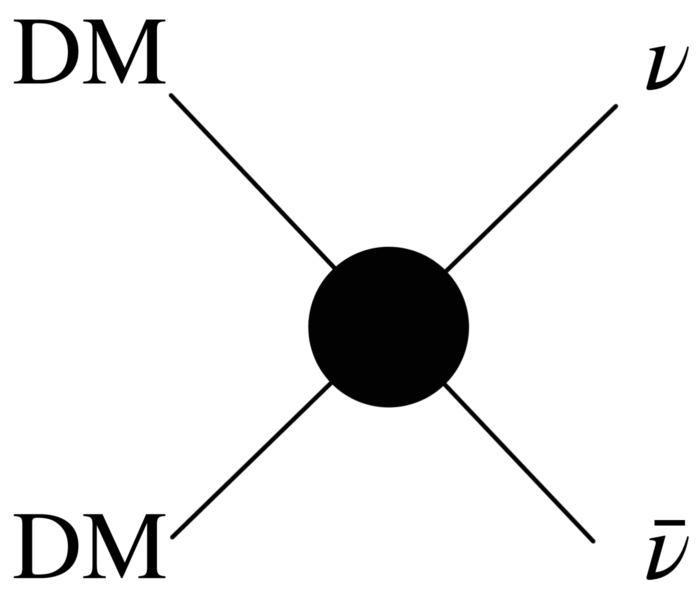
Introduction

Neutrino dark matter interactions

What if DM primarily interacts with neutrinos?



Avoid direct and (most) indirect detection searches

How should one search for these interactions?

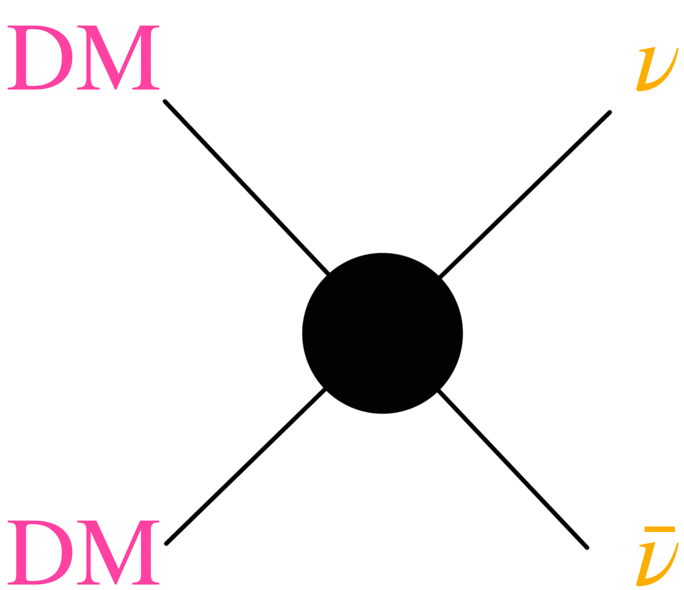
H. Yüksel et al., arXiv:0707.0196
S. Palomares-Ruiz & S. Pascoli, arXiv:0710.5420
A. Olivares-Del Campo et al., arXiv:1711.05283

Neutrino - DM portals

SM - dark sector portals

How can we obtain a dominant coupling between DM and neutrinos?

In the SM $$L_L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix}$$



B. Bertoni *et al*, arXiv:1412.3113
A. Arhrib *et al*, arXiv:1512.08796
B. Batell *et al*, arXiv:1709.07001
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X. Xi *et al*, arXiv:2310.16346
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P. B. Dev *et al*, arXiv:2507.01000
K. Babu *et al*, arXiv:2512.25035

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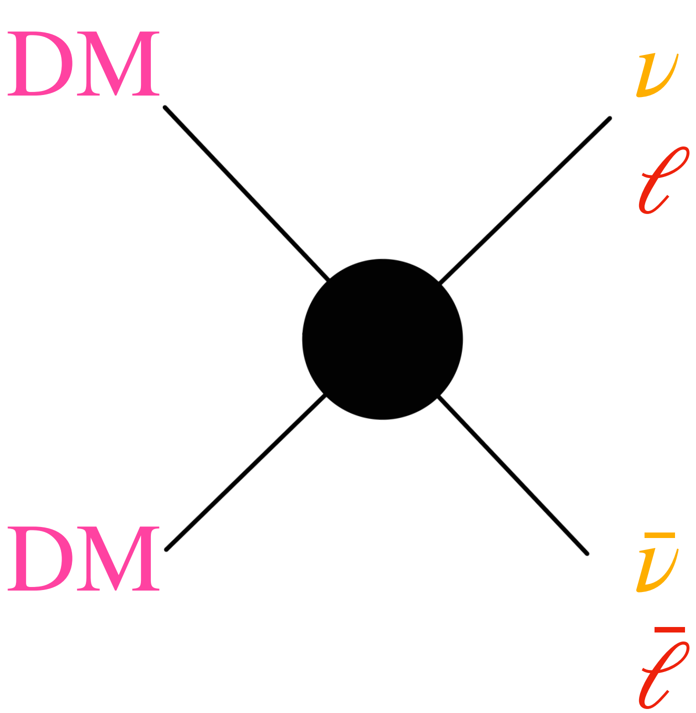
Dark sector

DM + mediators



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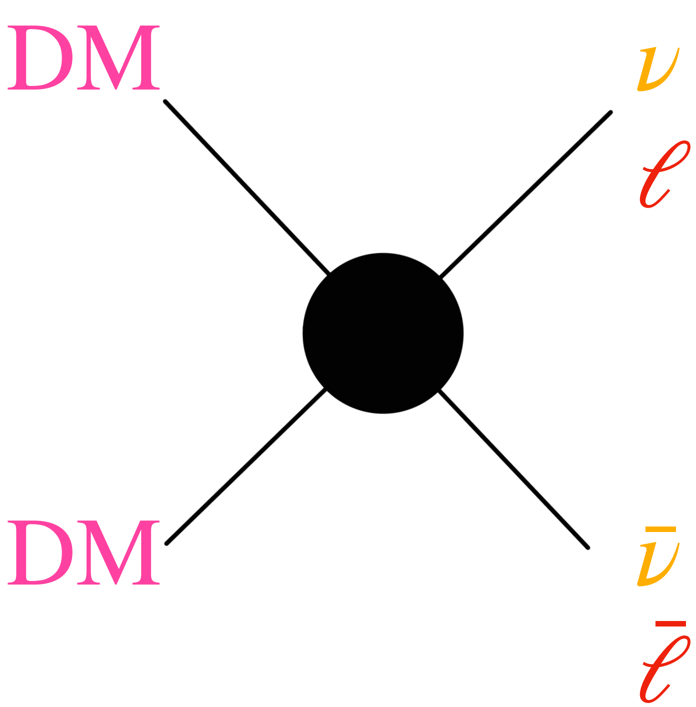

A. Olivares-Del Campo *et al (SRA)*, arXiv:1903.00006

Strong constraints from **indirect detection** and **energy injection** in the early Universe

Neutrino channel dominant if $m_{\rm DM} < m_\ell$

Intermezzo

Massive neutrinos

Neutrino oscillations

$\boxed{m_\nu \neq 0}$

Torn between identities - tau-, electron - or muon-neutrino?

Physics BSM

Intermezzo

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Physics BSM

Introduce **RH counterpart**, as for any other SM fermion

See e.g. Y. Cai *et al*., arXiv:1711.02180
One of the three ways to generate the Weinberg operator at tree-level

P. Minkowski, Phys. Lett. B (1977)
R. N. Mohapatra & G. Senjanovic, Phys. Rev. Lett (1980)
T. Yanagida, Conf. Proc C7902131 (1979)
M. Gell-Mann et al. Conf. Proc C790927 (1979)

$$\mathcal{L} \supset -\bar{L}_L Y_\nu \tilde{H} N_R \qquad + h.c.$$

SM singlet!

Intermezzo

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$$\mathcal{L} \supset -\bar{L}_L Y_\nu \tilde{H} N_R - \frac{1}{2}\bar{N}_R^c M N_R + h.c.$$

SM singlet!

New scale not related to EW symmetry breaking!

Lepton number violation

Intermezzo

Massive neutrinos

Neutrino oscillations

$\boxed{m_\nu \neq 0}$

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$$\mathcal{L} \supset -\bar{L}_L Y_\nu \tilde{H} N_R - \frac{1}{2}\bar{N}_R^c M N_R + h.c.$$

Mixing matrix measured in oscillations: **not unitary**

$$\nu_L \simeq \boxed{N}\nu_{\text{light}} + \theta n_{\text{heavy}}$$

Intermezzo

Massive neutrinos

Neutrino oscillations

$\boxed{m_\nu \neq 0}$

Torn between identities - tau-, electron - or muon-neutrino?

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$$\mathcal{L} \supset -\bar{L}_L Y_\nu \tilde{H} N_R - \frac{1}{2}\bar{N}_R^c M N_R + h.c.$$

Active-heavy mixing

$$\nu_L \simeq N\nu_{\text{light}} + \theta n_{\text{heavy}}$$

$$\boxed{\theta \sim m_D M^{-1} = v_H Y_\nu M^{-1}/\sqrt{2}}$$

Neutrino - DM portals

SM - dark sector portals

$$\mathcal{L} \supset -\bar{L}_L Y_\nu \tilde{H} N_R - \frac{1}{2}\bar{N}_R^c M N_R + h.c.$$

SM singlet!

What if N_R is part of a more complex dark sector?

Neutrino - DM portals

SM - dark sector portals

$$\mathcal{L} \supset -\bar{L}_L Y_\nu \tilde{H} N_R - \frac{1}{2}\bar{N}_R^c M N_R + h.c.$$

SM singlet!

SM

ν_L

$-\bar{L}_L Y_\nu \tilde{H} N_R$

Dark sector

DM + mediators

N_R

Portal between SM and DS

B. Bertoni *et al*, arXiv:1412.3113
A. Arhrib *et al*, arXiv:1512.08796
B. Batell *et al*, arXiv:1709.07001
A. Olivares-Del Campo *et al* ***(SRA)***, arXiv:1903.00006
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N. Bell *et al*, arXiv:2412.02994
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K. Babu *et al*, arXiv:2512.25035

Neutrino - DM portals

Example: Fermion DM + scalar mediator

$$\mathcal{L} \supset \mathcal{L}_\nu + \bar{\chi}\left(i\partial_\mu\gamma^\mu - m_{\mathrm{DM}}\right)\chi - y_L\bar{\chi}SN_R^c + h.c.$$

Neutrino - DM portals

Example: Fermion DM + scalar mediator

$$\mathcal{L} \supset \mathcal{L}_\nu + \bar{\chi}\left(i\partial_\mu\gamma^\mu - m_{\rm DM}\right)\chi - y_L \bar{\chi} S N_R^c + h.c.$$

After SSB we get ν masses and mixings

$$\mathcal{L}_{\rm DM-\nu} \supset y_L \theta^*_{\alpha i} \bar{\chi} S \nu_i + h.c.$$

Active-heavy mixing **cannot** be very small

Interactions with charged leptons and quarks are loop-suppressed!

$$\mathrm{DM}\,\mathrm{DM} \to \nu\,\nu \qquad \boxed{\langle\sigma v\rangle \simeq \frac{y_L^4 |\theta_{\alpha 4}|^4}{32\pi} \frac{m_{\rm DM}^2}{(m_{\rm DM}^2 + m_S^2)}}$$

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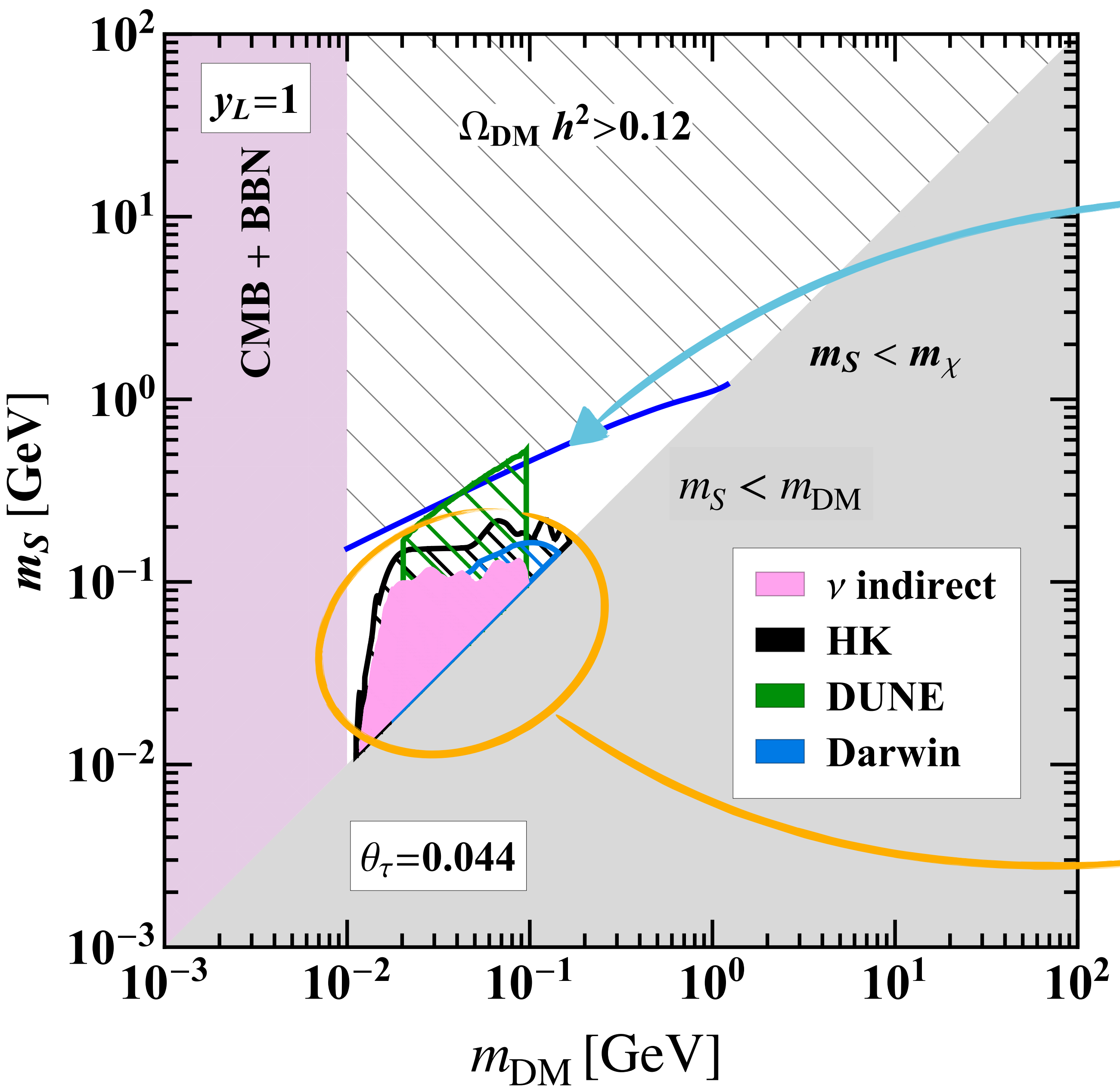


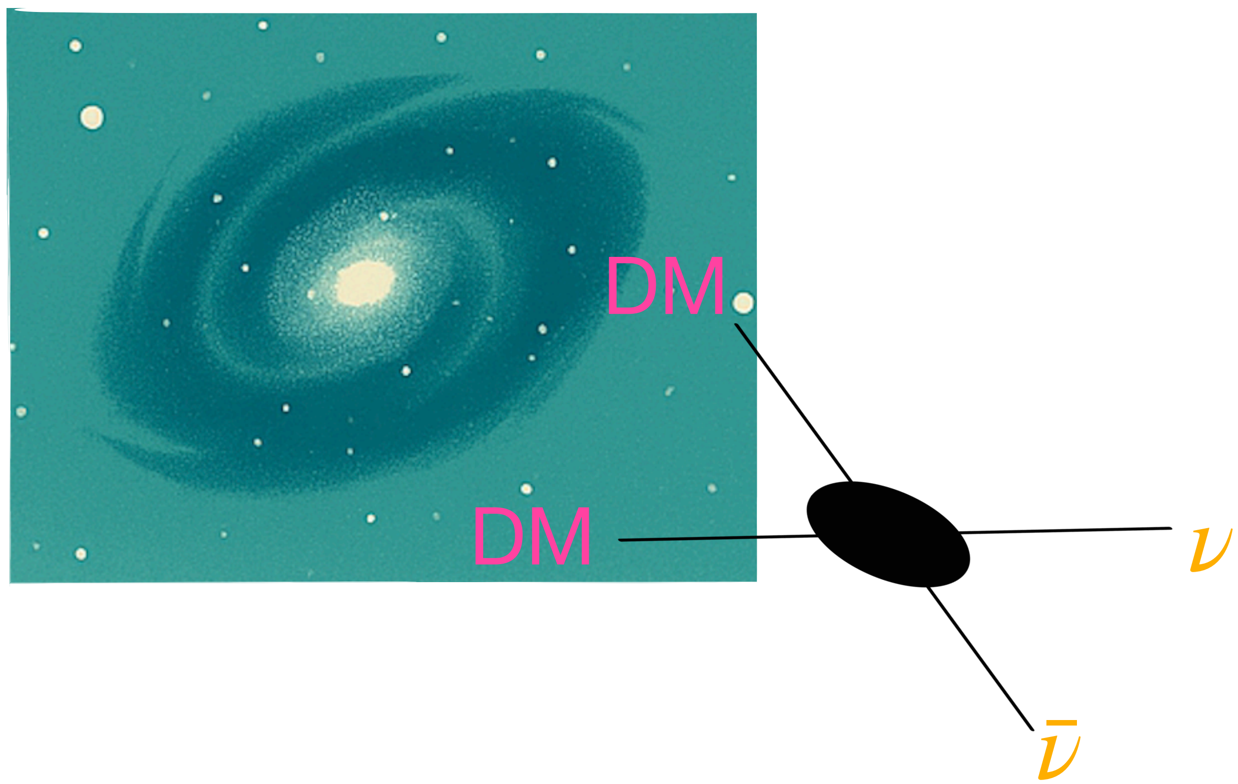
$$\boxed{\Omega_{\mathrm{DM}} h^2 = \Omega^{\mathrm{obs}}_{\mathrm{DM}} h^2}$$

$m_{\mathrm{DM}} \lesssim 1\,\mathrm{GeV}$

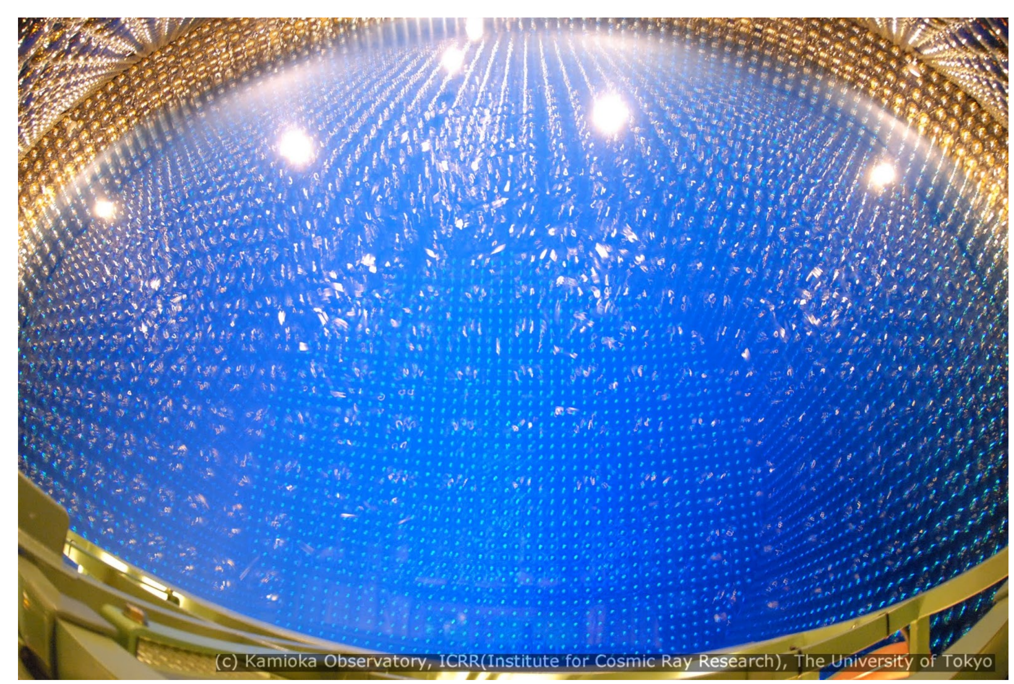
Dominant constraints and prospects from large ν detectors

Signal in ν detectors

$\mathrm{DM}\,\mathrm{DM} \rightarrow \nu\,\nu$ **signal**



Super Kamiokande detector



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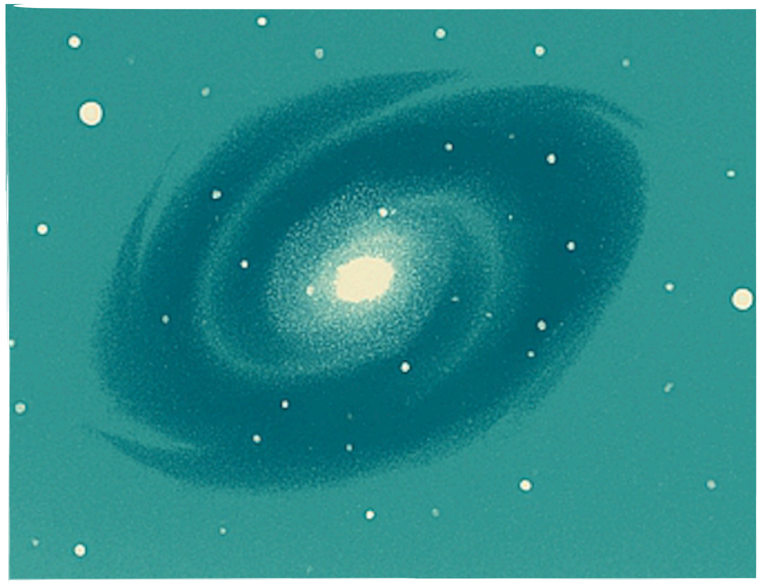
Signal in ν detectors

Diffuse Supernova Neutrino Background



Isotropic ν flux from all past SNe

$$\frac{d\phi_\nu}{dE_\nu} = \int_0^{z_{\max}} R_{\rm SN}(z) \frac{dN_\nu}{dE'_\nu}(1+z) \left|\frac{dt}{dz}\right| dz$$

A. Mirizzi *et al*, arXiv:1508.00785
J. Beacom *et al*, arXiv:0812.3157
C. Lunardini & A. Priya, arXiv:1705.02122
T. Ertl *et al*, arXiv:2010.04728

Signal in ν detectors

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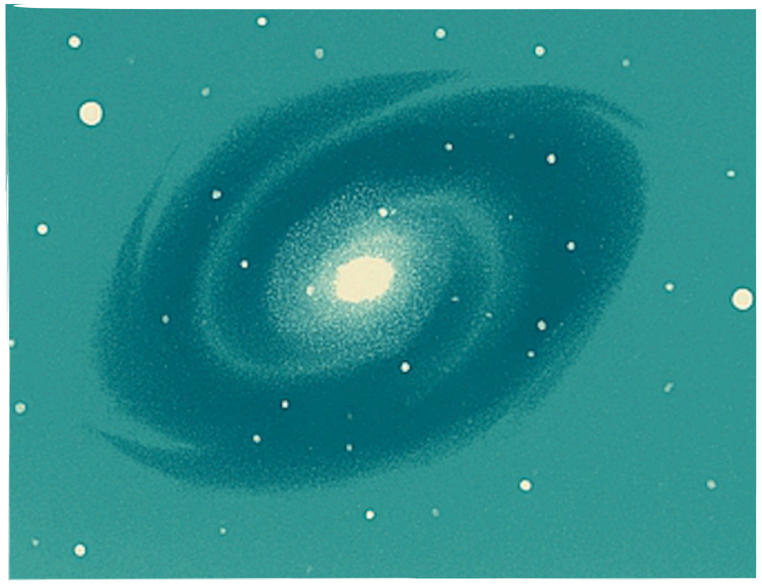

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- Star formation history
- Average ν energy (temperature)
- Fraction of failed SNe

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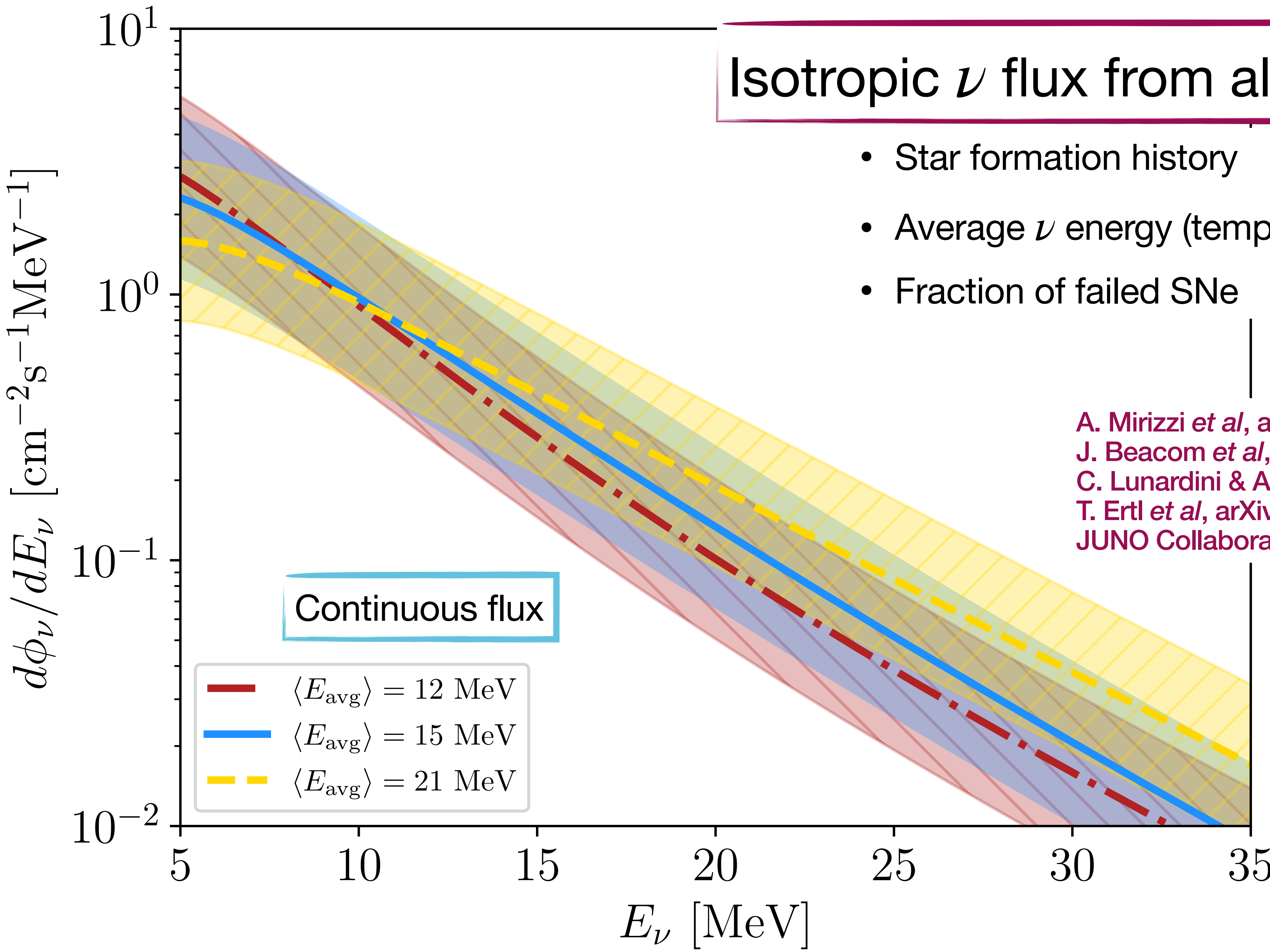

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JUNO Collaboration, arXiv:2205.08830

Signal in ν detectors

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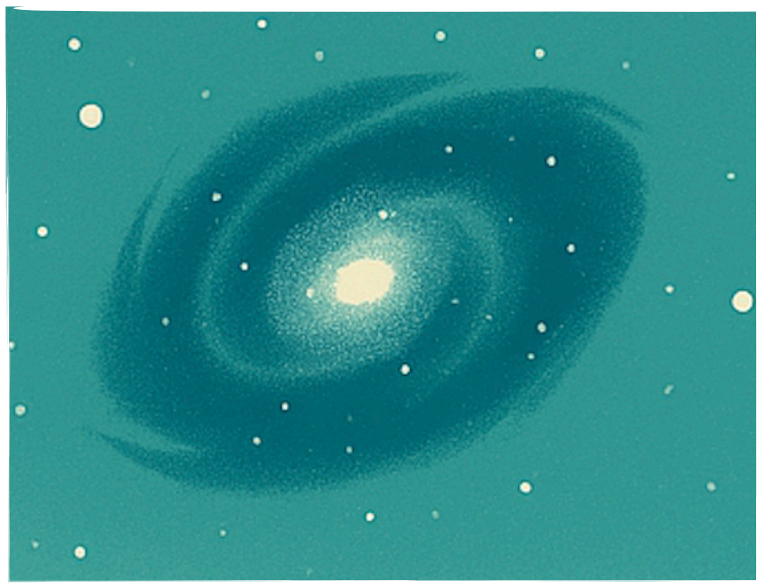


ν

$\bar{\nu}$ ν

ν ν $\bar{\nu}$

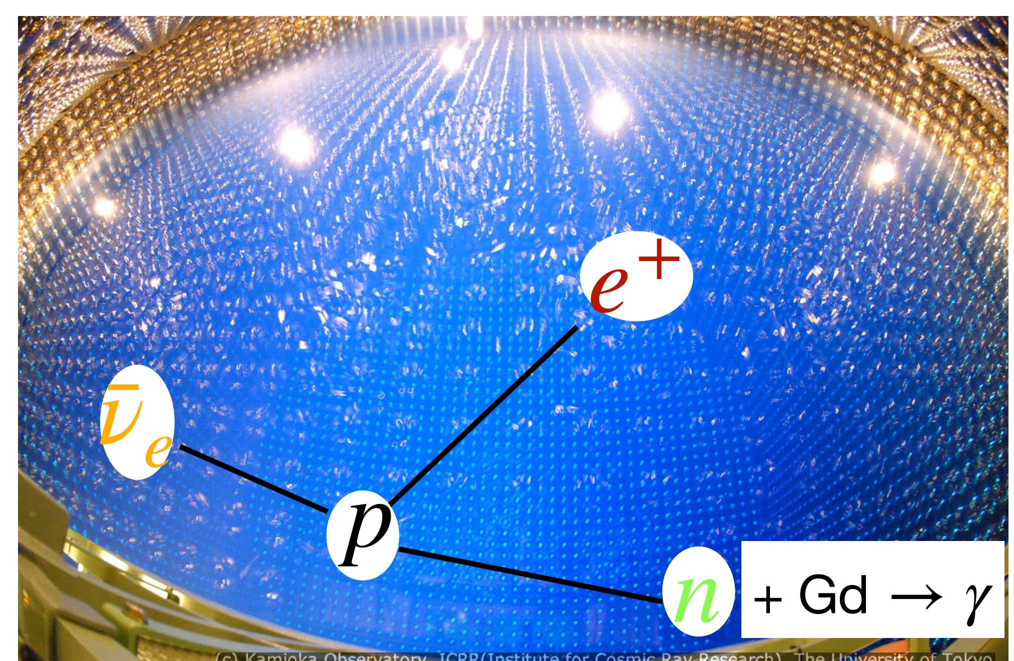
$\bar{\nu}$

$\bar{\nu}$

IBD reaction

$$\boxed{\bar{\nu}_e + p \rightarrow e^+ + n}$$

SK detector



Signal in ν detectors

Diffuse Supernova Neutrino Background

Gd-doped water Cherenkov detectors could be sensitive to the DSNB

J. Beacom & M. R. Vagins, arXiv:hep-ph/0309300

SK-I/II/III 2837 days

Pure water

SK-IV 2970 days

n-**tagging** (in protons)

IBD as main signal

SK-VI/VII 956.2 days

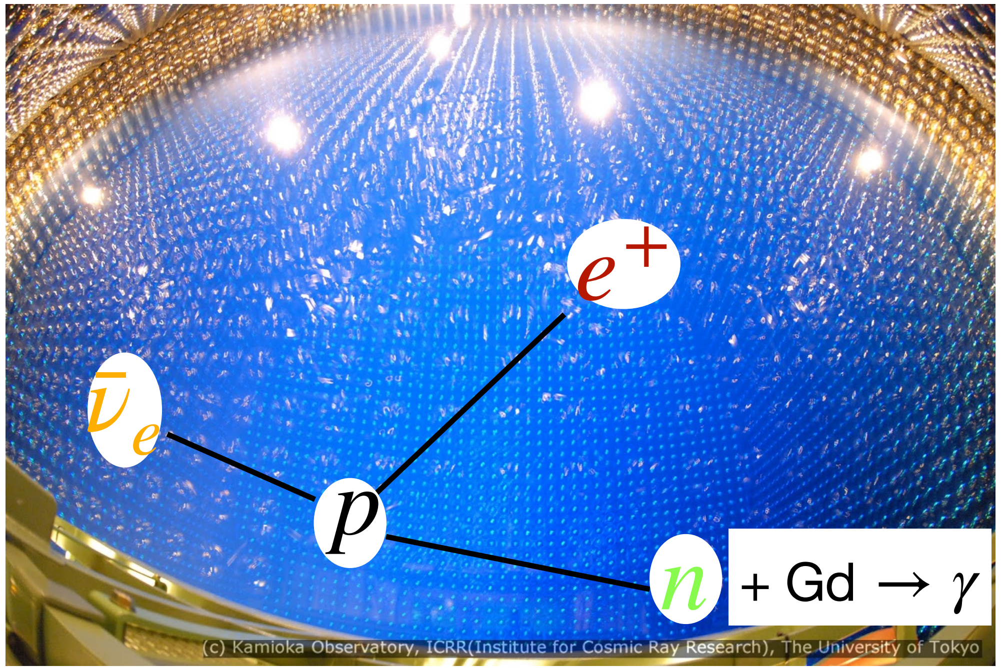
Gd doping

Increase n-tag efficiency
Further background reduction

IBD reaction

$$\bar{\nu}_e + p \to e^+ + n$$

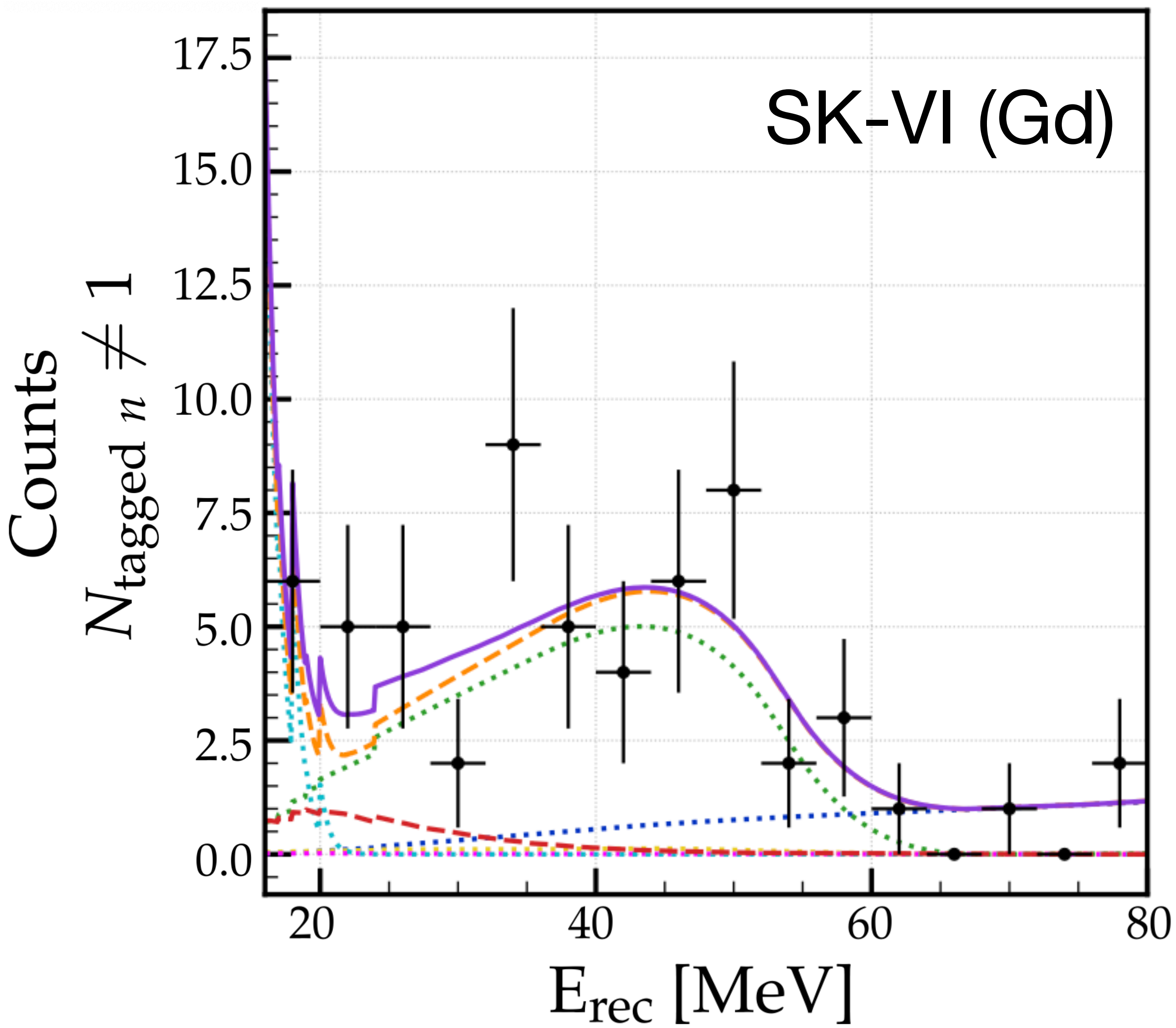
SK detector

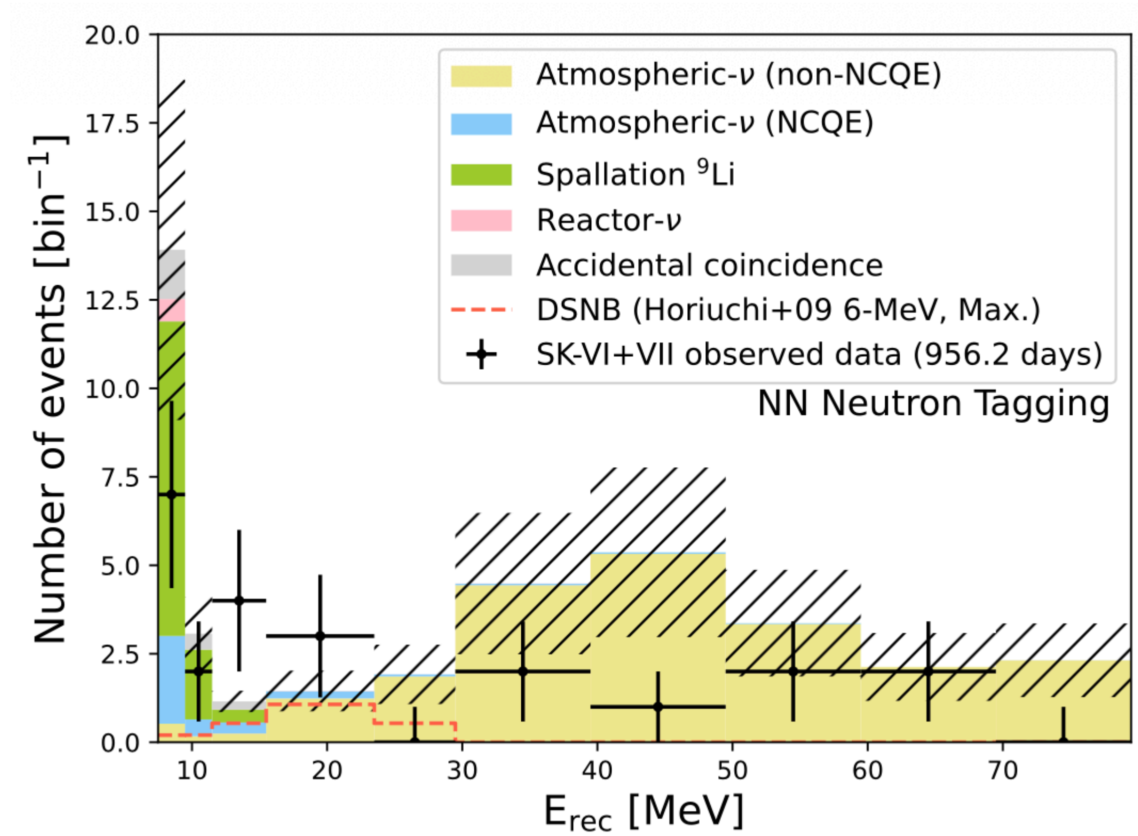


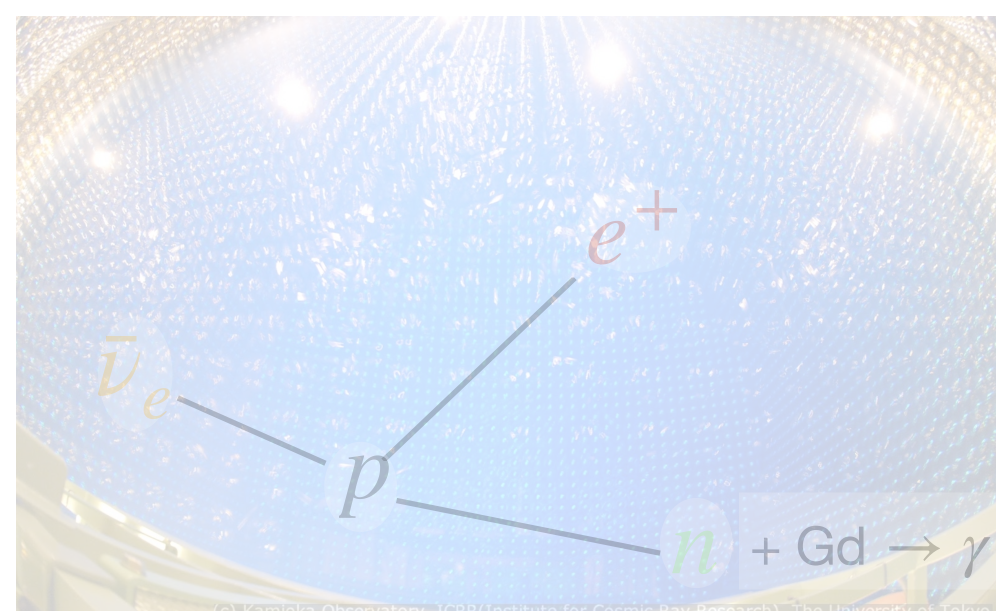
Signal in ν detectors

Diffuse Supernova Neutrino Background

Super Kamiokande Collaboration, 2511.02222







Signal in ν detectors

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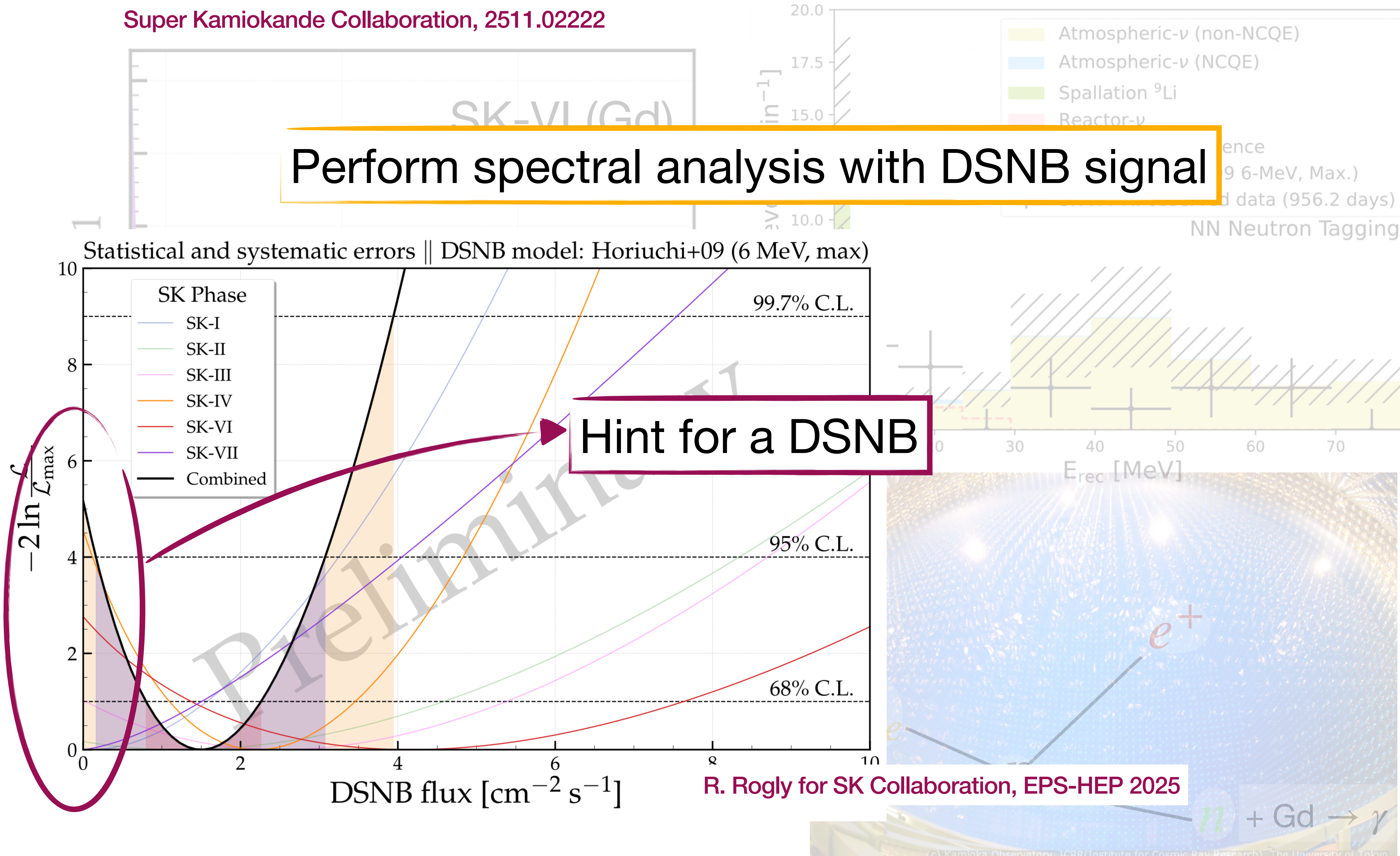

R. Rogly for SK Collaboration, EPS-HEP 2025

Signal in ν detectors

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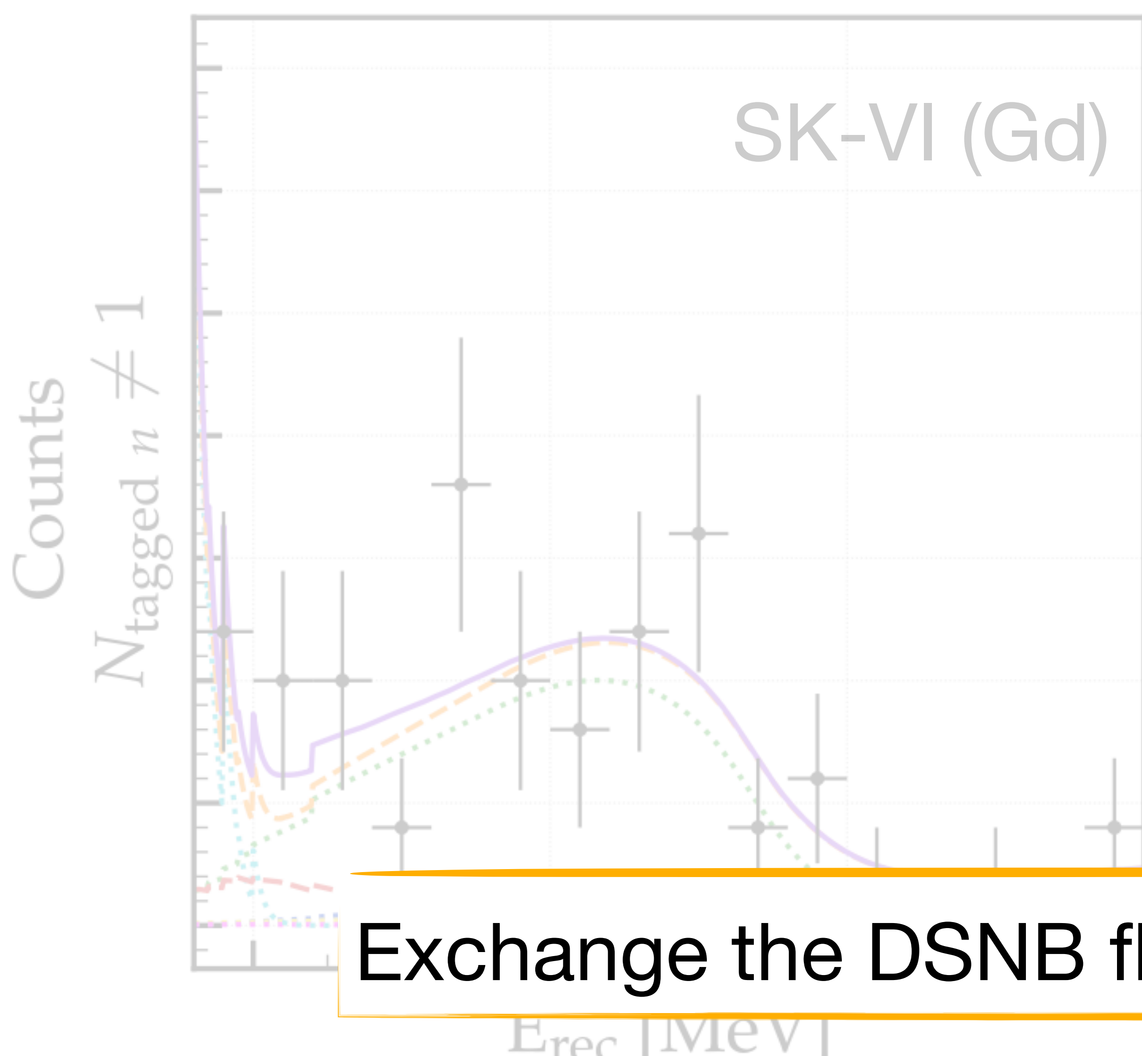
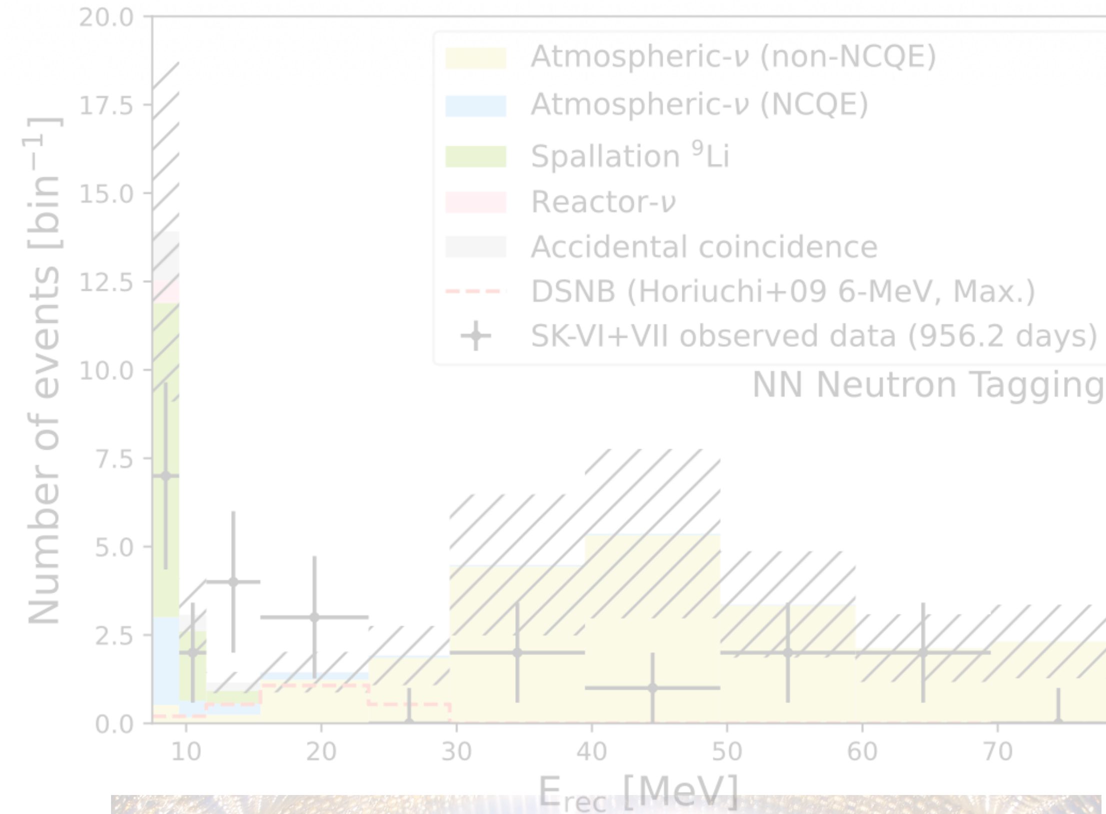
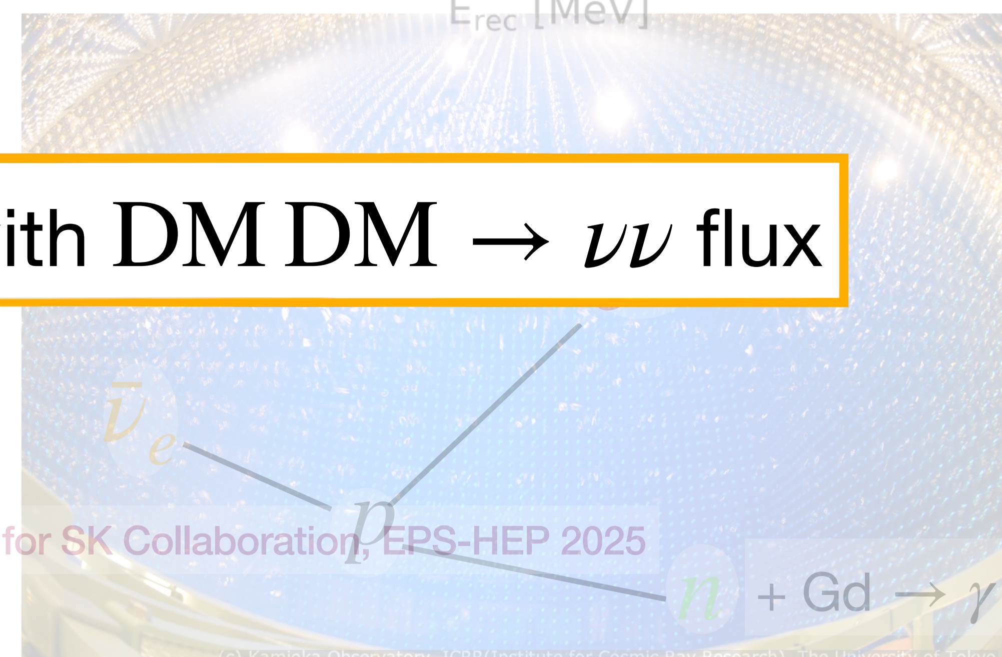




Exchange the DSNB flux with $\mathrm{DM}\,\mathrm{DM} \to \nu\nu$ flux



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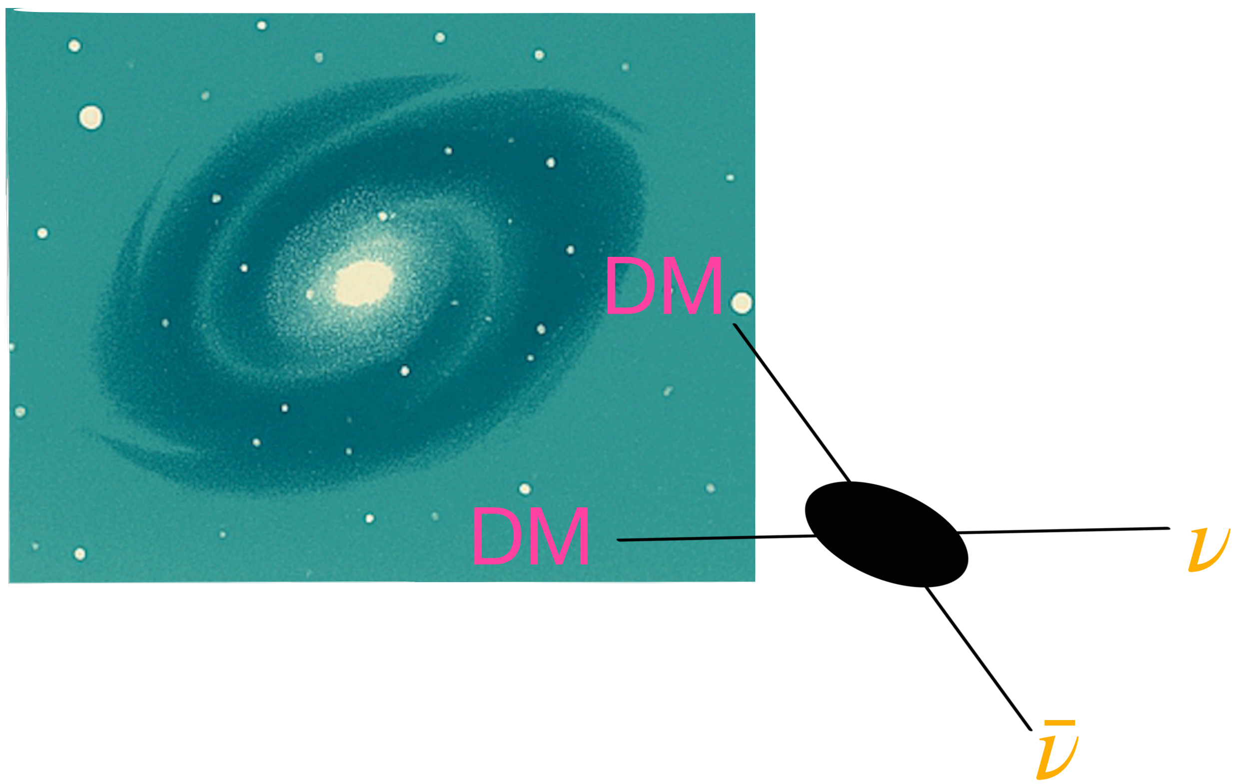
Signal in ν detectors

$\mathrm{DM}\,\mathrm{DM} \to \nu\,\nu$ **signal**

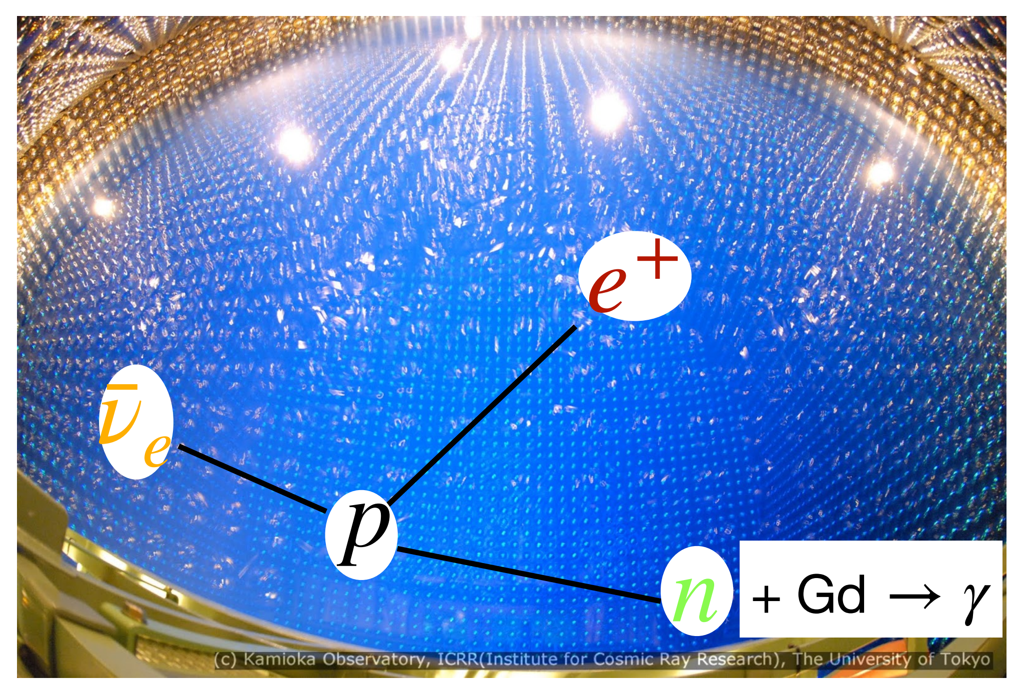


$$E_\nu = m_{\mathrm{DM}}$$

IBD reaction

$$\boxed{\bar{\nu}_e + p \to e^+ + n}$$

SK detector



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C. Bohem *et al*, arXiv:1711.05283
C. Argüelles *et al*, arXiv:1912.09486
A. Granelli *et al* **(SRA)**, arXiv:2605.20162

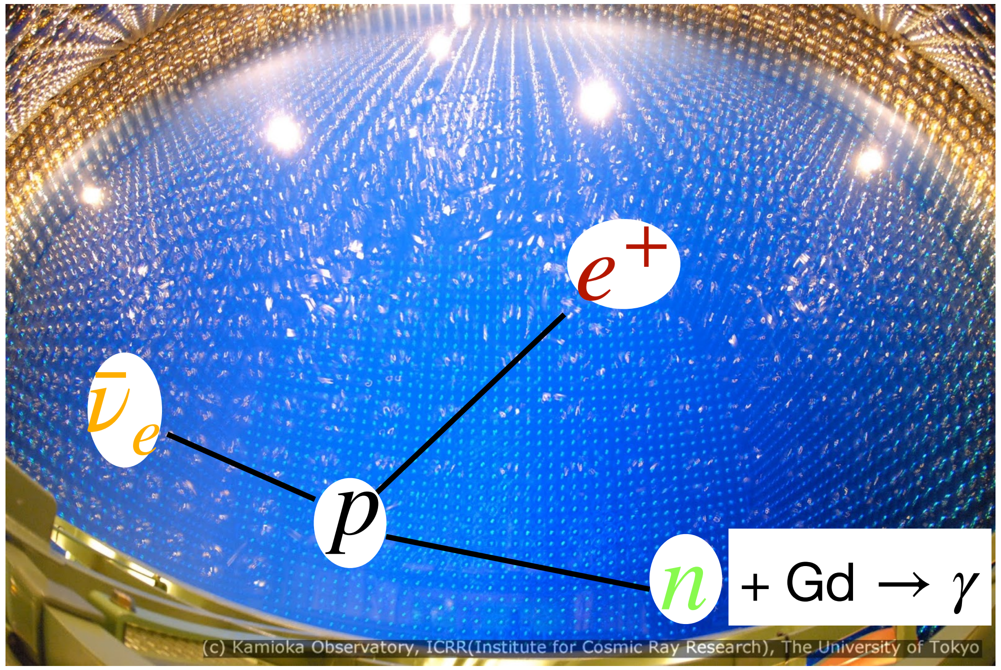
$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\langle \sigma v \rangle}{4\pi\kappa m_{\mathrm{DM}}^2}\frac{1}{3}\frac{dN_\nu}{dE_\nu} J$$

Annihilation cross section

IBD reaction

$$\boxed{\bar{\nu}_e + p \to e^+ + n}$$

SK detector



Signal in ν detectors

DM DM $\rightarrow \nu\,\nu$ signal

H. Yüksel et al., arXiv:0707.0196
S. Palomares-Ruiz & S. Pascoli, arXiv:0710.5420
C. Bohem *et al*, arXiv:1711.05283
C. Argüelles *et al*, arXiv:1912.09486
A. Granelli *et al* **(SRA)**, arXiv:2605.20162

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\langle \sigma v \rangle}{4\pi\kappa m_{\mathrm{DM}}^2}\,\frac{1}{3}\,\frac{dN_\nu}{dE_\nu}\,J$$

Number of $\bar{\nu}_e$ / annihilation / E_ν

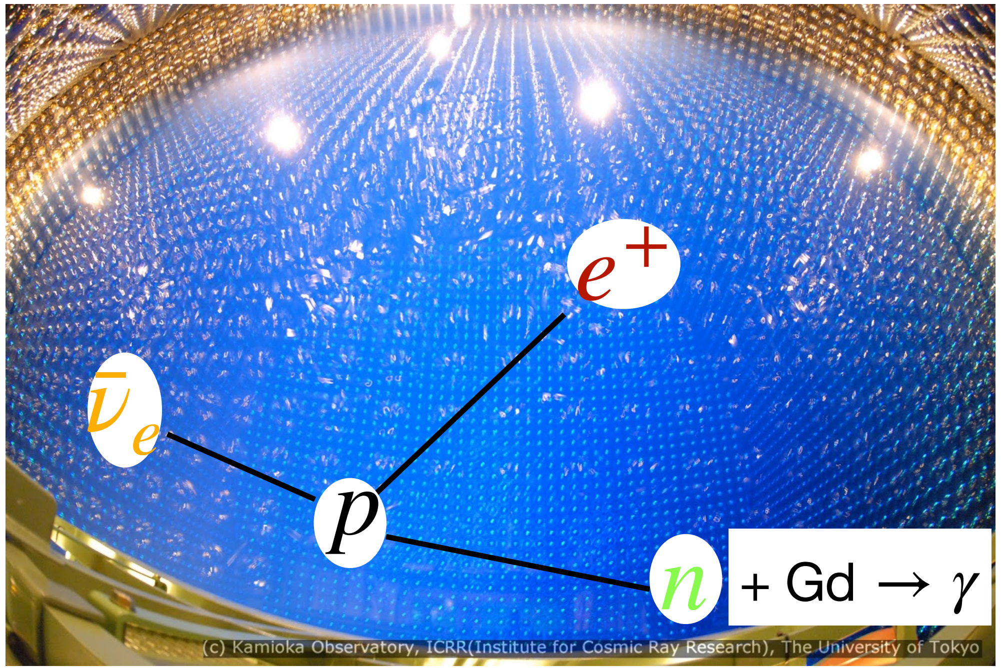
For direct annihilation:

$$\frac{dN_\nu}{dE_\nu} = \delta(E_\nu - m_{\mathrm{DM}})$$

IBD reaction

$$\boxed{\bar{\nu}_e + p \rightarrow e^+ + n}$$

SK detector



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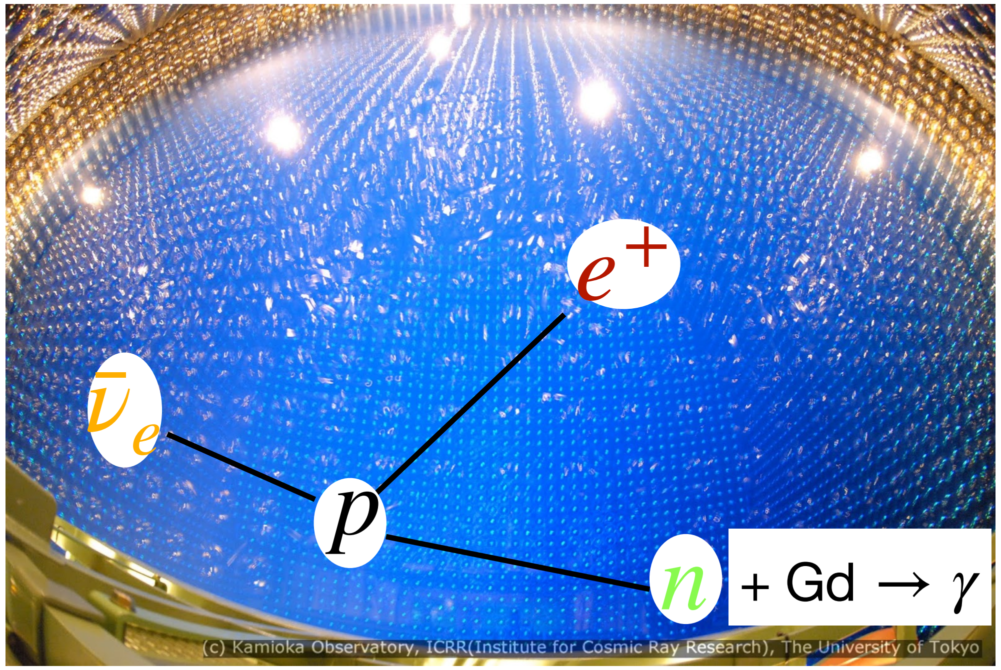
DM distribution in the Milky Way halo

$$J \equiv \int_\Delta \Omega \int_0^{l_{\rm max}} dl \rho_{\rm DM}^2$$

IBD reaction

$$\boxed{\bar{\nu}_e + p \rightarrow e^+ + n}$$

SK detector



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DM distribution in the Milky Way halo

$$J \equiv \int_\Delta \Omega \int_0^{l_{\max}} dl \rho_{\mathrm{DM}}^2$$

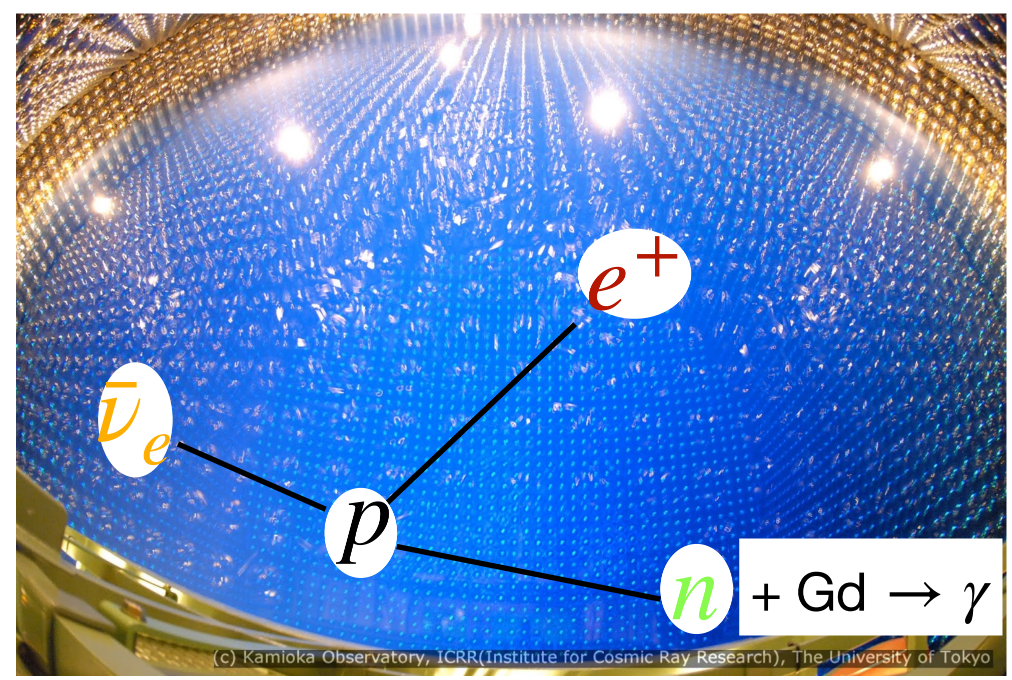
In the following we take a gNFW and define

$$\mathcal{J}_{\mathrm{avg}} \equiv J/(4\pi R_0 \rho_0^2)$$

IBD reaction

$$\boxed{\bar{\nu}_e + p \rightarrow e^+ + n}$$

SK detector



DM DM $\rightarrow \nu\,\nu$ signal

Results using SK's DSNB analysis

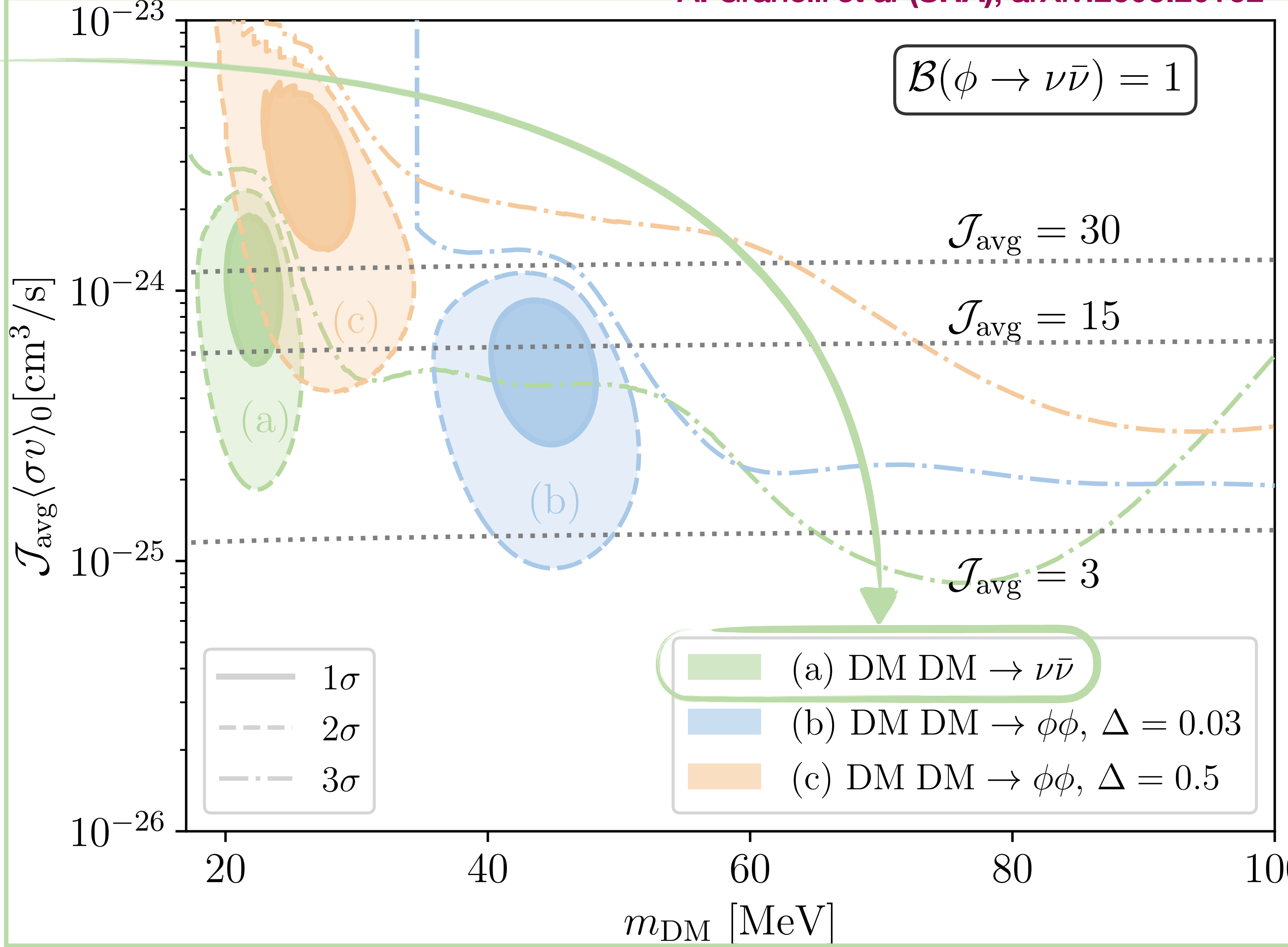
Direct annihilation

M. Benito *et al*, arXiv:1901.02460

For $5 \lesssim \mathcal{J}_{\rm avg} \lesssim 15$

$\langle \sigma v \rangle$ compatible with
thermal relic cross section

A. Granelli *et al* (SRA), arXiv:2605.20162



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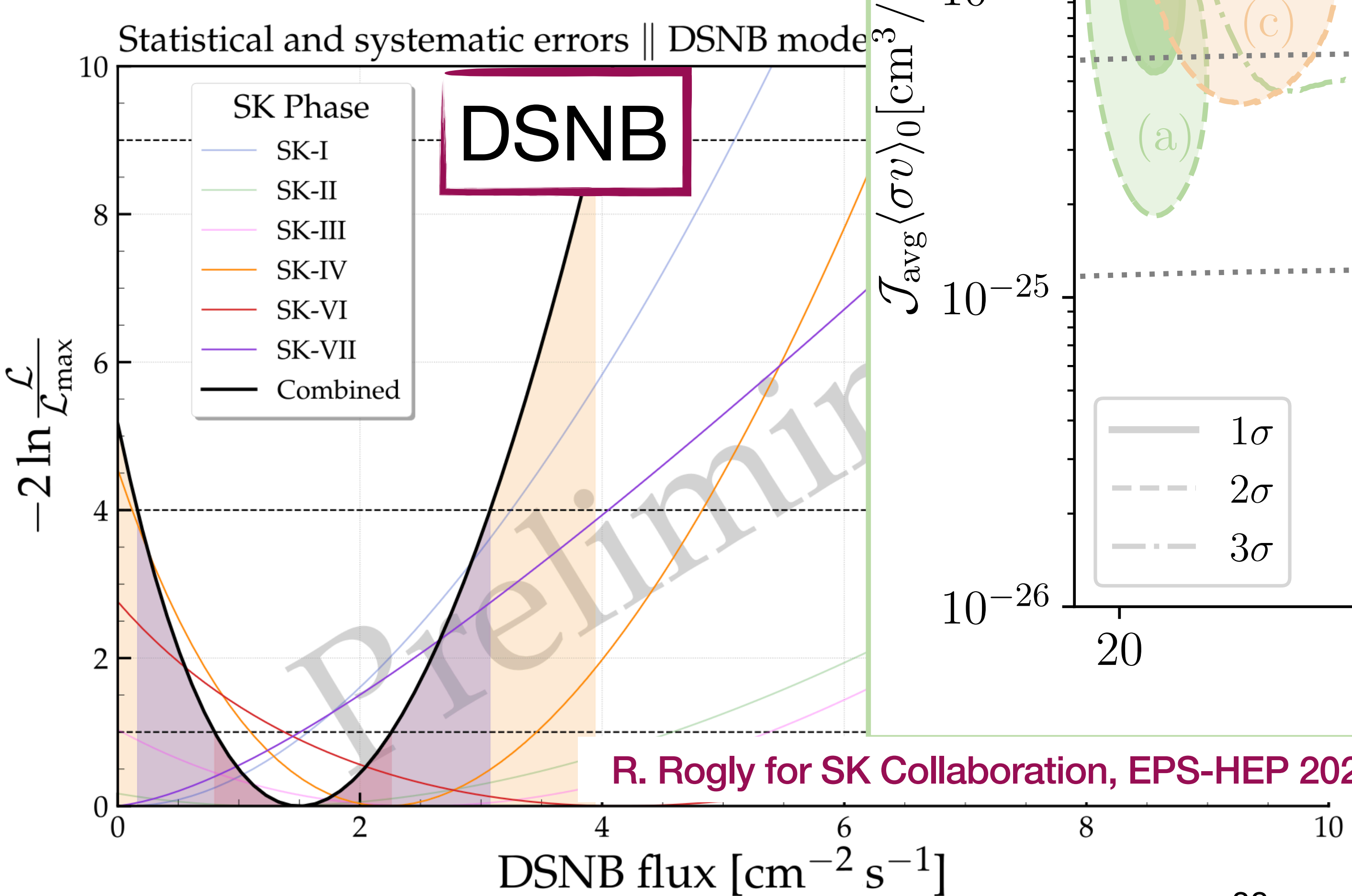

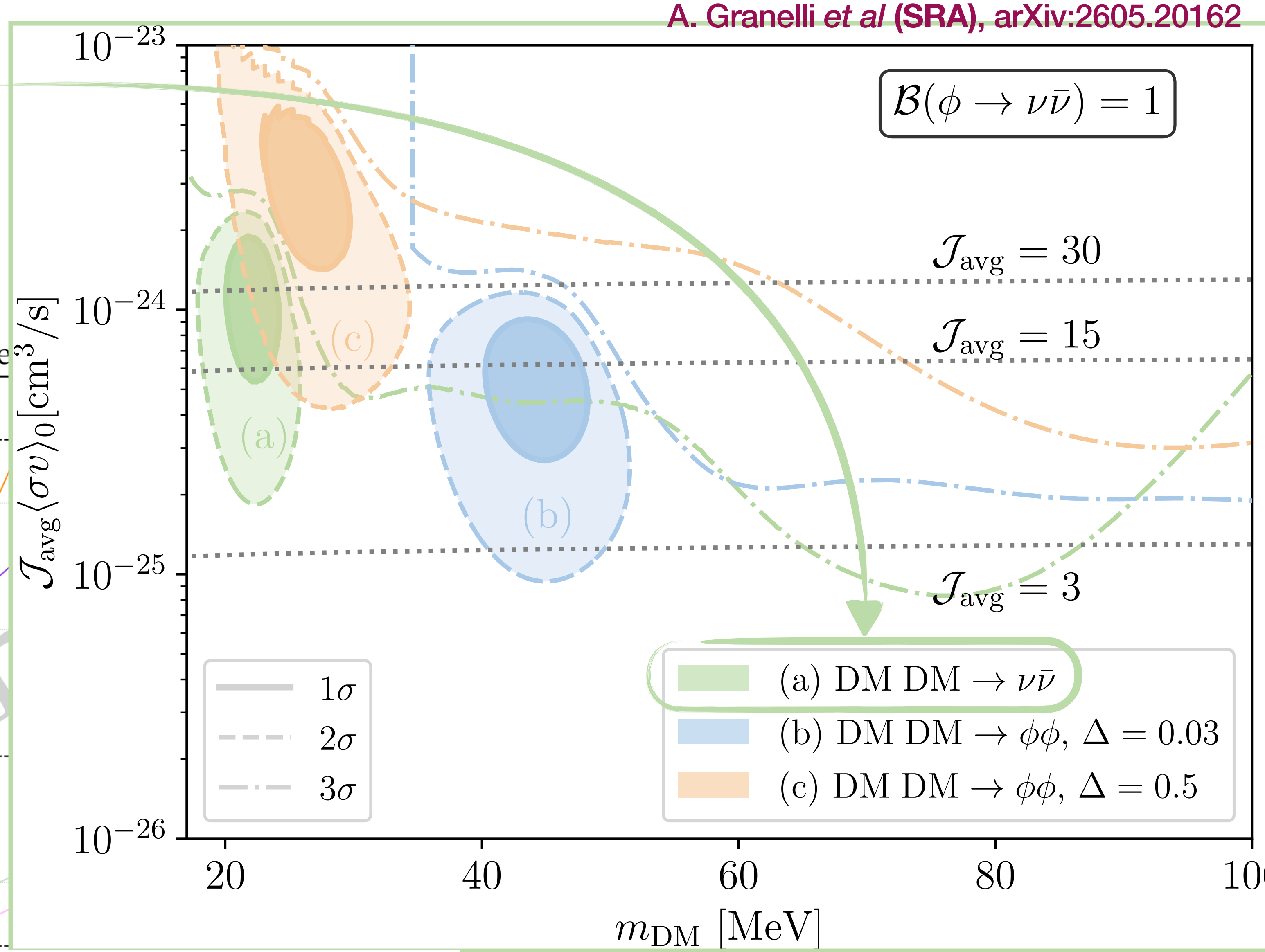

A. Granelli *et al* (SRA), arXiv:2605.20162

R. Rogly for SK Collaboration, EPS-HEP 2025

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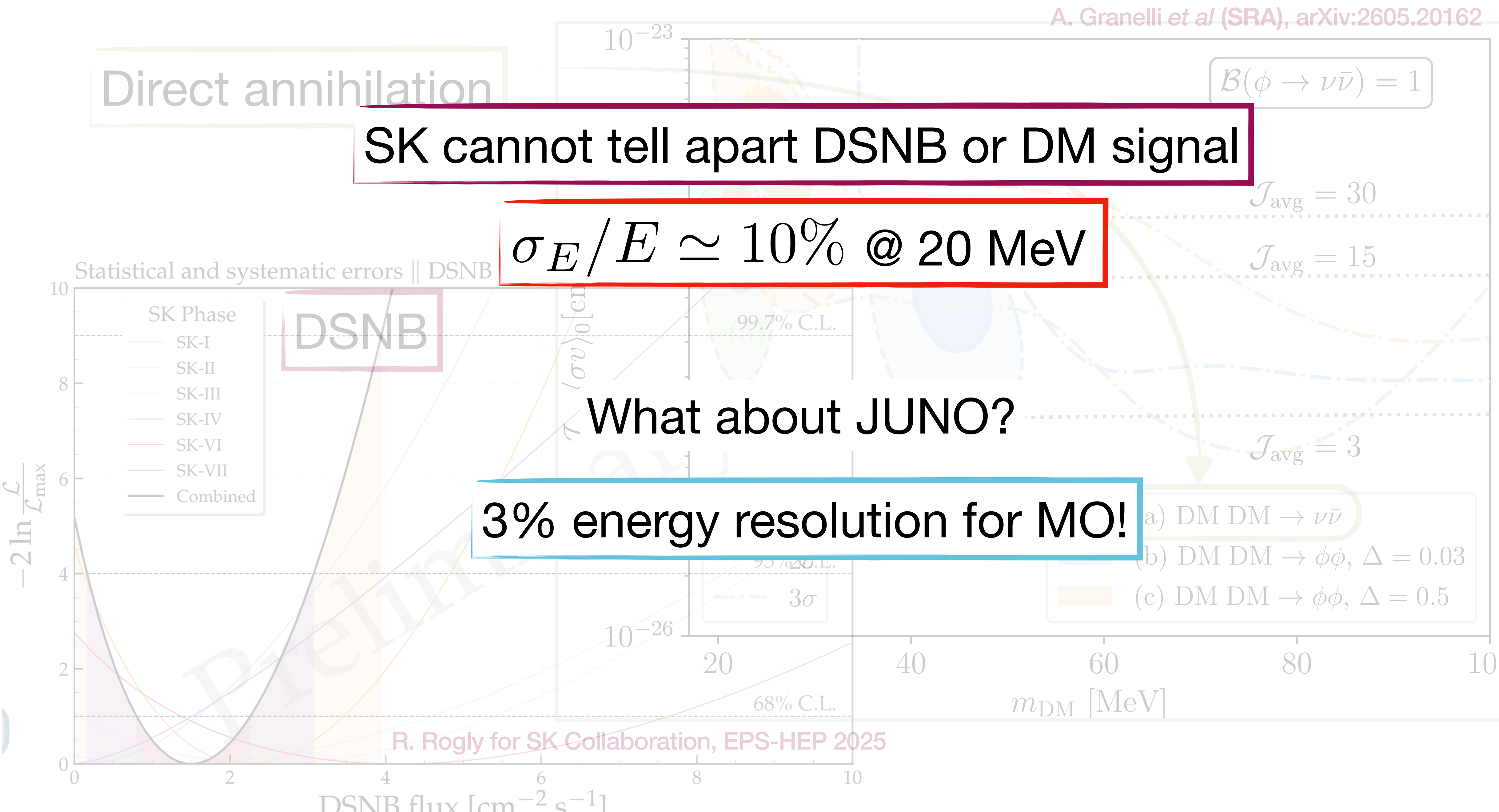


SK cannot tell apart DSNB or DM signal

$\sigma_E/E \simeq 10\%$ @ 20 MeV

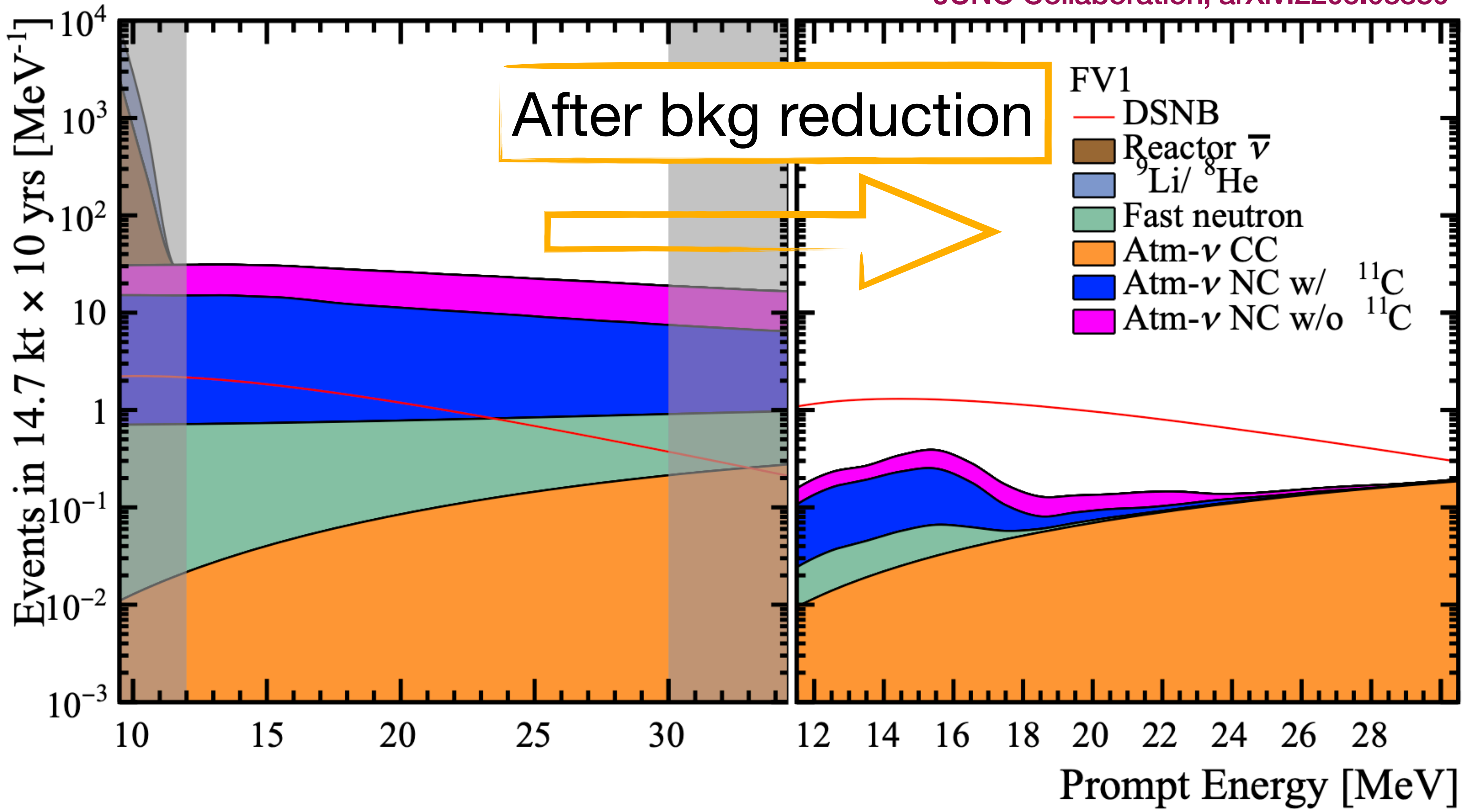
What about JUNO?

3% energy resolution for MO!

Expectations at JUNO

Can we differentiate the DSNB from a monochromatic flux?

JUNO Collaboration, arXiv:2205.08830



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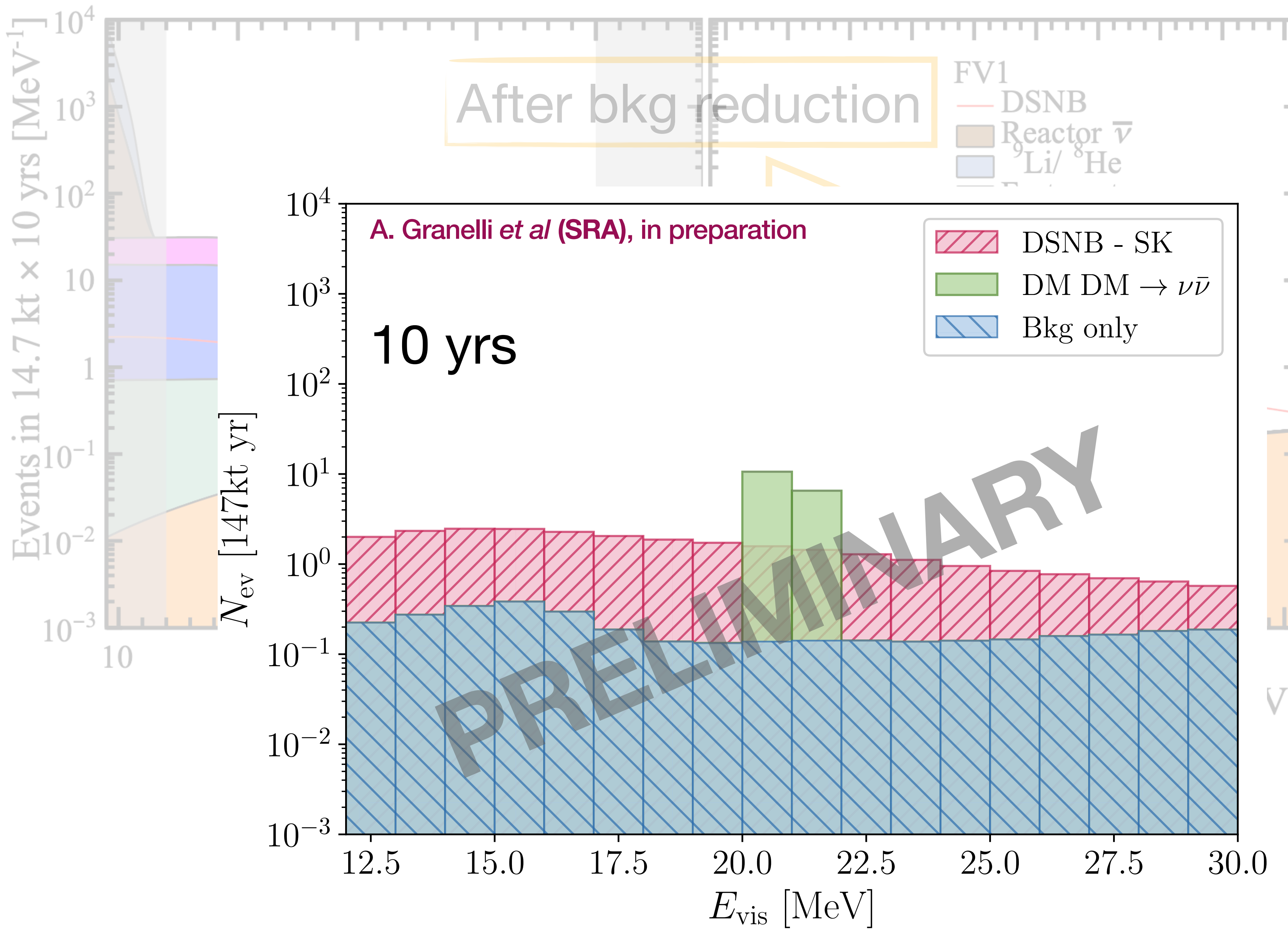

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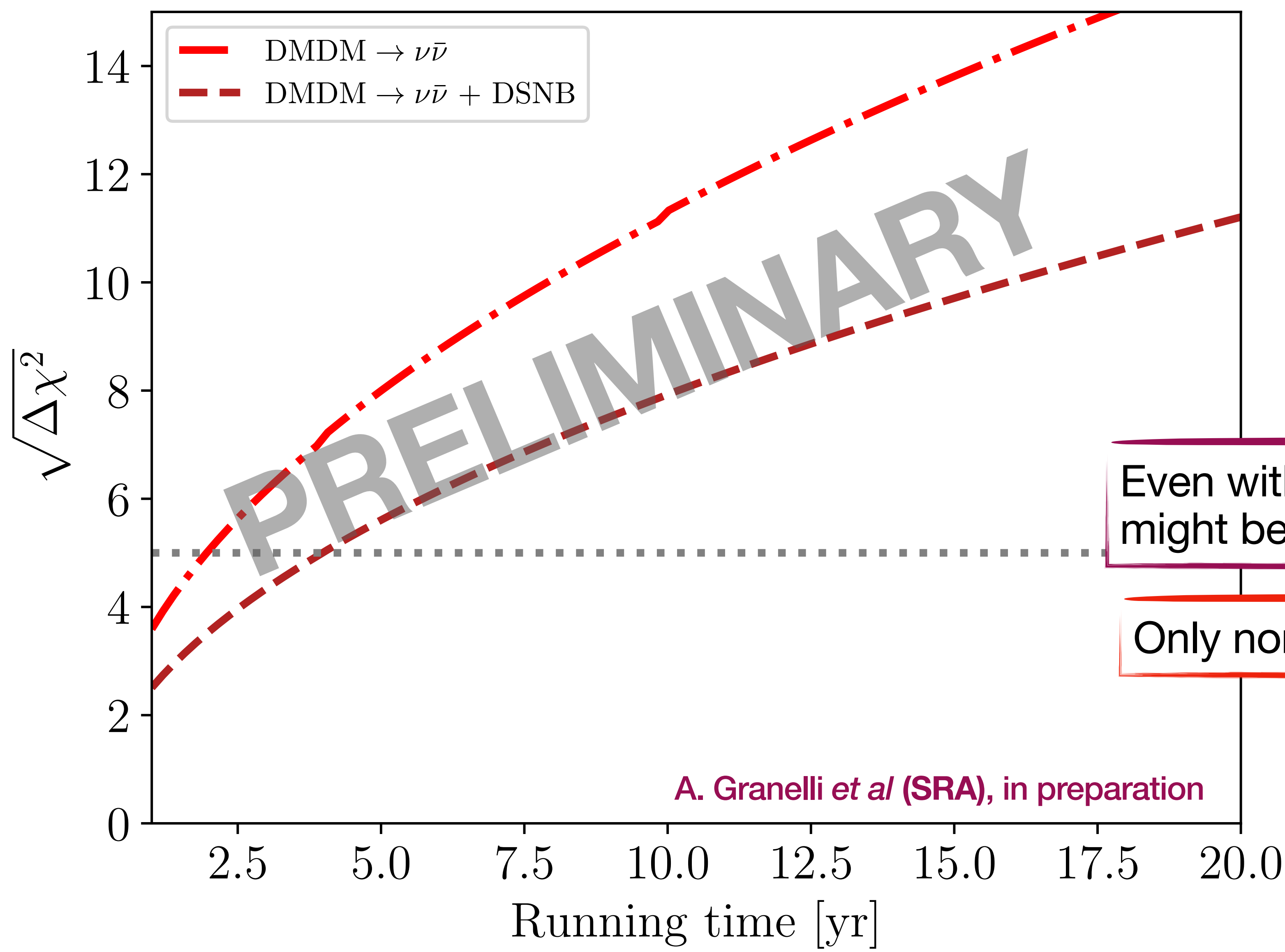


Even with DSNB as bkg JUNO might be able to tell signals apart

Only normalization systematics!

Conclusions

$\mathrm{DM} - \nu$ **interactions?**

Relic abundance through freeze-out

$$\boxed{\langle\sigma v\rangle \sim 4 \times 10^{-26}\mathrm{cm}^3/s}$$

Possible e.g. through neutrino portal with N_R

Avoid usual (in)direct searches

Conclusions

$\mathrm{DM} - \nu$ interactions?

Relic abundance through freeze-out

$\langle \sigma v \rangle \sim 4 \times 10^{-26} \mathrm{cm}^3/s$

Possible e.g. through neutrino portal with N_R

Avoid usual (in)direct searches

Search for them in large detectors!

We recast latest DSNB analysis in SK to explore $\mathrm{DM\,DM} \to \nu\bar{\nu}$

In terms of DM production

SK excess compatible with $\langle \sigma v \rangle \sim 4 \times 10^{-26} \mathrm{cm}^3/s$

SK could do their same analysis exchanging the DSNB for the DM flux!!

JUNO could differentiate between DM and DSNB!

Back up slides

Origin of neutrino masses

Type-I Seesaw

Introduce **RH counterpart**, as for any other SM fermion

$$\mathscr{L} \supset -\bar{L}_L Y_\nu \tilde{H} N_R - \frac{1}{2}\bar{N}^c_R M N_R + h.c.$$

$$U^T \mathscr{M}_\nu U \simeq \begin{pmatrix} N^T & -\theta^* \\ \theta^T & X^T \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix} \begin{pmatrix} N & \theta \\ -\theta^\dagger & X \end{pmatrix} = \begin{pmatrix} m_{\text{light}} & 0 \\ 0 & m_N \end{pmatrix}$$

$$\theta \sim m_D M^{-1} = v_H Y_\nu M^{-1}/\sqrt{2}$$

What is the scale of NP?

High-scale seesaw

$Y_\nu \sim 1, \quad M \sim \mathcal{O}(10^{15})\,\text{GeV}$ → $\theta \sim 10^{-13}$

Lightness of neutrino masses from hierarchy between v_H and M

$m_\nu \sim -m_D M^{-1} m_D^T$ M. Fukugita & T. Yanagida, '86

Leptogenesis, but **no** further **experimental signature**

Low-scale seesaw

$Y_\nu \sim 0.1, \quad M \sim \mathcal{O}(10^{2-3})\,\text{GeV}$ → $\theta \sim 10^{-2}$

Lightness of neutrino masses from approximate lepton number symmetry

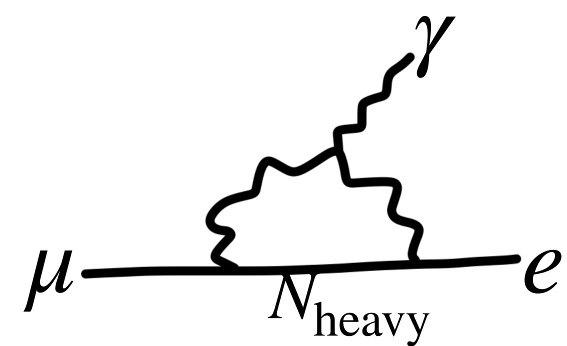
See e.g. R. Mohapatra & J. Valle, '86; M. Malinsky *et al.*, '05; B. Gavela *et al.*, '09; G. Senjanovic & F. Vissani, '11

Phenomenologically very attractive

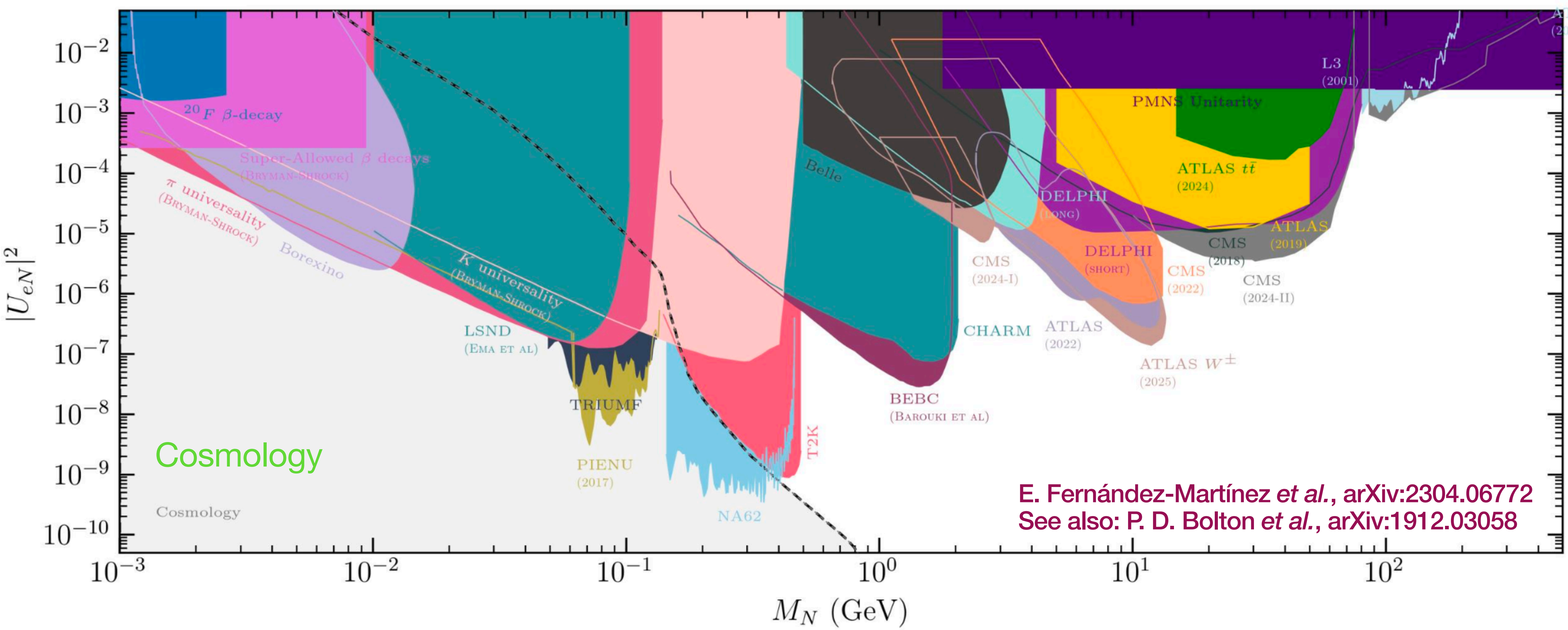
What is the NP scale?

Rich phenomenology

$$\mathscr{L} \supset -\bar{L}_L Y_\nu \tilde{H} N_R - \frac{1}{2}\bar{N}_R^c M N_R + h.c.$$



β decays Meson decays Beam dump Colliders EWPO & flavor observables



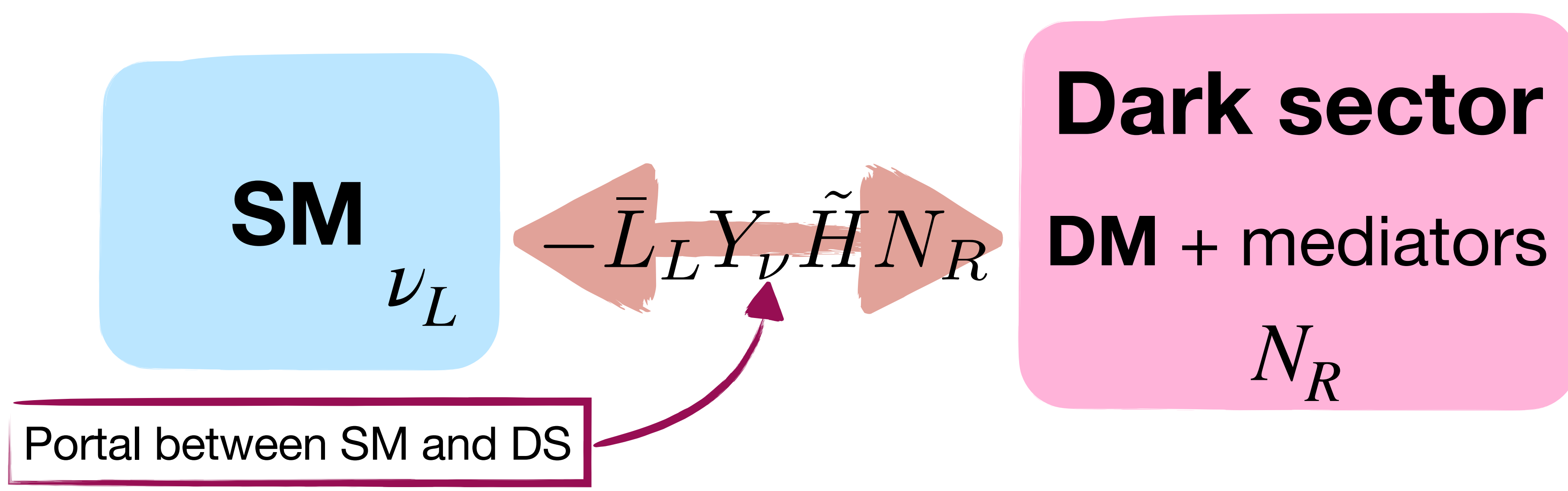
E. Fernández-Martínez *et al.*, arXiv:2304.06772
See also: P. D. Bolton *et al.*, arXiv:1912.03058

Neutrino - DM portals

SM - dark sector portals

$$\mathcal{L} \supset -\bar{L}_L Y_\nu \tilde{H} N_R - \frac{1}{2}\bar{N}_R^c M N_R + h.c.$$

SM singlet!



Only renormalizable SM coupling to singlet fermions

Other portals are:

Scalar portal ϕ, $\quad \mathscr{L} \sim \lambda_{H\phi}|\phi|^2(H^\dagger H)$

Vector portal Z'_μ, $\quad \mathscr{L} \sim -\epsilon Z'_{\mu\nu}B^{\mu\nu}$

Neutrino - DM portals

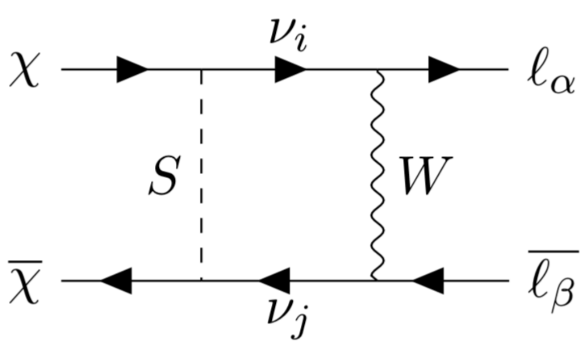
Example: Fermion DM + scalar mediator

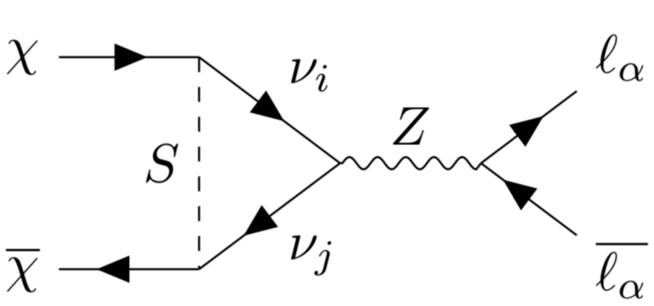
$$\mathcal{L} \supset \mathcal{L}_\nu + \bar{\chi}\left(i\partial_\mu\gamma^\mu - m_{\rm DM}\right)\chi - y_L \bar{\chi} S N_R^c + h.c.$$

After SSB we get ν masses and mixings

$$\mathcal{L}_{\rm DM-\nu} \supset y_L \theta^*_{\alpha i} \bar{\chi} S \nu_i + h.c.$$

Interactions with charged leptons and quarks are loop-suppressed!





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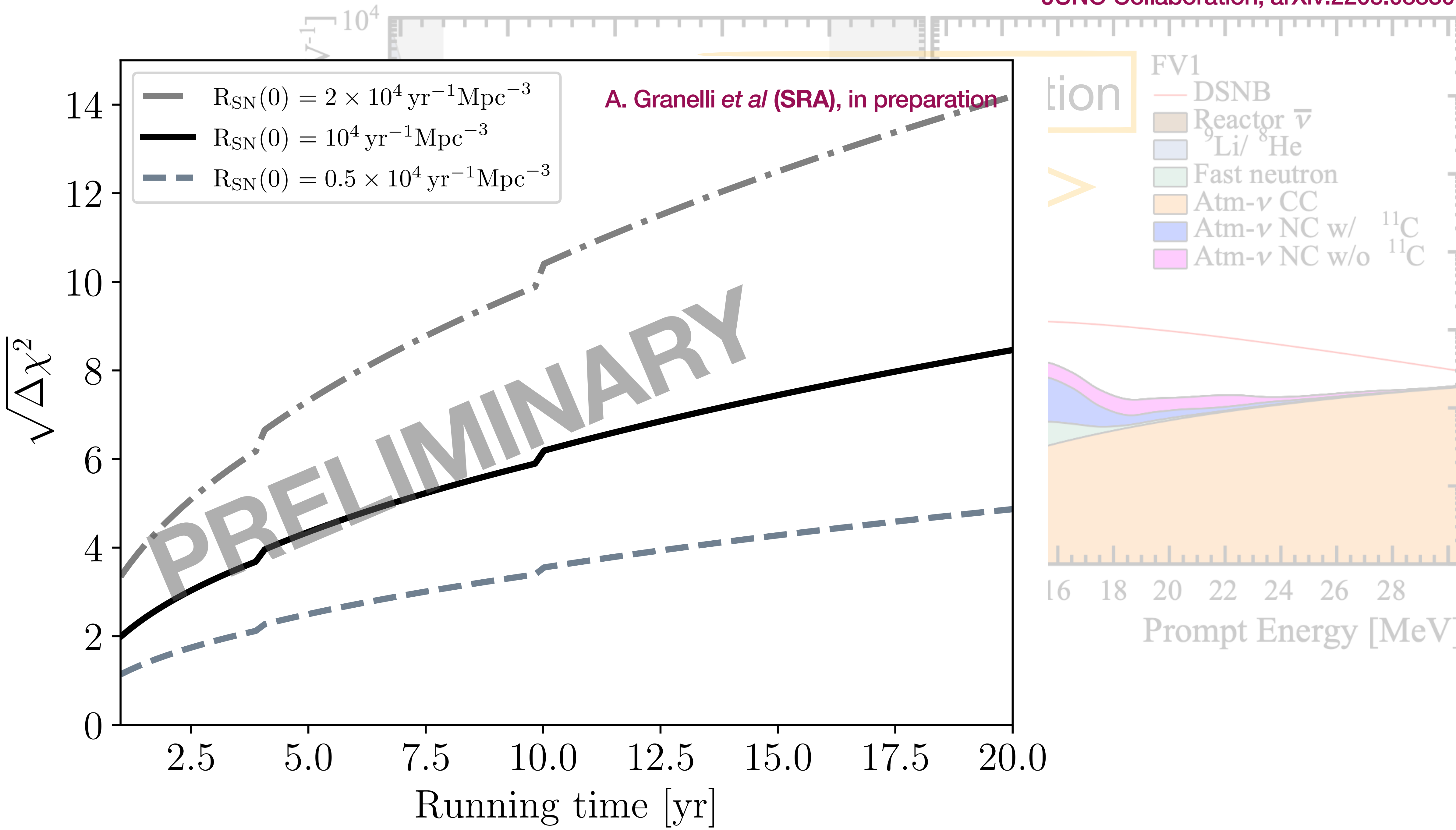

DM DM $\rightarrow \nu\,\nu$ signal

Event rate in a neutrino detector

$$A_i = N_{\rm tar} T \int_{E_{\rm vis}^i}^{E_{\rm vis}^{i+1}} dE_{\rm vis}\, \epsilon(E_{\rm vis}) \times$$

$$\int dE_e R(E_e, E_{\rm vis}) \int_{E_{\bar\nu}^{\rm min}} dE_{\bar\nu} \frac{d\sigma^{\rm IBD}}{dE_e} \frac{d\Phi_{\bar\nu}}{dE_{\bar\nu}}$$

In SK we have

$\boxed{\sigma_E/E \simeq 10\%}$ @ 20 MeV

Cannot really tell apart continuous from monochromatic signal