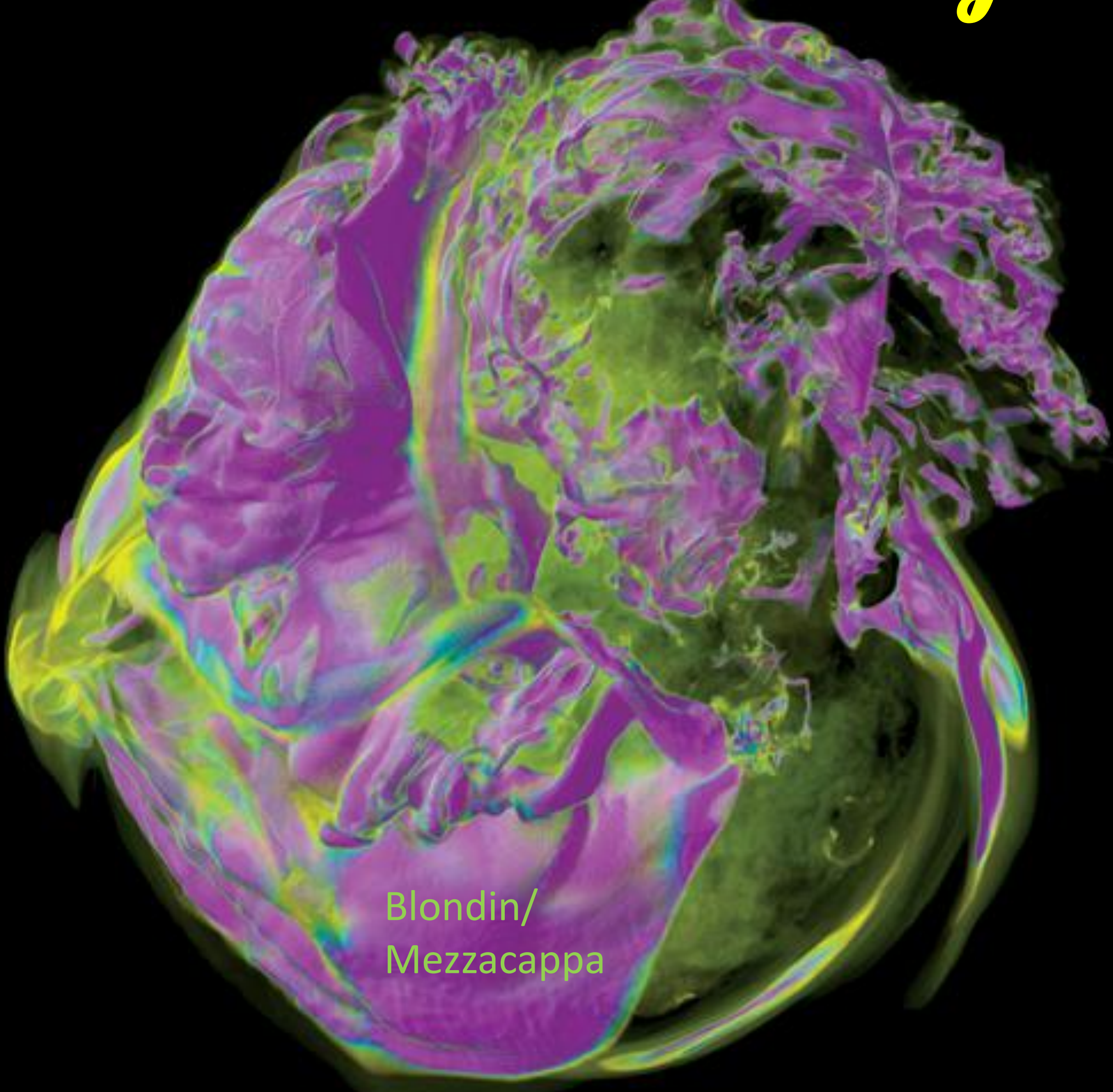
The next galactic supenova with the IceCube observatory



Lutz Köpke
Mainz 2017
Uppsala

One page supernova physics

- if star runs out of nuclear fuel, no radiative pressure to balance gravitational infall
- star fights desperately against collapse trying to relieve pressure
- bounce on hard core → outgoing shock wave → shock stalls eventually …

- neutrinos play important role:

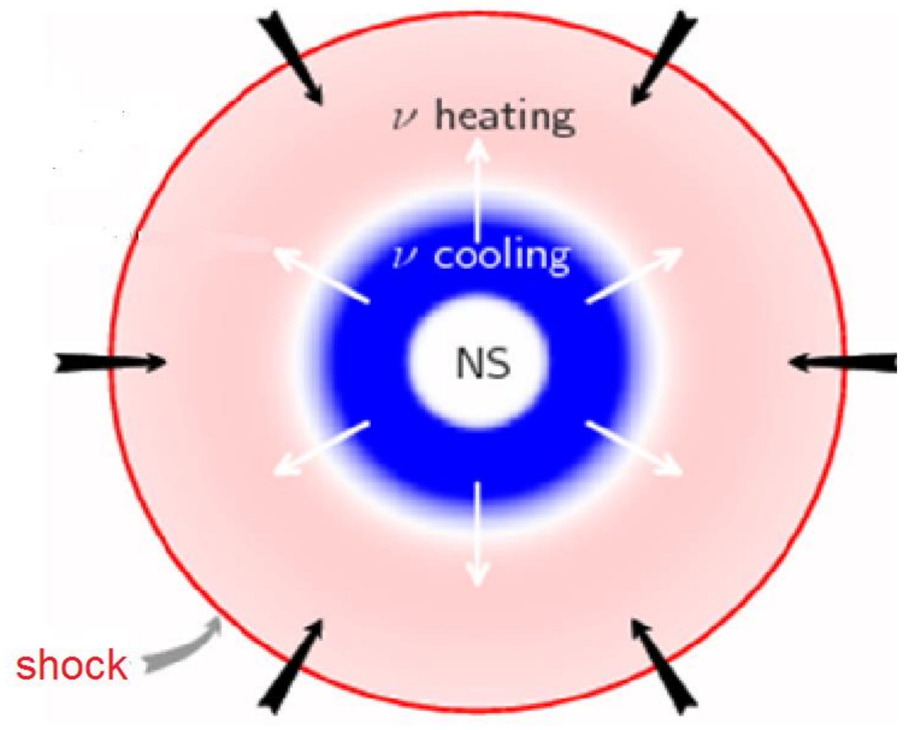
$$\nu_e + \mathrm{n} \underset{\rightarrow \text{heating}}{\overset{\leftarrow \text{cooling}}{\Leftrightarrow}} \mathrm{p} + \mathrm{e}^+$$

$$\bar{\nu}_e + p \underset{\rightarrow \text{heating}}{\overset{\leftarrow \text{cooling}}{\Leftrightarrow}} \mathrm{n} + \mathrm{e}^-$$

- about 2 supernovae / 100 y in our galaxy
  (45% probability in 30 years)
- energy release ($R_{core}=10^6$ m → $R_{NS}=10^4$ m)

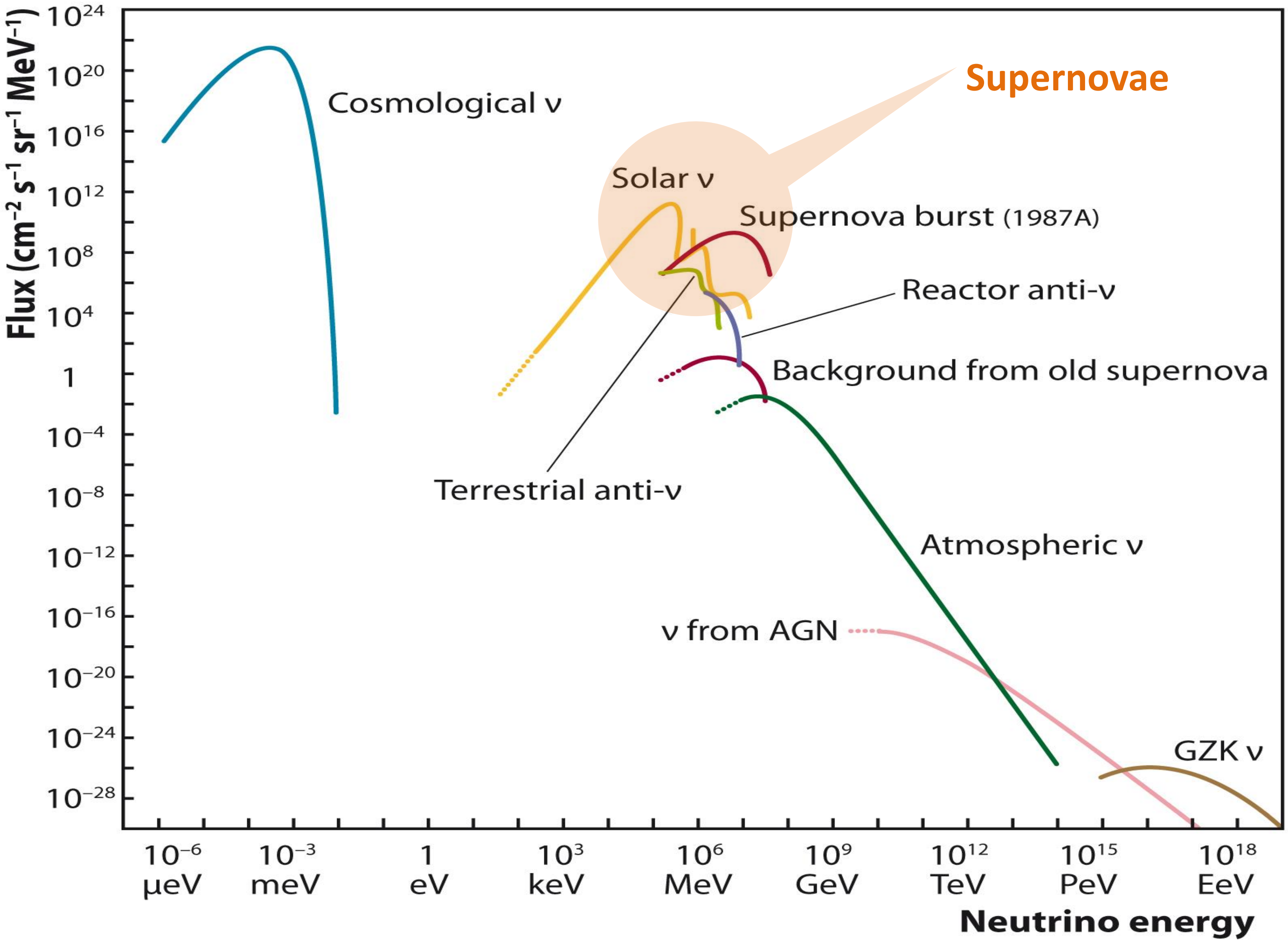
$$\Delta E = \frac{3}{5}\frac{GM_{NS}^2}{R_{NS}} - \frac{3}{5}\frac{GM_{NS}^2}{R_{core}} \approx 2 \cdot 10^{59}\,\mathrm{MeV}$$

$\Delta E_\nu \approx \Delta E$ (10^{58} ν's, <E> ~ 15 MeV)
$\Delta E_{kin} \approx 10^{-2}\,\Delta E$
$\Delta E_{em} \approx 10^{-4}\,\Delta E$

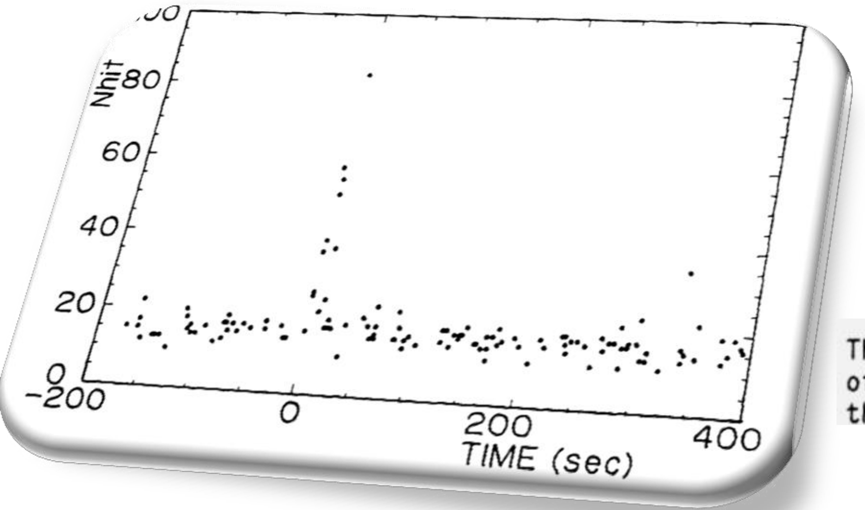


How does shock get revived?

Neutrinos in the sky



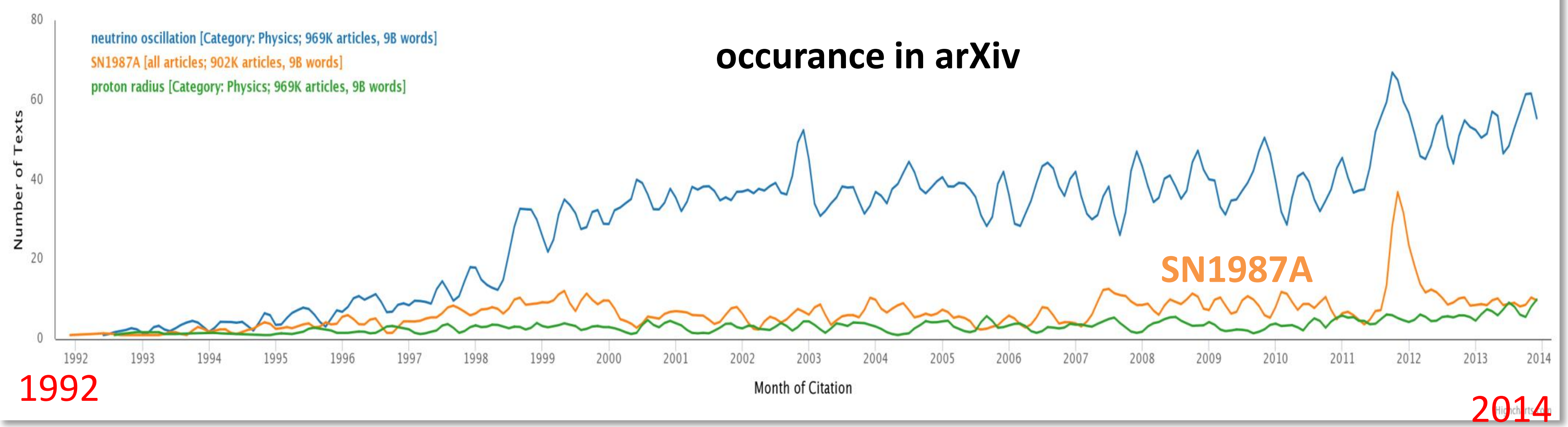
Supernova 1987A



One of those lucky moments in physics …

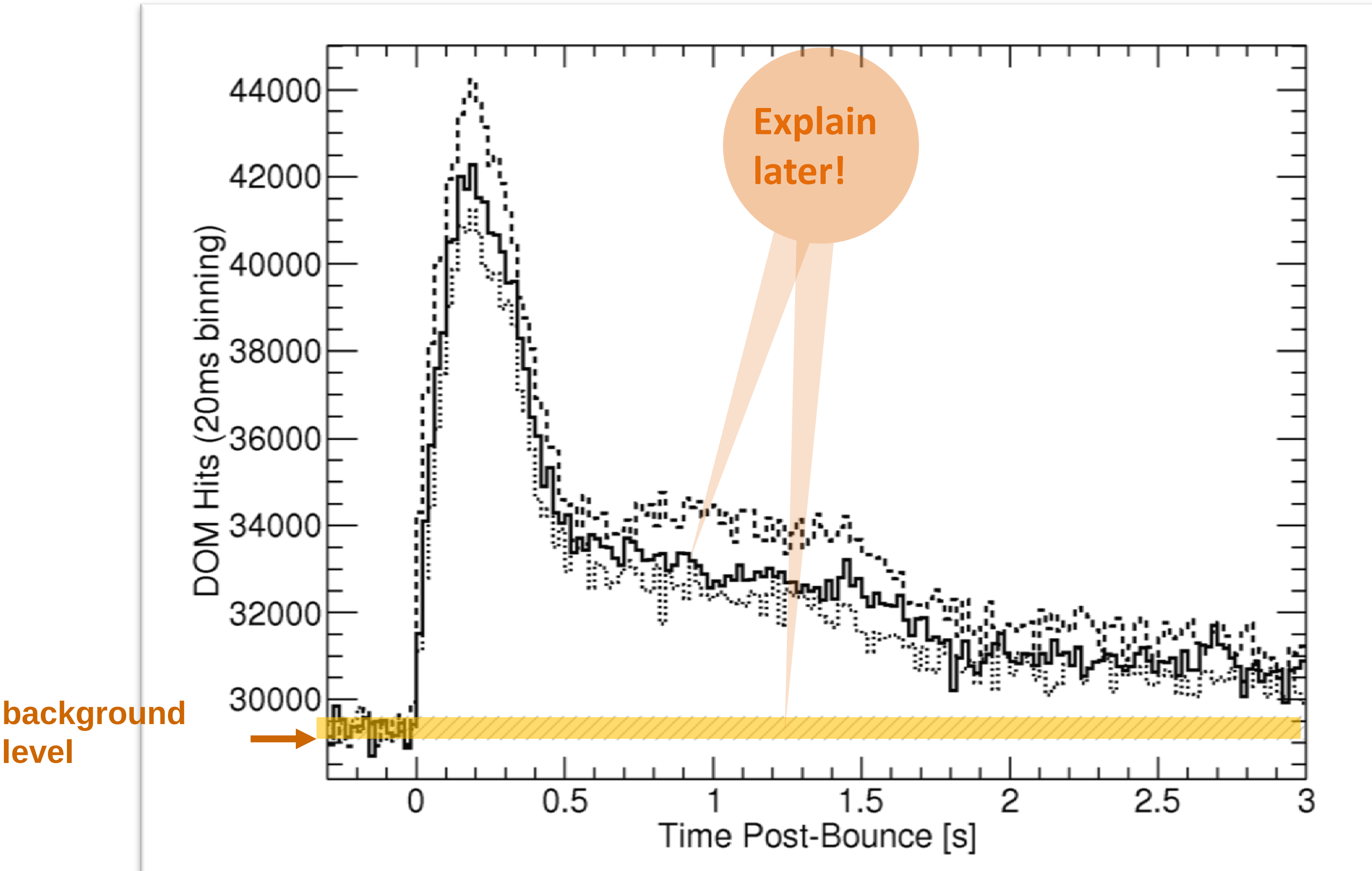
The supernova signal of the KAMIOKANDE-II experiment. It is a part of the laser printer output of the low energy raw data.Nhit is the number of hit photomultipliers.

Only two dozen neutrinos detected in 1987: still publications appearing!



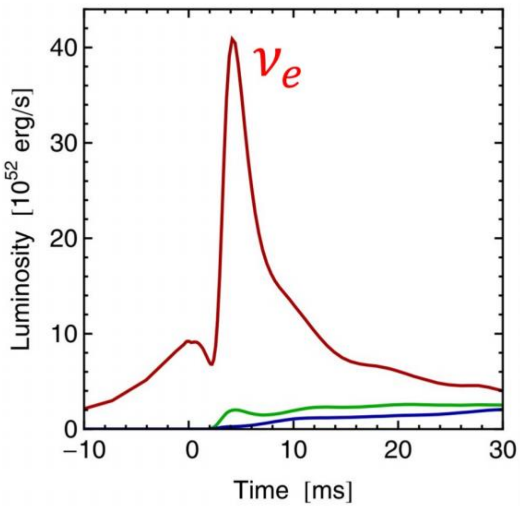
Preview IceCube

700,000 registered photons for SN at galactic center!



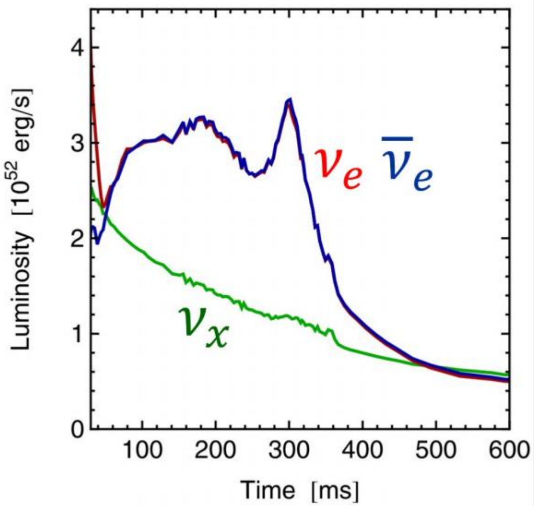
Three phases …

Prompt ν_e burst



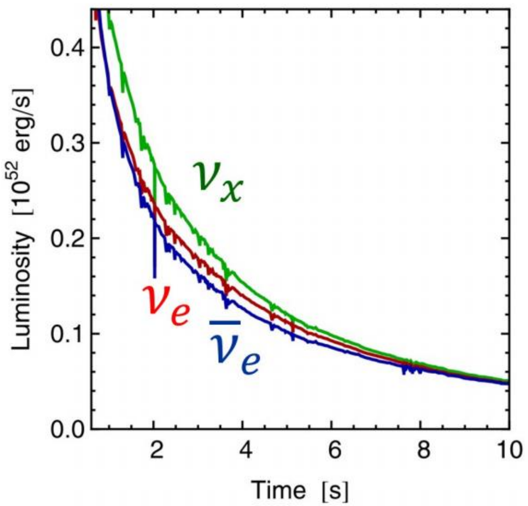
Shock breakout - outer core de-leptonization

Accretion



Shock stalls at ~ 150 km
Infalling matter powers ν's

Cooling

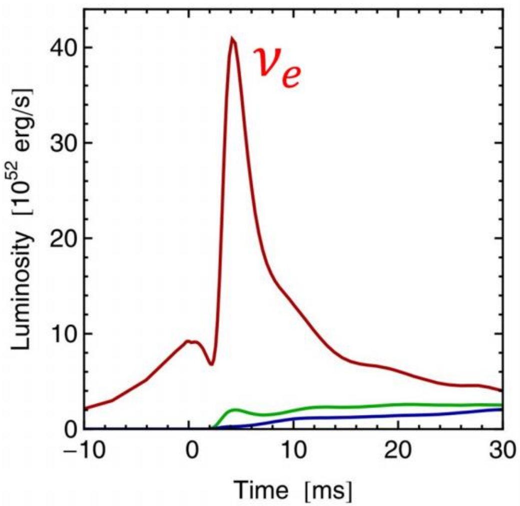


Cooling ∝ ν diffusion time scale

Spherically symmetric 10.8 $M_\odot$ model, explosion triggered by enhanced CC cross section
Fischer et al. A&A 517:A80, 2010

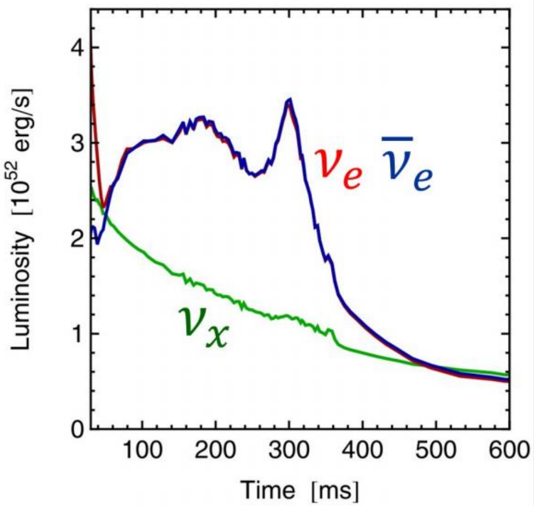
..three phases

Prompt ν_e burst



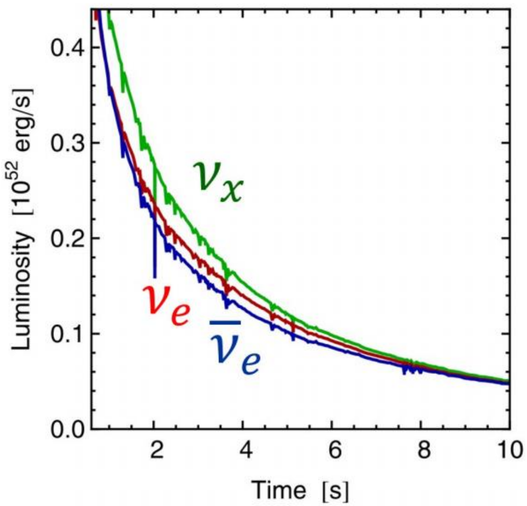
ν_e signal independent on SN mass and equation of state (EOS)

Accretion



Strongly varying signal (mass, 3D, EOS)

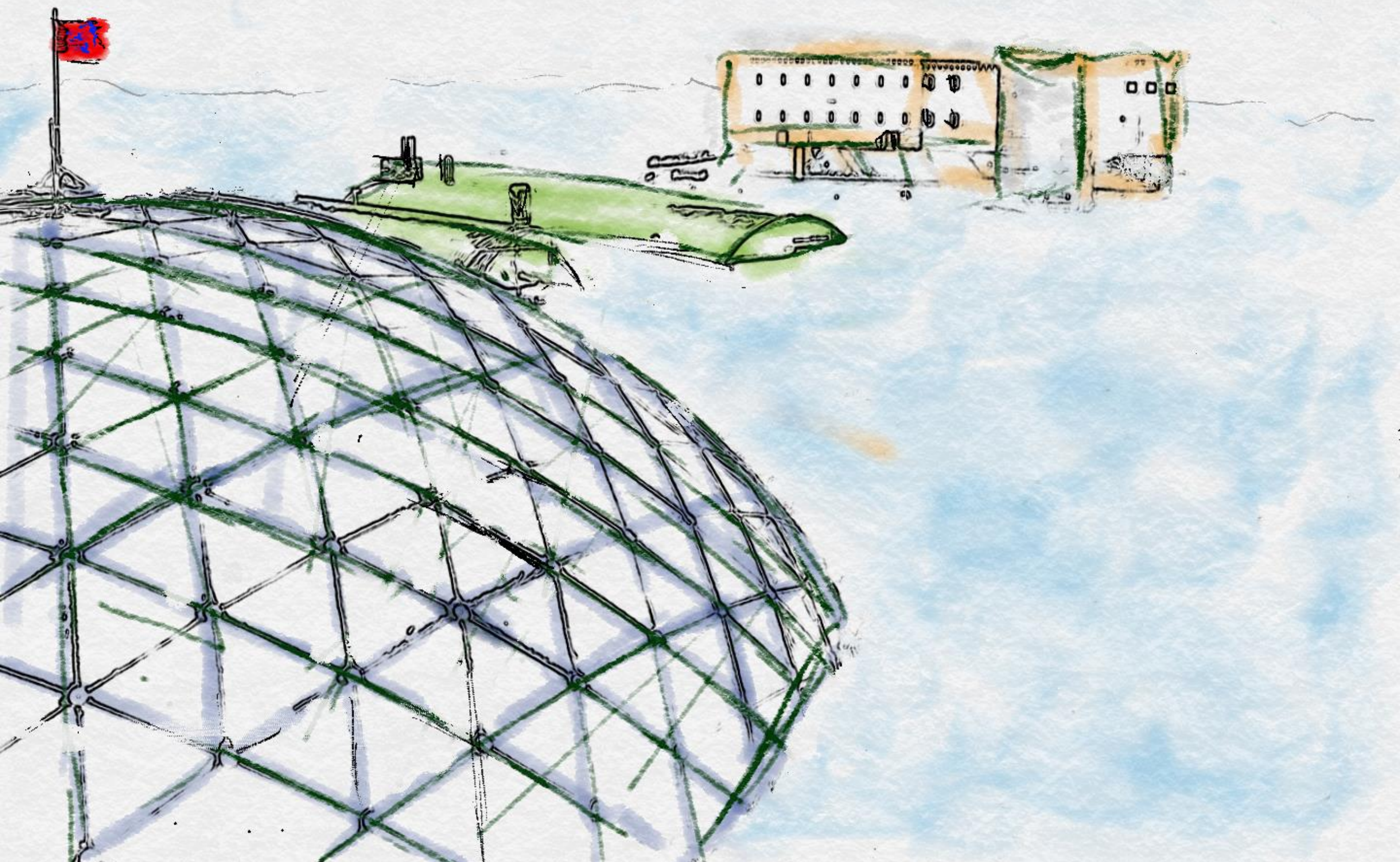
Cooling



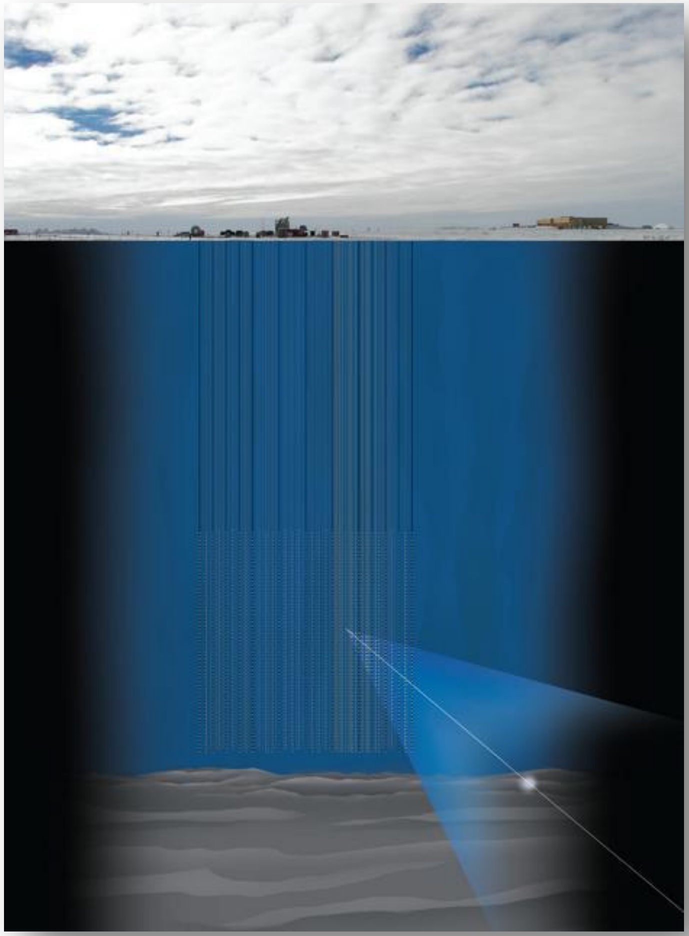
Mass and EOS dependence

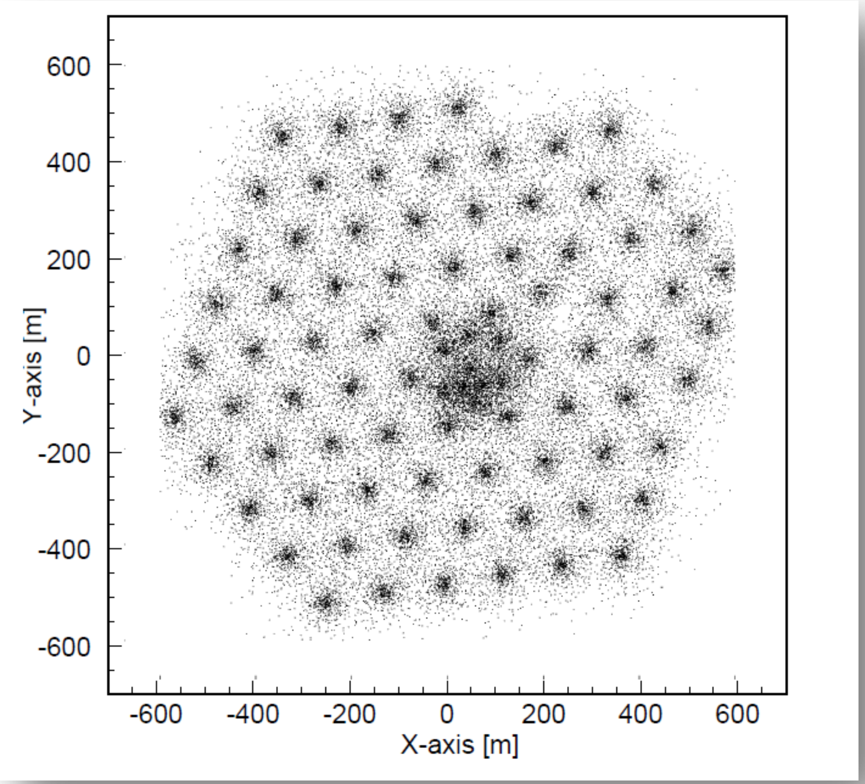
Spherically symmetric 10.8 $M_\odot$ model, explosion triggered by enhanced CC cross section
Fischer et al. A&A 517:A80, 2010

Supernovae at South Pole



SN neurtrinos in IceCube





Interaction vertices all hits
~600 m^3 effective volume/sensor

For O(10 MeV) ν's, IceCube counts single photons on top of dark rate background

One page supernova ν detection

dominant reaction: $\bar{\nu}_e + p \rightarrow e^+ + n$

cross section: $\propto E^2_\nu$ (count events)

Cherenkov γ's: $\propto$ $\mathbf{E^3}_\nu$ (count γ's)

cold and inert ice: dark rate ~ 500 Hz

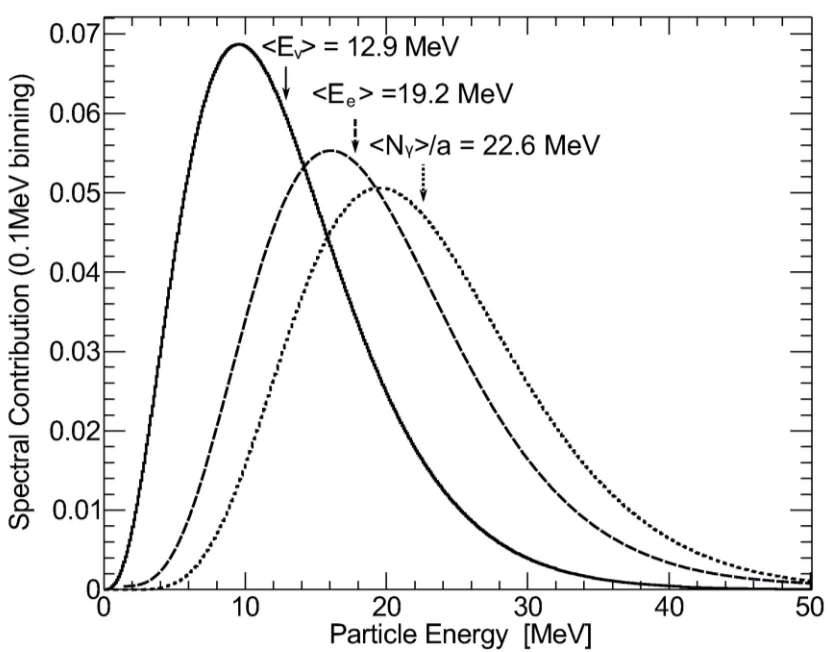
look for excess signal in 5160 sensors

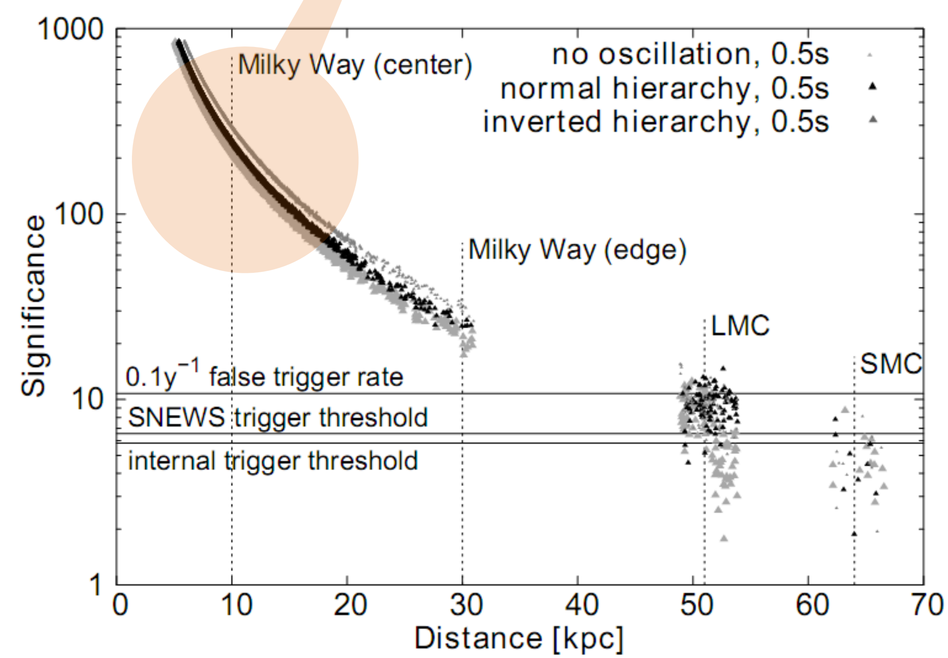
calculate significance:

e^+ track length ~ 0.56 cm x E_{e+} (MeV)

$N_\gamma^{300\text{-}600nm}$ ~ 180 x E_{e+} (MeV)

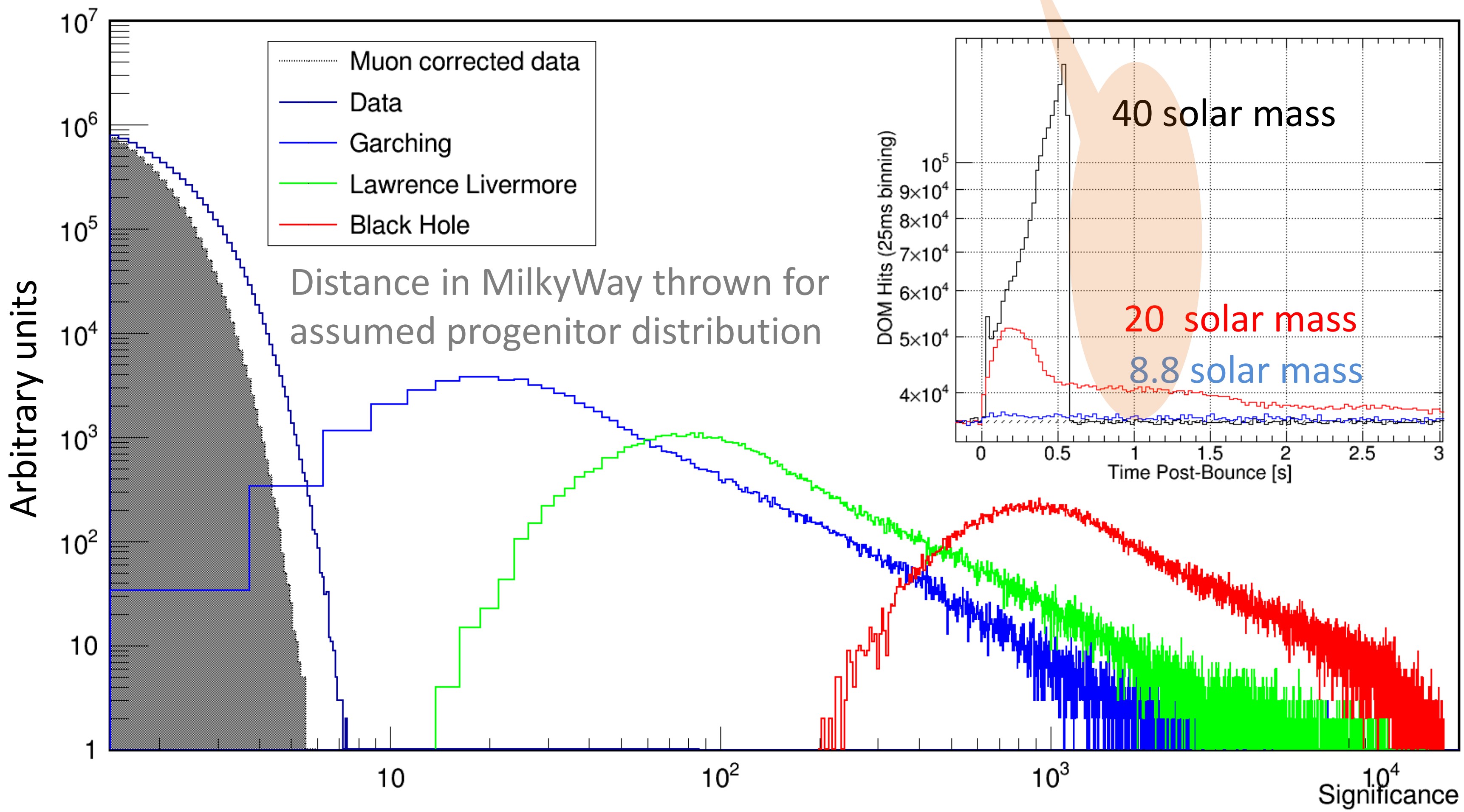
world's highest statistical accuracy …





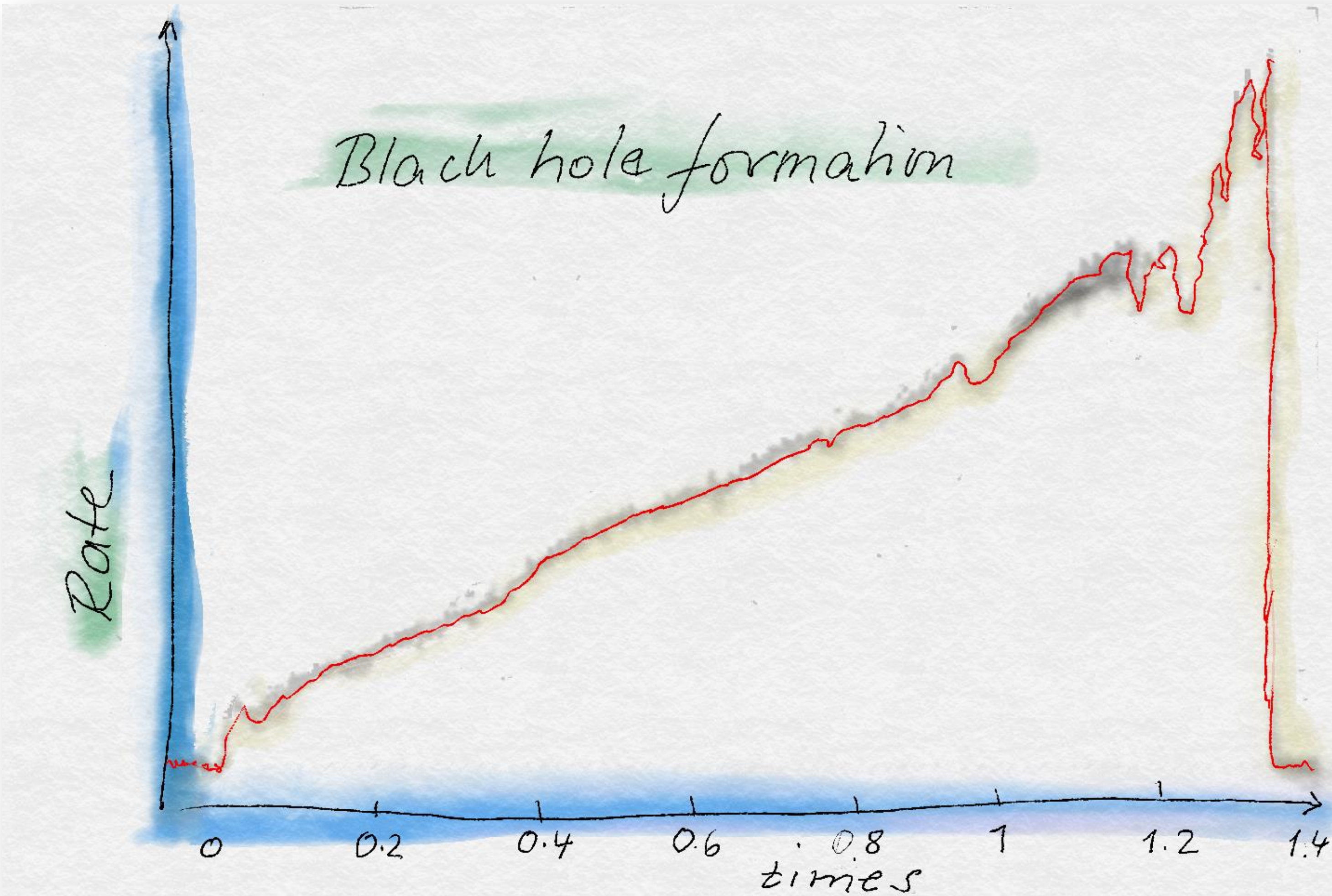
SN detection capability

Large variation between models (progenítor mass, neutrino energies)



- Only for lightest **progenitor** some overlap with dark noise
- Cosmic muon corrected data helpful for SN outside of central galaxy and trigger stability

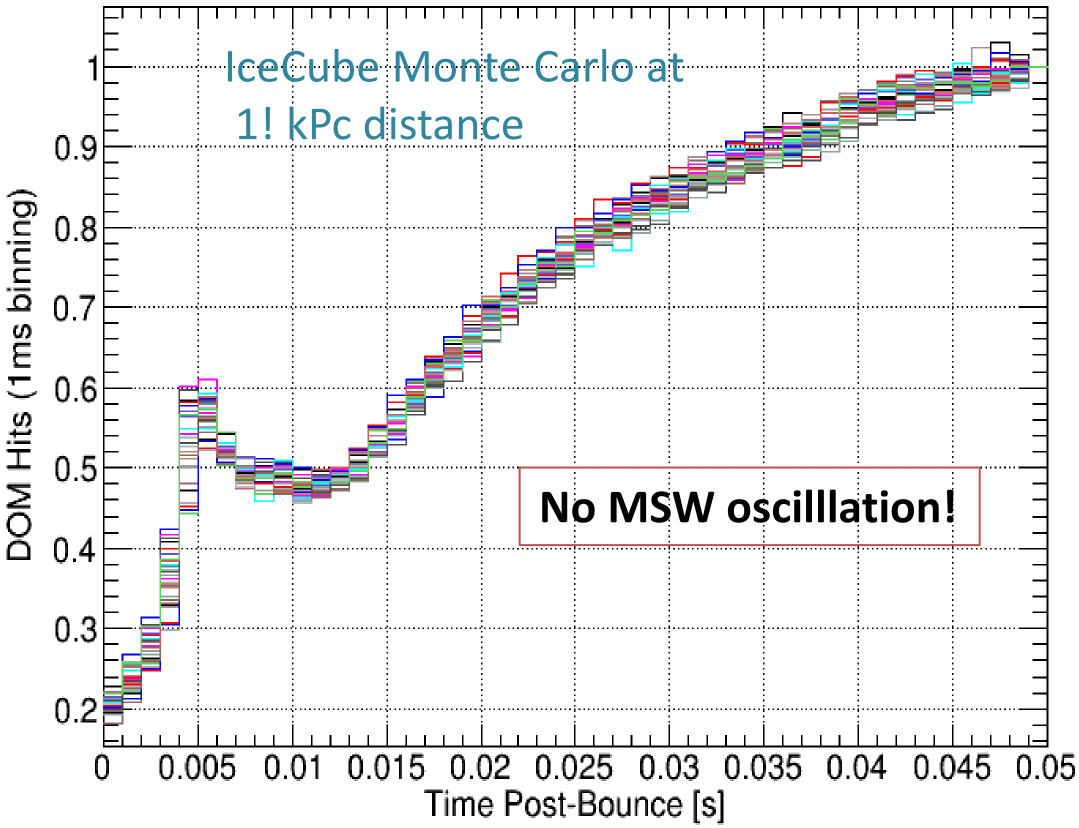
Neutrino lightcurve

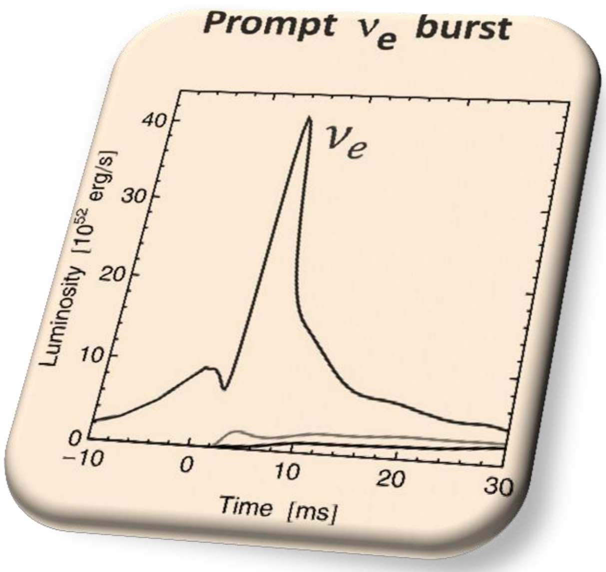


Supernova breakout burst

E.O'Conner, Ott , ApJ 762, 126 (2013) Latimer-Swesty EOS: **32** 1D models with progenitor masses between 12-120 $M_\odot$

preshock neutronization of the core $e^- + p \rightarrow n + \nu_e$ gives progenitor independent peak





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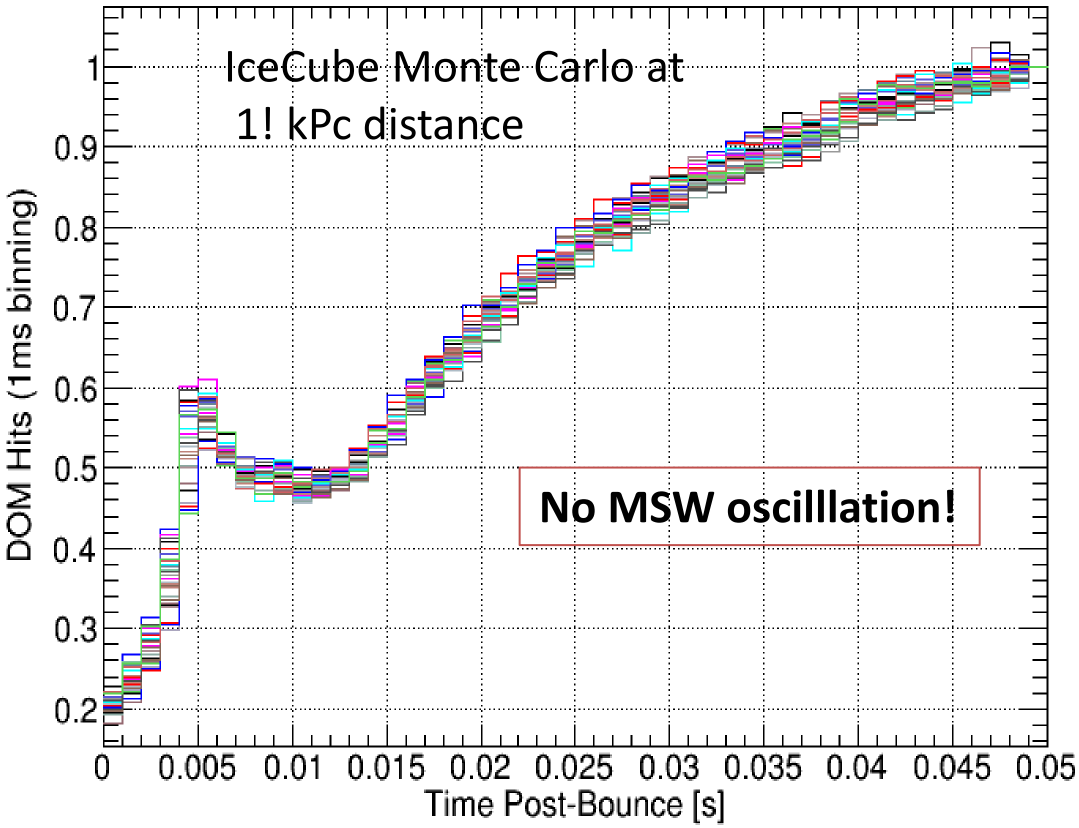


Unfortunately, water has small cross section for ν_e

Other media are better for ν_e:

@20 MeV:

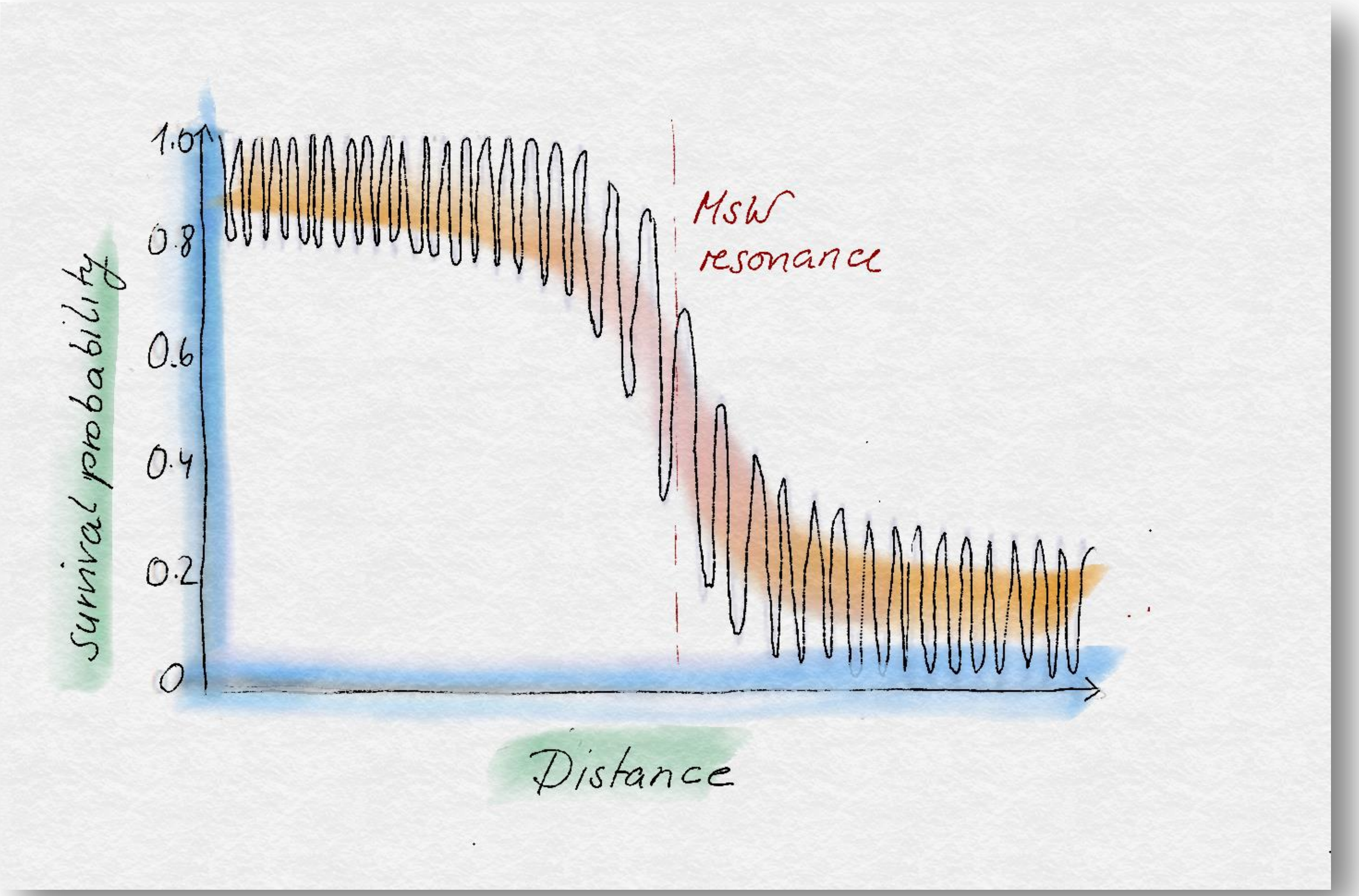
$\sigma(\nu_e + {}^{40}Ar) \sim 200 \times \sigma(\nu_e + e^-)$

$\sim 80 \times \sigma(\nu_e + C)$

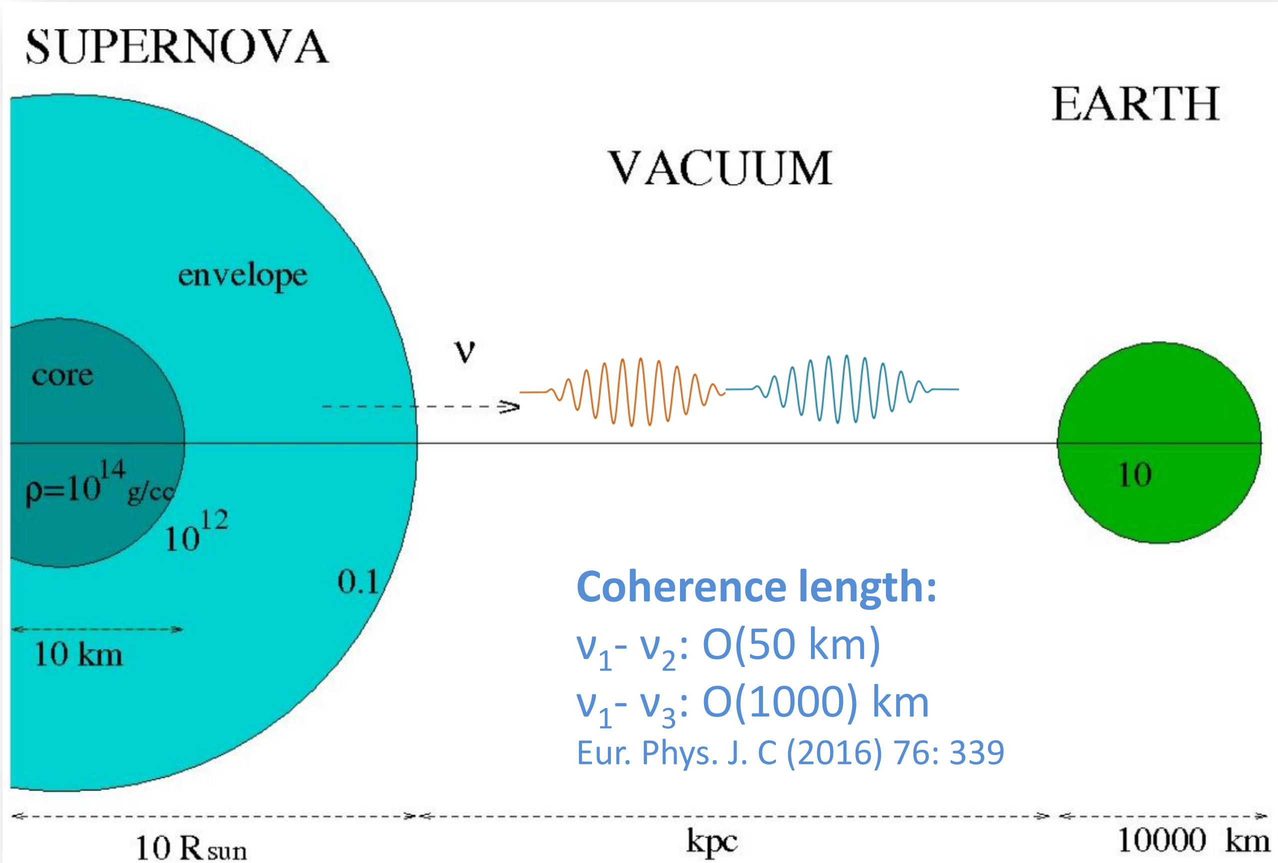
$\sim 2 \times \sigma(\overline{\nu}_e + p)$

however, physics is not very kind to us …

Oscillations



A word o neutrino oscillations



Coherence length:

$\nu_1 - \nu_2$: O(50 km)

$\nu_1 - \nu_3$: O(1000) km

Eur. Phys. J. C (2016) 76: 339

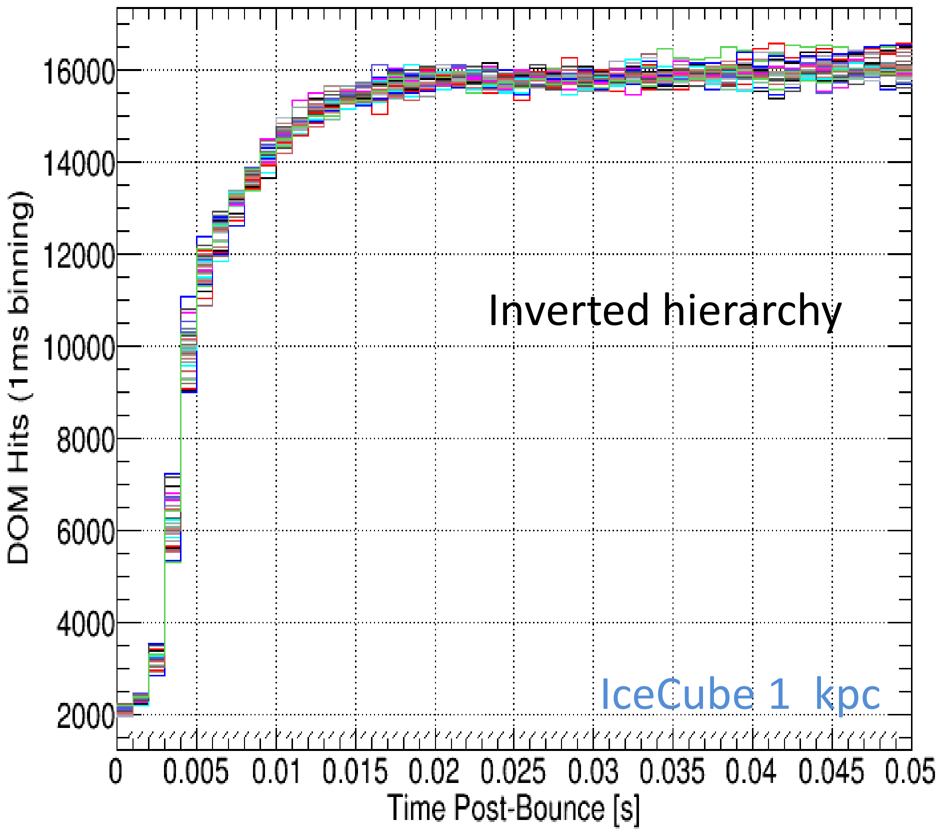
Inside SN:
„νν“ interactions &
MSW matter effect

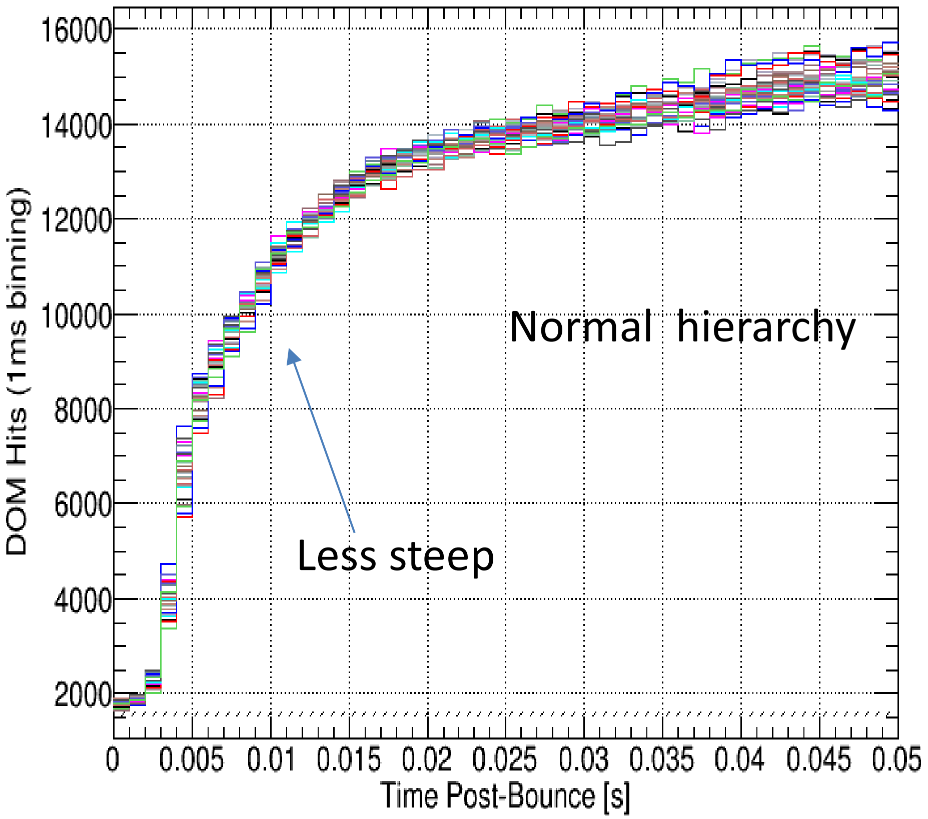
Between SN and Earth:
no flavor conversion
ν_i travel independently

In Earth:
MSW matter
effects

Supernova breakout burst

unfortunately, deleptonization peak disappears, when MSW oscillations are taken into account



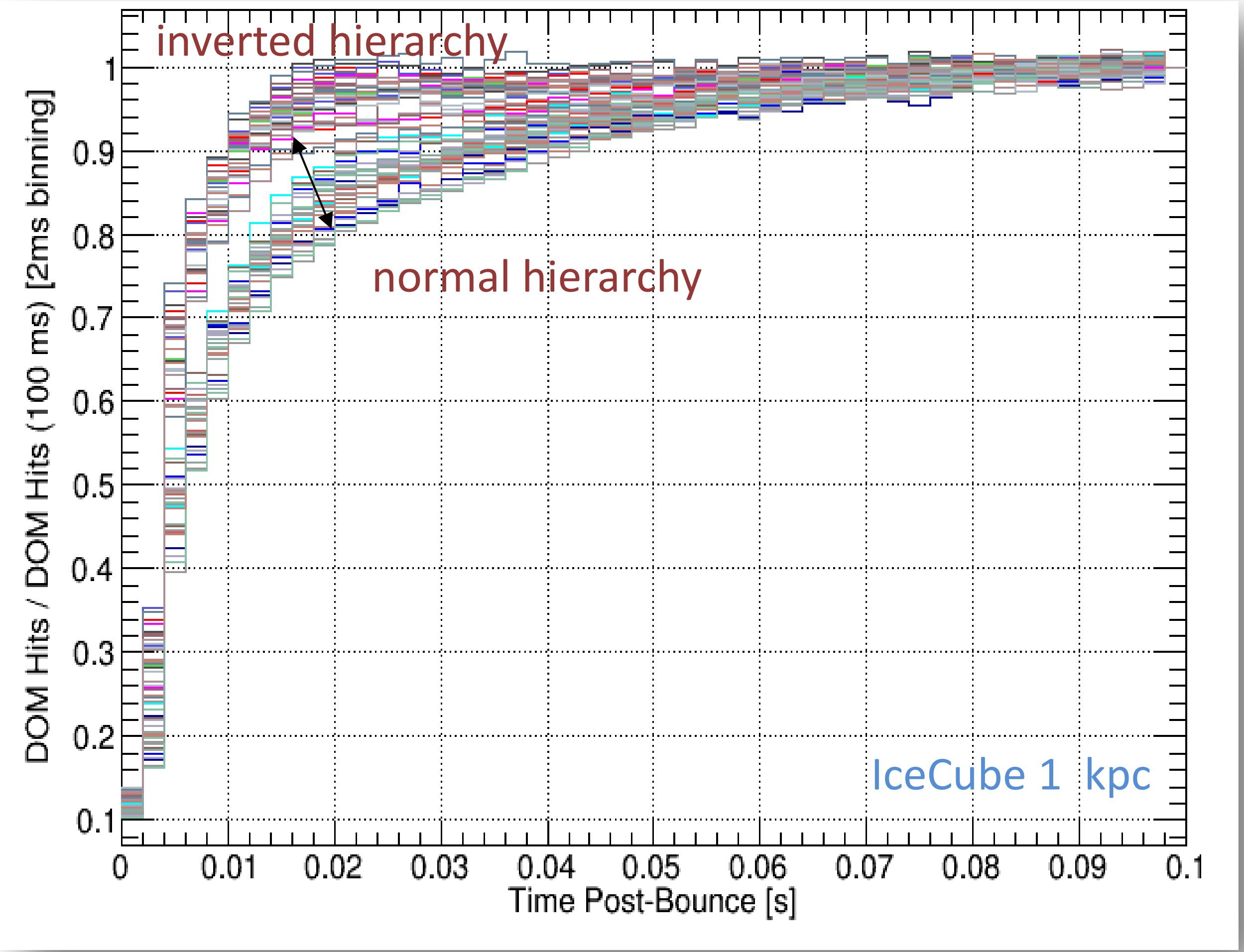


Ideal: detector sensitive to ν_e , e.g. Argon (DUNE)
1608.07853

Positive news:
rising edge progenitor insensitive!

Rising edge is robust!

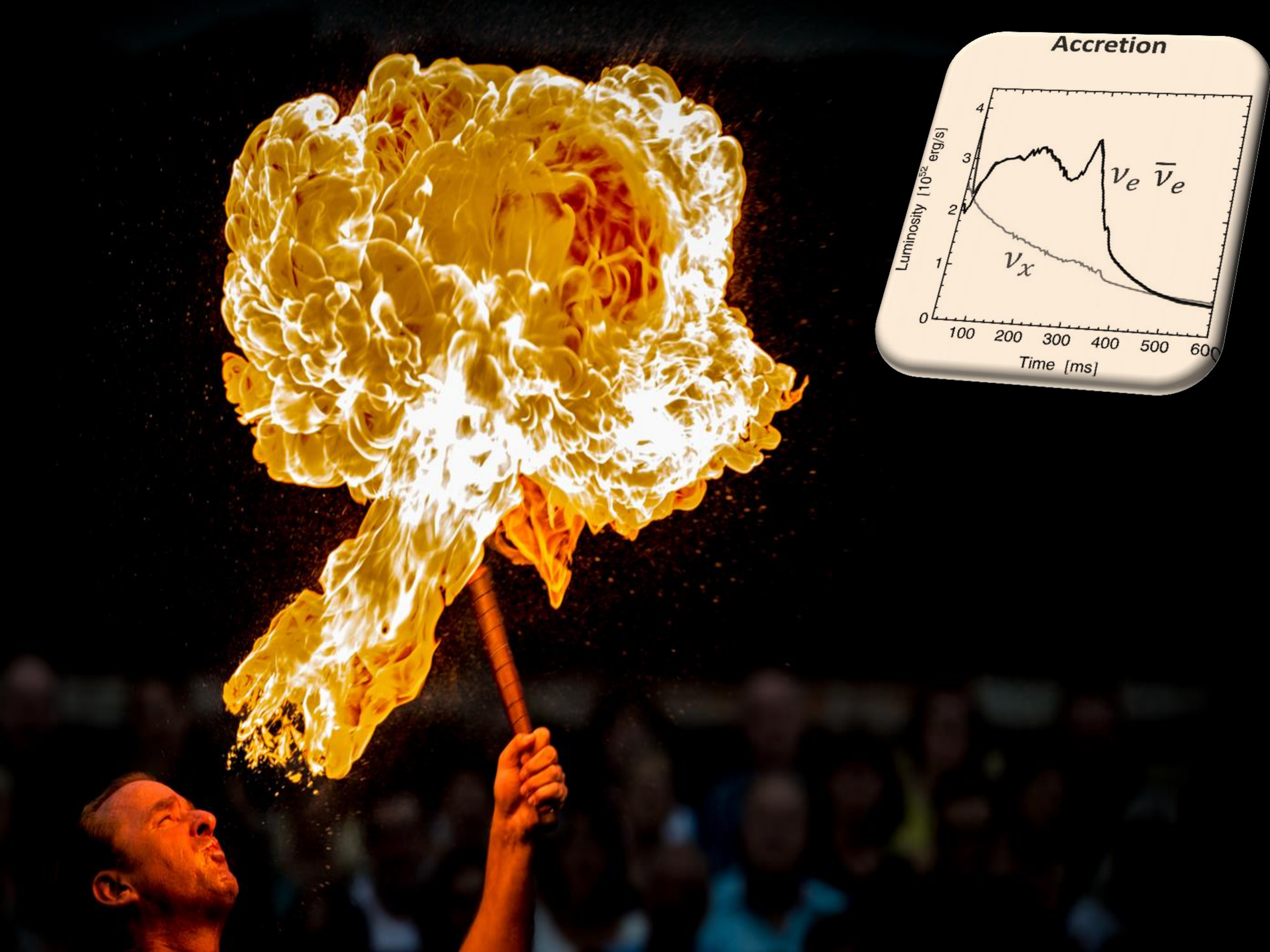
Clear shape difference between hierarchies with little progenitor mass dependence



Many papers on „robust“ methods to determine mass ordering:

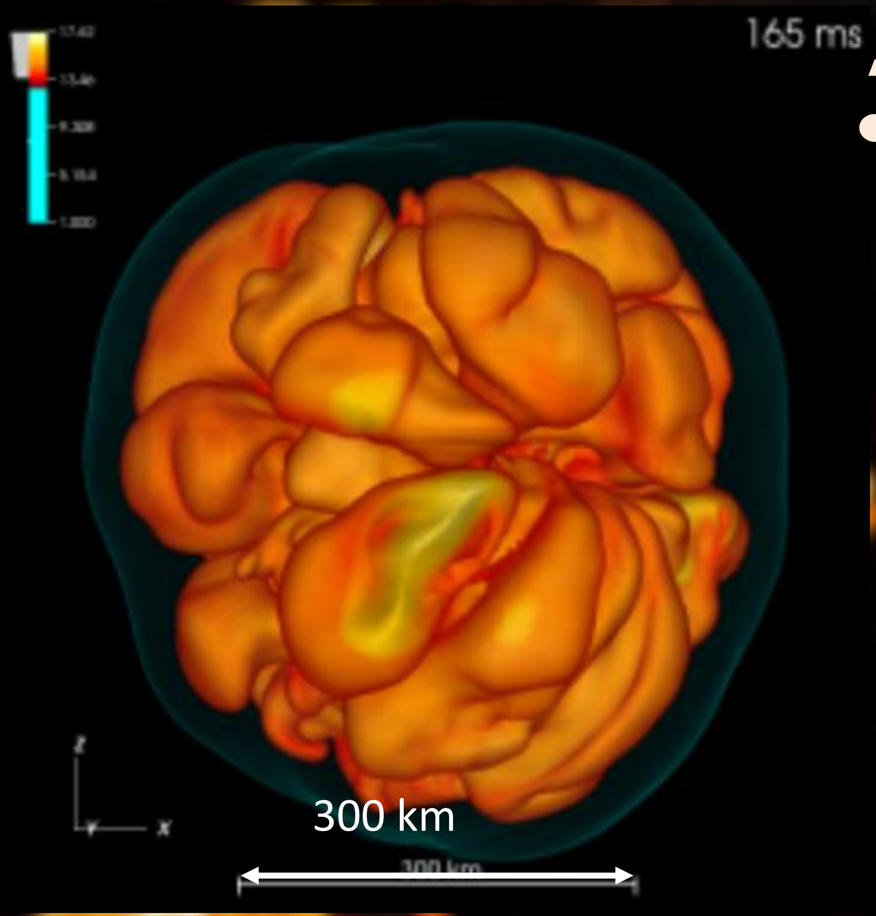
arXiv:1603.0692, 1509.07342, 1406.2584, 1312.4262, 1111.4483 …

Inverted hierarchy: faster rise!

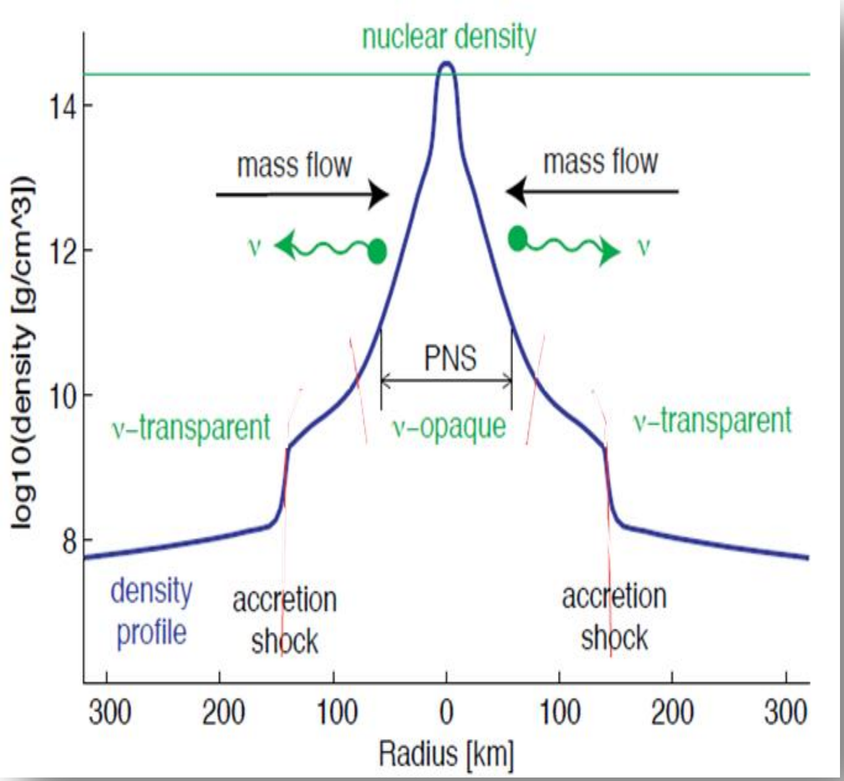


Accretion
Luminosity [10^52 erg/s]
0
1
2
3
4
100
200
300
400
500
600
Time [ms]
νe ν̄e
νx

3D Effects



Radial density @ 100 ms



Liebendörfer et al.

Infall terminates by accretion shock

→ *~ 150 km, almost stationary*

Large density contrast: PNS and hot mantle

How can material between PNS and accretion shock expand again rapidly?

Prevailing Theory: ν driven delayed supernova …

1D: Not sufficient to drive symmetric explosion …

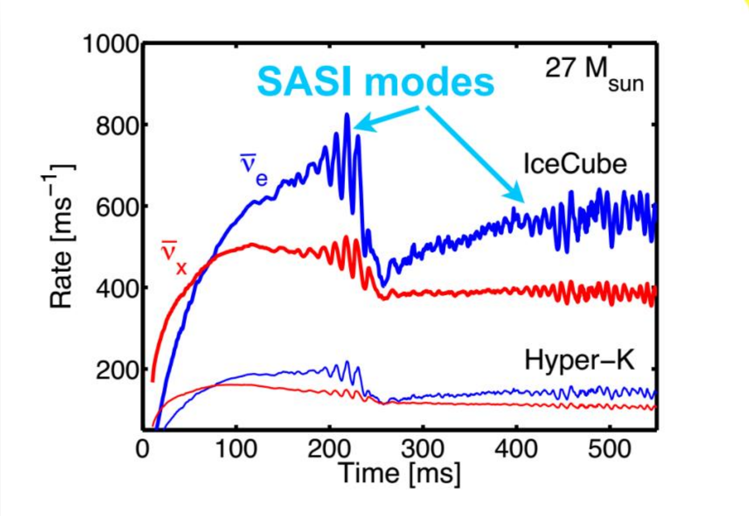
2D: explosion only for low-mass stars …

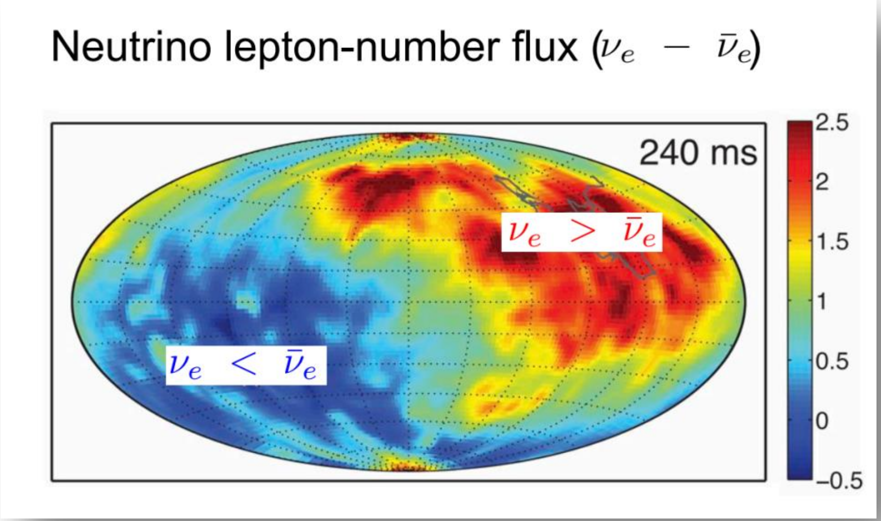
3D: Convective bubble: explosion is small surface instability effect ….

2016: explosion still not fully understood!

Interesting effects in 3D (convection, SASI, LESA), details important …
Garching, Oak-Ridge: rigorous neutrino transport and microphysics

2 interesting 3D effects ...





Irene Tamborra, Neutrino 2016

„standing accretion shock instability“ **(SASI)** leaves imprint on neutrino and gravitational wave signals

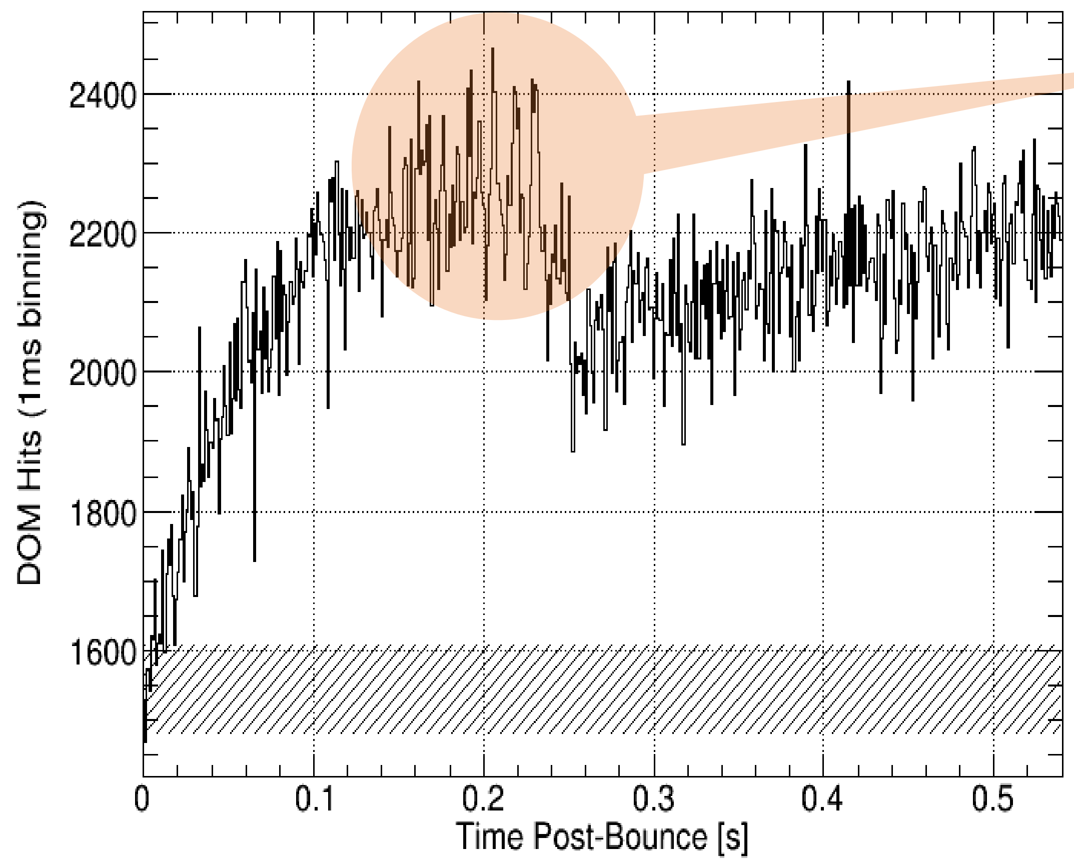
Lepton-number emission asymmetry **(LESA)** has implications for oscillations, nucleosynthesis and neutron star kicks

well, this is a theoretician‘s view ...

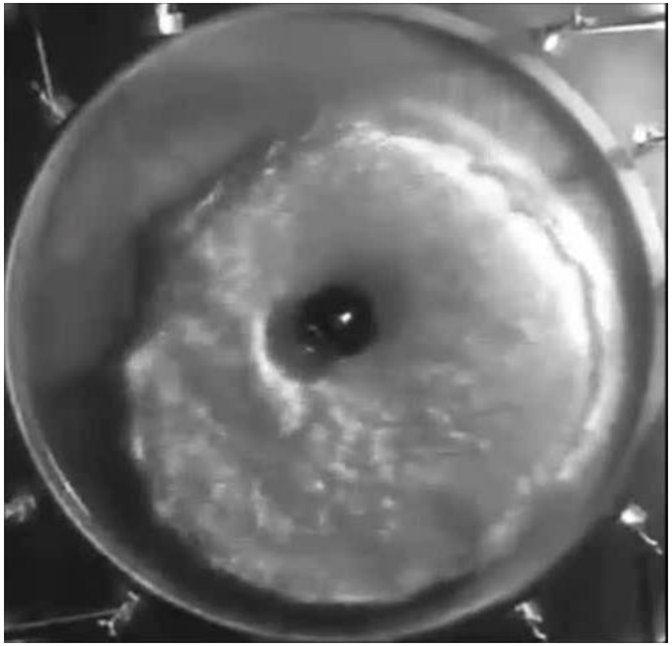
Standing accretion shocks

Tamborra et al, Phys. Rev. D.90, 045032 (2014), 27 solar mass → looking at „LESA“ direction

IceCube 10 kpc

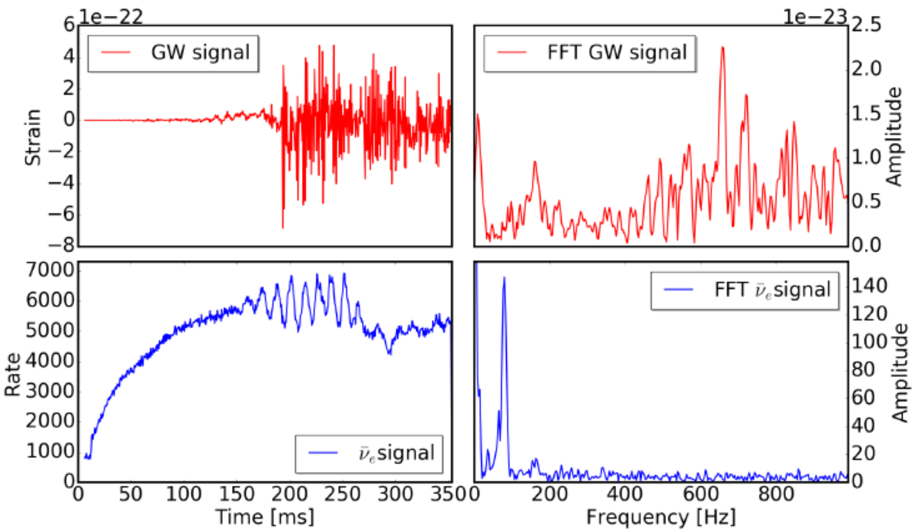


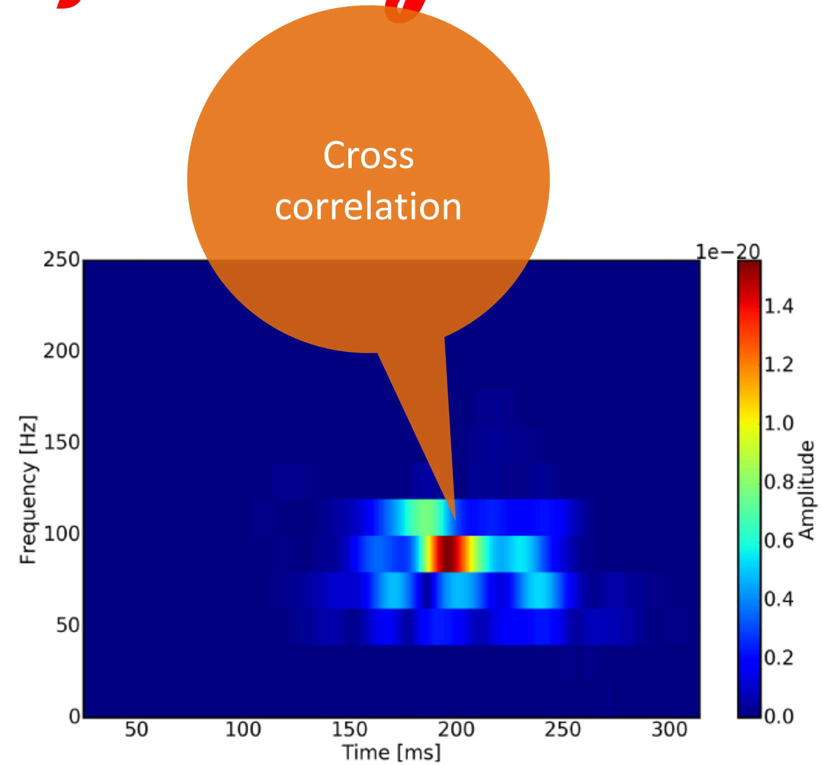
Neutrino imprint of accretion shocks



Compare with GW signal?

Time domain **frequency domain**





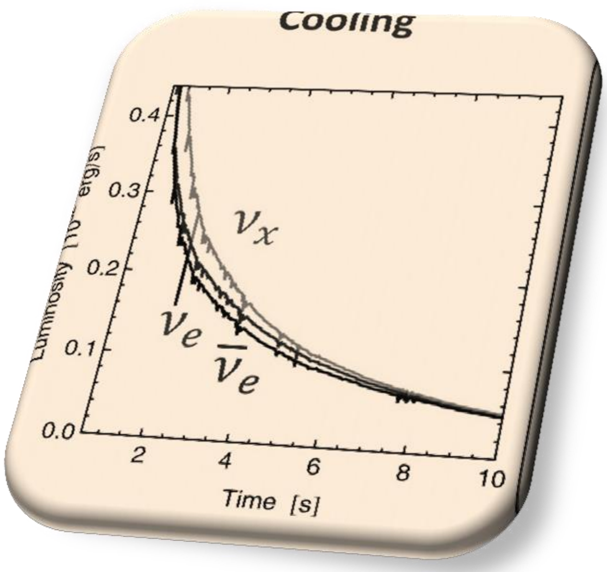
- See SASI signal at twice the frequency in gravitational waves (GW)
- Supernova signatures in GW weak and model dependent (quadrupole mass deformations)

Cooling Phase

PhysRevLett.104.251101, A&A 517, A80 (2010)

$$L_\nu \approx 0.74\times10^{35}\cdot\phi\cdot\langle\varepsilon_\nu\rangle^4 \frac{R^2}{1-2\frac{G\cdot M}{Rc^2}}\left[\frac{\text{erg}}{\text{cm}^2\text{s}}\right]$$

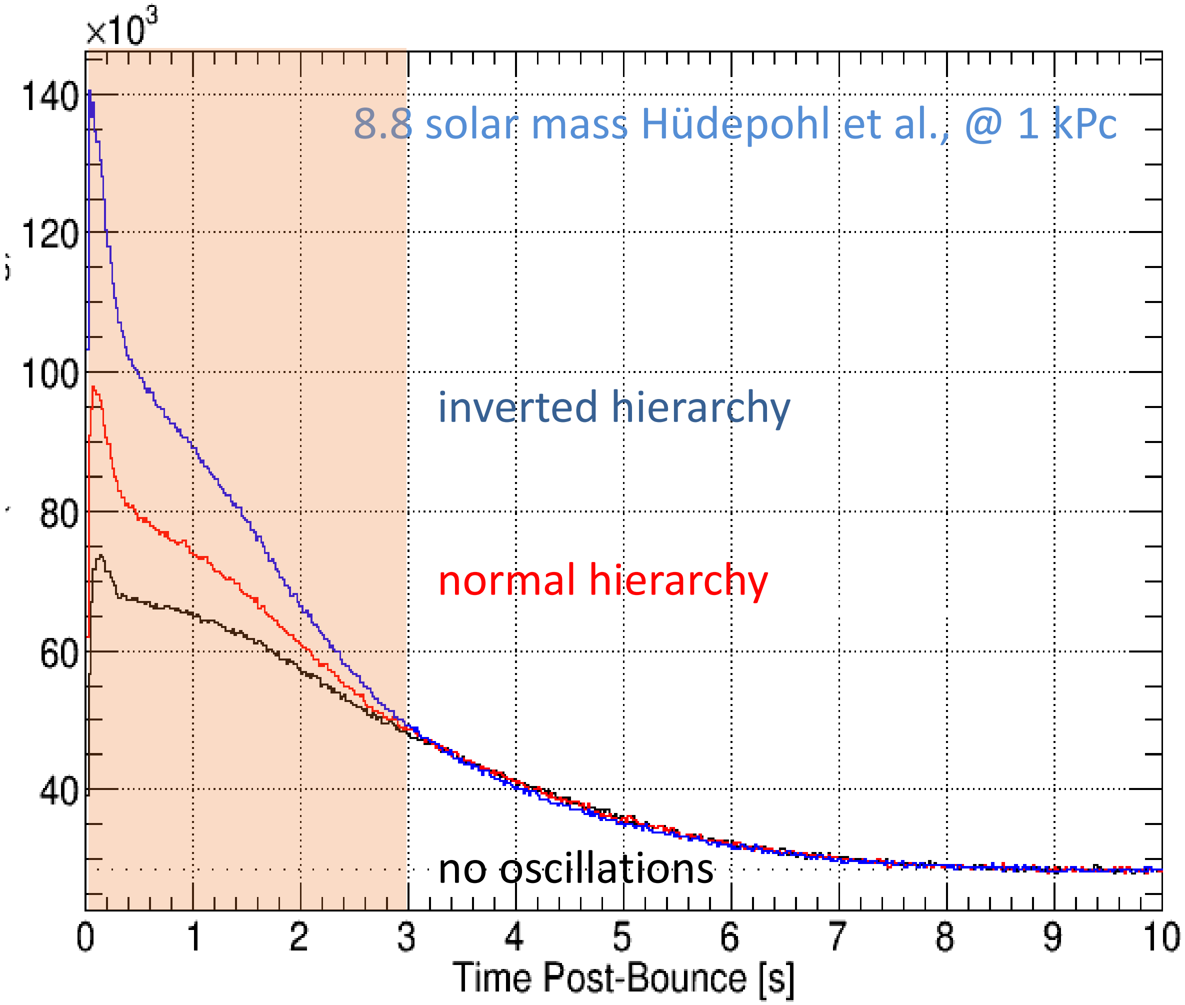
$$E_\nu^{total} \approx \frac{0.6\frac{GM^2}{R}}{1-\frac{GM}{2Rc^2}} \qquad \text{R : PNS radius @}10^{11}\ \text{g/cm}^3$$



- Almost perfect luminosity equipartition
- Little EOS dependence
- Cooling strongly affected by particles that may evaporate !

In principle can calculate R and M(PNS) from ν light curve

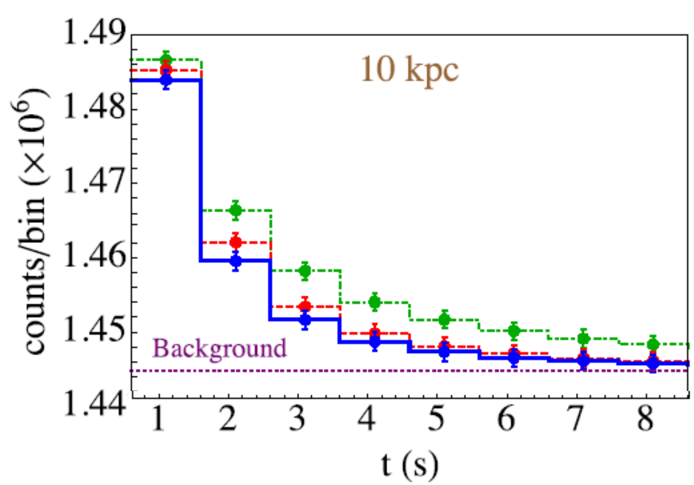
…Cooling phase



For t> 3 s: ν_e , ν_e-bar , ν_x fluxes and energy spectra very similar

Effect of axions:

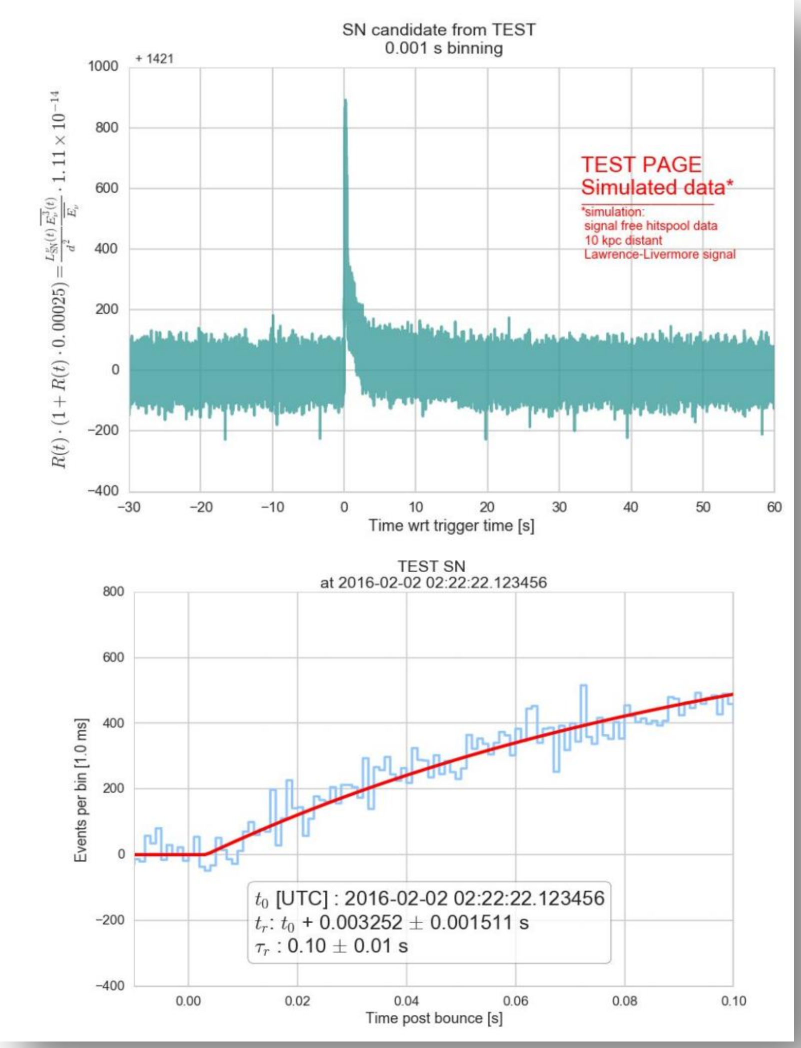
Fischer et al. Phys. Rev. D 94, 085012 (2016) →IceCube 10 kpc



But: Horowitz et al. „Nuclear Pasta?" https://arxiv.org/pdf/1611.10226.pdf
enhances flux due to rearranged tube (spagetti) or sheets (lasagne) at 10^{14} g/cm^2

Hitspooling

- retrieval of **all** buffered hits with O(10 ns) timing for adjustable time span
- (partly) automatic transfer and analysis

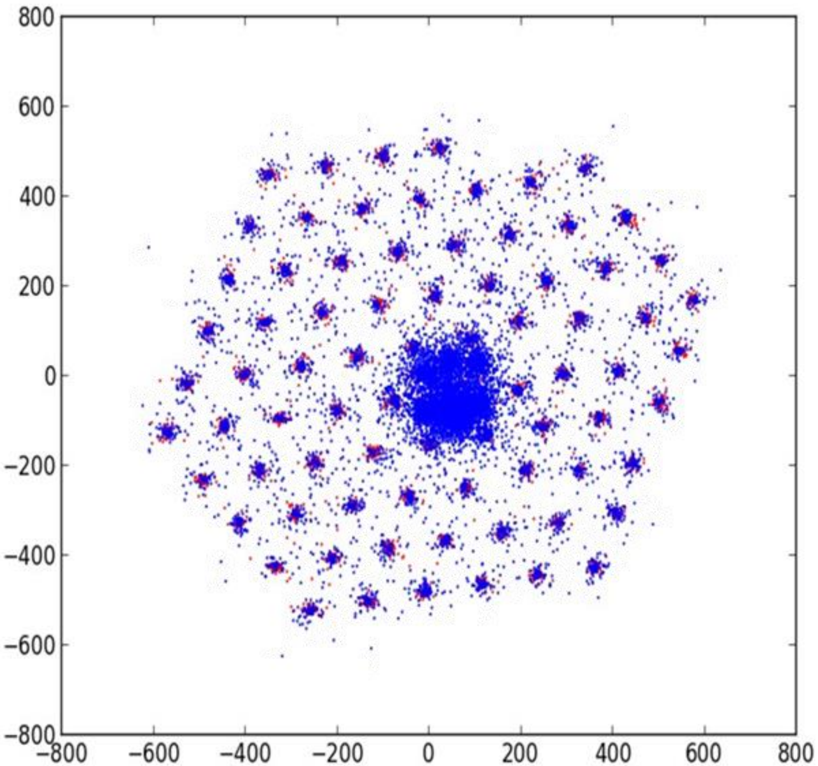


Advantage for SN search:

- Fine temporal structures
- Precision burst onset time
- Safety net for very close supernovae
  (e.g. Beteigeuze!), which may „kill DAQ“
- **Coincidences between moduls**
- etc.

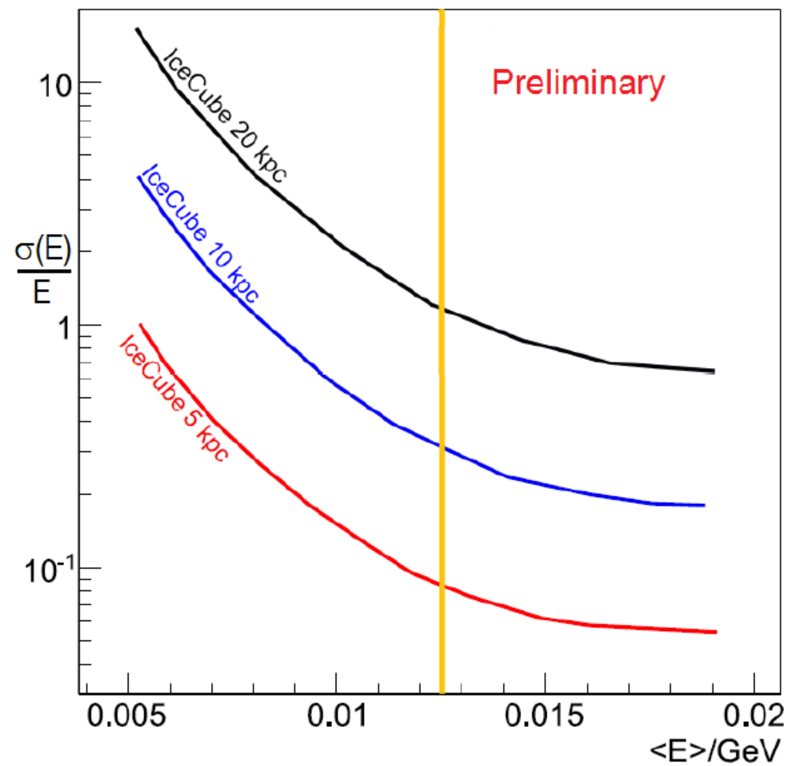
Exploiting coincidences …

hits in several sensors (only 0.25%)



denser detector (DeepCore) helps!

resolution on average neutrino energy

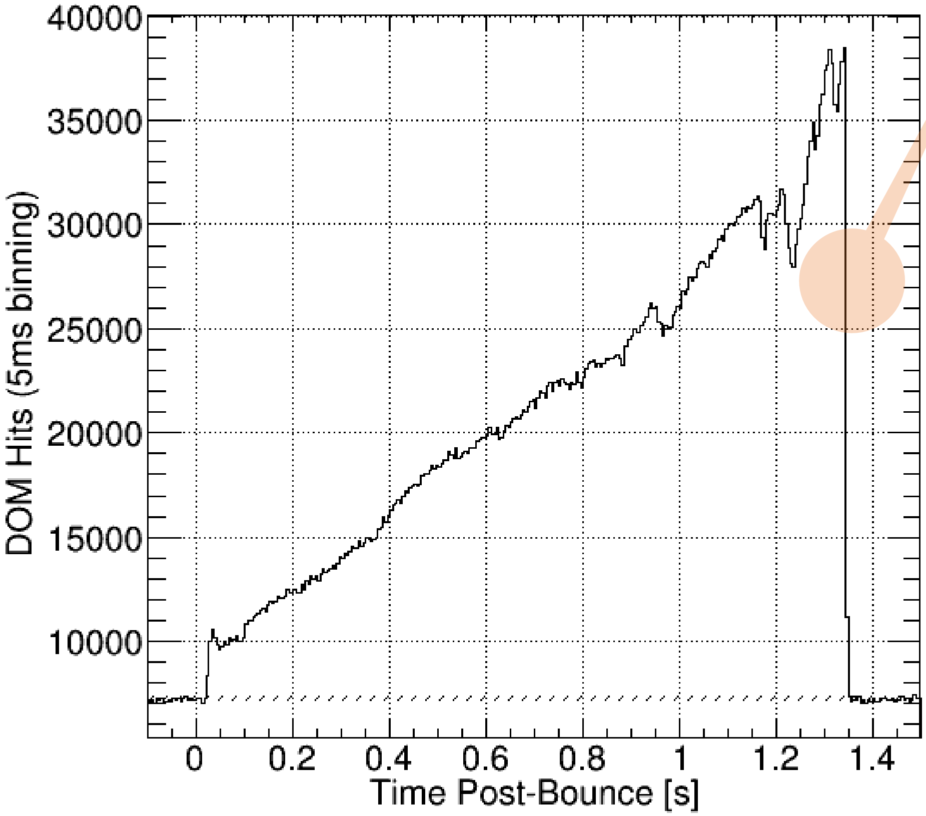


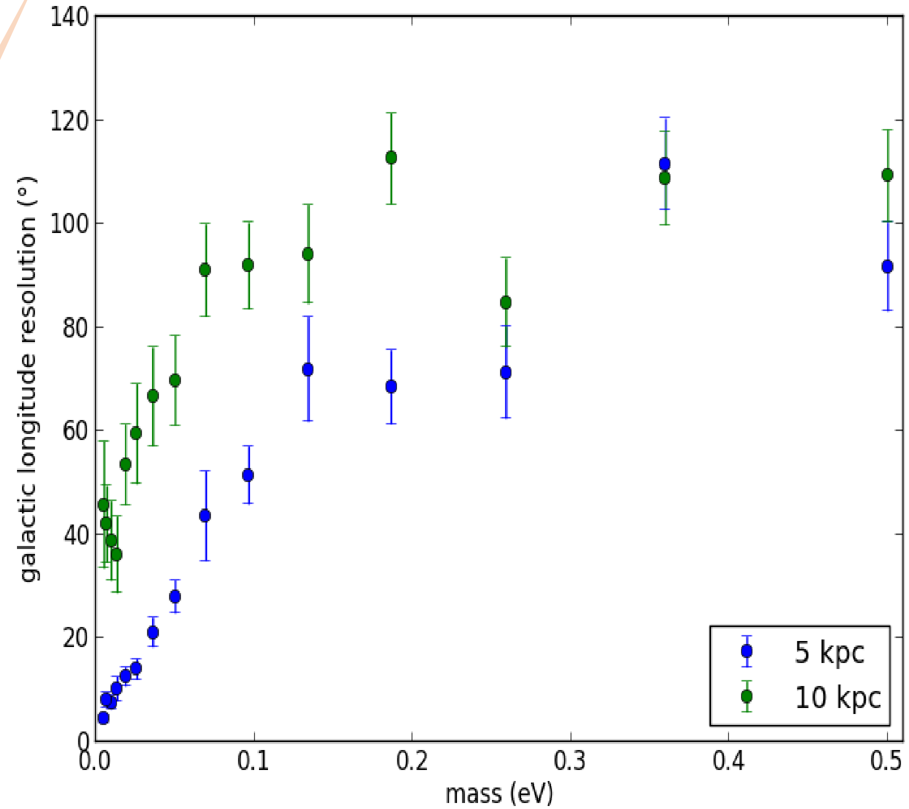
Double/single rate ≈ E_ν

Black hole forming SNe

Not really rare: Death watch“: 4 successfull core collapses, 1 failed (arXiv:1411.1761)
Likelihood fit on time arrrival pattern → some pointing information

black hole





Would gain strongly from several distant stations !

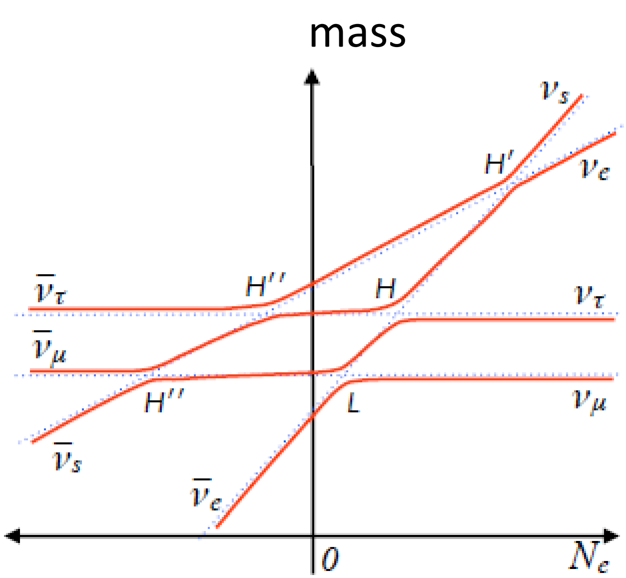
Sterile neutrinos

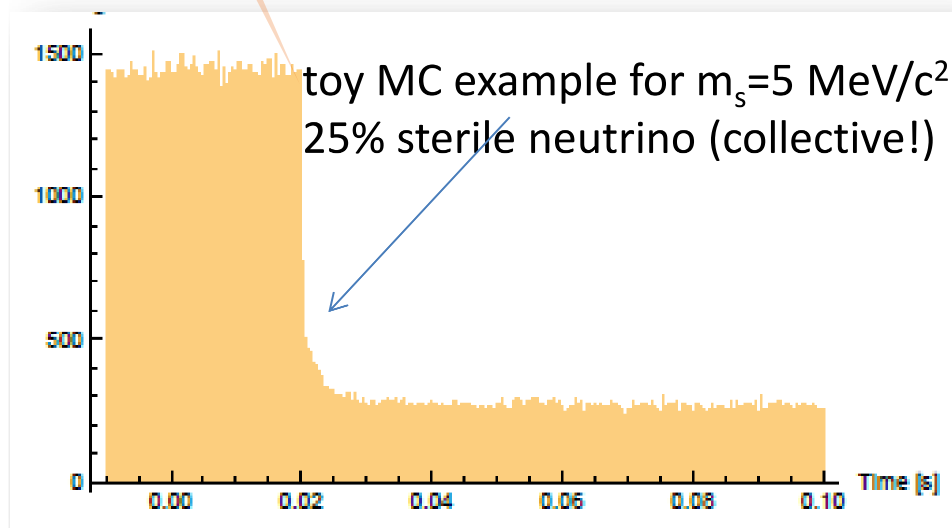
Use mass induced time delay in black hole forming supernovae: $\Delta t \propto \frac{m_\nu^2}{E_\nu^2} \cdot \text{distance}$

$$F_{\overline{\nu}_e}(E_\nu,t) \approx \bar{c}_{ee} F^0_{\overline{\nu}_e}(E_\nu,t) + |U_{ei}|^2 F^0_{\overline{\nu}_x}(E_\nu,t) + |U_{e4}|^2 F^0_{\overline{\nu}_x}\left(E_\nu, t - \frac{D}{2c}\left(\frac{m_4}{E_\nu}\right)^2\right)$$

i=2,3 for IH or NH

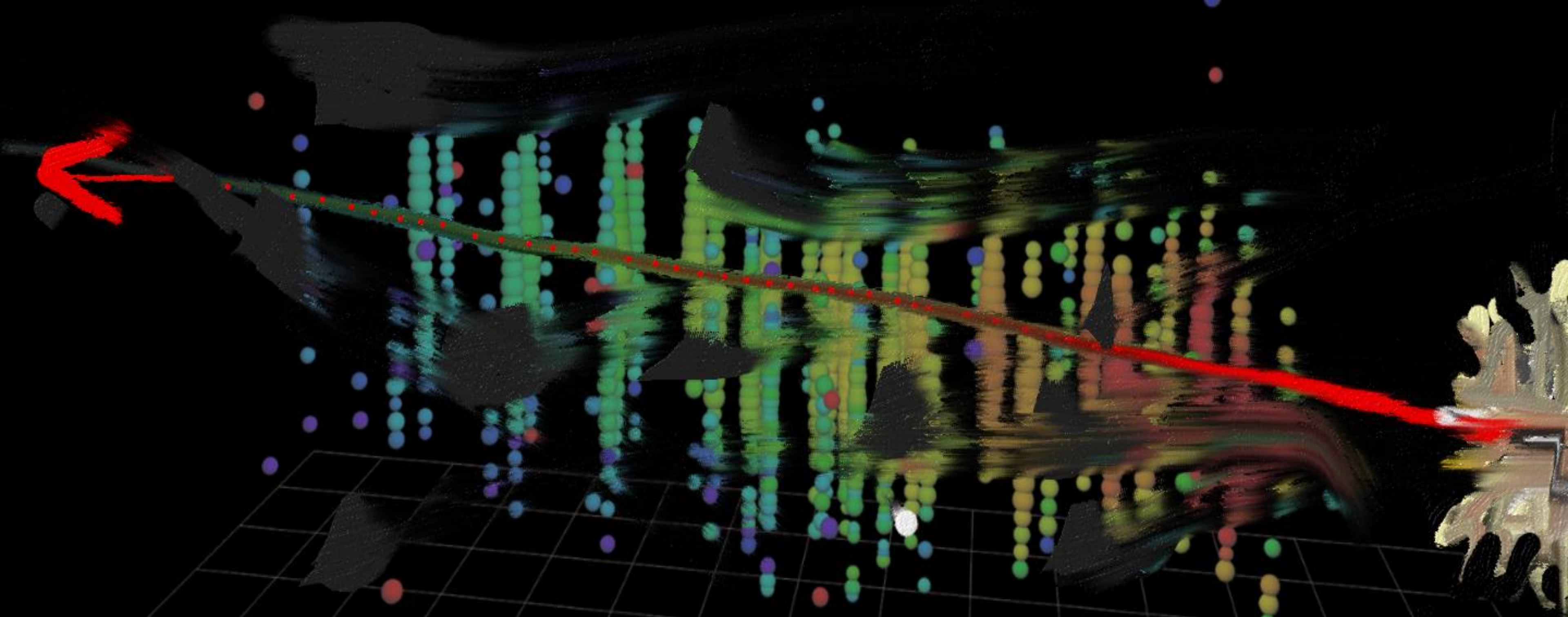
Example normal hierarchy:



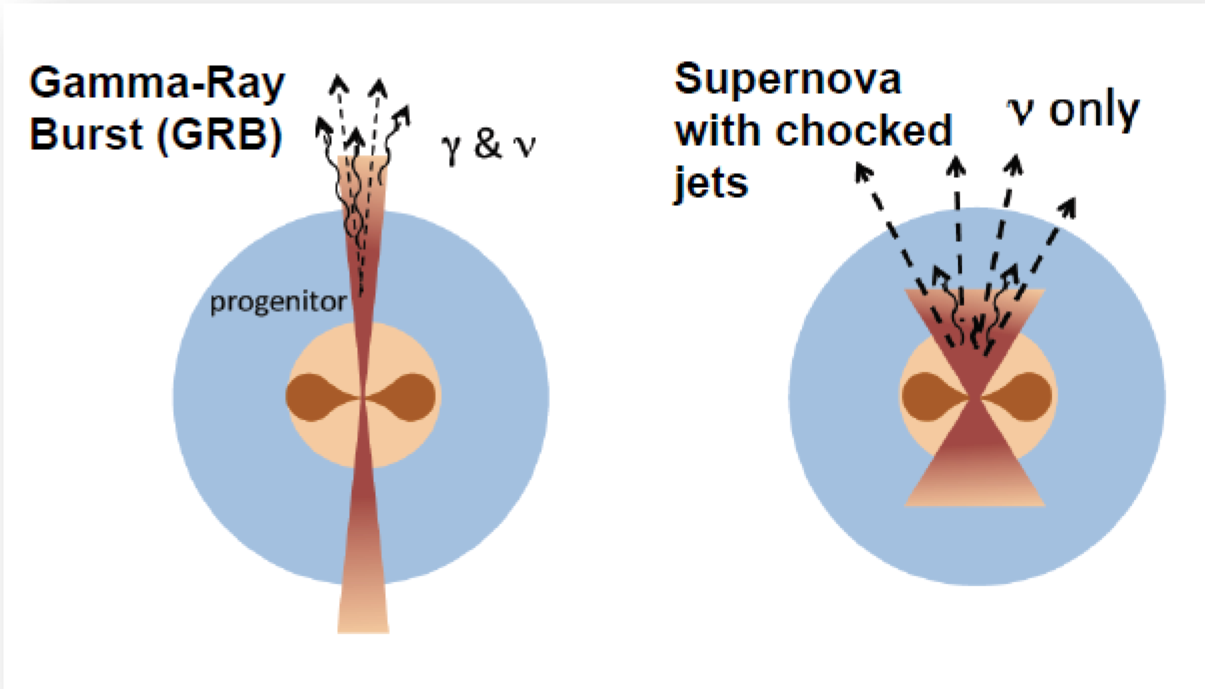


...for sufficiently high mixing angles masses and mixing well fitted

High energy ν's



High energy neutrinos in core collapse supernovae



Choked jet scenario:

- Jets die out in outer shell
- Similar to Gamma-Ray Bursts without γ !
- High energy ν's in second time scales

IceCube alert !

One of many IceCube alert systems that are sent out to the community …

IceCube-160427A

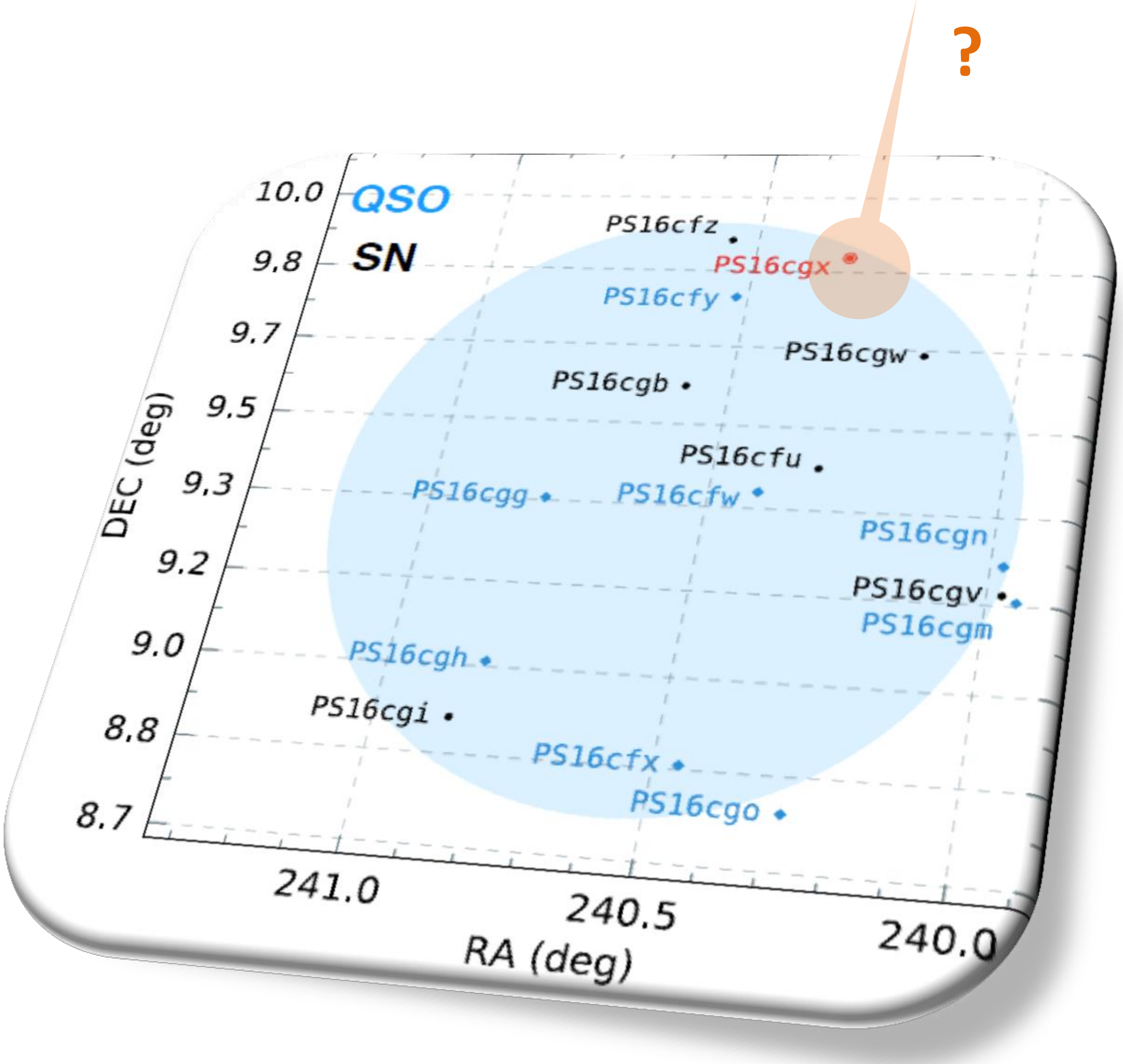
TITLE: GCN CIRCULAR
NUMBER: 19363
SUBJECT: ICECUBE-160427A neutrino candidate event: updated direction information
DATE: 16/04/29 16:29:47 GMT
FROM: Erik Blaufuss at U. Maryland/IceCube <blaufuss@icecube.umd.edu>

IceCube detected a candidate cosmic neutrino IceCube-160427A, "AMON ICECUBE HESE 127853 67093193" at 05:52:32.00 UT on 16/04/27 (http://gcn.gsfc.nasa.gov/notices_amon/67093193_127853.amon) The event was a high energy starting event (HESE) with track-like characteristics and it arrived when the IceCube detector was in a normal operating state.

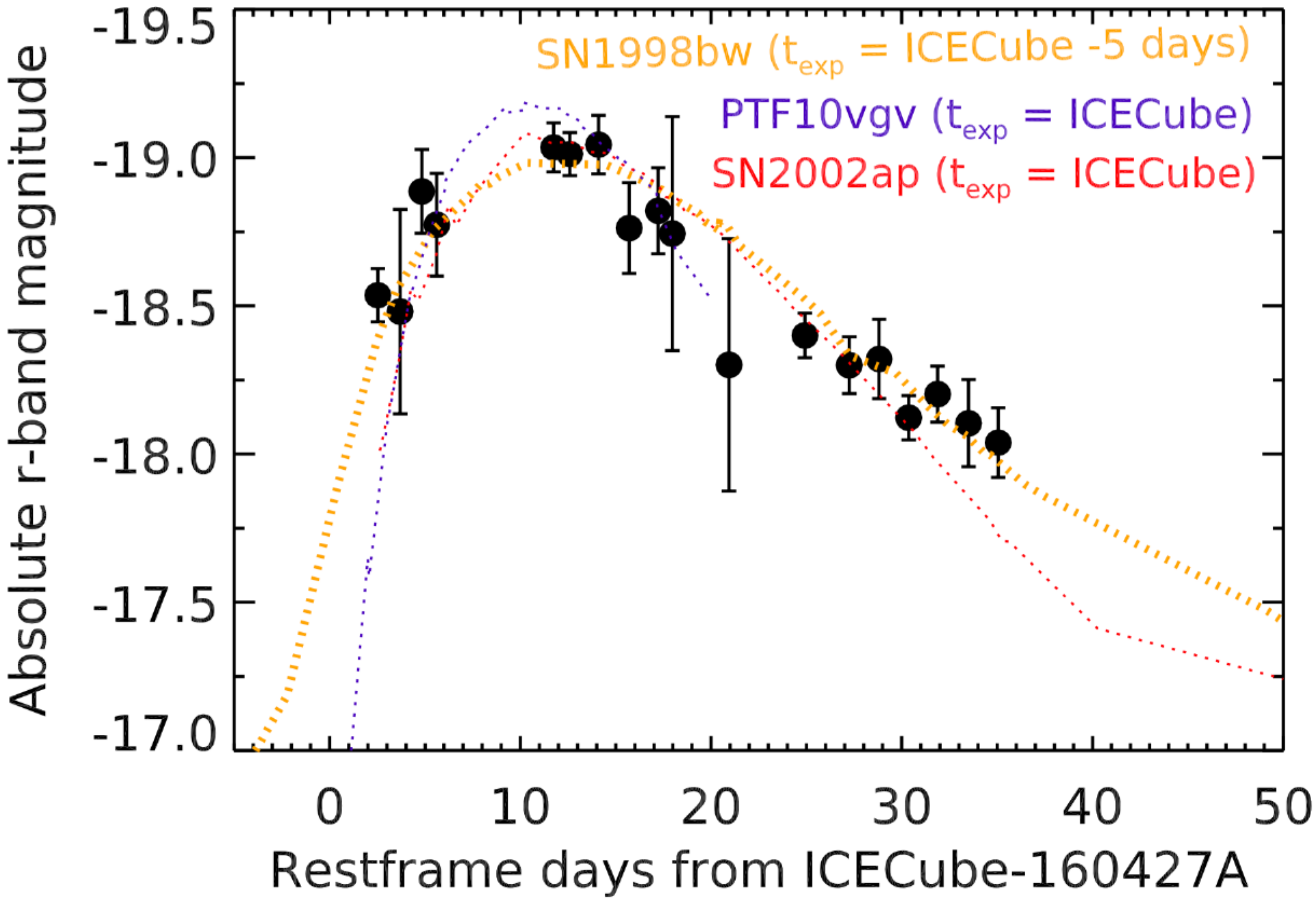
More sophisticated reconstruction algorithms have been applied offline, with the direction refined to RA=240.57d and DEC=+9.34d (J2000), and the position uncertainty reduced to an estimated 0.6 degrees or 36 arcminuntes radius (stat+sys, 90% containment). We encourage followup by ground and space-based instruments to help identify a possible astrophysical source for the neutrino.

The IceCube neutrino observatory is a cubic-kilometer neutrino detector operating at the geographic south Pole, Antarctica.
The IceCube realtime alert point of contact can be reached at roc@icecube.wisc.edu

High energy ν's from SNe



SN light curve on the rise...



for comparison ...

…however, probably a SN1a, unlikely to have high neutrino flux

Summary

- Neutrinos and their oscillations play deciding role in SNe
- Intriguing features in 3D simulations, explosion not yet settled
- IceCube provided 99.7% „SN availability“
- IceCube most precise instrument for close SNe
- will remain to be competitive in future
- much to learn from combination of measurements

Neutrino physics:
Absolute ν mass
Mass sequence
Matter and collective oscillations
Majorana vs Dirac neutrinos
Sterile neutrinos and axions

Supernova physics:
Pre-supernova evolution & progenitor structure
Neutronization & neutrino trapping
Shocks, turbulence, convective transport (SASI, LESA)
EOS, neutron star, phase transition, nucleosynthesis
Accretion, explosion cooling, black hole formation …