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EXTERNAL ALERT RESPONSE WITH ICECUBE MEV NEUTRINO DATA

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MOTIVATION

CORE-COLLAPSE SUPERNOVAE

Neutrino emission duration ~ 10 s

Many candidates for burst of MeV neutrinos
and other messengers (GW and EM)

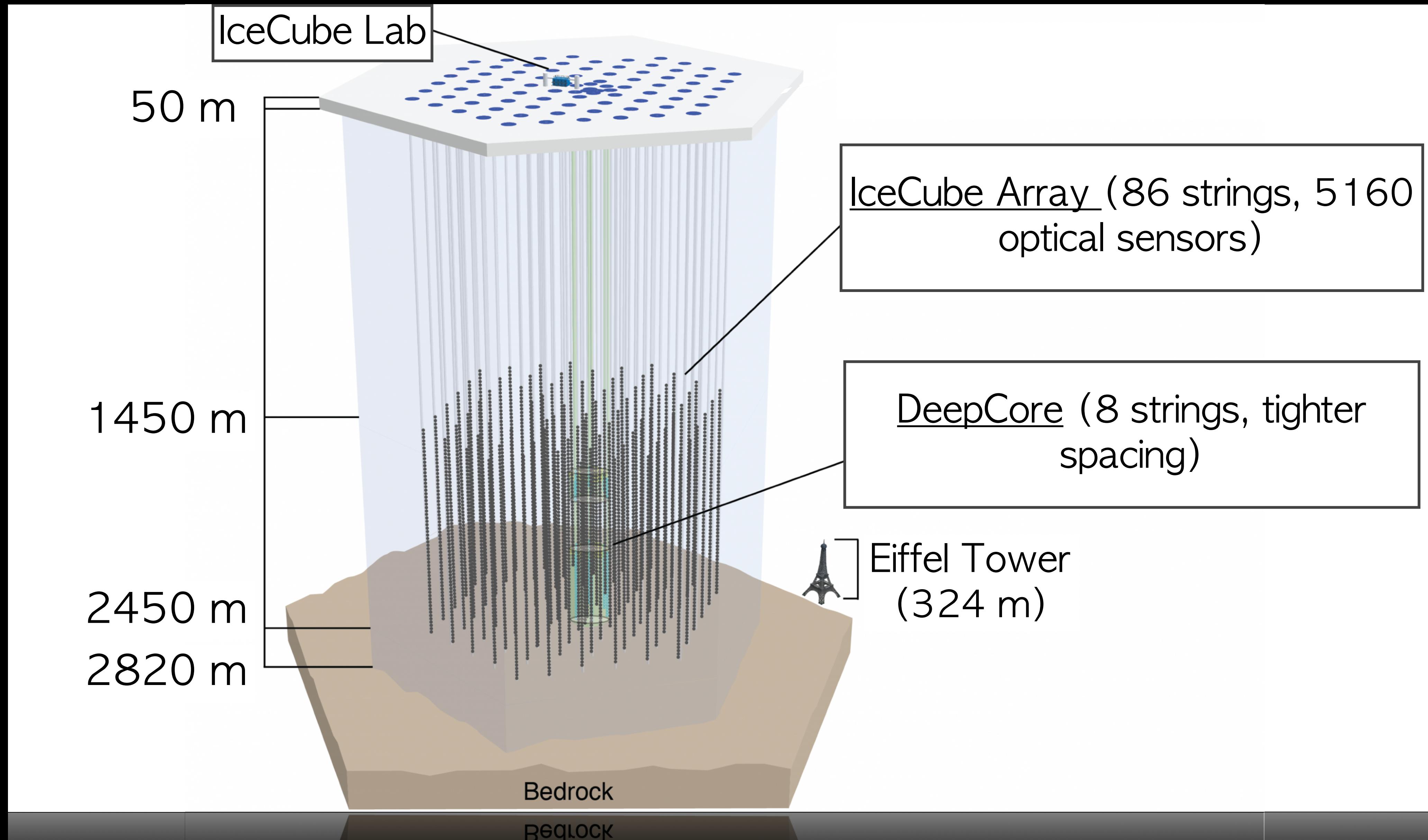
BINARY NEUTRON STAR MERGERS

NEUTRON STAR - BLACK HOLE MERGERS

Neutrino emission duration \sim ms to s

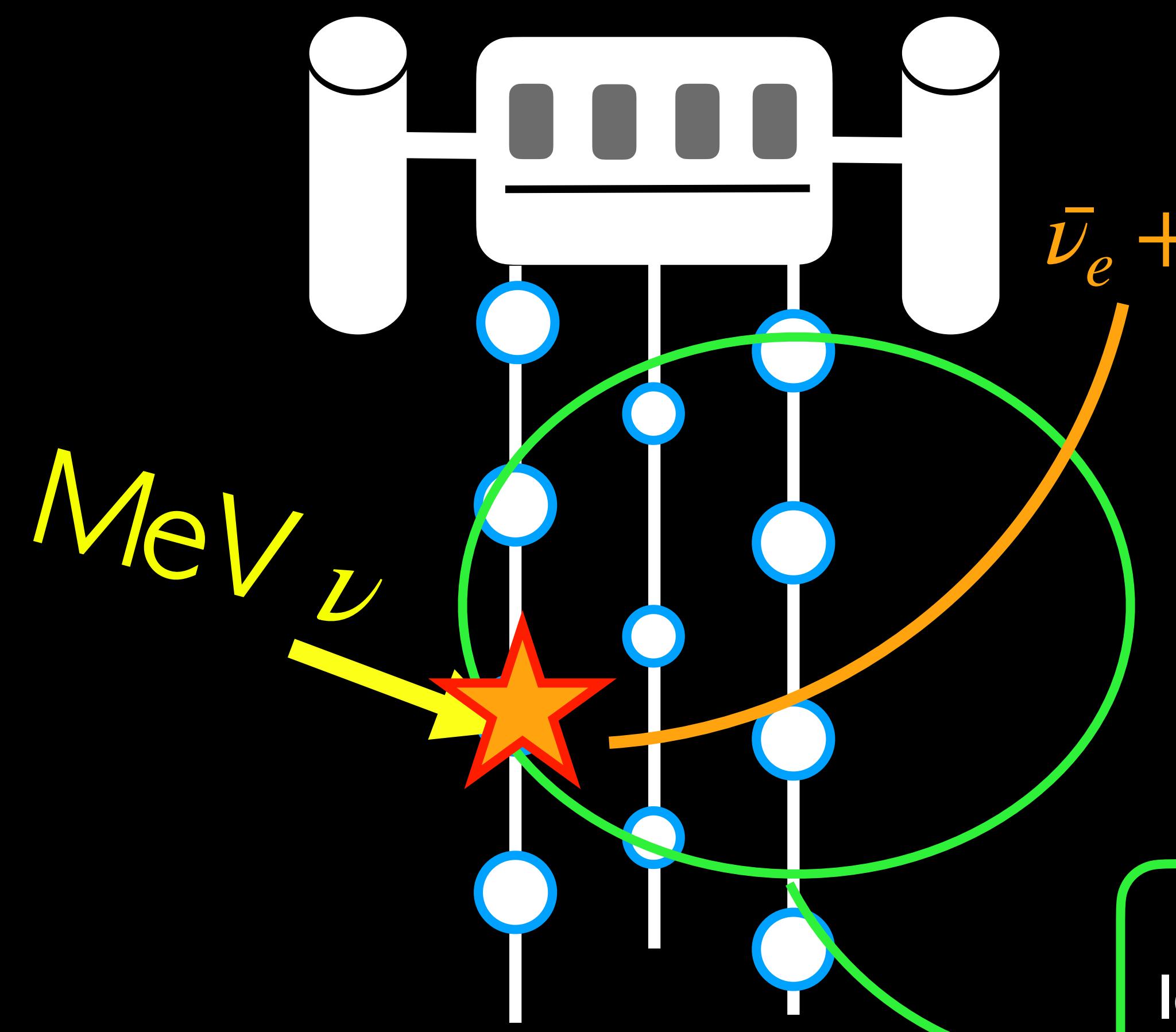
MeV ν can help us understand core dynamics from supernovae
and merger processes

ICECUBE NEUTRINO OBSERVATORY

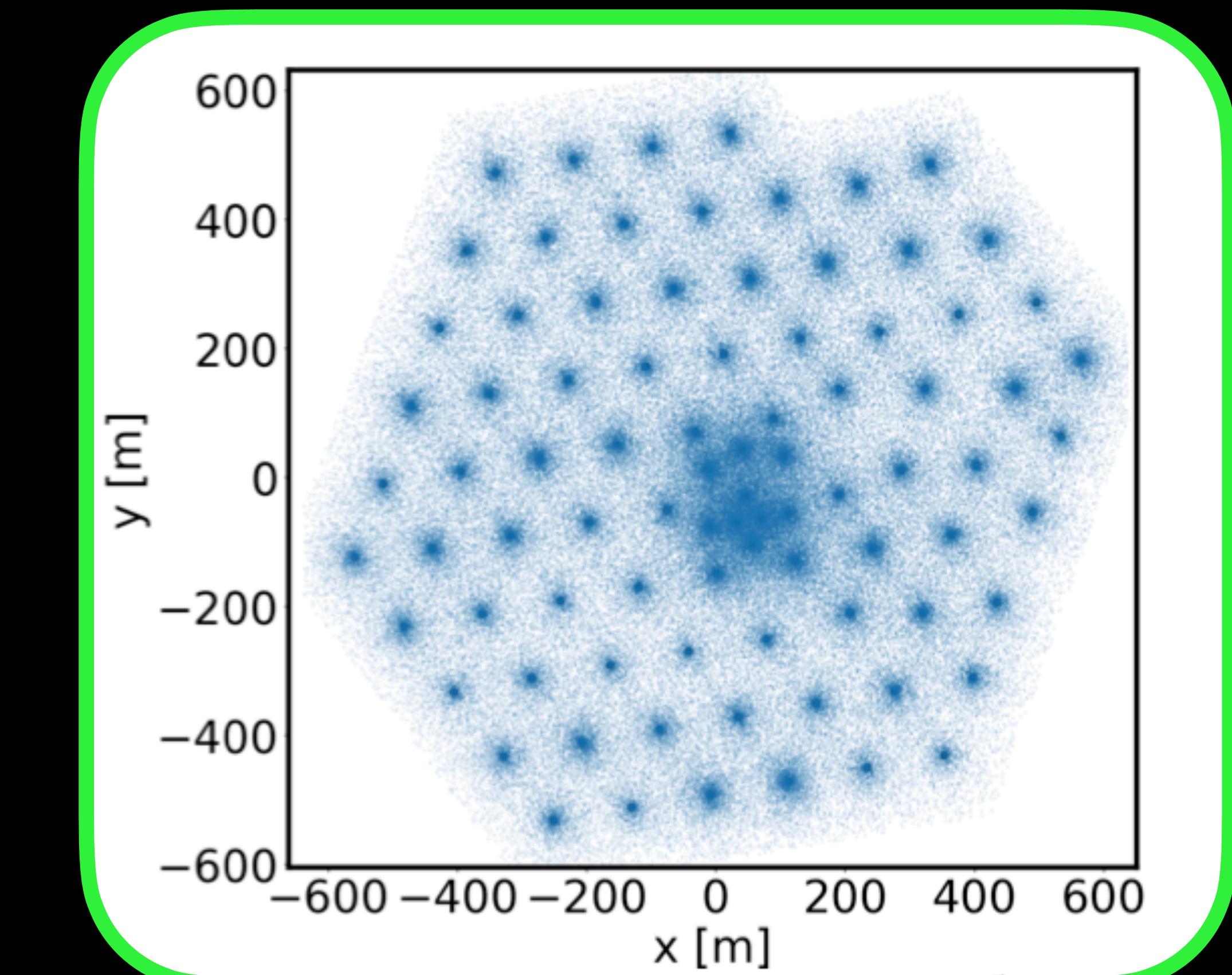


ICECUBE NEUTRINO OBSERVATORY

See Jakob Beise's talk (neutrino physics & astrophysics session 7A)

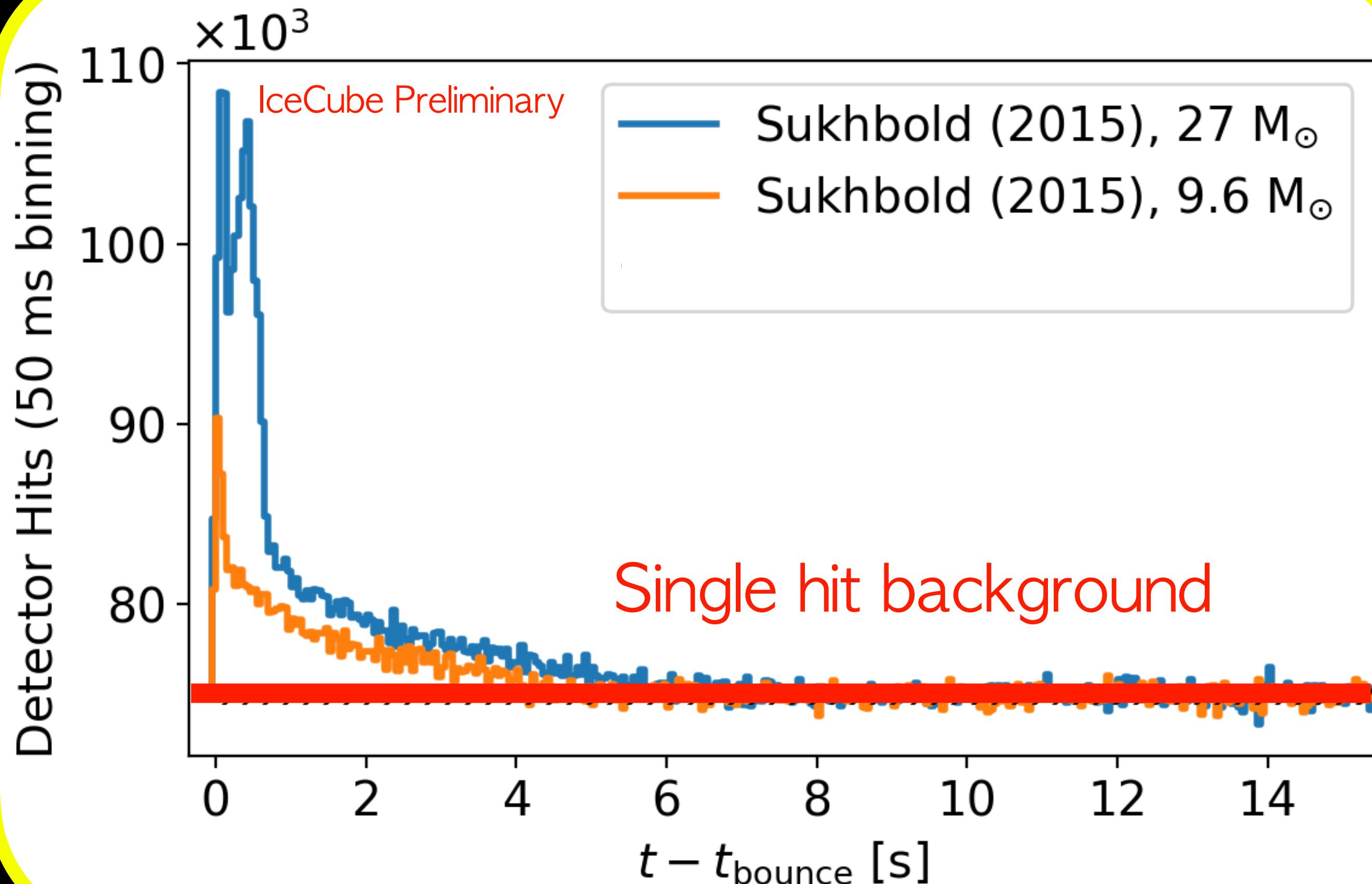


Short track
length + sparse
detector array



Simulation of single hits observable
in the array

SUPERNOVA DATA ACQUISITION SYSTEM



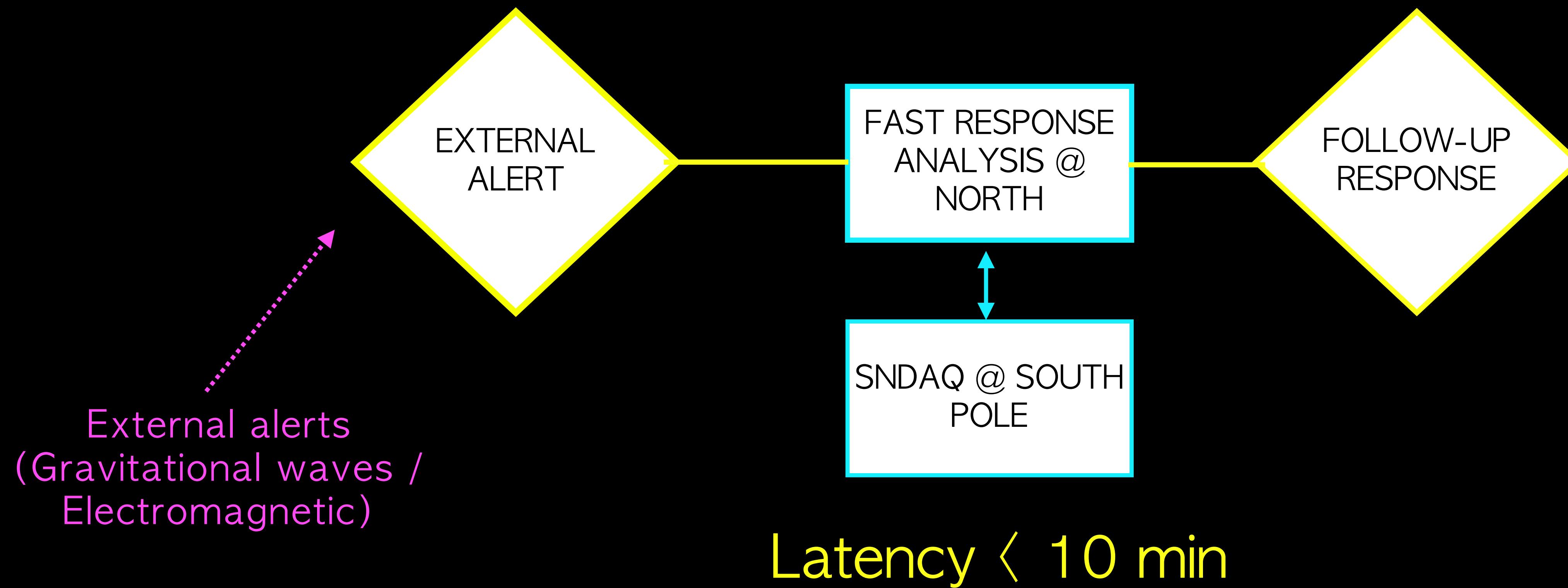
- A signal will be detectable when considering the rate increase in the entire array
- The Supernova Data Acquisition ([SNDAQ](#)) continuously monitors the detector rate, searching for a significant deviation from background for galactic supernovae or very bright extragalactic transients.

Jakob Beise (TAUP 2023 neutrino physics & astrophysics session 7A)

MEV NEUTRINO ALERT RESPONSE

Currently: we cannot use external information to trigger SNDAQ*

New framework will enable external SNDAQ triggering for IceCube's MeV neutrino data response, expanding to IceCube's full energy sensitivity, enhancing multi-energy and multi-messenger analyses.



*Currently we have offline access to MeV data for follow-up with a latency of 24-72 hrs

MEV NEUTRINO ALERT RESPONSE

Target

This framework will respond gravitational wave alerts classified as **bursts** (supernova candidates) and **mergers** involving a neutron star

Expected Frequency of LVK alerts

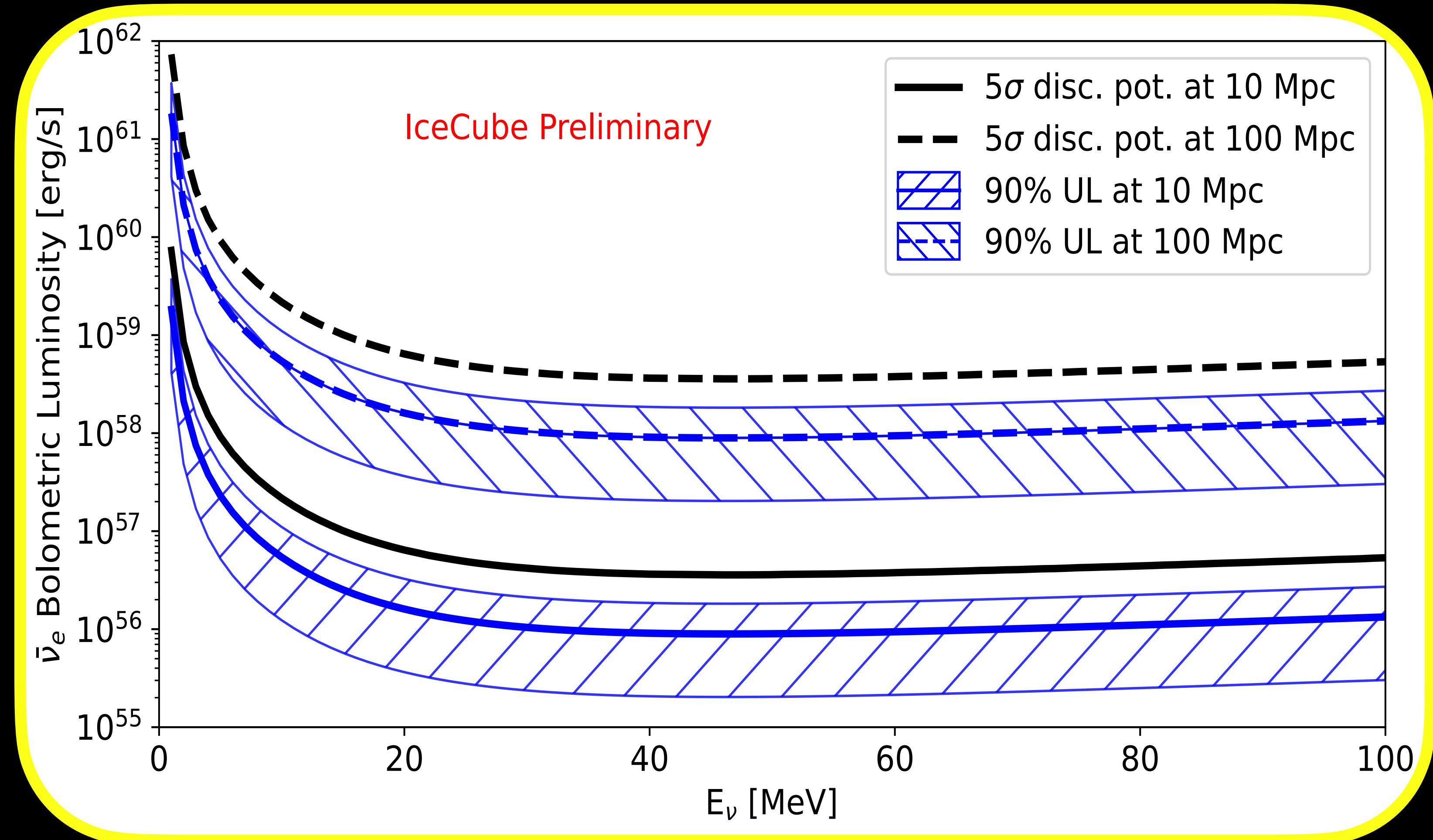
LVK RUN O4 Yearly
Expectation

36^{+49}_{-22} BNS / 6^{+11}_{-5} NSBH /
few bursts per year

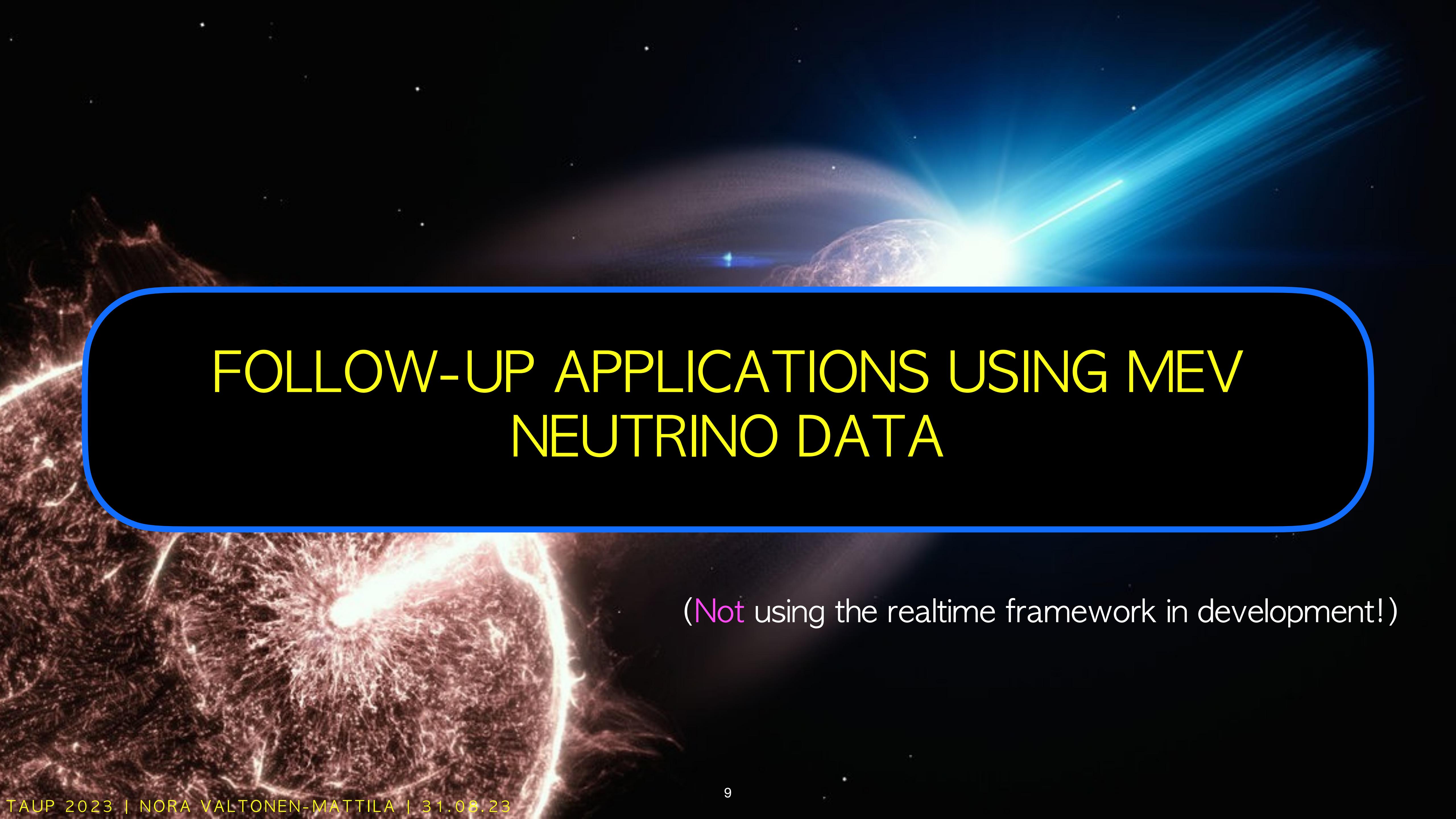
The system can also be employed for prompt responses to other alerts involving objects that are potential candidates for MeV neutrino production

SENSITIVITY AND DISCOVERY POTENTIAL

IceCube has sensitivity to **bright** extragalactic transients



Average supernova luminosity : $\sim 10^{52} - 10^{53}$ ergs



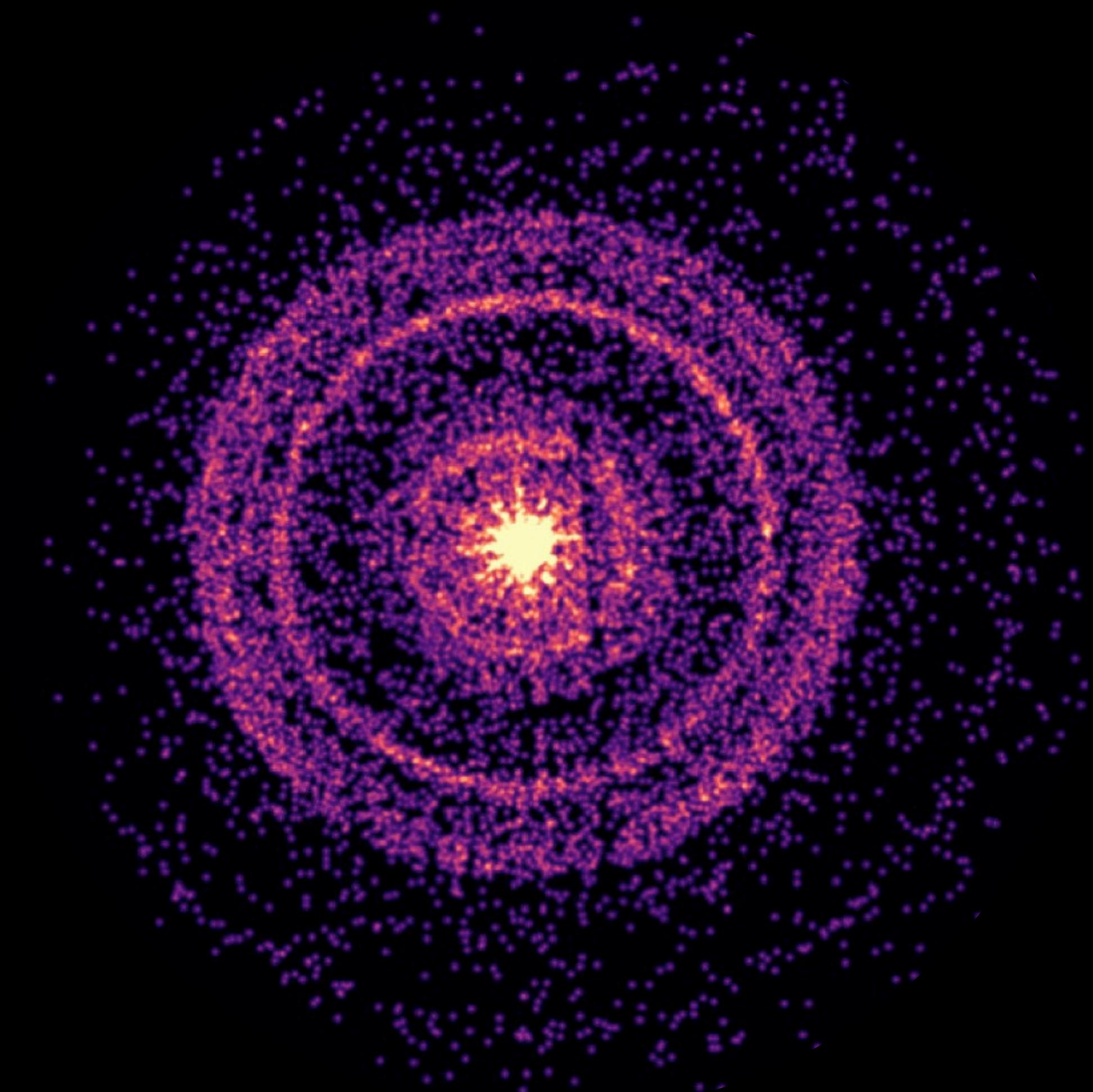
FOLLOW-UP APPLICATIONS USING MEV NEUTRINO DATA

(Not using the realtime framework in development!)

GRB 221009A

- First detected by GBM (Fermi gamma ray satellite) on the 9th of October 2022.
- One of the brightest gamma ray burst (GRB) and first $>\text{TeV}$ γ -rays detected. Bursts this bright occur only once every 10,000 years!
- Very close GRB (≈ 740 Mpc), or about 20 times closer than average GRB.

Given that GRBs can coincide with supernovae and can involve accretion disks around black holes, they possess the potential to generate MeV neutrinos



X-ray image of GRB 221009A emission scattering off dust
(Williams et al. 2023)

MODELS FOR MEV NEUTRINOS IN GRB'S

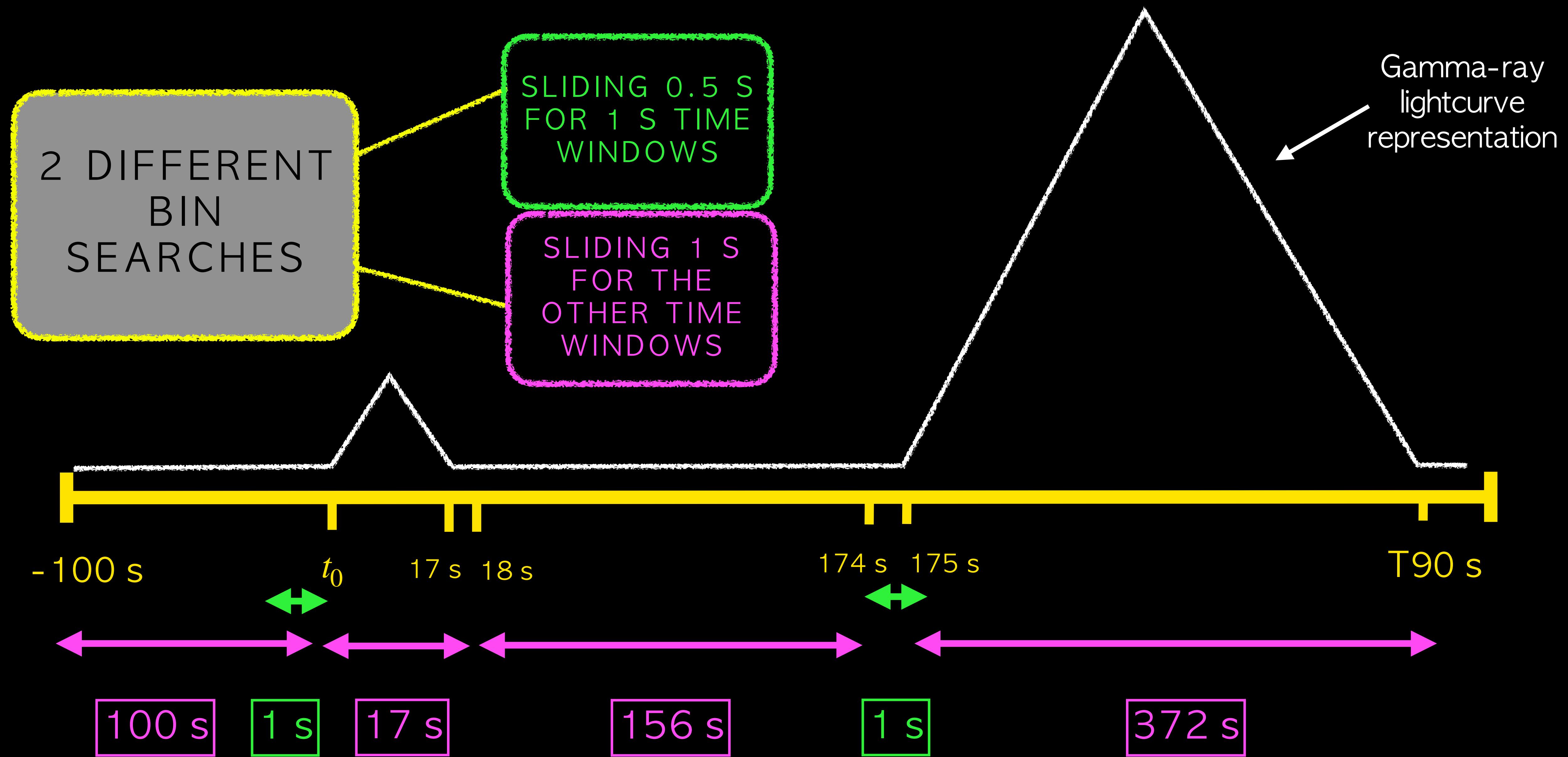
- Prior to gamma emission: CCSN neutrinos and fireball production of thermal neutrinos
- Prior and simultaneous to gamma emission: MeV neutrino production via Neutrino Dominated Accretion Flows

References, see: Wang et al. In: ApJ (2007), 664, 1026-1032, Modjaz et al. In: Nat Astron (2019), 3, 717-724, Wang & Mészáros In: ApJ (2007), 670, 1247, Morsony et al. In: ApJ (2007), 665, 569, Liu et al. In: Phys. Rev. D (2016), 93, 123004, Liu et al. In : New Astron. Rev. (2017), 79, 1-25, <https://iopscience.iop.org/article/10.3847/1538-4357/ab2187>, Halzen & Jaczko In: Phys. Rev. D (1996), 54, 2779

Methodology

1. Select search windows / bin size based on physics motivation (from models)
2. Characterize the background through trials on off-time data
3. Perform observation on on-time data
4. Place upper limits if results are not significant

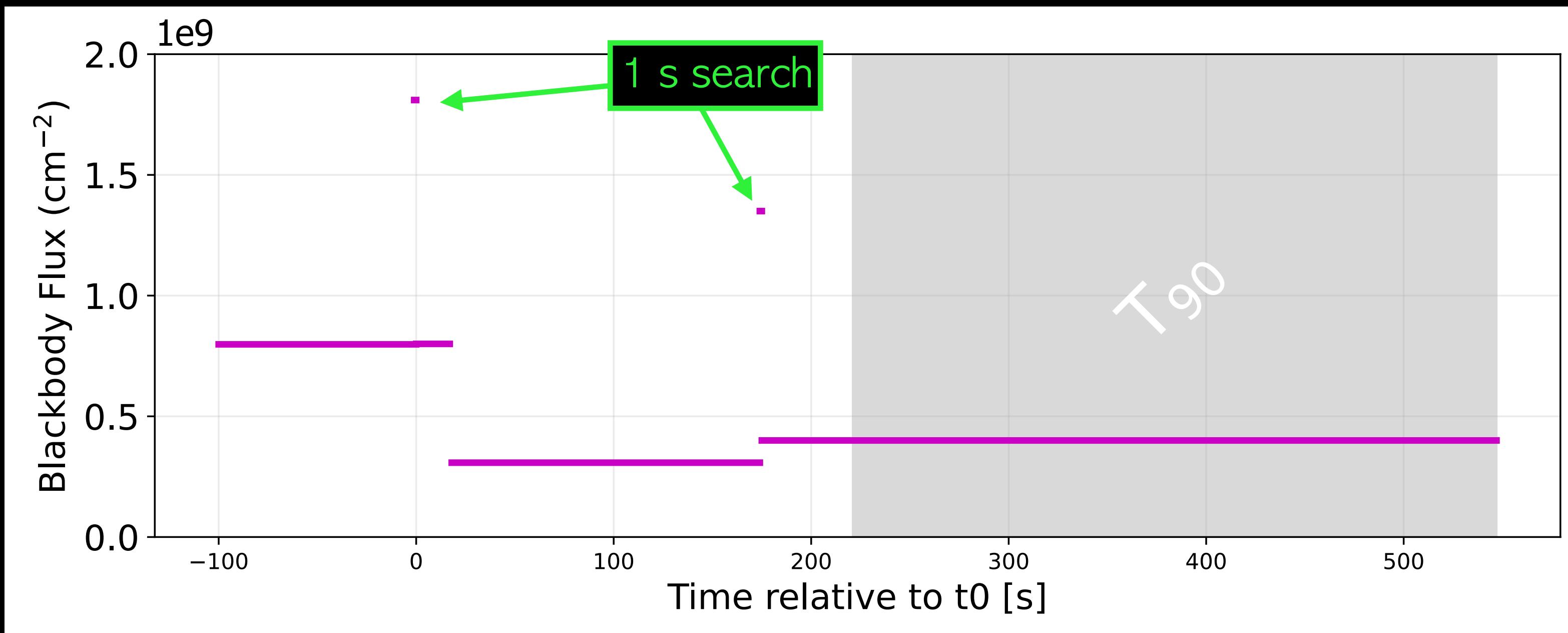
SEARCH WINDOWS FOR GRB 221009A



GRB 221009A RESULTS: UPPER LIMITS

Results

- We found no indication of MeV ν emission above background expectation (p-values > 0.3)
- Therefore we set upper limits



Publication: R. Abbasi et al 2023 ApJL 946 L26

CONCLUSIONS

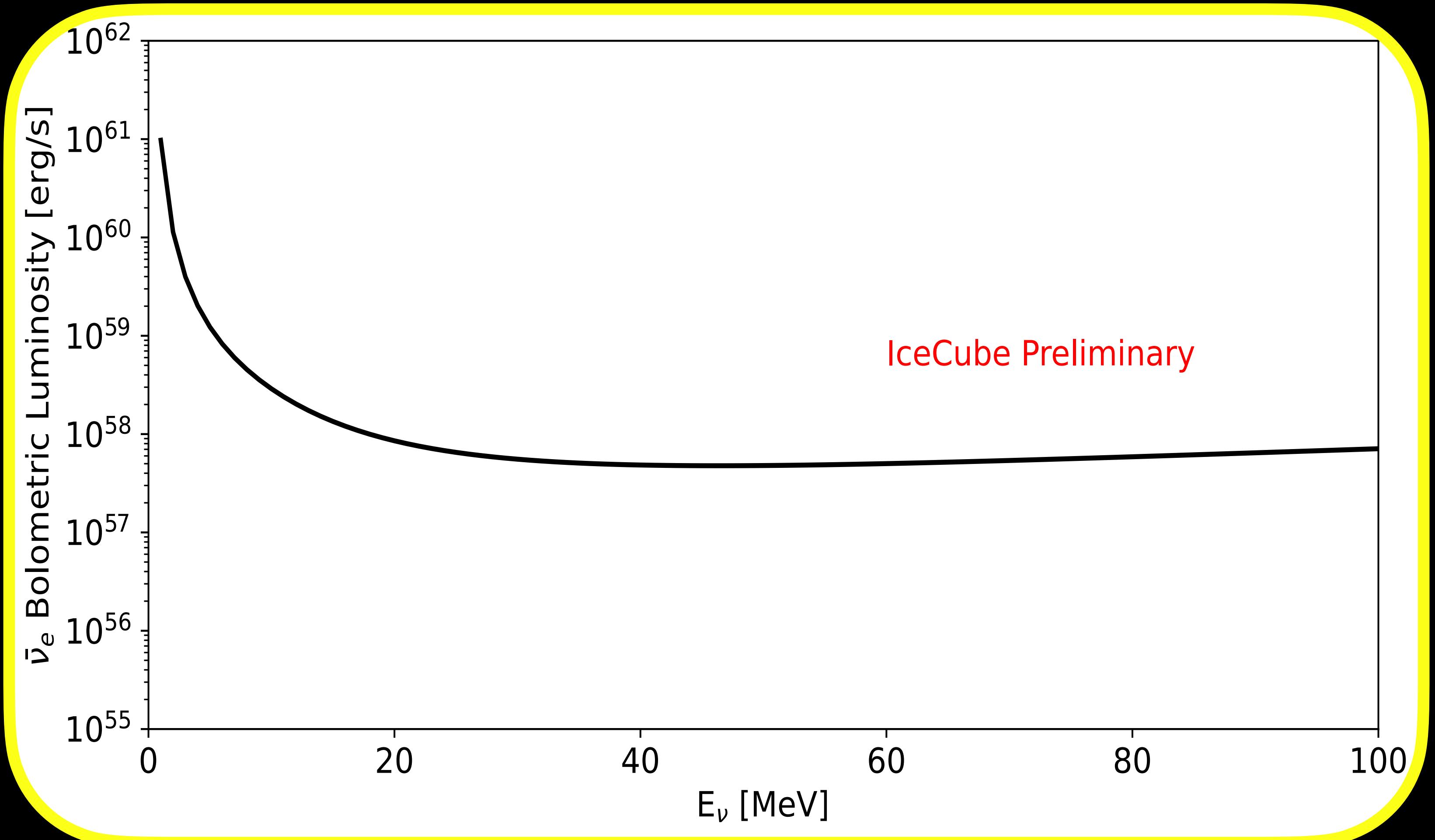
- IceCube's [low-energy](#) (MeV) neutrino data stream allows for a wide range of analyses of cataclysmic transients.
- Core-collapse supernovae and neutron star mergers are among the sources that can produce thermal neutrinos along with other messengers, such as [gravitational waves](#) and electromagnetic emission.
- [SNDAQ](#) handles the online data stream and analysis of low-energy neutrinos, forming the foundation for the fast response analysis system.
- The [upcoming](#) fast response system will allow for prompt responses to gravitational wave alerts and other external alerts.
- The analysis of GRB 221009A is a prime example of the applications of the [low-energy](#) neutrino data stream and potential follow-up objects with the realtime system.



THANK YOU!

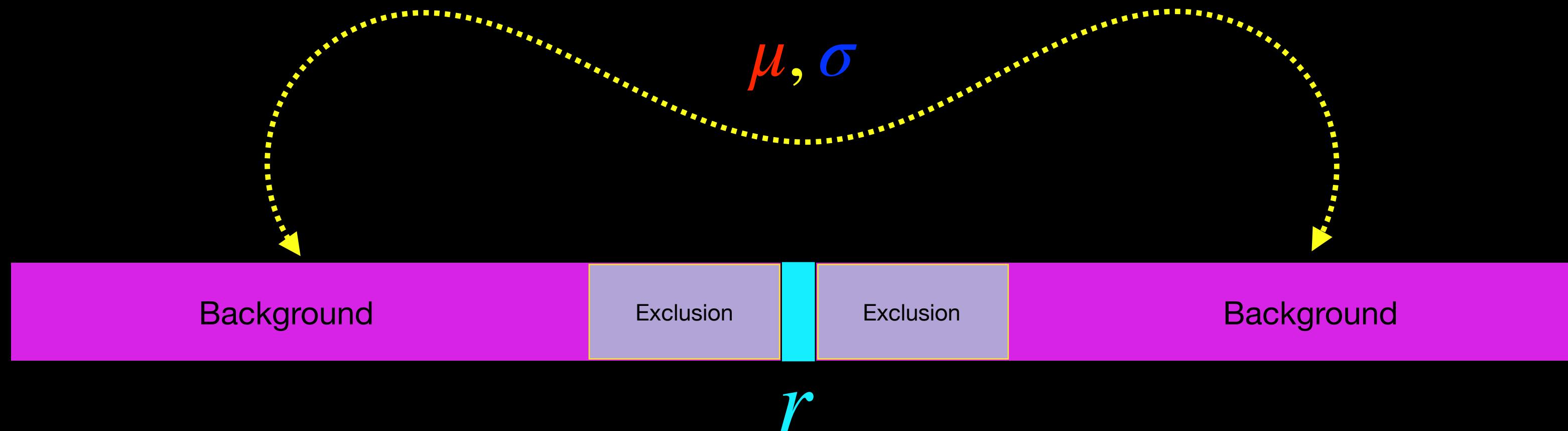
SN 2023IXF: UPPER LIMITS

Closest SN in past
five years!



SNDAQ ANALYSIS

SNDAQ monitors in realtime for a rate increase $\Delta\mu$ in the detector by comparing the search bin r to background μ mean and σ standard deviation.



$$\Delta\mu = \sigma_{\Delta\mu}^2 \sum_{i=1}^{N_{DOM}} \frac{\epsilon_i(r_i - \mu_i)}{\langle \sigma_i \rangle^2}$$

$$\sigma_{\Delta\mu}^2 = \left(\sum_{i_1}^{N_{DOM}} \frac{\epsilon_i^2}{\langle \sigma_i \rangle^2} \right)$$

A test statistic ξ is obtained, telling us how significant the detector rate deviation is.

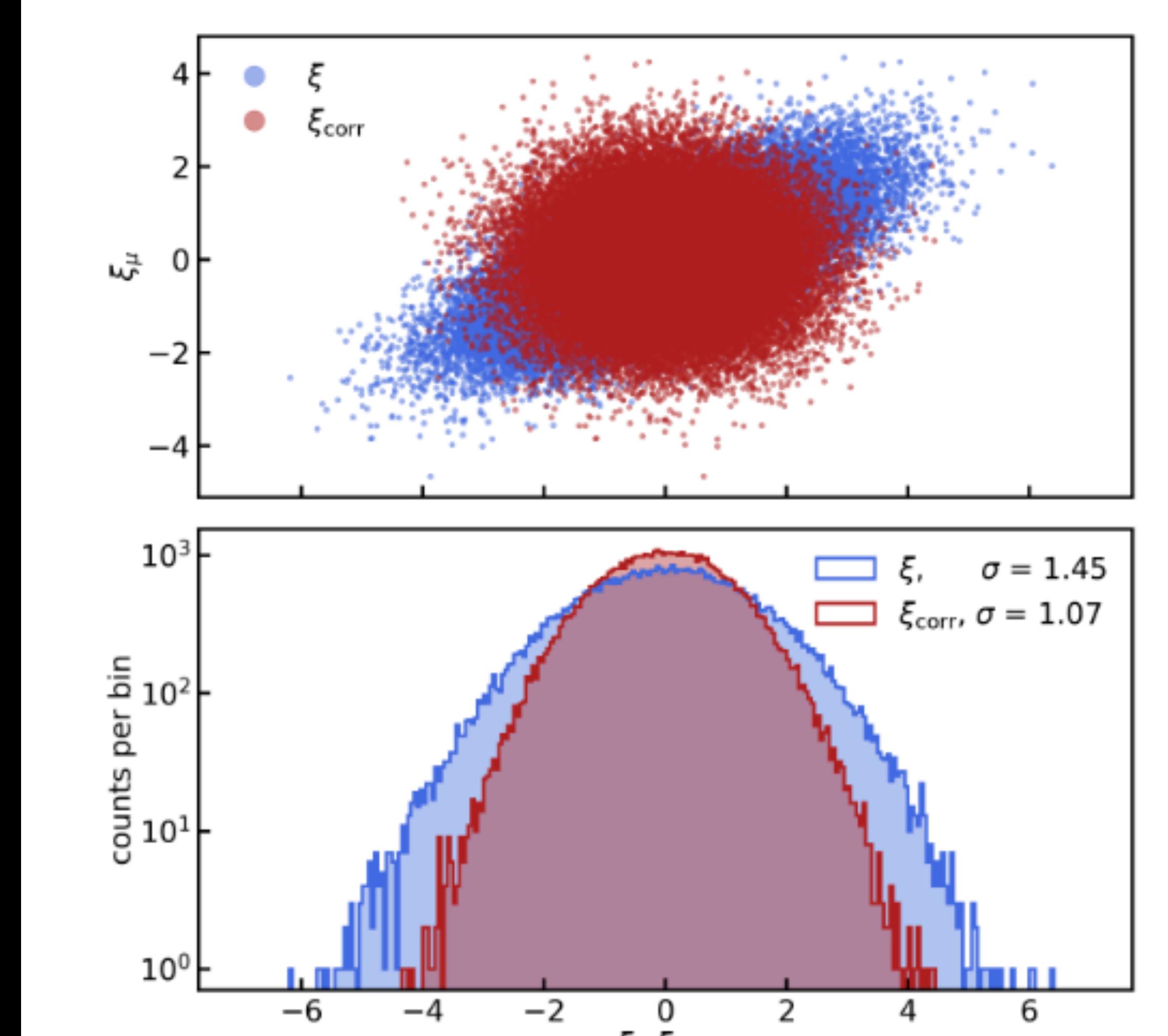
$$\xi = \frac{\Delta\mu}{\sigma_{\Delta\mu}}$$

MUON RATE / SIGNIFICANCE OF ALERT

Background sources: Atmospheric muons, thermal noise, radioactive decay

- First pass noise reduction: since a large fraction of the noise can be approximated to a Poissonian distribution, we apply a deadtime at the data acquisition stage.
- Second pass noise reduction: Since we are still left with noise, we apply a correction to our test statistic to remove the atmospheric muon contribution at the time of the trigger, which narrows the distribution.

Significance of alert: Using the distribution of our test statistic, we can determine whether the triggered search is significant or not

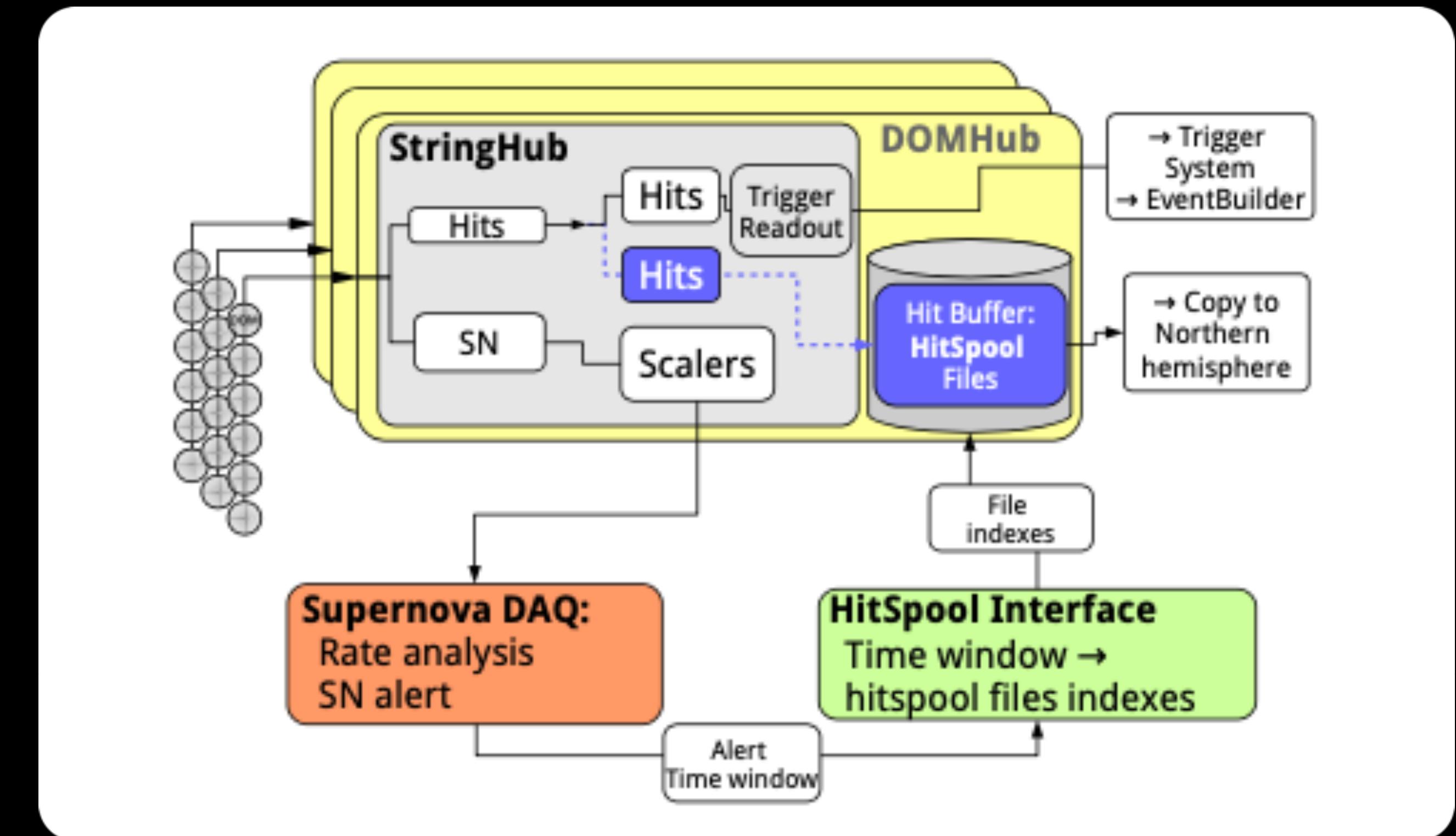


Credit: R. Abbasi+, IceCube Collaboration (submitted)

SUPERNOVA HITSPPOOL

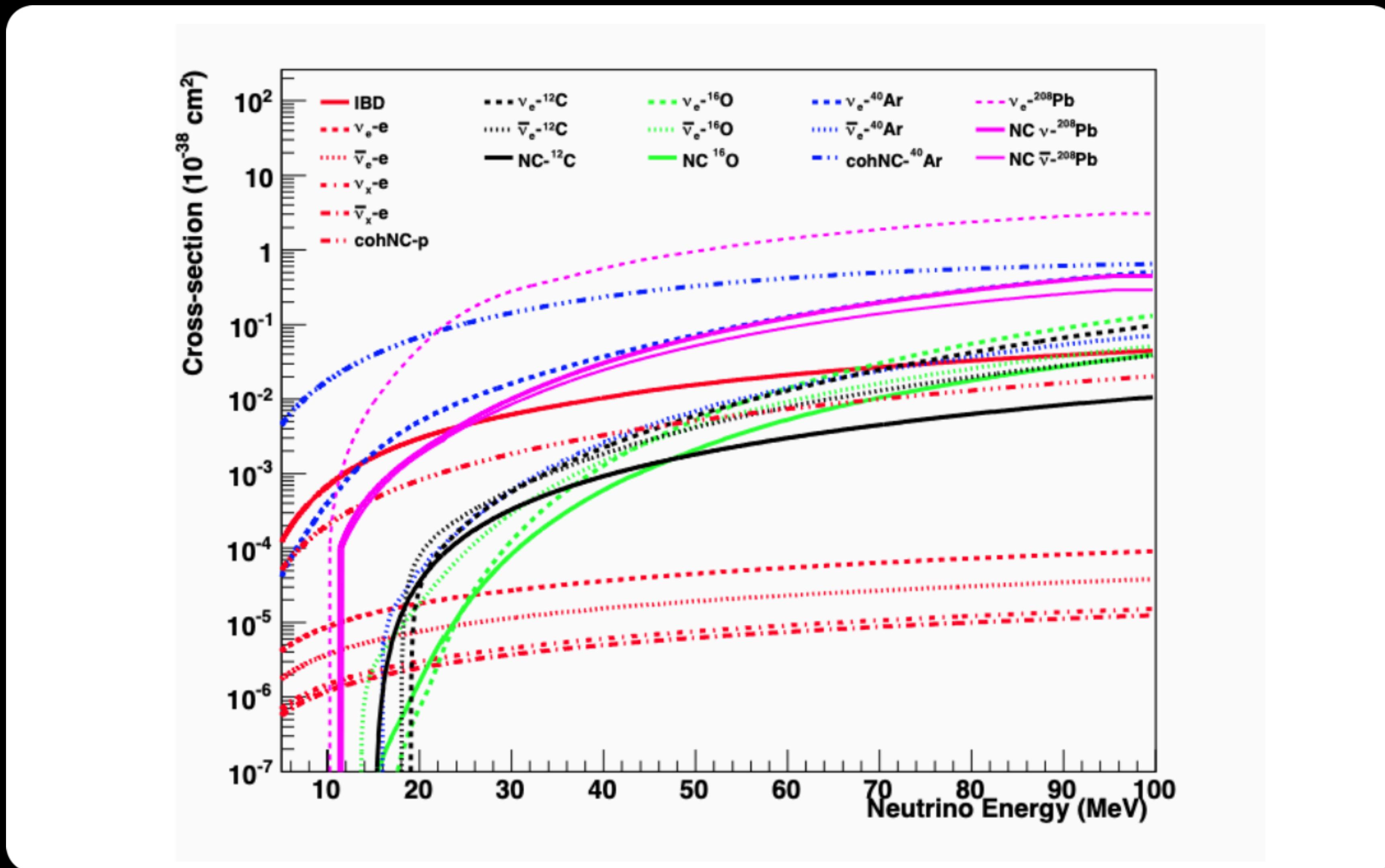
OFFLINE PROCESSING OF ALERTS

- Raw hits are buffered for ~2 weeks.
- This data stream provides us with full detector information.
- Processing of HitSpool data gives us full DOM waveform information 24 - 72 hrs after alert.



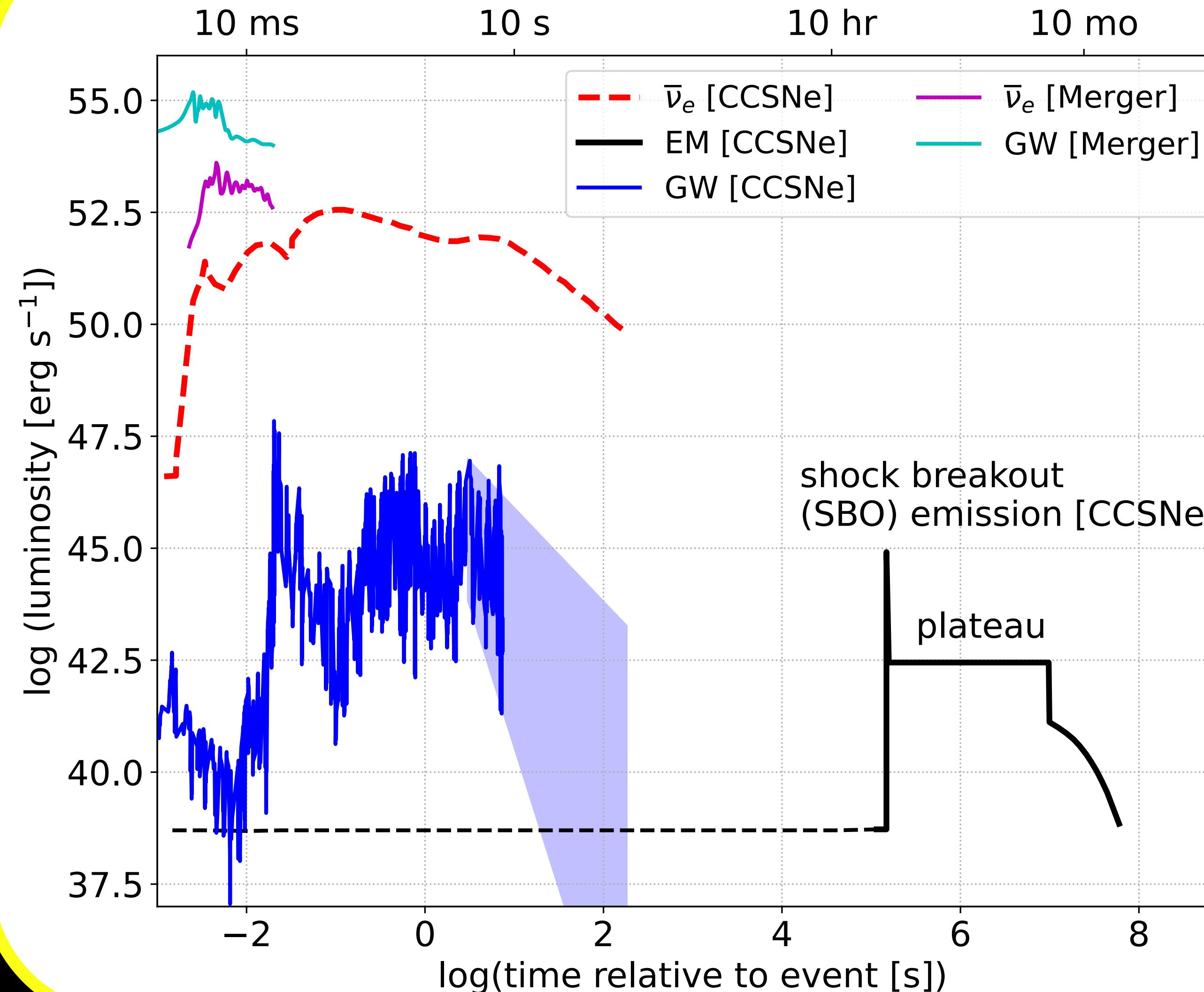
Credit: D.Heereman (Thesis, 2015)

MEV NEUTRINO CROSS SECTION

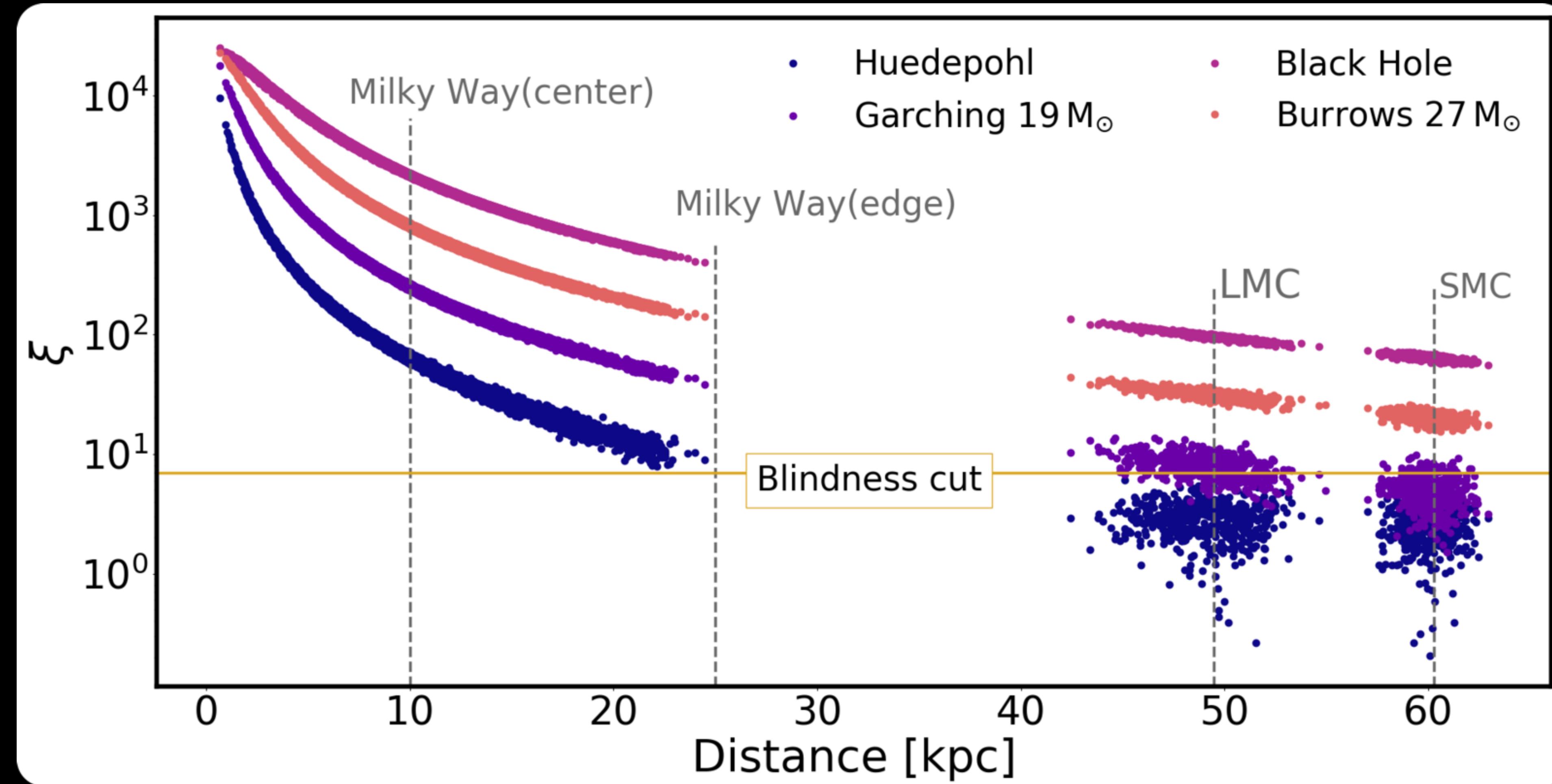


Credit: Scholberg In: Annu. Rev. Nucl. Part. (2012), 62, 81-103

GRAVITATIONAL WAVES / NEUTRINOS

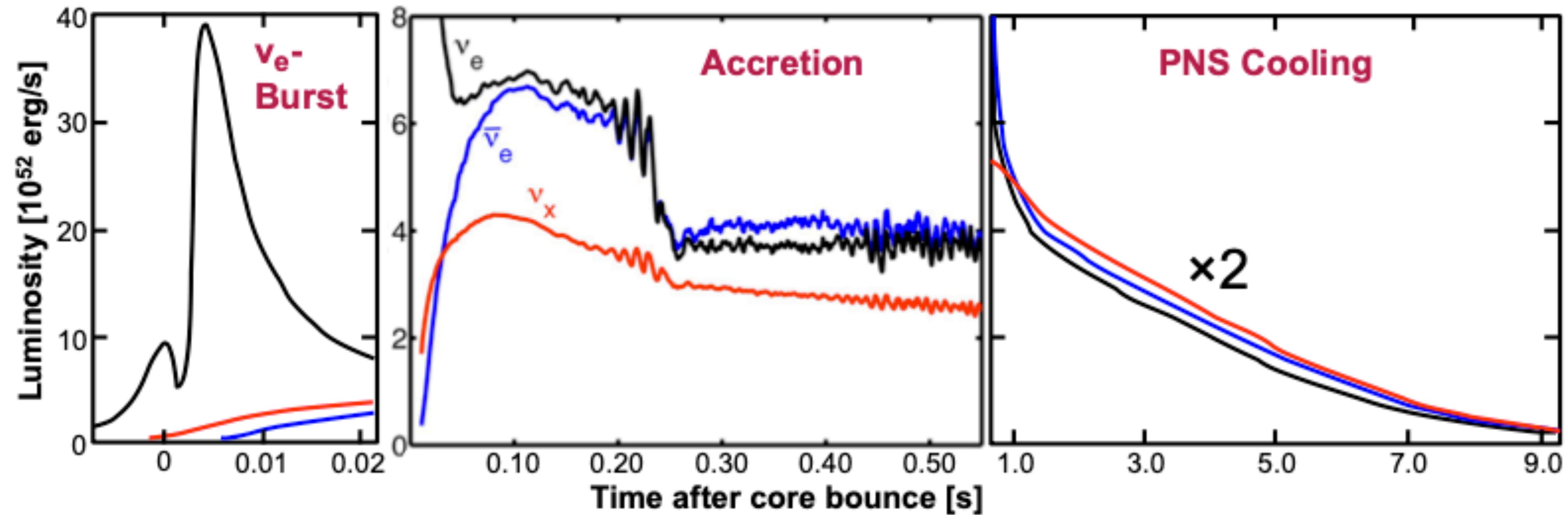


GALACTIC SENSITIVITY



Credit: R. Abbasi et al., IceCube Collaboration (submitted)

SUPERNOVAE: LOW ENERGY NEUTRINO LIGHTCURVE

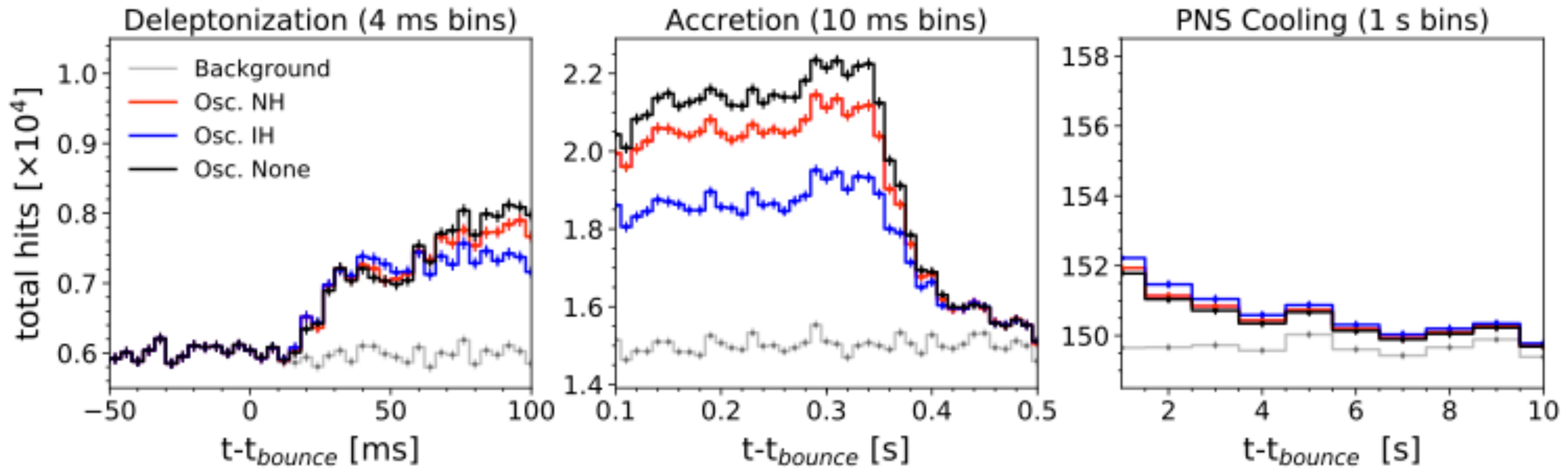


Burst of ν_e (electron capture)
 $e^- + p - \rightarrow \nu_e + n$

Positron capture increases $\bar{\nu}_e$ luminosity, and thermal pair production like $N + N \leftrightarrow N + N + \nu + \bar{\nu}$ increase the other flavor's luminosity

Rest of gravitational binding energy is released during the cooling phase

SUPERNOVAE: LOW ENERGY NEUTRINO LIGHTCURVE OBSERVABLE BY ICECUBE



Simulated DOM hits in IceCube for a Galactic Supernova

Credit: Cross,Fritz & Griswold. In: PoS ICRC2019, 889

OTHER MEV NEUTRINO DETECTORS

Number of events
depending on
CCSNe mass

Experiment	Type	Mass (kt)	Location	11.2 M _⊕	27.0 M _⊕	40.0 M _⊕
Super-K	H ₂ O/ $\bar{\nu}_e$	32	Japan	4000/4100	7800/7600	7600/4900
Hyper-K	H ₂ O/ $\bar{\nu}_e$	220	Japan	28K/28K	53K/52K	52K/34K
IceCube	String/ $\bar{\nu}_e$	2500*	South Pole	320K/330K	660K/660K	820K/630K
KM3NeT	String/ $\bar{\nu}_e$	150*	Italy/France	17K/18K	37K/38K	47K/38K
LVD	C _n H _{2n} / $\bar{\nu}_e$	1	Italy	190/190	360/350	340/240
KamLAND	C _n H _{2n} / $\bar{\nu}_e$	1	Japan	190/190	360/350	340/240
Borexino	C _n H _{2n} / $\bar{\nu}_e$	0.278	Italy	52/52	100/97	96/65
JUNO	C _n H _{2n} / $\bar{\nu}_e$	20	China	3800/3800	7200/7000	6900/4700
SNO+	C _n H _{2n} / $\bar{\nu}_e$	0.78	Canada	150/150	280/270	270/180
NO ν A	C _n H _{2n} / $\bar{\nu}_e$	14	USA	1900/2000	3700/3600	3600/2500
Baksan	C _n H _{2n} / $\bar{\nu}_e$	0.24	Russia	45/45	86/84	82/56
HALO	Lead/ ν_e	0.079	Canada	4/3	9/8	9/9
HALO-1kT	Lead/ ν_e	1	Italy	53/47	120/100	120/120
DUNE	Ar/ ν_e	40	USA	2700/2500	5500/5200	5800/6000
MicroBooNe	Ar/ ν_e	0.09	USA	6/5	12/11	13/13
SBND	Ar/ ν_e	0.12	USA	8/7	16/15	17/18
DarkSide-20k	Ar/any ν	0.0386	Italy	—	250	—
XENONnT	Xe/any ν	0.006	Italy	56	106	—
LZ	Xe/any ν	0.007	USA	65	123	—
PandaX-4T	Xe/any ν	0.004	China	37	70	—

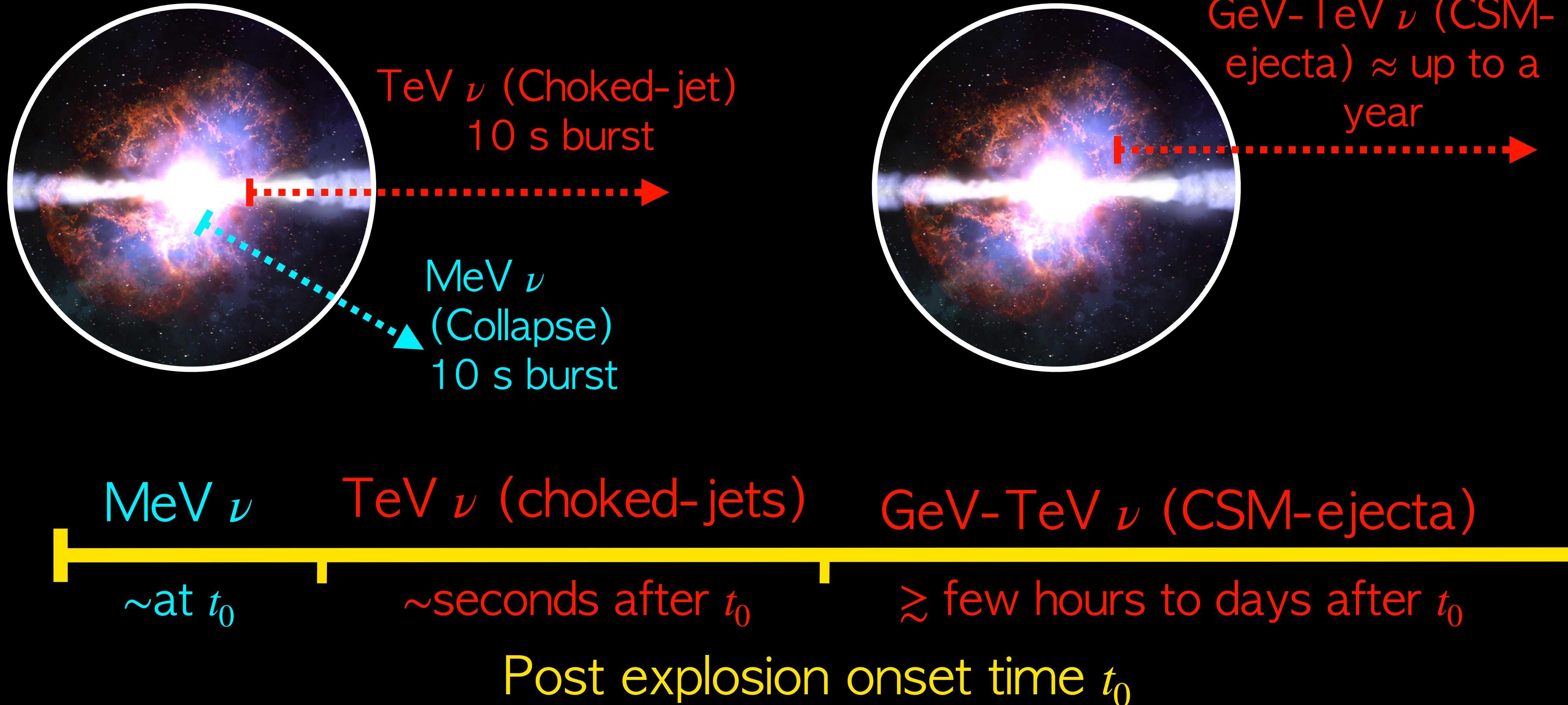
NEUTRINO PROCESSES: ENERGY REGIMES FOR ν OBSERVATION

Threshold-less processes		
Coherent scattering	$\nu + A_N^Z \rightarrow \nu + A_N^{*Z}$	NC
Low-energy processes ($\sim 1 - 100$ MeV)		
Inverse beta decay	$(\bar{\nu}_e, \nu_e) + (p, n) \rightarrow e^\pm + (n, p)$	CC
Intermediate energy processes ($\sim 0.1 - 100$ GeV)		
Elastic scattering off electrons	$(\bar{\nu}, \nu) + e^- \rightarrow (\bar{\nu}, \nu) + e^-$	NC
Elastic scattering off electrons	$(\bar{\nu}, \nu) + e^\pm \rightarrow (\bar{\nu}, \nu) + l^\pm$	CC
Quasi-elastic scattering off nucleon	$(\bar{\nu}, \nu) + N \rightarrow N + l^\pm$	CC
Elastic scattering off nucleon	$(\bar{\nu}, \nu) + N \rightarrow (\bar{\nu}, \nu) + N$	NC
Deep inelastic scattering (≥ 100 GeV)		
Charged current DIP	$(\bar{\nu}, \nu) + N \rightarrow l^\pm + X$	CC
Neutral current DIP	$(\bar{\nu}, \nu) + N \rightarrow (\bar{\nu}, \nu) + X$	NC

Table 3.2. Important neutrino interactions for the observation of CCSNe neutrinos [62, 149]. $N = n, p$, $X = \text{any final set of hadrons}$, and $l = \text{lepton}$

Credit: Valtonen-Mattila. 2022 Thesis: Expanding the observational reach of core-collapse supernovae for IceCube using high-energy neutrinos.

SUPERNOVAE: NEUTRINO TIMELINE



See more in : Valtonen-Mattila & O'Sullivan In: ApJ (2023), 945, 98

NEUTRINO PRODUCTION REGIME IN GRBS

MeV Domain

Beta processes	
e^- and ν_e capture by nucleons	$e^- + p \leftrightarrow n + \nu_e$
e^+ and $\bar{\nu}_e$ capture by nucleons	$e^+ + n \leftrightarrow p + \bar{\nu}_e$
e^- and ν_e absorption by nuclei	$e^- + (A, Z) \leftrightarrow (A, Z-1) + \nu_e$
Thermal pair production and annihilation processes	
Nucleon-nucleon Bremsstrahlung	$N + N \leftrightarrow N + N + \nu + \bar{\nu}$
Electron-positron pair process	$e^+ + e^- \leftrightarrow \nu + \bar{\nu}$
Neutrino scattering	
Neutrino scattering with nuclei	$\nu + (A, Z) \leftrightarrow \nu + (A, Z)$
Neutrino scattering with nucleons	$\nu + N \leftrightarrow \nu + N$
Neutrino scattering with e^\pm	$\nu + e^\pm \leftrightarrow \nu + e^\pm$
Neutrino-neutrino reactions	
Neutrino pair annihilation	$\nu_e + \bar{\nu}_e \leftrightarrow \nu_x + \bar{\nu}_x$
Neutrino scattering	$\nu_x + (\nu_e, \bar{\nu}_e) \leftrightarrow \nu_x + (\nu_e, \bar{\nu}_e)$

GeV-TeV Domain

Photohadronic

$$p + p \begin{cases} \rightarrow X + \pi^\pm \rightarrow X + \mu^\pm + \nu_\mu (\bar{\nu}_\mu) \rightarrow X + e^\pm + \nu_e (\bar{\nu}_e) + \nu_\mu (\bar{\nu}_\mu) \\ \rightarrow X + \pi^0 \rightarrow X + 2\gamma \end{cases}$$

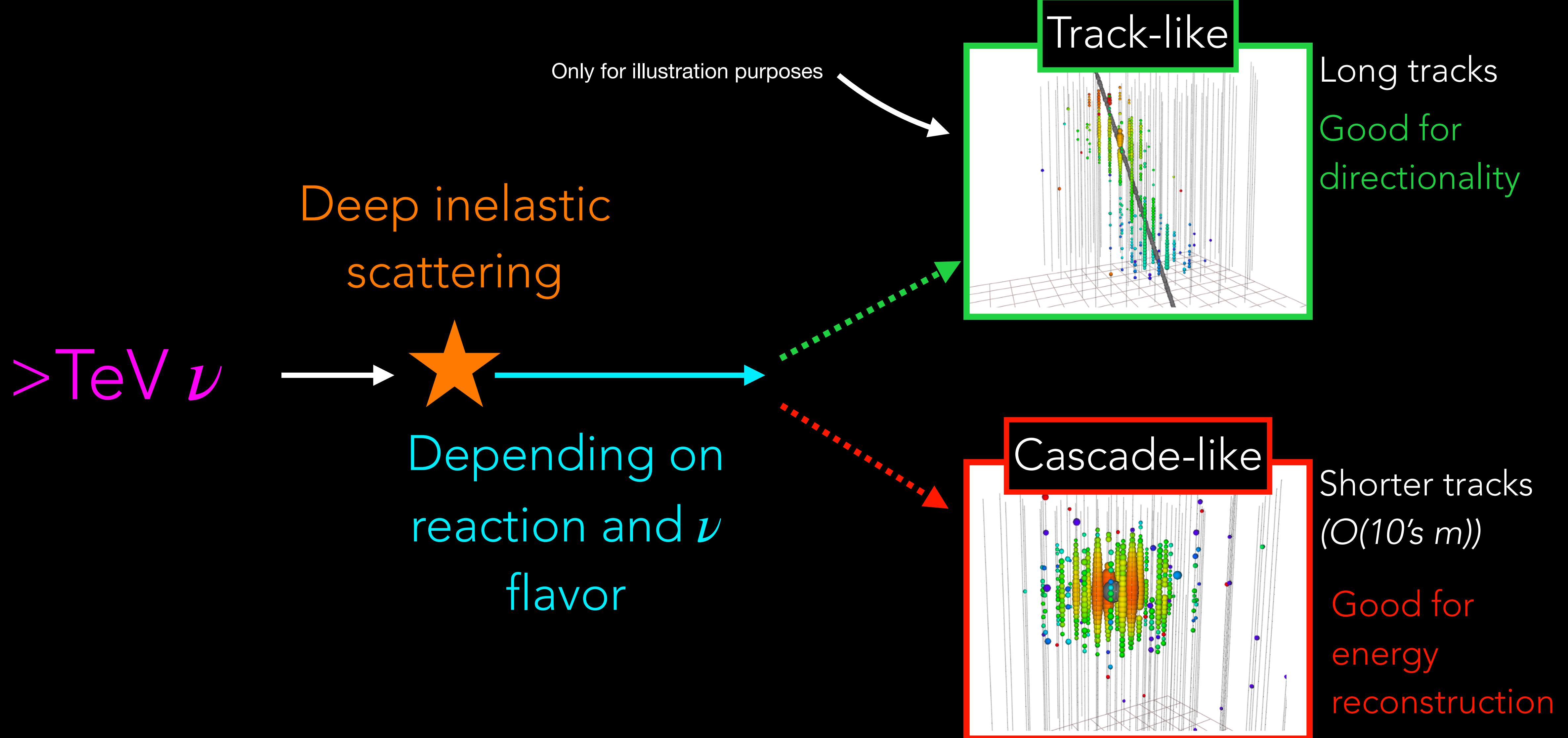
+ also pn interaction!

Hadronuclear

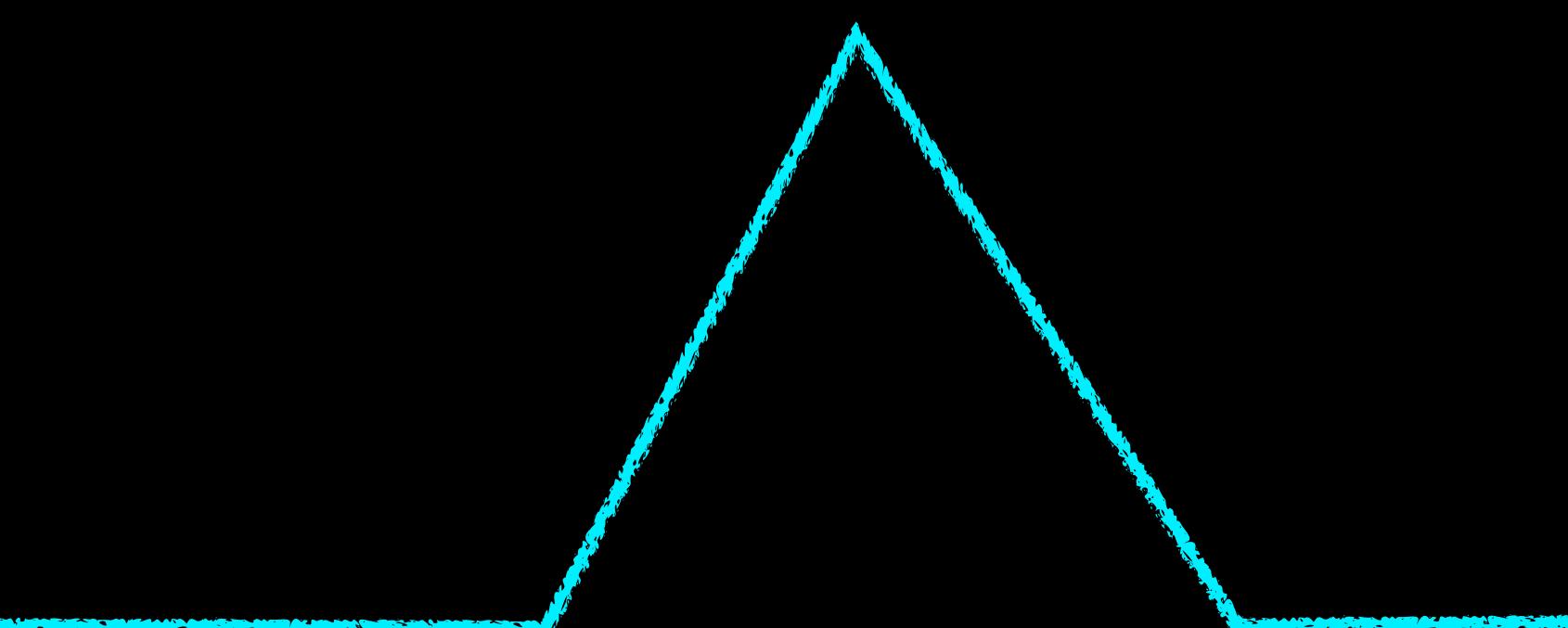
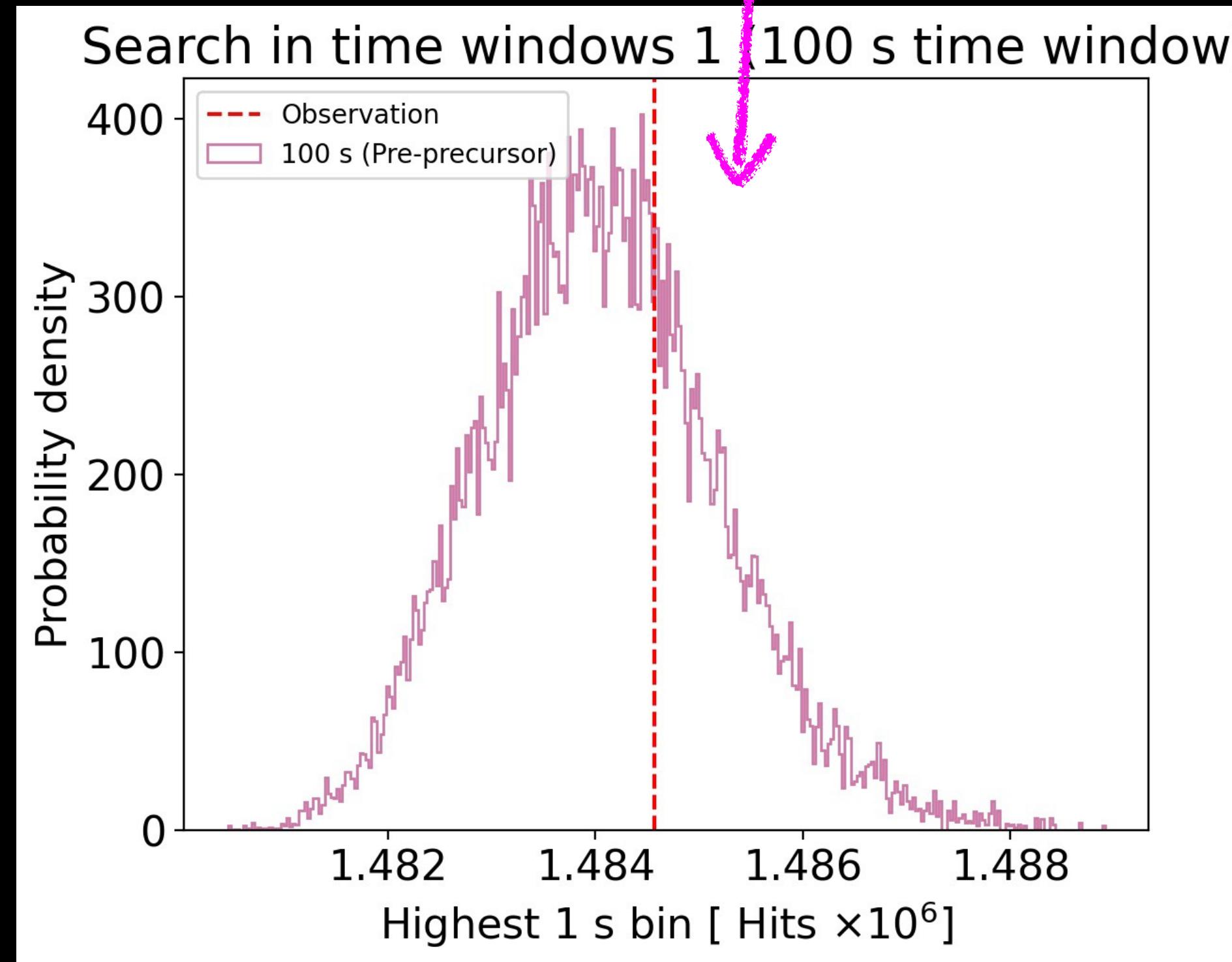
$$p + \gamma \rightarrow \Delta^+ \begin{cases} \rightarrow n + \pi^+ \rightarrow n + \mu^+ + \nu_\mu \rightarrow n + e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \\ \rightarrow p + \pi^0 \rightarrow p + 2\gamma \end{cases}$$

$$n + \gamma \rightarrow \Delta^0 \begin{cases} \rightarrow n + \pi^0 \rightarrow n + 2\gamma \\ \rightarrow p + \pi^- \rightarrow p + \mu^- + \bar{\nu}_\mu \rightarrow p + e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu \end{cases}$$

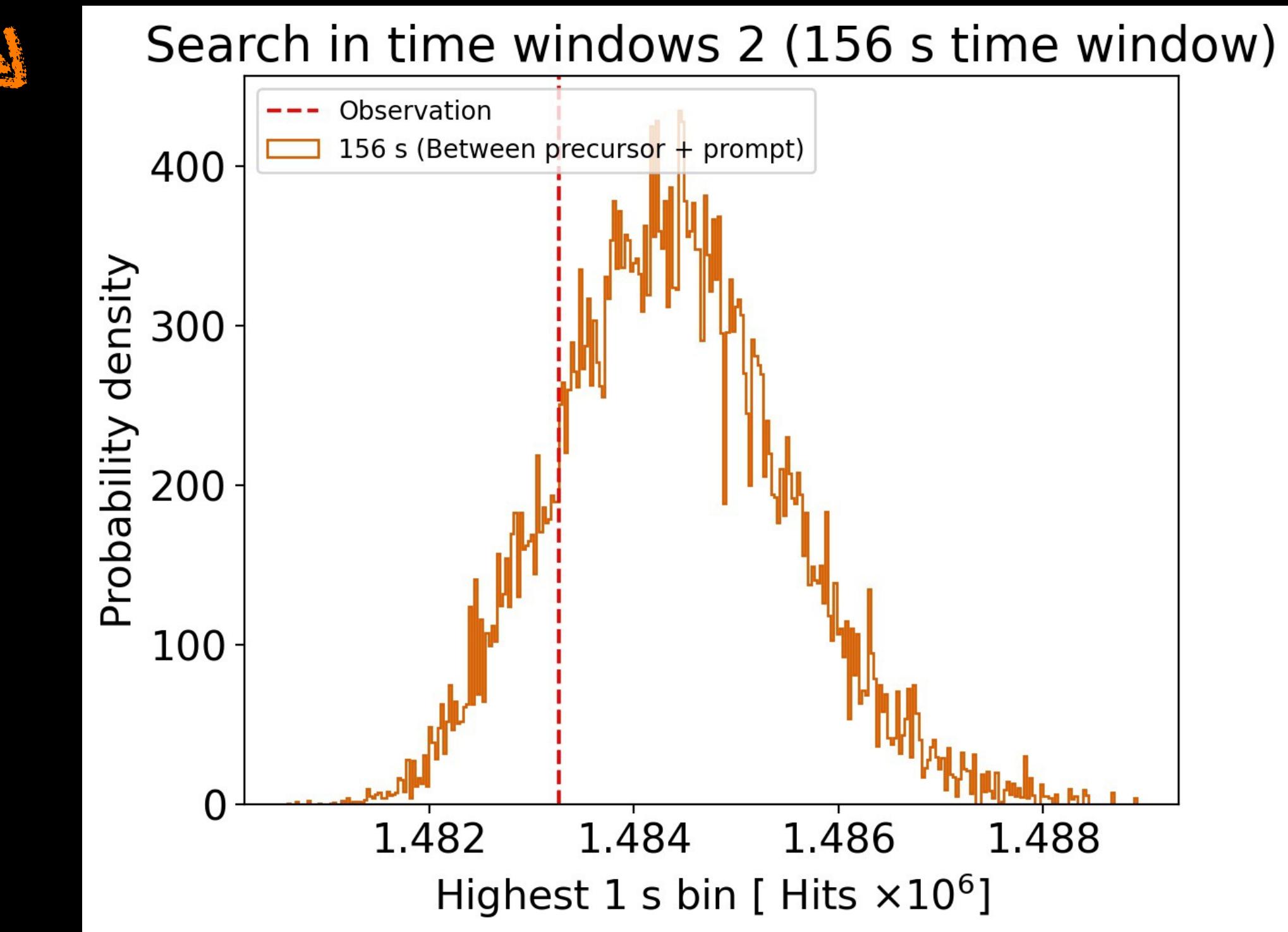
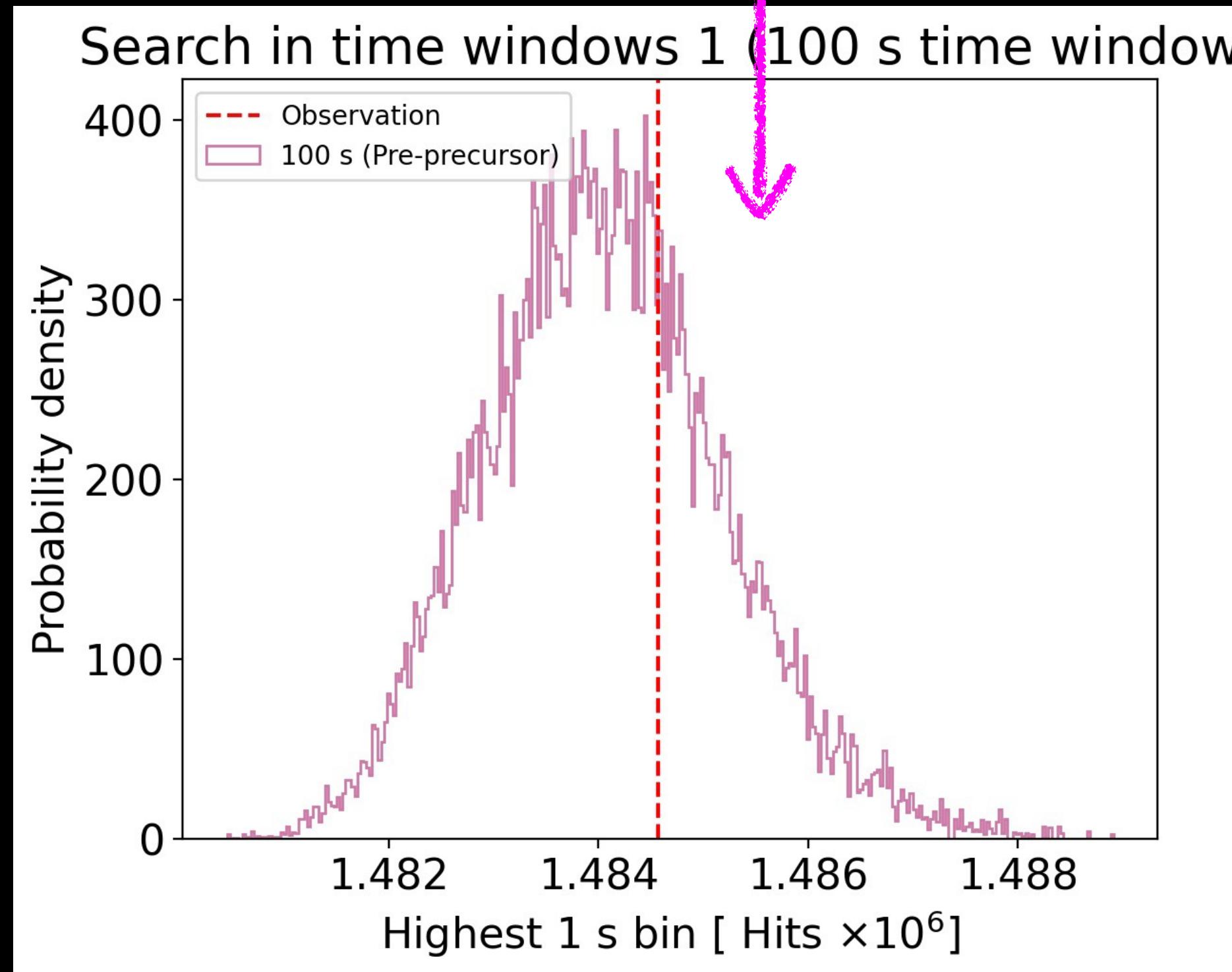
ICECUBE: HIGH-ENERGY NEUTRINOS



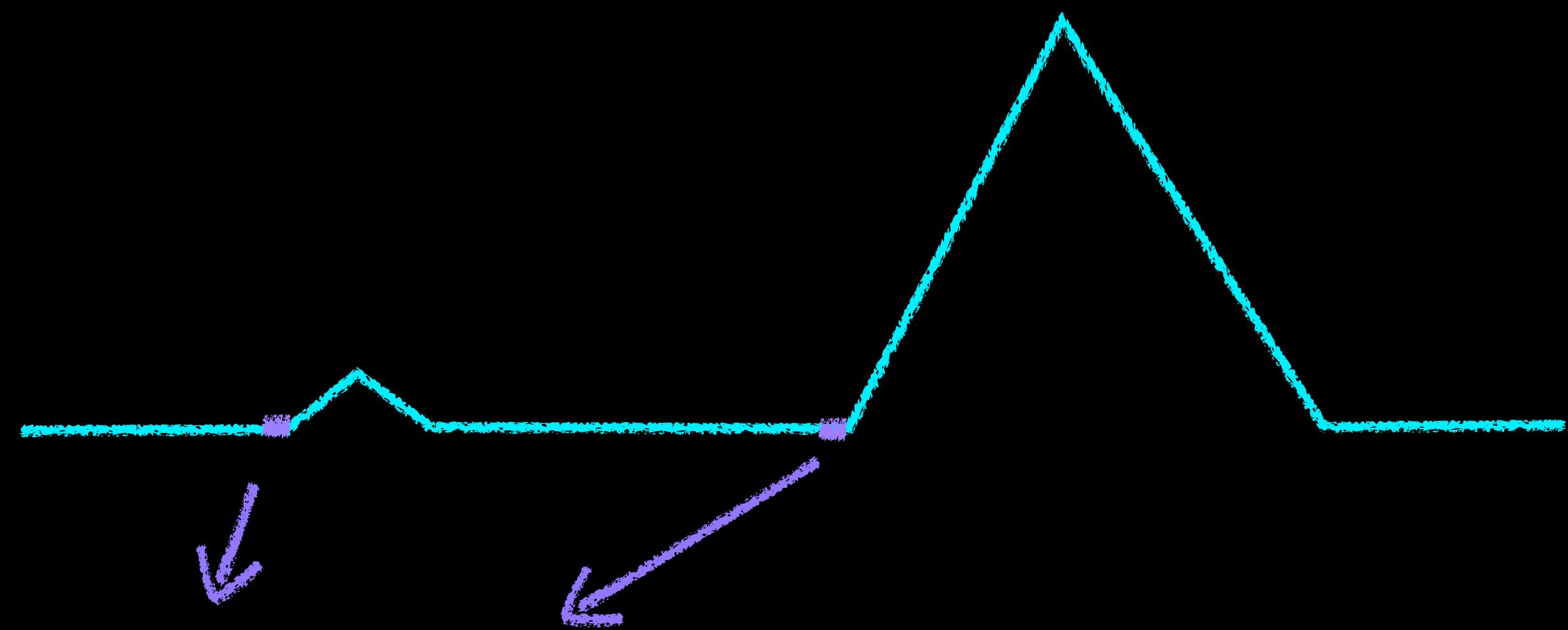
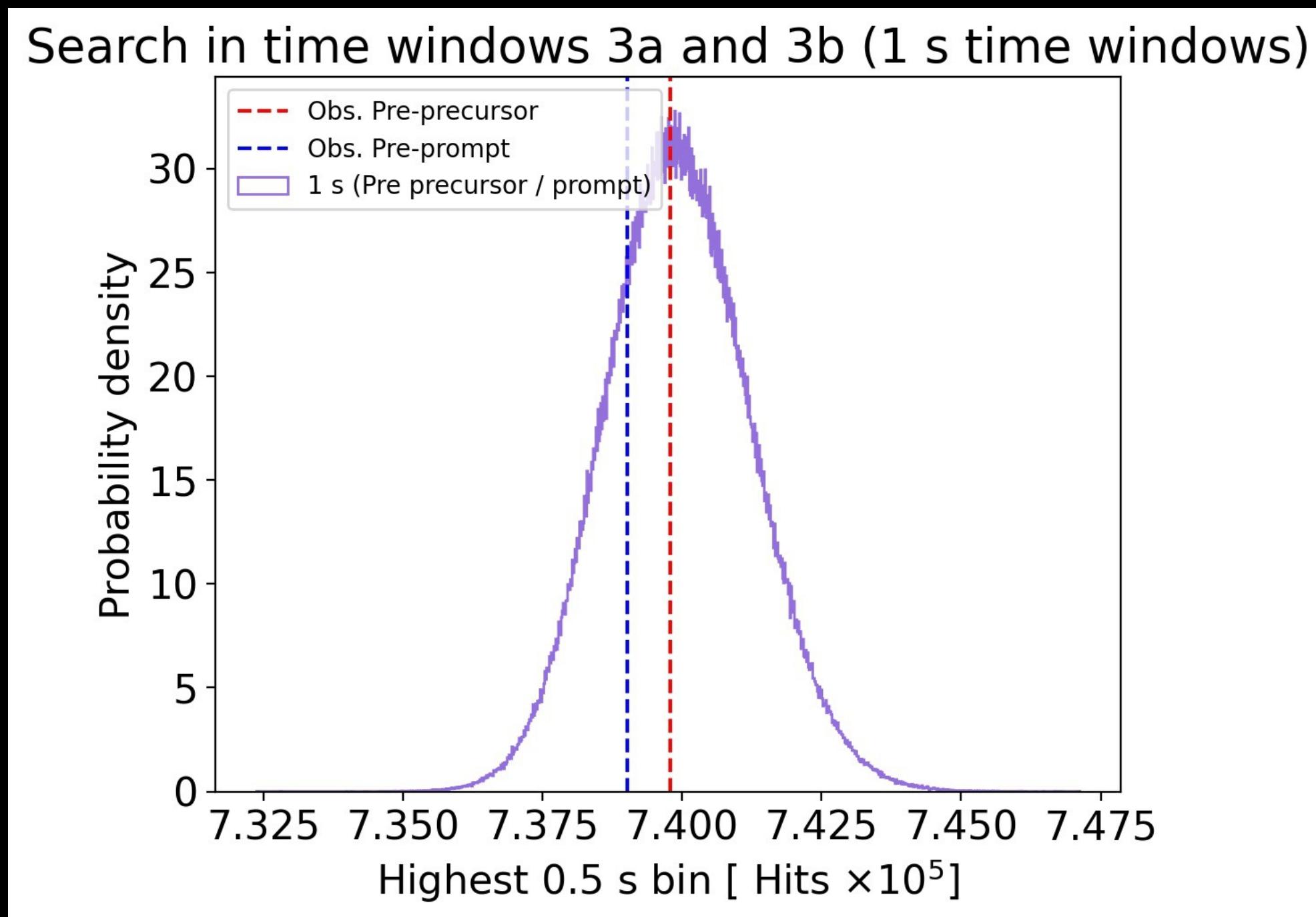
GRB 221009A BACKGROUND



GRB 221009A BACKGROUND



GRB 221009A BACKGROUND



GRB 221009A BACKGROUND

