Towards an extragalactic supernova neutrino detector at the South Pole

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Neutrinos from extragalactic core-collapse supernovae (SNe)

- With today's neutrino observatories, only Galactic SNe (~2-3 per century) visible [1]
- Need to extend sensitivity to neighboring galaxies (5-10 Mpc) for a routine detection of ~1 SN per year in neutrinos (see Figure 1)
- Physics motivation:
  - Measure the core-collapse SN rate accurately
  - Study the core-collapse mechanism
  - Trigger early optical observations of SNe
  - Probe for optically dark SNe (see below)
  - Set limits on neutrino mass

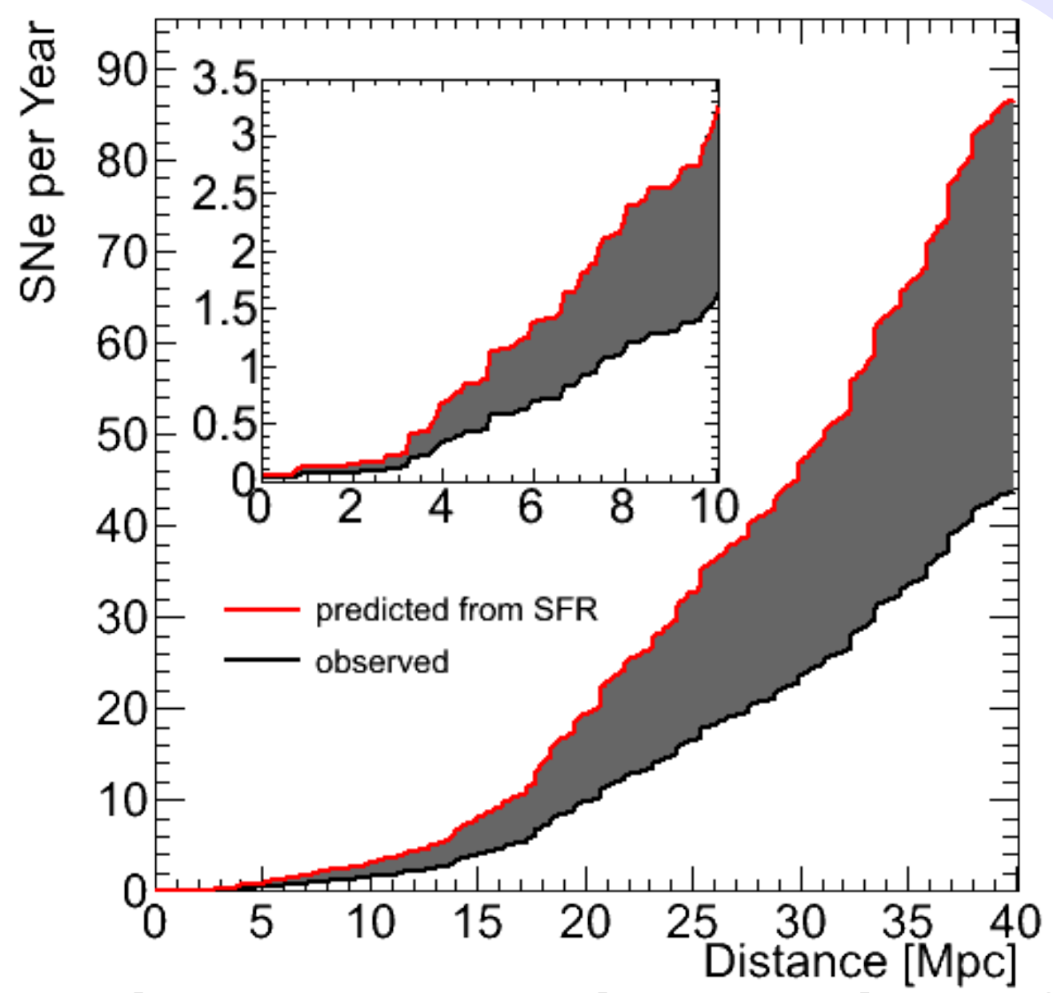

Fig. 1: Cumulative number of SNe per year, as predicted from star formation rate (red) [2,5] and as observed (black) [2,3,4]

Supernova models

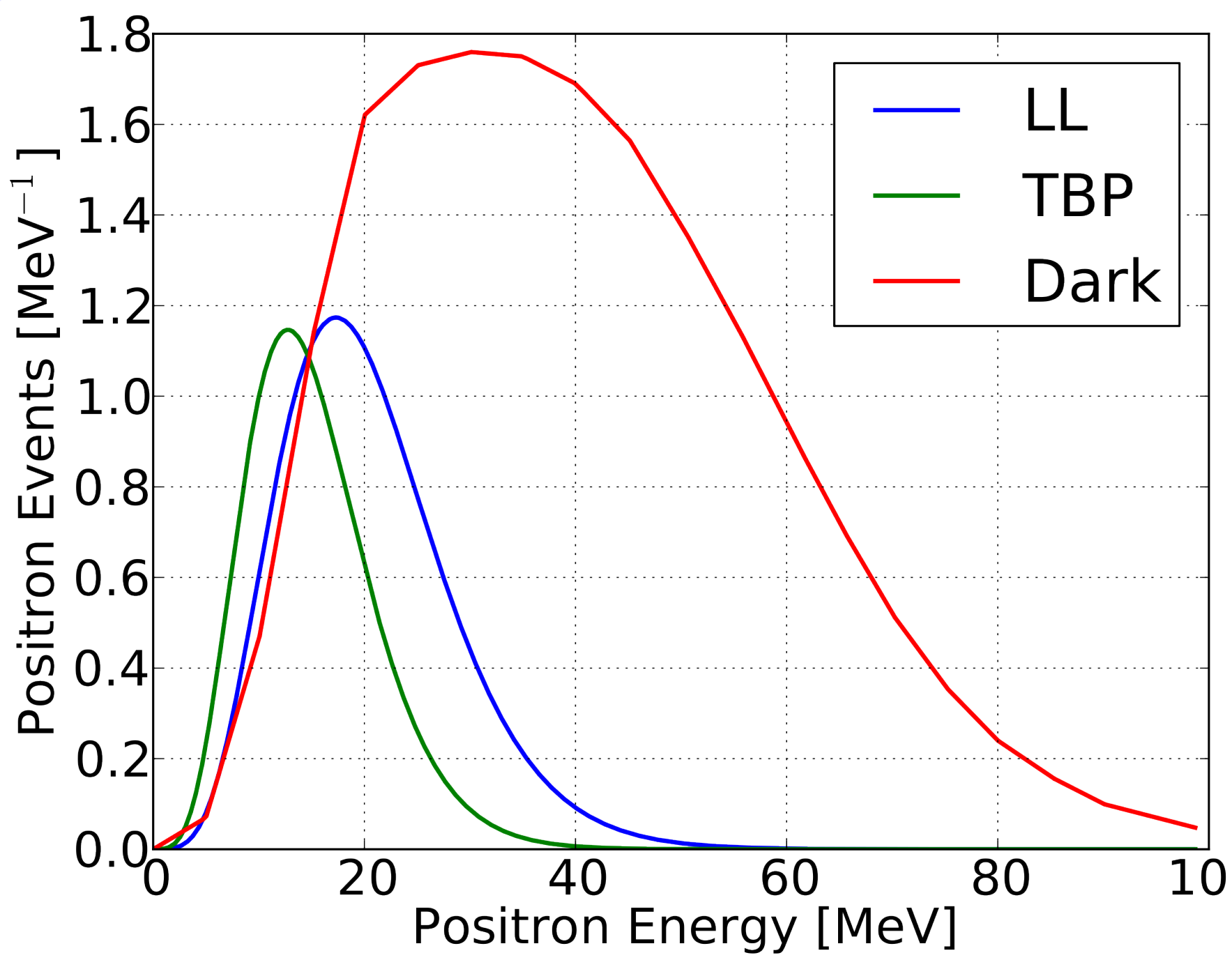

Fig. 2: Positron spectrum from SN in 1 Mpc distance for 1 Mton effective mass

- **Lawrence-Livermore model[6] (LL)**: One of the few model calculations leading to an explosion
- **Thompson-Burrows-Pinto model[7] (TBP)**: More recent than LL, but does not lead to an explosion.
- **Dark SNe[8]:** While the collapse of a fast-rotating star with ≳ 25 $M_\odot$ leads to a hypernova, a slow-rotating one might collapse to a black hole without emitting photons. These „dark“ SNe or failed SNe could be detected with a SN ν detector.

Simulation

Setup

- Probing two different regions for Cherenkov array in South Pole ice:
  - **diffuse ice** (750 – 1050 m depth)
  - **clear ice** (2150 – 2450 m depth)
- 61 strings arranged in hexagonal pattern
- Assuming 300 optical modules on each string with eff. photosensitive area:
  - ~78 cm² in diffuse ice
  - ~312 cm² in clear ice

  corresponding to 1.4 (5.5) high QE IceCube modules (~57 cm²)
- Photon propagation:
  - diffuse ice: random walk
  - clear ice: Photonics [9]
- Event trigger requirement:
  - 5 photon hits anywhere in the detector (no time window applied)
- SN trigger requirement:
  - ≥ 3 (10) ν events within 10 s

Ice properties: [10,11]
Clear ice has low scattering, diffuse ice “captures” photons

Ice type	Depth	Absorption Length	Scattering Length
diffuse	750-1050 m	350 m	0.3 m
clear	2150-2450 m	20-90 m	20-50 m

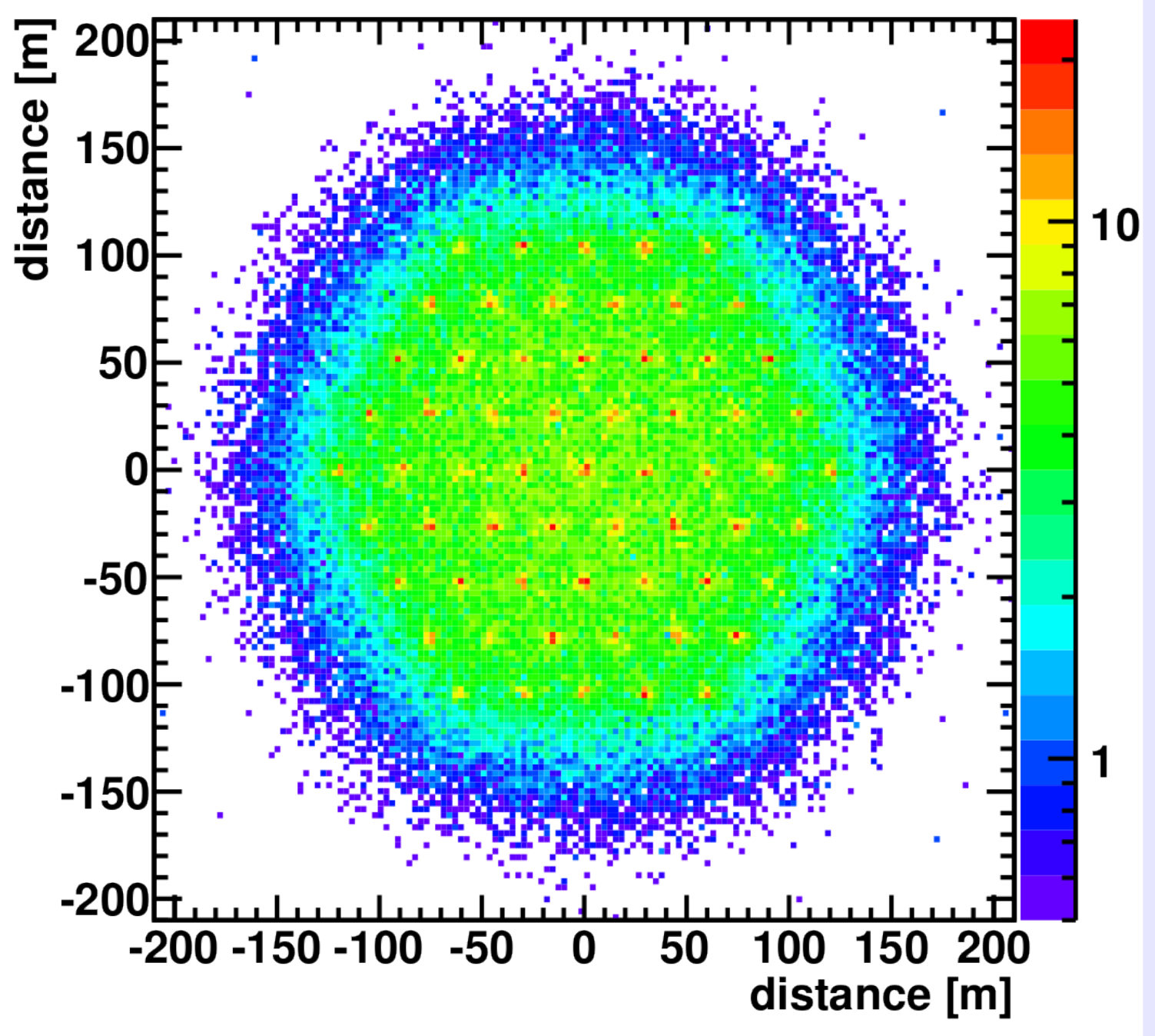

Fig. 3: Number of detected photons as function of neutrino vertex position in clear ice

Geometry optimization

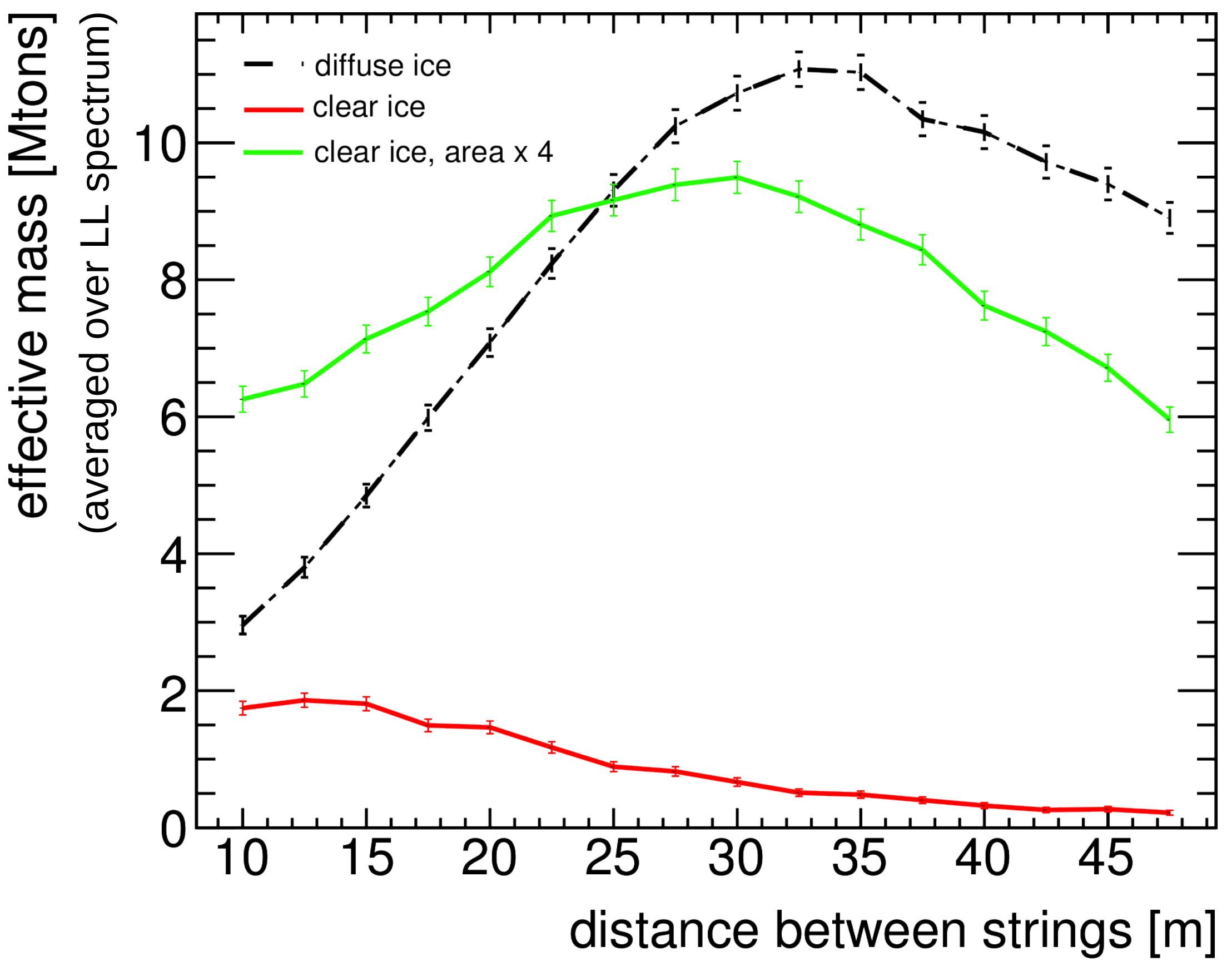

Fig. 4: Effective mass for positrons from LL spectrum as function of string spacing

- Optimizing string spacing for maximal effective volume/mass
- Diffuse ice:
  - Photon detection probability high due to large absorption length and short scattering length → over 10 Mton possible
  - But photon scattering prohibits directional reconstructions
- Clear ice:
  - Much lower eff. mass for the same module size (red curve)
  - Scaling each module's photosensitive area up by factor 4 (i.e. ~312 cm² per module), we obtain similar performance as for the diffuse ice (green curve)

Results

Detector reach and expected number of triggered SN events

- SN detection probability computed for optimal eff. mass (~9 Mton for clear ice); Fig. 5 shows probability for Nν≥3 as function of SN distance for the three SN models
- Using Fig. 5 and Fig. 1, we estimate the number of SN detections, taking observed SNe as lower and predicted SNe as upper limit (see table below, backgrounds not considered)

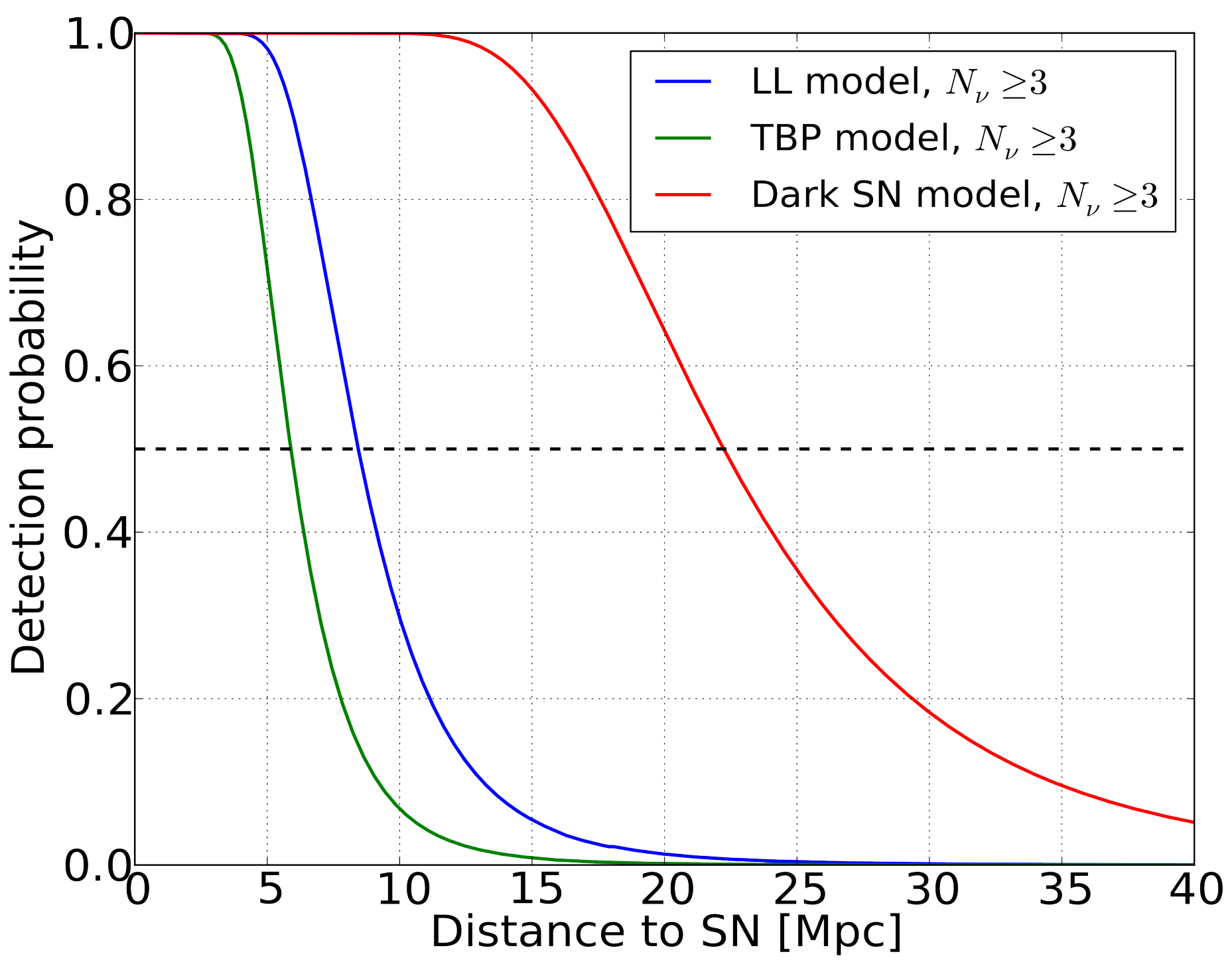

Fig. 5: SN detection probability (clear ice)

Number of SN detections per year:

Model	Nν ≥ 3	Nν ≥ 10
LL	1.7 – 3.3	0.4 – 0.8
TBP	0.8 – 1.6	0.2 – 0.3
Dark SN*	1.6	0.2

* = assuming dark SNe occur at 10% of observed SN rate

Backgrounds

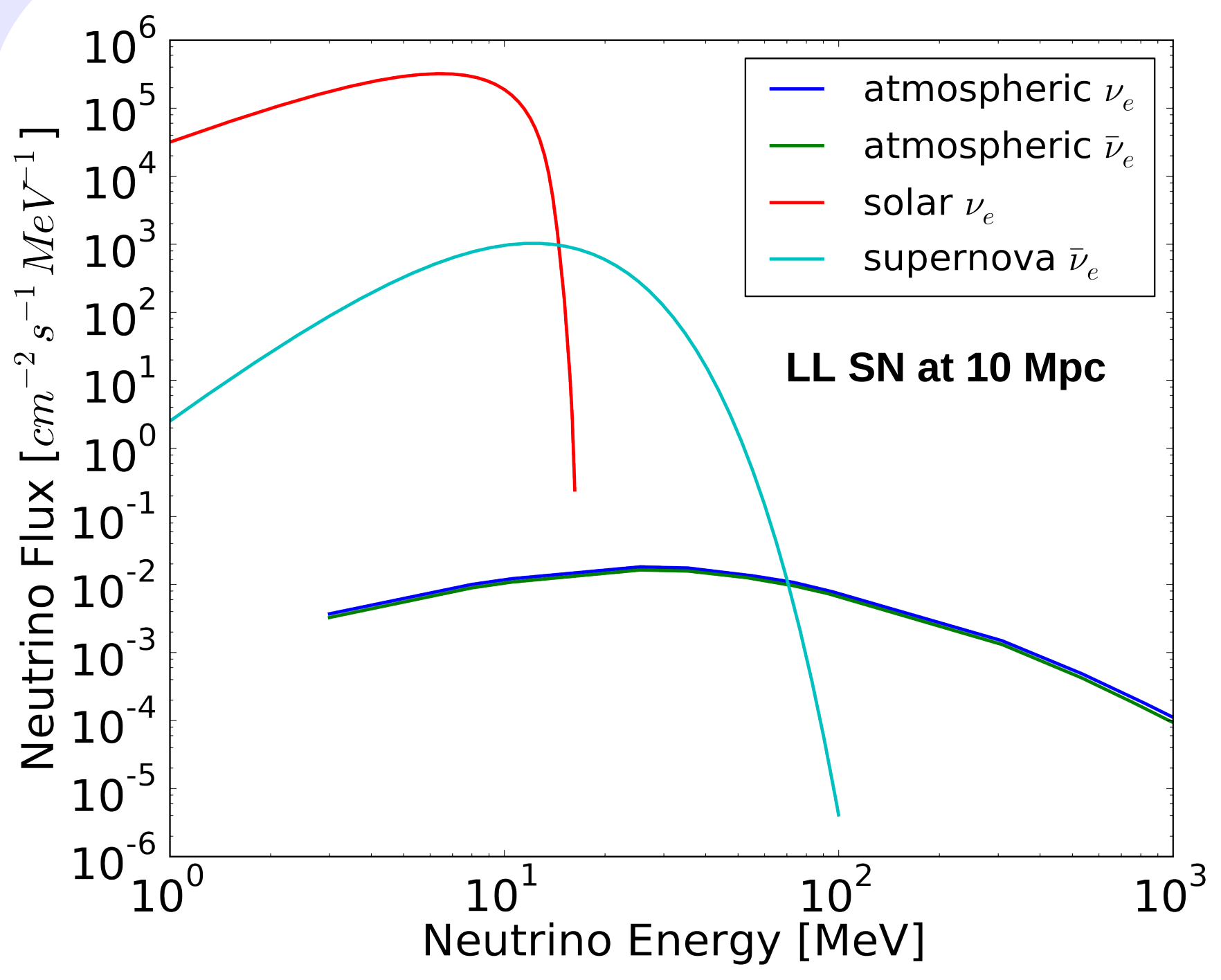

Fig. 6: Neutrino fluxes of BG and signal

Backgrounds are challenging, require BG rate <4 mHz to get at most 1 fake SN event/year

- **Atmospheric muons[12]**: Easily recognized if throughgoing. Need outer veto layers (IceCube) against stopping muons.

Ice type	μ passing rate	Dead time
clear ice	230 Hz	0.16%
diffuse ice	5000 Hz	14%

- **Solar neutrinos[13]**: Only ν_e, cannot interact via inverse beta decay (IBD), thus dominantly elastic scattering on electrons (lower x-sec than IBD).[14] High rate, possibility to discriminate via energy and direction (latter only in clear ice)
- **Atmospheric neutrinos[15]**: $\nu_e/\bar{\nu}_e$ component small, ν_μ contribute via invisible muons (under Cherenkov threshold) that decay to visible Michel electrons
- **Module noise**: Can be controlled during R&D. Assuming 500 Hz noise per module (IceCube DOMs ~300 Hz [16]). Temporal and spatial coincidence of signal must be exploited for discrimination of noise.

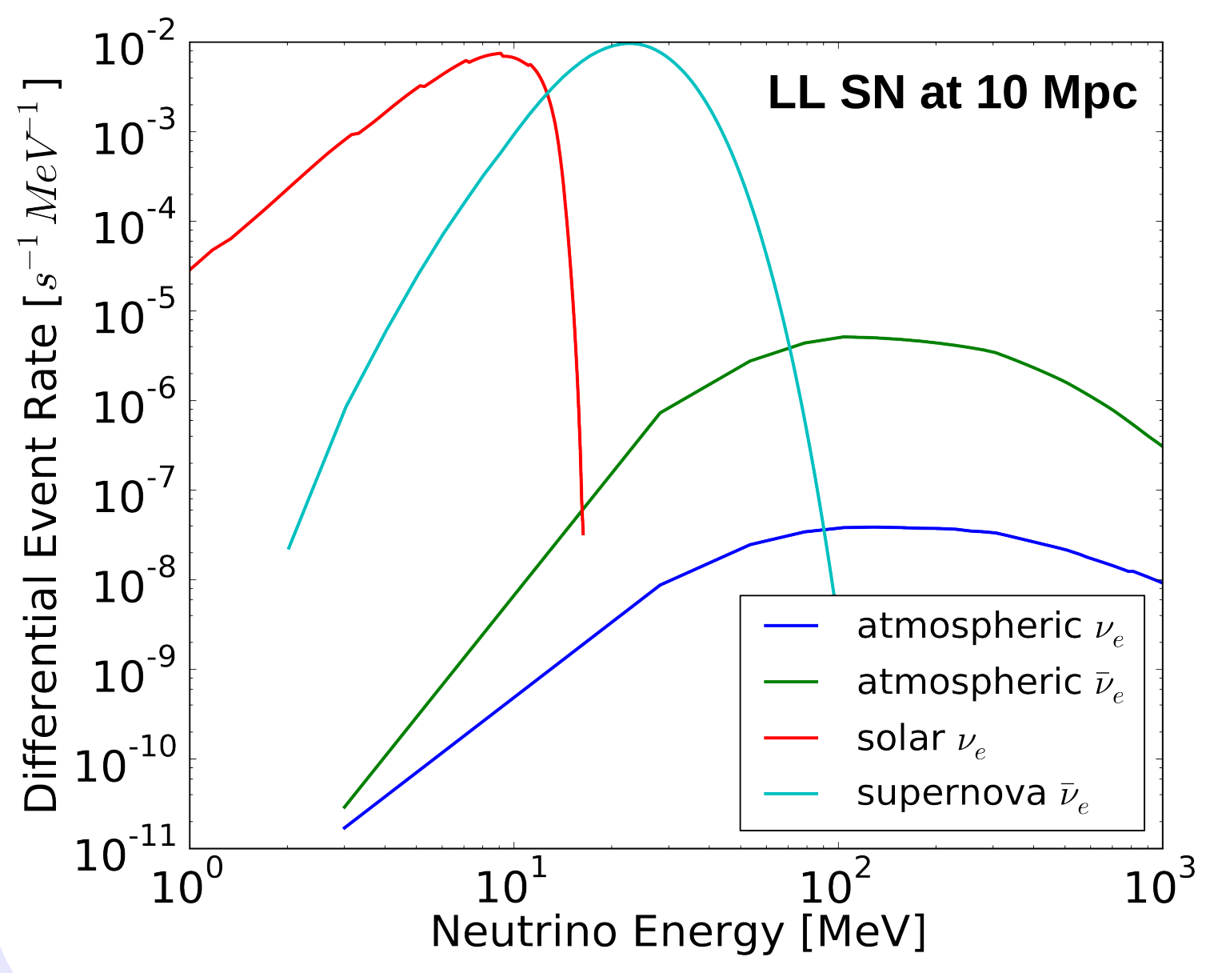

Fig. 7: Differential event rate

Rate [mHz]	Trigger 5 phot.	Trigger 7 phot.
Solar ν_e	20.9	3.8
Atm. ν_e	0.24	0.20
SN Signal	100%	55.6%
Michel e$^-$ (atm. ν_μ)	~1 mHz*	

* = SuperK measurement[17] scaled up

Title image from files.myopera.com/Matta/albums/89316/Supernova.jpg
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