Potential of SN neutrinos

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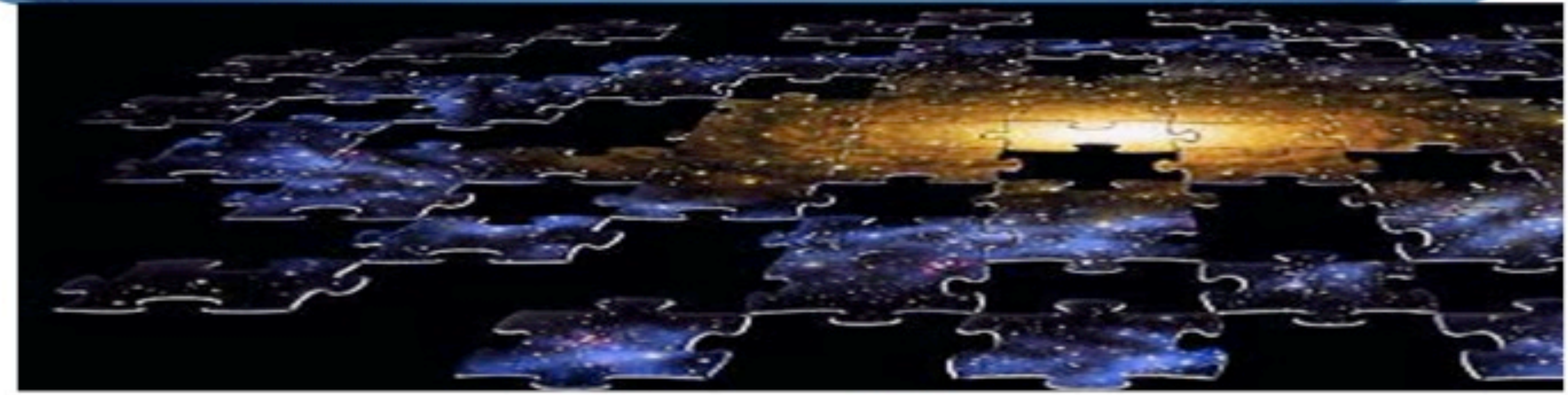
Summary

- Core-Collapse Supernovae and Neutrinos
- Model for Electronic Antineutrinos
- Application to Astrophysics
- Application to Neutrino Mass
- Application to Gravitational Waves search

The Supernova puzzle



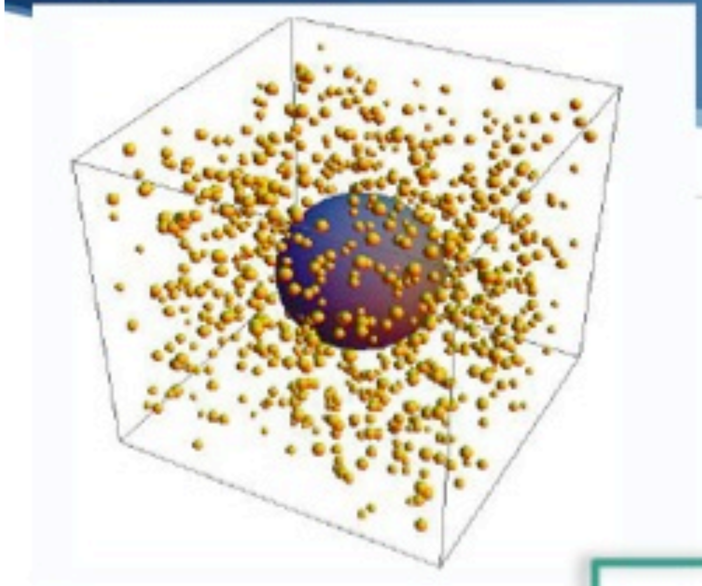
Astrophysics

Particles physics

Nuclear physics

Gravity

Neutrinos Expectations



ENERGY

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

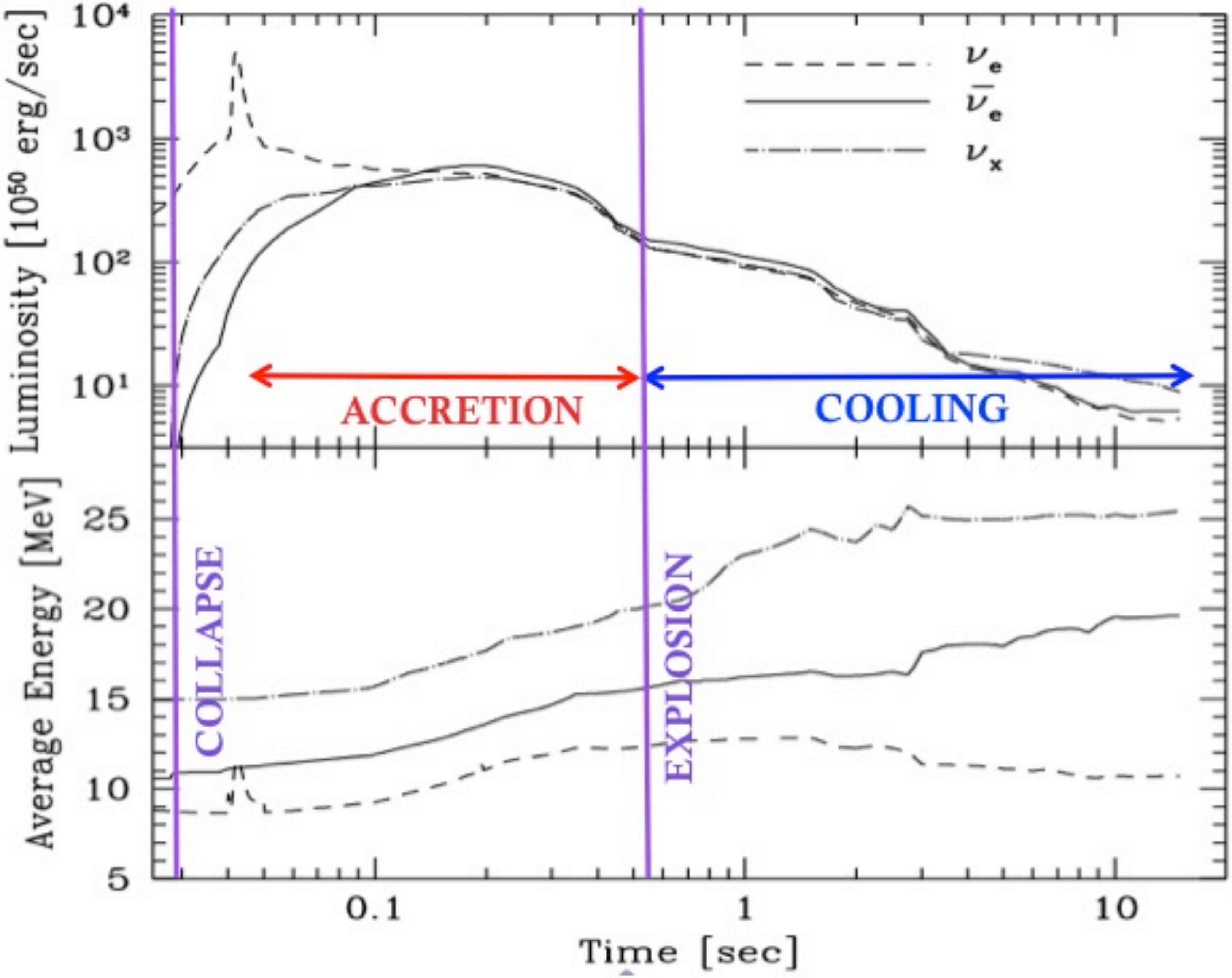
$$\varepsilon_\nu = 99\%\cdot\varepsilon_B$$

FLUENCE

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

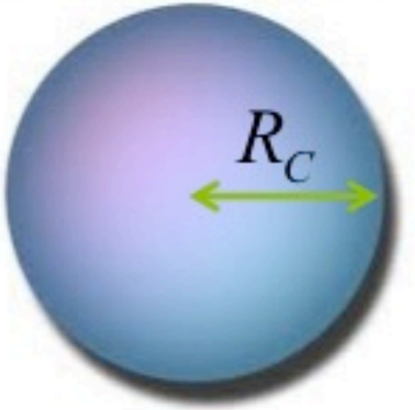
DURATION

$$\Delta t = 10\sec$$

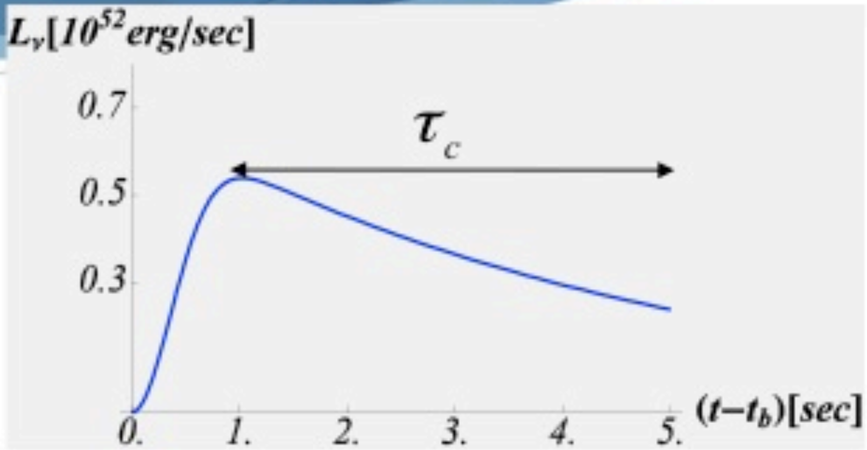

Luminosity [10^{50} erg/sec]
10^4
10^3
10^2
10^1
ν_e
$\bar{\nu}_e$
ν_x
ACCRETION
COOLING
Average Energy [MeV]
25
20
15
10
5
COLLAPSE
EXPLOSION
0.1
1
10
Time [sec]

COOLING PHASE

Thermal emission from cooling of the PNS



$$\boxed{90\% \cdot \varepsilon_\nu}$$



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

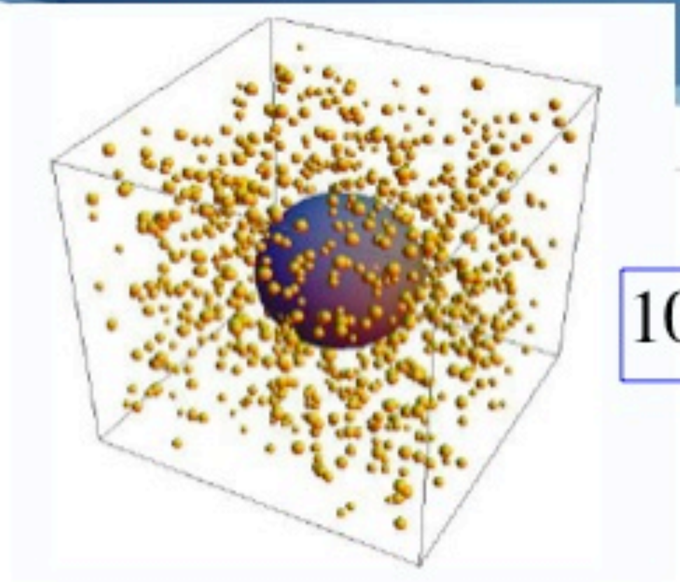
All species of neutrinos
are emitted by Urca processes

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

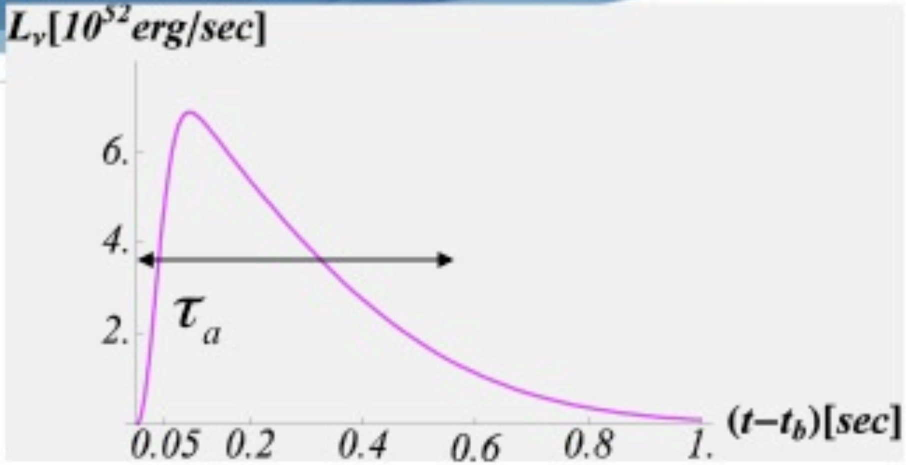
Model Parameters

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

ACCRETION PHASE



$$\boxed{10\% \cdot \varepsilon_\nu}$$



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

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

Microscopic parameterization of the flux

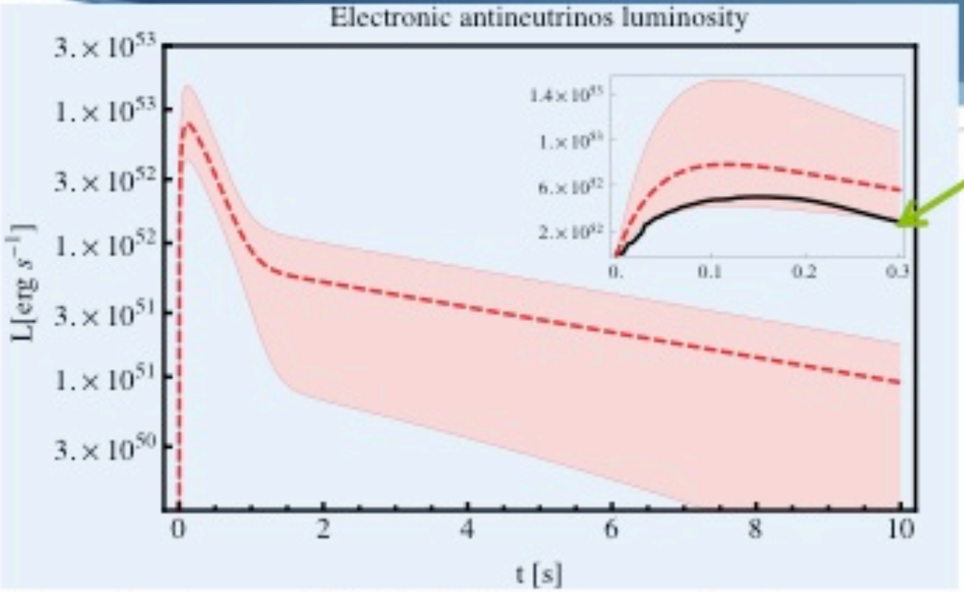
$$\Phi_{\bar{\nu}_e}(E_\nu,t) \propto \frac{N_n(t)}{D^2}\sigma_{e^+n}(E_{e^+})\frac{{E_{e^+}}^2}{1+e^{\left(\frac{E_{e^+}}{T_a(t)}\right)}}$$

Model Parameters

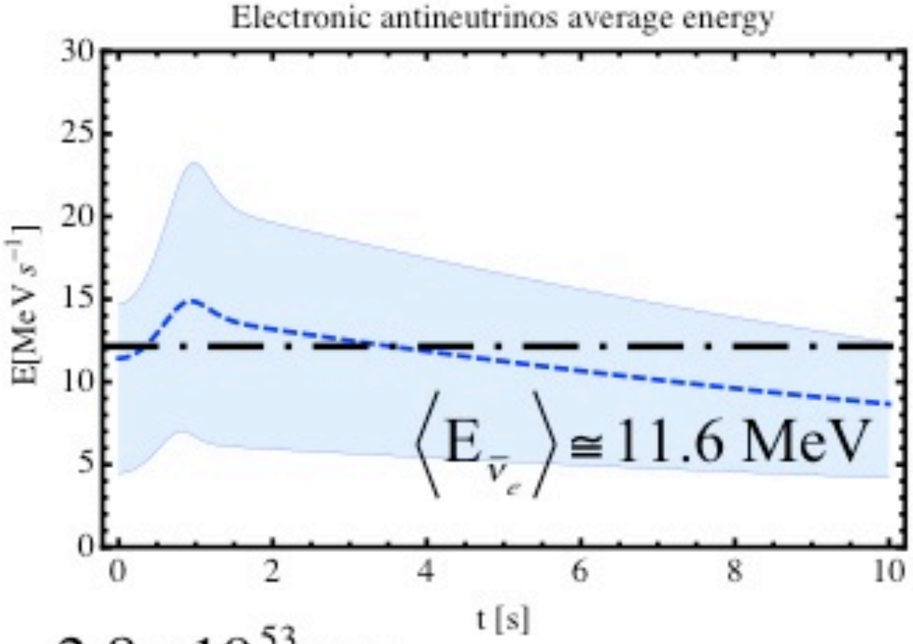
$M_a \; T_a \; \tau_a$

3 more free parameters

SN1987A vs Simulations



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



$\left\langle E_{\bar{\nu}_e} \right\rangle \cong 11.6\ \text{MeV}$

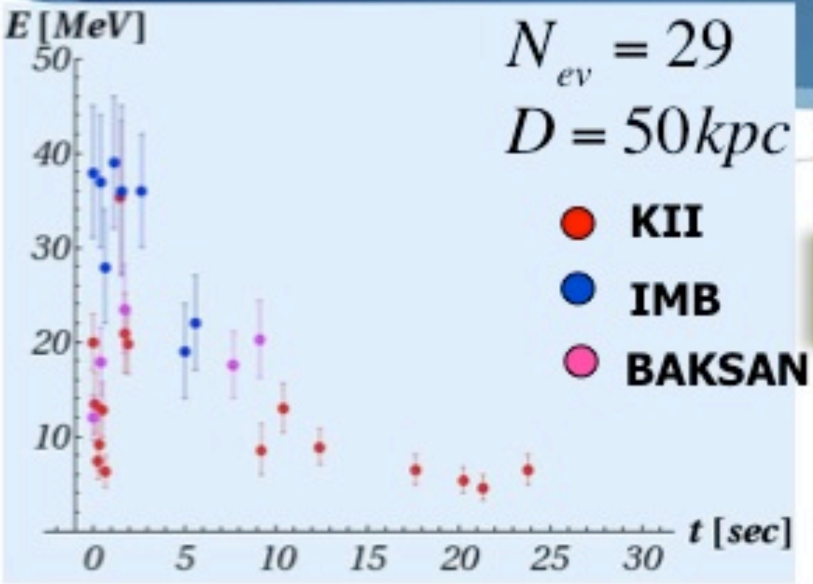
Results from SN1987A data analysis
Astroparticle Physics 31 (2009) 163–176

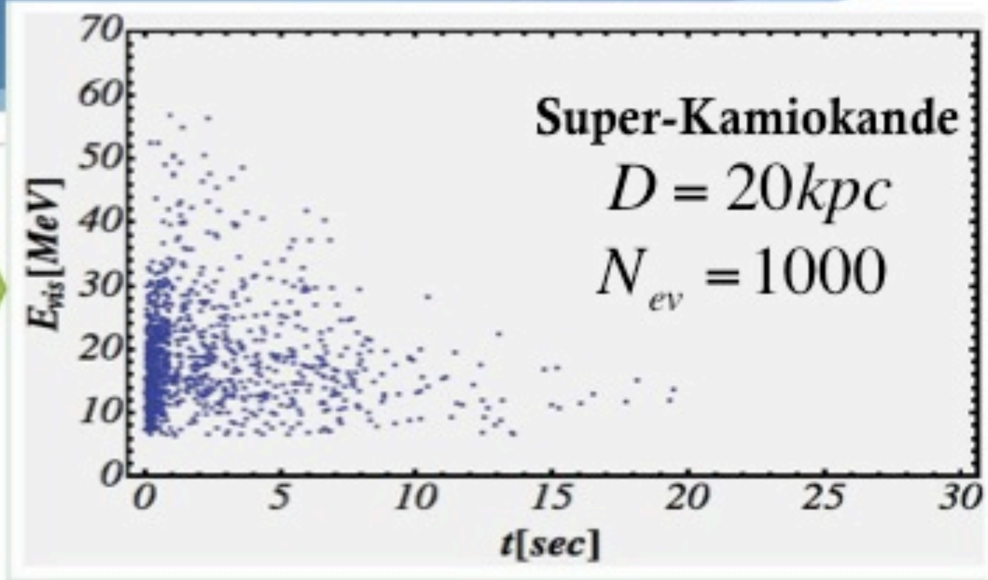
$M_a = 0.22^{+0.68}_{-0.15} M_\Theta$ $\quad R_C = 16^{+9}_{-5}\,\text{km}$

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

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

SN1987A vs Future



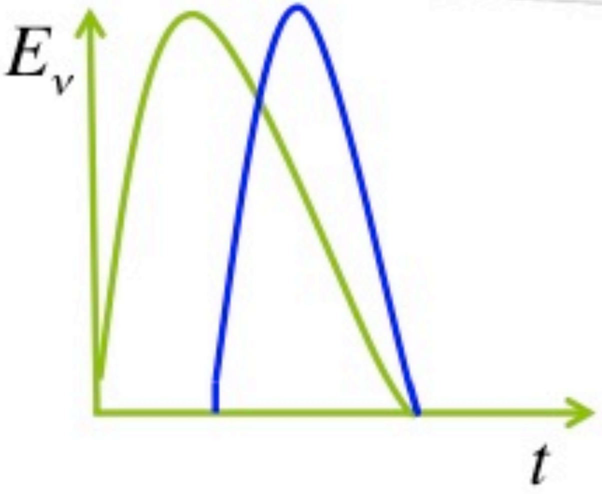


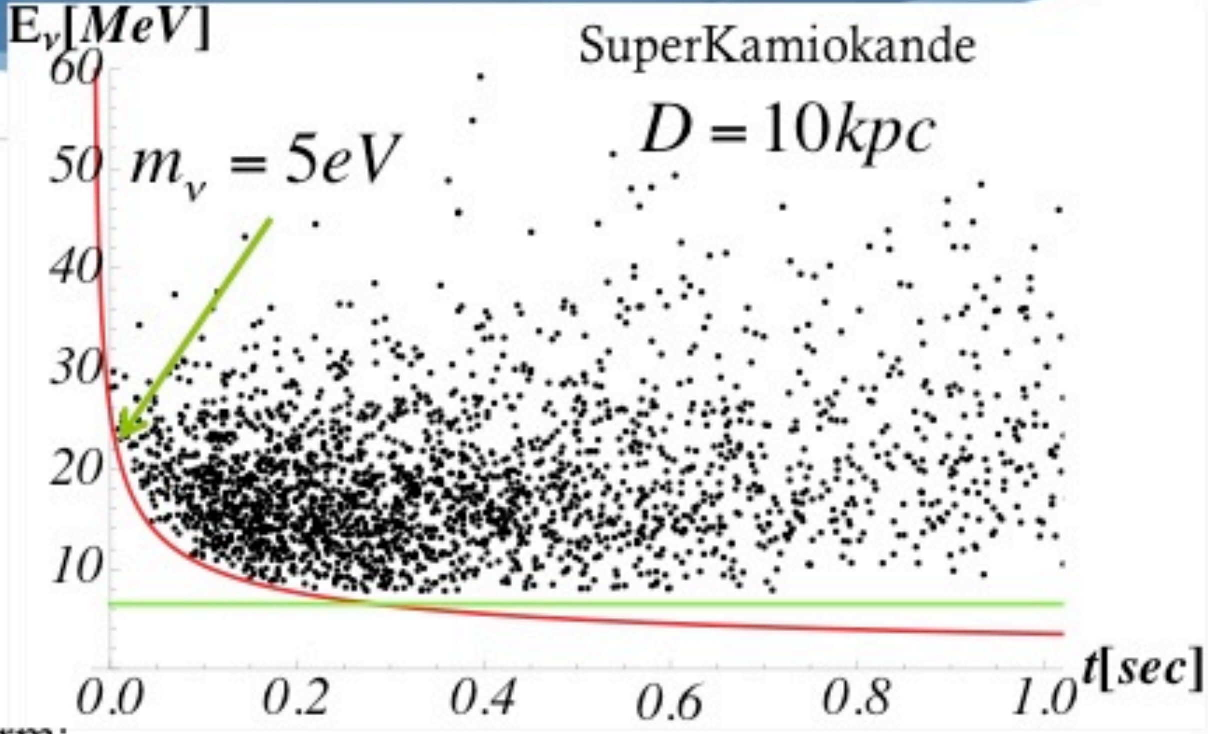
Yesterday	**Tomorrow**
$\delta R_c = 44\%$	$\delta R_c = 7\%$
$\delta T_c = 15\%$	$\delta T_c = 2\%$
$\delta \tau_c = 31\%$	$\delta \tau_c = 2\%$
$\delta M_a = 188\%$	$\delta M_a = 27\%$
$\delta T_a = 36\%$	$\delta T_a = 3\%$
$\delta \tau_a = 36\%$	$\delta \tau_a = 7\%$

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

NEUTRINO MASS EFFECT

1968 Zatsepin

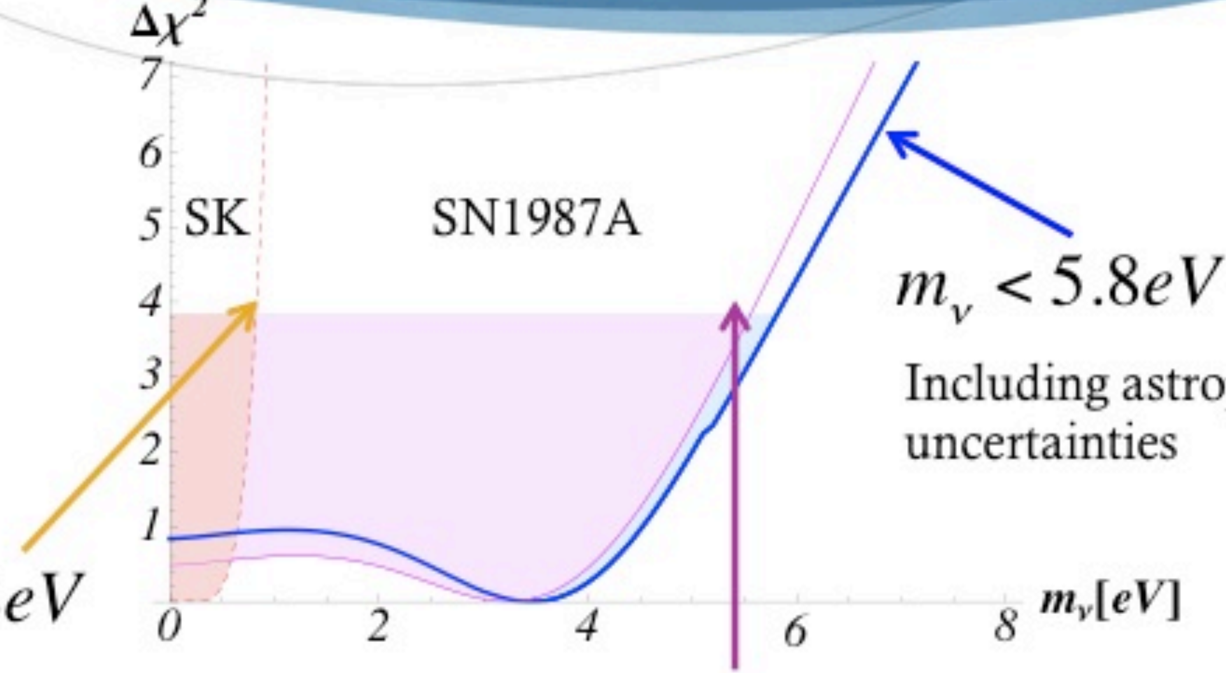




Distortion of the emitted Spectrum due to the mass term:

$$\Delta t_i = \frac{D}{2c}\left(\frac{m_\nu}{E_i}\right)^2 \cong 2.6\sec\left(\frac{D}{50kpc}\right)\left(\frac{10MeV}{E_i}\right)^2\left(\frac{m_\nu}{10eV}\right)^2$$

SN1987A BOUND



$m_\nu < 5.8 eV$ at 95%C.L.

Including astrophysical uncertainties

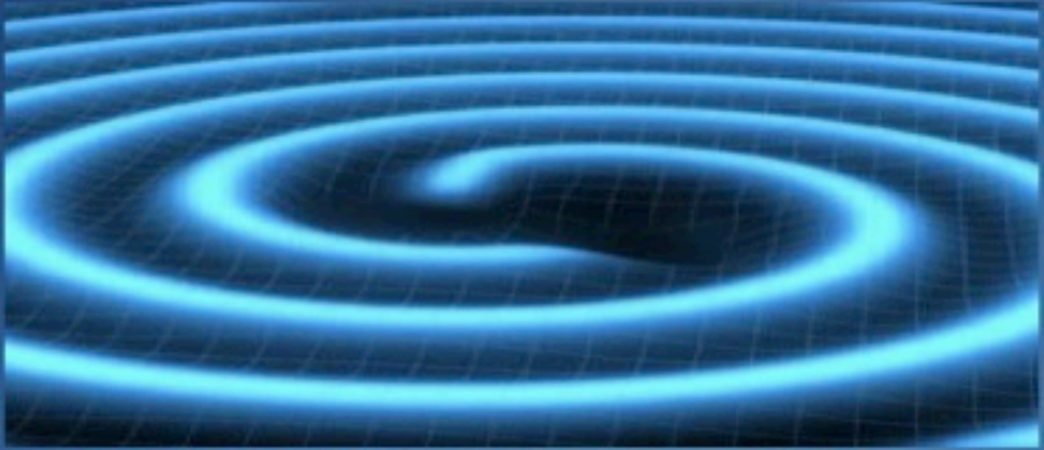
$m_\nu < 0.8 eV$

at 95%C.L

With SK detector and a 10 kpc SN including astrophysical uncertainties

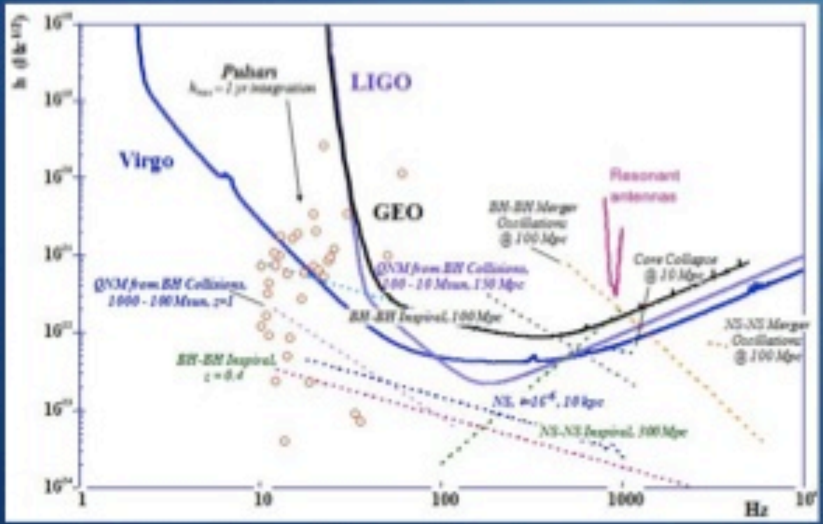
$m_\nu < 5.6 eV$ at 95%C.L.

Assuming that the astrophysical parameters of neutrino emission are known.

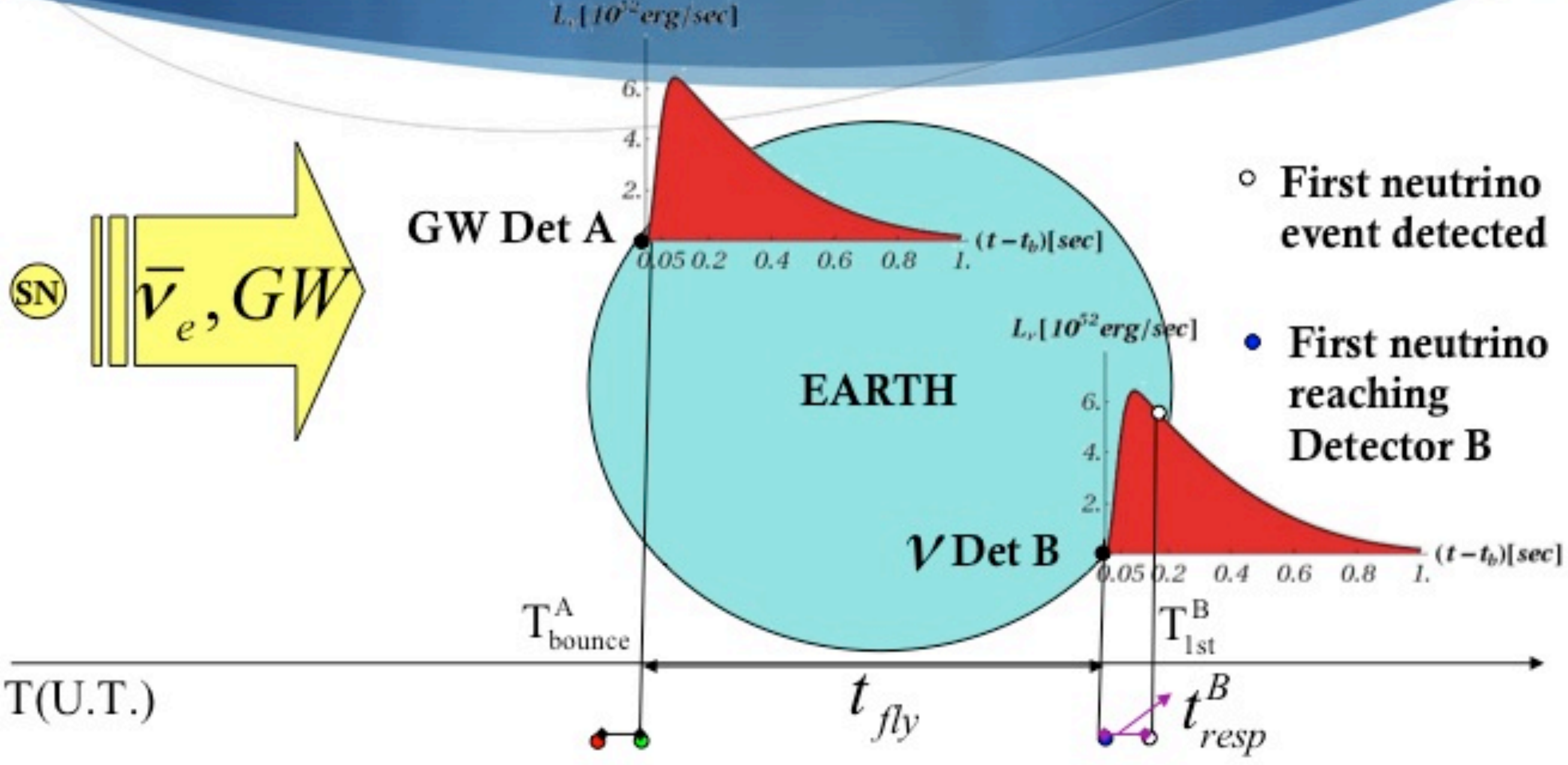


GRAVITATIONAL WAVES

Multi-messengers Astronomy



THE IDEA



○ **First neutrino event detected**

● **First neutrino reaching Detector B**

$$T^{A}_{bounce} = T^{B}_{1st} - (\overset{\bullet-\circ}{t}_{resp} \pm \overset{\bullet-\bullet}{t}_{fly} + t_{mass} + \overset{\circ-\circ}{t}_{GW})$$

RESULT

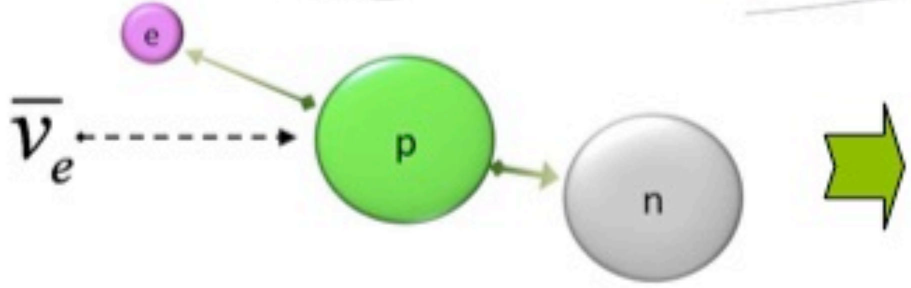
Exploiting our model and the neutrino signal detected by SK for a SN event at 20 kpc, we deduce the Universal Time of the bounce with an average error:

$$\delta \mathrm{T}_{\mathrm{bounce}} = \sqrt{\delta \mathrm{T}_{\mathrm{1st}}^2 + \delta \mathrm{t}_{\mathrm{GW}}^2 + \delta t_{\mathrm{mass}}^2 + \delta t_{\mathrm{fly}}^2 + \delta t_{\mathrm{resp}}^2}$$

$$\cong \sqrt{\delta t_{\mathrm{GW}}^2 + \delta t_{\mathrm{fly}}^2 + \delta t_{\mathrm{resp}}^2} = \sqrt{2 + 25 + 25} = 7.2\mathrm{ms}$$

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

Inverse Beta Decay (IBD)



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

$$\boxed{\sigma_{\mathrm{IBD}}(\mathrm{E}_\nu) \sim 9\cdot 10^{-44}\cdot \mathrm{E}_\nu^2\ \mathrm{cm}^2}$$

$$\mathrm{N}_{e\nu} = \mathrm{N}_{\mathrm{p}} \int_{E_{thr}}^{\infty} \mathrm{dE}_{e^+}\sigma_{\mathrm{IBD}}(\mathrm{E}_\nu)\eta(\mathrm{E}_{\mathrm{e}^+})\mathrm{F}_{\bar{\nu}_{\mathrm{e}}}(\mathrm{E}_\nu)\mathrm{G}(\mathrm{E}_\nu,\mathrm{E}_{\mathrm{e}^+})$$

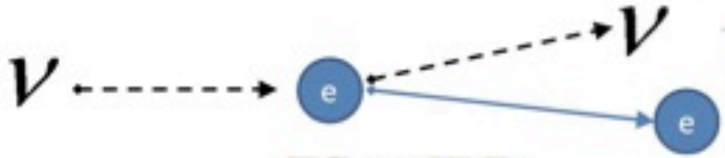
$$\mathrm{N}_{\mathrm{p}} \approx 1\mathrm{kton}\times\frac{10^9\,\mathrm{g}}{\mathrm{kton}}\times\frac{6\cdot 10^{23}}{\mathrm{g}}\times\frac{2}{18}\approx 6\cdot 10^{31}$$

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

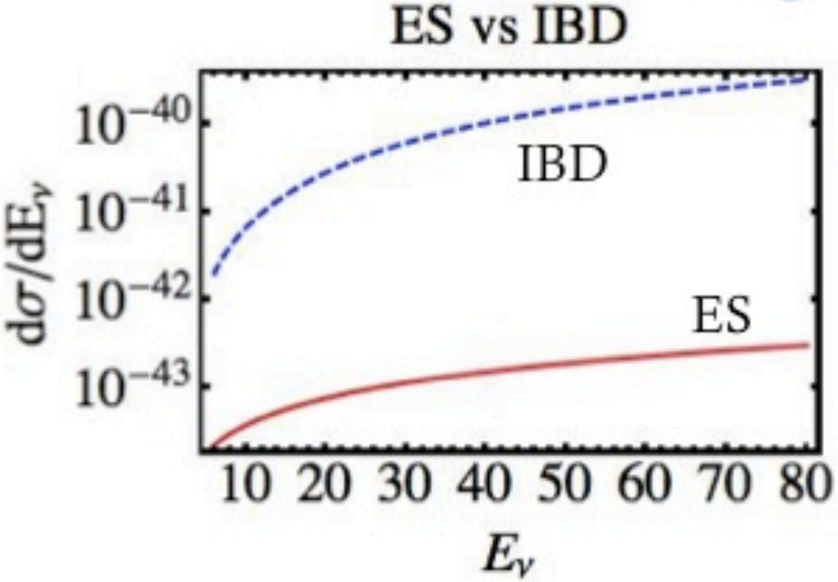
NOW 2012

Elastic Scattering (ES)

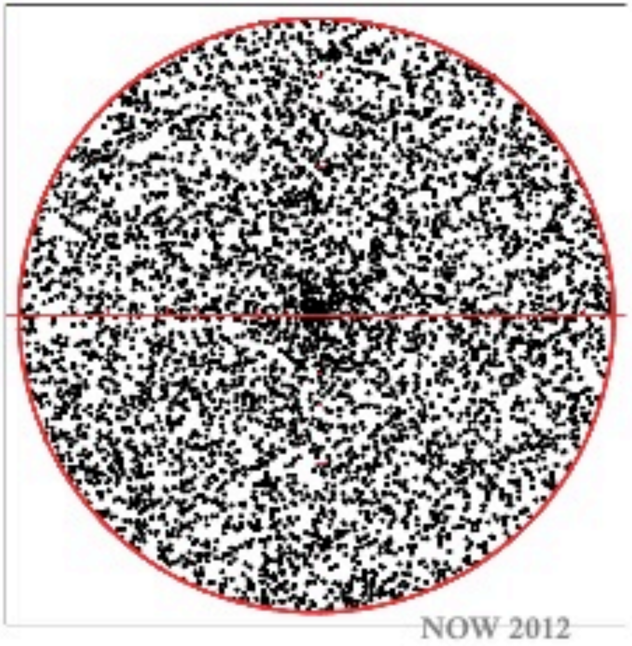
Directional interaction:



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



POINTING:
300 ES
directional events among the IBD events



NOW 2012

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