

TeV Particle Astrophysics 2026 (TeVPA2026)

Tendo, September 3rd, 2026

On the optical-neutrino synchronized observation of interaction-powered supernovae

The Astrophysical Journal Letters, Volume 1005, Number 2 (2026)

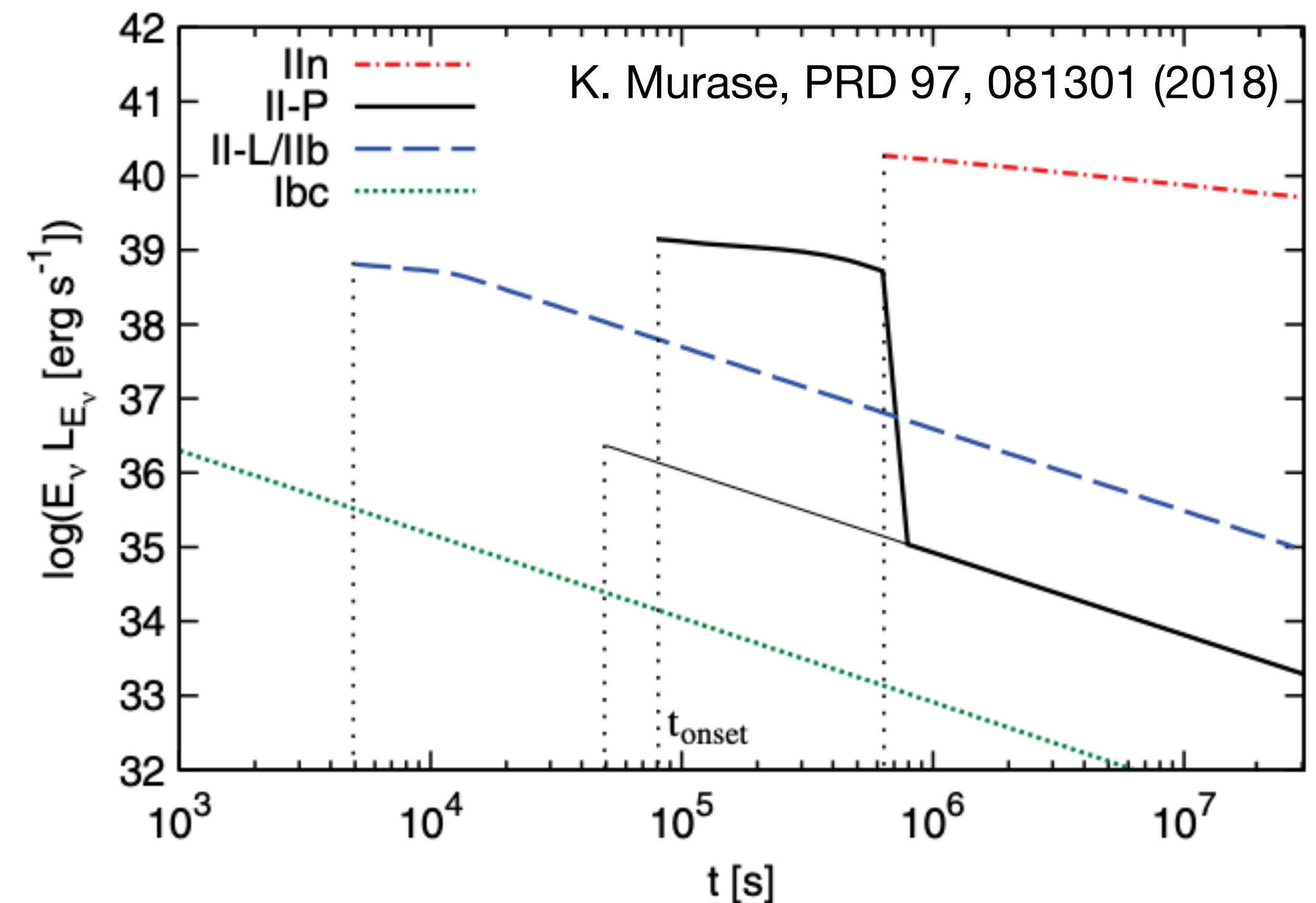
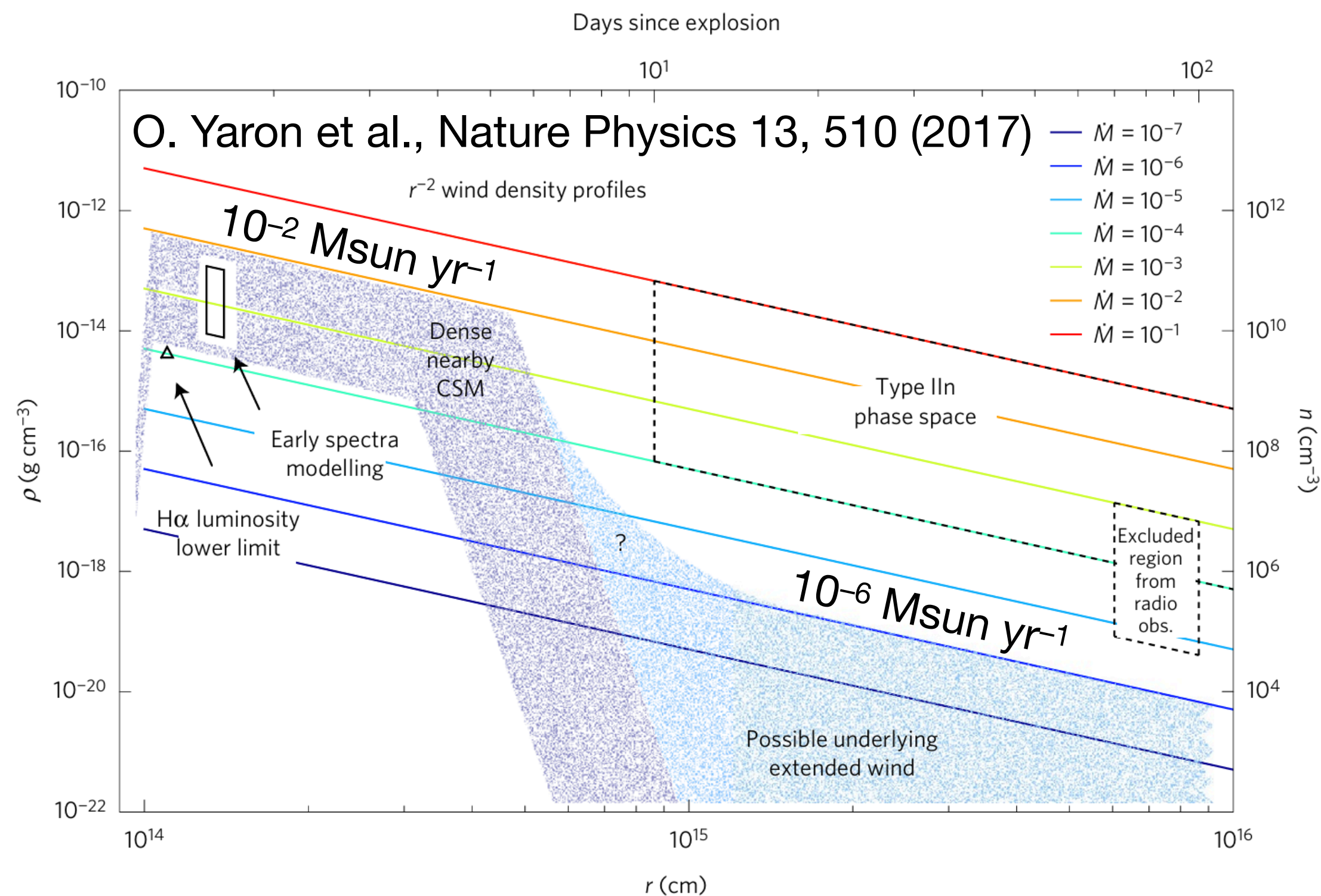
Yosuke Ashida (Tohoku University)

Ryo Sawada (RIKEN), Yusuke Inoue (Kyoto University)

Interacting Supernovae

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- Light curve of supernovae is largely shaped by the surrounding environment.
- ~10% of core-collapse supernovae (Type **IIn** or **Ibn**) are classified as *interacting supernovae*, indicating ejecta interactions with *circumstellar material (CSM)*.
- Such SNe may be a place where efficient *particle acceleration* happens, and therefore *high-energy neutrino productions* (via *pp*) as well.

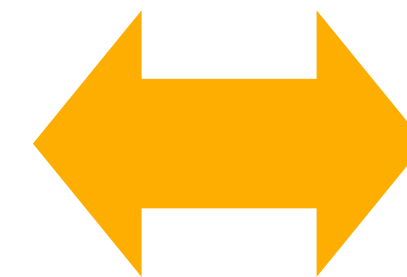


Optical-Neutrino Coincidence

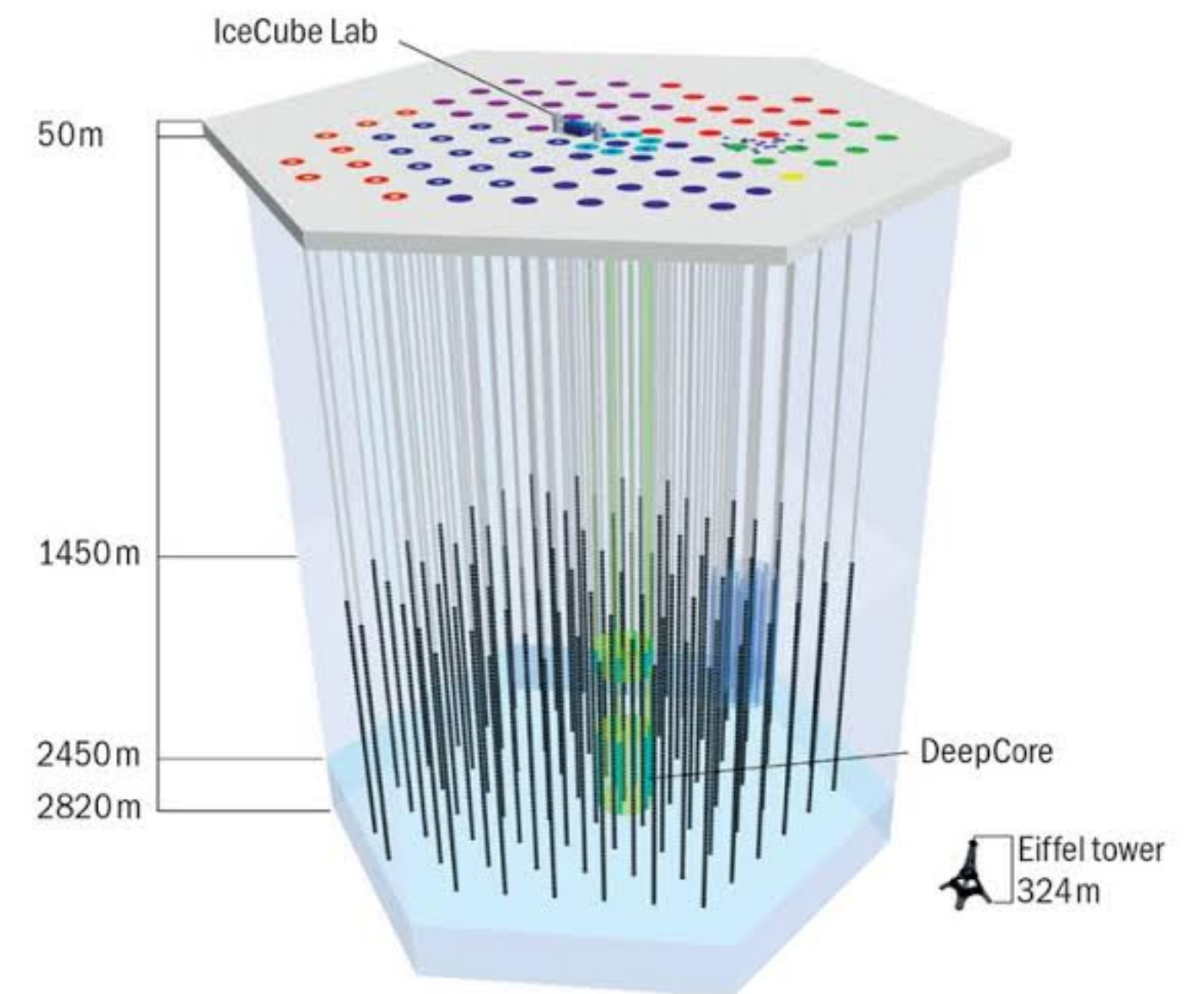
Recently, many temporal, spacial correlations at a $2\sim 3\sigma$ level between *optical* and *neutrino* are reported.

- **2023uqf (lbn, ~723 Mpc):** R. Stein et al., arXiv:2508.08355 [astro-ph.HE] Focus of this talk
- 2023syx (lln, ~160 Mpc): M. X. Lu et al., ApJ 997, 145 (2026)
- 2025cbj (lln, ~290 Mpc): M. X. Lu et al., ApJ 997, 145 (2026)
- 2017hcd (lln, ~159 Mpc): S. Ji et al., arXiv:2603.03679 [astro-ph.HE]
- 2021foa (lln/lbn, ~35 Mpc): M. X. Lu et al., arXiv:2606.06409 [astro-ph.HE]
- ... and more?

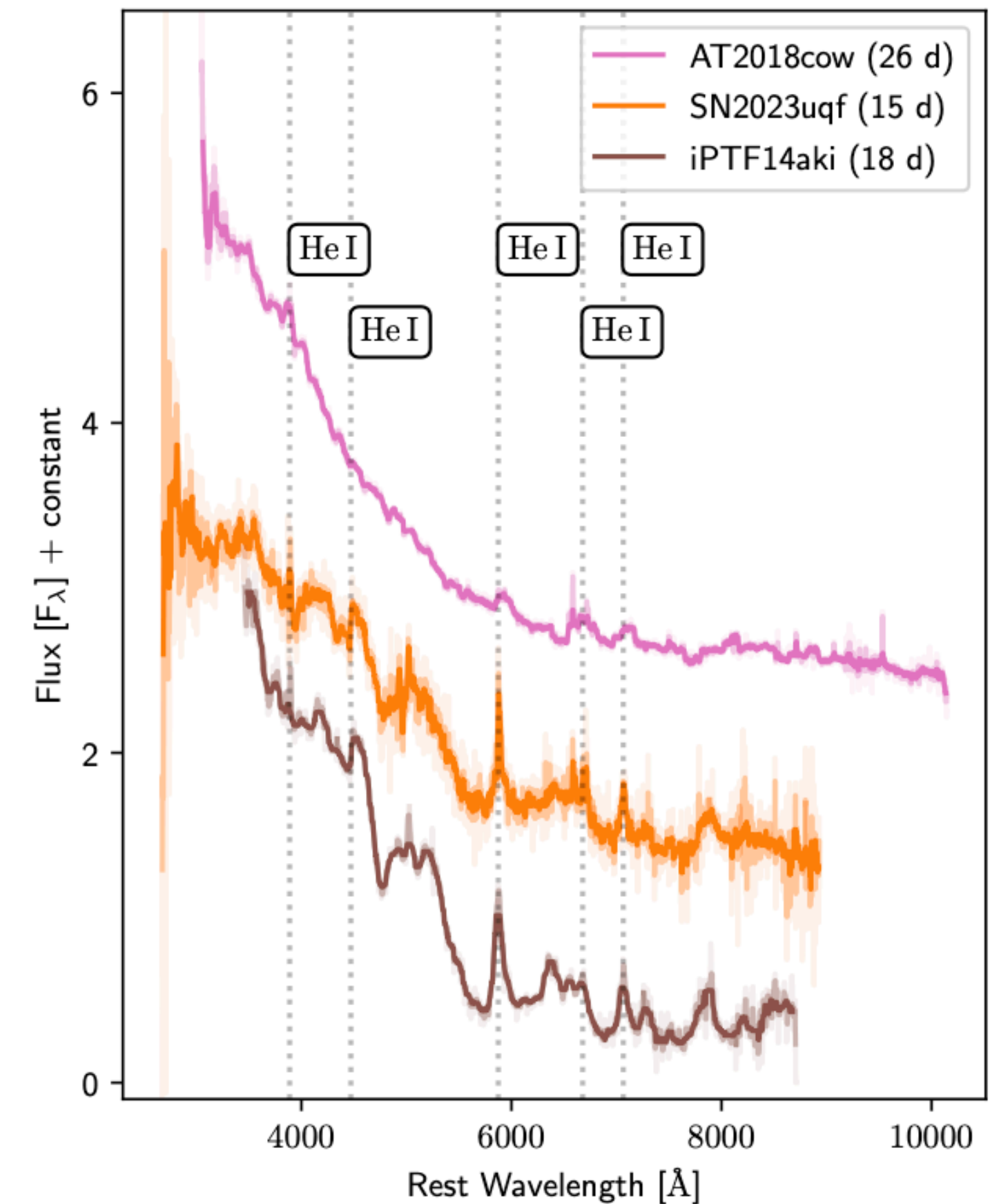
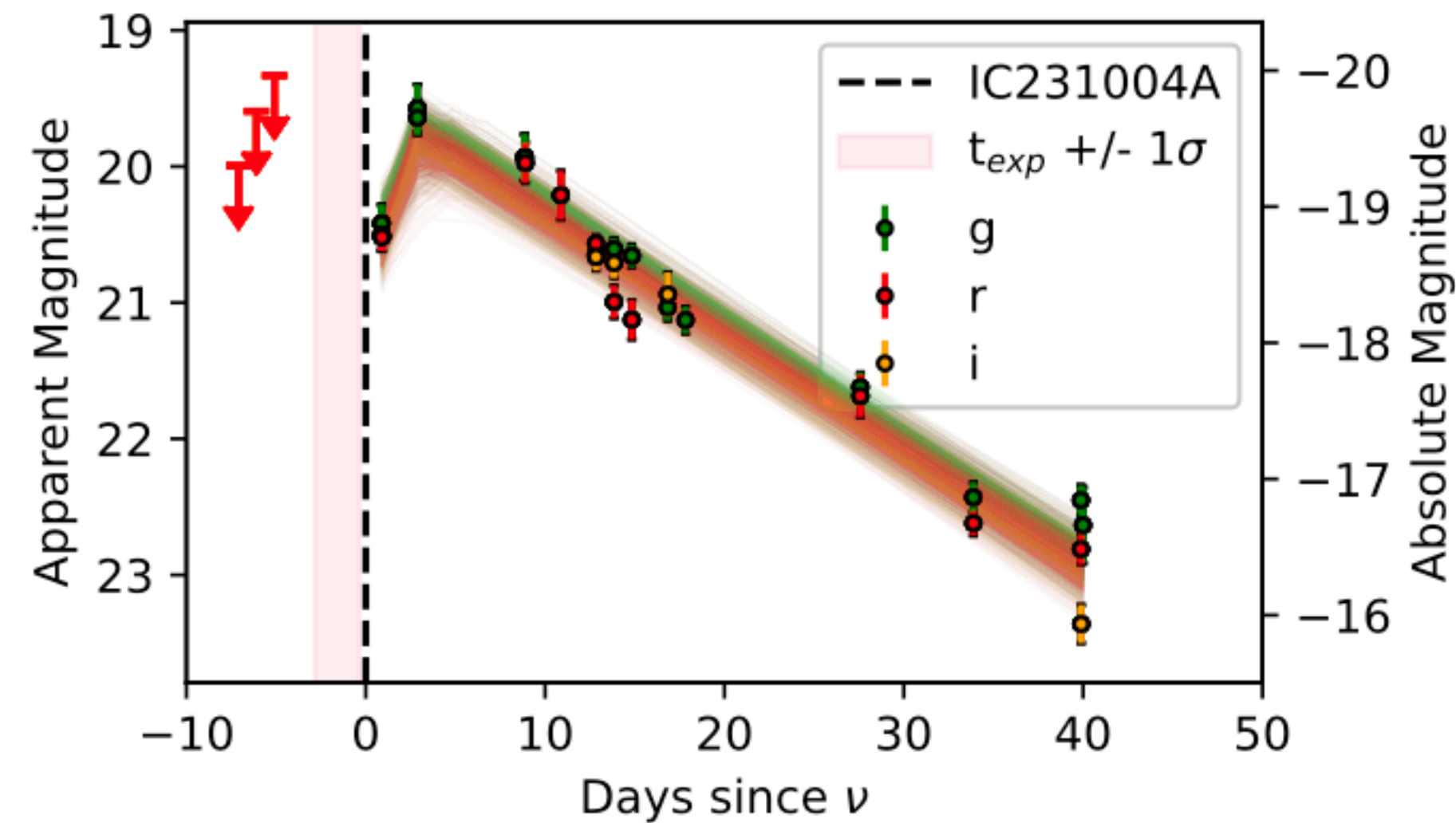
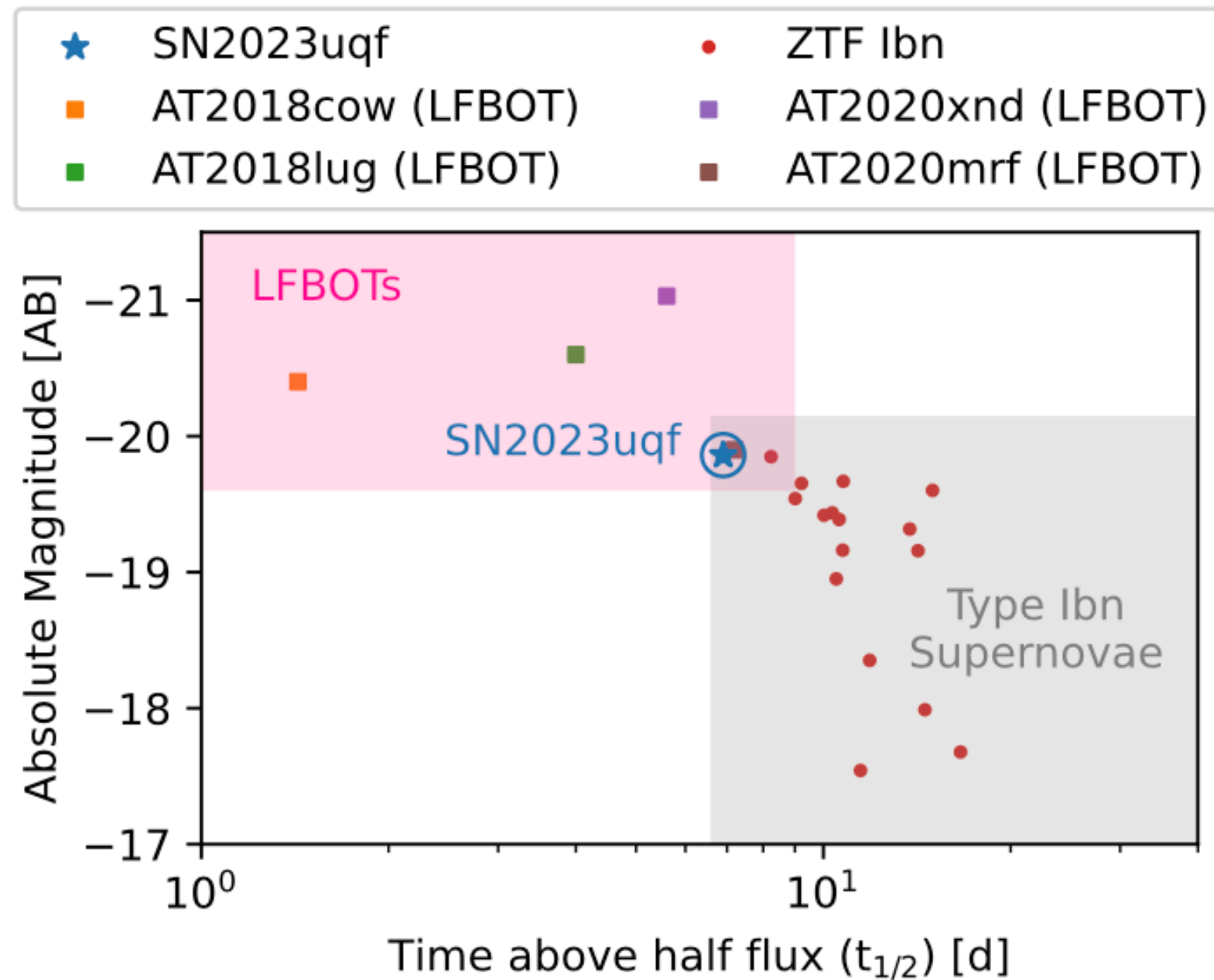
Optical (ZTF, ASAS-SN, ...)



Neutrino (IceCube)



- On October 4th 2023, a **442 TeV** high-energy neutrino alert was issued with an astrophysical probability of 84%, and followed up by ZTF.
- This was classified as Type Ibn from its spectral feature.
- Its **high luminosity** ($M_g = -19.7$) and **fast decay** ($t_{1/2} \sim 8$ d) shows similarity between 2023uqf and LFBOTs.
- Light curve analysis was performed by MOSFiT (semianalytic model).

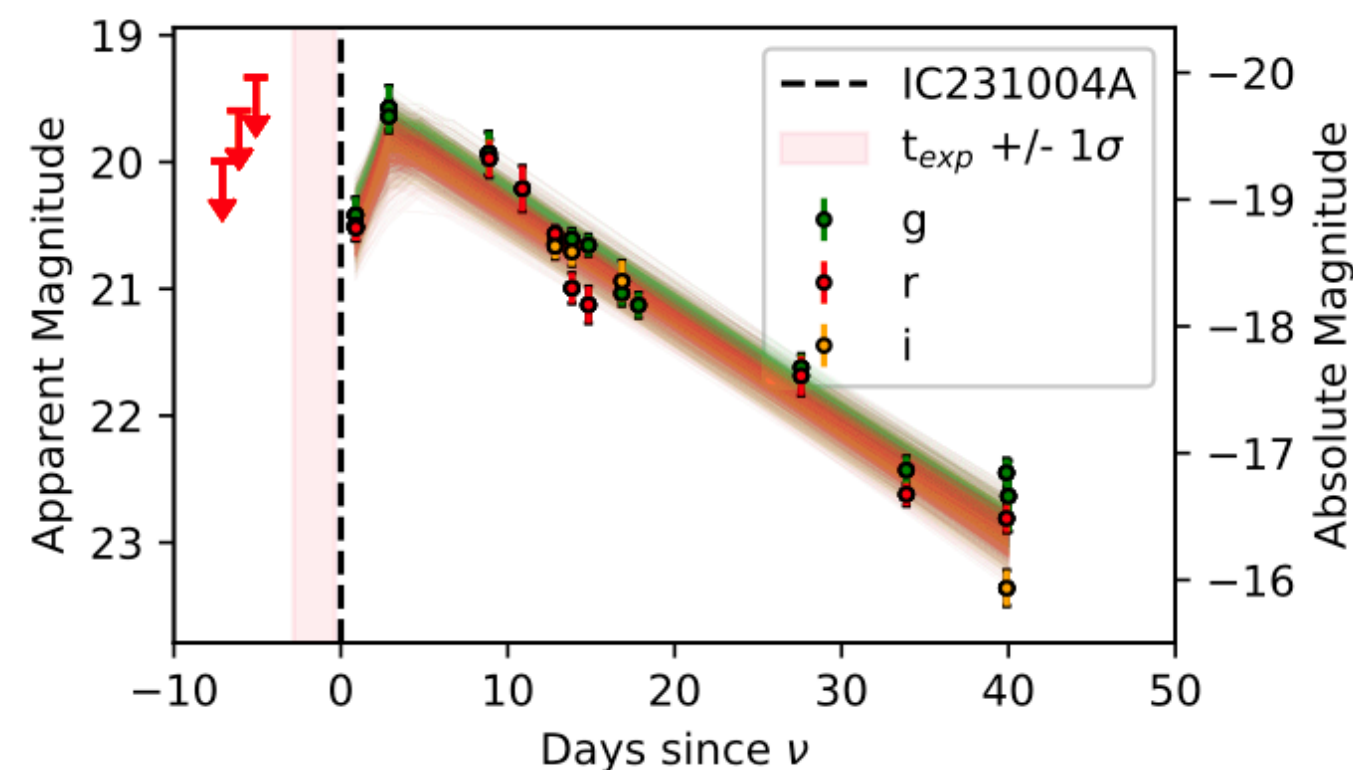


Framework of This Work

- We perform calculations based on a **radiation-hydrodynamic (RHD)** model, while based on observational constraints obtained by R. Stein et al. 2025.
- This achieves a proper test on whether the optically inferred environment can support an efficient particle acceleration to **PeV** scales.

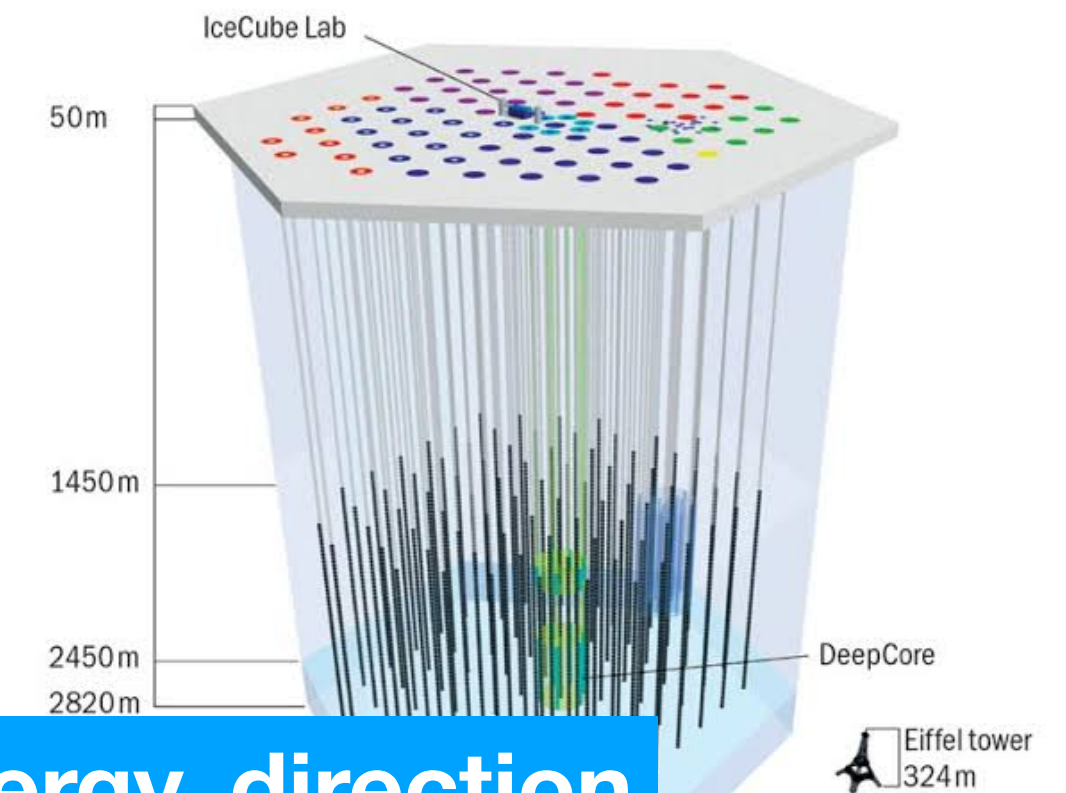


Light curve (ZTF)



Optical modeling (STELLA)
+
Shock evolution & particle acceleration
+
Neutrino detectability (IceCat-1)

Neutrino energy, direction
(IceCube)



STELLA

S. I. Blinnikov et al. 1998

S. Blinnikov et al. 2000

S. I. Blinnikov et al. 2006

GCN Circular 34797

Subject IceCube-231004A - IceCube observation of a high-energy neutrino candidate track-like event
Event [IceCube-231004A](#)
Date 2023-10-04T15:46:15Z (3 years ago)
From Massimiliano Lincetto at Ruhr-Universitaet Bochum <lincetto@astro.ruhr-uni-bochum.de>
Via Web form

The IceCube Collaboration (<http://icecube.wisc.edu/>) reports:

On 2023-10-04 at 14:39:41.18 UT IceCube detected a track-like event with a high probability of being of astrophysical origin. The event was selected by the ICECUBE-Astrotrack-GOLD alert stream. The average astrophysical neutrino purity for Gold alerts is 50%. This alert has an estimated false alarm rate of 0.4490 events per year due to atmospheric backgrounds. The IceCube detector was in a normal operating state at the time of detection.

After the initial automated alert (https://gcn.gsfc.nasa.gov/notices_amon_g_b/138415_56188508_amon_02), more sophisticated reconstruction algorithms have been applied offline, with the direction refined to:

Date: 2023-10-04
Time: 14:39:41.18 UT
RA: 143.79 (+1.10, -1.01 deg 90% PSF containment) J2000
Dec: -25.04 (+1.03, -1.21 deg 90% PSF containment) J2000

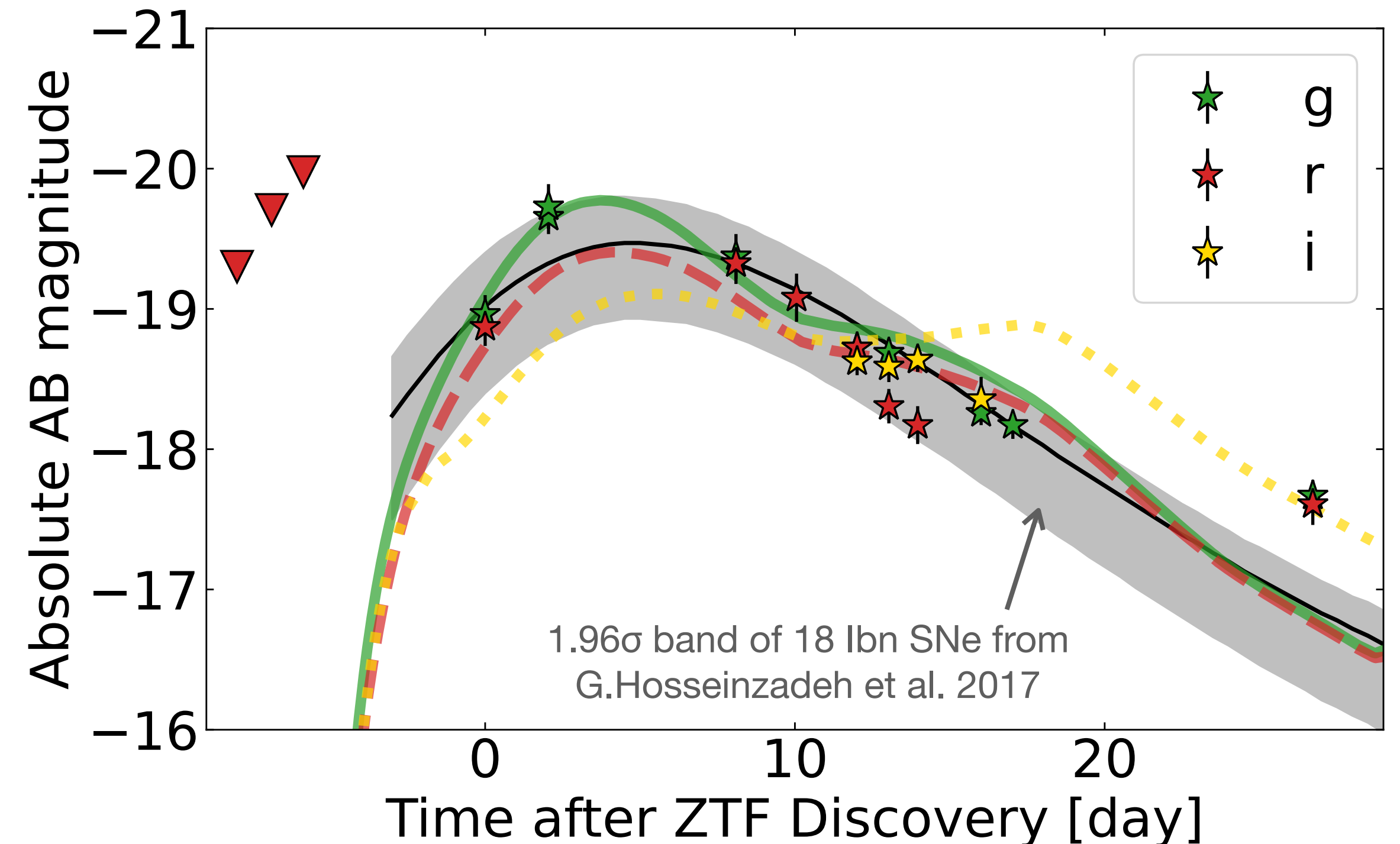
We encourage follow-up by ground and space-based instruments to help identify a possible astrophysical source for the candidate neutrino.

There are no Fermi 4FGL-DR4 or 3FHL catalog sources in the 90% uncertainty region of the event. The nearest gamma-ray source in either catalog is 4FGL J0927.2+2454 at RA: 141.82 deg, Dec: -24.90 deg (1.79 deg away from the best-fit alert position).

The IceCube Neutrino Observatory is a cubic-kilometer neutrino detector operating at the geographic South Pole, Antarctica. The IceCube realtime alert point of contact can be reached at roc@icecube.wisc.edu

- RHD calculation setup
 - Fixed ejecta mass = $2 M_{\text{sun}}$, kinetic energy = 10^{51} erg (from a representative eject model).
 - **CSM density follows a power law with r^{-3}** (steeper than wind-like r^{-2} for Ibn).
 - **Helium-rich composition** (He : C : O = 0.90 : 0.06 : 0.04)
- A choice of normalization $D' = 50$ gives a nicely matching light curve.
 - Luminous side of observed Type Ibn SNe.
 - Some mismatch after ~ 10 days for a simplified power law CSM structure etc.

$$\rho_{\text{CSM}}(r) = 10^{-14} D' \left(\frac{r}{5 \times 10^{14} \text{ cm}} \right)^{-3} \text{ g cm}^{-3},$$

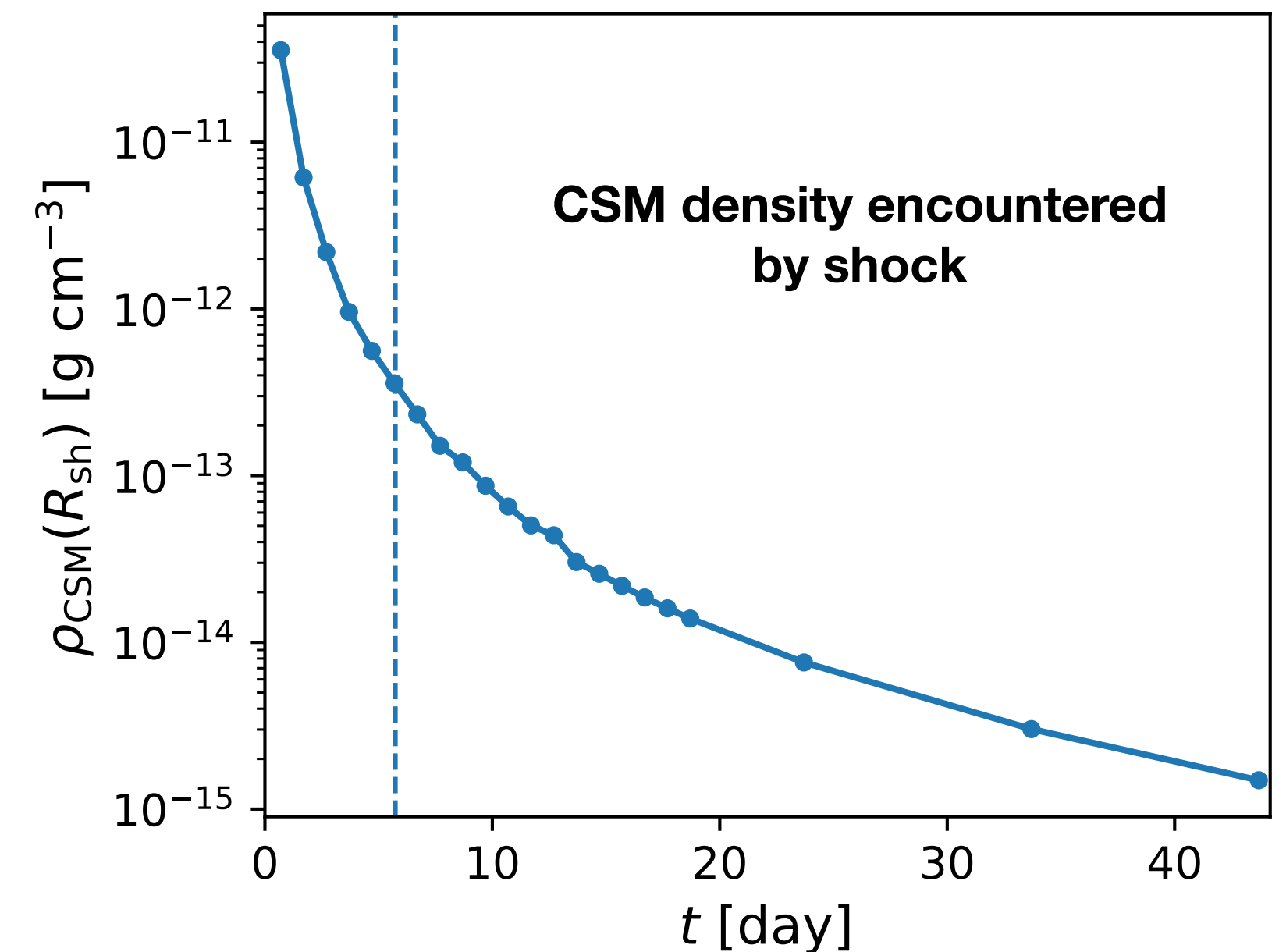
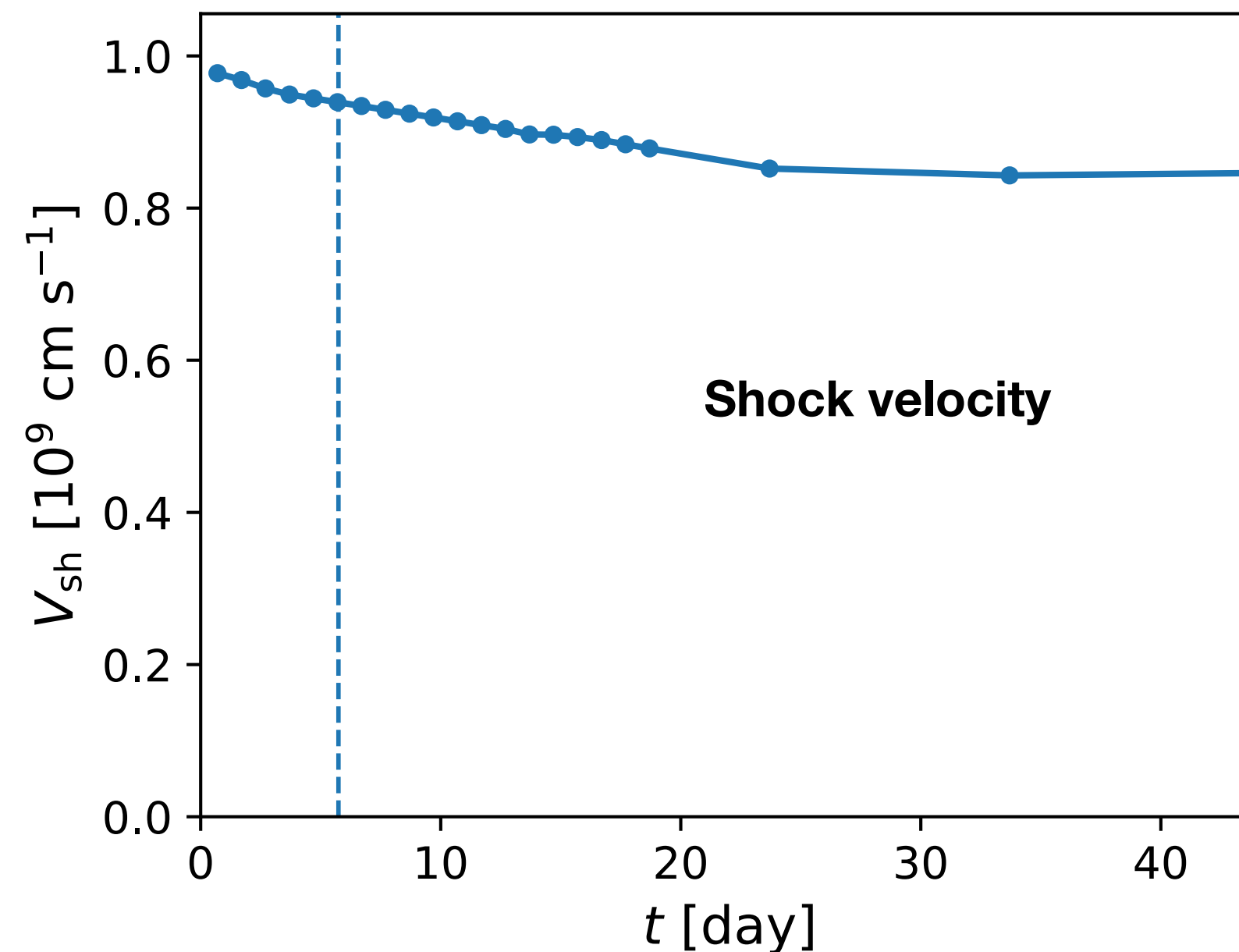
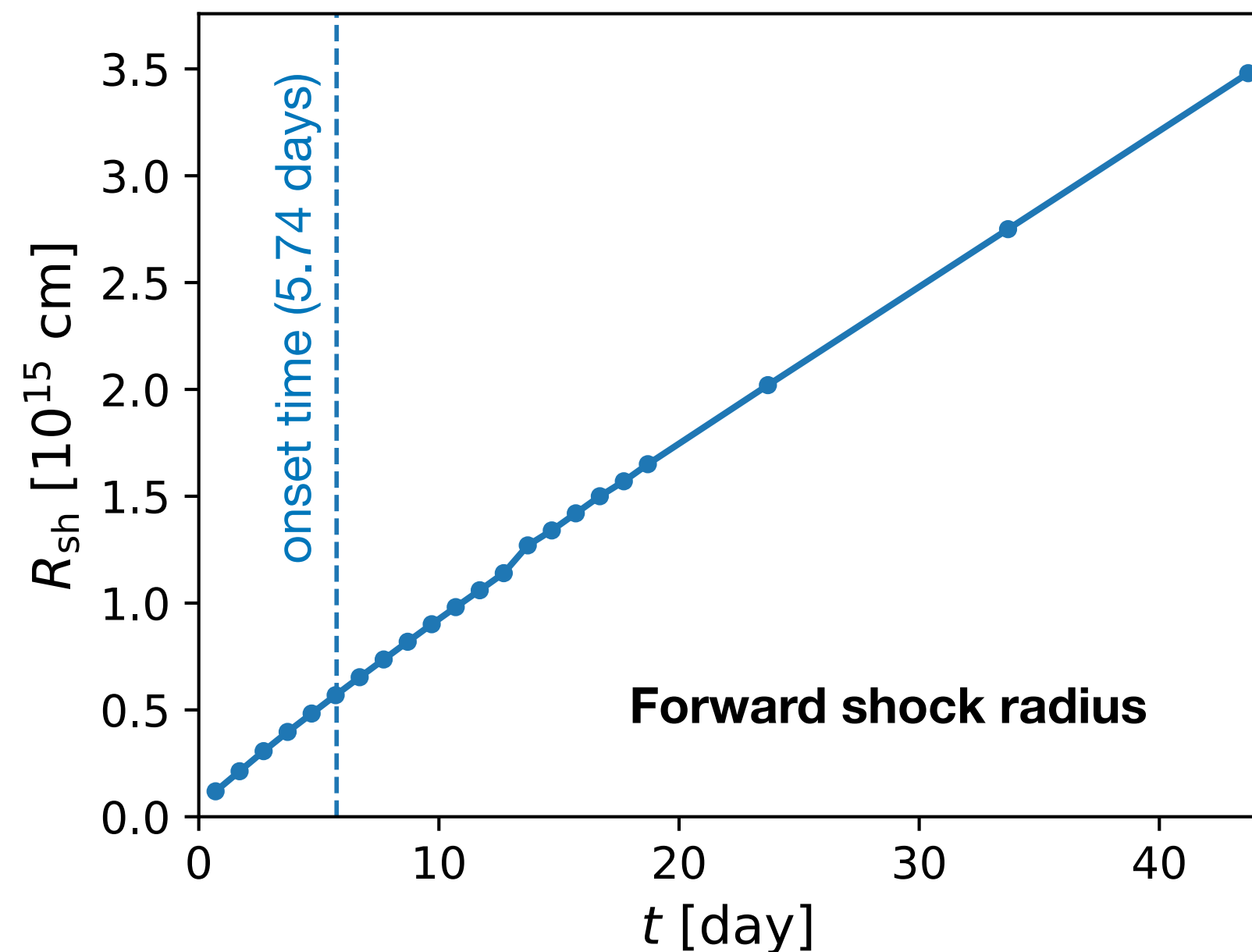


Shock Evolution

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- Our calculation provides the dynamical shock quantities used in the later neutrino calculation.
- Shock velocity is nearly constant, $\sim 10^9 \text{ cm s}^{-1}$; this and the steep density profile determines the **onset time** after which **collision-less acceleration** is possible (approximating onset time $\sim$ break-out time).

$$t_{\text{onset}} \sim 5.3 \left(\frac{D'}{50} \right)^{1/2} \left(\frac{V_{\text{sh}}}{10^9 \text{ cm s}^{-1}} \right)^{-1/2} \text{ day}$$



Non-detection of Radio & X-rays

- Ejecta interactions with dense CSM are generally expected to produce both radio and X-ray emissions; however, for SN 2023uqf, such are not detected.
 - Radio** (VLA): 10 GHz, 20 and 75 days after ZTF
 - X-rays** (Chandra): 0.3–10 keV, 24 days after ZTF
- Our dense, steep density profile is consistent with these non-detections ($\tau \gg 1$).
 - Radio**: optical depth $\sim 3.3 \times 10^4$ (20 days), $\sim 1.8 \times 10^2$ (75 days) @10 GHz
 - X-rays**: optical depth $\sim 2.7 \times 10^3$ @1 keV, ~ 6 @10 keV (24 days)



Radio $\tau_{\text{ff}}(\nu) \simeq 8 \times 10^{11} \left(\frac{T_e}{10^5 \text{ K}} \right)^{-3/2} \left(\frac{\nu}{10 \text{ GHz}} \right)^{-2} \left(\frac{t}{\text{day}} \right)^{-5}.$

X-rays $\tau_{\text{bf}}(E, t) \simeq 3.2 \times 10^6 \left(\frac{E}{\text{keV}} \right)^{-8/3} \left(\frac{t}{\text{day}} \right)^{-2}.$

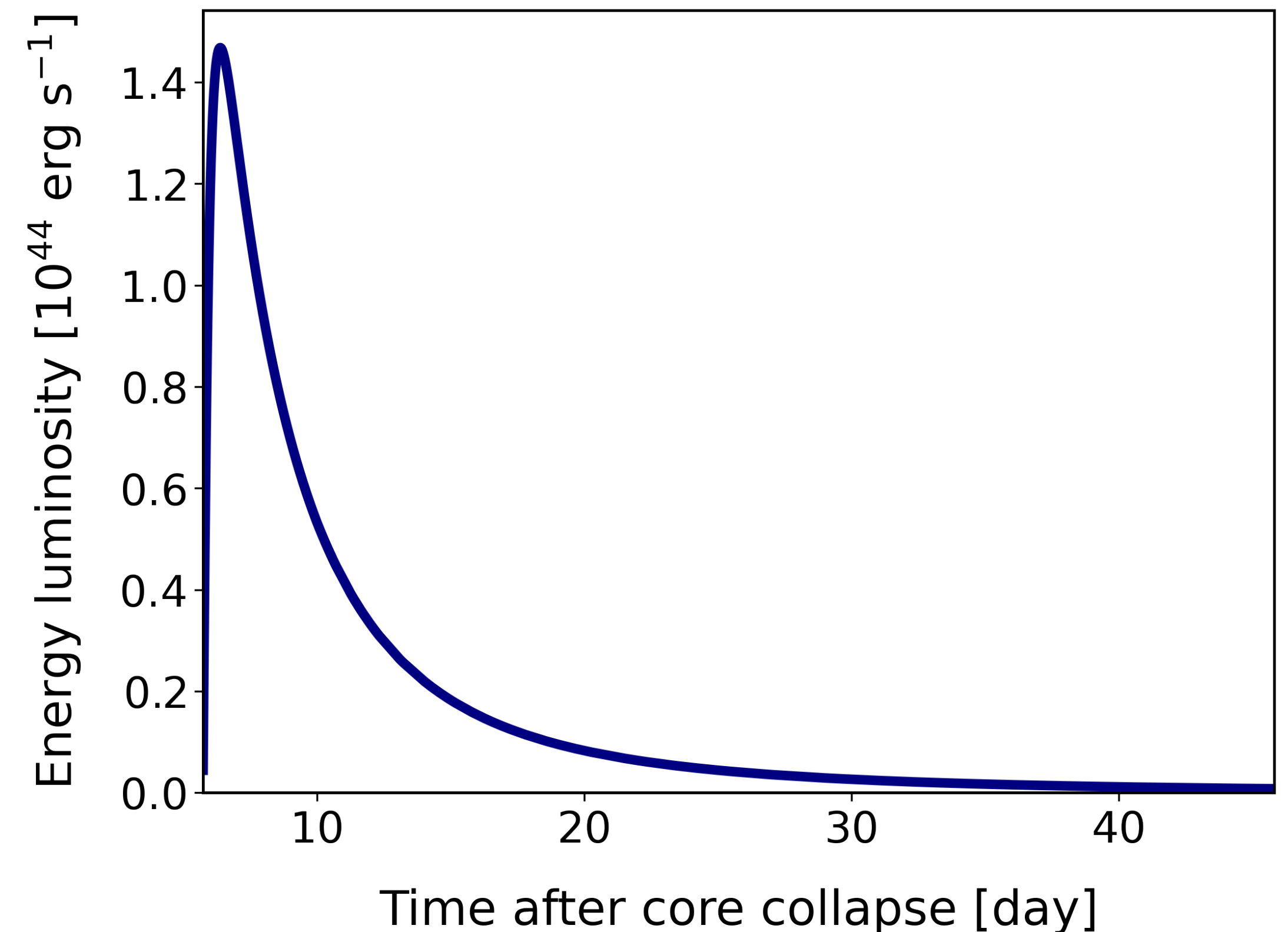
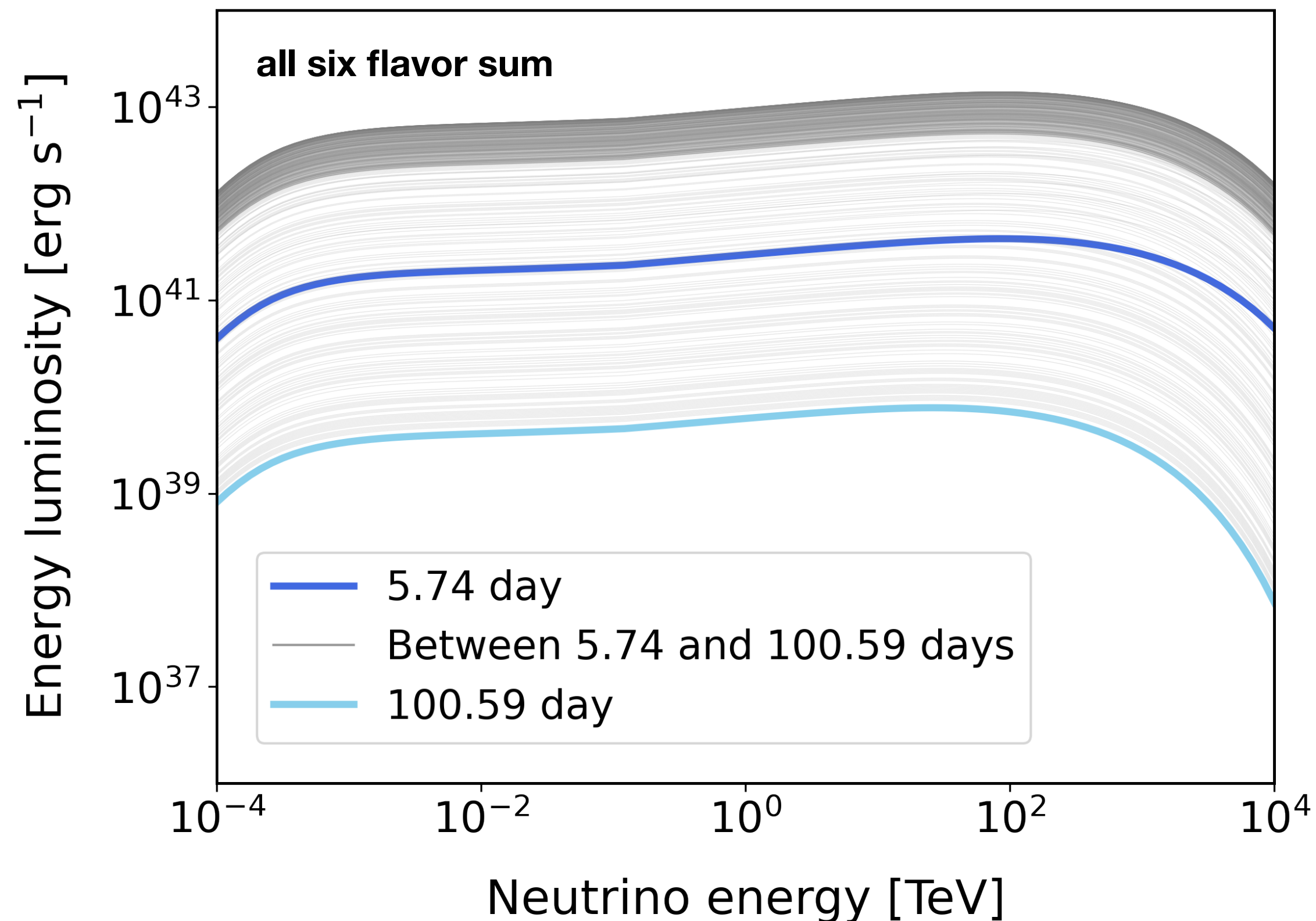
High Energy Neutrino Emission

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- Calculated neutrino emission from onset up to ~100 days.
- Our setup can accelerate particles up to **multi-PeV**.
- We consider helium-rich conditions in the calculation.

$$E_A^{\max} \simeq 6.3 Z \left(\frac{\epsilon_B}{0.01} \right)^{1/2} \left(\frac{D'}{50} \right)^{1/2} \left(\frac{R_{\text{sh}}}{5 \times 10^{14} \text{ cm}} \right)^{-1/2} \left(\frac{V_{\text{sh}}}{10^9 \text{ cm s}^{-1}} \right)^3 \text{ PeV}.$$

$$\Phi(E_\nu) \approx \int_{E_{\min}}^{\infty} \sigma_{pp}(E_p) \cdot F_\nu(E_\nu, E_p) \cdot A \cdot n_{\text{CR}}^{(A)}(E_A) \frac{dE_p}{E_p},$$

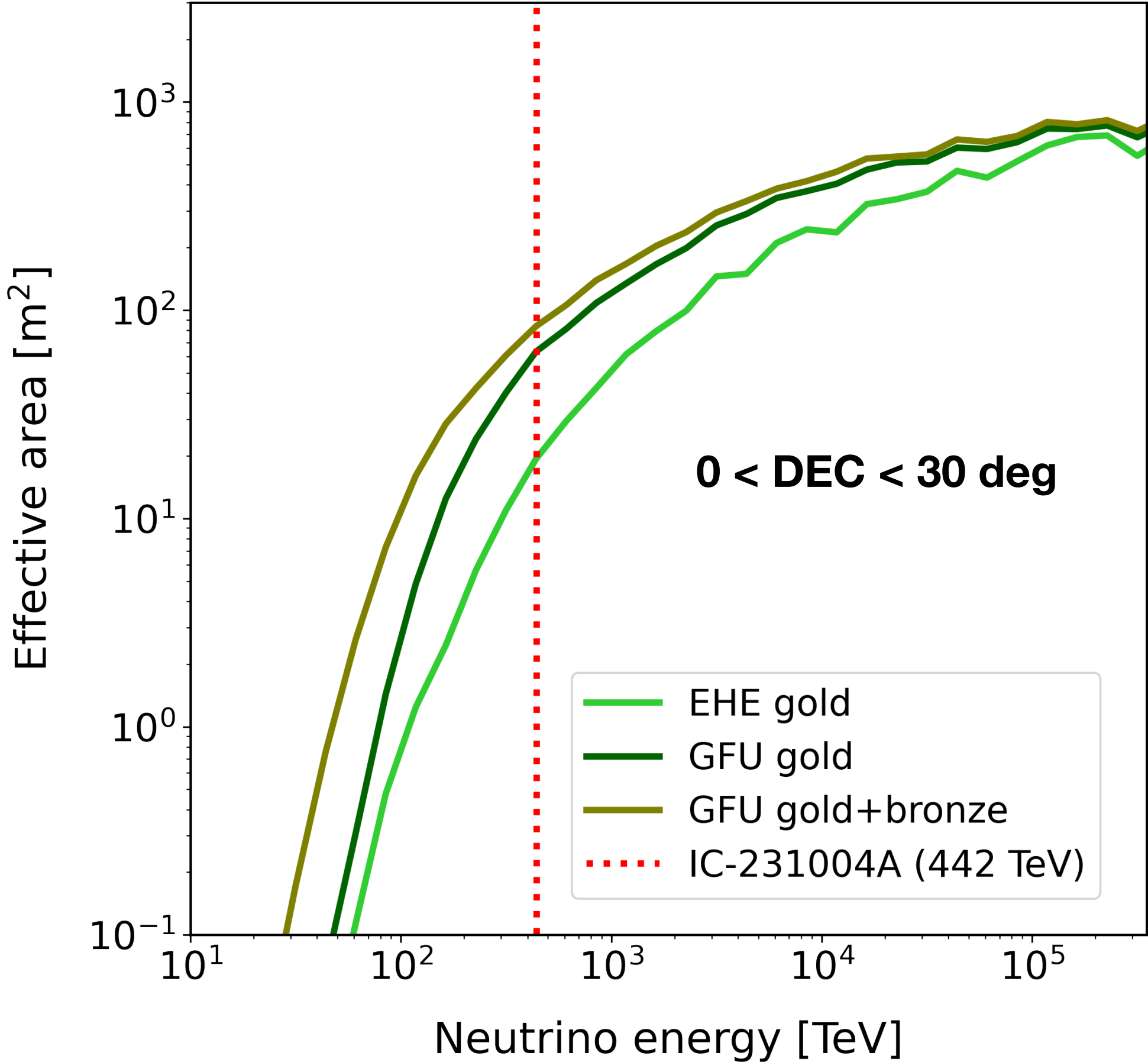


- Use effective areas calculated for the declination angle between 0 and 30 deg (2023uqf is in 25 deg).
- Consider only muon-type neutrinos as the observed event is track-like.

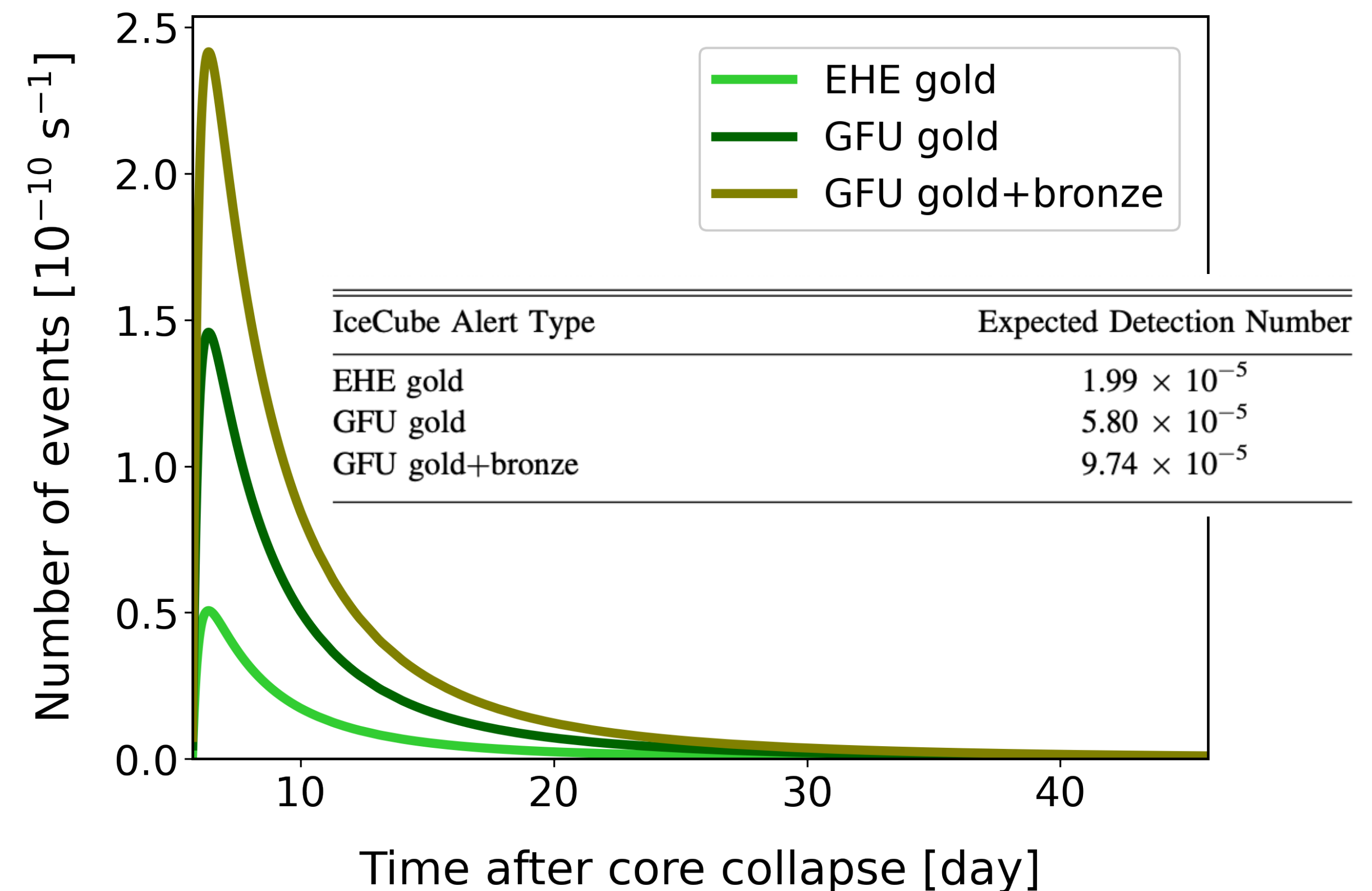
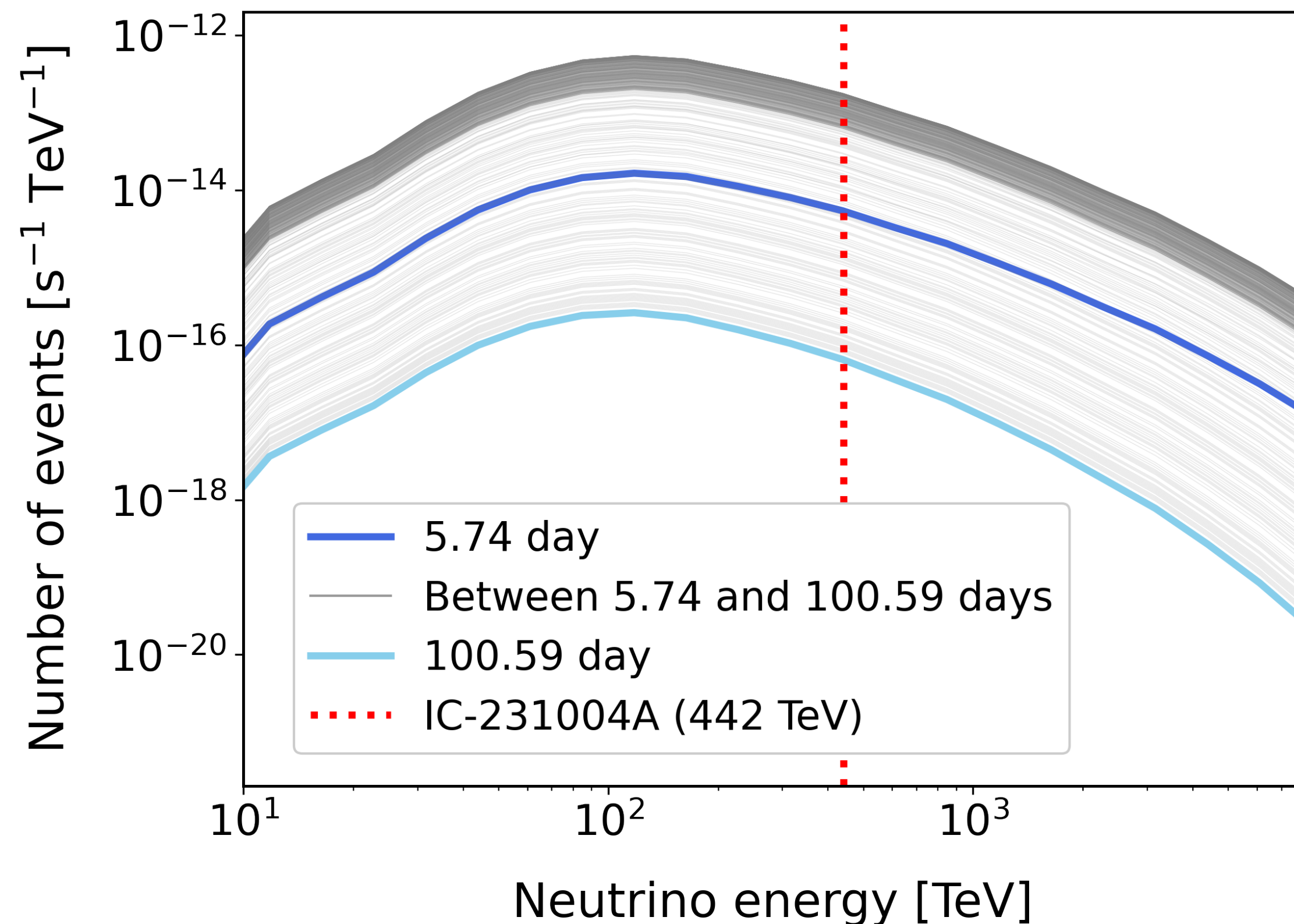
$$\frac{dN_{\text{event}}}{dt} = \frac{1}{4\pi d^2} \int_{E_{\text{min}}}^{E_{\text{max}}} \frac{\Phi_{\text{SN}-\nu}(E_{\nu}, t)}{3} \cdot \mathcal{A}_{\text{eff}}(E_{\nu}) dE_{\nu},$$

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////////////////////////////////////
TITLE: GCN/AMON NOTICE
NOTICE_DATE: Wed 04 Oct 23 14:40:25 UT
NOTICE_TYPE: ICECUBE Astrotrack Gold
STREAM: 24
RUN_NUM: 138415
EVENT_NUM: 56188508
SRC_RA: 143.7656d {+09h 35m 04s} (J2000),
144.1063d {+09h 36m 26s} (current),
143.0471d {+09h 32m 11s} (1950)
SRC_DEC: +25.0511d {+25d 03' 04"} (J2000),
+24.9442d {+24d 56' 39"} (current),
+25.2746d {+25d 16' 29"} (1950)
SRC_ERROR: 30.80 [arcmin radius, stat-only, 90% containment]
SRC_ERRORS0: 12.00 [arcmin radius, stat-only, 50% containment]
DISCOVERY_DATE: 20221 TJD; 277 DOY; 23/10/04 (yy/mm/dd)
DISCOVERY_TIME: 52781 SOD {14:39:41.18} UT
REVISION: 0
ENERGY: 4.4218e+02 [TeV]
SIGNALNESS: 8.4178e-01 [dn]
FAR: 0.4490 [yr^-1]
SUN_POSTN: 190.22d {+12h 40m 53s} -4.40d {-04d 23' 53"}
SUN_DIST: 53.53 [deg] Sun_angle= 3.1 [hr] (West of Sun)
MOON_POSTN: 77.06d {+05h 08m 14s} +27.15d {+27d 08' 55"}
MOON_DIST: 59.53 [deg]
GAL_COORDS: 204.10, 46.14 [deg] galactic lon,lat of the event
ECL_COORDS: 137.92, 10.11 [deg] ecliptic lon,lat of the event
COMMENTS: IceCube Gold event.
COMMENTS: The position error is statistical only, there is no systematic added.
```

R. Abbasi et al., ApJS 269, 25 (2023)



- Detected 442 TeV is likely from the expected event rate distribution (PDF).
- Expected event is $\sim 10^{-5}$ from a single source; considering $O(10^3)$ Ibn SNe within the distance and $O(10^1)$ observational period, a single detection could be possible.



■ **Interacting SNe are a promising source for high-energy neutrinos observed in IceCube.**

- Efficient particle acceleration mechanism
- Frequent event ($\sim 10\%$ of CCSNe)

■ **Optical modeling of SN 2023uqf is performed using the RHD calculation.**

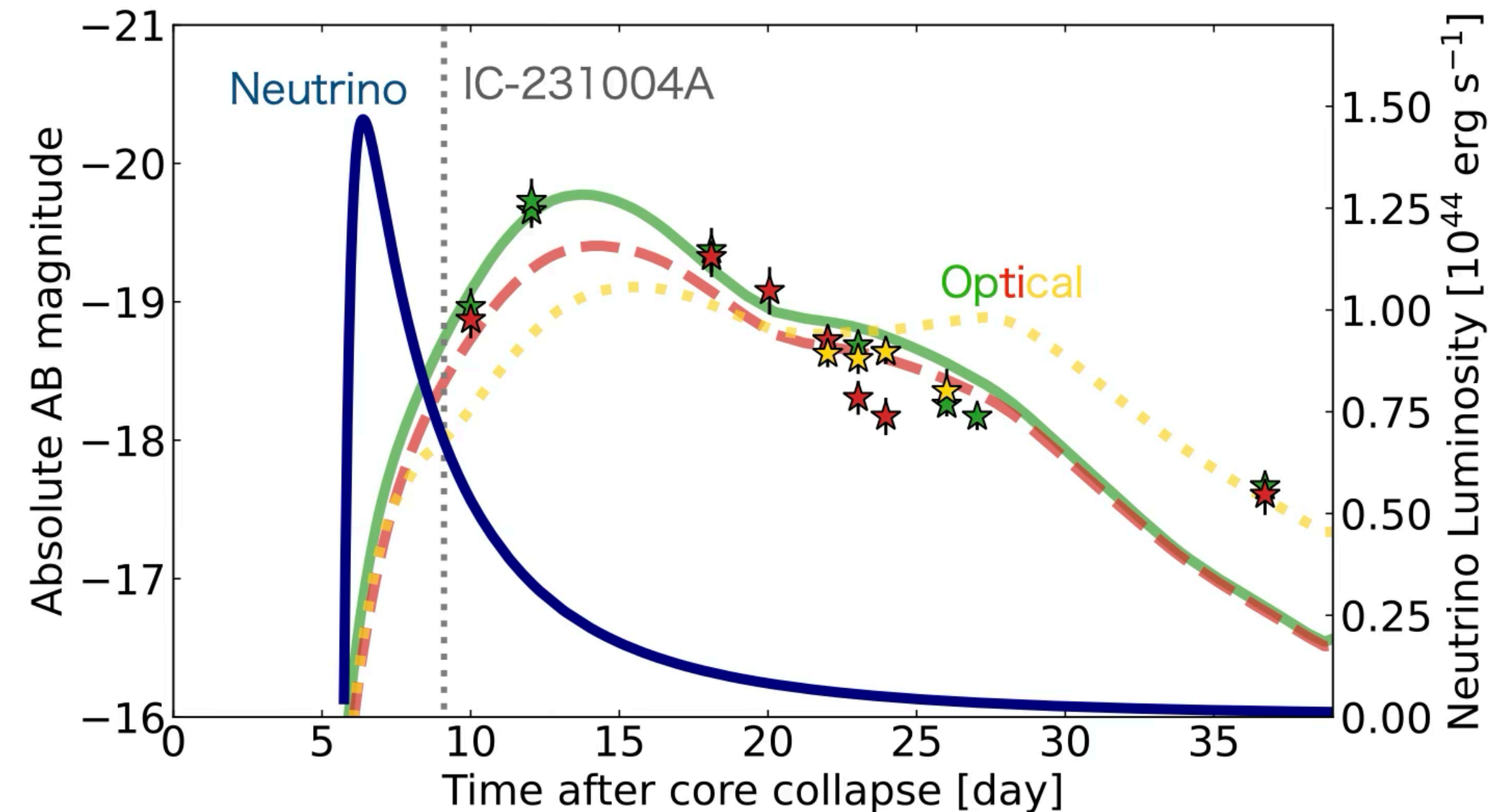
- ZTF-observed light curve was produced in the Ibn-motivated configuration.
- Consequent neutrino production as a function of time is made.

■ **Detection probability at IceCube is shown.**

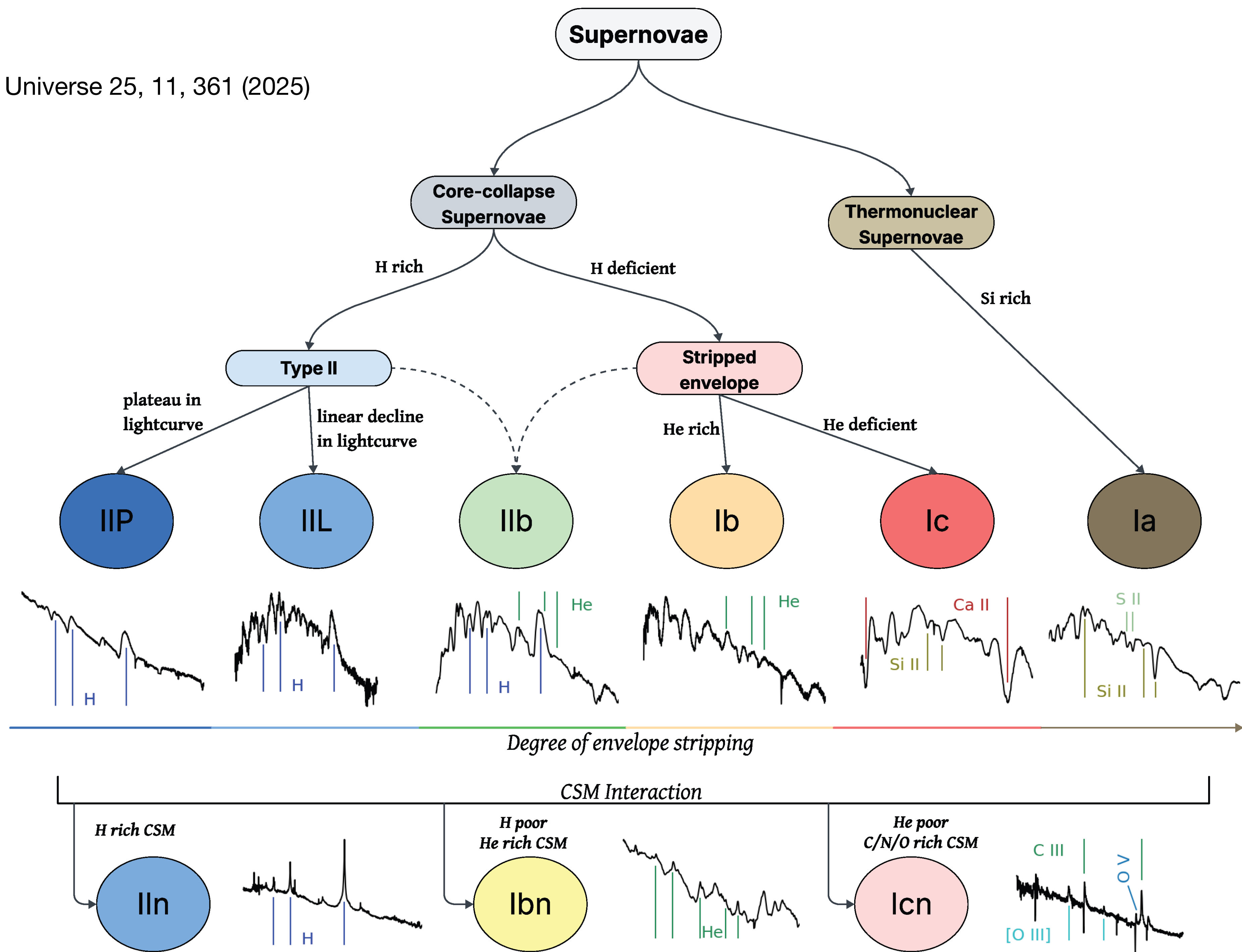
- Our estimation shows a possible single detection.
- The current scheme can apply to Ibn SNe.
- The diffuse flux from interacting SNe will be calculated.

Thanks for your attention!

Our paper: [ApJL 1005, 2 \(2026\)](#)



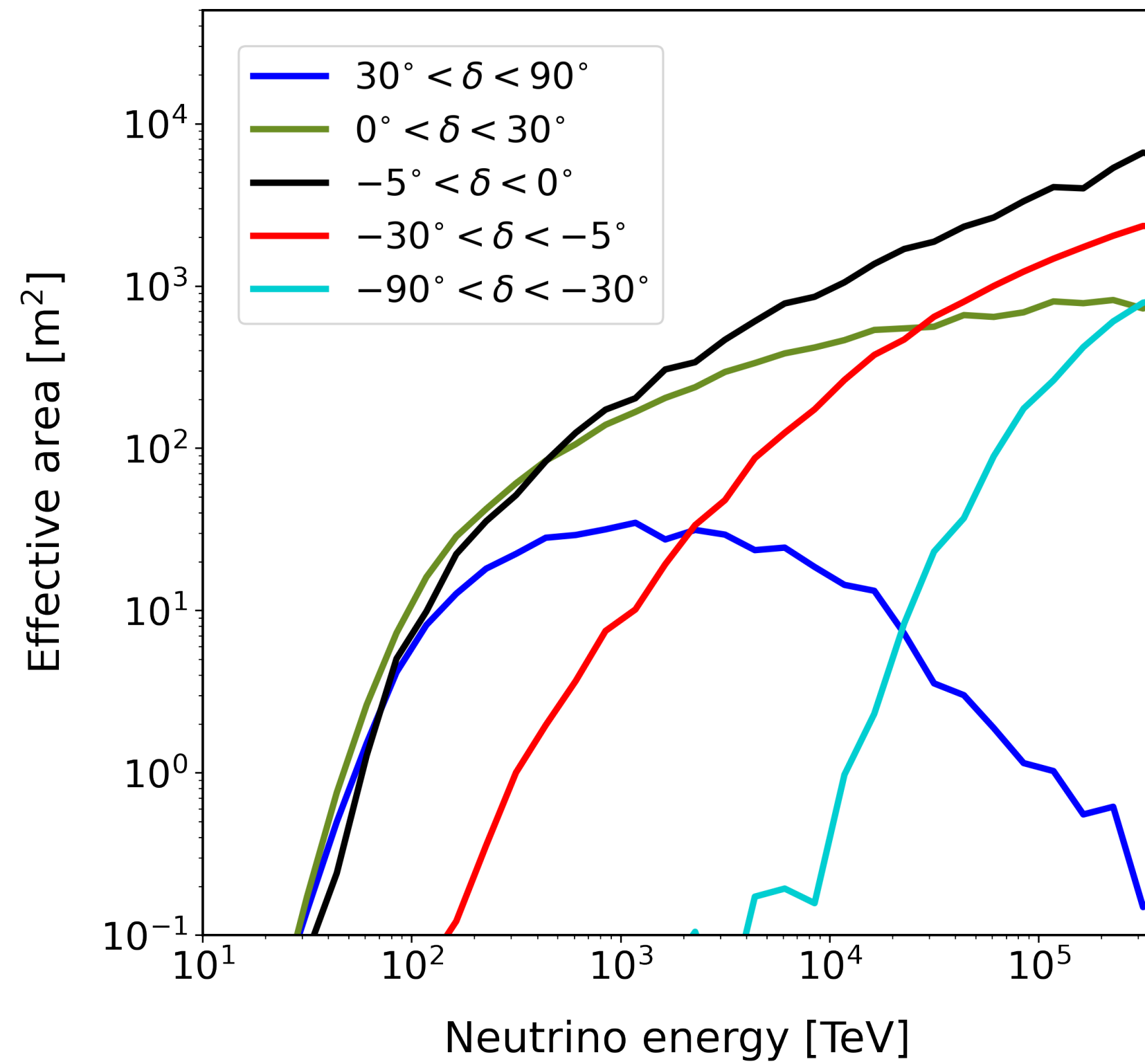
Supplements



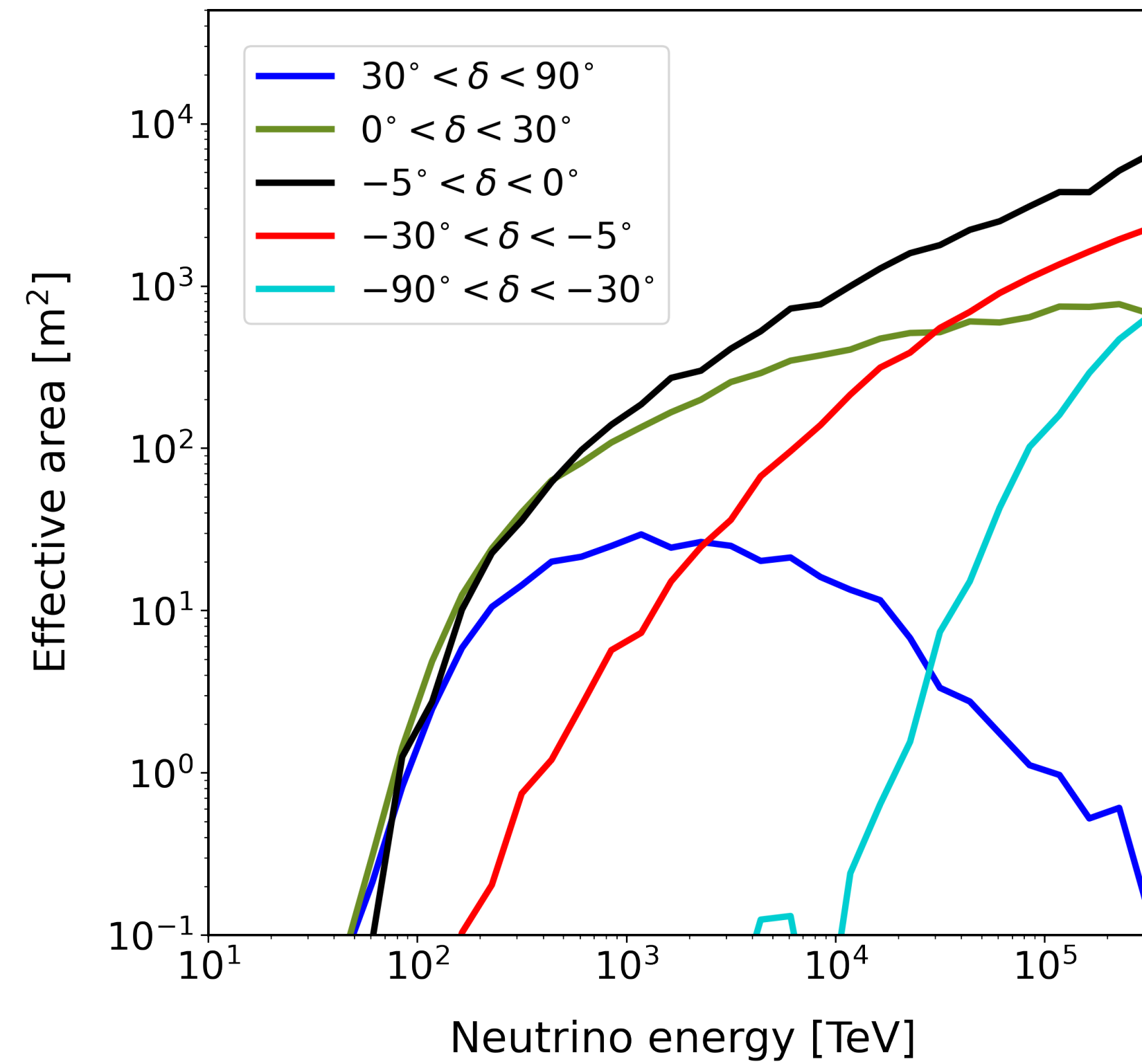
- **Track**-like events only (~muon neutrino charged-current interactions).
- Two ranks, “Gold” and “Bronze”, depending on signalness.
 - **Gold**: signalness > 50%
 - **Bronze**: 30% < signalness < 50%
 - Assumed astrophysical spectrum follows $E^{-2.19}$.
- Three different analysis selections with a hierarchical order.
 - Selections: GFU, EHE, HESE (no Bronze for EHE)
 - GFU Gold > EHE Gold > HESE Gold
 - GFU Bronze > HESE Bronze

$$\text{Signalness}(E, \delta) = \frac{N_{\text{signal}}(E, \delta)}{N_{\text{signal}}(E, \delta) + N_{\text{background}}(E, \delta)}$$

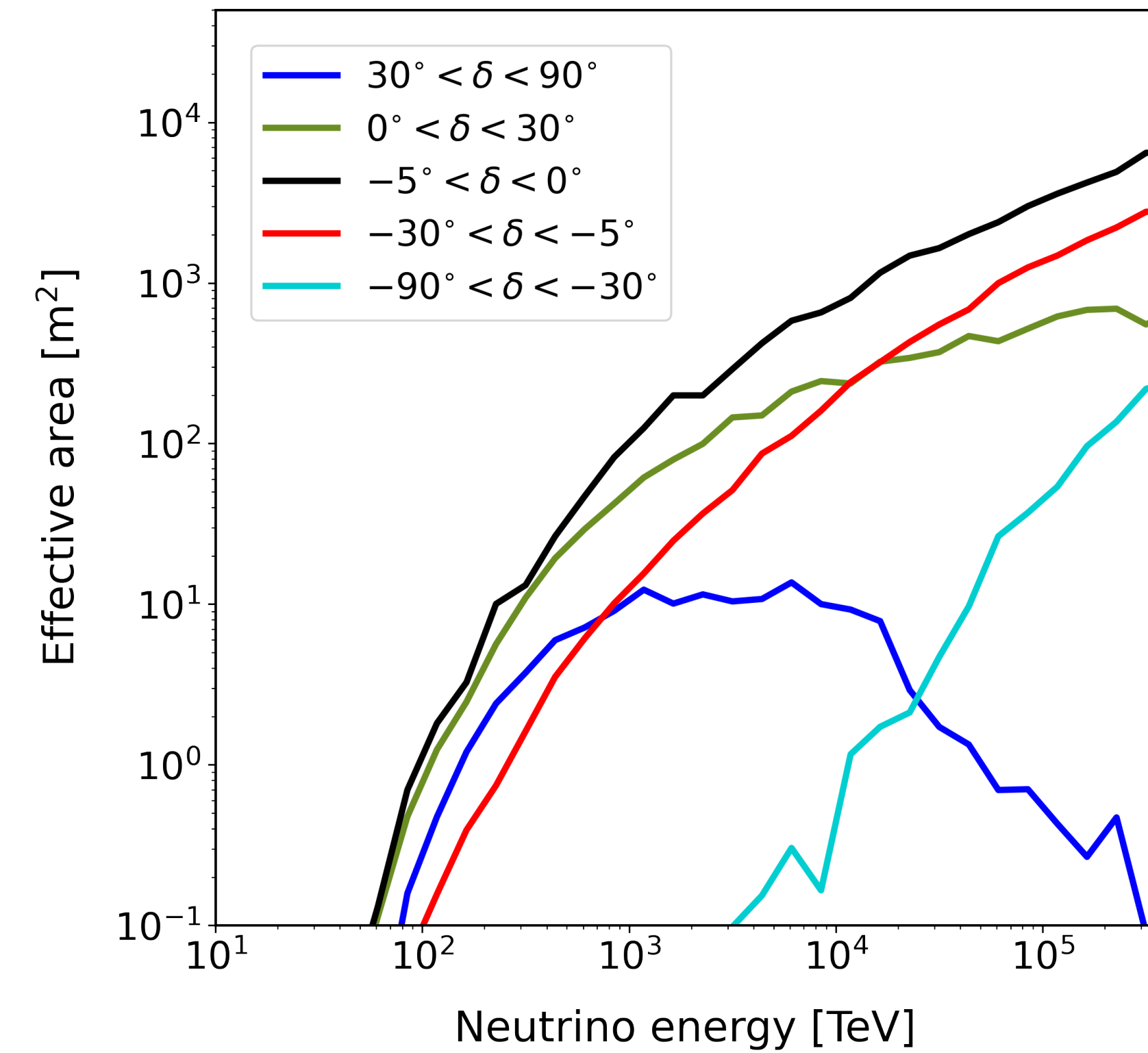
GFU Gold+Bronze



GFU Gold



EHE Gold



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Dec: +25.04 (+1.03, -1.21 deg 90% PSF containment) J2000

Signalness: 84.2% (*Gold*)
Energy: 442.2 TeV
RA: 143.79 deg
DEC: +25.04 deg

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SRC_ERROR50:    12.00 [arcmin radius, stat-only, 50% containment]
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