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# High-Energy Neutrinos from Core-Collapse Supernovae

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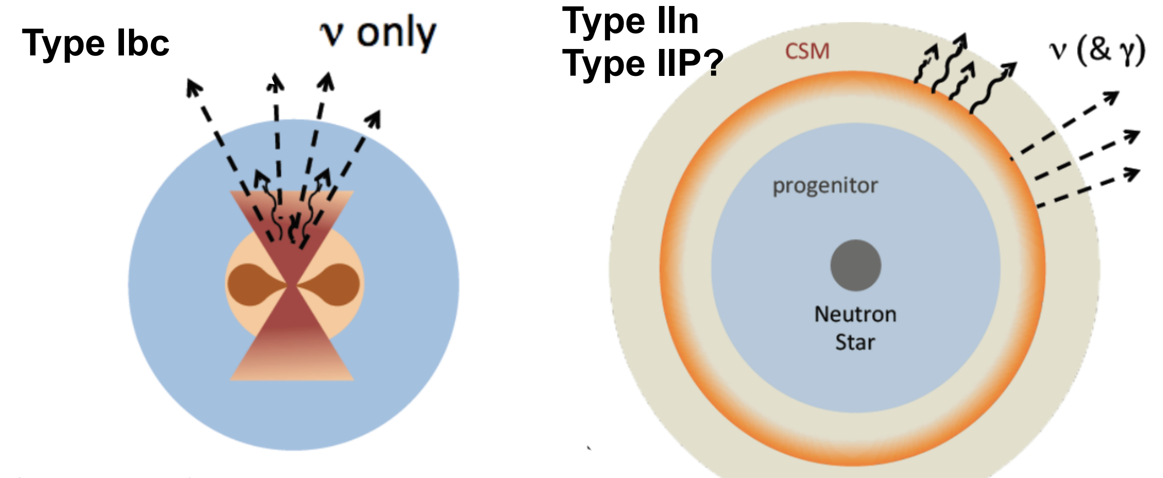
ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

## Neutrino Production Scenarios




Credit: Kowalski&Bartos [1]

### Particle Acceleration in Supernovae

**Choked-jet** Supernovae [2]

- **jet** is emanating **from the collapsing core**
- neutrinos produced when it is **interacting with** the remaining **envelope**
- associated spectral type: **Ibc**

**interacting** Supernovae [4]

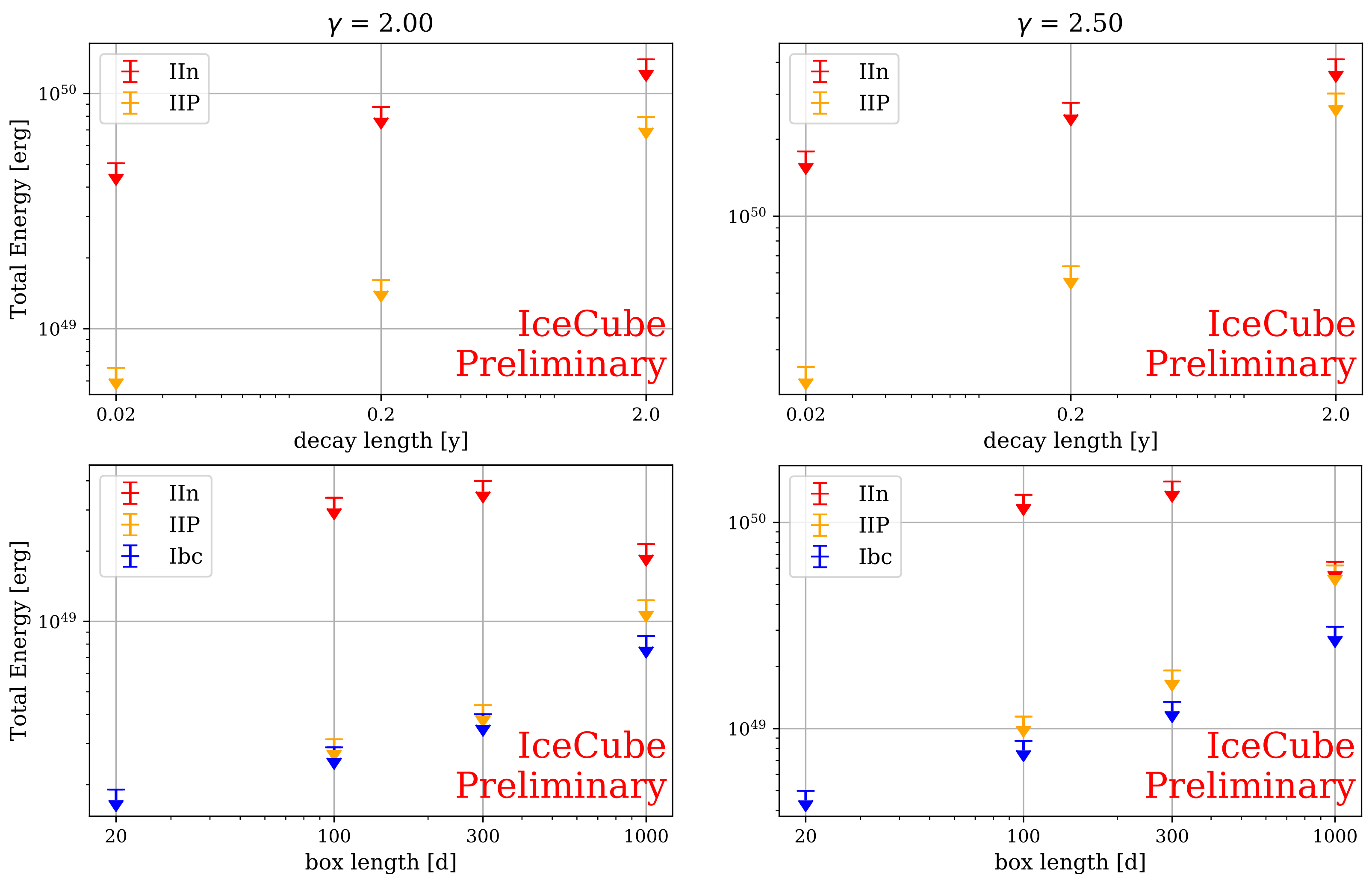
- supernova explosion in **dense circumstellar medium (CSM)**
- shock fronts develop → particle acceleration
- associated spectral type: **IIn**, possibly **IIP**

### Time Models

- **box window, 20 days** prior to explosion

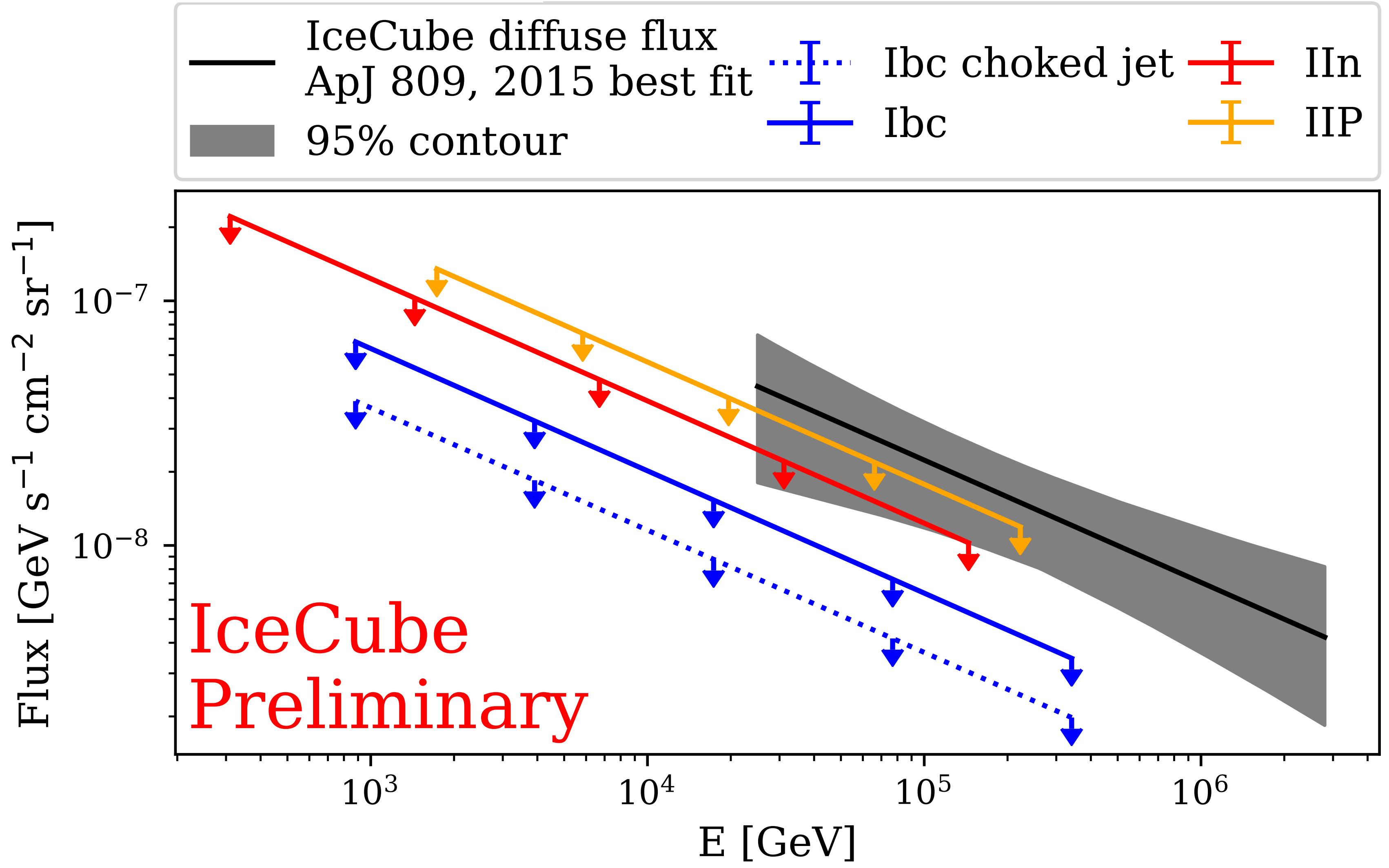
- **box window, 100, 300 and 1000 days** after explosion
- **decaying flux** $\sim (1 + t/t_{pp})^{-1}$ **with** $t_{pp}$ **= 0.02, 0.2 and 2.0 years,** starting at explosion

## Constraining the Neutrino flux from Supernovae




### Total Emitted Neutrino Energy

- **flux normalisation** from
  - measured test statistic if measured test statistic > background test
  - background test statistic if measured test statistic < background test statistic
- Assume spectra index $\gamma$ → **limit on energy emitted in neutrinos** per supernova
- limits in erg for $\gamma = 2.5$:
  **IIn**: $6.4 \times 10^{49}$, **IIP** $1.1 \times 10^{49}$, **Ibc** $8.7 \times 10^{48}$, **Ibc choked jet** $5.0 \times 10^{48}$




### Contribution to diffuse neutrino flux

- average **total neutrino energy** per supernova + supernova **rate** $\rho(z)$ **+ relative abundance** of supernova subtype
  → upper limit on **contribution to diffuse neutrino flux**
- **IIn** 55.2%, **IIP** 79.6%, **Ibc** 28.6%, **Ibc choked jet** 16.4%
- driving ingredient:
  - IIn: low relative abundance of ~6% of all supernovae [6] → tight constraint
  - IIP: high relative abundance of ~52% of all supernovae [6] → loose constraint
  - Ibc choked jet: small time window allows for excluding background → tight constraint

## Neutrino Dataset

### The 7 year Point Source sample [5]

- high angular resolution, through-going **track events**
- **used for looking for correlation** between neutrino emission and sources detected with other messengers
- April 2008 - May 2015

## Supernova Catalogue

### Assembly from Open Source Catalogues

- sources from **WiseRep, ASAS-SN** survey data and **Open Supernova Catalogue**
- merging by requiring **angular distance** $\Psi \geq 0.1^{\circ}$ or **50 days apart**
- **387 IIn, 167 IIP, 824 Ibc**

### Extracting High-Quality Subsample

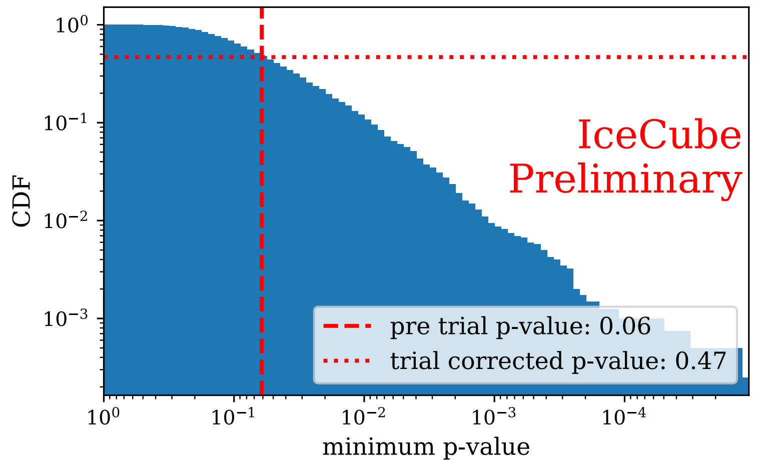
- **calculate expected flux** under assumption of $E^{-2}$ spectrum
- order by expected flux
- high-quality sample: brightest sources, that contribute **70% of the total expected flux**
- **final sample: 15 IIn, 20 IIP and 19 Ibc**

## Likelihood Analysis

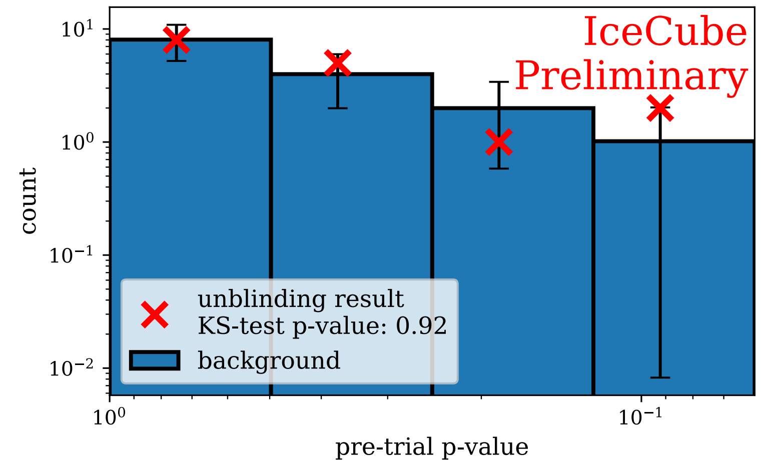
### Stacking Likelihood

$$\mathscr{L}(\vec{n_s}, \gamma) = \prod_{i=0}^{N} \left[ \frac{1}{N} \sum_{j=0}^{M} n_{s,j} \cdot \mathcal{S}_j(\theta_i, \gamma) + \left(1 - \frac{\sum_j n_{s,j}}{N}\right) \mathscr{B}(\theta_i) \right]$$

- **signal PDF** $\mathcal{S}$: depends on **neutrino properties** $\theta$ and **spectral index assumption** $\gamma$
- **background PDF** $\mathscr{B}$ **modelled from data**
- **Stacking** $M$ sources, looking for correlation with $N$ neutrino events
- **free parameters**: spectral index $\gamma$, **number of neutrinos from each source**: $\vec{n_s} = (n_{s,1}, n_{s,2}, \ldots, n_{s,M})$




- comparison of the minimum data fit (pre-trial) p-value of 0.06 to the cumulative distribution of minimum p-values from $4 \times 10^3$ background simulations
- correlation at least as significant as **expected in about half of the cases**




- **comparison of distribution of all p-values with background expectation** of p-value distribution
- **compatible with background**


### References

[1] „Multimessenger Astronomy“, Kowalski & Bartos (2017)
[2] „Choked Jets and Low-Luminosity Gamma-Ray Bursts as Hidden Neutrino Sources“, Senno et al (2016)
[3] „A combined Maximum-Likelihood Analysis of the High-Energy Astrophysical Neutrino Flux measured with IceCube“, IceCube Collaboration (2015) ApJ 809
[4] „New Class of High-Energy Transients from Crashes of Supernova Ejecta with Massive Circumstellar Material Shells“, Murase et al (2011)
[5] „All-sky search for time-integrated neutrino emission from astrophysical sources with 7 years of IceCube data“, IceCube Collaboration (2017)
[6] „Nearby Supernova Rates from the Lick Observatory Supernova Search. II. The Observed Luminosity Functions and Fractions of Supernovae in a Complete Sample“, Li et al (2010)