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RESPONDING TO ASTROPHYSICAL ALERTS WITH THE ICECUBE MEV NEUTRINO DATA STREAM

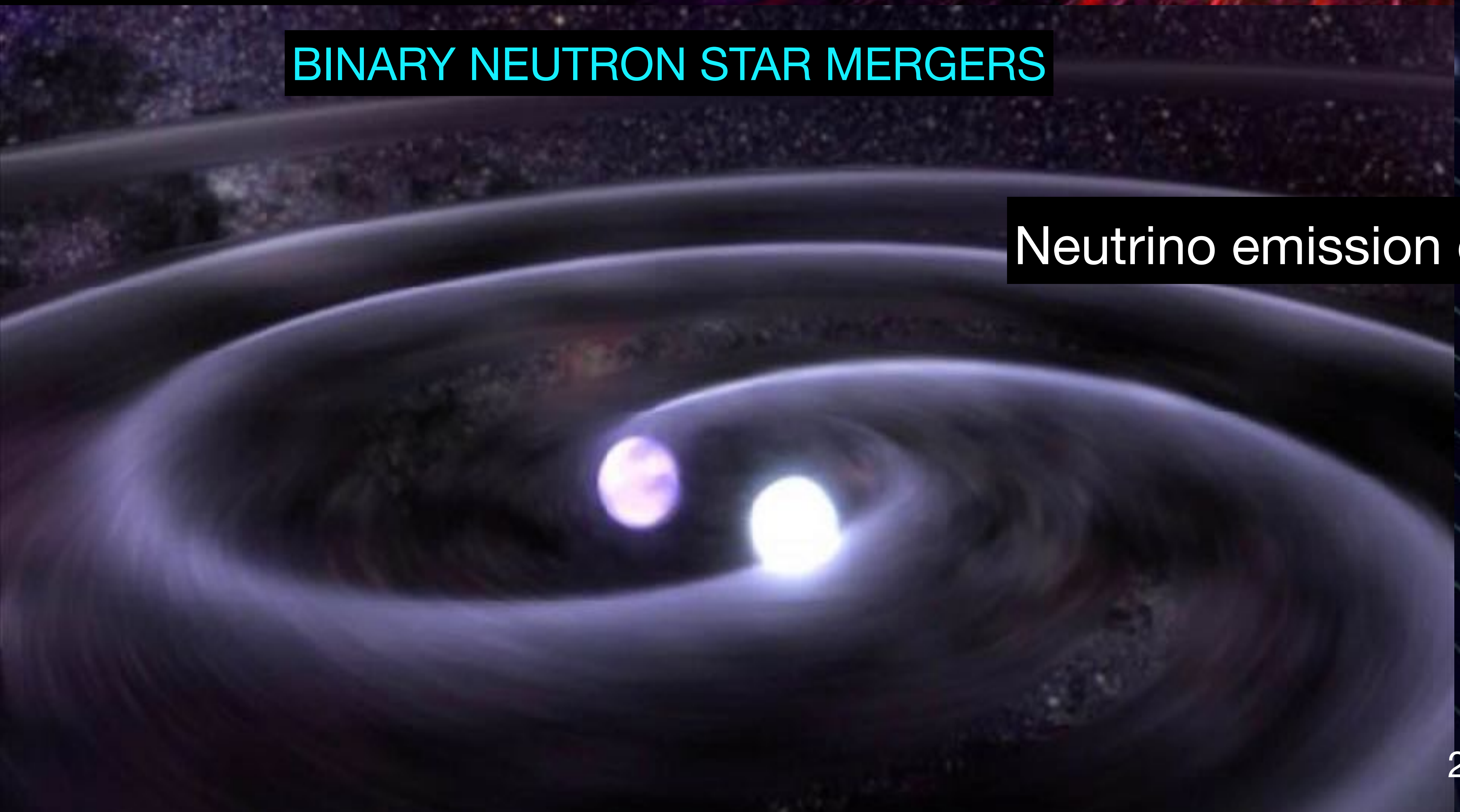
FYSIKDAGARNA 2023 | STOCKHOLM | 23.06.16

W H Y ?

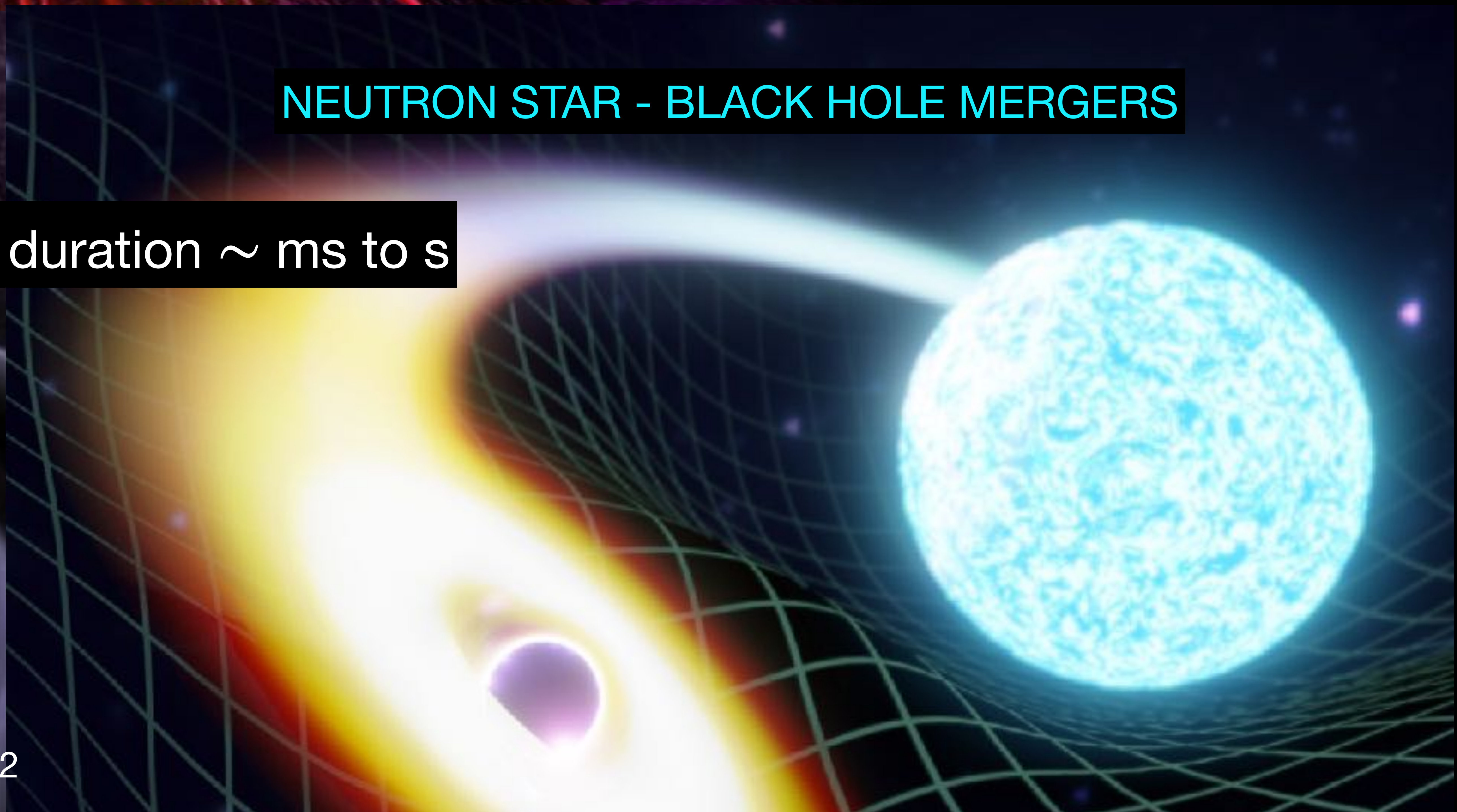
CORE-COLLAPSE SUPERNOVAE

Neutrino emission duration ~ 10 s

Candidates for both gravitational waves and burst of MeV neutrinos



BINARY NEUTRON STAR MERGERS



NEUTRON STAR - BLACK HOLE MERGERS

Neutrino emission duration $\sim$ ms to s

OUTLINE

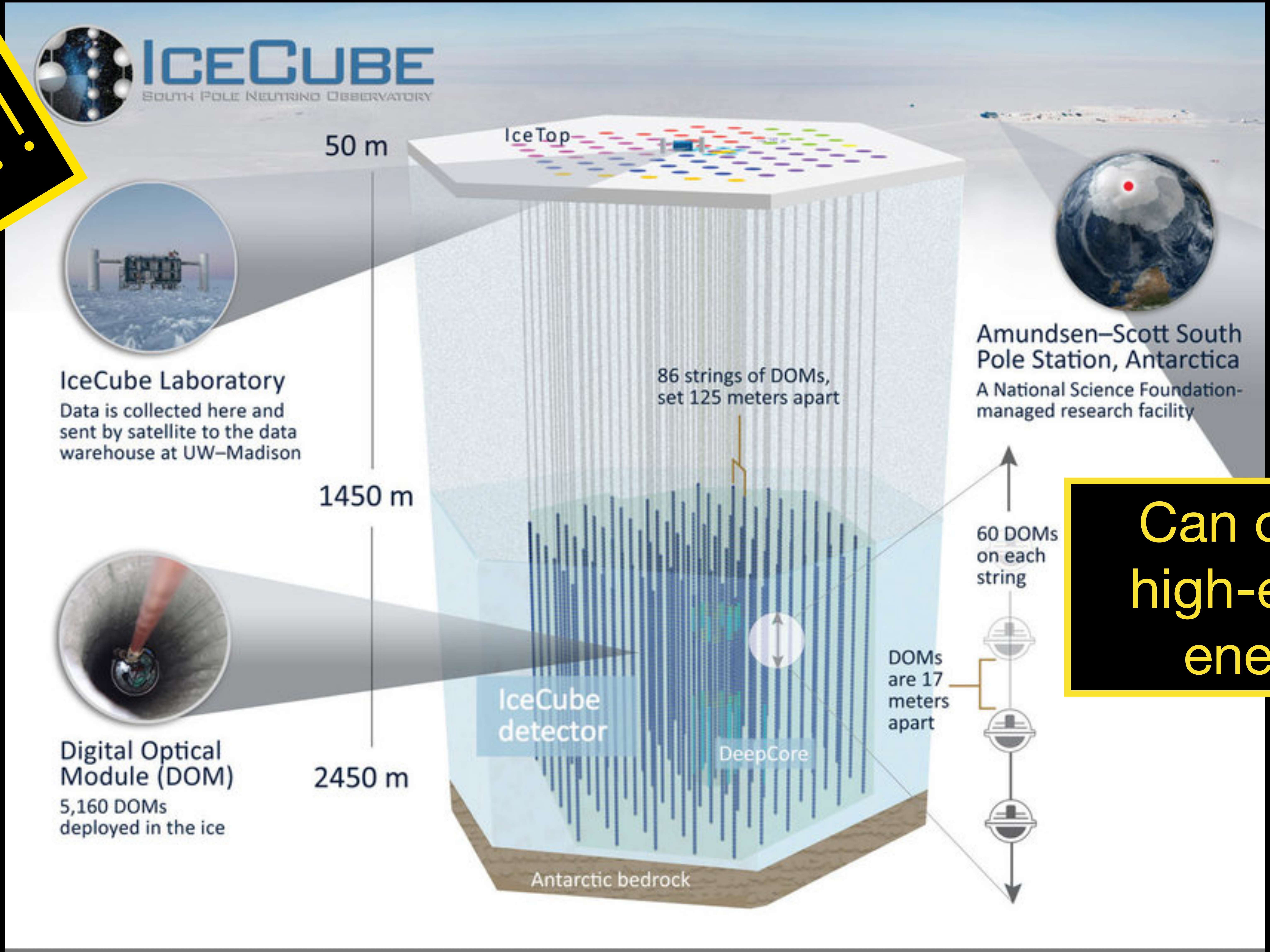
- Responding to astrophysical alerts: Low-energy neutrino data to respond swiftly to gravitational wave alerts

- Additional applications: Exploring the supernova data stream through examples like GRB 221009A

- Conclusions: Summarizing the findings and implications of the analysis

ICECUBE NEUTRINO OBSERVATORY

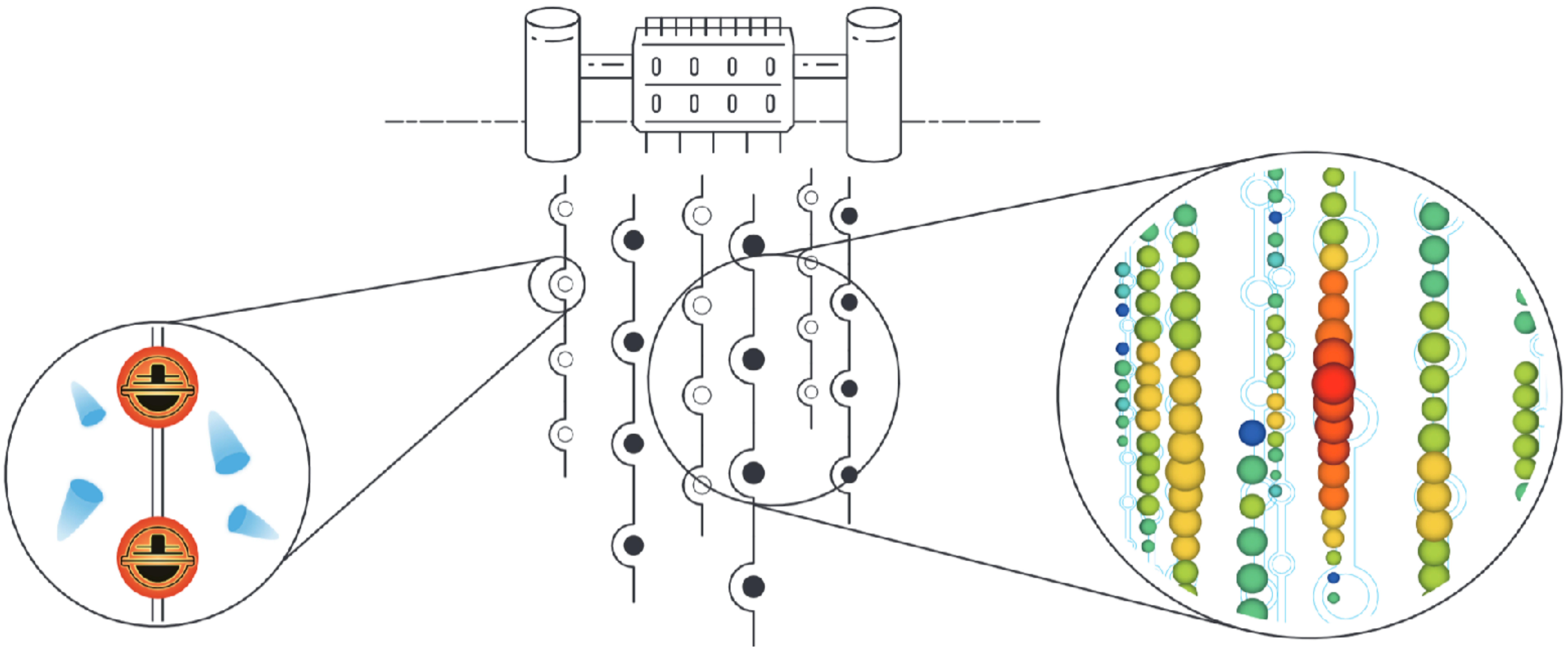
$1km^3$!!



Can observe from high-energy to low energy (MeV) !

Credit: IceCube Collaboration. 'Neutrinos and Cosmic Rays Observed by IceCube' (2017)

ICECUBE NEUTRINO OBSERVATORY

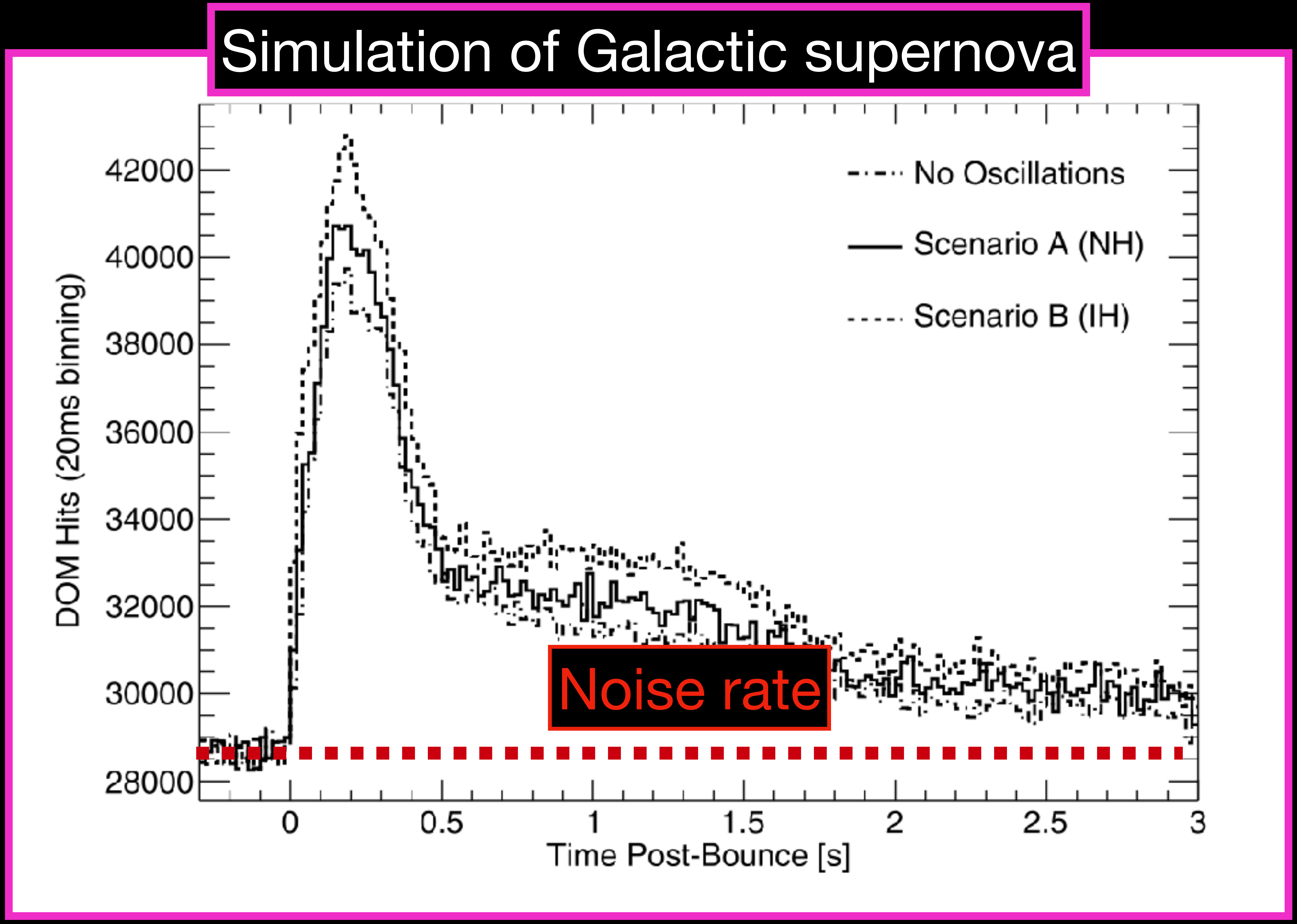


Low energy neutrinos result in short tracks in the ice. Interactions that occur near the photosensors can be detected.

High energy neutrinos result in long tracks in the ice. Many photosensors across different strings detect photons.

Credit: IceCube Collaboration. 'Neutrinos and Cosmic Rays Observed by IceCube' (2017)

SUPERNOVA DATA ACQUISITION SYSTEM



- Since neutrinos are observed as single hits, signal is mixed with noise rate.
- A signal will be detectable when considering the rate increase in the entire array.
- The Supernova Data Acquisition (SNDAQ) monitors continuously the detector rate, searching for a significant deviation from background

MEV NEUTRINO ALERT RESPONSE

Currently: we can not trigger an analysis externally.
Target: Develop a system that can allow response to external alerts

GOAL

Respond to Ligo-Virgo-Kagra (LVK) gravitational wave alerts classified as bursts (supernova candidates) and mergers involving a neutron star

Expected frequency LVK alerts

LVK RUN O4 Yearly Expectation:
36^{+49}_{-22} BNS / 6^{+11}_{-5} NSBH / few bursts per year

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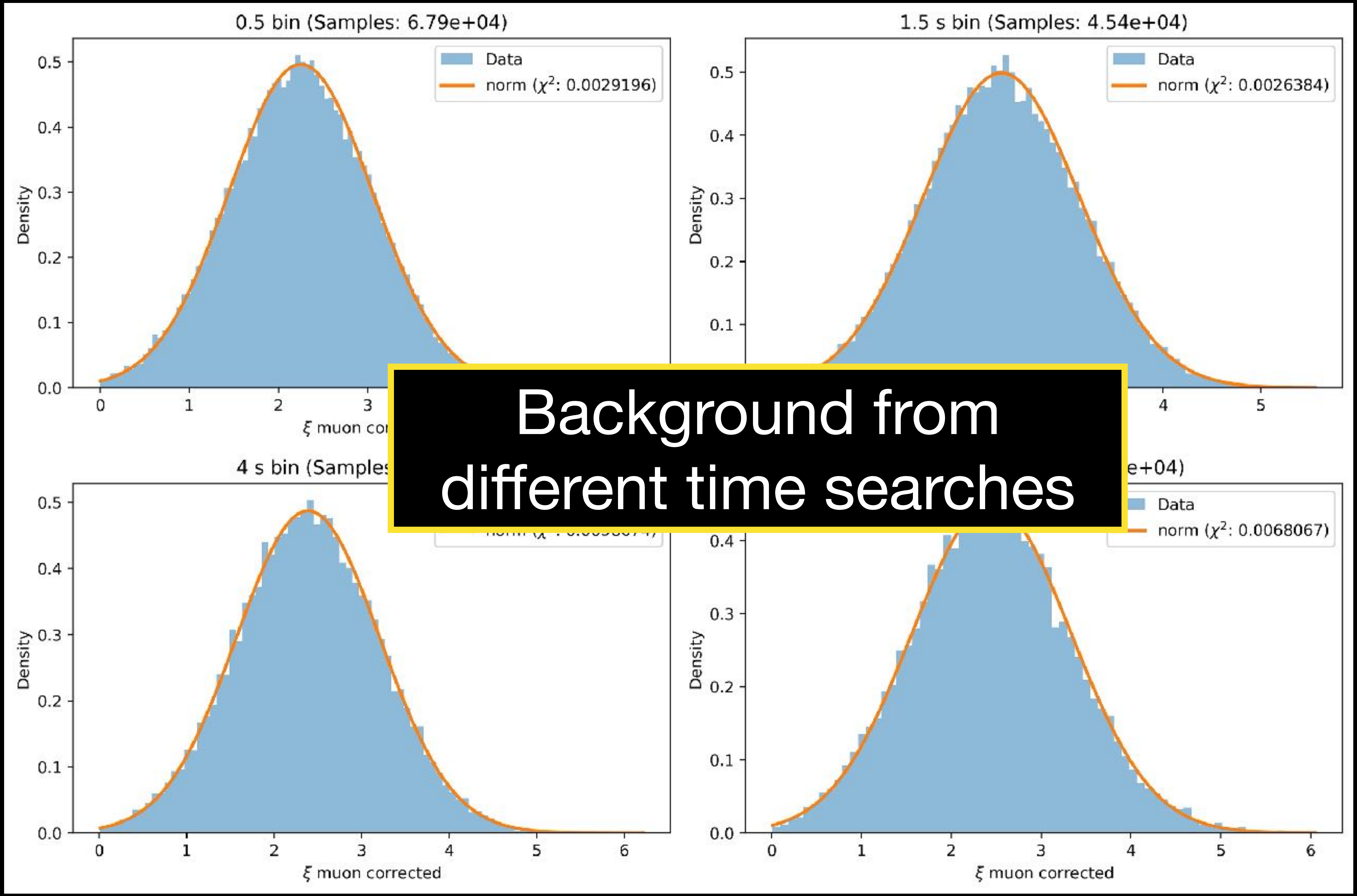
The system can also be employed for prompt responses to other alerts involving objects that are potential candidates for MeV neutrino production

DETERMINING SIGNIFICANCE

Through the characterization of background in various analysis time bins, we can establish a threshold for the alerts that warrant a response



Background from different time searches

CASE STUDY: GRB 221009A

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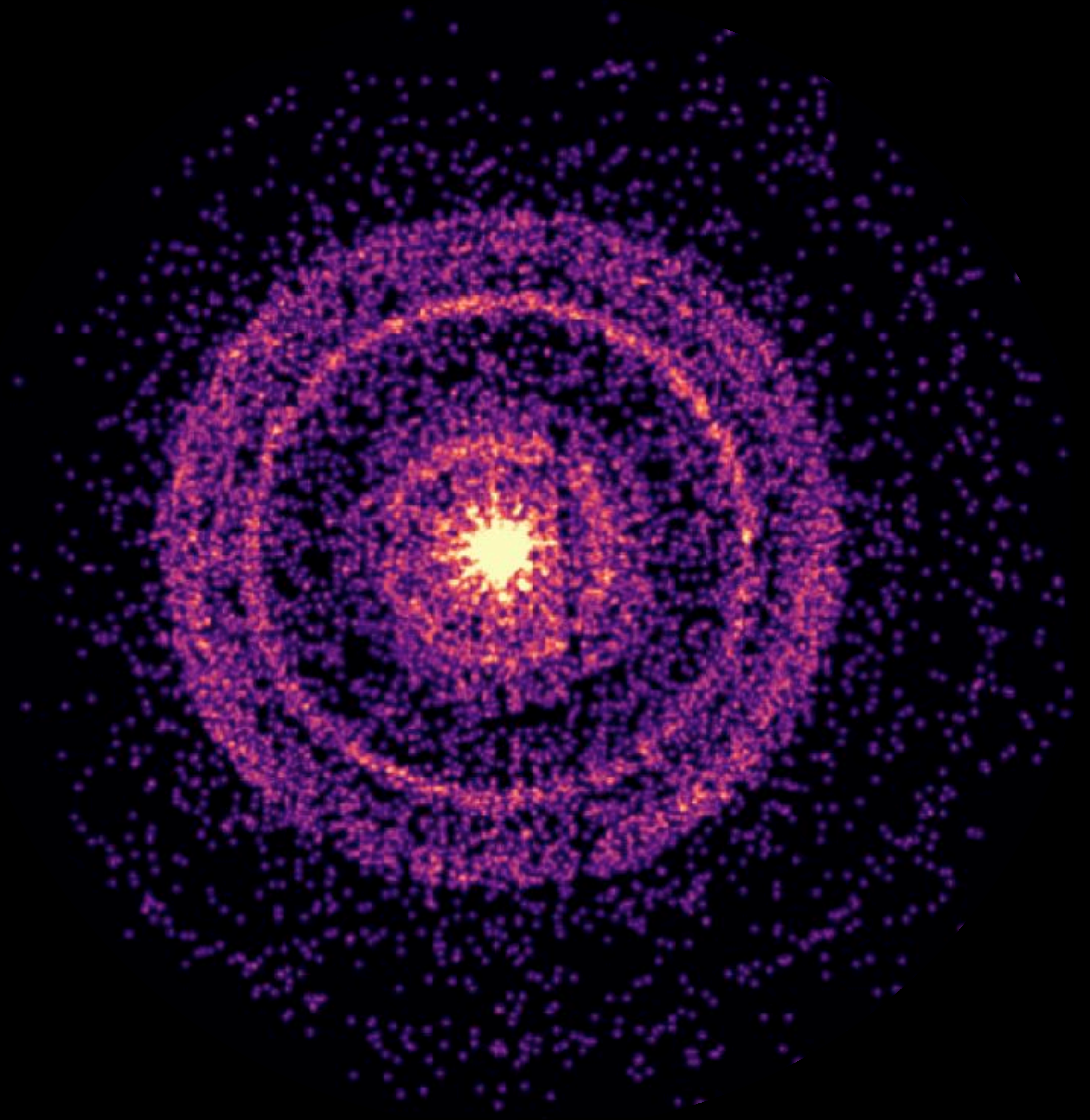
- First detected by GBM (Fermi gamma ray satellite) on the 9th of October 2022.
- One of the brightest gamma ray burst (GRB) and first >TeV γ-rays detected. Bursts this bright occur only once every 10,000 years!
- Very close GRB ($\approx$ 740 Mpc), or about 20 times closer than average GRB.

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



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

GRB 221009A ANALYSIS

Low-energy data is background dominated. We rely on transient timing information.

METHODOLOGY

- Selecting time windows / bin size based on physics motivation
- Characterize the background through trials on off-time data
- Perform observation on on-time data
- Place upper limits

MOTIVATION FOR THE DIFFERENT SEARCHES

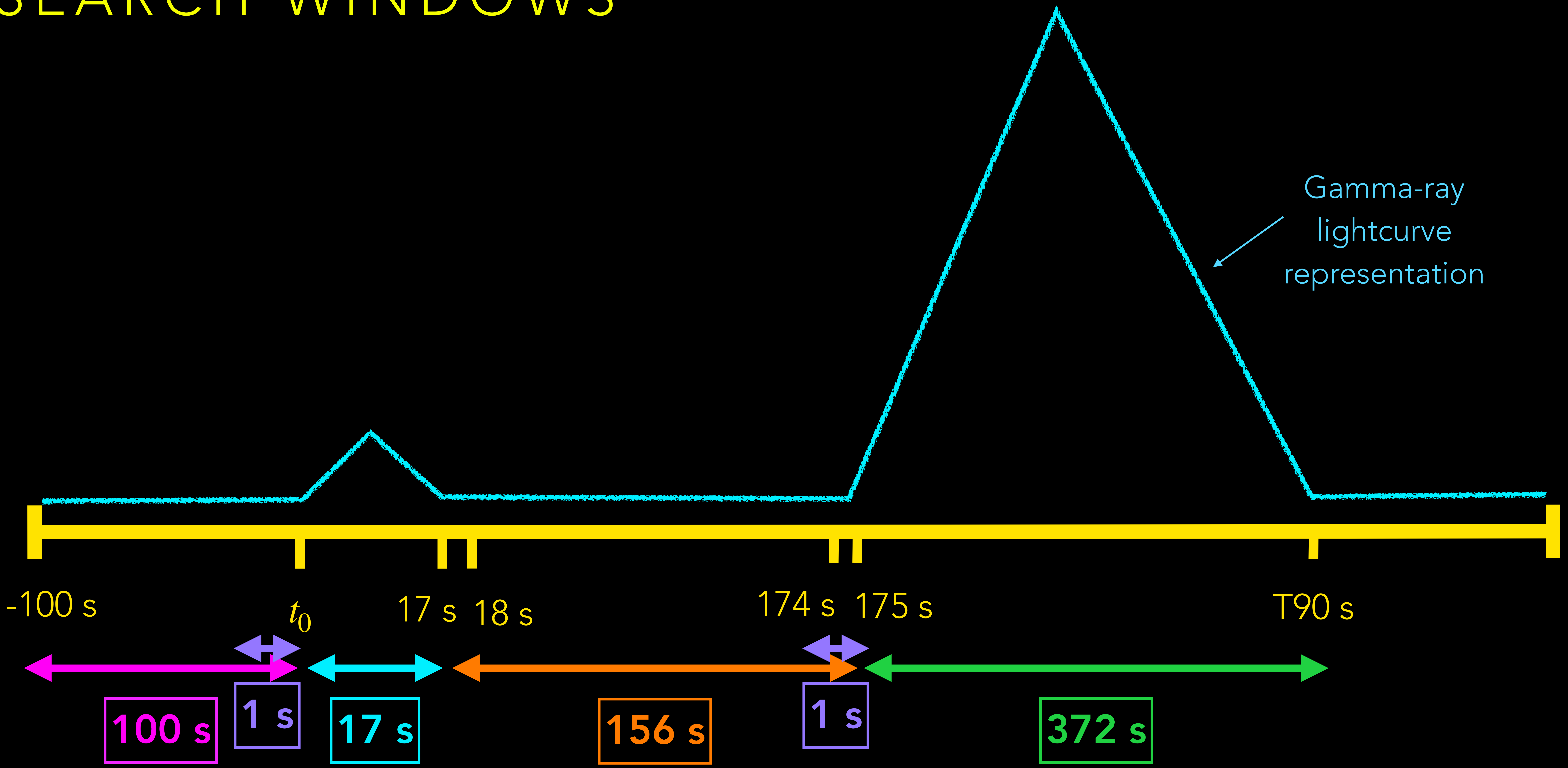
- Typical CCSNe neutrino emission prior to optical shock breakout: SBO could be boosted to x-ray/gamma-ray [1,2]

- MeV neutrinos could be produced through Neutrino Dominated Accretion Flows (NDAF), producing $\bar{E}_\nu \approx$ 10-20 MeV neutrinos that appear [3,4,5a,5b,5c]

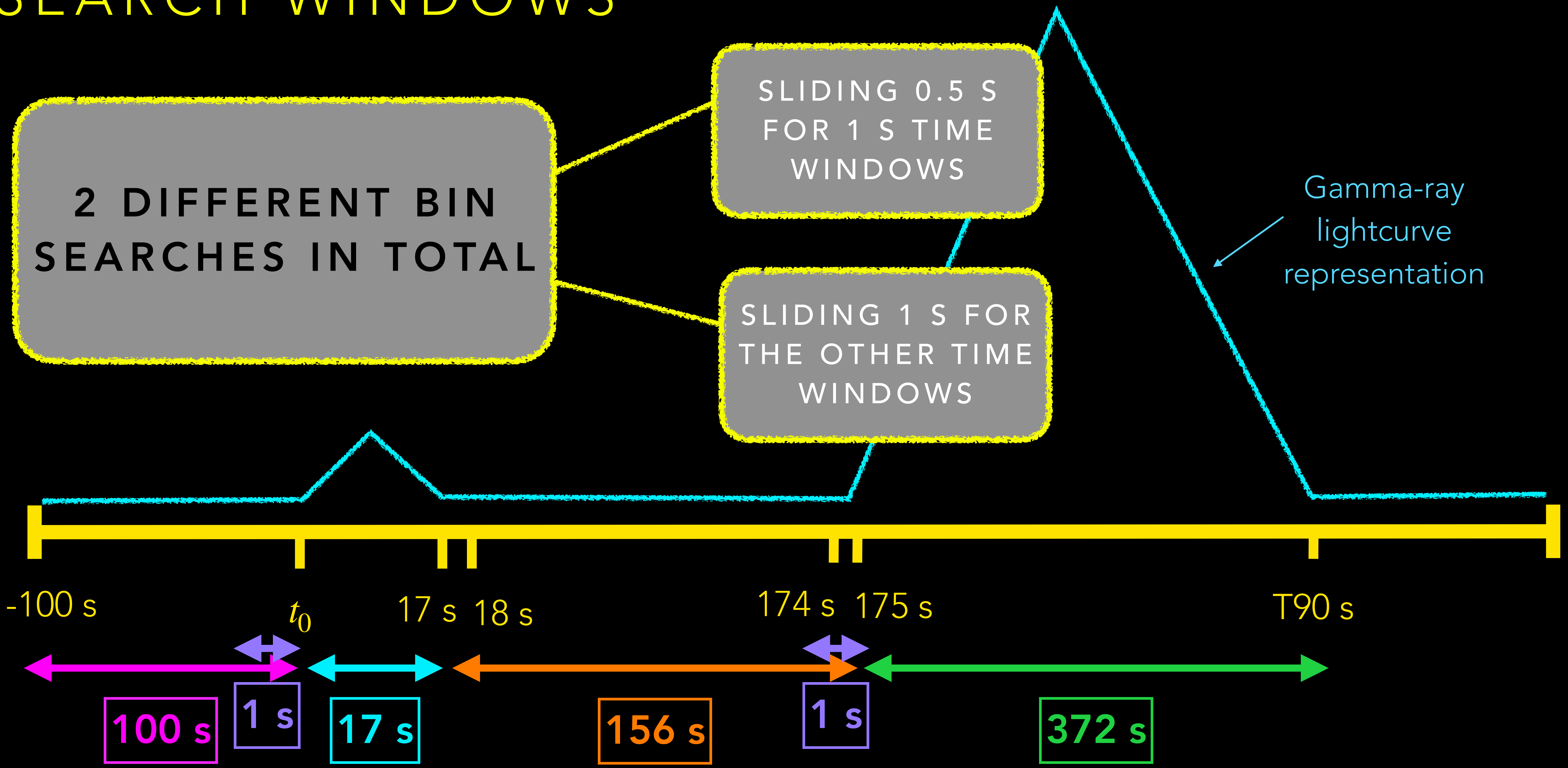
- Fireball production of thermal neutrinos [6]

- All models have isotropic emission

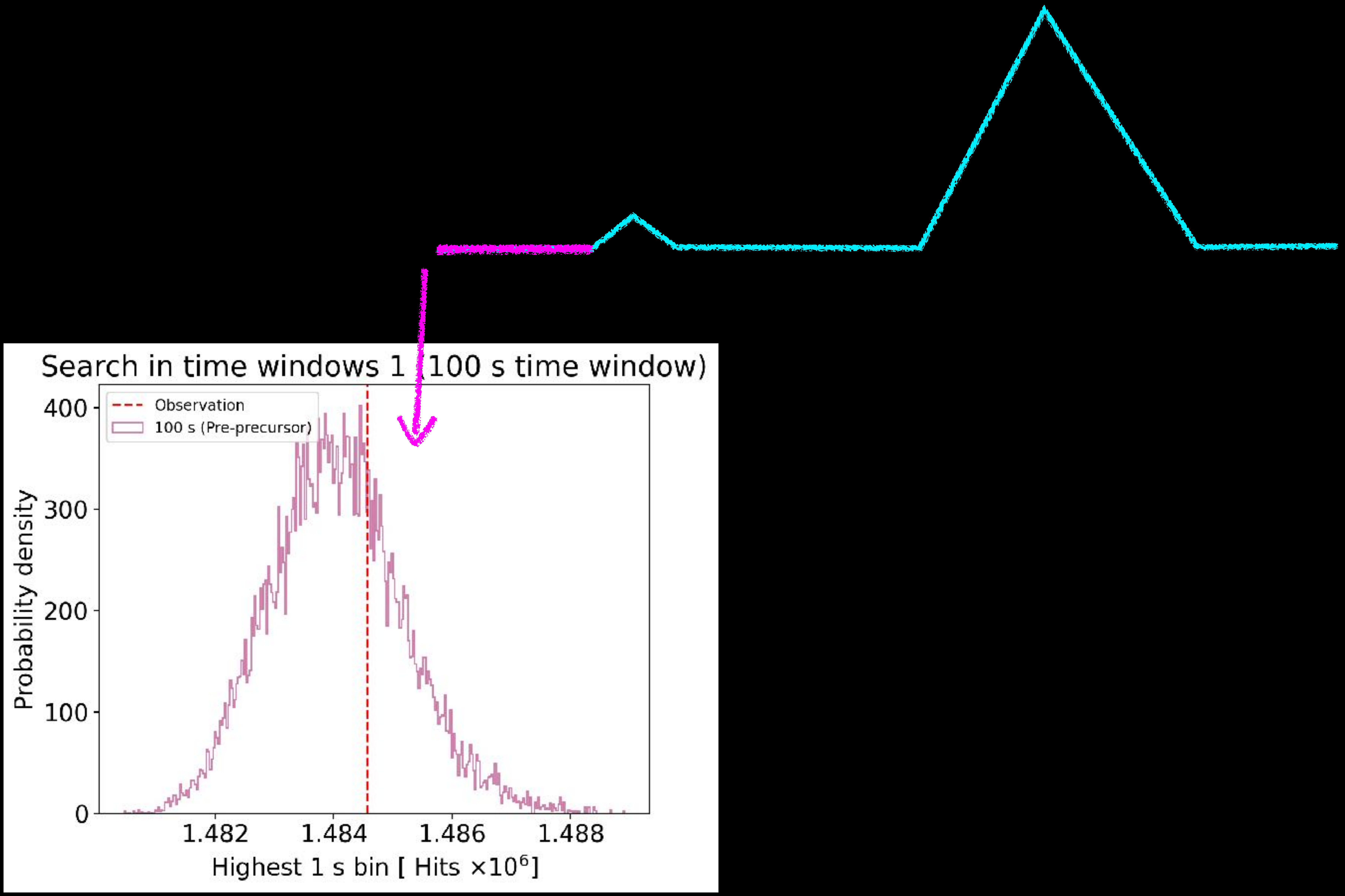
SEARCH WINDOWS



SEARCH WINDOWS



BACKGROUND CHARACTERIZATION



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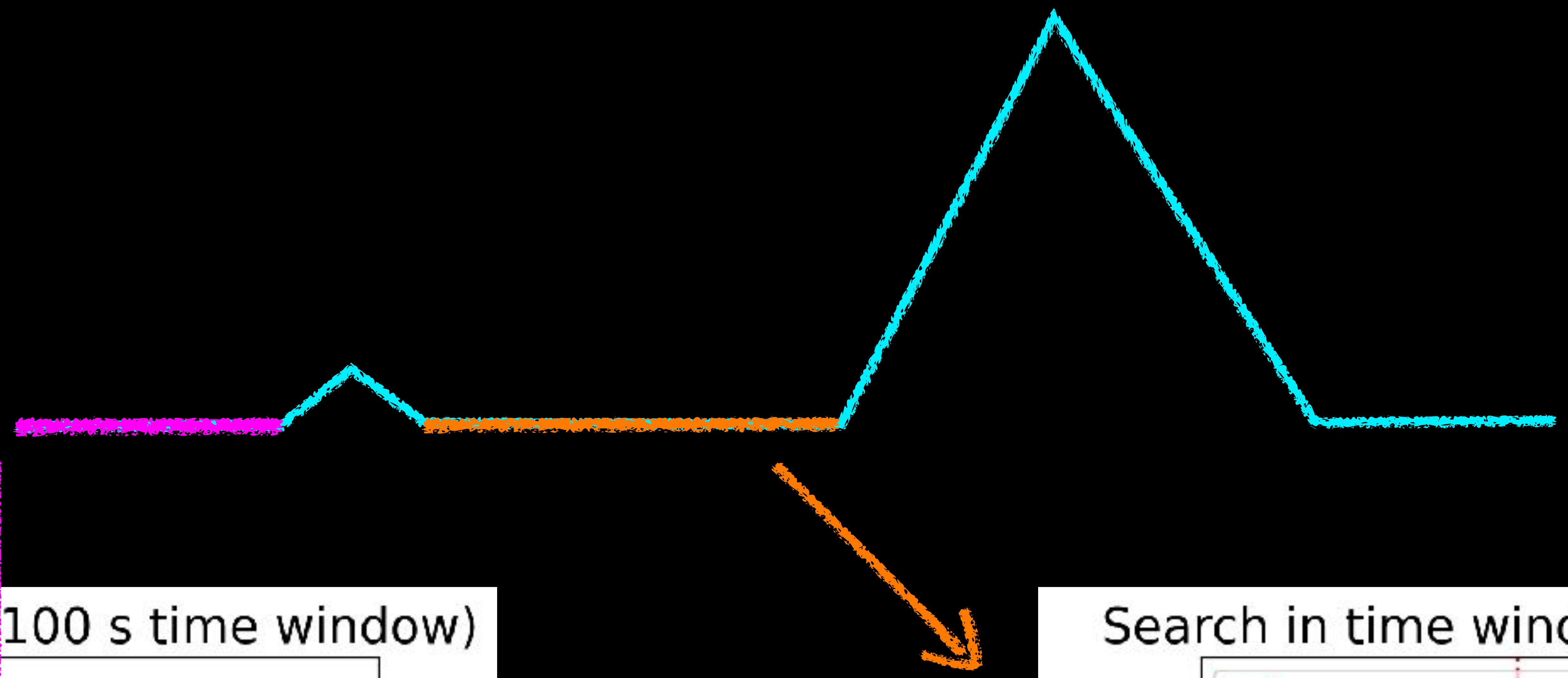

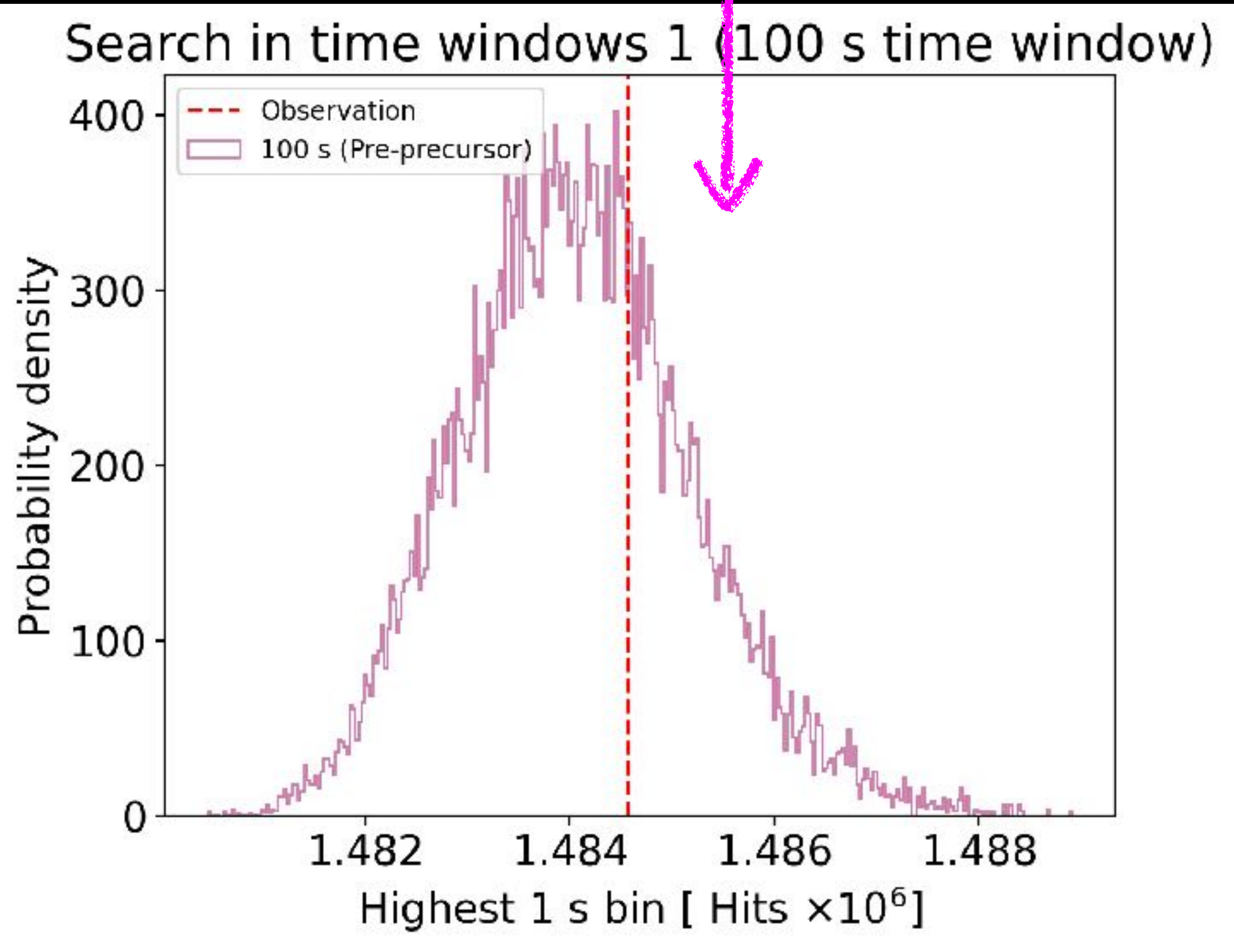

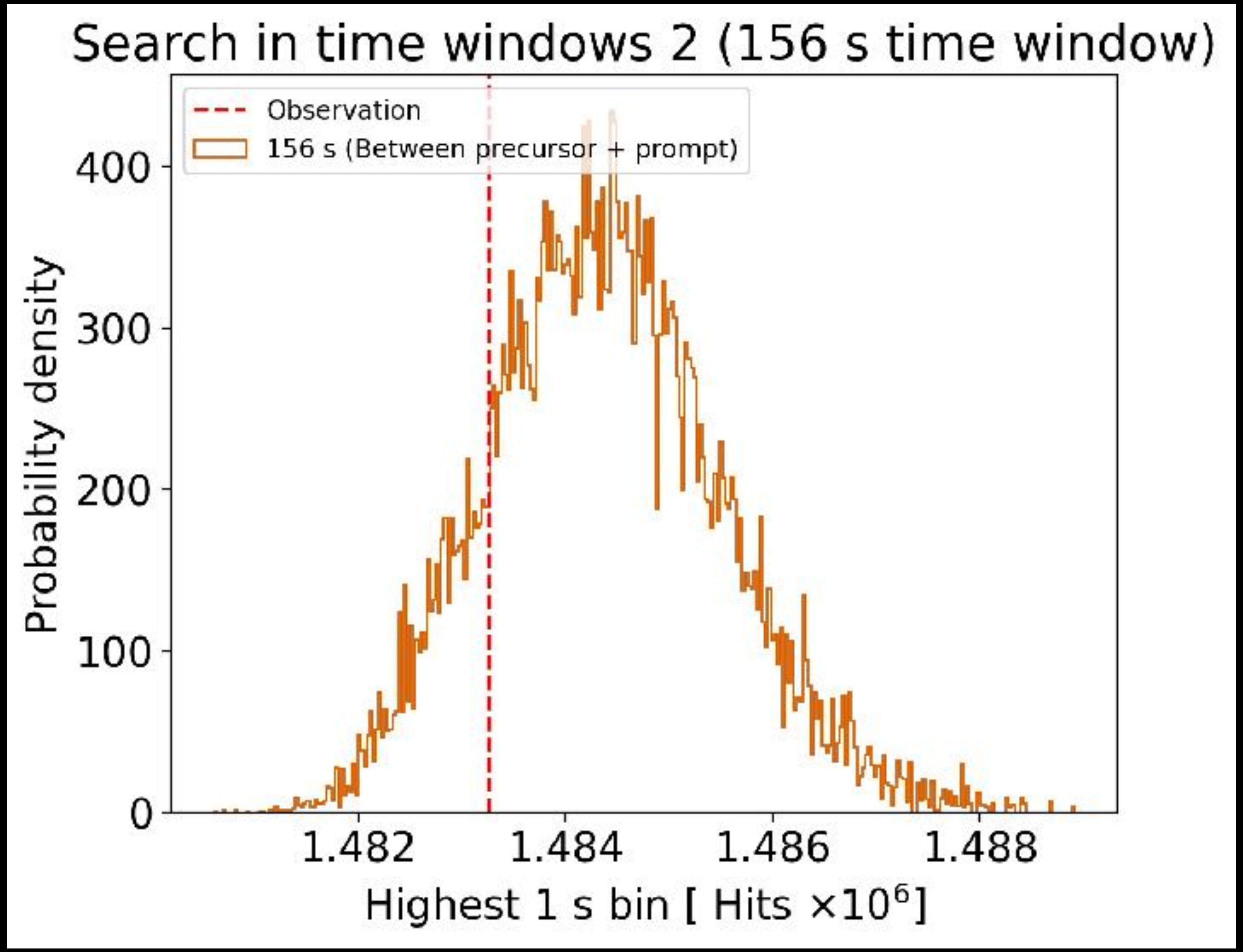

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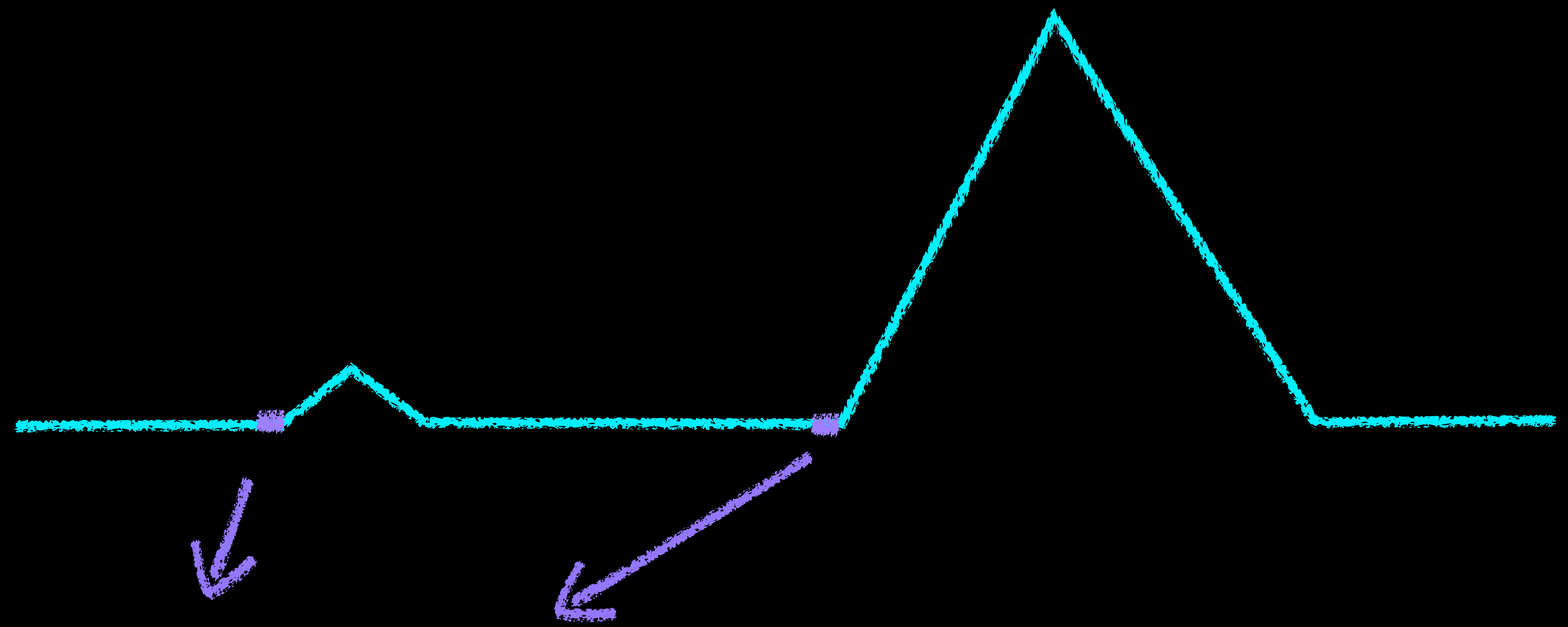

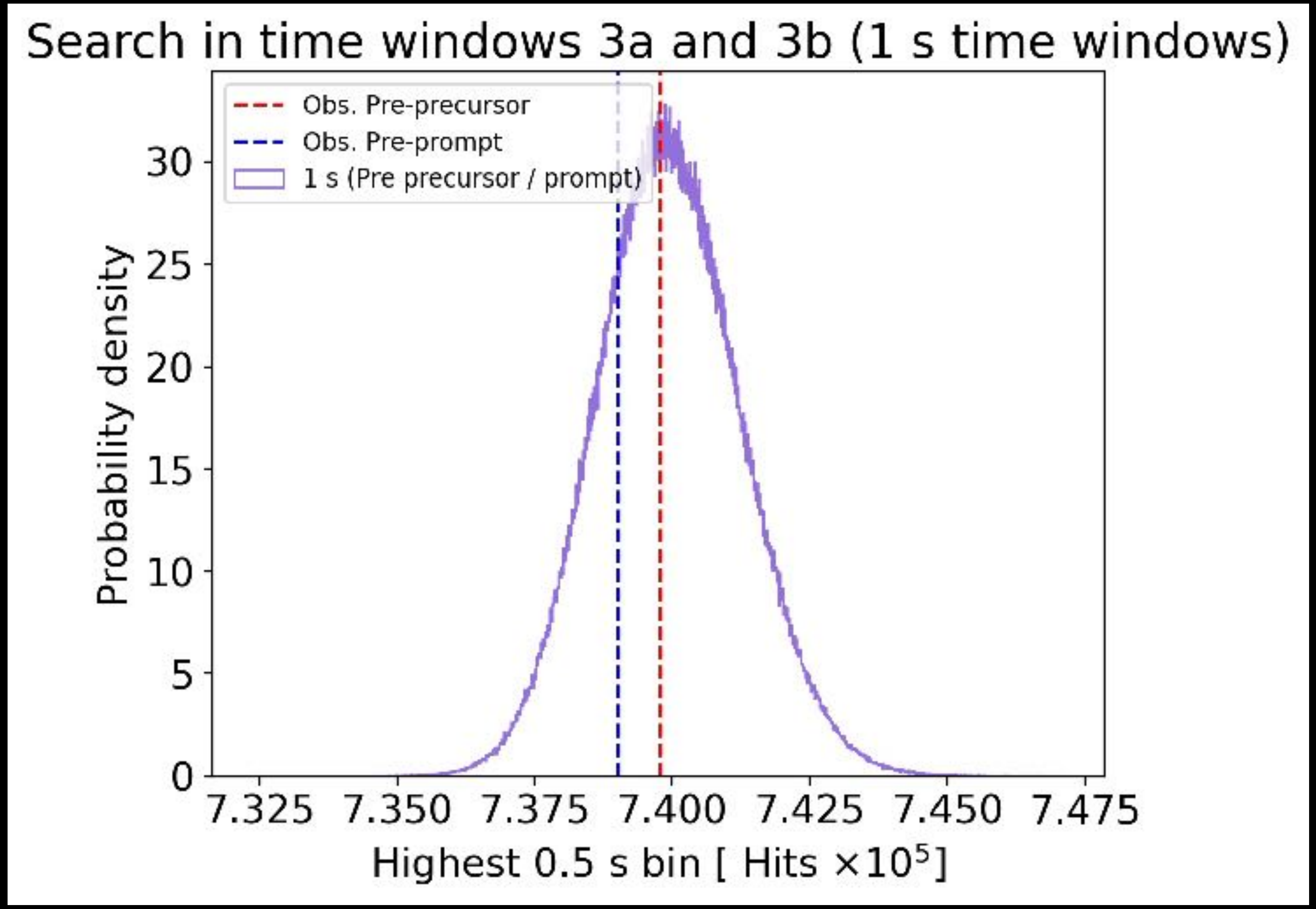

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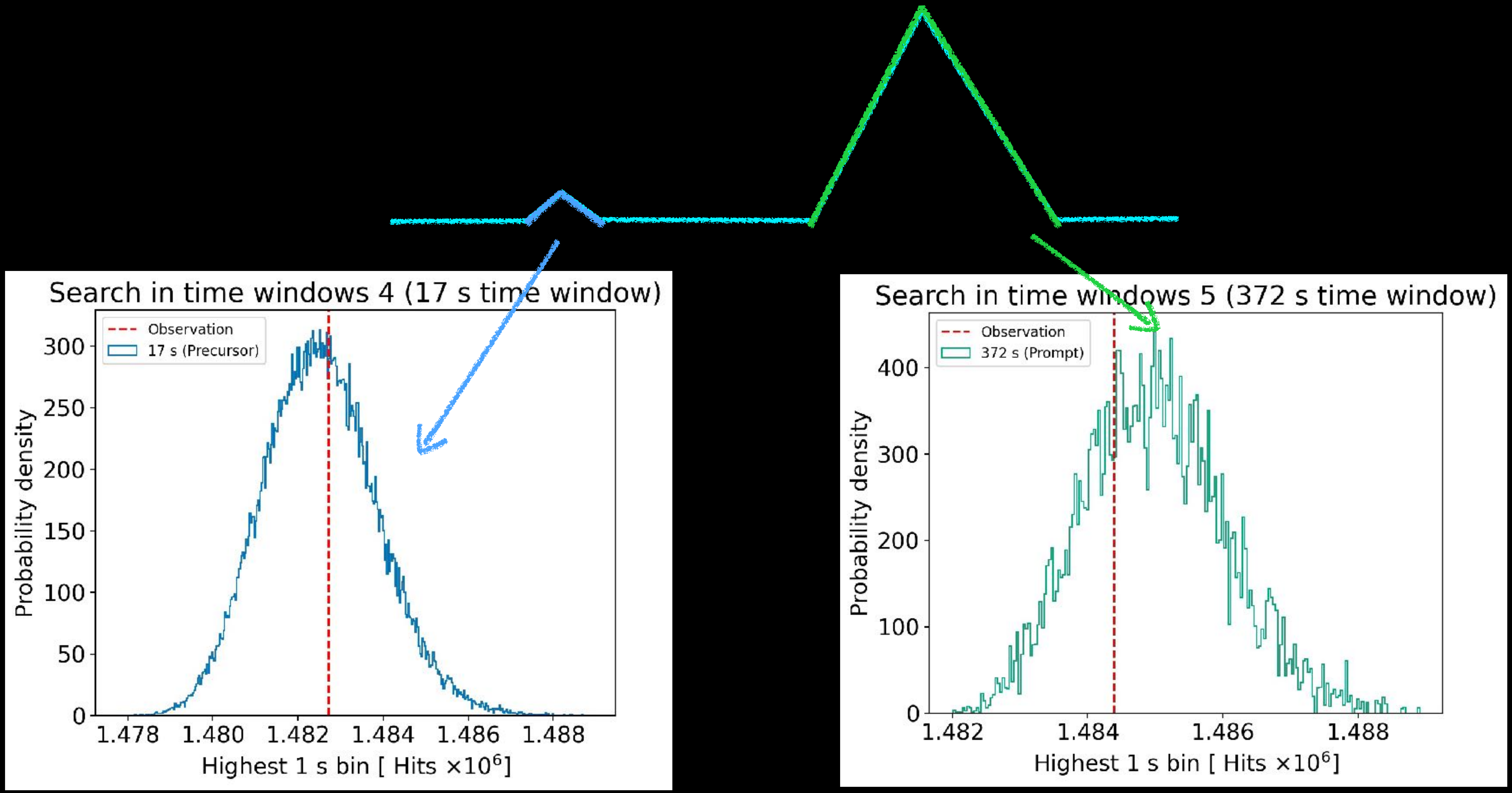
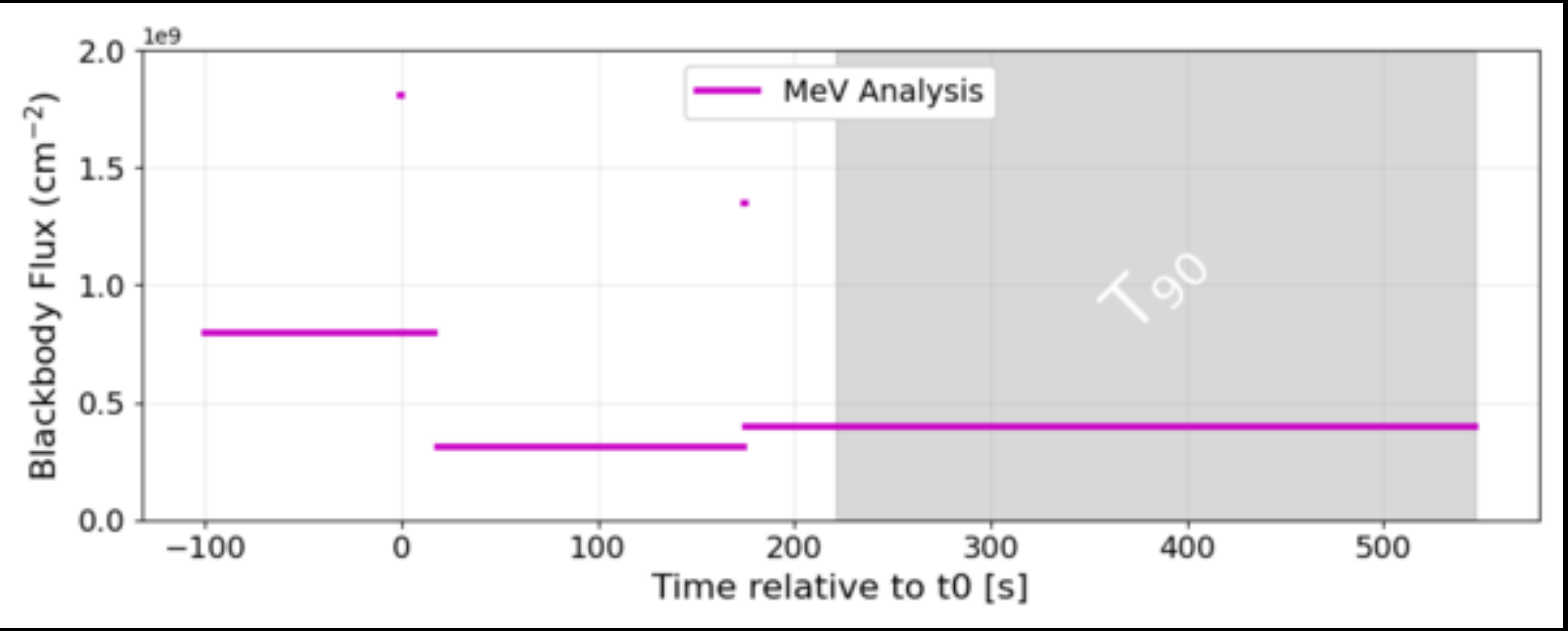


RESULTS: UPPER LIMITS

Publication: R. Abbasi et al 2023 ApJL 946 L26

Results

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



Upper limit for MeV neutrino emission for GRB 221009A assuming a black body spectrum with mean energy of 15 MeV

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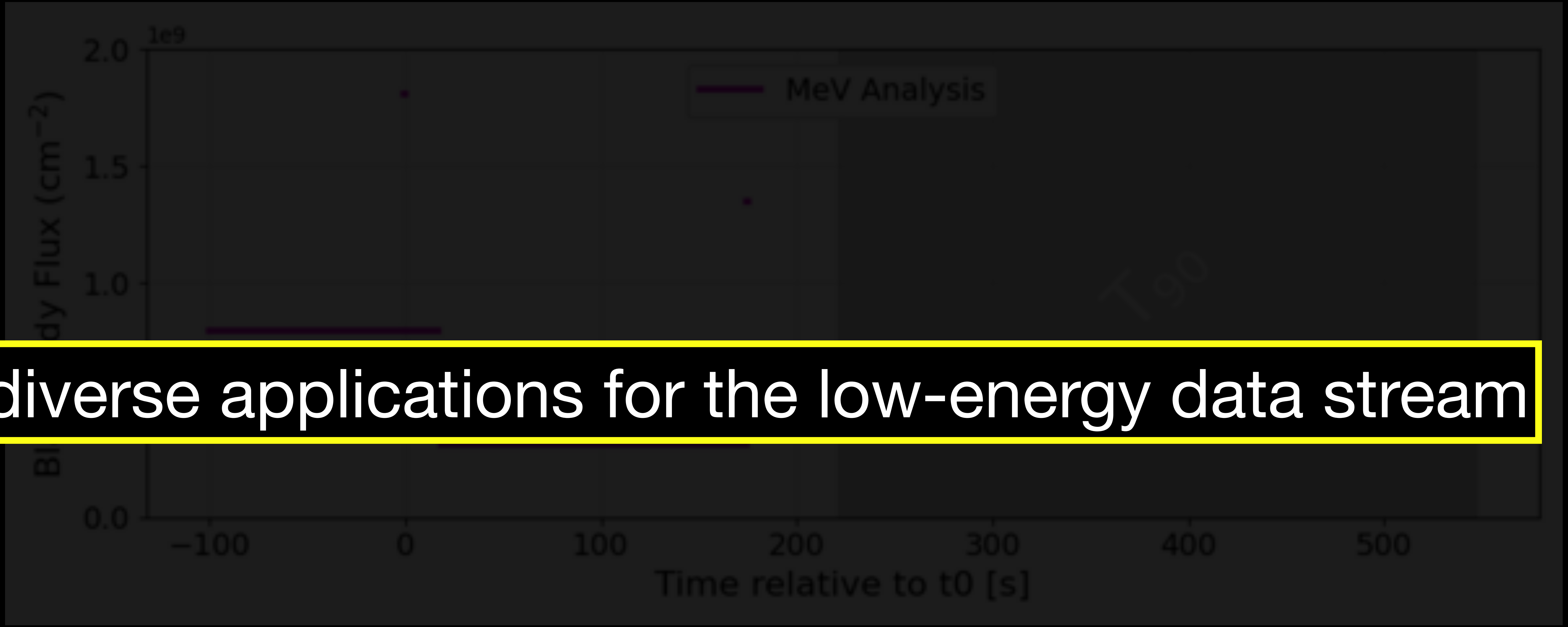


Upper limit for MeV neutrino emission for GRB 221009A assuming a black body spectrum with mean energy of 15 MeV

This analysis showcases the diverse applications for the low-energy data stream

CONCLUSIONS

- IceCube has the capability to observe neutrinos across a wide energy range, from high-energy to low-energy.
- Core-collapse supernovae and neutron star mergers are among the sources that can generate both gravitational waves and thermal neutrinos.
- SNDAQ handles the data stream and analysis of low-energy neutrinos, forming the foundation for the fast response analysis system.
- The analysis of GRB 221009A is a prime example of the applications of the low-energy neutrino data stream.
- The fast response system is designed to effectively respond to gravitational wave alerts and other external alerts.

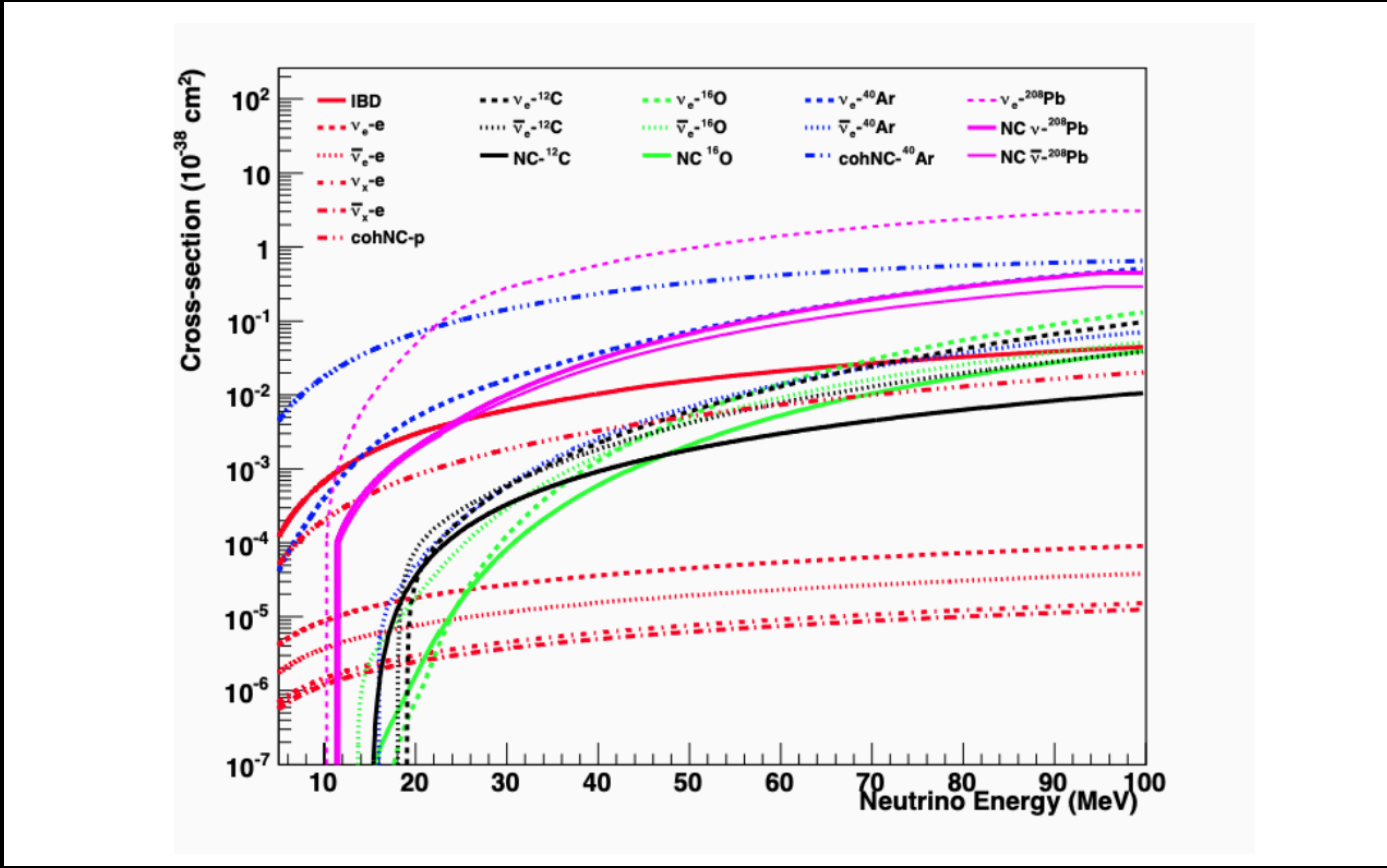
THANK YOU!

NEUTRINO PROCESSES: ENERGY REGIMES FOR 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 = any final set of hadrons, and l = lepton*

MEV NEUTRINO CROSS SECTION



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

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

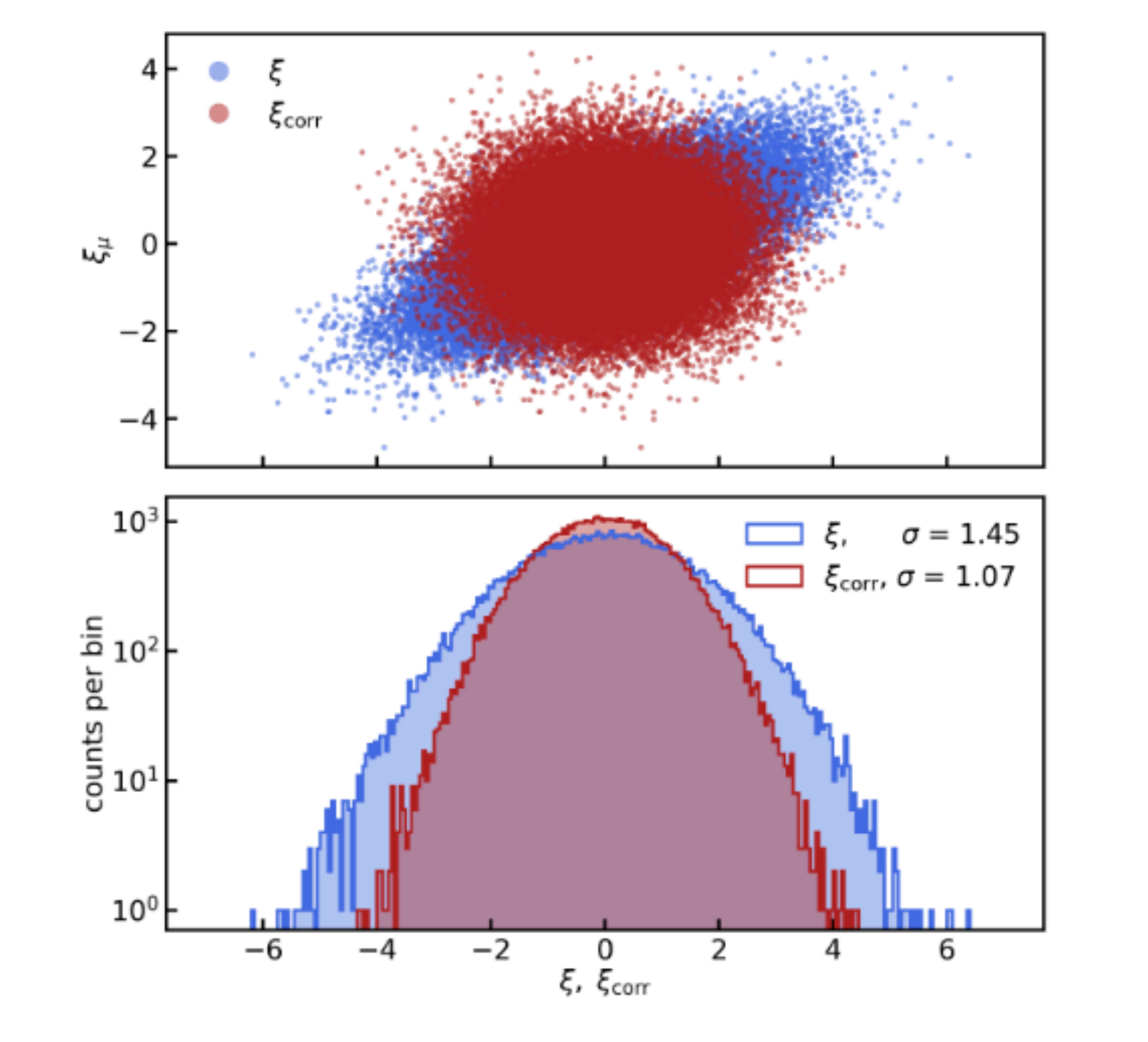
+ also pn interaction!

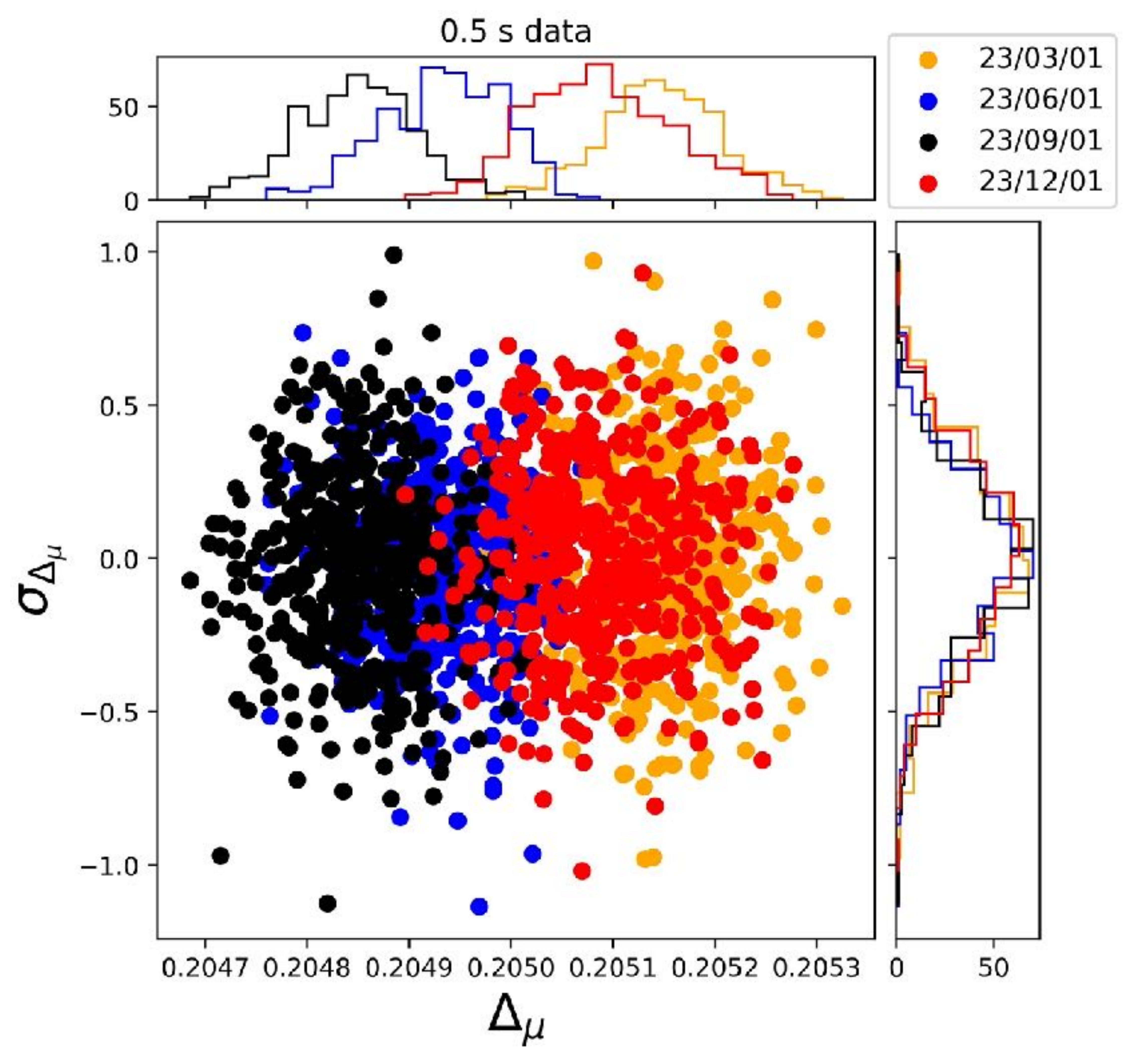
Hadronuclear

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

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

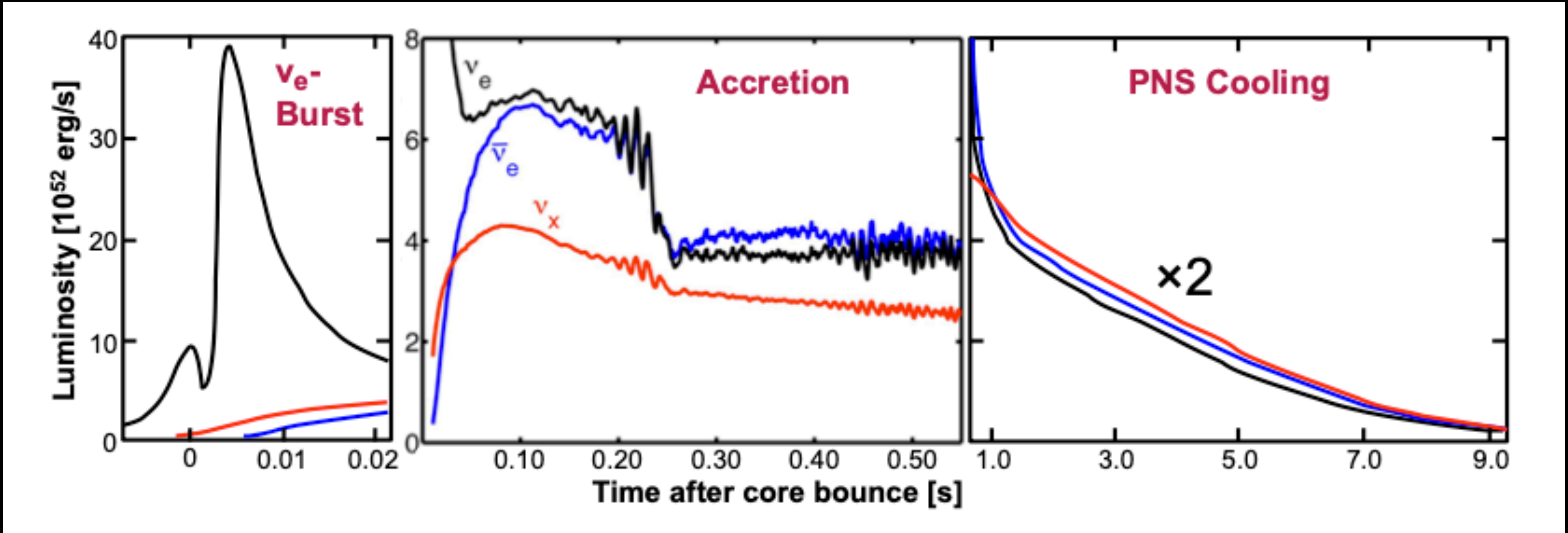
MUON RATE - SEASONAL





Credit: IceCube Collaboration

SUPERNOVAE: LOW ENERGY NEUTRINO LIGHTCURVE



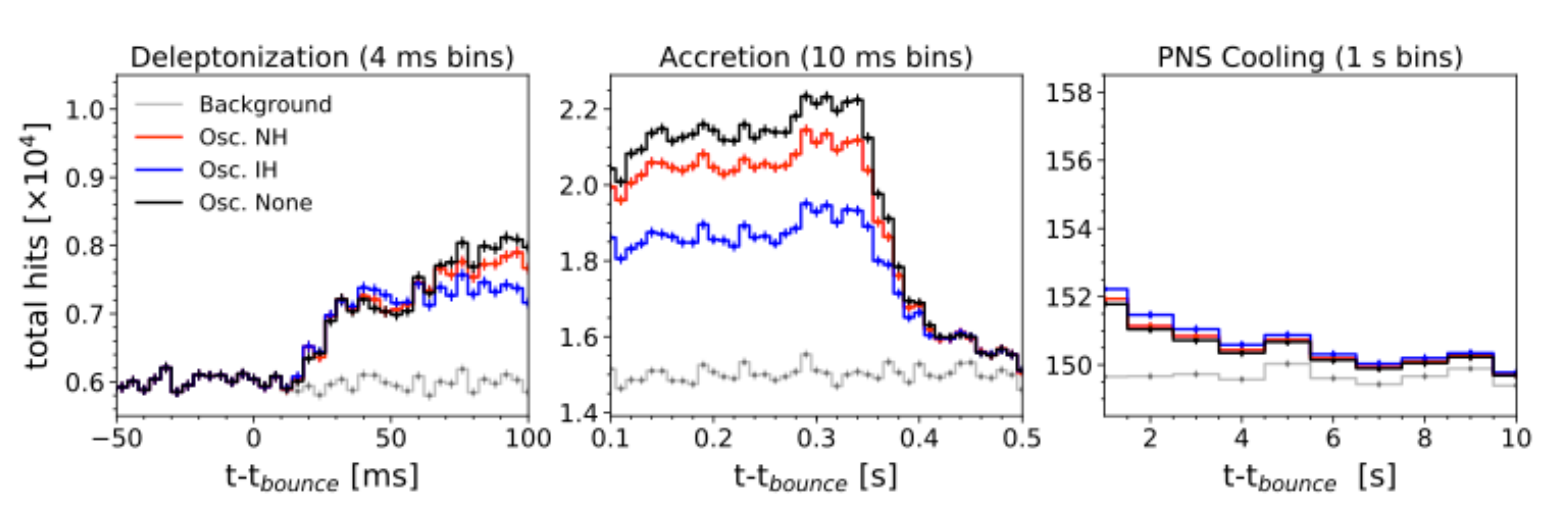
The burst of ν_e comes from electron capture:
$e^- + p -> \nu_e + n$

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

Credit: H. Thomas Janka, Florian Hanke, Lorenz Huedepohl, et al. Core-Collapse Supernovae: Reflections and Directions. *Progress of Theoretical and Experimental Physics*, 2012(1), 12 2012.

SUPERNOVAE: LOW ENERGY NEUTRINO LIGHTCURVE OBSERVABLE BY ICECUBE



Credit:Robert Cross, Alexander Fritz, and Spencer Griswold. Eleven Year Search for Supernovae with the IceCube Neutrino Observatory. In *International Cosmic Ray Conference*. Proceedings of Science, 2019

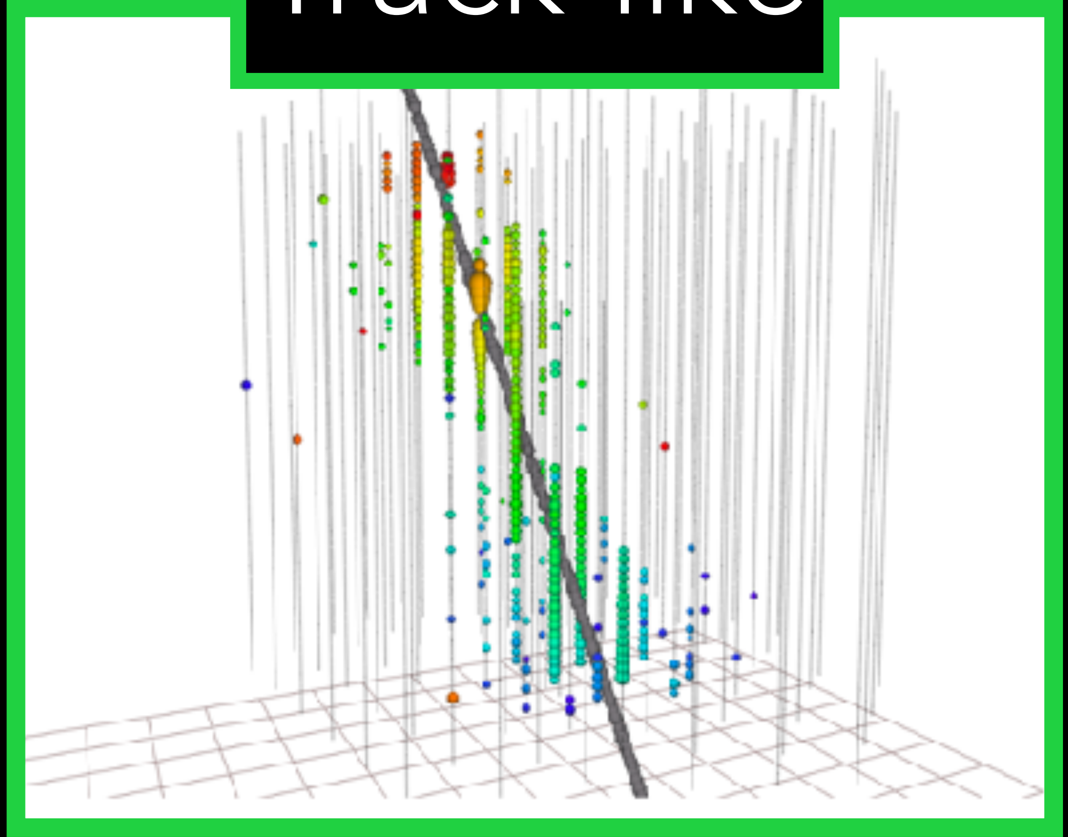
ICECUBE: HIGH-ENERGY NEUTRINOS

$>$TeV ν

Deep inelastic scattering

Depending on reaction and ν flavor

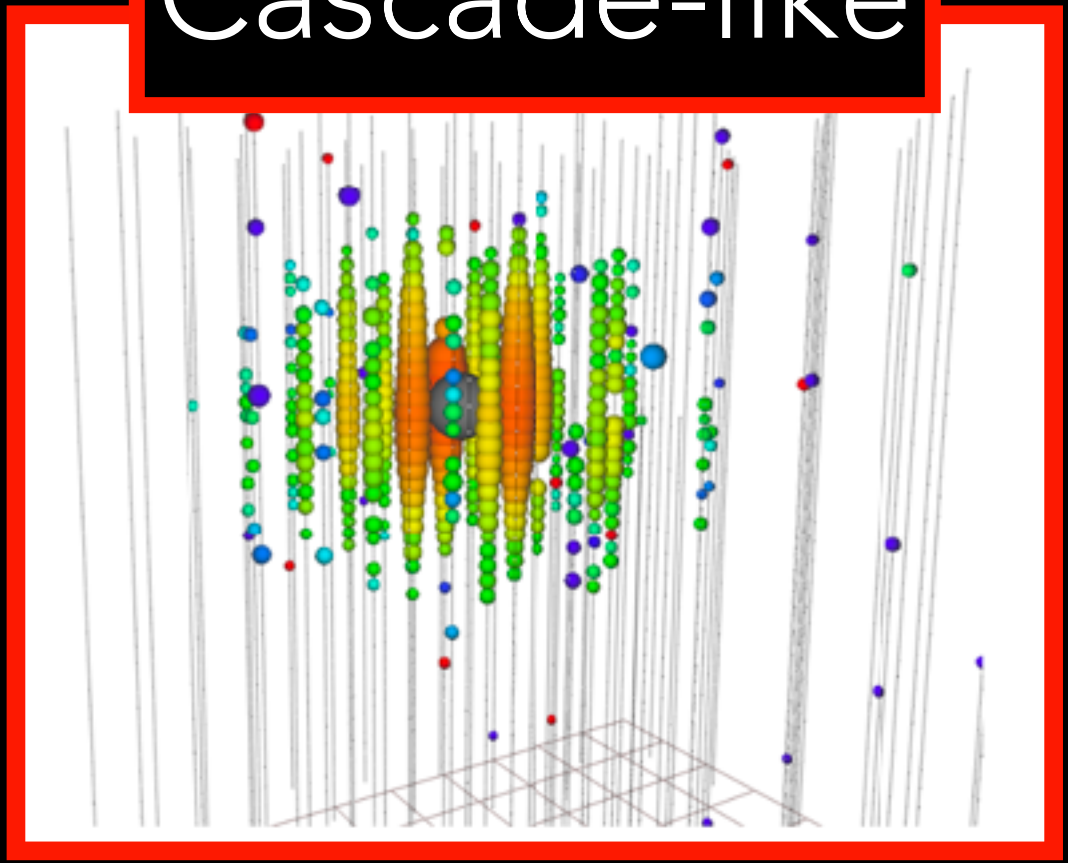
Track-like



Long tracks

Good for directionality

Cascade-like

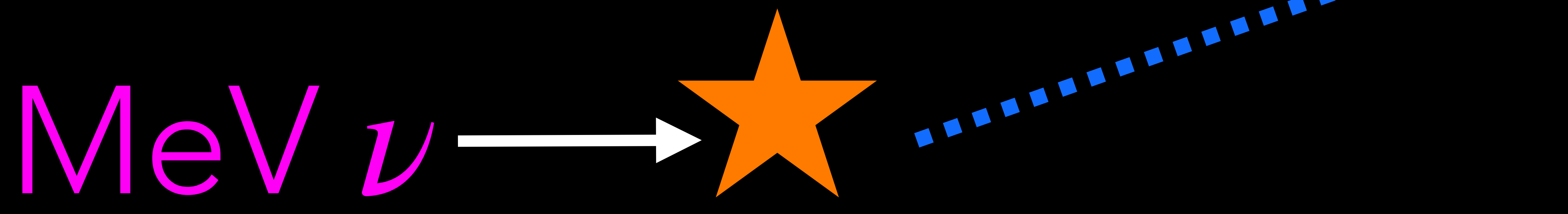


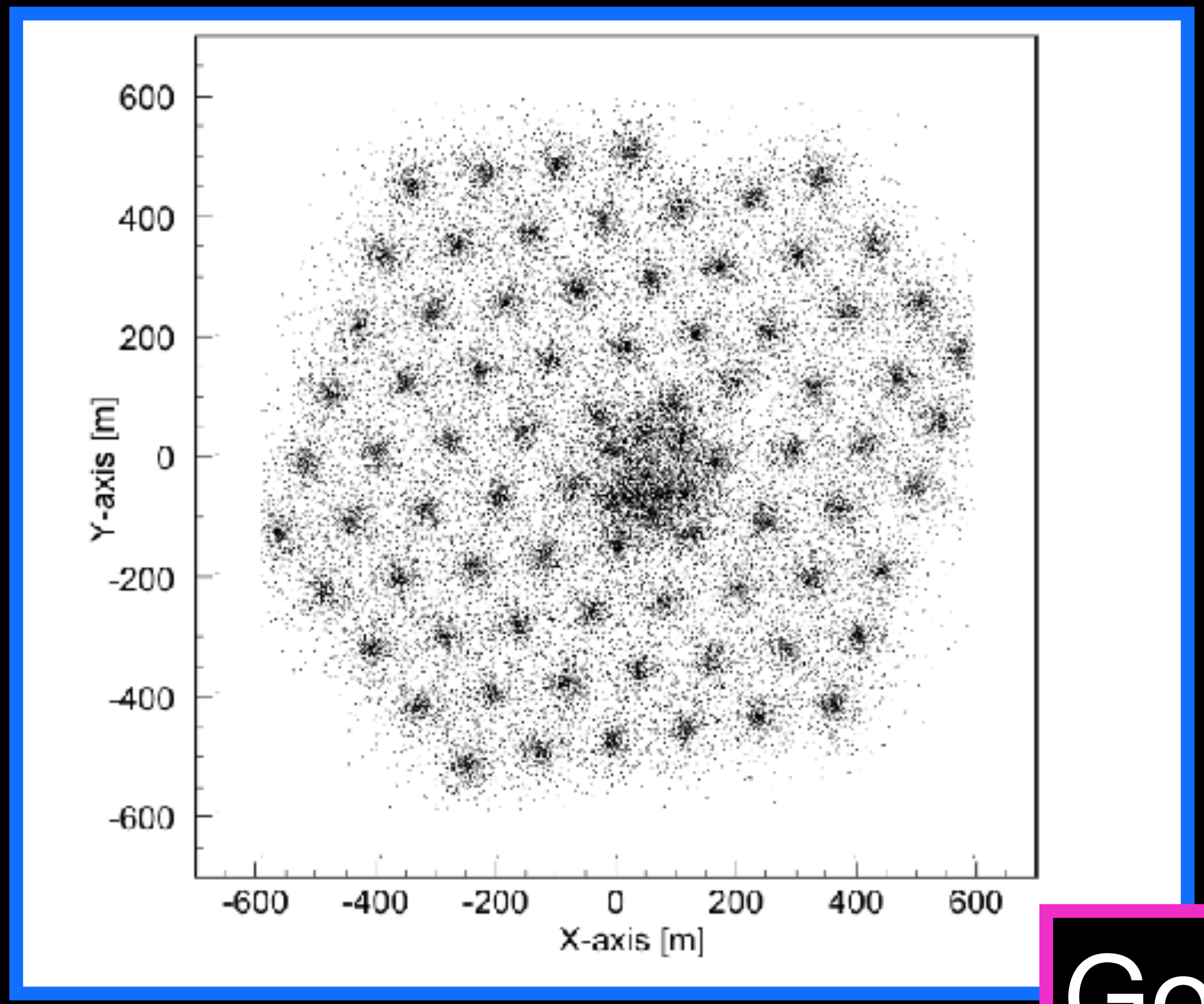
Shorter tracks *(O(10's m))*

Good for energy reconstruction

ICECUBE: LOW-ENERGY NEUTRINOS

Inverse beta decay (>99% of our signal)

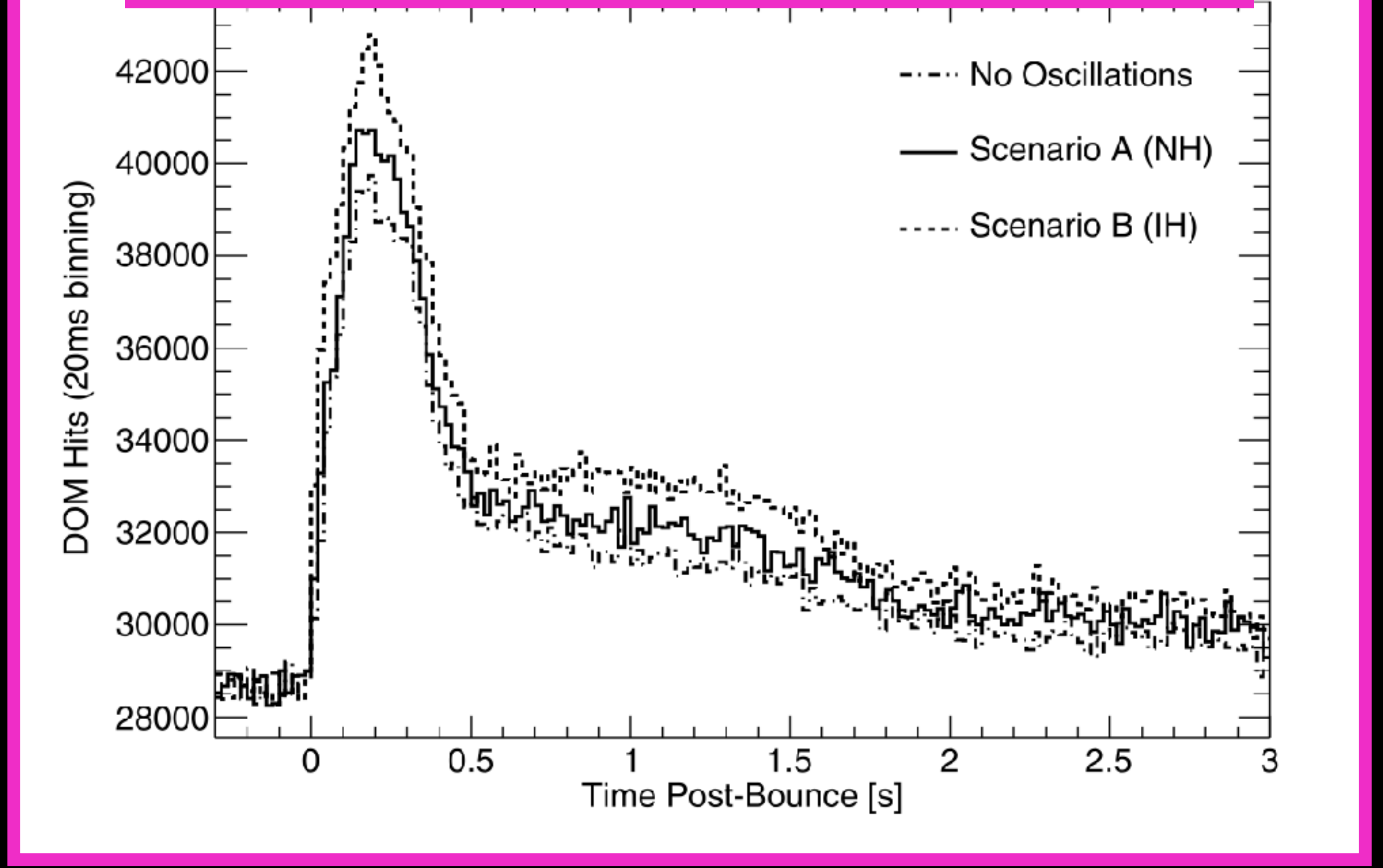




Very short tracks (*O(cm)*)

No directionality (unlike HE neutrinos)

Good timing resolution

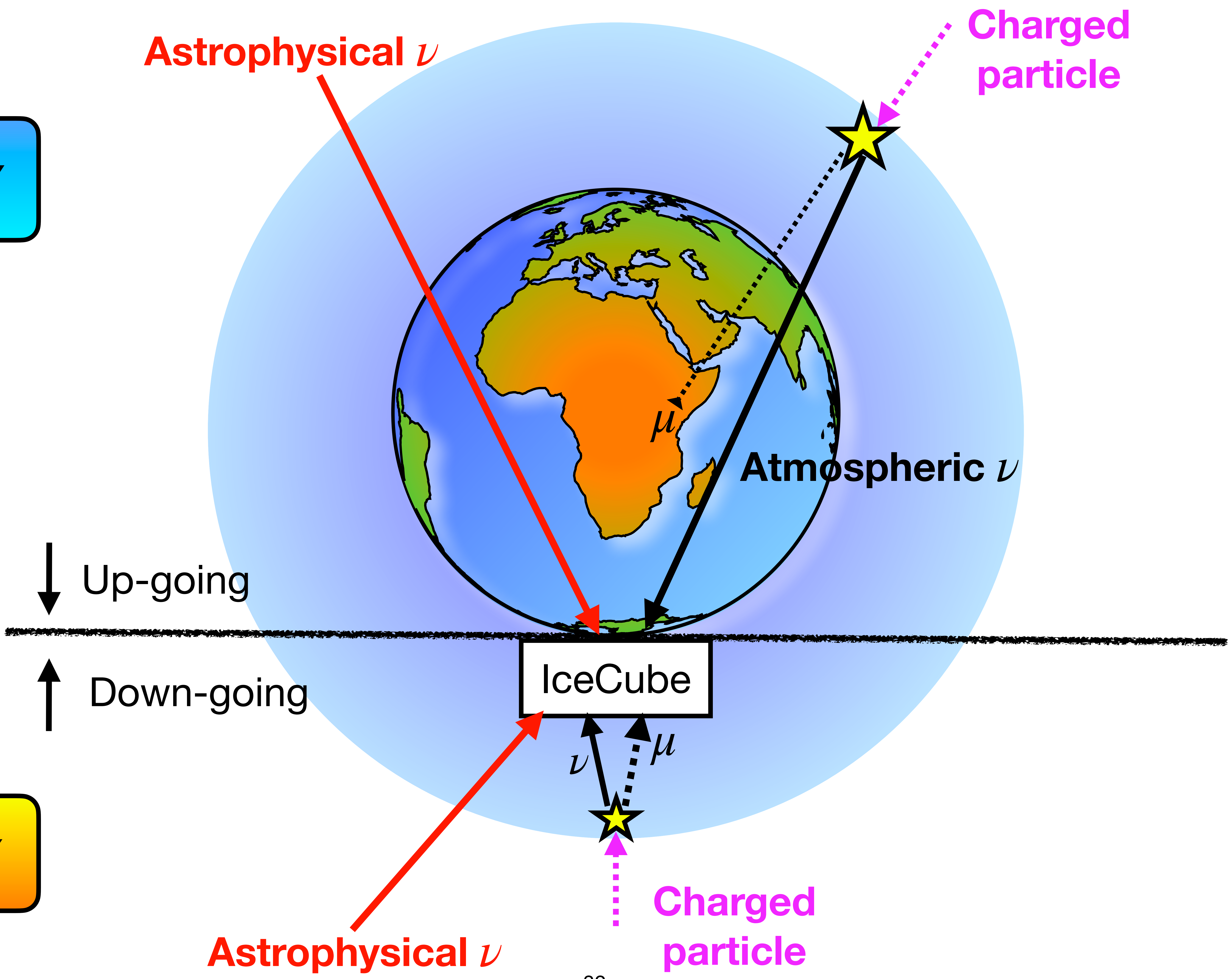


We need quite a high flux of neutrinos to raise our counts above noise floor

Credit: R. Abbasi and IceCube Collaboration. 'IceCube Sensitivity for Low-Energy Neutrinos from Nearby Supernovae' (2011) Astronomy & Astrophysics 535, 12

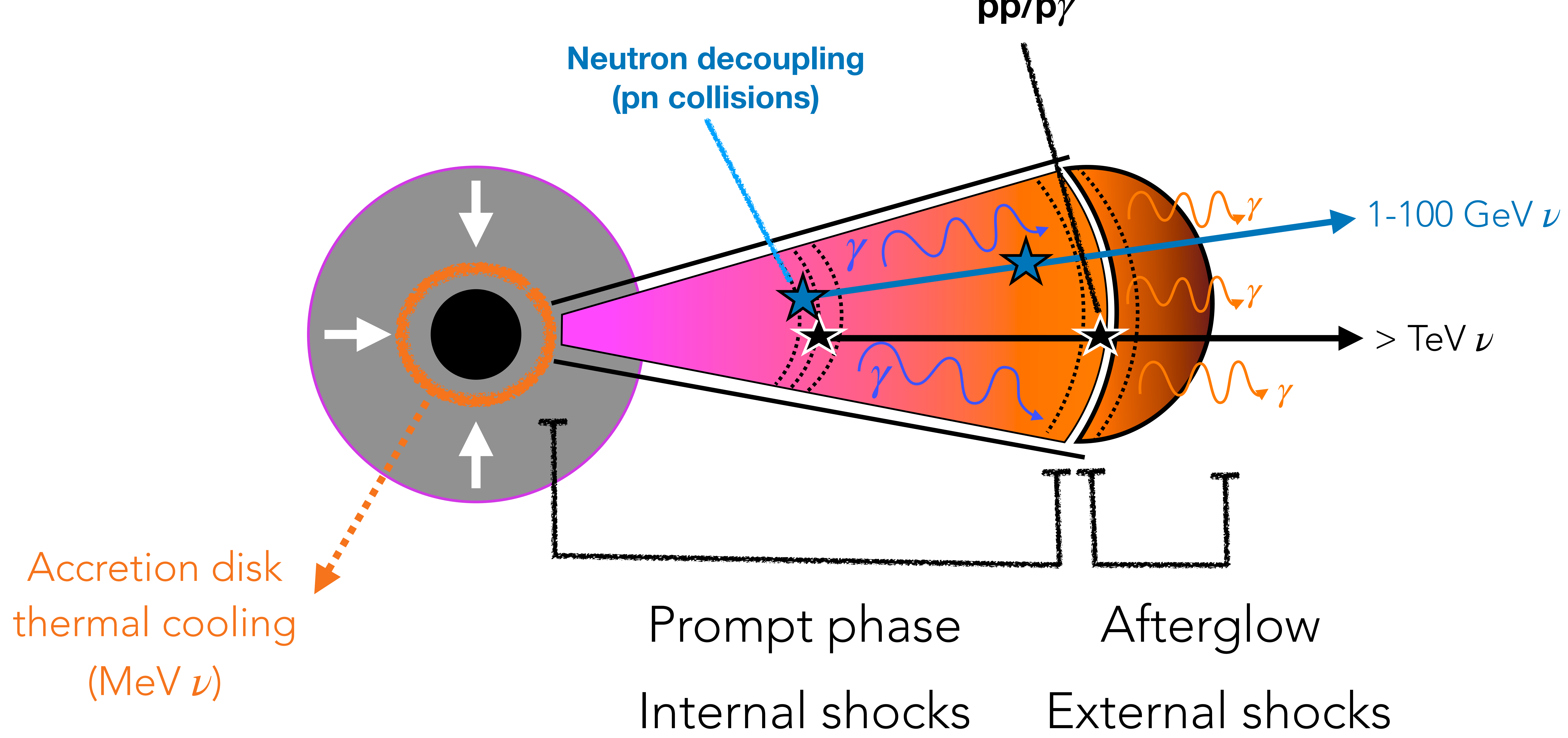
ICECUBE: BACKGROUND

NORTHERN SKY



SOUTHERN SKY

PRODUCTION REGIONS



SNDAQ ANALYSIS

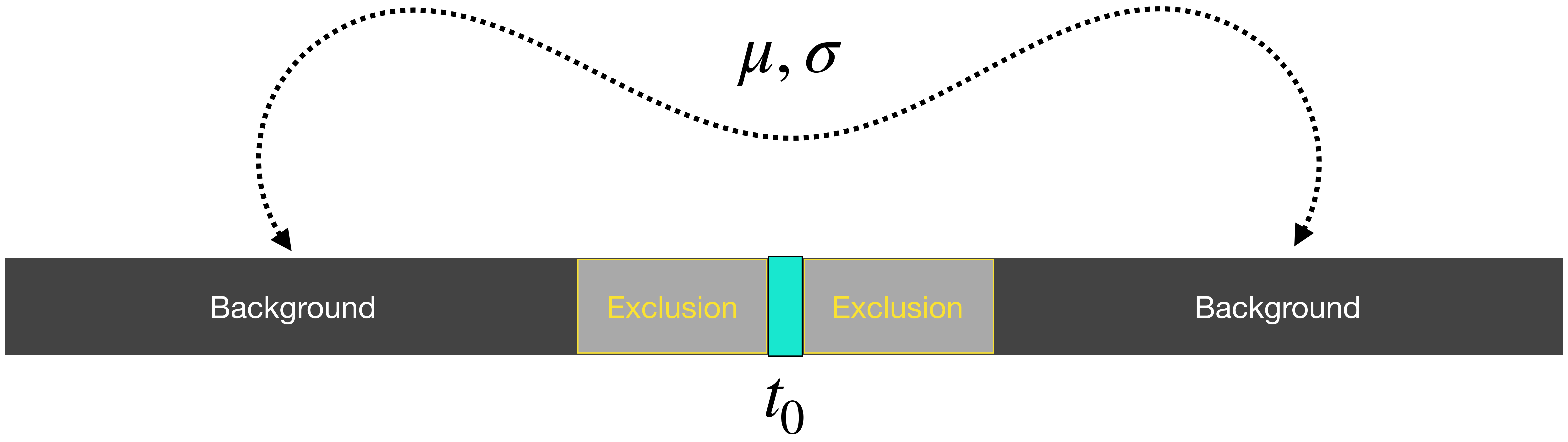
Form of weighted average

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

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

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

Significance



0.5 s, 1 s, 1.5 s, 4 s and 10 s