Search for Neutrino Emission from Fast Radio Bursts with IceCube

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for the IceCube Collaboration

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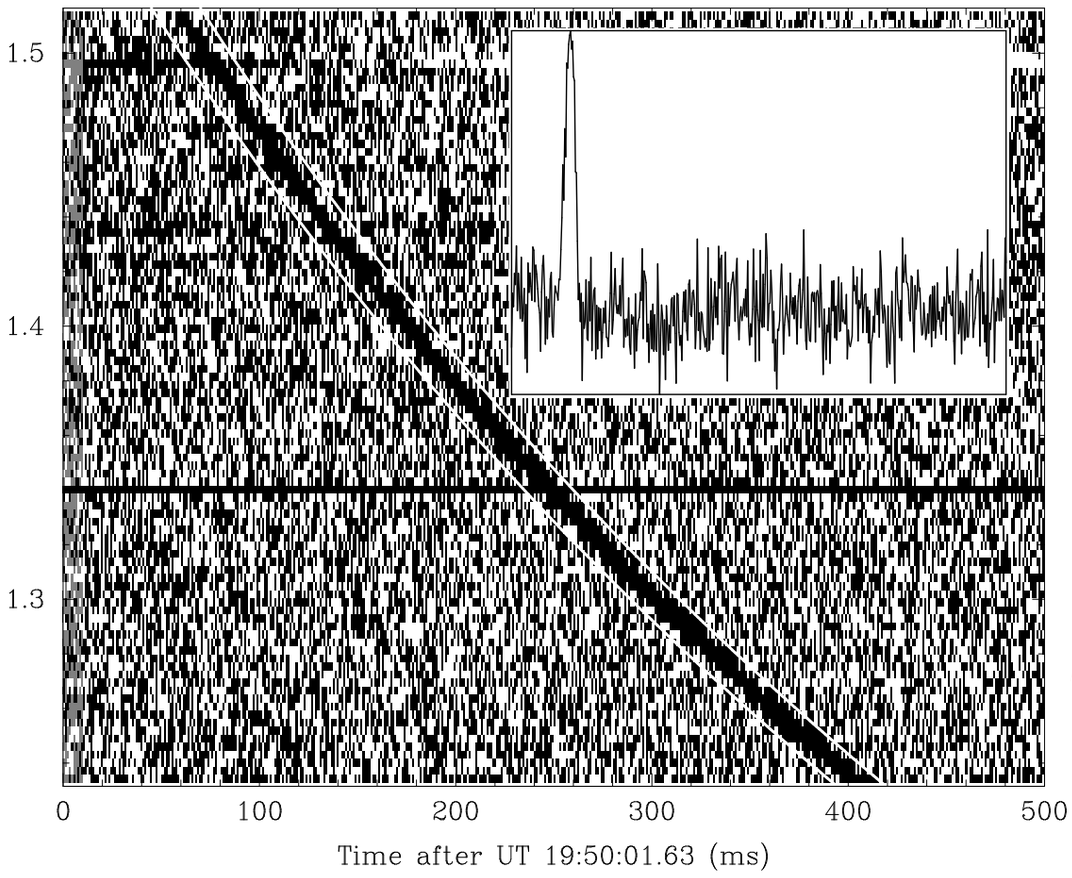
IceCube
South Pole Neutrino Observatory

Fast Radio Bursts - Discovery in 2007

*Lorimer et al.,**Science** 318 (5851): 777-780*



$$\Delta t_{\rm delay} = \frac{e^2}{2\pi m_e c^3} \cdot {\rm DM} \cdot w^{-2}$$

$$= 1.5 \times 10^{-24}\,{\rm s} \cdot {\rm DM} \cdot w^{-2}$$

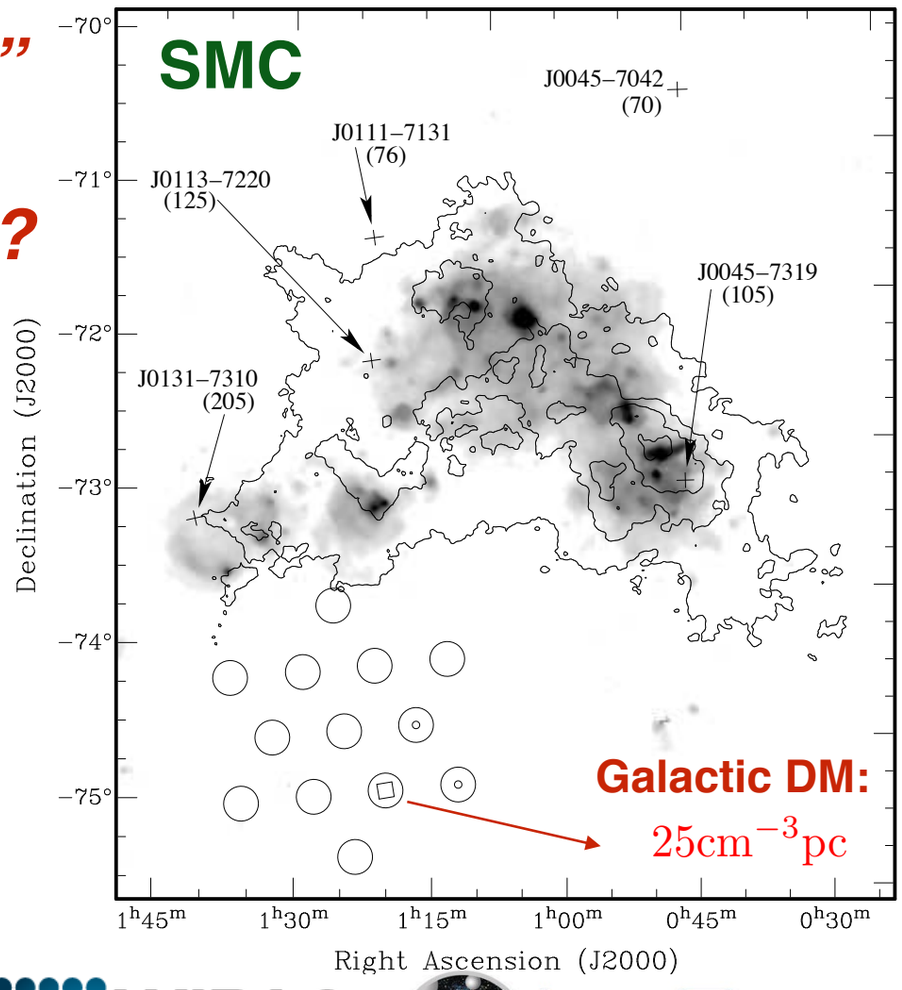
$$\delta t_{\rm width} = 4.6\,{\rm ms}\,(\frac{\omega}{1.4{\rm GHz}})^{-4.8\pm0.4}$$

$${\rm DM} = \int n_e dl = 375 \pm 1 {\rm cm}^{-3}{\rm pc}$$

$$\int dt I_\omega \simeq 150 \pm 50 {\rm Jy\,ms} \,@\, 1.4\,{\rm GHz}$$

"very compact"

"extragalactic"?



- A total of ~**23** FRBs detected to date. Estimated FRB event rate is **~1,000/day**

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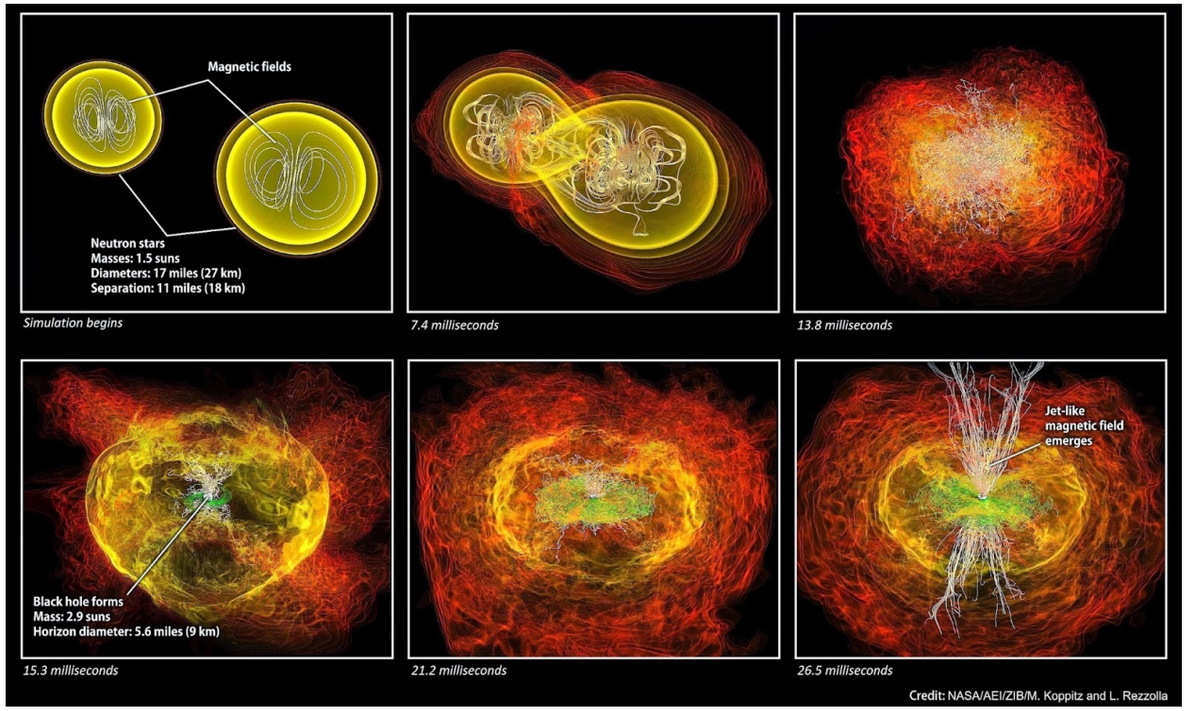
Fast Radio Bursts Emitting Neutrinos?

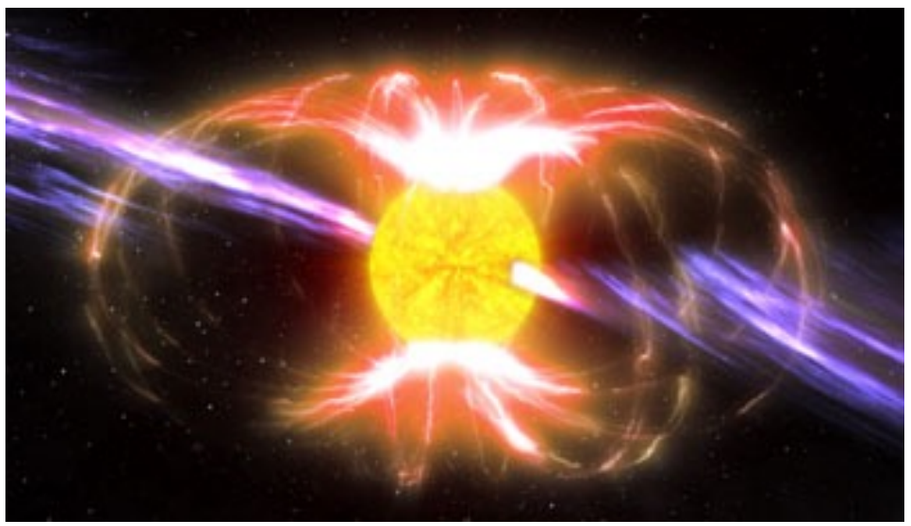
- **Blitzar** **"Cataclysmic"**
  [H. Falcke and L. Rezzolla, A&A 562, A137 (2014)]

- **Binary neutron star merger**
  [T. Totani, Pub. Astron. Soc. Jpn. 65, L12 (2013)]

- **Evaporating primordial black holes**
  [Halzen *et al.*, PRD 1995]
  "MeV neutrinos"



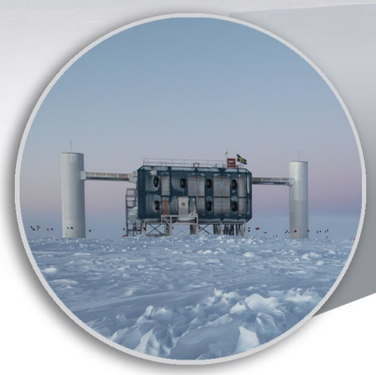
- **Magnetar/SGRs hyperflares**
  [S. B. Popov and K. A. Postnov, arXiv:1307.4924]
  [Halzen *et al.* (2005) astro-ph/0503348]
  "TeV neutrinos"? → this work



IceCube
South Pole Neutrino Observatory

Goal: detecting TeV-PeV astrophysical neutrinos
Construction completed in December 2010

50 m

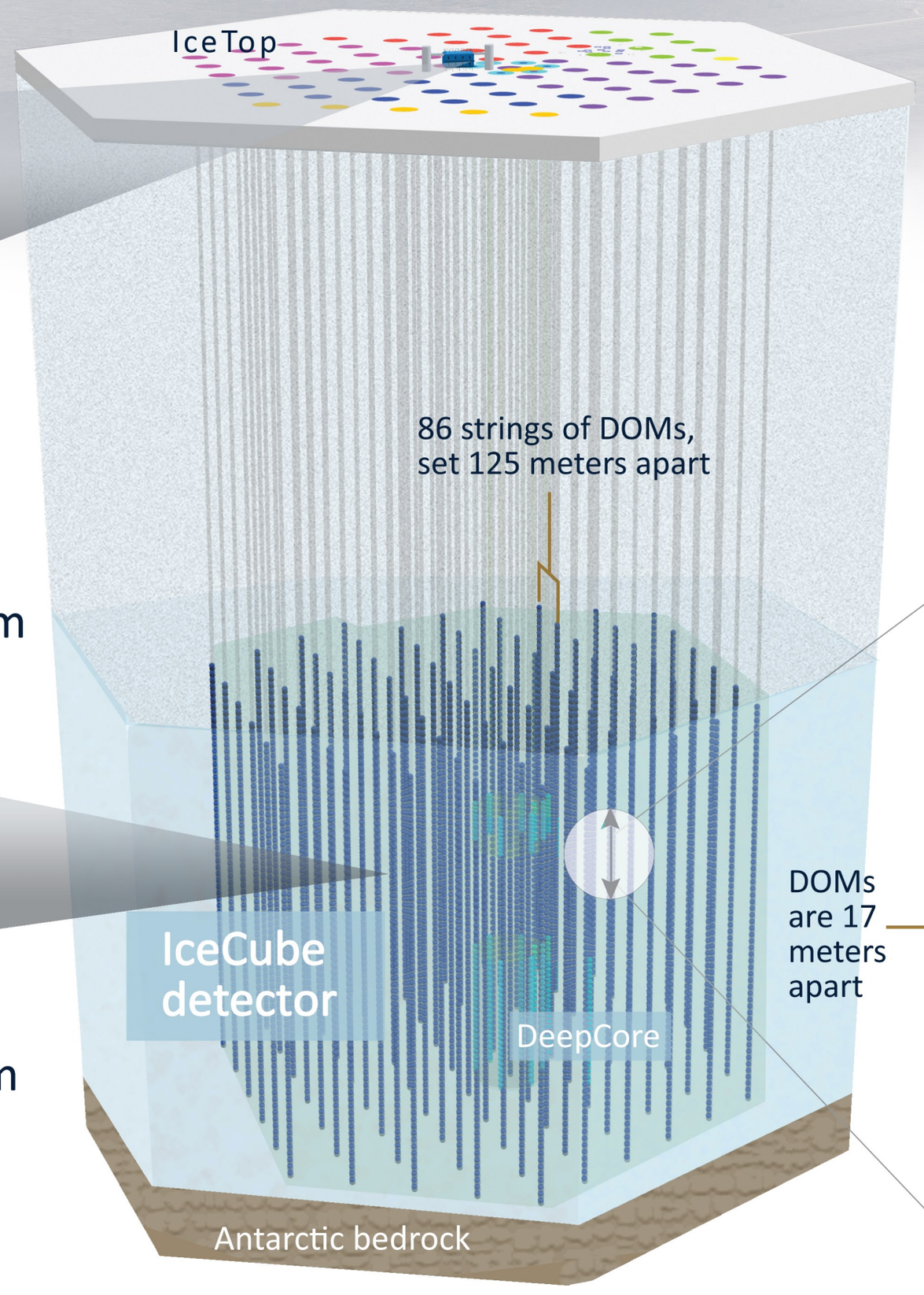


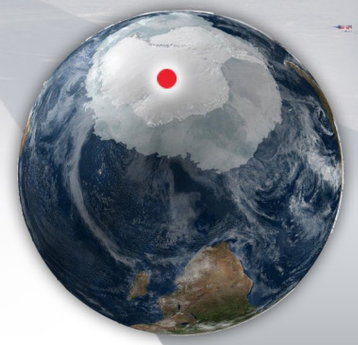
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison

1450 m

Digital Optical Module (DOM)
5,160 DOMs deployed in the ice

2450 m

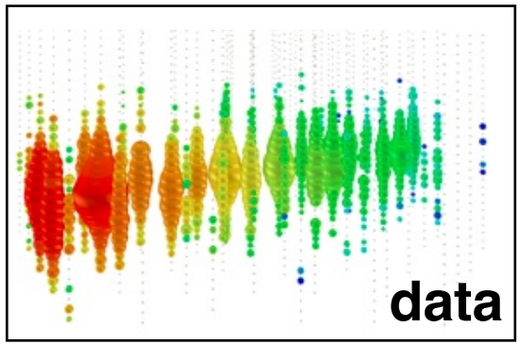




Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

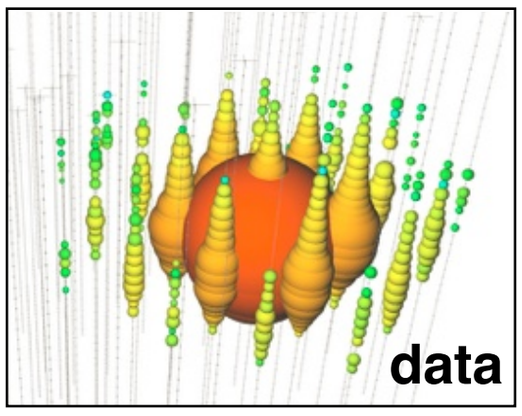
(1) Track: charged current ν_μ

- **<1° Angular resolution**
- **Factor ~ 2 energy resolution**

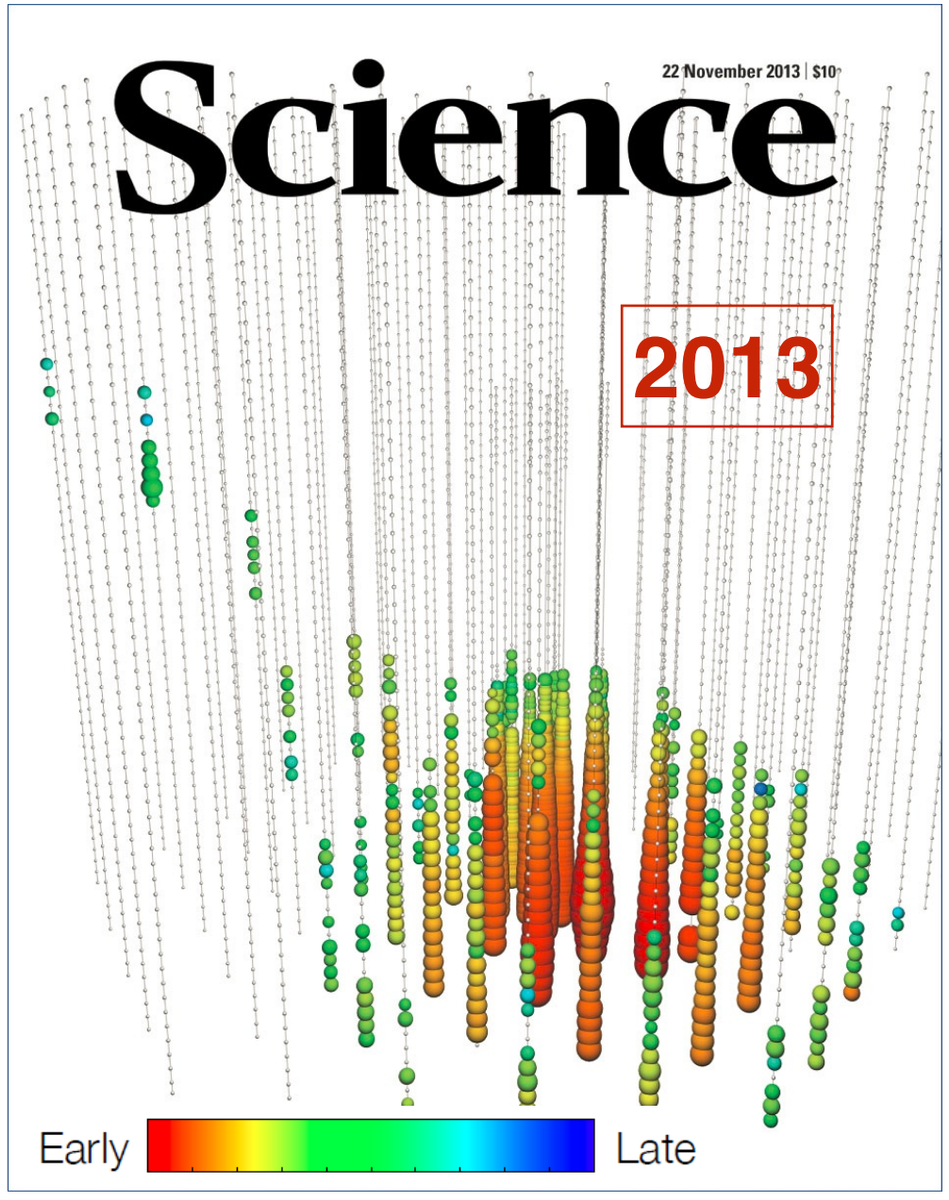


(2) Cascade / Shower: all neutral current, charged current ν_e, low-E charged current ν_τ

- **10° Angular resolution above100 TeV**
- **15% energy resolution on deposited energy**



"high degeneracy"



IceCube has detected a diffuse astrophysical neutrino flux, but **no TeV neutrino point sources** have been identified to date.

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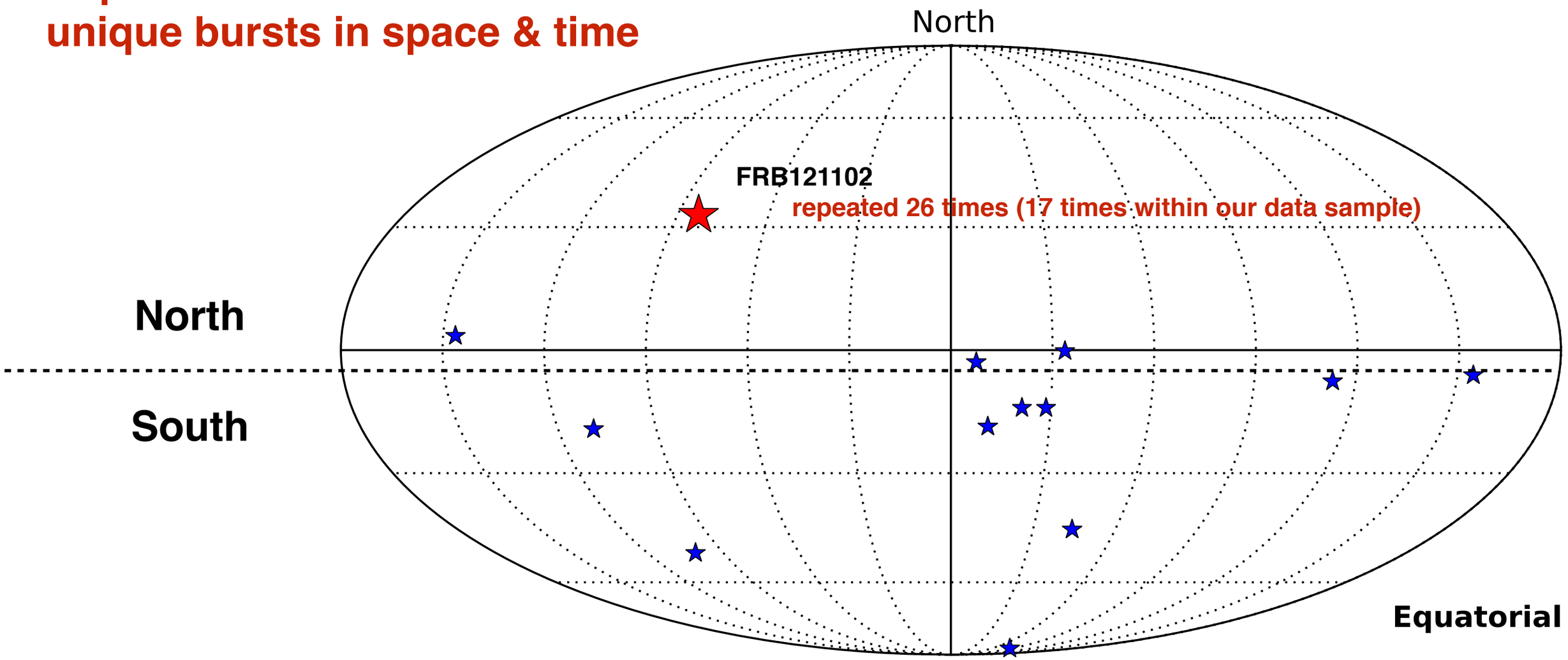
All Sky Fast Radio Bursts with IceCube Coverage

- Burst times cover IceCube data taking seasons from 2010 to 2015 (6 years)
- A total of **29** FRBs (**11** unique locations).

Repeated bursts are treated as unique bursts in space & time

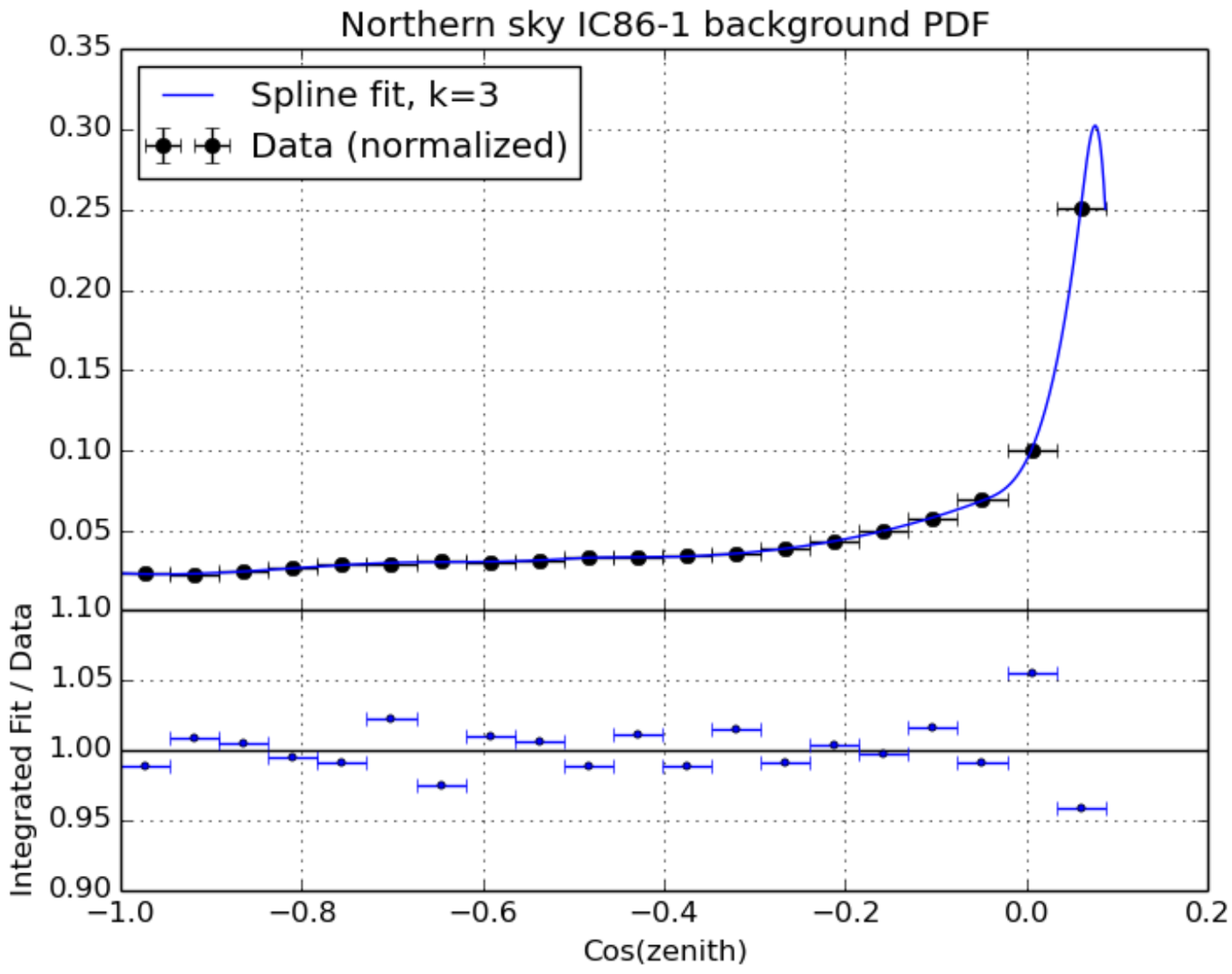


Event Samples & Background Modeling

North (DEC >= -5°)	South (DEC < -5°)
842,597 events	**379,261 events**
(collected from 2011-2015)	***(collected from 2010-2014)***
dominated by atmospheric neutrinos	**dominated by atmospheric muons**

A total of 1.2 million events in 6 years

Background PDF derived from off-time data



2015 ApJ 805 L5 ApJ 845 (2017), 1, 14

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Analysis Method: Unbinned Maximum Likelihood

The likelihood for observing N events with properties $\{x_i\}$ for $(n_s + n_b)$ expected number of events is:

$$L(N, \{x_i\}; n_s + n_b) = \frac{(n_s + n_b)^N}{N!} \cdot \exp(-(n_s + n_b)) \cdot \prod_{i=1}^{N} P(x_i)$$

The normalized probability of observing event i is $P(x_i)$:

$$P(x_i) = \frac{n_s S(x_i) + n_b B(x_i)}{n_s + n_b}$$

$$S_i = S_{\text{time}}(t_i) \cdot S_{\text{space}}(\vec{x}_i)$$

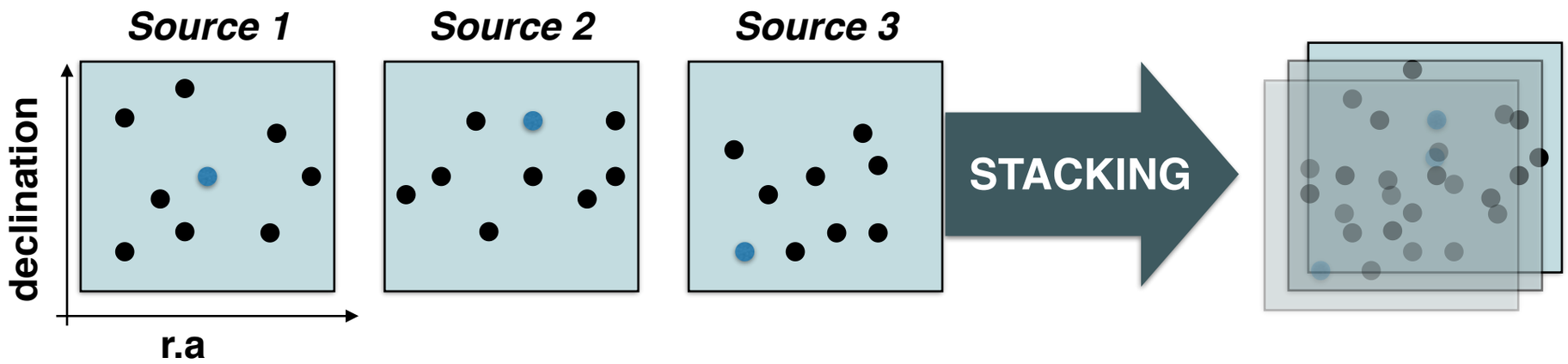
$$B_i = B_{\text{time}}(t_i) \cdot B_{\text{space}}(\vec{x}_i)$$

“temporal” + “spatial”

$$T := \ln \frac{L(N, \{x_i\}; n_s + n_b)}{L_0(N, \{x_i\}; n_b)}$$

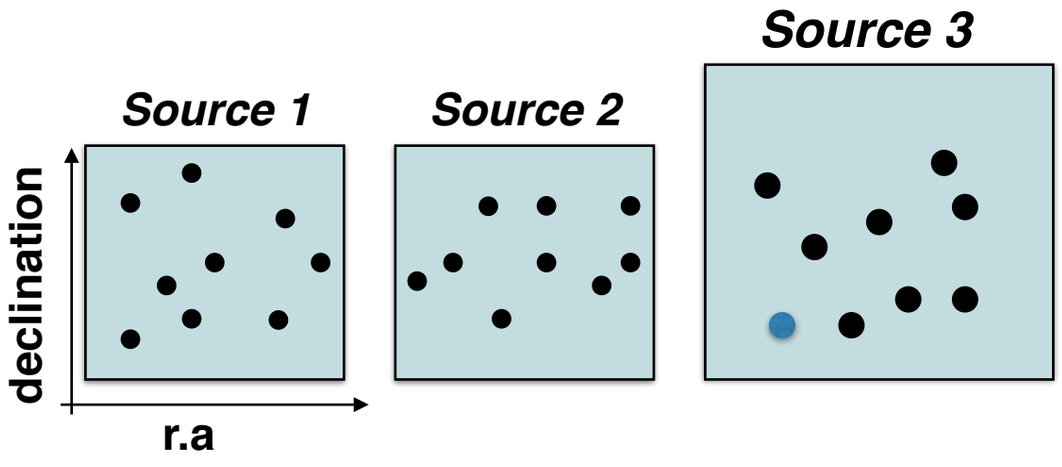
$$T := -\hat{n}_s + \sum_{i=1}^{N} \ln(1 + \frac{\hat{n}_s S_i}{< n_b > B_i})$$

- **Stacking** **"Distributed fluence test"**



- **Max-burst**

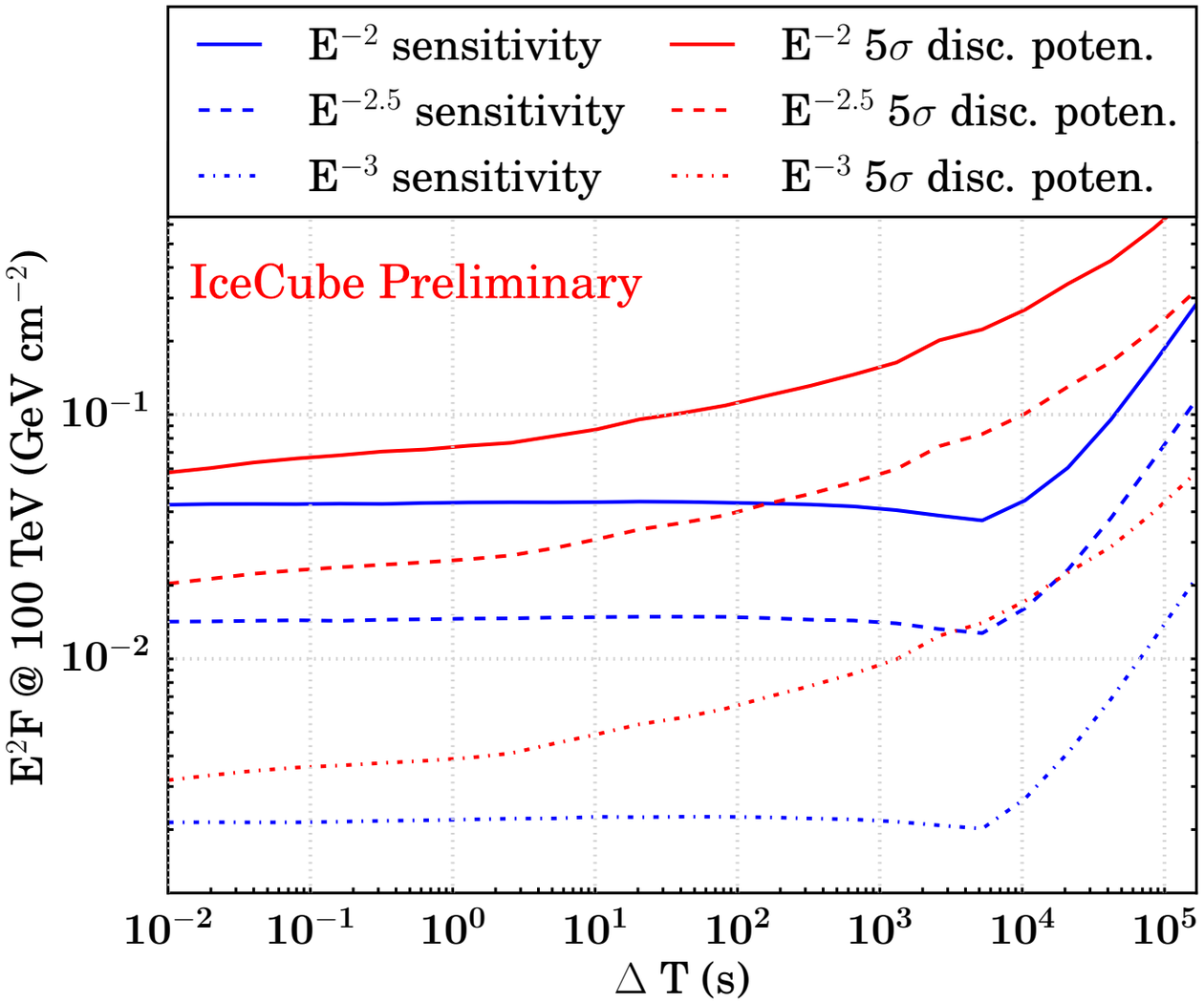
"Single bright neutrino source test"



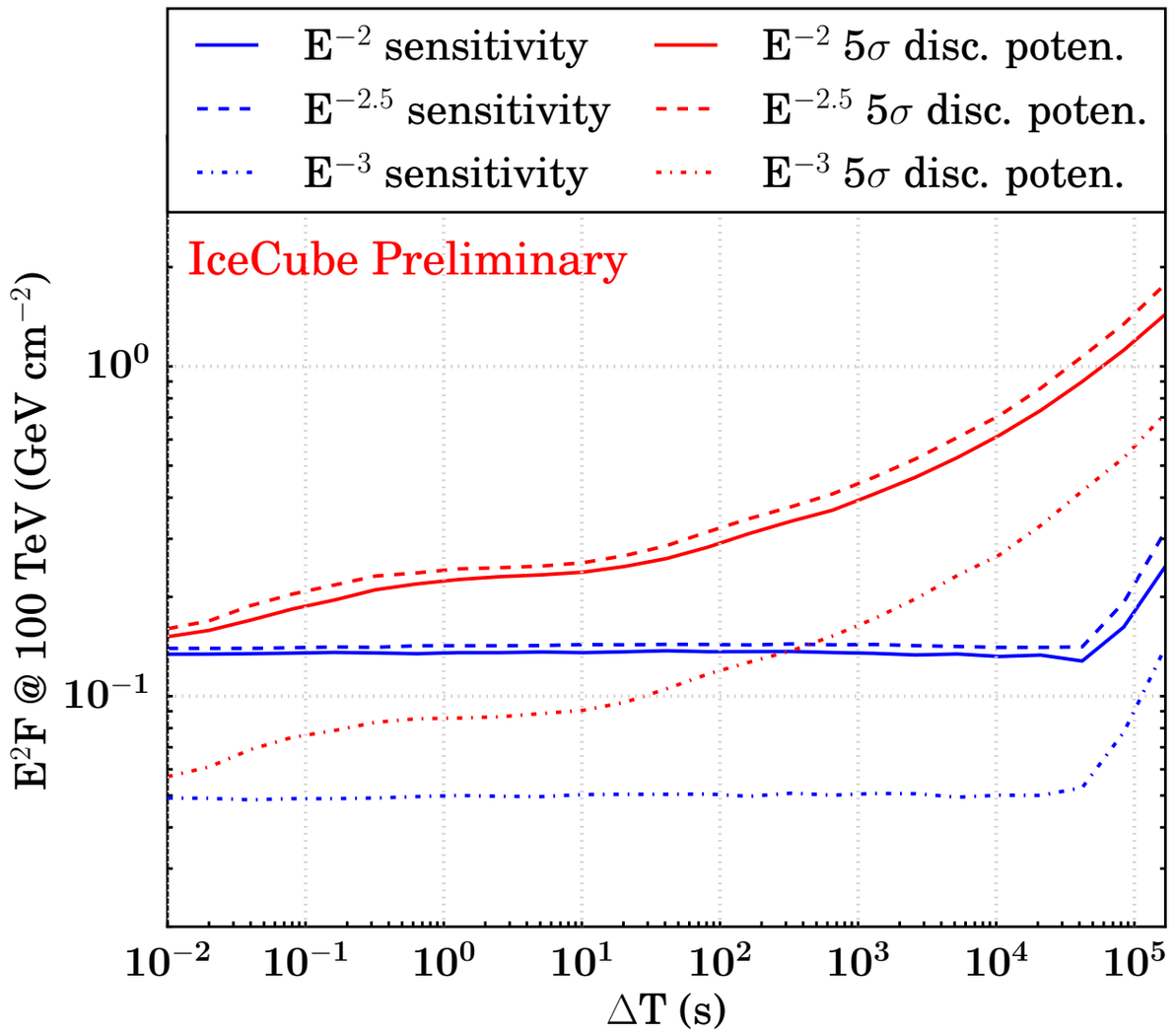
- **Model independent**
- **Expanding time windows centered at burst times**
- **25 time windows from 10 ms to 2 days, expanding as $2^i x 10$ ms (i =0, …, 24)**

Sensitivity & Discovery Potentials - Stacking

North



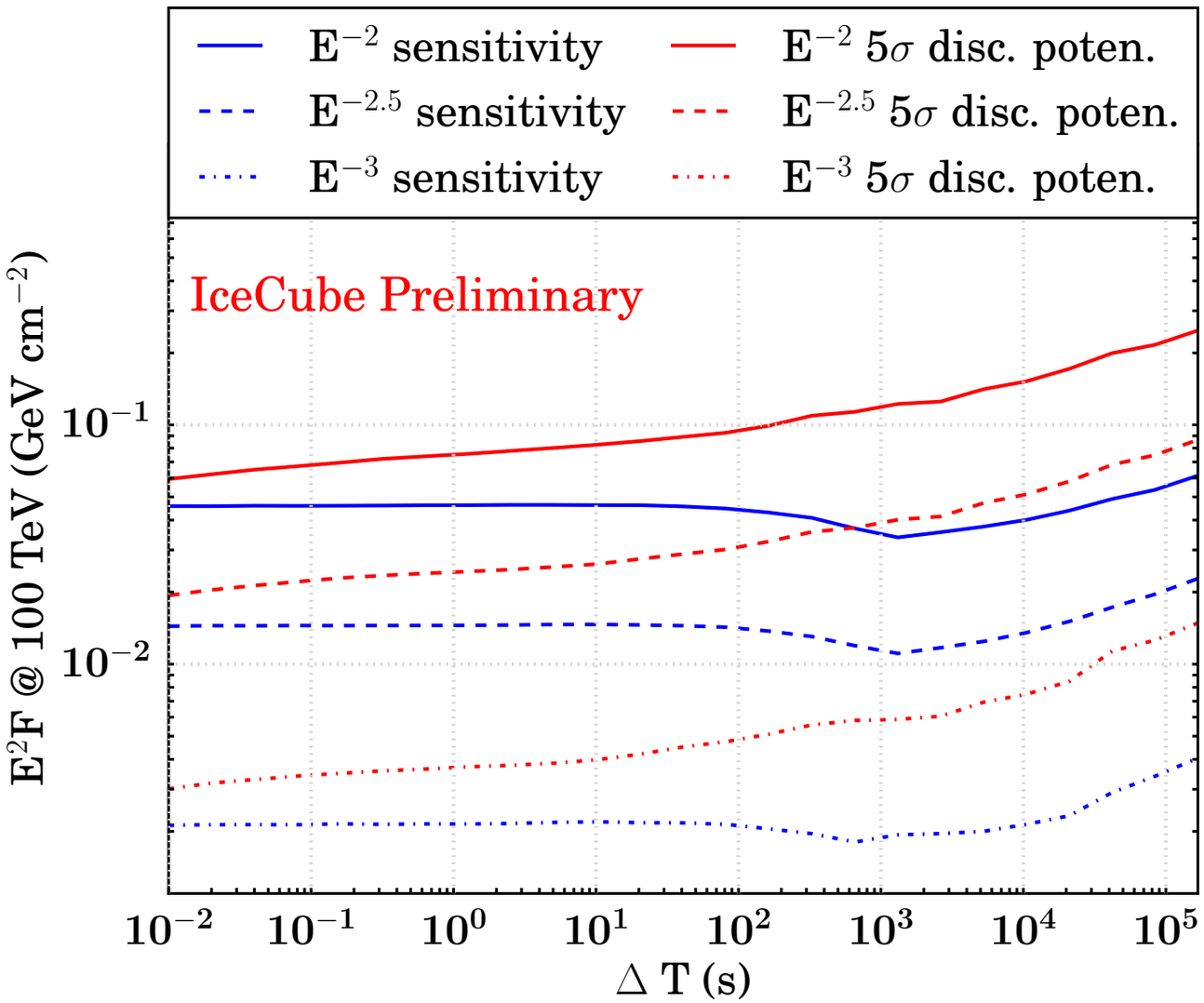
South



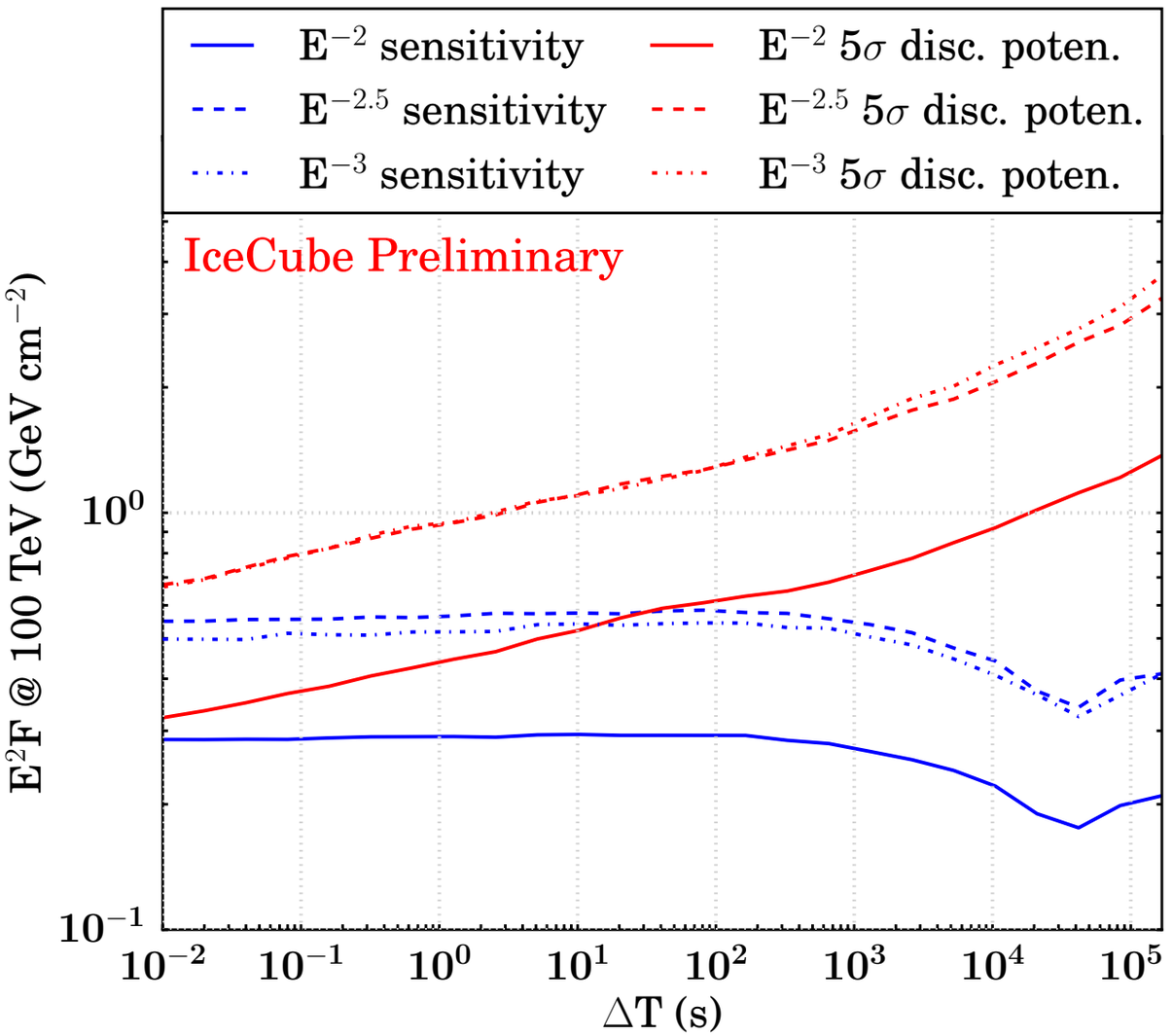
- 25 time windows from 10 ms to 2 days, expanding as $2^i x 10$ ms (i =0, …, 24)
- One coincident event can be discovery in the short time windows

Sensitivity & Discovery Potentials - Max-burst

North



South

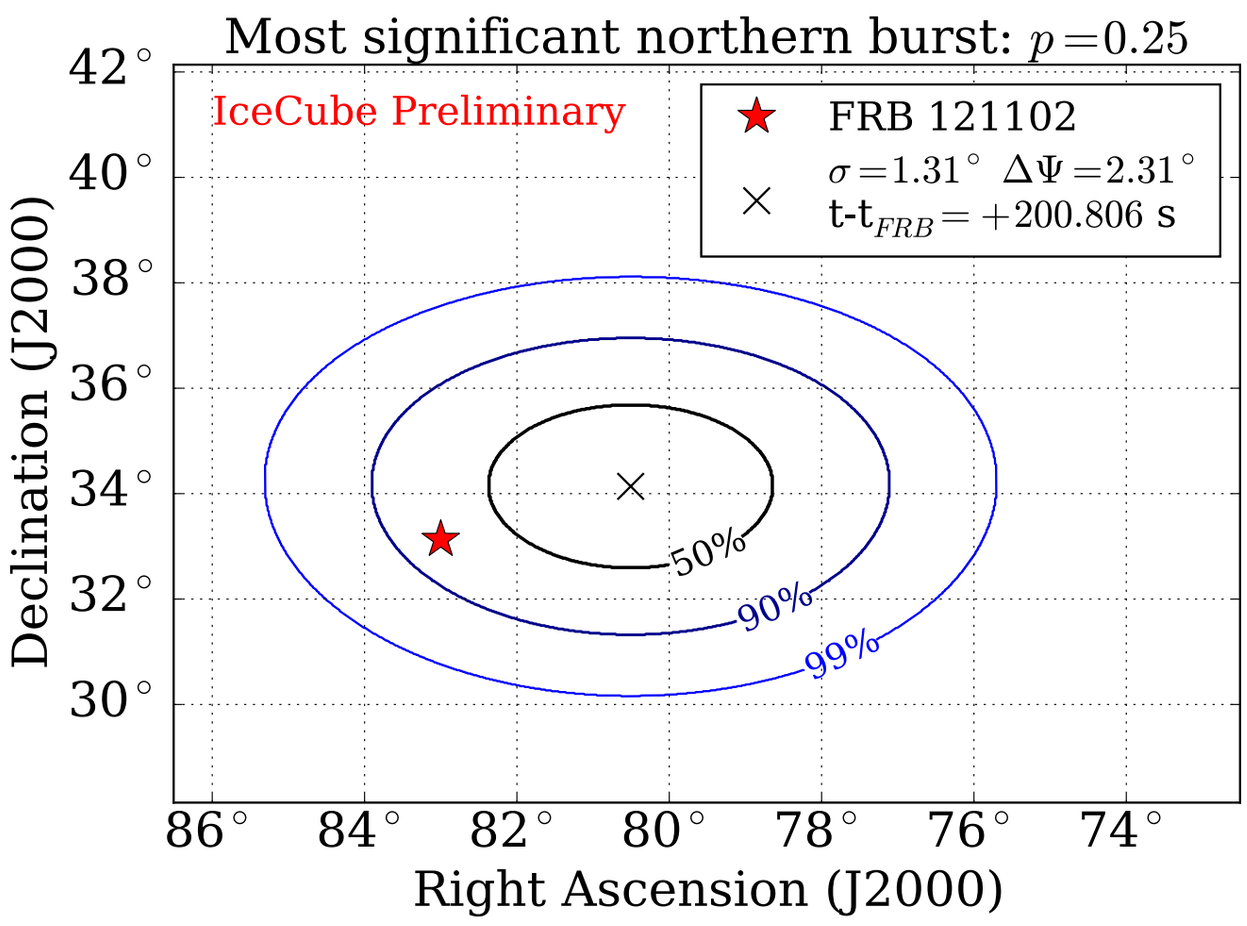


- 25 time windows from 10 ms to 2 days, expanding as $2^i x 10$ ms (i =0, …, 24)
- One coincident event can be discovery in the short time windows

North Max-burst

Most significant time window:

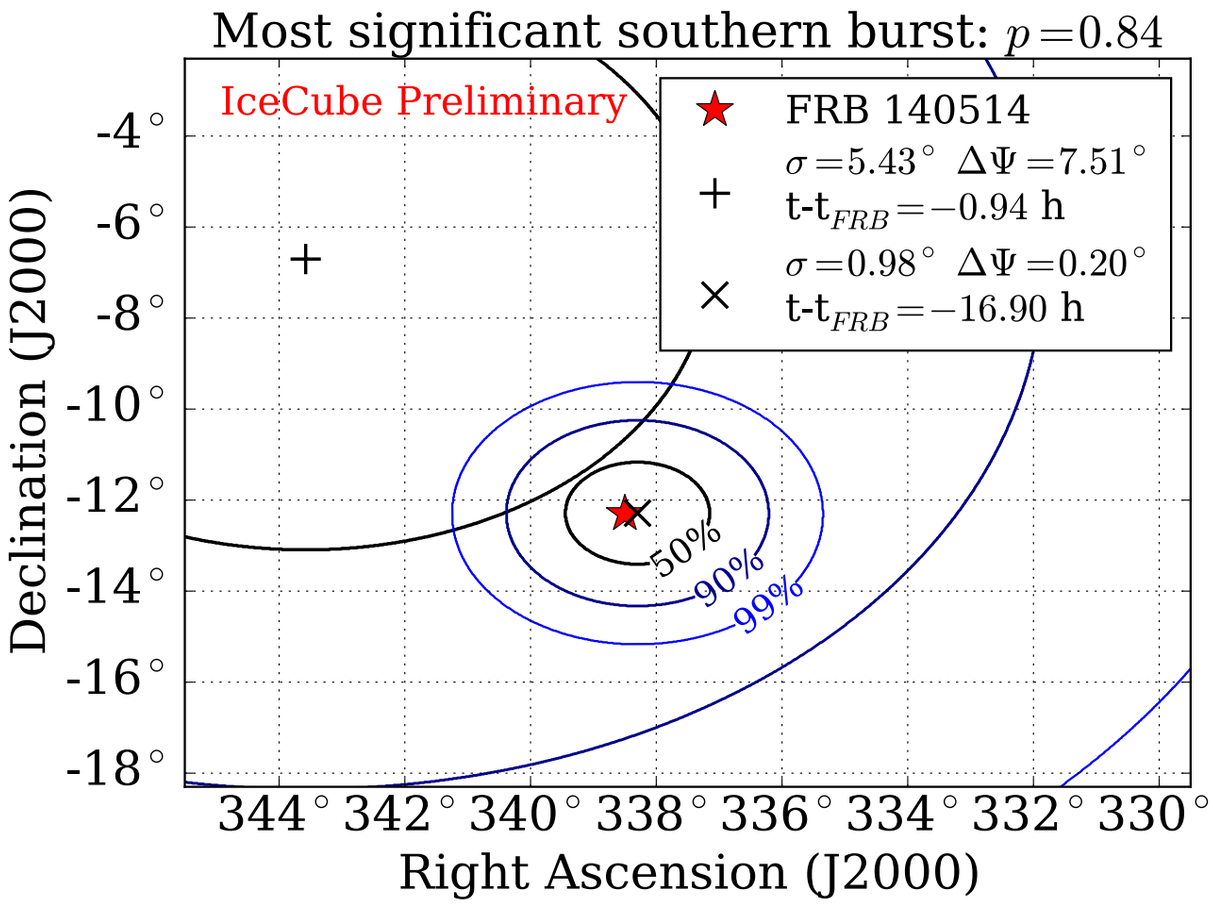
$$\Delta T = 655.36\,\mathrm{s}$$



South Max-burst

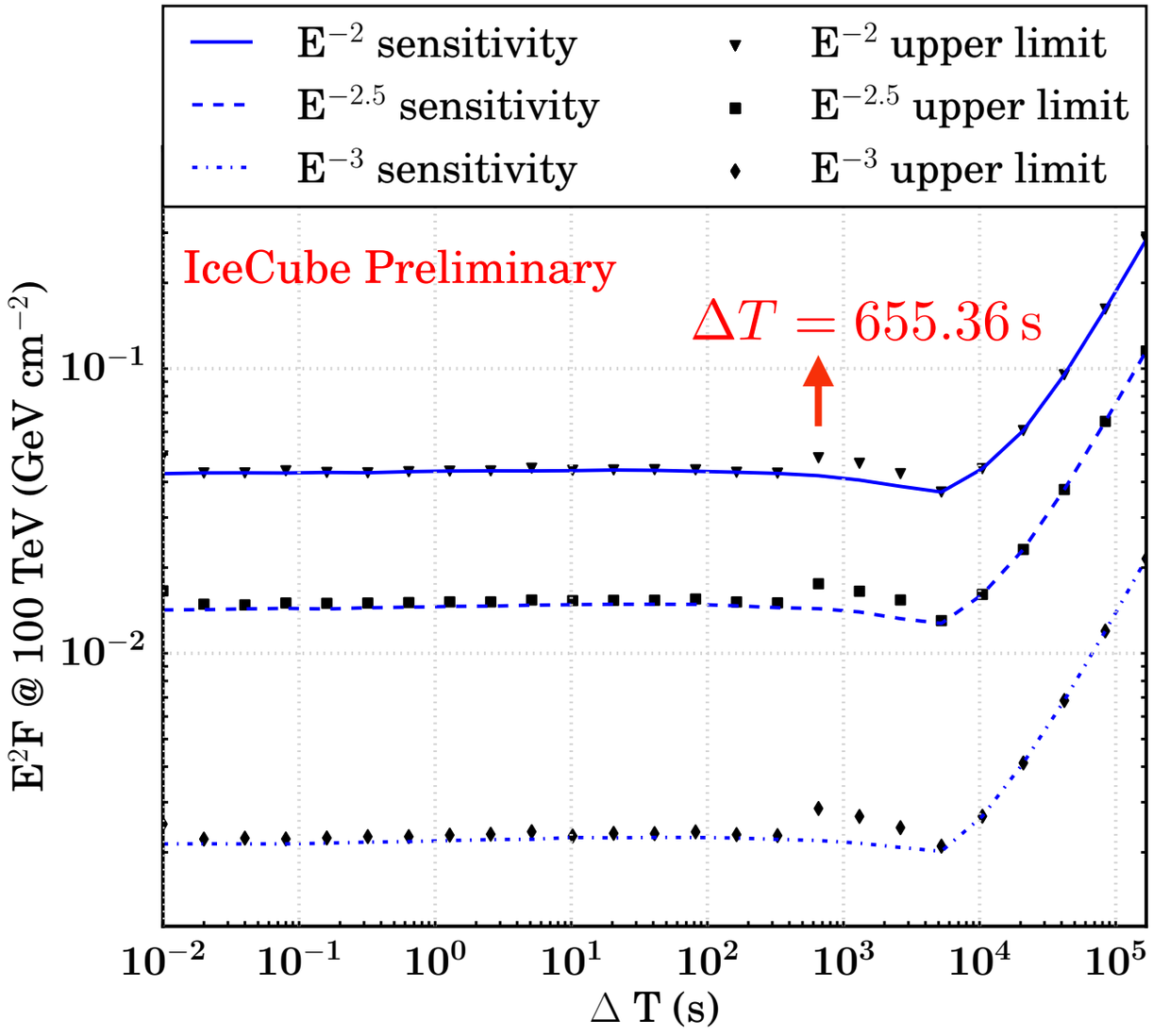
Most significant time window:

$$\Delta T = 167772.16\,\mathrm{s}$$

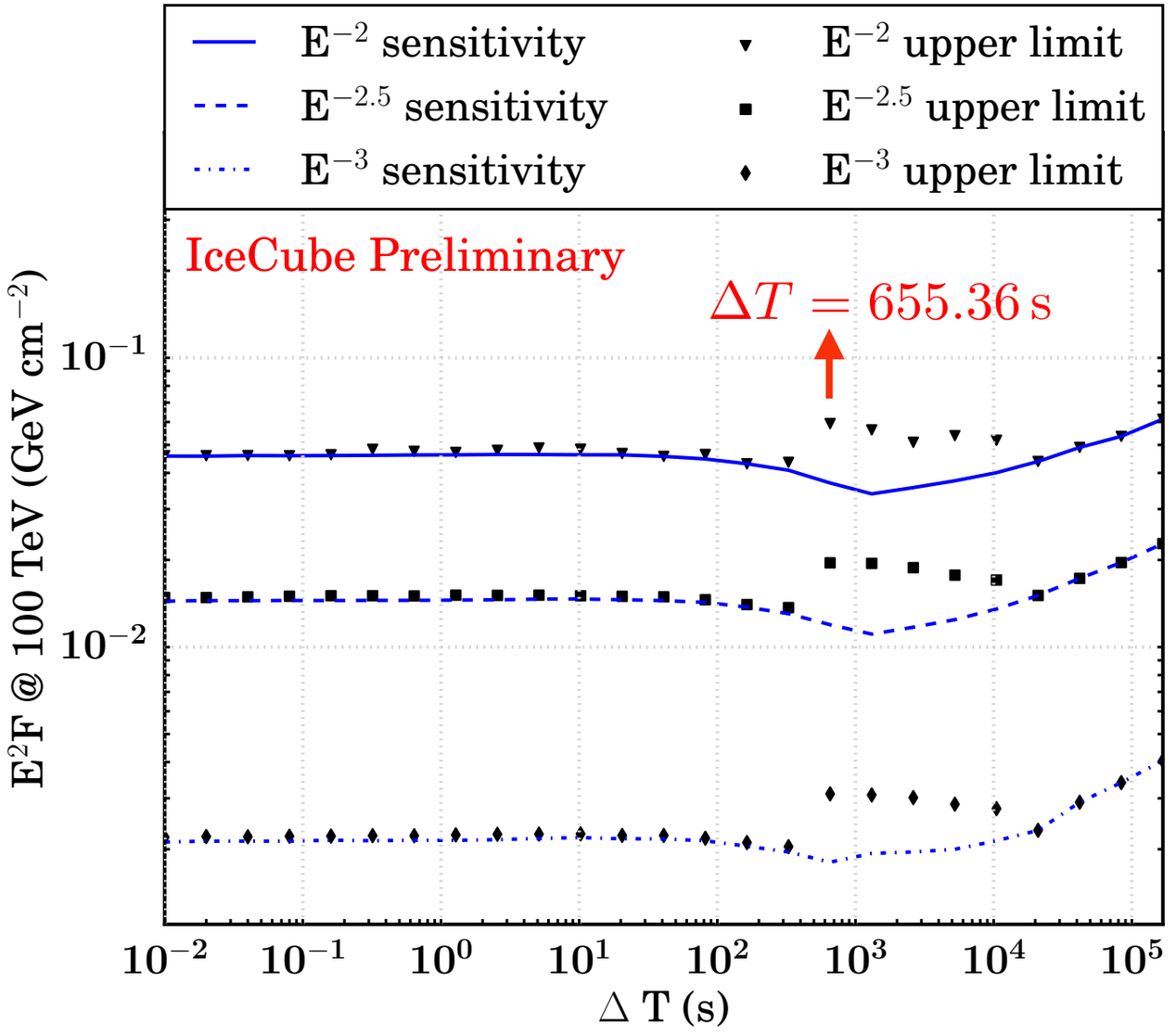


Results - Upper Limits

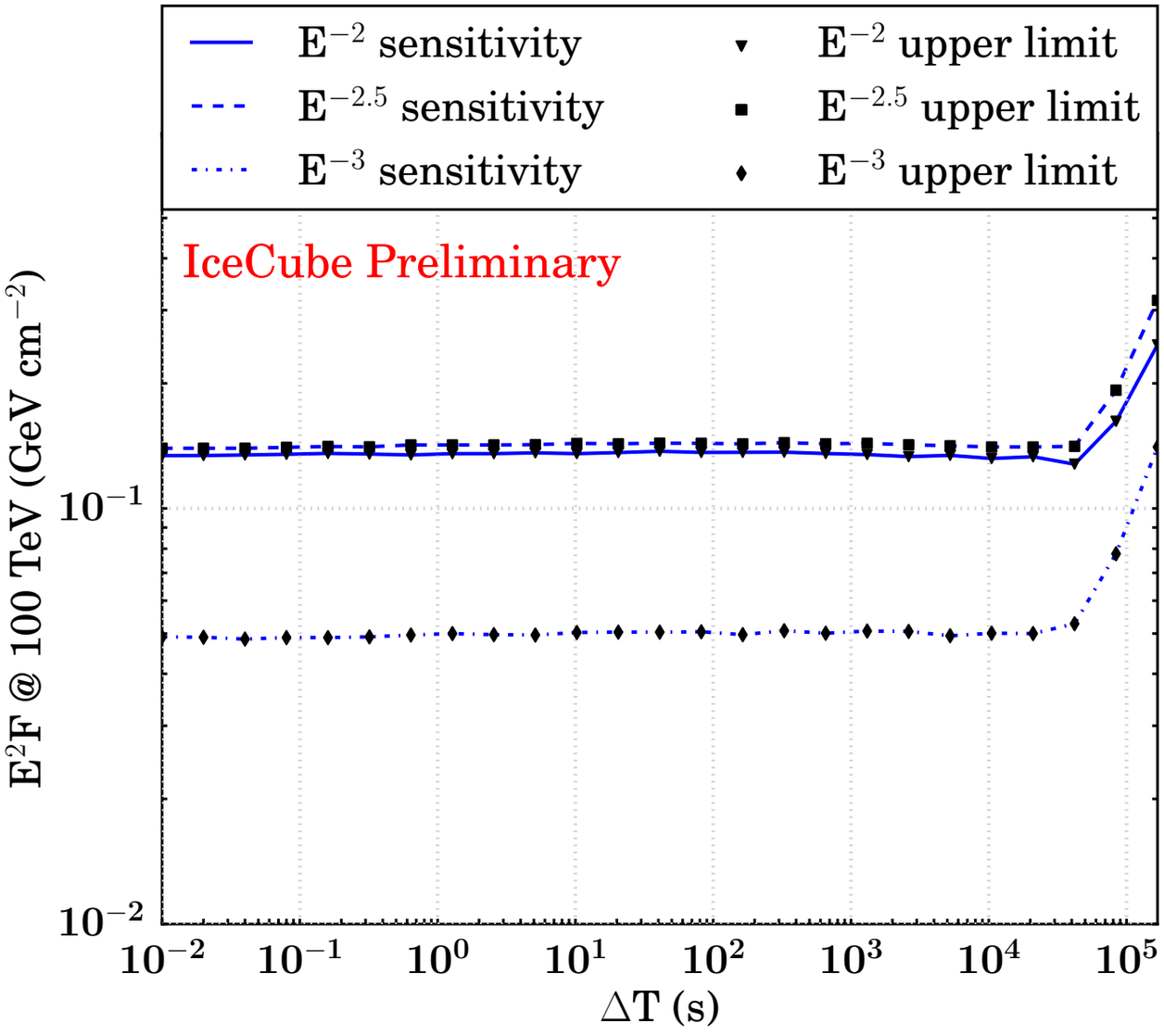
North Stacking



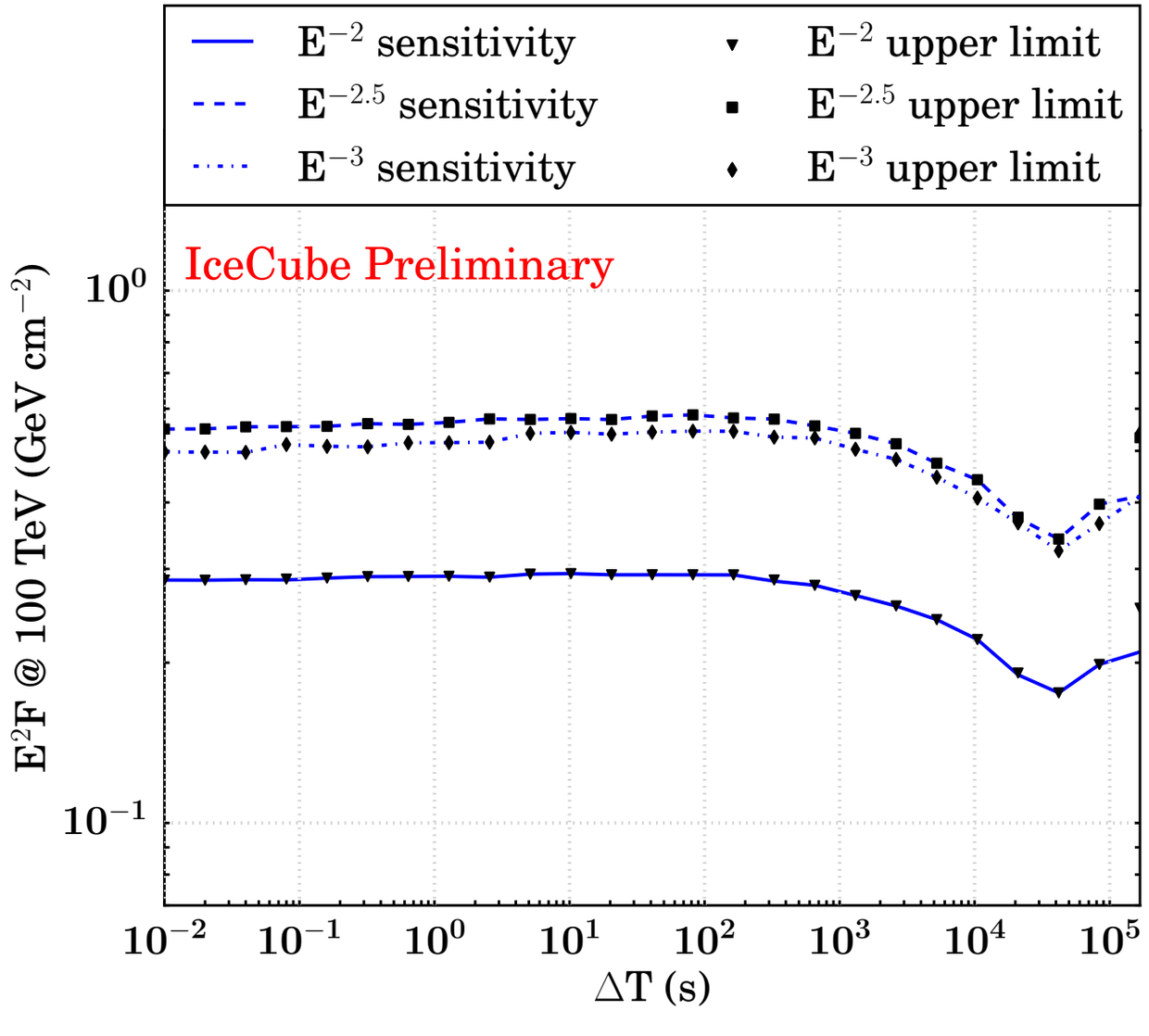
North Max-burst



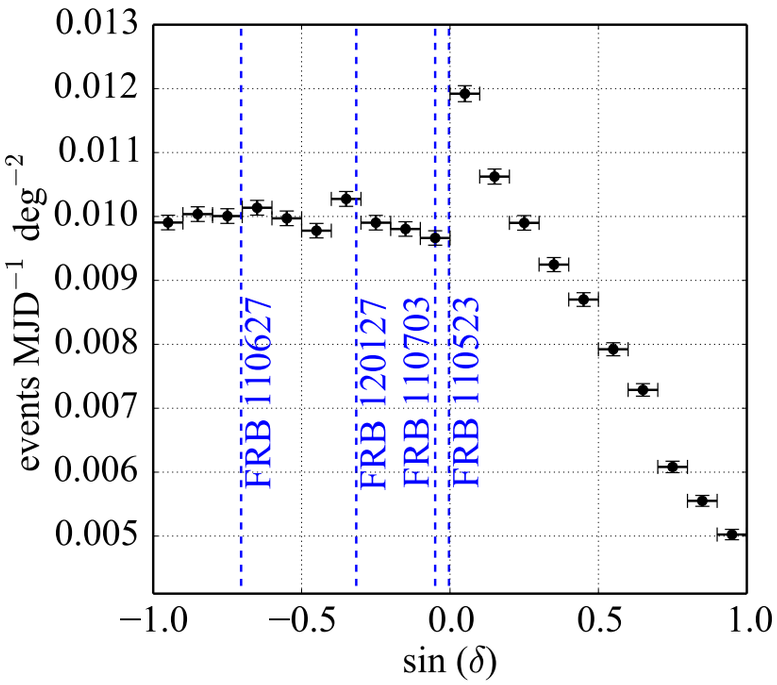
South Stacking

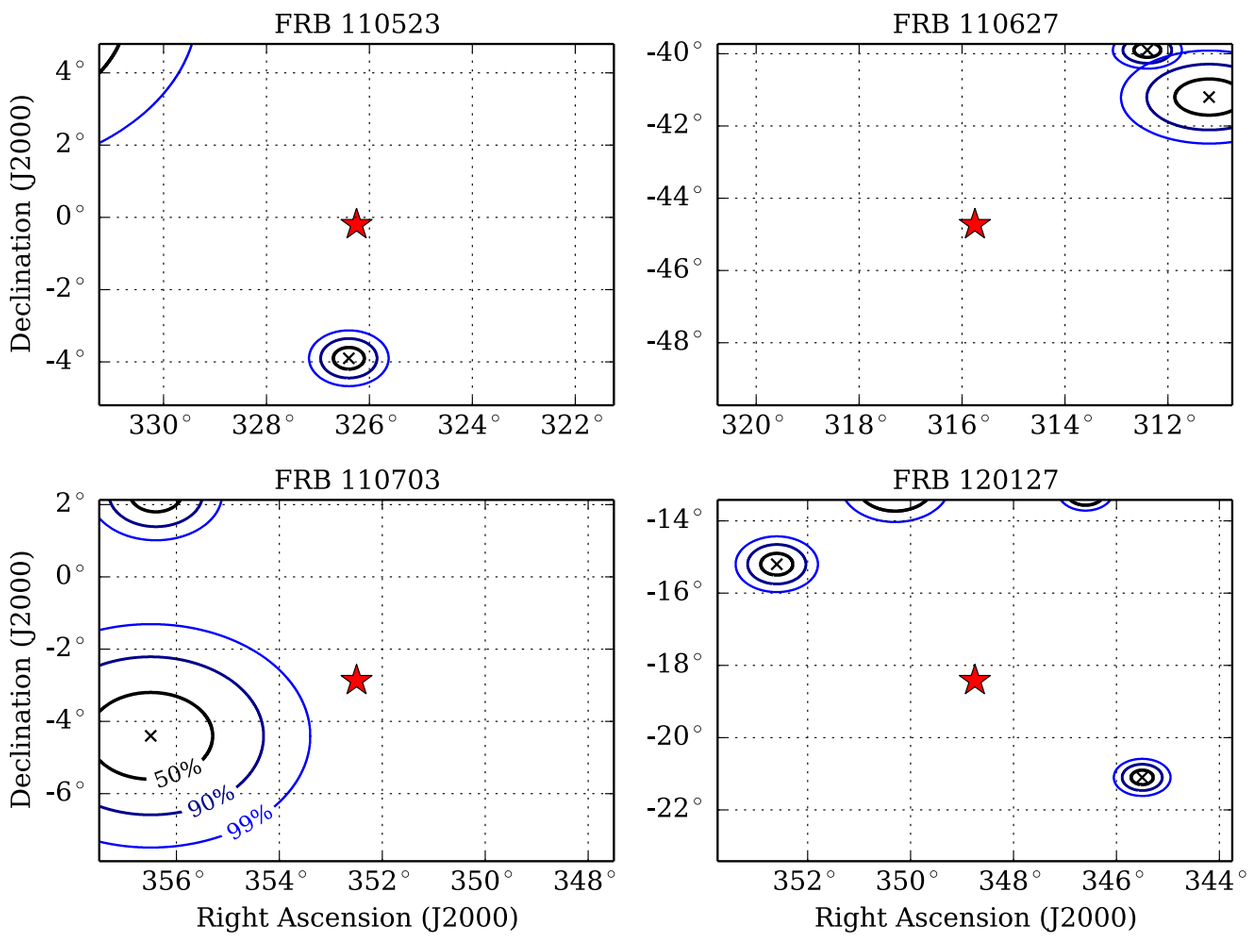


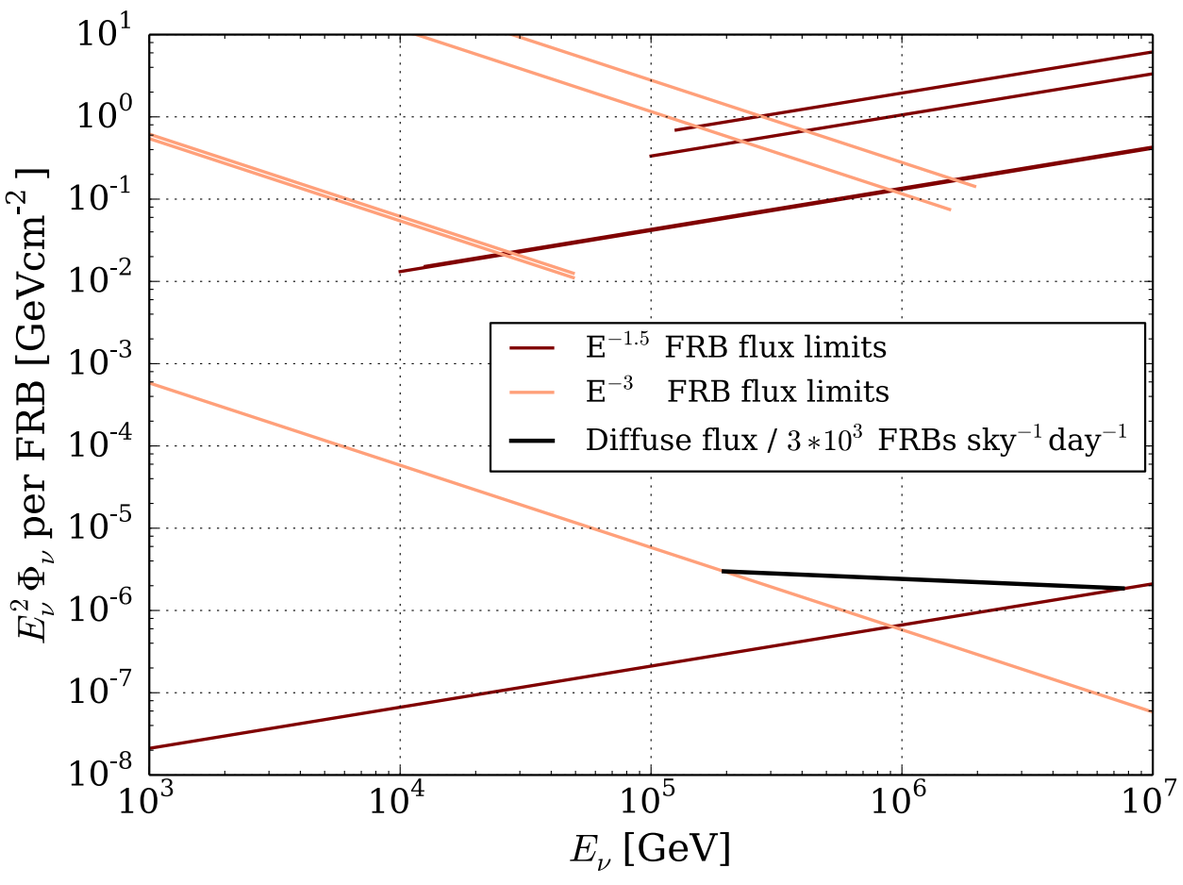
South Max-burst



Results from a previous search ...







Data used is public:

http://icecube.wisc.edu/science/data/PS-IC86-2011

S. Fahey, A. Kheirandish, J. Vandenbroucke, D. Xu
ApJ 845 (2017) 1, 14

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Conclusion & Outlook

- **Fast radio bursts (FRBs) could emit high energy neutrinos**
- **A maximum likelihood analysis has been established to search for spatial and temporal coincidence between IceCube neutrinos and FRBs**
- **No significant correlations between IceCube neutrinos and FRBs were found in 6 years of data.**
- **Most stringent limits on neutrino fluence from FRBs have been set to be ~0.04 GeV cm^{-2}. Publication is in preparation.**
- **IceCube can now quickly follow up on the FRBs to be detected in the forthcoming future, adding a multi-messenger window to help untangle the FRB mystery**

Back up slides

Assume the same escape time t_0:

$$\Delta t = D \cdot |\frac{1}{c} - \frac{1}{v_\nu}| = D \cdot (\frac{1}{\sqrt{(1 - \frac{1}{\gamma^2})}} - 1)\ \mathrm{s}$$

$$\gamma = \frac{E_\nu}{m_\nu},\ c = 1$$

$$\Delta t \simeq \frac{1}{2} \cdot D \cdot (\frac{m_\nu}{E_\nu})^2$$

$$\Delta t \simeq \frac{1}{2} \cdot (\frac{m_\nu}{\mathrm{eV}})^2 \cdot (\frac{\mathrm{MeV}}{E_\nu})^2 \cdot (\frac{D}{10\,\mathrm{kpc}})$$

For $z \simeq 0.5,\ D_{\rm light} \simeq 2\ {\rm Gpc}$

For 10 MeV neutrinos:

$$\Delta t \simeq \frac{1}{2} \cdot (\frac{1\,{\rm eV}}{\rm eV})^2 \cdot (\frac{\rm MeV}{10\,{\rm MeV}})^2 \cdot (\frac{2\,{\rm Gpc}}{10\,{\rm kpc}}) \simeq 1000\ {\rm s}$$

For 1 TeV neutrinos:

$$\Delta t \simeq \frac{1}{2} \cdot (\frac{1\,{\rm eV}}{\rm eV})^2 \cdot (\frac{\rm MeV}{1\,{\rm TeV}})^2 \cdot (\frac{2\,{\rm Gpc}}{10\,{\rm kpc}}) \simeq 1.0 \times 10^{-7}\ {\rm s}$$

Photon trapped time unknown