Sensitivity of IceCube to a Galactic Supernova

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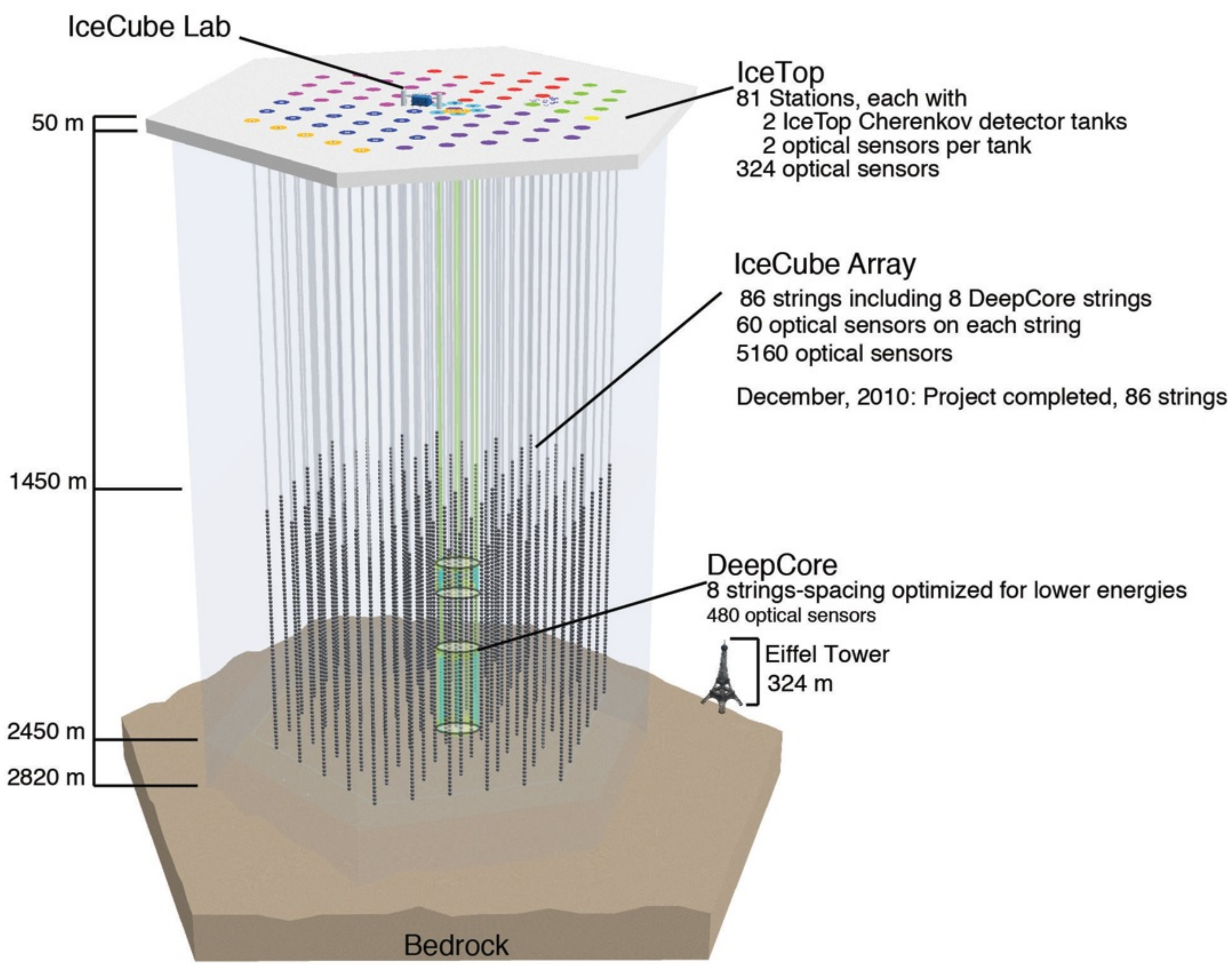
Overview

- The IceCube Neutrino Observatory
  - Detector layout, Digital Optical Modules, ice properties.
- The IceCube supernova system
  - Accessible neutrino physics, sensitivity, limitations.
  - IceCube scaler system, SNDAQ, realtime alerts.
- Current and future improvements to sensitivity
  - Software: HitSpooling, Bayesian Blocks analysis.
  - Hardware: mDOMs, Gd doping of the ice?

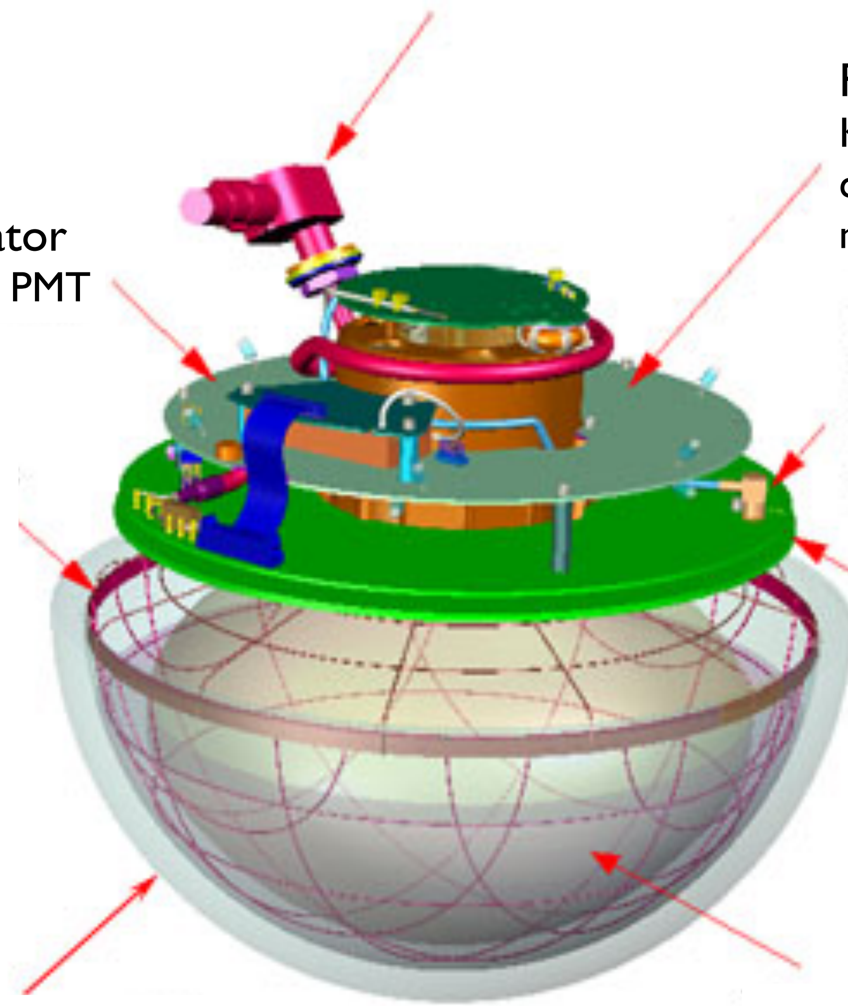
The IceCube
Neutrino Observatory

The IceCube Detector



- 86 strings 1 km below South Pole ice sheet.
- 5160 DOMs (86x60).
- 17 m vertical spacing.
- 125 m string spacing.
- 1 km^3 (1 Gt instrumented volume).
- Optimized for detection of atm. & astrophysical ν's above ~10 GeV.

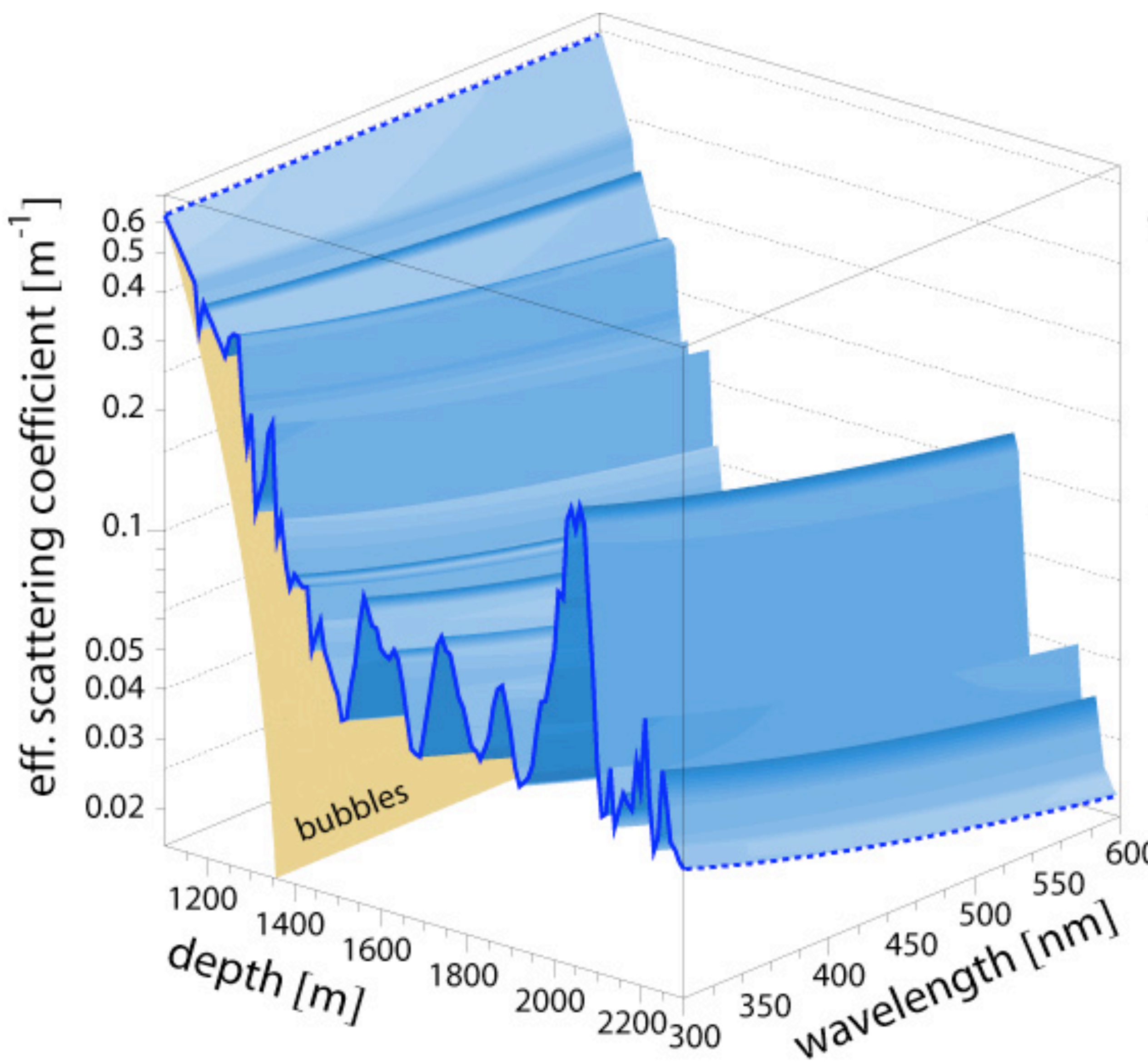
Digital Optical Modules

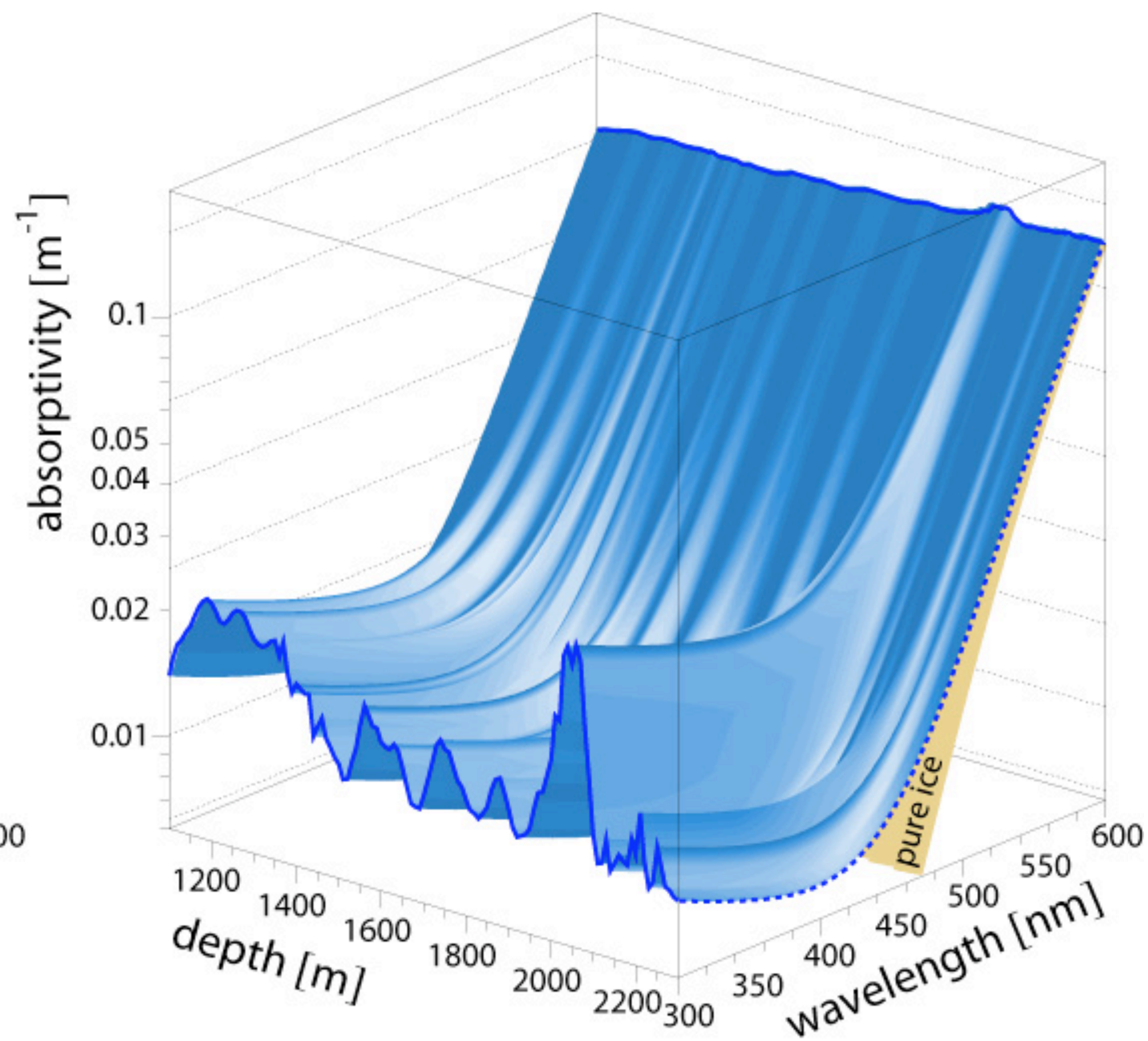


Optical Properties of the Ice

- A very absorbent dust layer bisects the detector.
- Scattering is anisotropic and not uniform as a function of z.

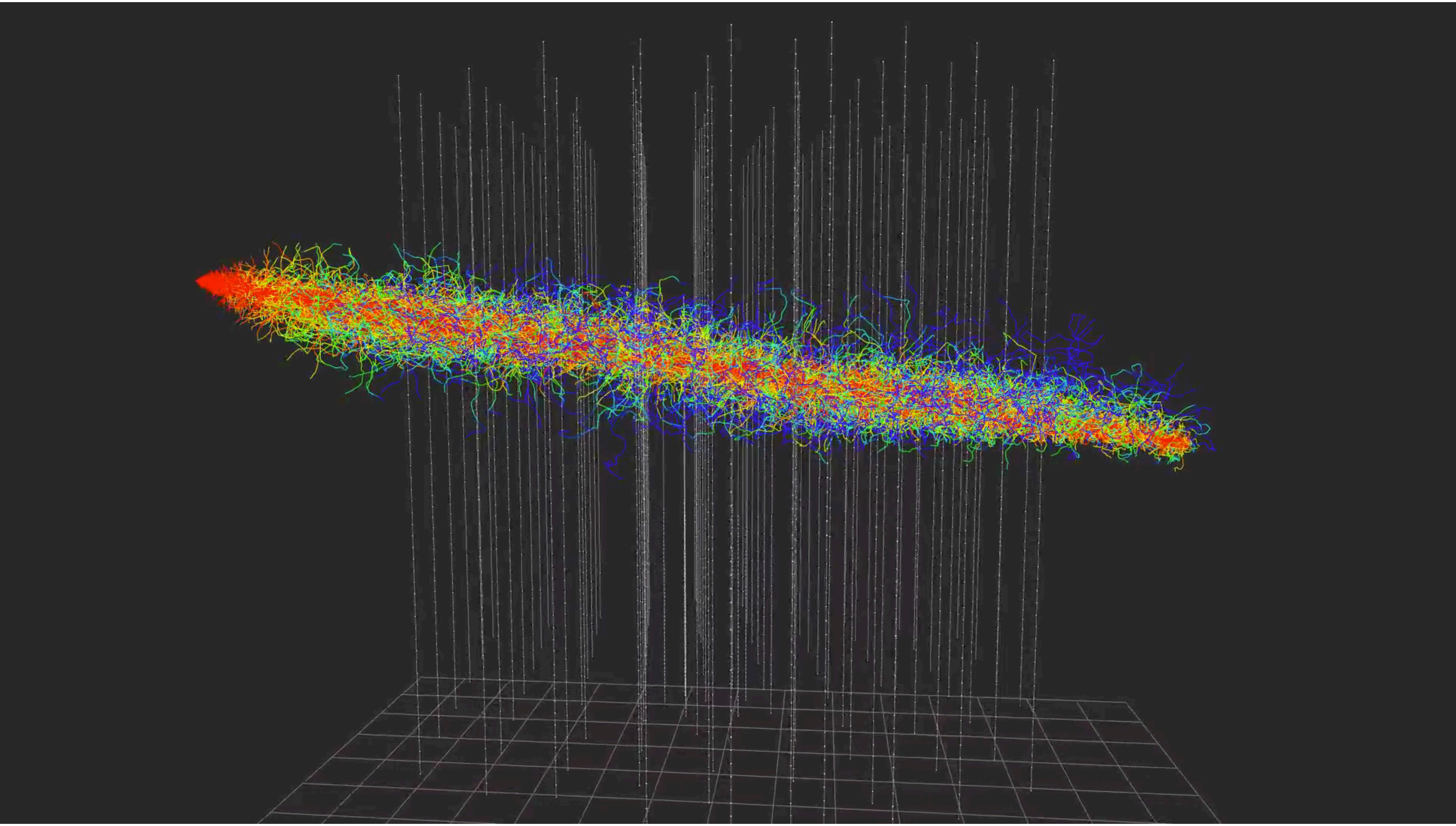
M. Ackermann et al., J. Geophys. Res. 111:2006





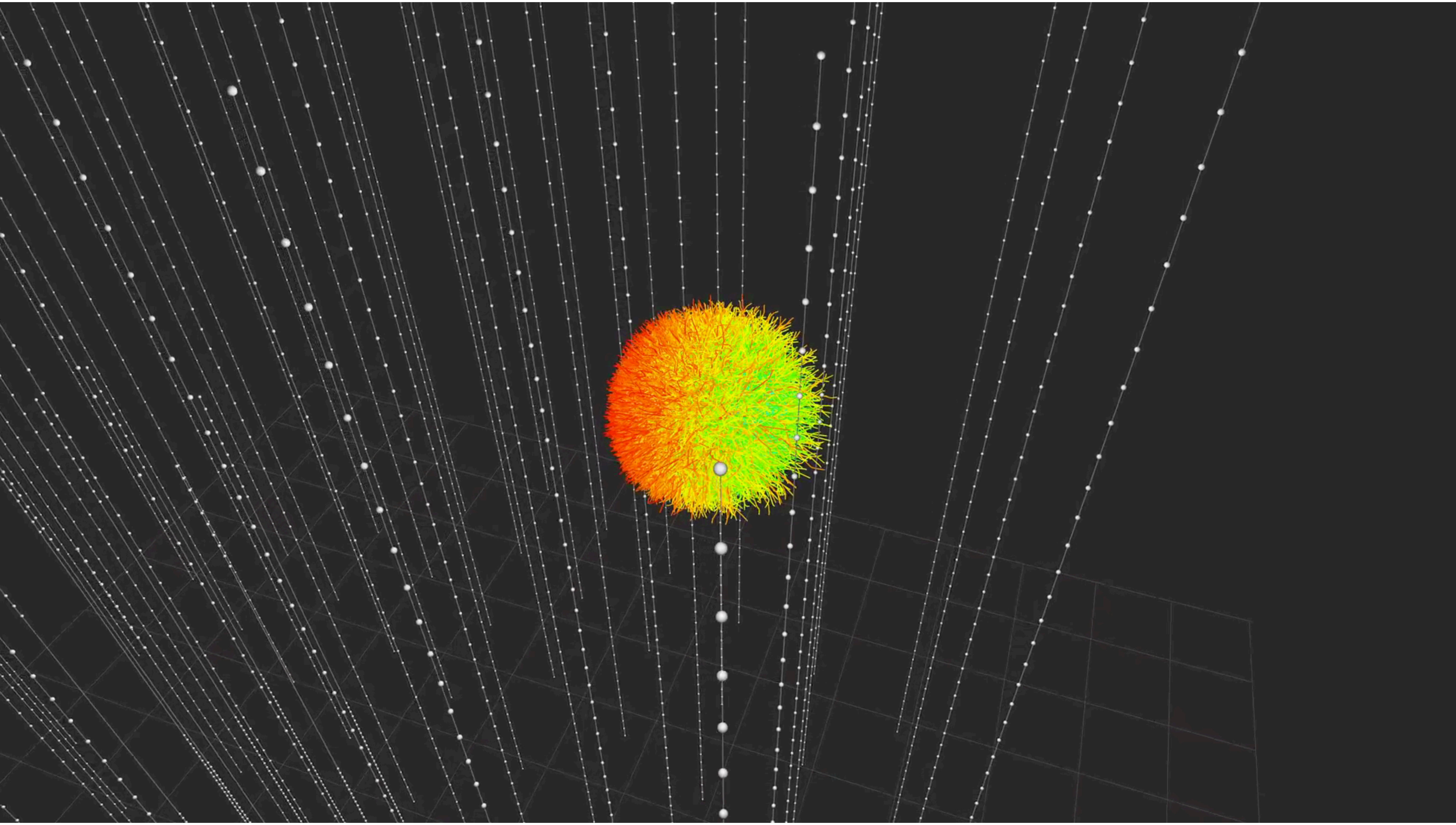
Simulated Track Event

Animation from Claudio Kopper



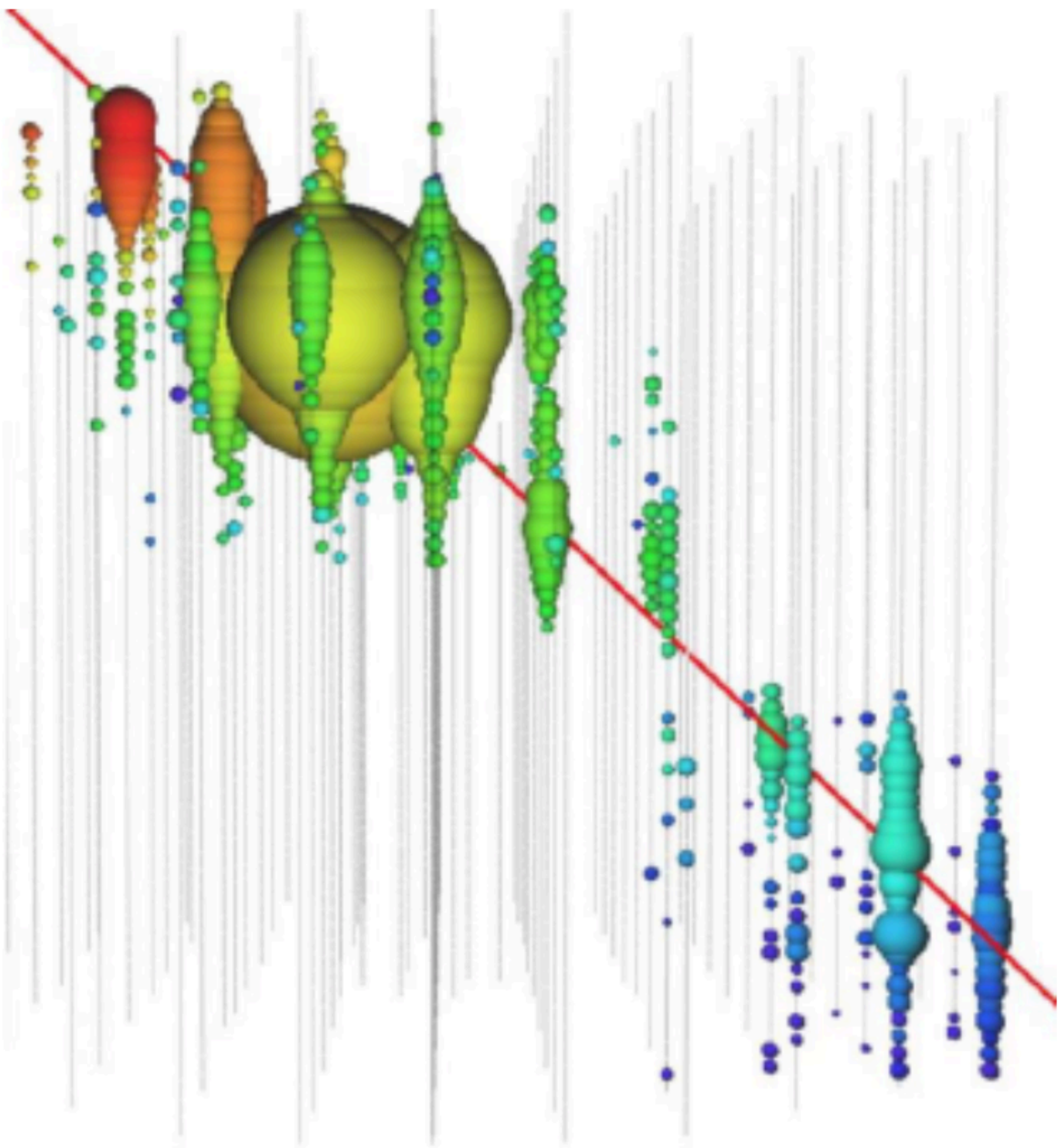
Simulated Cascade Event

Animation from Claudio Kopper

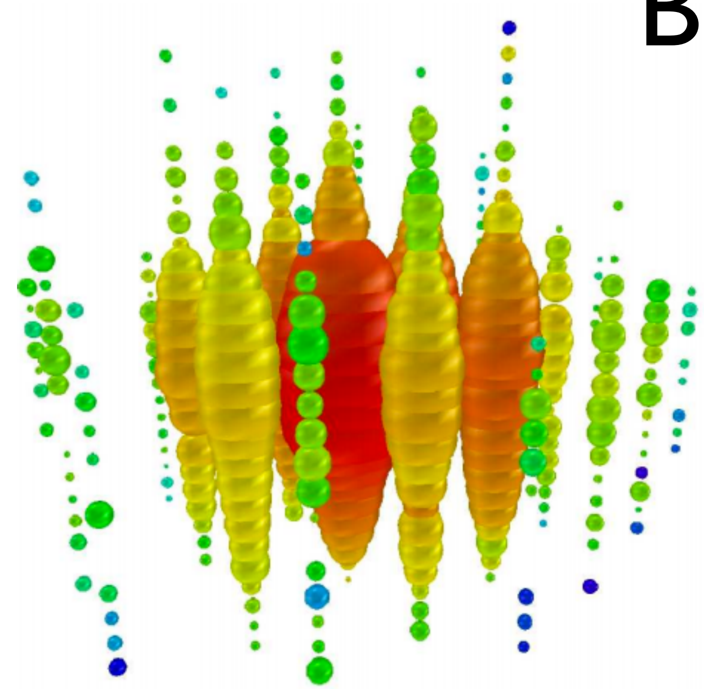


High-Energy Events

Simulated cosmic muon

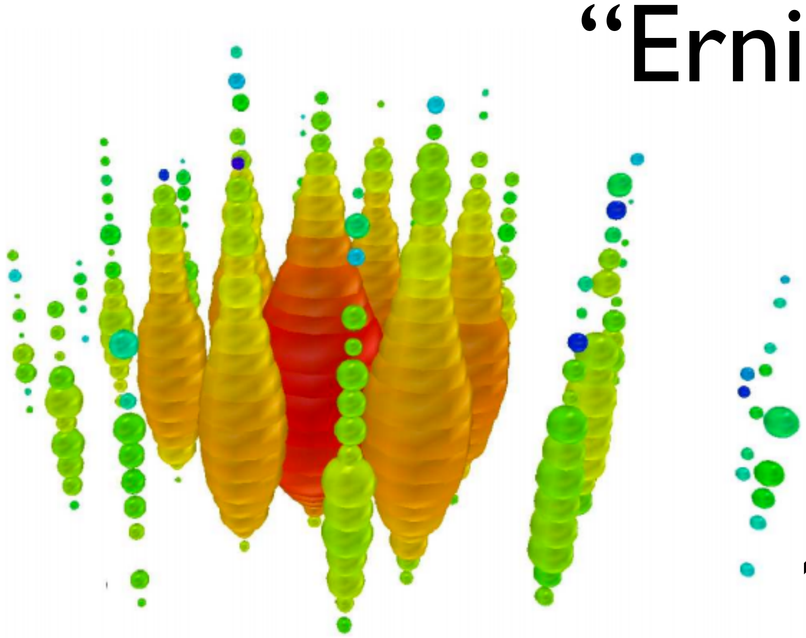


“Bert”



~1.0 PeV

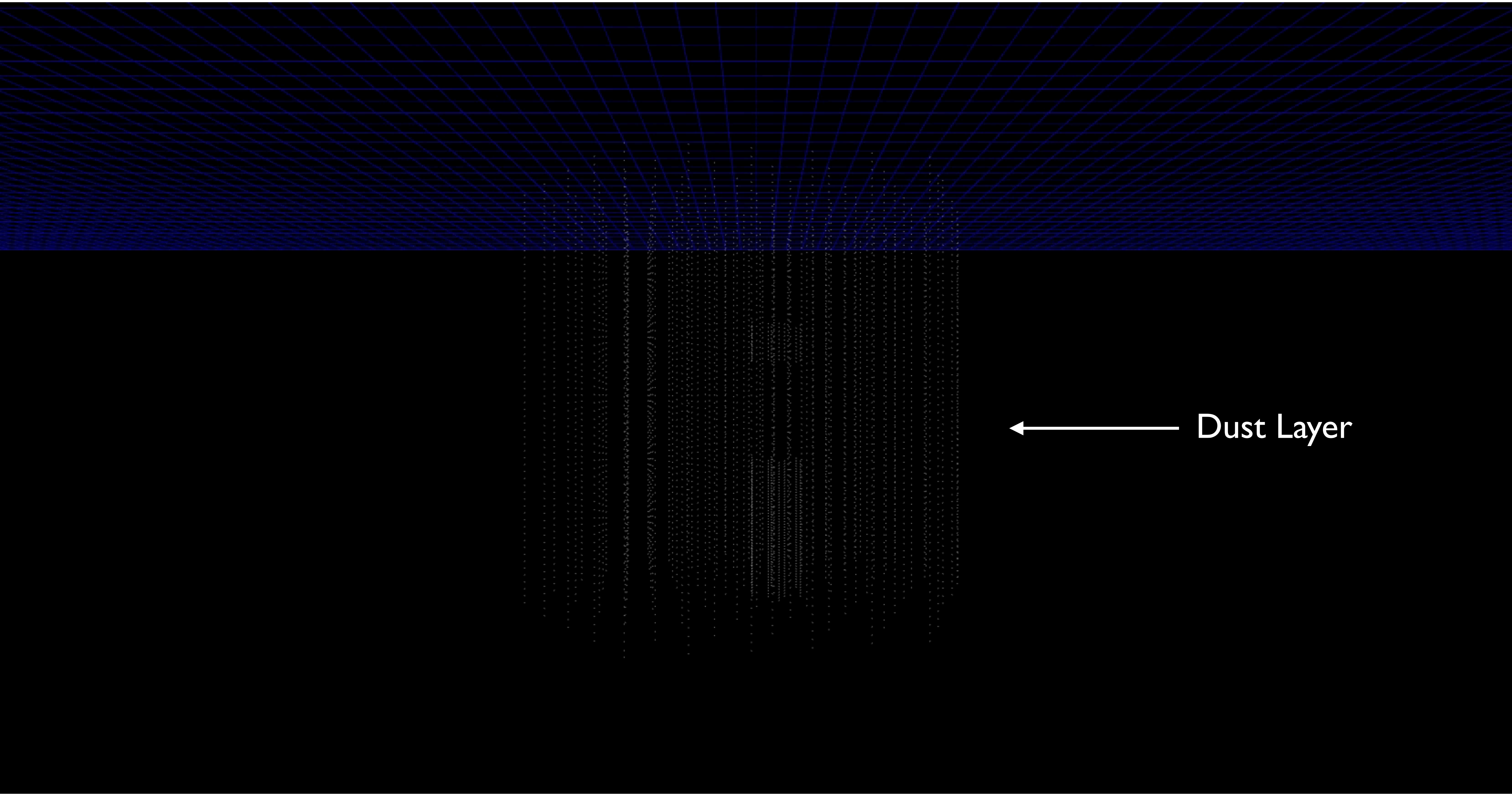
“Ernie”



~1.1 PeV

Simulated Galactic SN

Animation from Benedikt Riedel



Supernova Detection with IceCube

ν Interactions

- The supernova neutrino signal in IceCube is dominated by $\bar{\nu}_e + p \rightarrow n + e^+$.

Abbasi et al., A&A 535:2011, A109

Reaction	# Targets	Signal fraction
$\bar{\nu}_e + p \rightarrow e^+ + n$	6×10^{37}	93.8% (94.4%)
$\nu_e + e^- \rightarrow \nu_e + e^-$	3×10^{38}	1.7% (1.4%)
$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$	3×10^{38}	0.5% (0.4%)
$\nu_{\mu+\tau} + e^- \rightarrow \nu_{\mu+\tau} + e^-$	3×10^{38}	0.5% (0.4%)
$\bar{\nu}_{\mu+\tau} + e^- \rightarrow \bar{\nu}_{\mu+\tau} + e^-$	3×10^{38}	0.4% (0.4%)
$\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + \mathrm{X}$	3×10^{37}	1.5% (0.9%)
$\bar{\nu}_e + {}^{16}\mathrm{O} \rightarrow e^+ + \mathrm{X}$	3×10^{37}	1.3% (1.7%)
$\nu_{\mathrm{all}} + {}^{16}\mathrm{O} \rightarrow \nu_{\mathrm{all}} + \mathrm{X}$	3×10^{37}	0.3% (0.3%)
$\nu_e + {}^{17/18}\mathrm{O}/{}^2_1\mathrm{H} \rightarrow e^- + \mathrm{X}$	6×10^{34}	0.2% (0.2%)

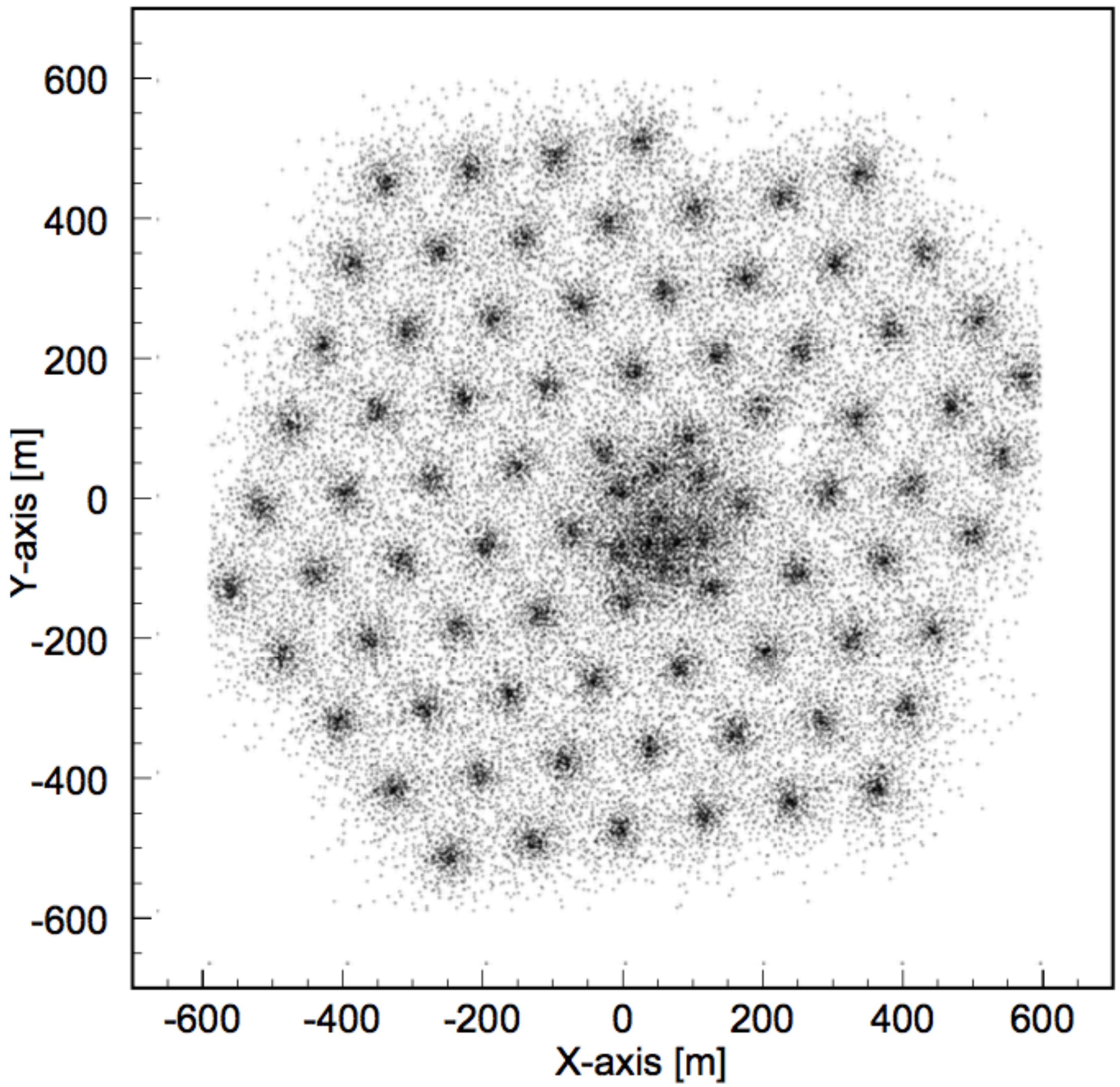
SN Neutrinos in IceCube

- IBD cross section: $\propto E_\nu{}^2$
- # Cherenkov γ's: $\propto E_\nu{}^3$
- e^+ track length:

  0.56 cm × (E_{e+}/MeV)
- # γ's bet. 300-600 nm:

  180 × (E_{e+}/MeV)
- Due to the sparseness of the detector, IceCube counts single photons on top of a ~500 Hz/DOM background rate.

Abbasi et al., A&A 535:2011, A109

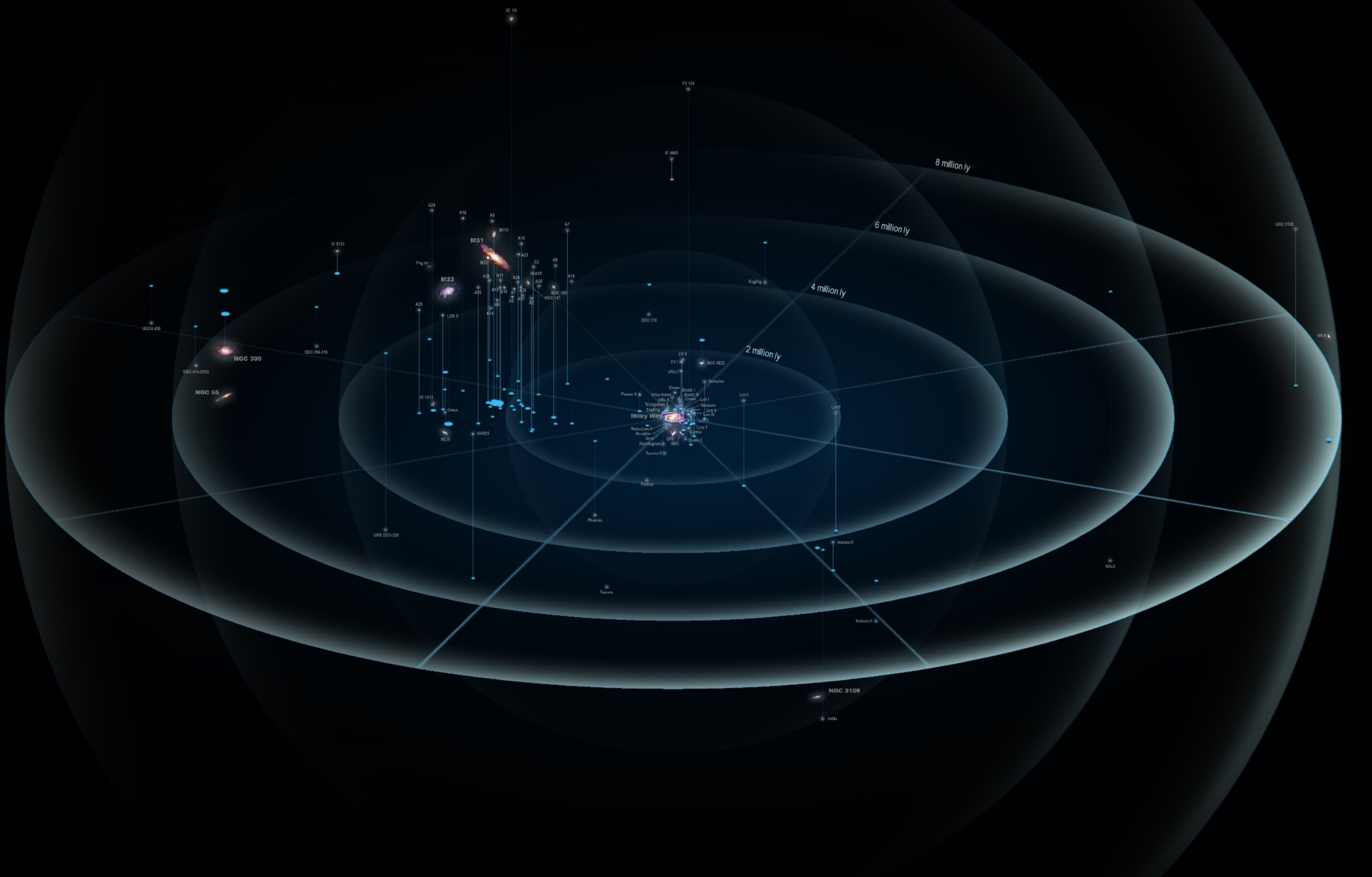


IceCube in Context

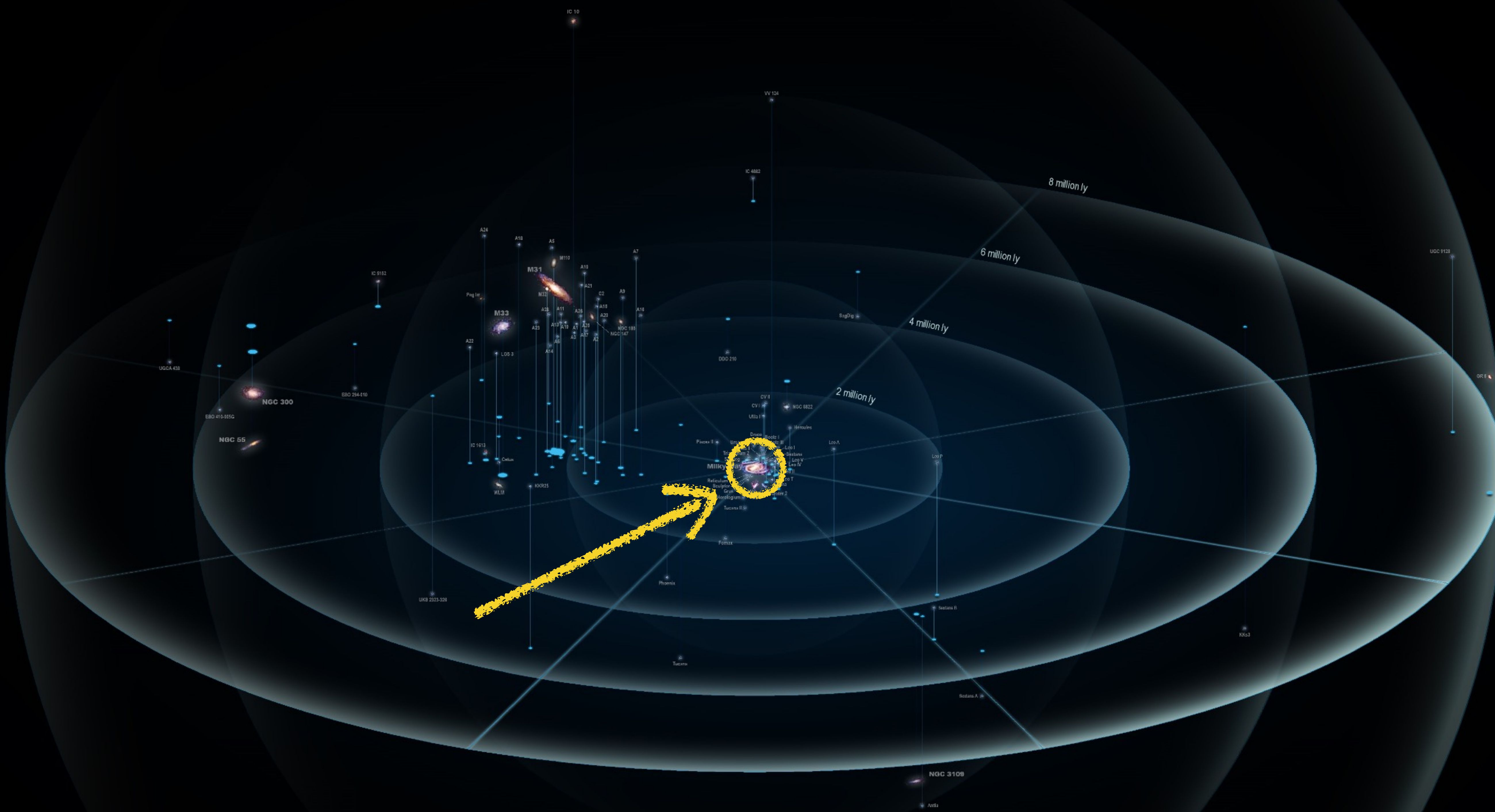
From K. Scholberg, J. Phys G 45:2017

Detector	Type	Mass (kt)	Location	Events [10 kpc]
IceCube	**long string**	**600**	**South Pole**	**1,000,000**
*Hyper-K**	*H_2O*	*374*	*Japan*	*75,000*
*DUNE**	*Ar*	*40*	*USA*	*3,000*
Super-K	H_2O	32	Japan	7,000
*JUNO**	*C_nH_{2n}*	*20*	*China*	*6,000*
NOvA	C_nH_{2n}	15	USA	4,000
LVD	C_nH_{2n}	1	Italy	300
KamLAND	C_nH_{2n}	1	Japan	300
SNO+	C_nH_{2n}	0.8	Canada	300
Baksan	C_nH_{2n}	0.33	Russia	50
Daya Bay	C_nH_{2n}	0.33	China	100
Borexino	C_nH_{2n}	0.3	Italy	100
MicroBooNE	Ar	0.17	USA	17
HALO	Pb	0.08	Canada	30

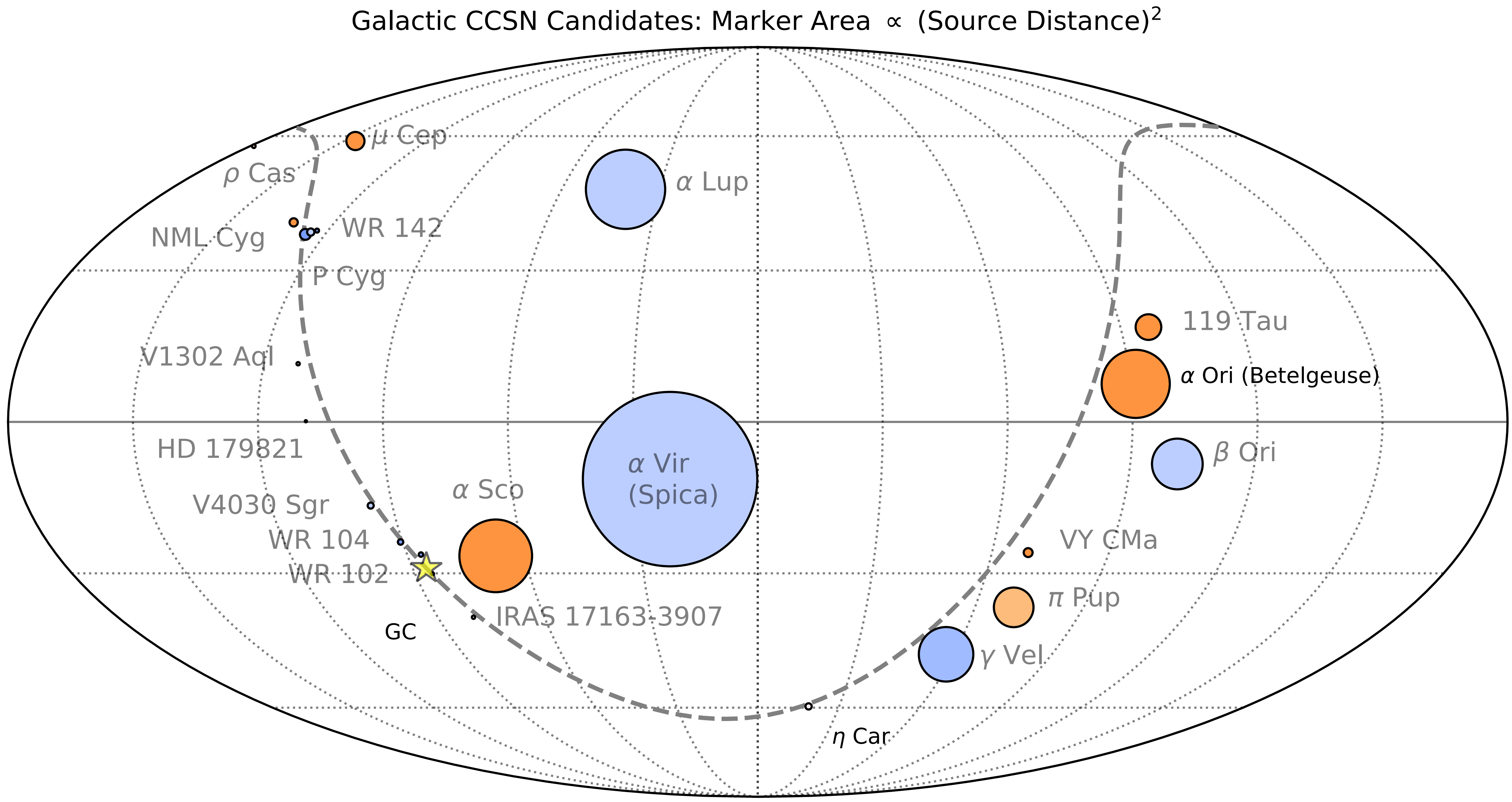
CCSN Horizon



CCSN Horizon



Potential Galactic CCSN



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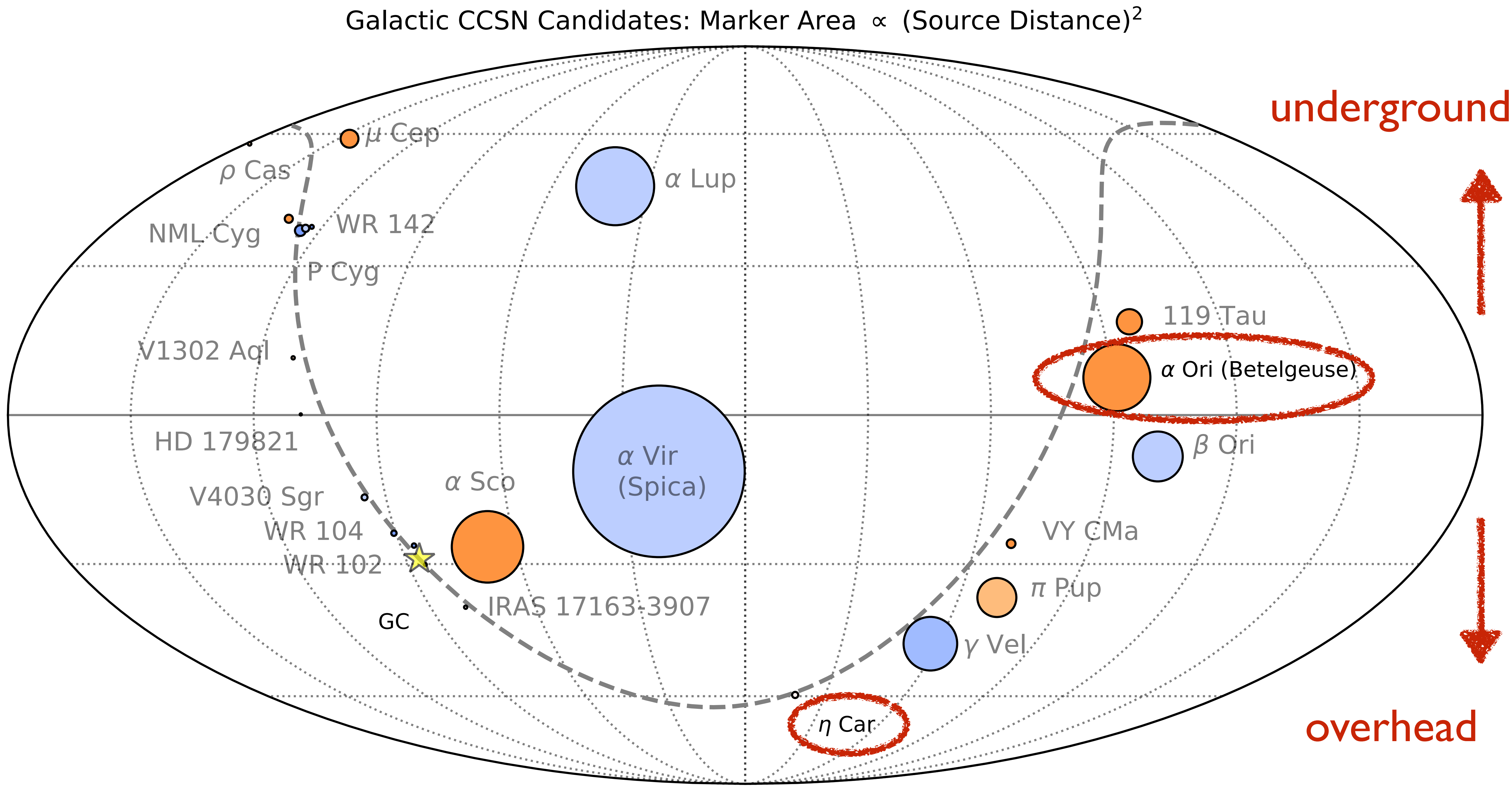

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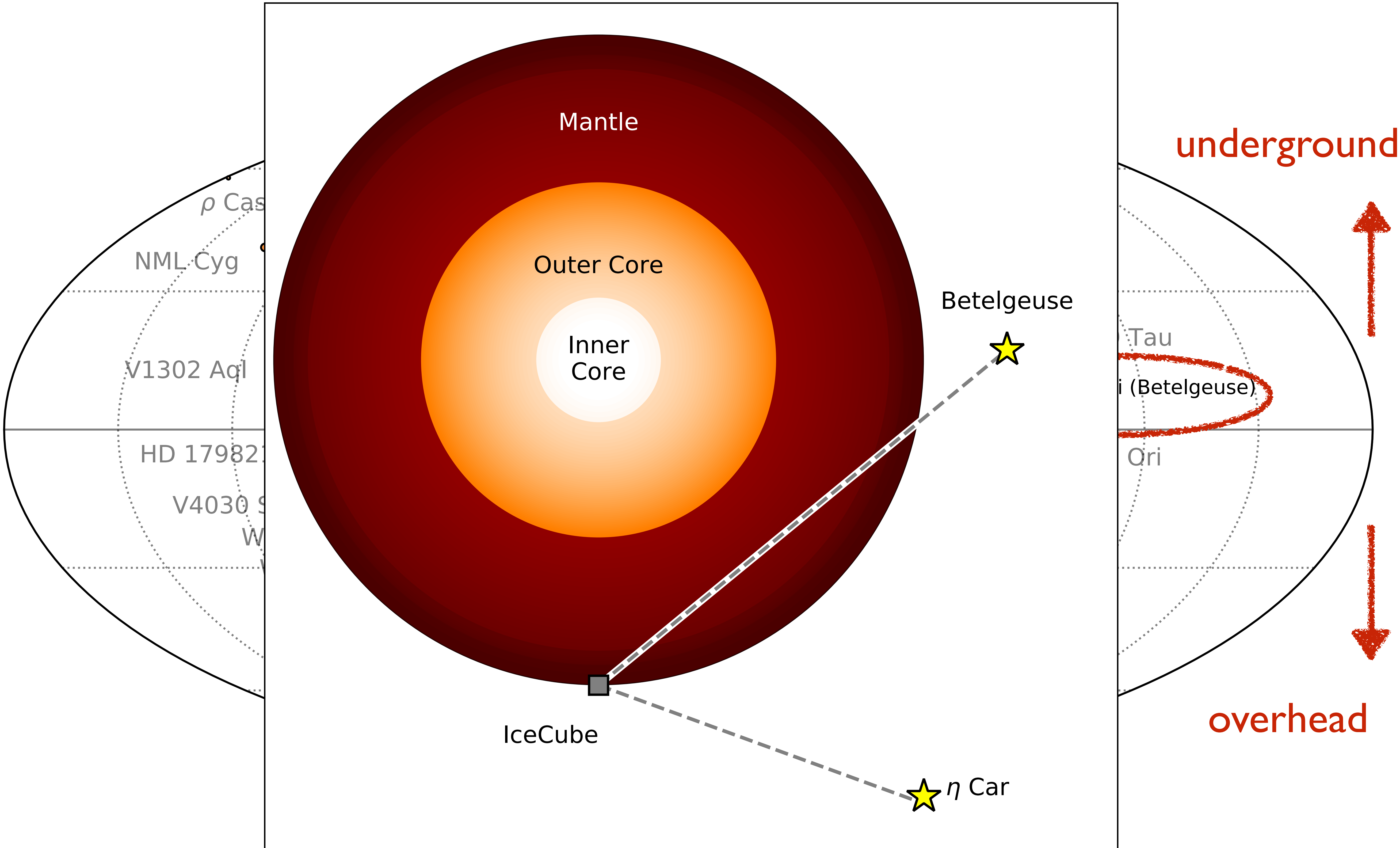
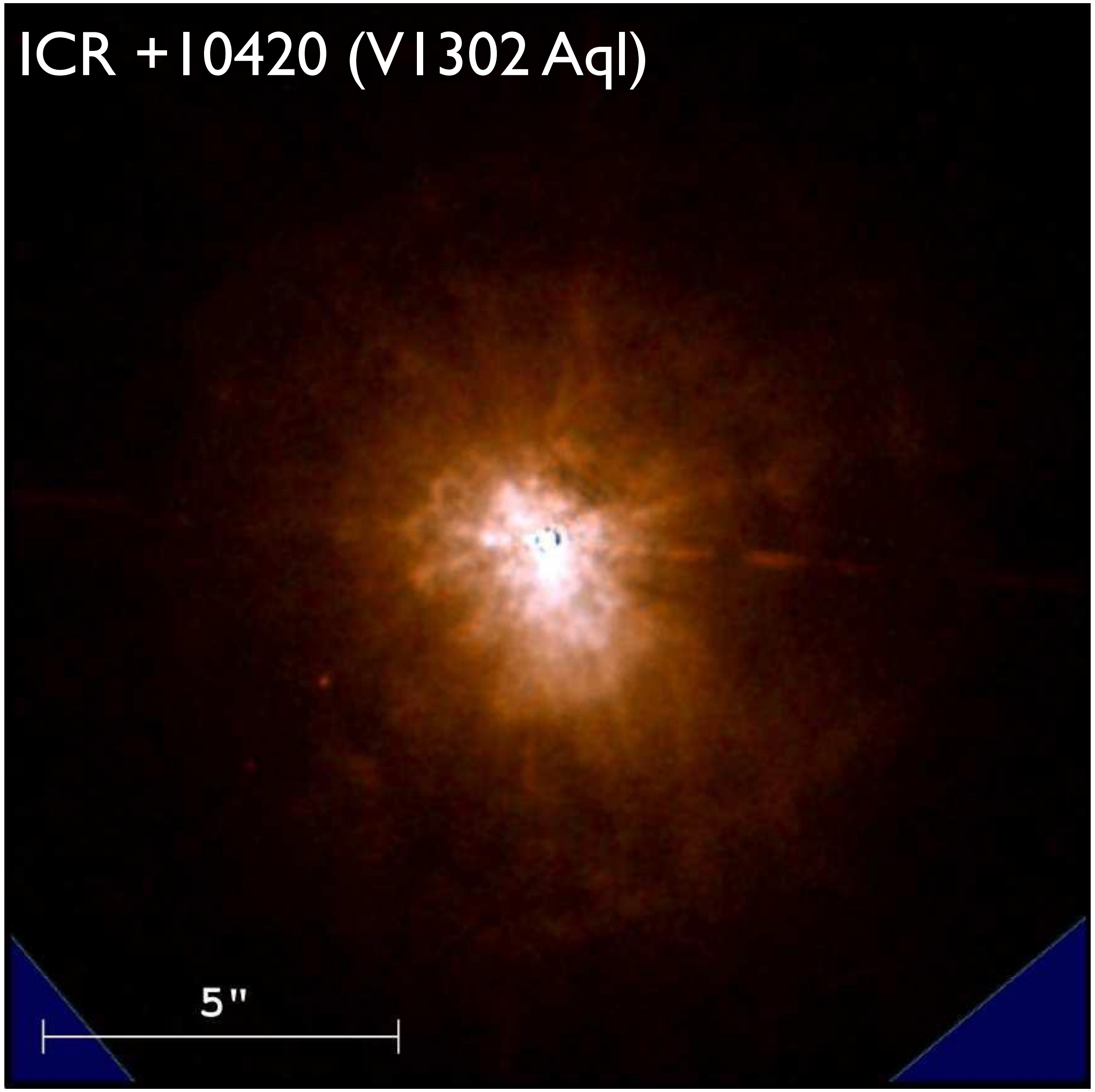
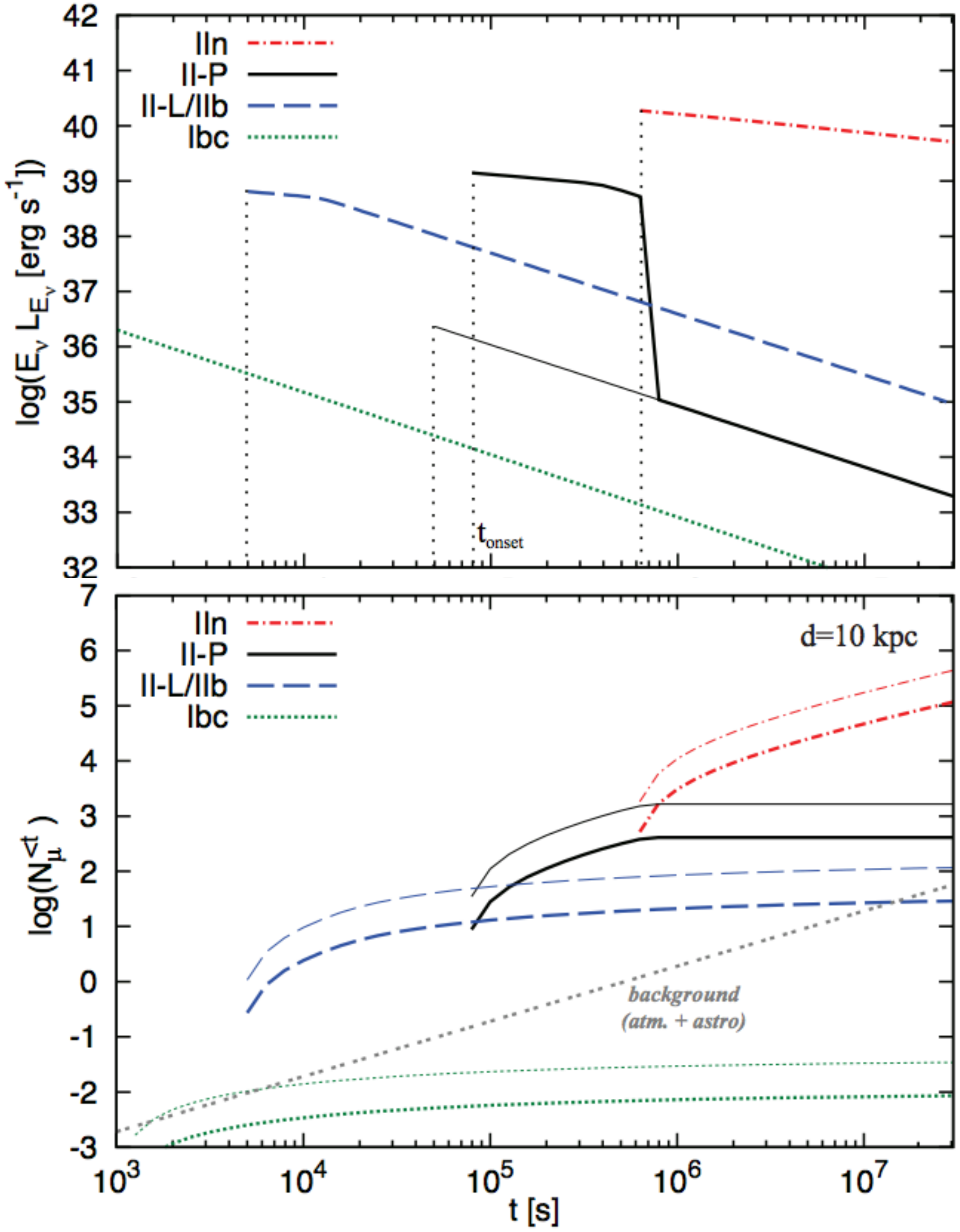


Post-Collapse TeV ν_μ Burst?

R.M. Humphreys, J. Phys.: Conf. Ser. 728:022007, 2016

K. Murase, PRD 97:08131, 2018





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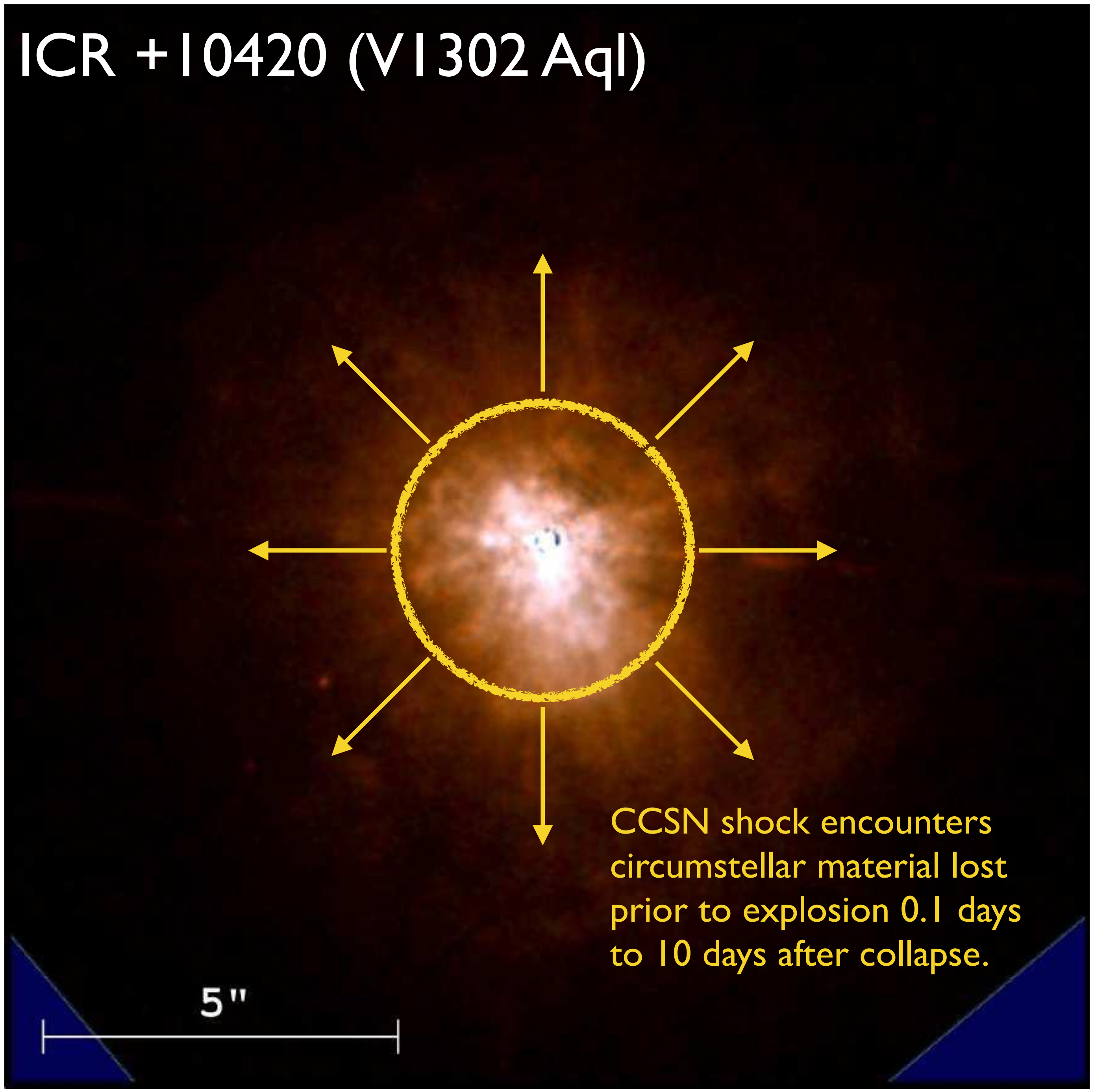

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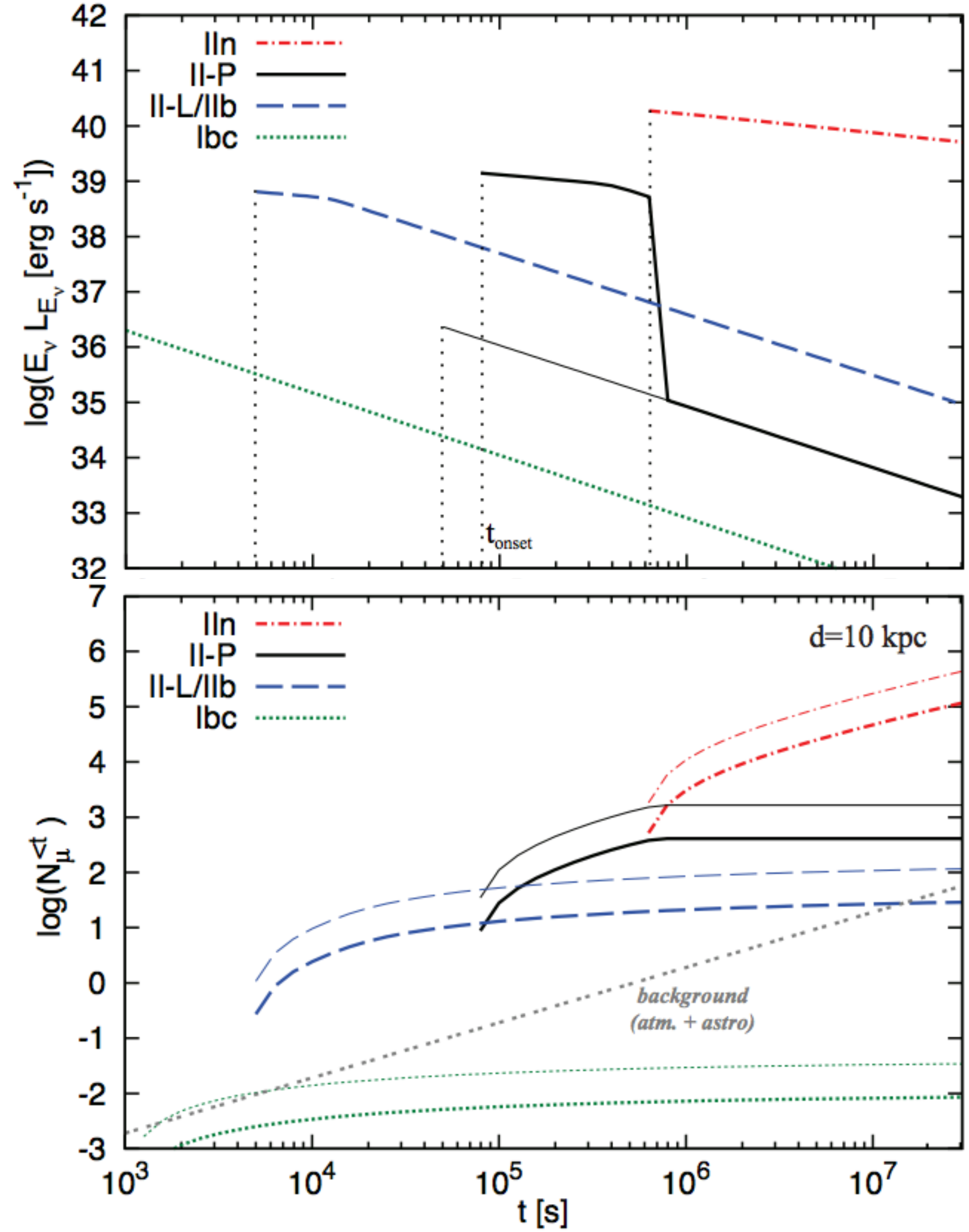
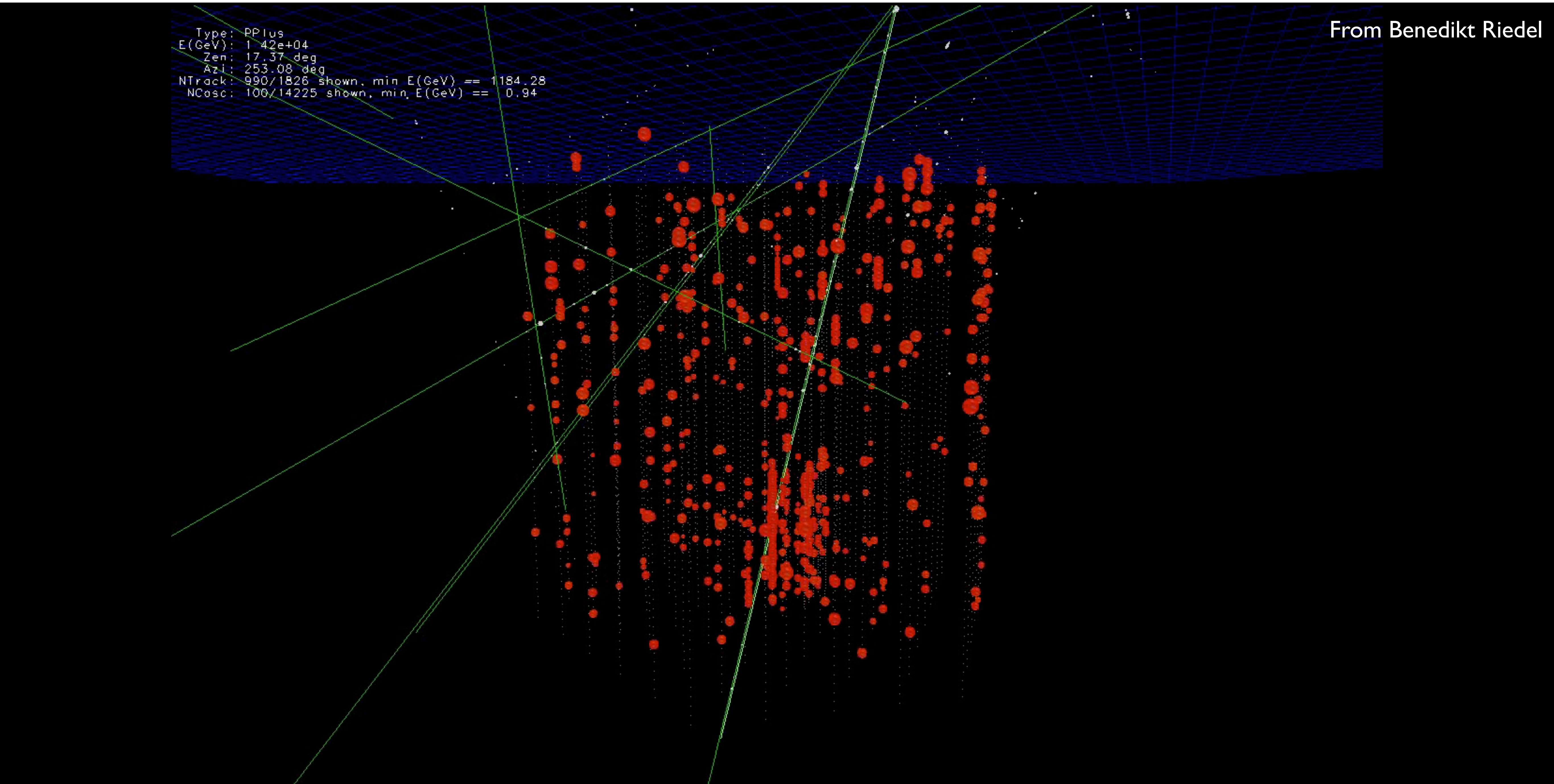


IceCube Supernova System

Cosmic Ray Backgrounds

- DOMs triggered in a random 10 ms interval:

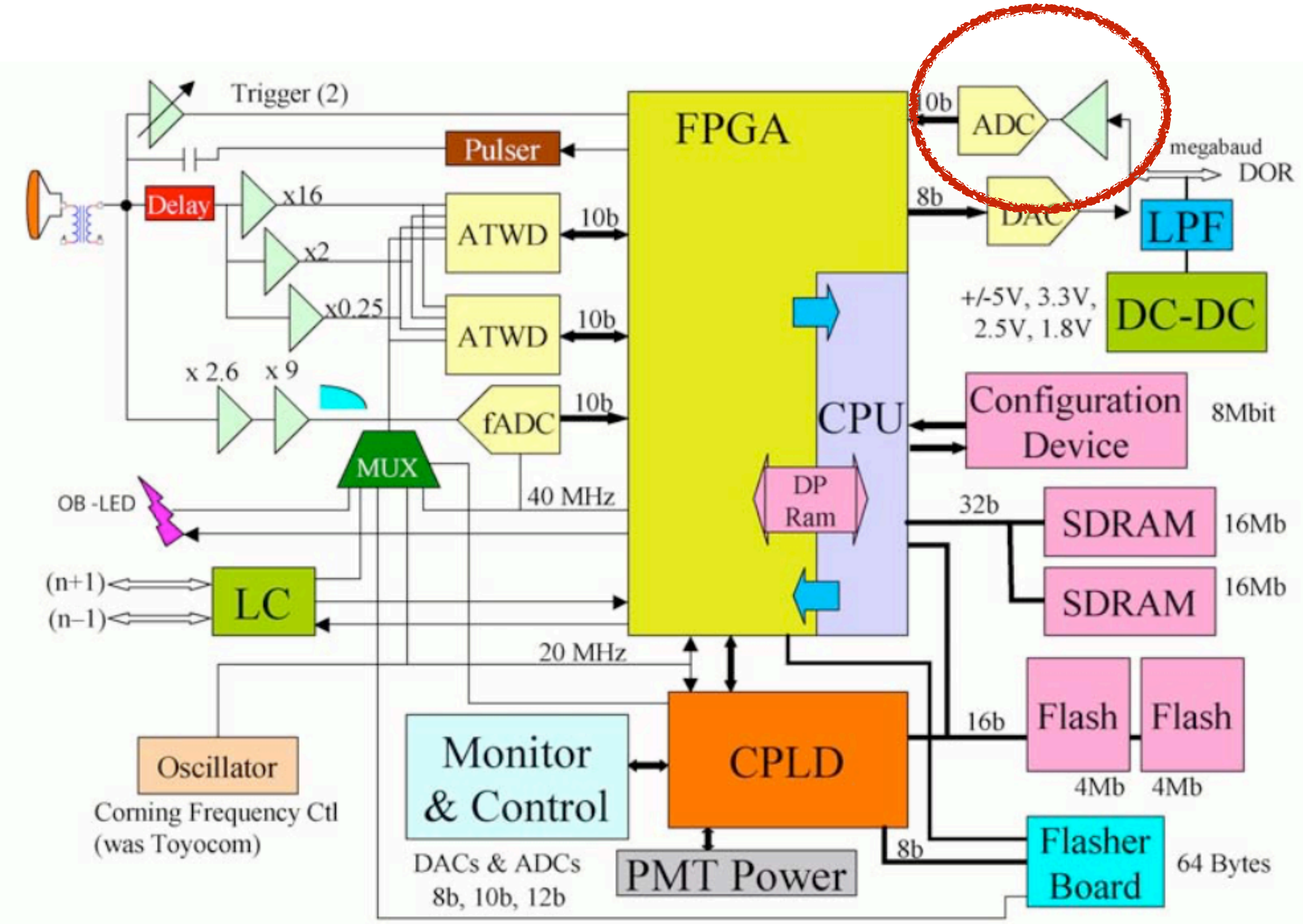


From Benedikt Riedel

Cosmic Ray Backgrounds

- Geometric triggers for supernovae are not possible due to cosmic ray backgrounds and other sources of light.
- SMT8 trigger rate due to TeV muons is about 3 kHz.
- Muon bundles from cosmic ray showers can easily light up the full detector.
- Even for short integration windows, a trigger based on coincident hits in all DOMs will be dominated by background photons.
- Note: some of the contamination due to cosmic rays can be removed.

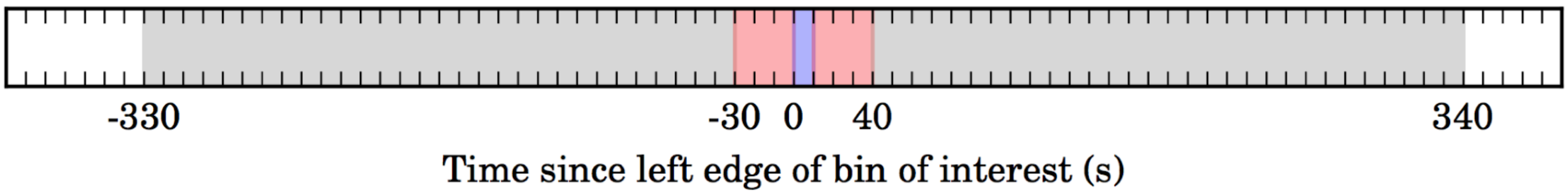
Supernova Scaler System



- Independent DOM trigger set to 0.25 PE.
- FPGA in main board counts discriminator crossings ("hits") in 2^{16} clock cycles.
- Integration window: 2^{16}/40 MHz ≈ 1.6384 ms, stored for 10 s and rebinned in 2 ms bins.
- Rate reduced with 250 μs non-paralyzing deadtime.

Search for Excess Counts

- SNDAQ: online software which searches for correlated rises in DOM rates above background. Counts rebinned 2 ms → 0.5 s.



- Search windows:
  - 0.5 s: optimized for very short neutrino bursts (BH formation).
  - 1.5 s: optimized for bulk of flux (based on Lawrence-Livermore).
  - 4.0 s: optimized for cooling time of the proto-neutron star.
  - 10.0 s: optimized for full detection window of SN1987A.
- Significant alerts forwarded to SNEWS with a latency of 5 minutes. Latency due to two-sided background estimation window.

Alert Significance

- SNDAQ sliding window maximum likelihood:

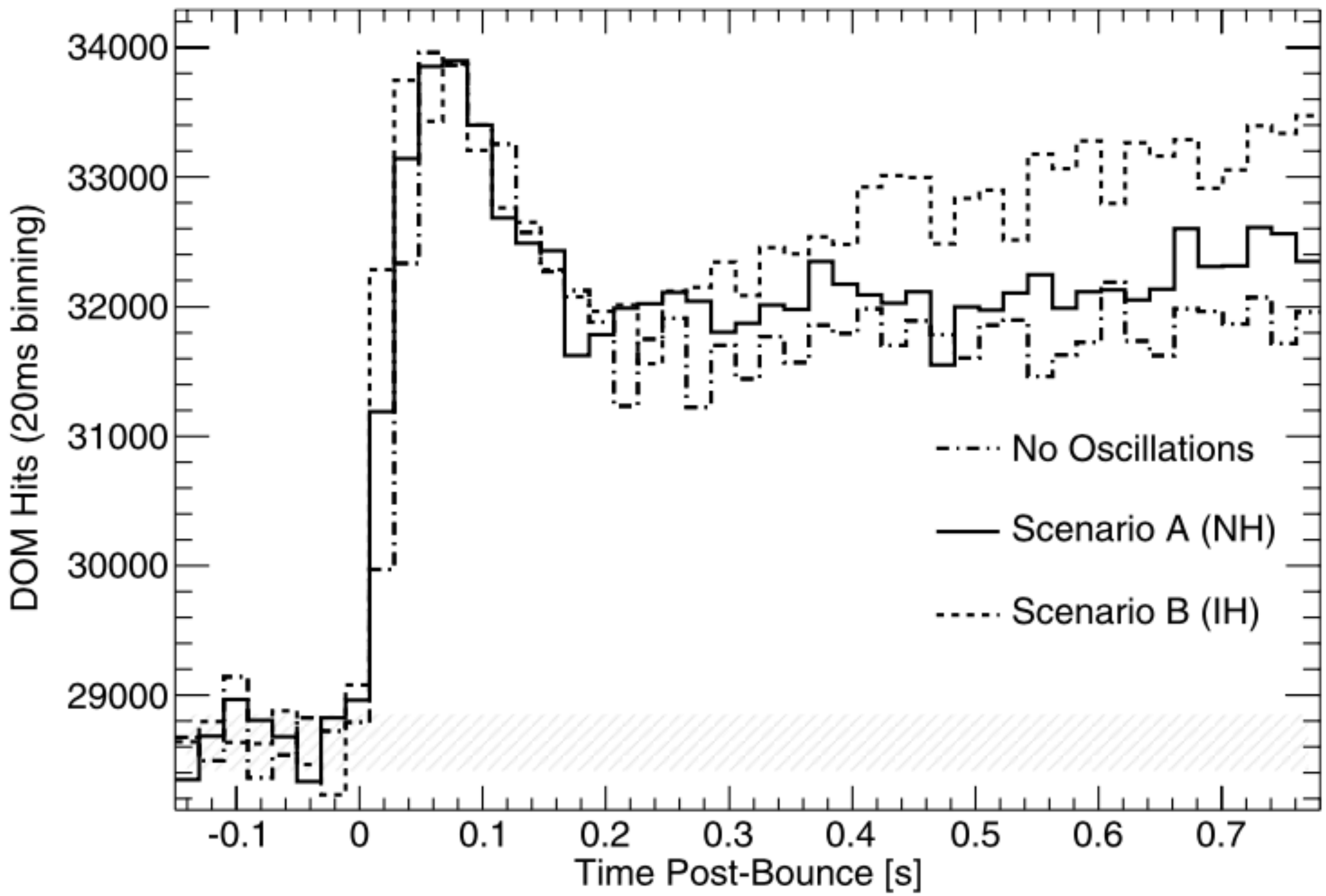
$$\ln \mathscr{L}(\Delta\mu) = \sum_{i=1}^{N_{\mathrm{DOM}}} -\frac{\left[r_i - (\langle r_i \rangle + \epsilon_i \Delta\mu)\right]^2}{2\langle \sigma_i \rangle^2} - \frac{1}{2} \ln 2\pi \langle \sigma_i \rangle^2$$

- r_i = count rate in DOM *i*
- σ_i = count rate uncertainty in DOM *i*
- ϵ_i = relative efficiency of DOM *i*
- $\Delta\mu$ = correlated increase in DOM rates across the full detector within sliding search window(s).

Example Light Curve

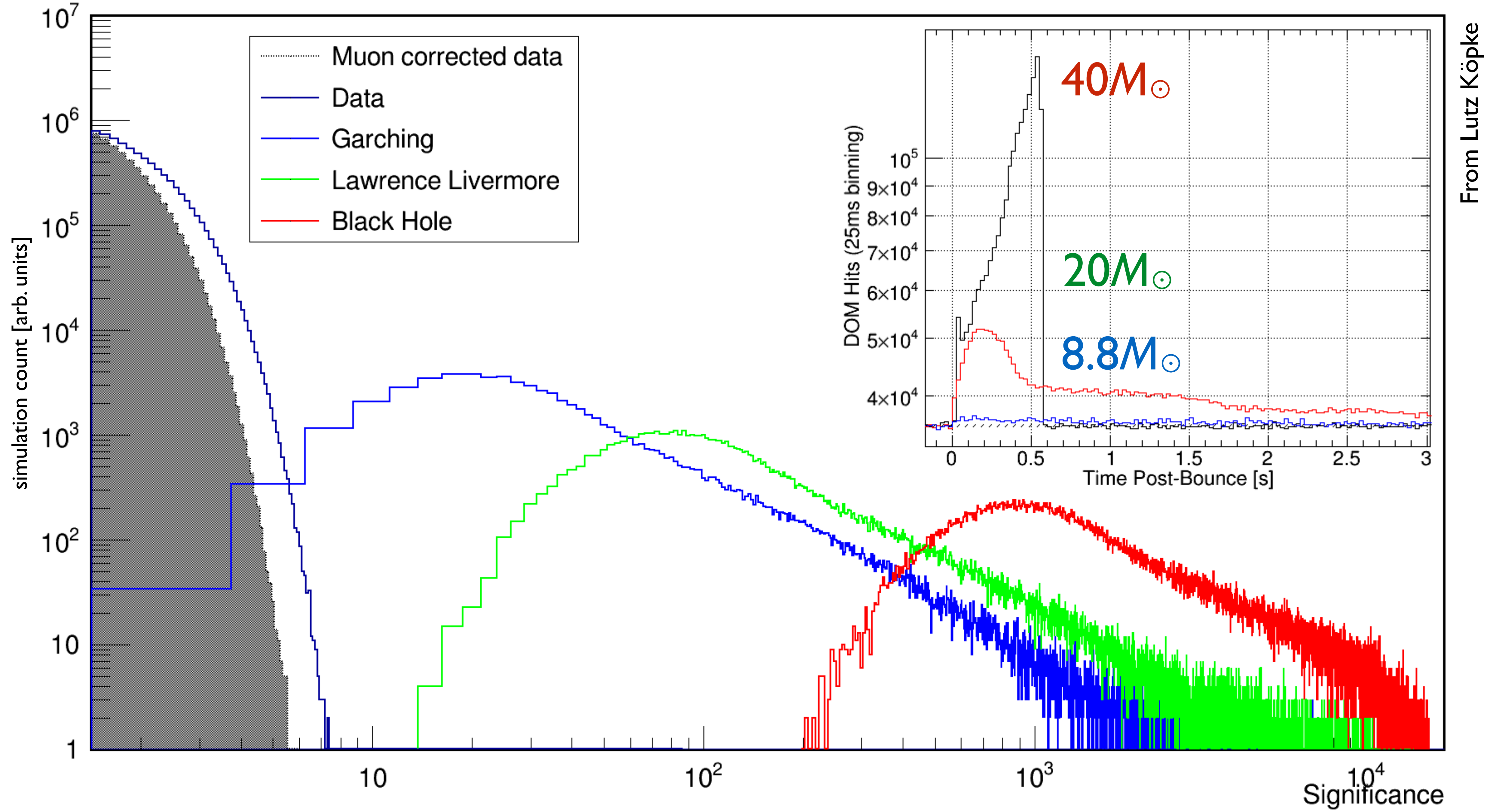
- Lightcurve for 10 kpc CCSN, Garching model, L&S EOS:

R. Abbasi et al., A&A 535:A109, 2011



SN Detection Capability

- SN progenitor randomly distributed in MW. Strong model dependence, but significance only intersects detector backgrounds for lightest progenitor.



SN Performance of IceCube

- Because the detector is so sparse, it is not possible to reconstruct the energies of $\mathcal{O}$(10 MeV) supernova neutrinos*
- IceCube also cannot identify the direction of a supernova**, though triangulation with other detectors is possible.
- Main contribution: very high statistics measurements of the neutrino lightcurve; Southern hemisphere location may probe matter effects.
- Potential detection of TeV ν's from shock interaction with CSM.

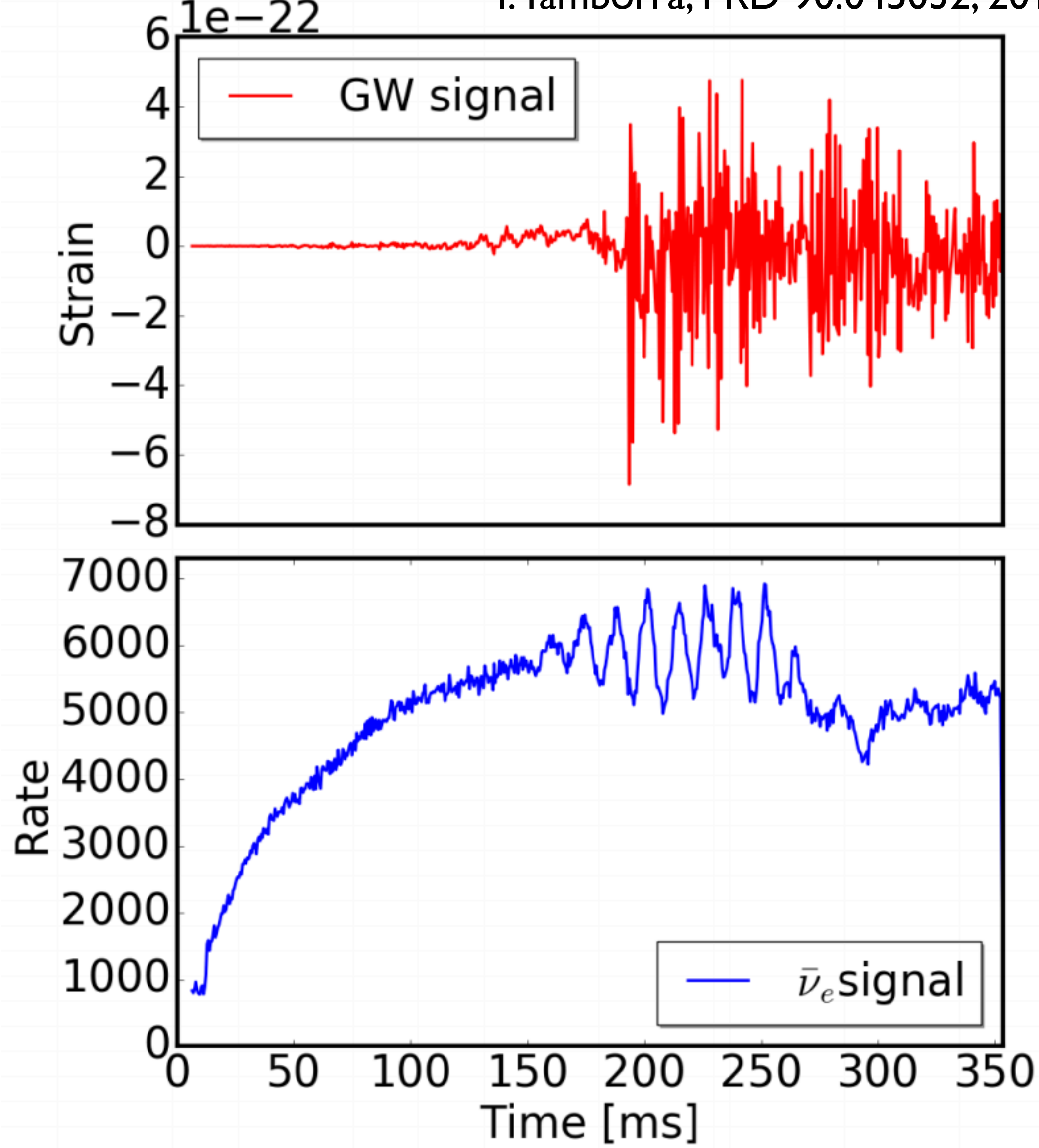
* *Using coincident hits, an average neutrino energy can be estimated [Eberhardt: ICRC 2015; Lozano: Neutrino 2018].*

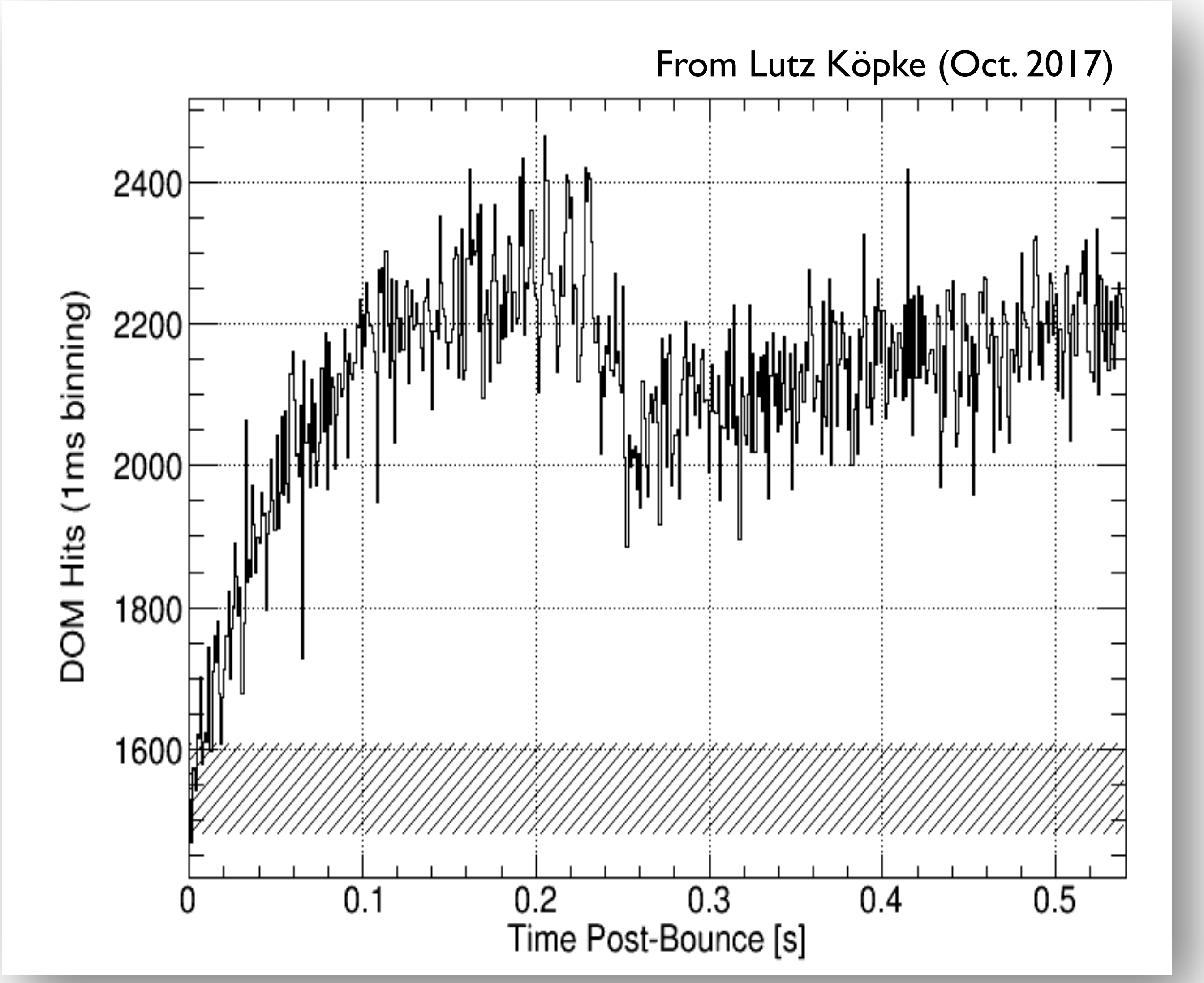
** *Signal cutoff due to BH formation allows for crude estimate of arrival direction, possibly $\mathcal{O}(20^{\circ})$ [Eberhardt: ICRC 2015].*

Standing Accretion Shocks

- With precise measurements of lightcurve, potential sensitivity to imprint of short time-scale phenomena.

I. Tamborra, PRD 90:045032, 2016





ν Physics: Mass Ordering

- Sensitivity to the mass hierarchy using supernova neutrinos:

From K. Scholberg, J. Phys G 45:2017

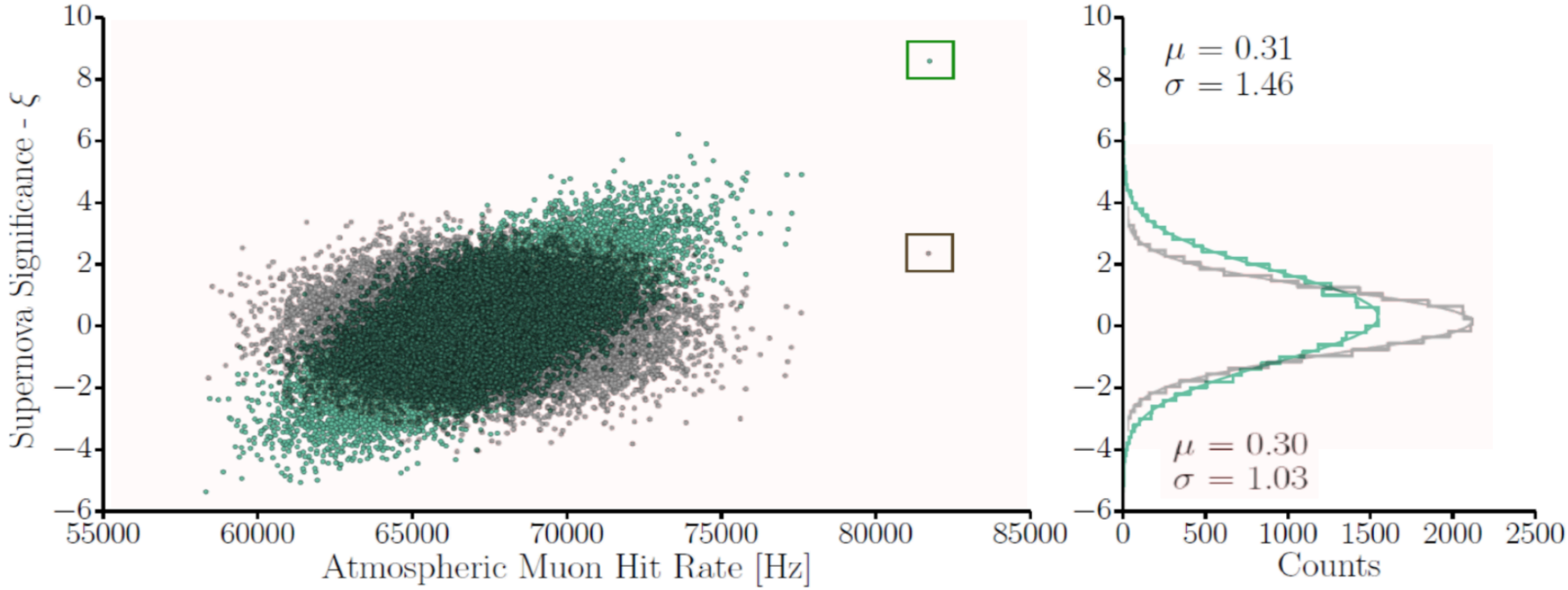
Signature	Normal	Inverted	Robustness	Observability
Neutronization	very suppressed	suppressed	excellent	good, need ν_e
Early time profile	**low, then high**	**flattened**	**good**	**good (IceCube)**
Shock wave	*t*-dependent	*t*-dependent	fair	statistics limited?
Collective effects	*E*, *t*-dependent	*E*, *t*-dependent	unknown	want all flavors
Earth matter	Wiggles in $\bar{\nu}_e$	Wiggles in ν_e	excellent	difficult; need energy resolution + Earth shadowing
Type Ia	lower flux	higher flux	moderate	very nearby

Current and Future Improvements

Cosmic-Ray Subtraction

- Cosmic muon rate is correlated with significant alerts.

V. Baum, B. Eberhardt, B. Riedel, et al., ICRC 2015



- SMT8 rate from pDAQ transmitted to SNDAQ and used to adjust alert significances. Removes strong seasonal effect in false alarm rate.
- With correction, detection efficiency for LMC improves from10% → 80%. False positives to SNEWS now <0.5 month^{-1}.

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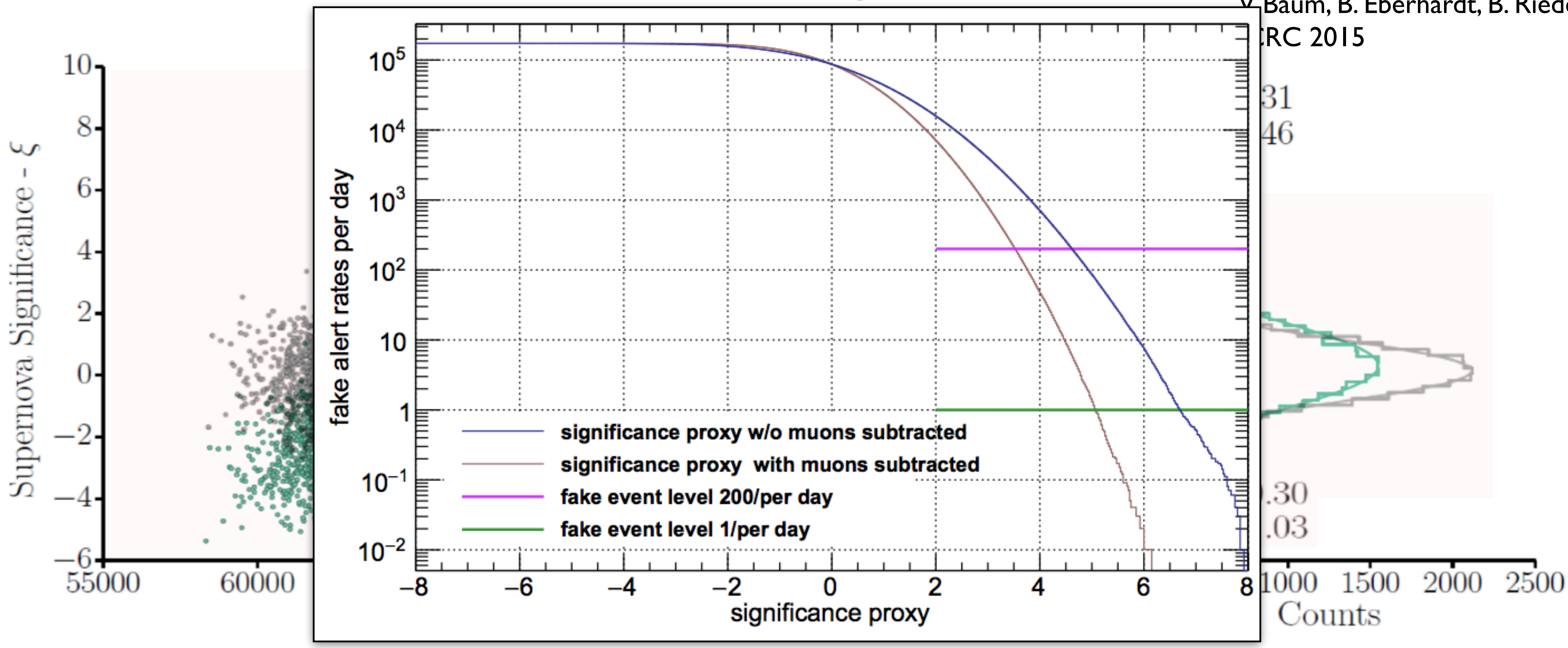

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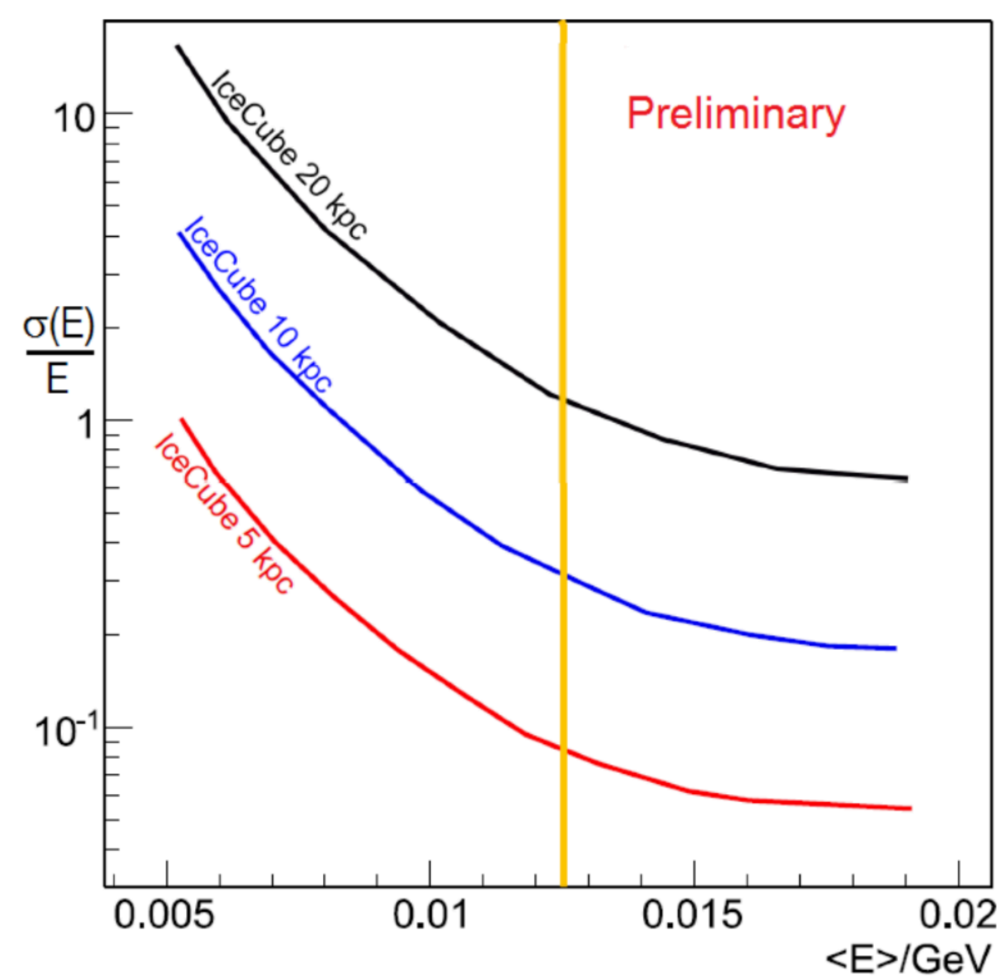
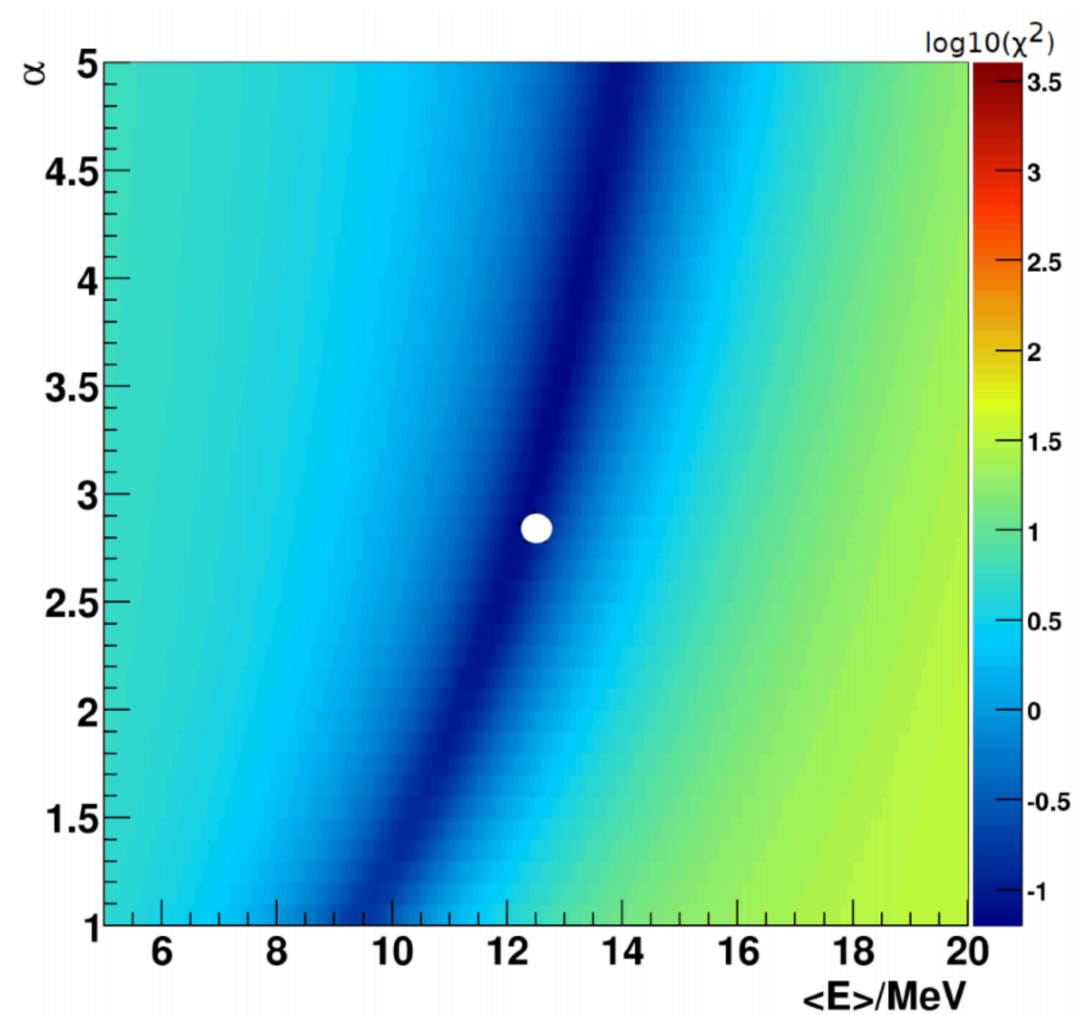
Sensitivity to $\langle E_\nu \rangle$

- Coincident hit distributions depend on shape of energy spectrum. Use χ^2 method to produce 2D constraints in $\langle E_\nu \rangle$ and pinch parameter α.
- Assumes 8.8 $M_\odot$ O-Ne-Mg core collapse. Energy resolution is ~30%.

Lutz Köpke, 8th Int. Symp. on Large TPCs (Dec. 2017)

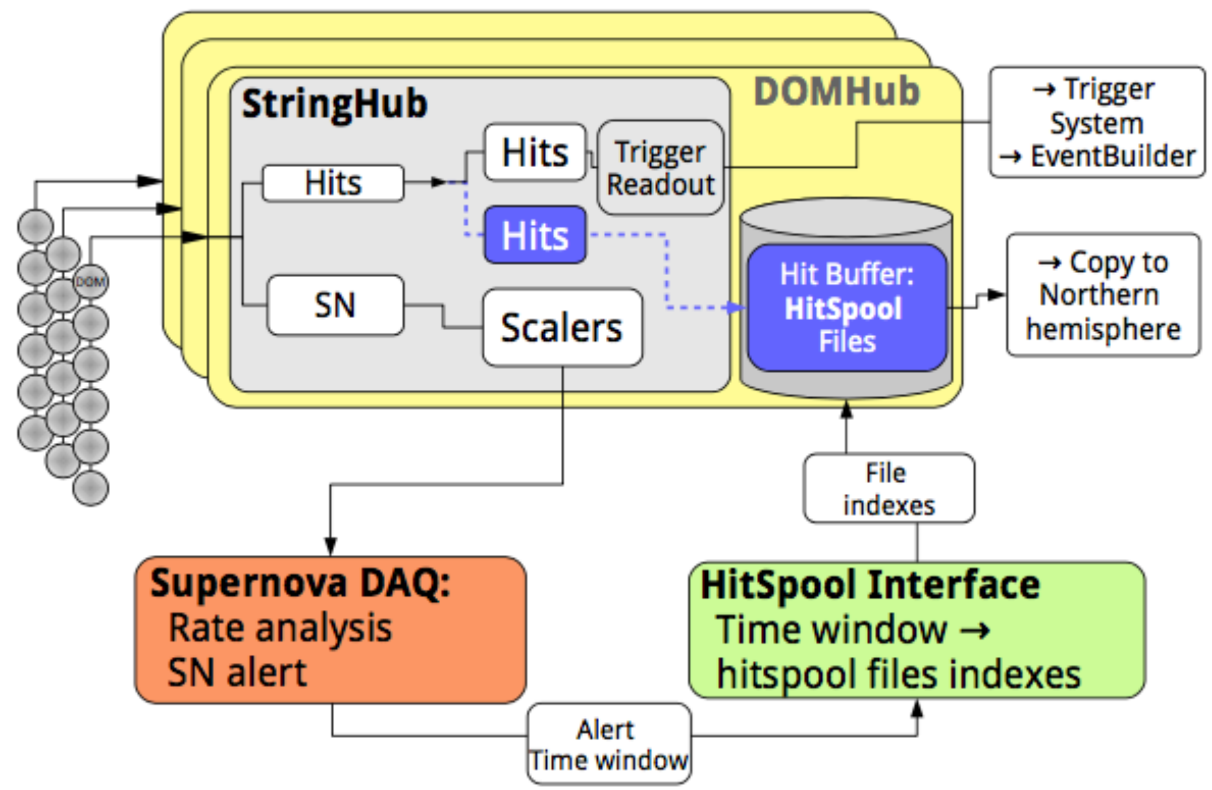




HitSpooling

- High-significance SNDAQ alerts trigger capture of full DOM waveforms.

From D. Heereman (Ph.D. thesis, 2015)

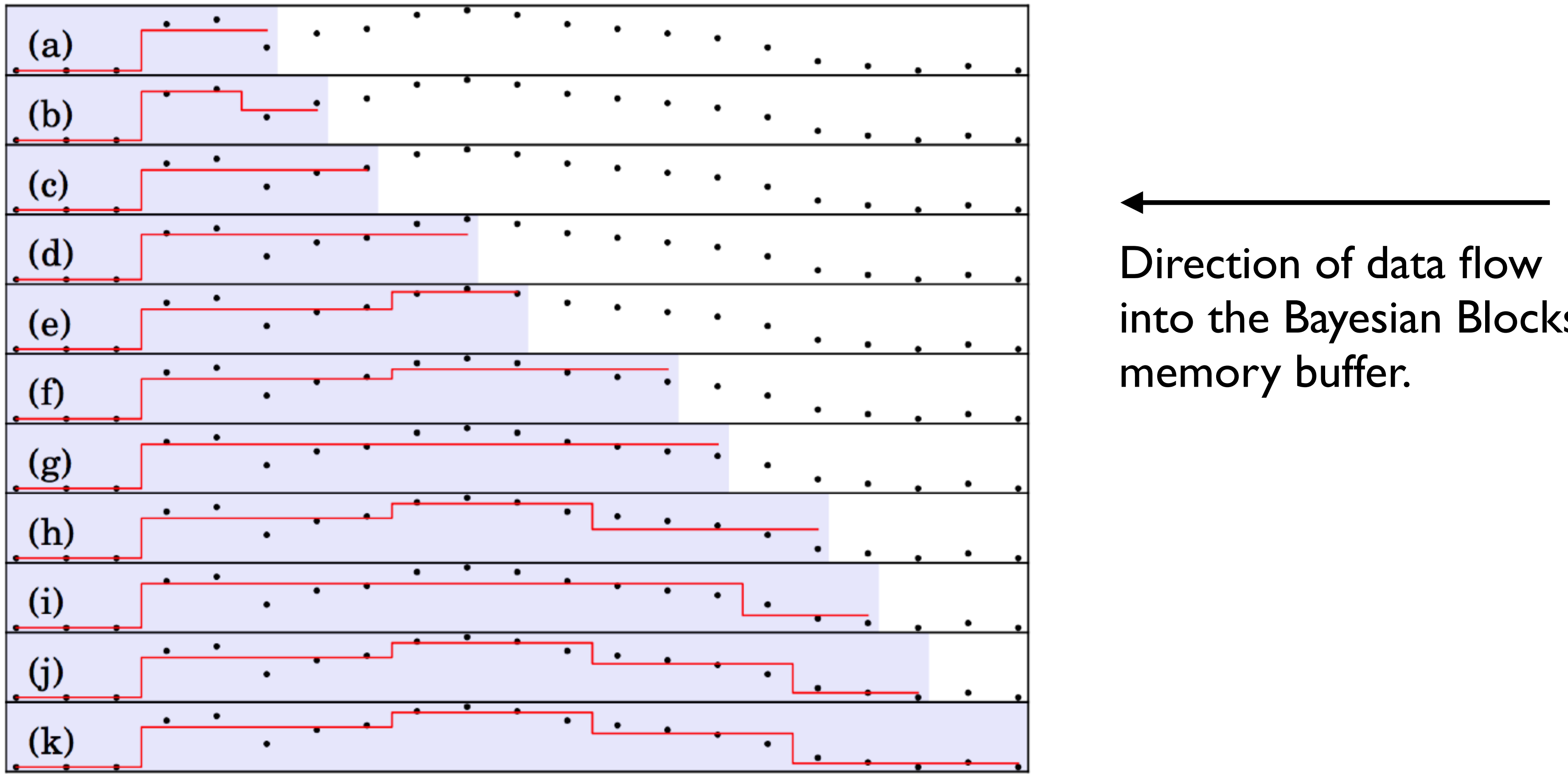


- Data transferred to UW-Madison for offline analysis.
- Primary advantage: not limited to 2 ms resolution of the online scaler system.

Bayesian Blocks

- Instead of model-dependent binning of SNDAQ online search, let the data themselves identify significant changes in the event rate [Scargle et al., 1998 & 2013].

Robert Cross, ICRC 2017

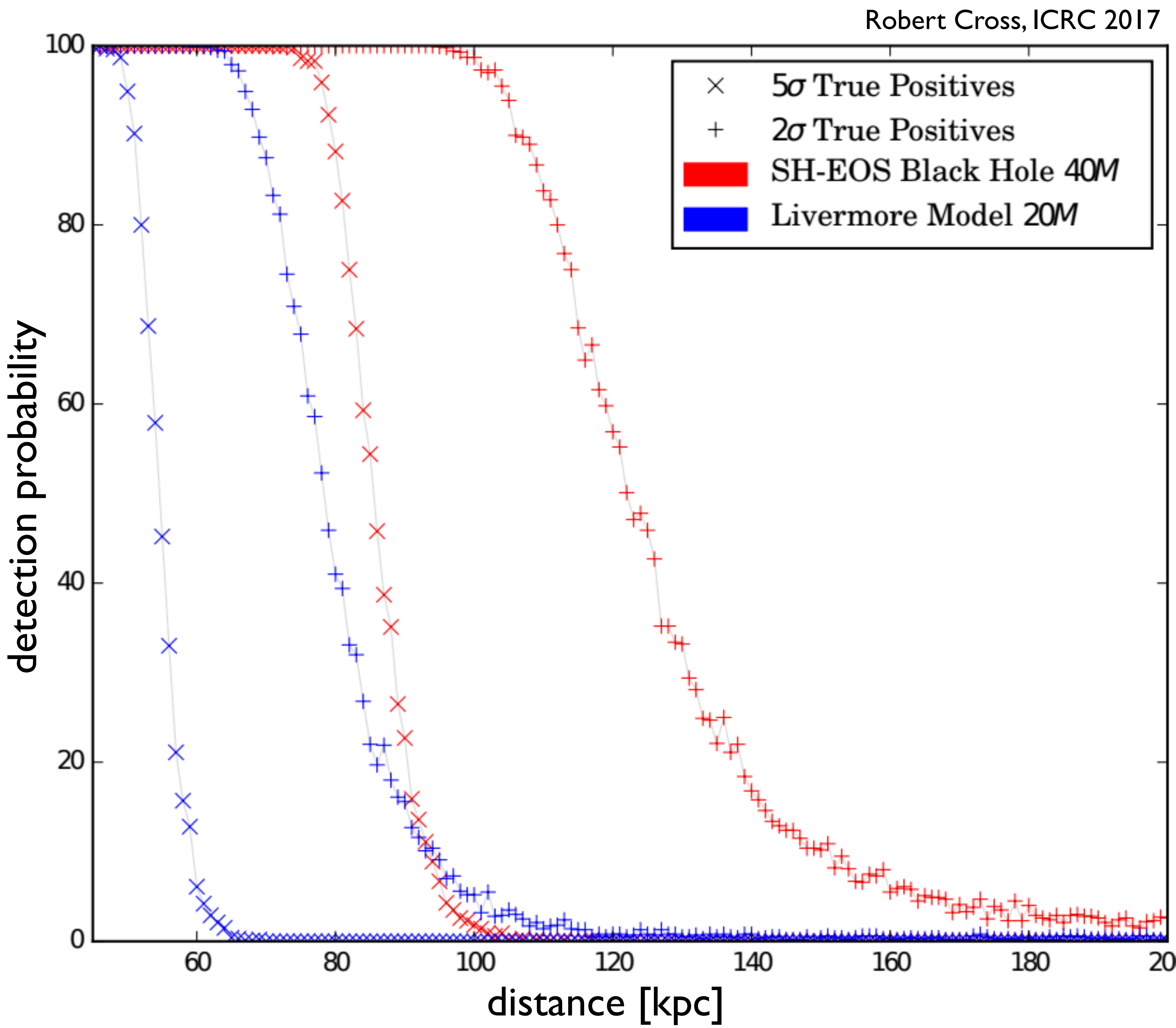


Direction of data flow into the Bayesian Blocks memory buffer.

- Implementation of BB algorithm for sliding window searches with tunable false-positive rate. Integration into SNDAQ: summer 2018.

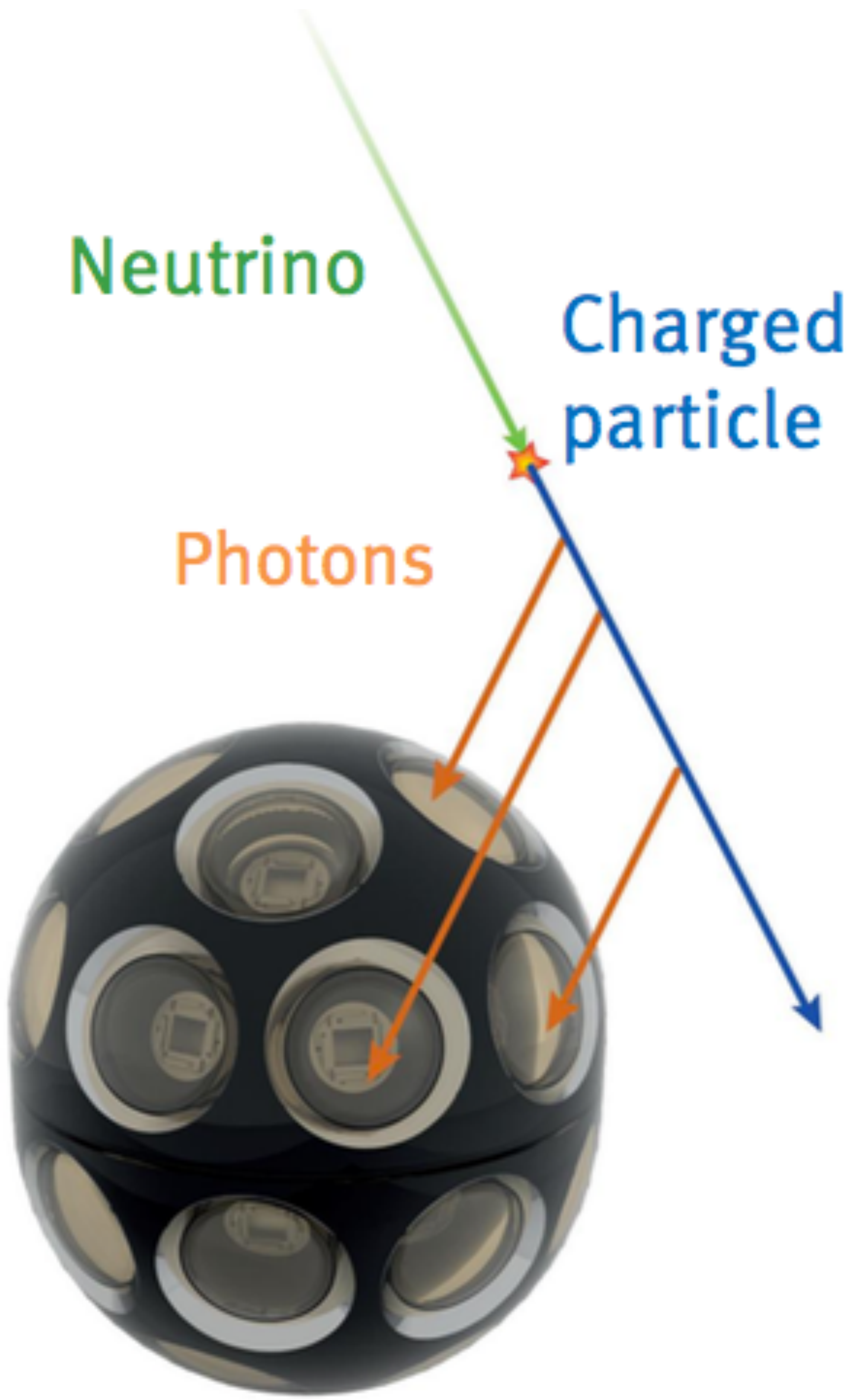
Bayesian Blocks

- Instead ... let the data th... Scargle et al., 199...



- Implem... with tunable false-po...

New Hardware: mDOM



- Directional sensitivity, 4π acceptance, more photocathode area than current DOMs.
- Improved low-energy sensitivity with local coincidences.

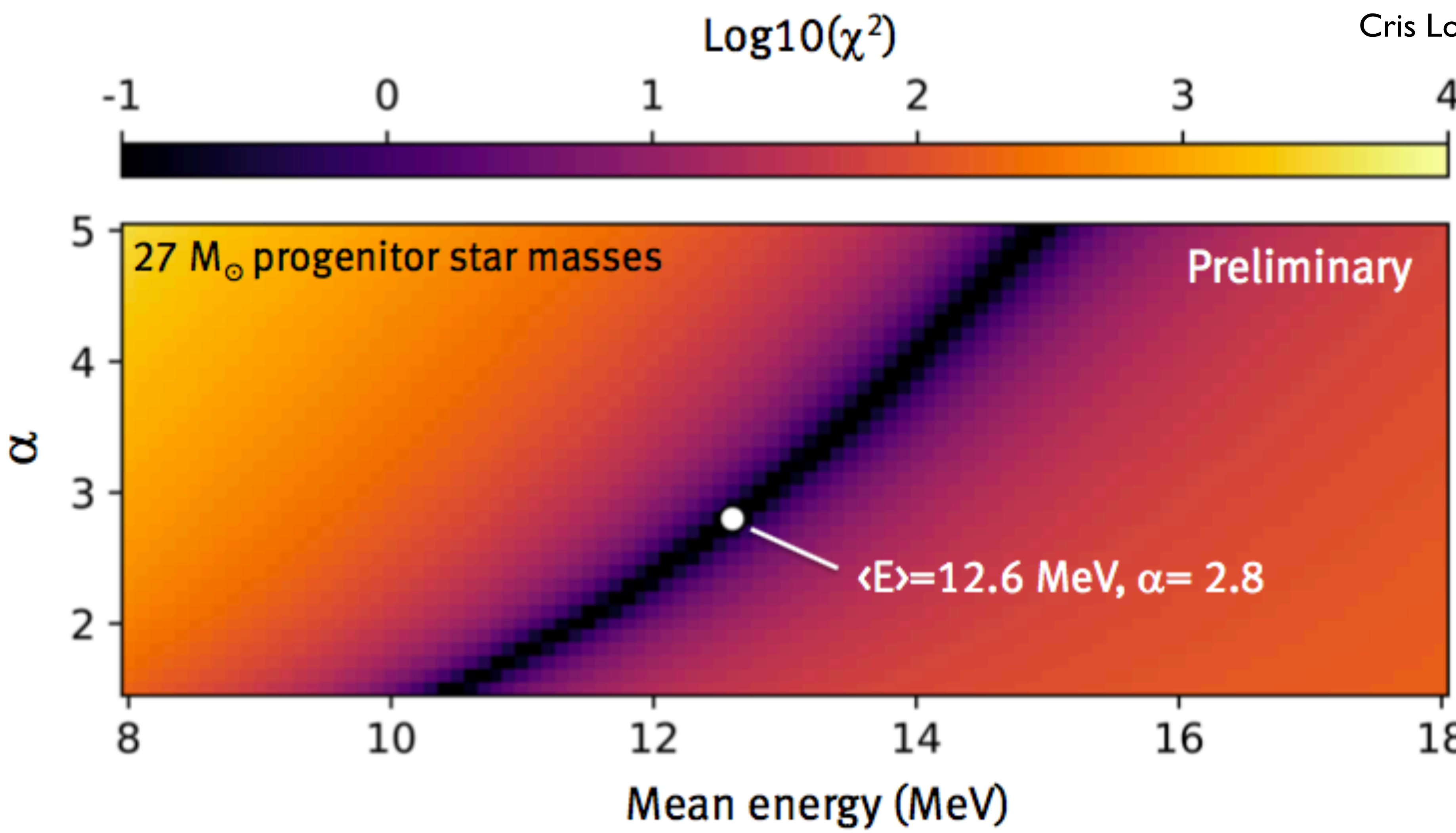
n_{coinc}	N_ν	False SN rate (yr^{-1})	d [kpc] for 50% SN detection $27 M_\odot$ ($9.6 M_\odot$)
≥5	51	1.7	177 (109)
≥5	55	0.04	170 (105)
≥6	7	3.3	323 (193)
≥6	**9**	**<0.001**	**286 (171)**

Cris Lozano, Neutrino 2018

mDOMs: Sensitivity to $\langle E_\nu \rangle$

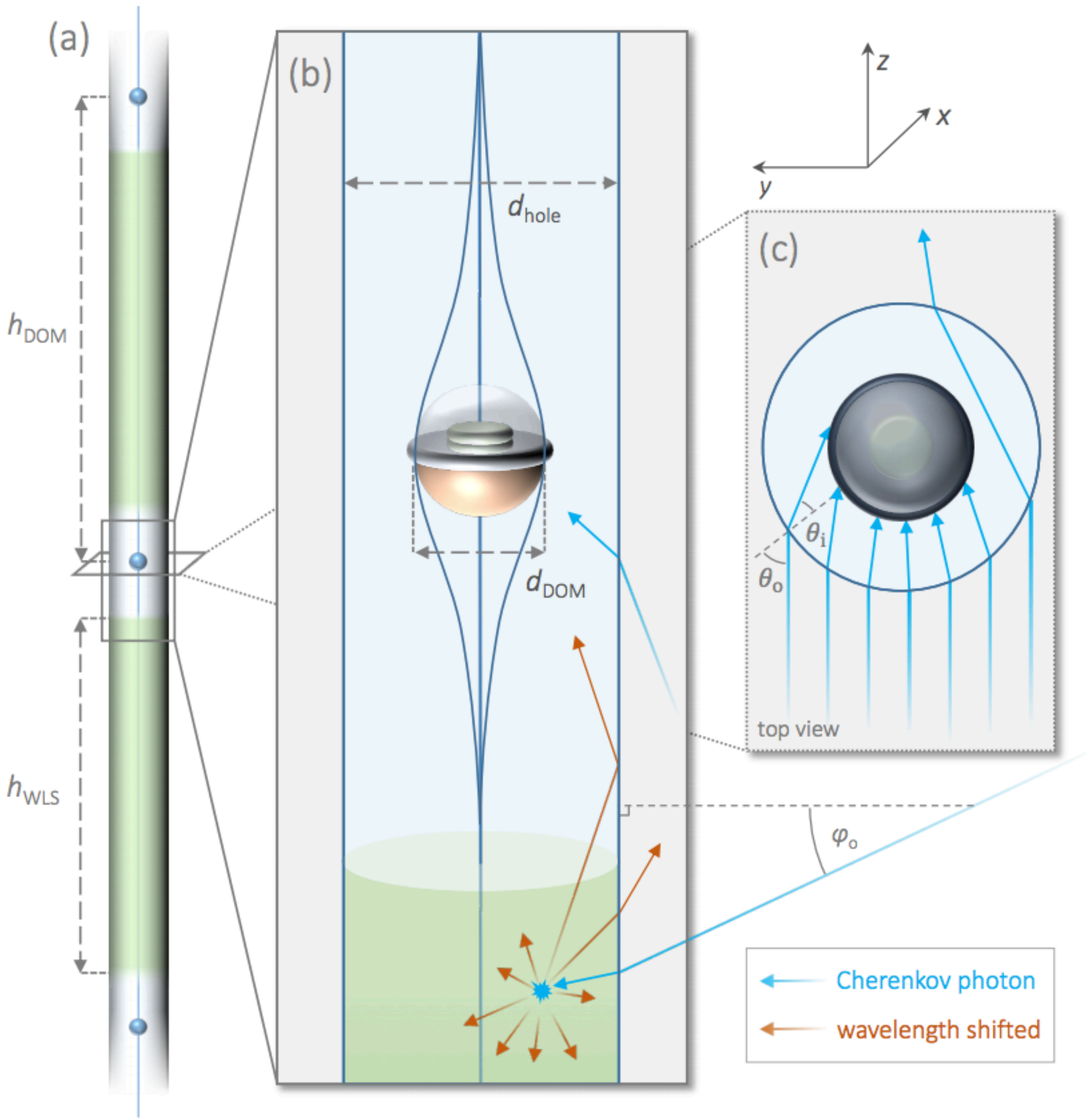
- Use ratio of 5-fold coincidences over ≥6-fold coincidences with χ^2 method, Δt = 20 ns.
- Energy resolution is ~5%, compared to ~30% in IC-86.

Cris Lozano, Neutrino 2018



Infused Ice?

Imre Bartos et al., Nature Comm. 9:1236, 2018



- IceCube Gen-2: infuse hole ice with WLS?
- Potential realization of >2x improvement in IceCube photon detection.
- Evaluating whether or not this can improve SN sensitivity.
- Gut feeling: filtering out background hits will provide the most gain.

Summary

- IceCube has largest eff. volume for SN neutrinos of any current detector.
- For a CCSN, will provide high-statistics measurements of $\bar{\nu}_e$ light curve.
  - With coincident hits in single DOMs, sensitivity to spectral shape.
  - If sharp cutoffs in flux (BH formation), some sensitivity to direction.
  - ~80% detection probability of SN in LMC and SMC.
  - Potential detection of burst of TeV neutrinos 1-10 days after core collapse.
- Improvements to analysis reduce effect of cosmic rays, model dependence of online trigger (BB), time binning limitations (HitSpooling).
- IceCube Gen-2: hardware solutions being investigated which may substantially improve background reduction and photon detection efficiency.
- Potential for extragalactic neutrino detection: see talk by Sebastian Böser.