IceCube's Sensitivity Prospects of MeV-scale Axion-Like Particles from Core-Collapse Supernovae

Nora Valtonen-Mattila†, Segev BenZvi & Shlok Shah

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DEATH OF STARS AND BEYOND

$$E_{tot} \sim 10^{53}\, erg$$

Supra-nuclear densities

End of star's lifecycle

ν

99% of energy!

Nucleosynthesis of heavy elements

Gives birth to neutron stars and black holes!

Very very hot (MeV)

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Also good probes for the dark sector!

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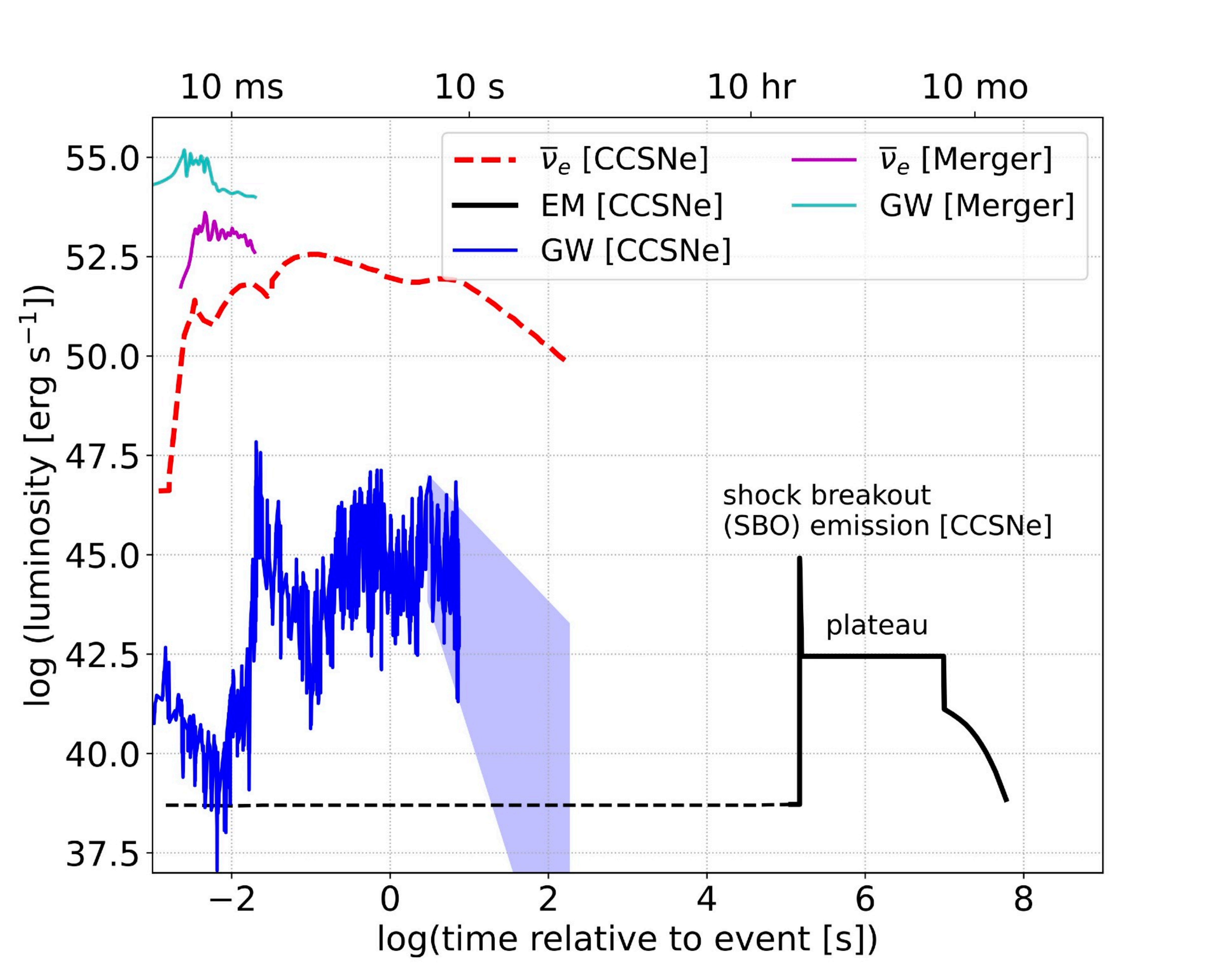
MESSENGERS FROM SUPERNOVAE

One example. Not exhaustive!



Galactic rate: ~1 every 40 years

Numerous messengers

On top of that, we can have dark scale sector

Adapted from Cusinato et al. Eur. Phys. J. A (2022) **58**: 99, and Nakamura et al. MNRAS, Volume 461, Issue 3, 21 September 2016, Pages 3296–3313

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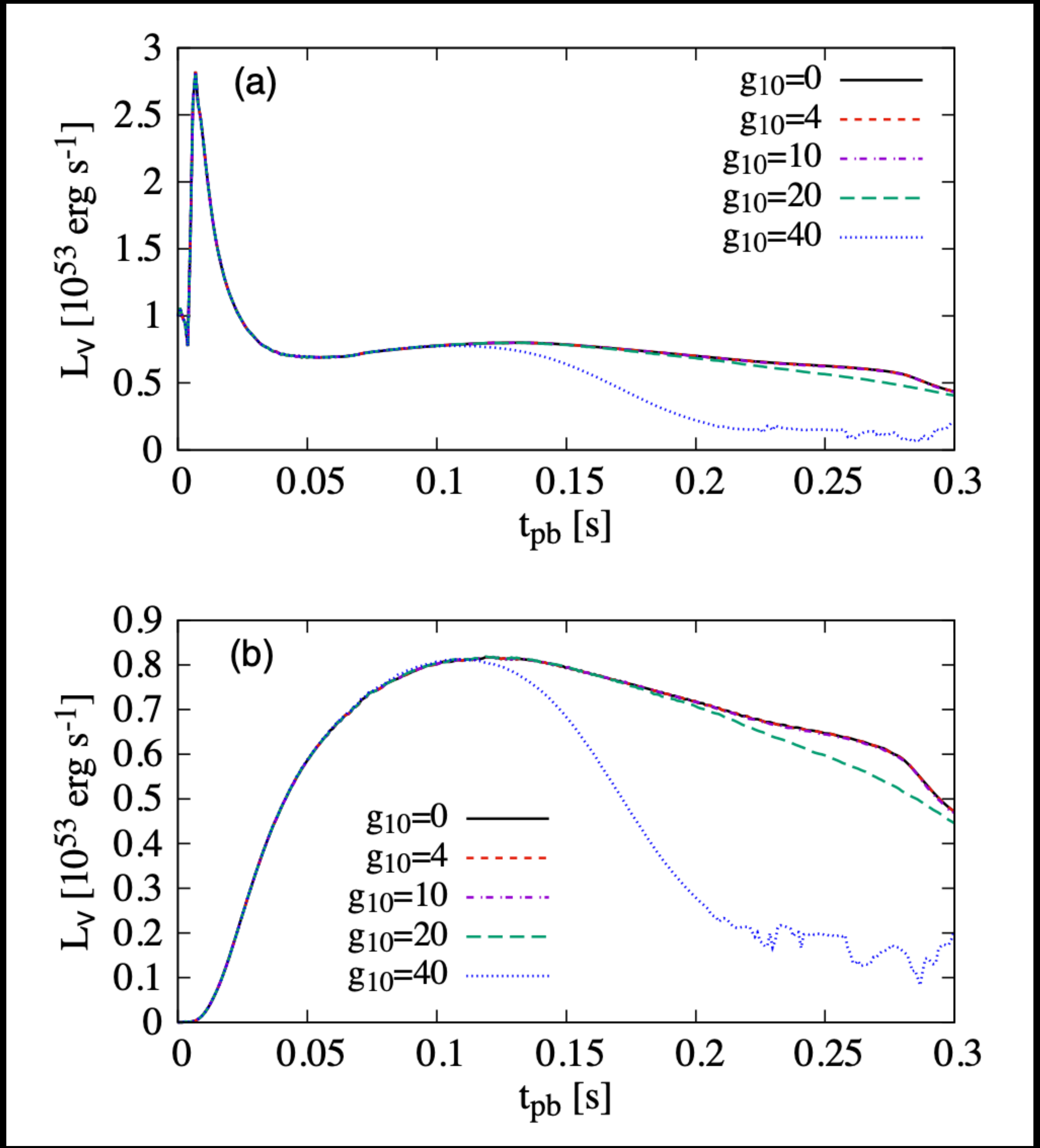
- ALPs can be produced via nucleon-nucleon bremsstrahlung or pion-nucleon processes
- They can escape the SN, carrying away energy —〉 this can have an impact on the neutrino lightcurve

ALPs + neutrino lightcurve

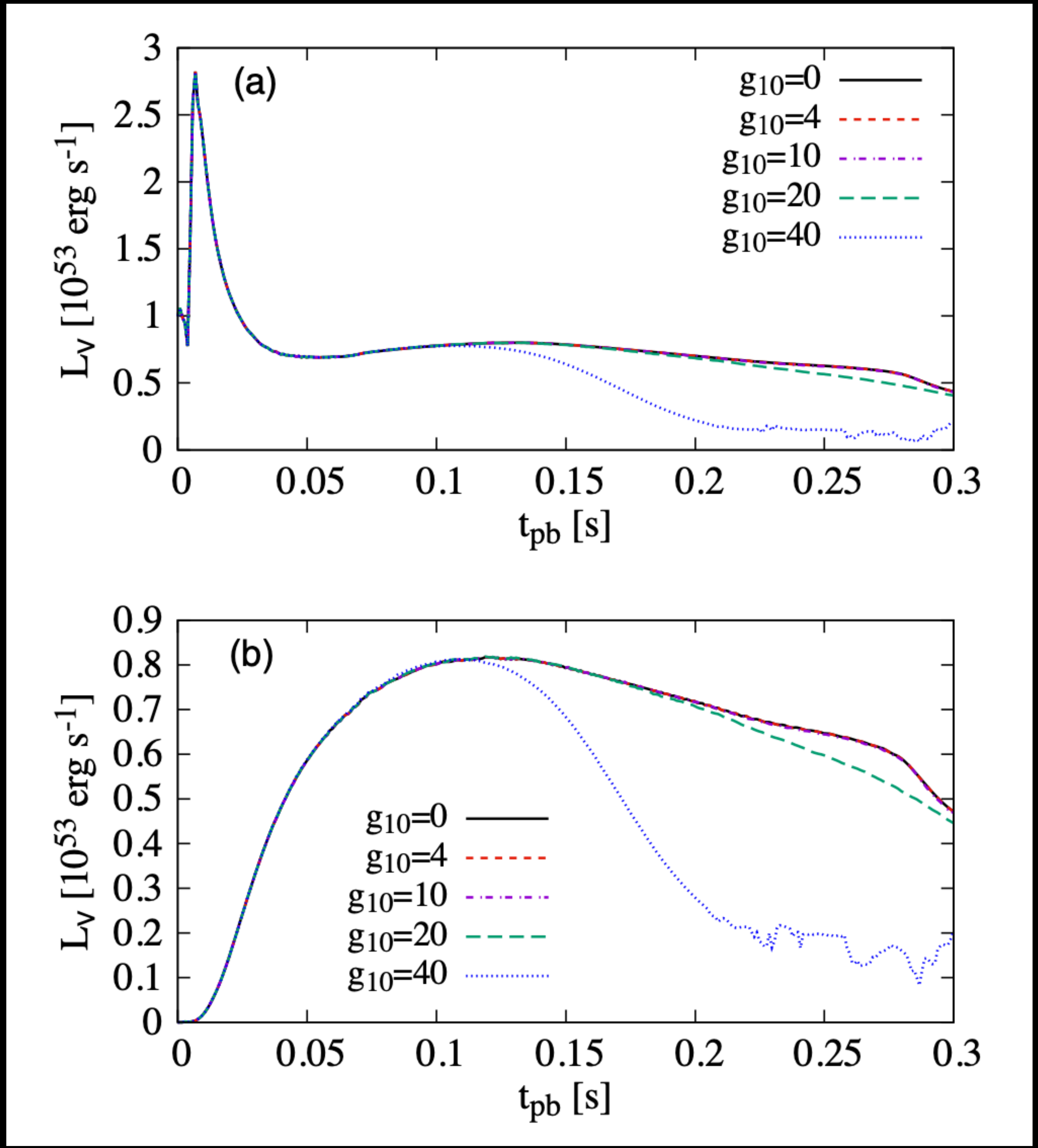


If ALPs would be produced, they could take away energy that would otherwise go to neutrinos ⟶ dampening the neutrino emission

This could allow us to indirectly detect ALPs during the next Galactic CCSNe

Mori et al., 2022 Phys. Rev. D. 105, 063009

ALPs + neutrino lightcurve



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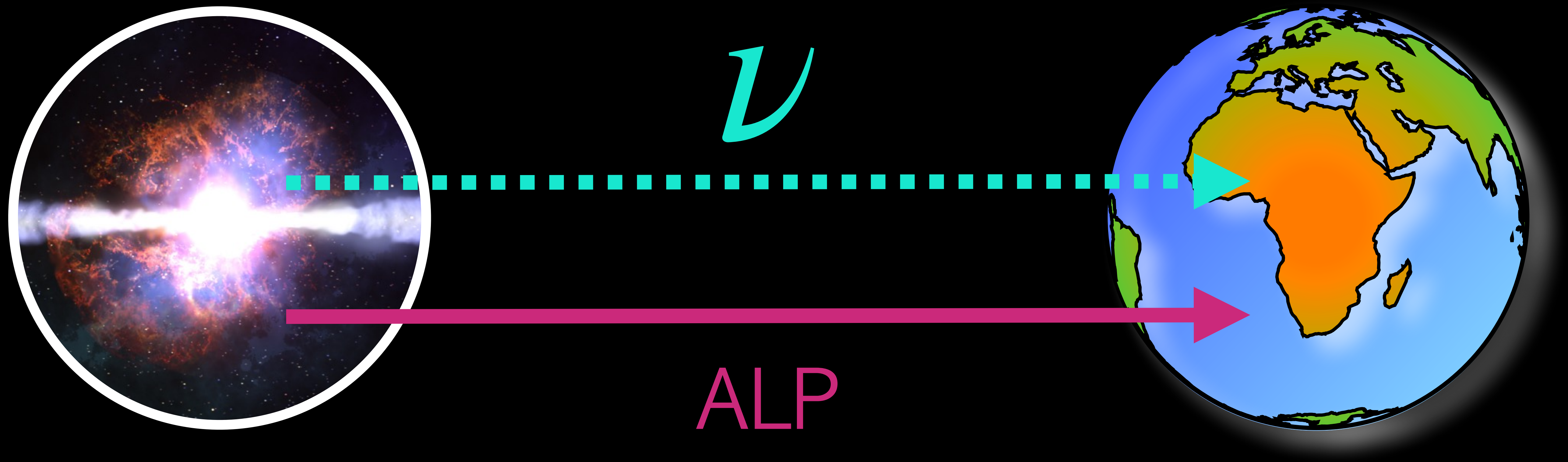
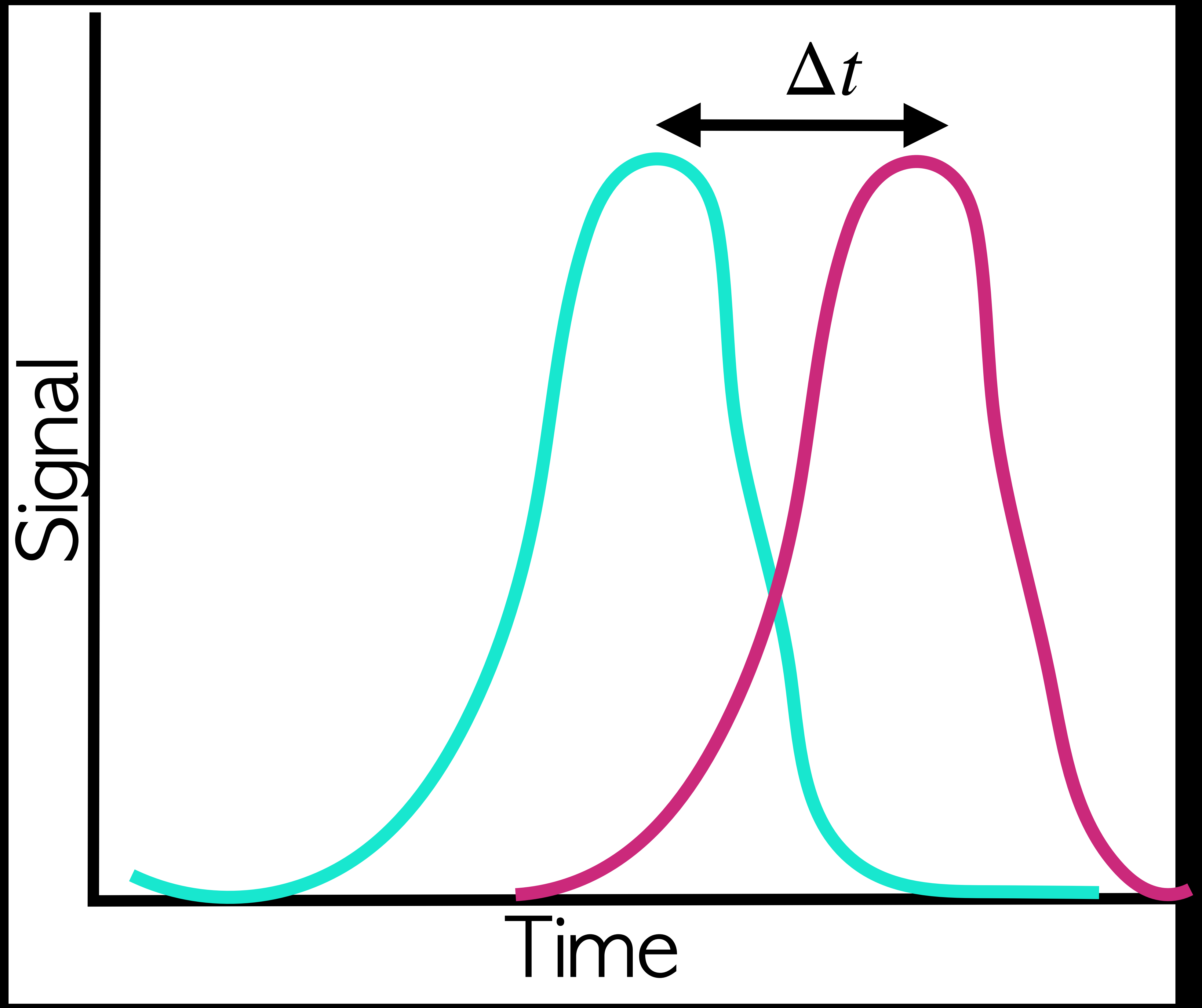
What if we could detect ALPs directly?

This work is an based on the work by P. Carenza, D. Alonso-González, A. Lella and more

Time-delay





ALPs from CCSNe can be massive —› eV to few hundred MeV

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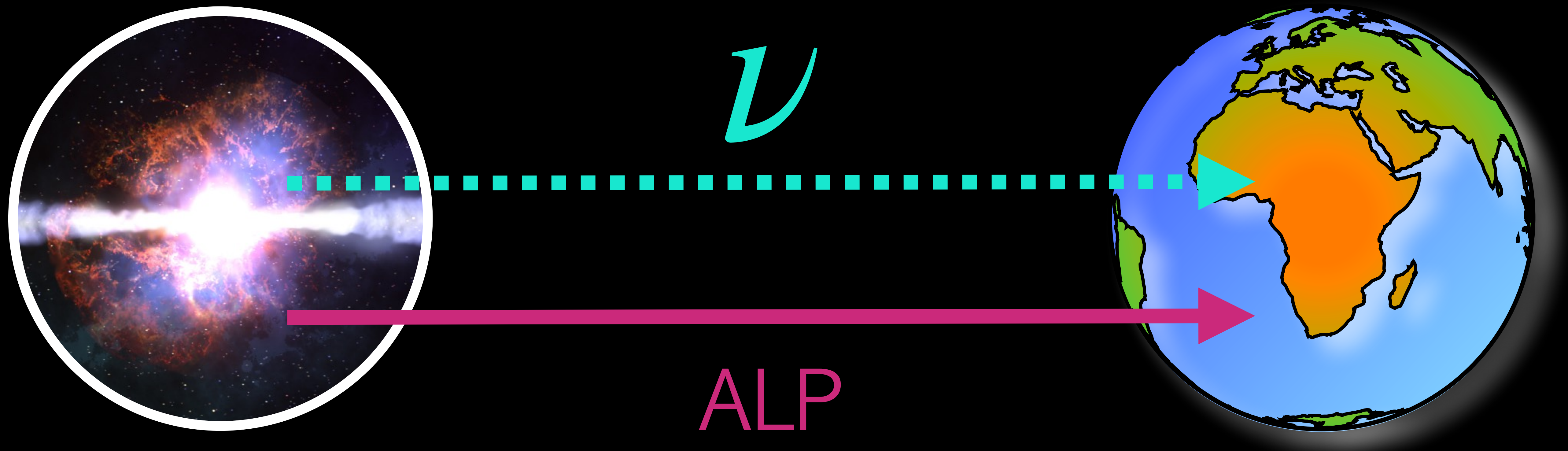

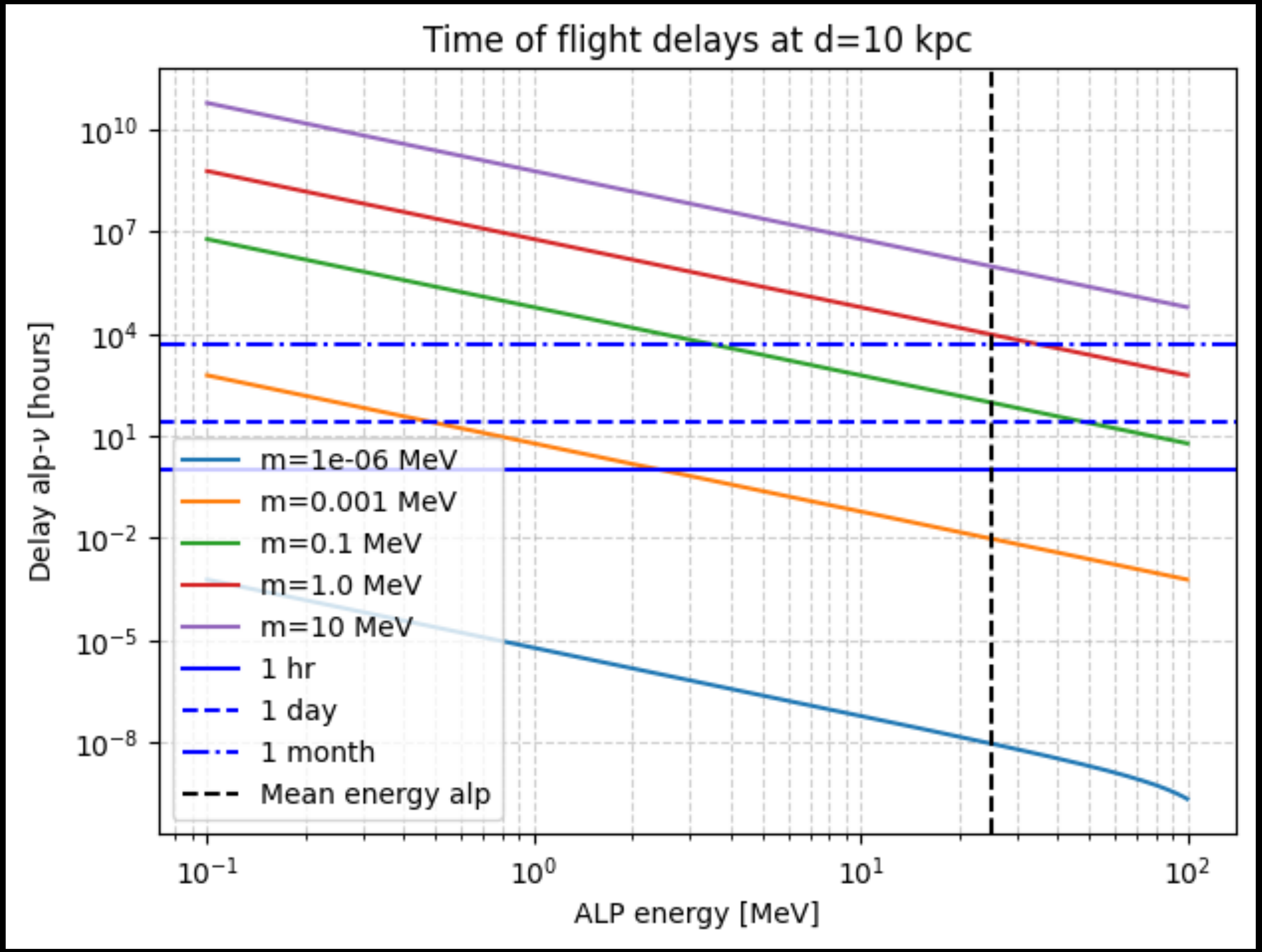

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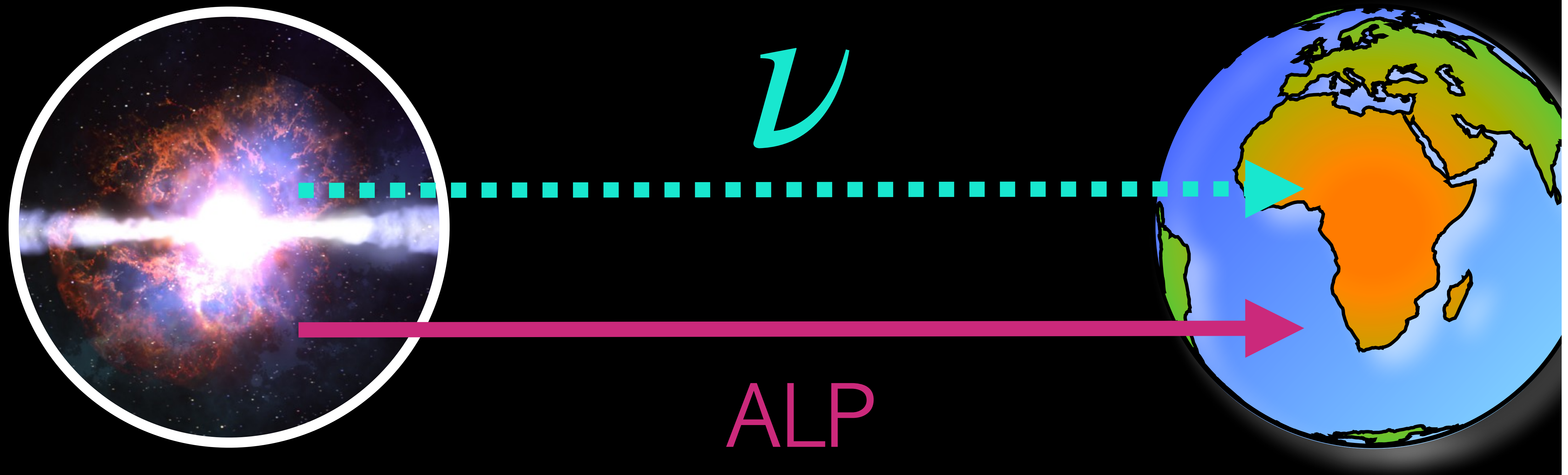
$m_\nu \leq 0.12\,\text{eV}$ $E_\nu = 15\,\text{MeV}$

Time-delay



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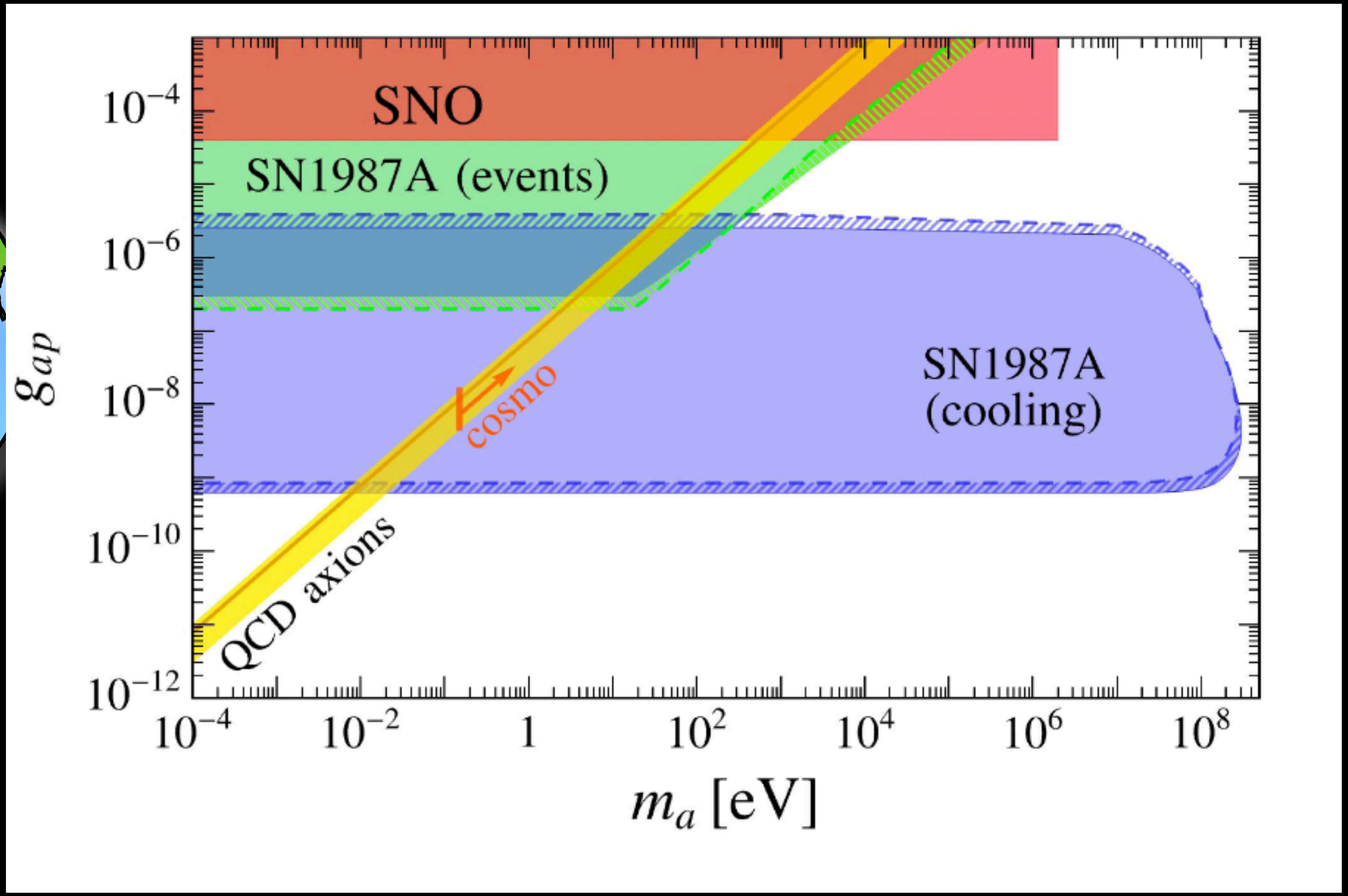
However, very light ALPs have been constrained with SN 1987A



Lella et al., 2024 Phys. Rev. D. 109, 023001

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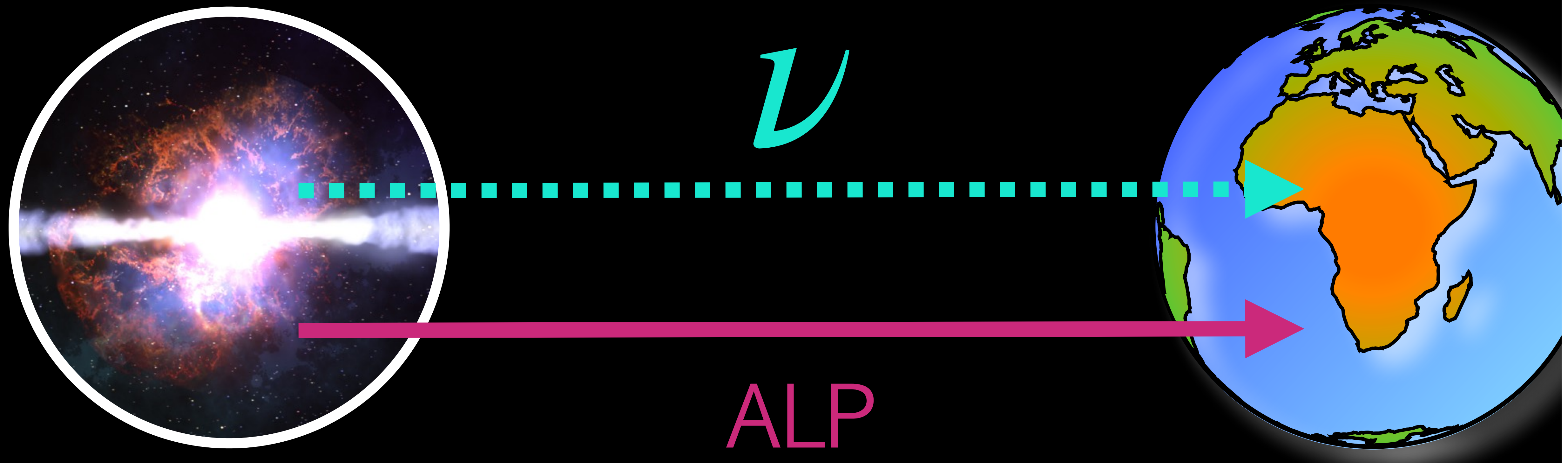

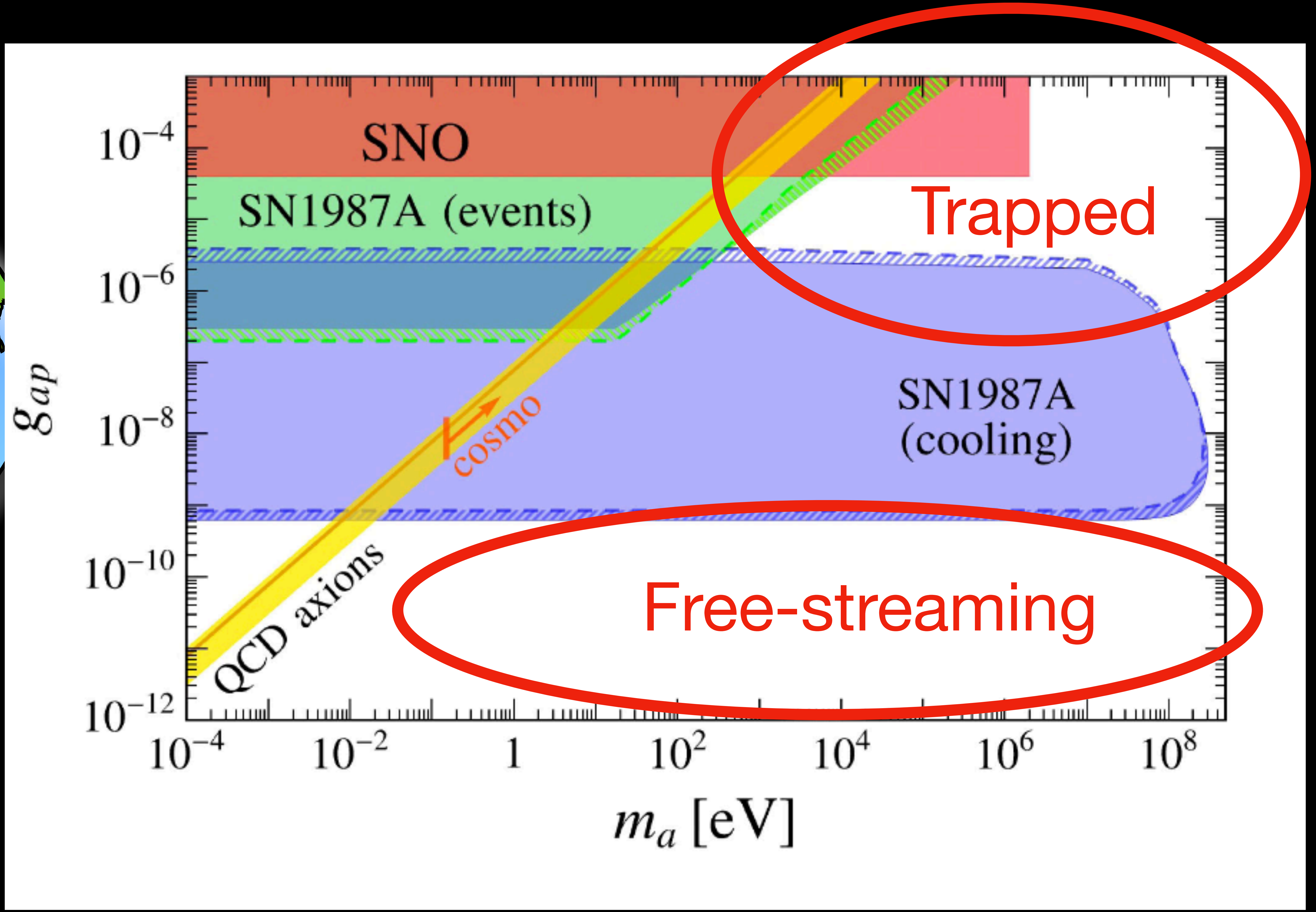

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Wide parameter space left to investigate with the next supernova

ALP fluxes

- High flux / luminosity
- Produced at the same time as neutrinos

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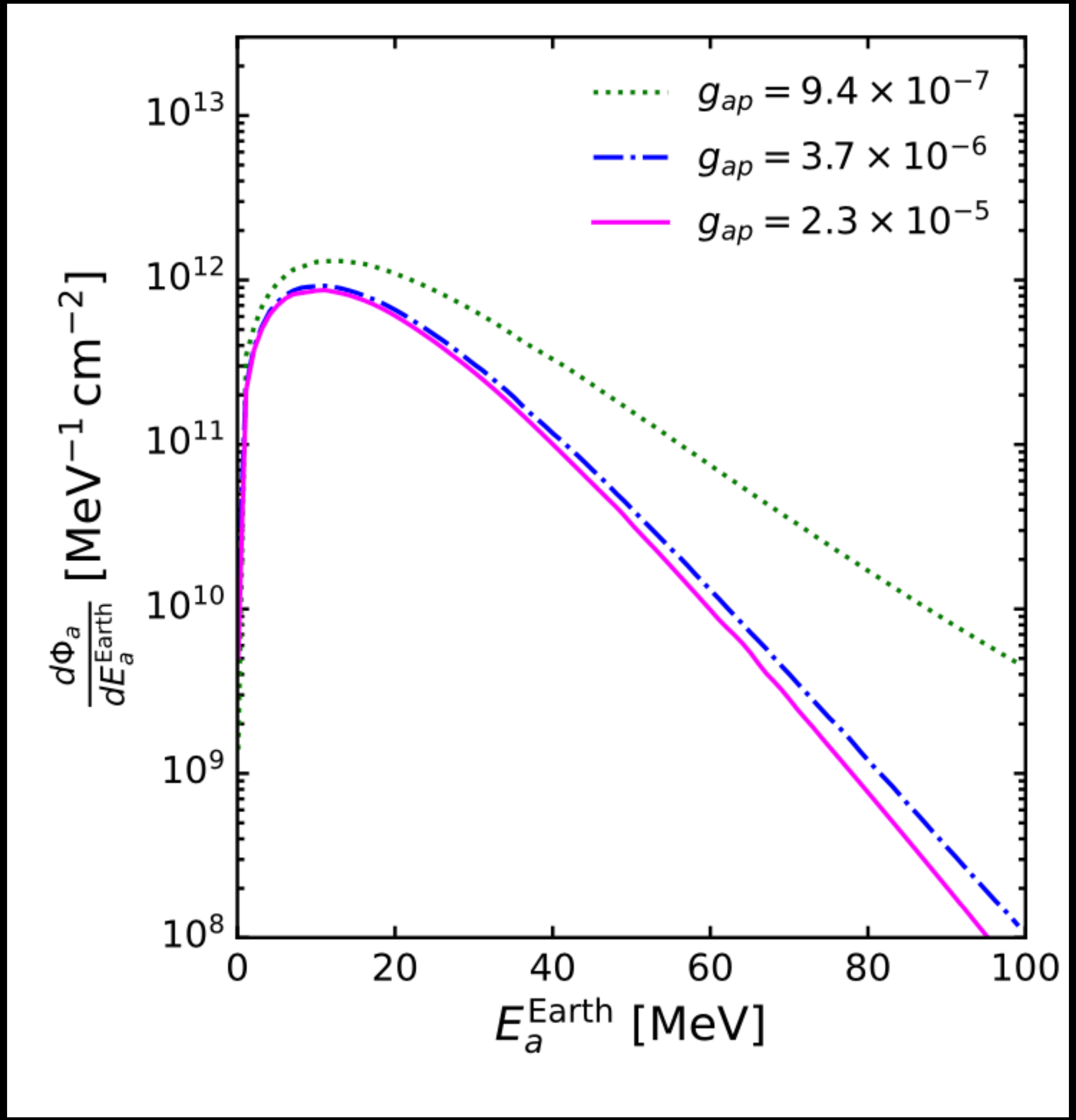

Alonso-Gonzalez et al. 2025 Phys. Rev. D, 111, 083029

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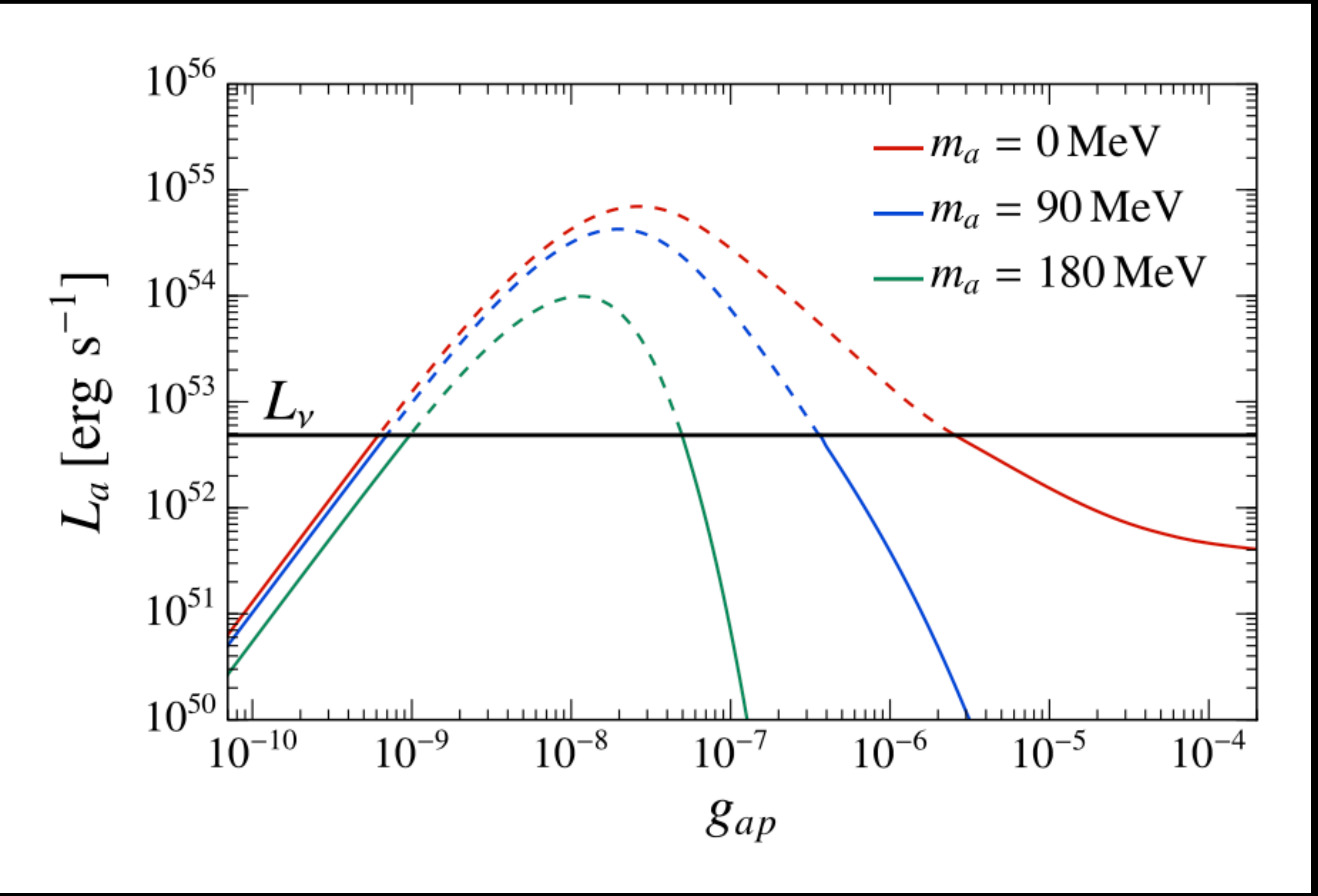
See talk by A. Lella DM parallel session 1B



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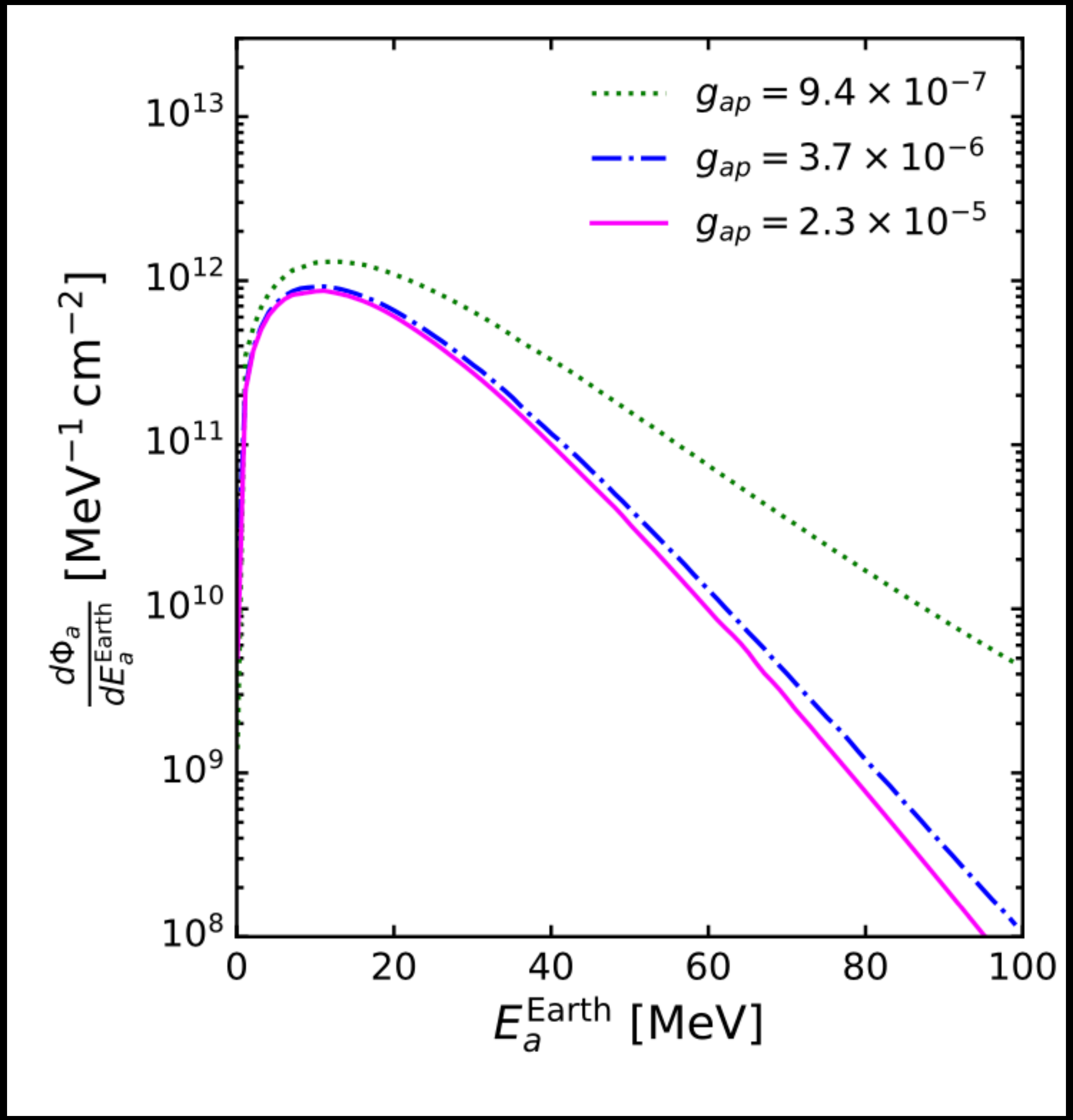

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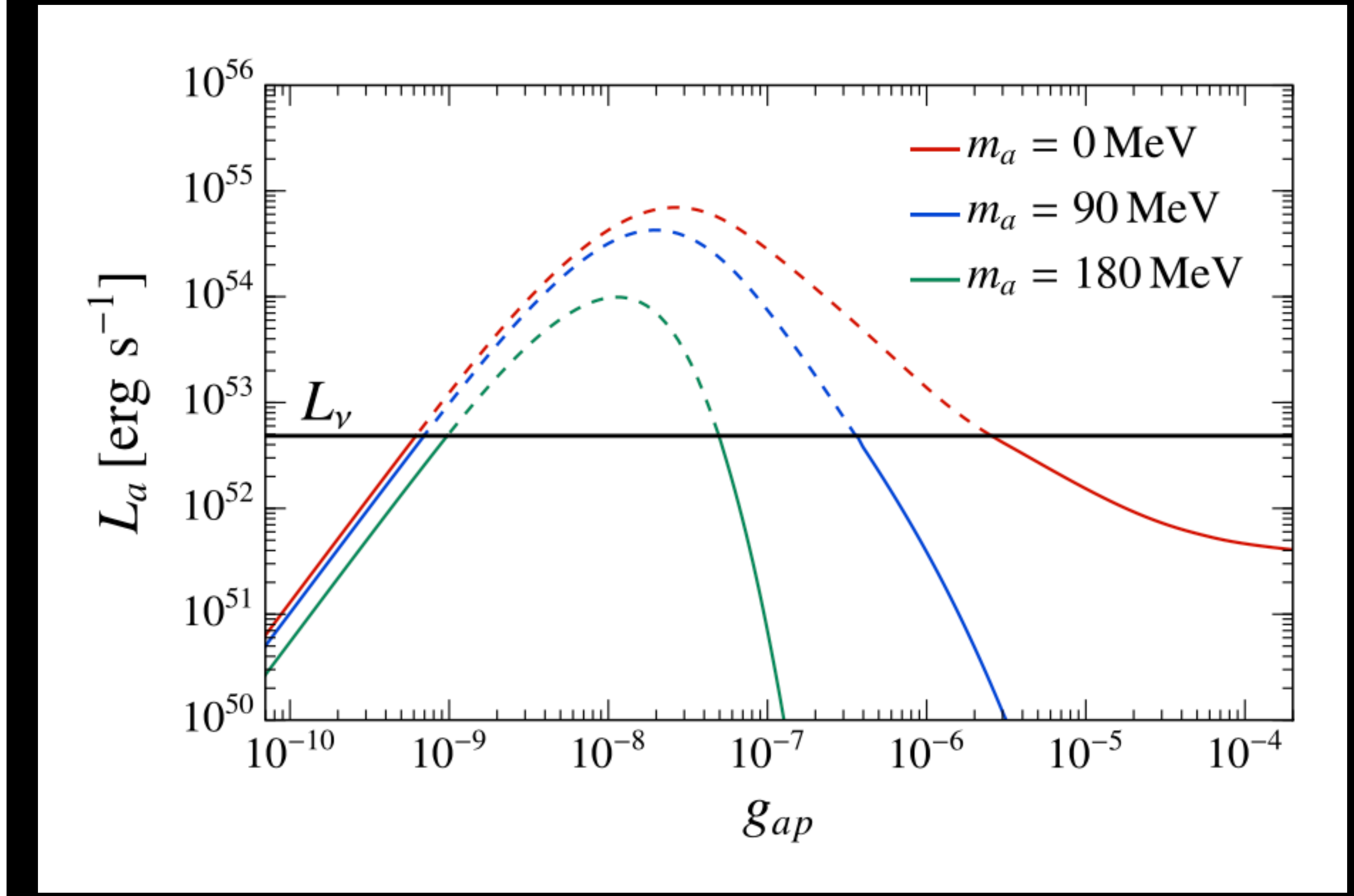

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Two aspects:

1. Could be produced copiously
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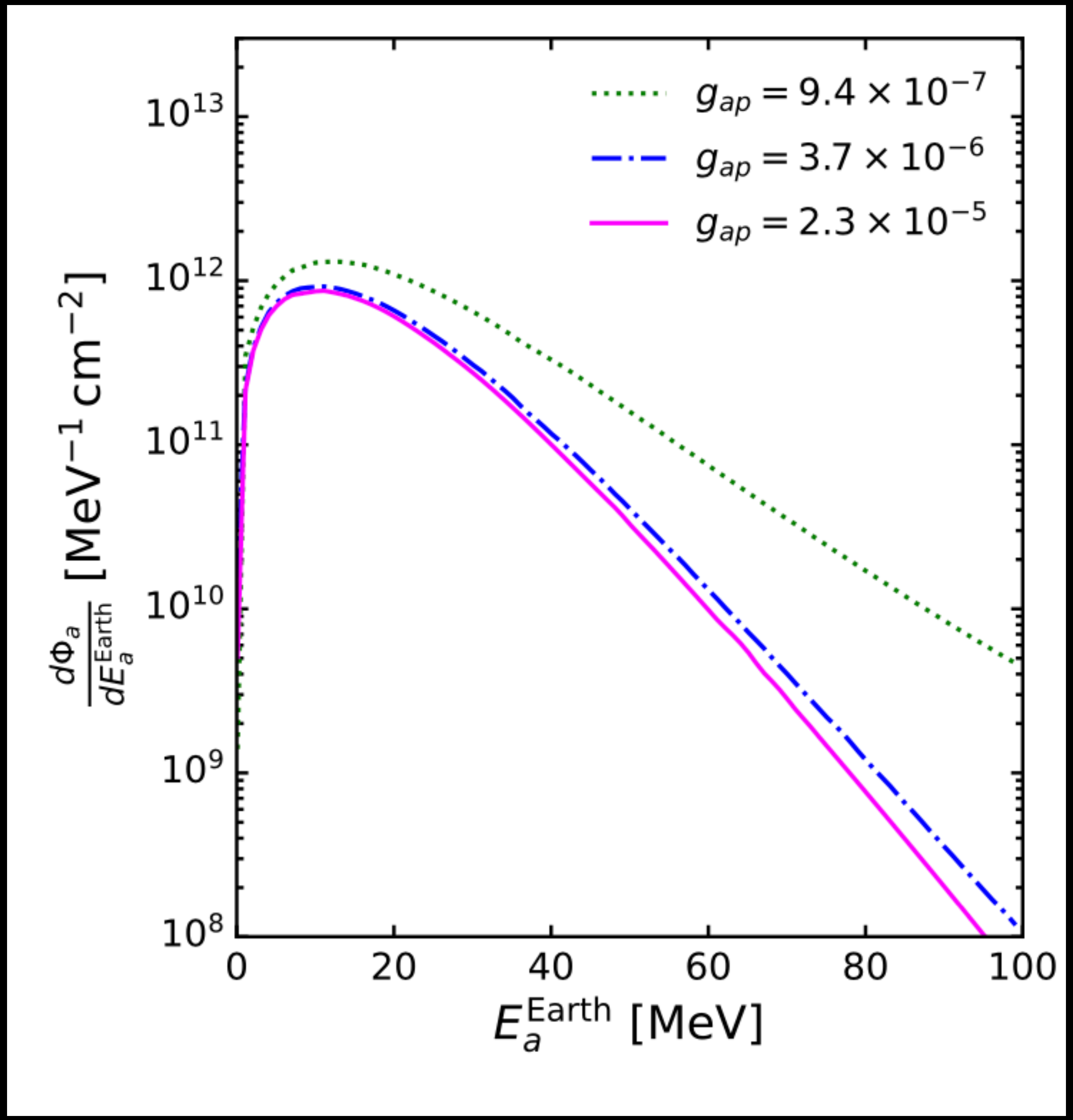

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We consider this flux to do some very preliminary estimates

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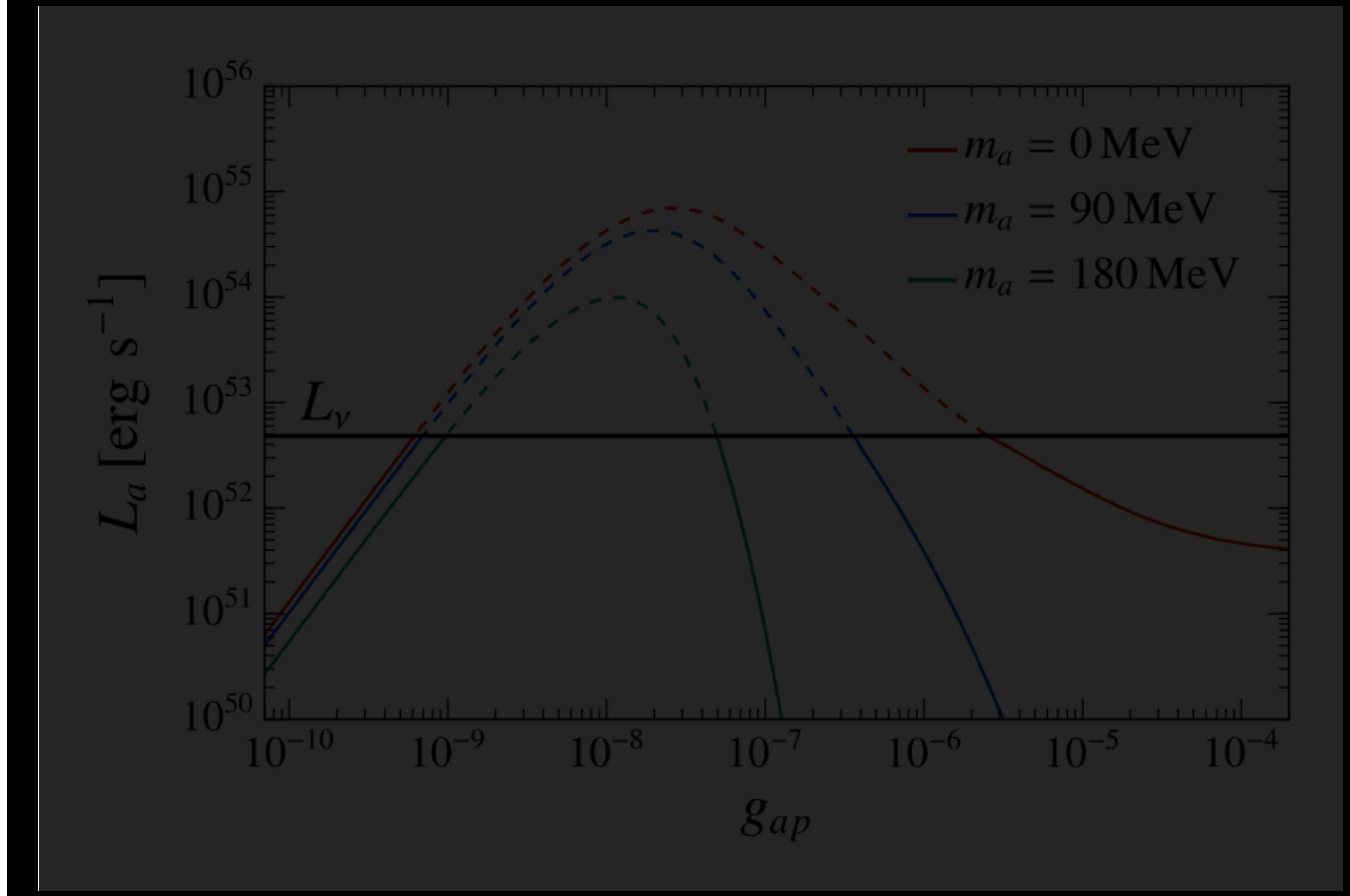

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- Water/ice —〉 cheap medium
- ALPs could interact with O^{16} and protons (and other nucleons).

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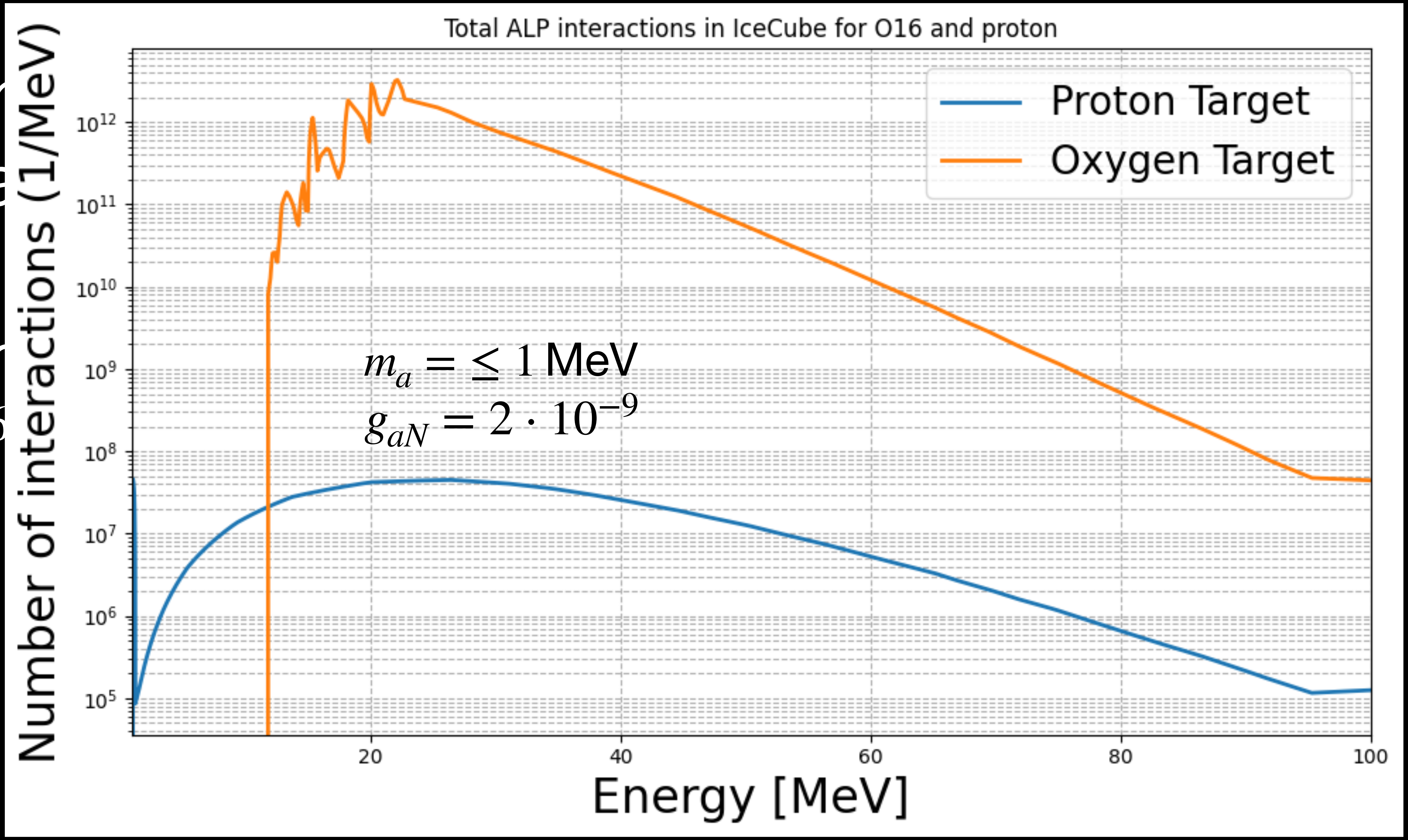

At d=1 kpc

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Can produce $e^{\pm}$ via:

- Pair-production
- Compton
- Photoelectric

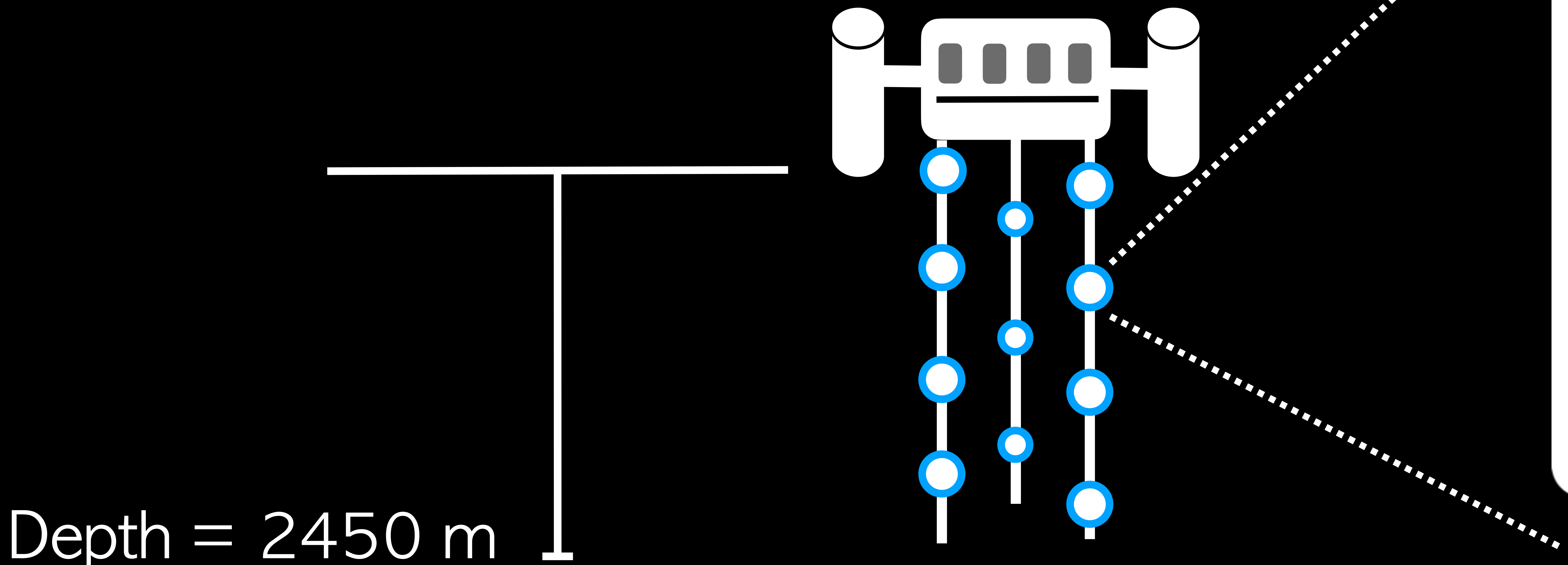
↓

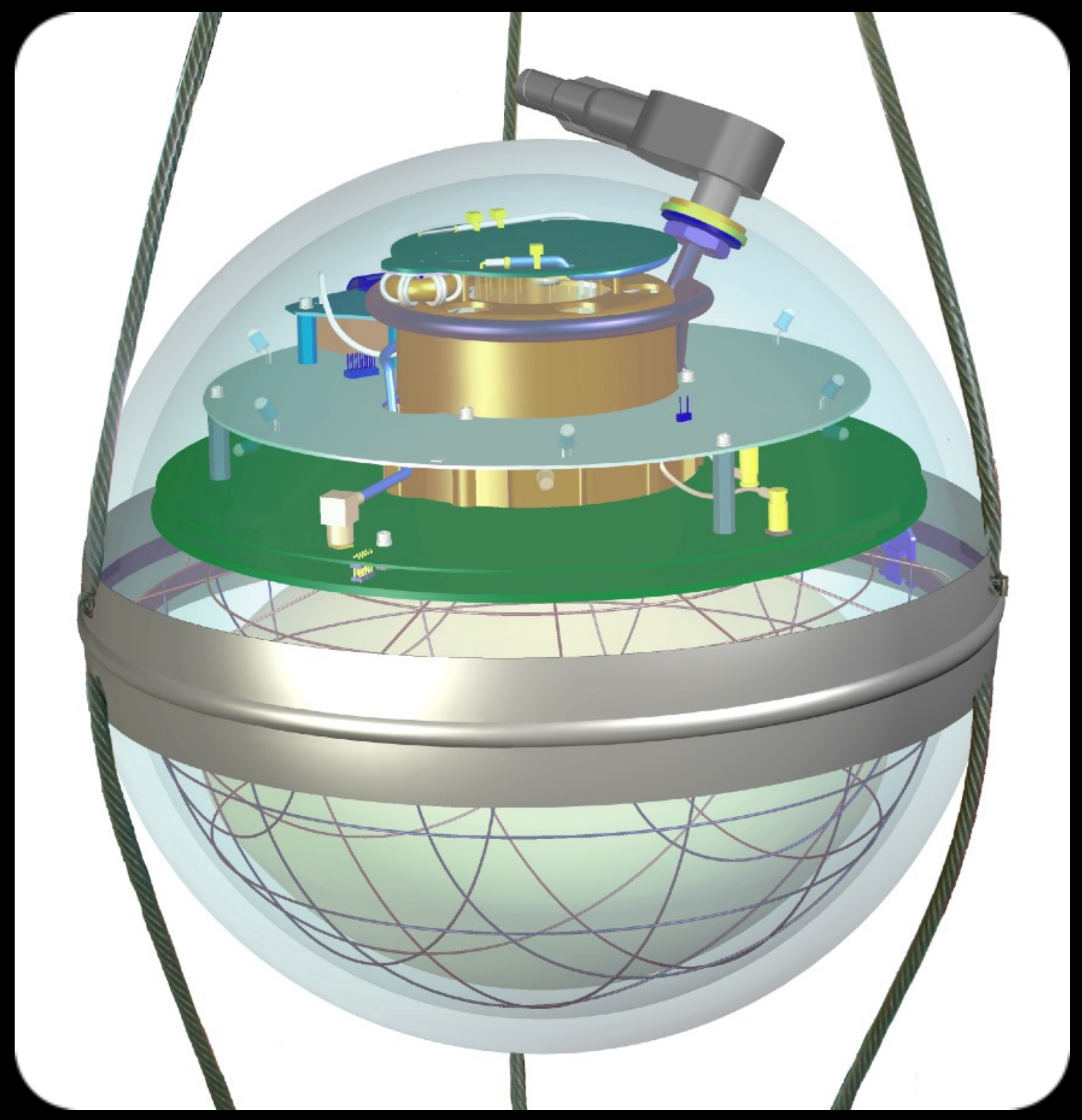
Cherenkov radiation

ICECUBE NEUTRINO OBSERVATORY

Located at the South Pole

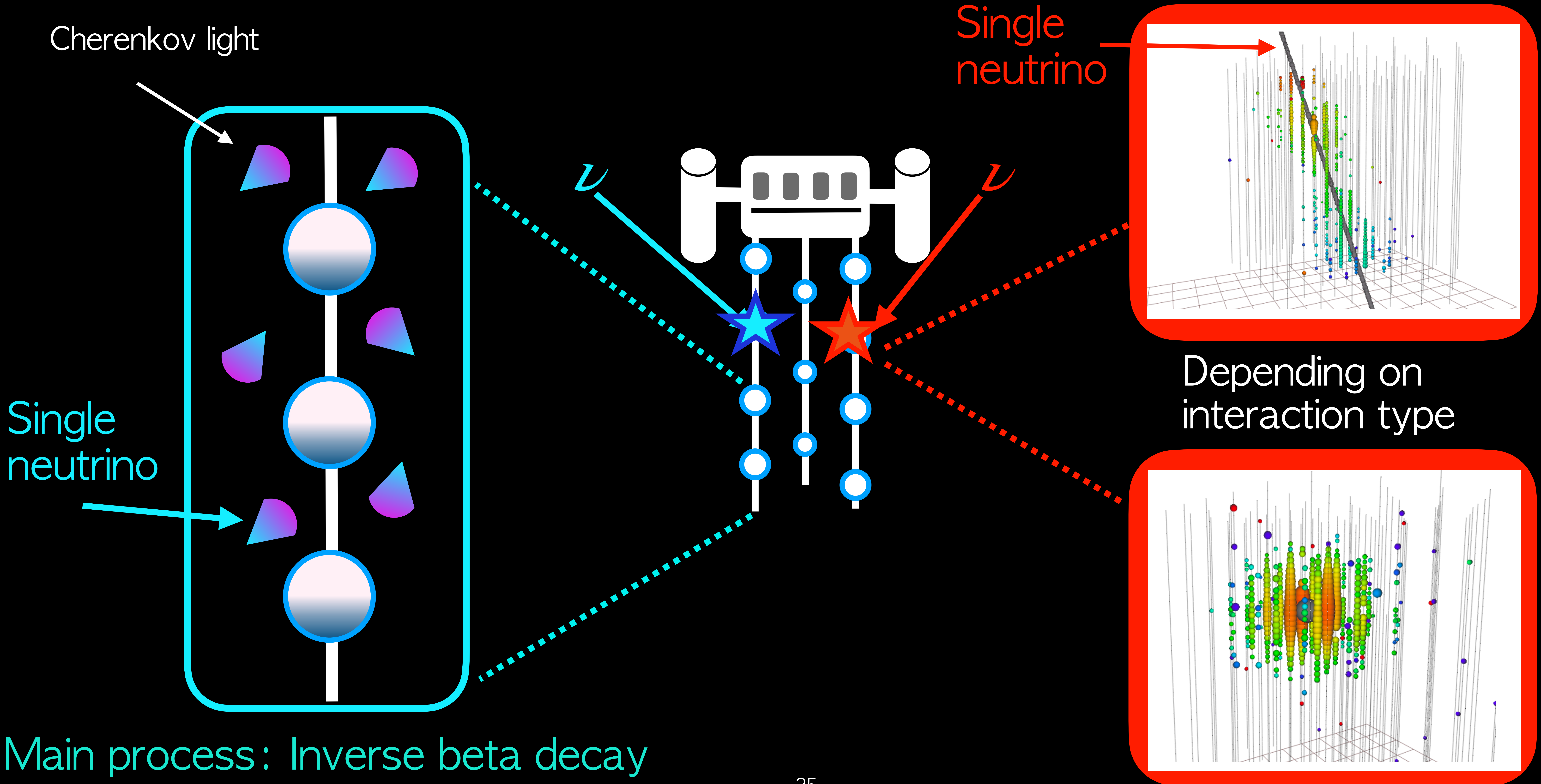
5160 sensors buried in 1km^3 of ice





We detect Cherenkov light produced when charged particles pass through ice

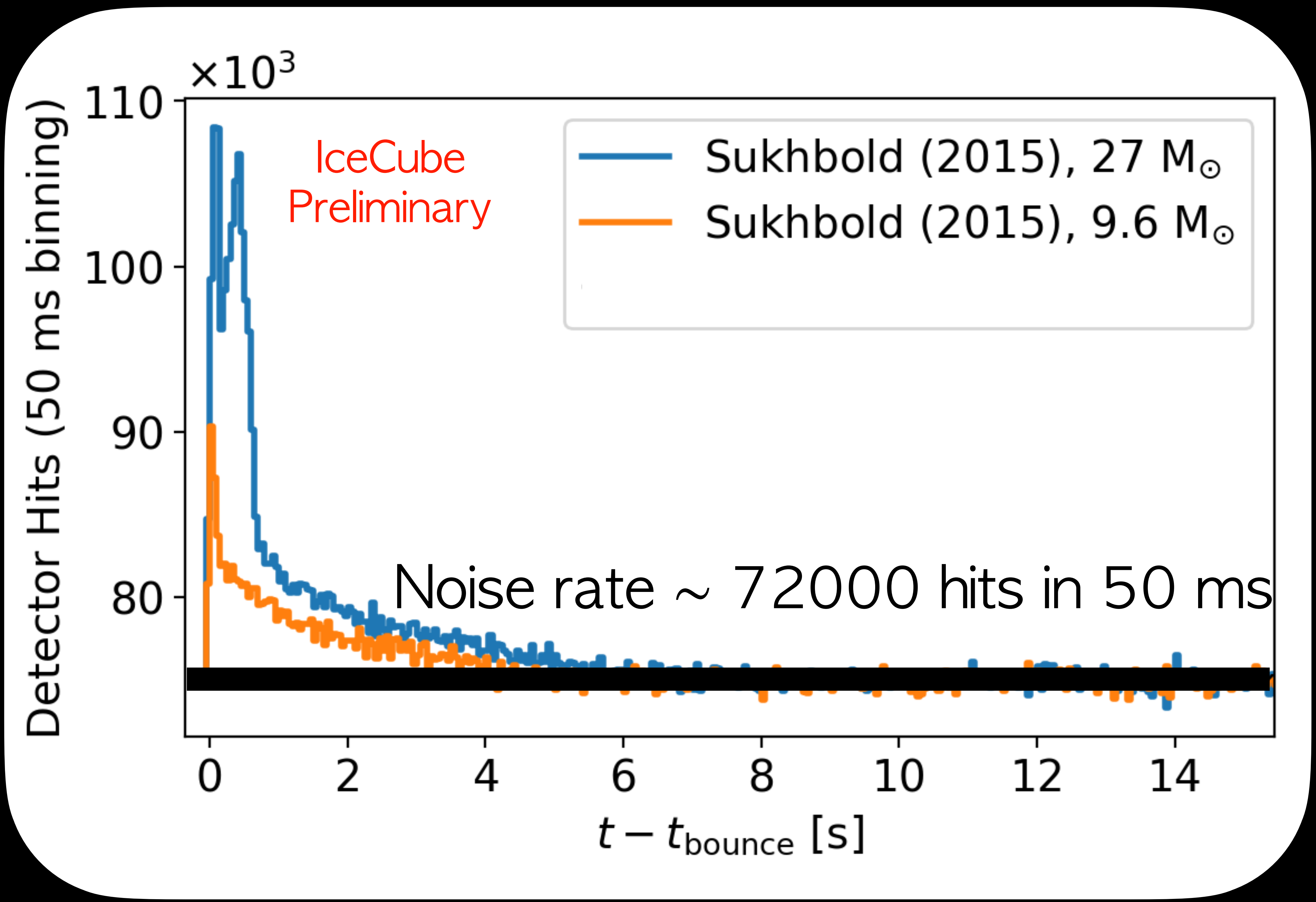
MeV ν → >GeV - PeV ν



MeV ν | >GeV - PeV ν

We need a burst

CCSNe model at d = 10 kpc



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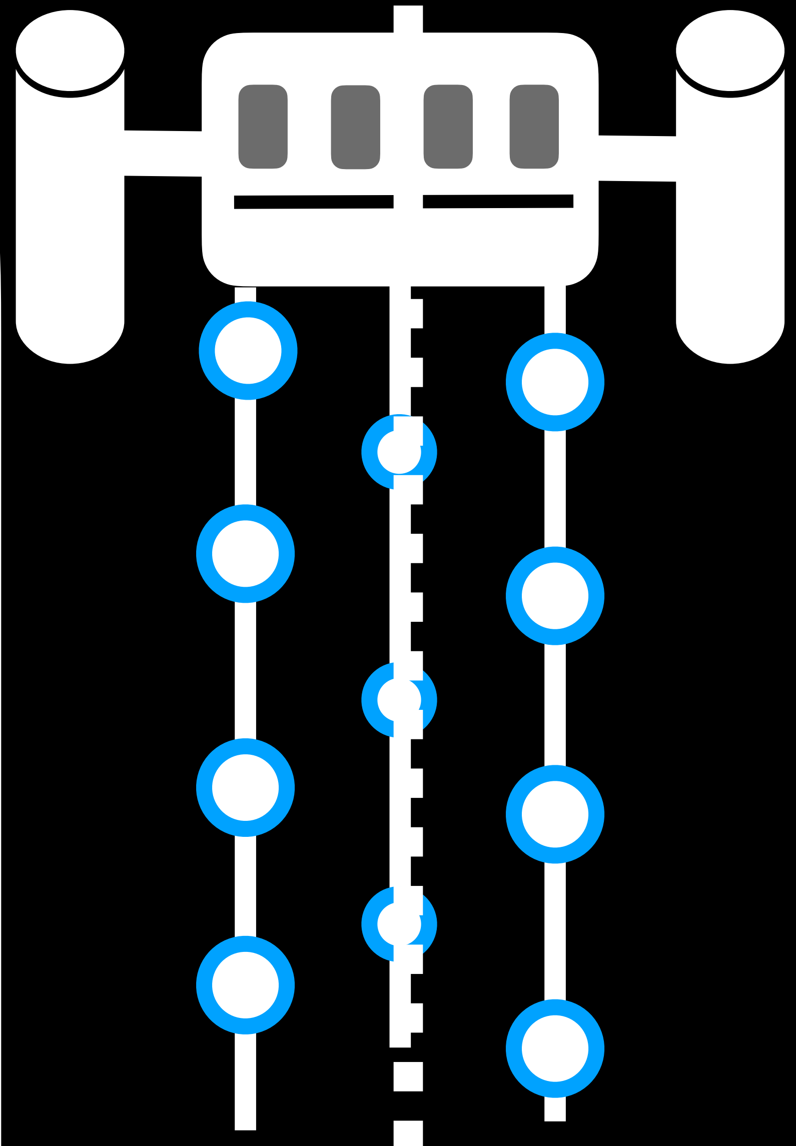


- We can reconstruct direction and energy of neutrinos
- We search for astrophysical neutrinos using direction and energy information to separate from noise: we can use single neutrinos.

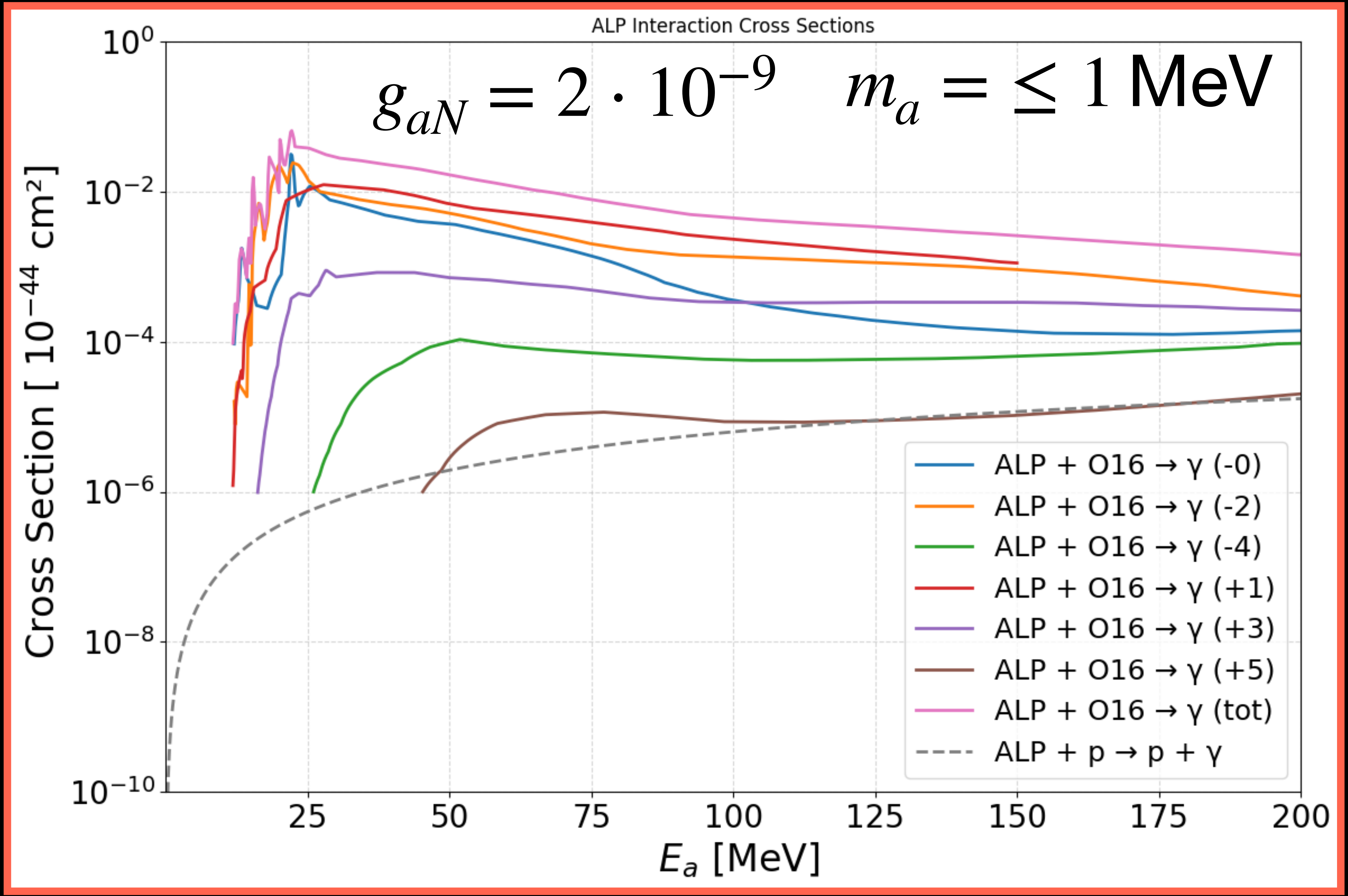
Background: 1.4 MHz

Signal: 2.2 MHz

From ALP to detectable signal

We simulate the detector response for both O16 and proton interactions.

We fold in the cross section to obtain a gamma-ray spectrum.



$a + p \rightarrow p + \gamma$ → [Alonso-Gonzalez et al., 2025 Phys. Rev. D. 111, 083029]

$a + O^{16} \rightarrow O^{16*} \rightarrow O^{16} + \gamma$ → [Carenza et al., 2023 Phys. Rev. D. 109, 015501]

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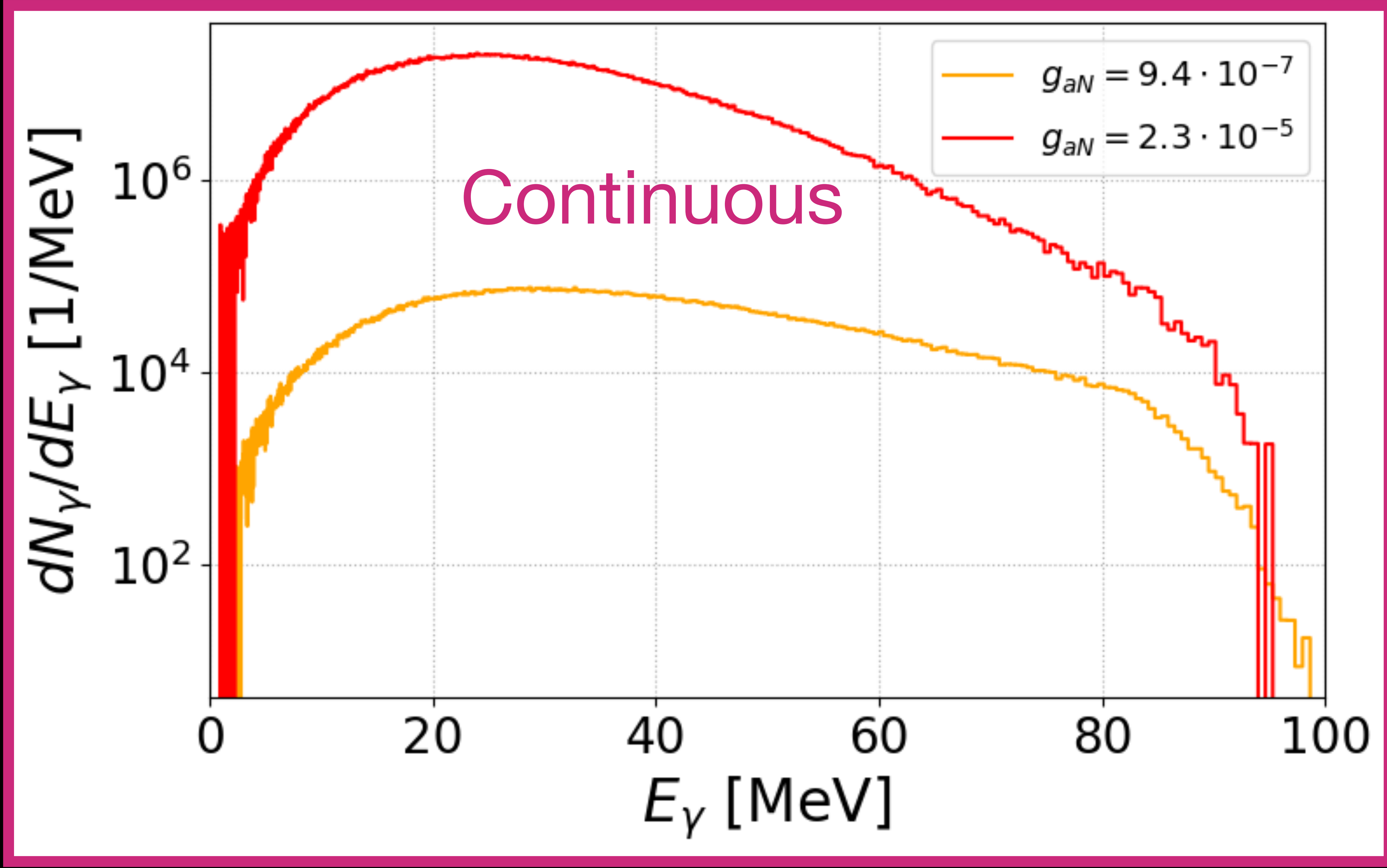

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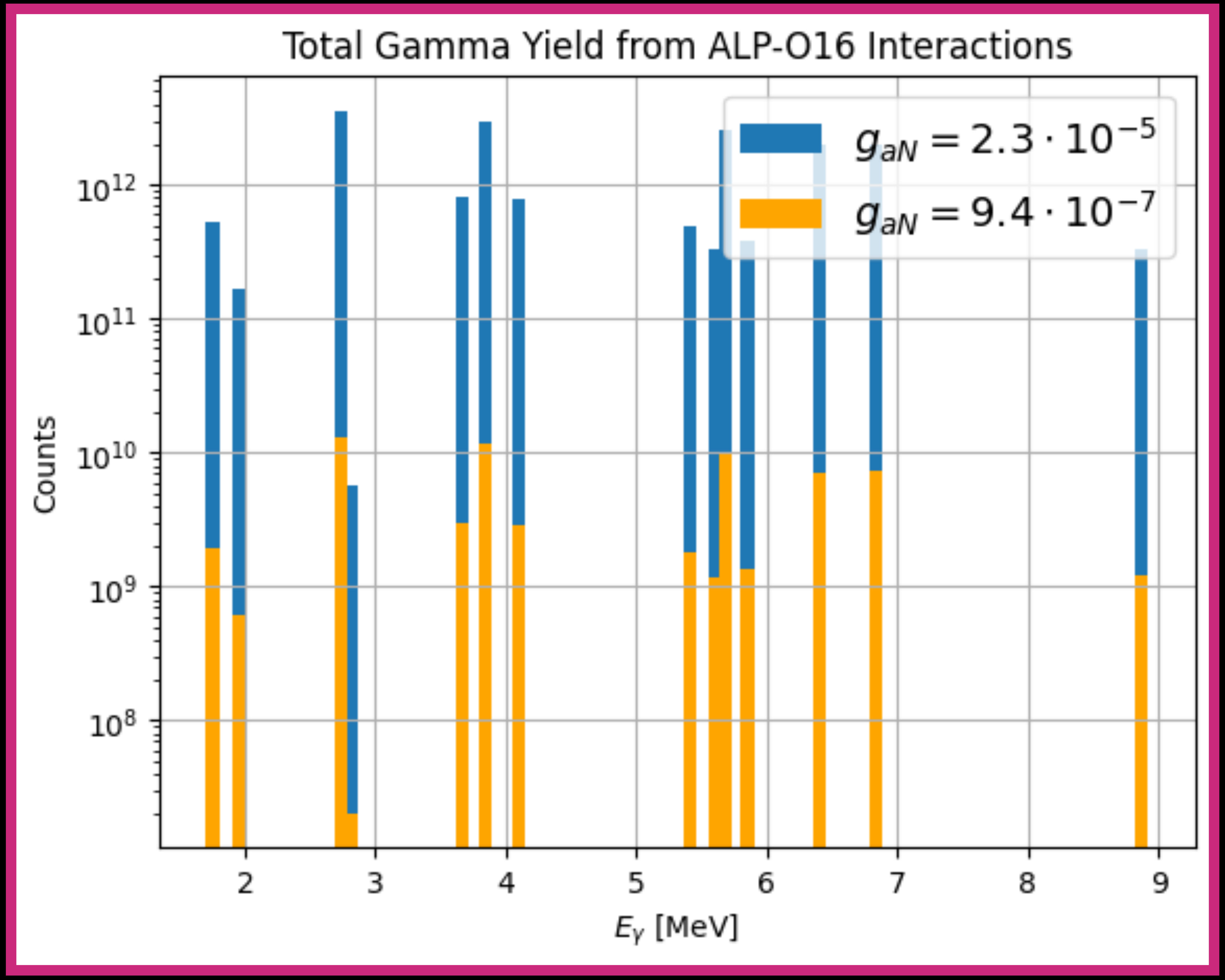

Discrete

From ALP to detectable signal

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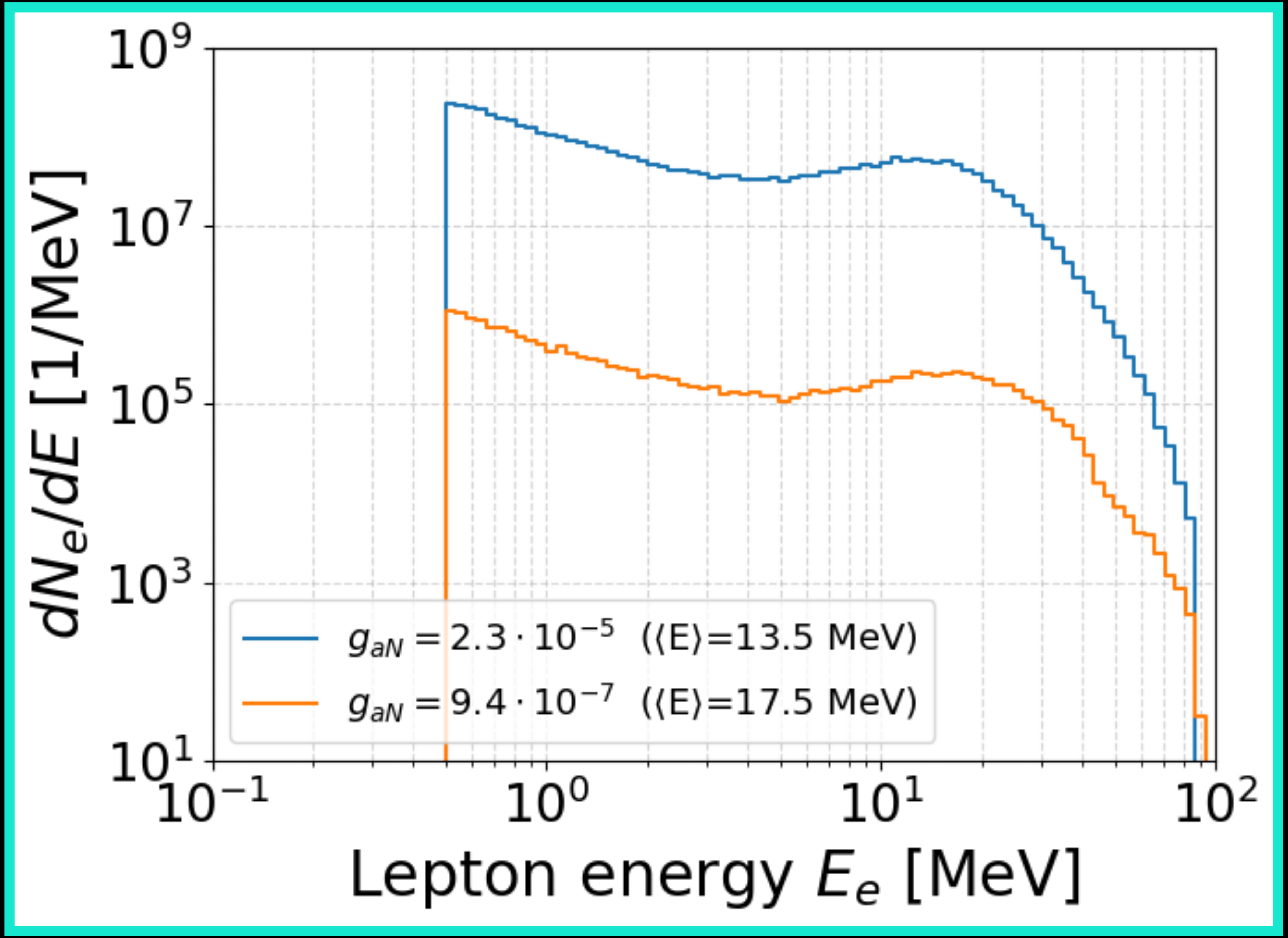
We simulate the production of leptons in ice



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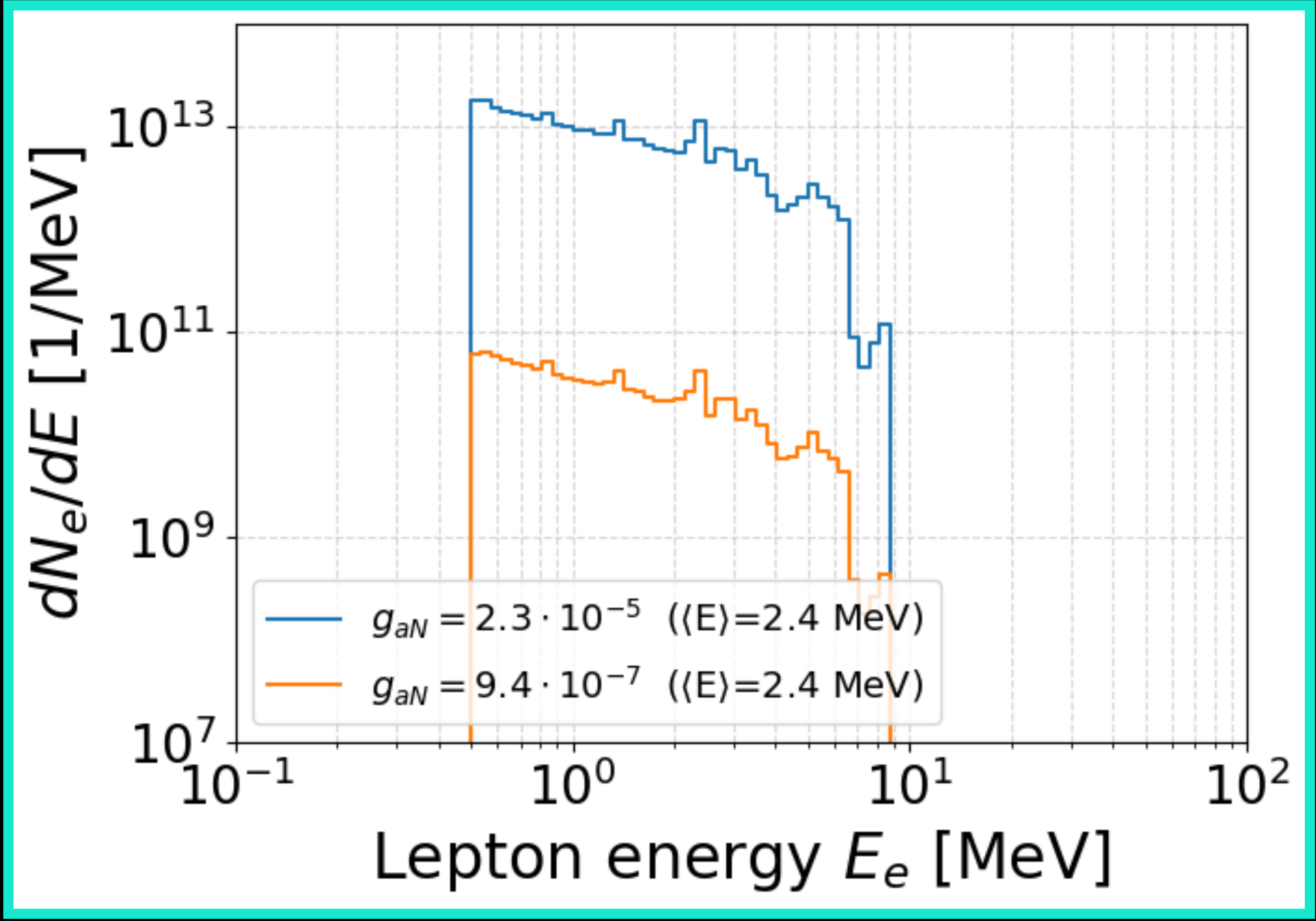

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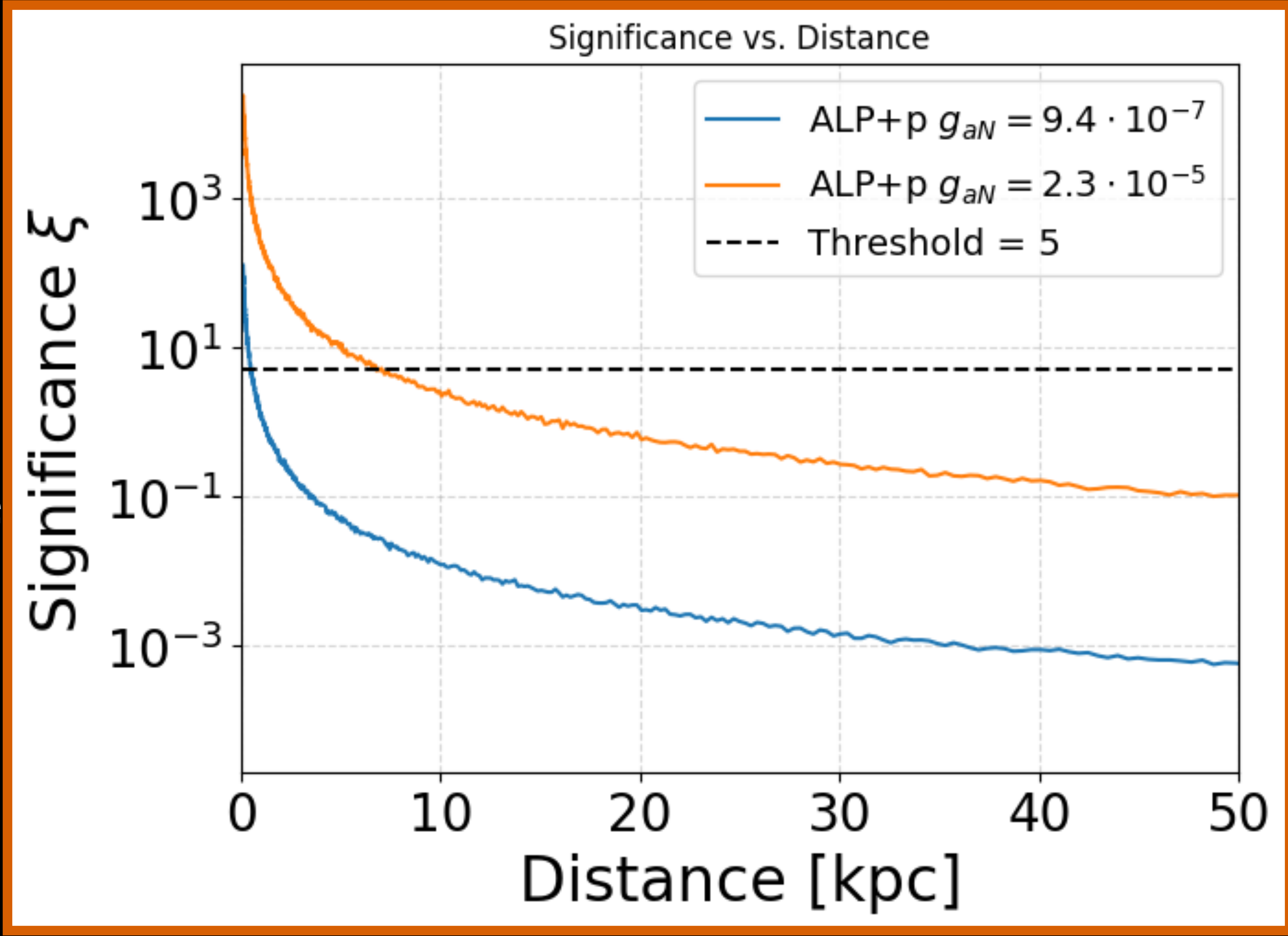
We fold in the Cherenkov production and simulate the detector response to obtain a detection horizon

Preliminary: Without t.o.f effects, for the given fluxes/models, we could directly detect ALPs up to the Galactic Center



0.5 - 7 kpc

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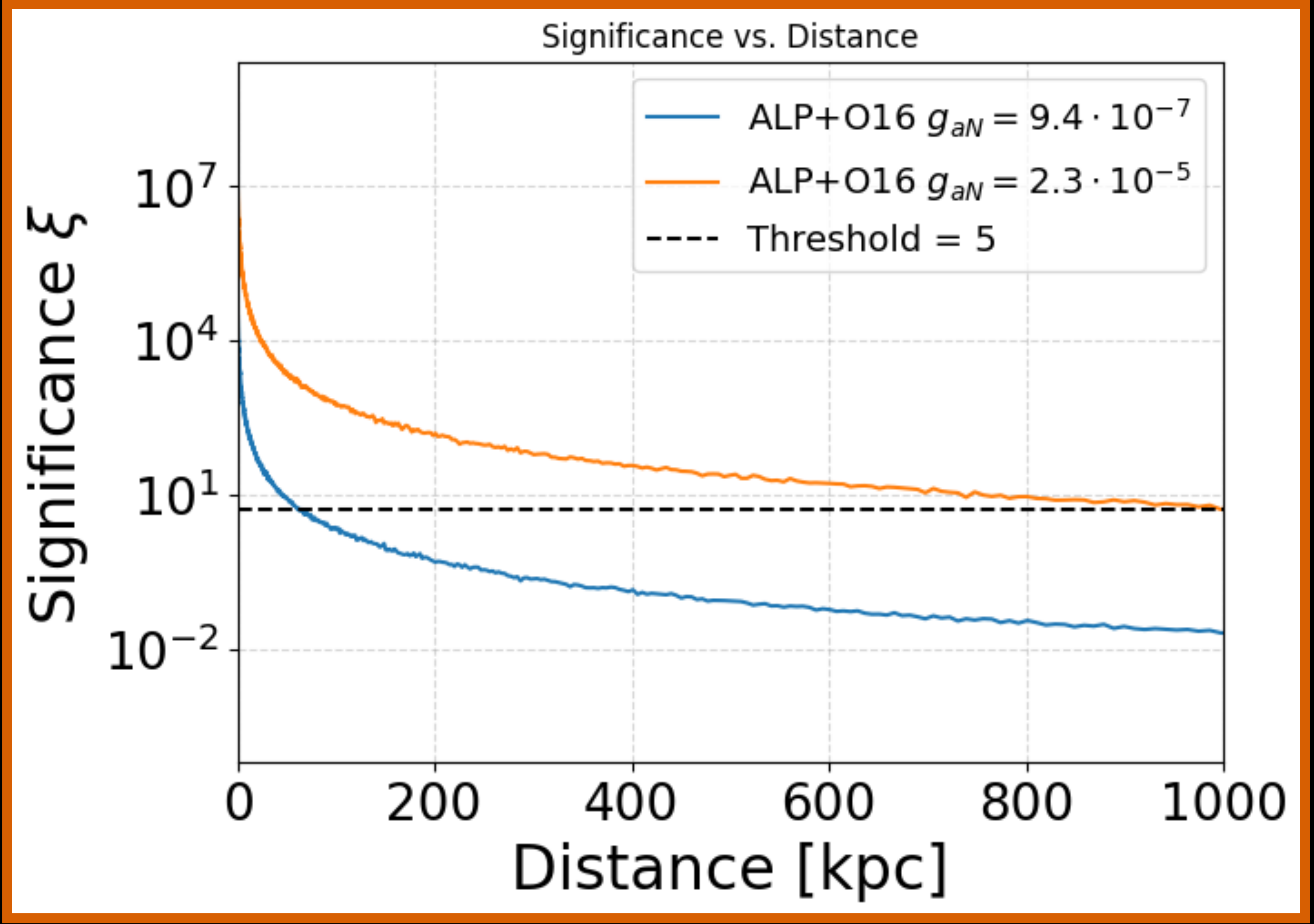

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65 - 1000 kpc

From ALP to detectable signal

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Note: We only looked at the trapped regime

The free-streaming regime will likely have detection horizon in O(10 kpc)

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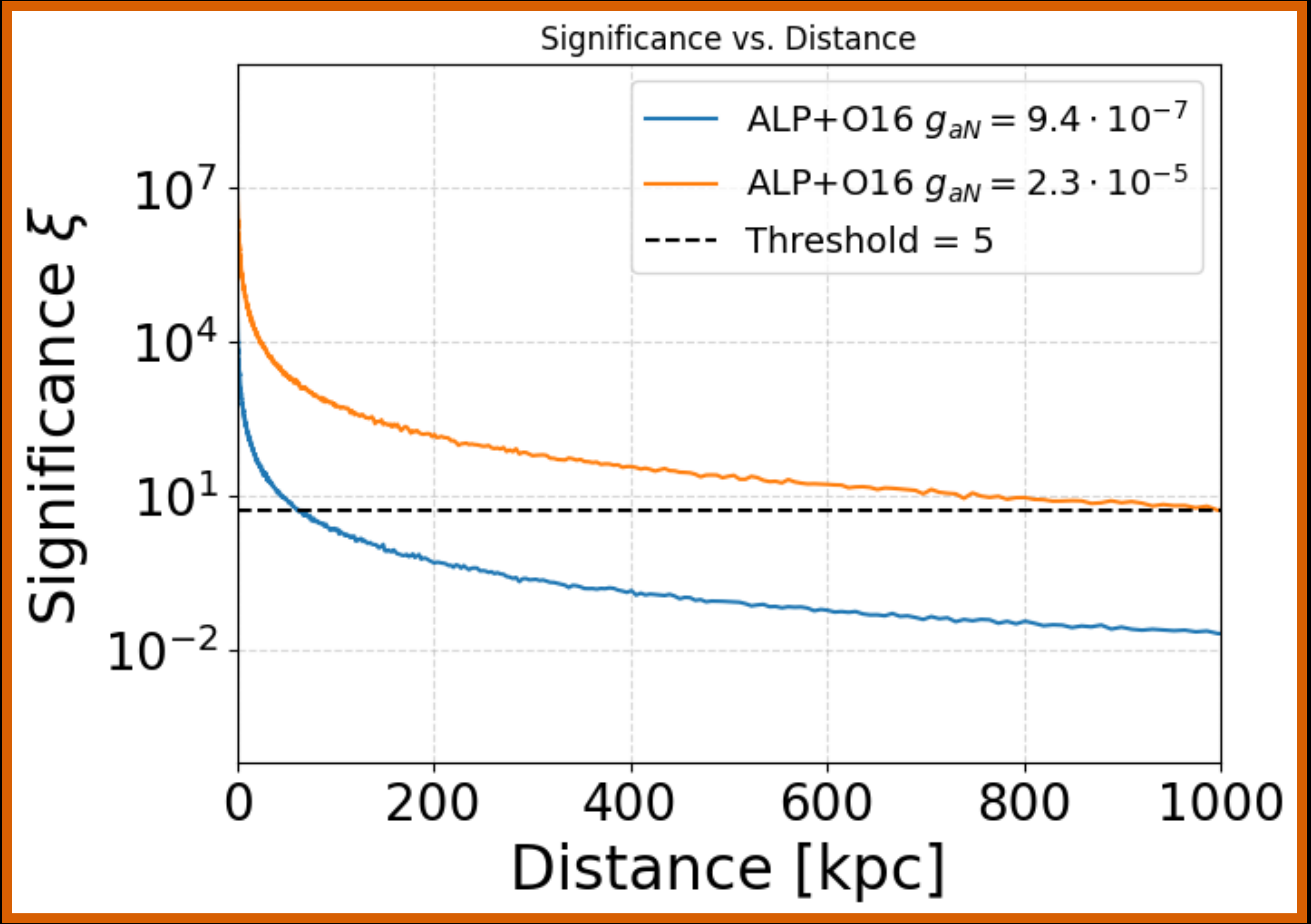
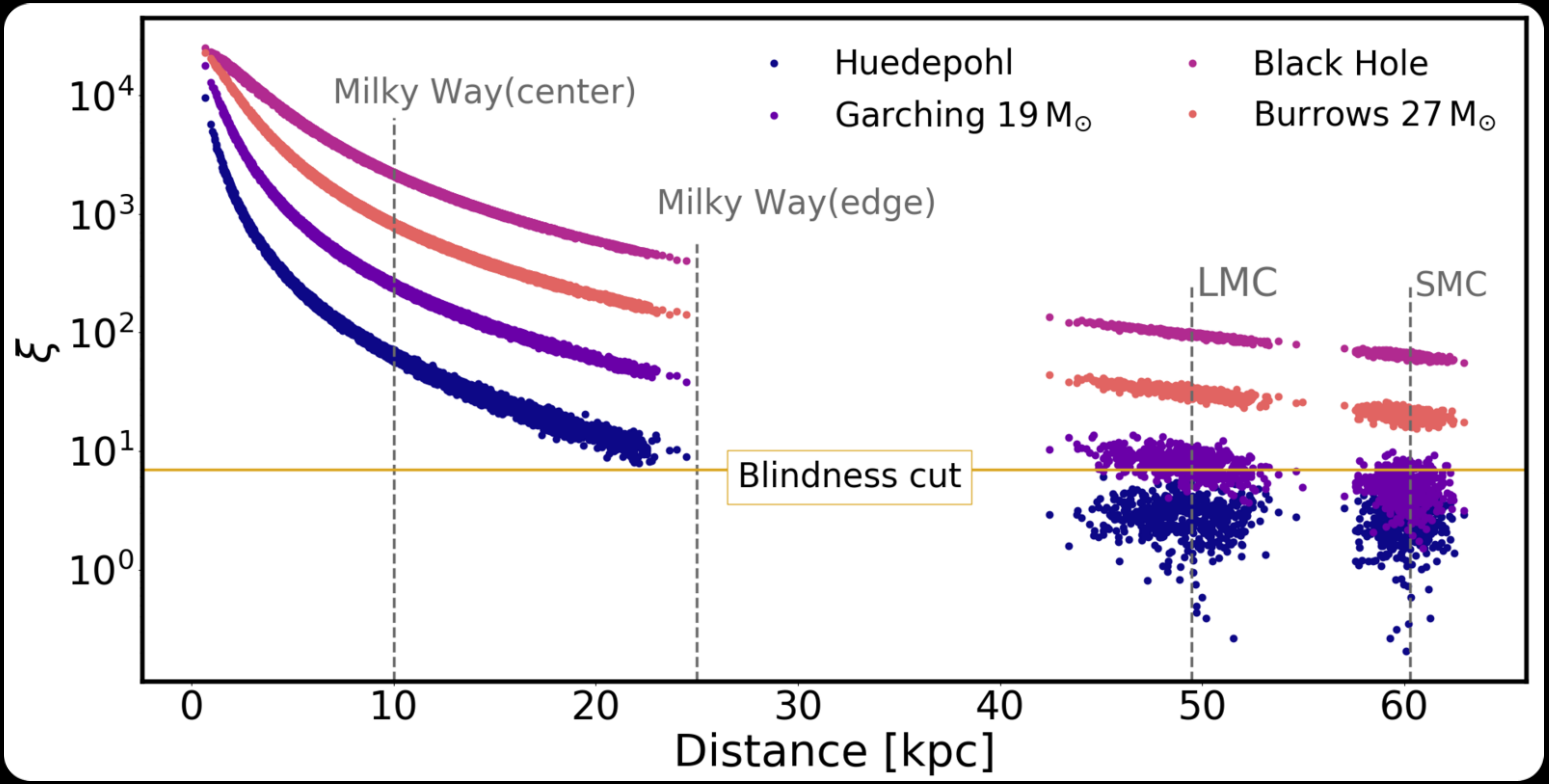


65 - 1000 kpc

Summary

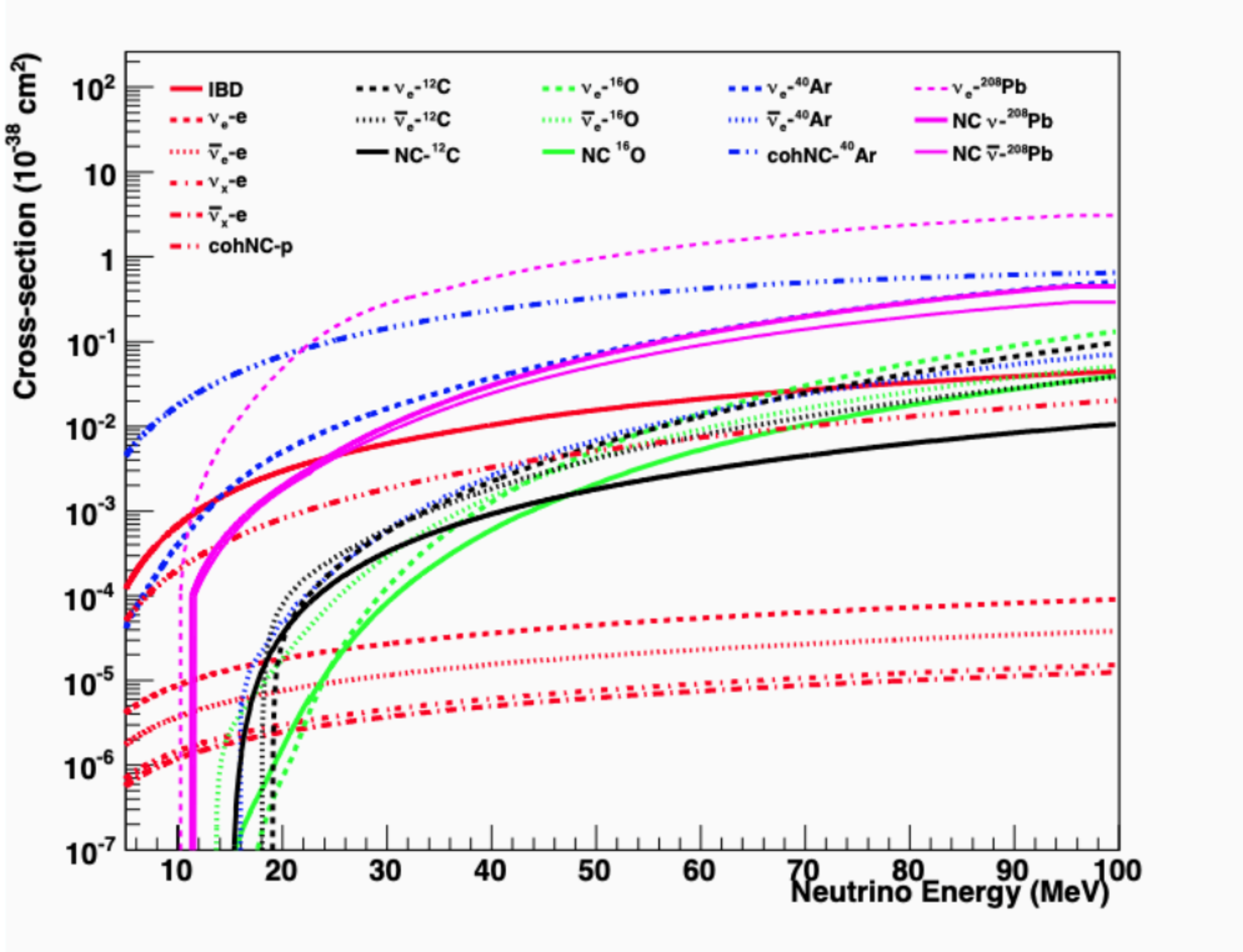
- ALPs could be produced copiously in CCSNe and they could couple to matter, interacting at Earth in water/ice producing gamma-rays. These could produce $e^{\pm}$ which could produce Cherenkov light.
  - Use large-scale Cherenkov neutrino detectors to observe this.
- We presented preliminary estimates of the detection horizon for IceCube.
- Preliminary results show that we could potentially observe ALPs from Galactic CCSNe and beyond, with O16 interaction yielding the longest detection horizon.
- Future: enhancements to our simulations, include t.o.f delay and test for more models (mass/coupling). Stay tuned for more!

GALACTIC SENSITIVITY



Credit: R. Abbasi at al., IceCube Collaboration, 2024, ApJ 961, 84

MEV NEUTRINO CROSS SECTION



Credit: Scholberg In: Annu. Rev. Nucl. Part. (2012), 62, 81-103