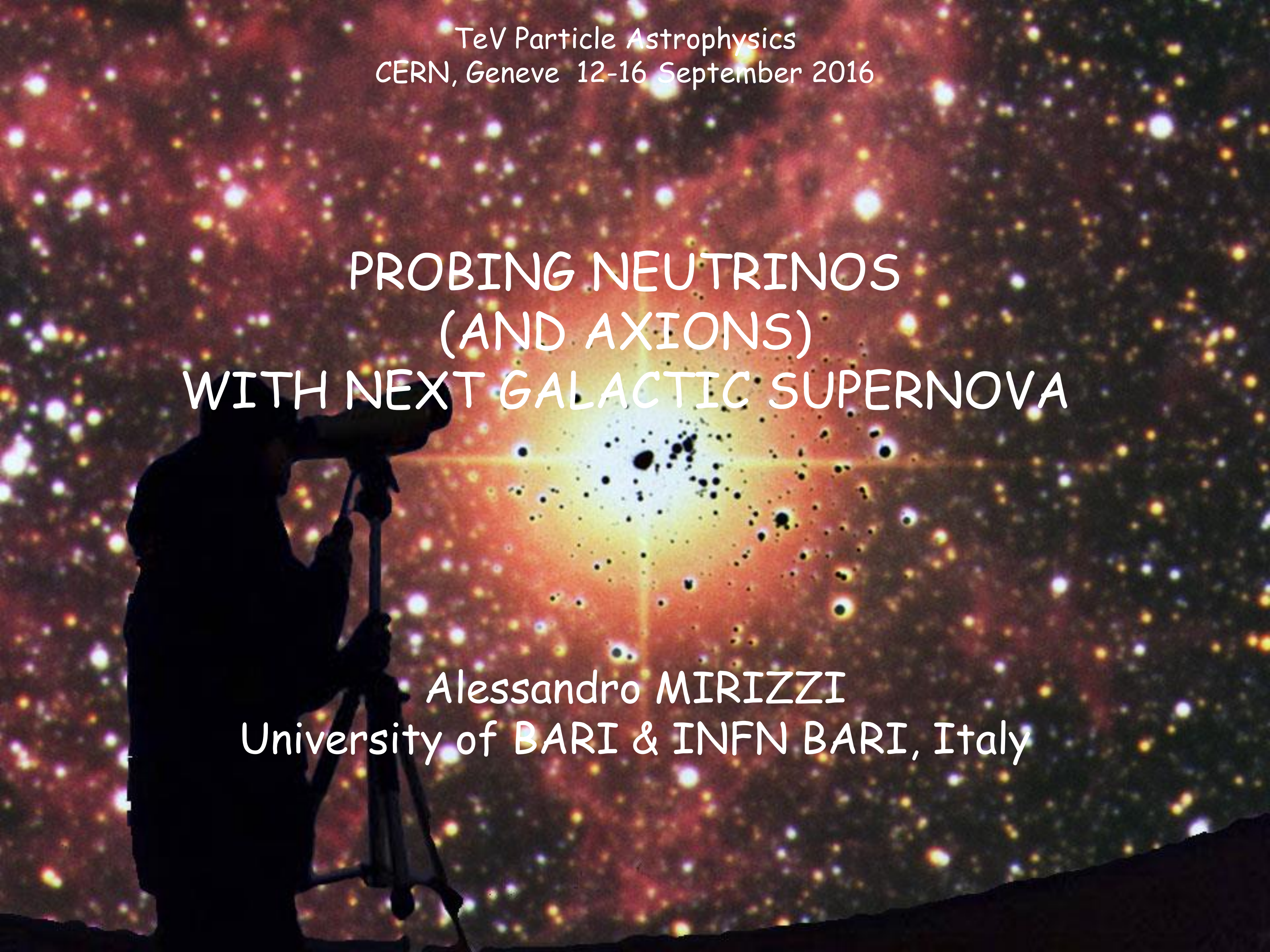

TeV Particle Astrophysics
CERN, Geneve 12-16 September 2016

PROBING NEUTRINOS (AND AXIONS) WITH NEXT GALACTIC SUPERNOVA

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OUTLINE

- Introduction to SN & neutrinos
- SN nu light curve in current and future detectors
- Signatures of neutrino flavor conversions
- Impact of axion emission on neutrino signal
- Conclusions

SUPERNOVA NEUTRINOS

Core collapse SN corresponds to the terminal phase of a massive star [$M \gtrsim 8\,M_\odot$] which becomes unstable at the end of its life. It collapses and ejects its outer mantle in a shock wave driven explosion.

- **ENERGY SCALES:** 99% of the released energy (~ 10^{53} erg) is emitted by ν and $\bar{\nu}$ of all flavors, with typical energies E ~ O(15 MeV).
- **TIME SCALES:** Neutrino emission lasts **~10 s**
- **EXPECTED:** **1-3 SN/century** in our galaxy (d ≈ O (10) kpc).

THREE PHASES OF NEUTRINO EMISSION

[A.M., Tamborra, Janka, Saviano, Scholberg et al., arXiv:1508.00785 [astro-ph.HE]]

27 M_{sun} progenitor mass
(spherically symmetric model)

Neutronization burst

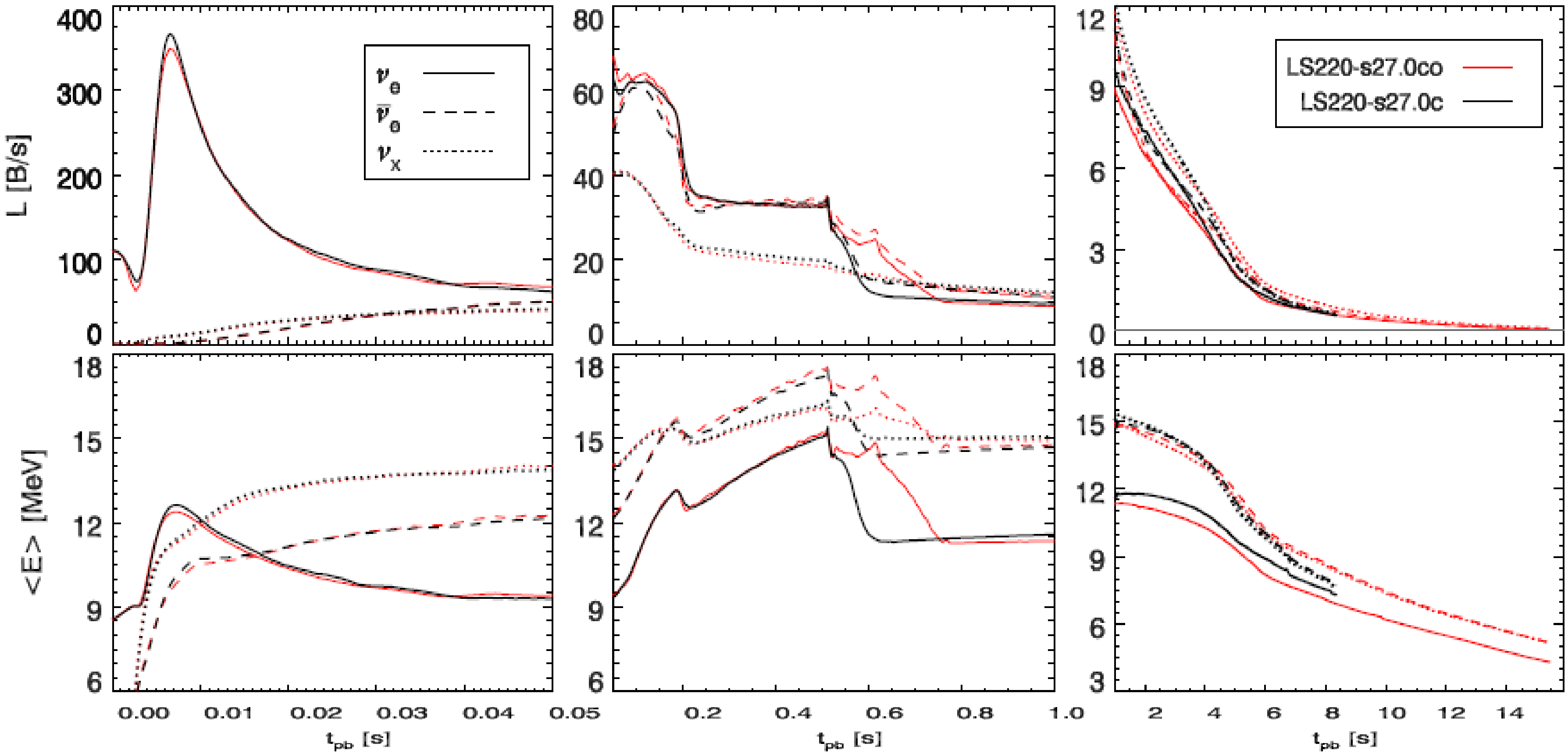
- Shock breakout
- De-leptonization of outer core layers

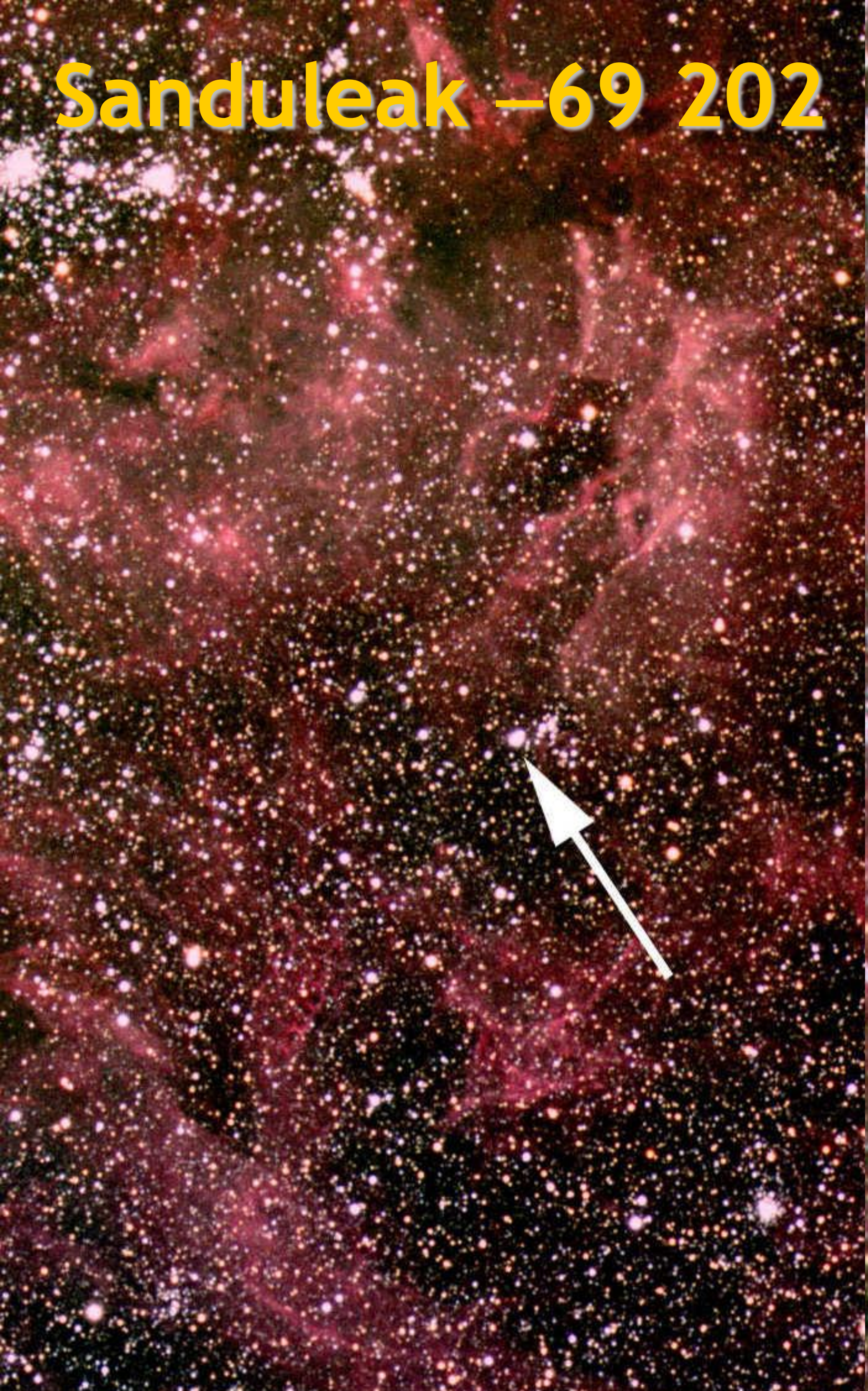
Accretion

- Shock stalls ~ 150 km
- ν powered by infalling matter

Cooling

- Cooling on ν diffusion time scale



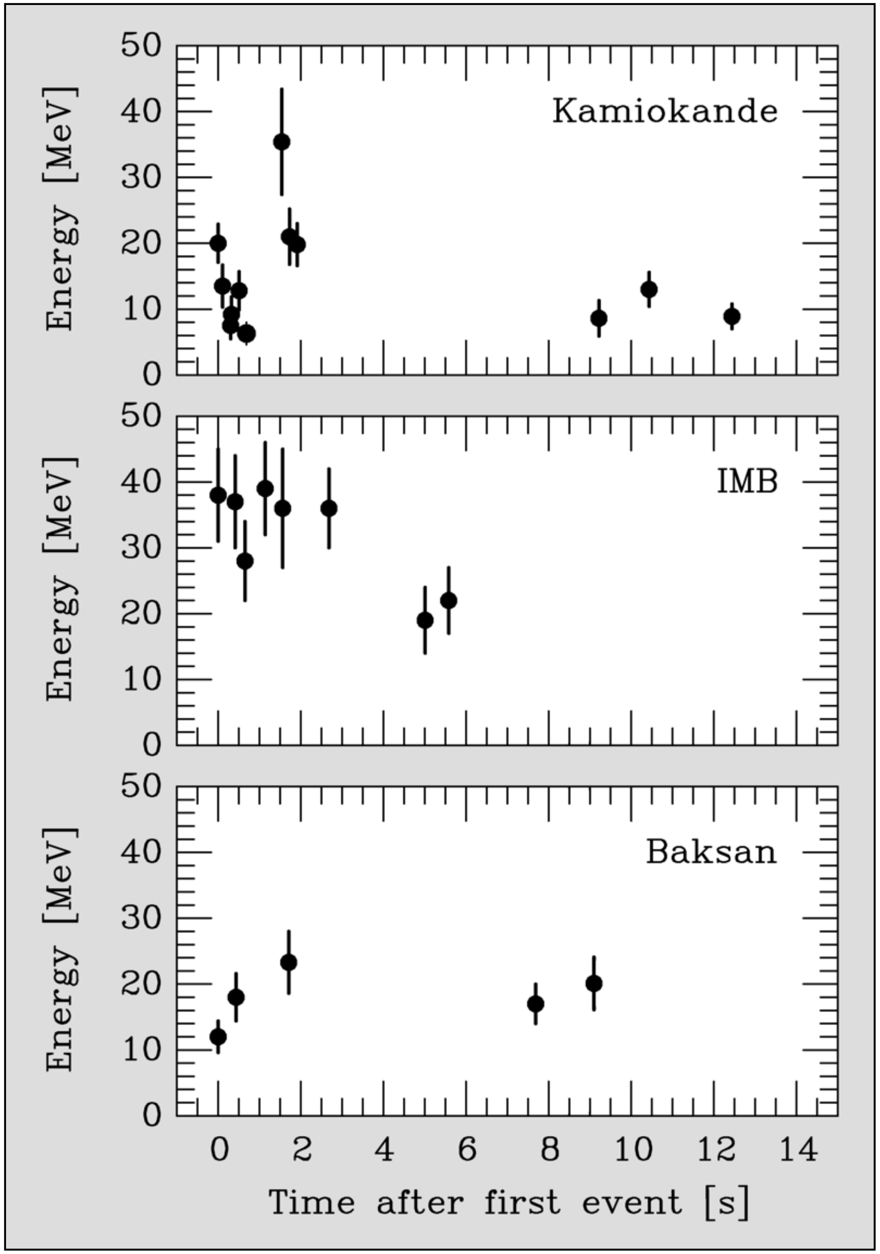


Sanduleak −69 202

Supernova 1987A

23 February 1987

NEUTRINO SIGNAL OF SUPERNOVA 1987A



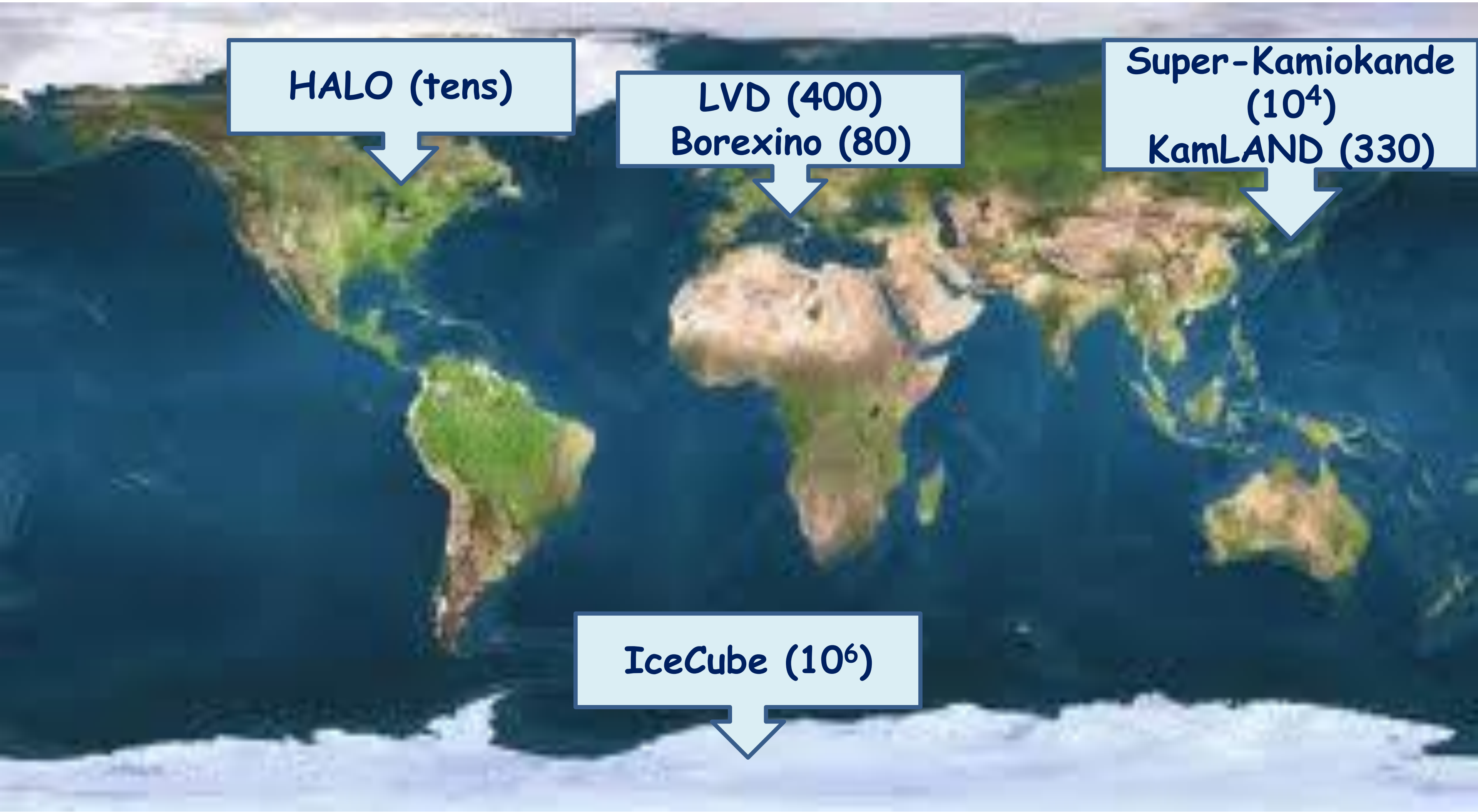
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/-54 s

Within clock uncertainties,
signals are contemporaneous

Large Detectors for Supernova Neutrinos



HALO (tens)

LVD (400)
Borexino (80)

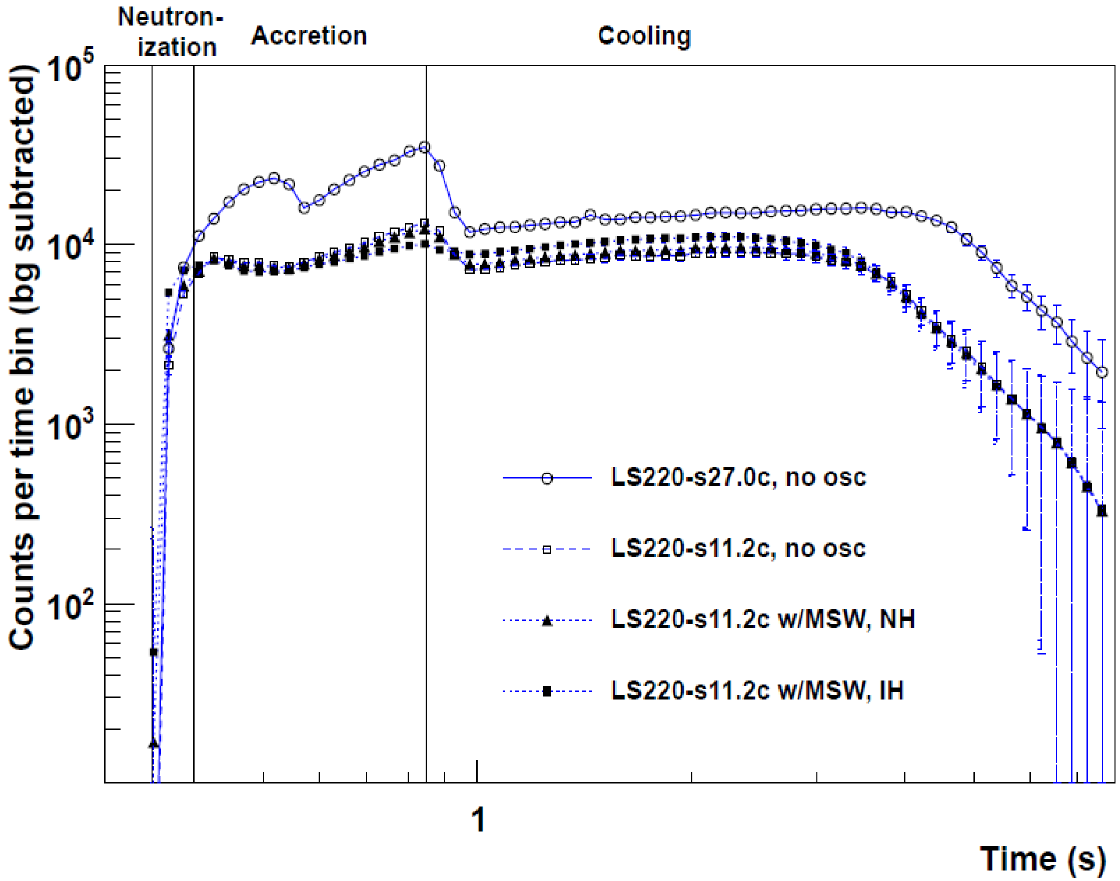
Super-Kamiokande (10^4)
KamLAND (330)

IceCube (10^6)

In brackets events for a "fiducial SN" at distance 10 kpc

SN NU SIGNAL IN ICECUBE

[A.M., Tamborra, Janka, Saviano, Scholberg et al., arXiv:1508.00785 [astro-ph.HE]]



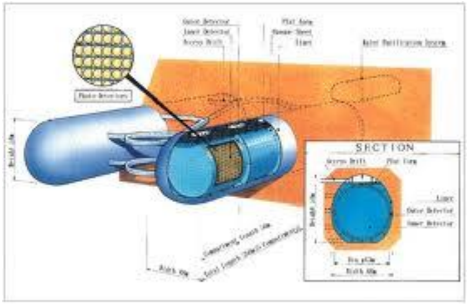
High statistics reconstruction of the nu light curve. Possible to distinguish the different post-bounce phases.

NEXT-GENERATION DETECTORS

Mton scale water Cherenkov detectors

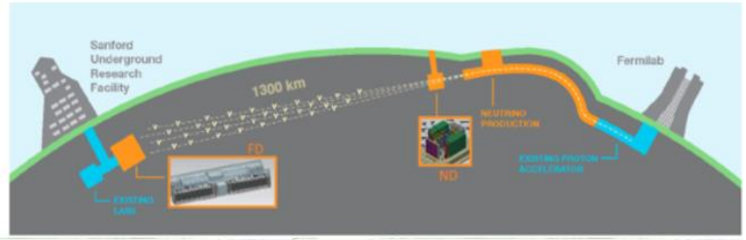
(10^5 events) $(\bar{\nu}_e)$

HYPER-KAMIOKANDE



40 kton Liquid Argon TPC

(3000 events) (ν_e)



DUNE

Dark matter detectors

DARWIN

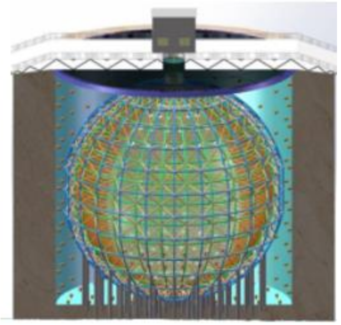
40 tons

(700 events)

$(\nu_{e,x}, \bar{\nu}_{e,x})$

20 kton scintillator

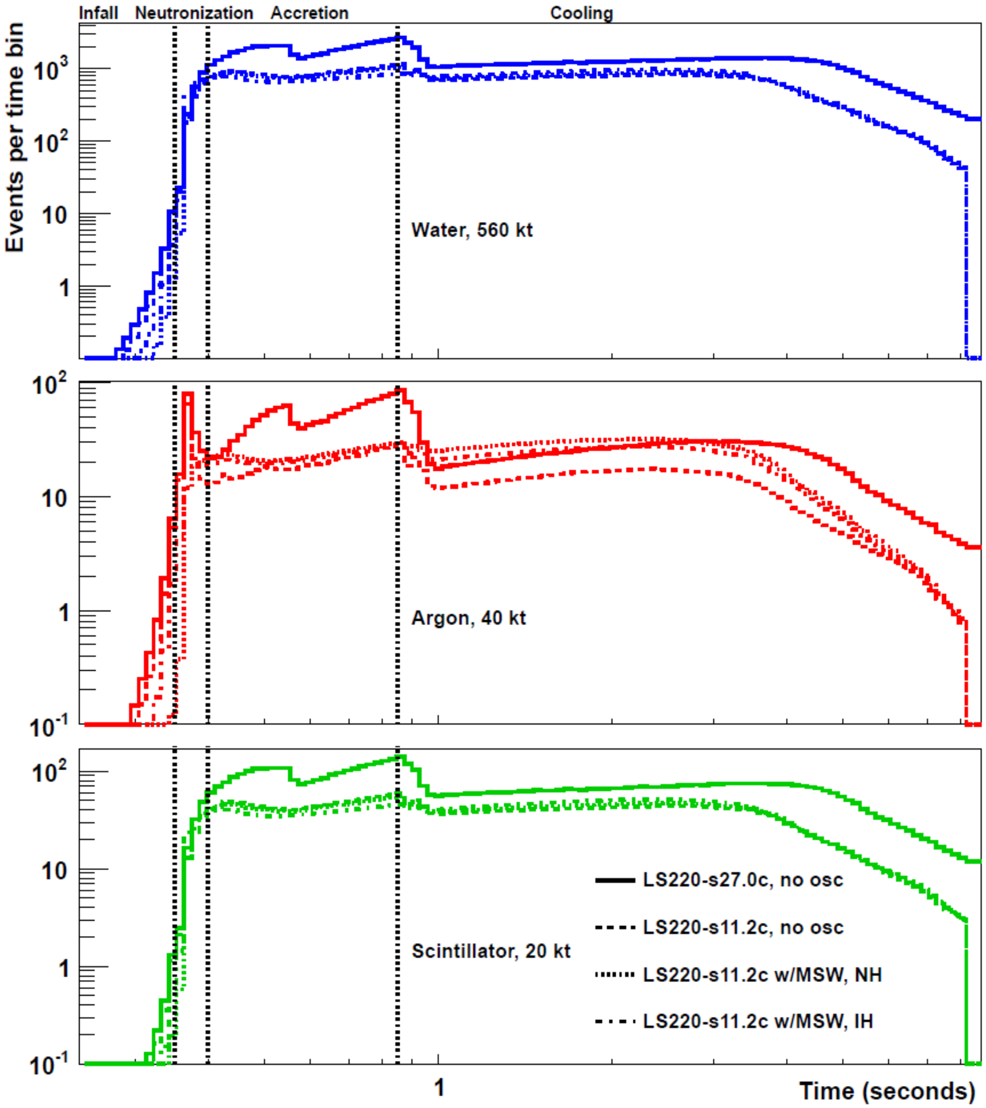
(6000 events) $(\bar{\nu}_e)$



JUNO

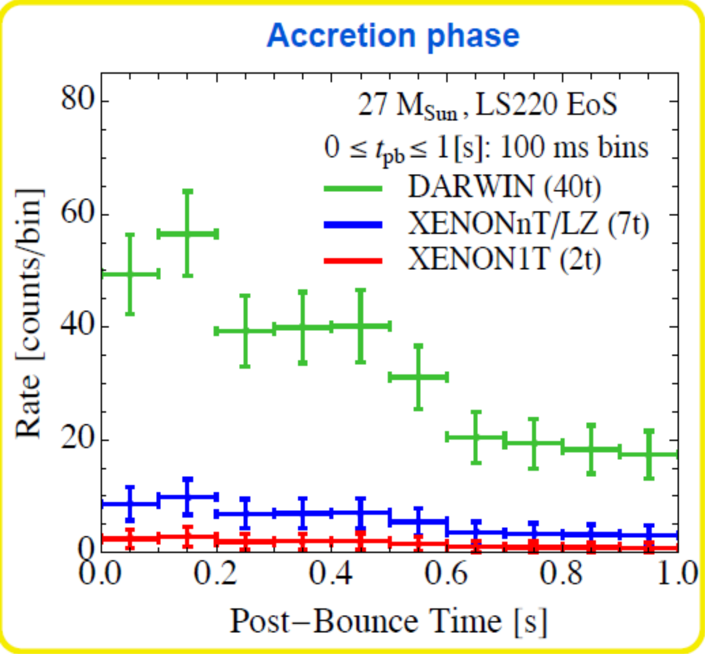
SN NU SIGNAL IN FUTURE DETECTORS

[A.M., Tamborra, Janka, Saviano, Scholberg et al., arXiv:1508.00785 [astro-ph.HE]]

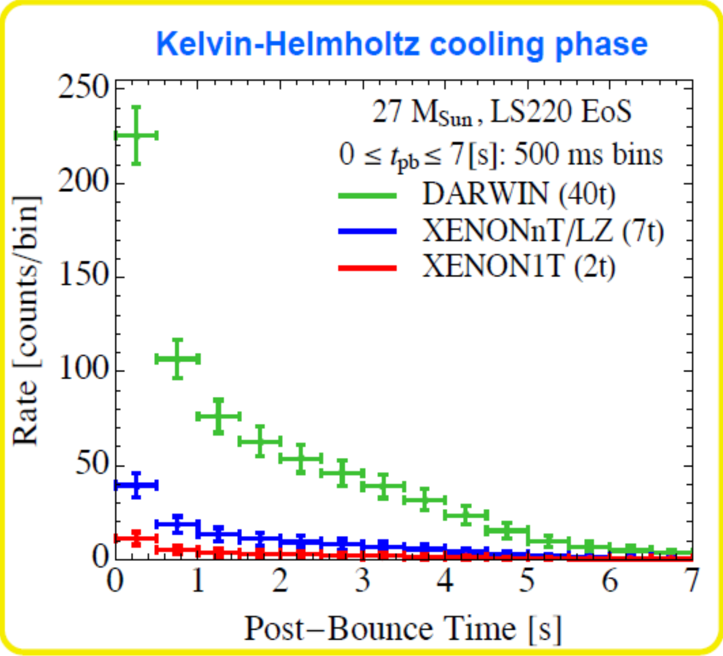


SN NU SIGNAL IN DM DETECTORS

[Lang,McCabe, Reichard, Selvi & Tamborra, arXiv:1606.09243 [astro-ph.HE]]



Accretion phase



Kelvin-Helmholtz cooling phase

DARWIN will be able to clearly reconstruct the neutrino light-curve and to differentiate among phases of neutrino signal. Partial sensitivity with XENONnT/LZ.

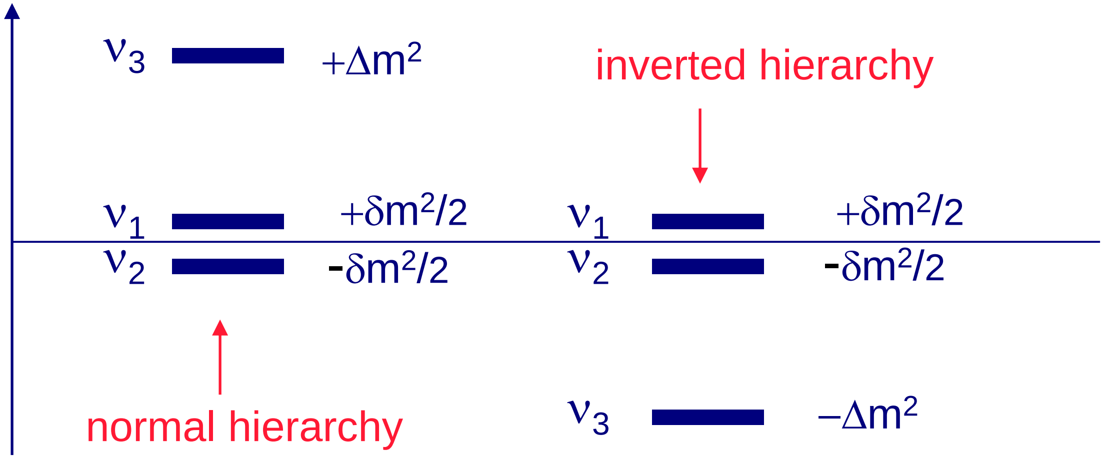
3ν FRAMEWORK

- **Mixing parameters:** $U = U(\theta_{12}, \theta_{13}, \theta_{23}, \delta)$ as for CKM matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & e^{-i\delta} s_{13} \\ & 1 & \\ -e^{-i\delta} s_{13} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$c_{12} = \cos\theta_{12}$, etc., δ CP phase

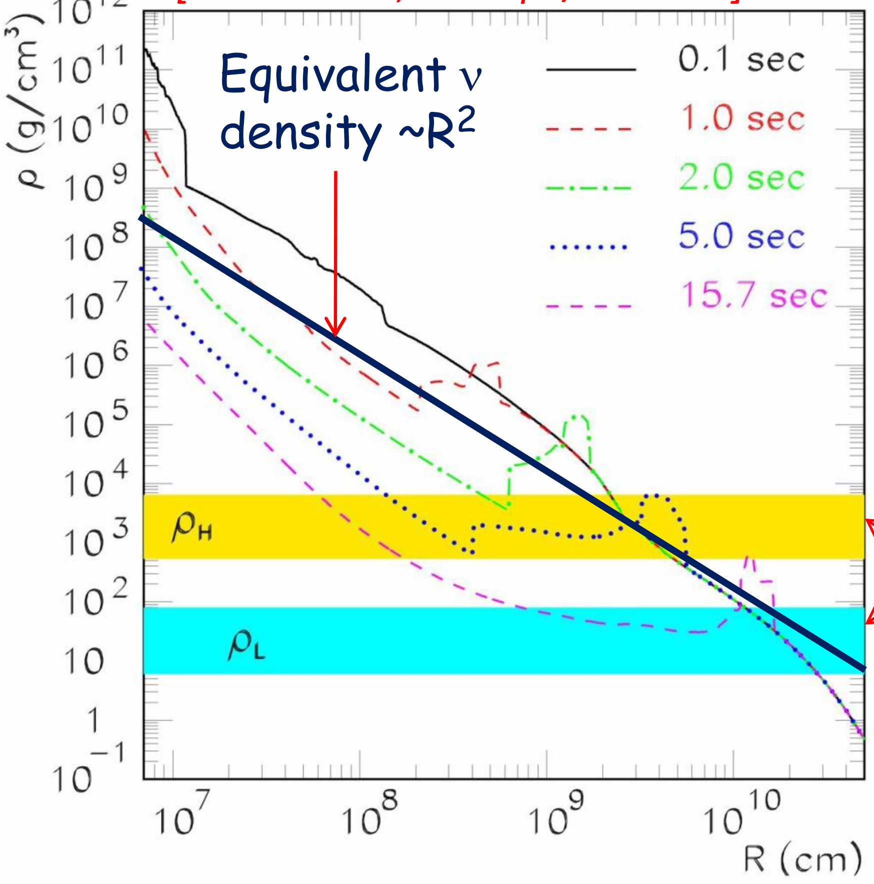
- **Mass-gap parameters:** $M^2 = \Big(\underbrace{-\frac{\delta m^2}{2},\ +\frac{\delta m^2}{2}}_{\text{“solar”}},\ \underbrace{\pm \Delta m^2}_{\text{“atmospheric”}} \Big)$



SN neutrinos are sensitive to the unknown mass hierarchy

SNAPSHOT OF SN DENSITIES

[Tomas et al., astro-ph/0407132]



- Matter bkg potential

$$\lambda = \sqrt{2} G_F N_e \quad \sim R^{-3}$$

- ν–ν interaction

$$\mu = \sqrt{2} G_F n_\nu \quad \sim R^{-2}$$

- Vacuum oscillation frequencies

$$\omega = \frac{\Delta m^2}{2E}$$

When $\mu >> \lambda$, SN ν oscillations dominated by ν-ν interactions

Collective flavor transitions at low-radii [O (10^2 – 10^3 km)]

Far more complicated than expected

Spontaneous symmetry breaking in collective oscillations!

SUPPRESSION OF COLLECTIVE OSCILLATIONS

At the moment, predictions are more robust in the phases where collective effects are suppressed, i.e.:

- Neutronization burst (t < 20 ms): large ν_e excess and ν_x deficit *[Hannestad et al., astro-ph/0608695]*
- Accretion phase (t < 500 ms): dense matter term dominates over nu-nu interaction term *[Chakraborty, A.M. , Saviano et al., 1104.4031, 1105.1130, 1203.1484, Sarikas et al., 1109.3601]*

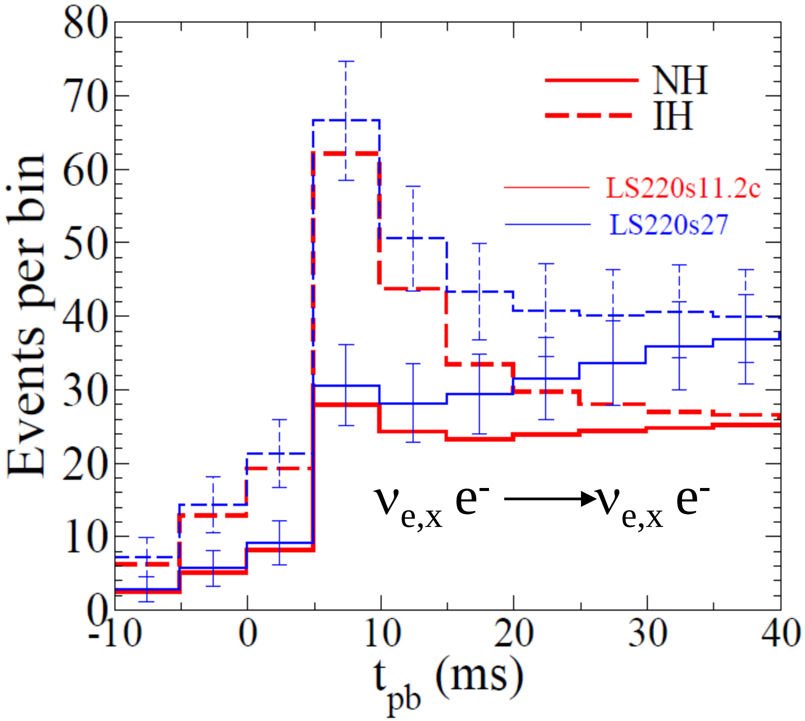
Large flux differences during the neutronization and accretion phase

Best cases for ν oscillation effects !

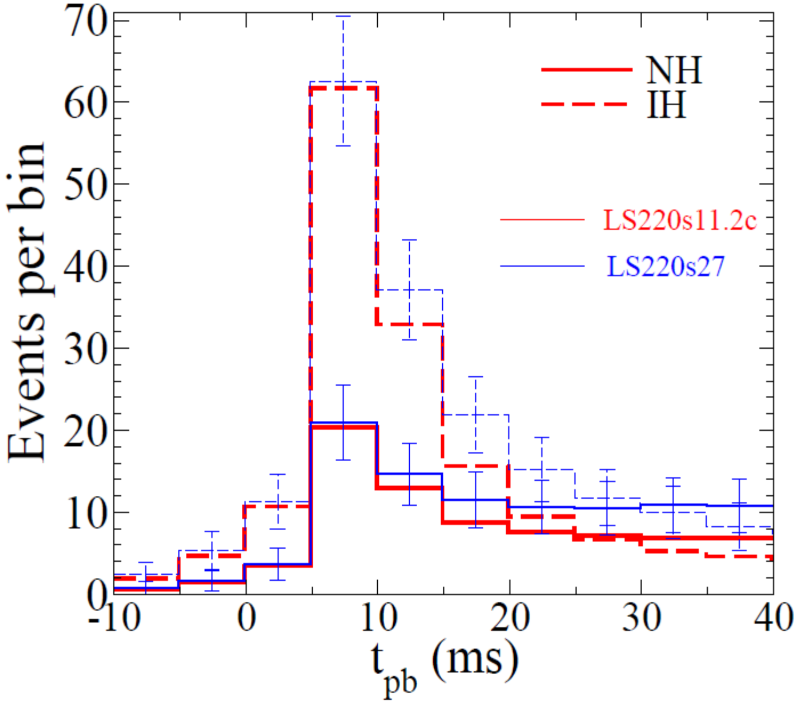
NEUTRONIZATION BURST

[A.M., Tamborra, Janka, Saviano, Scholberg et al., arXiv:1508.00785 [astro-ph.HE]]

560 kton Water Cherenkov



40 kton LAr



Robust feature of SN simulations

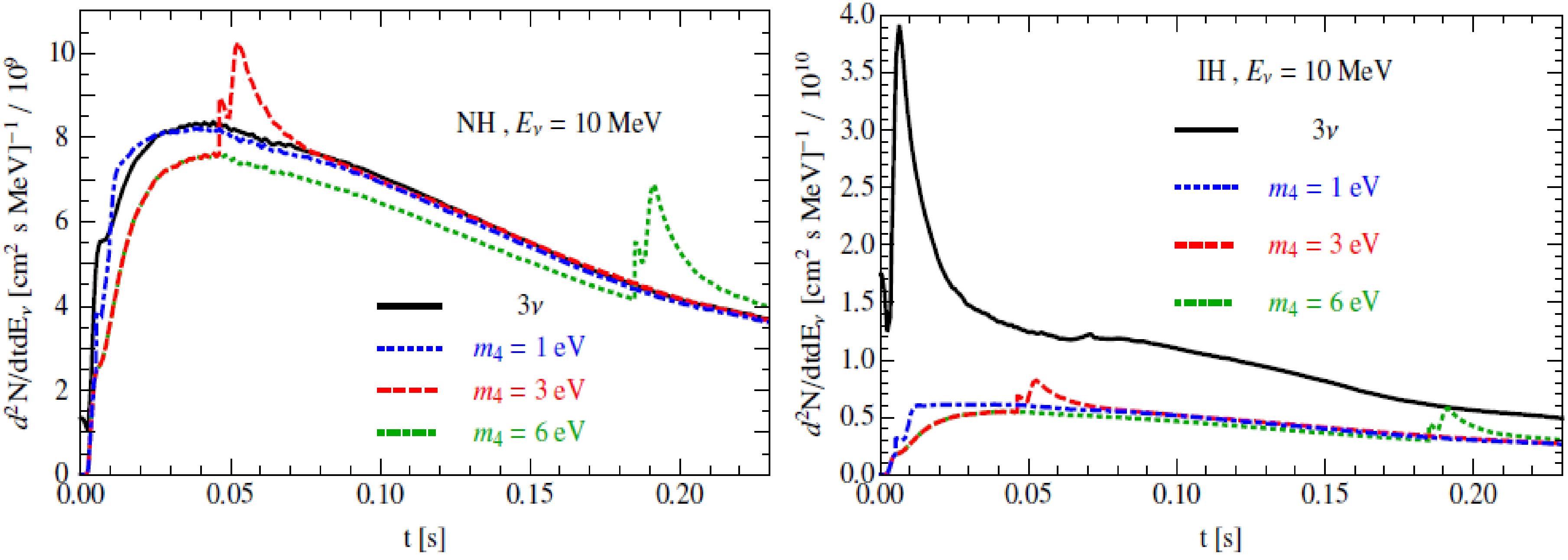
[Kachelriess et al., astro-ph/0412082, Gil-Botella & Rubbia, hep-ph0307244]

At “large” θ_{13} (like recently measured!):

- The peak <u>is not seen</u> → The hierarchy is normal (if one could see it…)
- The peak <u>is seen</u> → The hierarchy is inverted (more robust)

PROBING eV STERILE NU WITH NEUTRONIZATION BURST

[Esmaili, Peres & Serpico, 1402.1453]

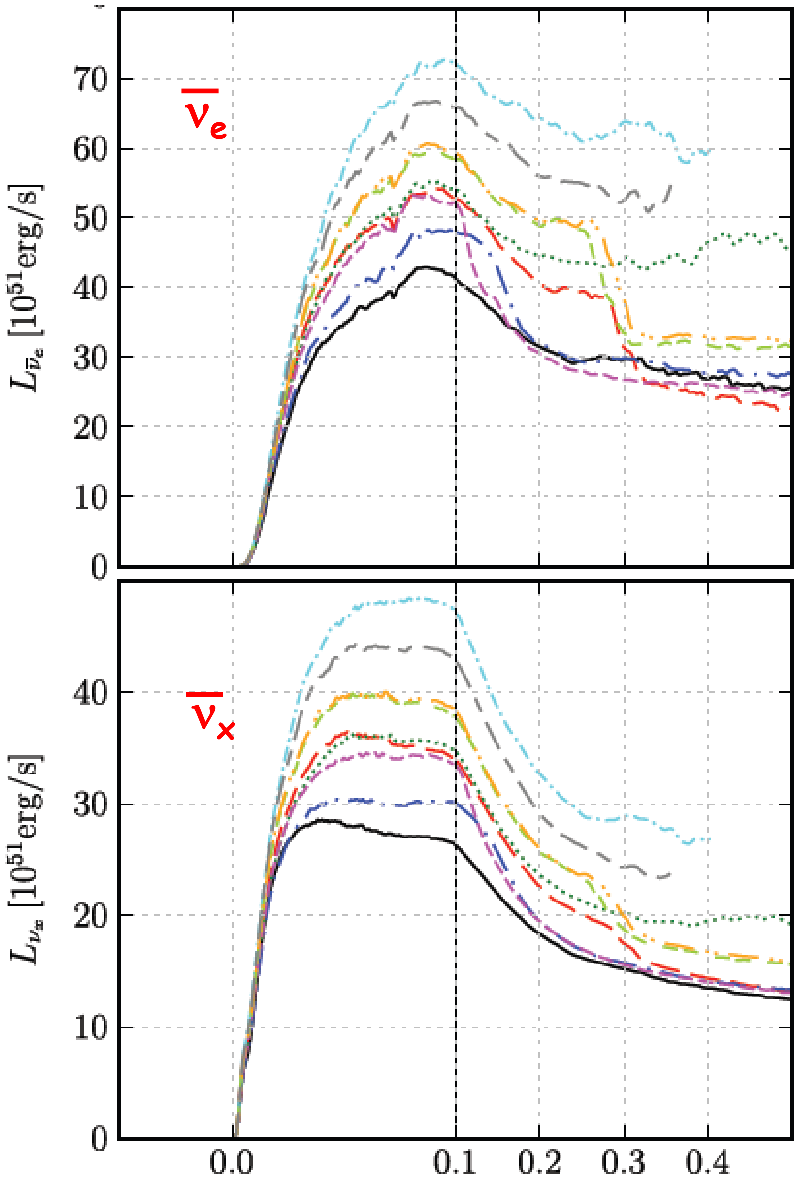


(a) (b)

3+1 scheme

- IH: disappearence of neutronization peak. Possible appearence of delayed peak due to the fraction of heavy ν_4 component in ν_e (kinematical reason).
- Peculiar time-energy distribution in LAr TPC.

RISE TIME OF SN NEUTRINO SIGNAL IN ANTI-NU



Garching group, 2011

- The production of $\bar{\nu}_e$ is more strongly suppressed than that of ν_x during the first tens of ms after bounce because of the high degeneracy of e and ν_e .
- $\bar{\nu}_e$ are produced more gradually via cc processes (e captures on free nucleons) in the accreting matter; ν_x come fastly from a deeper region

The lightcurves of the two species in the first O(100) ms are quite different.

RISE TIME ANALYSIS: HIERARCHY DETERMINATION

[see Serpico, Chakraborty, Fischer, Hudepohl, Janka & A.M., 1111.4483]

In accretion phase one has

$$F^D_{\bar{\nu}_e} = \cos^2\theta_{12} F_{\bar{\nu}_e} + \sin^2\theta_{12} F_{\bar{\nu}_x}$$ NH

$$F^D_{\bar{\nu}_e} = F_{\bar{\nu}_x}$$ IH

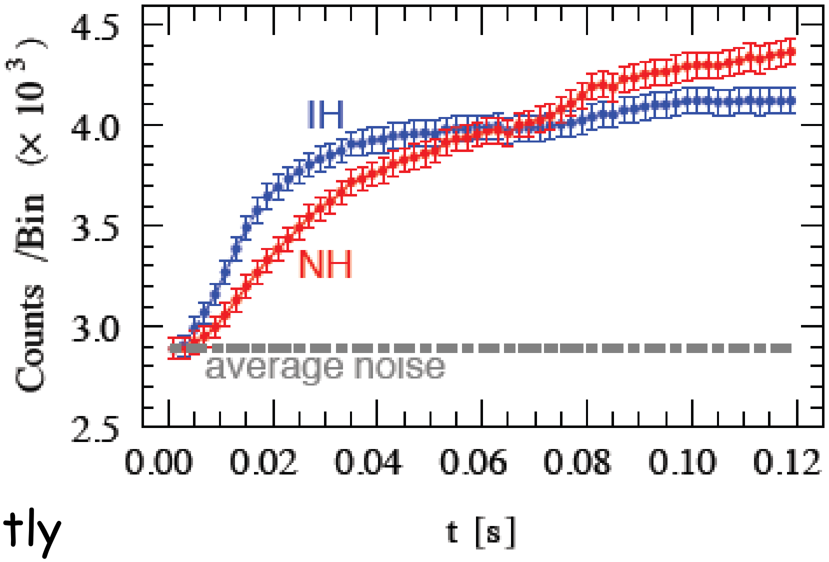
A high-statistics measurment of the rise time shape may distinguish the two scenarios

- Are the rise time shapes enough robustly predicted to be useful?

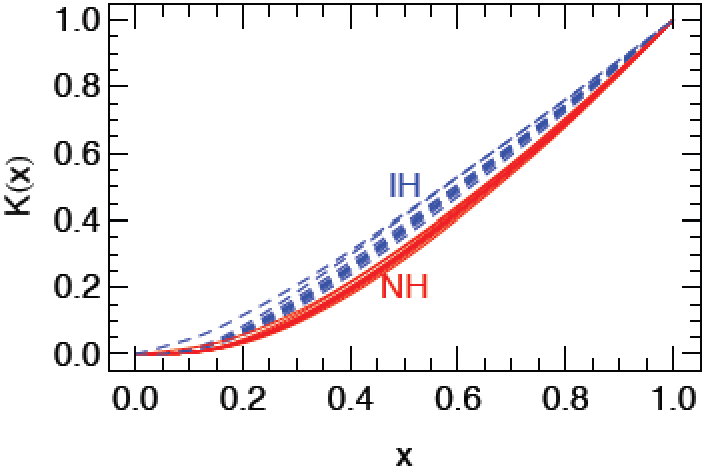
Models with state-of-the art treatment of weak physics (Garching simulations) suggest so: one could attribute a "shape" to NH and IH.

Given these promising early results, it would be mandatory in future to explore the robusteness of the signature with other simulations. *[see Ott et al., 1212.4250]*

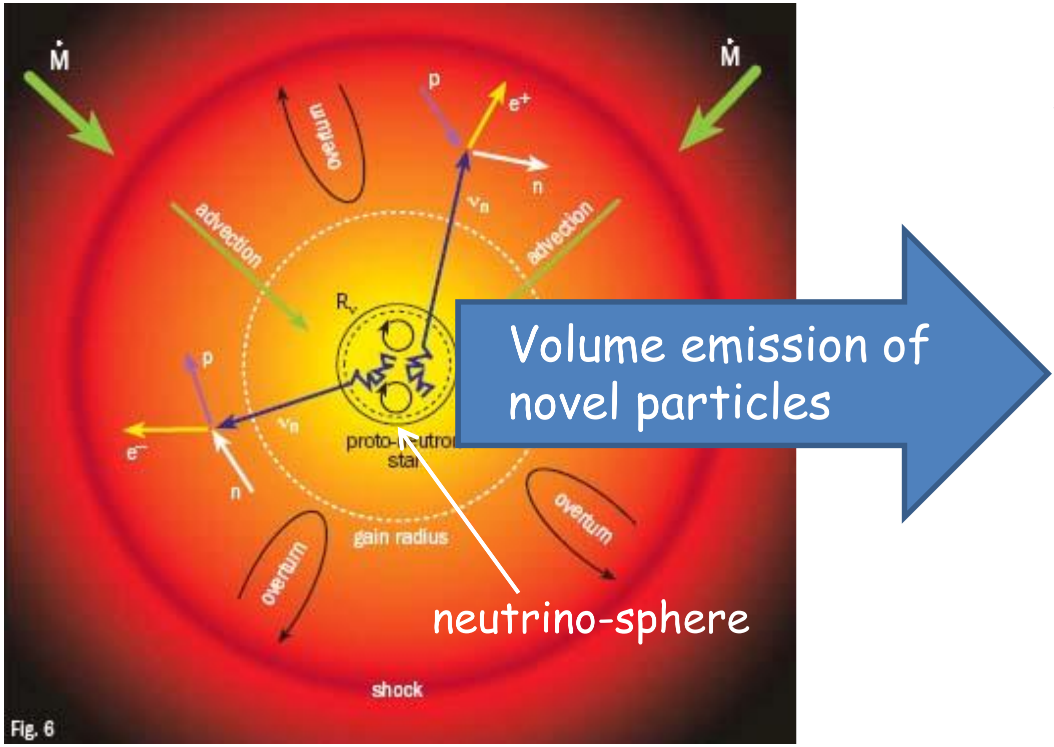
SN ν signal in Icecube



Cumulative distribution



ENERGY-LOSS ARGUMENT



Volume emission of novel particles

neutrino-sphere

Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.

Assuming that the SN 1987A neutrino burst was not shortened by more than ~½ leads to an approximate requirement on a novel energy-loss rate of

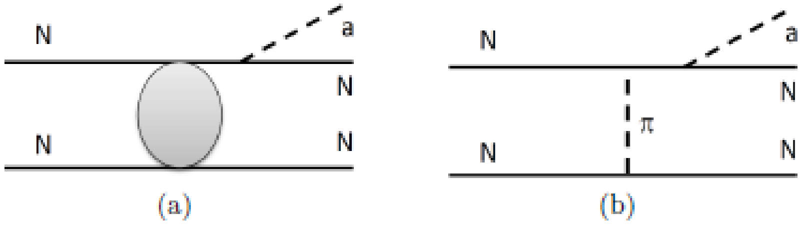
$$\varepsilon_x < 10^{19}\ \mathrm{erg\ g^{-1}\ s^{-1}}$$

for $\rho \approx 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$ and $T \approx 30$ MeV

AXION EMISSION FROM A NUCLEAR MEDIUM

$$NN \to NNa$$

nucleon-nucleon bremsstrahlung



Bulk nuclear interaction One pion exchange

$$\boxed{L_{aN} = \frac{g_{aN}}{2m_N}\overline{N}\gamma_\mu\gamma_5 N\partial^\mu a}$$

$$g_{aN} = C_N \frac{m}{f_a}$$

Non-degenerate energy-loss rate $\varepsilon_a = g_{aN}^2\, 2\times10^{39}\,\mathrm{erg\ g^{-1}\ s^{-1}}\rho_{15}T_{30}^{3.5}$

$$\begin{pmatrix} T_{30} = T/30\ \mathrm{MeV} \\ \rho_{15} = \rho/10^{15}\,\mathrm{g\ cm^{-3}} \end{pmatrix}$$

$$\langle\rho_{15}\rangle \approx 0.4$$

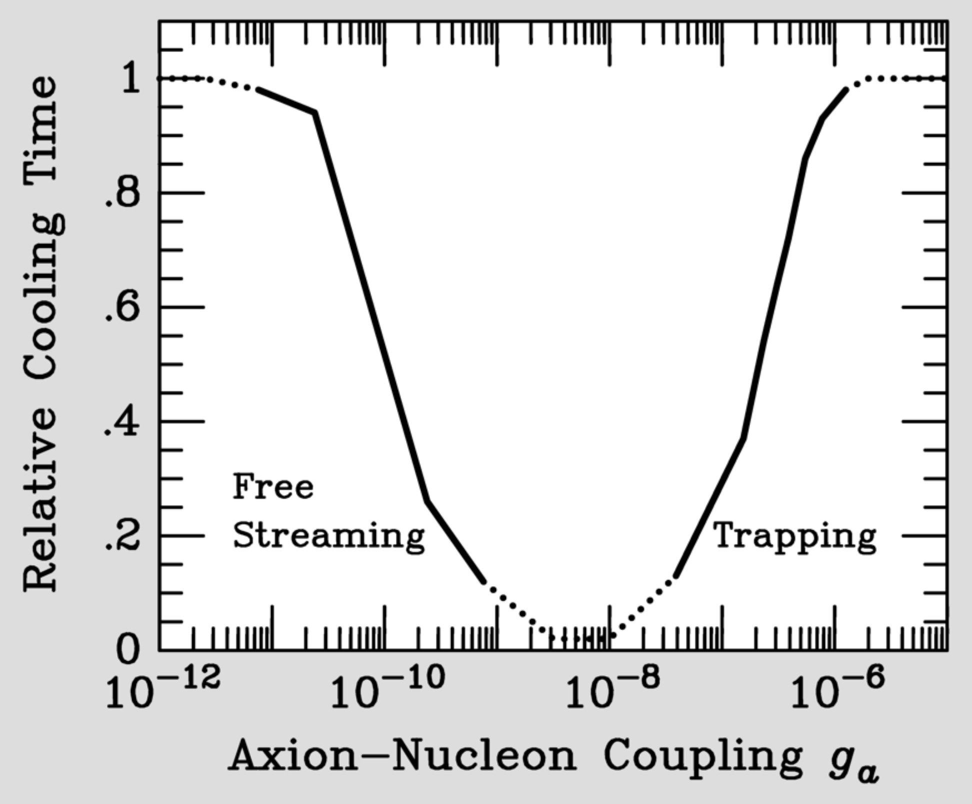
$$\langle T_{30}^{3.5}\rangle \approx 1.4$$

$$\Rightarrow \quad g_{aN} < 9\times10^{-10}$$

SN 1987A AXION LIMITS

Free streaming
[Burrows, Turner & Brinkmann, PRD 39:1020,1989]

Volume emission of axions



Trapping
[Burrows, Ressell & Turner, PRD 42:3297,1990]

Axion diffusion from an "axion-sphere"

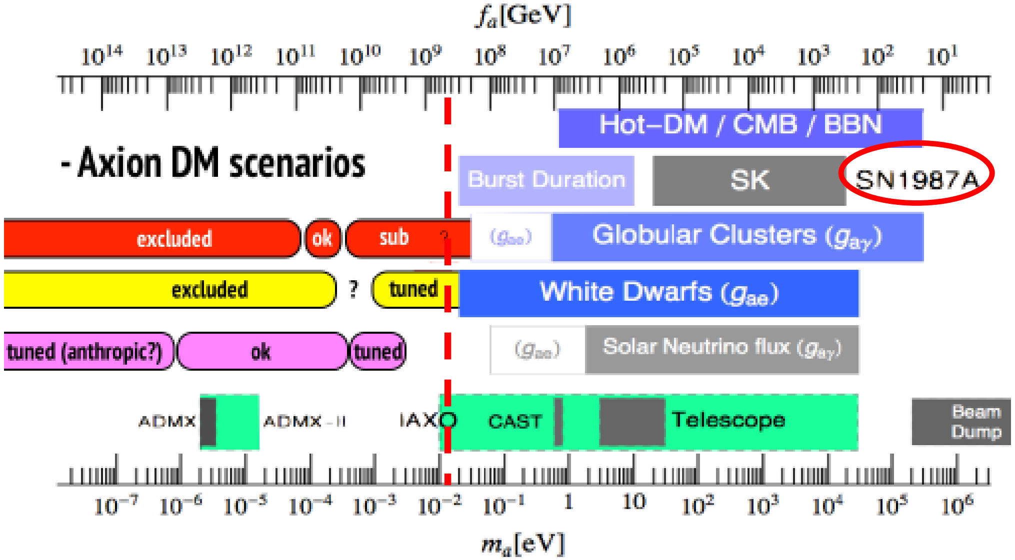
Possible detection in a water Cherenkov detector via oxygen nuclei excitation

Hadronic axion (m_a ~ 1 eV, f_a~10^6 GeV) not excluded by SN 1987A. Possible hot-dark matter candidate. The "hadronic axion window" is closed by cosmological mass bounds.

WHAT WE LEARNT FROM SN 1987A?

- General confirmation of core-collapse paradigm (total energy, spectra, time scale)

- No unexpected energy-loss channel: Restrictive limits on axions…but we a lot of uncertainties….



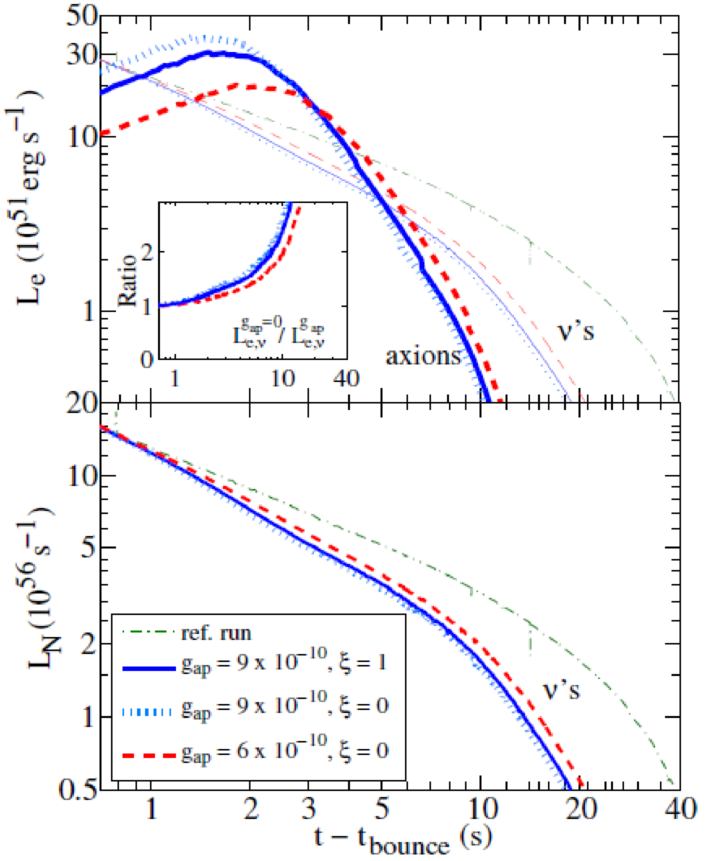
- Improving Energy-Loss Limits with Next Supernova?
  Sensitivity comparable to IAXO one. Important for hadronic axions where WD bounds are absent.

A REAPPRISAL OF AXION EMISSION WITH STATE OF ART SIMULATIONS

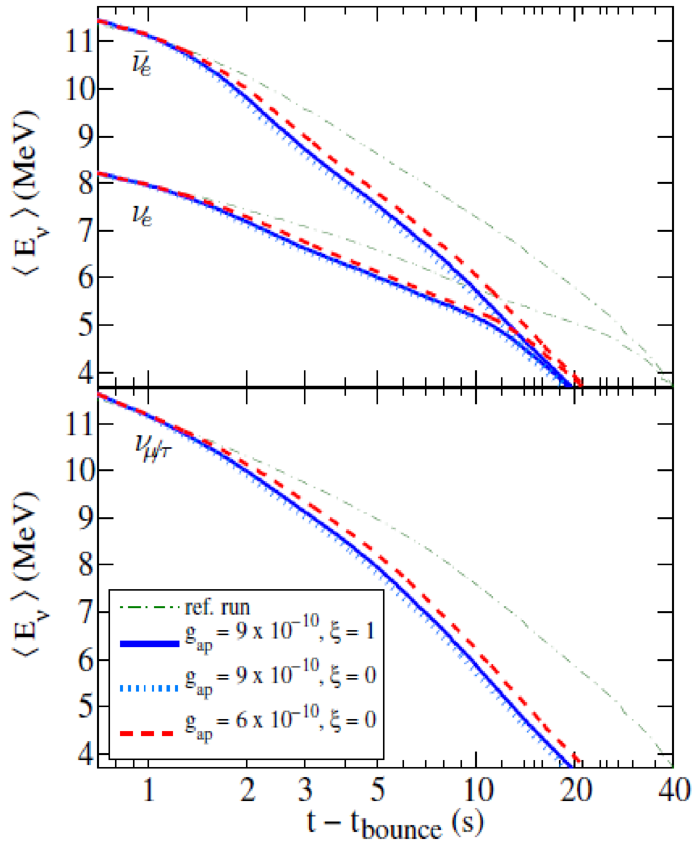
[Fischer, Chakraborty, Giannotti A.M. , *Payez & Ringwald, 1605.08780*]

18 M_{sun} progenitor mass

(spherically symmetric with Boltzmnann ν transport)



(a) Energy and number luminosities

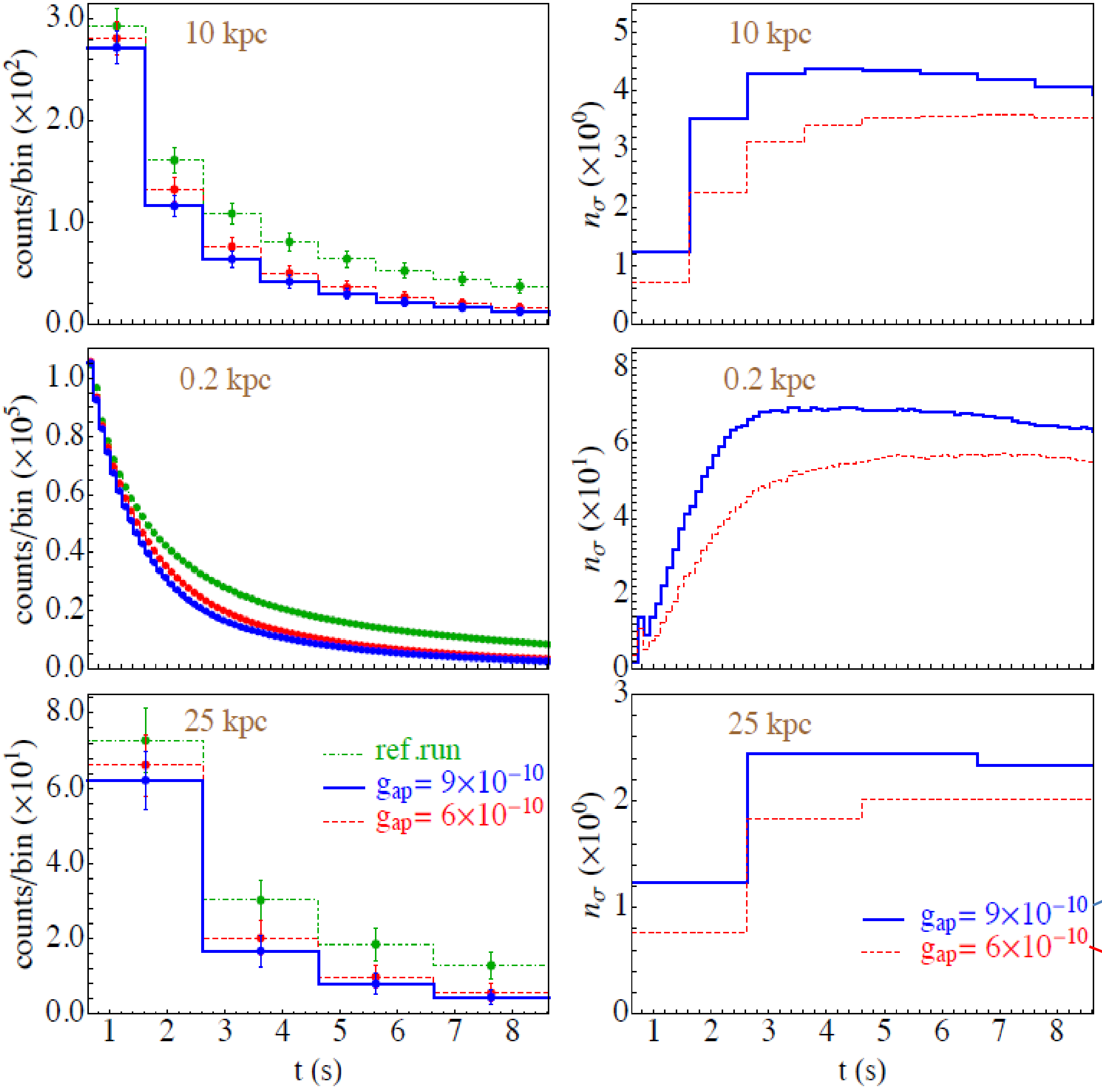


(b) Average neutrino energies

KSVZ hadronic axion model (g_{an} =0)

IMPACT ON NEUTRINO SIGNAL

@ Super-Kamiokande



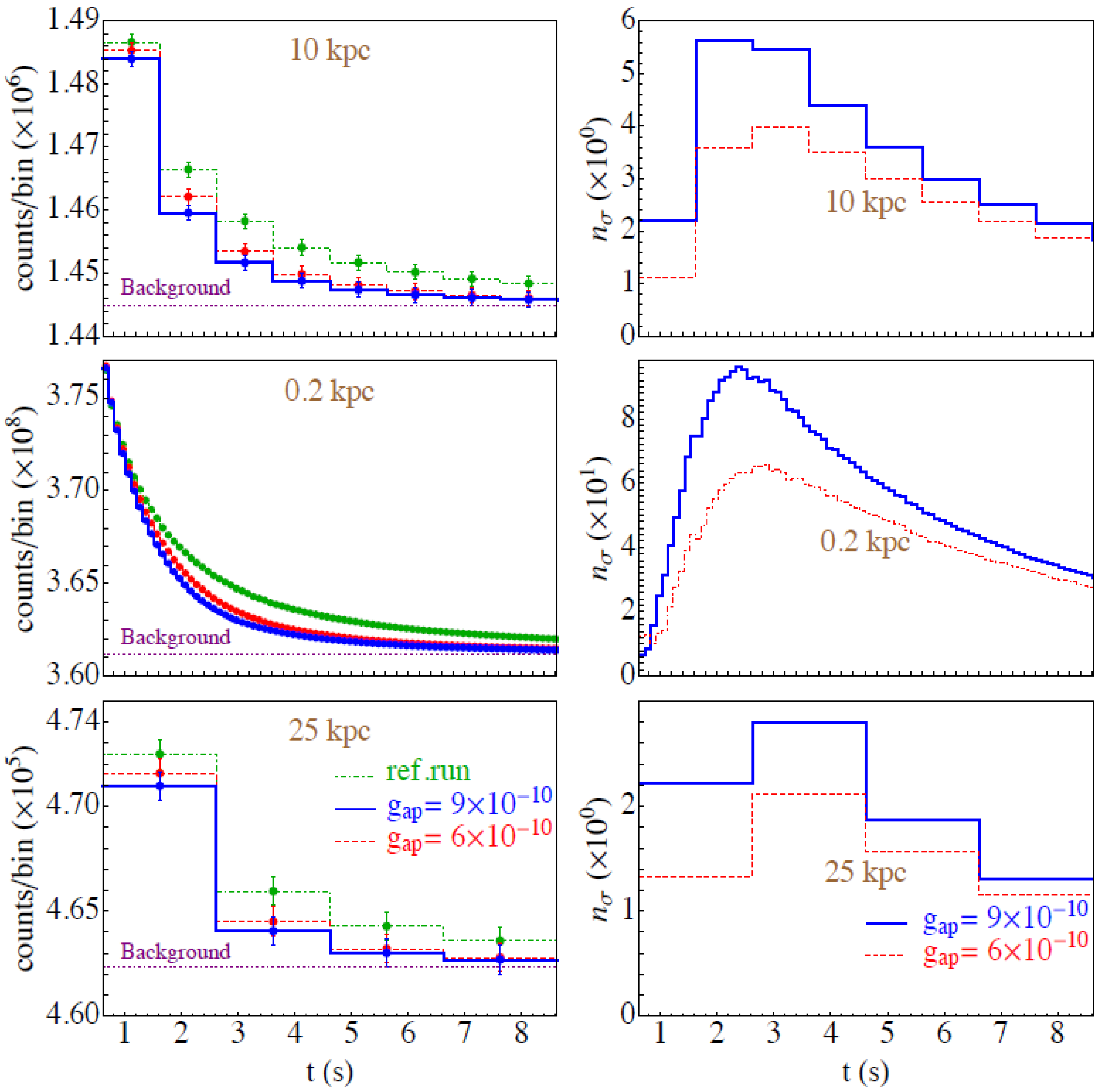
(~ GC)

(Betelgeuse)

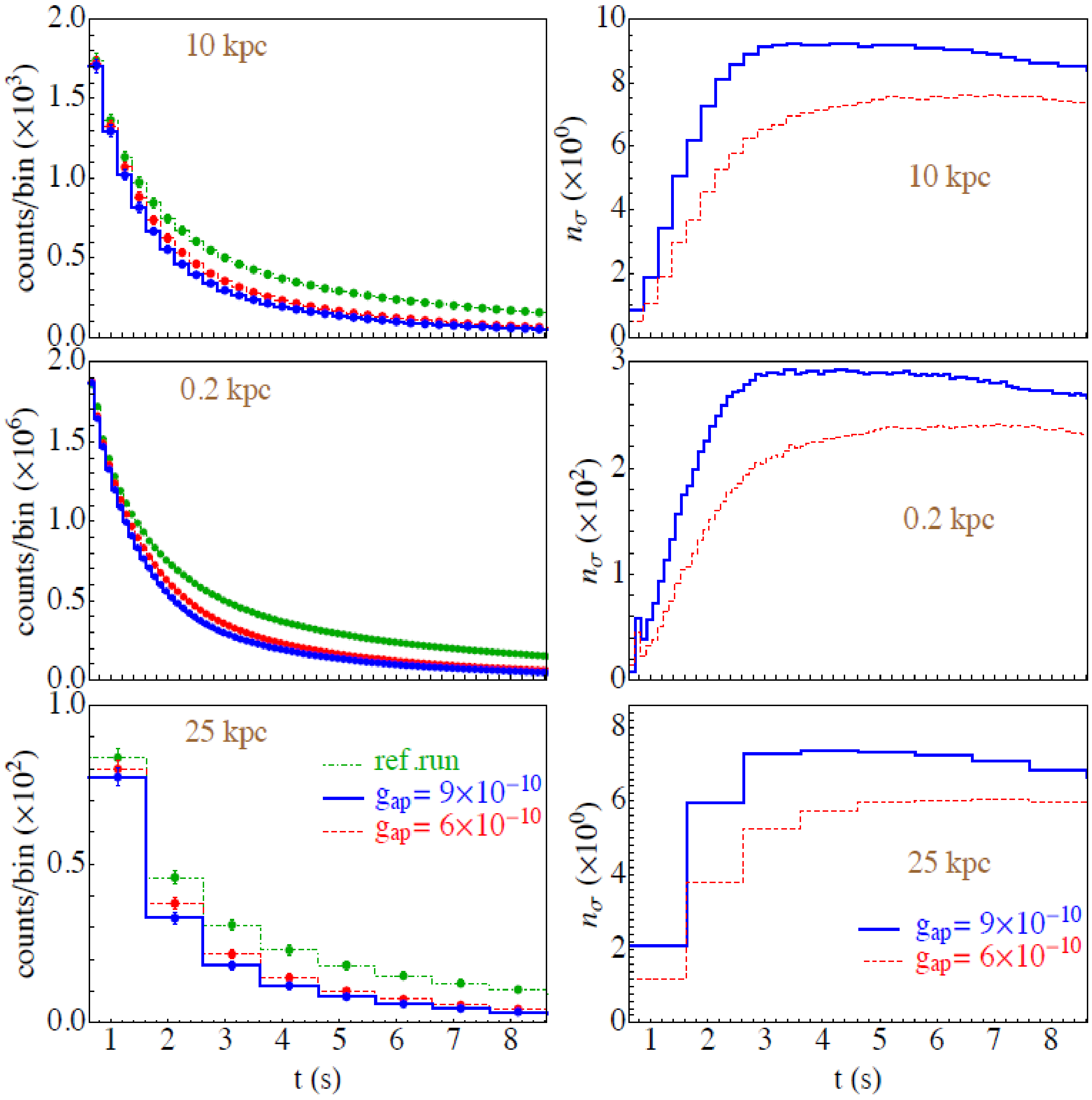
$m_a = 3 \times 10^{-2}\ eV,$
$f_a = 4.8 \times 10^{8} GeV$

$m_a = 8 \times 10^{-2}\ eV,$
$f_a = 7.3 \times 10^{8} GeV$

signal @ Icecube



@ 400 kton WC detector



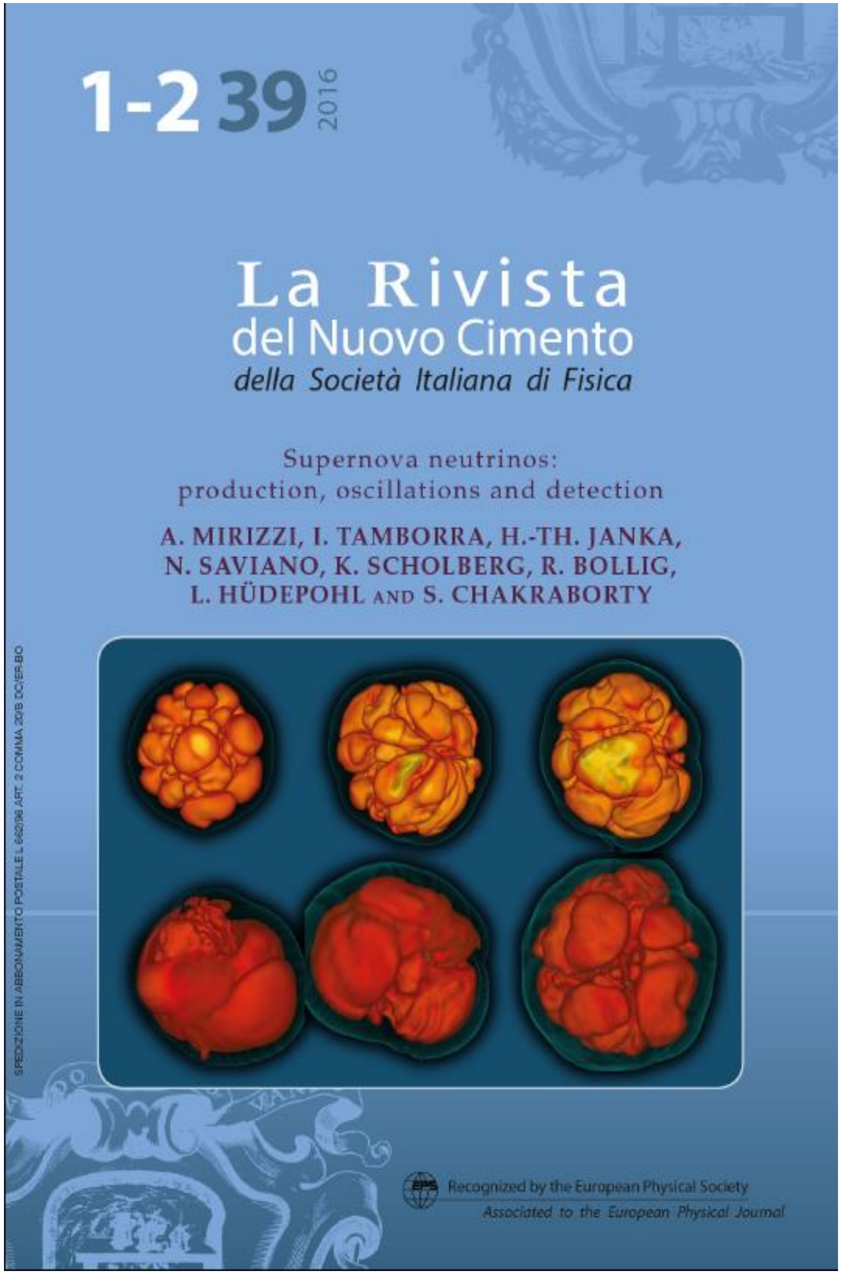
CONCLUSIONS

Observing SN neutrinos is the next frontier of low-energy neutrino astronomy

The physics potential of current and next-generation detectors in this context is enormous, both for particle physics and astrophysics.

Flavor conversions in SNe would provide valuable information on the neutrino mass hierarchy. Further investigations necessary on collective oscillations.

Neutrino signal duration provides most useful particle-physics information. Neutrino signal from next nearby SN would make this argument much more precise.



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La Rivista del Nuovo Cimento della Società Italiana di Fisica

Supernova neutrinos: production, oscillations and detection

A. MIRIZZI, I. TAMBORRA, H.-TH. JANKA, N. SAVIANO, K. SCHOLBERG, R. BOLLIG, L. HÜDEPOHL AND S. CHAKRABORTY

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