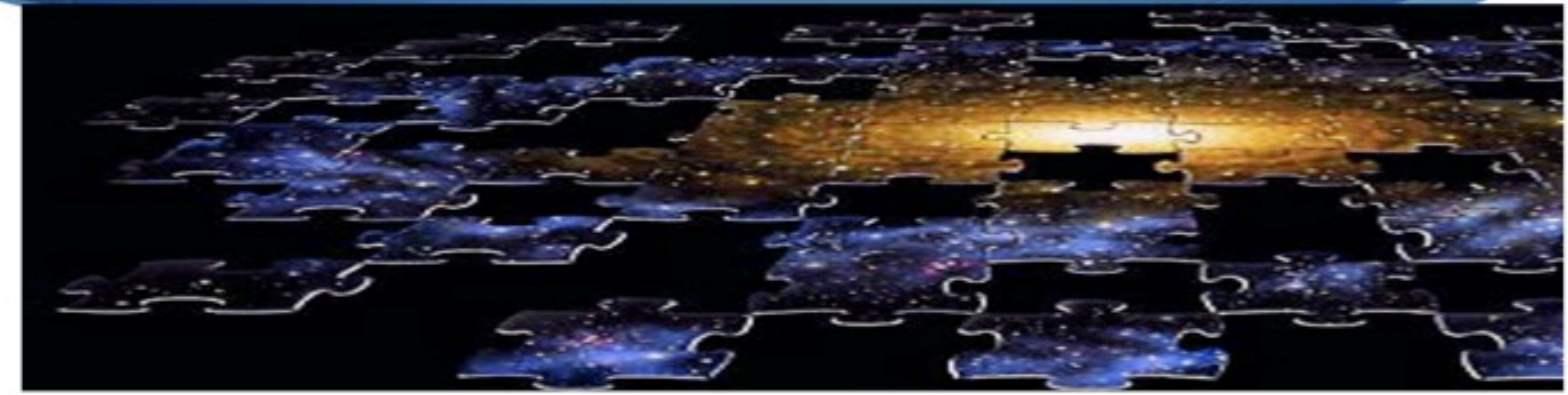
Potential of SN neutrinos

G.Pagliaroli
LNGS-Theory Group

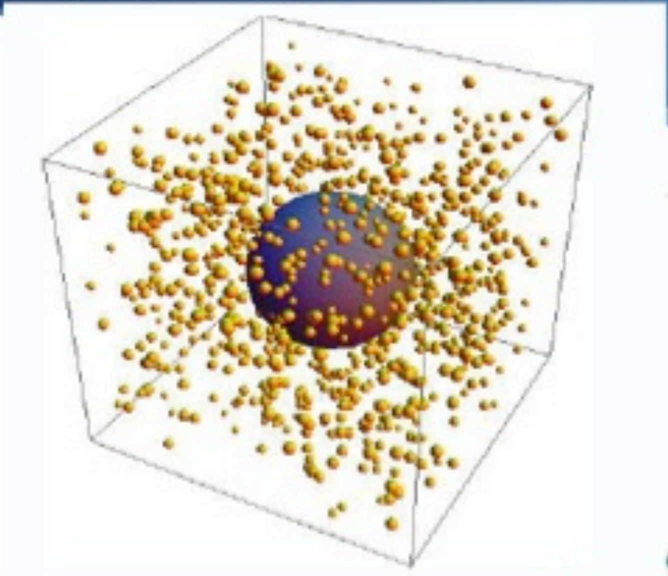
Summary

- Core-Collapse Supernovae and Neutrinos
- Model for Electronic Antineutrinos
- Application to Astrophysics
- Application to Relic Supernova Neutrinos search

The Supernova puzzle



Neutrinos Expectations



ENERGY

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

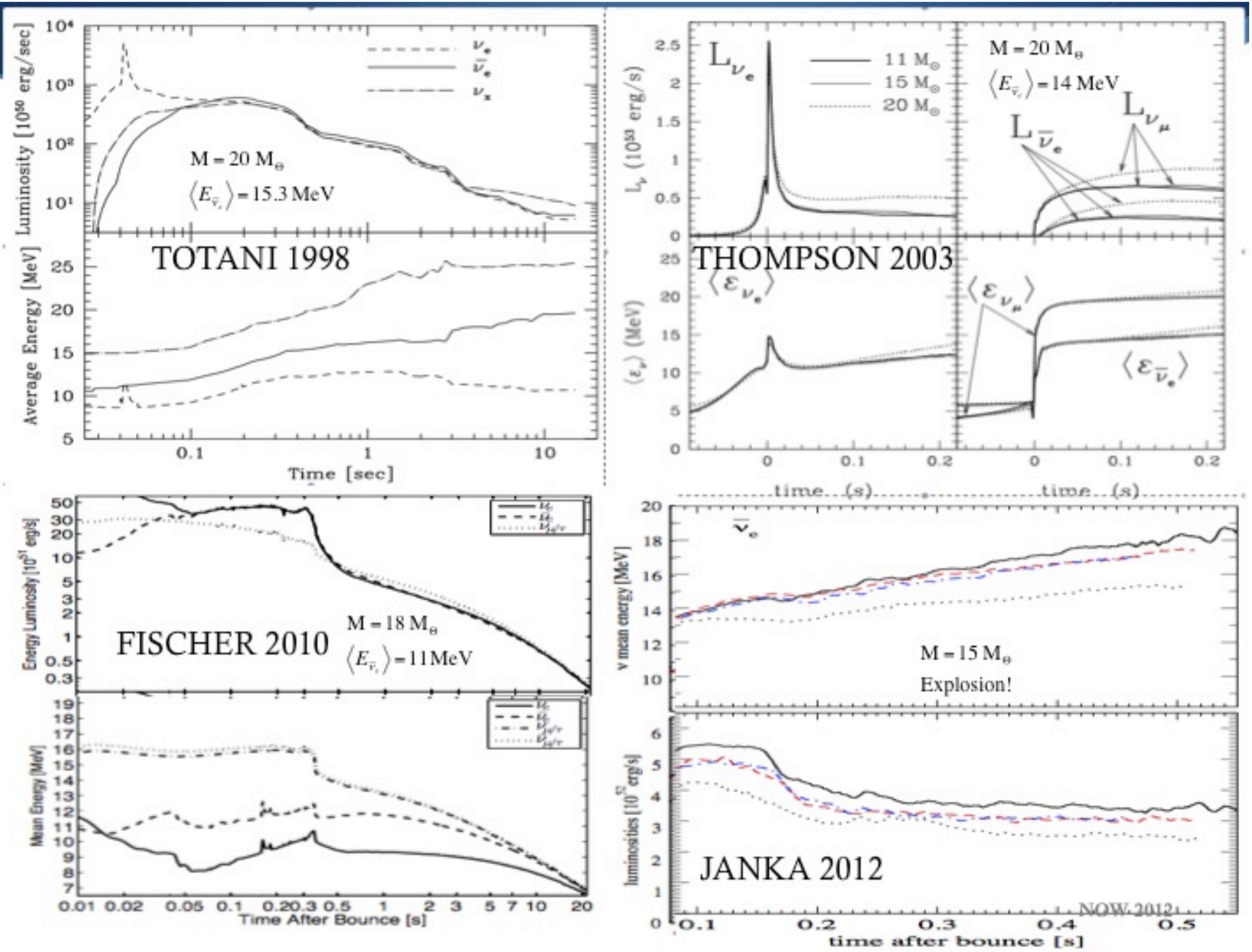
$$\varepsilon_\nu = 99\% \cdot \varepsilon_B$$

FLUENCE

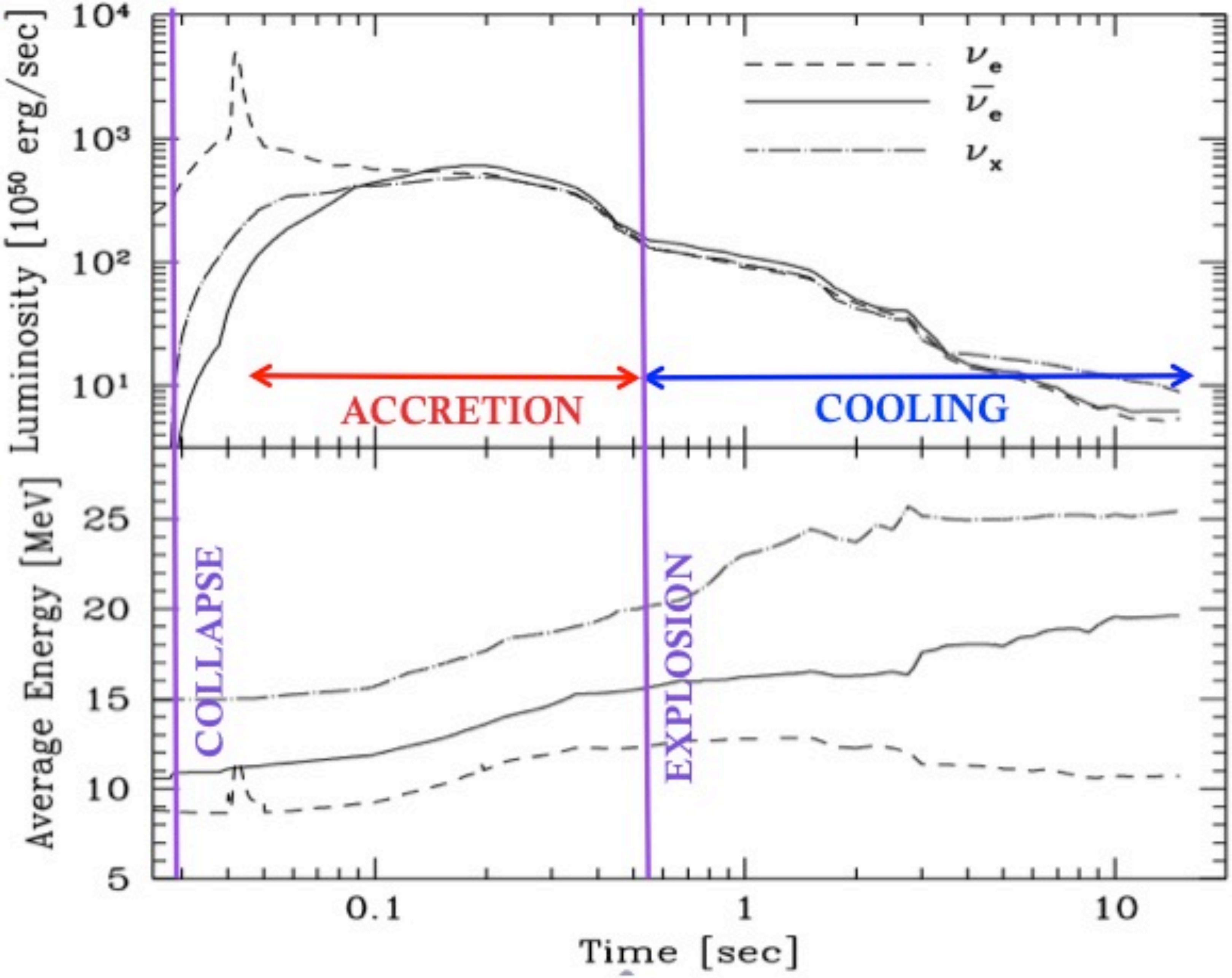
$$F_{\nu_x} \cong \frac{\varepsilon_B}{6\langle E_{\nu_x}\rangle}\frac{1}{4\pi D^2} \approx 5\cdot 10^{10}\left(\frac{20\ \text{kpc}}{D}\right)^2 \frac{10\text{MeV}}{\langle E_{\nu_x}\rangle}\frac{\nu_x}{cm^2}$$

DURATION

$$\Delta t = 10\sec$$



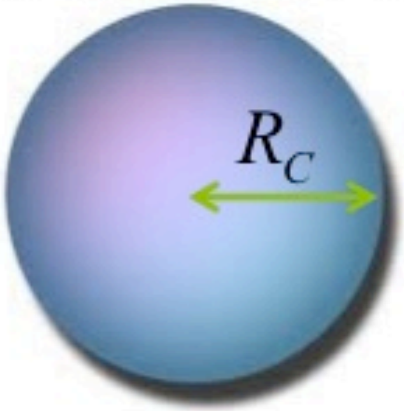
TOTANI 1998
M = 20 M☉
⟨E_ν̄e⟩ = 15.3 MeV
Luminosity [10^50 erg/sec]
Average Energy [MeV]
Time [sec]
THOMPSON 2003
M = 20 M☉
⟨E_ν̄e⟩ = 14 MeV
11 M☉
15 M☉
20 M☉
L_ν (10^53 erg/s)
⟨ε_ν⟩ (MeV)
time (s)
FISCHER 2010
M = 18 M☉
⟨E_ν̄e⟩ = 11 MeV
Energy Luminosity [10^51 erg/s]
Mean Energy [MeV]
Time After Bounce [s]
JANKA 2012
M = 15 M☉
Explosion!
ν mean energy [MeV]
luminosities [10^52 erg/s]
time after bounce [s]
NOW 2012



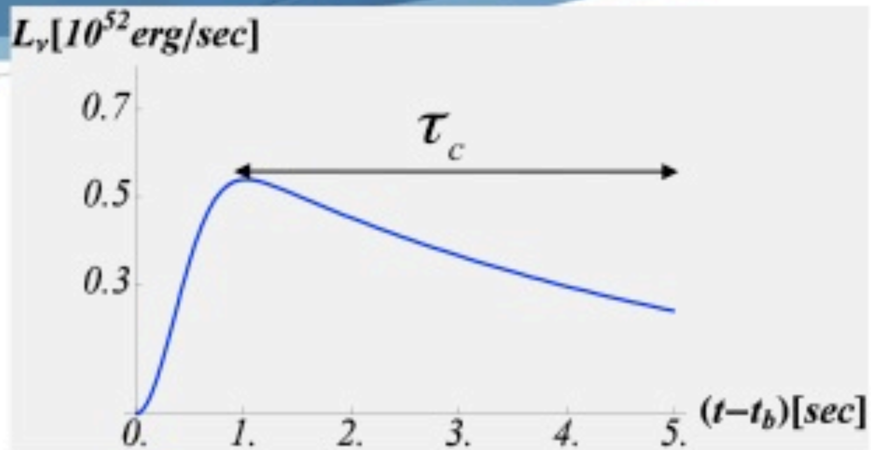
Luminosity [10^{50} erg/sec]
10^4
10^3
10^2
10^1
ν_e
$\bar{\nu}_e$
ν_x
ACCRETION
COOLING
Average Energy [MeV]
25
20
15
10
5
COLLAPSE
EXPLOSION
0.1
1
10
Time [sec]

COOLING PHASE

Thermal emission from cooling of the PNS



$$90\% \cdot \varepsilon_\nu$$



$$L_{\bar{\nu}_e} \sim 5\times10^{51}\frac{\text{erg}}{\text{sec}}\left(\frac{R_C}{10\text{km}}\right)^2\left(\frac{T_C}{5\text{MeV}}\right)^4$$

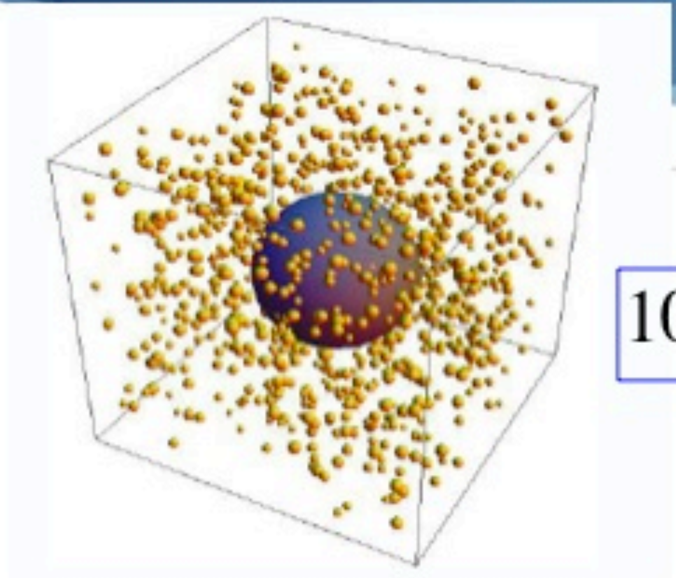
All species of neutrinos
are emitted by Urca processes

$$\Phi^0_{\bar{\nu}_e}(E_\nu,t) = \frac{4\pi R_C^2}{4\pi D^2}\frac{\pi c}{(hc)^3}\frac{E_\nu^2}{1+e^{\left(\frac{E_\nu}{T_c(t)}\right)}}$$

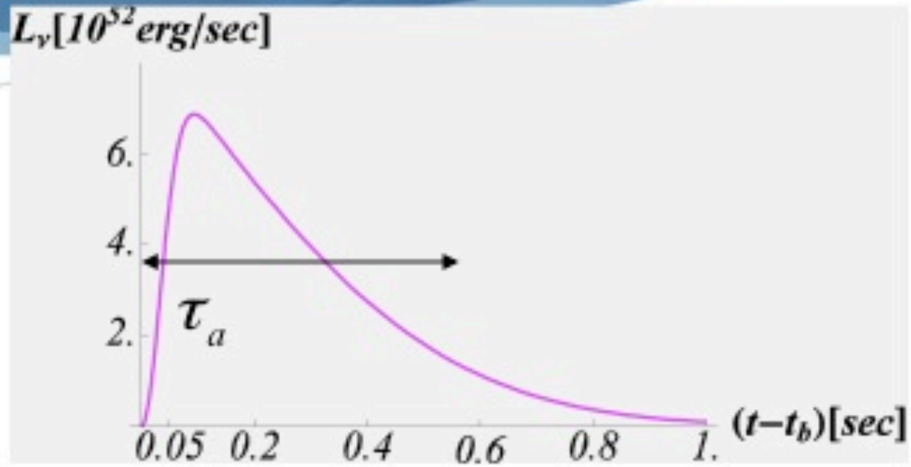
Model Parameters

$$R_C \quad T_C \quad \tau_C$$

ACCRETION PHASE



$$10\% \cdot \varepsilon_\nu$$



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

$$L_{\bar{\nu}_e} \sim 5 \times 10^{52} \frac{\text{erg}}{\text{sec}} \left(\frac{M_a}{0.1 M_e} \right) \left(\frac{T_a}{2\text{MeV}} \right)^6$$

Microscopic parameterization of the flux

$$\Phi_{\bar{\nu}_e}(E_\nu, t) \propto \frac{N_n(t)}{D^2} \sigma_{e^+ n}(E_{e^+}) \frac{E_{e^+}{}^2}{1 + e^{\left(\frac{E_{e^+}}{T_a(t)}\right)}}$$

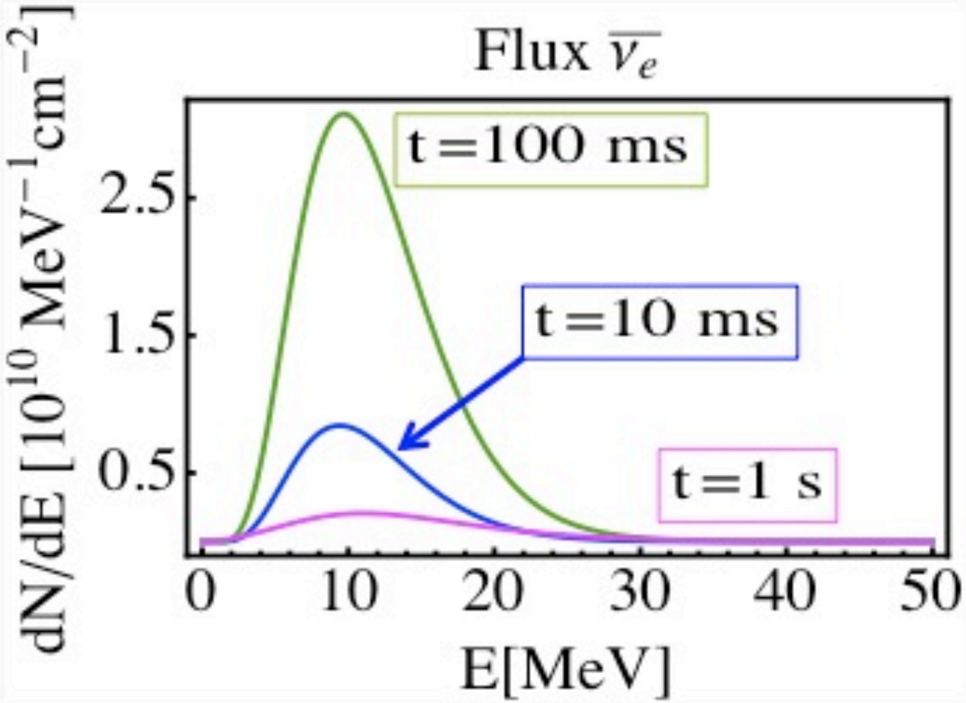
Model Parameters

$$M_a \quad T_a \quad \tau_a$$

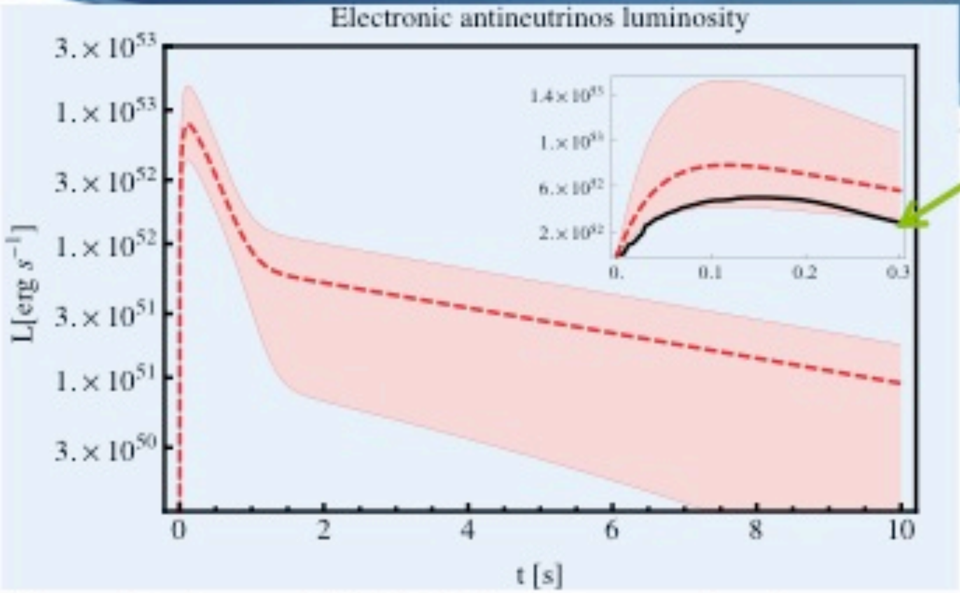
3 more free parameters

GLOBAL FEATURES

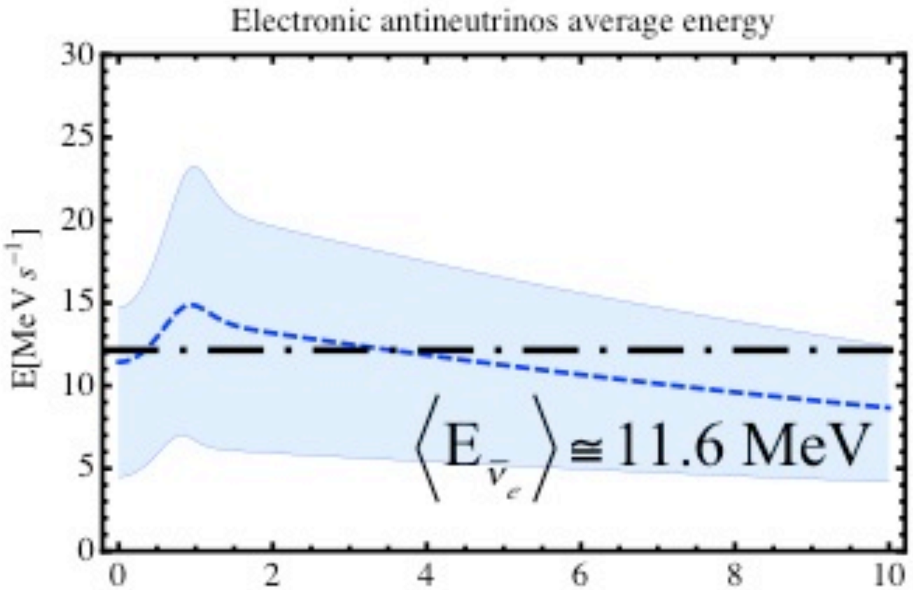
- Neutrino spectrum not thermal at fixed time
- Neutrino average energy time dependent
- Neutrino integrated spectrum different from a Fermi-Dirac or a Maxwell-Boltzman



SN1987A vs Simulations



Result from simulation
Mueller *et al.*
Astrophys.J.Suppl. 189 (2010) 104-133



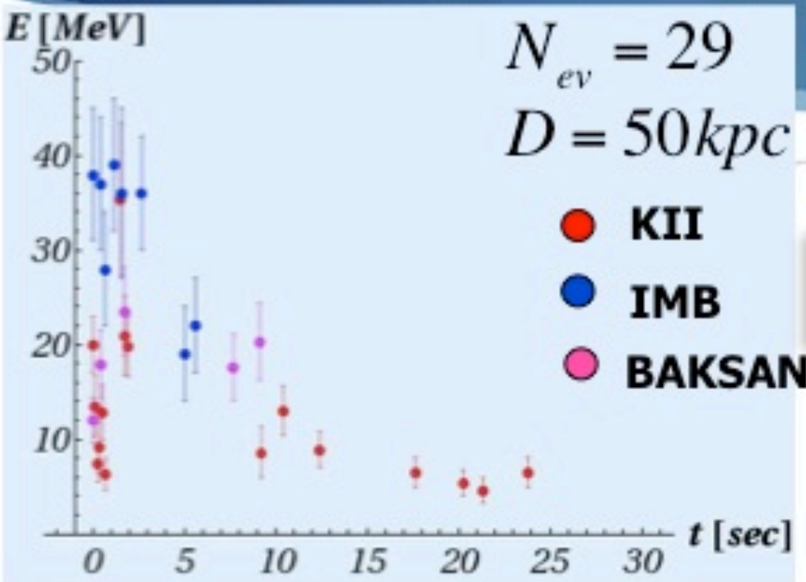
Results from SN1987A data analysis
Astroparticle Physics 31 (2009) 163–176

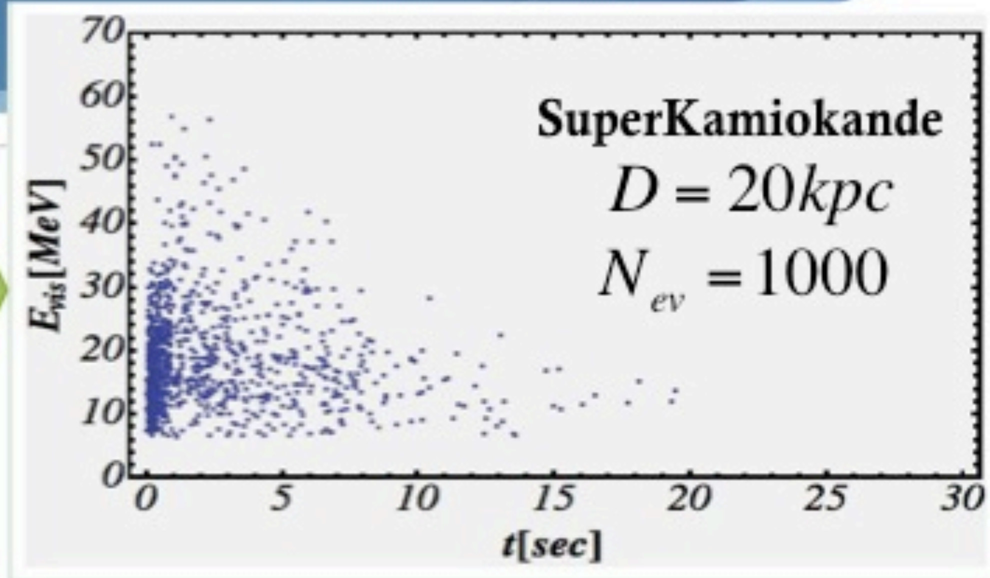
$M_a = 0.22^{+0.68}_{-0.15} M_\Theta$ $\quad R_C = 16^{+9}_{-5}\,\text{km}$

$T_a = 2.4^{+0.6}_{-0.4}\,\text{MeV}$ $\quad T_C = 4.6^{+0.7}_{-0.6}\,\text{MeV}$

$\tau_a = 0.55^{+0.58}_{-0.17}\,\text{s}$ $\quad \tau_C = 4.7^{+1.7}_{-1.2}\,\text{s}$ $\quad E_b = 2.8 \times 10^{53}\,\text{erg}$

SN1987A vs Future





Yesterday

$$\delta R_c = 44\%$$
$$\delta T_c = 15\%$$
$$\delta \tau_c = 31\%$$
$$\delta M_a = 188\%$$
$$\delta T_a = 36\%$$
$$\delta \tau_a = 36\%$$

Tomorrow

$$\delta R_c = 7\%$$
$$\delta T_c = 2\%$$
$$\delta \tau_c = 2\%$$
$$\delta M_a = 27\%$$
$$\delta T_a = 3\%$$
$$\delta \tau_a = 7\%$$

GP *et al.* **PRL 103, 031102 (2009)**

Relic Supernova Neutrinos

Diffuse Supernova Neutrinos Background

$$\frac{d\phi(E)}{dE} = \frac{c}{H_0}\int_0 dz \frac{R_{CCSN}(z)}{\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}} \frac{dN(E')}{dE'}$$

$$\frac{dN}{dE'} \approx \frac{k}{T^3} \frac{E'^2}{1 + exp[E'/T - \eta]}$$

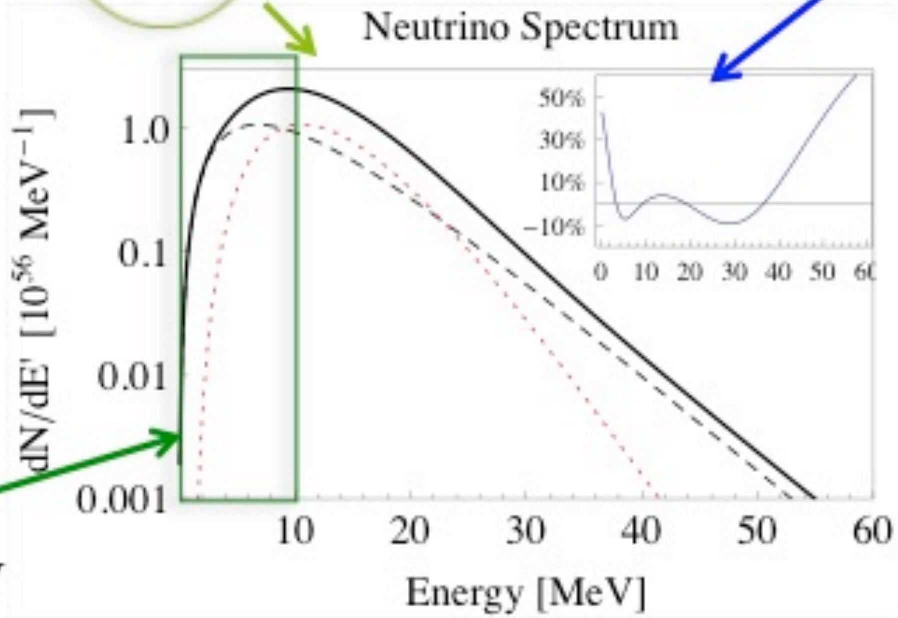
$k = 2.97 \times 10^{57}$

$T = 3.76\ MeV$

$\eta = 0.679$

Reddening effect: $E = \frac{E'}{(1+z)}$

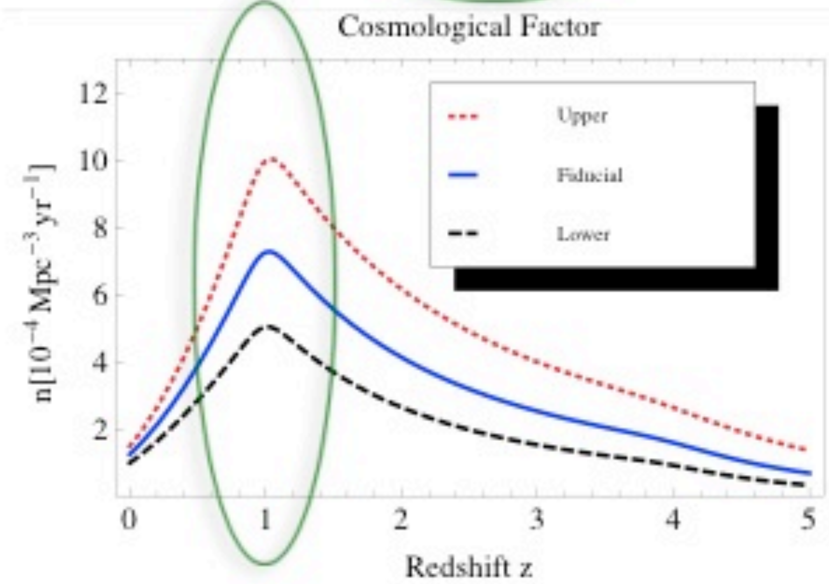
50% below 11.2 MeV

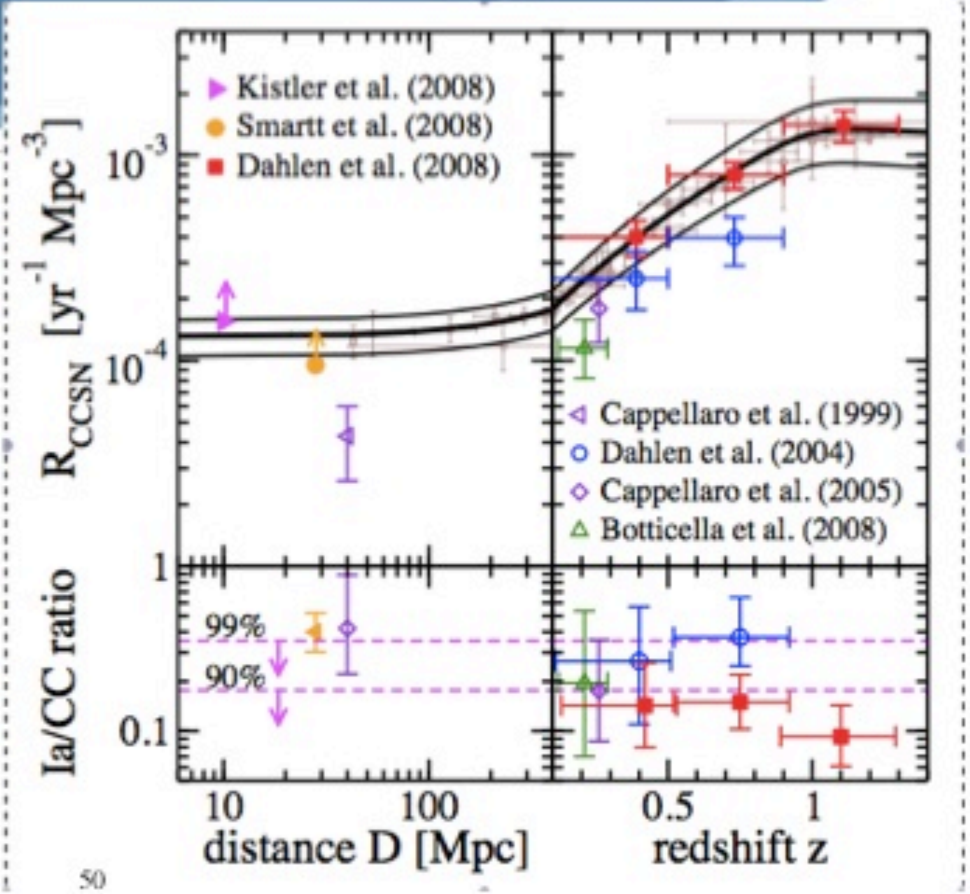


The detector Energy threshold plays a crucial role!

THE COSMOLOGICAL FACTOR

$$\frac{d\phi(E)}{dE} = \frac{c}{H_0}\int_0 dz \frac{R_{CCSN}(z)}{\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}} \frac{dN(E')}{dE'}$$

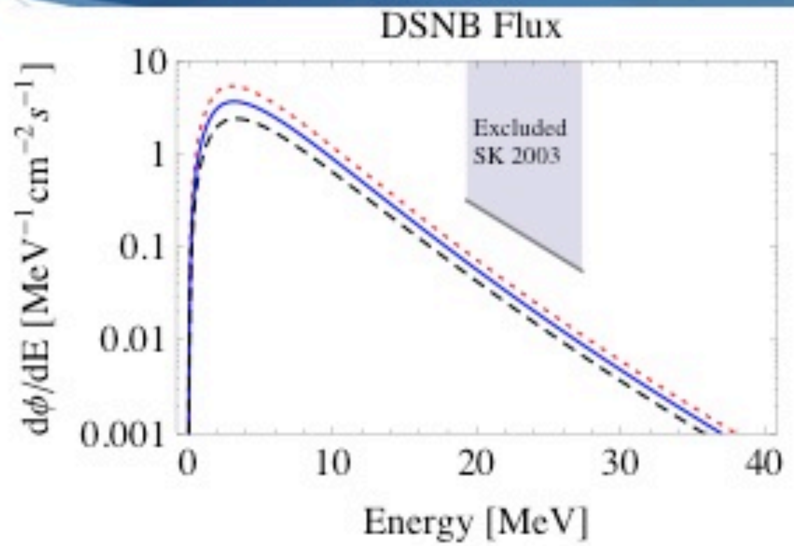




$$z = 1 \Rightarrow D \cong 4200\,\mathrm{Mpc}$$

$$R_{CCSN}(z) = R_{SF}(z)\frac{\int_8^{50}\psi_{IMF}(M)\,dM}{\int_{0.1}^{100} M\,\psi_{IMF}(M)\,dM}$$

THE EXPECTATIONS

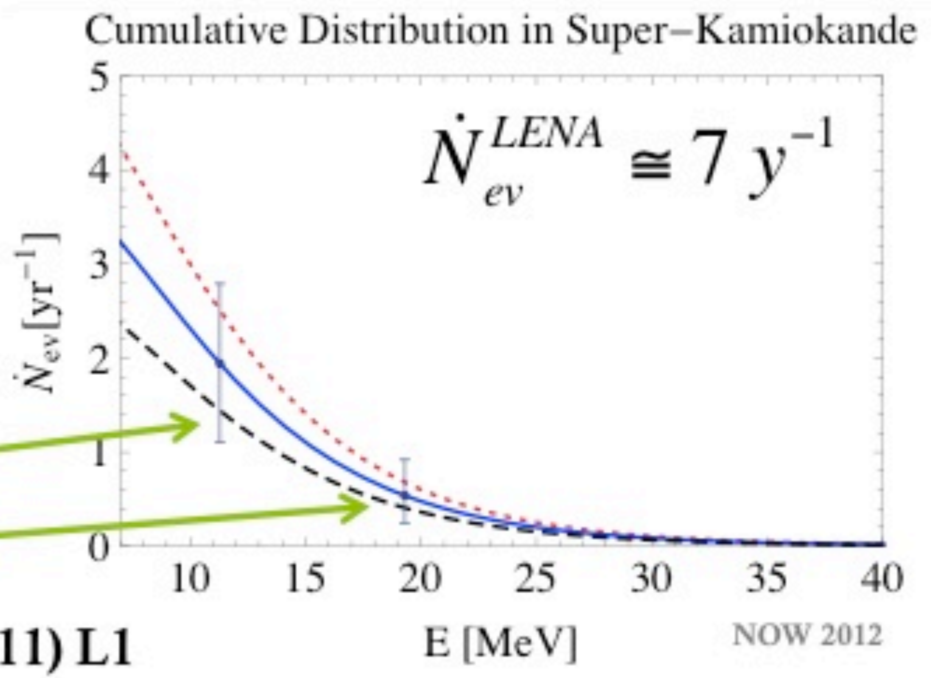


$$\phi_{DSNB} = 27.2\ cm^{-2}s^{-1}$$

$$1\% \cdot \phi_{DSNB} \text{ for } E_{\nu} > 19.3\ \mathrm{MeV}$$

$$8\% \cdot \phi_{DSNB} \text{ for } E_{\nu} > 11.3\ \mathrm{MeV}$$

$$\dot{N}_{ev} = N_p \int_{E_{thr}} dE\,\eta(E)\sigma(E)\frac{d\phi}{dE}$$



$$\dot{N}_{ev}(E_{thr} = 11.3\,\mathrm{MeV}) = 1.35 - 2.35\ y^{-1}$$

$$\dot{N}_{ev}(E_{thr} = 19.3\,\mathrm{MeV}) = 0.39 - 0.65\ y^{-1}$$

Vissani *and GP*, **Astron. Astrophys. 528 (2011) L1**

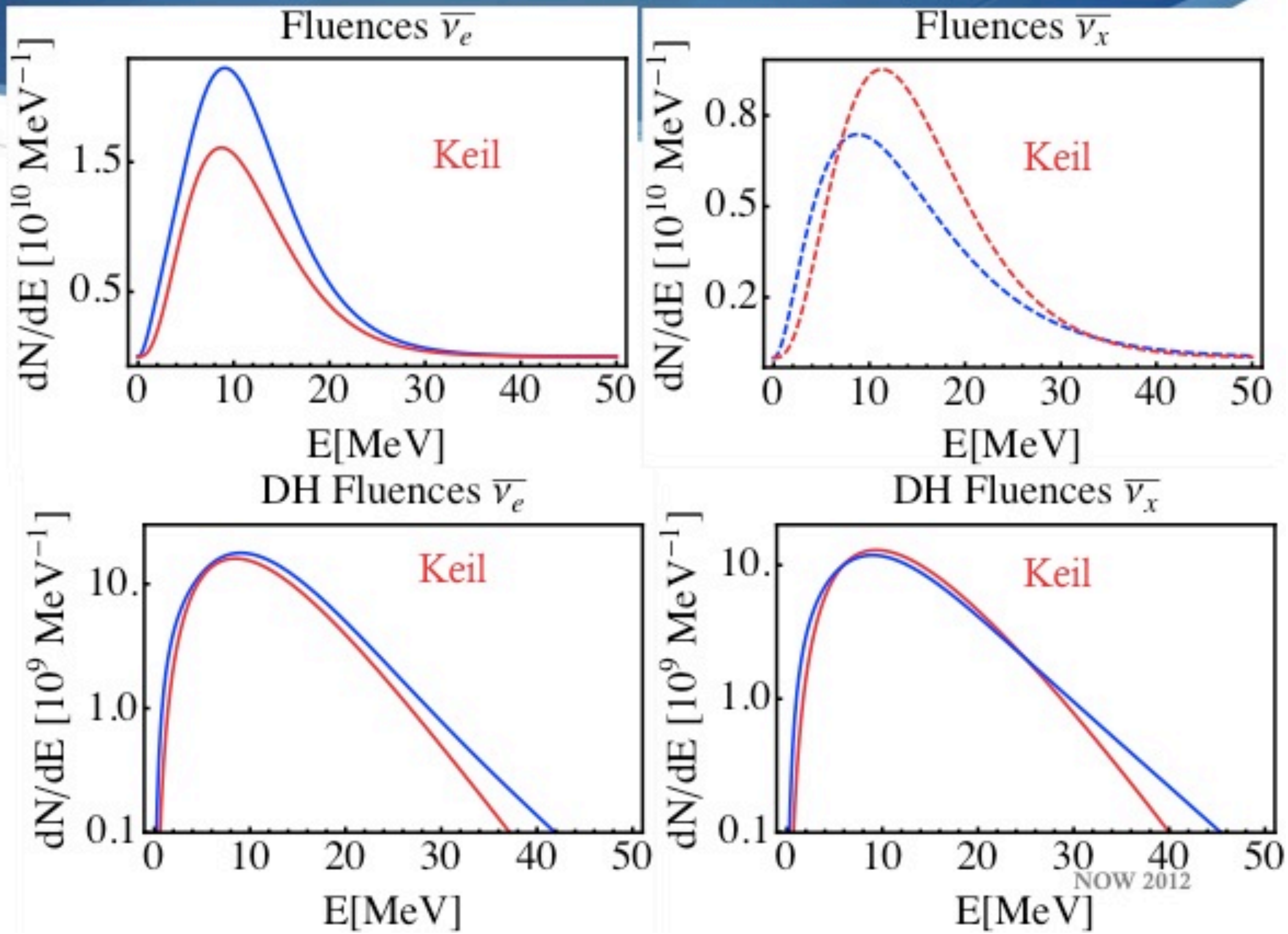
Conclusion

- Core-Collapse SN ⟹ COMPLEX
- Parametric Model for next Galactic SN ⟹ NEEDED
- Time Integrated spectrum ⟹ DEPENDENT
- Detection of Relic Supernova Neutrinos ⟹ HARD!!!

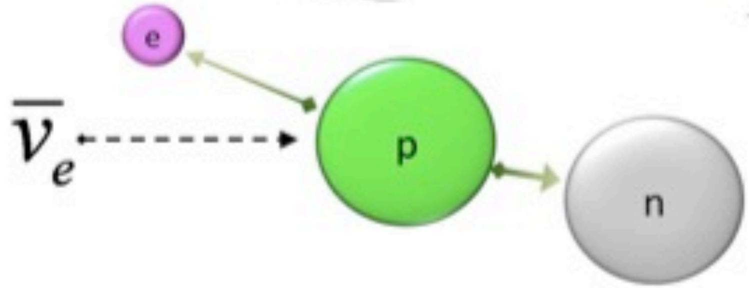
Comparison with Keil

Emission

Detection



Inverse Beta Decay (IBD)



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

$$\sigma_{\rm IBD}(E_\nu) \sim 9 \cdot 10^{-44} \cdot E_\nu^2 \ {\rm cm}^2$$

$$N_{e\nu} = N_p \int_{E_{thr}}^{\infty} dE_{e^+} \sigma_{\rm IBD}(E_\nu) \eta(E_{e^+}) F_{\bar{\nu}_e}(E_\nu) G(E_\nu, E_{e^+})$$

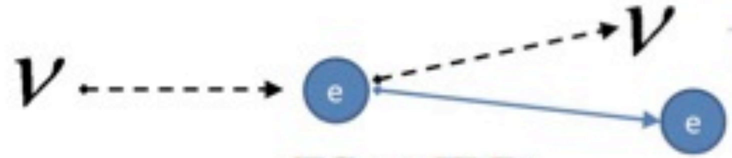
$$N_p \approx 1{\rm kton} \times \frac{10^9 {\rm g}}{\rm kton} \times \frac{6 \cdot 10^{23}}{\rm g} \times \frac{2}{18} \approx 6 \cdot 10^{31}$$

5000 IBD events expected in SK=32 kton for a SN in the GC

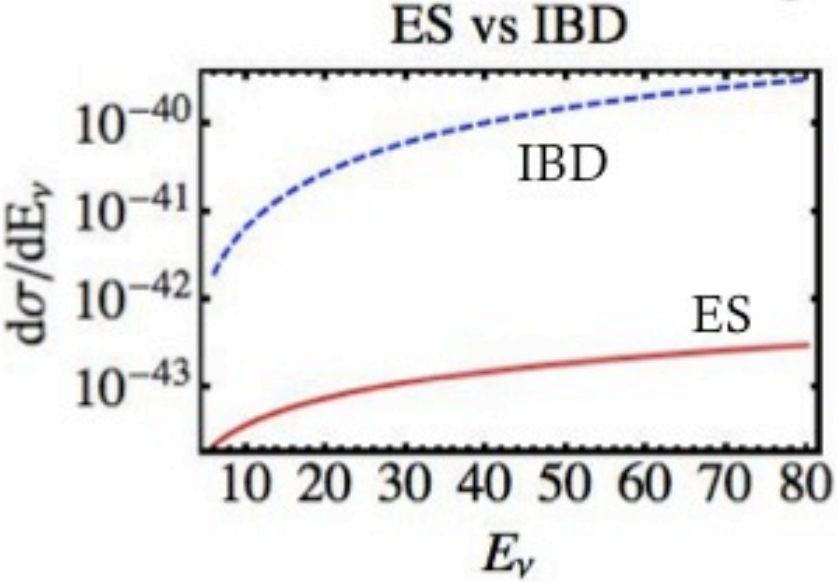
NOW 2012

Elastic Scattering (ES)

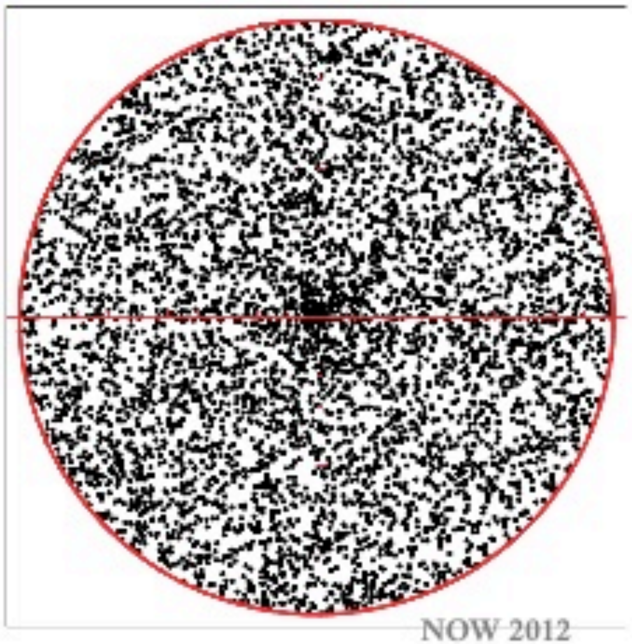
Directional interaction:



$$\nu_x + e^- \rightarrow \nu_x + e^-$$



POINTING:
300 ES
directional events among the IBD events



$$N_{e^-} \approx 1\text{kton} \times \frac{10^9\,\text{g}}{\text{kton}} \times \frac{6 \cdot 10^{23}}{\text{g}} \times \frac{10}{18} \approx 3 \cdot 10^{32}$$