Possibility of detecting high energy neutrinos from galactic supernovae with ATLAS

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MAYORANA School Minitalk

July 8, 2023

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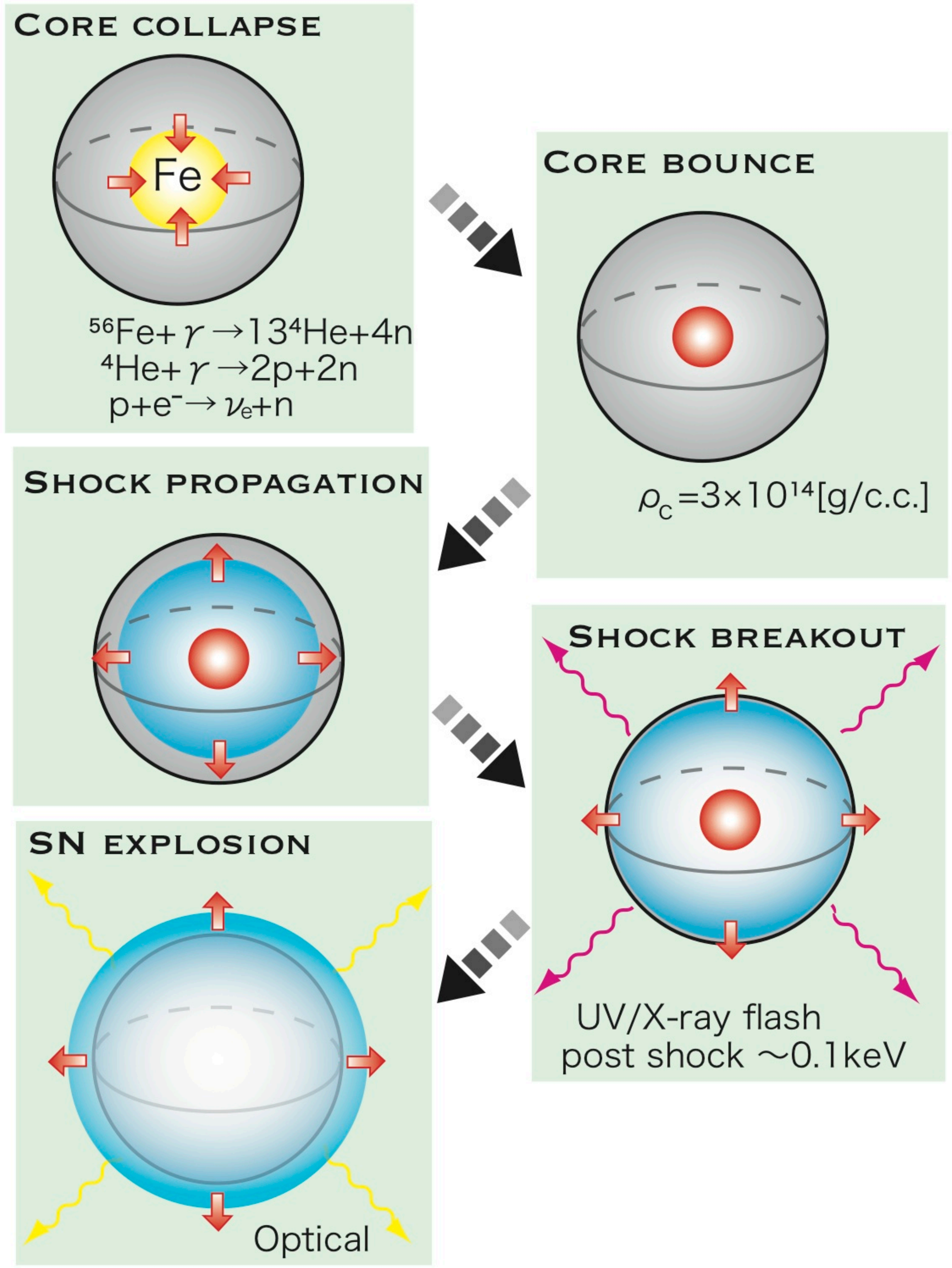
CCSN are environments for neutrino physics.



- Low energy neutrinos from nuclear processes

$e^- + p \rightarrow \nu_e + n$ | $n \rightarrow p + e^- + \bar{\nu}_e$ | ~ 10 MeV

- High-energy neutrino production from collisions

$p + p \rightarrow \pi + \ldots \rightarrow \nu_\mu, \nu_e + \ldots$ | > 100 MeV

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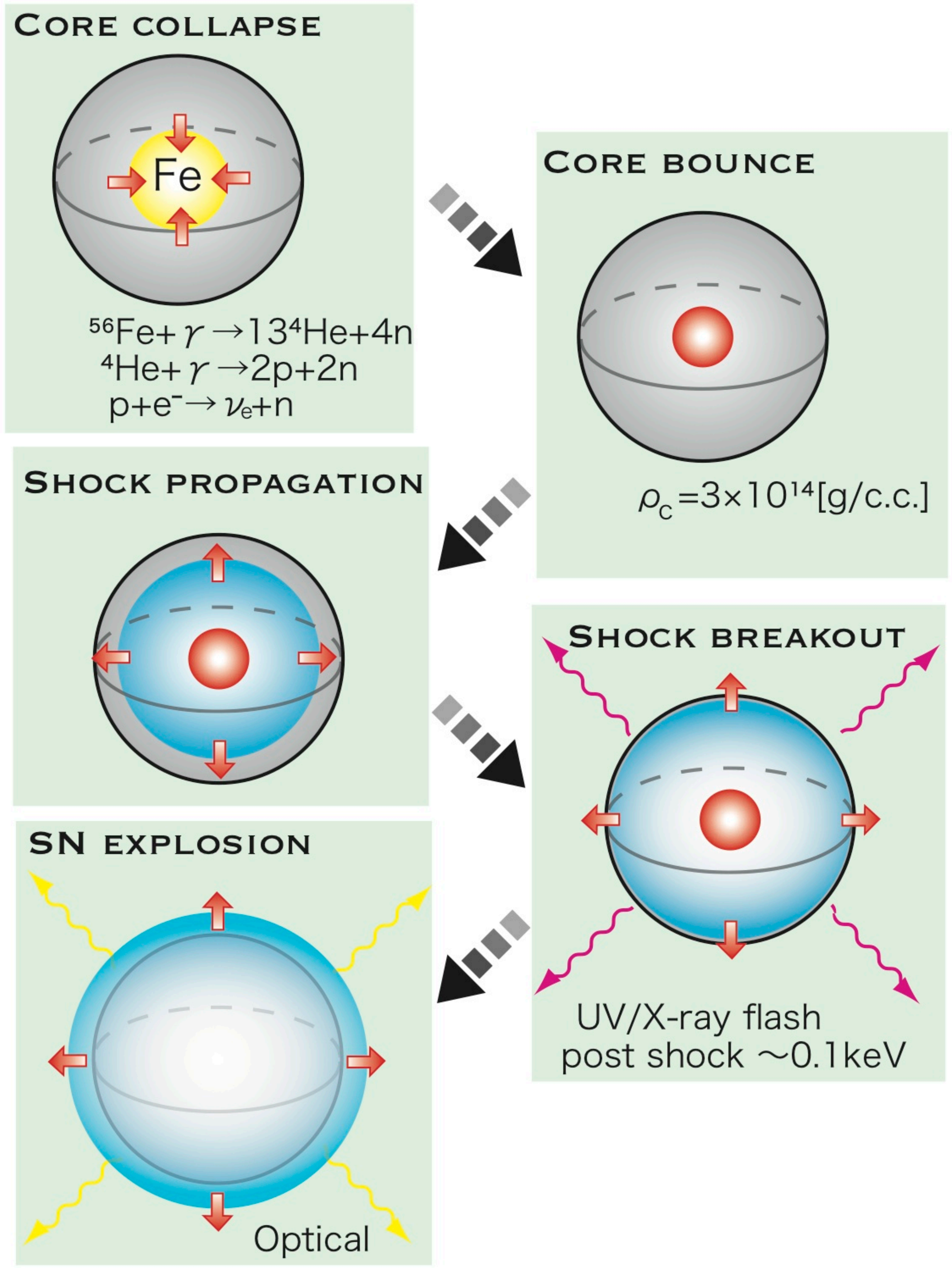

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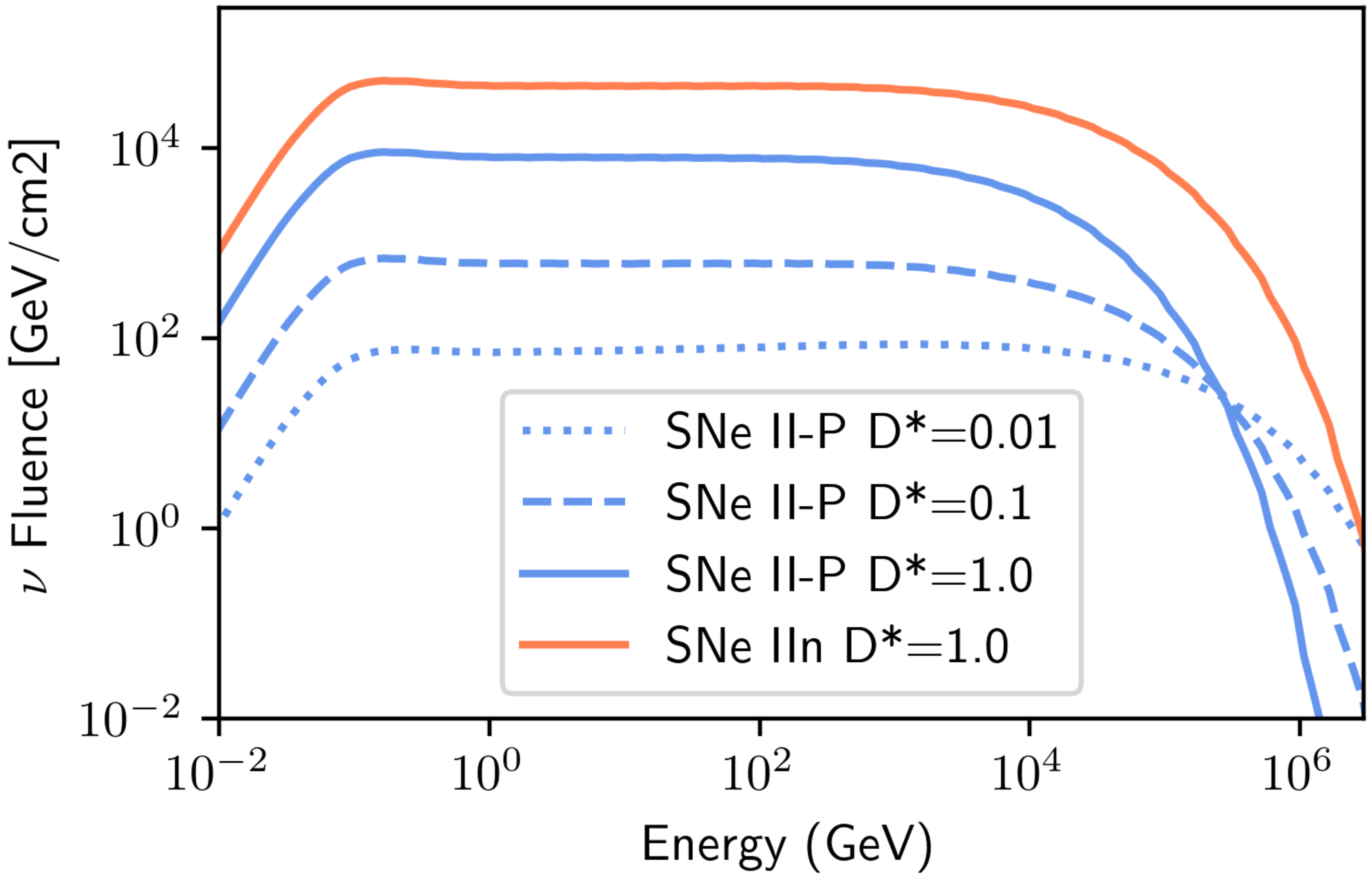
$p + p \to \pi + \ldots \to \nu_\mu, \nu_e + \ldots$ | > 100 MeV

We are interested in this case

SN with CSM produce appreciable neutrino fluxes.



Fluences
Murase & Kheirandish (arXiv:2204.08518)

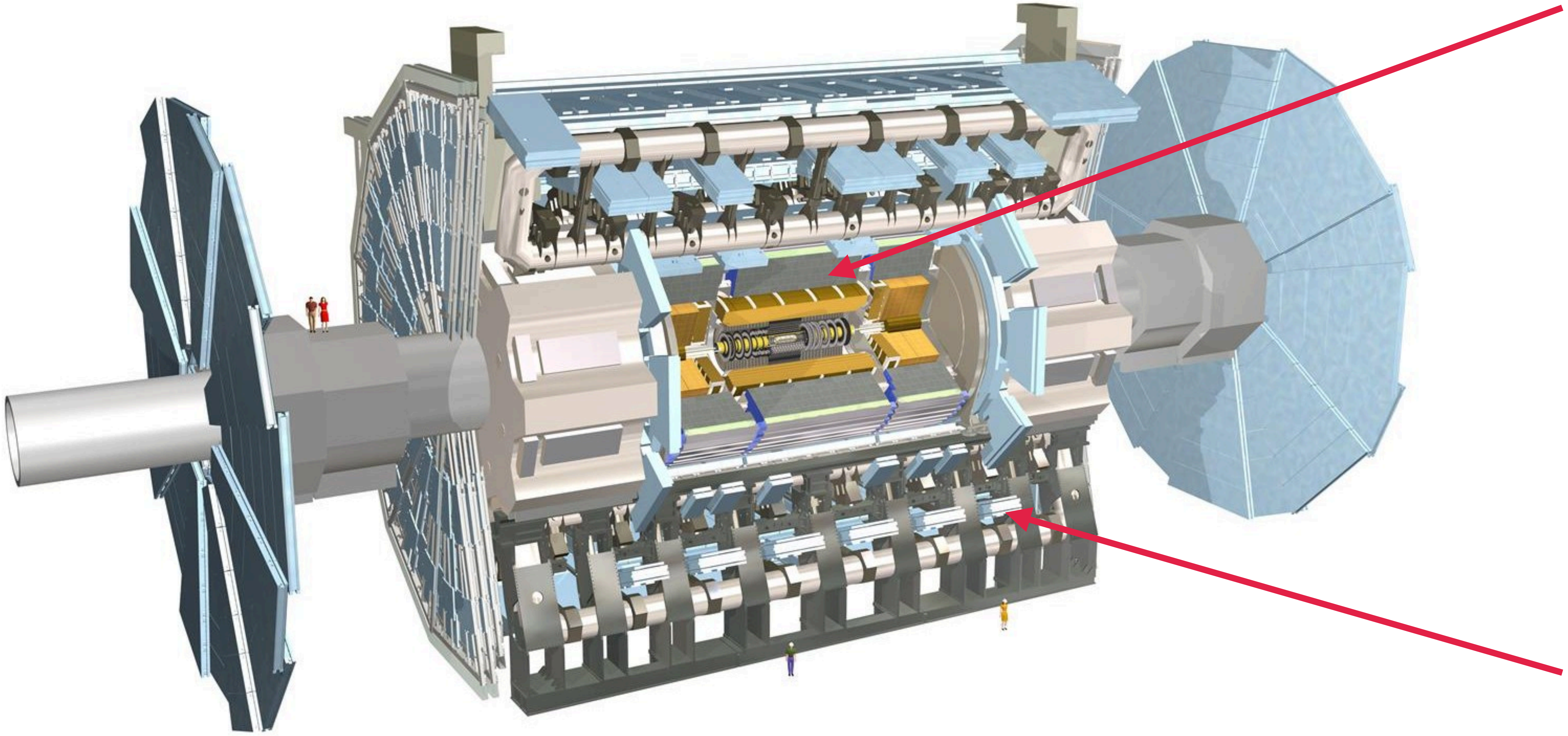
Dominant contributions from

- type IIn (~10% of all CCSN)
- type II-P (~50% of all CCSN)

The density profile of the CSM is dependent on parameter D_*:

$$\rho \propto D_* r^{-2}$$

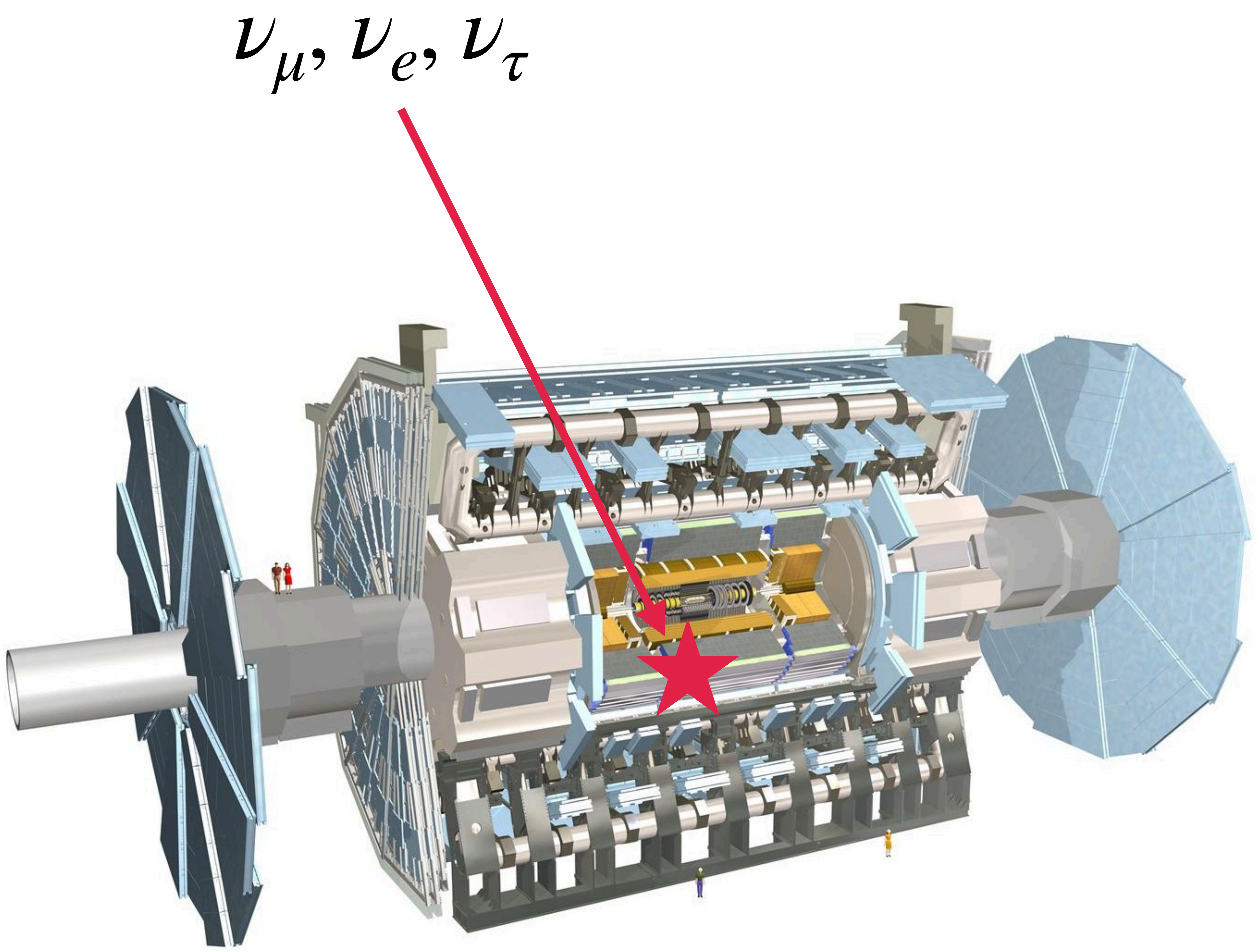
ATLAS is just a large, densely-instrumented, mass.



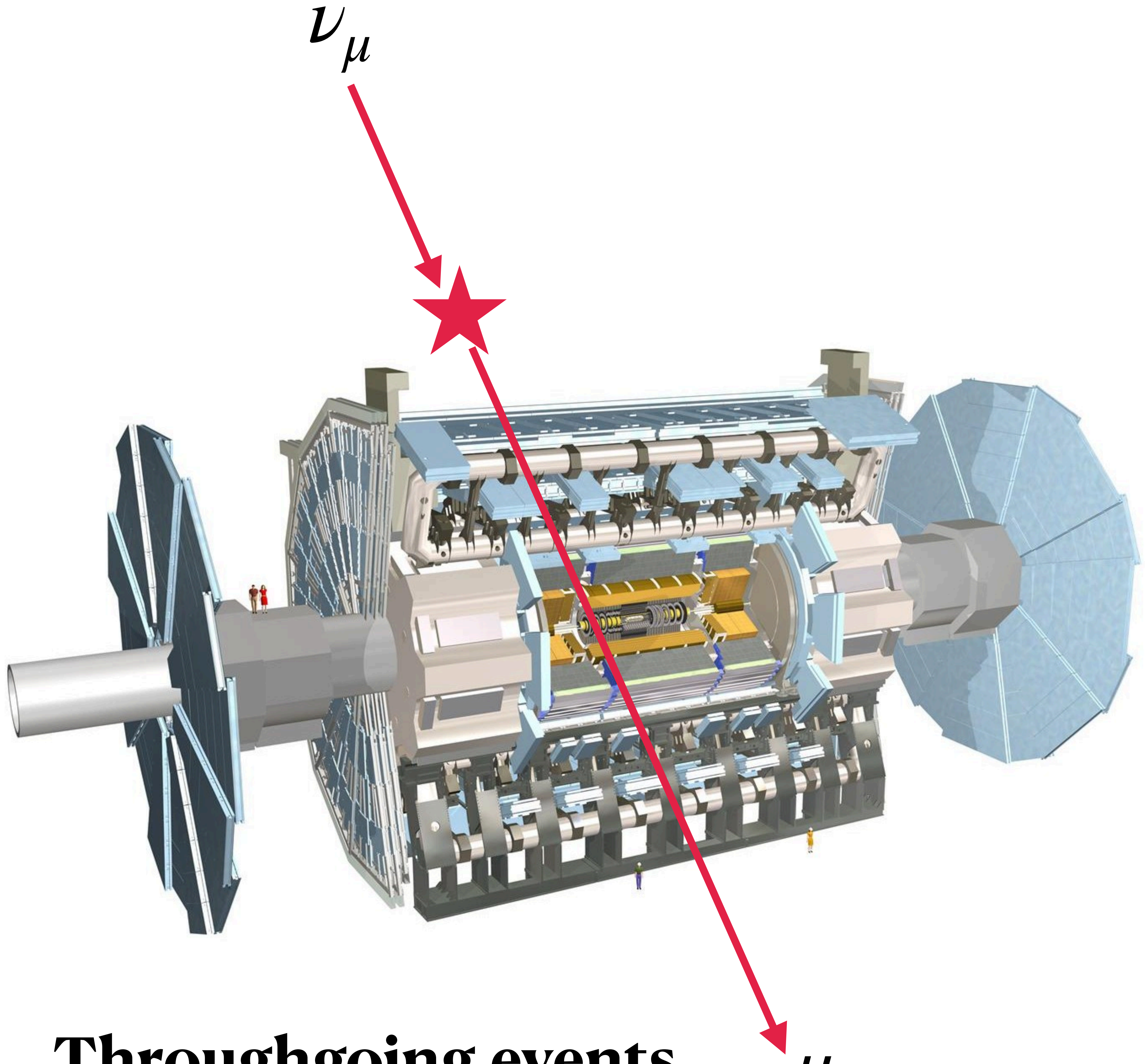
Hadronic calorimeter
4000 tons!

Muon system
(monitored drift tubes)

The detector is sensitive to multiple types of events.

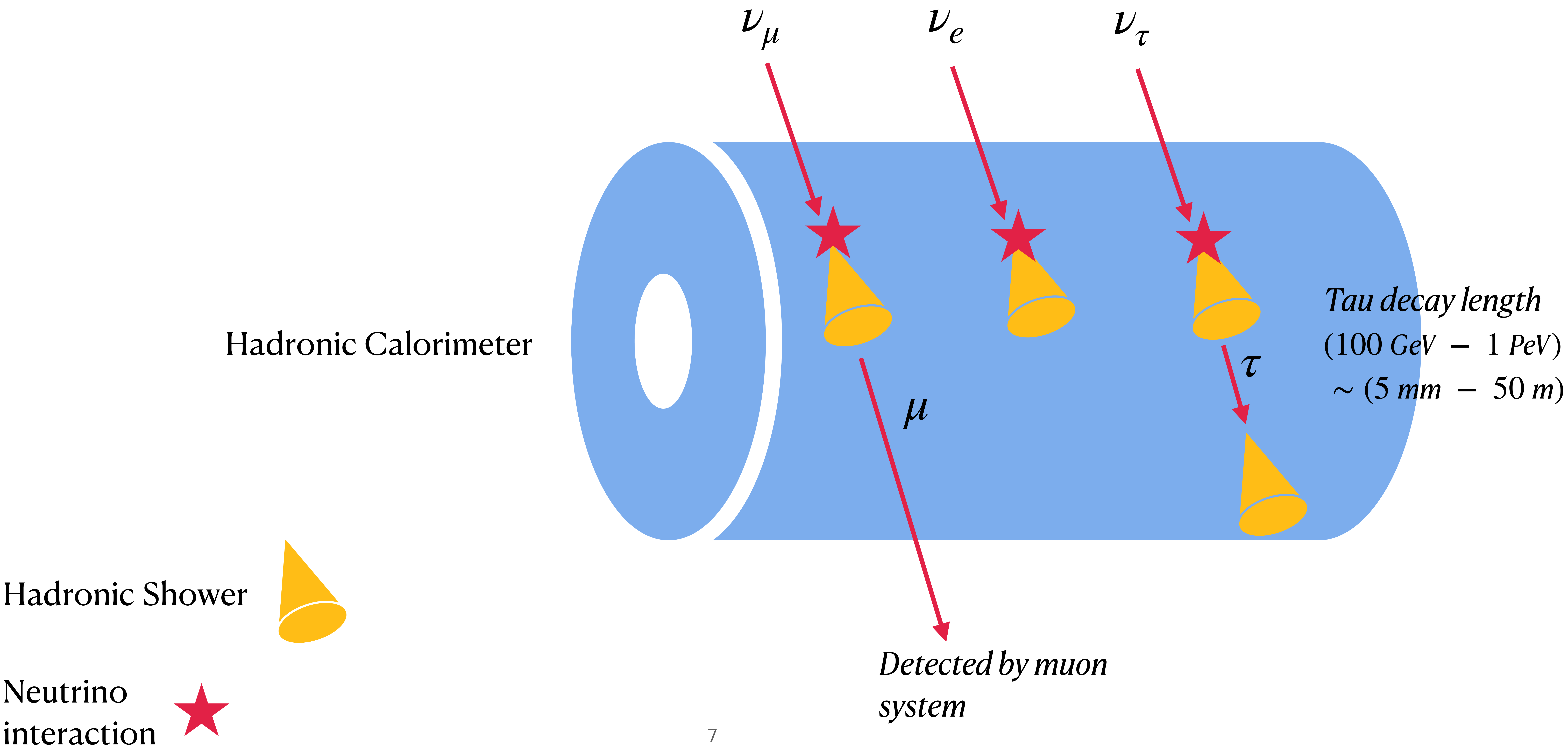


Starting events

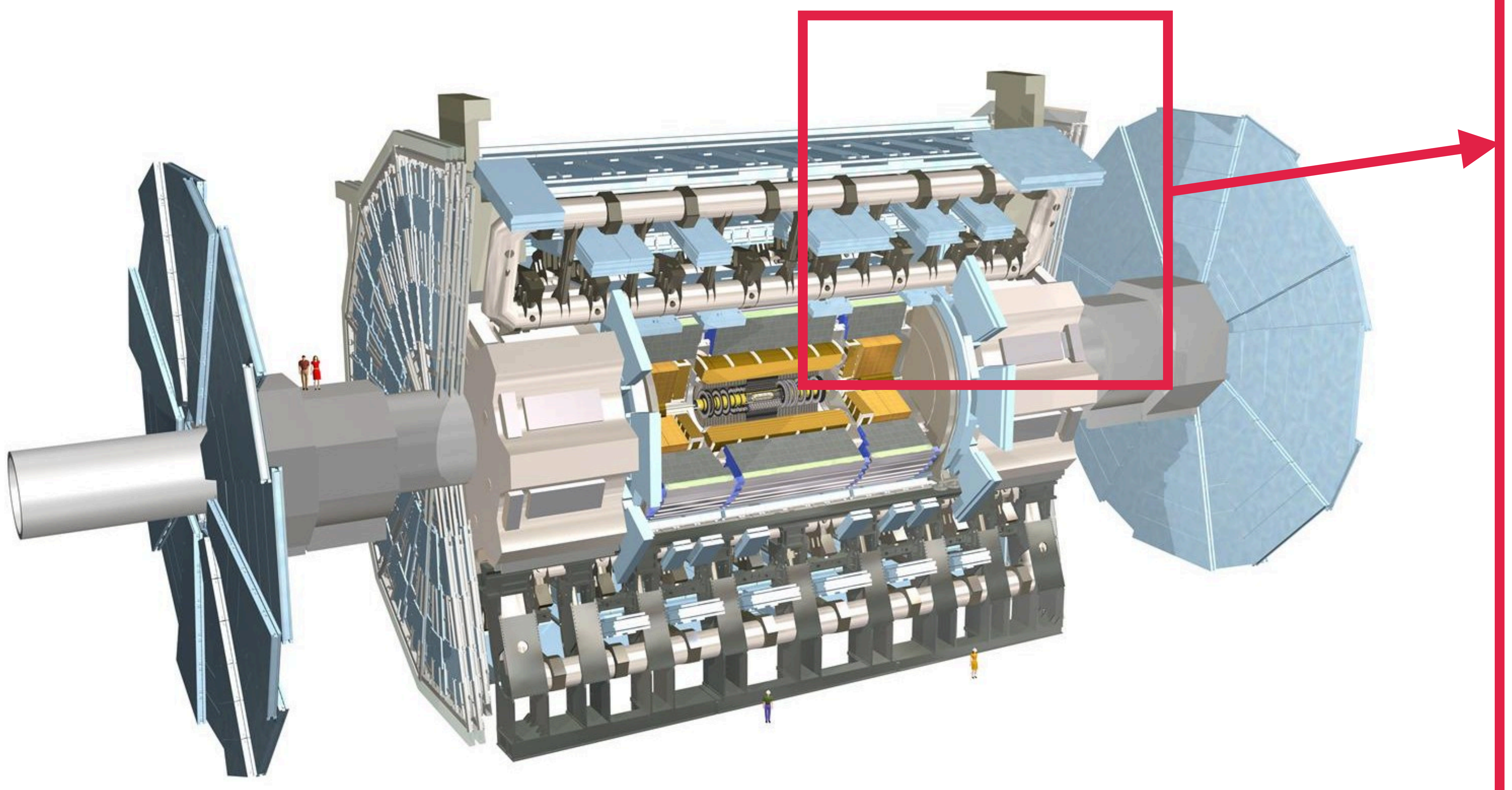


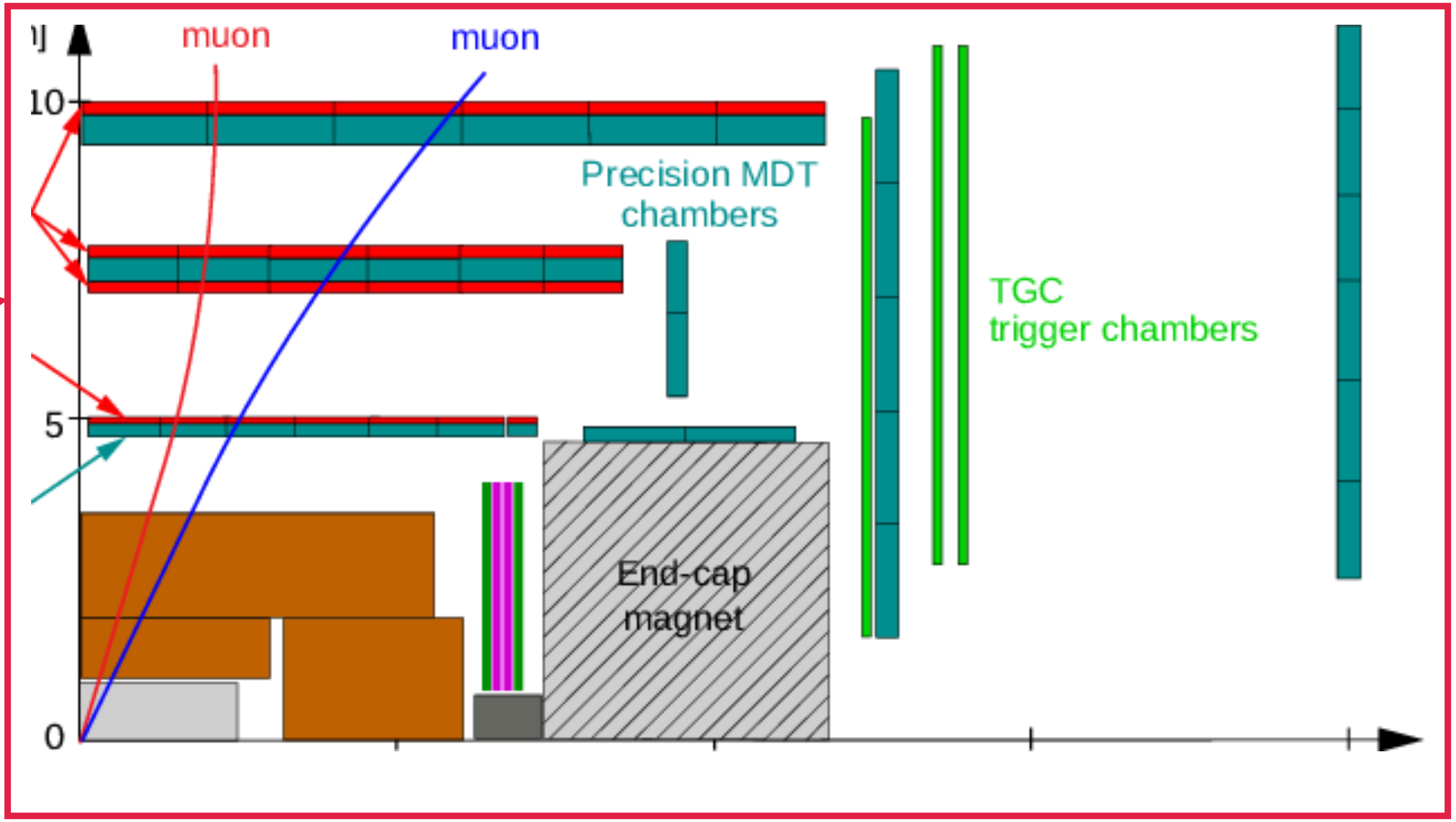
Throughgoing events

Flavor discrimination is possible for starting events.



Charge discrimination is also possible.



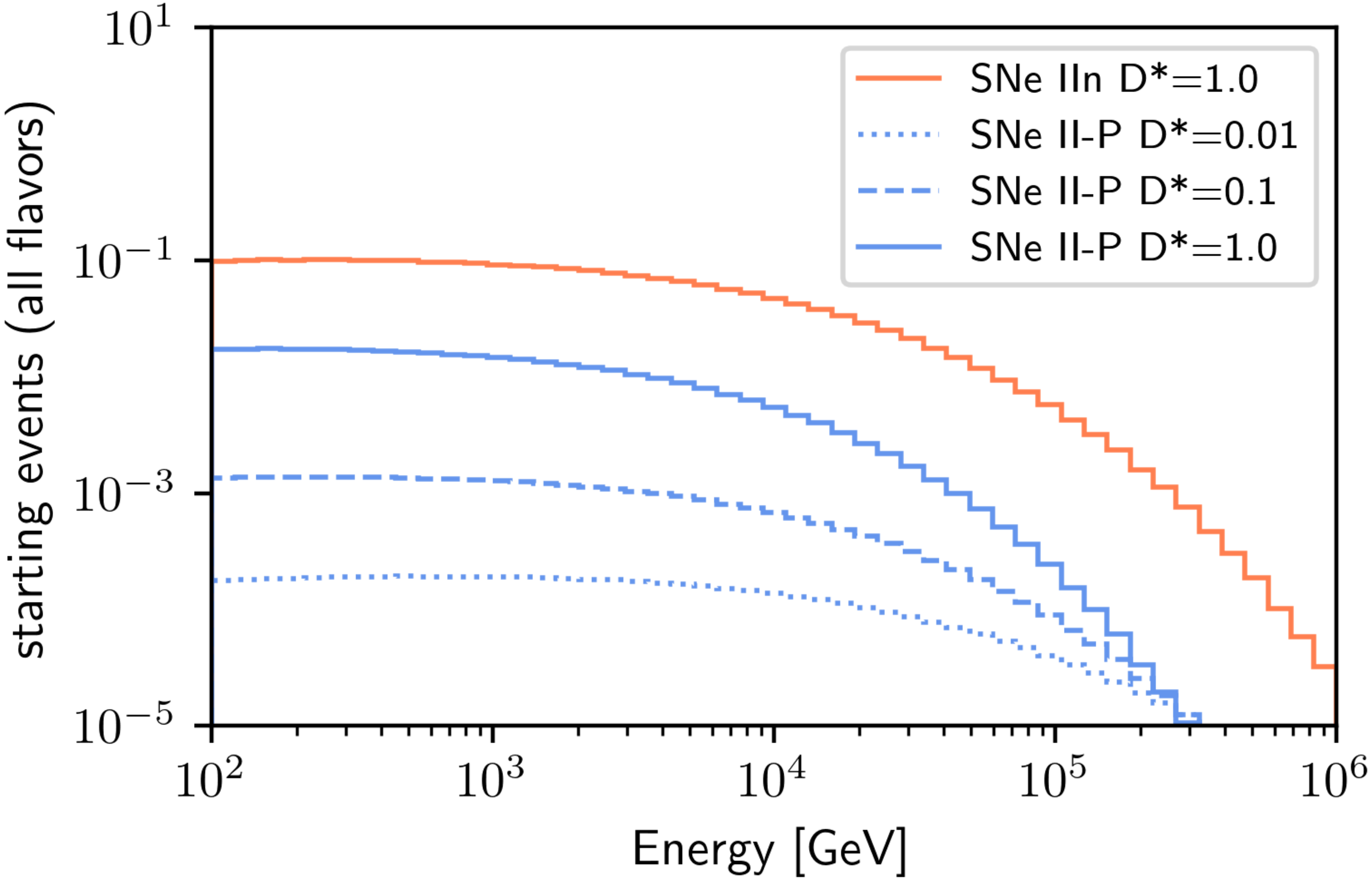


Possible to calculate starting events directly…

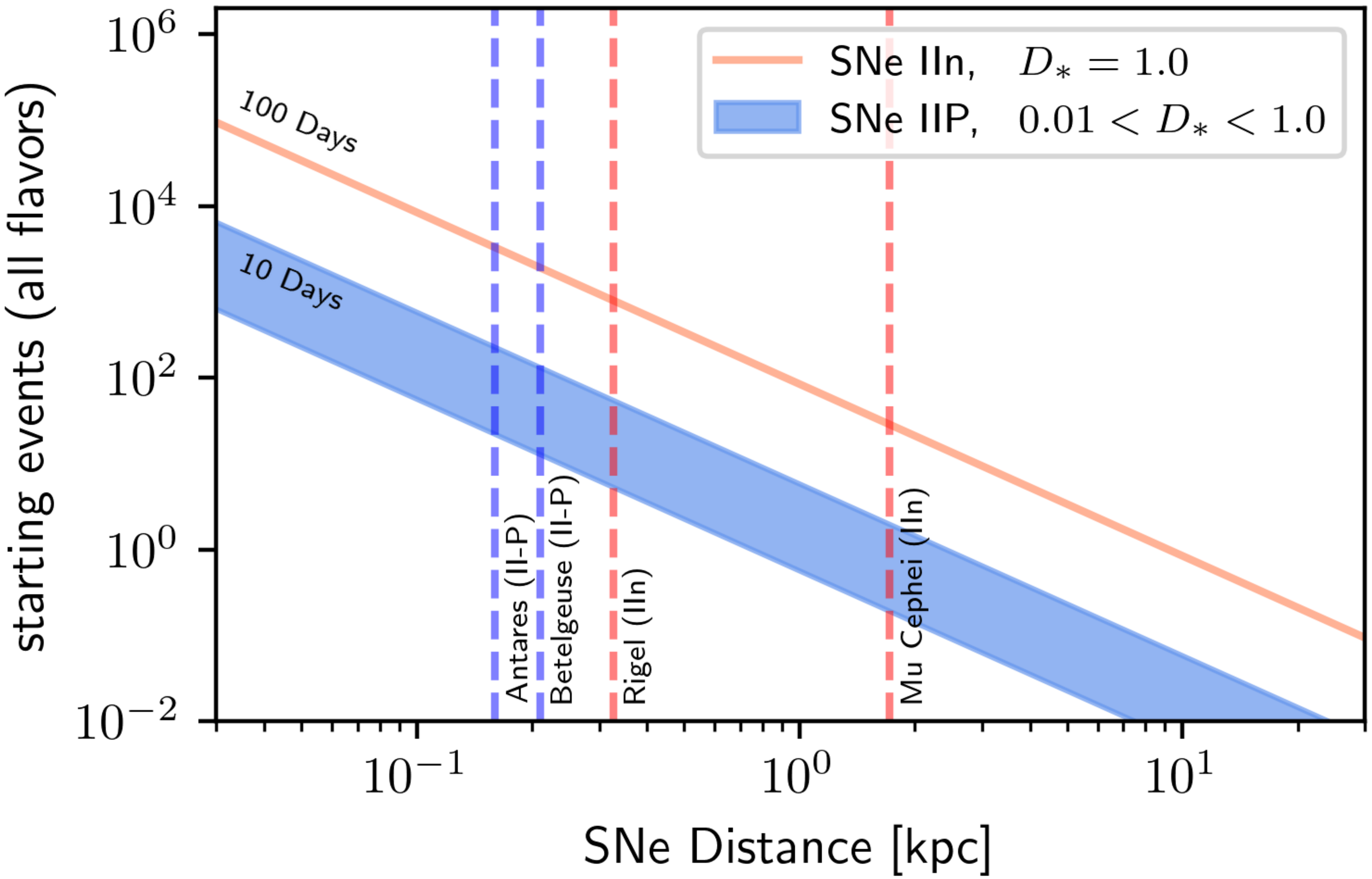
We know:

- Flux
- Cross sections
- Detector mass

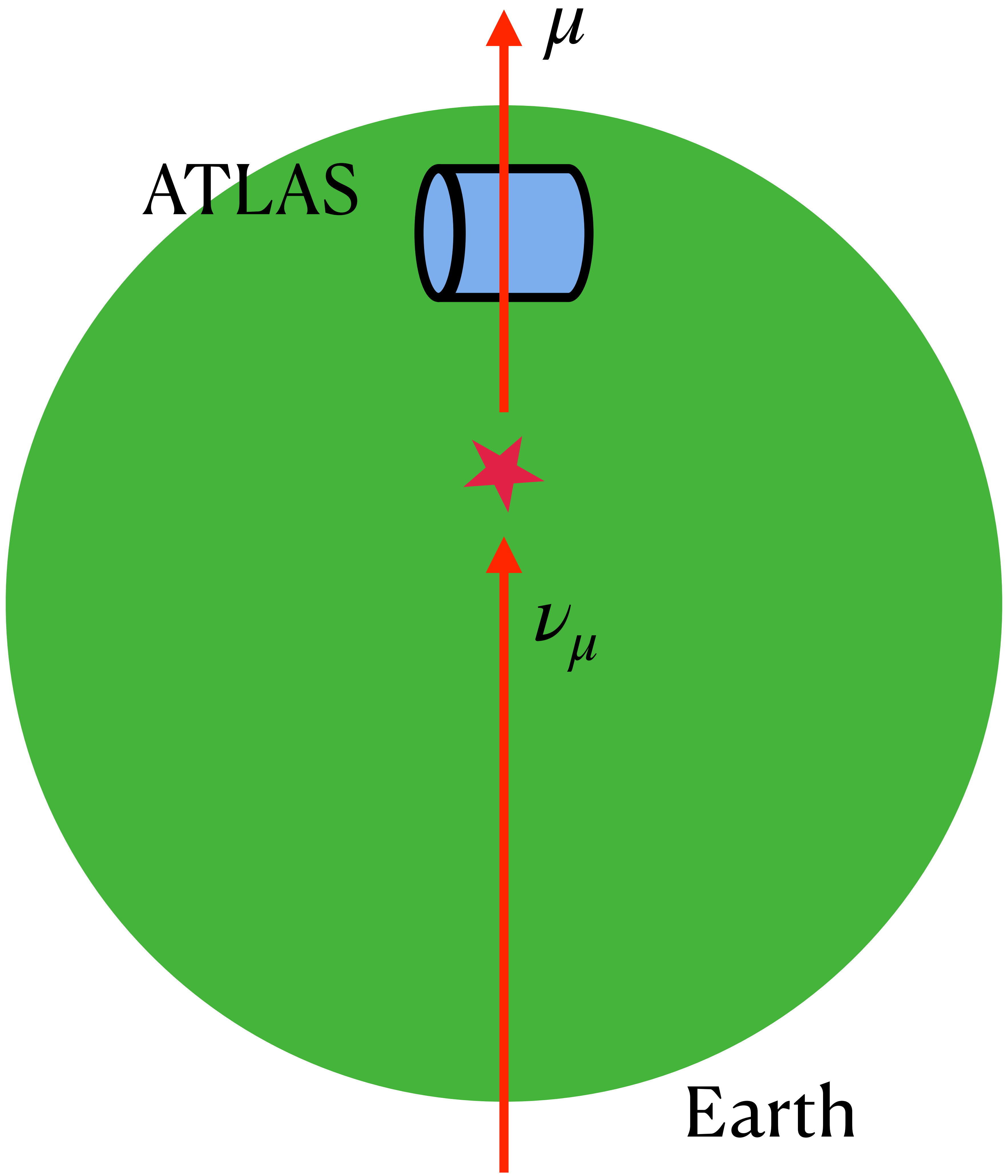
Starting events energy distribution



We get meaningful numbers of starting events from the galaxy.



Simulation of thoroughgoing events is in progress.

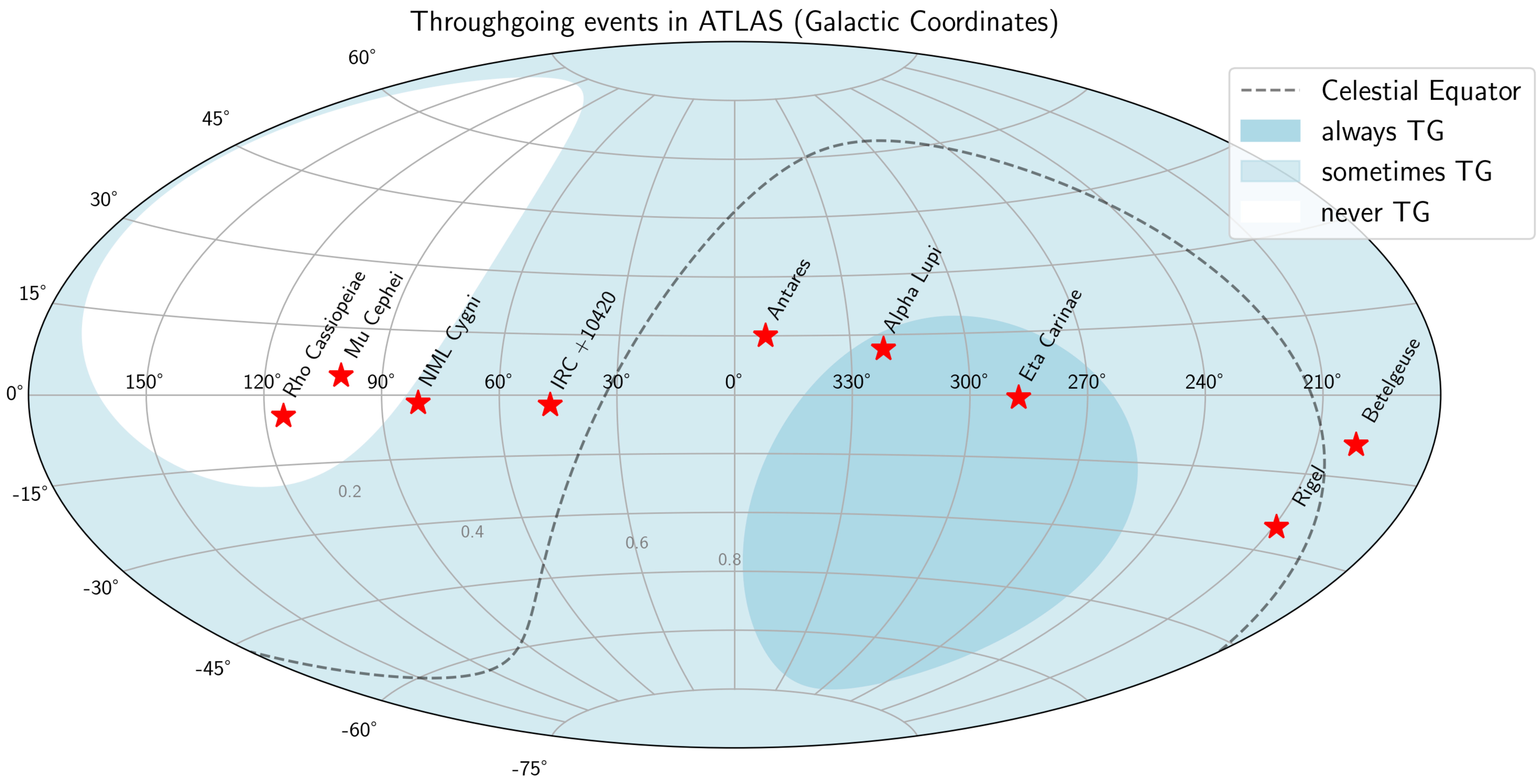


- Effectively increase detector volume
- Throughgoing events $\sim$ 100 times more than starting

PROPOSAL - muon propagator
(github.com/tudo-astroparticlephysics/PROPOSAL)

LeptonInjector - event generator
(github.com/Harvard-Neutrino/LeptonInjector)

ATLAS offers different thoroughgoing sky coverage.



Why ATLAS?

- Different detector tech
- More events
- Sky coverage
- Other similar experiments
- Flavor & charge ID
- Exists

Conclusion: it’s worth considering ATLAS as a neutrino detector.

Thank you. Questions?

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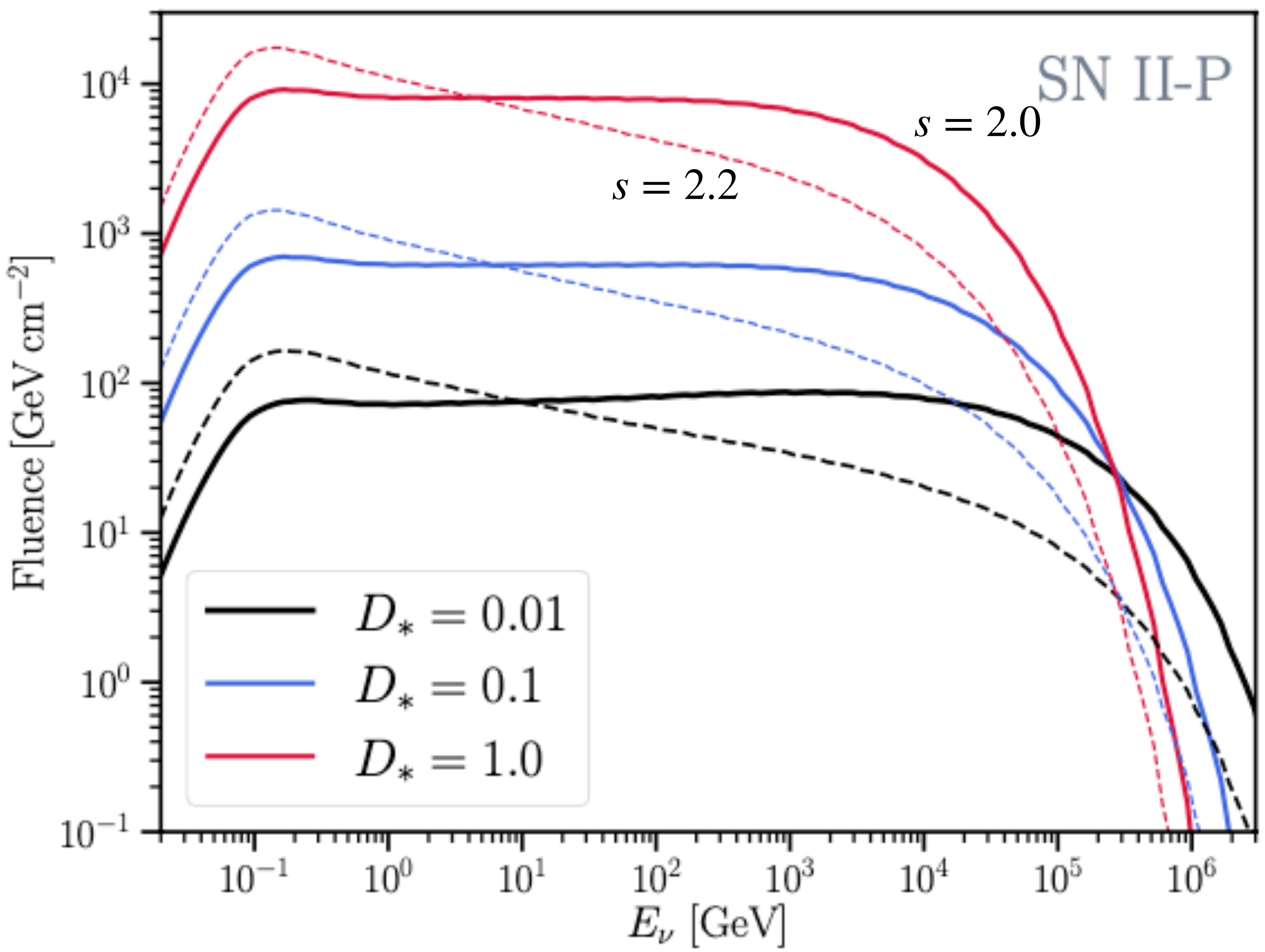
Backup

SN with CSM are characterized by a spectral index and density parameter.



Fluence for SN II-P
Murase & Kheirandish (arXiv:2204.08518)

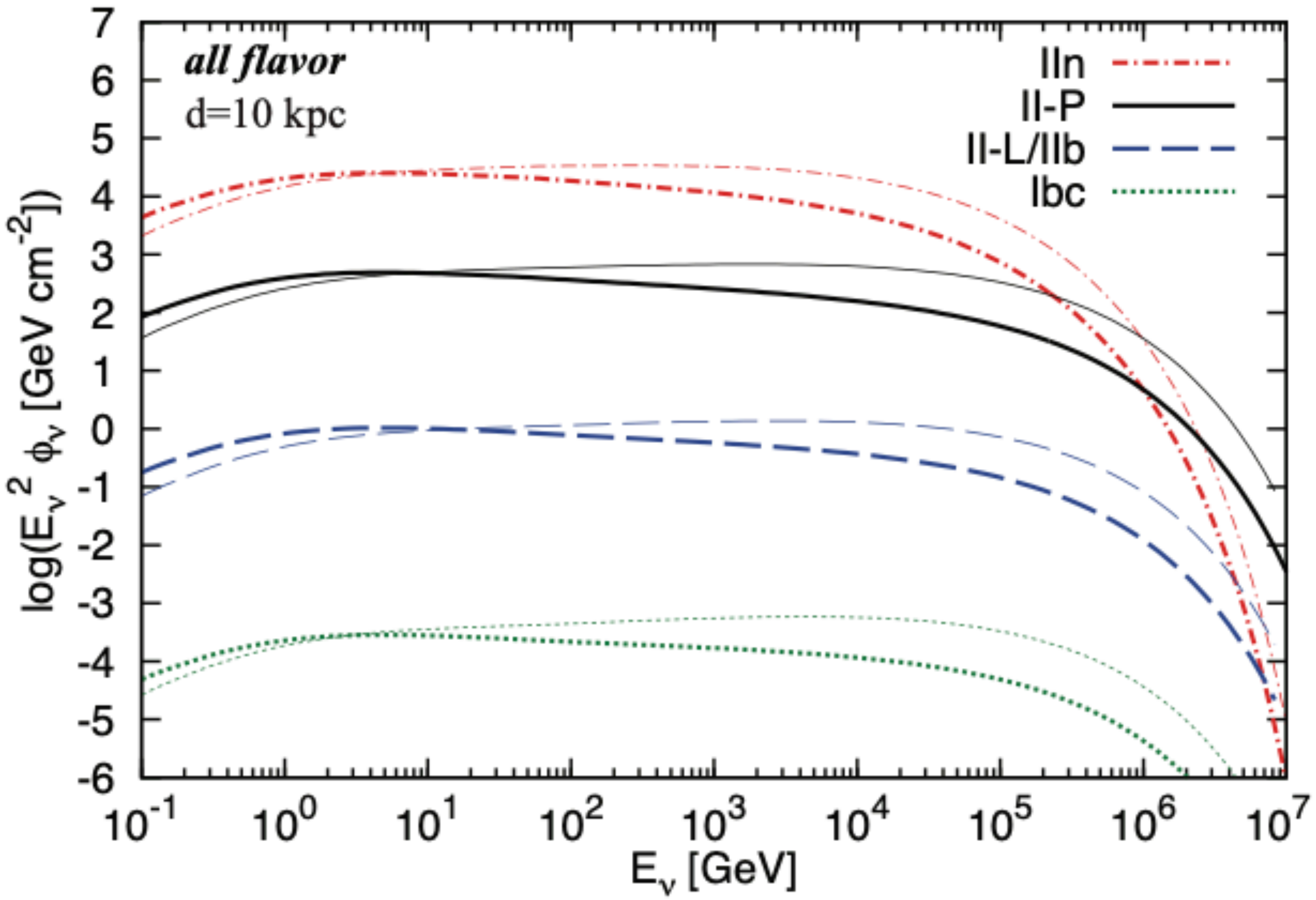
The cosmic ray number density is a function of proton momentum p :

$$\frac{dN_{cr}}{dp} \propto p^{-s}$$

The density profile of the CSM is dependent on parameter D_*:

$$\rho \propto D_* r^{-2}$$

Certain SN produce large fluxes of high-energy neutrinos.



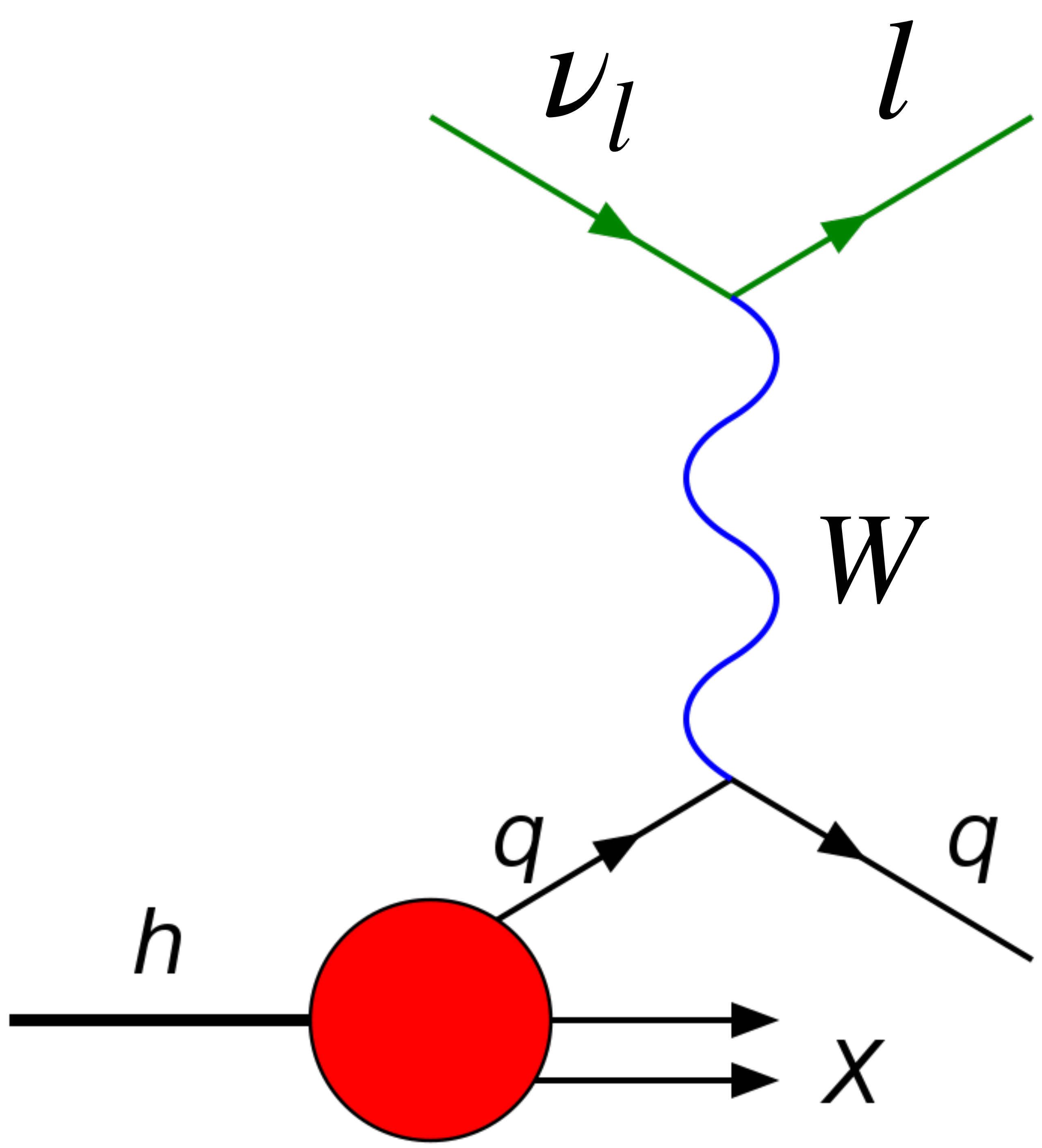
Time-integrated neutrino flux from CCSN
Murase (arXiv:1705.04750)

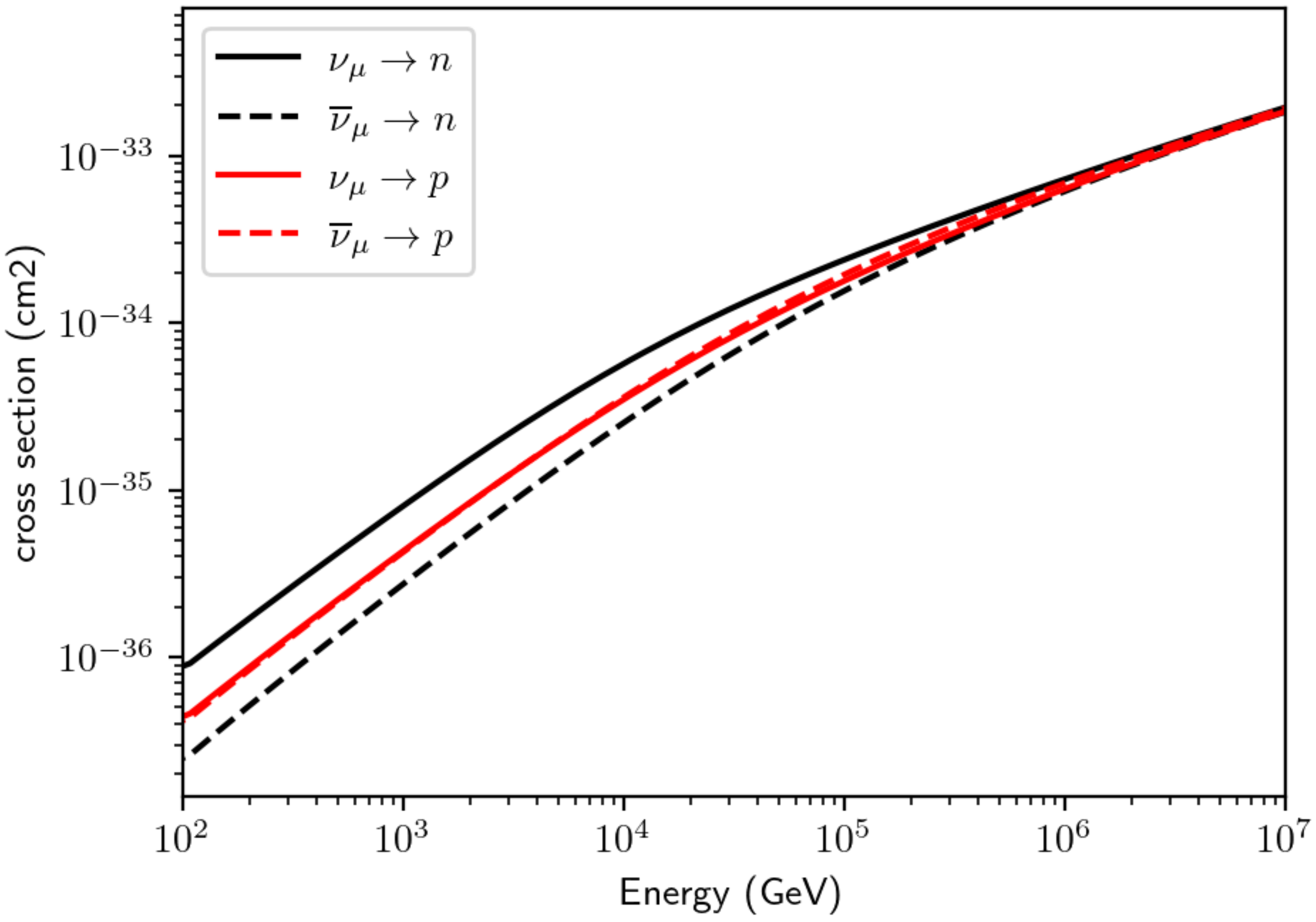
Efficient production of high-energy neutrinos as SN explosion hits circumstellar medium (CSM)

Dominant contributions from

- type IIn (~10% of all CCSN)
- type II-P (~50% of all CCSN)

High-energy neutrinos primarily undergo deep inelastic scattering (DIS).





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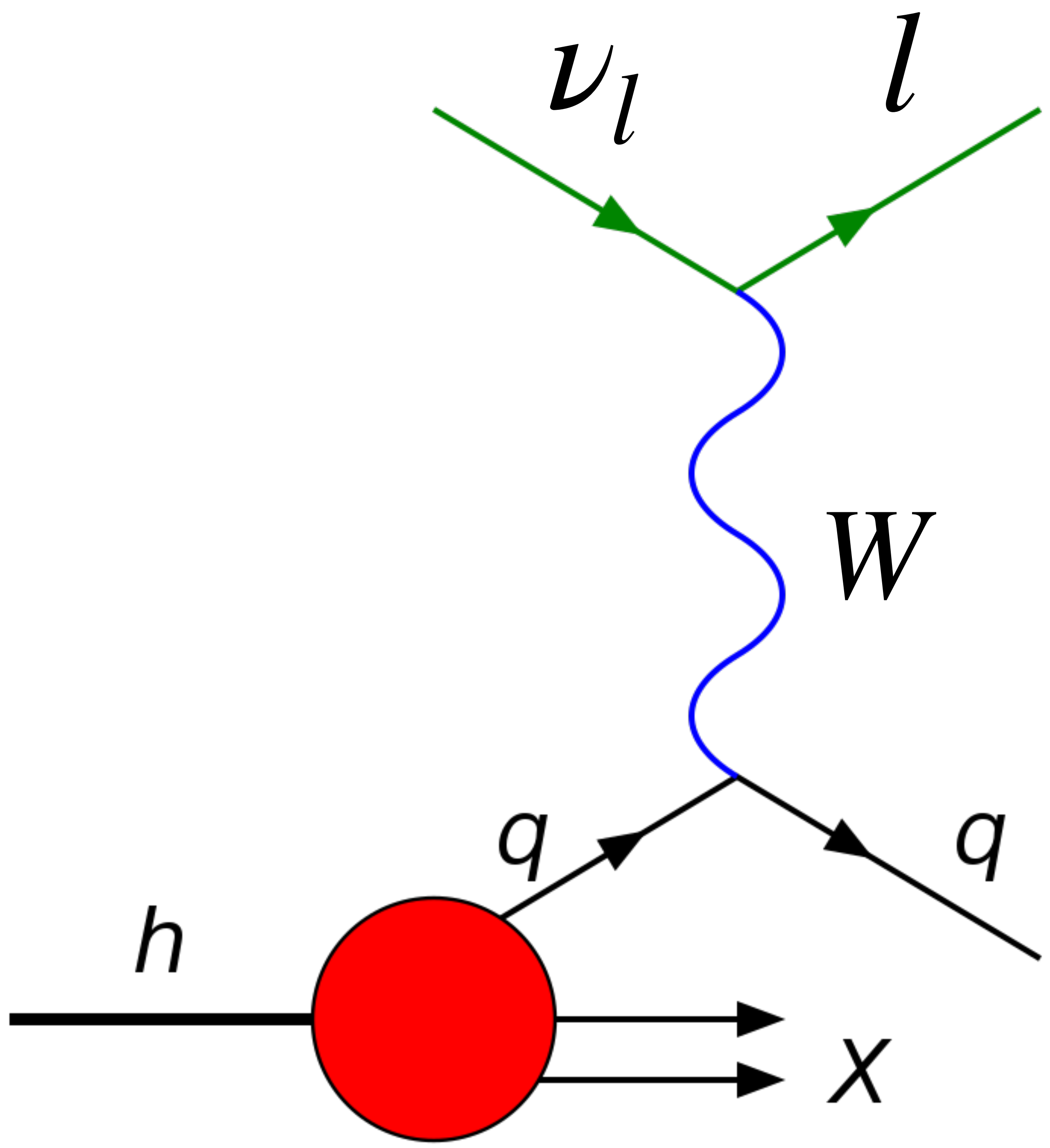
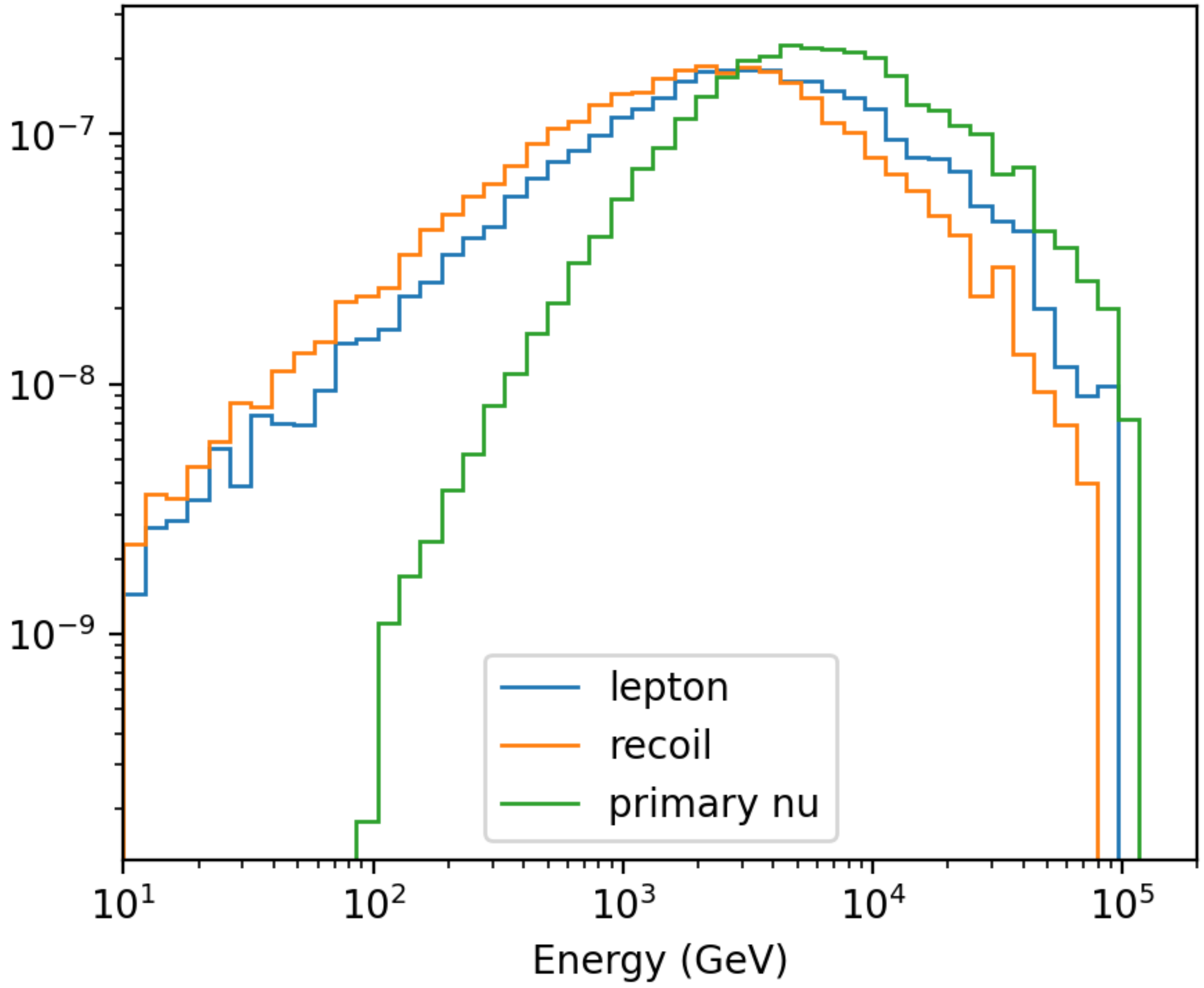
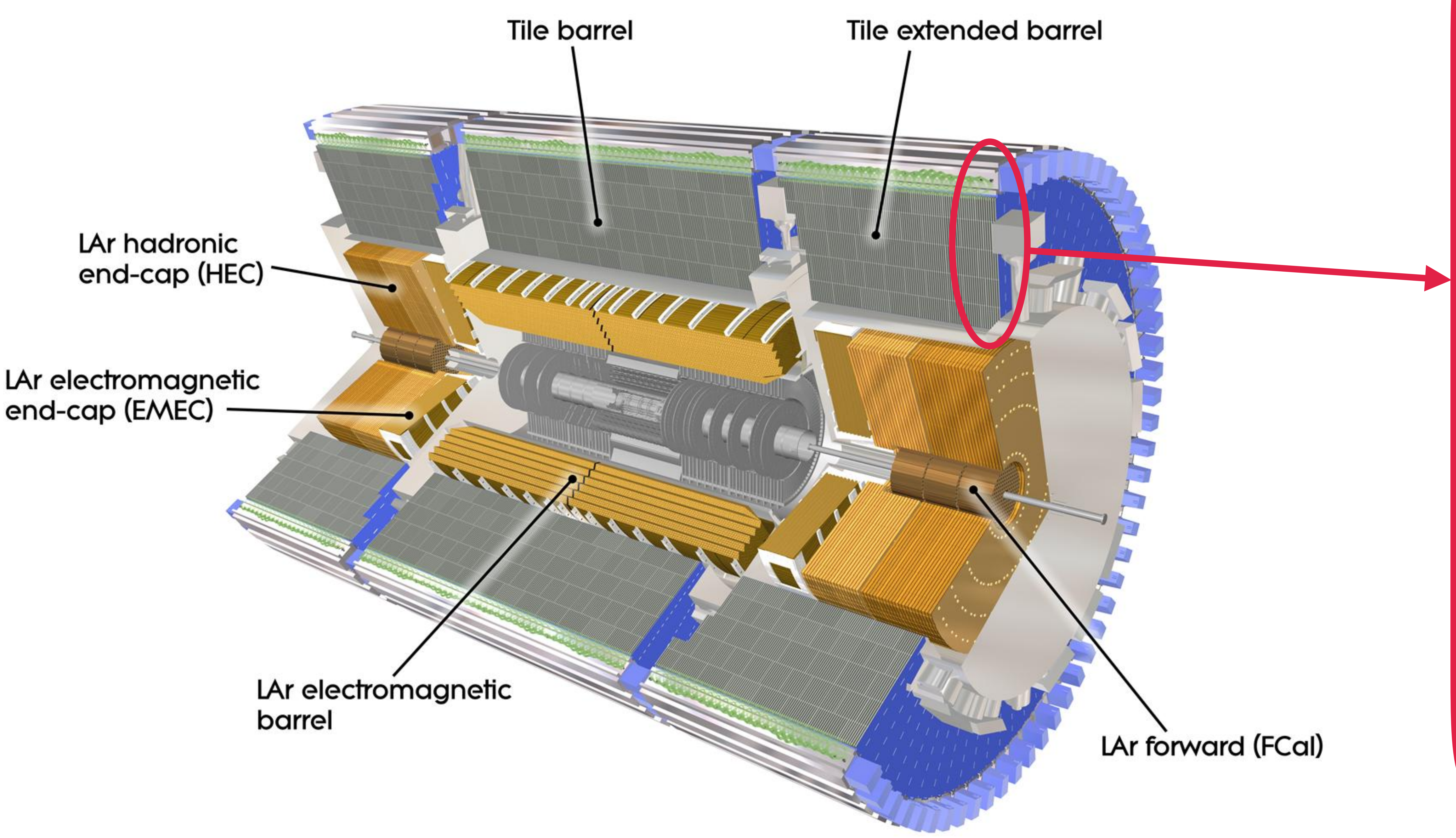
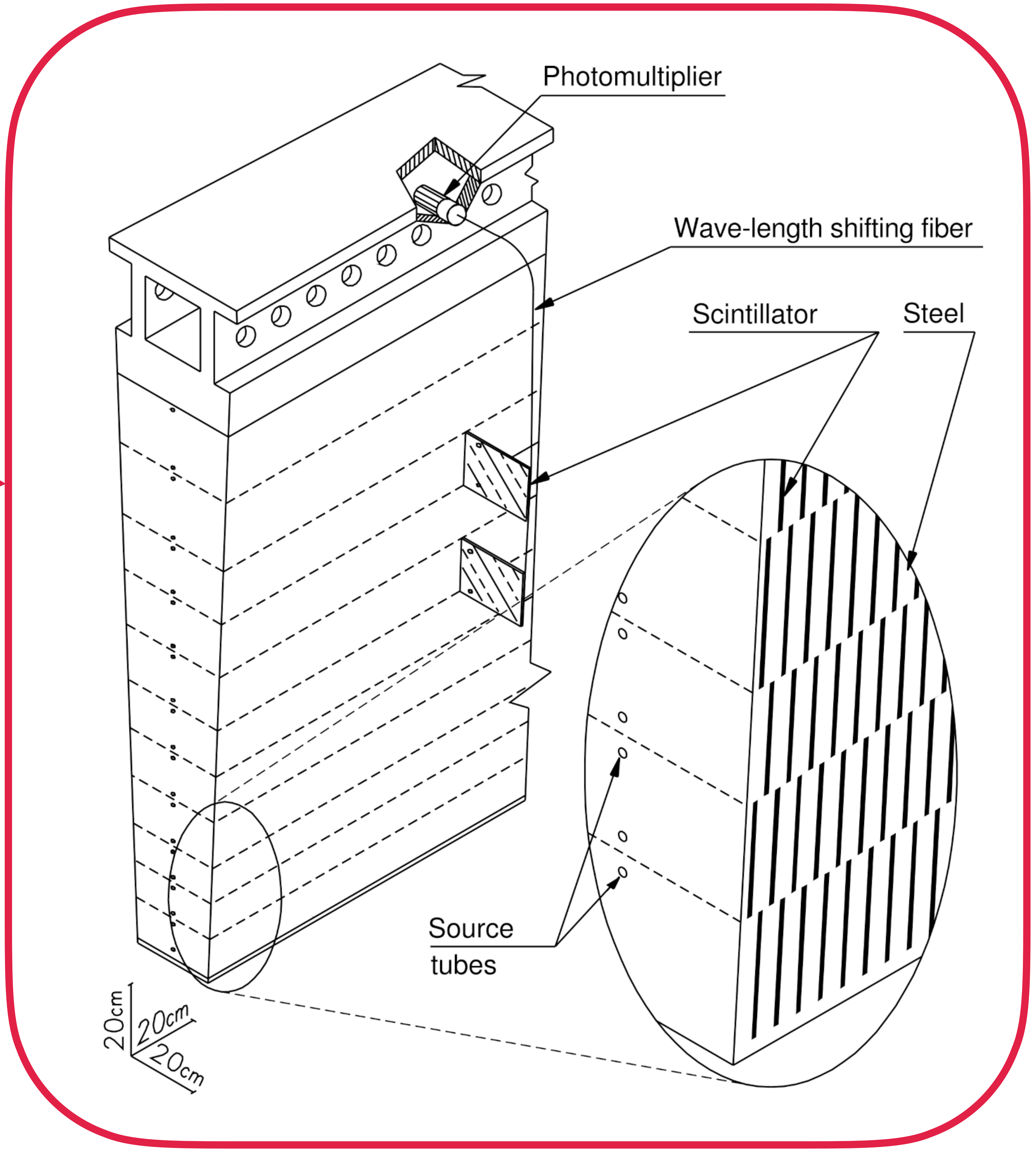




The hadronic calorimeter, weighing 4000 tons, is useful as a fiducial volume.

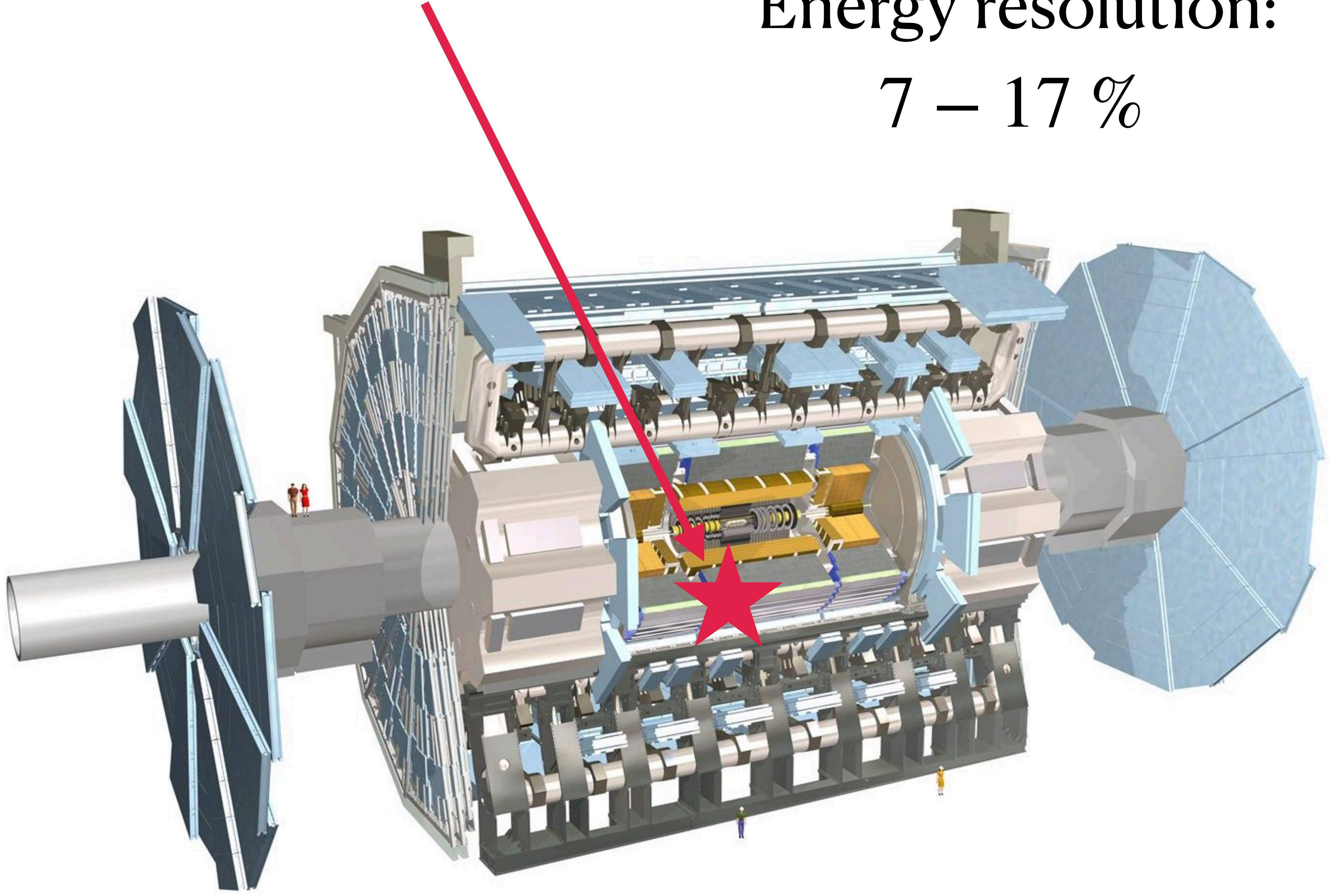




The detector is sensitive to multiple types of events.

ν_μ, ν_e, ν_τ

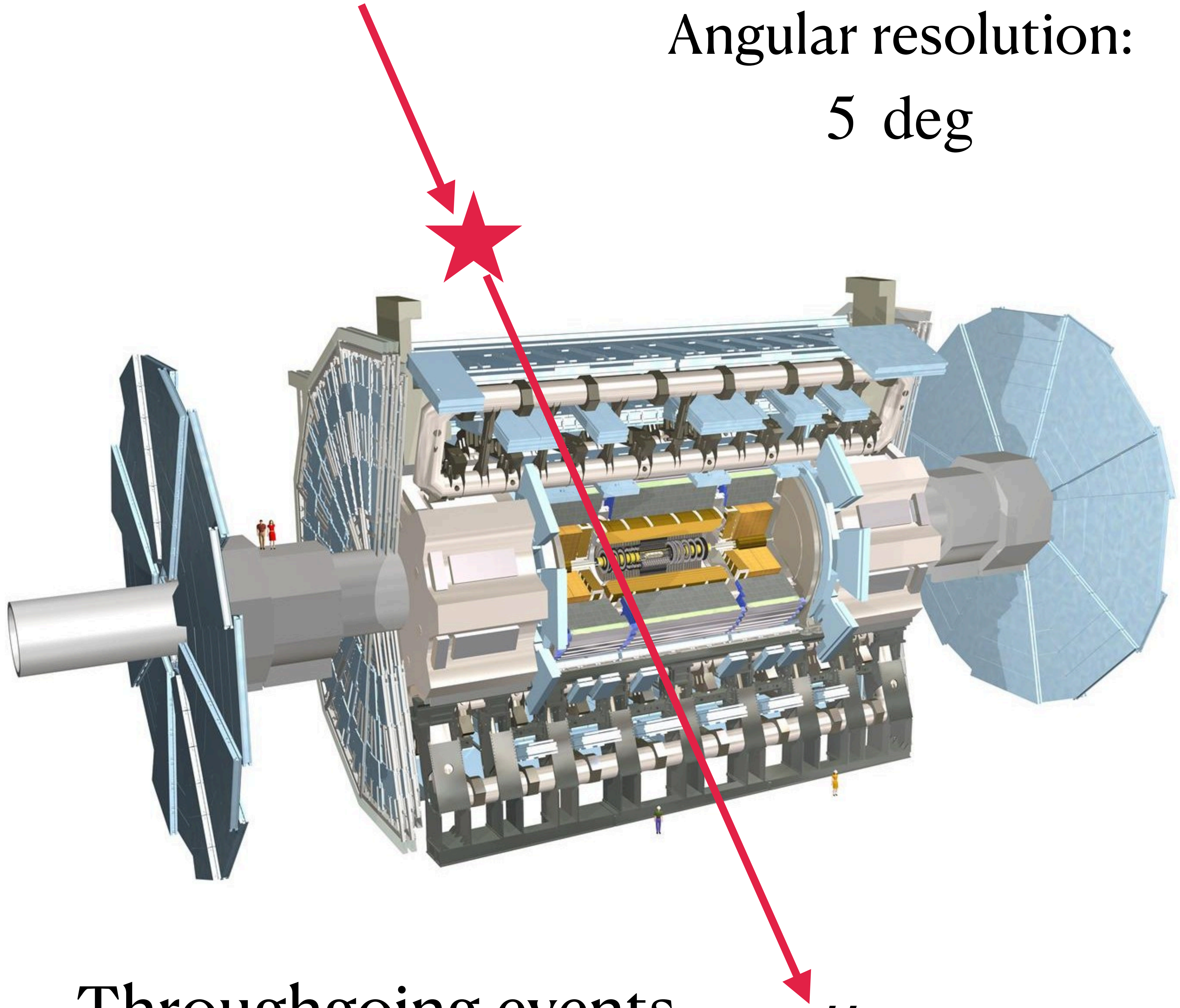
Angular resolution:
5 – 15 deg
Energy resolution:
7 – 17 %



Starting events

ν_μ

Angular resolution:
5 deg

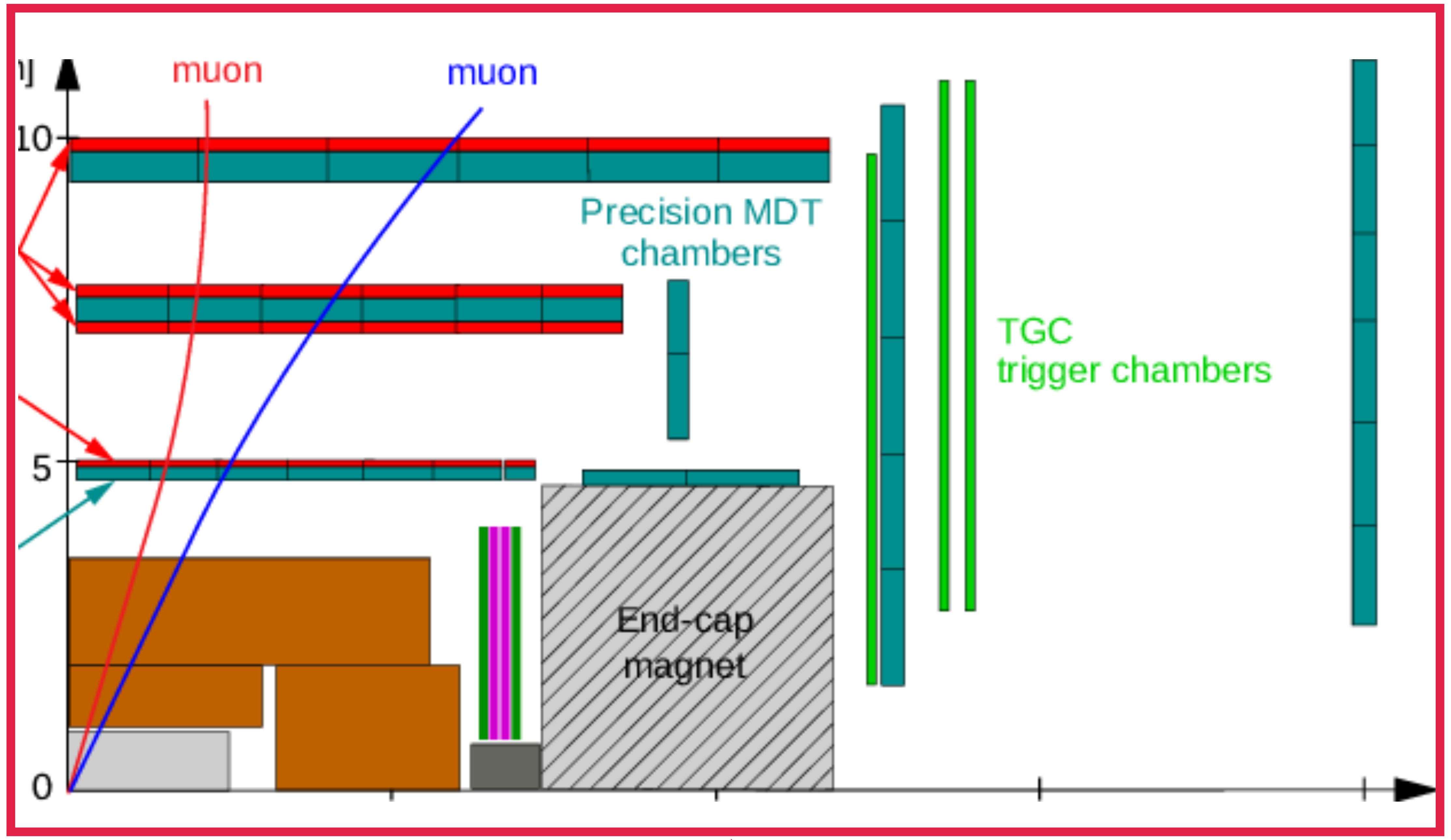


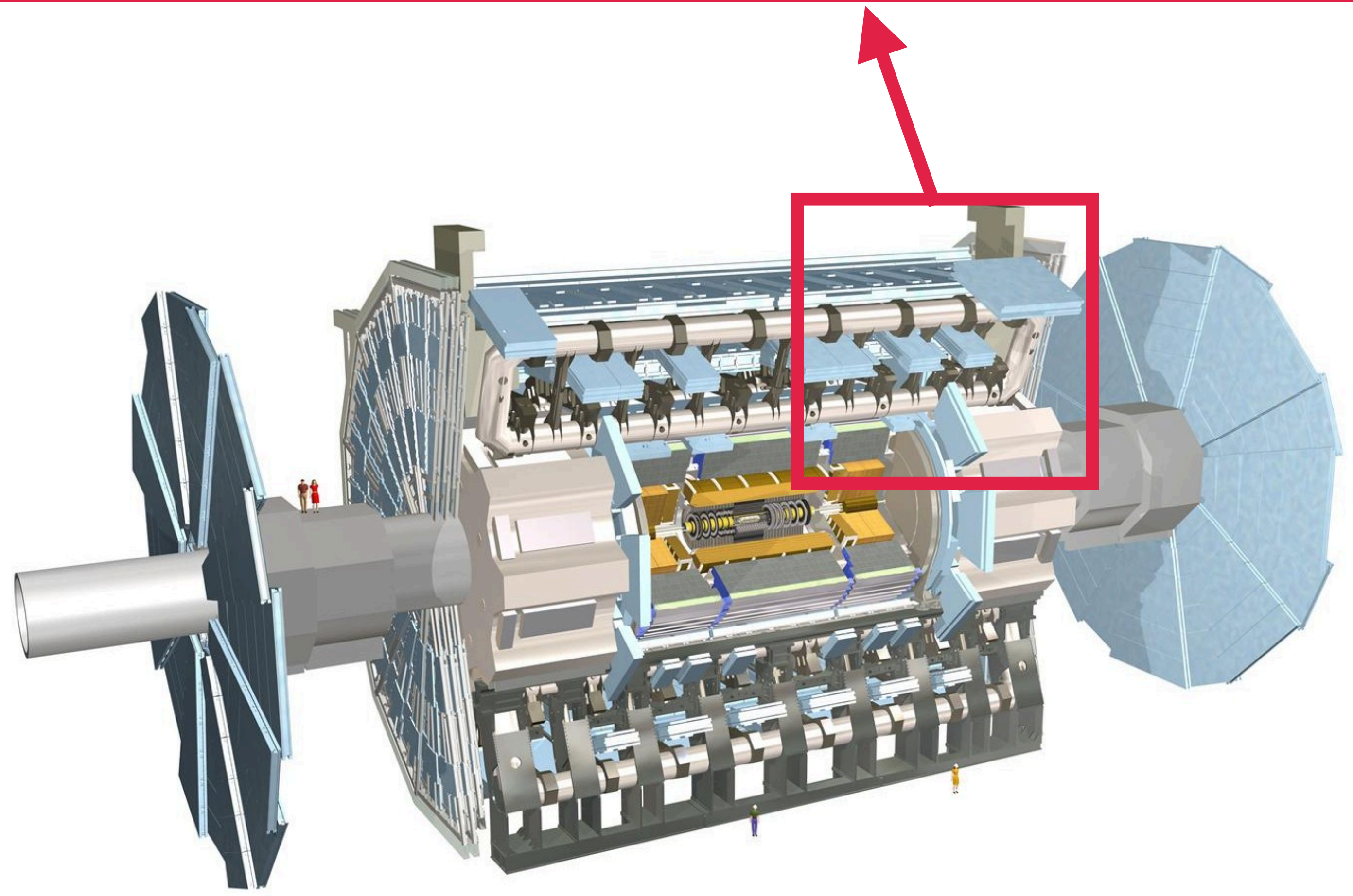
Throughgoing events

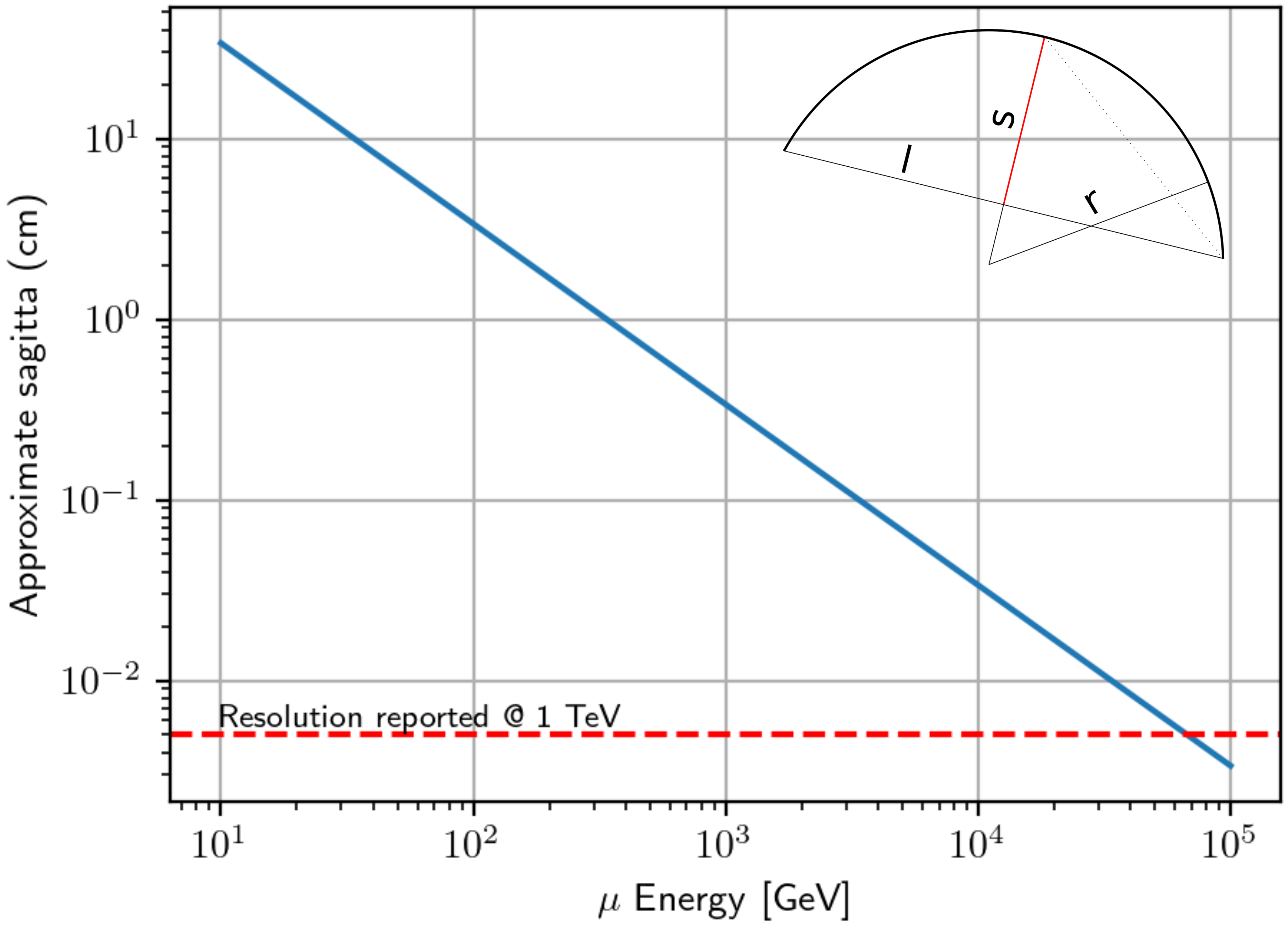
μ

Resolutions estimated by Kopp & Lindner (arXiv:0705.2595)

Charge discrimination is also possible.







Muon track sagitta as a function of energy, for a typical path length

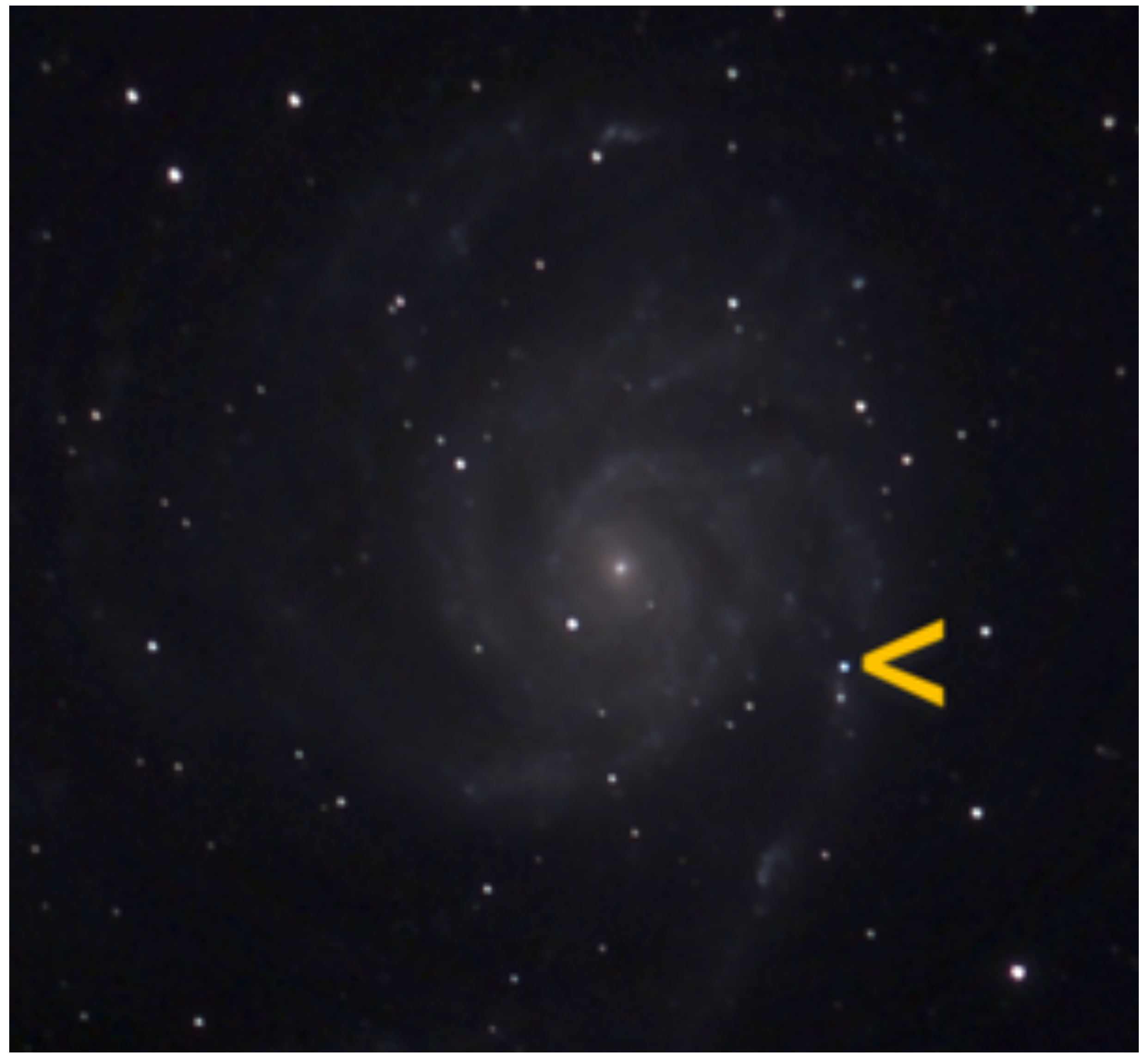
Supernovae are exploding stars.

A star that's exploding via

- Thermal runaway
- Core collapse (CCSN)

They are classified based on

- No hydrogen in spectrum (type I)
- Hydrogen in spectrum (type II)



SN 2023ixf

SN Classification

- Type I: no hydrogen in spectrum
  - Ia: ionized silicon → Thermal runaway
  - Ib: no silicon, non-ionized helium
  - Ic: no silicon, no helium
- Type II: hydrogen in spectrum
  - II-P: no narrow lines, **P**lateau light curve
  - II-L: no narrow lines, **L**inear light curve
  - IIn: some narrow lines
  - IIb: spectrum evolves to be similar to type Ib

(Ib through IIb) } Core-collapse (~ 3/century)

SN Classification

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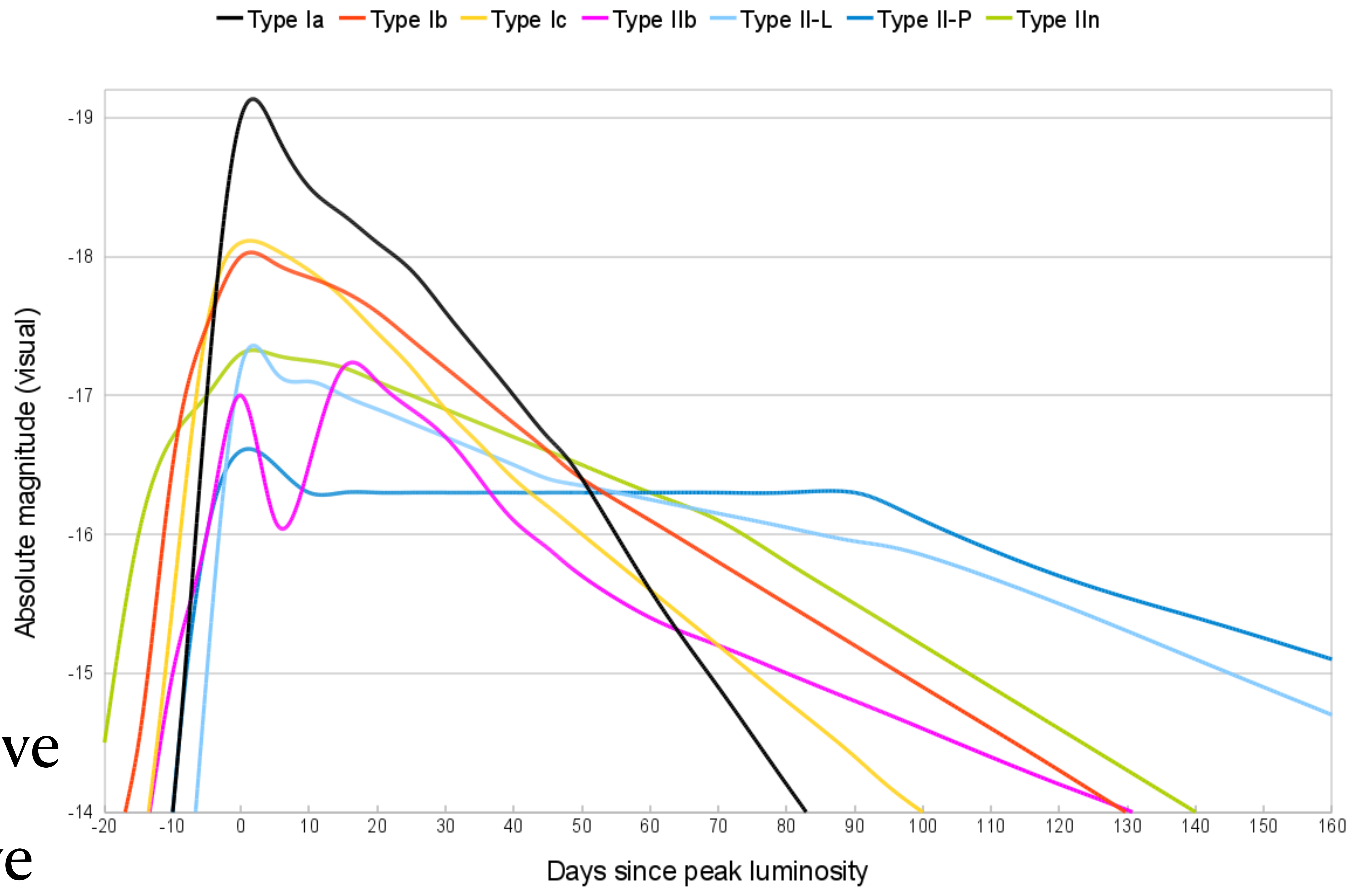
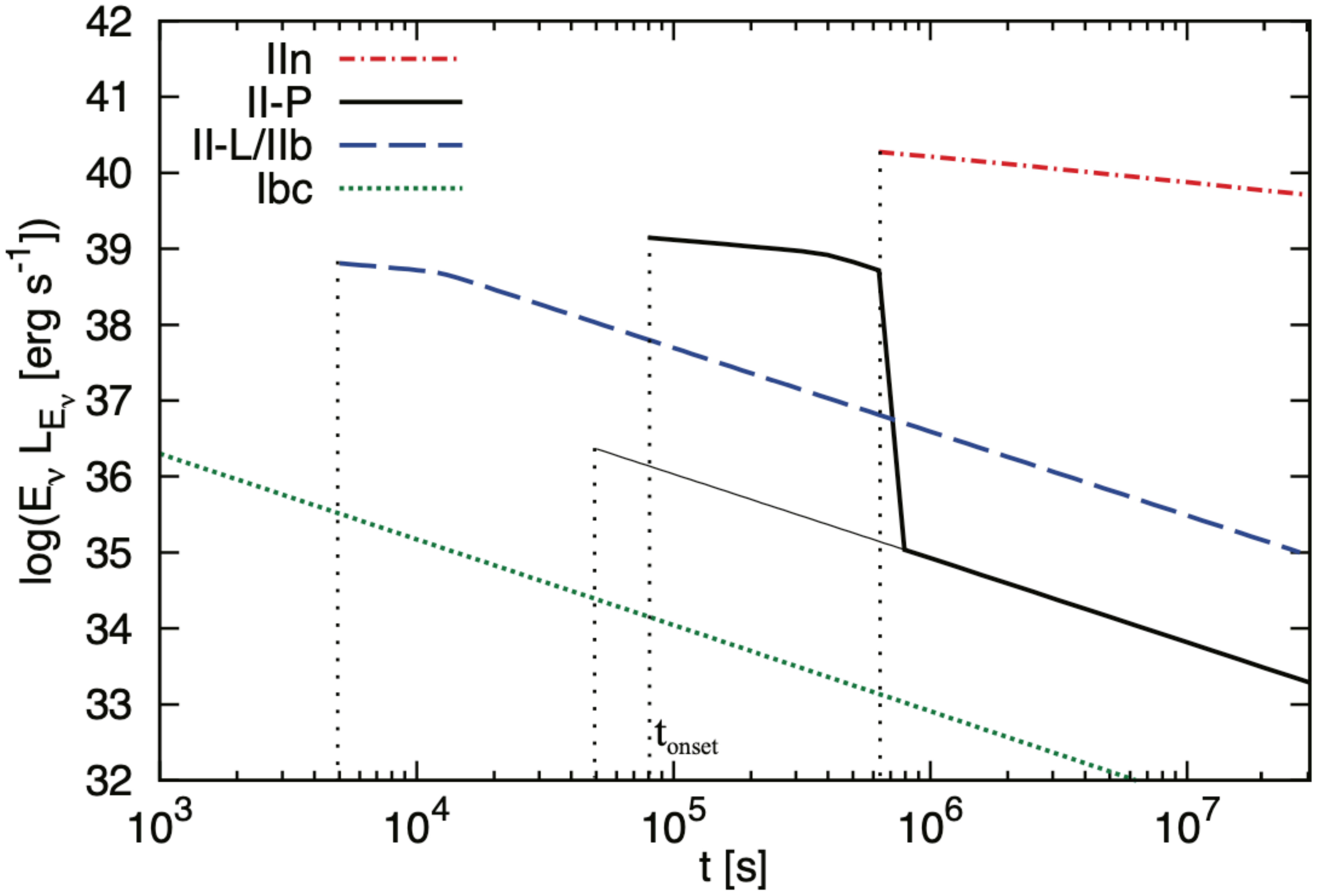


Significant flux lasts for tens to hundreds of days.



Murase (arXiv:1705.04750)

IceCube has good prospects for detection of type II-P and IIn in our galaxy

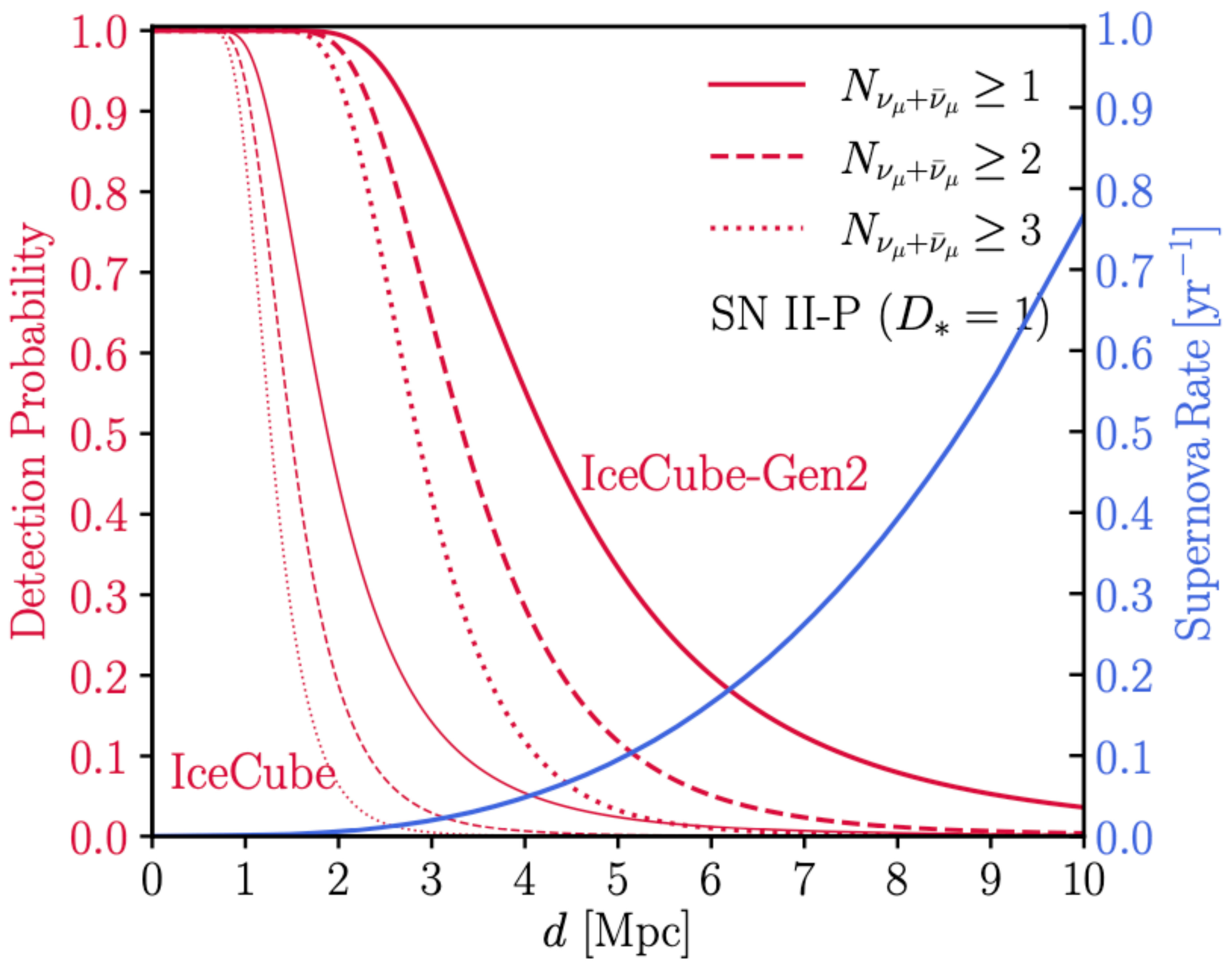
Model	s	$\mathcal{N}_{\mu,>1\ \mathrm{TeV}}^{\mathrm{sig},<10^7\ \mathrm{s}}$	$\mathcal{N}_{\mu,>0.1\ \mathrm{TeV}}^{\mathrm{sig},<10^7\ \mathrm{s}}$	$\mathcal{N}_{\mu,>0.1\ \mathrm{TeV}}^{\mathrm{sig},<t_{\mathrm{max}}}$	t_{max} [s]
IIn	2.2	2.7×10^4	4.6×10^4	1.2×10^5	$10^{7.5}$
(10 kpc)	2.0	1.1×10^5	1.7×10^5	4.5×10^5	$10^{7.5}$
II-P[a]	2.2	2.8×10^2	4.1×10^2	3.8×10^2	$10^{5.8}$
(10 kpc)	2.0	1.2×10^3	1.6×10^3	1.5×10^3	$10^{5.8}$
II-P[b]	2.2	5.5×10^2	8.4×10^2	3.5×10^2	$10^{5.4}$
(0.197 kpc)	2.0	2.3×10^3	3.3×10^3	1.4×10^3	$10^{5.4}$
II-L/IIb	2.2	18	27	8.9	$10^{4.6}$
(10 kpc)	2.0	78	110	36	$10^{4.6}$
Ibc	2.2	5.4×10^{-3}	8.1×10^{-3}	2.8×10^{-3}	$10^{3.8}$
(10 kpc)	2.0	2.4×10^{-2}	3.2×10^{-2}	1.4×10^{-2}	$10^{4.0}$

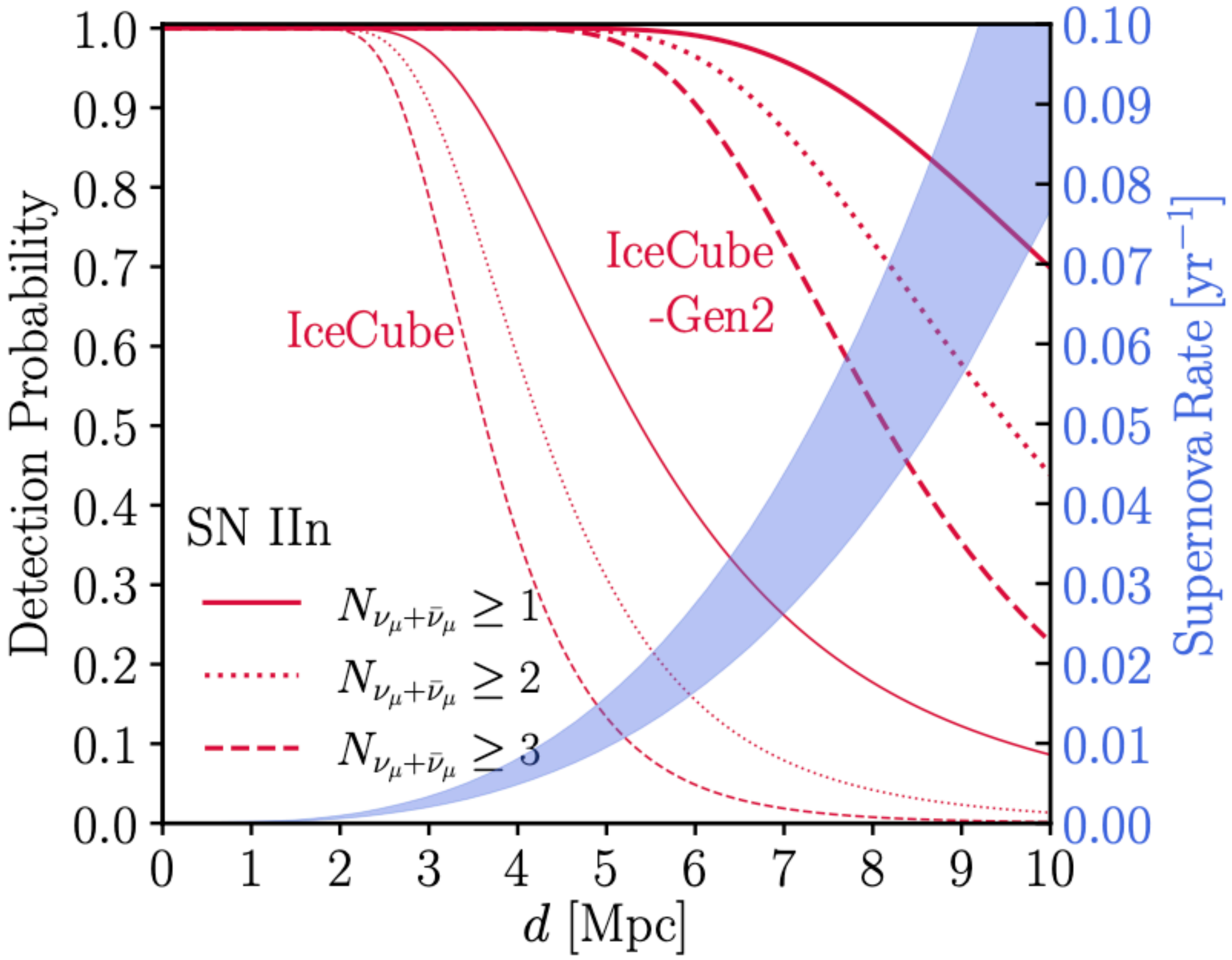
Betelgeuse →

Will easily detect anything in the galaxy (~25 kpc)

Total number of through going muon tracks
Murase (arXiv:1705.04750)

IceCube also has good prospects for *extragalactic* detection of type II-P and IIn in the northern sky





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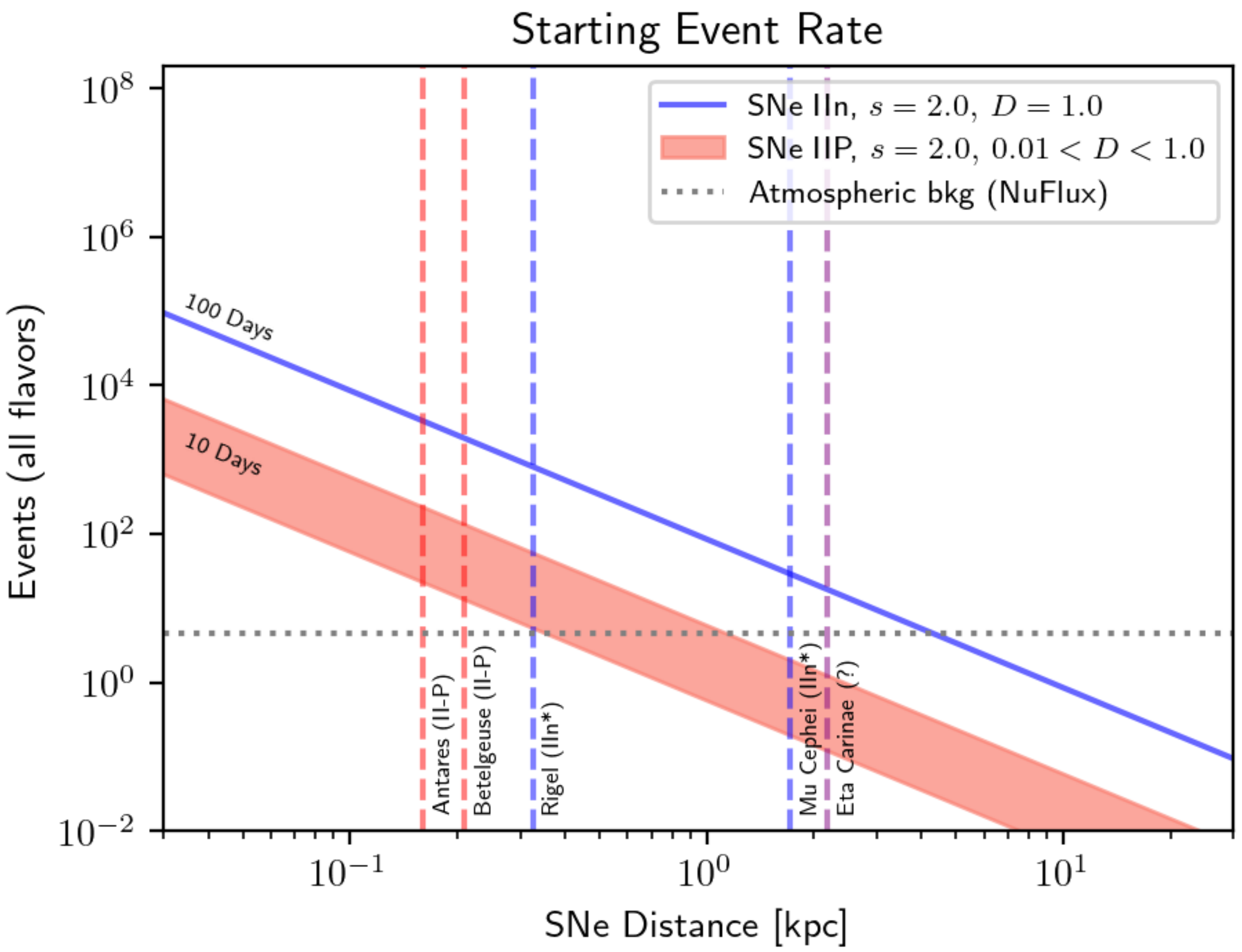
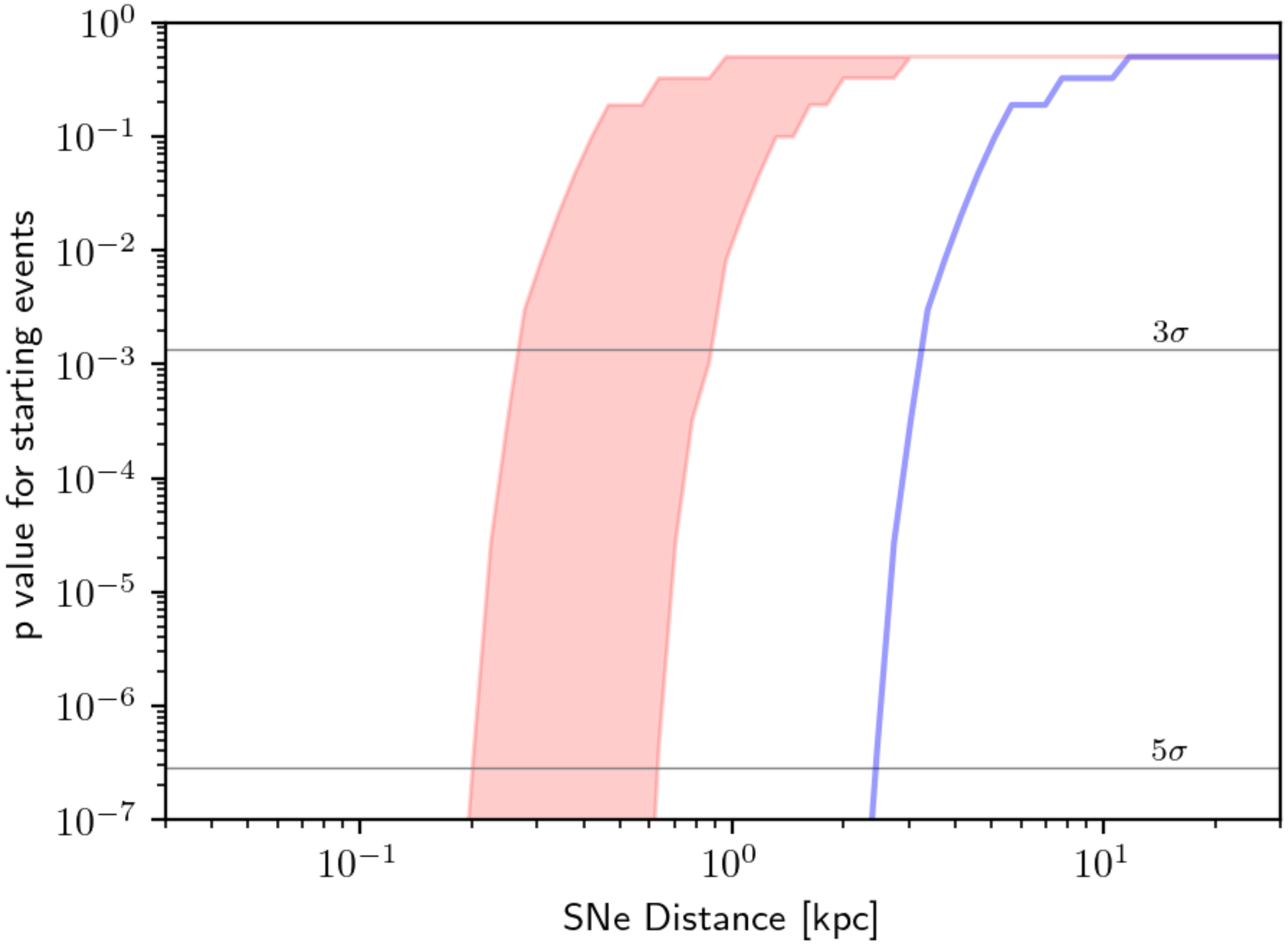
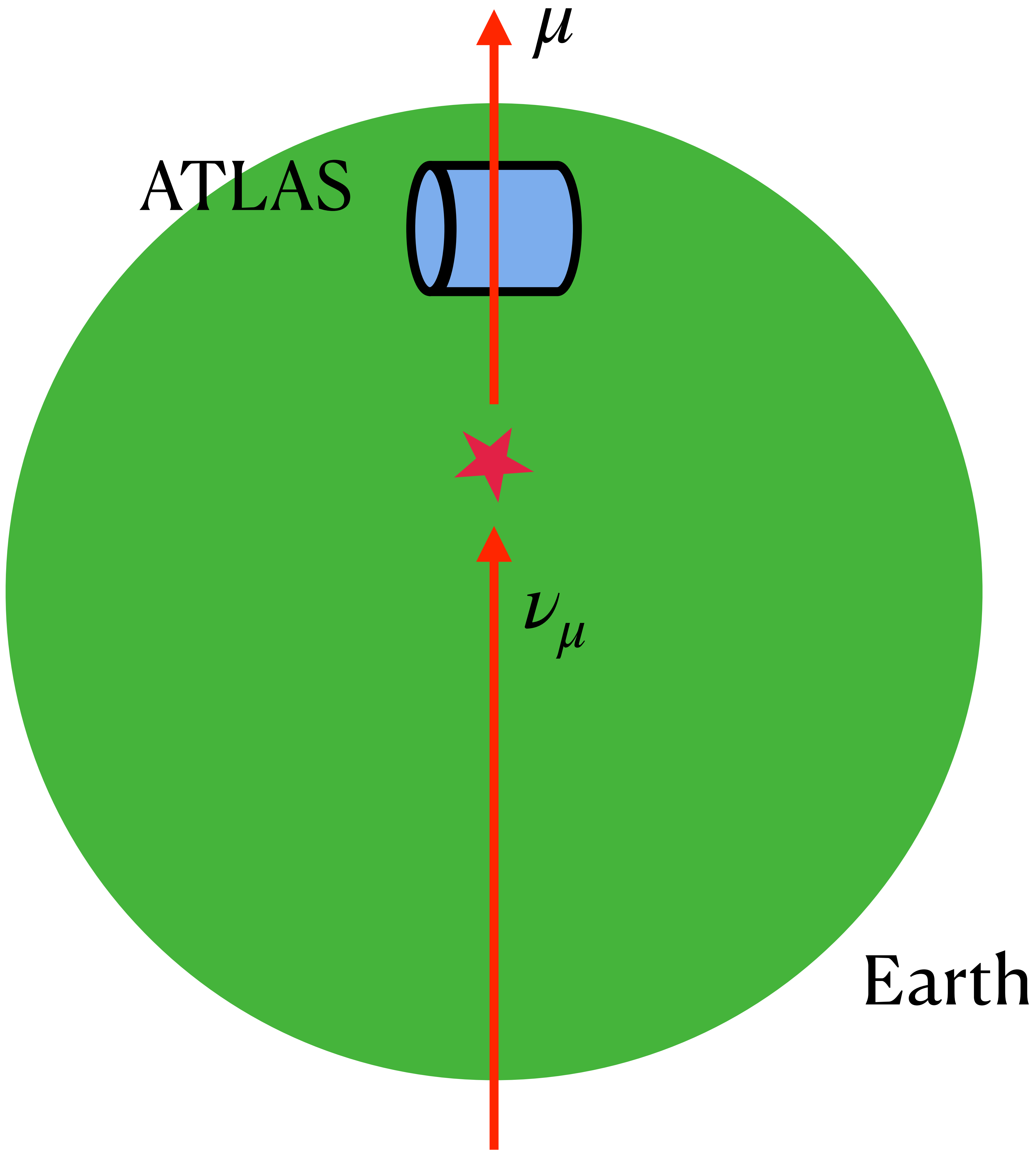




Simulation of thoroughgoing events is in progress.



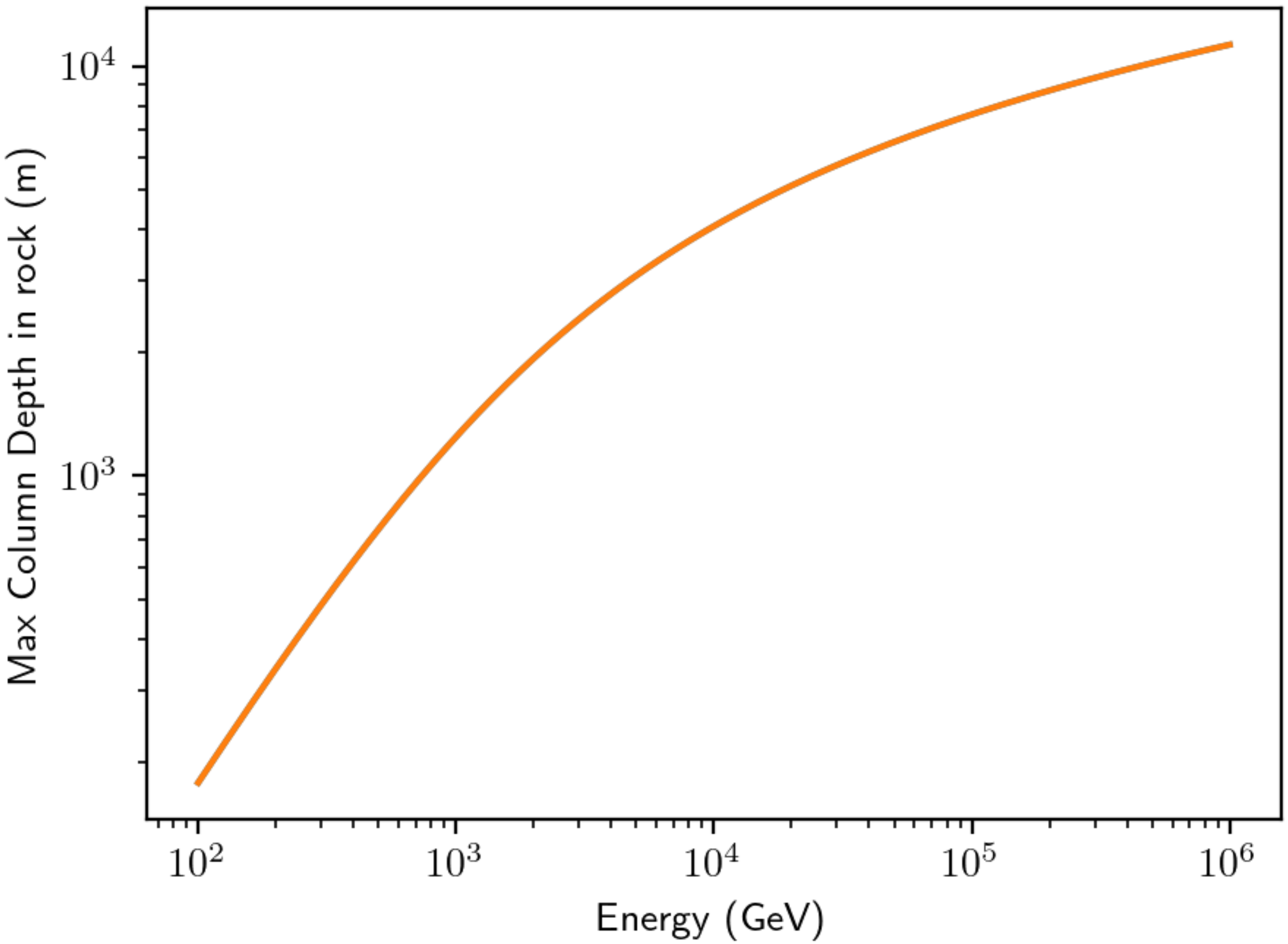
Effectively increase detector volume.

A column of rock
- 1 km long (range scale of muon)
- 40 by 20 m cross-section
- 2.6 g/cm^3

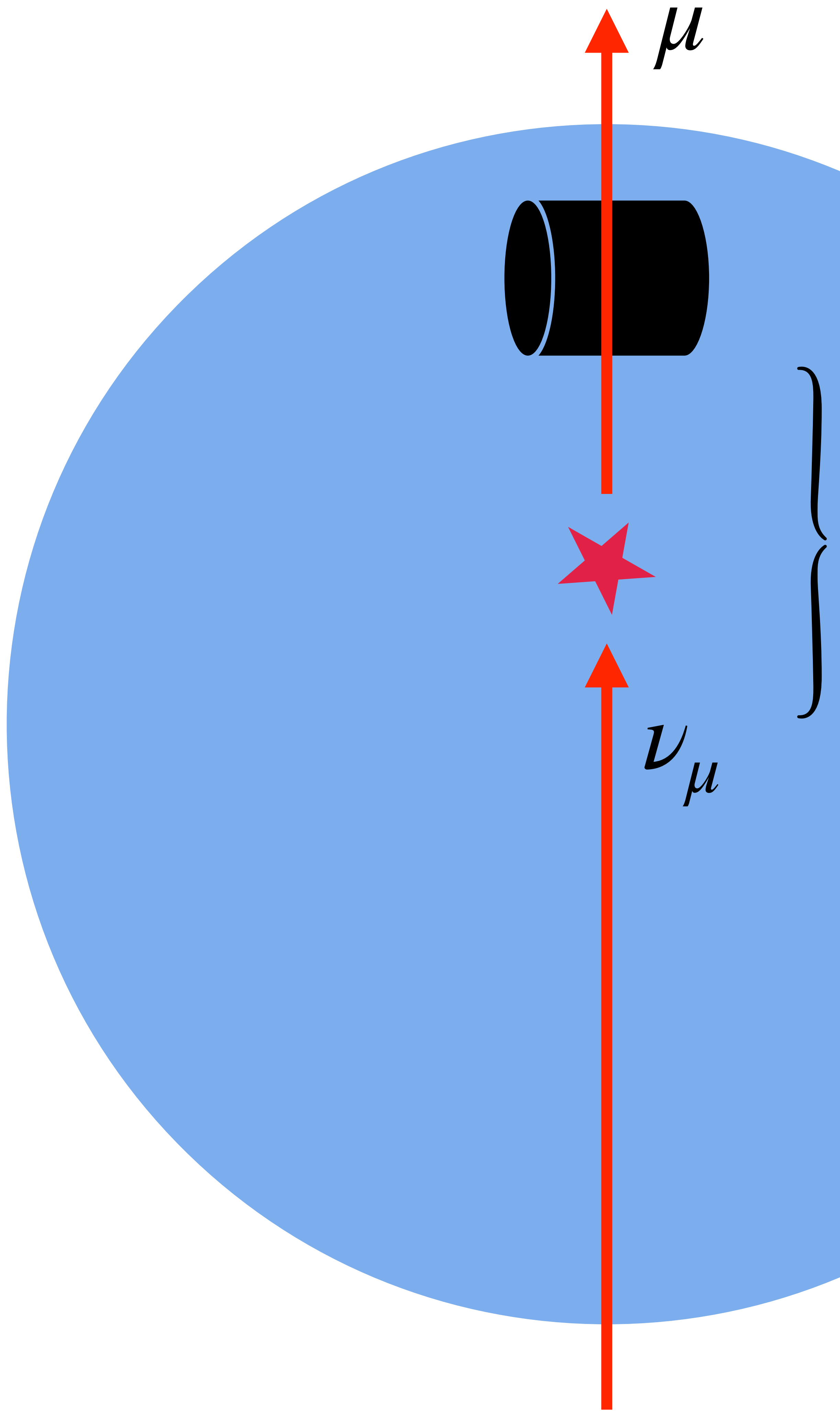
...weighs around 2×10^9 kg or 2000 kt

ATLAS HCal weighs 4 kt
We can expect amplification of ~500 times more events (assuming high efficiency)

Muons travel far in matter.



Throughgoing events are expected to make a significant contribution.



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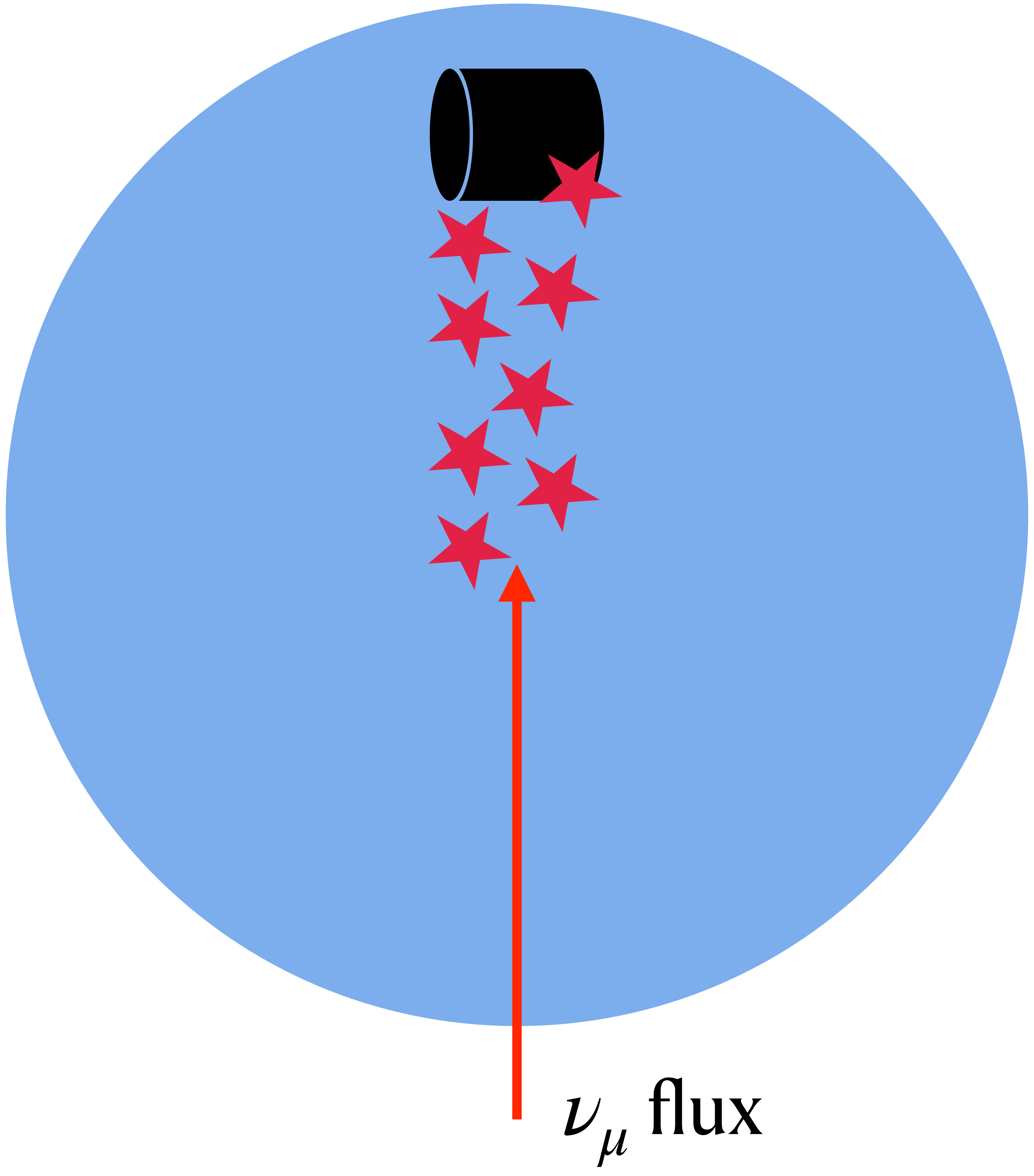
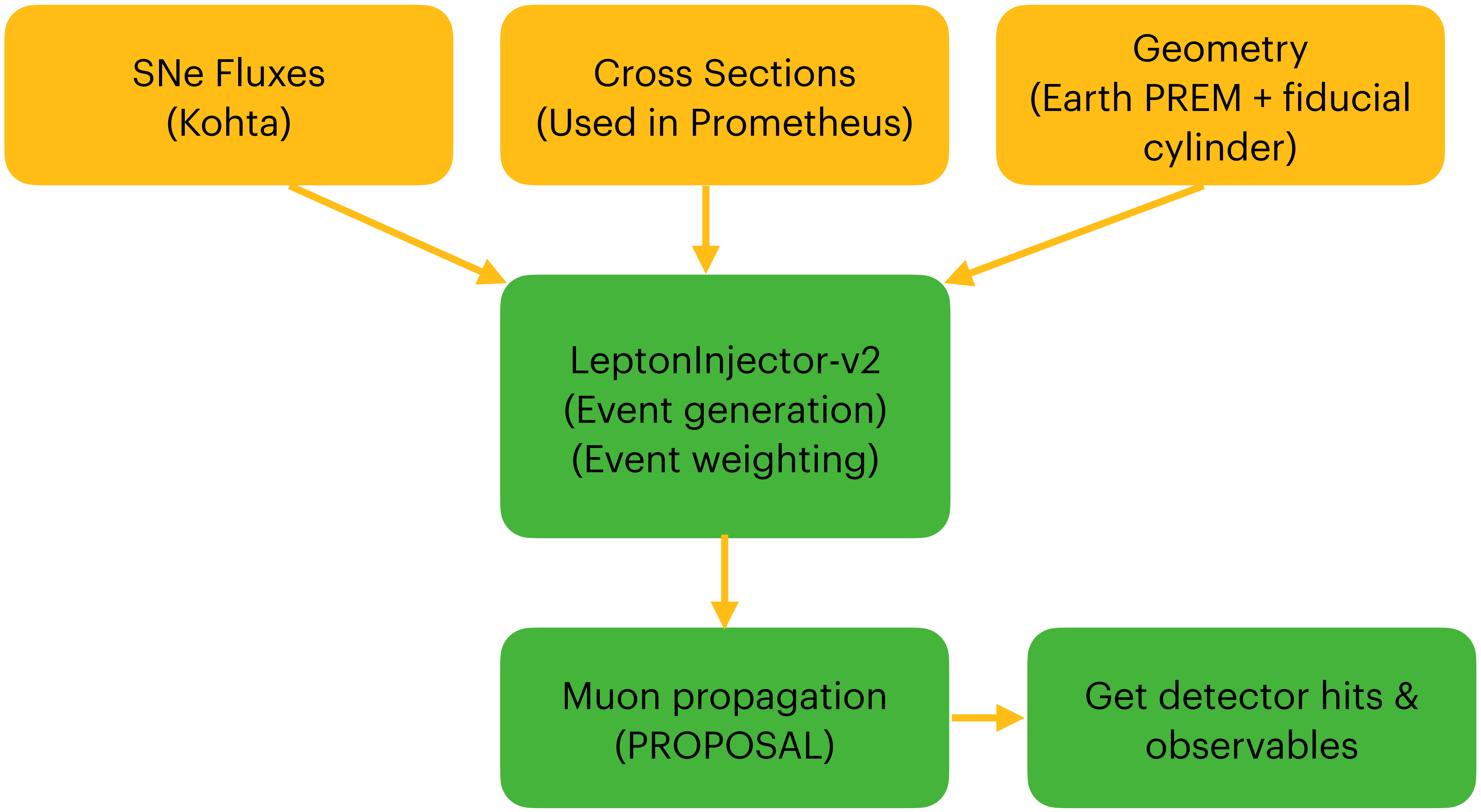
Event generator for thoroughgoing events.

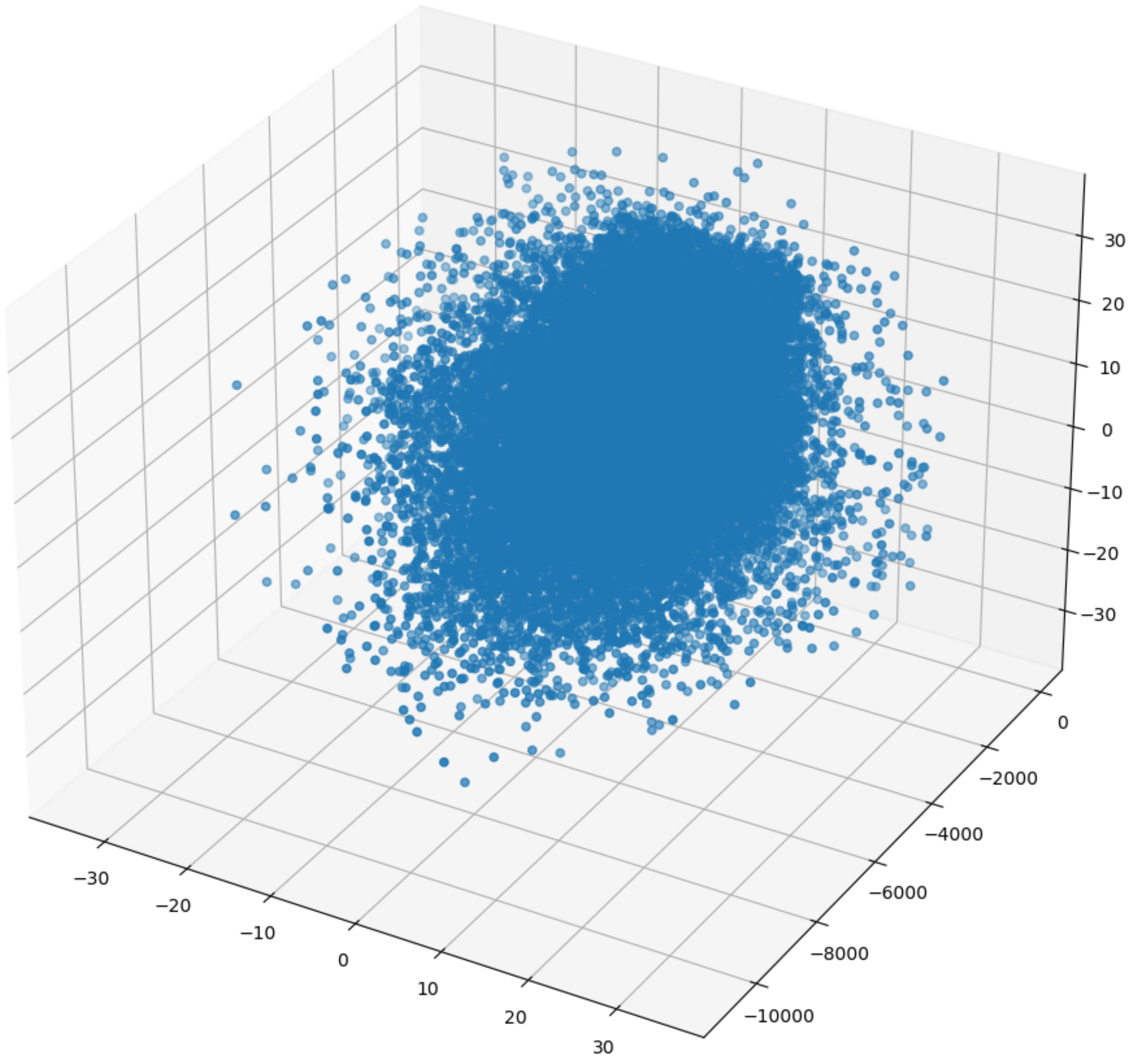


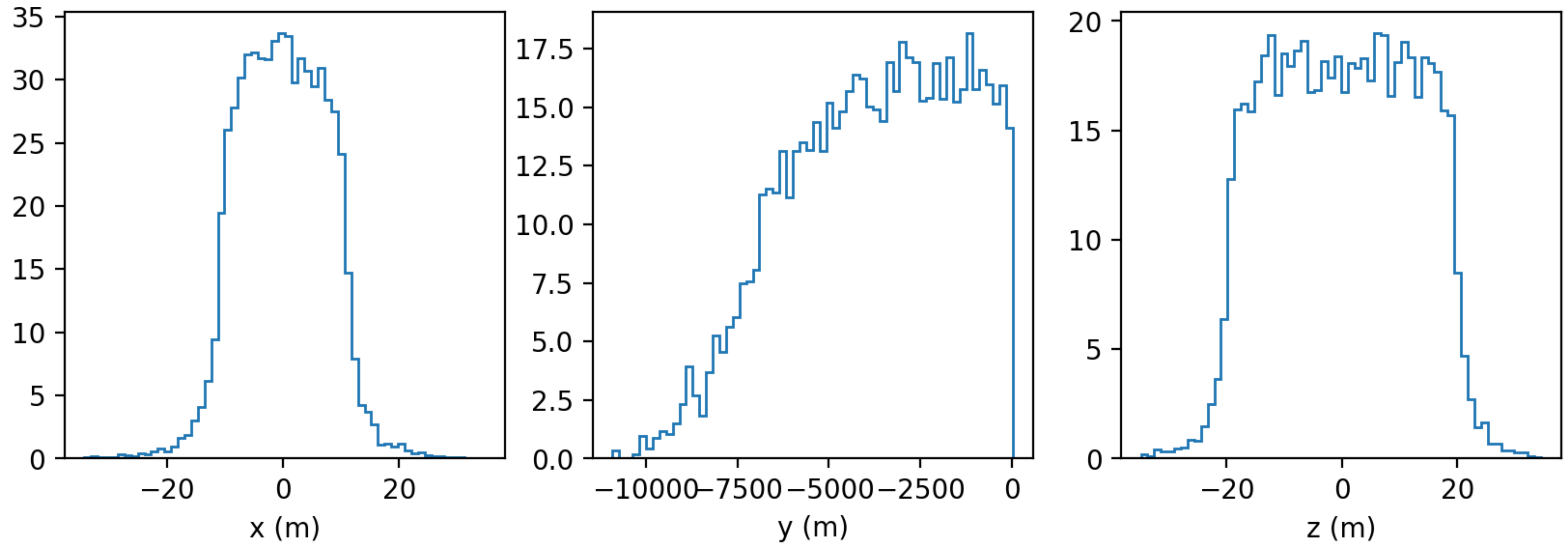
The distribution of **weighted** events will give meaningful physical information.

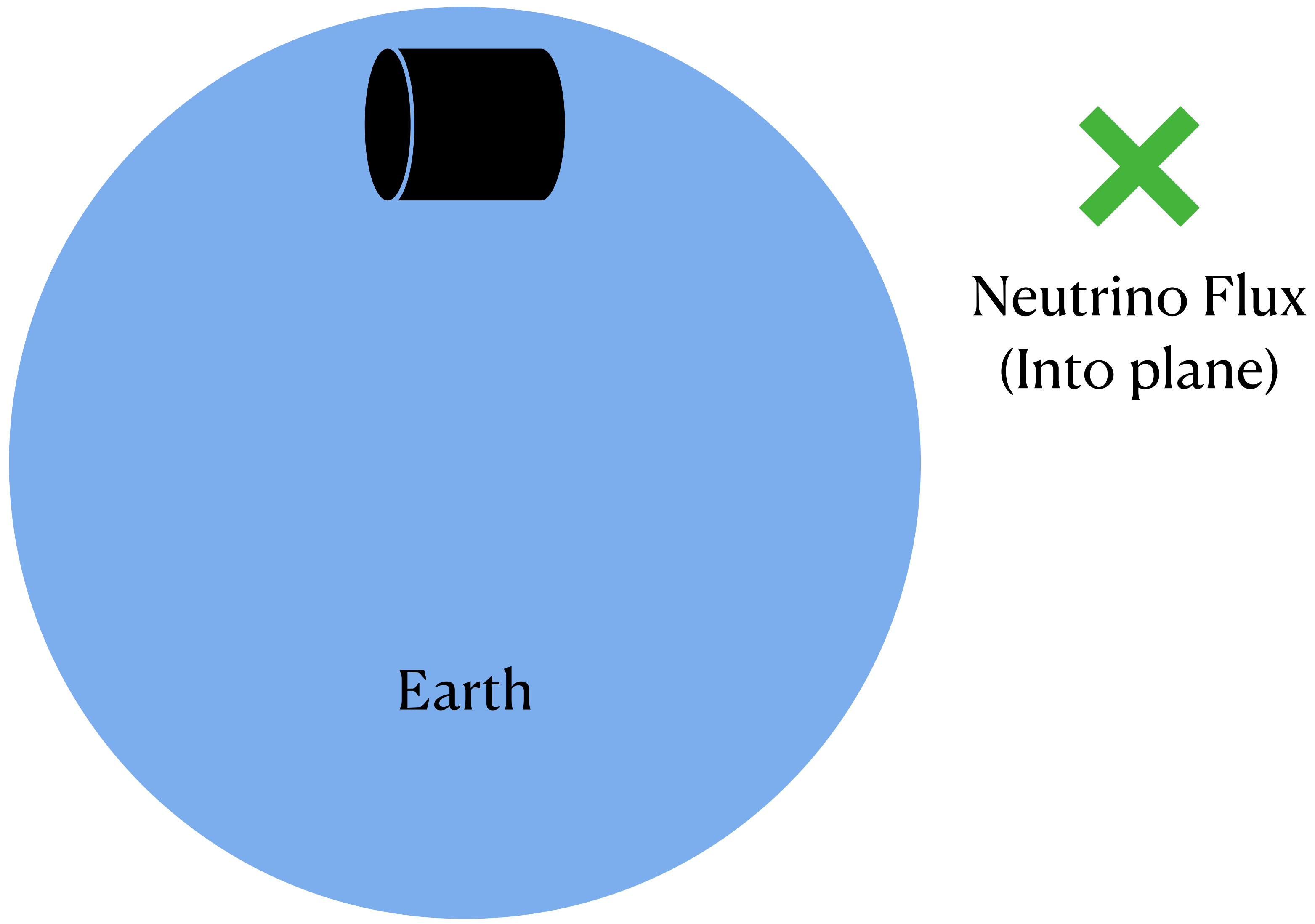
Thoroughgoing events are generated with LeptonInjector.



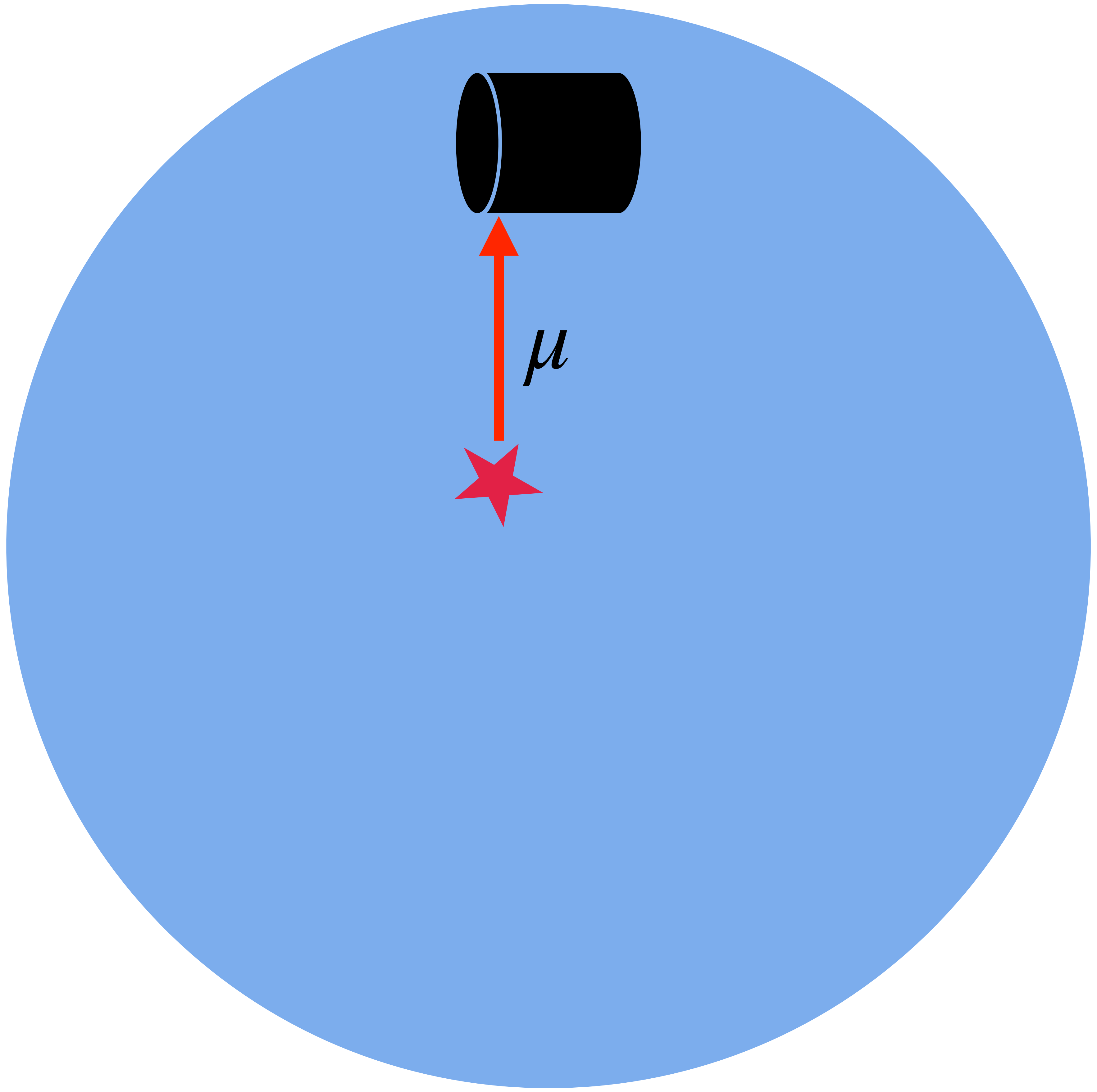
Event generation is working as intended.

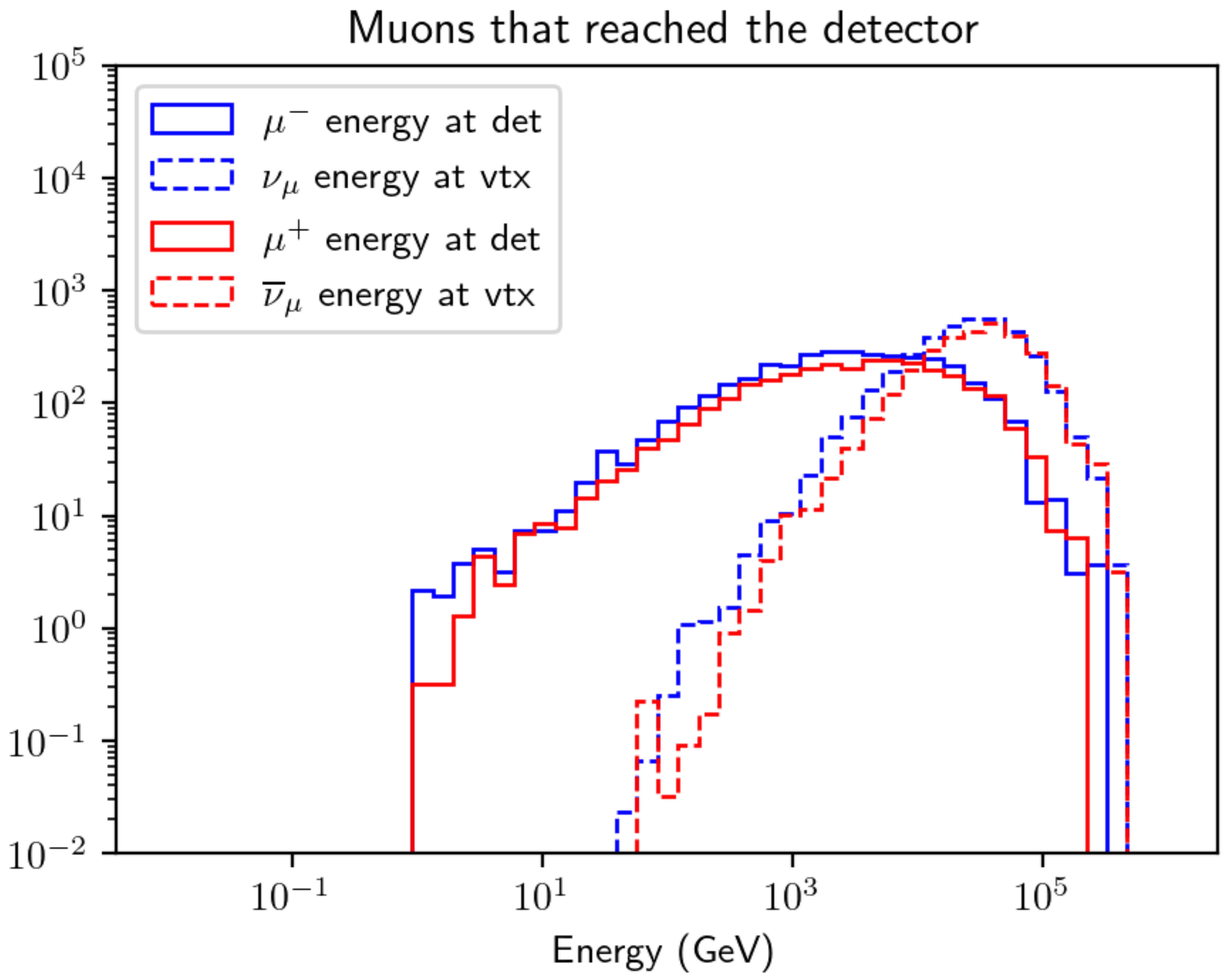






The muons are propagated to the detector successfully using PROPOSAL.





PROPOSAL accounts for stochastic (and continuous) energy losses.

Many relevant inputs to calculate event weight.

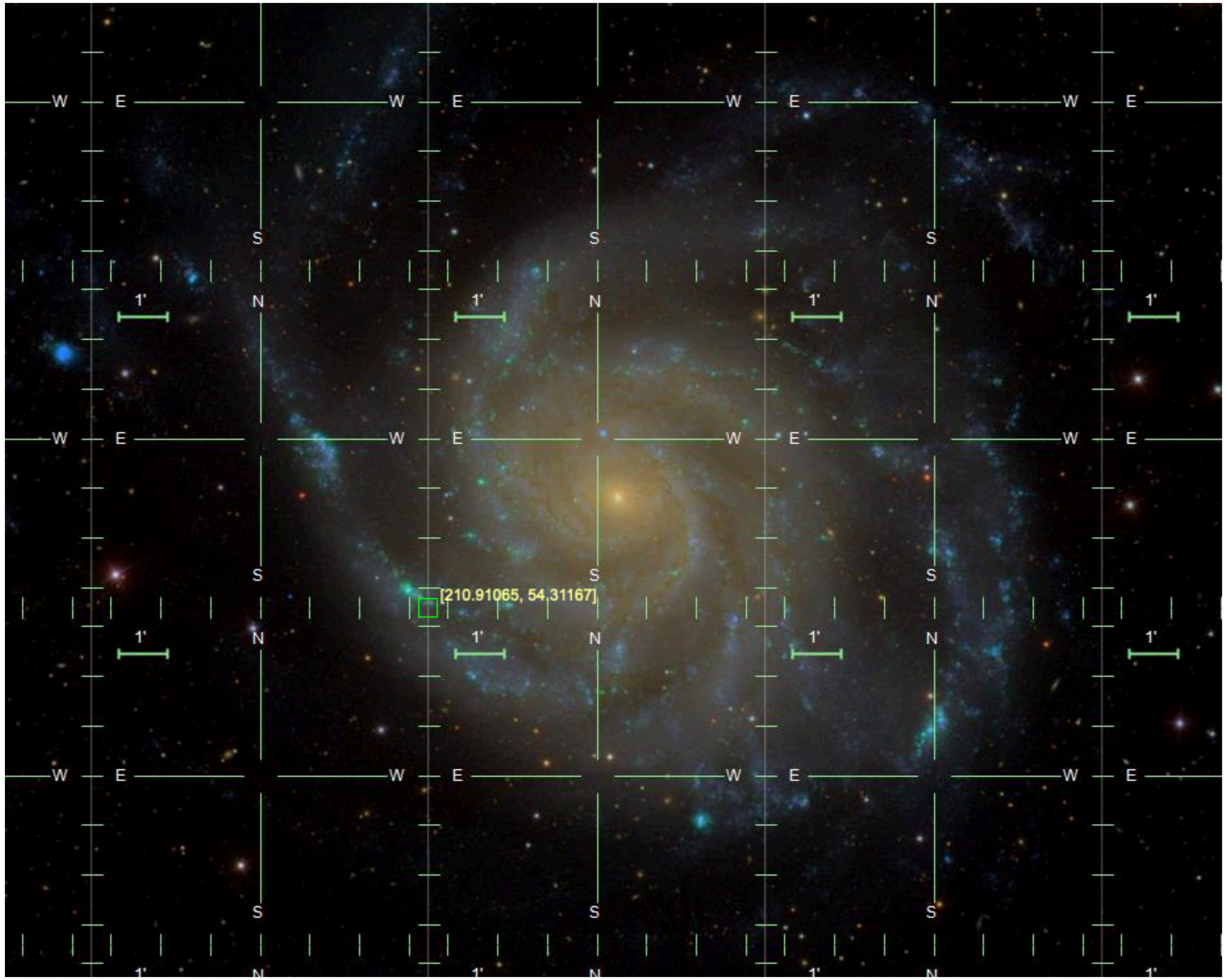
Generation Probabilities:
- Energy
- Direction
- Impact
- Depth
- Kinematics
- N events Generated

Physical Probabilities:
- Energy
- Direction
- Impact
- Depth
- Kinematics
- N events physically
- Interaction

$$w_{\mathrm{MC}} = \frac{N_{\mathrm{physical}}}{N_{\mathrm{gen}}} p_{\mathrm{physical}}^{\mathrm{interaction}} \frac{p_{\mathrm{physical}}^{\mathrm{neutrino\ type}}}{p_{\mathrm{gen}}^{\mathrm{neutrino\ type}}} \frac{p_{\mathrm{physical}}^{\mathrm{interaction\ type}}}{p_{\mathrm{gen}}^{\mathrm{interaction\ type}}} \frac{p_{\mathrm{physical}}^{\mathrm{energy}}}{p_{\mathrm{gen}}^{\mathrm{energy}}} \frac{p_{\mathrm{physical}}^{\mathrm{direction}}}{p_{\mathrm{gen}}^{\mathrm{direction}}} \frac{p_{\mathrm{physical}}^{\mathrm{impact}}}{p_{\mathrm{gen}}^{\mathrm{impact}}} \frac{p_{\mathrm{physical}}^{\mathrm{depth}}}{p_{\mathrm{gen}}^{\mathrm{depth}}} \frac{p_{\mathrm{physical}}^{\mathrm{kinematics}}}{p_{\mathrm{gen}}^{\mathrm{kinematics}}}.$$

SN 2023ixf observed on May 19, 2023

In M101 galaxy @ 6.4 Mpc



https://www.wis-tns.org/object/2023ixf

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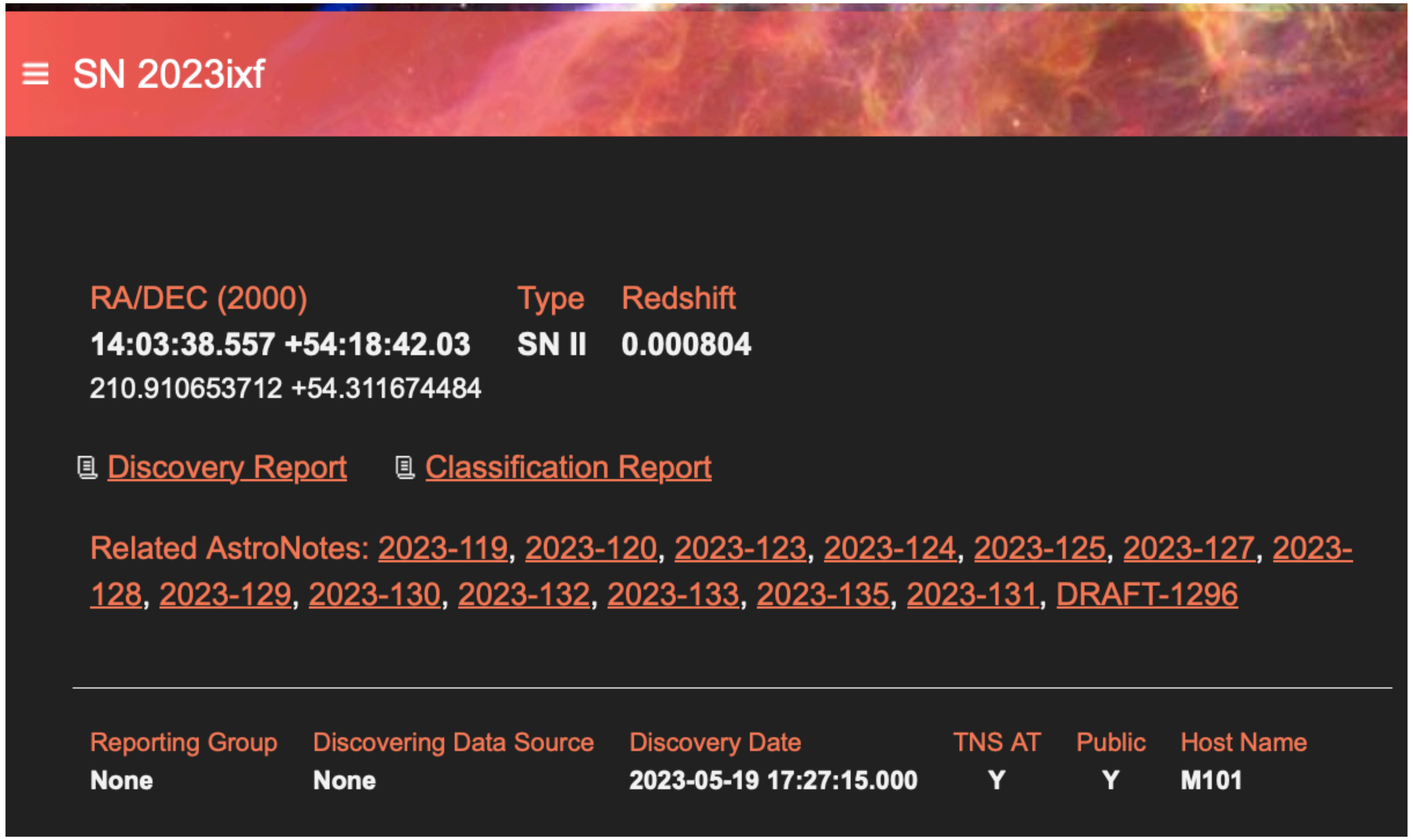


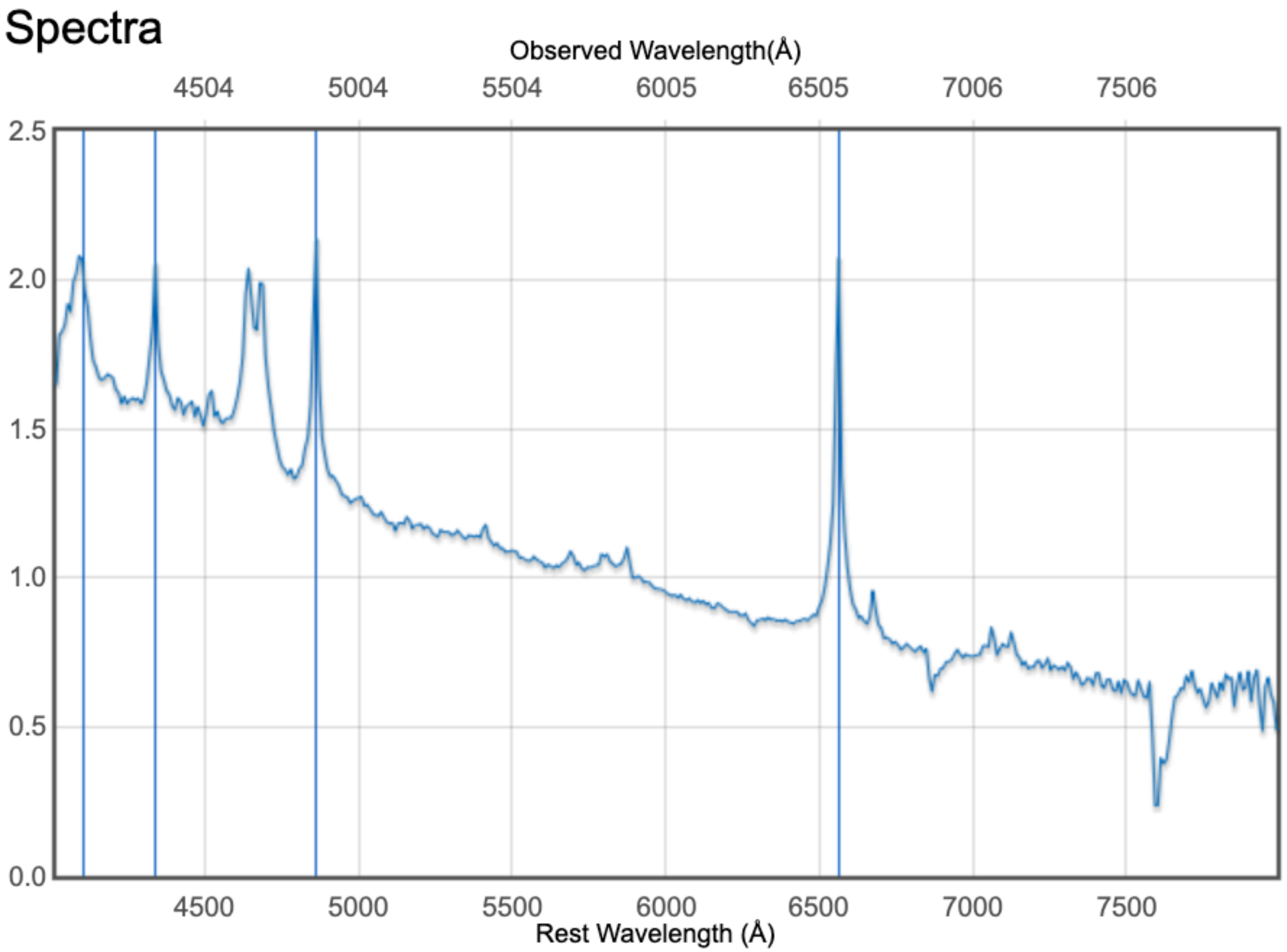
≡ SN 2023ixf

RA/DEC (2000)	Type	Redshift
14:03:38.557 +54:18:42.03 210.910653712 +54.311674484	**SN II**	**0.000804**

Discovery Report   Classification Report

Related AstroNotes: 2023-119, 2023-120, 2023-123, 2023-124, 2023-125, 2023-127, 2023-128, 2023-129, 2023-130, 2023-132, 2023-133, 2023-135, 2023-131, DRAFT-1296

Reporting Group	Discovering Data Source	Discovery Date	TNS AT	Public	Host Name
None	**None**	**2023-05-19 17:27:15.000**	**Y**	**Y**	**M101**



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SN 2023ixf observed on May 19, 2023

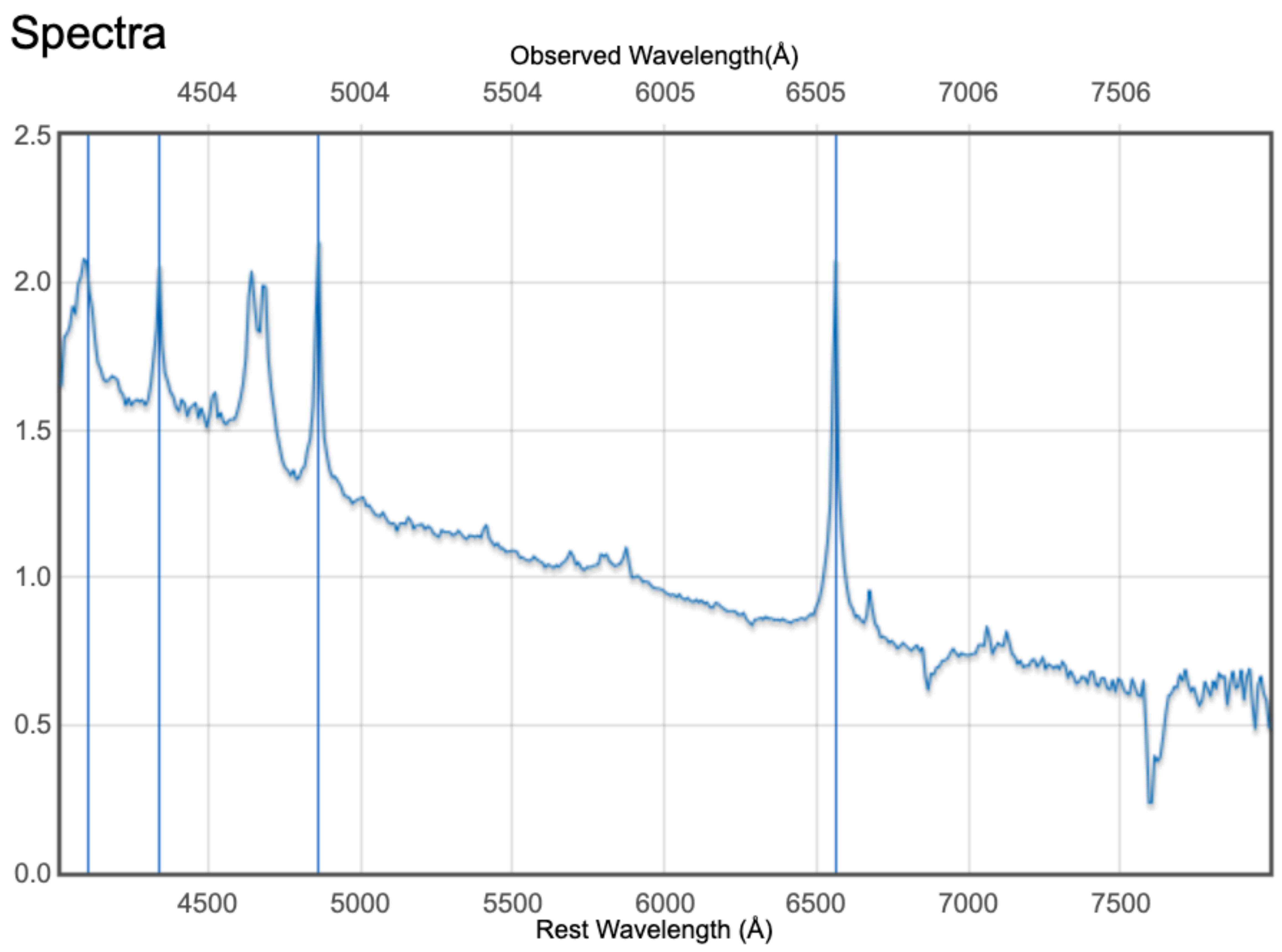
In M101 galaxy @ 6.4 Mpc

Definitively type II

To early to tell which subtype - need more observation time for light curve & spectrum

Reminders: with IceCube:

- Type II-P has negligible detection probability
- Type IIn has small (30%?) detection probability



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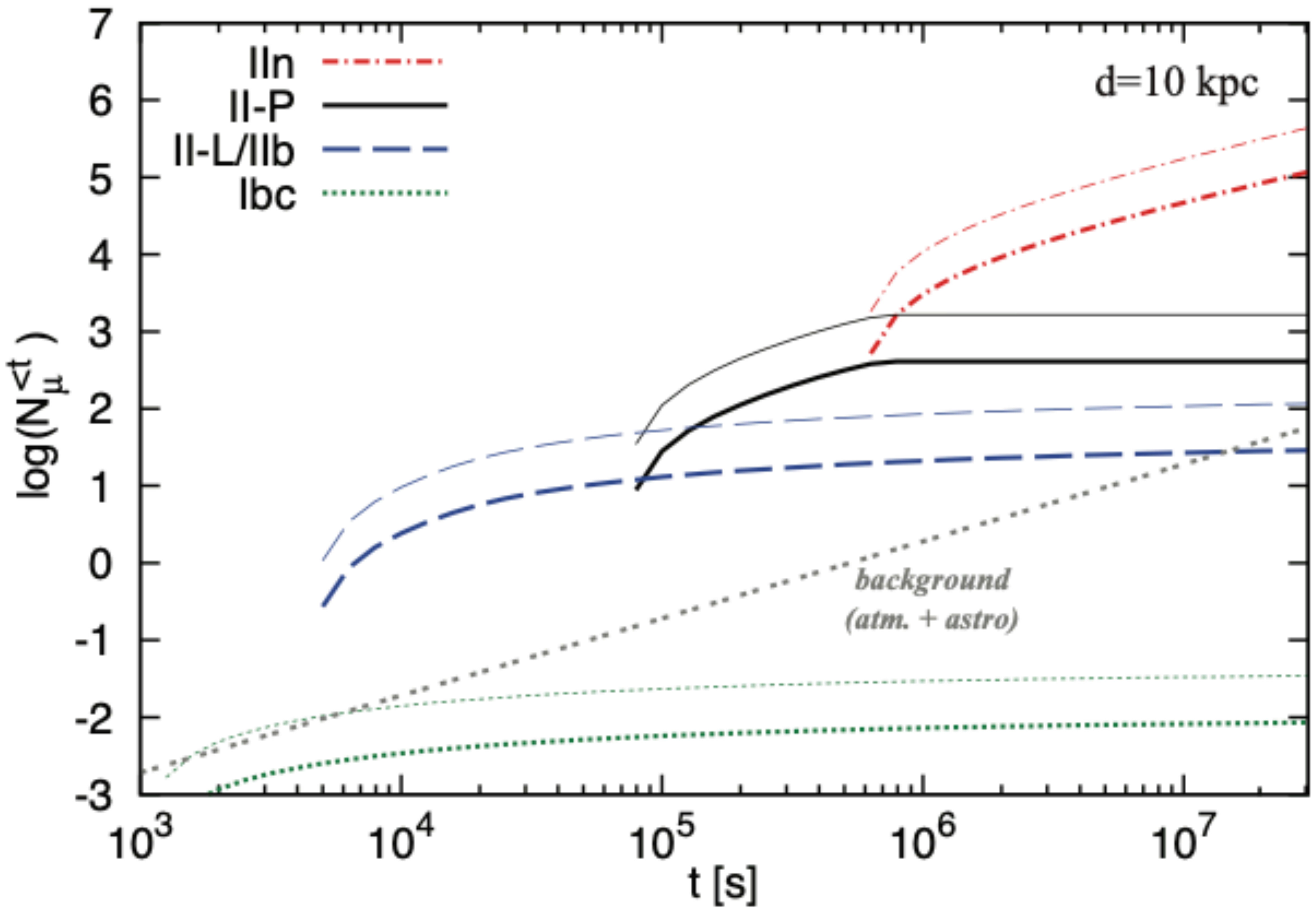
IceCube has good prospects for detection of type II-P and IIn in our galaxy



Number of through going muon tracks as function of observation time
Murase (arXiv:1705.04750)

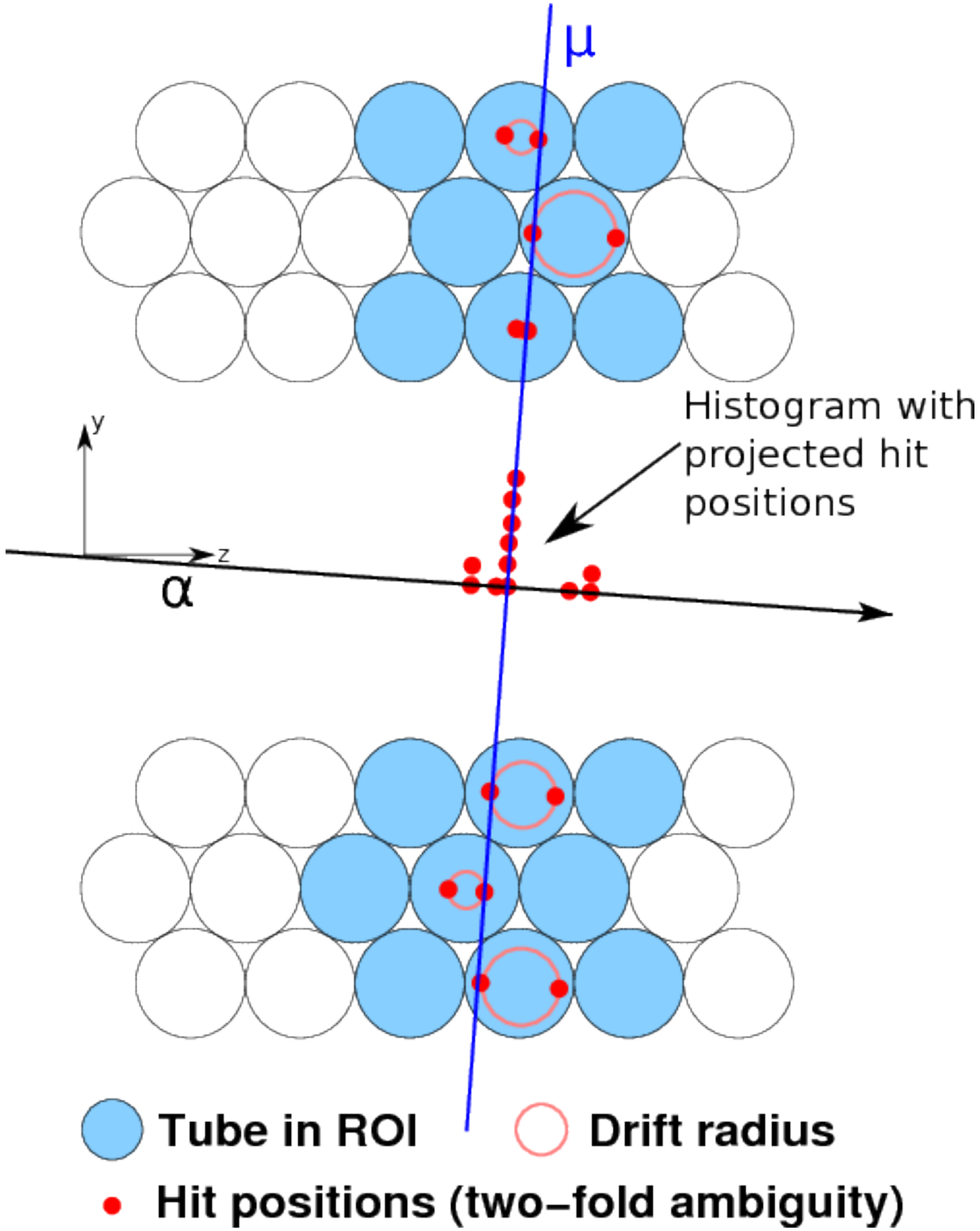
The time range is
~ 10's of days for II-P
~ 100's of days for IIn

Even so, the signal easily dominates over background

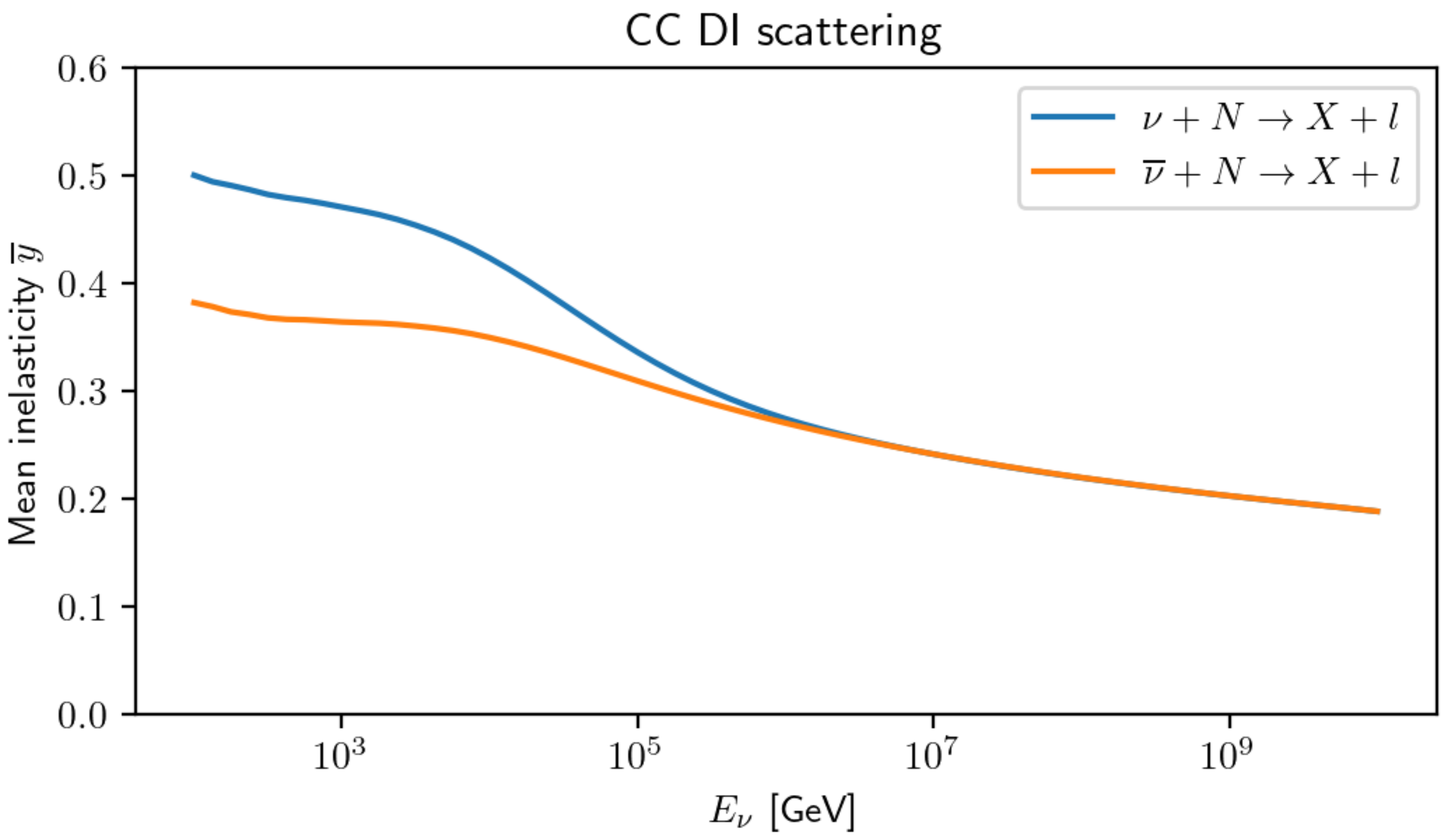
IceCube performed a fast search

https://www.astronomerstelegram.org/?read=16043

- Search for muon-like track events in the time period +/- 2 days from report (May 17 - 21)
- Assuming E^{-2} spectrum, most events at this coordinate would be in the range [600 GeV, 250 TeV]
- $p = 0.18$; consistent with background
- ν_μ flux upper limit of $E^2 \frac{dN}{dE} = 7.3 \times 10^{-2}$ GeVcm^{-2}



ATLAS MDT system
for muon detection



CC DI scattering
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Mean inelasticity $\overline{y}$
10^3
10^5
10^7
10^9
E_ν [GeV]
$\nu + N \rightarrow X + l$
$\overline{\nu} + N \rightarrow X + l$