arXiv: https://arxiv.org/abs/2206.00450

UPPSALA UNIVERSITET

Fysikdagarna 2022

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DETECTION HORIZON OF NEUTRINOS FROM CORE-COLLAPSE SUPERNOVAE USING HIGH ENERGY NEUTRINOS

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SUPERNOVAE

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

End of star's lifecycle

Nucleosynthesis of heavy elements

Gives birth to neutron stars and black holes!

ν

99% of kinetic energy!

Some supernovae can also produce high-energy neutrinos

WHY NEUTRINOS?

ν Production

O(10)MeV

Post-explosion

O(10 s)

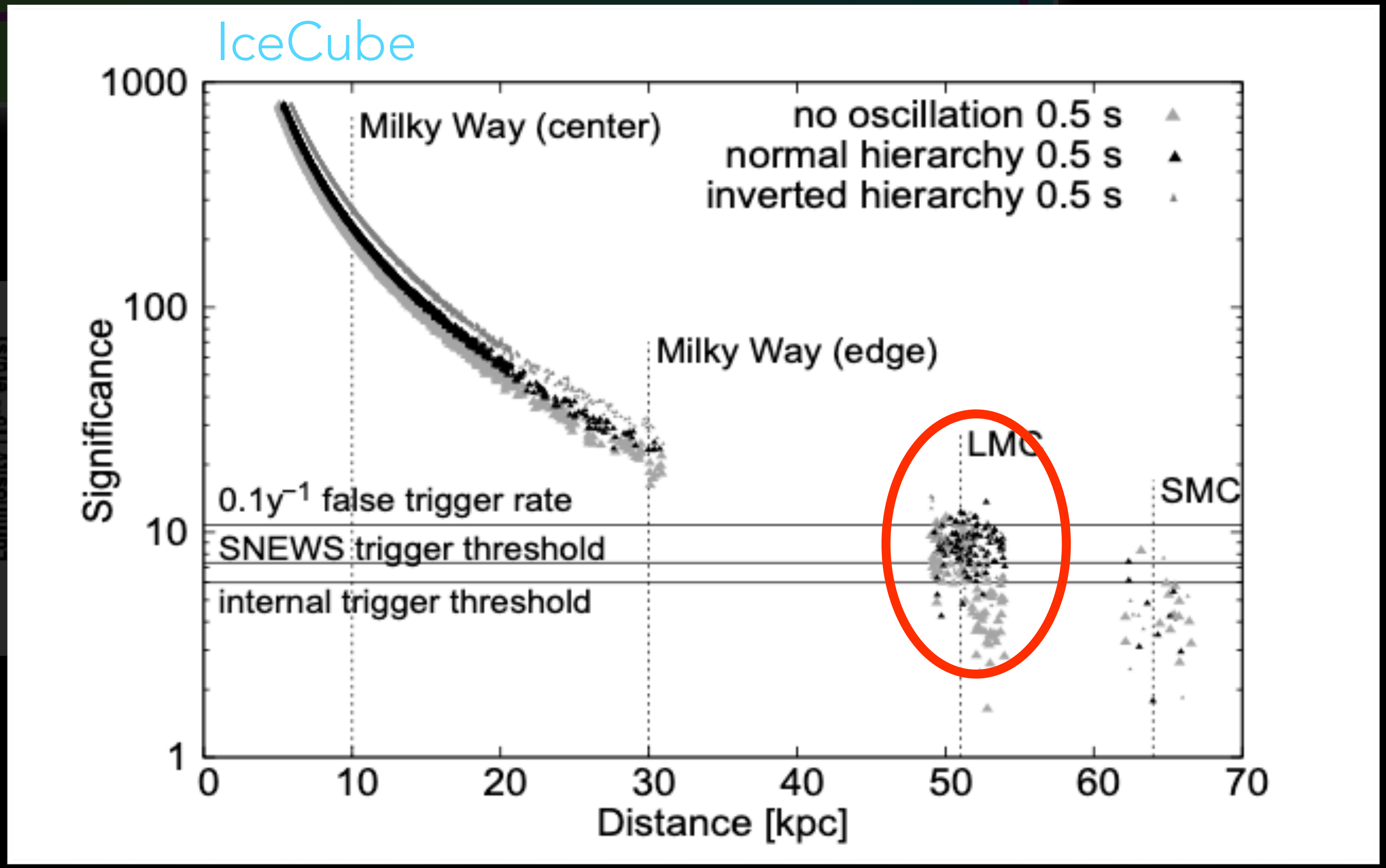
Explosion driven mechanism. 99% of E_{kin} released as MeV ν

Probing with neutrinos will give us insight on the explosion mechanism

In case of a black-hole formation, no EM emission will be emitted, but neutrinos can escape

Neutrino echoes

However, the detection horizon is limited to the 10's of kpc for MeV neutrinos



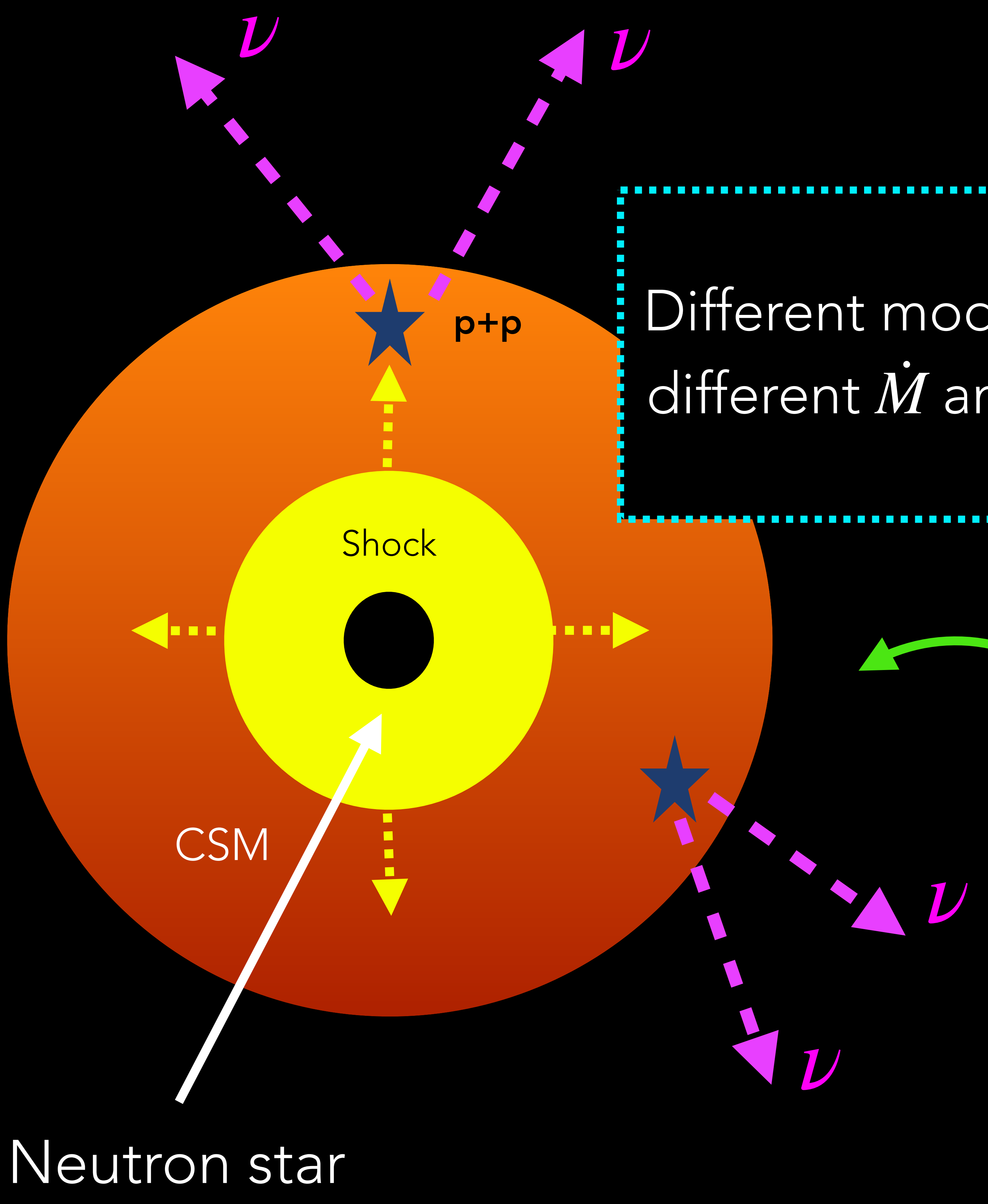
1: H. -Th. Janka https://arxiv.org/abs/1702.08713

2: S. Gullin, E.P. O'Connor, J. -Sh. Wang & J. Tseng (2022) ApJ, 926, 2

Ref: IceCube collaboration. M.G. Aartsen et al. (2011) A&A, 535, 18.

EXTENDING THE HORIZON USING HE ν

CSM-EJECTA MODEL

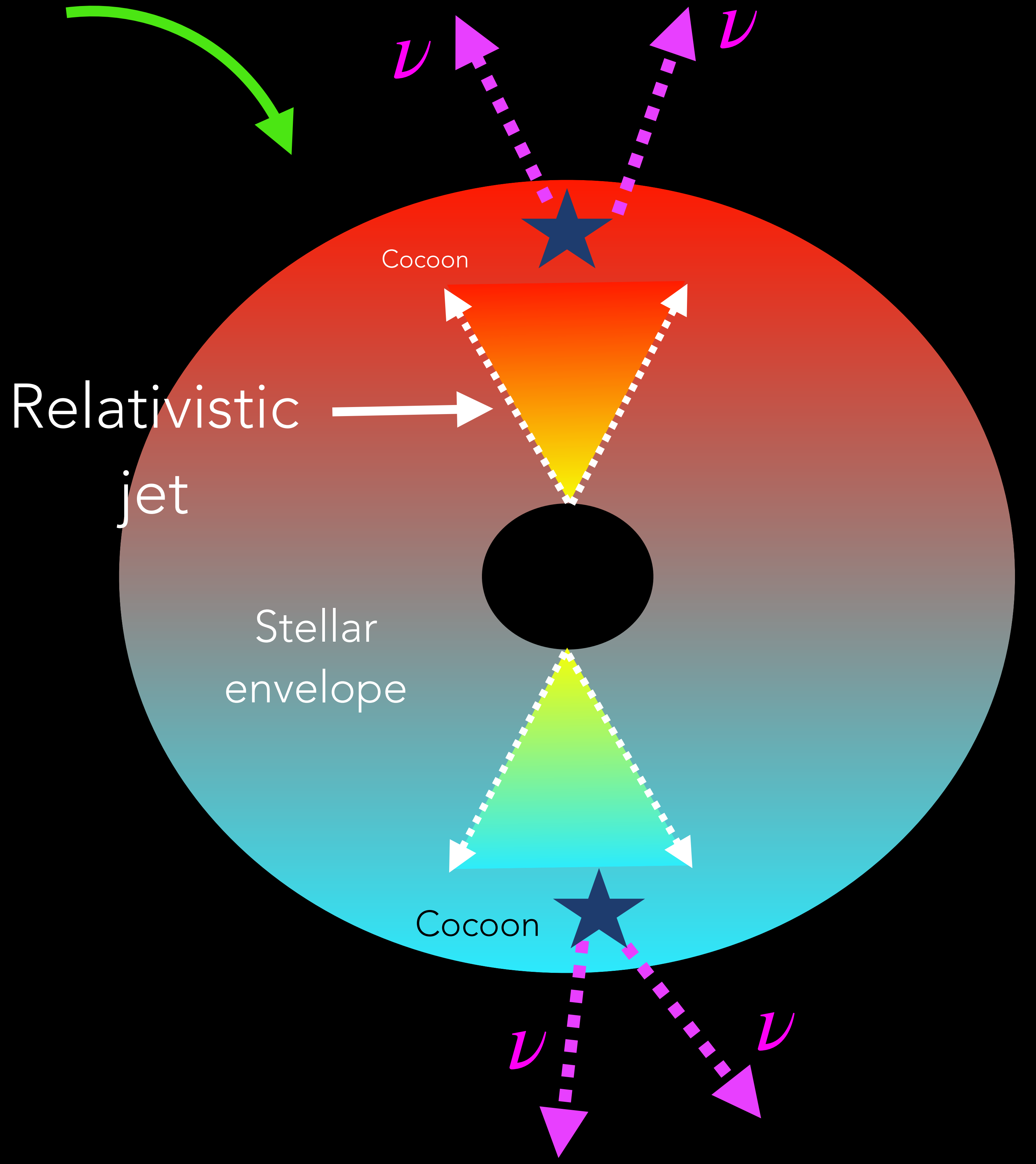


Different models = different $\dot{M}$ and V_w

$t_{emission} \sim$ 0.1 day to 1 year

CHOKED-JET MODEL

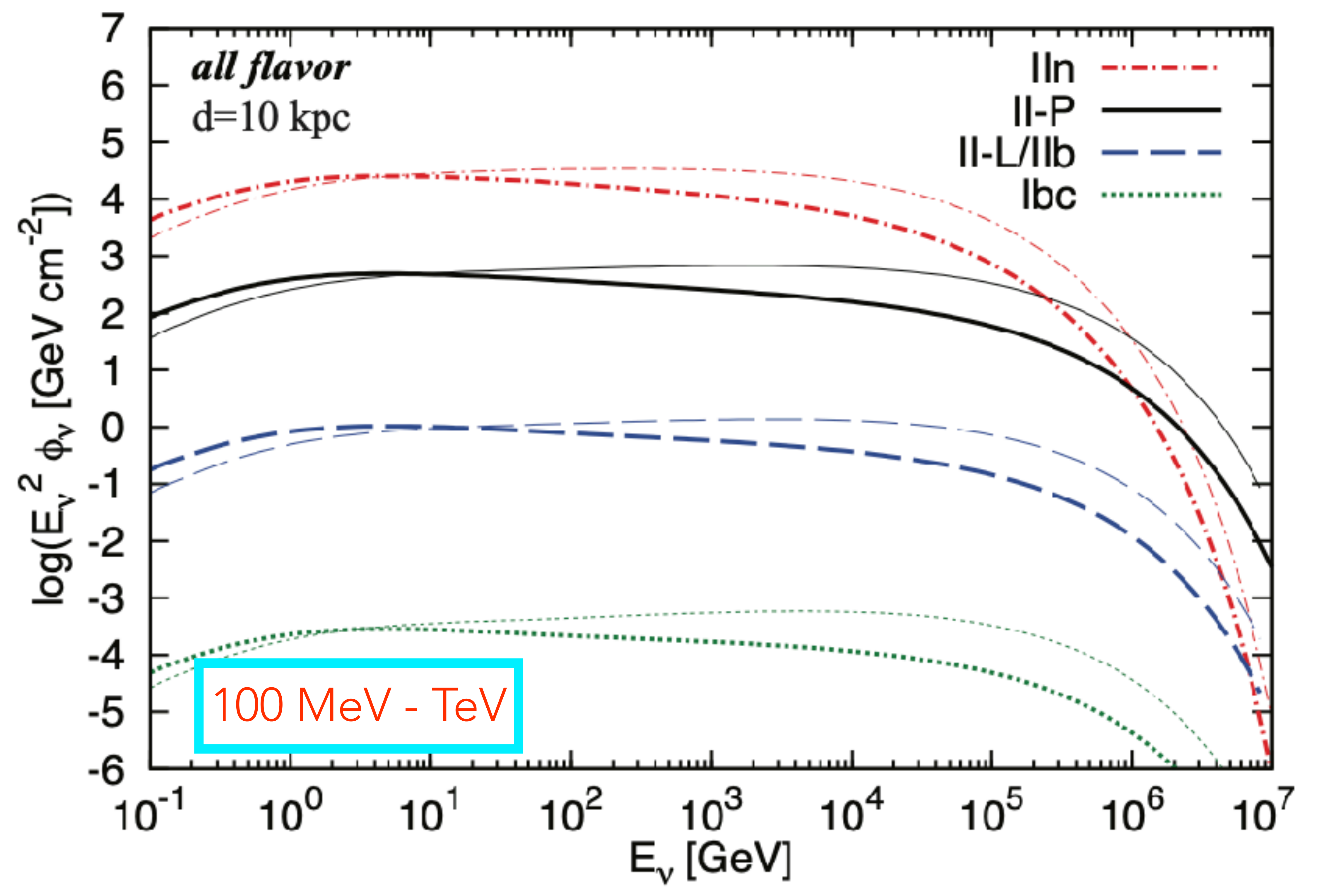
$t_{emission} \sim$ 10s



HE ν FLUX MODELS

CSM-EJECTA MODEL

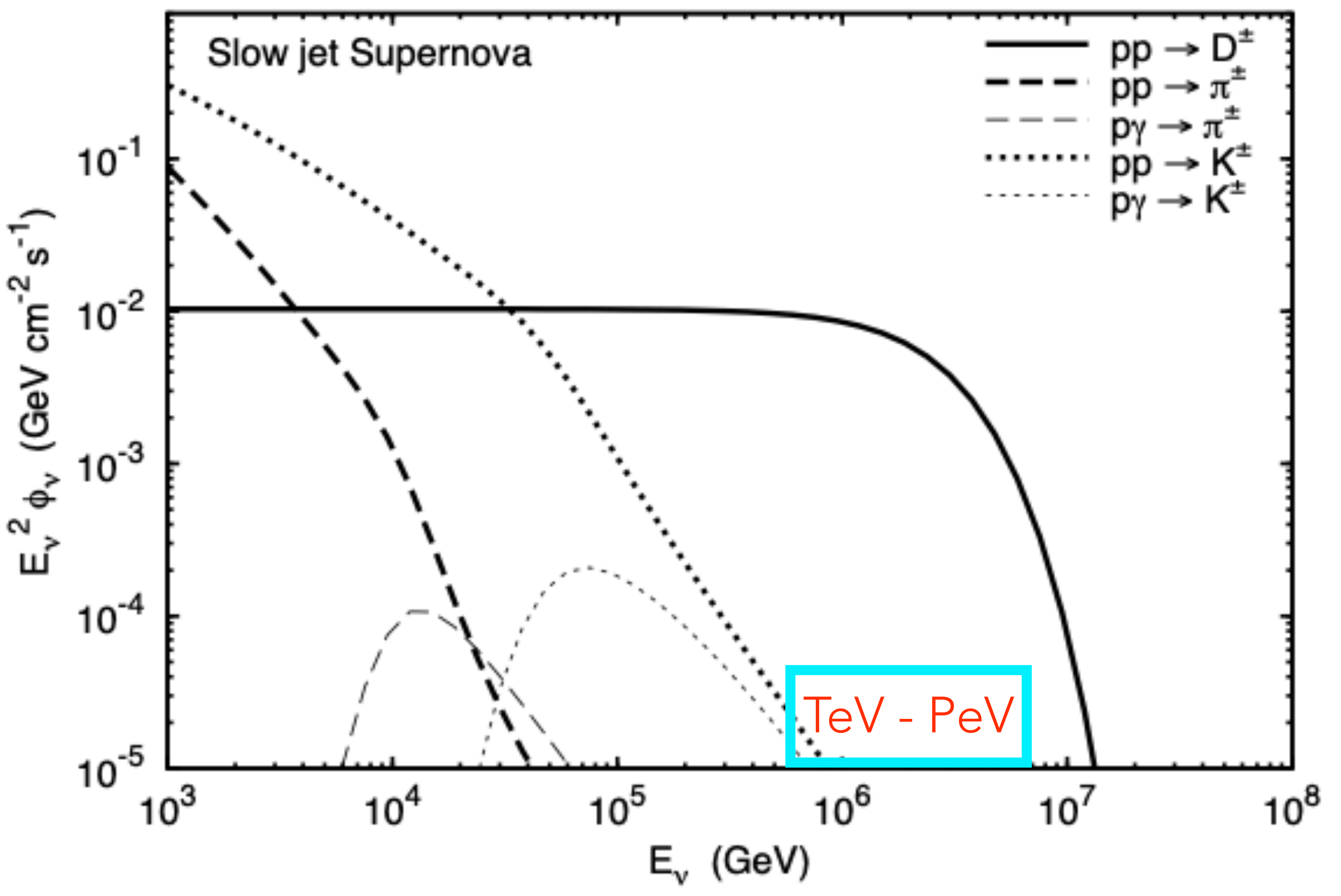
Ref: K. Murase (2018) PhRvD, 97



Neutrino fluence for all flavor ν at
$d = 10\,kpc$ and $t_{max} = 10^7\,s$

CHOKED-JETS MODEL

Ref: R. Enberg, M. Hall Reno & I. Sarcevic (2009) PhRvD, 79



Neutrino flux for ν_μ and $\bar{\nu_\mu}$
at $d = 20\,Mpc$

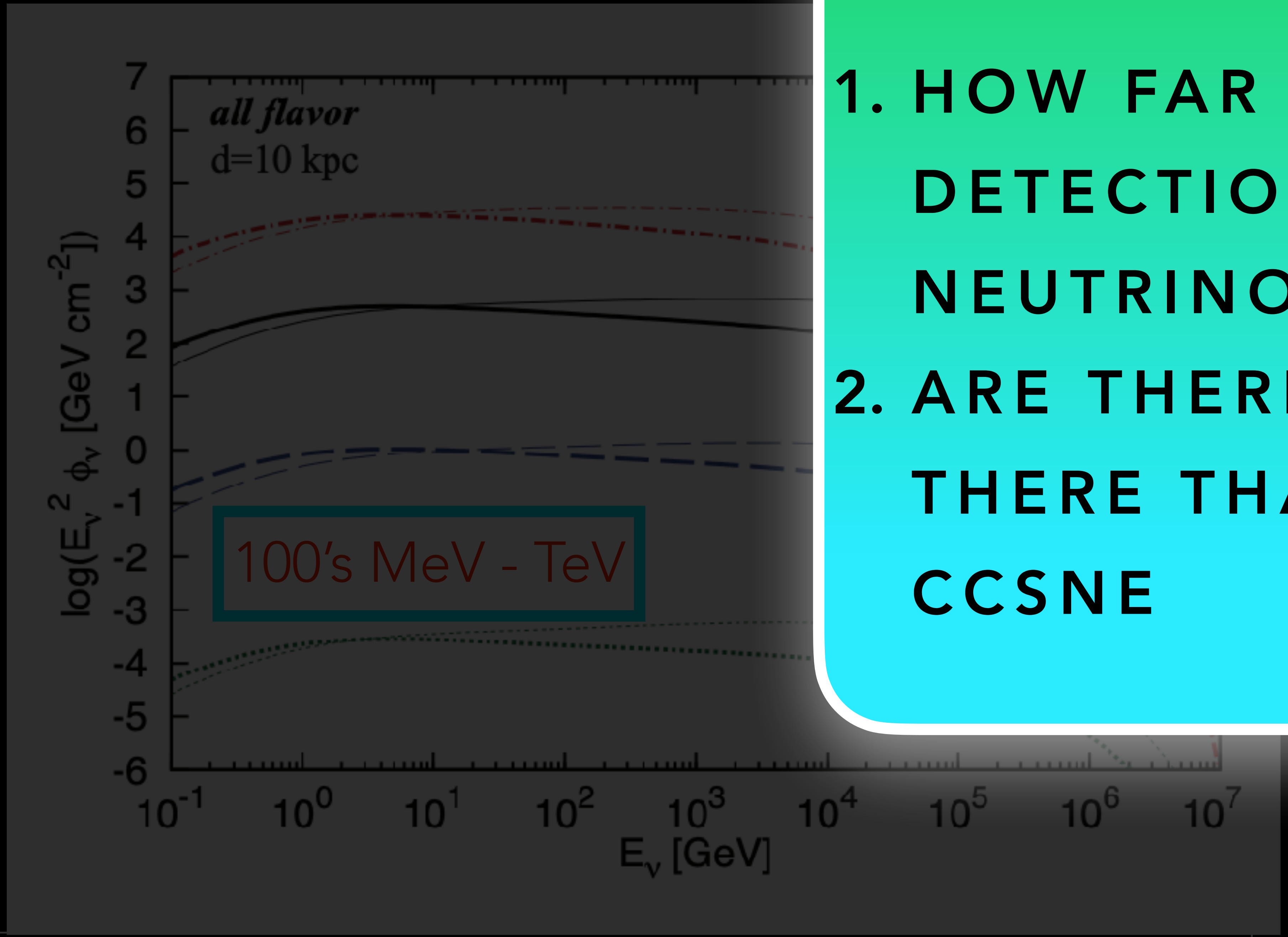
HE FLUX MODELS

O(10) MeV ~Post-explosion TeV

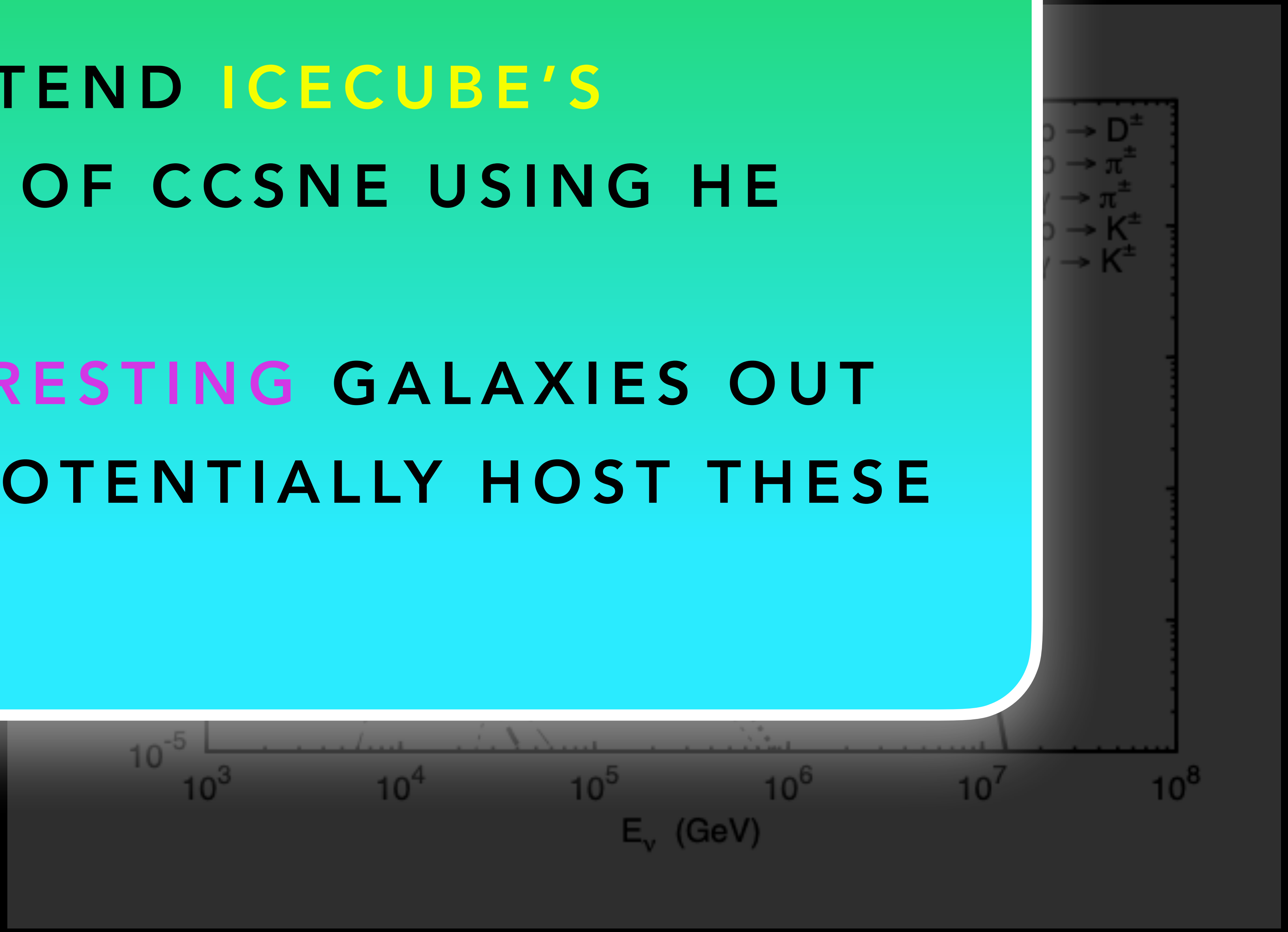
O(10 s) O(days-years)

- Around or post-explosion
- High-flux of high-energy neutrinos

CSM-EJECTA MODEL



Neutrino fluence for all flavor ν at $d = 10\,kpc$ and $t_{max} = 10^7\,s$



Neutrino flux for ν_μ and $\bar{\nu}_\mu$ at $d = 20\,Mpc$

KEY QUESTIONS:

1. HOW FAR CAN WE EXTEND ICECUBE'S DETECTION HORIZON OF CCSNE USING HE NEUTRINOS
2. ARE THERE ANY INTERESTING GALAXIES OUT THERE THAT COULD POTENTIALLY HOST THESE CCSNE

NUMBER OF OBSERVABLE NEUTRINOS

Effective area: neutrino detection sensitivity. It is as a function of neutrino direction (declination) and energy.

Observation time

$$N_\nu = \frac{1}{(d/d_{ref})^2} \int_{t_{min}}^{t_{max}} \int_{E_{min}}^{E_{max}} \phi_\nu(E_\nu, t)\, A_{eff}(E_\nu)\, dt\, dE_\nu$$

I have averaged the declination for northern/southern sky.

Gives the mean number of neutrinos that IceCube would observe

Reference distance for each model

Neutrino energy

Best sensitivity for northern sky

10 YEAR DATA SAMPLE

Tracks

Best sensitivity for southern sky

2 YEAR CONTAINED EVENTS SAMPLE

Mostly cascades

NUMBER OF OBSERVABLE NEUTRINOS

Effective area: neutrino detection sensitivity. It is as a function of neutrino direction (declination) and energy.

Observation time

$N_\nu = $

Gives the mean number of neutrino that IceCube would observe

Reference distance for each model

WHY DO WE HAVE BETTER SENSITIVITY WITH THESE SAMPLES?

Best sensitivity for northern sky

10 YEAR DATA SAMPLE

Tracks

Best sensitivity for southern sky

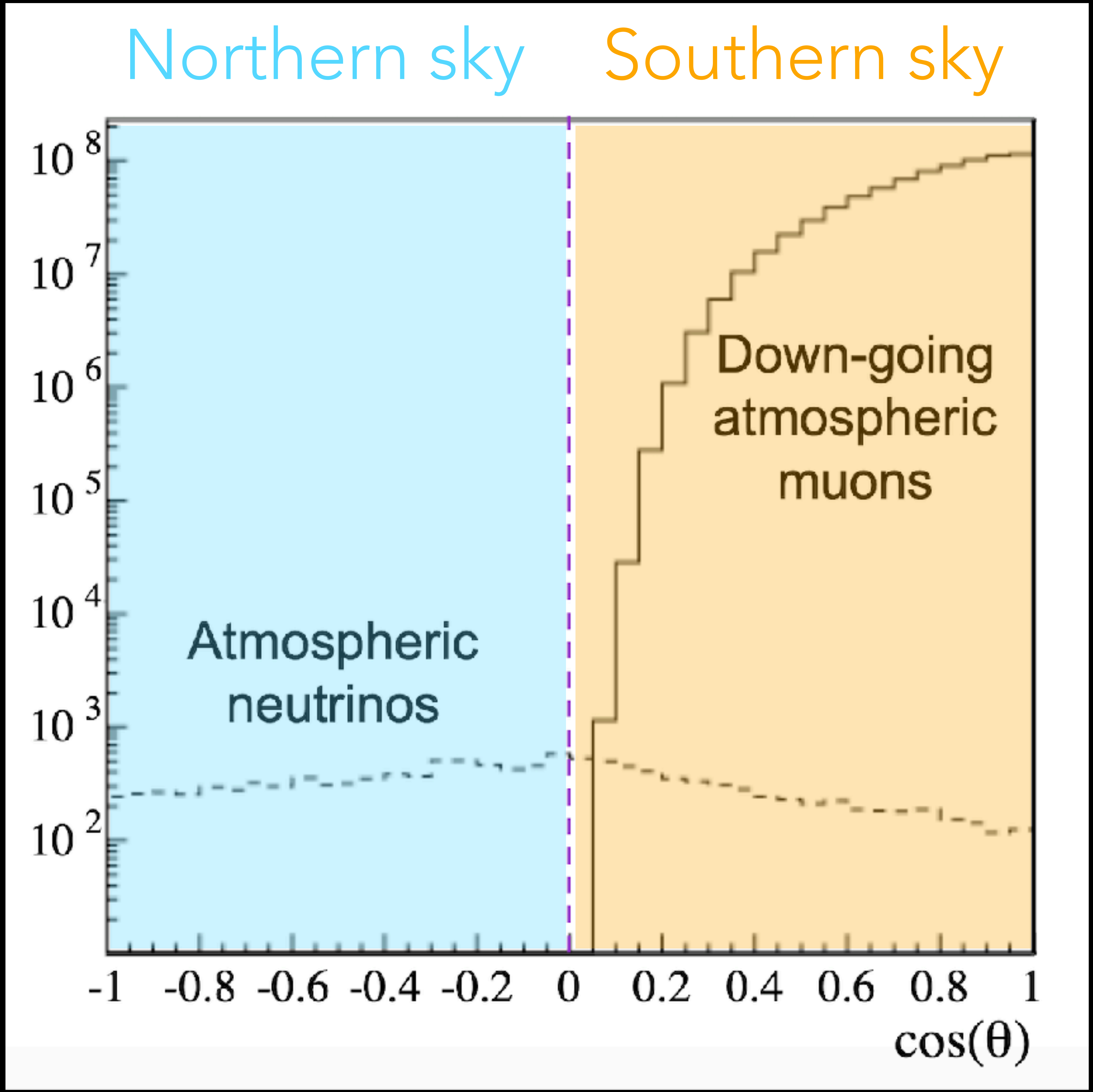
2 YEAR CONTAINED SAMPLE

Mostly cascades

ICECUBE SENSITIVITY

Northern sky —> Earth provides a filter for the atmospheric muons

Southern sky (coming from above the detector) Earth does not filter. One way to filter is through contained events.



DETECTION HORIZON FOR CSM-EJECTA MODEL

SUPERNOVAE FRACTIONS: CSM-EJECTA

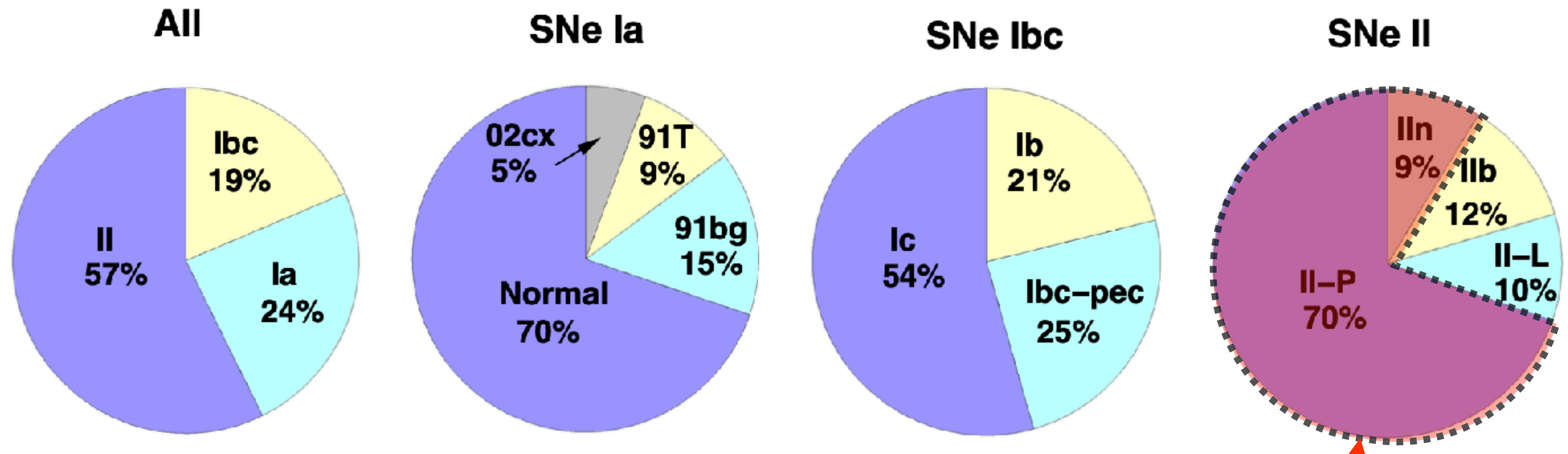
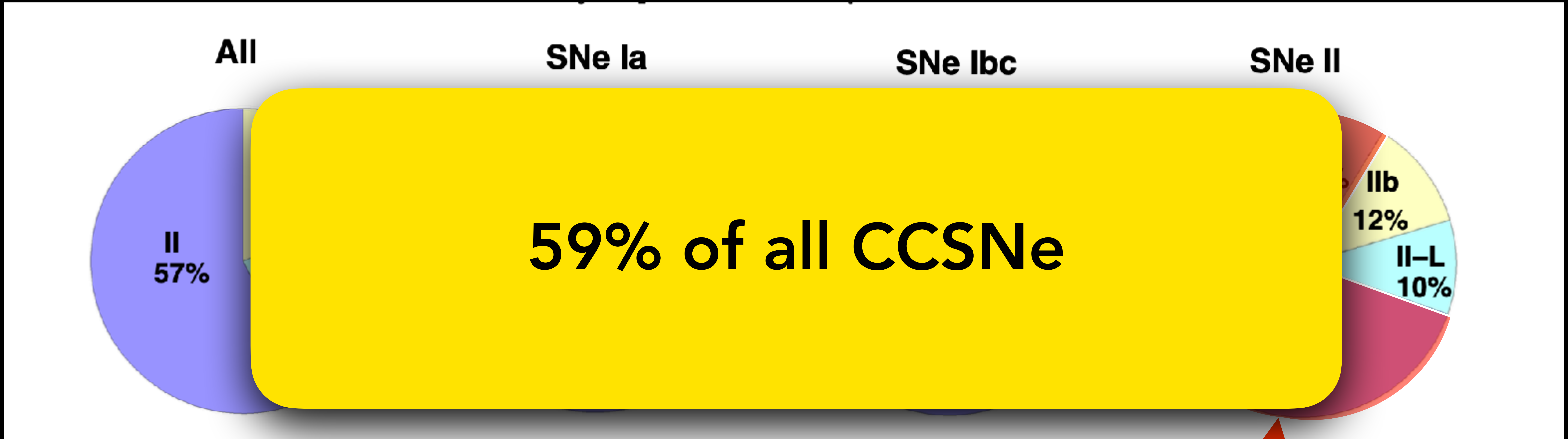


Figure 9. The observed fractions of the subclasses of SNe in a volume-limited sample, illustrated as pie charts. The fractions of SNe Ic and IIb are upper limits, while that of SN 1991T-like objects is a lower limit. Also, the subclass of SNe Ibc-pec consists of broad-lined SNe Ic, peculiar objects, and the "Ca-rich" objects (see text for more details).

Interaction powered SN (CSM-EJECTA)

Reference: https://arxiv.org/abs/1006.4612v2

SUPERNOVAE FRACTIONS: CSM-EJECTA



59% of all CCSNe

Figure 9. The observed fractions of the subclasses of SNe in a volume-limited sample, illustrated as pie charts. The fractions of SNe Ic and IIb are upper limits, while that of SN 1991T-like objects is a lower limit. Also, the subclass of SNe Ibc-pec consists of broad-lined SNe Ic, peculiar objects, and the "Ca-rich" objects (see text for more details).

Interaction powered SN
(CSM-EJECTA)

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DETECTION HORIZON (CSM-EJECTA MODEL)

NORTHERN SKY

SOUTHERN SKY

Number of neutrinos observable by IC scaled to distance, both for track sample (solid) and contained events sample (dashed), for type II-P and IIn. Horizontal lines represent background.

Ref model 1:https://arxiv.org/abs/1705.04750v2

DETECTION HORIZON (CSM-EJECTA MODEL)

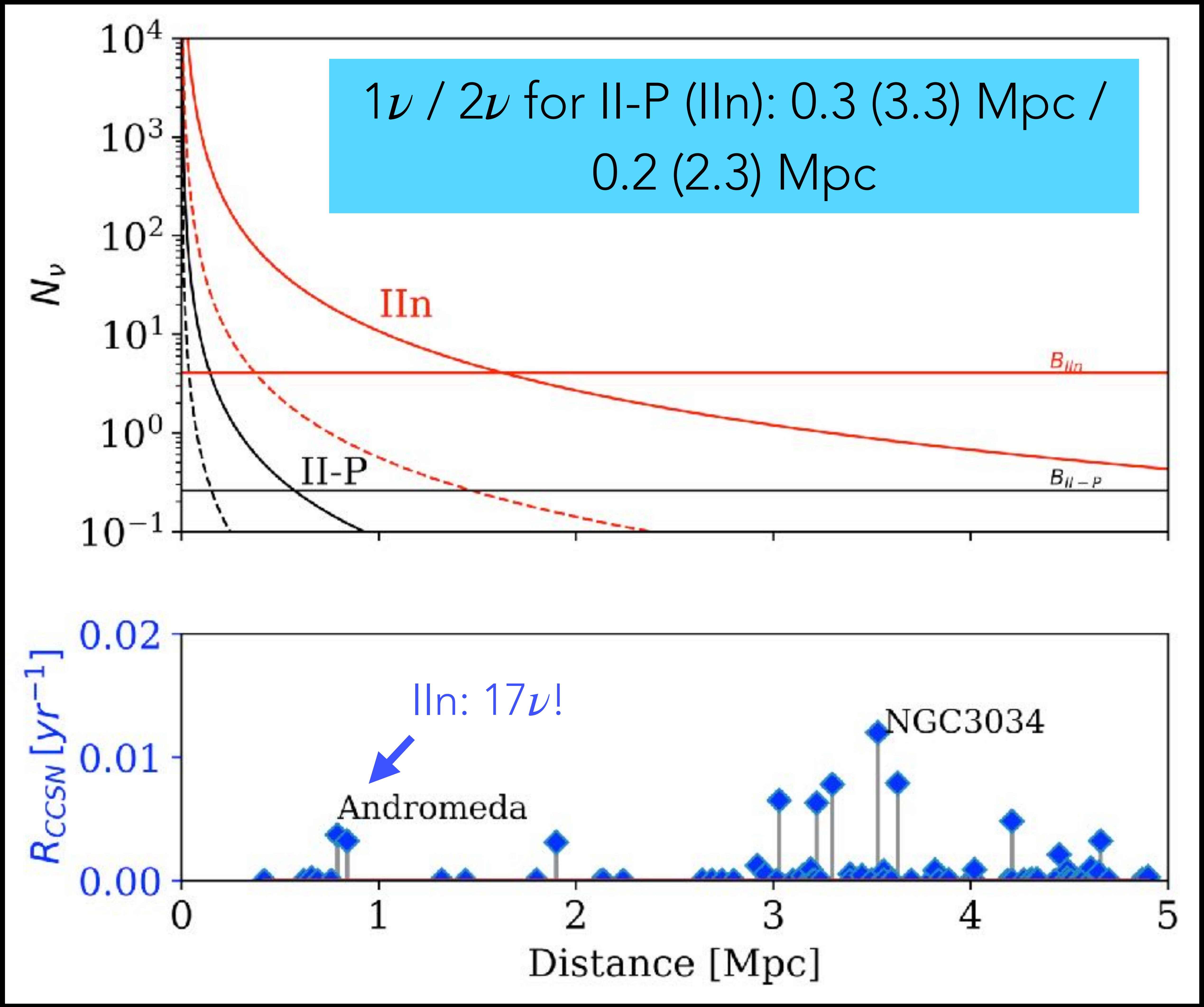
NORTHERN SKY

SOUTHERN SKY

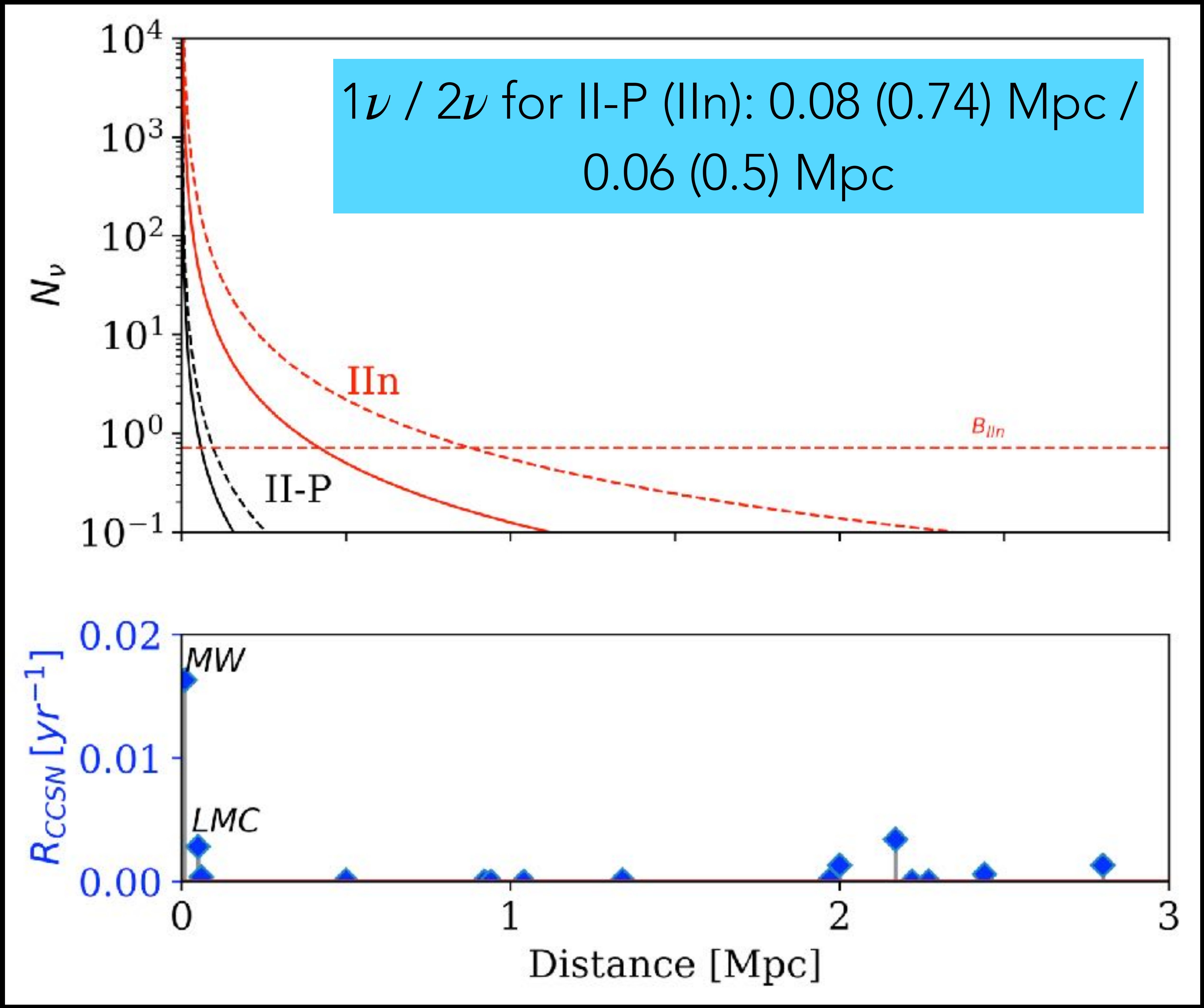
CCSNe rate for each galaxy in the nearby region of 5 (2.5) Mpc.

DETECTION HORIZON (CSM-EJECTA MODEL)

NORTHERN SKY



SOUTHERN SKY



Ref model:https://arxiv.org/abs/1705.04750v2

TOP 20 GALAXIES (CSM-EJECTA)

Considering background, we can reach these galaxies

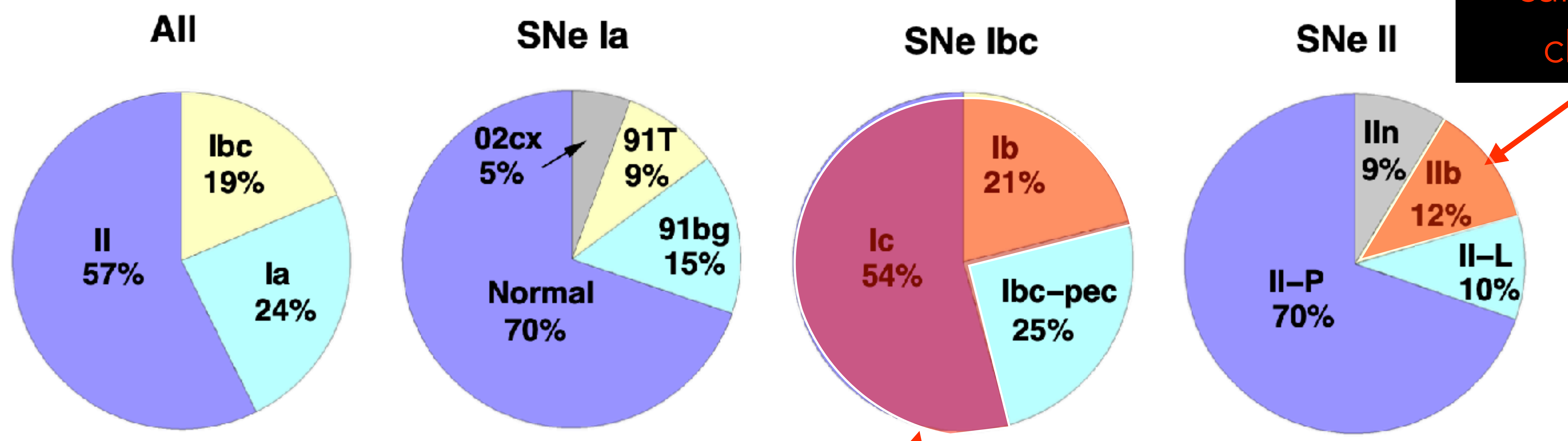
Table 1. Top 20 galaxies

Galaxy Name (1)	RA (Deg) (2)	Dec (Deg) (3)	Distance (Mpc) (4)	CCSN Rate (yr^{-1}) (5)	N_ν[II-P] Number (6)	N_ν[IIn] Number (7)	N_ν[Choked jets] Number (8)
NGC 5236	204.25	-29.87	4.47	0.0240	0.0003	0.028	17
NGC 3034	148.97	69.68	3.53	0.0120	0.0069	0.86	575
NGC 253	11.89	-25.29	3.94	0.0120	0.0004	0.0353	25
NGC 5128	201.37	-43.02	3.66	0.0092	0.0005	0.041	29
NGC 3031	148.89	69.07	3.63	0.0079	0.0065	0.82	544
Maffei 2	40.48	59.60	3.30	0.0078	0.008	1	658
UGC 2847	56.70	68.09	3.03	0.0065	0.009	1.17	780
NGC 4945	196.37	-49.47	3.60	0.0064	0.0005	0.042	30
NGC 2403	114.21	65.60	3.22	0.0063	0.008	1.04	691
NGC 4449	187.05	44.09	4.21	0.0048	0.005	0.60	404
NGC 1313	49.57	-66.49	4.47	0.0044	0.0004	0.032	23
M 31	10.69	41.27	0.79	0.0037	0.137	17.2	$1.15 \cdot 10^4$
NGC 7793	359.46	-32.59	3.90	0.0037	0.0004	0.036	26
NGC 55	3.73	-39.19	2.17	0.0034	0.0013	0.117	83
NGC 598	23.46	30.66	0.84	0.0032	0.12	15.3	$1.02 \cdot 10^4$
NGC 4736	192.72	41.12	4.66	0.0032	0.004	0.4955	330
NGC 1569	67.70	64.85	1.90	0.0031	0.024	2.98	$2 \cdot 10^3$
LMC	80.89	-69.76	0.05	0.0028	2.65	219.5	$2.87 \cdot 10^6$
NGC 4236	184.18	69.46	4.45	0.0021	0.004	0.543	362
NGC 247	11.79	-20.76	3.65	0.0020	0.0005	0.041	29

NOTE—This table shows the top 20 galaxies that comprise 87% of all the CCSN rate within 5 Mpc from Nakamura et al. (2016)

DETECTION HORIZON FOR CHOKED-JETS MODEL

SUPERNOVAE FRACTIONS: CHOKED-JETS



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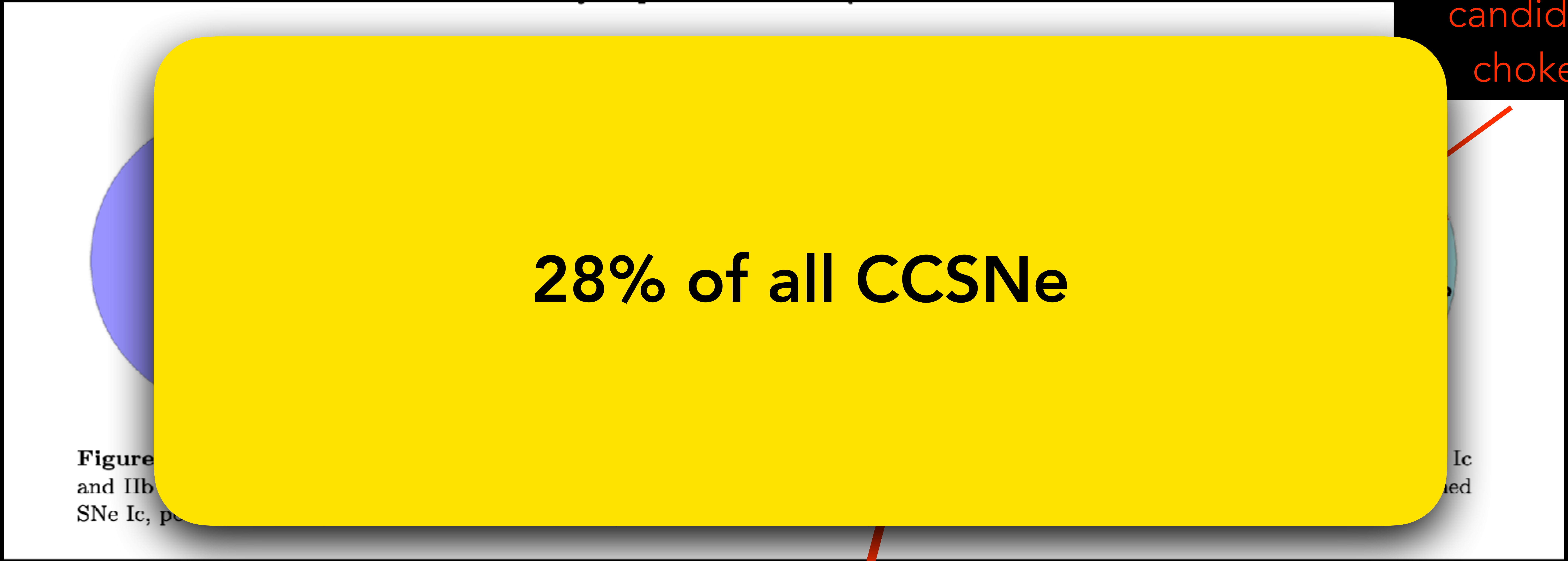
Could also potentially be candidates for choked jets

Choked jets

Reference: https://arxiv.org/abs/1006.4612v2

SUPERNOVAE FRACTIONS: CHOKED-JETS

Could also potentially be candidates for choked jets



28% of all CCSNe

Choked jets

Reference: https://arxiv.org/abs/1006.4612v2

HOW FAR COULD WE OBSERVE (CHOKED-JETS)

NORTHERN SKY

SOUTHERN SKY

Ref model 2: https://arxiv.org/abs/0808.2807v2

HOW FAR COULD WE OBSERVE (CHOKED-JETS)

NORTHERN SKY

SOUTHERN SKY

Observed CCSNe (choked-jet type) = cumulative optically observed [yearly] (ZTF and ZTF+ASAS-SN)

Expected in ν = Scaling. Expected to be observable by IC with suppression factor [yearly]

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Observed CCSNe (choked-jet type) = cumulative optically observed [yearly] (ZTF and ZTF+ASAS-SN)

Expected in ν = Scaling. Expected to be observable by IC with suppression factor [yearly]

Suppression factor arises from the fact that from the population, only ~10% have jets, and from those only a few point to Earth!

Ref model 2: https://arxiv.org/abs/0808.2807v2

HOW FAR COULD WE OBSERVE (CHOKED-JETS)

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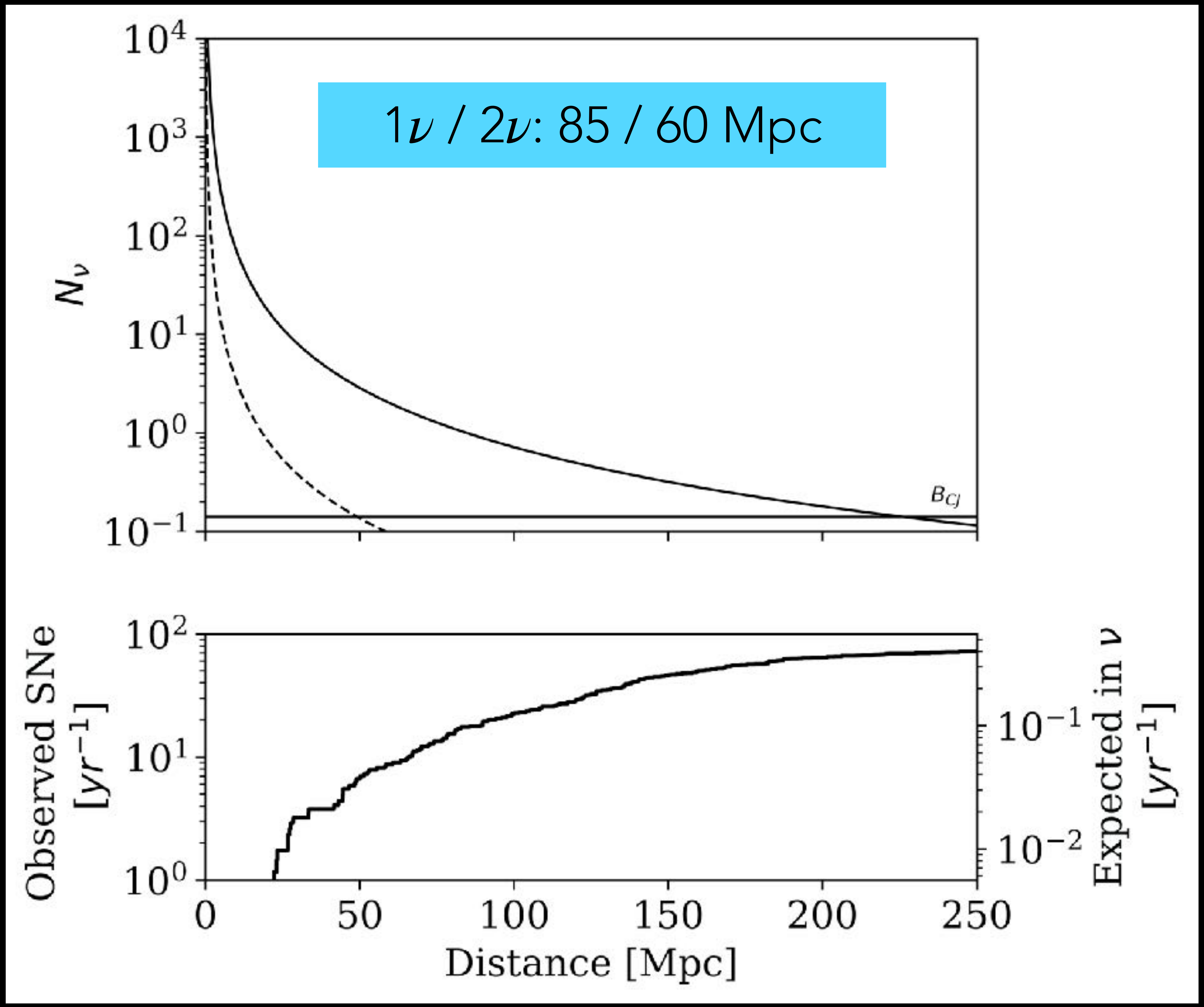
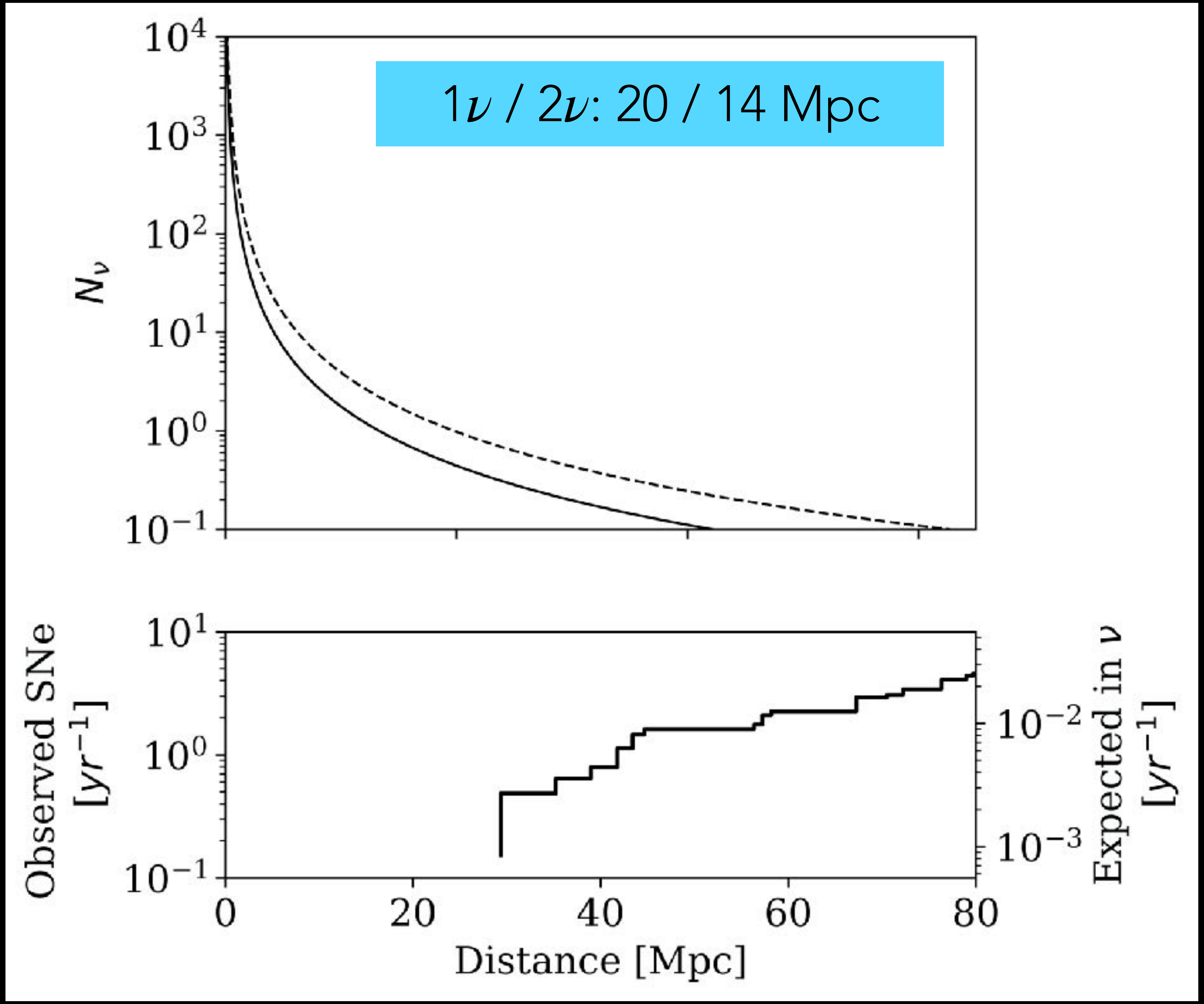


SOUTHERN SKY



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TOP 20 GALAXIES (CHOKED-JETS)

We can reach all of the top 20 galaxies

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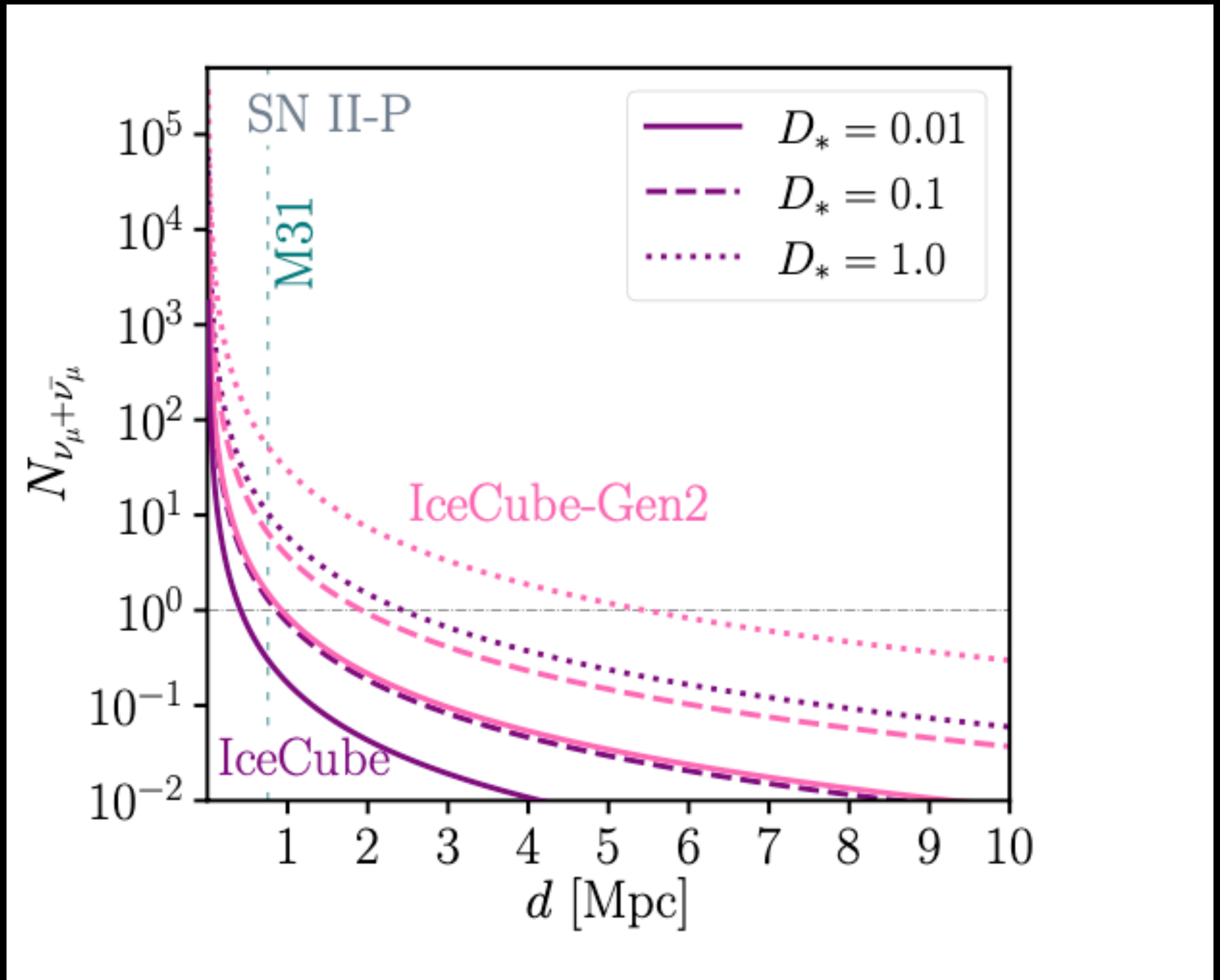
CONCLUSIONS

- **CSM-interaction model:**
  - Models considered in this study consist of 59% of all CCSNe.
  - **Northern sky:** For type II-P (IIn), the detection horizon with a doublet is extended 0.2 (2.32) Mpc, and for a singlet up to 0.3 (3.3) Mpc. For type IIn, we could observe M31 (17 ν) and NGC 598 (15 ν).
  - **Southern sky:** We can reach past the LMC with both II-P and IIn, with a doublet reach of 0.06 (0.5) Mpc and with a singlet to 0.08 (0.74) Mpc. We could observe 220 ν from the LMC with type IIn.
- **Choked jets model:**
  - We can reach all of the top 20 galaxies nearby with high statistics.
  - **Northern sky reach:** It extends to ZTF range, with a singlet detection horizon at 85 Mpc. At this distance ZTF observes 15 CCSNe yearly that would be candidates. After suppression factor (1/180 point to Earth), we expect **1 such CCSNe to be observable through ν in 10 years**.
  - **Southern sky reach:** With a singlet we can reach 20 Mpc, however the first observed CCSNe candidate is at 30 Mpc.

FUTURE PROSPECTS

NEW II-P ESTIMATES



IMPROVEMENT IN RECONSTRUCTION

Southern sky detection horizon will improve by a factor of 3-4

GEN2

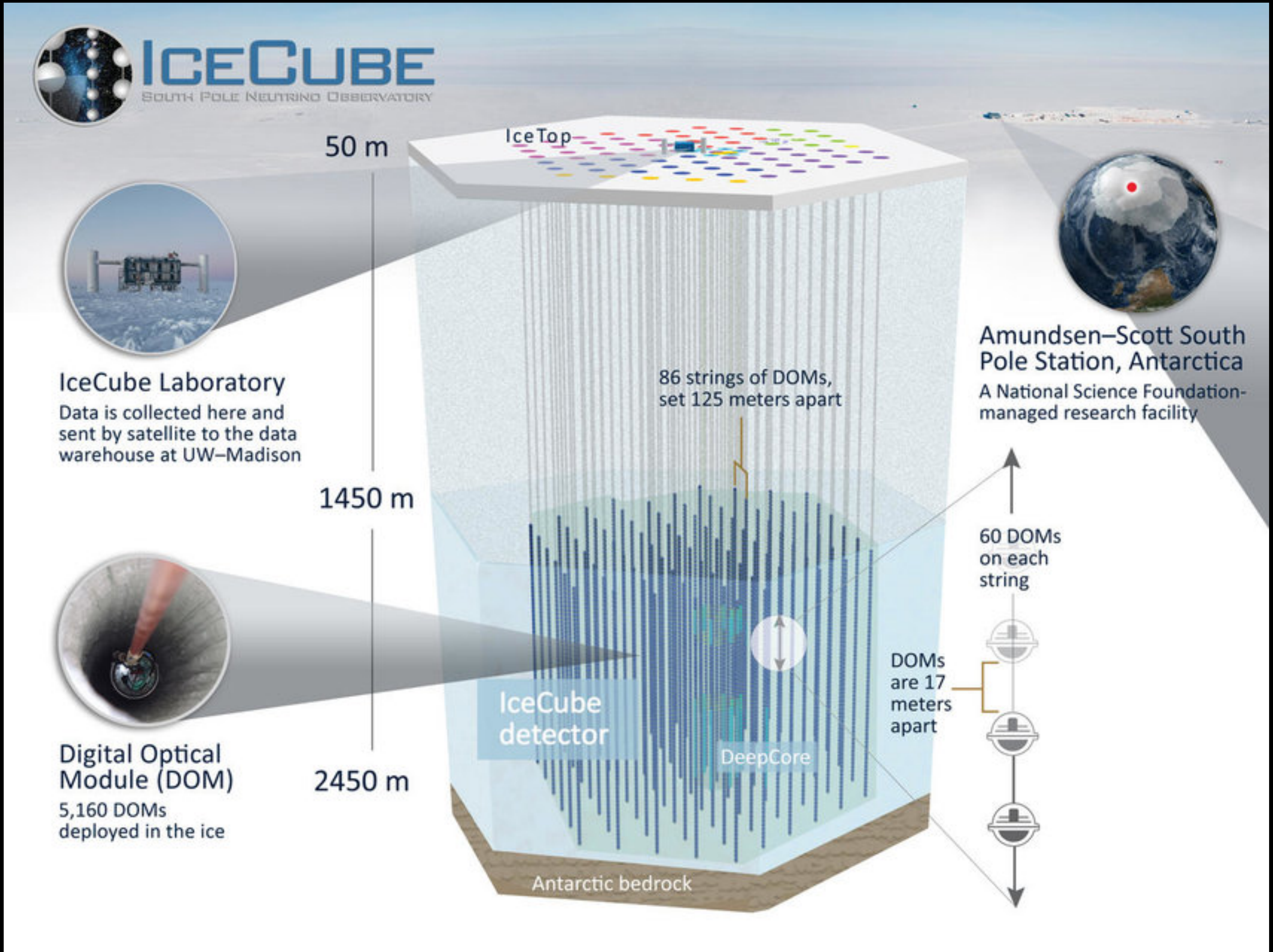
Expected improvement in detection horizon by a factor of 3

Ref: A. Kheirandish, K. Murase arxiv: 2204.08518

THANK YOU!

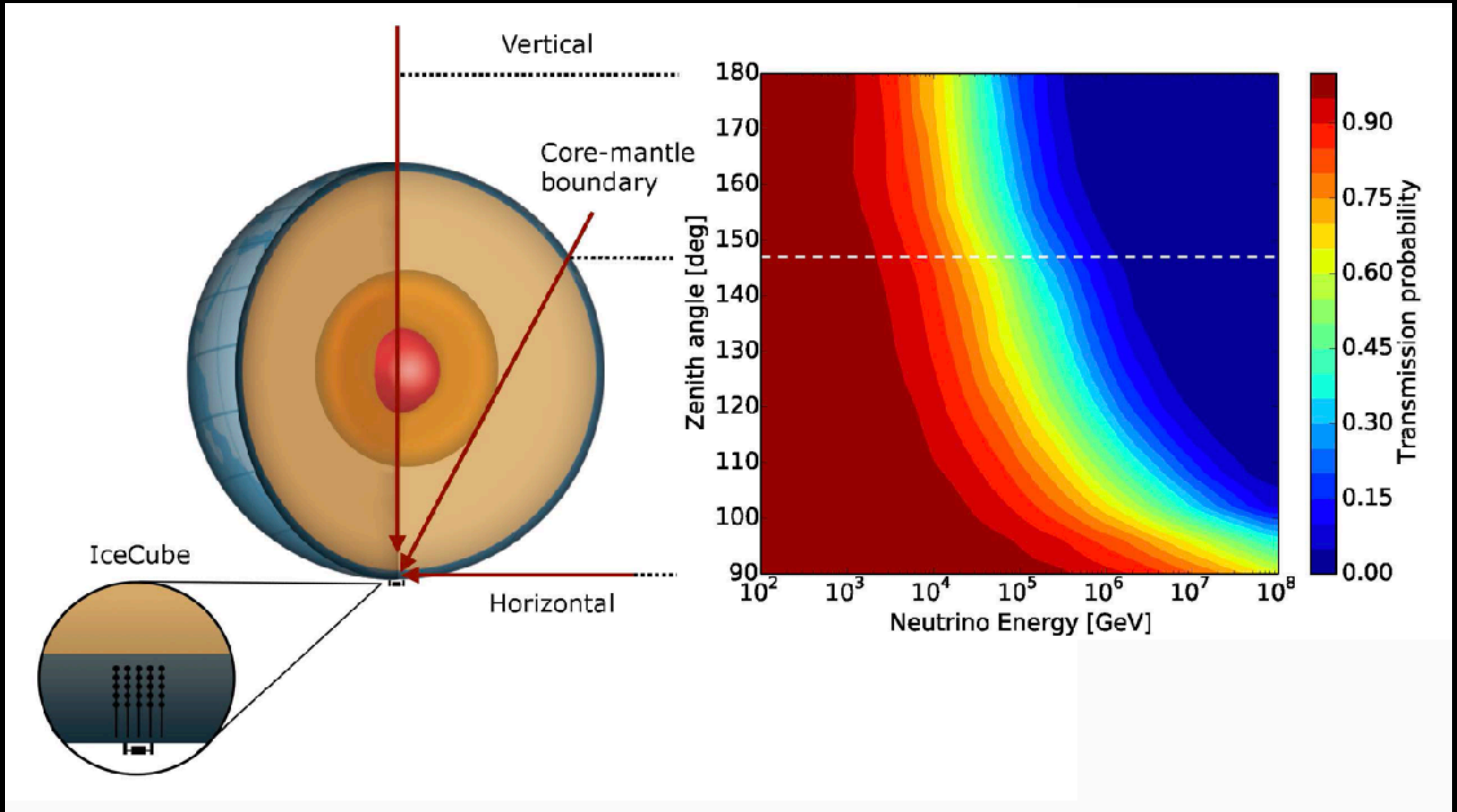
BACK UP

ICECUBE DETECTOR



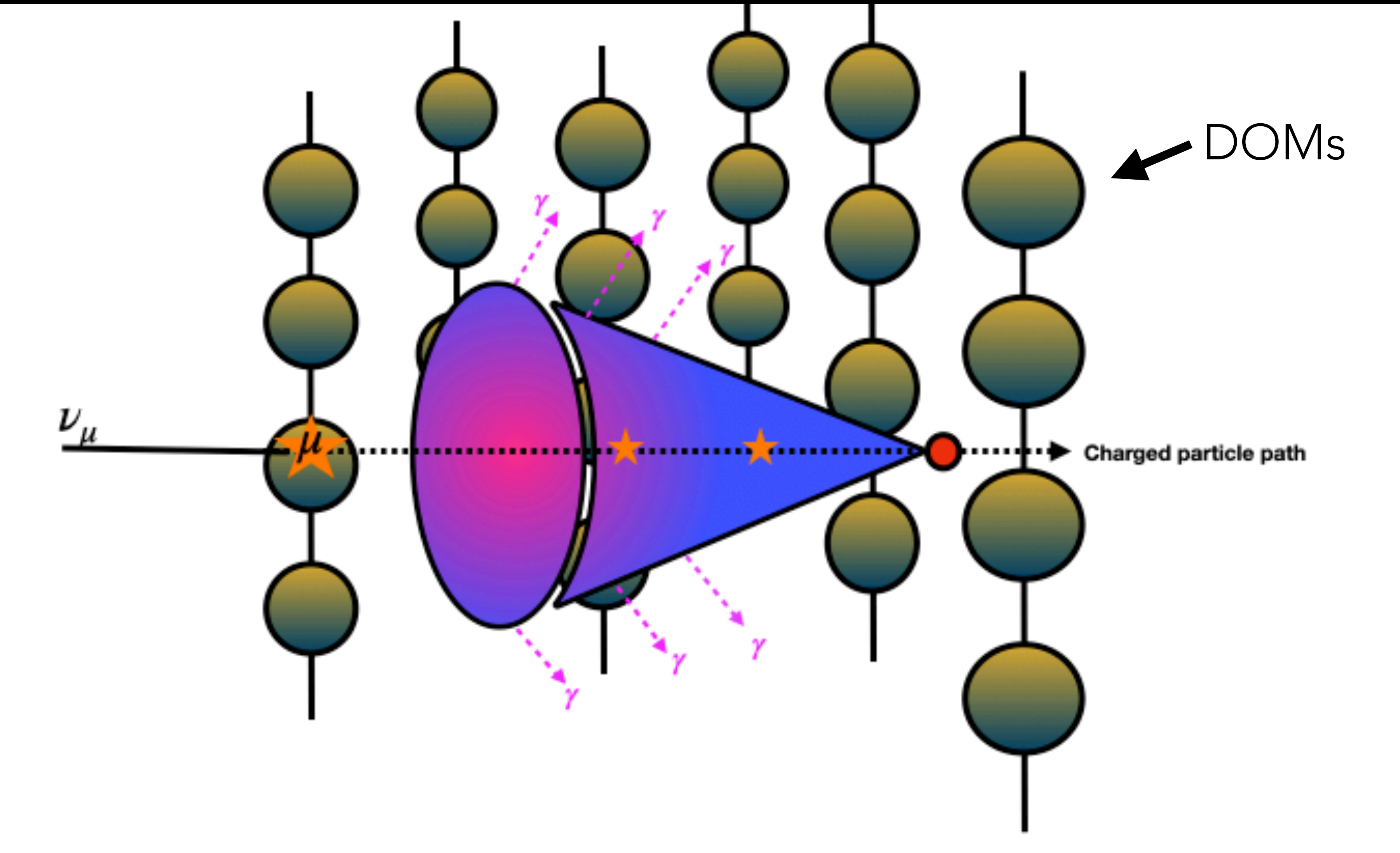
https://arxiv.org/pdf/1701.03731.pdf

NEUTRINO TRANSMISSION



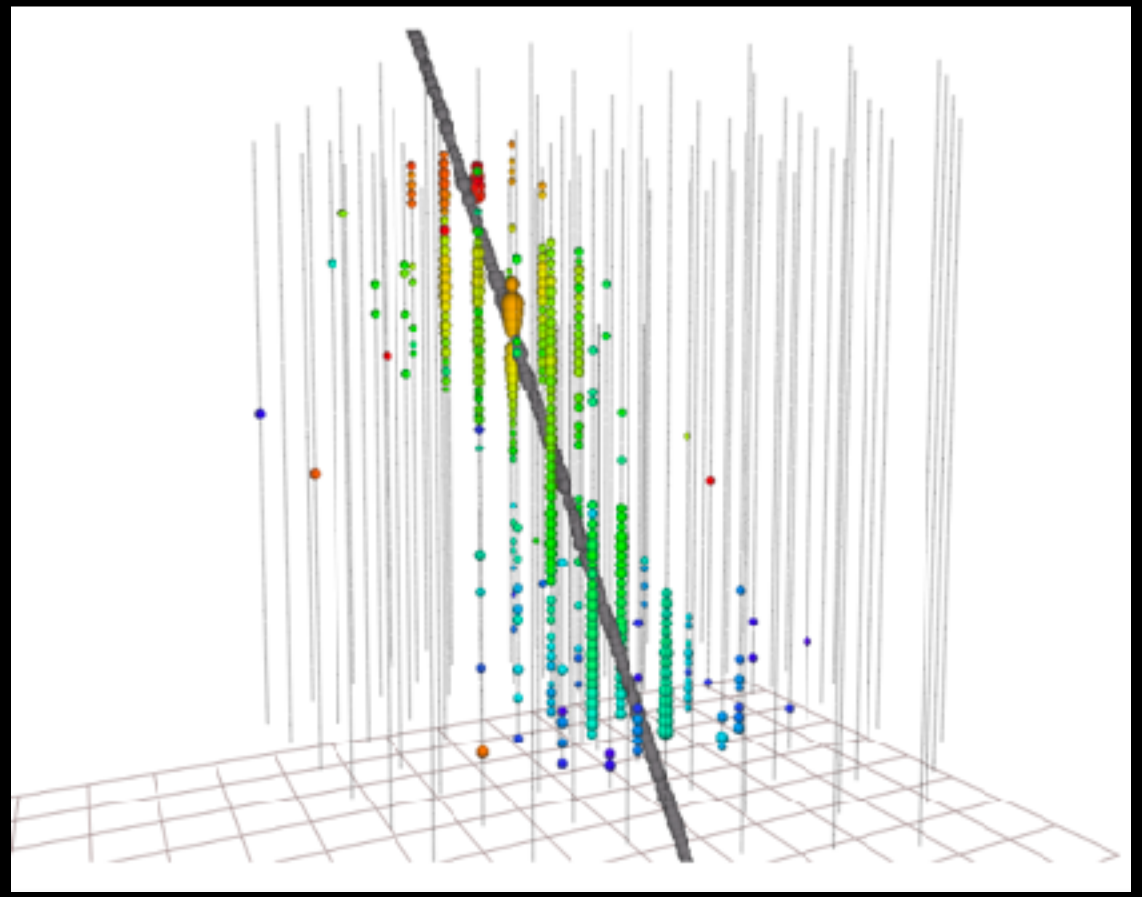
HOW DOES ICECUBE OBSERVE HE NEUTRINOS?

CHERENKOV LIGHT FROM SECONDARIES



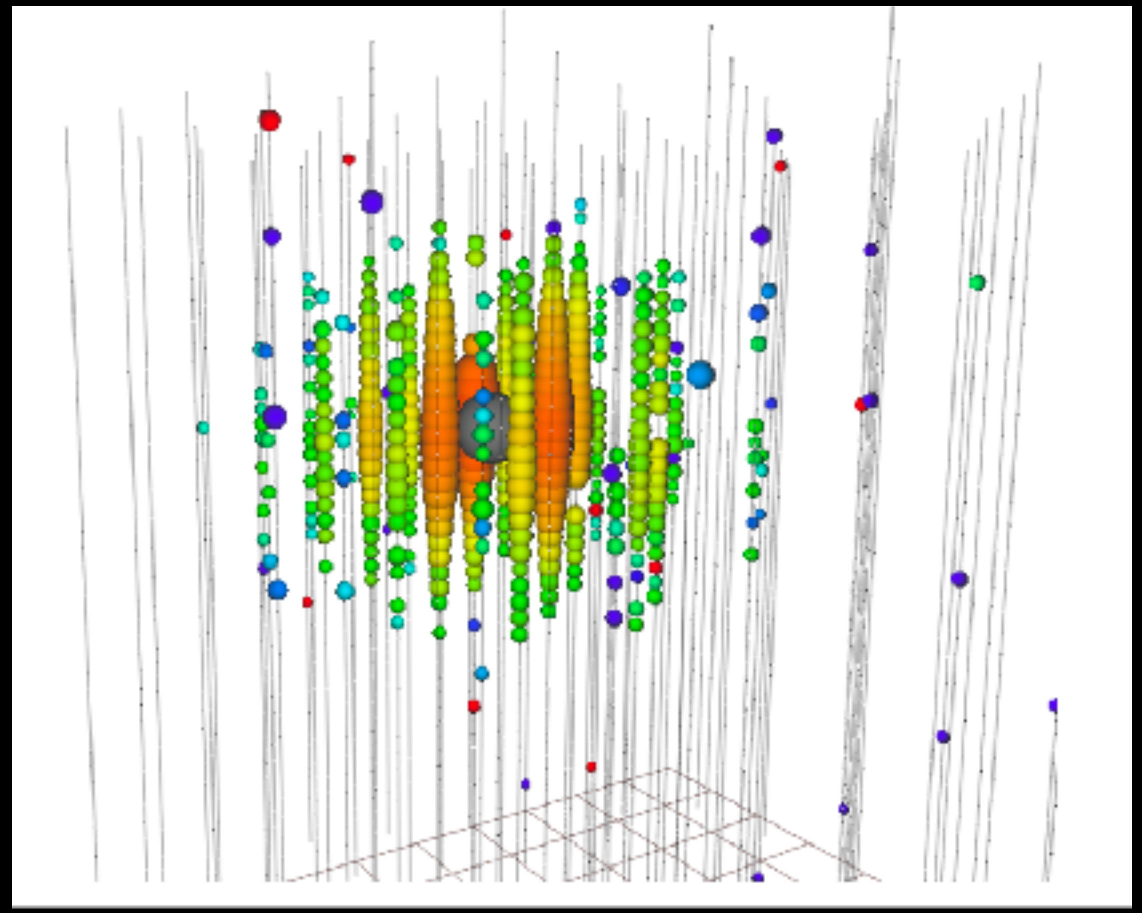
There are 2 event topologies

TRACKS



- CC: $\nu_\mu + N -> \mu + X$
- Good angular resolution (~0.5°)
- Can be difficult to estimate neutrino energy

CASCADES



- CC: ν_e, ν_τ
- NC: ν_e, ν_τ, ν_μ
- Good energy reconstruction
- Not the best angular resolution (~few degrees)

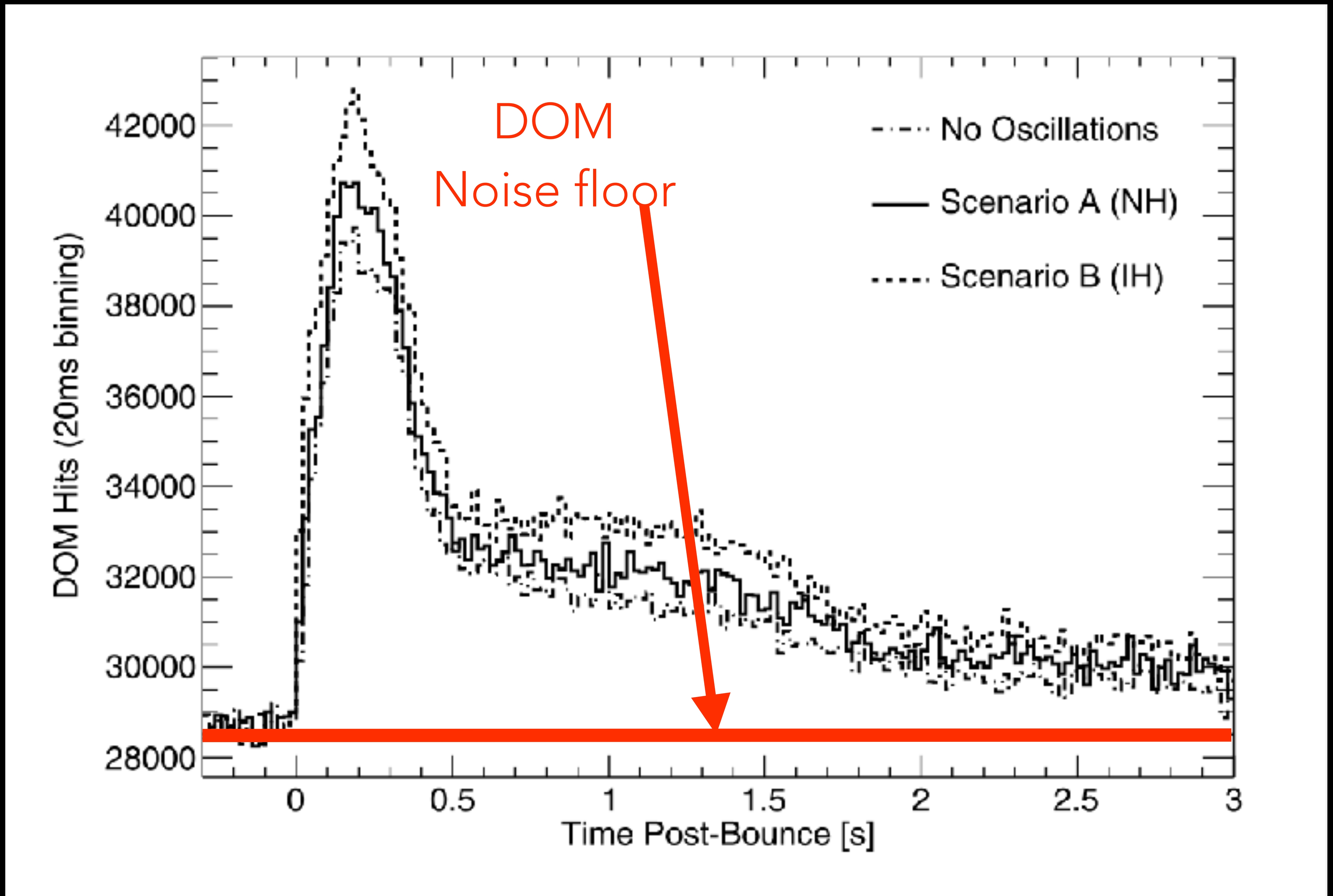
HOW DOES ICECUBE LOW ENERGY NEUTRINOS? OBSERVE NEUTRINOS?

Dominant: Inverse beta decay

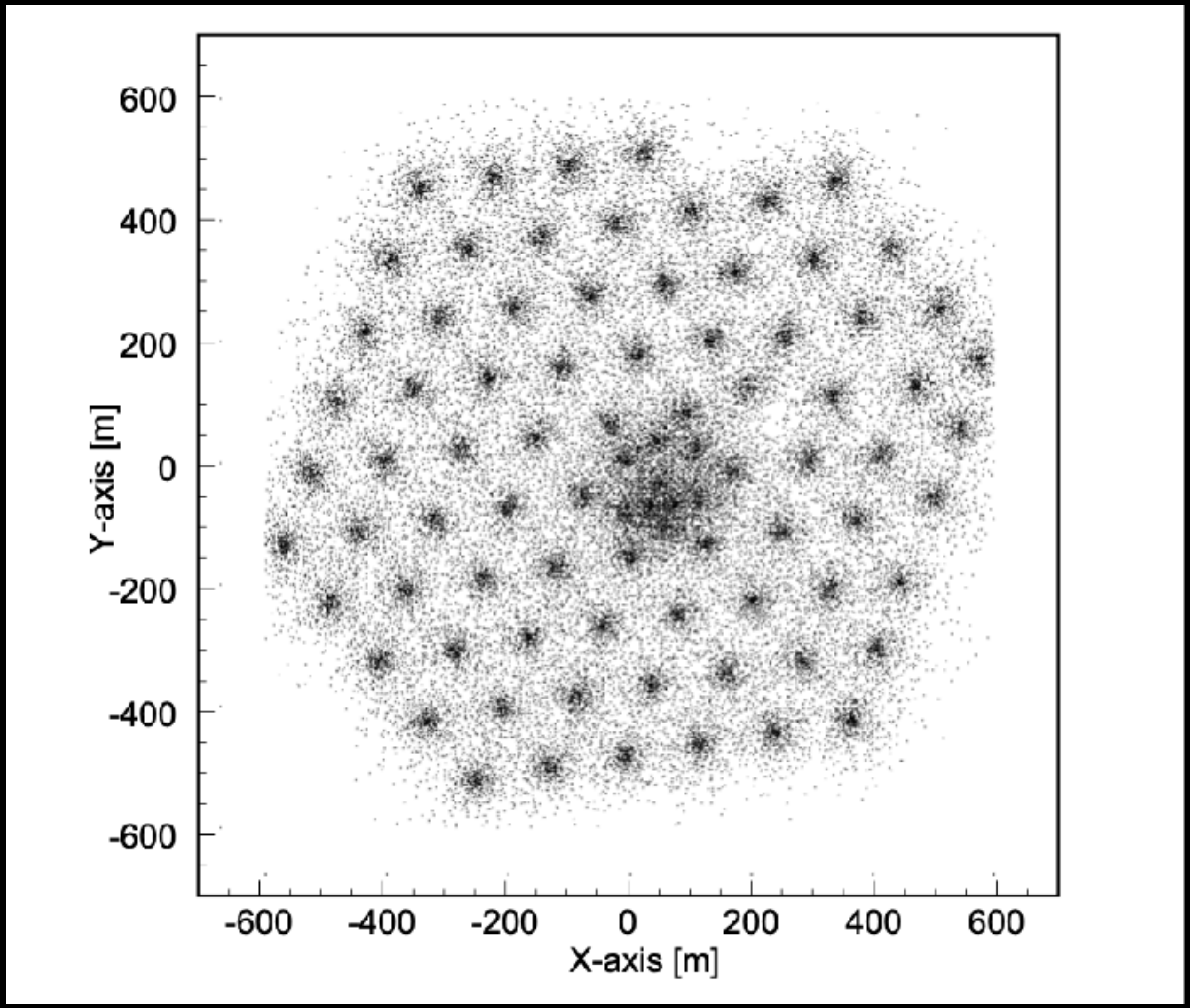
$\bar{\nu}_e + p -> n + e^+$

Very small contribution elastic scattering

Track length for e^+ —> $0.5\, cm \cdot \frac{E_\nu}{MeV}$



Expected DOM noise rate change for a galactic SN (d~10 kpc)

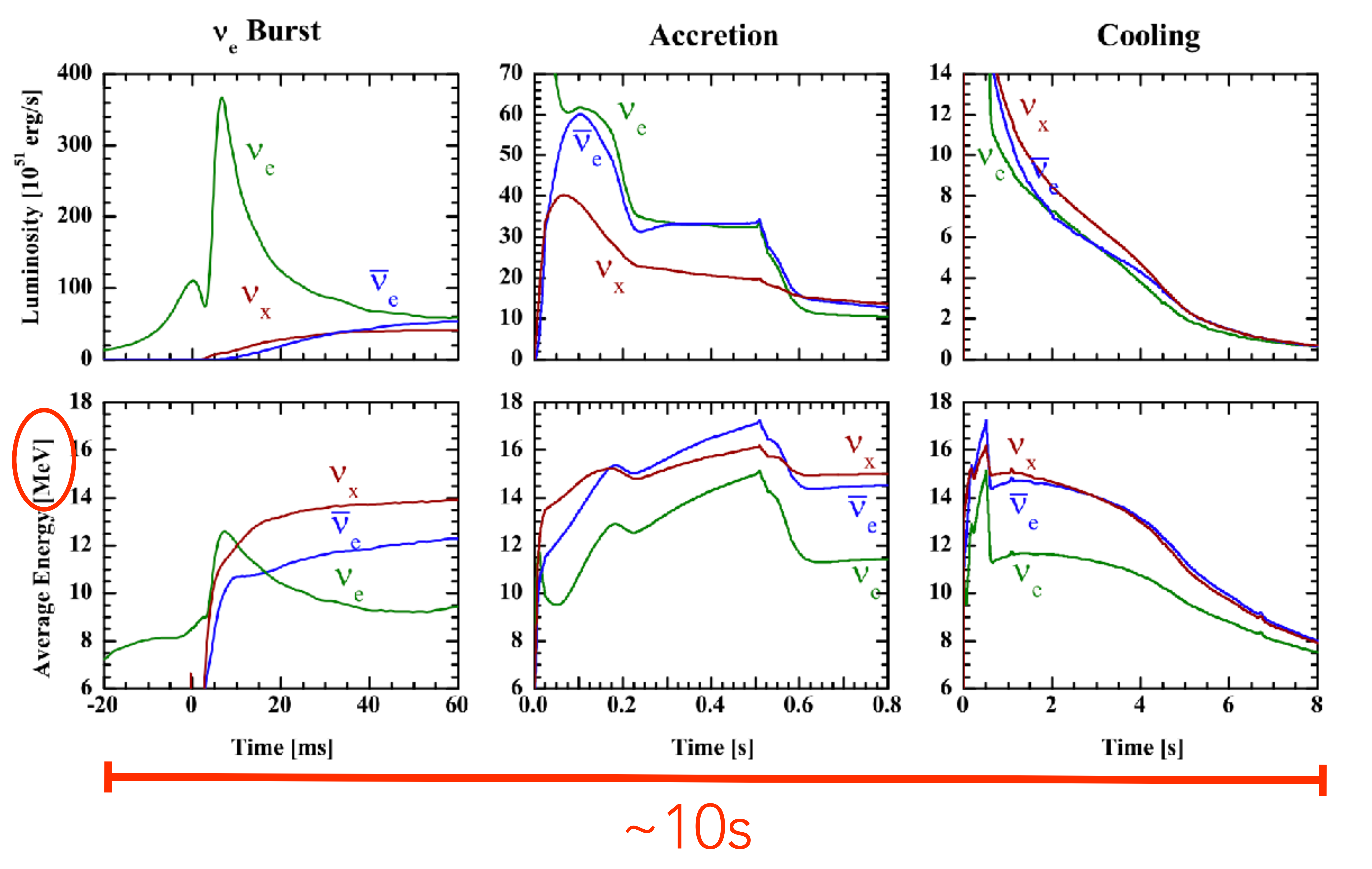


LOW ENERGY NEUTRINOS

Neutrinos emitted by SN ~ 10^{58} neutrinos

IceCube observes $\bar{\nu}_e$

Oscillations will affect the spectra that IceCube observes



WHY NEUTRINOS?

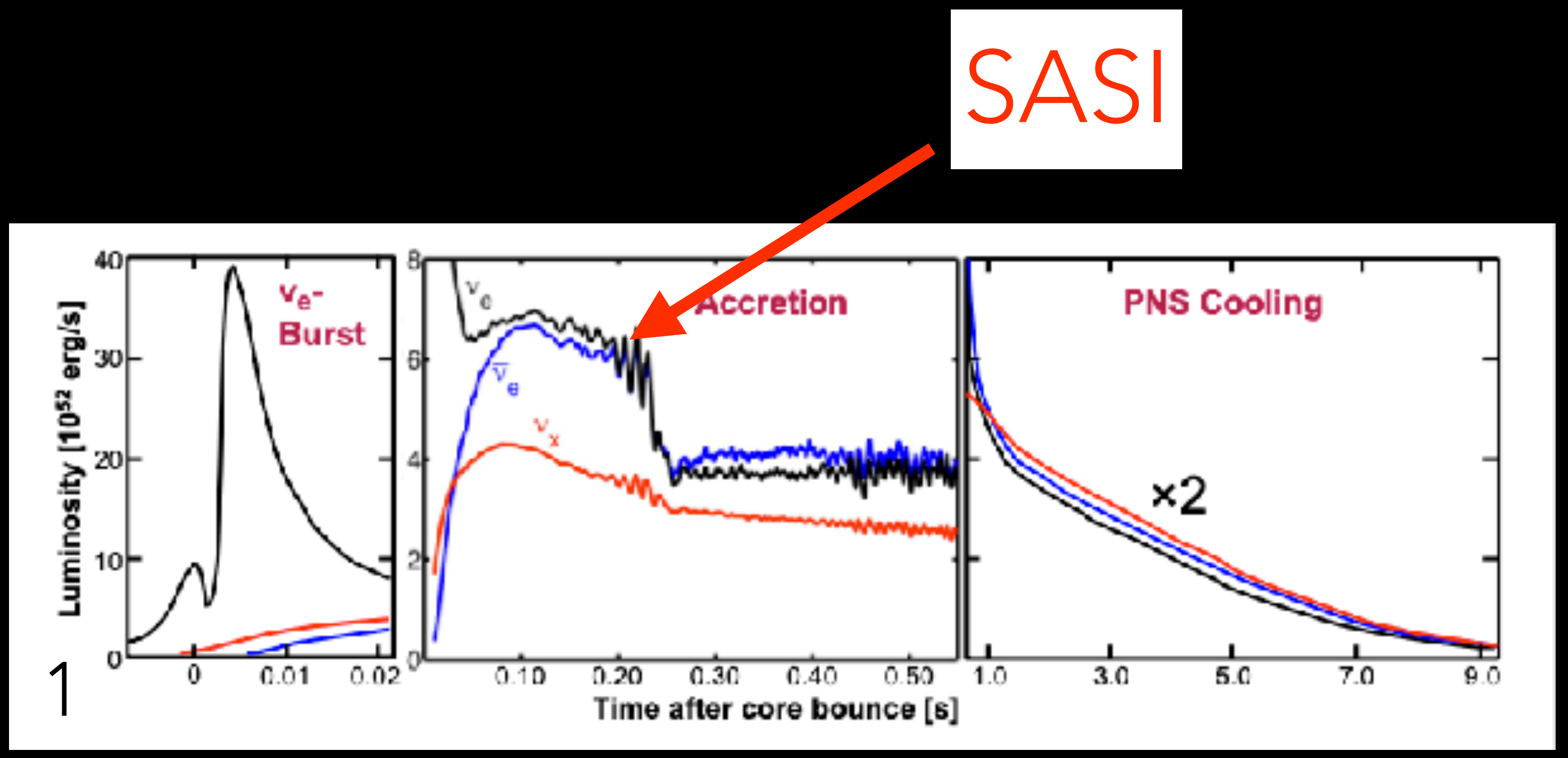
ν Production

O(10)MeV → Post-explosion **TeV**

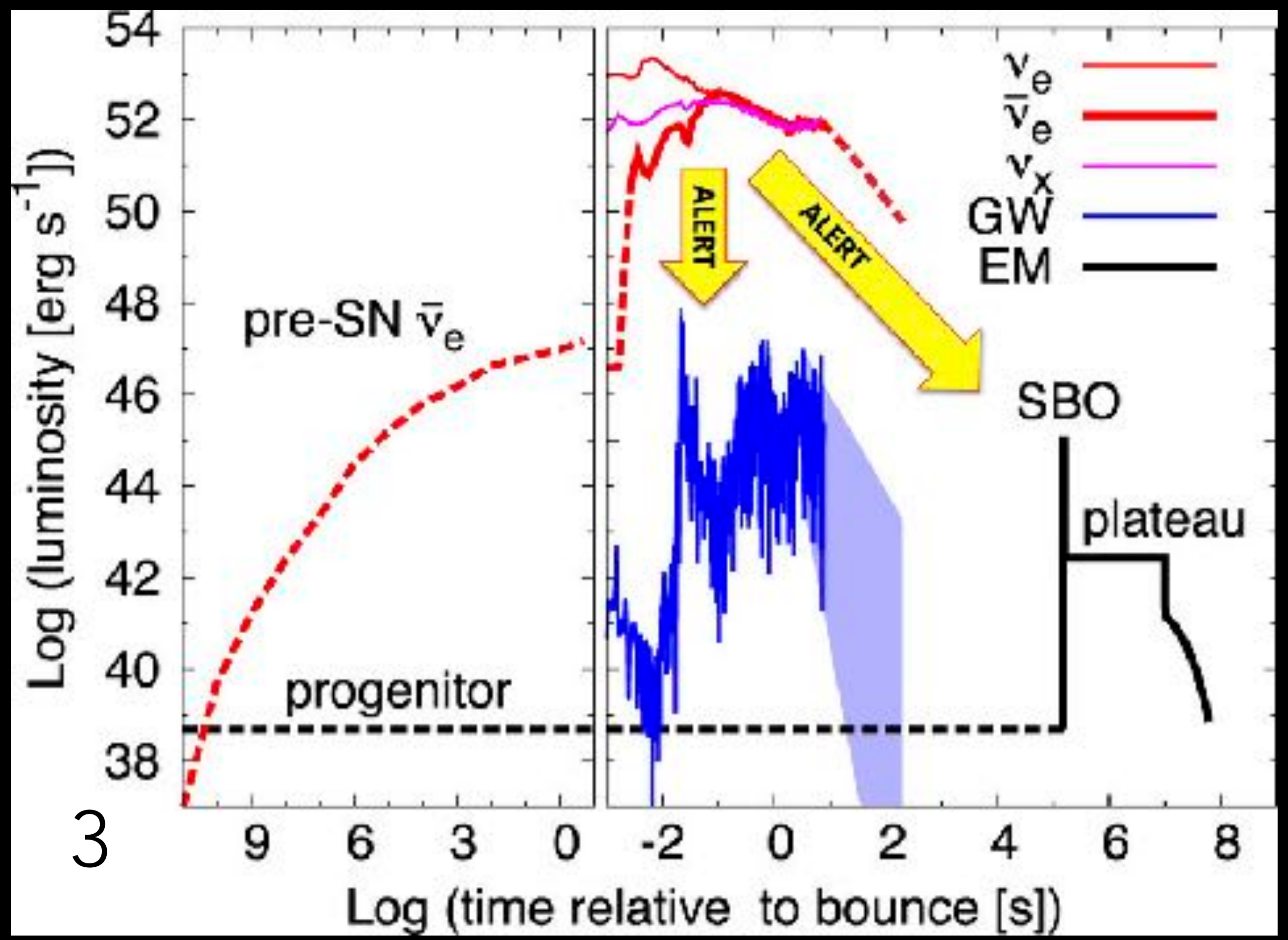
O(10 s) — O(days-years)

Explosion driven mechanism.
99% of E_{kin} released as MeV ν

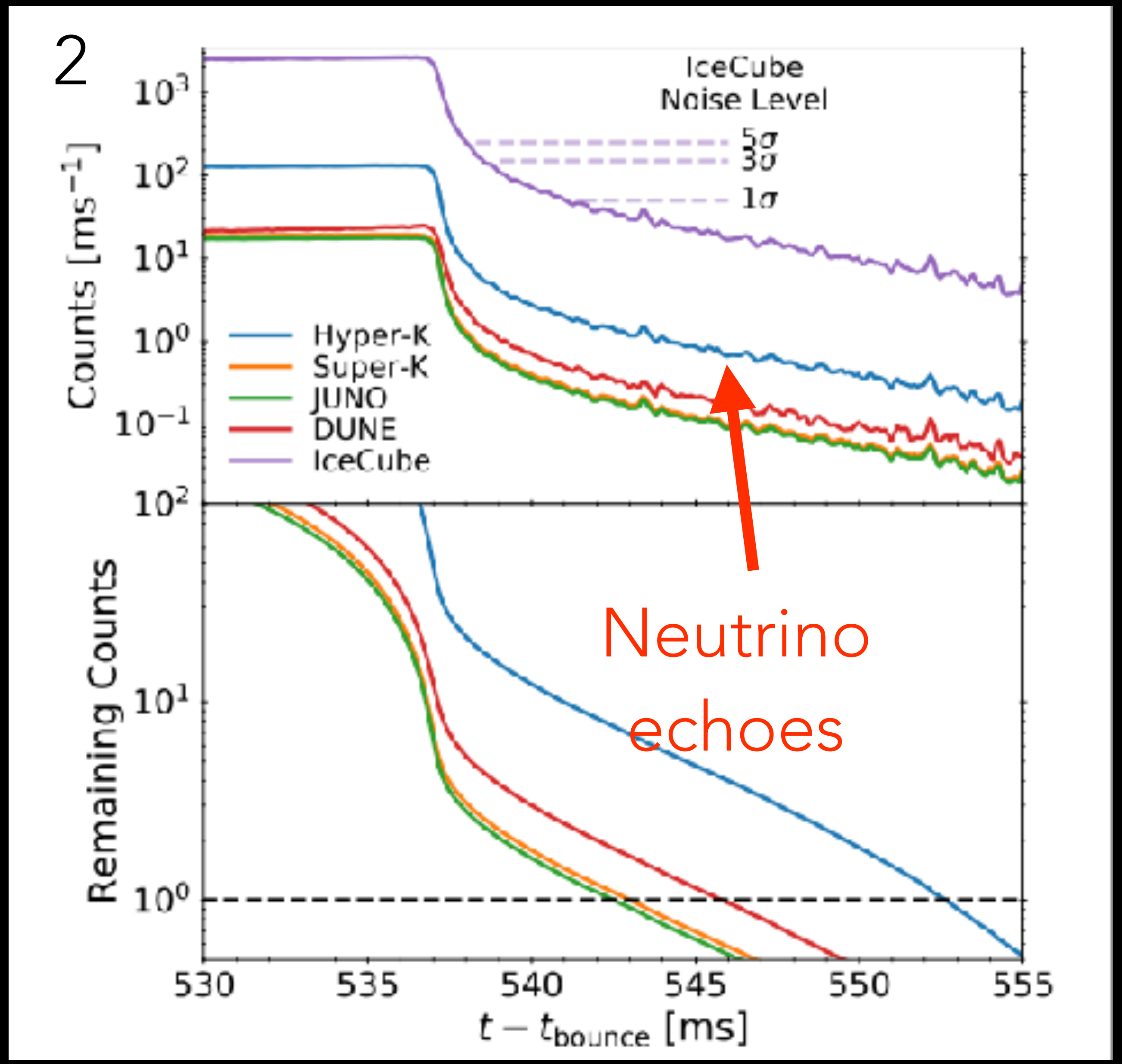
Probing with neutrinos will give us insight on the explosion mechanism



Can provides us with an early warning prior to EM emission



In case of a black-hole formation, no EM emission will be emitted, but neutrinos can escape



1: H. -Th. Janka https://arxiv.org/abs/1702.08713
2: S. Gullin, E.P. O'Connor, J. -Sh. Wang & J. Tseng (2022) ApJ, 926, 2
3: S. Al Kharusi el at. (2021), New J. Phys., 23

TYPES OF SUPERNOVAE

- To categorize supernovae, we need both the spectra and the light curve.
- The spectra gives us the presence of elements that helps us categorise the type of supernovae, but the light curve gives us information on the subtype of supernovae.