# Search for Neutrino Emission from Fast Radio Bursts with IceCube


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**for the IceCube Collaboration**



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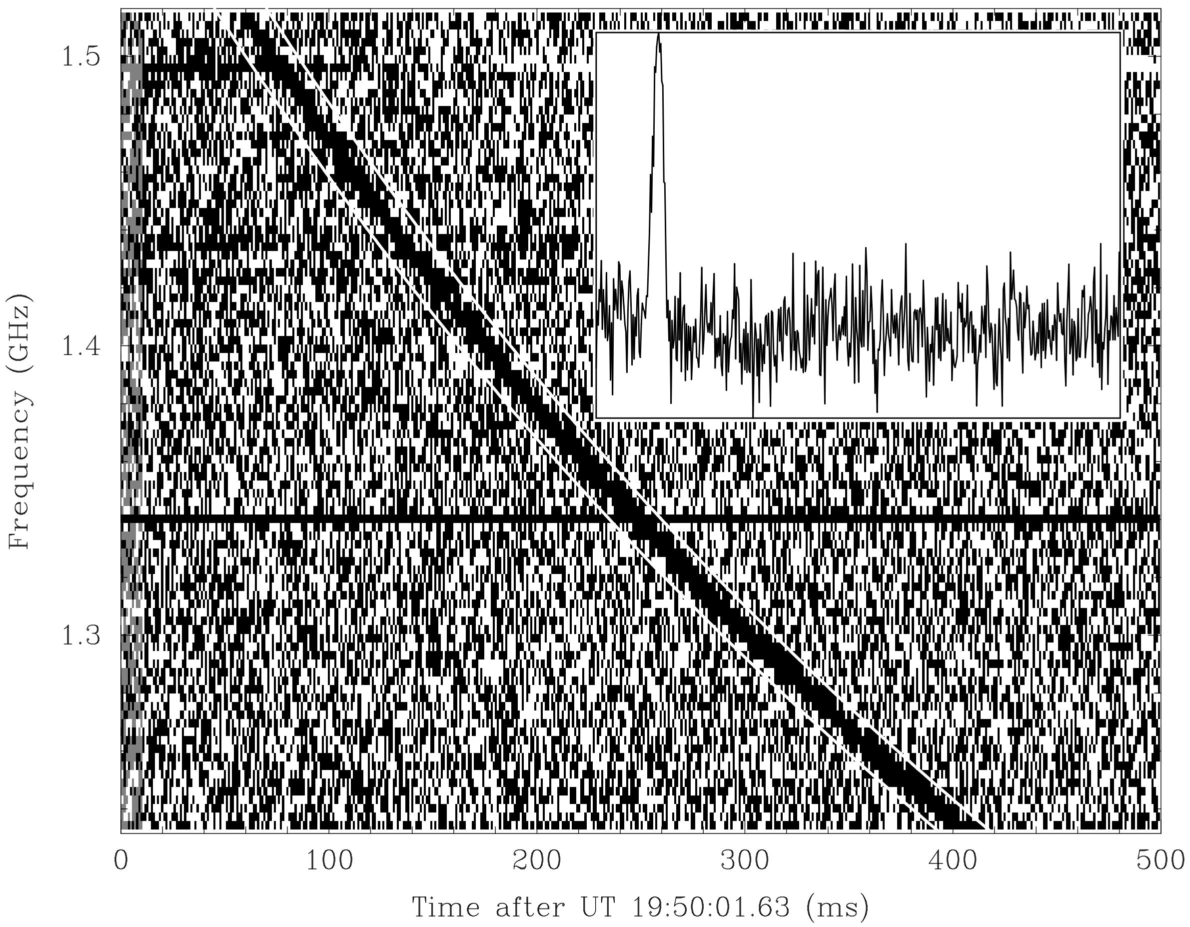
# Fast Radio Bursts - Discovery in 2007

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




$$\Delta t_{\mathrm{delay}} = \frac{e^2}{2\pi m_e c^3} \cdot \mathrm{DM} \cdot w^{-2}$$
$$= 1.5 \times 10^{-24}\,\mathrm{s} \cdot \mathrm{DM} \cdot w^{-2}$$

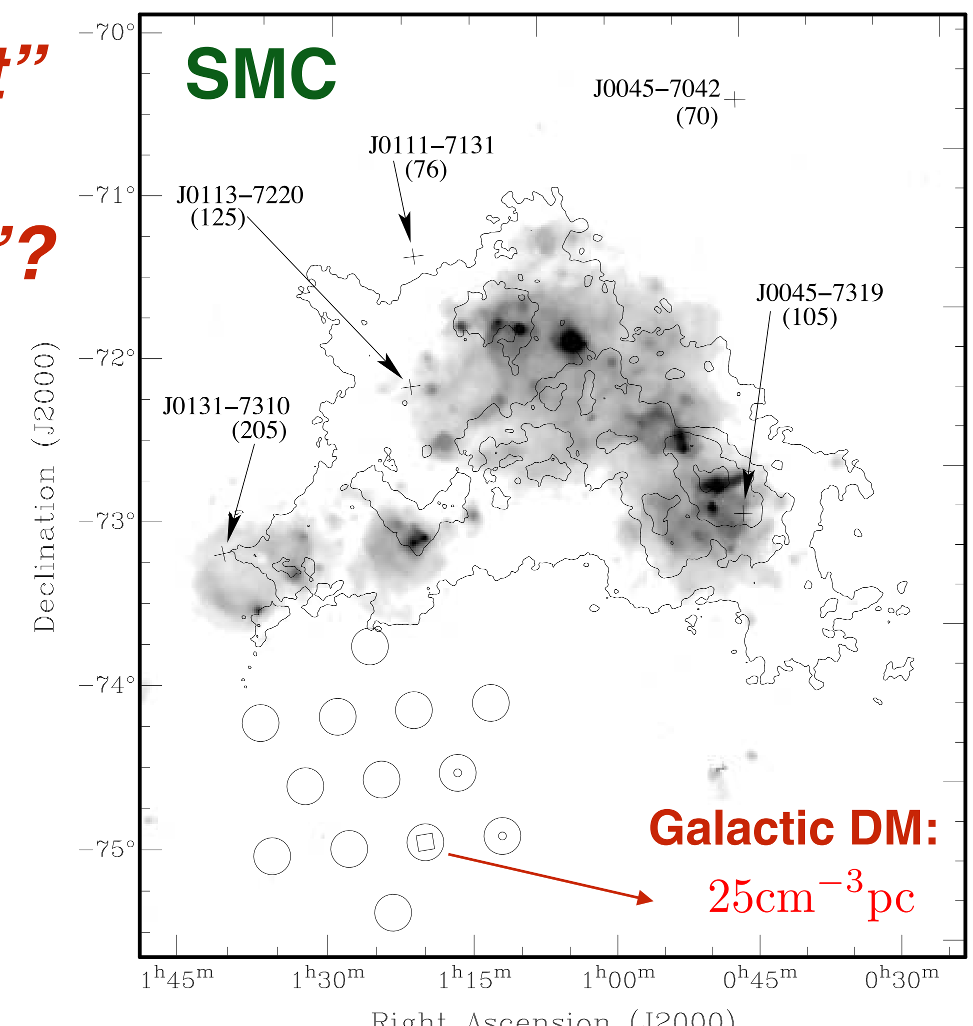
$$\mathrm{DM} = \int n_e dl = 375 \pm 1 \mathrm{cm}^{-3}\mathrm{pc}$$

***"very compact"***

***"extragalactic"?***

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

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

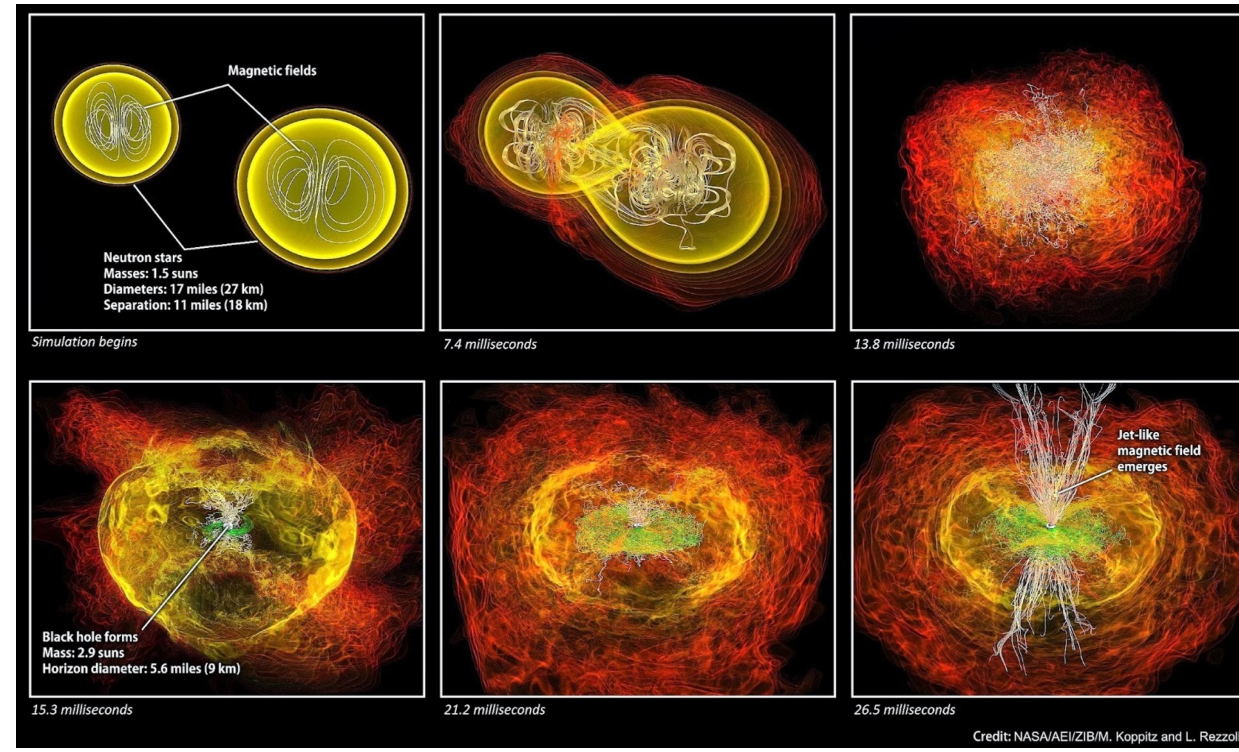


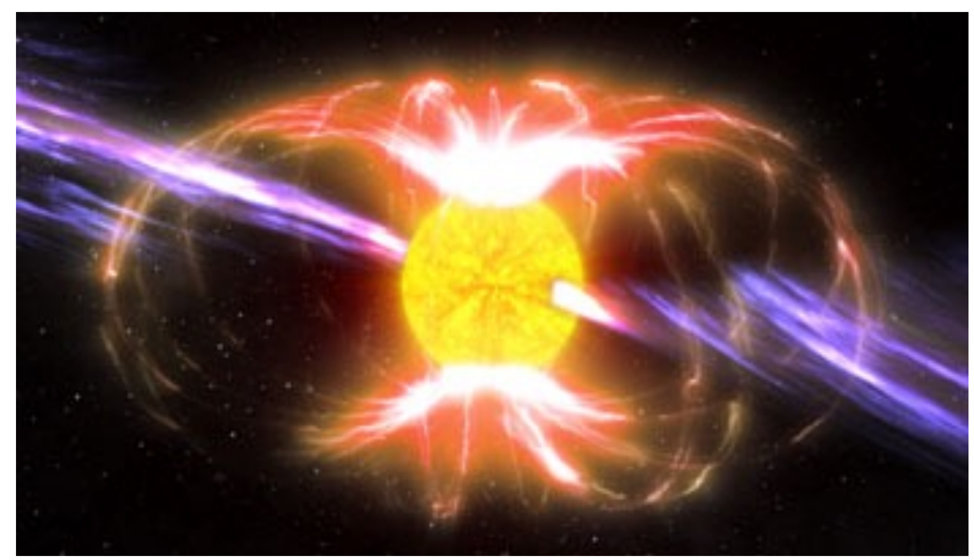

- A total of ~**23** FRBs detected to date. Estimated FRB event rate is **~1,000/day**

# Fast Radio Bursts Emitting Neutrinos?

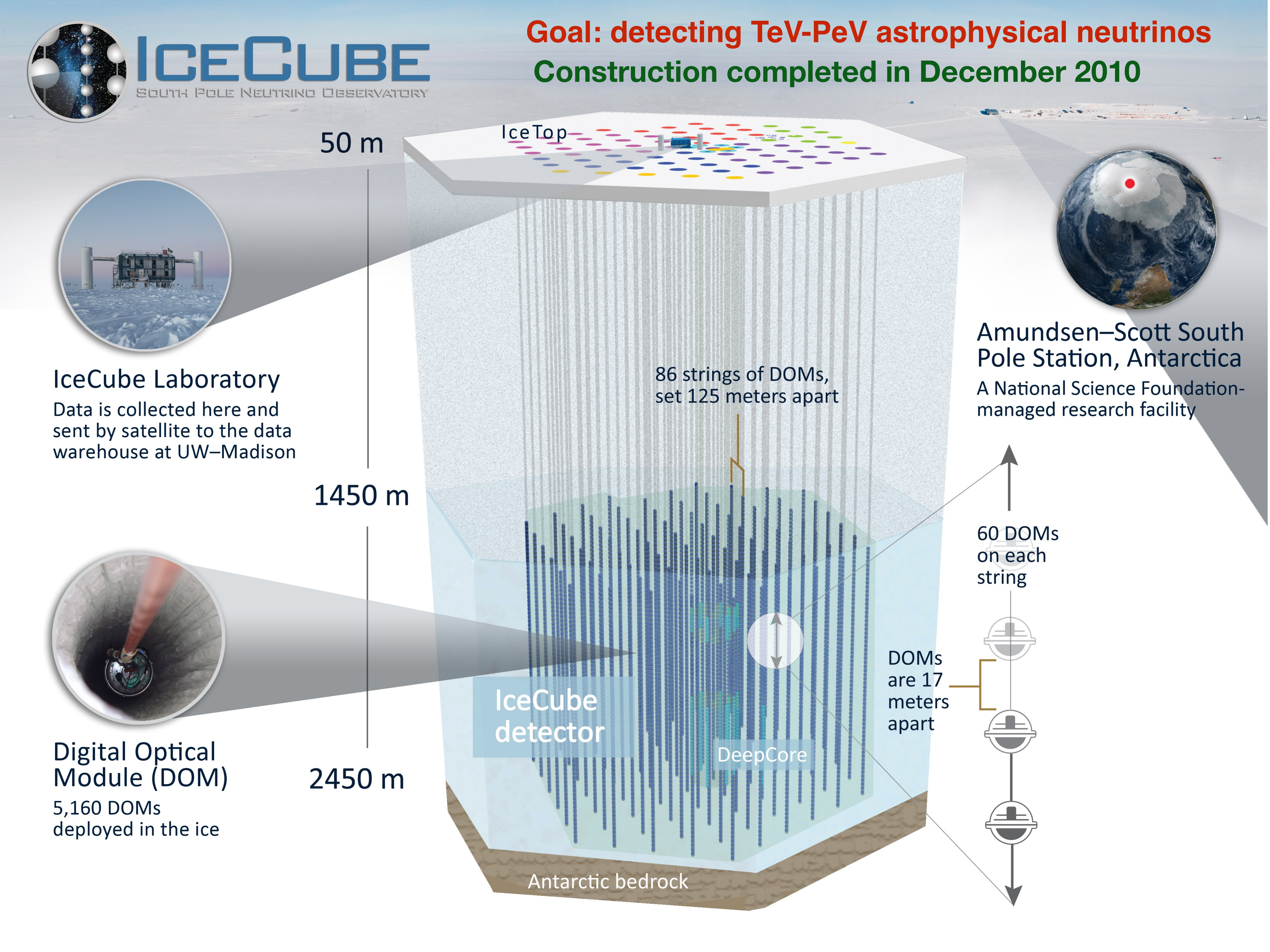


- **Blitzar** **“Cataclysmic”**
  [H. Falcke and L. Rezzolla, A&A 562, A137 (2014)]
- **Binary neutron star merger**
  [T. Totani, Pub. Astron. Soc. Jpn. 65, L12 (2013)]
- **Evaporating primordial black holes**
  [Halzen *et al*., PRD 1995]
  **“MeV neutrinos”**
- **Magnetar/SGRs hyperflares**
  [S. B. Popov and K. A. Postnov, arXiv:1307.4924]
  [Halzen *et al.* (2005) astro-ph/0503348]
  **“TeV neutrinos”? → this work**



**No concrete neutrino production models yet**

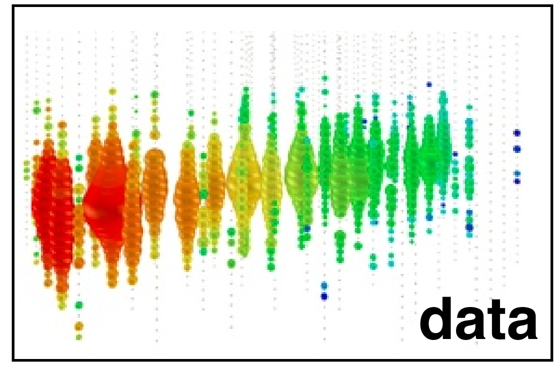


ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
Goal: detecting TeV-PeV astrophysical neutrinos
Construction completed in December 2010
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
86 strings of DOMs, set 125 meters apart
IceCube detector
DeepCore
Antarctic bedrock
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart

# Neutrino Signatures in IceCube

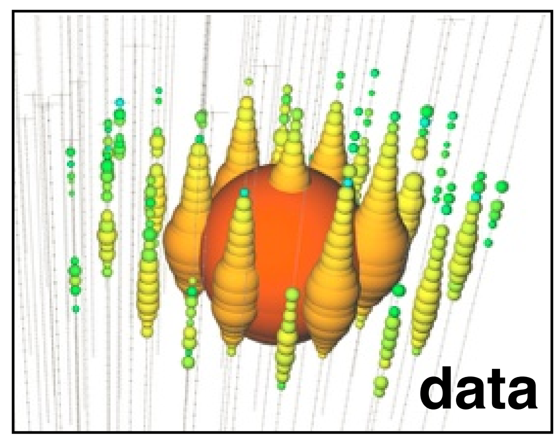
## (1) Track: charged current $\nu_\mu$

- $<1^{o}$ Angular resolution
- Factor ~ 2 energy resolution

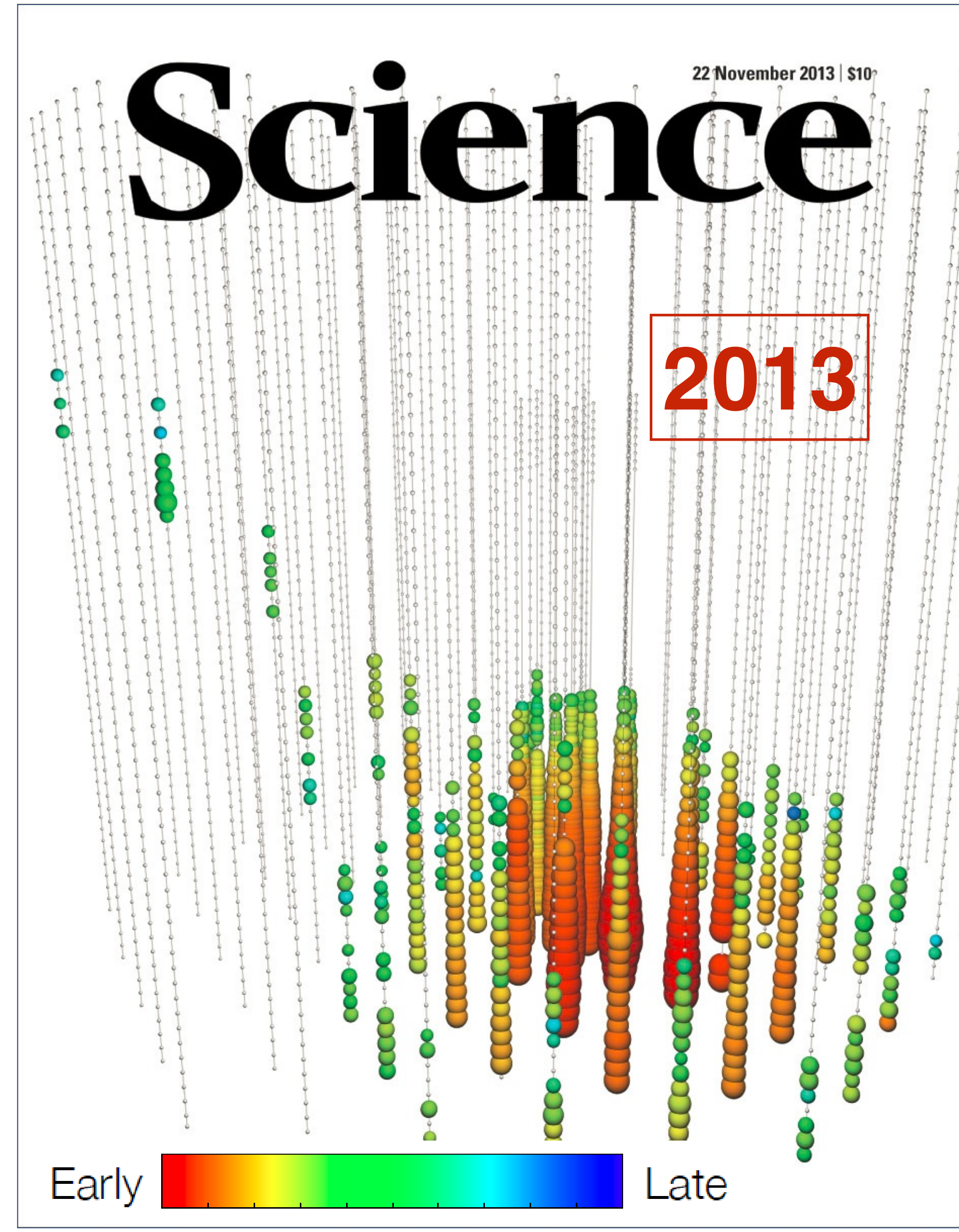



## (2) Cascade / Shower: all neutral current, charged current $\nu_e$, low-E charged current $\nu_\tau$

- $10^{o}$ Angular resolution above100 TeV
- 15% energy resolution on deposited energy




"high degeneracy"



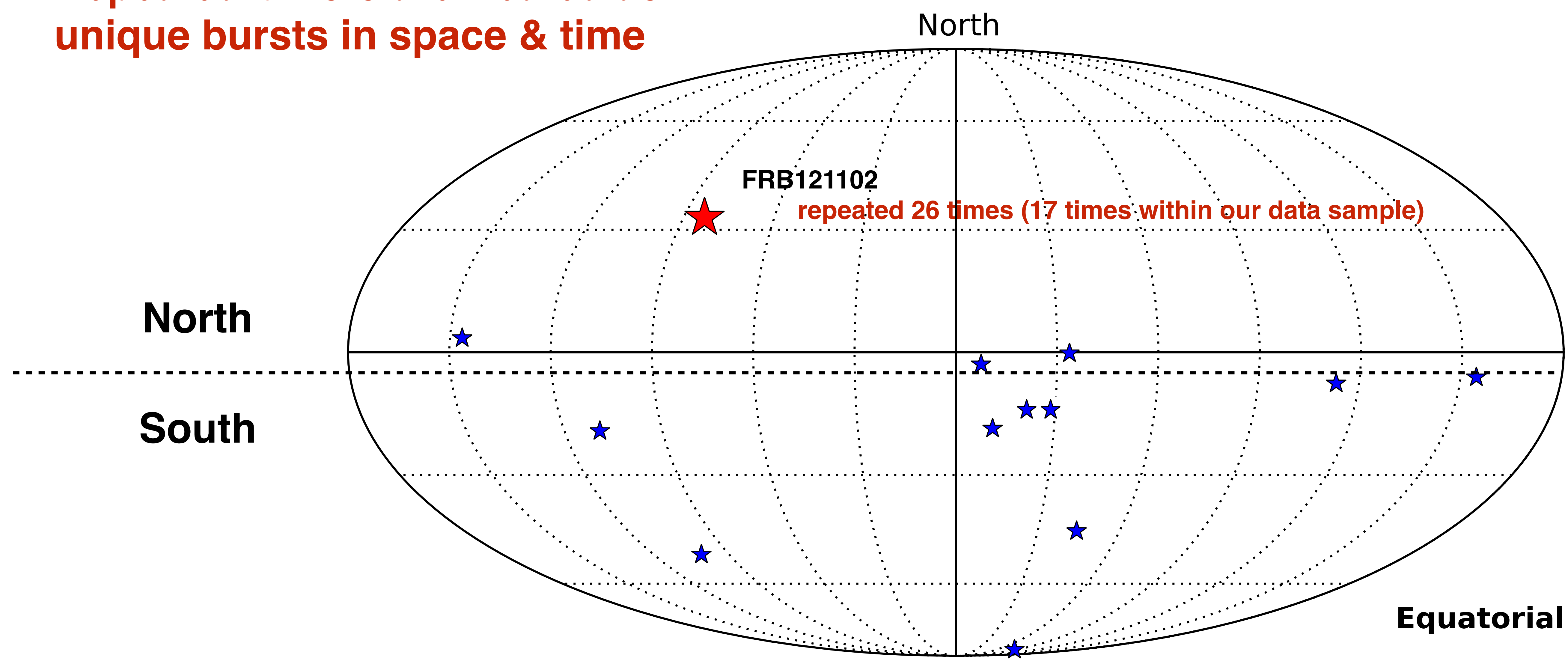

IceCube has detected a diffuse astrophysical neutrino flux, but **no TeV neutrino point sources** have been identified to date.

# 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



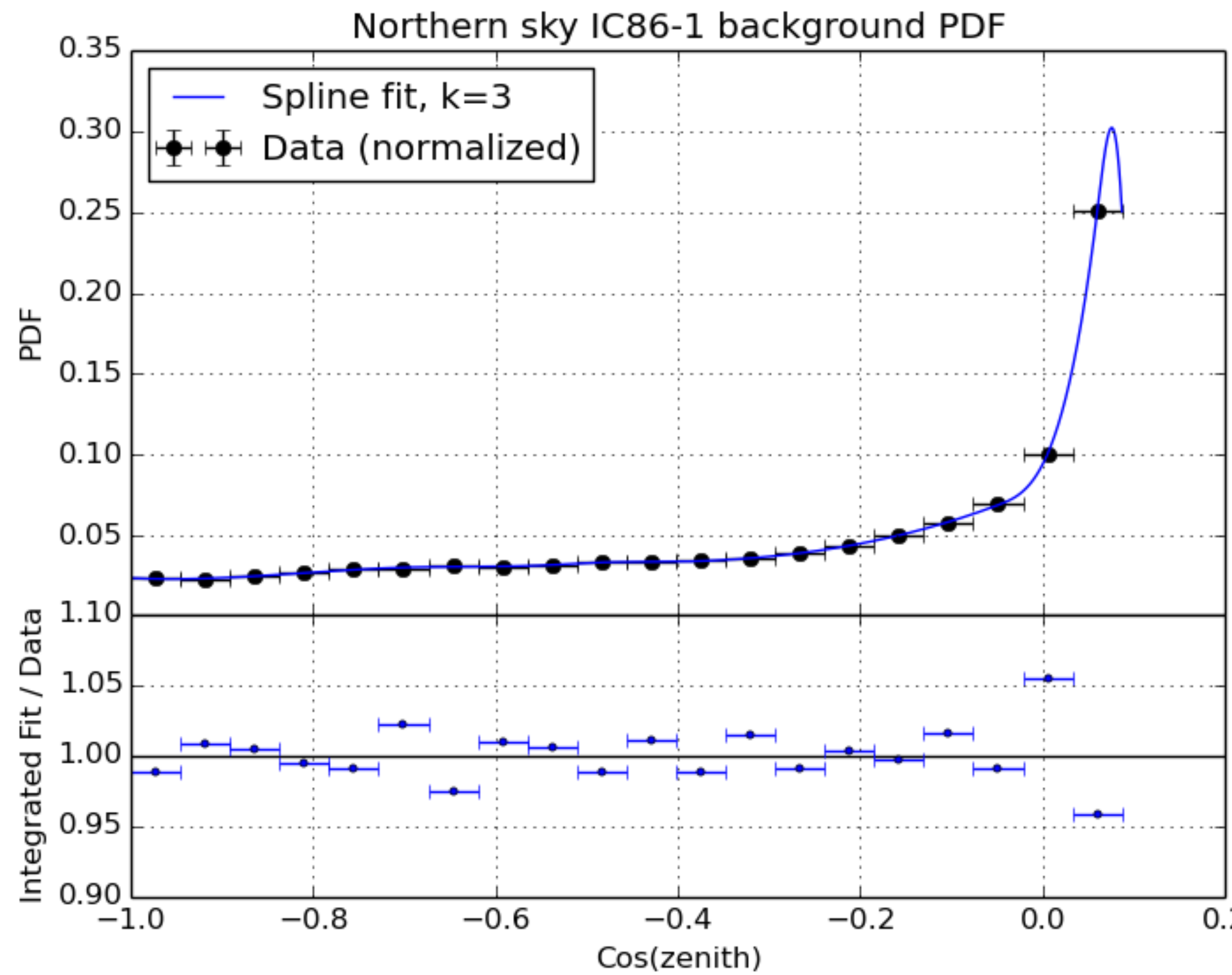
| North (DEC >= -5°) | South (DEC < -5°) |
|---|---|
| **842,597 events** *(collected from 2011-2015)* | **379,261 events** *(collected from 2010-2014)* |
| **"dominated by atmospheric neutrinos"** | **"dominated by atmospheric muons"** |

**A total of 1.2 million events in 6 years**

2015 ApJ 805 L5

arXiv:1702.06868

**Background PDF derived from off-time data**






WIPAC Wisconsin IceCube Particle Astrophysics Center

IceCube South Pole Neutrino Observatory

# 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 $P(x_i)$:**

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

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

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

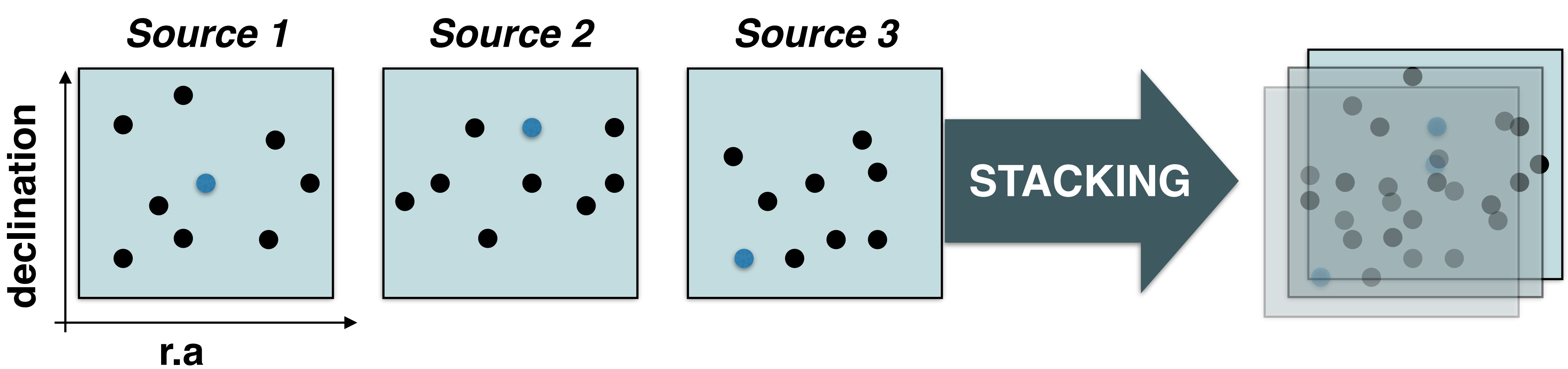
**"temporal" + "spatial"**

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

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

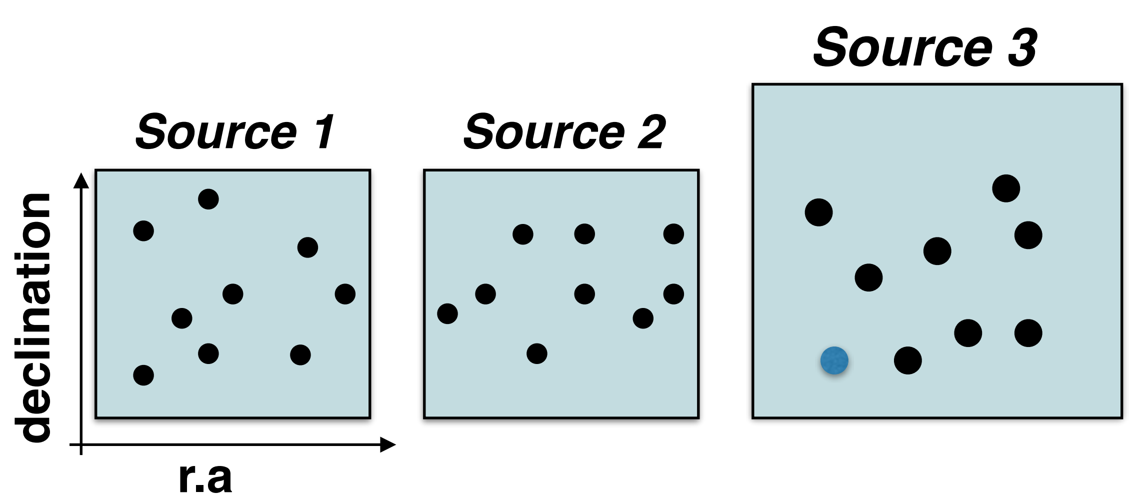
# Search Strategy

- **Stacking** "Distributed fluence test"




- **Max-burst**

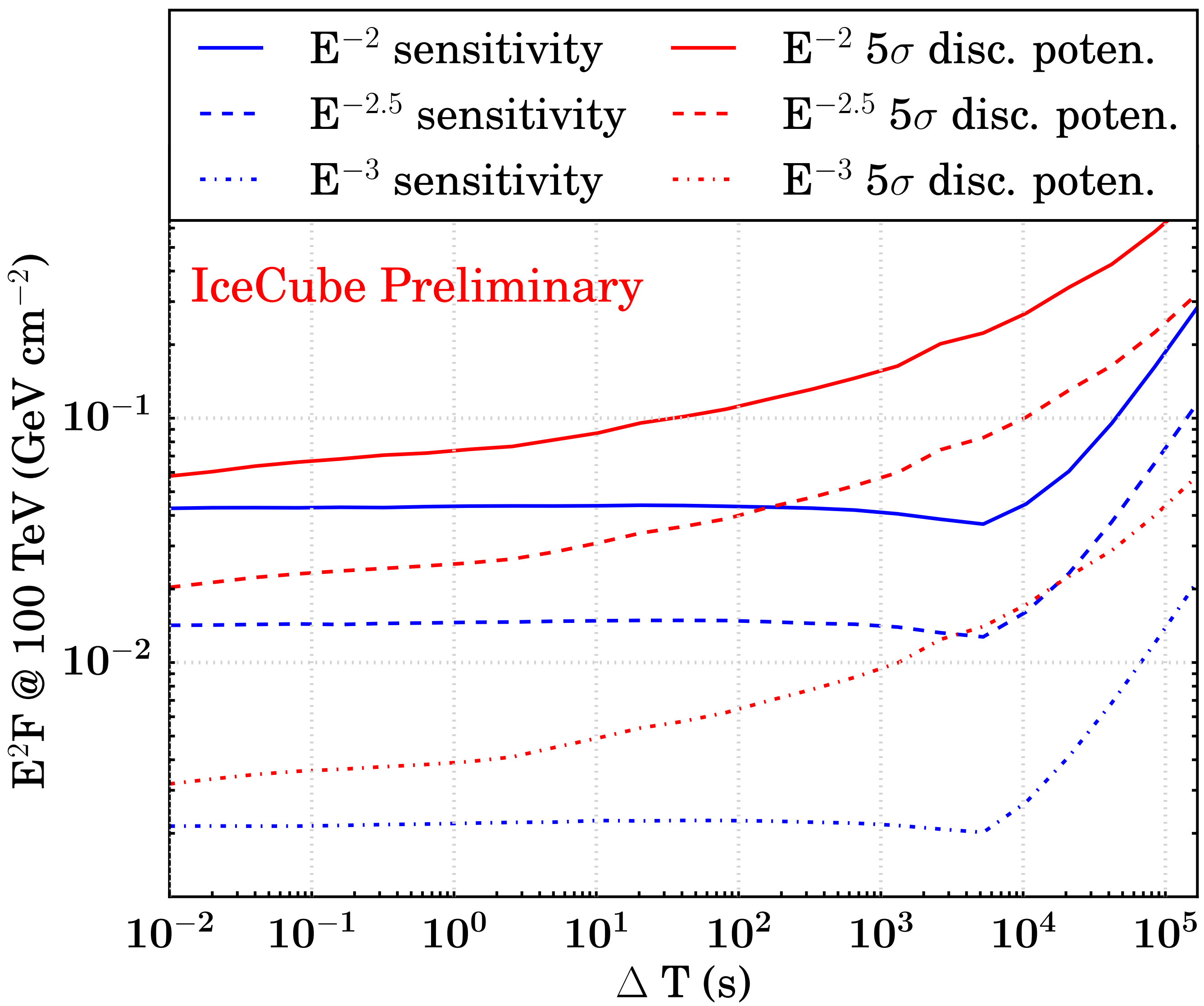
"Single bright neutrino source test"



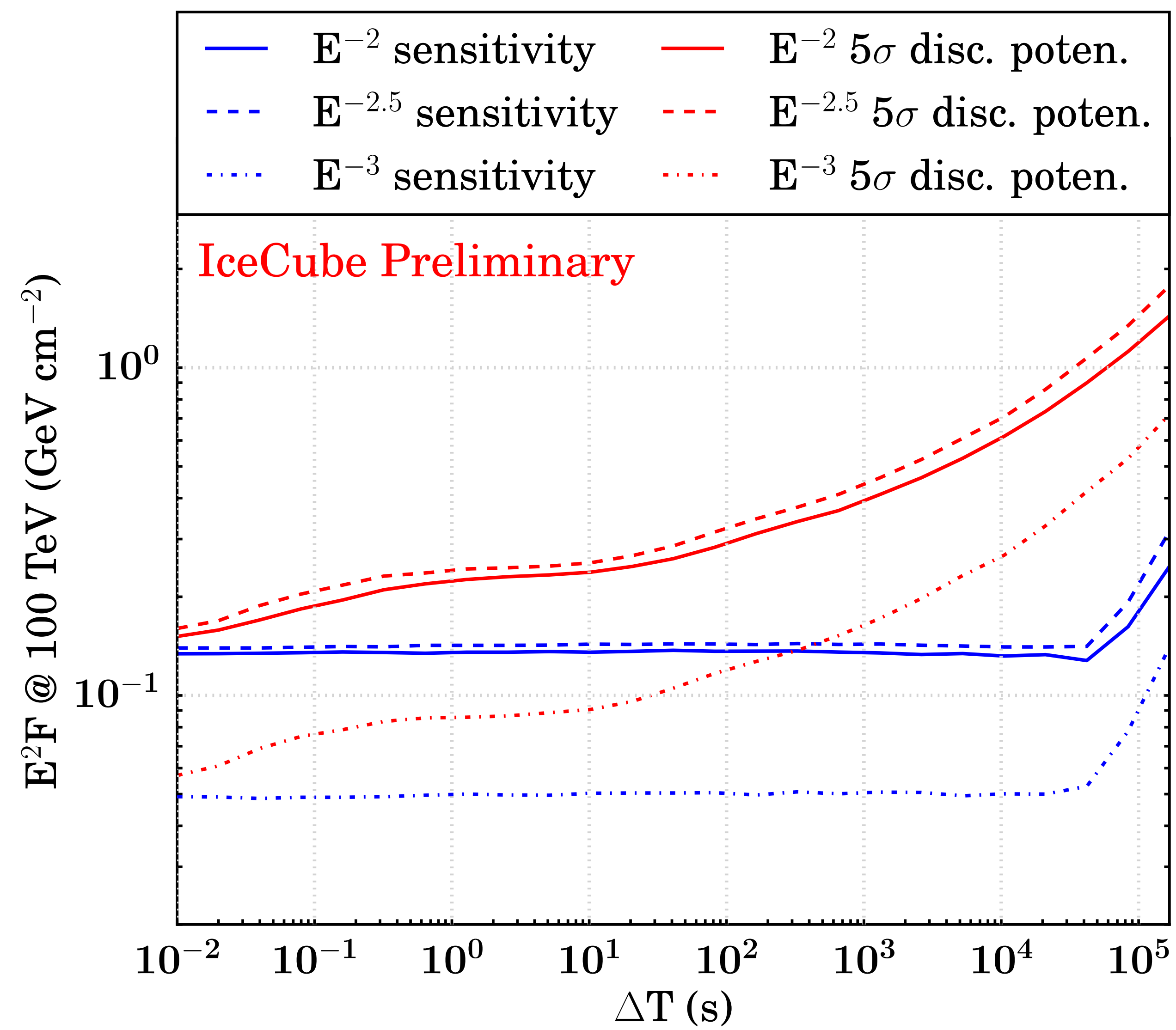

- Model independent
- Expanding time windows centered at burst times
- 25 time windows from 10 ms to 2 days, expanding as $2^i x 10$ ms (i =0, …, 24)

# Sensitivity & Discovery Potentials - Stacking

## North



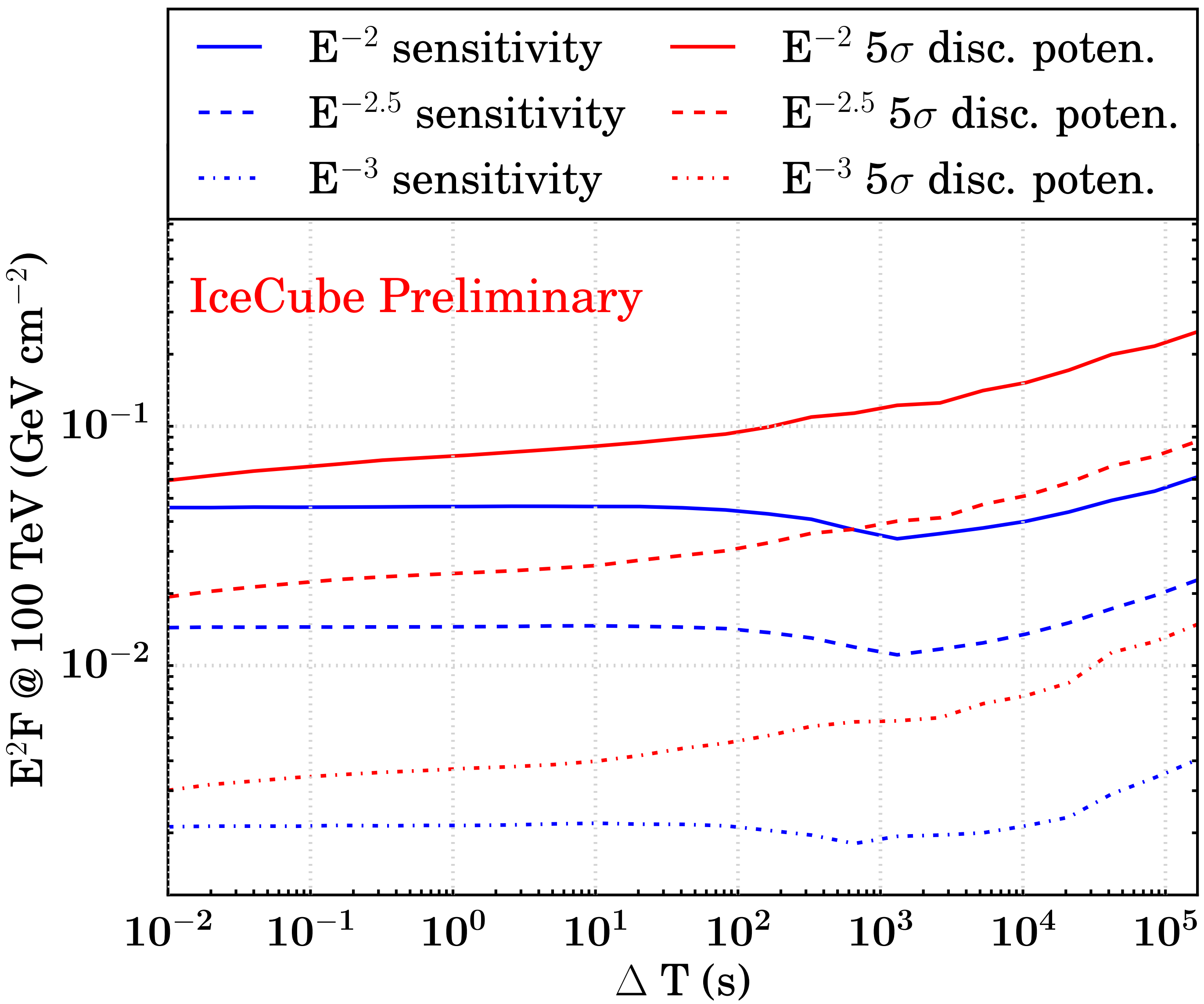

## South



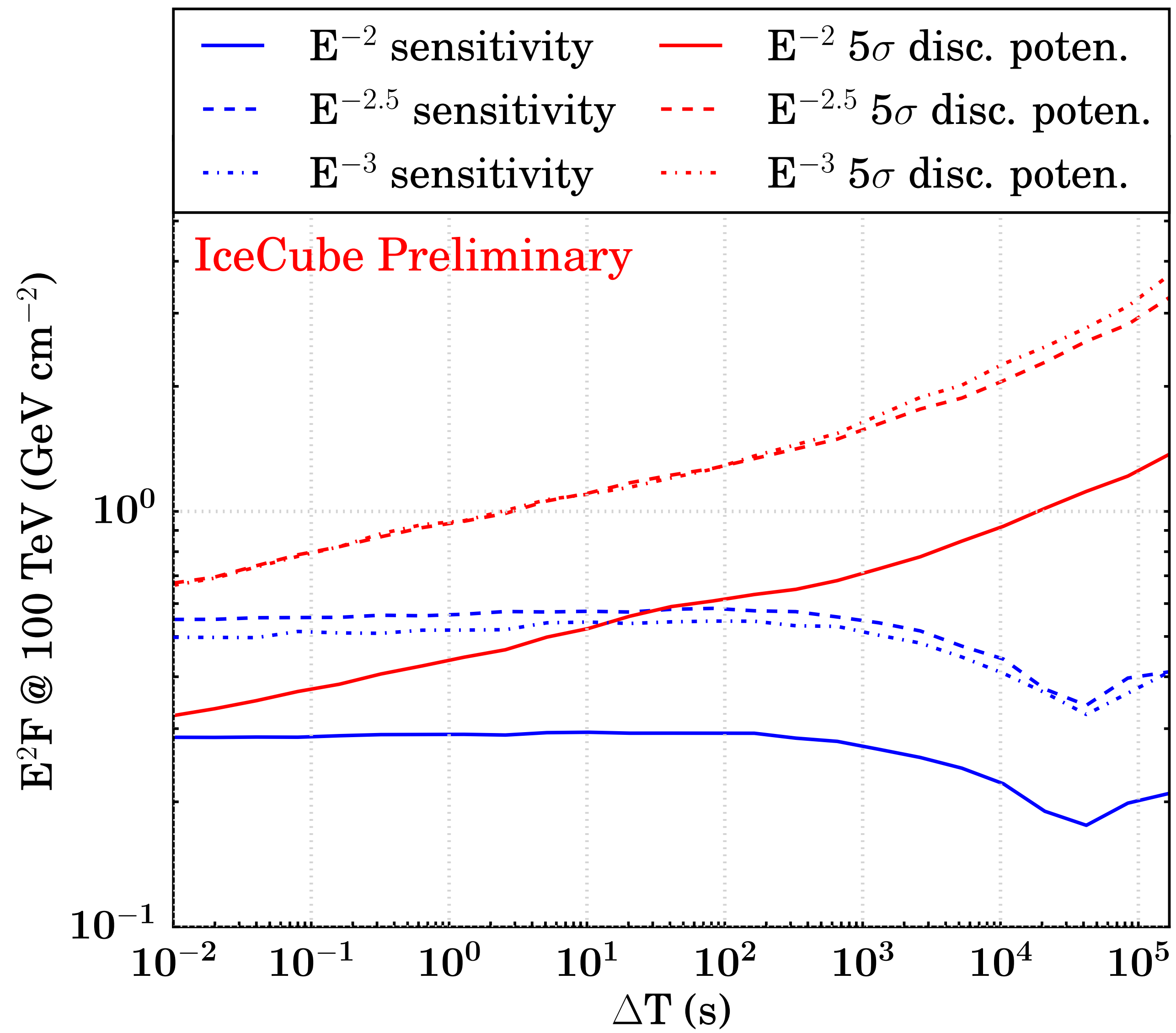

- 25 time windows from 10 ms to 2 days, expanding as $2^i$x10 ms (i =0, …, 24)
- One coincident event can be discovery in the short time windows

# Sensitivity & Discovery Potentials - Max-burst

## North




## South

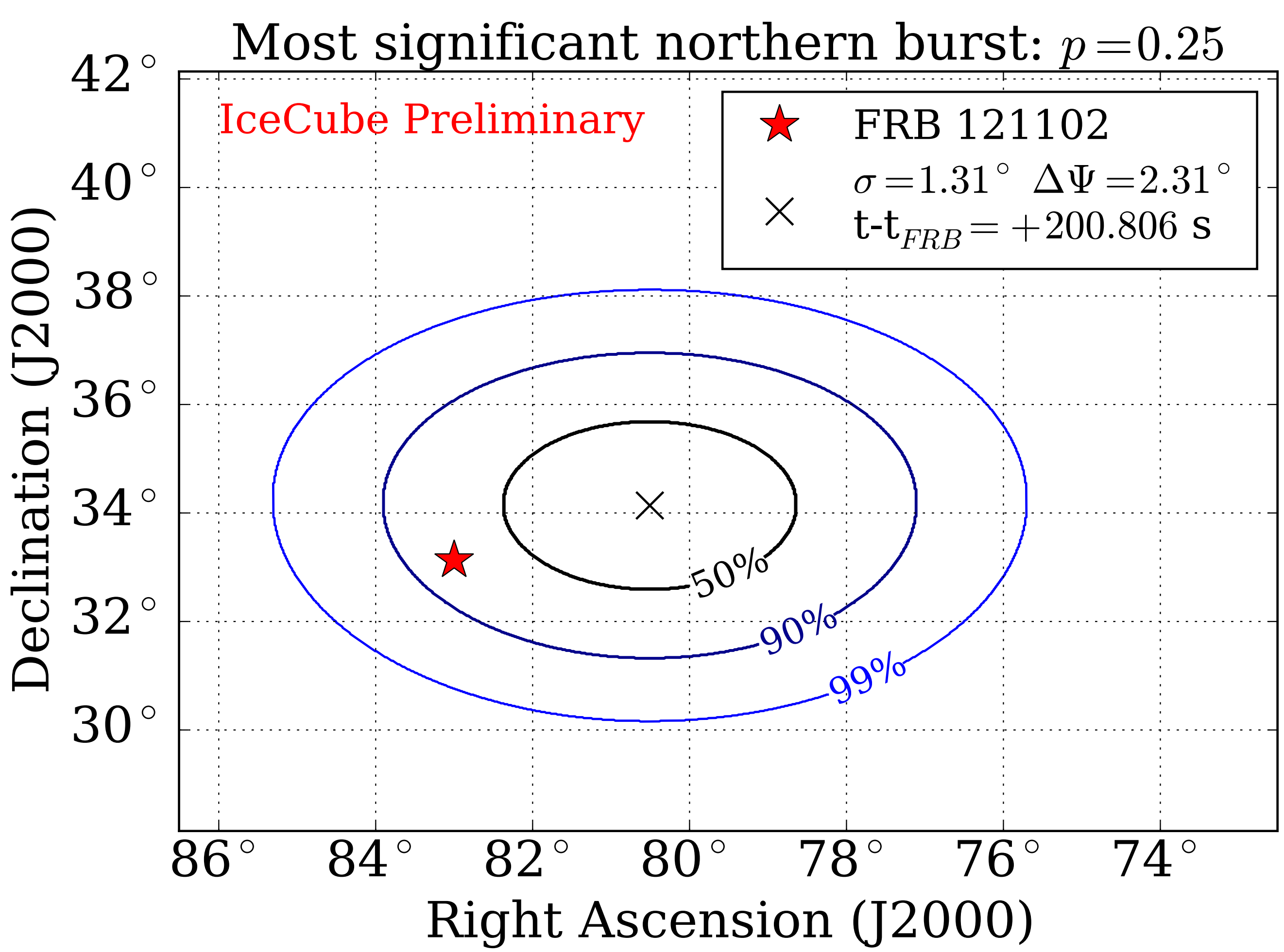



- 25 time windows from 10 ms to 2 days, expanding as $2^i$x10 ms (i =0, …, 24)
- One coincident event can be discovery in the short time windows

## North Max-burst

**Most optimal time window:**

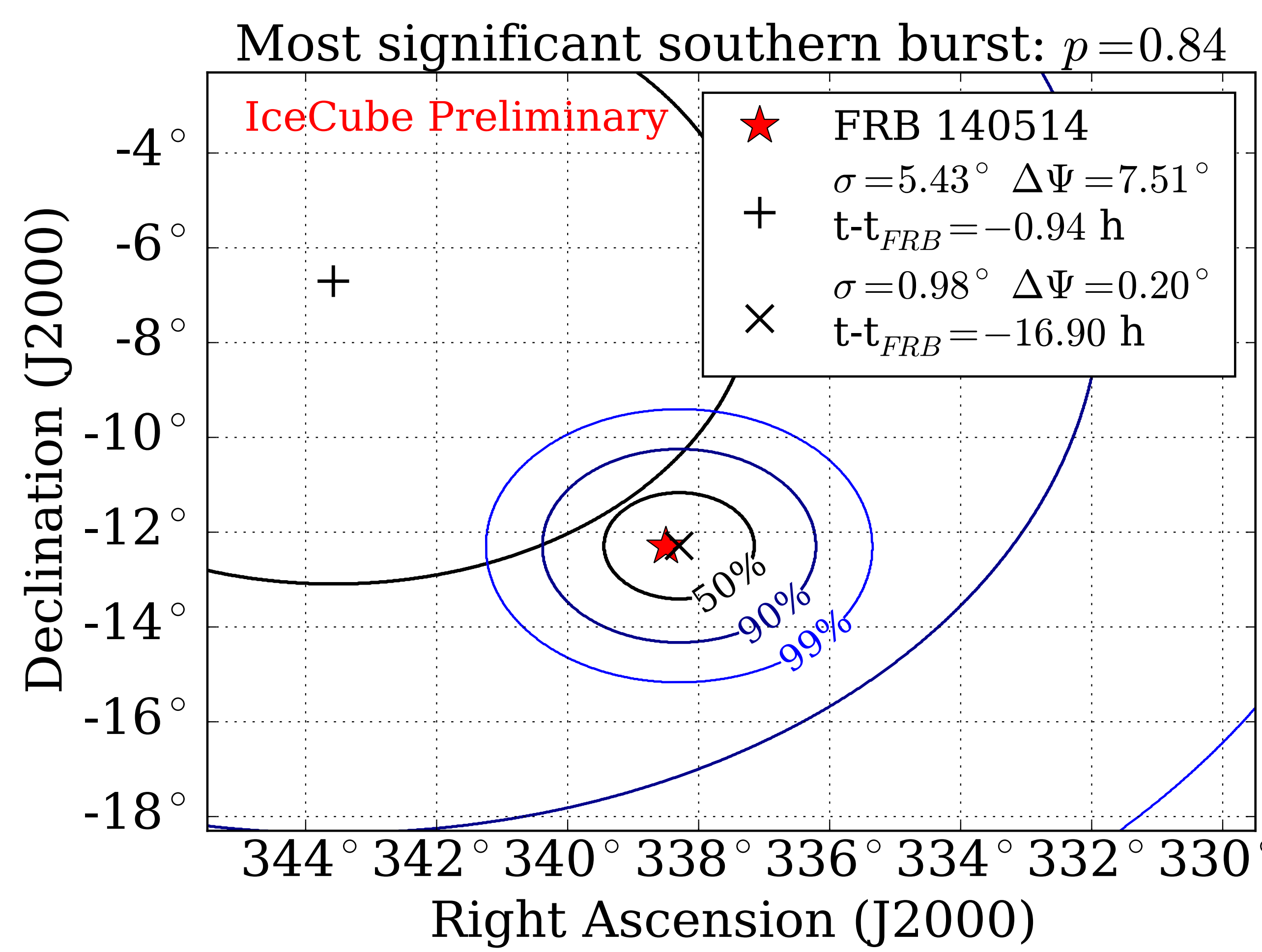
$$\Delta T = 655.36\,\mathrm{s}$$



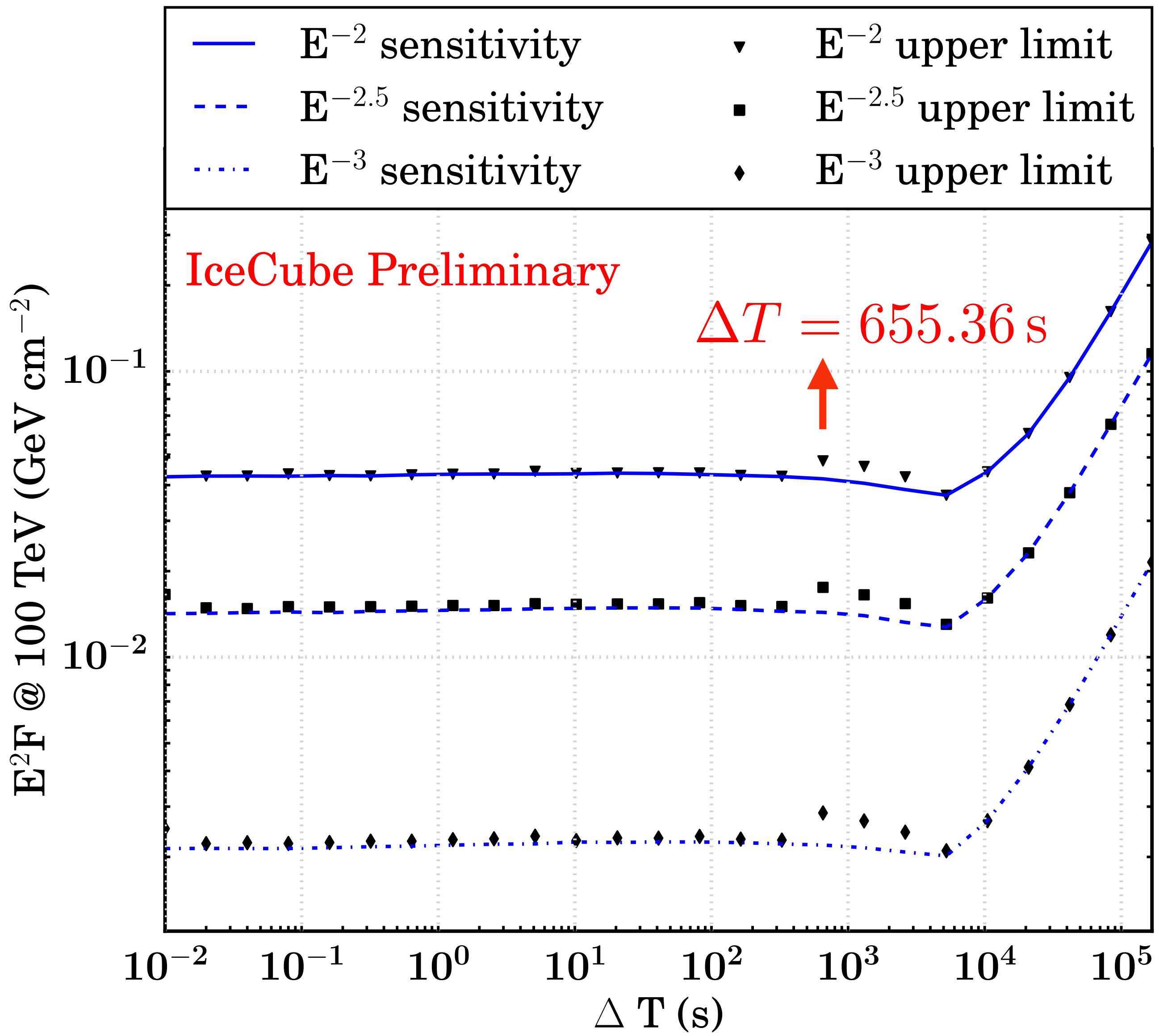

## South Max-burst

**Most optimal time window:**

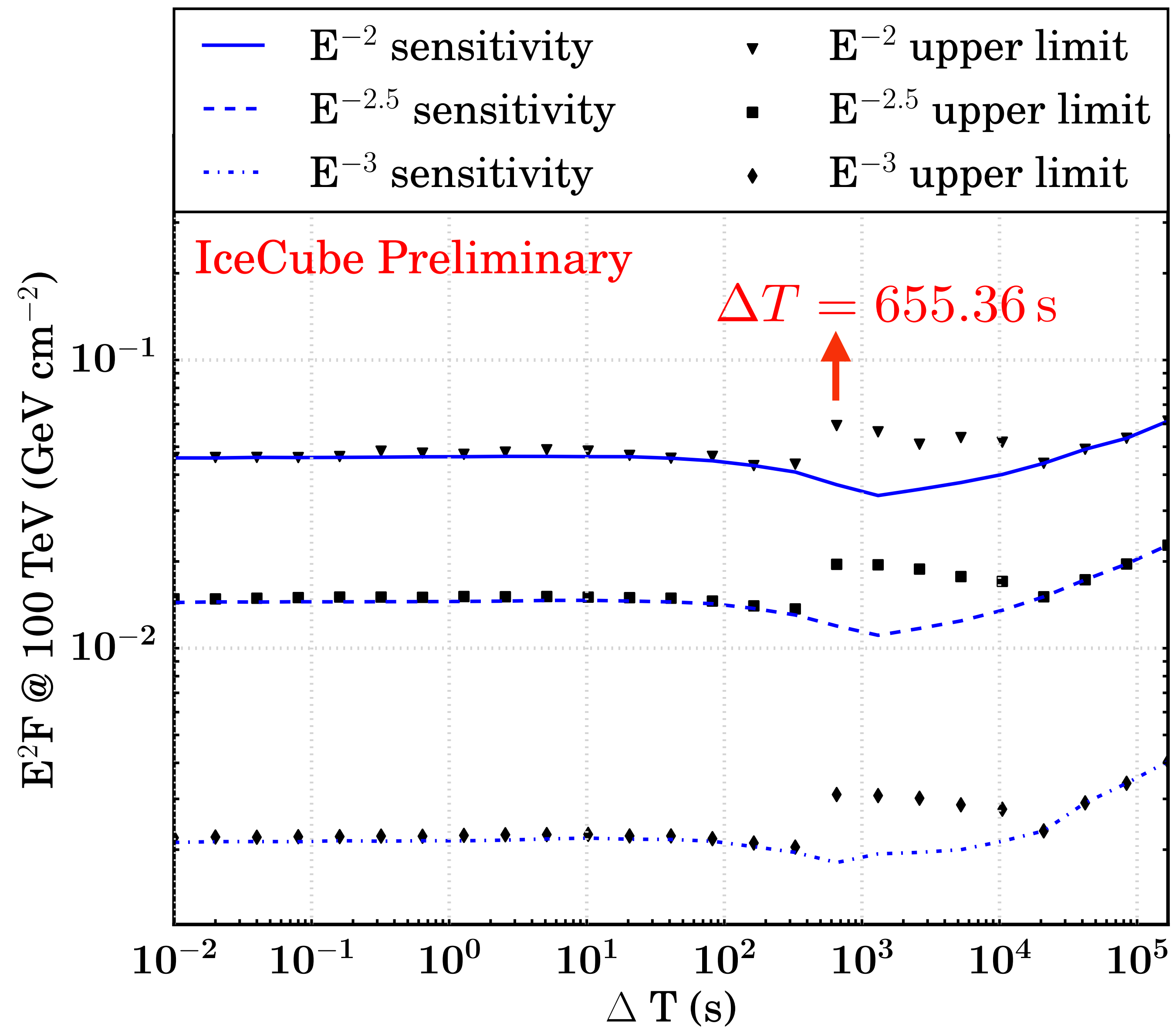
$$\Delta T = 167772.16\,\mathrm{s}$$



## North Stacking

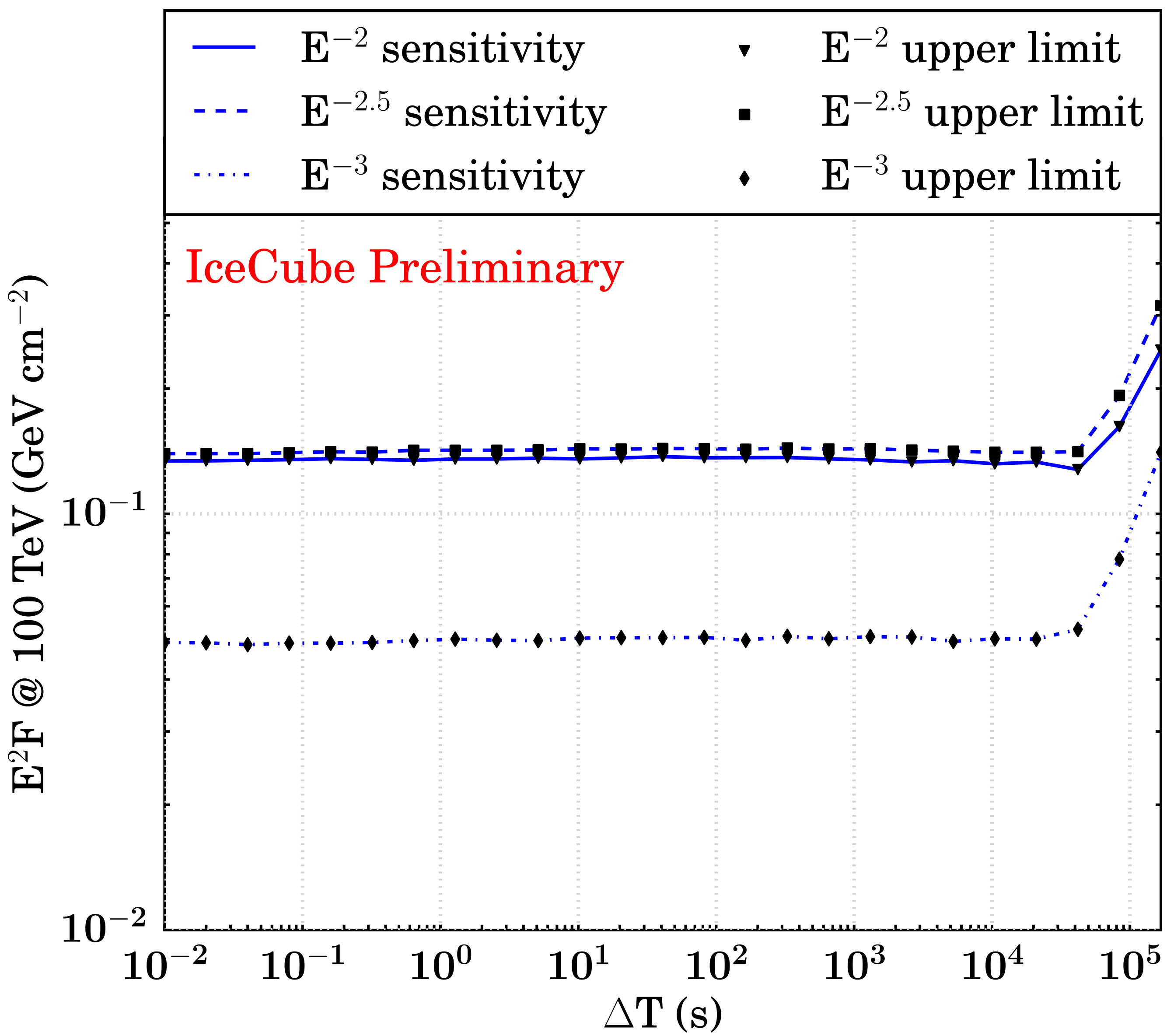



## North Max-burst

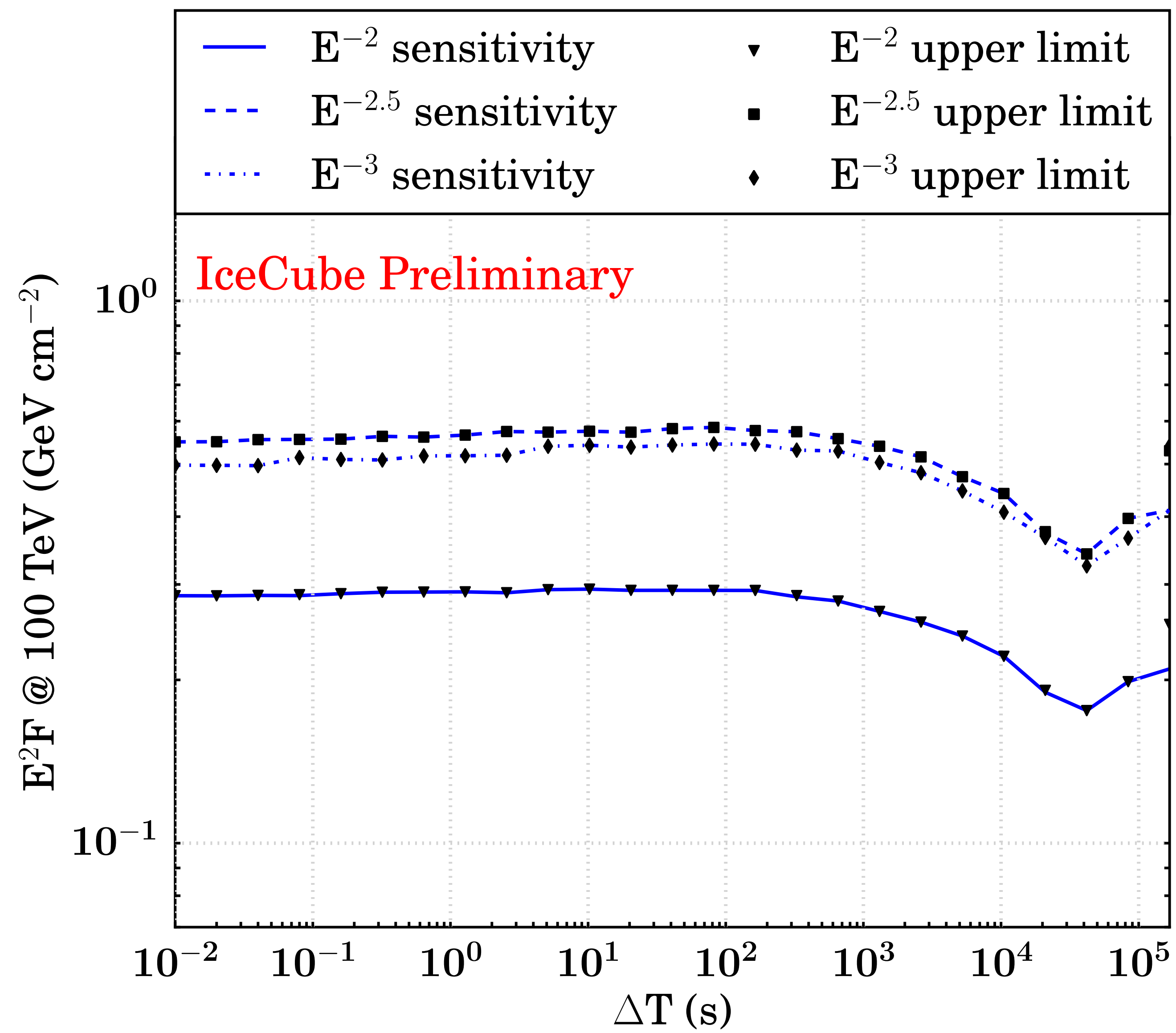


# Results - Upper Limits

## South Stacking




## South Max-burst



- **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 $t_0$:**

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

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

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

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

# Neutrino vs Photon Arrival Times

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

For 10 MeV neutrinos:

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

For 1 TeV neutrinos:

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

**Photon trapped time unknown**