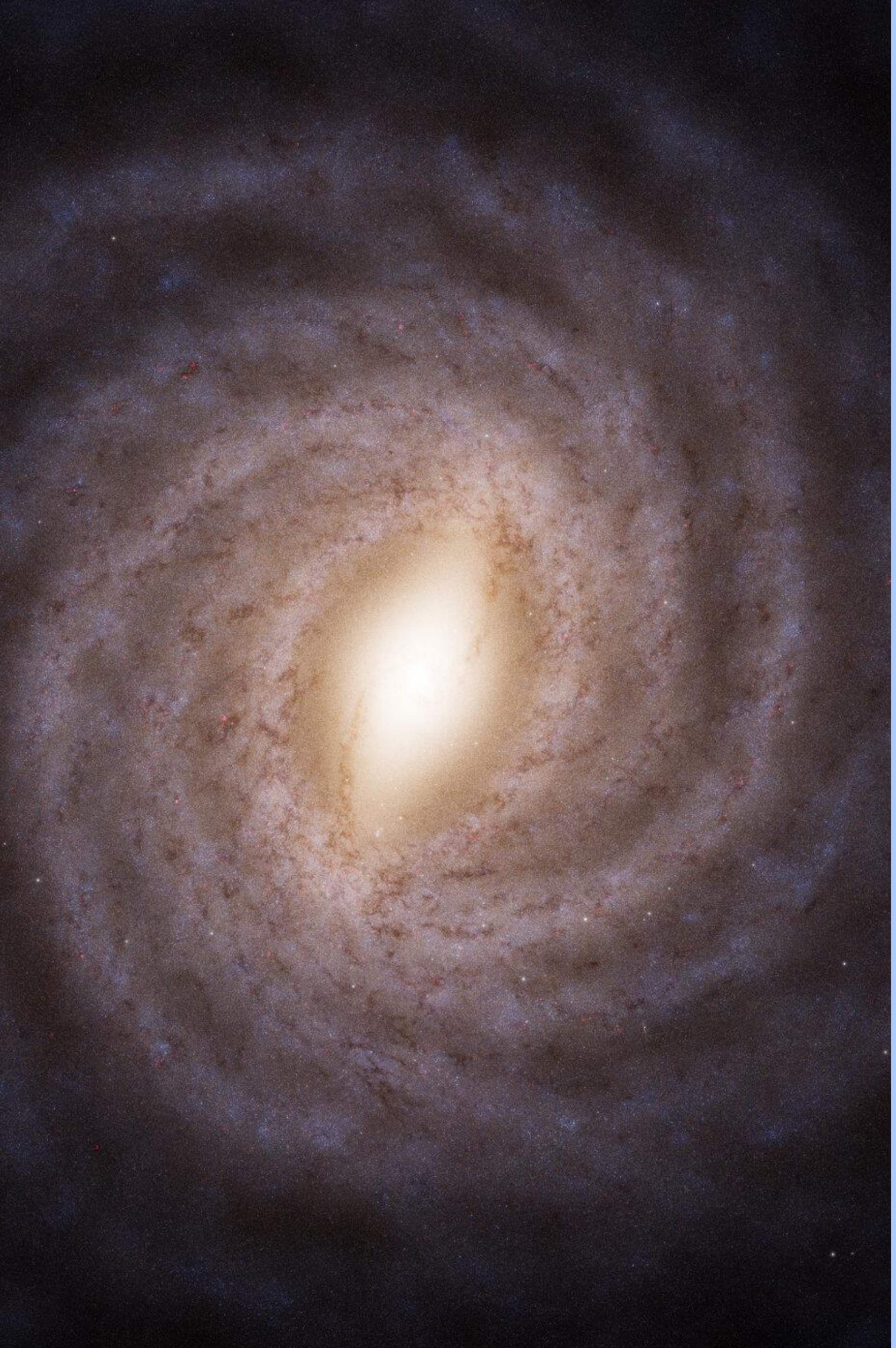


From Smooth to Stochastic: Galactic Supernova Fluxes of MeV Dark Matter and ALPs

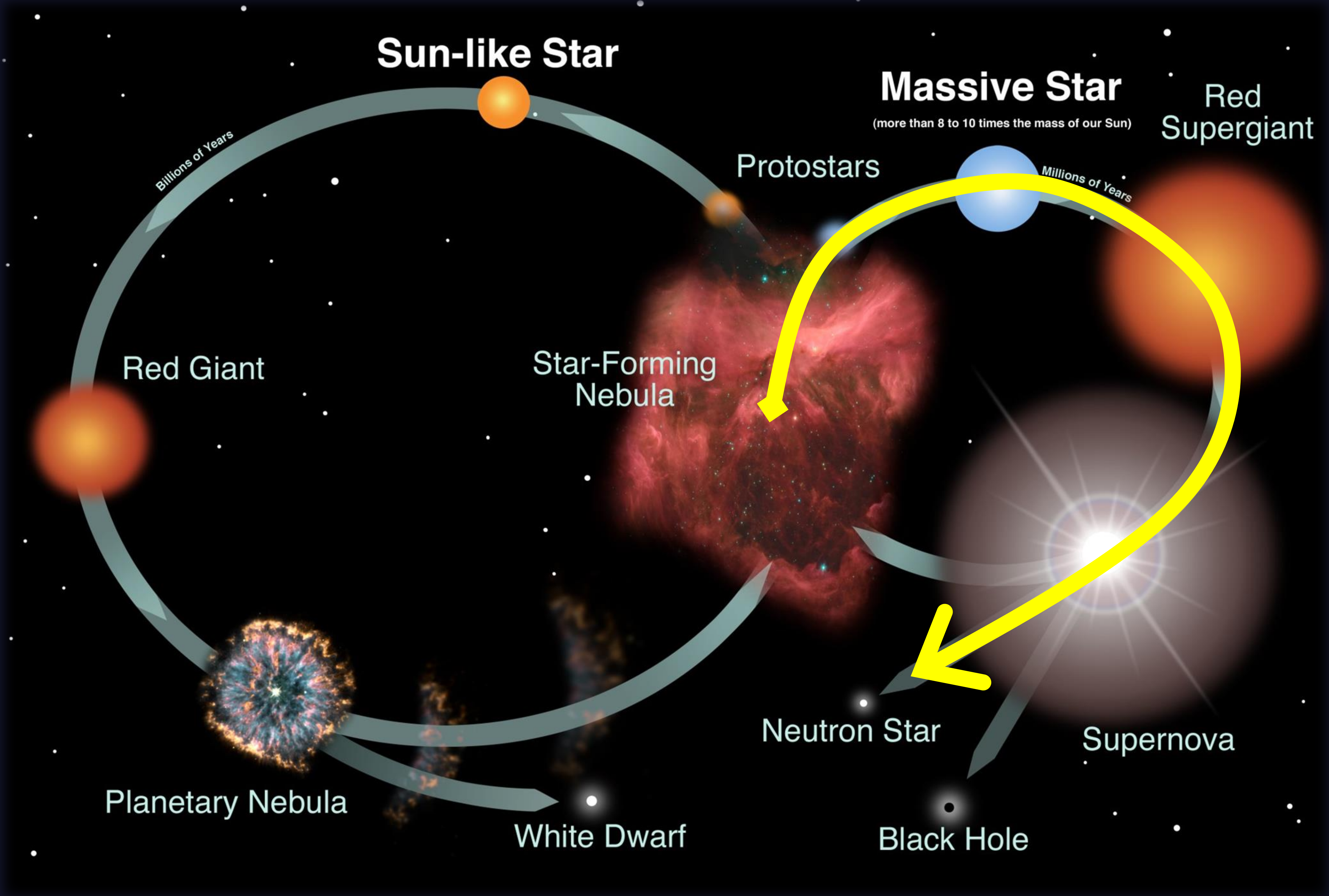
DAVID ALONSO-GONZÁLEZ (he/him)
with D. Cerdeño, M. Cermeño & A.D. Perez

Based on [2602.17597]

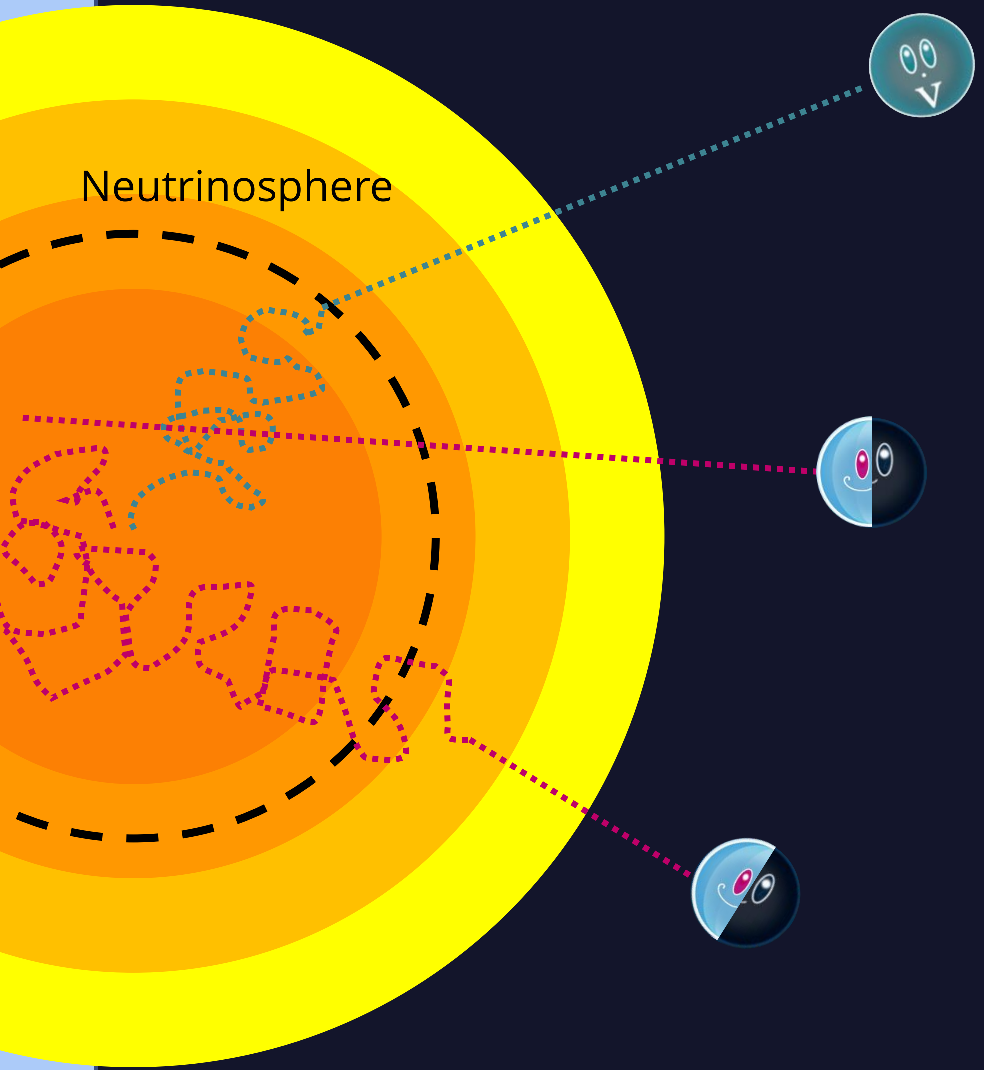
Identification of Dark Matter 2026
(June 4th, Zaragoza)

Instituto de Física Teórica UAM-CSIC
Universidad Autónoma de Madrid

david.alonsogonzalez@uam.es


Sun-like Star
Massive Star
(more than 8 to 10 times the mass of our Sun)
Red Supergiant
Protostars
Billions of Years
Millions of Years
Red Giant
Star-Forming Nebula
Planetary Nebula
White Dwarf
Neutron Star
Supernova
Black Hole

Weakly interacting particles in SNe



Neutrinos are produced in the interior of the proto-NS. They are trapped and diffuse out until they reach colder and less dense layers where their mean free path increases.

$$\underbrace{\text{Diffusion time} \sim 1\text{ s} \qquad \text{Total energy} \sim 10^{53}\text{ erg}}_{\text{SN 1987A}}$$

New, weakly interacting particles (DM, ALPs) can be also produced:

Coupling to SM

→ **trapping regime:** reabsorption becomes relevant…

…but particles may still escape!

free-streaming regime:

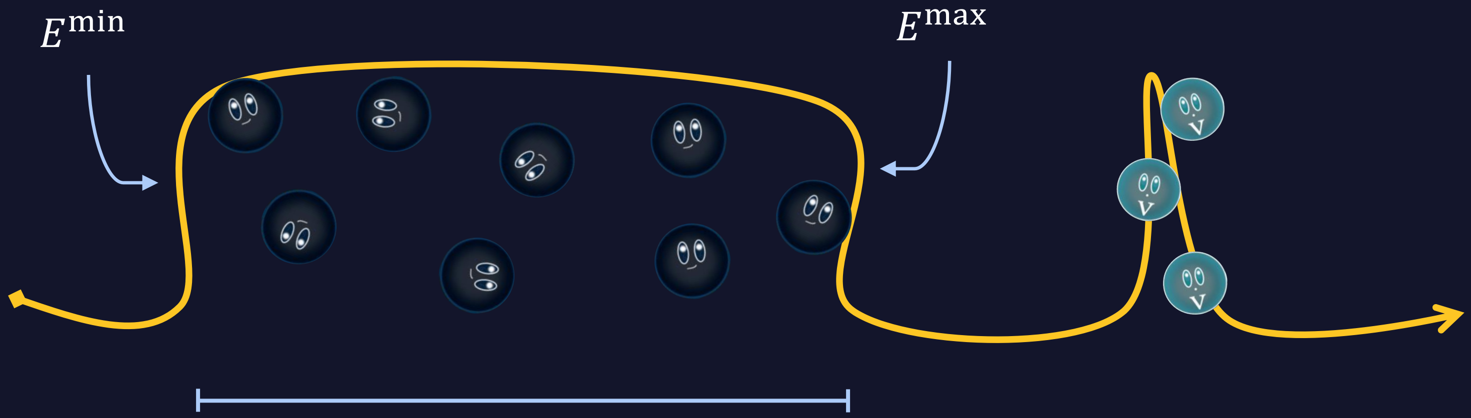
→ less energy for neutrinos
→ reduce the duration of neutrino signal

→ **cooling bound!**

→ very small coupling: not enough exotic particles are produced

MeV particle flux from galactic SNe

Neutrinos are ~ massless → once they are emitted, they travel to Earth at the speed of light, regardless of their energy.



$$\Delta t = t\left(E^{\min}\right) - t\left(E^{\max}\right) \quad \text{with } t(E) = \frac{d_{\mathrm{SN}}}{\sqrt{1-\left(\frac{m}{E}\right)^2}}$$

(not to scale!)

Exotic particles with $m \geq 1$ MeV would be emitted with a spread of semi relativistic velocities → Difference in arrival times from the high- and low- velocity particles

Diffuse MeV particle flux from galactic SNe

For a SN at the Galactic Center, particles with $\boldsymbol{m} \approx$ **1−100 MeV** will arrive at Earth in a time window of $\boldsymbol{\Delta t \approx 5 \times \left(10^2\text{–}10^3\right)}$ **yrs**

Since the galactic SN rate is
$\sim$ **1.63 events per century**
we expect that
$\sim$ **10−100 SN fluxes**
overlap at Earth at the same time

→ near constant
diffuse MeV particle flux!

Smooth Approximation

Galactic SN Rate:

$$\frac{dn_{\mathrm{SN}}}{dt} = A\, e^{-\frac{r}{R_d}}\, e^{-\frac{|z|}{H}}$$

For core-collapse SNe:

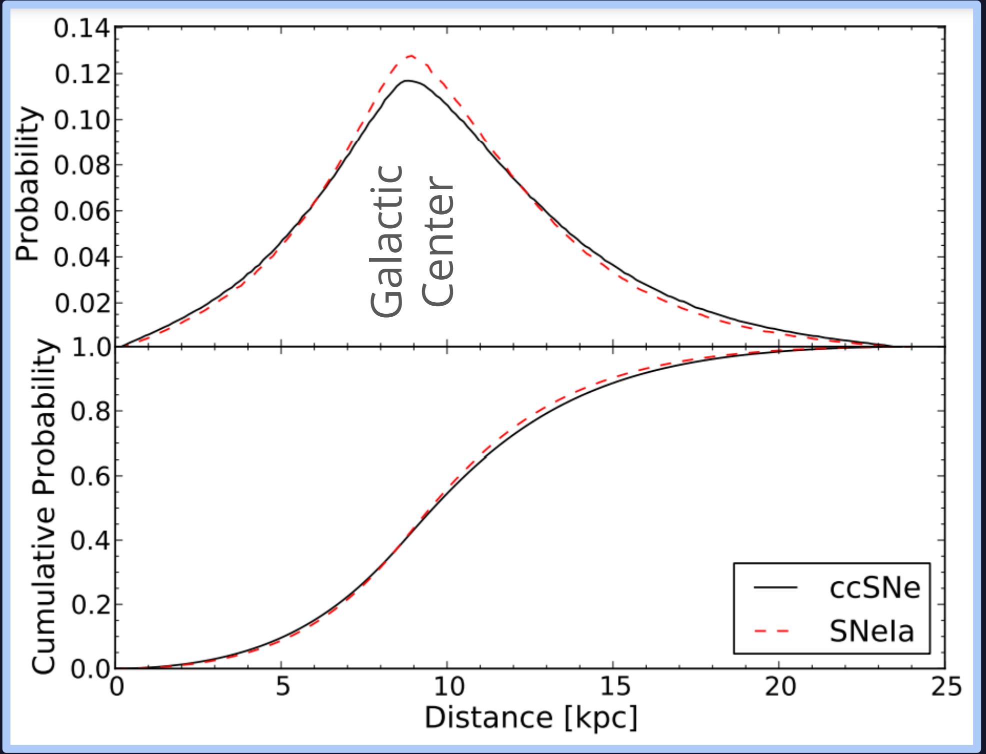
$R_d = 2.6$ kpc

$H = 0.3$ kpc

$A = 1.65 \times 10^{-3}$ kpc^{-3} yr^{-1}

↑

1.63 SN per century!



Adams et al. ApJ 778 (2013) 164

Diffuse Galactic SN MeV Particle Flux arriving at Earth:

$$\frac{d\Phi}{dE^{\mathrm{Earth}}} = \underbrace{\frac{dN}{dE^{\mathrm{Earth}}}}_{\uparrow\ \text{spectrum from a single SN}} \underbrace{\int_{-\infty}^{\infty}\int_{0}^{2\pi}\int_{0}^{\infty} \frac{dn_{\mathrm{SN}}}{dt} \frac{r}{4\pi\left(\vec{r} - \vec{R}_E\right)^2}\, dr\, d\theta\, dz}_{\text{flux factor}}$$

$R_E = 8.7$ kpc

Smooth Approximation

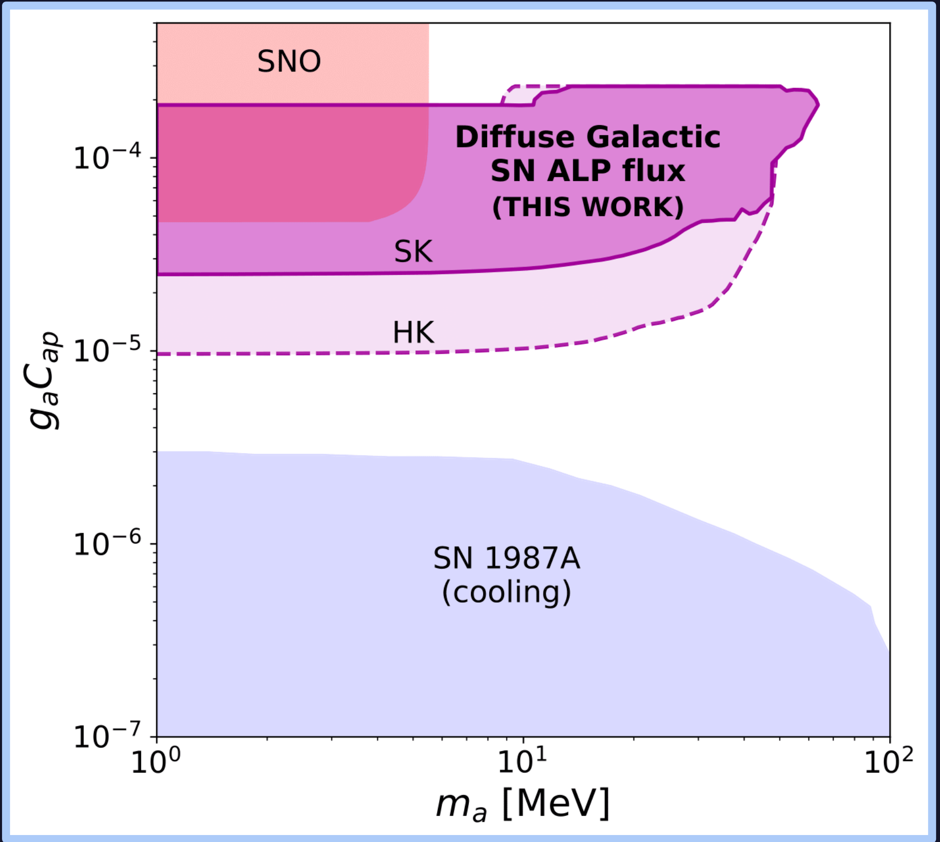
This has been used to derive bounds on exotic particle models:

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E^{\mathrm{Earth}}} = 1.3 \times 10^{-55}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \frac{\mathrm{d}N}{\mathrm{d}E^{\mathrm{Earth}}}$$

↑ flux factor

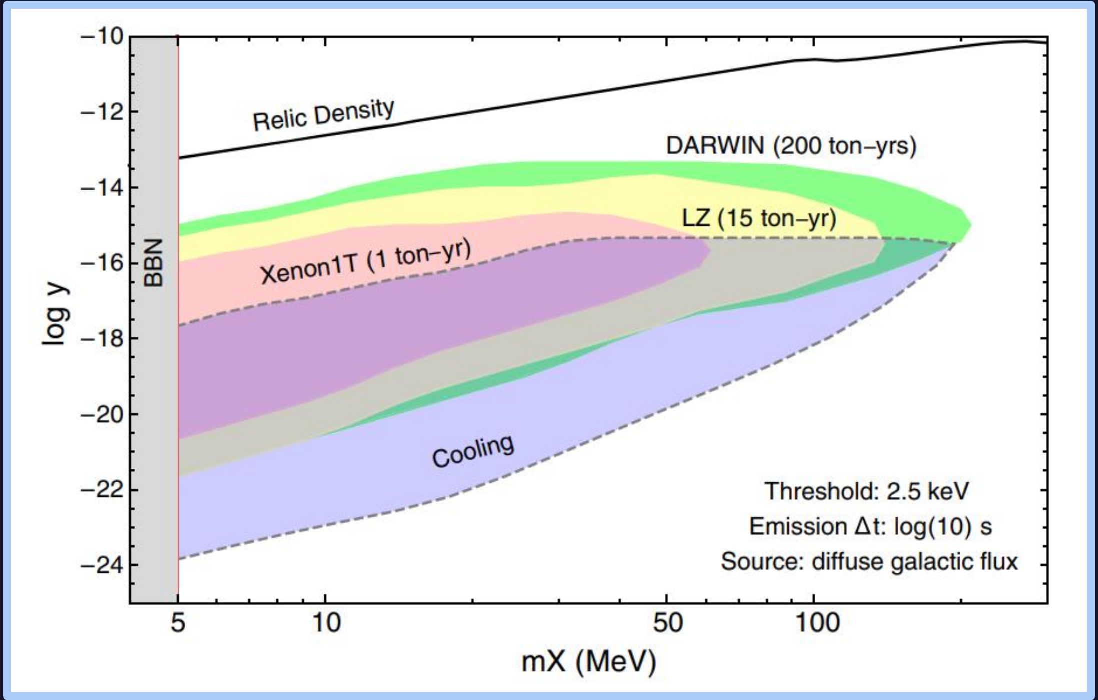
↑ spectrum from a single SN

ALPs



DAG et al. *Phys. Rev. D 111, 083019*

Light Dark Matter

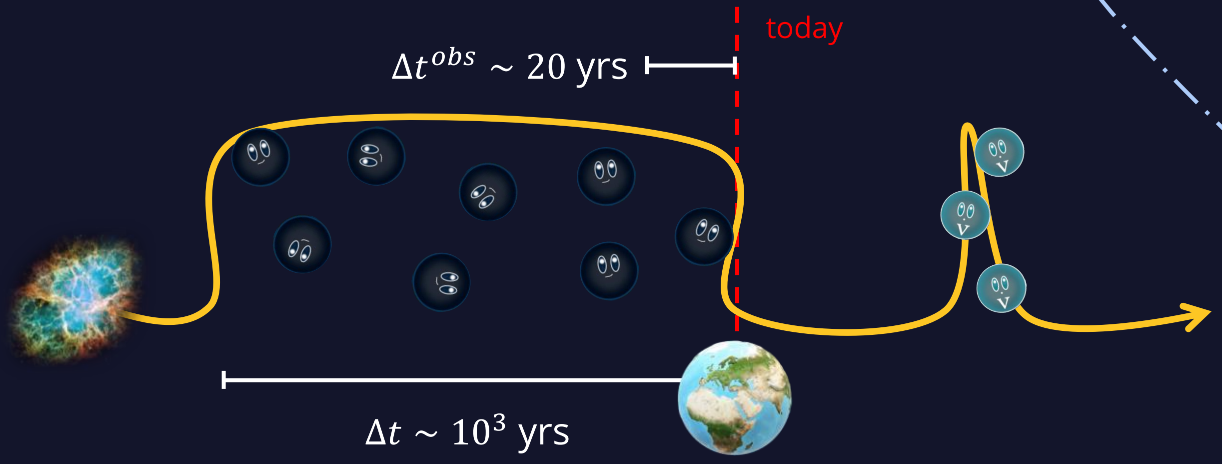


DeRocco et al. *Phys. Rev. D 100, 075018*

Smooth Approximation

Two key effects are missing from this approximation:

1) The observational time window in the experiment is finite and small

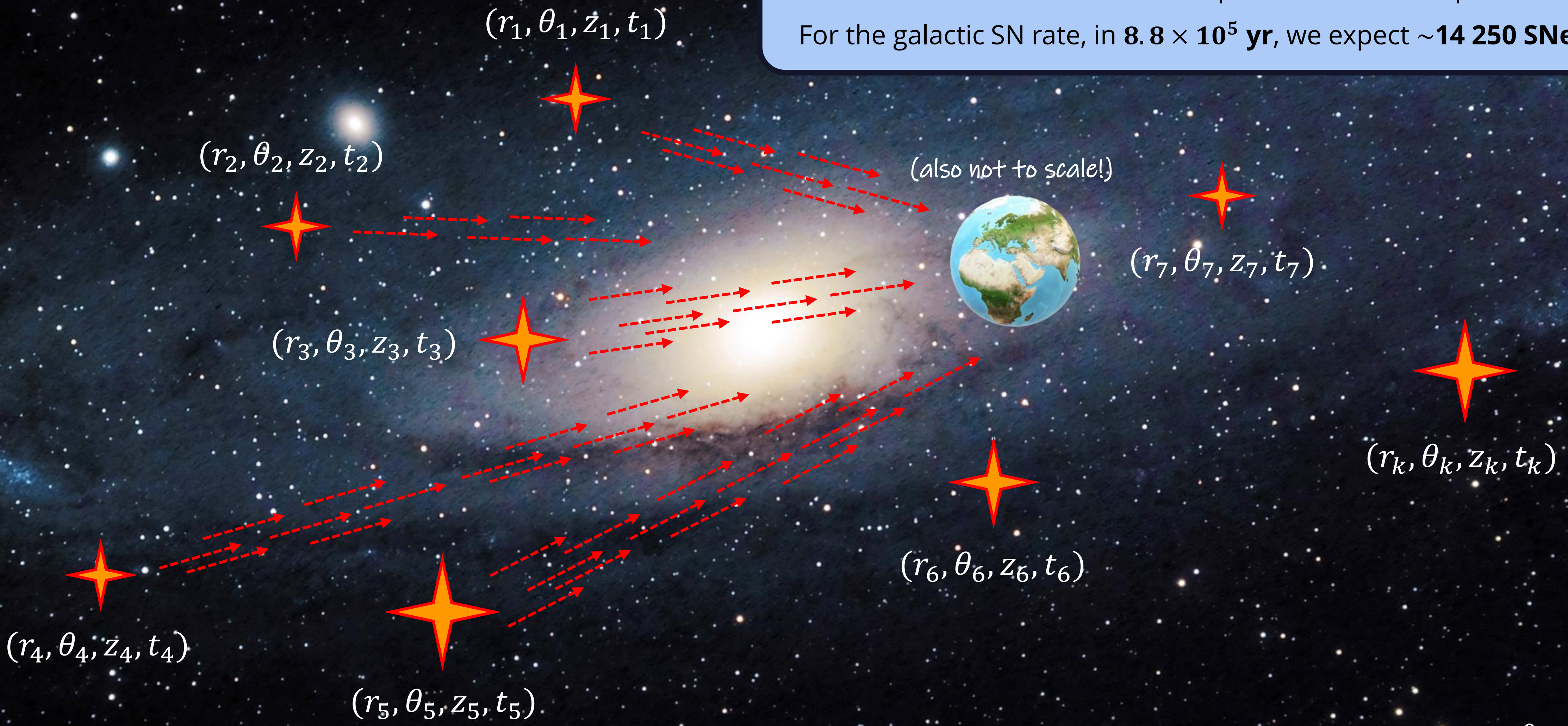


2) For some SNe, particles arriving at Earth have too little energy, since the energetic ones have already passed.

Stochastic Approach

In order to determine the exact galactic flux at Earth, one would need to know the location and explossion time of all past SNe.

For the galactic SN rate, in $\mathbf{8.8 \times 10^5}$ **yr**, we expect ~**14 250 SNe.**



Numerical Simulation

Galactic SN Rate:

$$\frac{\mathrm{d}n_{\mathrm{SN}}}{\mathrm{d}t} = A\, e^{-\frac{r}{R_d}}\, e^{-\frac{|z|}{H}}$$

For core-collapse SNe:

$$R_d = 2.6 \text{ kpc}$$

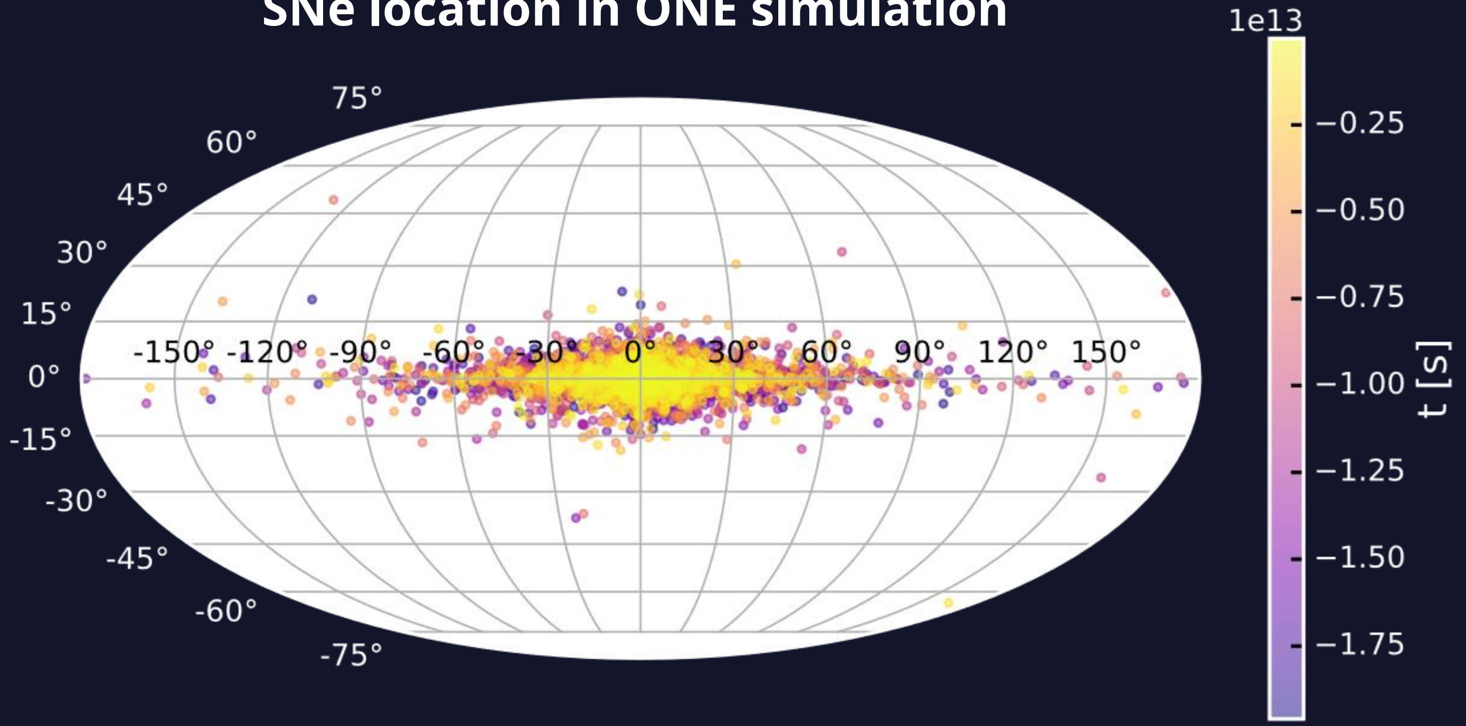
$$H = 0.3 \text{ kpc}$$

$$A = 1.65 \times 10^{-3} \text{ kpc}^{-3} \text{ yr}^{-1}$$

↑

1.63 SN per century!

SNe location in ONE simulation



Flux from galactic SNe

Smooth Approximation

flux factor

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E^{\mathrm{Earth}}} = \frac{\mathrm{d}N}{\mathrm{d}E^{\mathrm{Earth}}} \int_{-\infty}^{\infty} \int_{0}^{2\pi} \int_{0}^{\infty} \frac{\mathrm{d}n_{\mathrm{SN}}}{\mathrm{d}t} \frac{r}{4\pi \left(\vec{r} - \vec{R}_E\right)^2} \,\mathrm{d}r \,\mathrm{d}\theta \,\mathrm{d}z = \bar{\Phi} \frac{\mathrm{d}N}{\mathrm{d}E^{\mathrm{Earth}}}$$

spectrum from a single SN

Stochastic Approach

sum over every SN contribution

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E^{\mathrm{Earth}}}(t) = \sum_k \frac{1}{4\pi d_k^2} \frac{\mathrm{d}N_k}{\mathrm{d}E^{\mathrm{Earth}}} \,\delta\left(t - t_{\mathrm{arr}}\left(E^{\mathrm{Earth}}\right)\right)$$

the arrival time depends on:

- the time of the SN event
- the travel time

$$\frac{d_{\mathrm{SN}}}{v(E)} = \frac{d_{\mathrm{SN}}}{\sqrt{1 - \left(\frac{m}{E}\right)^2}}$$

Flux from galactic SNe

Smooth Approximation

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E^{\mathrm{Earth}}} = \frac{\mathrm{d}N}{\mathrm{d}E^{\mathrm{Earth}}} \int_{-\infty}^{\infty} \int_{0}^{2\pi} \int_{0}^{\infty} \frac{\mathrm{d}n_{\mathrm{SN}}}{\mathrm{d}t} \frac{r}{4\pi \left(\vec{r} - \vec{R}_E\right)^2} \,\mathrm{d}r\, \mathrm{d}\theta\, \mathrm{d}z = \bar{\Phi} \frac{\mathrm{d}N}{\mathrm{d}E^{\mathrm{Earth}}}$$

$$\int_{t_0}^{t_0+\Delta t} \frac{\mathrm{d}\Phi}{\mathrm{d}E^{\mathrm{Earth}}} = \bar{\mathcal{F}} \frac{\mathrm{d}N}{\mathrm{d}E^{\mathrm{Earth}}}$$

with $\bar{\mathcal{F}} = \Delta t\, \bar{\Phi}$

Smooth fluence factor

Stochastic Approach

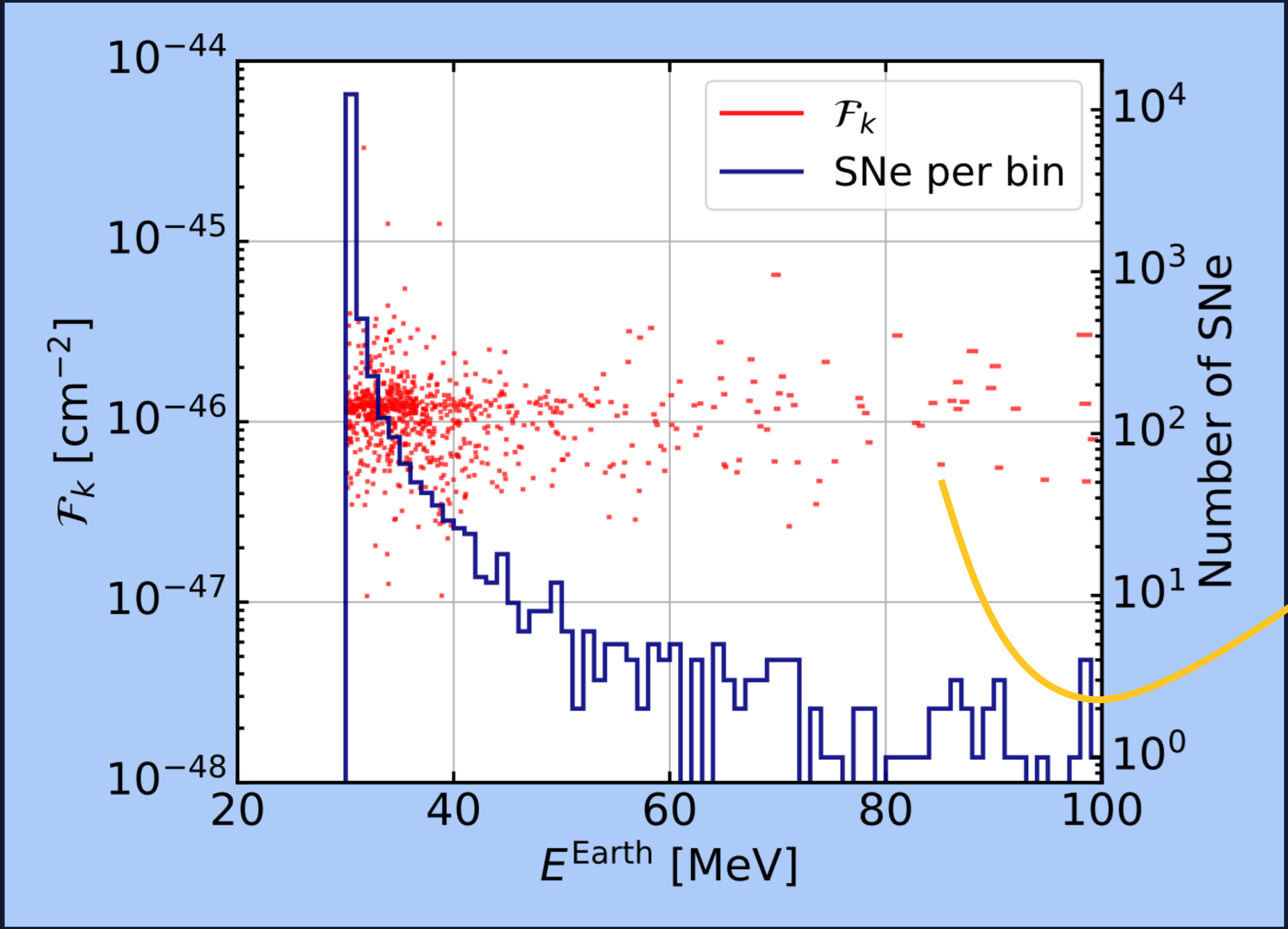
$$\frac{\mathrm{d}\Phi}{\mathrm{d}E^{\mathrm{Earth}}}(t) = \sum_k \frac{1}{4\pi d_k^2} \frac{\mathrm{d}N_k}{\mathrm{d}E^{\mathrm{Earth}}} \,\delta\left(t - t_{\mathrm{arr}}\left(E^{\mathrm{Earth}}\right)\right)$$

$$\int_{t_0}^{t_0+\Delta t} \frac{\mathrm{d}\Phi}{\mathrm{d}E^{\mathrm{Earth}}}(t) = \sum_k \frac{1}{4\pi d_k^2} \frac{\mathrm{d}N_k}{\mathrm{d}E^{\mathrm{Earth}}} \Theta\left(E^{\mathrm{Earth}} - E_k^{\mathrm{min}}\right) \Theta\left(E^{\mathrm{Earth}} - E_k^{\mathrm{max}}\right) =$$

$$= \frac{\mathrm{d}N}{\mathrm{d}E^{\mathrm{Earth}}} \sum_k \mathcal{F}_k\left(E^{\mathrm{Earth}}\right) = \frac{\mathrm{d}N}{\mathrm{d}E^{\mathrm{Earth}}} \mathcal{F}\left(E^{\mathrm{Earth}}\right)$$

Stochastic fluence factor

Fluence factor in ONE simulation

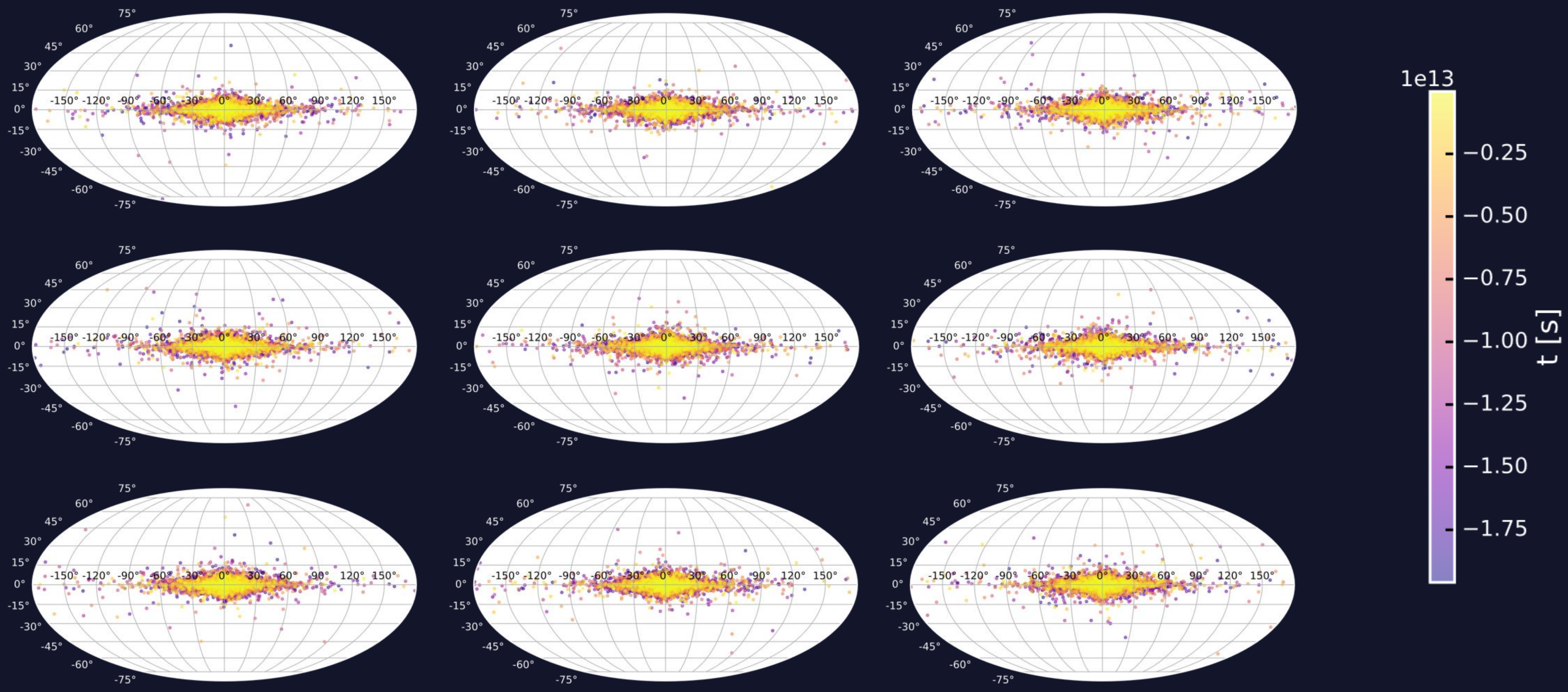


$\Delta t^{\mathrm{obs}} = 20$ yr
$m = 30$ MeV

each red line is the contribution of 1 SN in the energy bin

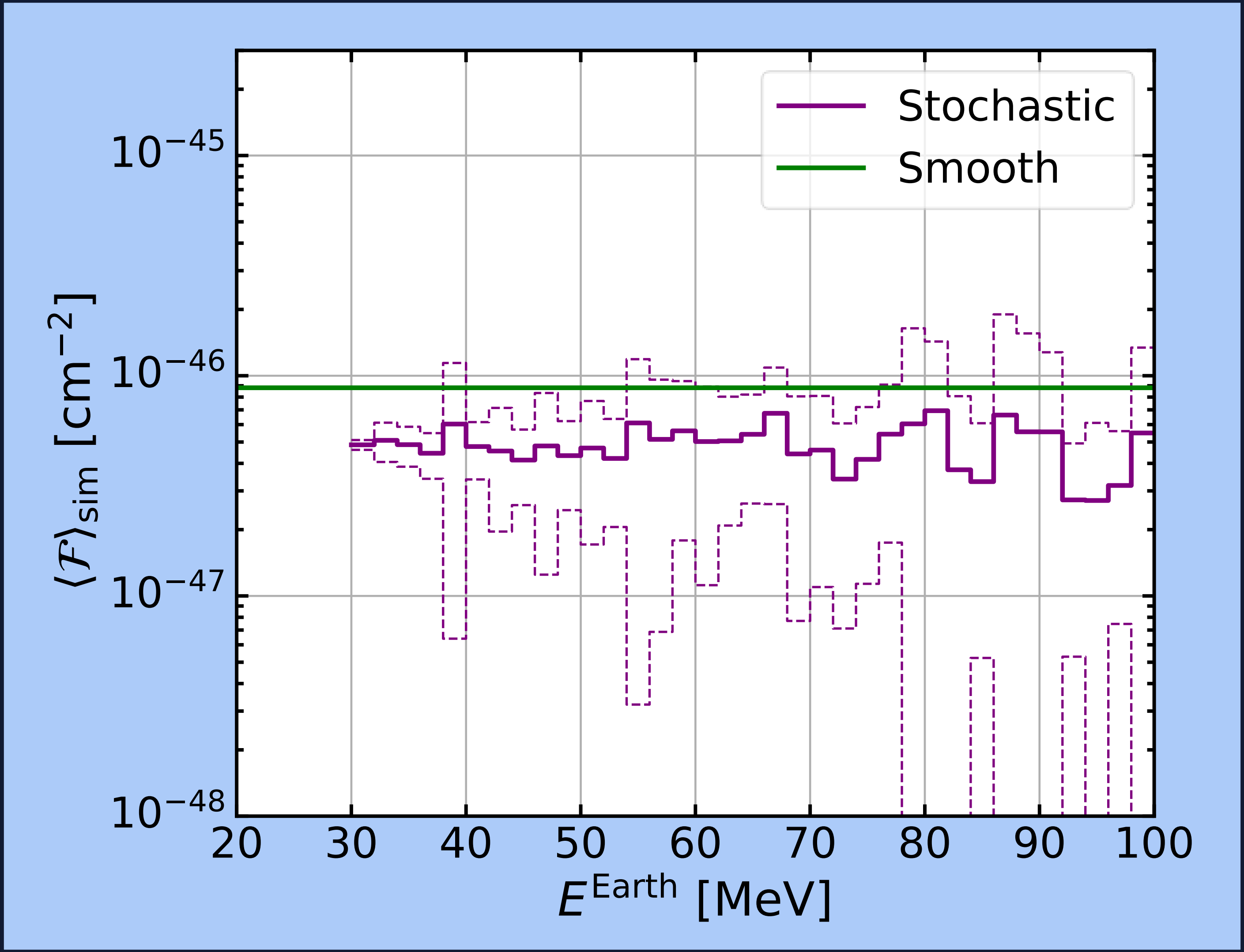
Numerical Simulation

https://github.com/AndresDanielPerez/SGaSNoF



We perform a total of 20 simulations!

Fluence factor over 20 simulations



$\Delta t^{\rm obs} = 20$ yr
$m = 30$ MeV

mean fluence factor per energy bin and per Universe simulation:

$$\langle \mathcal{F}(E_j) \rangle_{\rm sim} = \frac{1}{\Delta E_j} \left\langle \int_{E_j}^{E_{j+1}} \mathcal{F}(E)\ dE \right\rangle_{\rm sim}$$

Dark Matter

MODEL dark fermions χ mediated by a heavy dark photon A' with gauge coupling g_D that kinetically mixes with the SM with mixing parameter ϵ

$$\mathcal{L}_{\text{int}} = \frac{e\epsilon g_D}{\Lambda^2}\bar{\chi}\gamma_\mu\chi J^\mu_{\text{em}}$$

two parameters

$$\begin{cases} m_\chi & : \textbf{DM mass} \\ y = \epsilon^2\alpha_D\left(\dfrac{m_\chi}{m_{A'}}\right) & : \textbf{coupling} \end{cases}$$

PRODUCTION IN SN dominant production channels are:

- ❖ electron-positron annihilation: $e^-e^+ \to \bar{\chi}\chi$
- ❖ neutron-proton bremsstrahlung: $np \to np\bar{\chi}\chi$

relevant processes in the trapping regime:

- ❖ DM annihilation into electron-positron: $\bar{\chi}\chi \to e^-e^+$
- ❖ scattering on free electrons: $\chi e \to \chi e$
- ❖ scattering on free protons: $\chi p \to \chi p$

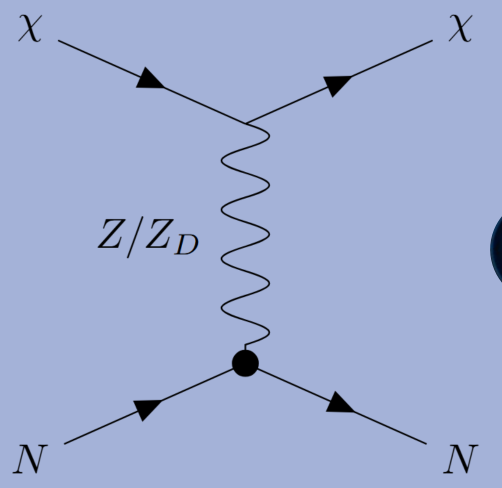
thermal exchange with plasma

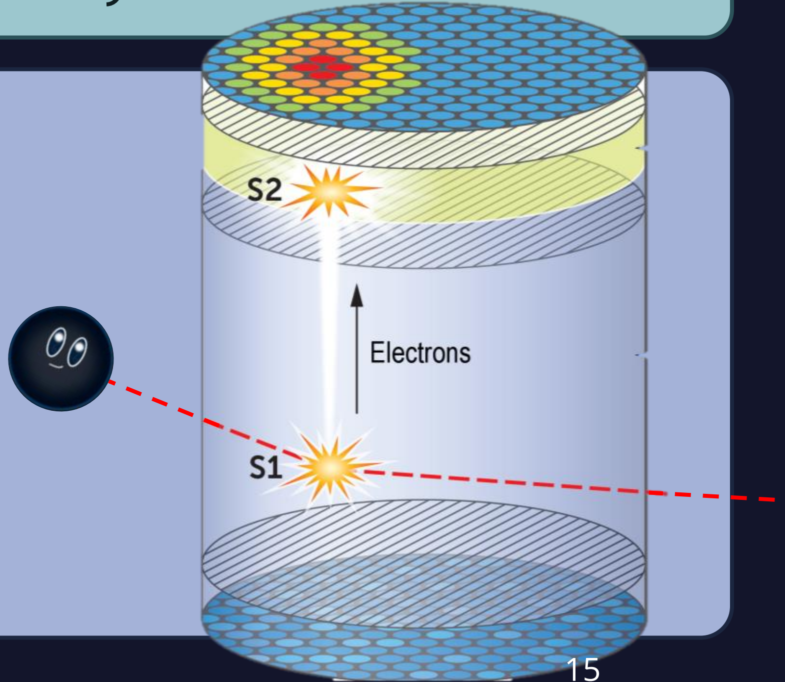
DETECTION AT EARTH

nuclear recoils at dark matter direct detection experiments based on Xenon

- LZ (4.2 ton yr)
- XENONnT (3.1 ton yr)
- PandaX-4T (1.54 ton yr)

$$\frac{\mathrm{d}N}{\mathrm{d}E_{rec}} = N_t \int_{E_\chi^{\min}} \mathrm{d}E_\chi^{\text{Earth}} \frac{\mathrm{d}\Phi_\chi}{\mathrm{d}E_\chi^{\text{Earth}}} \frac{\mathrm{d}\sigma_{\chi\text{Xe}}}{\mathrm{d}E_{\text{rec}}}$$

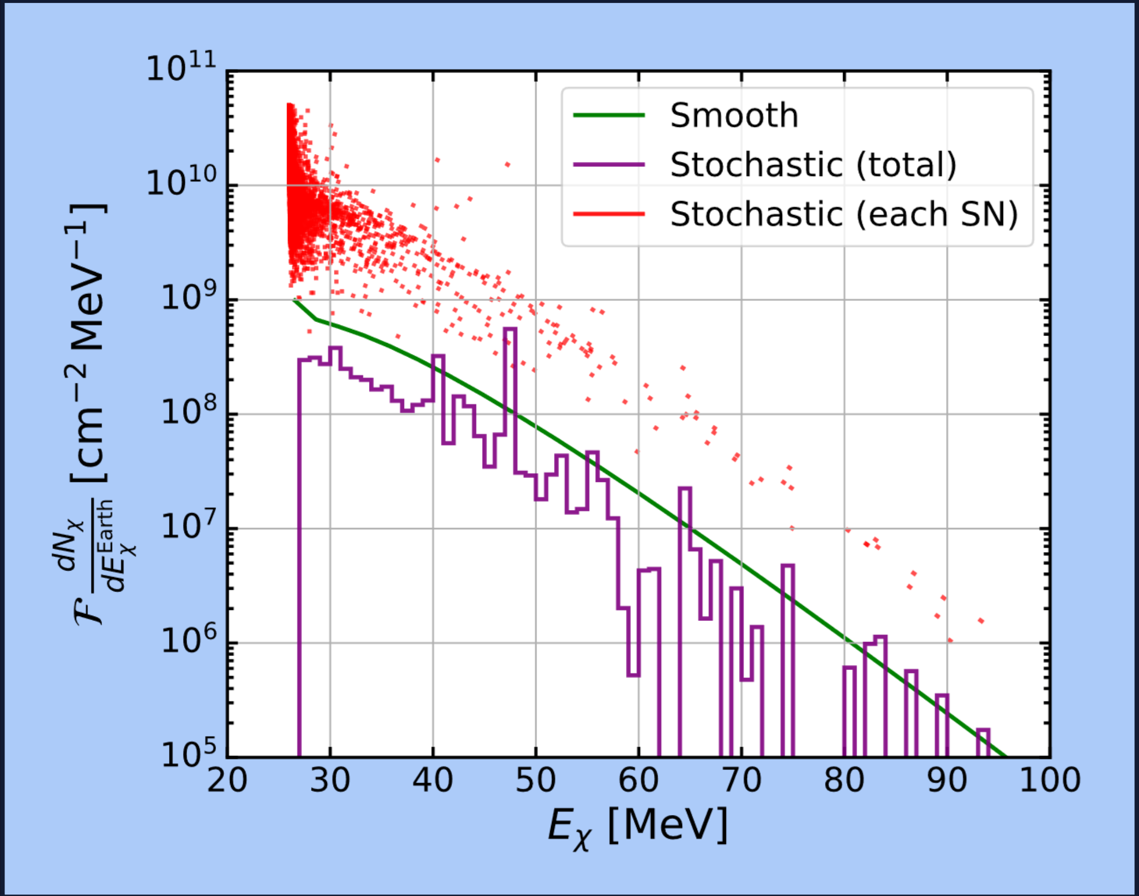


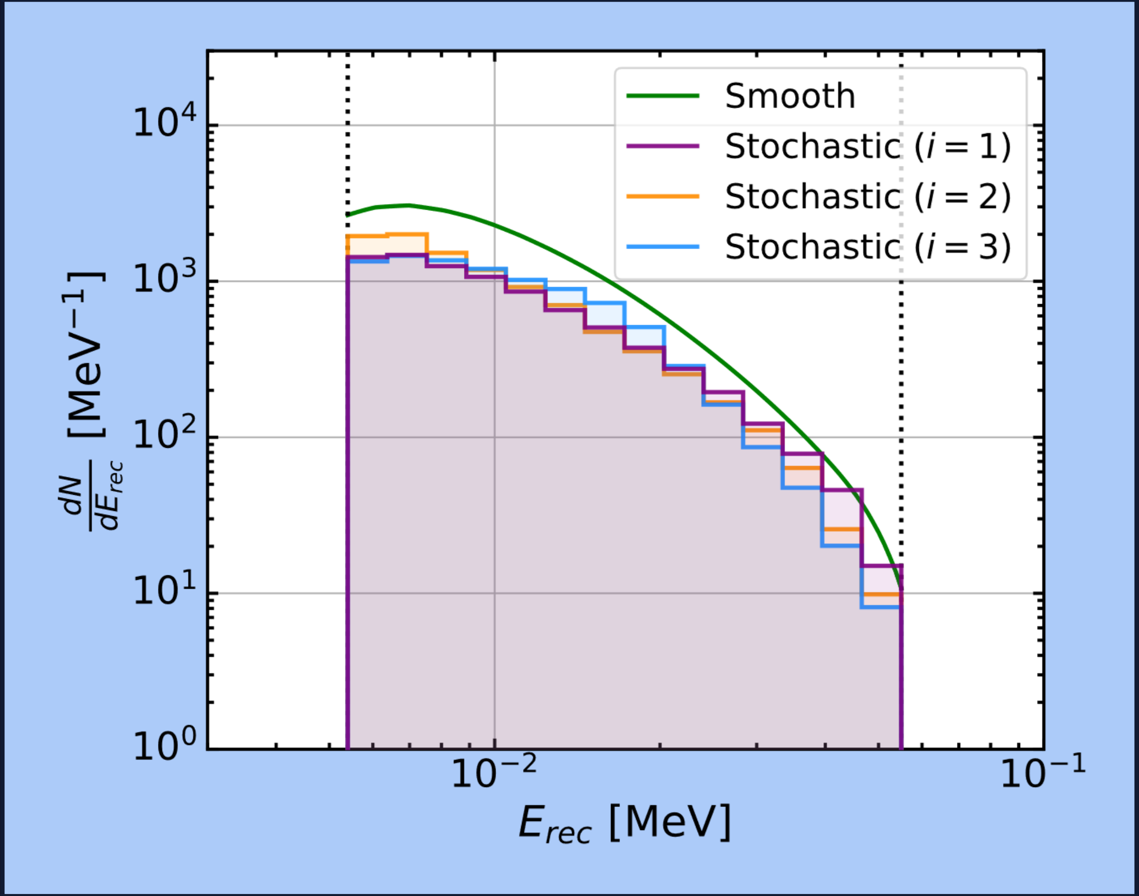


Dark Matter

$$\Delta t^{\rm obs} = 2.74\ {\rm yr}$$
$$m_\chi = 26\ {\rm MeV}$$
$$\log y = -15.3$$

Total fluence of DM at Earth in one universe.

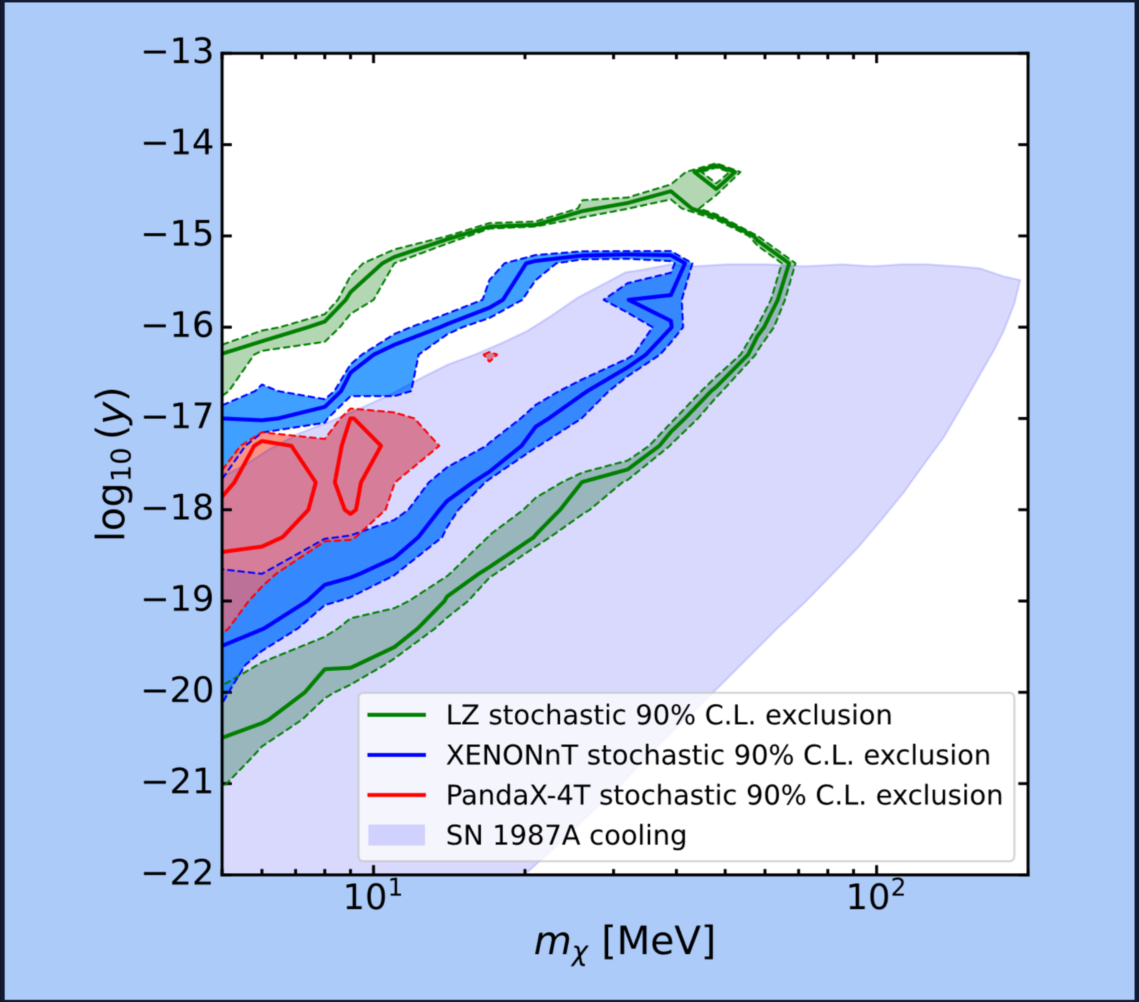


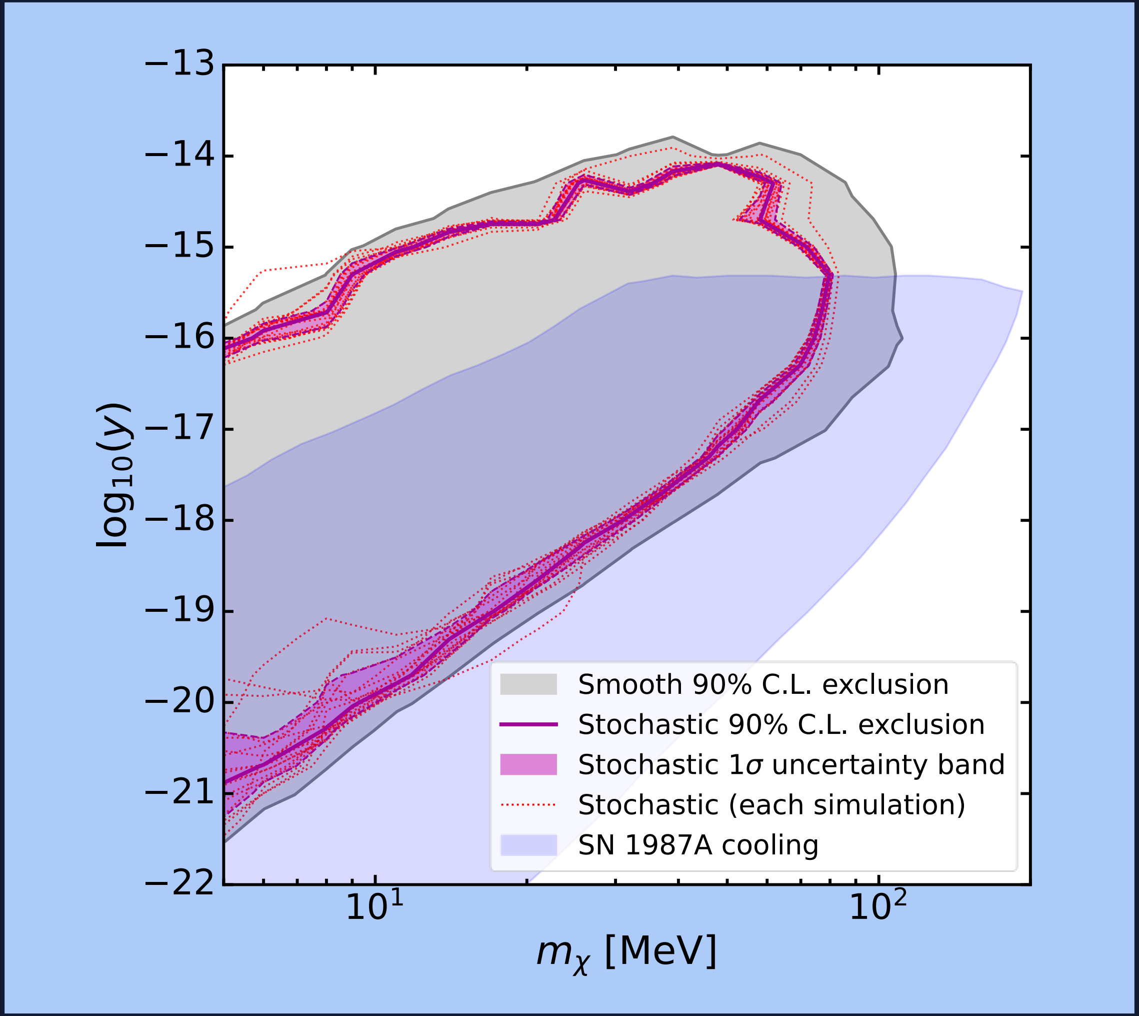


Expected DM event rate in LZ with 15 ton · yr exposure in three different universes.

Dark Matter

Current constraints with 1σ uncertainty bands.





Projected bound for LZ with 15 ton · yr exposure.

Axion Like Particles

MODEL ALPs a coupled to nucleons

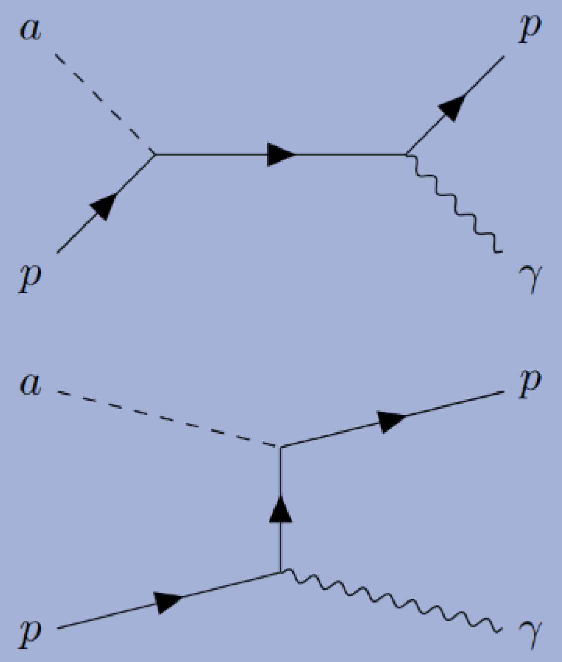
$$\mathcal{L}_{int} = g_a \frac{\partial_\mu a}{2\, m_N} \Big[C_{ap}\, \bar{p}\, \gamma^\mu \gamma_5\, p + C_{an}\, \bar{n}\, \gamma^\mu \gamma_5\, n + \frac{C_{a\pi N}}{f_\pi} \left(i\, \pi^+\, \bar{p}\, \gamma^\mu\, n - i\, \pi^-\, \bar{n}\, \gamma^\mu\, p \right) + C_{aN\Delta} \left(\bar{p}\, \Delta^+_\mu + \overline{\Delta^+_\mu}\, p + \bar{n}\, \Delta^0_\mu + \overline{\Delta^0_\mu}\, n \right) \Big]$$

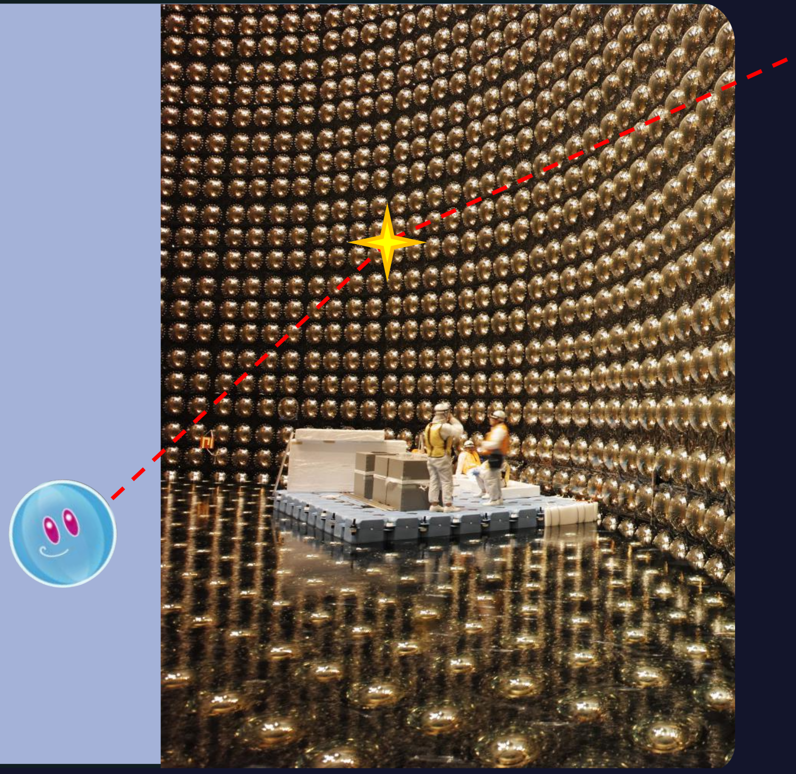
two parameters $\begin{cases} m_a & : \textbf{ALP mass} \\ g_{ap} = g_a C_{ap} & : \textbf{coupling to protons} \end{cases}$

PRODUCTION IN SN dominant production channels are:

- ❖ nucleon-nucleon bremsstrahlung: $NN \to NNa$
- ❖ neutron-proton bremsstrahlung: $N\pi \to Na$

Trapping regime: re-absorption effects given by the inverse of production processes.





DETECTION AT EARTH $p + a \to p + \gamma$

- Rate **smaller** than oxygen de-excitation:

$$a + {}^{16}O \longrightarrow {}^{16}O^* \longrightarrow {}^{16}O + \gamma$$

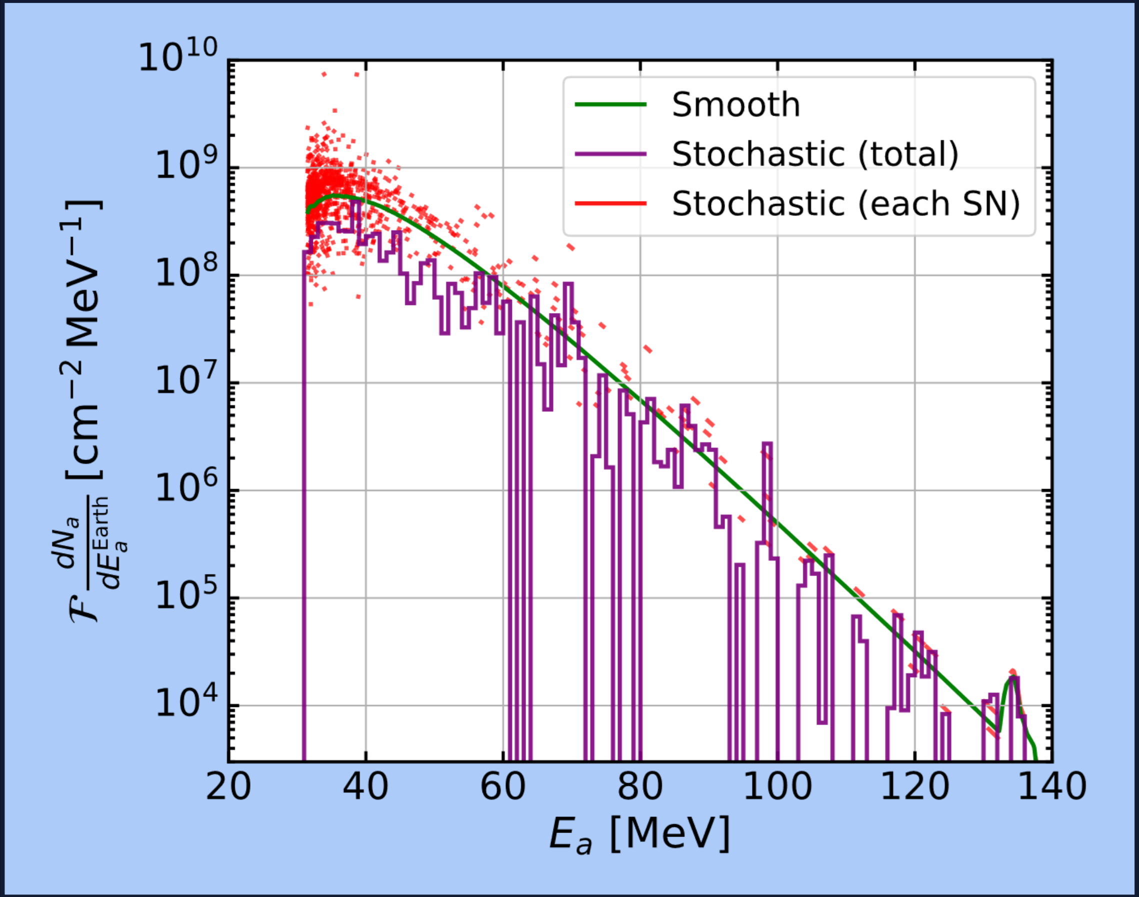
- Released photon more energetic and almost **background free**

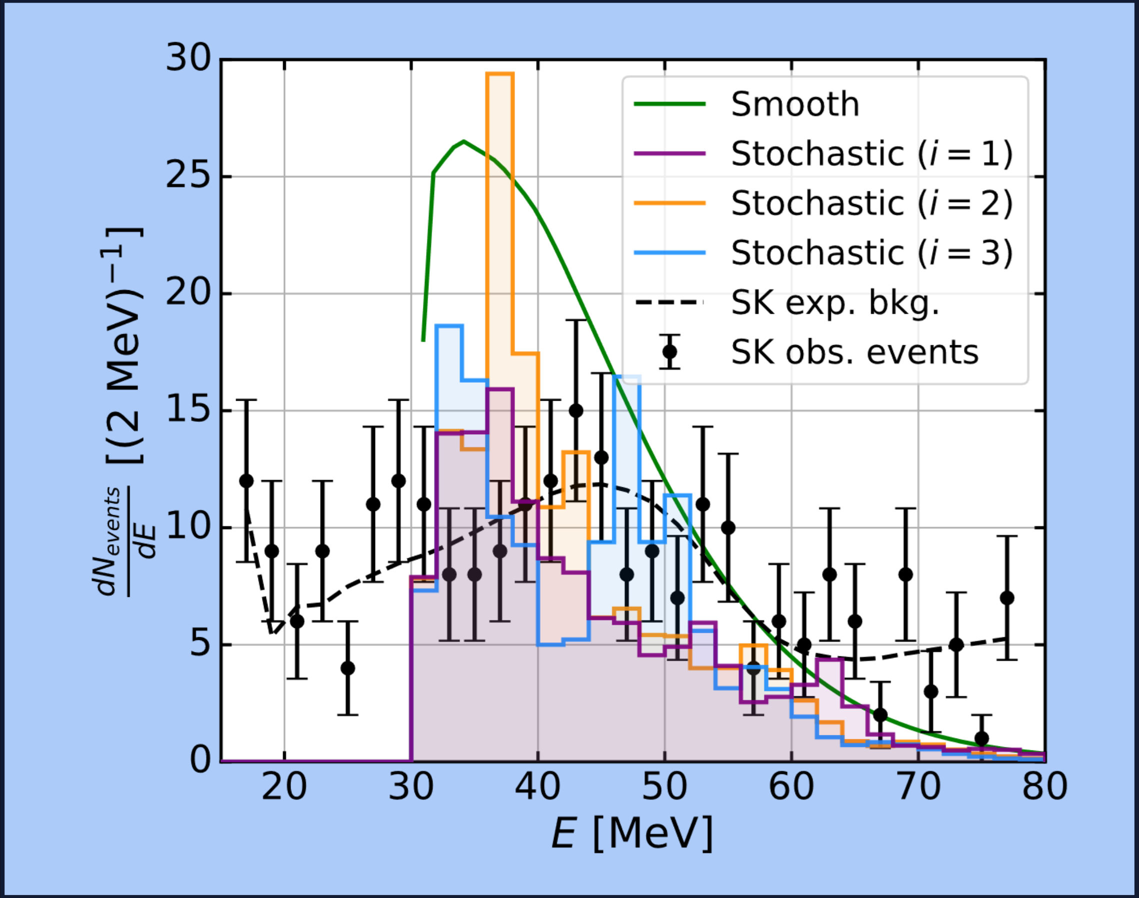
$$\frac{dN_\gamma}{dE_\gamma} = N_t \int_{E_a^{min}(E_\gamma)}^{E_a^{max}(E_\gamma)} dE_a^{Earth}\, \frac{d\Phi_a}{dE_a^{Earth}}\, \frac{d\sigma_{ap}}{dE_\gamma}$$

ALPs

$m_a = 30$ MeV
$g_{ap} = 9.4 \times 10^{-5}$

Total fluence of ALPs at Earth in one universe for $\Delta t = 20$ yr.

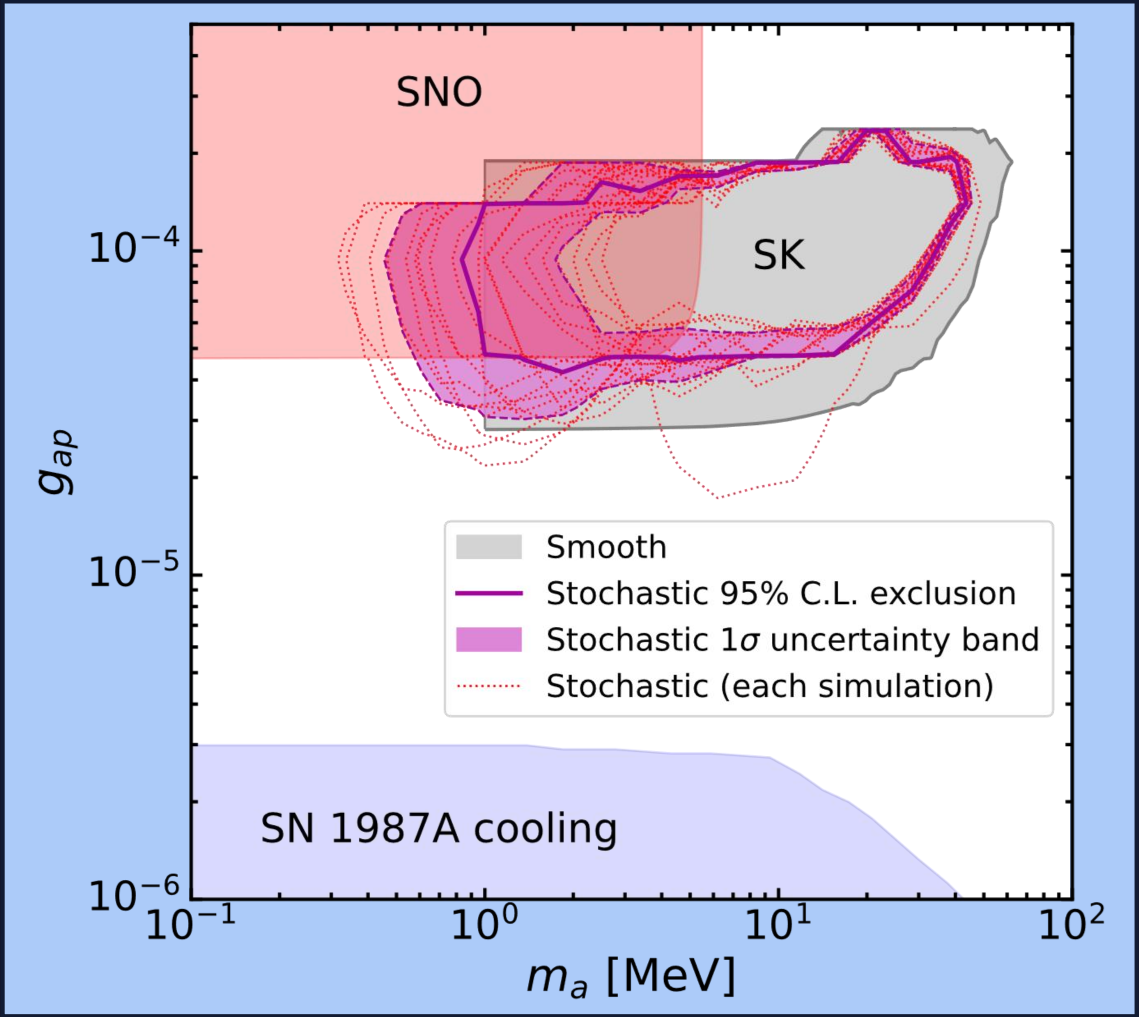


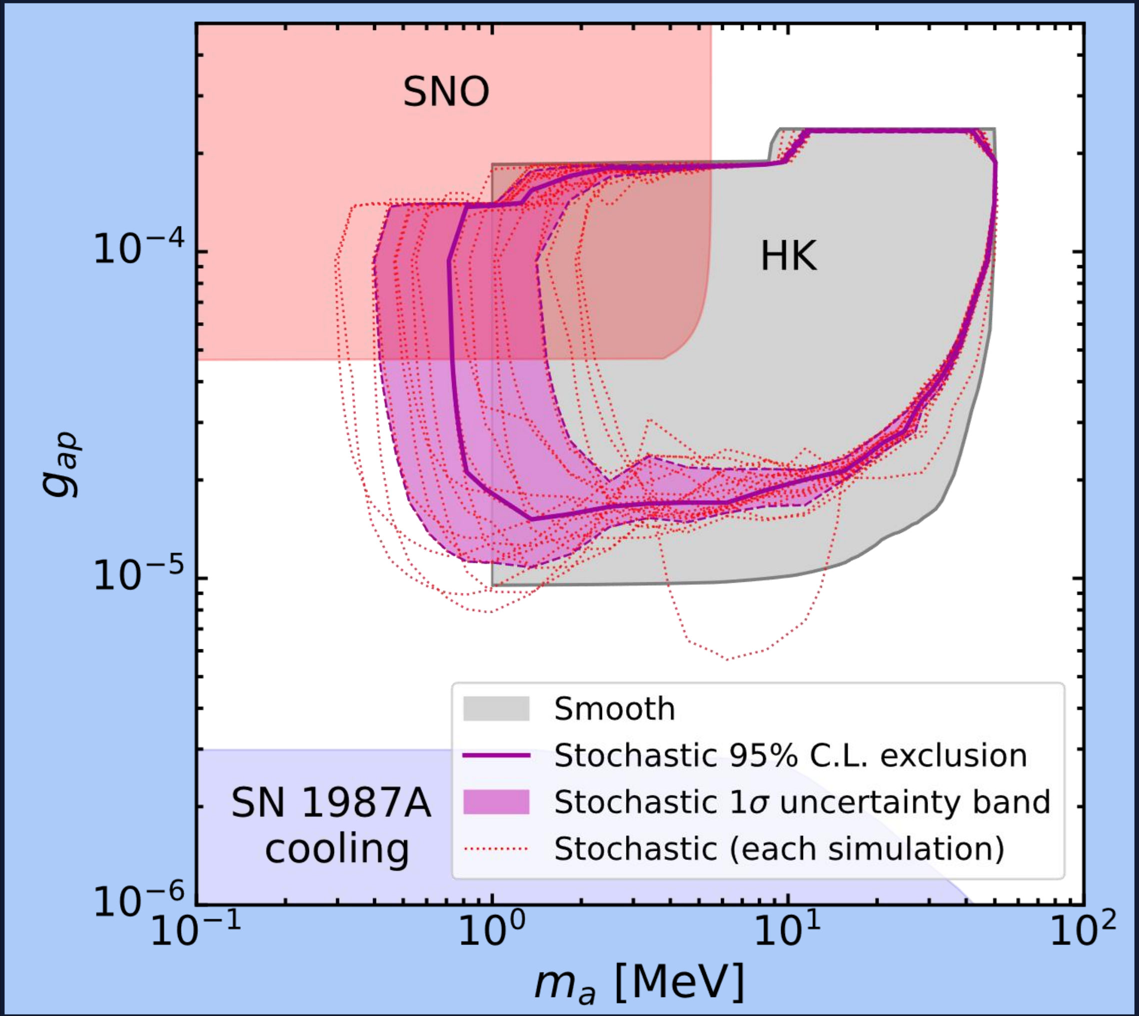


Expected event rate in Super-Kamiokande phase IV with 15 ton · yr exposure.

ALPs

Current constraints from Super-Kamiomande.





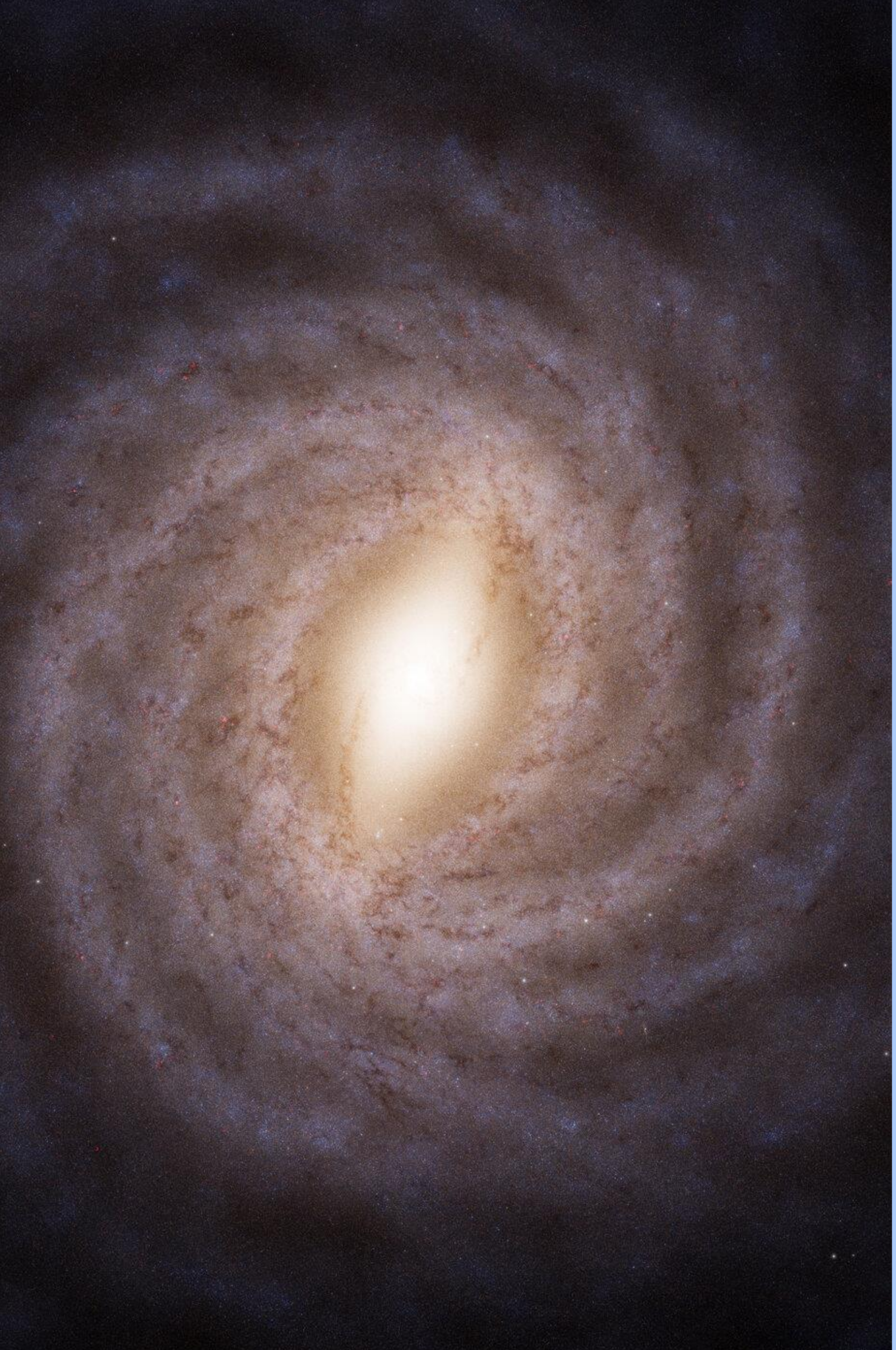
Projected constraints from Hyper-Kamiomande.

CONCLUSIONS

- Core-collapse Supernovae are very interesting factories of new particles.
- If the new particles have masses above MeV, they can form a continuous flux from all past galactic SNe.
- The smooth diffuse approximation presents two important limitations:
  - Due to the small observational window, only a narrow energy range of the spectrum can be detected in experiments.
  - For some combinations of distance, time and mass, the relevant part of the produced signals have already passed Earth at the time of observation.
- We deal with these features by performing a numerical simulation of the galactic history of SNe.
- Resulting MeV particle fluxes exhibit sizeable fluctuations in the spectral shape, reflecting the stochastic nature of SN population.
- In this framework, we revisit current bounds on direct detection of fermionic DM (and Axion-Like Particles).

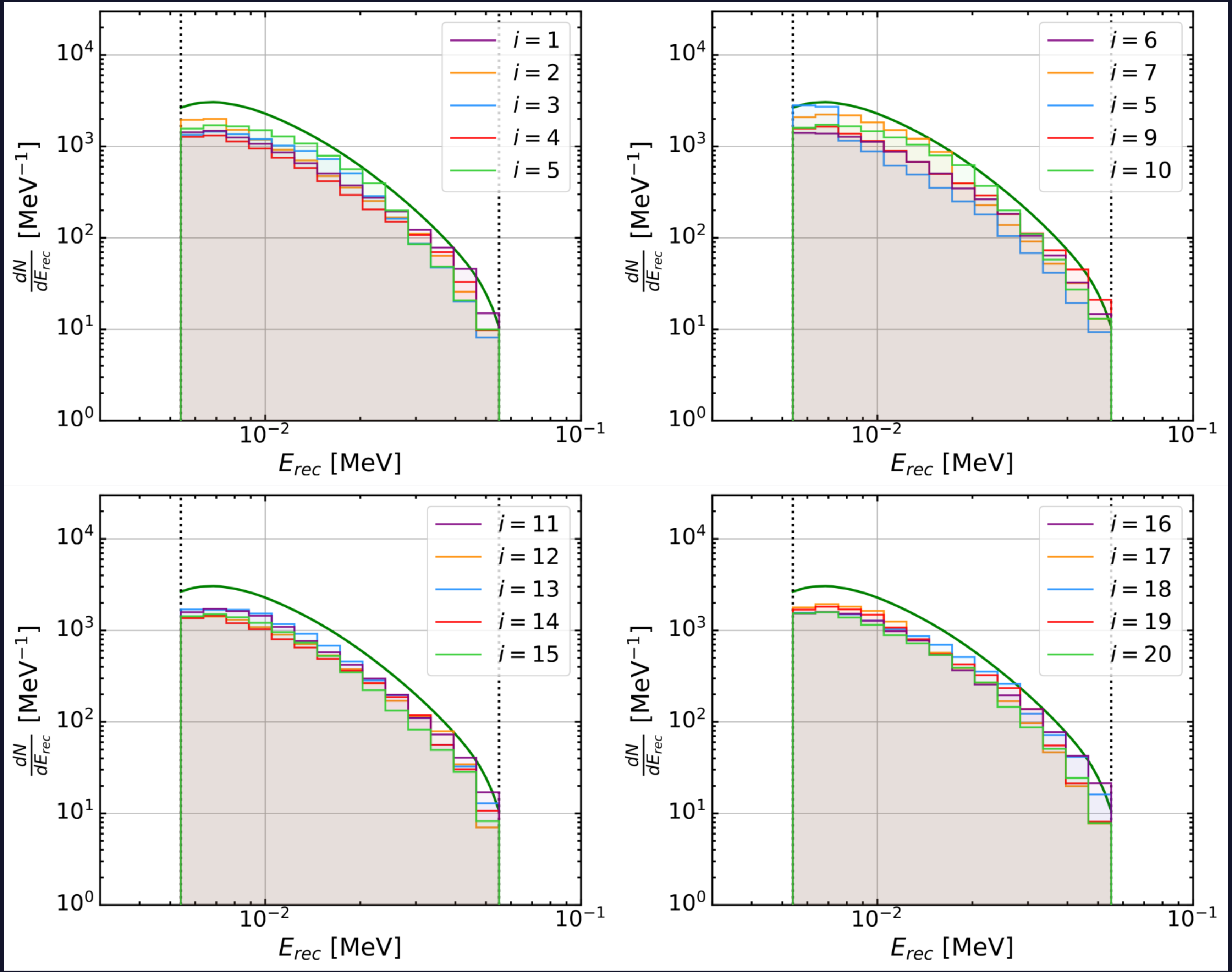
Thanks for your attention!

https://github.com/AndresDanielPerez/SGaSNoF



Backup Slides

Dark Matter Signal Variability



ALPs Signal Variability