Supernova Neutrinos
Status and Perspectives

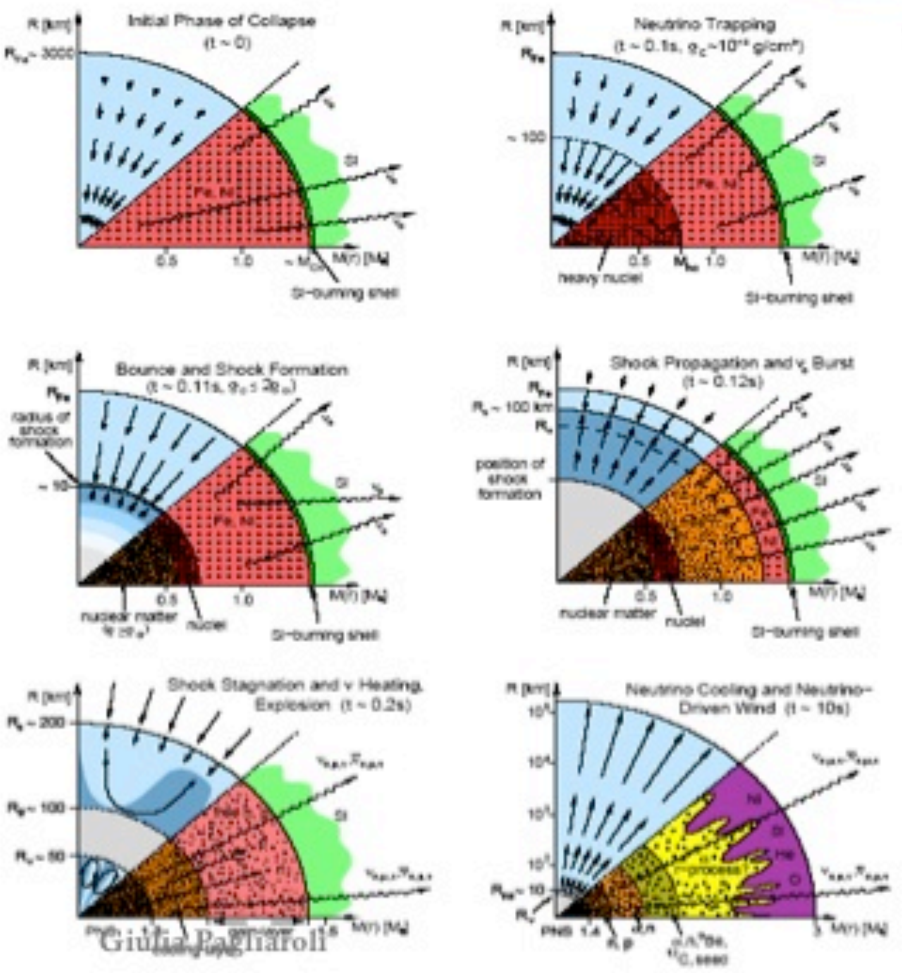
Giulia Pagliaroli

Laboratori Nazionali del Gran Sasso

Outline

- Core Collapse Sne
- Neutrinos Expectations
- Detection Channels
- Particle Physics vs Astrophysics
- Conclusions

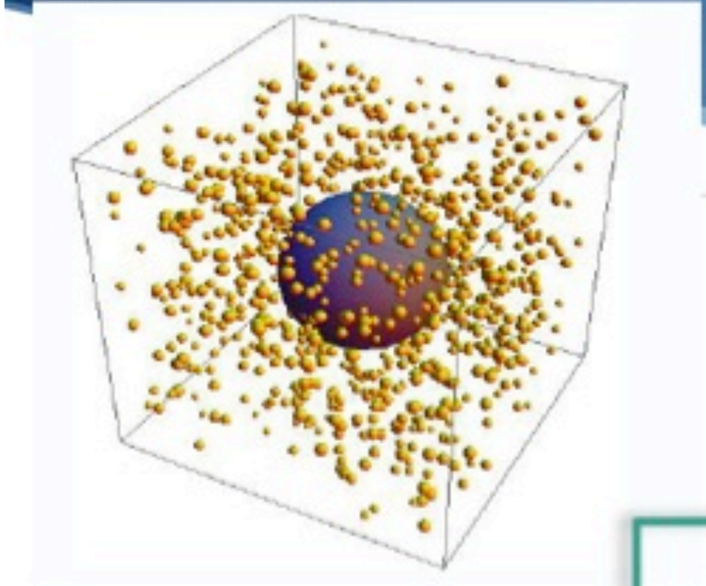
Core-Collapse SNe



1. Collapse
2. Bounce
3. Shock Propagation
4. Shock Stagnation
5. Accretion
6. Cooling PNS

From JANKA et al. Phys.Rev. 442 (2007)

Neutrinos Expectations



ENERGY

$$\varepsilon_B = (1-5)\cdot 10^{53}\, erg$$

$$\varepsilon_\nu = 99\% \cdot \varepsilon_B$$

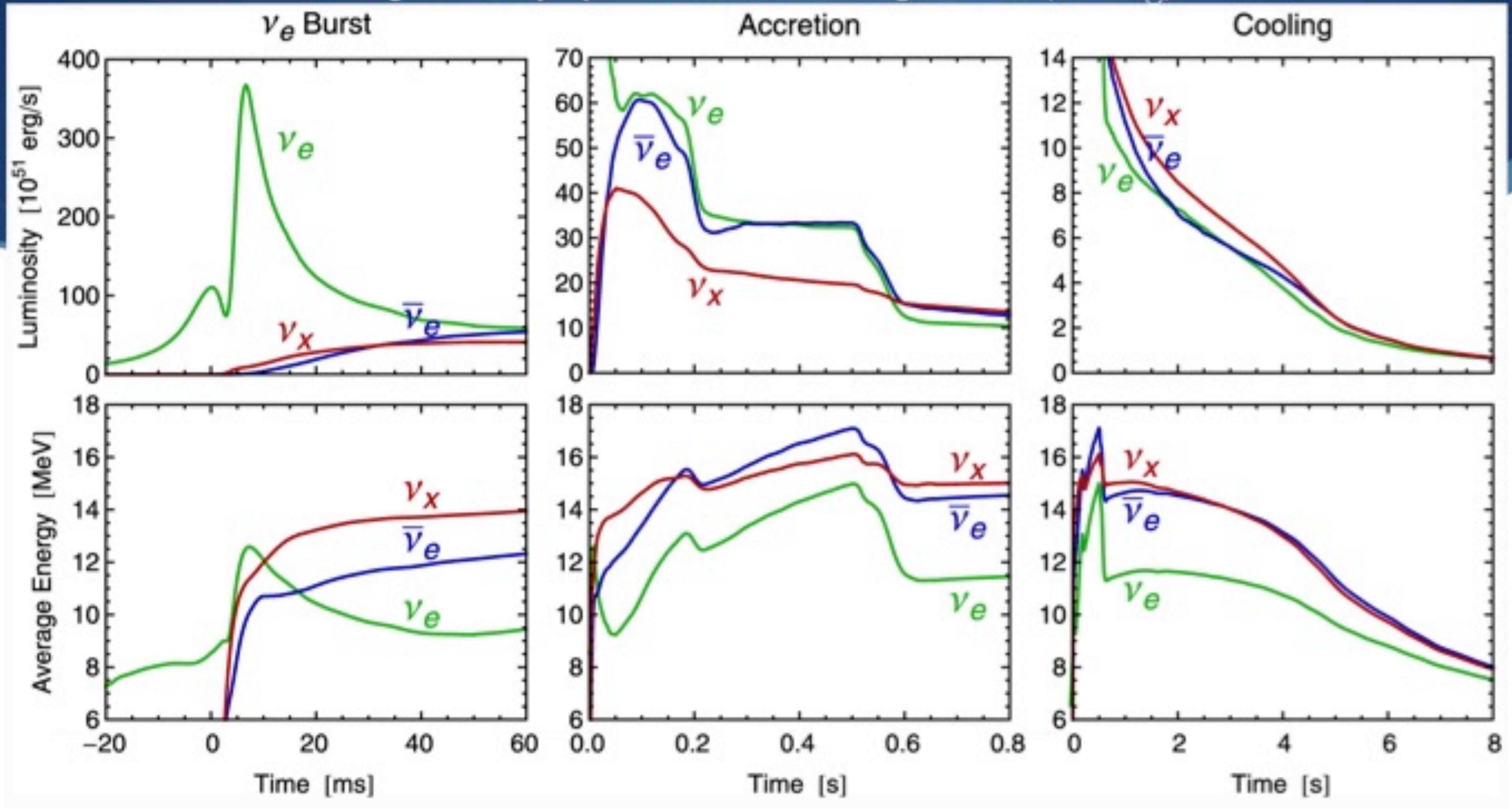
FLUENCE

$$F_{\nu_x} \cong \frac{\varepsilon_B}{6\langle E_{\nu_x}\rangle}\frac{1}{4\pi D^2} \approx 5\cdot 10^{10}\left(\frac{20\text{ kpc}}{D}\right)^2 \frac{10\text{MeV}}{\langle E_{\nu_x}\rangle}\frac{\nu_x}{cm^2}$$

DURATION

$$\Delta t = 10\,\text{sec}$$

Spherically symmetric Garching model (25 $M_\odot$)



- Neutronization burst
- Standard Candle

- Not thermal spectra
- 10% of the total energy
- Explosion Mechanism??

- Trapped Neutrinos
- Thermal spectra
- 90% of the total energy

Production vs Oscillation

- Neutrinos are produced in the most internal regions $R < 10^2\,km$
  - Neutronization and Accretion: $R < 10^2\,km$
  - Cooling: $R < 10\,km$
- Neutrinos free-stream: $R > 10^2\,km$
- Oscillations relevant for:
  - Collective Conversion $R \sim 10^3\,km$
  - Standard MSW $R \sim 10^4\,km$

Collective Effects

- Depend on the Mass Hierarchy
  - NH: No Collective Effects
  - IH:

$$P_{ee}^{\nu\nu} = \begin{cases} 0 & E > 8\,\mathrm{MeV} \\ 1 & E < 8\,\mathrm{MeV} \end{cases} \qquad P_{\overline{ee}}^{\nu\nu} = P(t)$$

Relevant in a limited time window

Saviano *et al*. **Phys.Rev. D85 (2012) 113002**

Complicated phenomenology: further investigations are required

Even in the IH case, the effects are less relevant when time and energy integrated signals are considered

MSW

Normal Hierarchy

$$P_{ee}^{MSW} = 0 \quad P_{\overline{ee}}^{MSW} \cong 0.7$$

$$F_e = F_x^0$$

$$F_{\overline{e}} = 0.7 \cdot F_{\overline{e}}^0 + 0.3 \cdot F_x^0$$

Inverted Hierarchy

$$P_{ee}^{MSW} \cong 0.3 \quad P_{\overline{ee}}^{MSW} \cong 0$$

$$F_e = 0.3 \cdot F_e^0 + 0.7 \cdot F_x^0$$

$$F_{\overline{e}} = F_x^0$$

Time Integrated Features

Total energy budget

$$\mathrm{E}_b = 3 \cdot 10^{53}\, erg$$

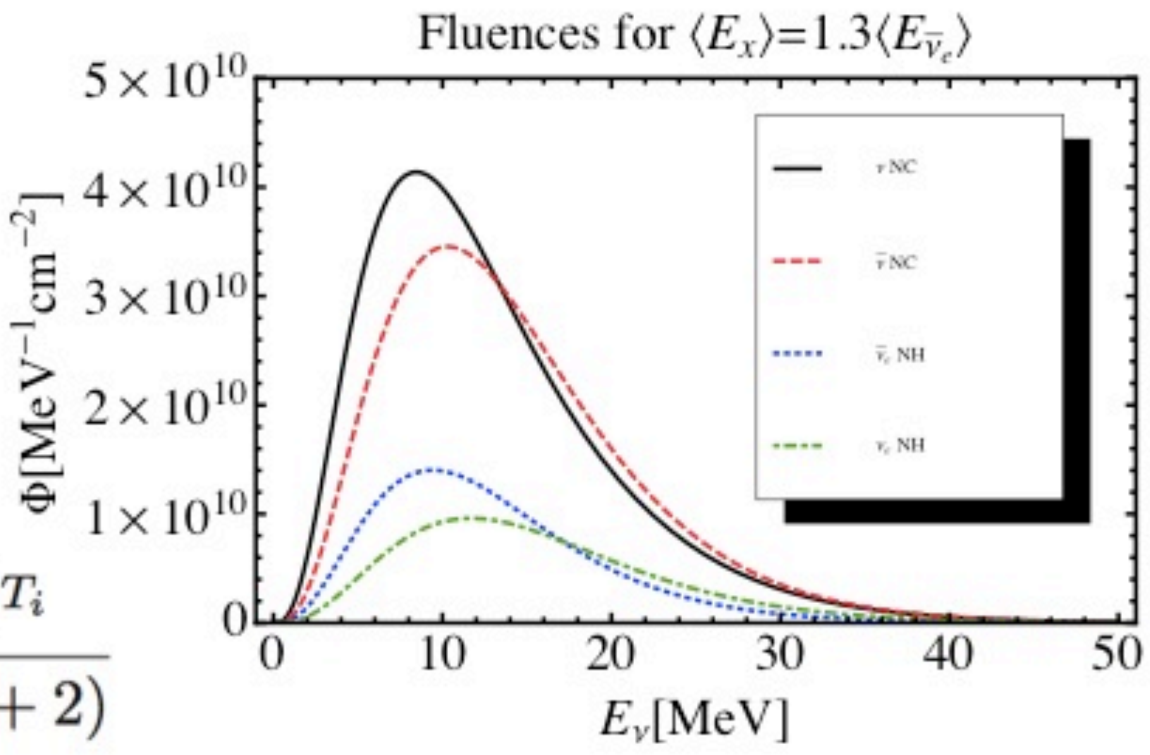
Equipartition Hypothesis

$$\varepsilon_i = \mathrm{E}_b \cdot f_i$$

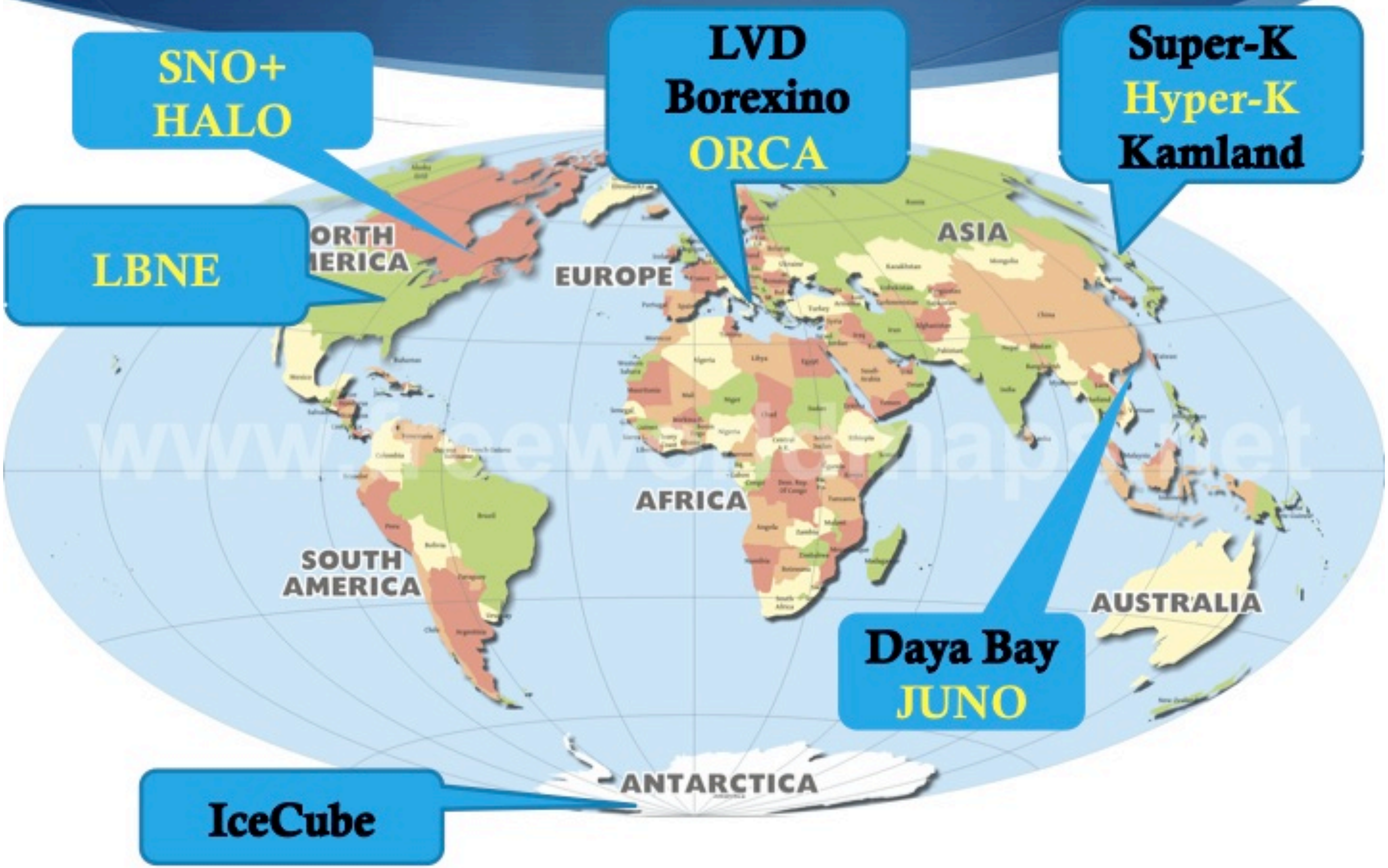
$$f_i = 1/6$$

Fluence at the Earth

$$\Phi_i = \frac{\mathcal{E}_i}{4\pi D^2} \times \frac{E^\alpha e^{-E/T_i}}{T_i^{\alpha+2}\Gamma(\alpha+2)}$$


Fluences for $\langle E_x \rangle = 1.3 \langle E_{\bar{\nu}_e} \rangle$

Pinched spectra with $\alpha = 3 \quad T_i = \langle E_i \rangle / (\alpha + 1)$



SNO+
HALO

LBNE

LVD
Borexino
ORCA

Super-K
Hyper-K
Kamland

Daya Bay
JUNO

IceCube

Main Channels for Detection

$$N_{ev} \propto N_t \int_{E_{thr}}^{\infty} dE_{vis}\, \sigma_{Int}(E_\nu) F_\nu(E_\nu)$$

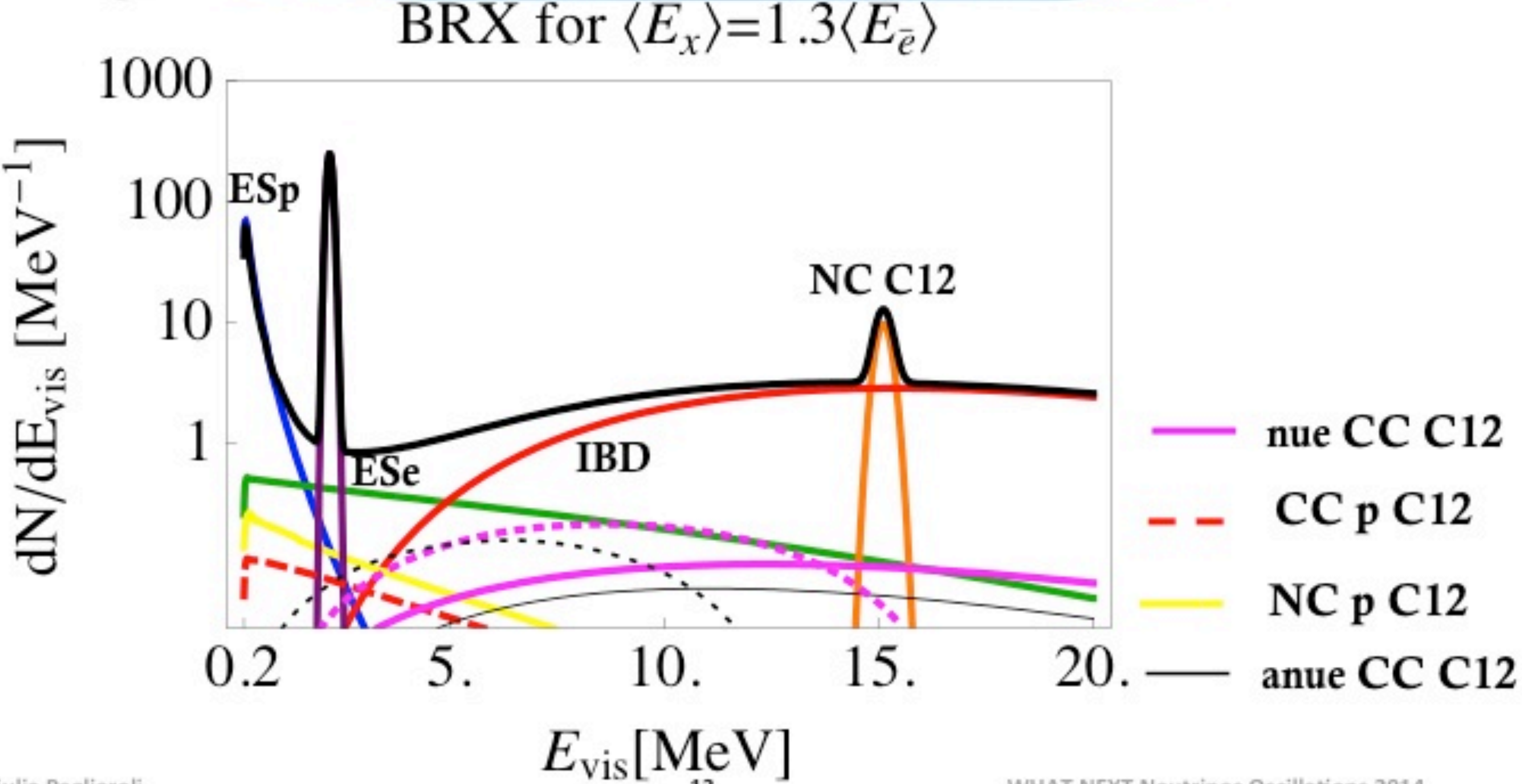
- Charge-Current processes for $\bar{\nu}_e$
  - IBD tagged by n-capture $O(10^2 / kton)$
  - $^{12}C\, /\, ^{16}O\, /\, ^{40}Ar$ Tagged by ex. states $O(10 / kton)$
- Charge-Current processes for ν_e
  - ^{208}Pb producing electron $O(10^2 / kton)$
  - ^{40}Ar Tagged by excited state $O(10^2 / kton)$
  - $^{12}C\, /\, ^{16}O$ Tagged by excited states $O(few / kton)$
- Neutral-Current processes for ν_x
  - Elastic Scattering on proton $O(10^2 / kton)$
  - ^{208}Pb $O(10^2 / kton)$
  - ^{12}C Gamma line $O(10 / kton)$

Ultrapure Liquid Scintillators
SN at 10 kpc

Channel	Color code	Signal	BRX	KAM	SNO+
$\bar{\nu}_e + p \rightarrow n + e^+$	red	e^+	54.1 (49.6)	256.5 (235.3)	175.8 (161.2)
$n + p \rightarrow D + \gamma_{2.2\text{ MeV}}$	purple	γ	46.0 (42.1)	200.1(183.5)	149.4 (137.1)
$\nu + p \rightarrow \nu + p$	blue	p	16.0 (5.7)	29.0 (6.2)	74.9 (29.2)
$\nu +^{12} C \rightarrow \nu +^{12} C^*$	orange	γ	4.7 (2.1)	15.0 (6.7)	12.3 (5.5)
$\nu + e^- \rightarrow \nu + e^-$	green	e^-	4.4 (4.6)	14.8 (15.5)	12.0 (12.4)
$\nu_e +^{12} C \rightarrow e^- +^{12} N$	magenta	e^-	2.0 (0.7)	6.4 (2.1)	5.3 (1.7)
$\bar{\nu}_e +^{12} C \rightarrow e^+ +^{12} B$	black thin	e^+	1.2 (0.8)	3.7 (2.6)	3.0 (2.1)
$\nu +^{12} C \rightarrow \nu + p +^{11} B$	yellow	p	0.8 (0.2)	2.4 (0.6)	2.1 (0.6)
$\nu_e +^{12} C \rightarrow e^- + p +^{11} C$	red dashed	p	0.5 (0.1)	1.5 (0.3)	1.3 (0.2)

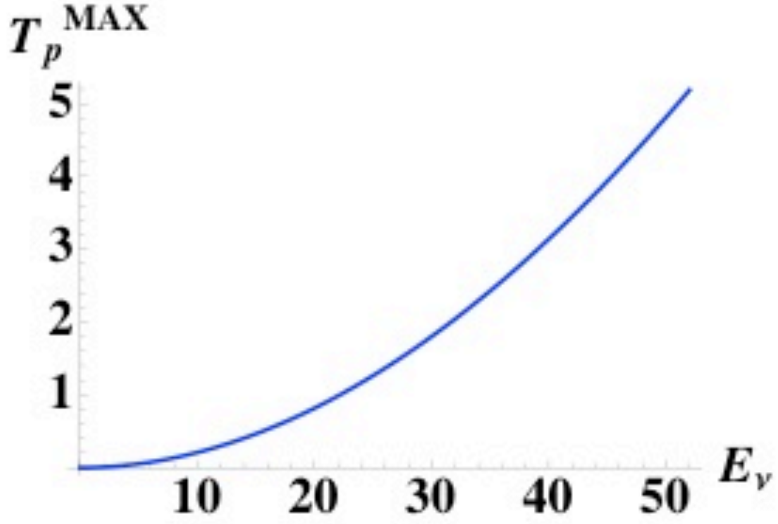
C. Lujan-Peschard, GP and F. Vissani **JCAP 1407 (2014) 051**

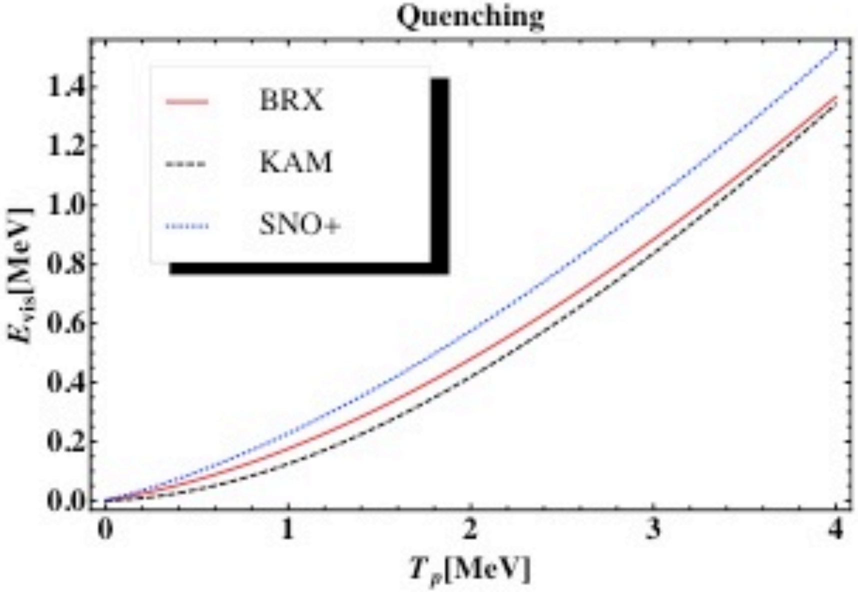
BOREXINO SPECTRUM



NC ES on protons vs Quenching

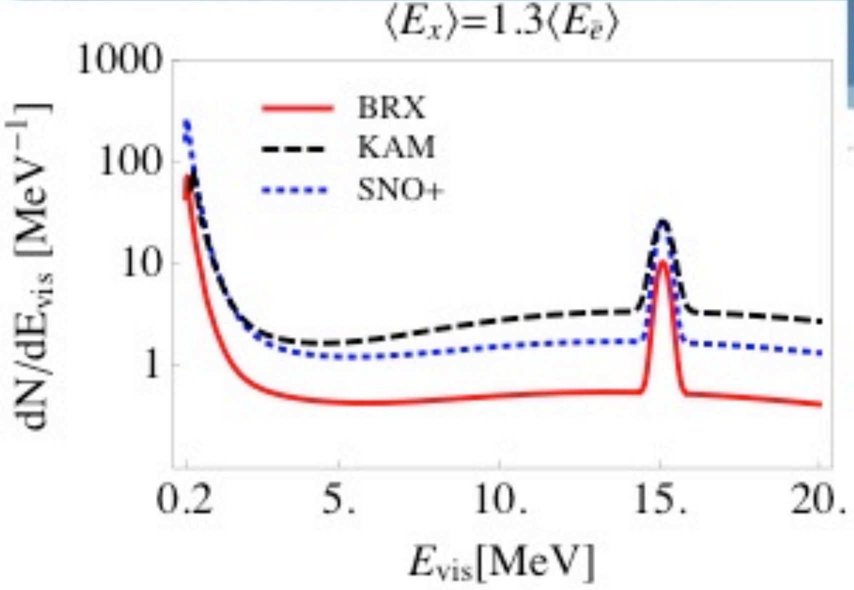
$$E_\nu = 20\ \mathrm{MeV} \Rightarrow \mathrm{T}_p^{Max} \cong 0.8\ \mathrm{MeV} \Rightarrow \mathrm{E}_{vis} = 0.13\ \mathrm{MeV}$$





For SNO+ (best LY) $\mathrm{E}_{vis} > 200\ k\mathrm{eV} \Rightarrow E_\nu > 22\ \mathrm{MeV}$

Statistics vs Systematics



- ES on proton: 20% of systematic for cross section and 2% for quenching.
- C12 line: 20% of systematic for cross section
- Signals not tagged due to other channels represent small but irreducible uncertainty
- Future Mton detectors dominated by the systematics

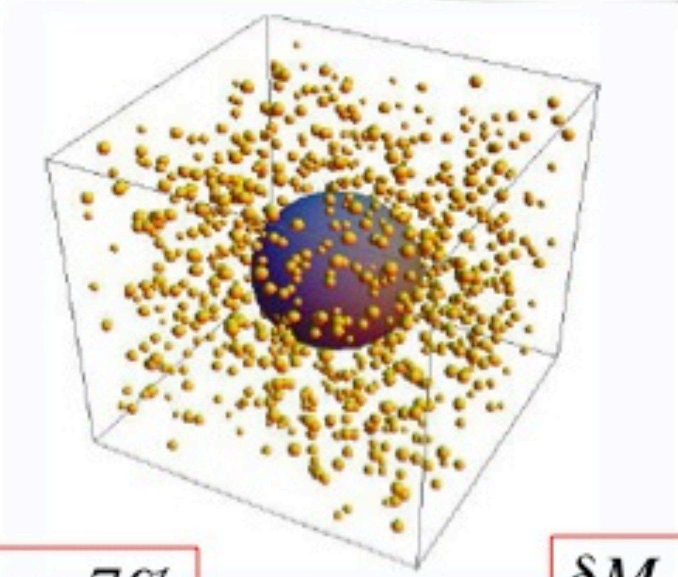
	$[E_{thr}, 1.8]$ MeV		[14,17] MeV	
	NC± stat ± syst	Background	NC± stat ± syst	Background
BRX	$18.0 \pm 4.2 \pm 3.6$	0.9	$4.7 \pm 2.2 \pm 0.9$	1.6
KAM	$28.9 \pm 5.4 \pm 5.8$	2.8	$15.0 \pm 3.9 \pm 3.0$	10.0
SNO+	$74.9 \pm 8.7 \pm 14.9$	2.5	$12.3 \pm 3.5 \pm 2.5$	5.0

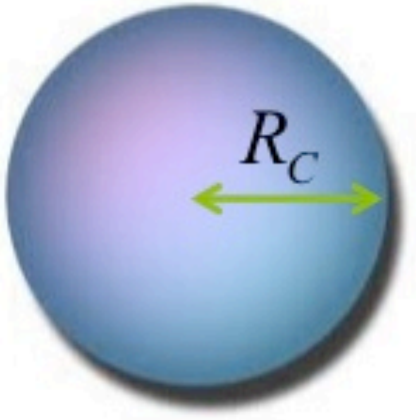
Astrophysics with Neutrinos

Super-Kamiokande detector and a SN distance of 20 kpc
GP *et al.* PRL 103, 031102 (2009)

ACCRETION PHASE

COOLING PHASE





$\boxed{\delta\tau_a = 7\%}$ $\boxed{\delta T_a = 3\%}$ $\boxed{\delta M_a = 27\%}$

$\boxed{\delta T_c = 2\%}$ $\boxed{\delta R_c = 7\%}$ $\boxed{\delta\tau_c = 2\%}$

Matter properties below the shock-wave
during the accretion phase->Explosion Mechanism

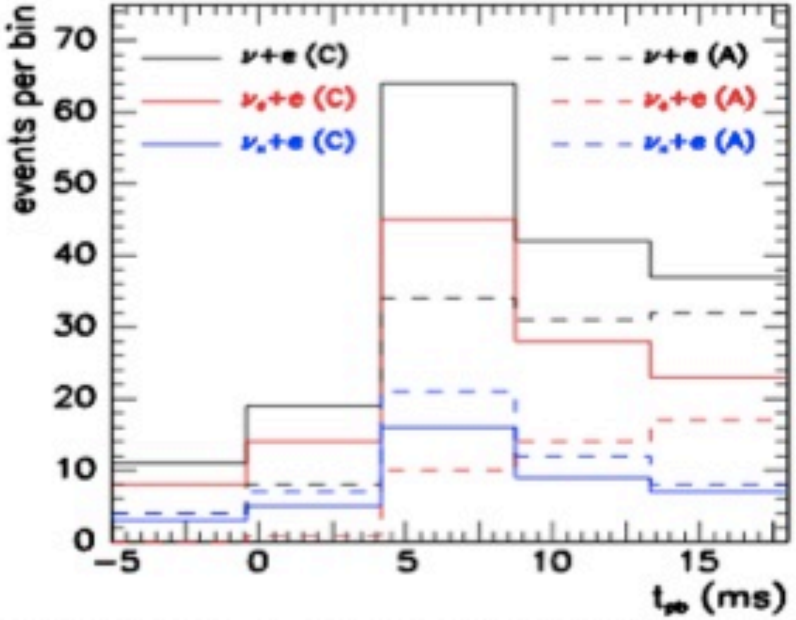
Properties of the proto-neutron
Star->EoS sensitivity

Particle Physics with Neutrinos

Mton detectors and SN at 10 kpc

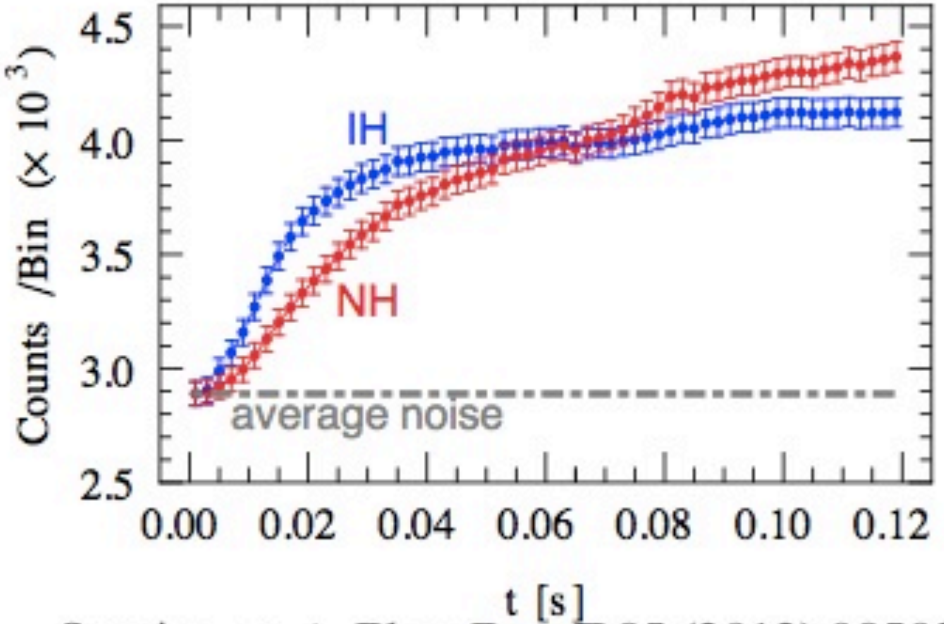
Mass Hierarchy using fast temporal structures: Mton detectors with a good time resolution

Using Neutronization burst



Kachelriess *et al.* Phys.Rev. D71 (2005) 063003

IceCube Using Rise Time



Serpico *et al.*, Phys.Rev. D85 (2012) 085031

Mass Hierarchy vs SN(10 kpc)

Earth Matter effect of Neutrinos Oscillations

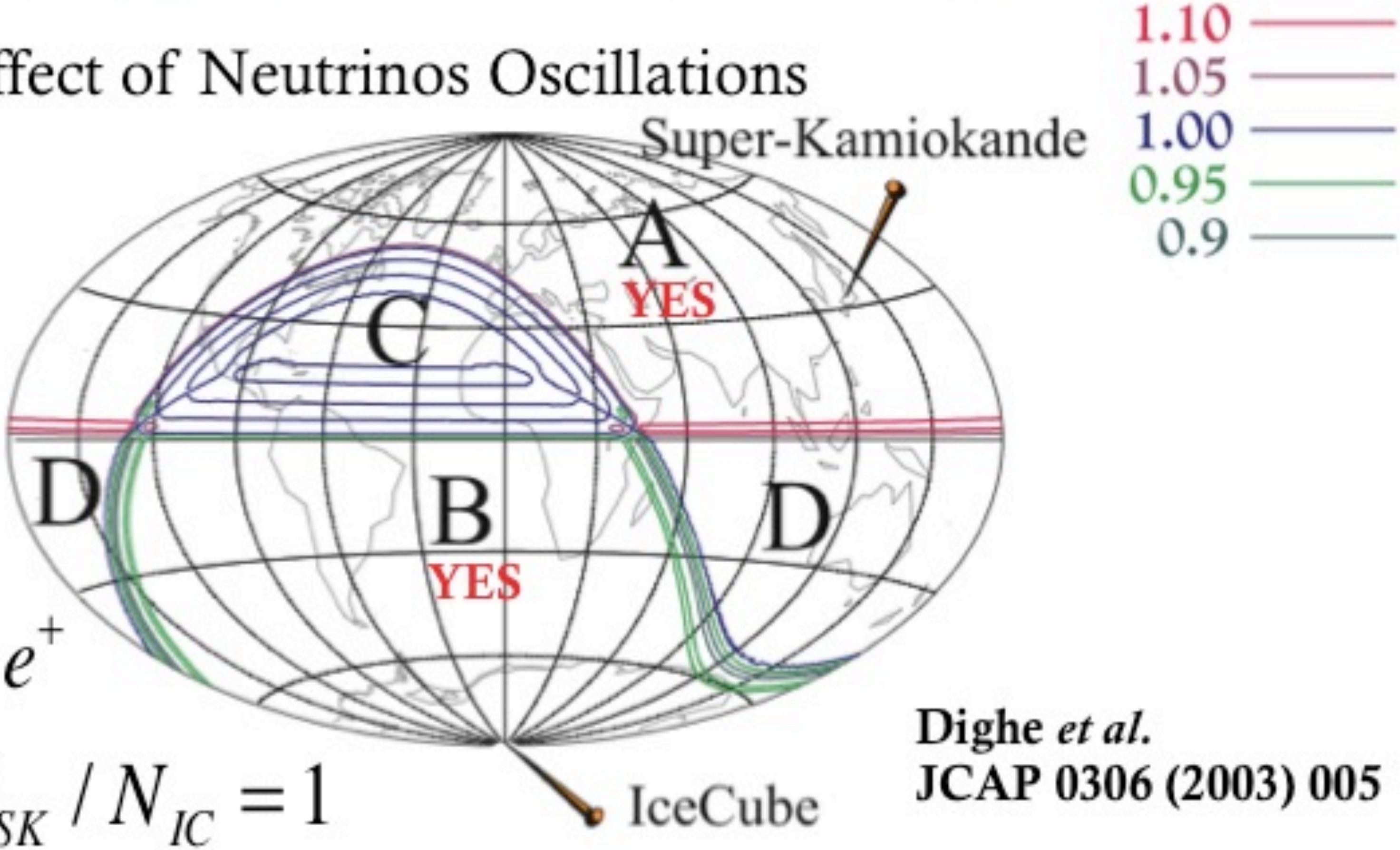
NH	IH
$\bar{\nu}_e$	ν_e

YES

Channel

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

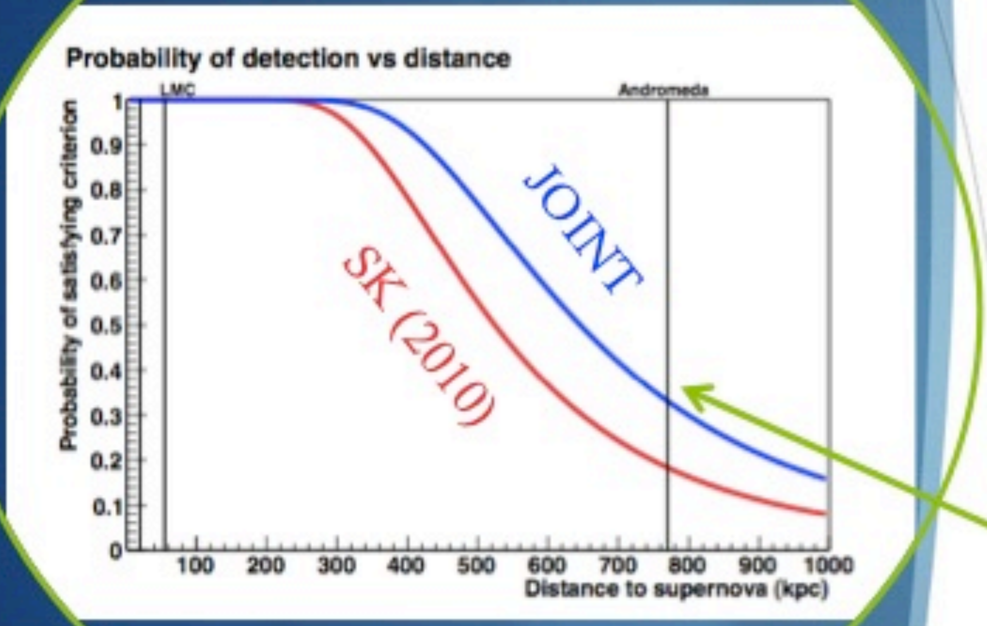
IH shows $N_{SK} / N_{IC} = 1$



**Dighe *et al.*
JCAP 0306 (2003) 005**

Multi-Messenger Physics

Network of Neutrinos and GW detectors
Ligo-Virgo-Borexino-LVD and IceCube
Started a data exchange



Distance Reach

- Super-Kamiokande 's recent "distant" burst search requiring two neutrino events (with energy threshold 17 MeV) within 20 seconds shows a ~**18%** probability of detecting a SN in M31
- Requiring the coincidence with a GW trigger it is possible to lower the threshold to 8.5 MeV increasing the detection probability to the ~**35%**

Leonor et al. Class.Quant.Grav. 27 (2010) 084019

Conclusions

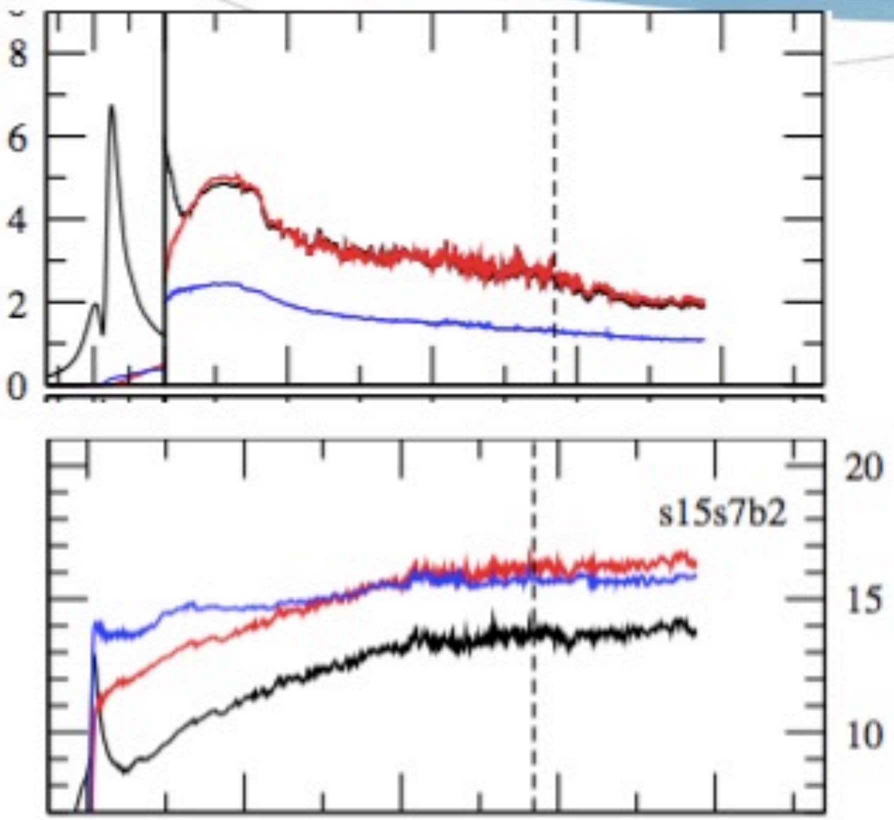
- Neutrinos emitted from CCSNe can be fundamental probes to infer about the explosion mechanism and mass hierachy
- For future Mton detectors efforts are needed to reduce systematic uncertainty
- A complete picture can be obtained only by combining different detectors techniques

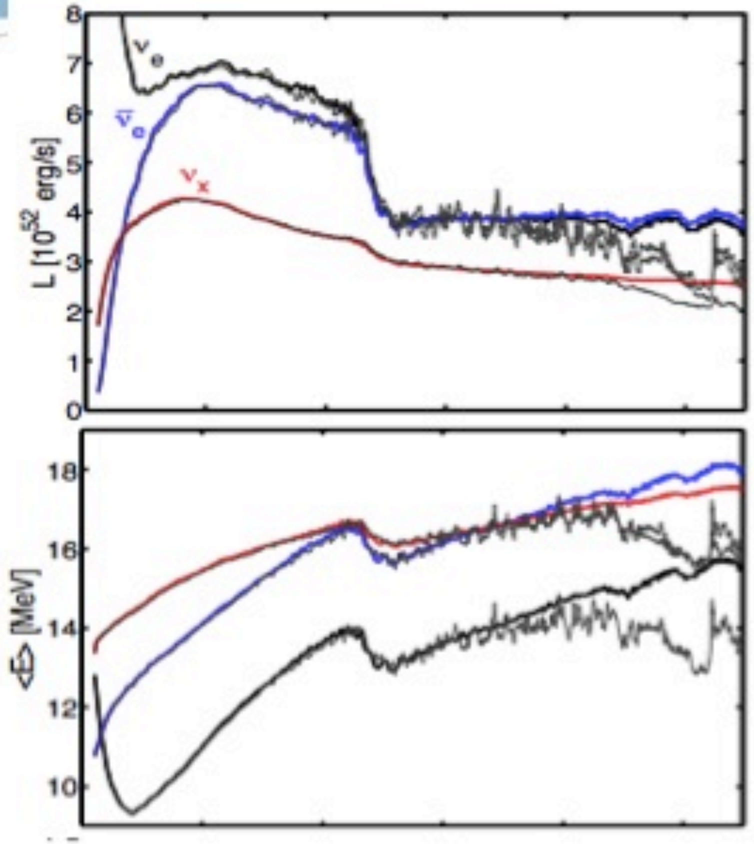
Extra-Slides

Predictions vs Time

full-scale 3D simulation 27 M

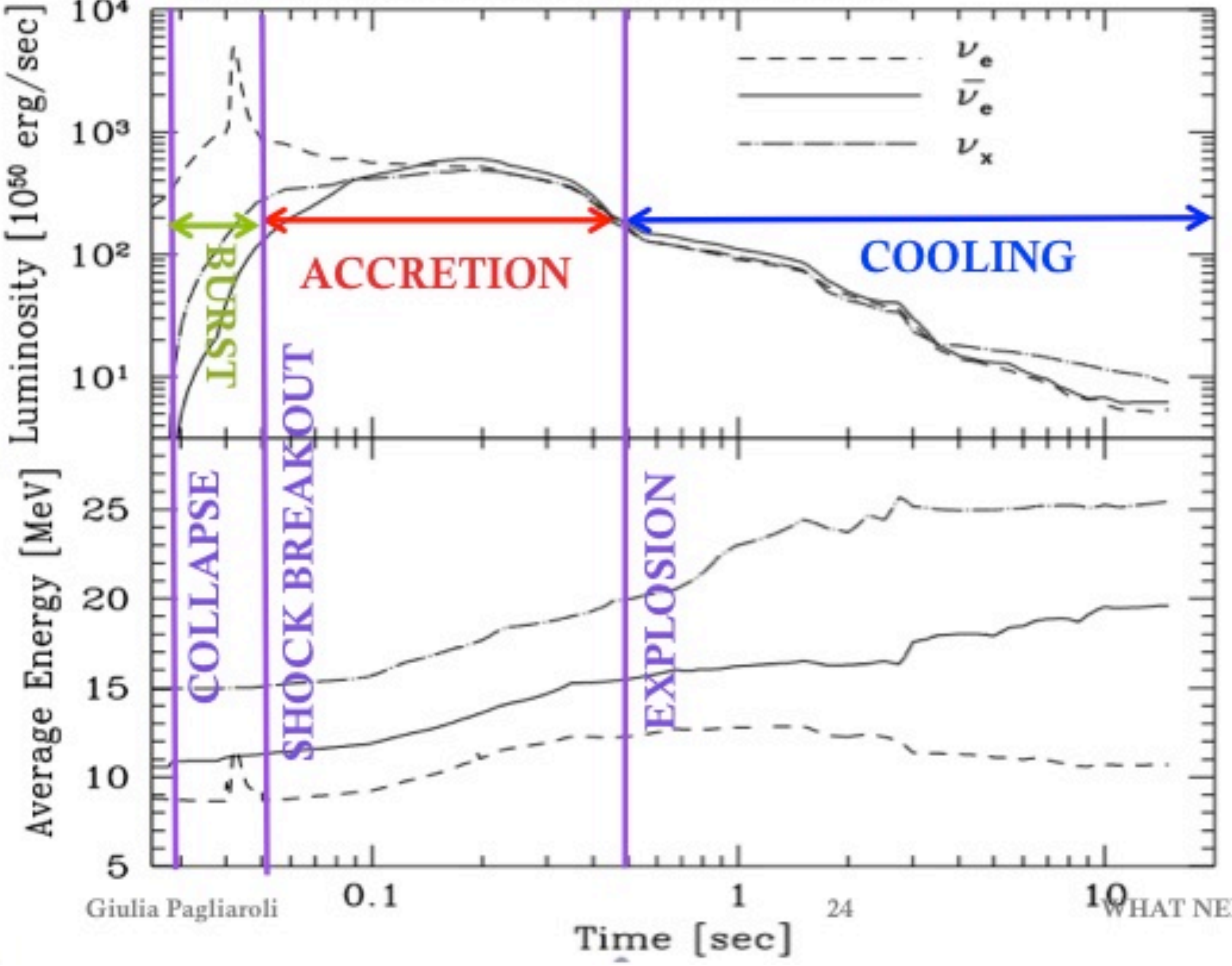
Axisymmetric (2D) simulations 15 M





Astrophys.J. 788 (2014) 82

Neutrino Emission Phases



Totani *et al.* **Astrophys.J. 496 (1998) 216-225**

Luminosity:

$$L_{\max} = (1-5)\cdot 10^{52}\,\frac{erg}{\sec}$$

$$M = 20\ M_{\Theta}$$

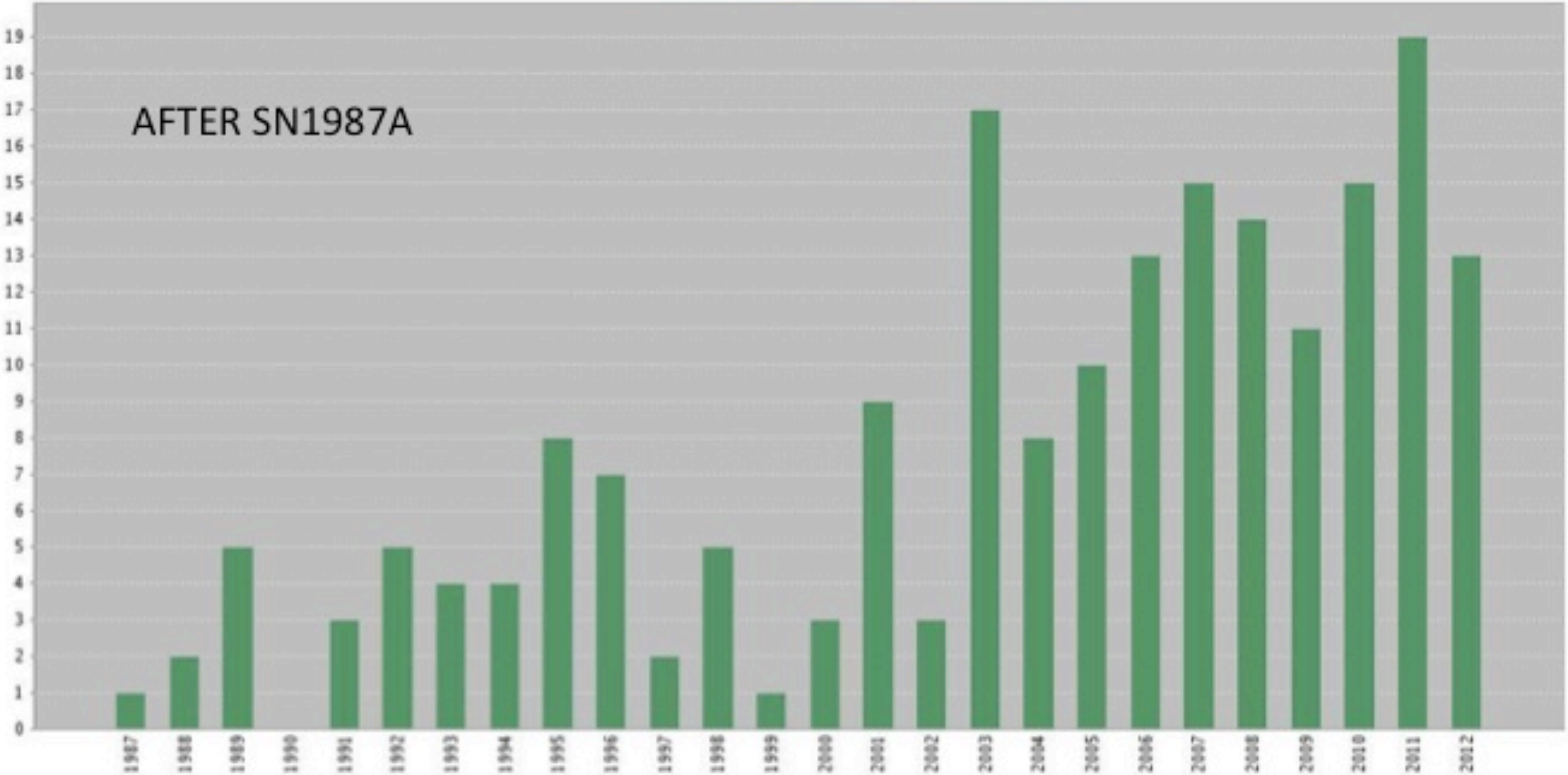
$$\left\langle E_{\bar{\nu}_e} \right\rangle = 15.3\,\mathrm{MeV}$$

Improvements

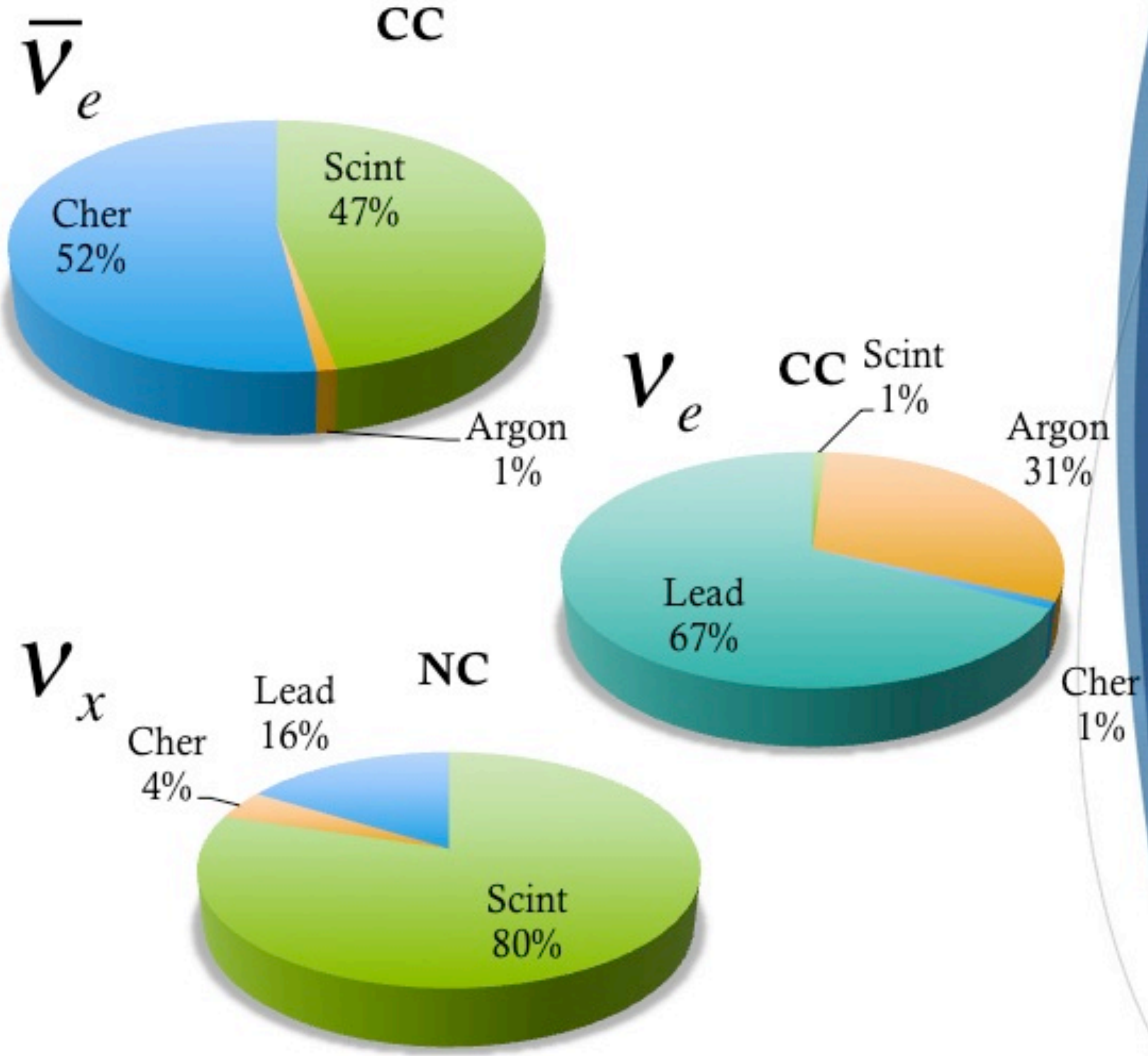
- From Newtonian gravity to Full General Relativity
- A large sets of Equations of State
- Improvement on Neutrino Transport
- Increasing of the list of Weak interactions
- Increasing the number of Dimensions from 1D to 3D--→New effects SASI, LESA…

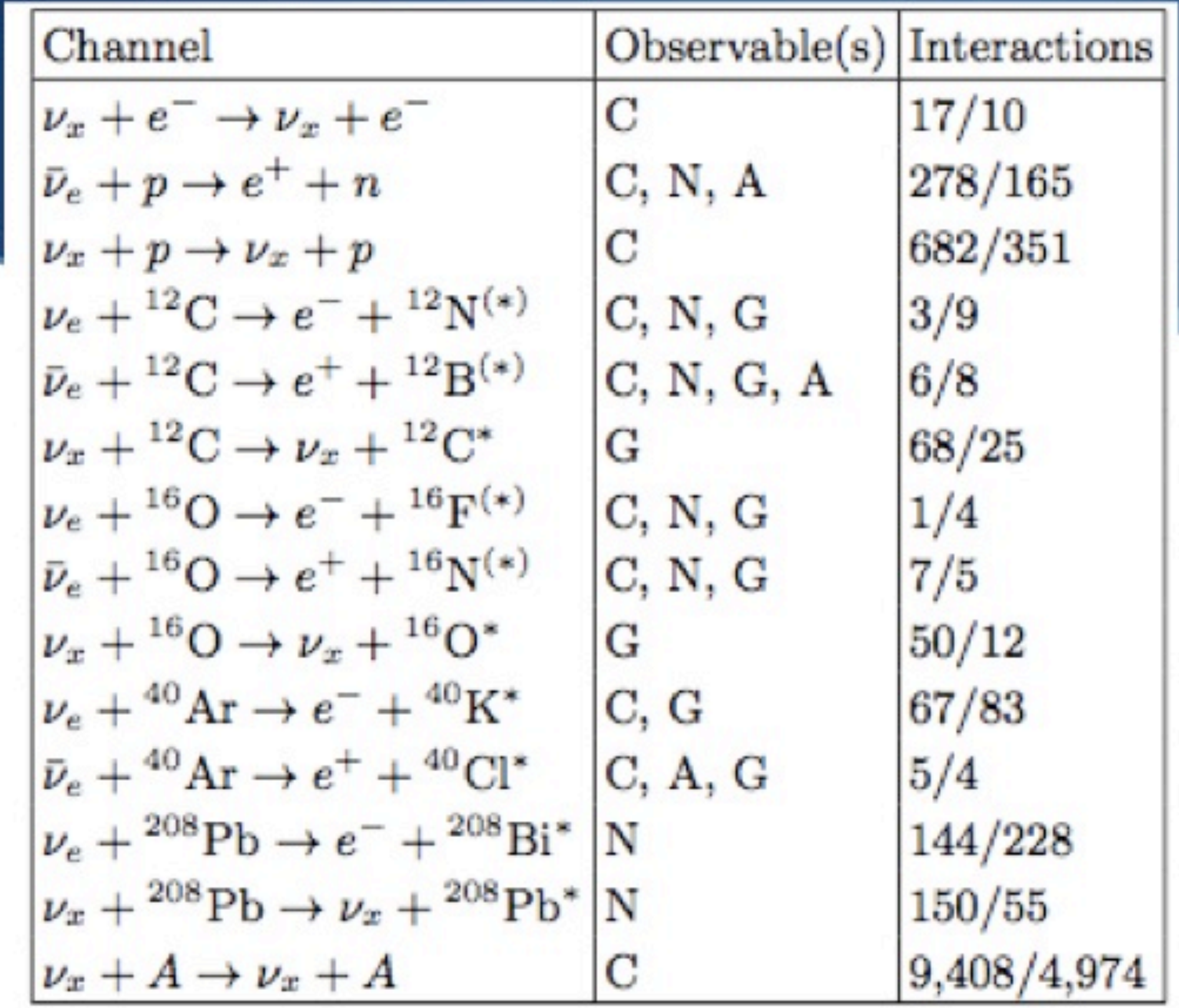
EXPLOSION MECHANISM IS STILL UNCERTAIN

NUMERICAL SIMULATIONS



Flavor Sensitivity





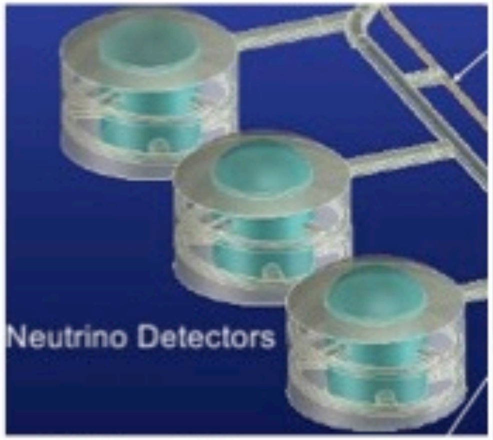
Channel	Observable(s)	Interactions
$\nu_x + e^- \rightarrow \nu_x + e^-$	C	17/10
$\bar{\nu}_e + p \rightarrow e^+ + n$	C, N, A	278/165
$\nu_x + p \rightarrow \nu_x + p$	C	682/351
$\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}^{(*)}$	C, N, G	3/9
$\bar{\nu}_e + {}^{12}\mathrm{C} \rightarrow e^+ + {}^{12}\mathrm{B}^{(*)}$	C, N, G, A	6/8
$\nu_x + {}^{12}\mathrm{C} \rightarrow \nu_x + {}^{12}\mathrm{C}^*$	G	68/25
$\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F}^{(*)}$	C, N, G	1/4
$\bar{\nu}_e + {}^{16}\mathrm{O} \rightarrow e^+ + {}^{16}\mathrm{N}^{(*)}$	C, N, G	7/5
$\nu_x + {}^{16}\mathrm{O} \rightarrow \nu_x + {}^{16}\mathrm{O}^*$	G	50/12
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	C, G	67/83
$\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	C, A, G	5/4
$\nu_e + {}^{208}\mathrm{Pb} \rightarrow e^- + {}^{208}\mathrm{Bi}^*$	N	144/228
$\nu_x + {}^{208}\mathrm{Pb} \rightarrow \nu_x + {}^{208}\mathrm{Pb}^*$	N	150/55
$\nu_x + A \rightarrow \nu_x + A$	C	9,408/4,974

C, energy loss of a charged particle; N, produced neutrons; G, de-excitation γ s; A, positron annihilation γ s.

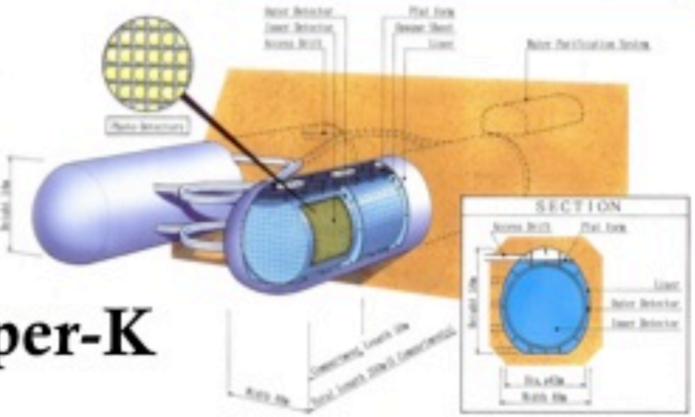
K. Scholberg , **Ann.Rev.Nucl.Part.Sci. 62 (2012) 81-103**

Next Generation Large-Scale Detector Concepts

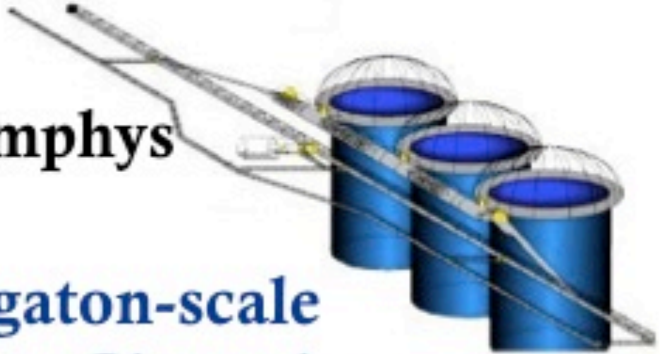
DUSEL
LBNE



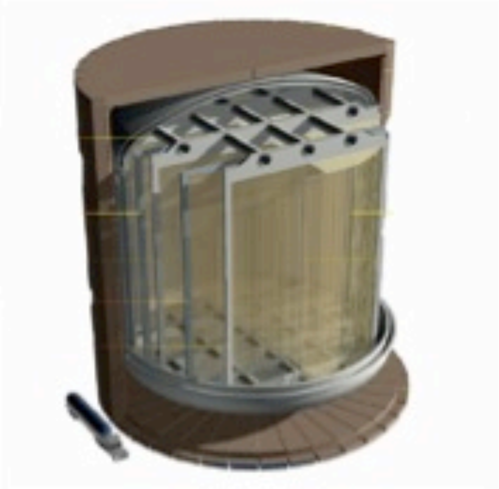
Hyper-K



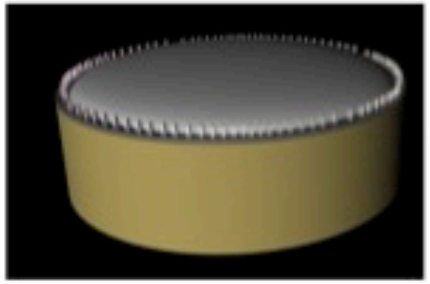
Memphys



Megaton-scale water Cherenkov



5-100 kton liquid Argon



100 kton scale scintillator

LENA
HanoHano
Juno

Flavor Sensitivity for 1kton of targets

- IBD tagged by n-capture
- C12/O16/Ar40 Tagged Exited States

$\bar{\nu}_e$

- Pb208 (electron for discrimation?)
- Ar40
- C12/O16

ν_e

- ES on p ->quenching?
- Pb208*
- C12* spectral peak/O16 gamma near threshold

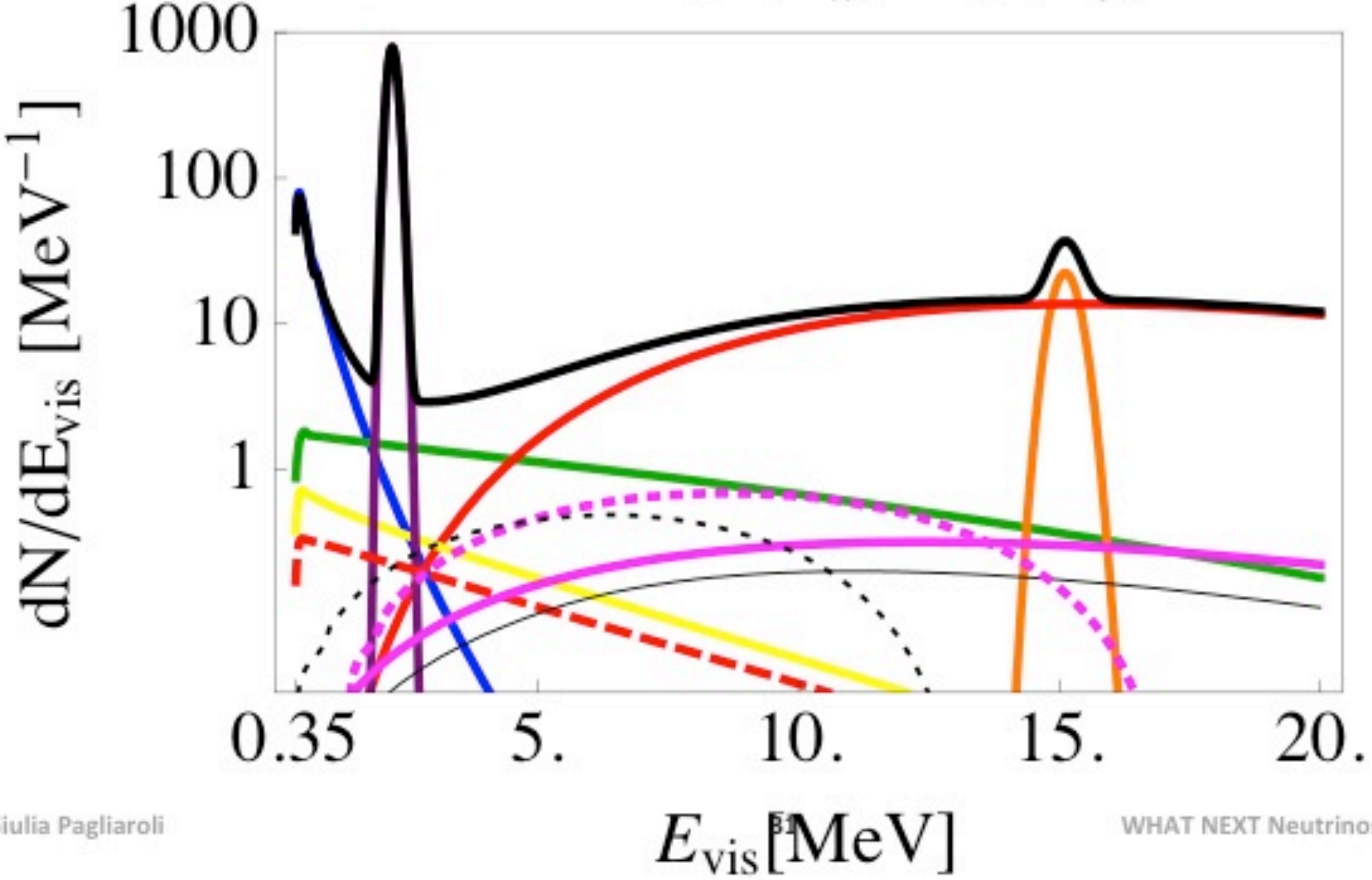
ν_x

Liquid Scintillators
Water Cherenkov
Lead Based
Argon Based
Ice Cherenkov

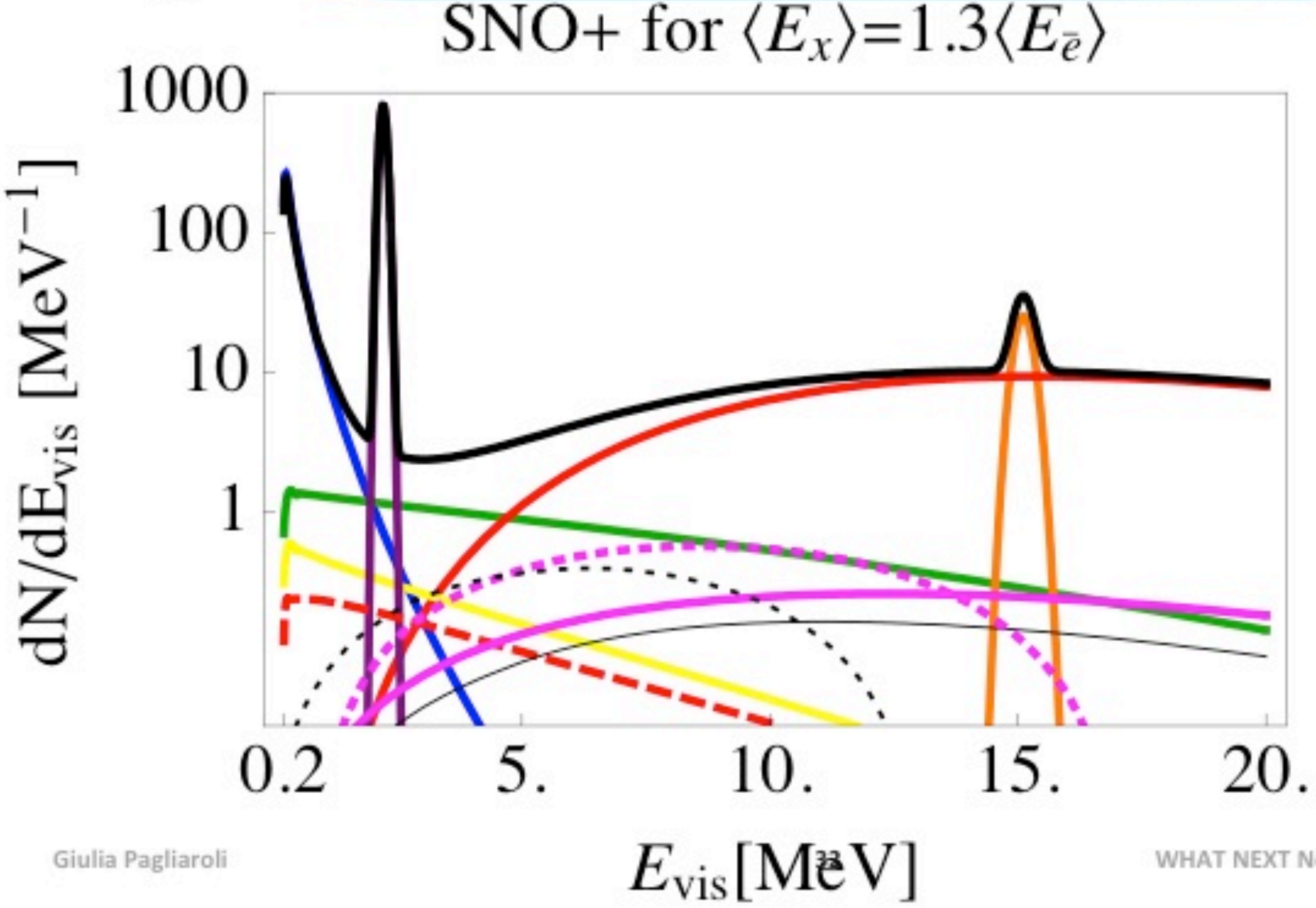
$$N_{ev} \propto N_t \int_{E_{thr}}^{\infty} dE_{vis}\, \sigma_{Int}(E_\nu) F_\nu(E_\nu)$$

KAMLAND SPECTRUM

KAM for $\langle E_x \rangle = 1.3 \langle E_{\bar{e}} \rangle$

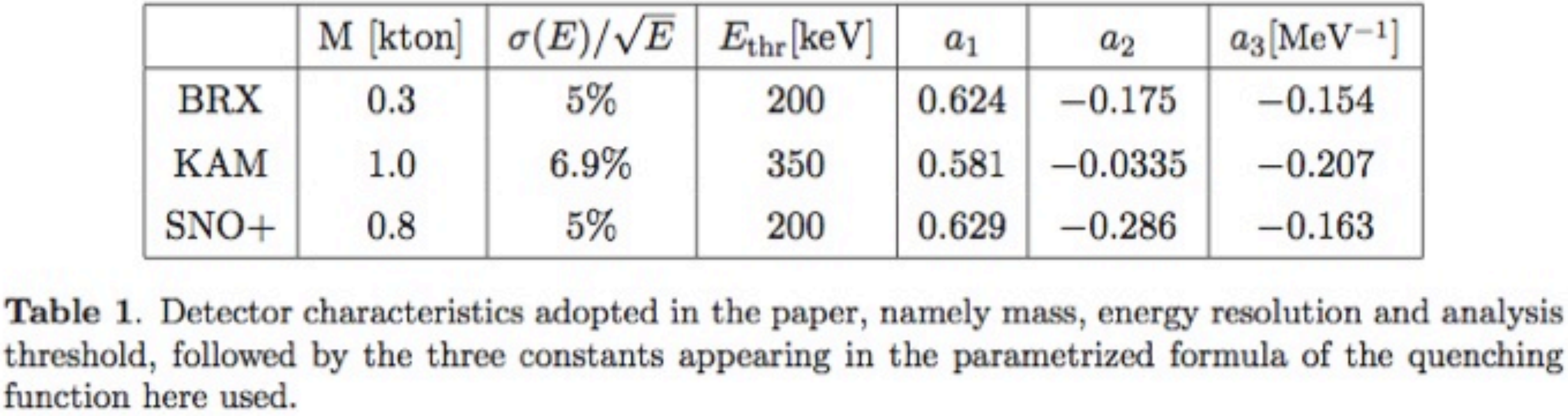


SNO+ SPECTRUM



ULTRAPURE SCINTILLATORS

PRESENT



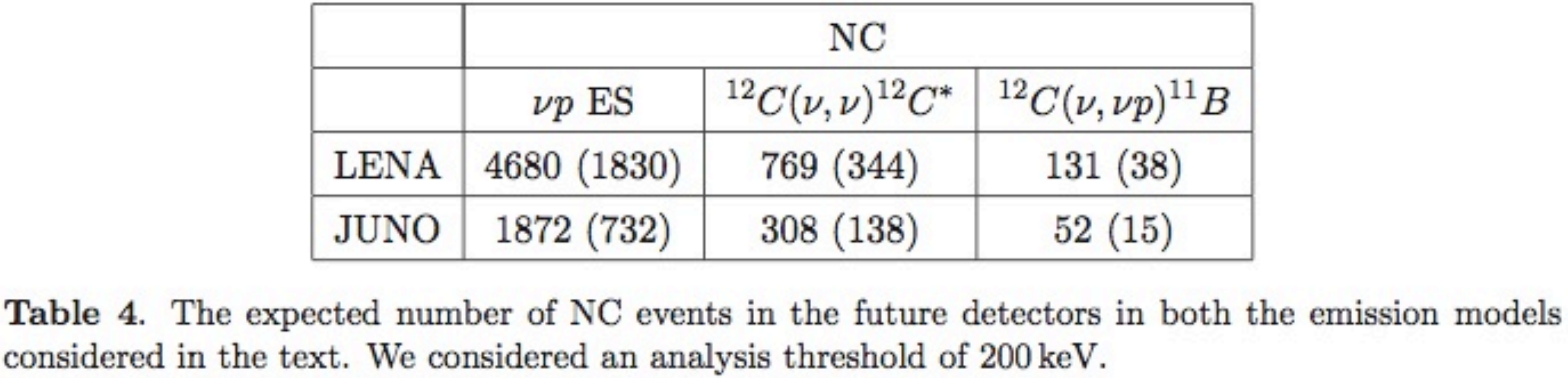
	M [kton]	$\sigma(E)/\sqrt{E}$	E_{thr}[keV]	a_1	a_2	$a_3[\mathrm{MeV}^{-1}]$
BRX	0.3	5%	200	0.624	−0.175	−0.154
KAM	1.0	6.9%	350	0.581	−0.0335	−0.207
SNO+	0.8	5%	200	0.629	−0.286	−0.163

Table 1. Detector characteristics adopted in the paper, namely mass, energy resolution and analysis threshold, followed by the three constants appearing in the parametrized formula of the quenching function here used.

FUTURE LAB-Based detectors

LENA	**50 kton**	**5%**	**200 keV**
JUNO	20 kton	3%	200 keV

JUNO vs LENA



	NC		
	νp ES	$^{12}C(\nu,\nu)^{12}C^*$	$^{12}C(\nu,\nu p)^{11}B$
LENA	4680 (1830)	769 (344)	131 (38)
JUNO	1872 (732)	308 (138)	52 (15)

Table 4. The expected number of NC events in the future detectors in both the emission models considered in the text. We considered an analysis threshold of 200 keV.