Detection of Supernova Neutrinos at JUNO

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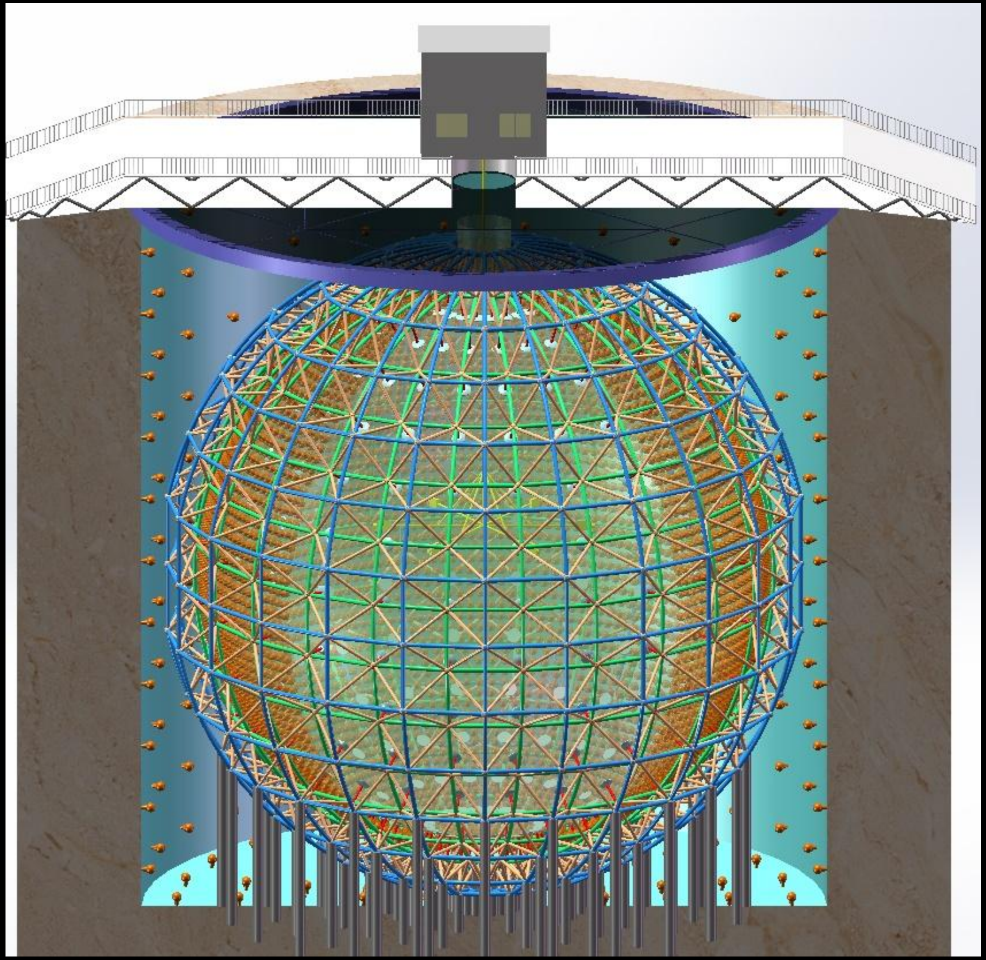
IHEP, Beijing

The JUNO Workshop on Neutrino Astronomy and Astrophysics
Nanjing University, 2016-04-17

The JUNO Experiment

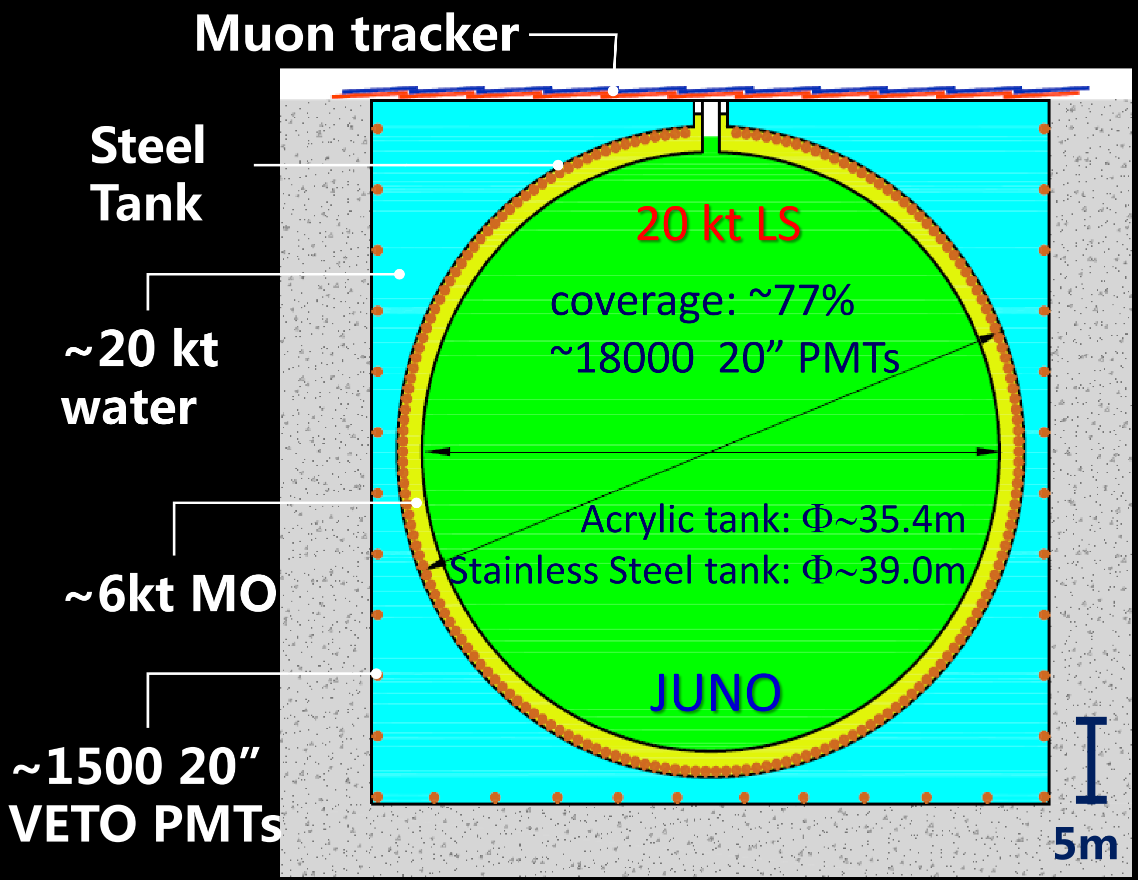
- **Jiangmen Underground Neutrino Observatory (JUNO), a multiple-purpose neutrino experiment, approved in Feb. 2013 (~ 300 M$), construction started in Jan. 2015.**

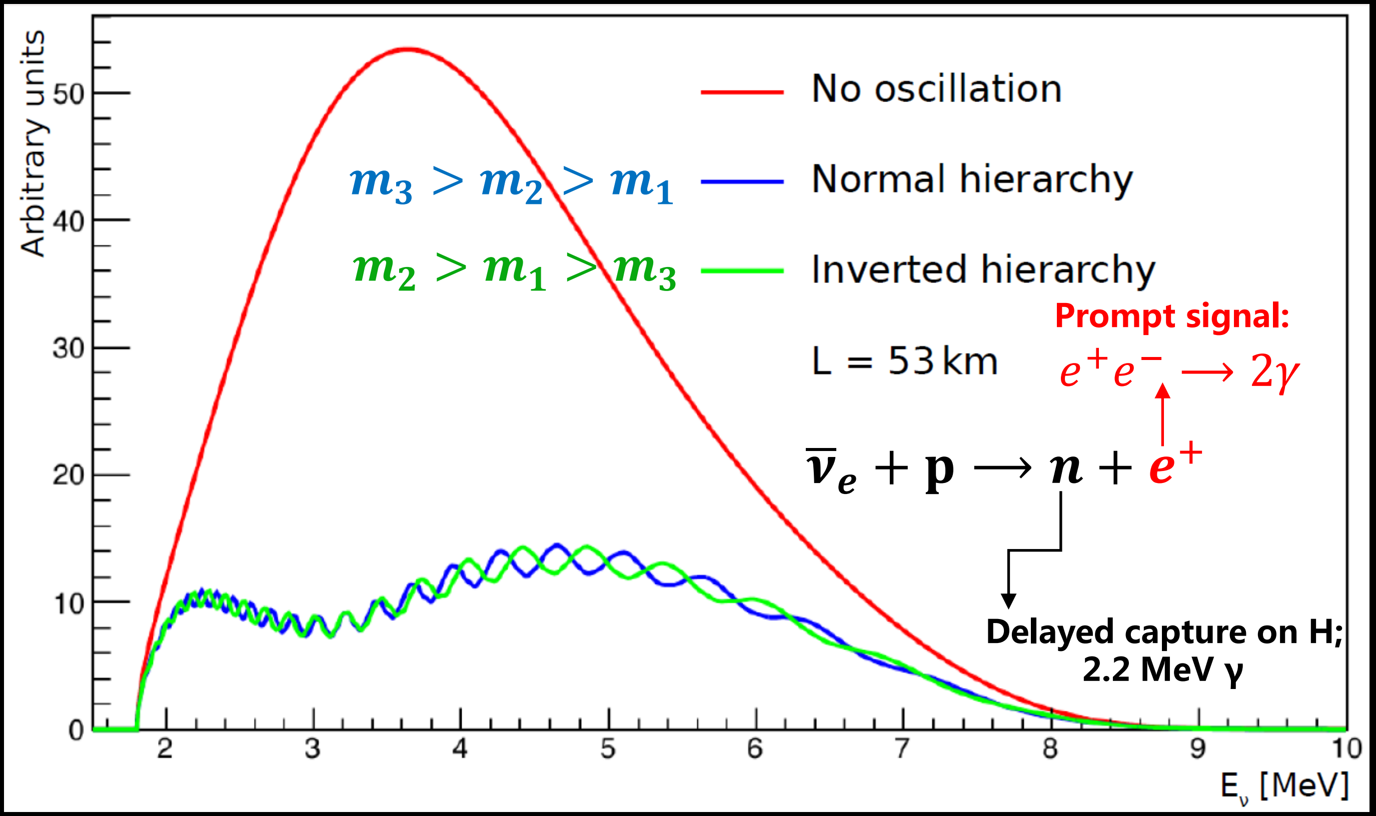


- **20 kton LS detector**
- **3% energy resolution**
- **700 m underground**
- **Rich Physics Possibilities**
  - **Reactor Neutrinos for neutrino mass hierarchy & precision measurement of oscillation parameters**
  - ***Supernova Neutrino Burst***
  - ***Diffuse Supernova Neutrino Background***
  - **Geoneutrinos**
  - **Solar Neutrinos**
  - **Atmospheric Neutrinos**
  - **Proton Decays**
  - **Exotic Searches**

Talks by Y.F. Wang at ICFA Seminar 2008, Neutel 2011; by J. Cao at NeuTel 2009, NuTurn 2012, NeuTel 2015 ; Papers by L. Zhan, Y.F. Wang, J. Cao, L.J. Wen, PRD78:111103, 2008; PRD79:073007,2009; Y.F. Li, J. Cao, Y.F. Wang, L. Zhan, PRD 88: 013008, 2013.

High-precision, Giant LS detector

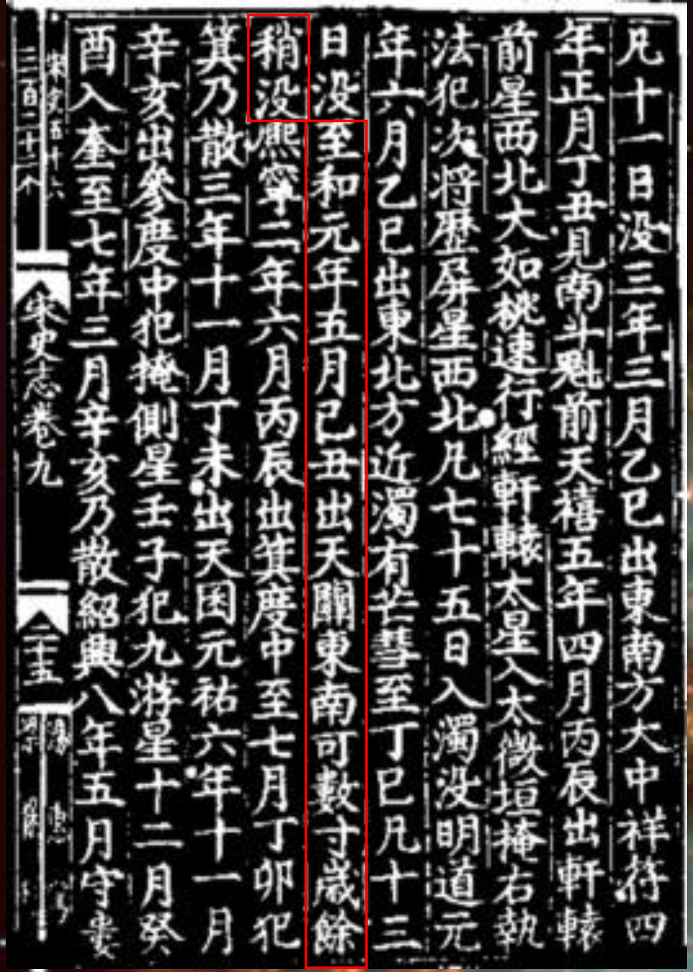




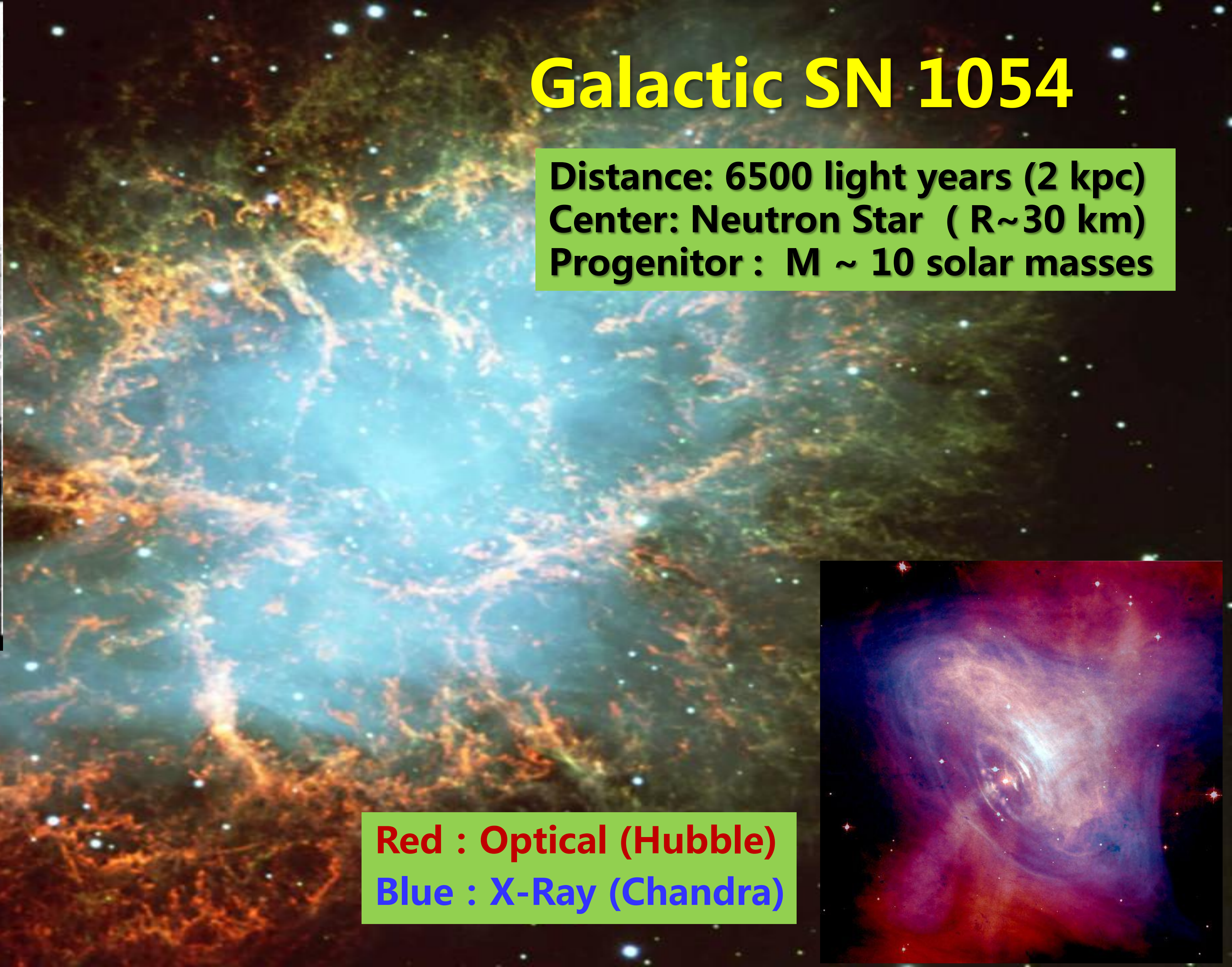
	KamLAND	BOREXINO	JUNO
LS mass	1 kt	0.5 kt	20 kt
Energy Resolution	$6\%/\sqrt{E}$	$5\%/\sqrt{E}$	$3\%/\sqrt{E}$
Light yield	250 p.e./MeV	511 p.e./MeV	1200 p.e./MeV

Run for 6 yrs	Relative	Absolute Δm^2
Statistics	4σ	5σ
Realistic	3σ	4σ

Galactic SN 1054


凡十一日沒三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅太星入太微垣掩右執
法犯次將歷屏星西北凡七十五日入濁沒明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日沒至和元年五月己丑出天關東南可數寸歲餘
稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁

宋史志卷九

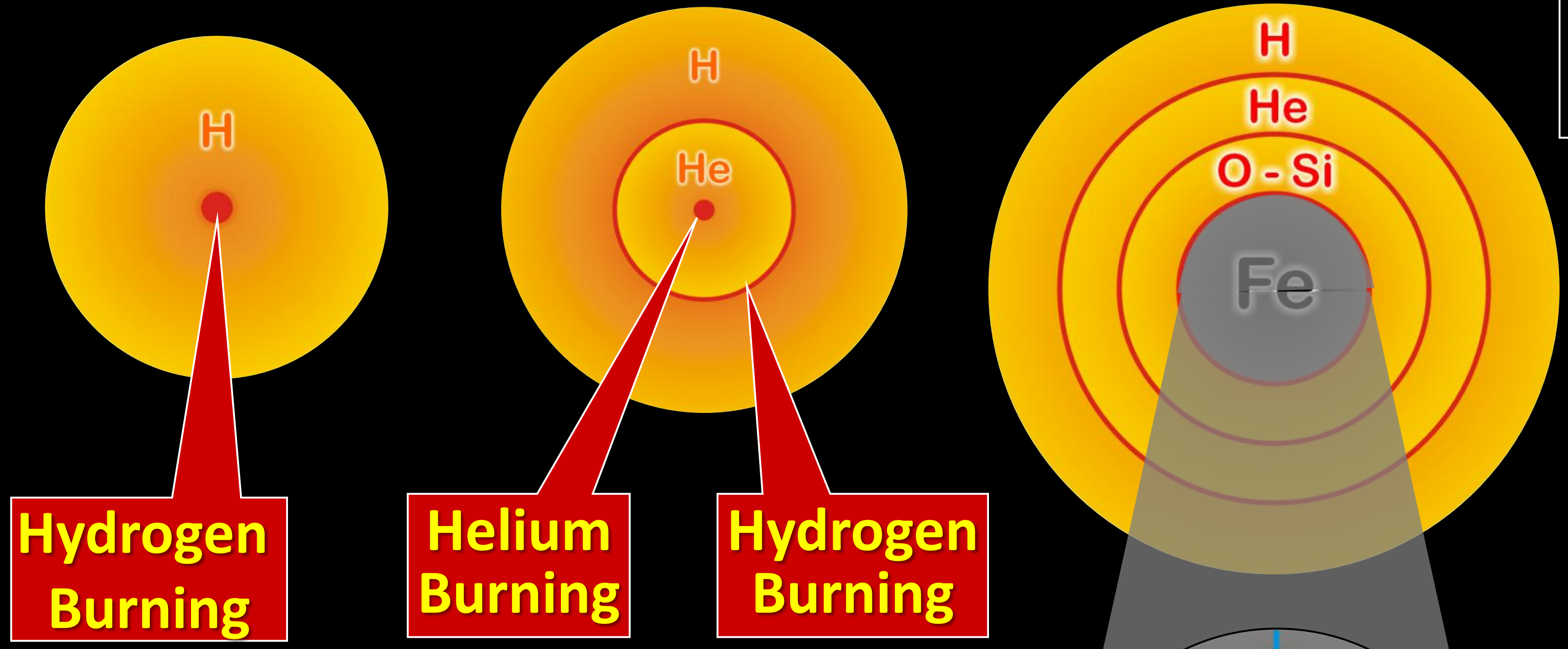


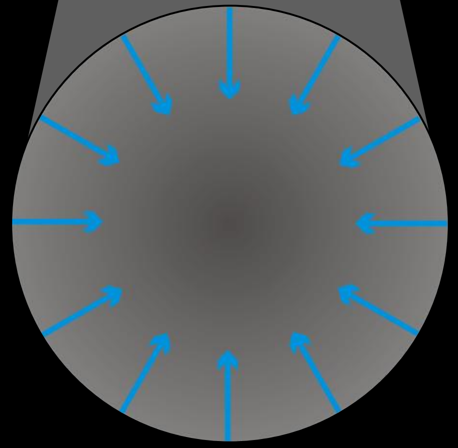
Distance: 6500 light years (2 kpc)
Center: Neutron Star (R~30 km)
Progenitor : M ~ 10 solar masses

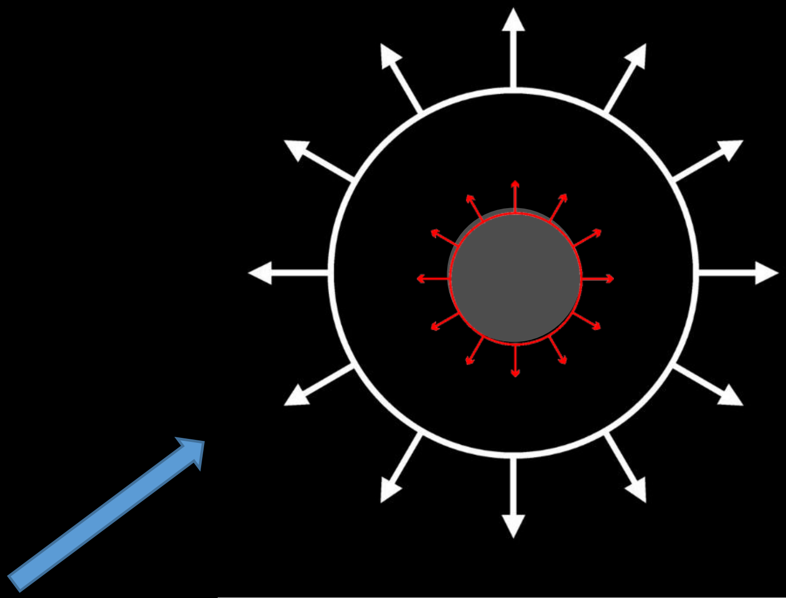
Red : Optical (Hubble)
Blue : X-Ray (Chandra)

Stellar Collapse and SN Explosion

Main-sequence star   Helium-burning star







Grav. binding energy $E_b \approx 3 \times 10^{53}$ erg

99% Neutrinos

1% Kinetic energy of explosion

(1% of this into cosmic rays)

0.01% Photons, outshine host galaxy

1. > 8 Solar Masses
2. Collapse→Bounce
3. Shock wave halted
4. ν energy deposited
5. Final SN explosion

Degenerate iron core:

$\rho \approx 10^9\ \mathrm{g\ cm^{-3}}$

$T \approx 10^{10}\ \mathrm{K}$

$M_{Fe} \approx 1.5\ M_{sun}$

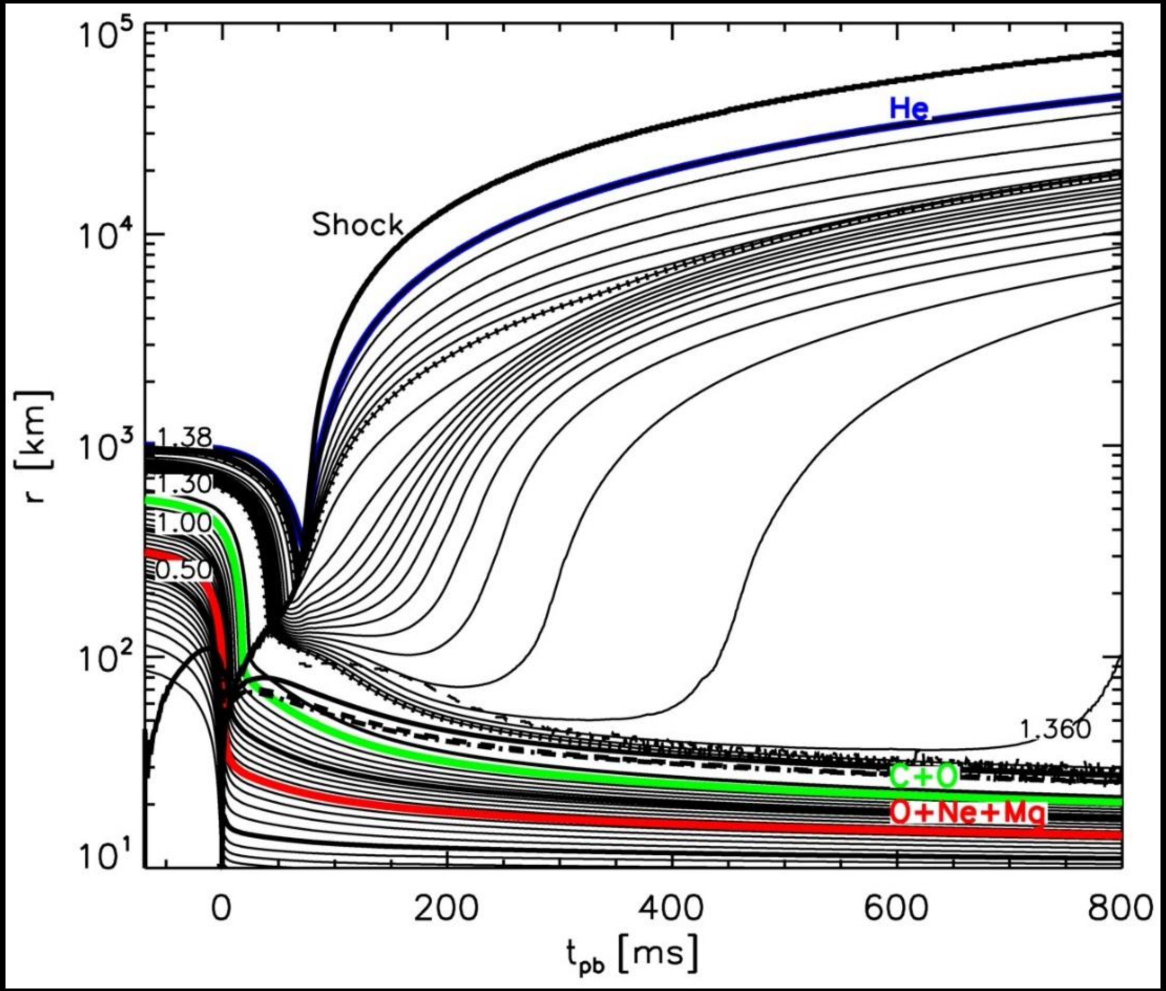
$R_{Fe} \approx 8000$ km

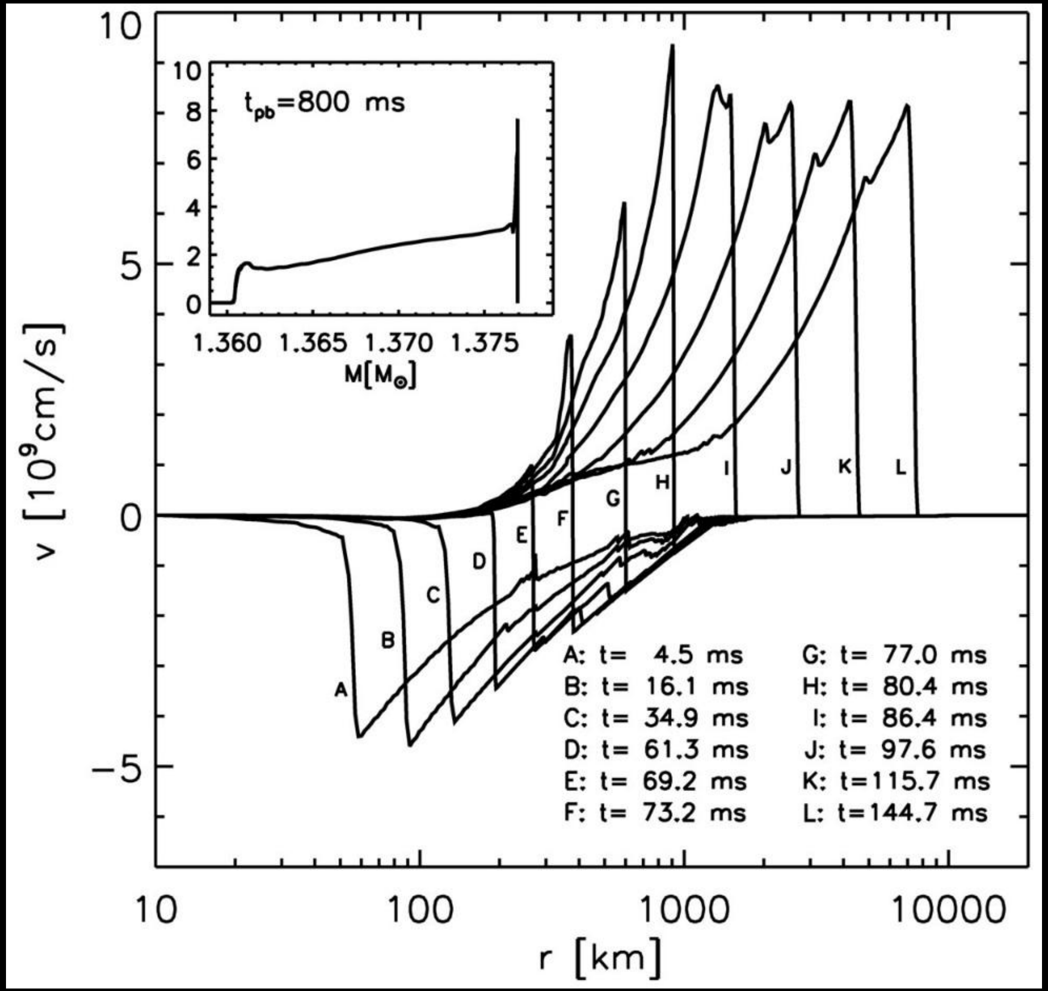
Proto-Neutron star:

$\rho \sim \rho_{nuc} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

$T \sim 30$ MeV

Exploding Models (8–10 Solar Masses)

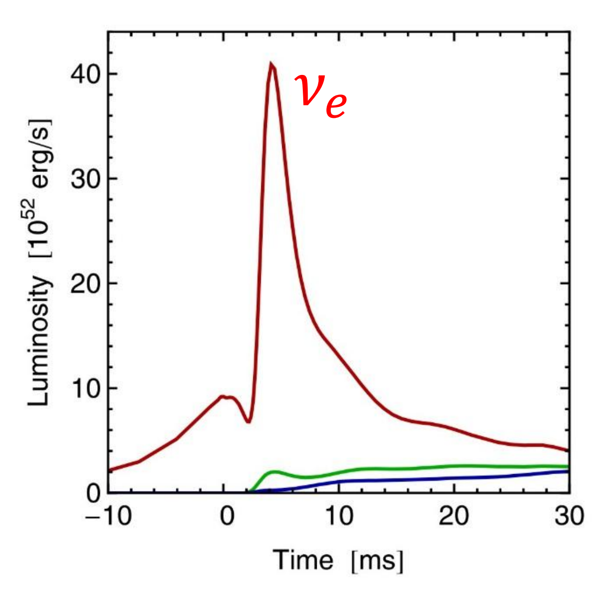




Kitaura, Janka & Hillebrandt: “Explosions of O-Ne-Mg cores, the Crab supernova, and subluminous type II-P supernovae”, astro-ph/0512065

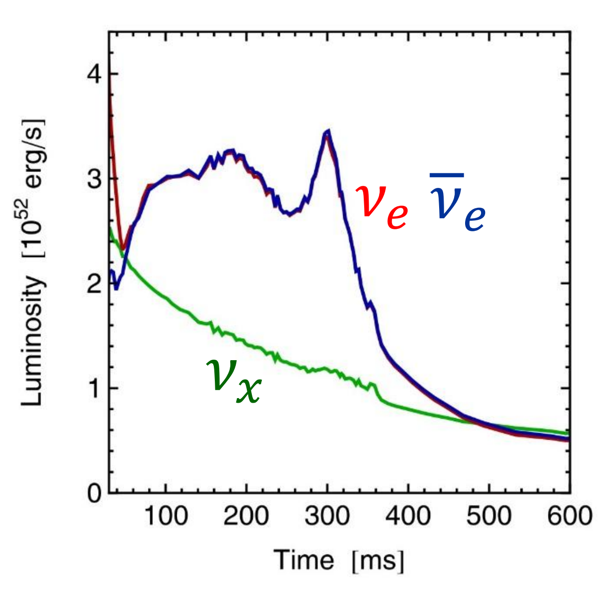
Three Phases of Neutrino Emission

Prompt ν_e burst



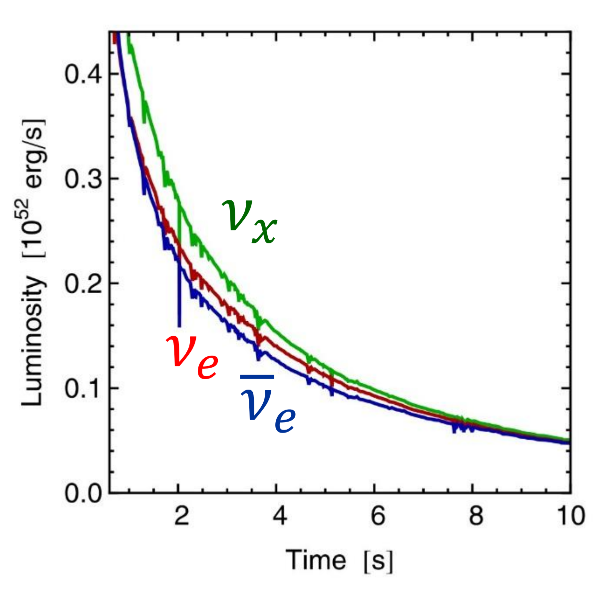
- Shock breakout
- De-leptonization of outer core layers

Accretion



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

Cooling

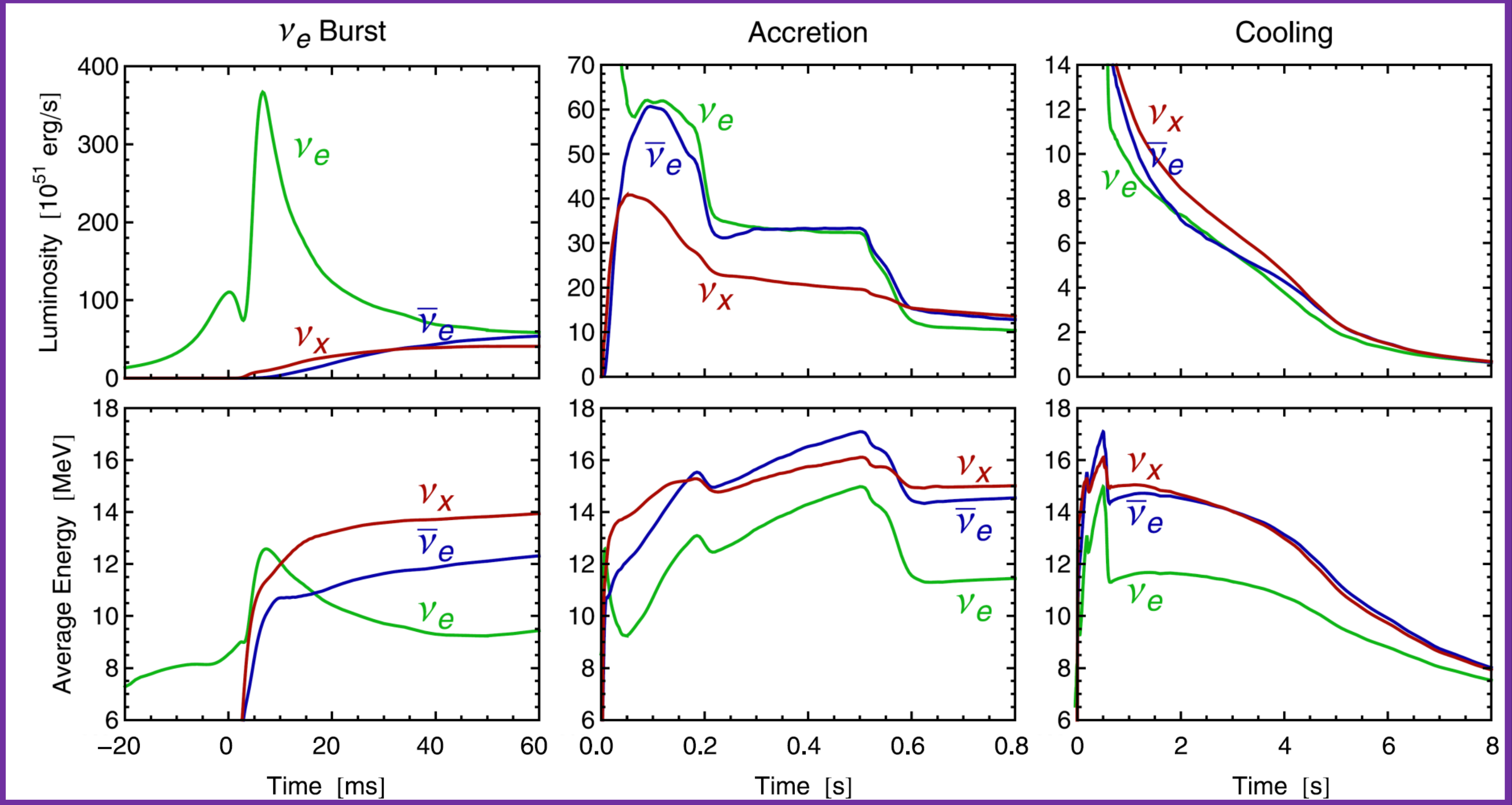


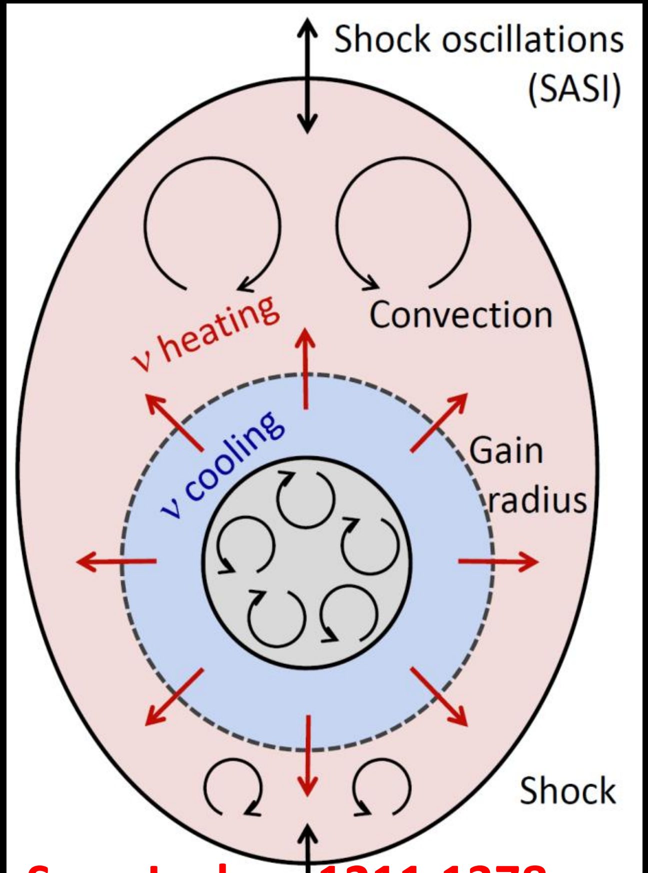
Cooling on neutrino diffusion time scale

- Spherically symmetric model (10.8 $M_\odot$) with Boltzmann neutrino transport
- Explosion manually triggered by enhanced CC interaction rate

Fischer et al. (Basel group), A&A 517:A80, 2010 [arxiv:0908.1871]

Galactic SN Neutrinos





See, Janka, 1211.1378

Detect $\bar{\nu}_e$, ν_e, ν_x from a galactic SN @ 10 kpc

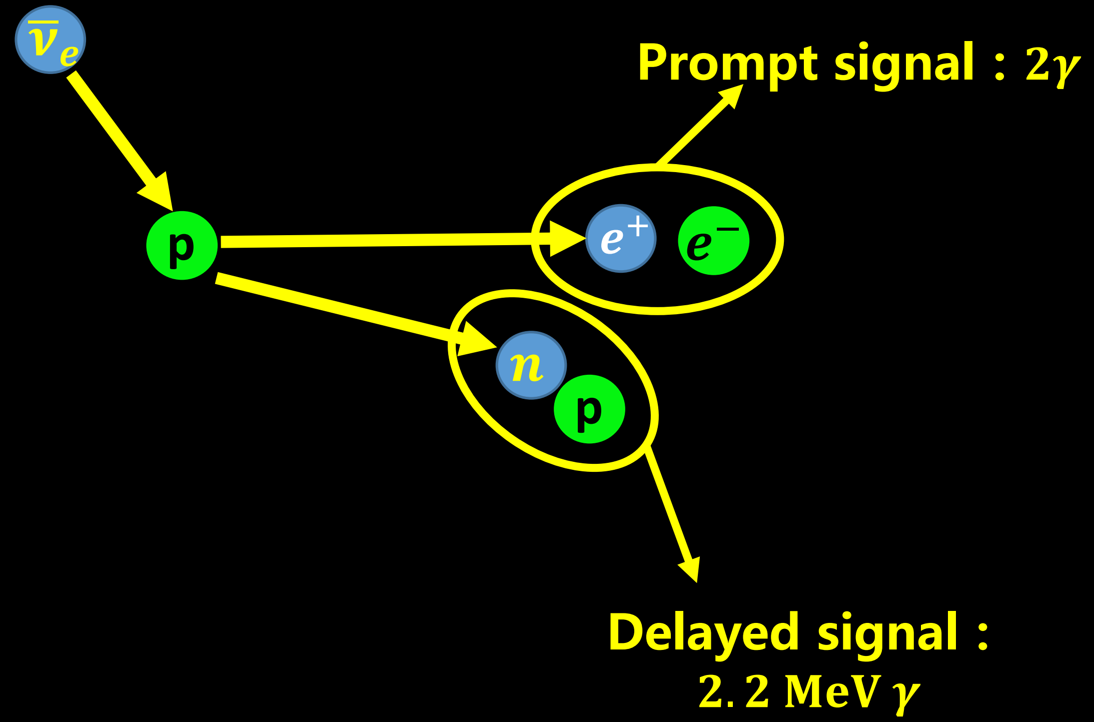
- real-time meas. of three-phase ν signals
- distinguish between different ν flavors
- reconstruct ν energies and luminosities
- almost background free due to time info

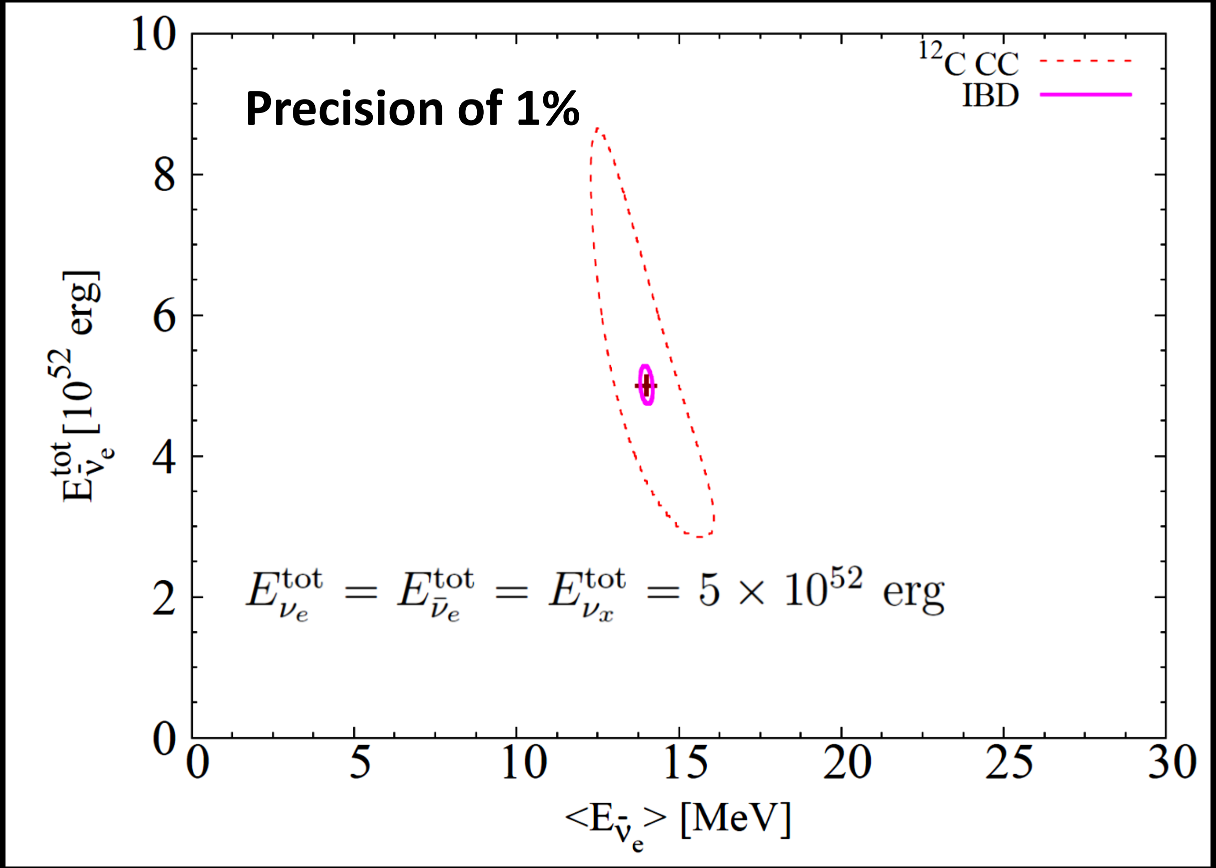
Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \rightarrow e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \rightarrow \nu + p$	NC	6.0×10^2	1.2×10^3	2.0×10^3
$\nu + e \rightarrow \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\mathrm{C} \rightarrow \nu + {}^{12}\mathrm{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}$	CC	4.7×10^1	9.4×10^1	1.6×10^2
$\overline{\nu}_e + {}^{12}\mathrm{C} \rightarrow e^+ + {}^{12}\mathrm{B}$	CC	6.0×10^1	1.1×10^2	1.6×10^2

Detection of SN Neutrinos at JUNO

Inverse beta decay (IBD) $\overline{\nu}_e + \mathrm{p} \longrightarrow n + e^+$

Spectra $$F^0_\alpha(E) = \frac{1}{4\pi D^2}\frac{E^{\rm tot}_\alpha}{\langle E_\alpha\rangle}\frac{(1+\gamma_\alpha)^{1+\gamma_\alpha}}{\Gamma(1+\gamma_\alpha)}\left(\frac{E}{\langle E_\alpha\rangle}\right)^{\gamma_\alpha}\exp\left[-(1+\gamma_\alpha)\frac{E}{\langle E_\alpha\rangle}\right]$$



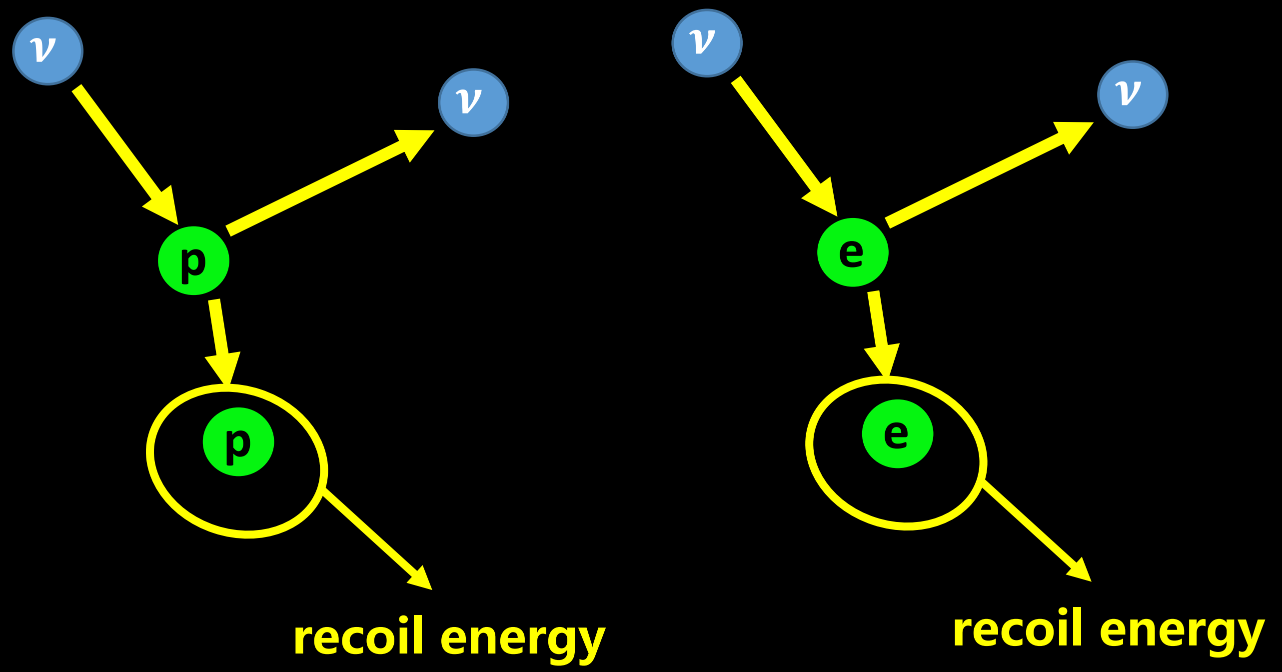


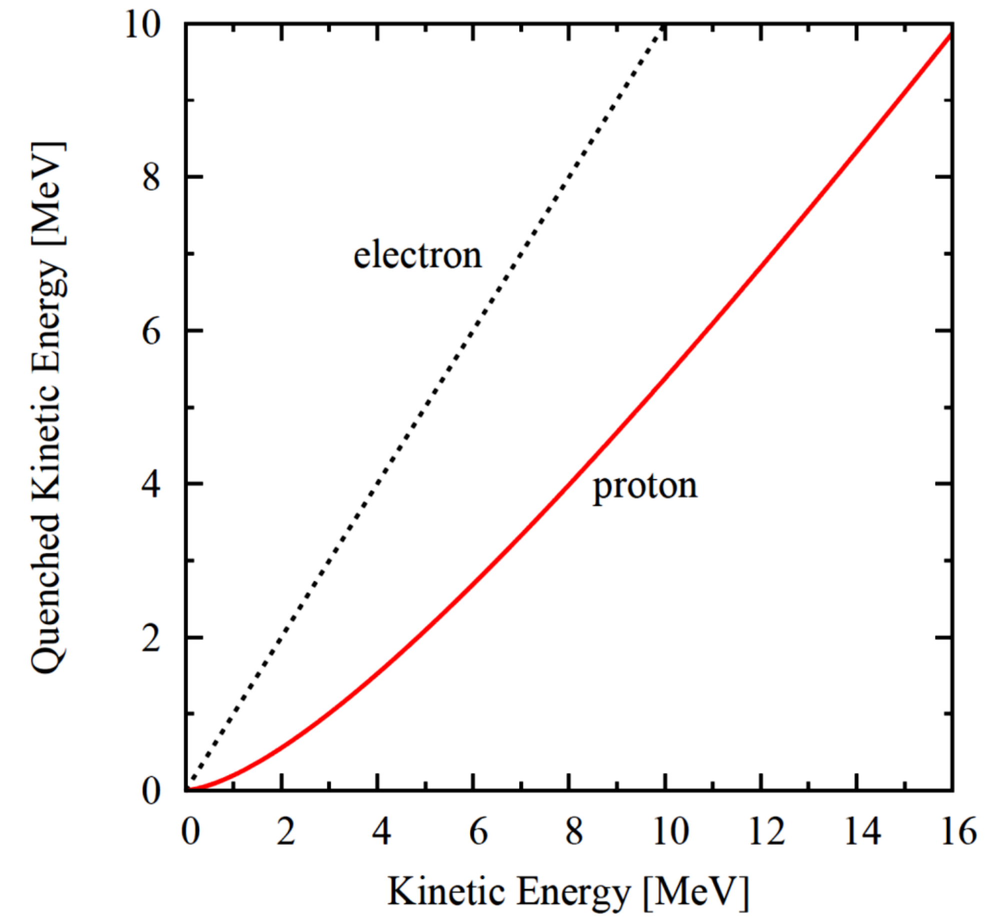
- 5000 IBD events, golden channel for SN neutrino observations
- Coincidence of prompt and delayed signals: least background
- Dominant channel for electron anti-ν, good reconstruction of E_ν

Detection of SN Neutrinos at JUNO

Elastic ν − p Scattering (pES) $\nu + p \longrightarrow \nu + p$

Elastic ν − e Scattering (eES) $\nu_e + e \longrightarrow \nu_e + e$

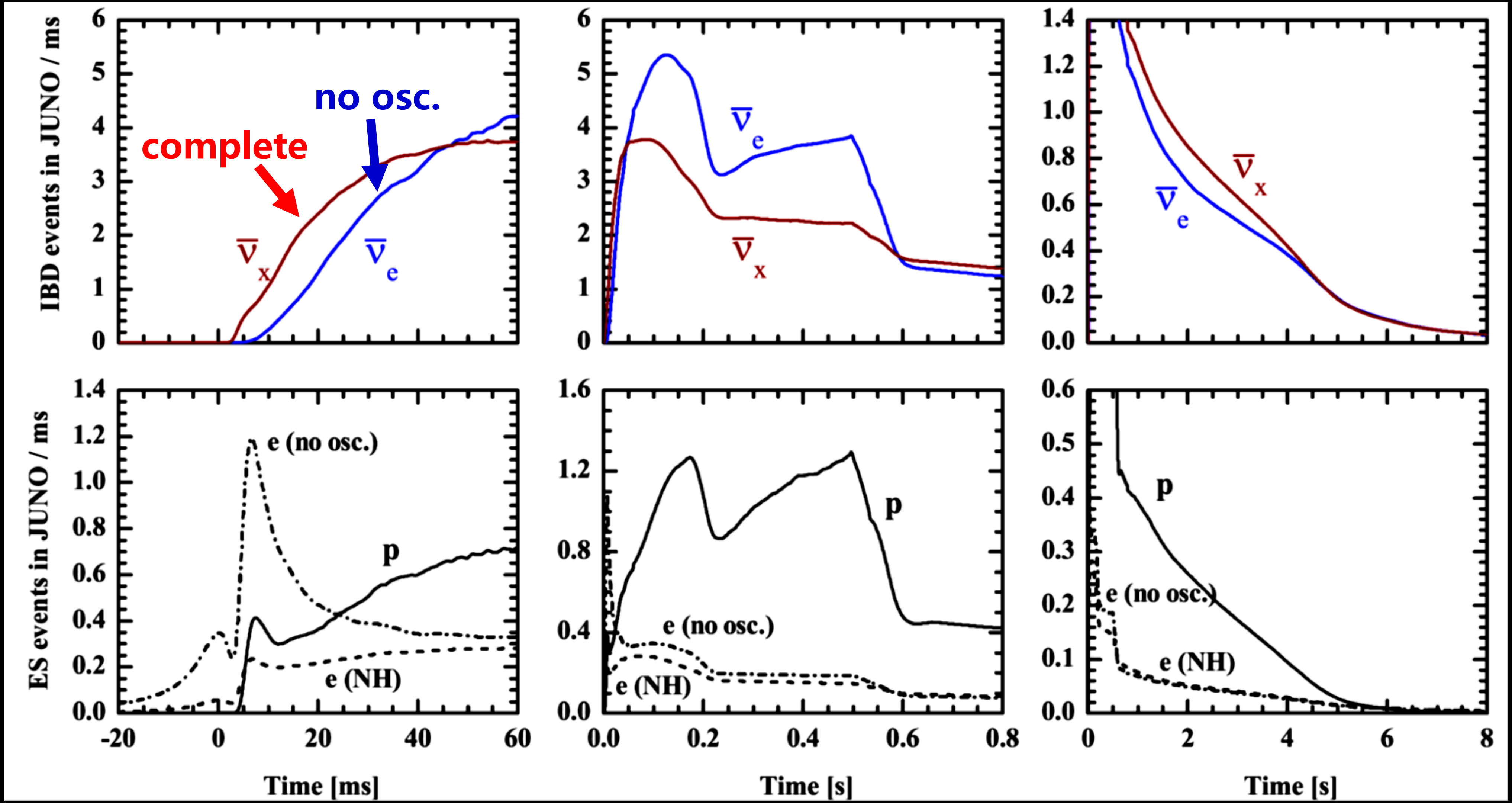




- 2000 pES events, dominant channel for muon & tau neutrinos
- Low threshold for visible energy: nominal value = 0.2 MeV
- reconstruction of neutrino energy spectrum: high-energy tail

Detection of SN Neutrinos at JUNO

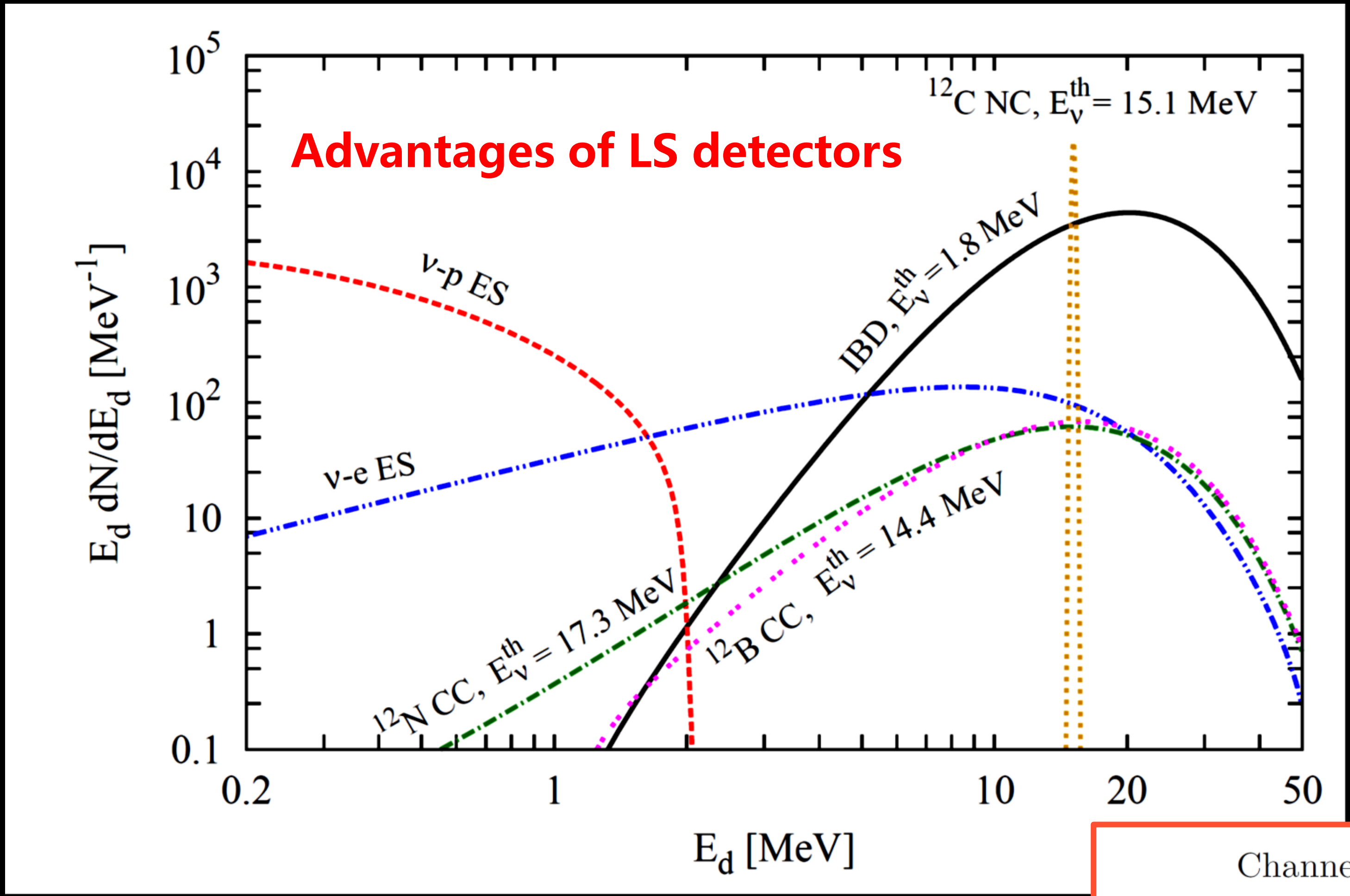
F.P. An et al, JUNO Yellow Book, published in JPG, 1507.05613

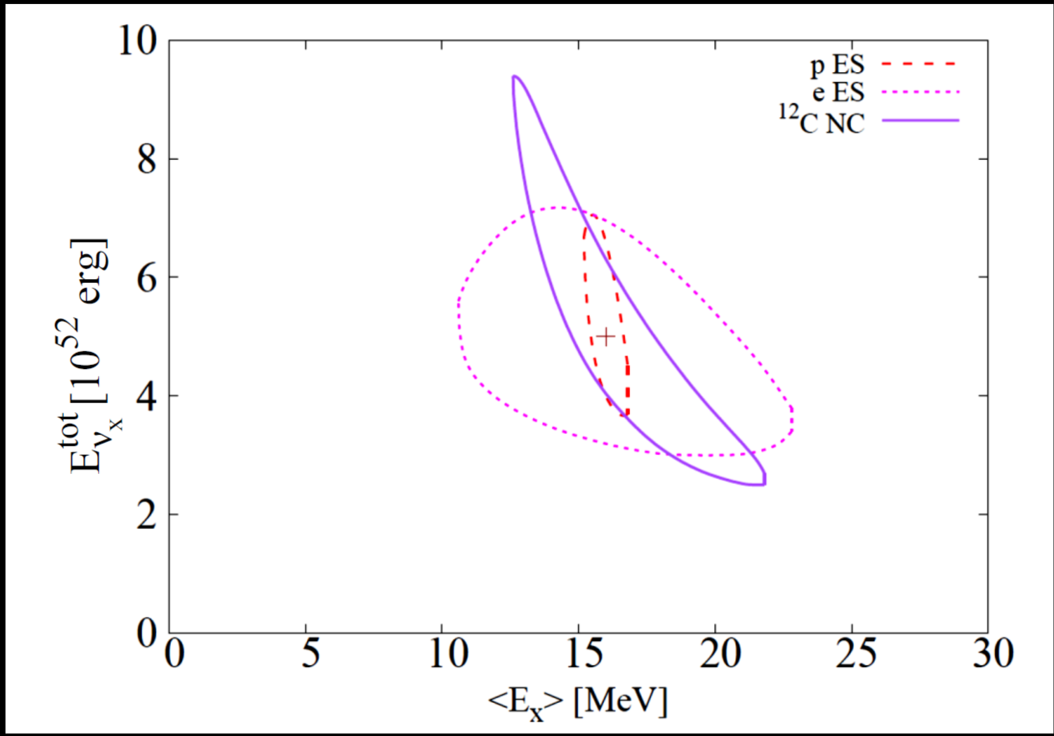


Impact of neutrino flavor conversions

Meng-Ru's talk

Detection of SN Neutrinos at JUNO





Global analysis of all channels

Channel	Type	Events for different $\langle E_\nu \rangle$ values		
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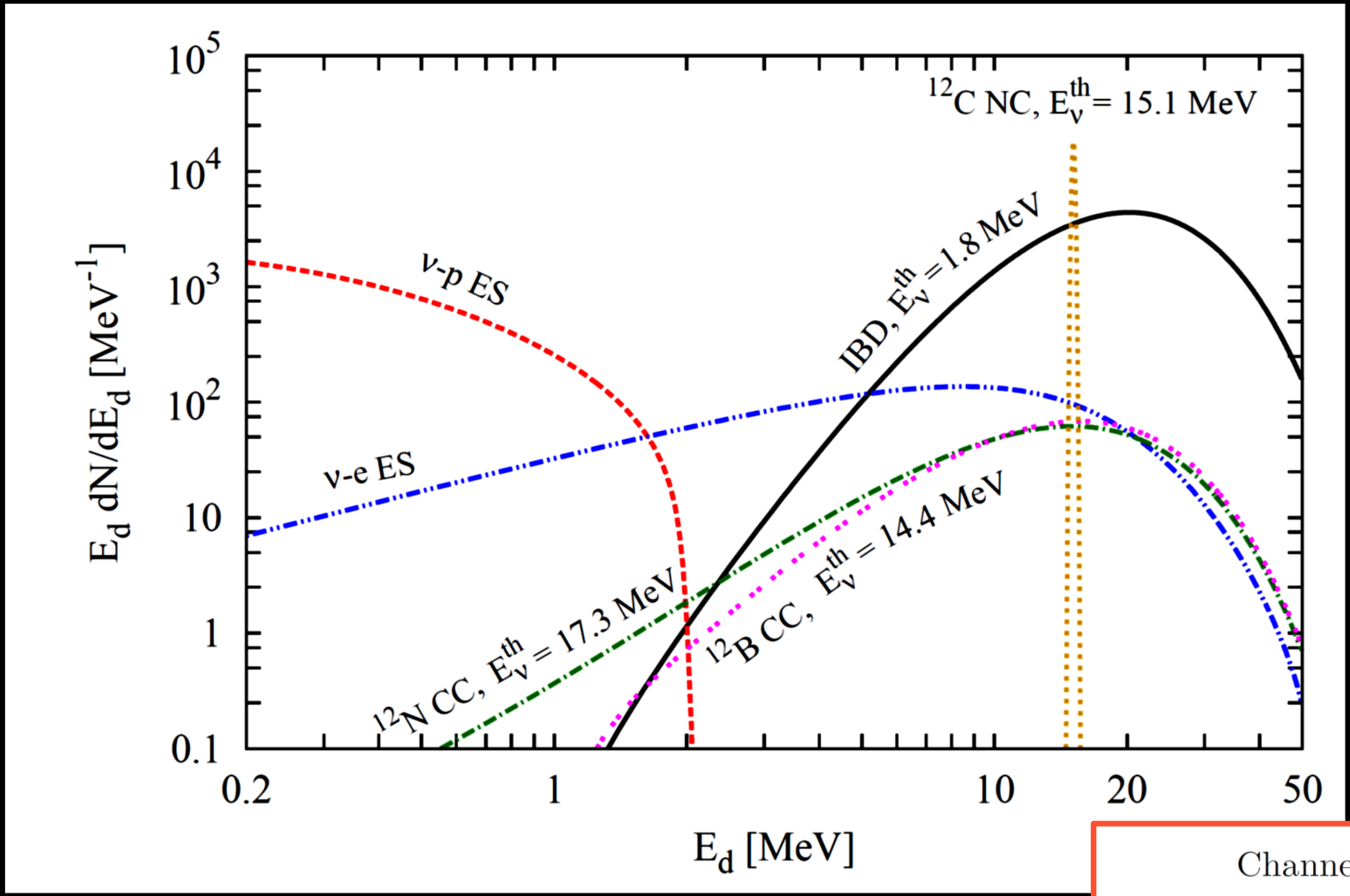
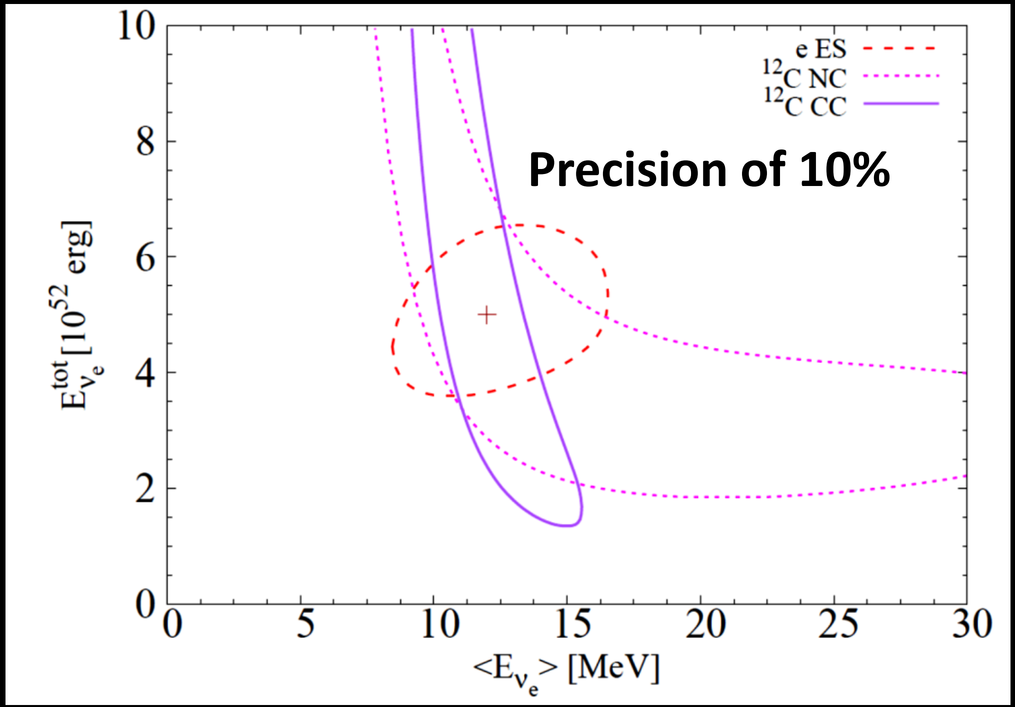
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	CC	4.7×10^1	9.4×10^1	1.6×10^2
$\overline{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	CC	6.0×10^1	1.1×10^2	1.6×10^2

Detection of SN Neutrinos at JUNO





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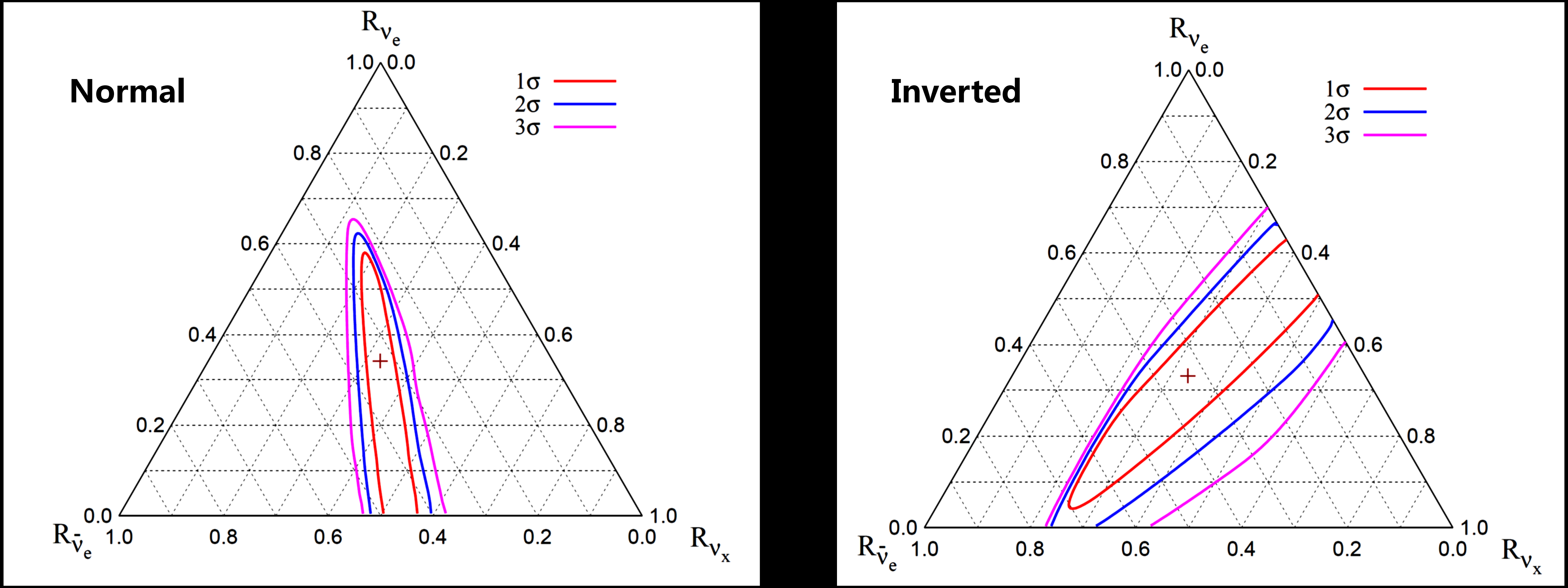
$\overline{\nu}_e + {}^{12}C \to e^+ + {}^{12}B$	CC	6.0×10^1	1.1×10^2	1.6×10^2

Hypothesis of Energy Equipartition

Jia-Shu Lu et al, to appear

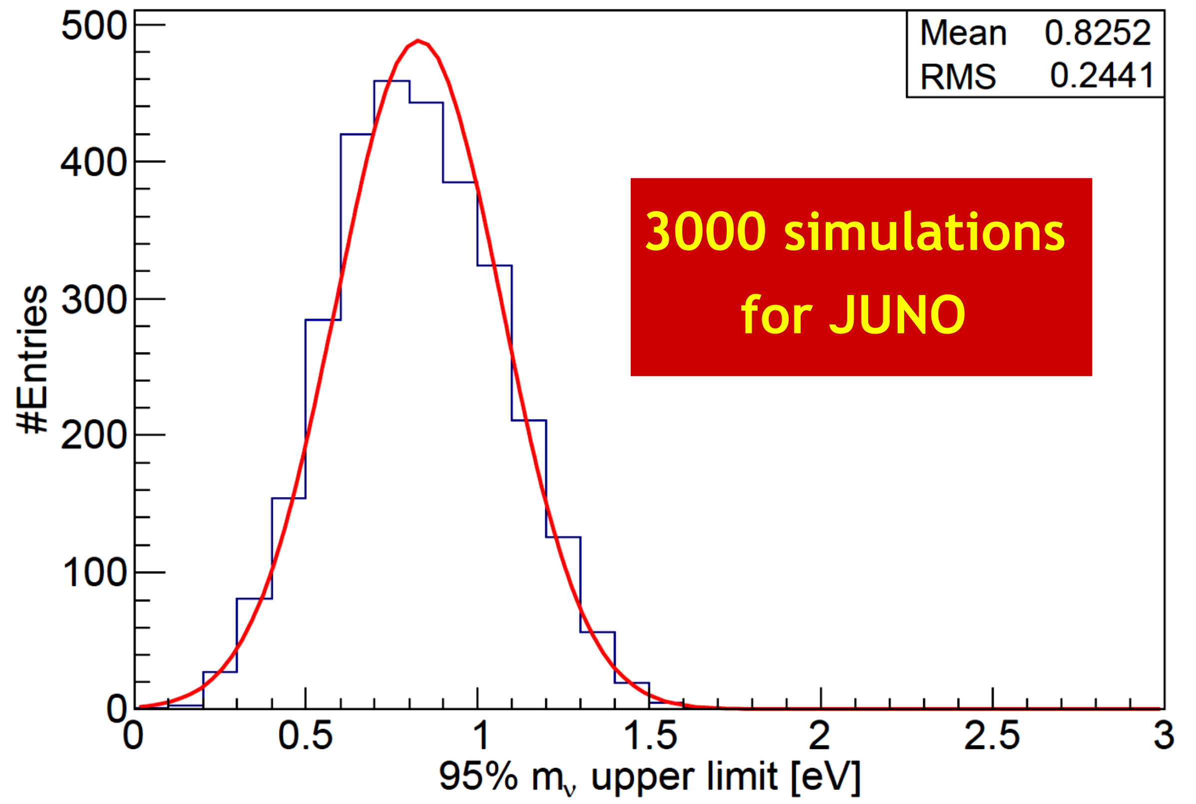


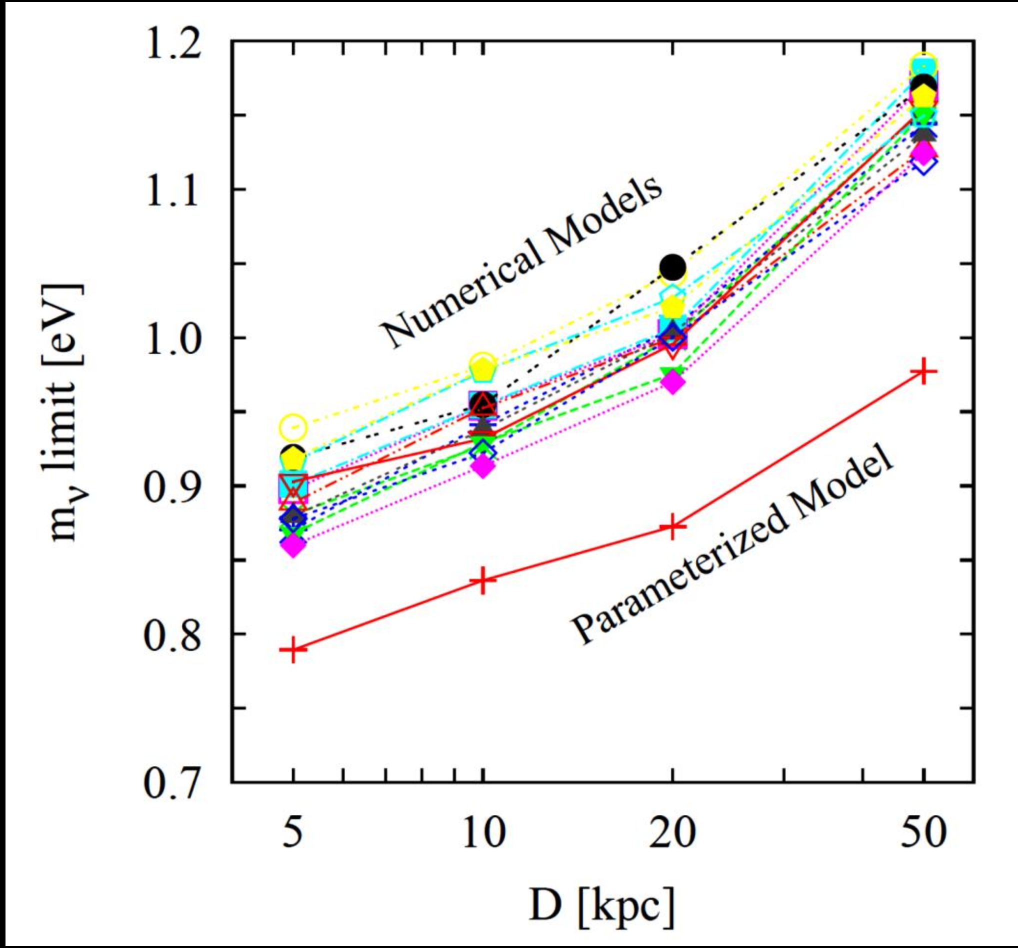
Only the MSW effects in the supernova are considered, and the energy fractions can be constrained.

Neutrino Mass Bound @ JUNO

Time delay of massive neutrinos

$$\Delta t(m_\nu, E_\nu) = 5.14\ \text{ms}\ \left(\frac{m_\nu}{\text{eV}}\right)^2 \left(\frac{10\ \text{MeV}}{E_\nu}\right)^2 \frac{D}{10\ \text{kpc}}$$

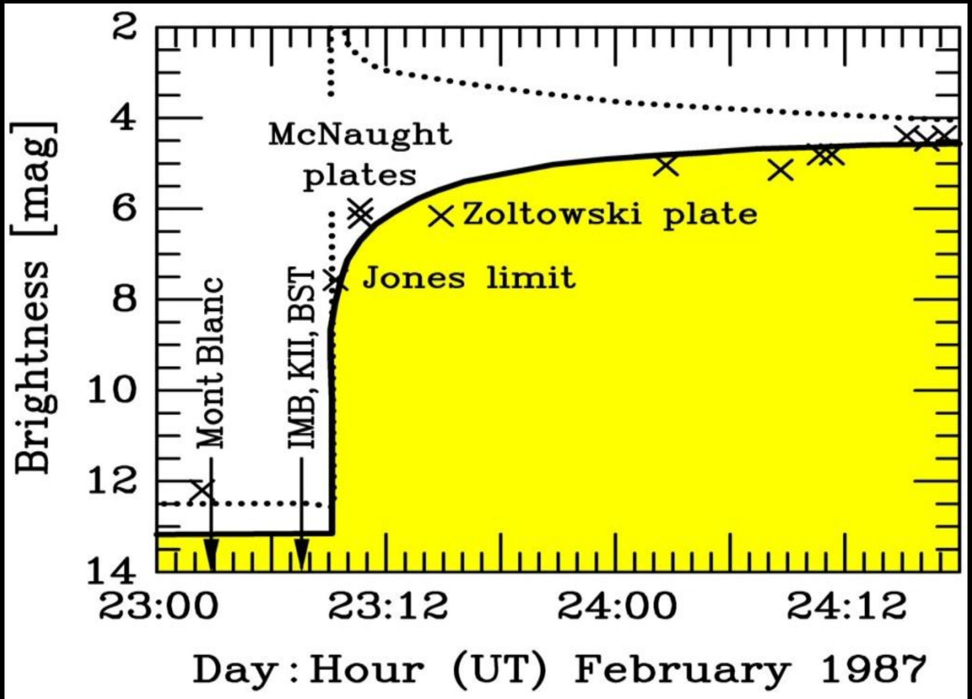




J.S. Lu et al., JCAP 15', 1412.7418

Galactic SN Neutrinos

- For Optical Observations： SuperNova Early Warning System (SNEWS)   Ya-Ping Cheng et al, to appear



SNEWS

Daya Bay

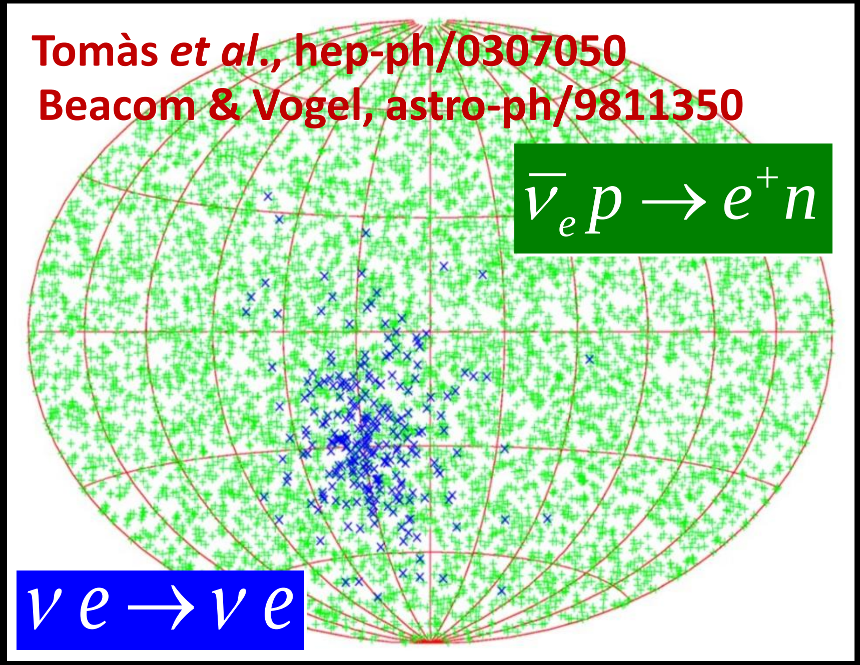
Super-K

IceCube

LVD

Borexino

Alert @BNL



n-tagging efficiency		
None	90 %	
7.8°	3.2°	SK

95% CL half-cone opening angle

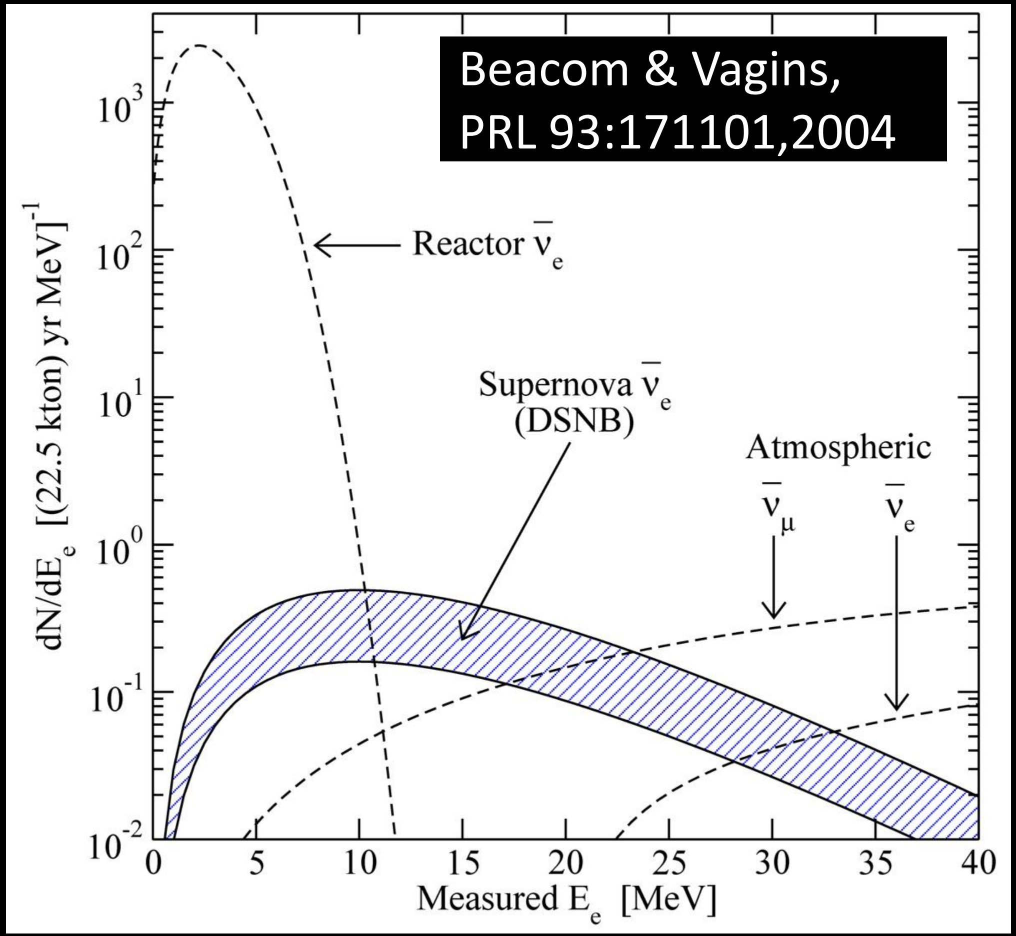
Neutrinos arrive several hours before photons; to alert astronomers several hours in advance

Locating a galactic SN @ 10 kpc

e^+-n correlation + Cherenkov: 8° @JUNO

Diffuse Supernova Neutrino Background (DSNB)

- Approx. 10 core collapses/sec in the visible universe
- Emitted ν energy density
  ~ extra galactic background light
  ~ 10% of CMB density
- Detectable $\bar{\nu}_e$ flux at Earth
  $\sim 10\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
  mostly from redshift $z \sim 1$
- Confirm star-formation rate
- Nu emission from average core collapse & black-hole formation
- Pushing frontiers of neutrino astronomy to cosmic distances!



Window of opportunity between reactor $\bar{\nu}_e$ and atmospheric ν bkg

Diffuse SN Background (DSNB)

Neutrinos from all the SNe in our Universe

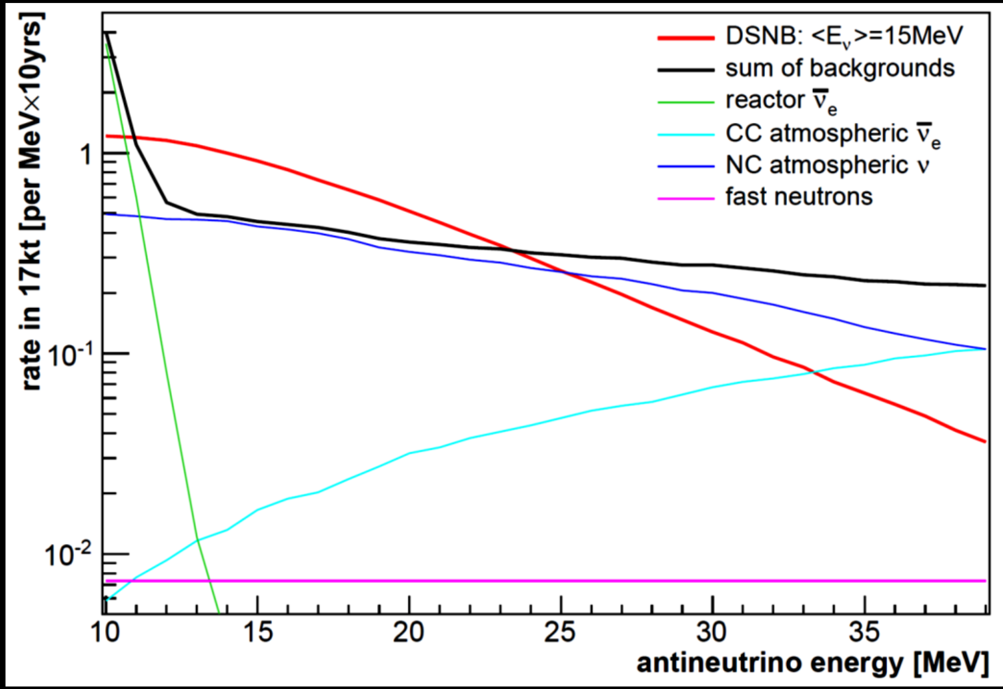
# of SNe per yr per Mpc³(un. SFR, IMF)

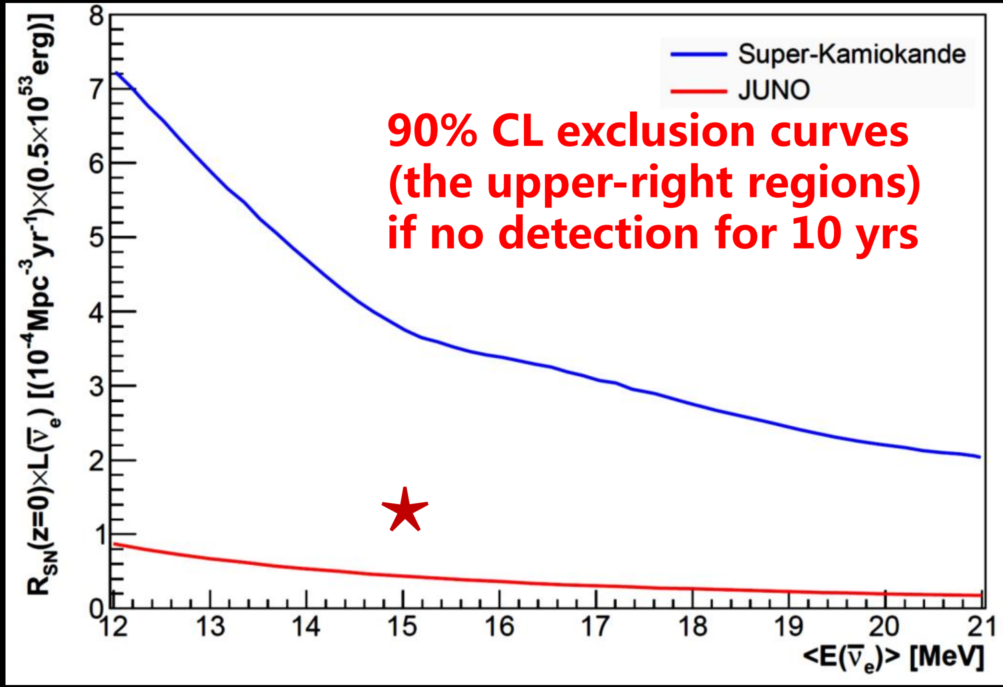
$$\frac{dF_{\bar{\nu}_e}}{dE_{\bar{\nu}_e}} = \frac{c}{H_0}\int_0^{z_{\max}} dz \frac{R_{\rm SN}(z)}{\sqrt{\Omega_{\rm m}(1+z)^3+\Omega_\Lambda}} \frac{dN_{\bar{\nu}_e}(E'_{\bar{\nu}_e})}{dE'_{\bar{\nu}_e}}$$

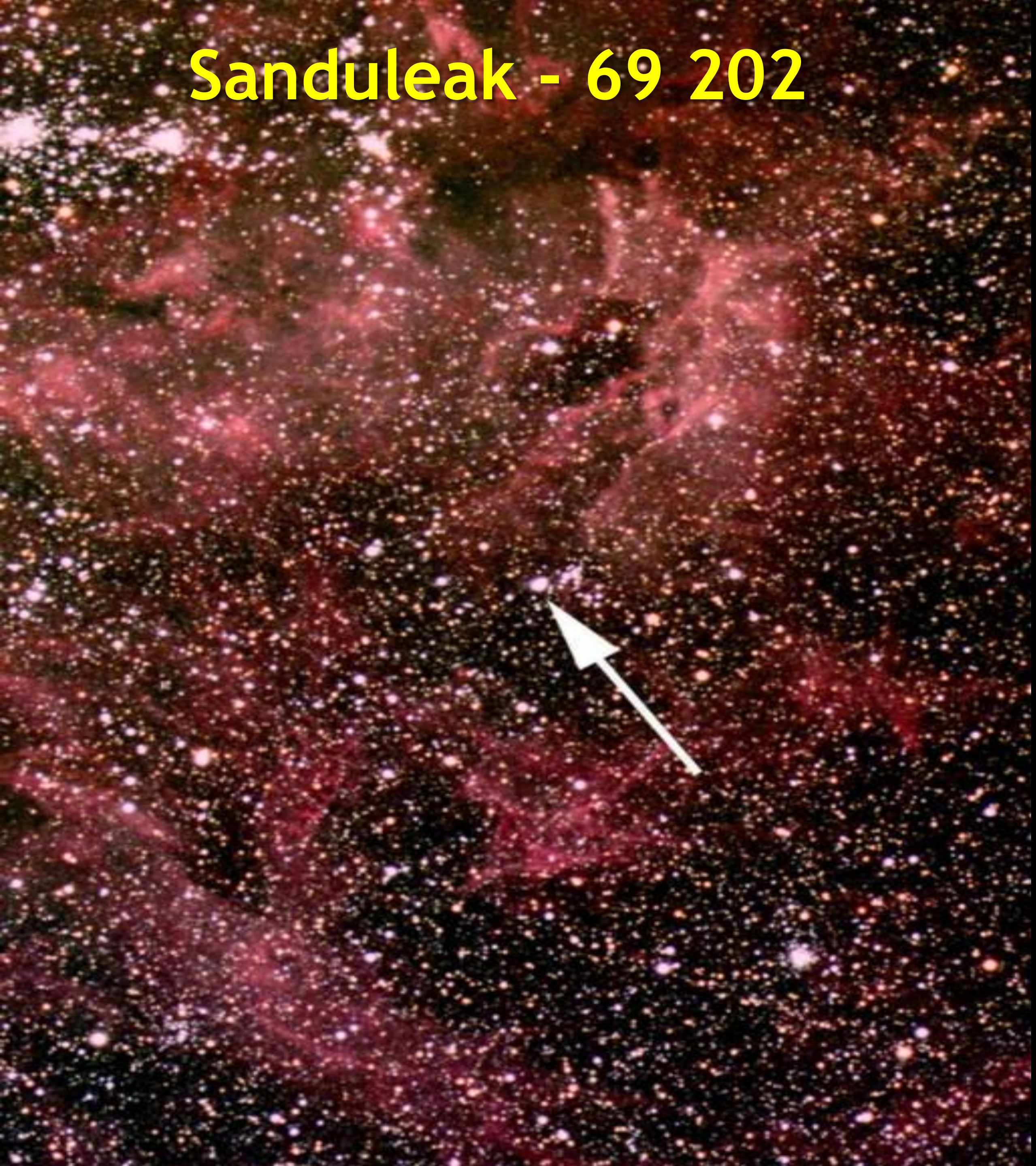
Cosmological evolution **ν spectrum**

- Observation window: 11 MeV < E_ν < 30 MeV
- PSD techniques for NC atmospheric ν
- Fast neutrons: r < 16.8 m (equiv. 17 kt mass)

Syst. uncertainty BG	5 %		20 %	
$\langle E_{\bar{\nu}_e}\rangle$	rate only	spectral fit	rate only	spectral fit
12 MeV	$1.7\,\sigma$	$1.9\,\sigma$	$1.5\,\sigma$	$1.7\,\sigma$
15 MeV	$3.3\,\sigma$	$3.5\,\sigma$	$3.0\,\sigma$	$3.2\,\sigma$
18 MeV	$5.1\,\sigma$	$5.4\,\sigma$	$4.6\,\sigma$	$4.7\,\sigma$
21 MeV	$6.9\,\sigma$	$7.3\,\sigma$	$6.2\,\sigma$	$6.4\,\sigma$

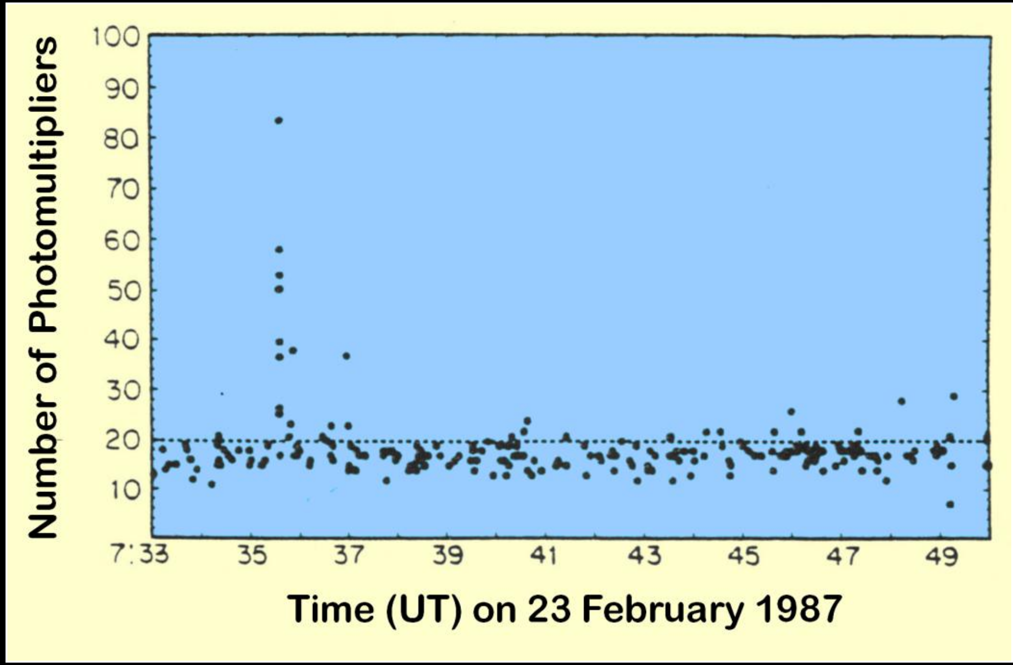


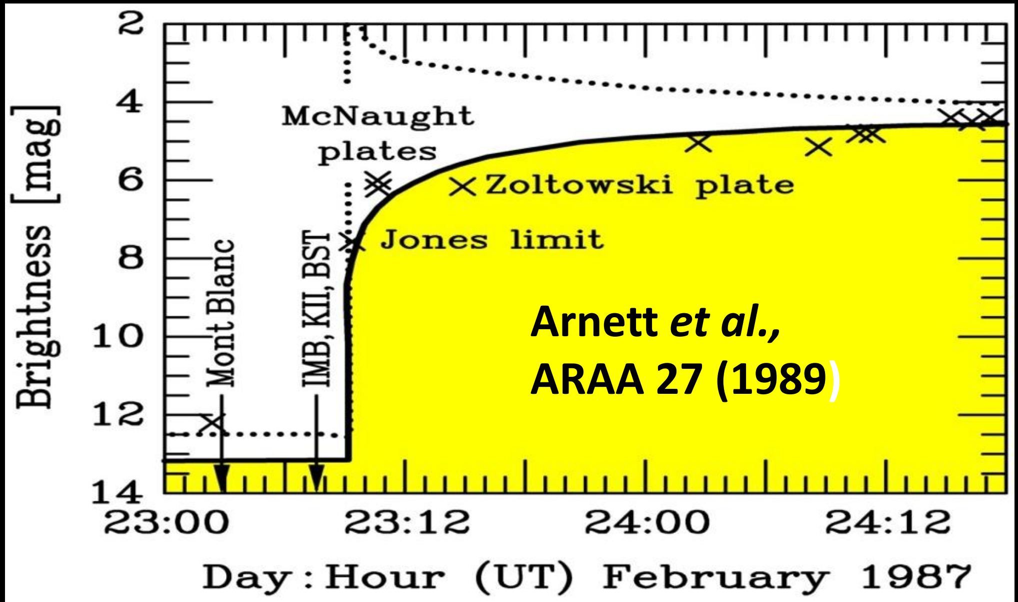



Sanduleak - 69 202

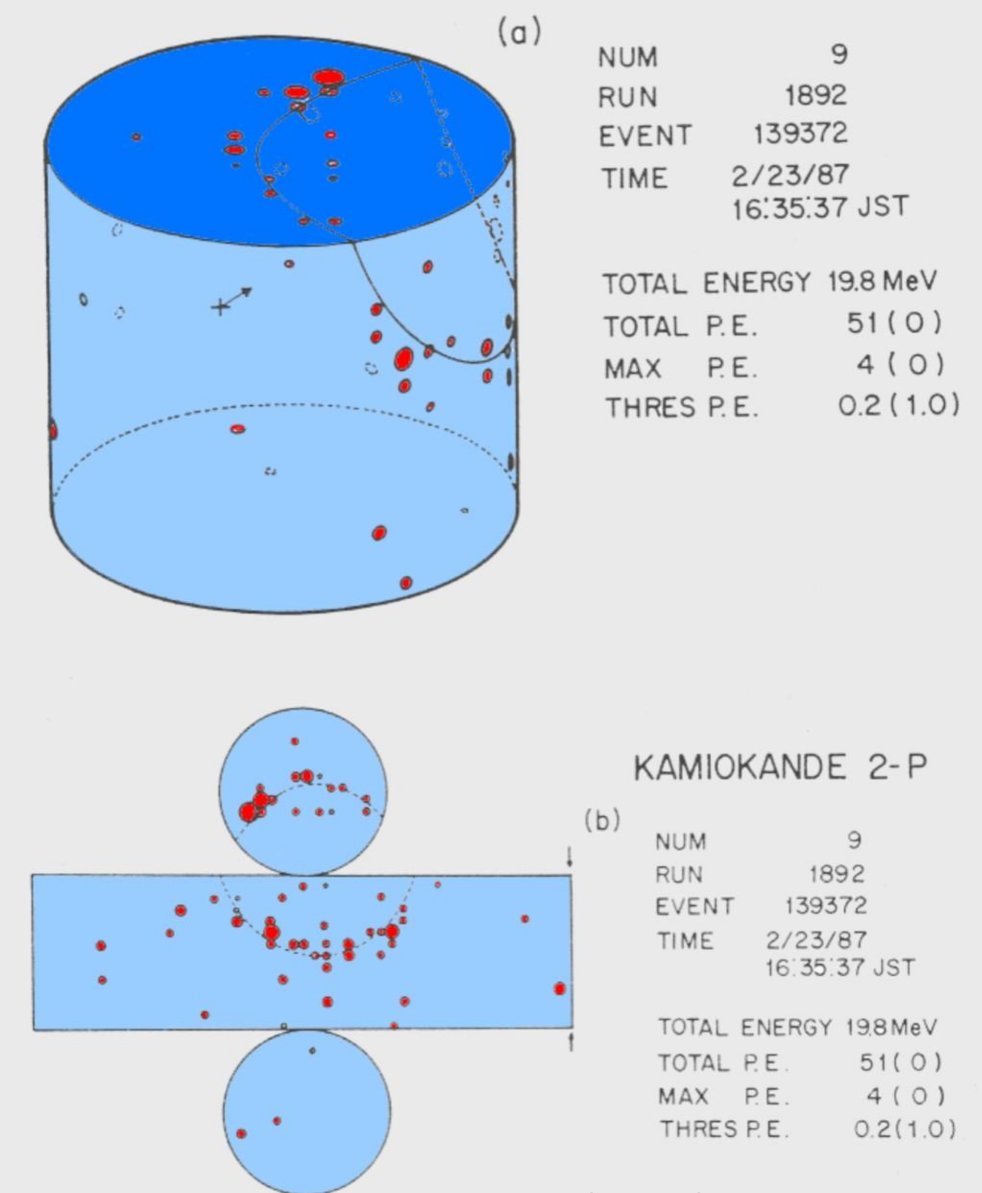

Supernova 1987A
23 February 1987
Large Magellanic Cloud SN 1987A
Distance： 165 000 light yrs (50 kpc)
Center： Neutron Star
(expected, but not found)
Progenitor： M ~ 18 solar masses

Supernova Neutrinos: SN 1987A





Arnett *et al.*, ARAA 27 (1989)



Hirata et al., PRD 38 (1988) 448

Supernova Neutrinos: SN 1987A

Kamiokande-II (Japan):

- Water Cherenkov (2,140 ton)
- Clock Uncertainty ± 1 min

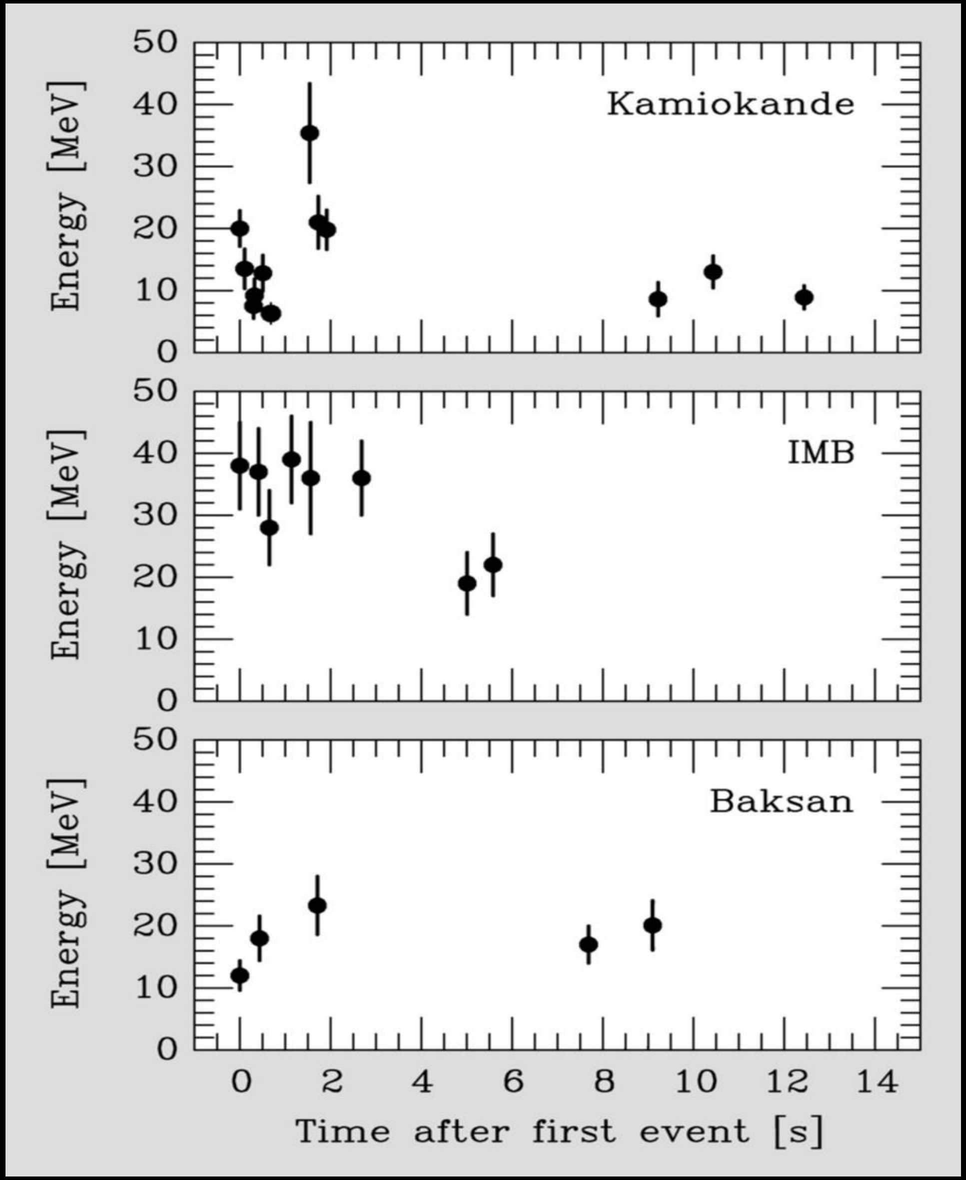
Irvine-Michigan-Brookhaven (US):

- Water Cherenkov (6,800 ton)
- Clock Uncertainty ±50 ms

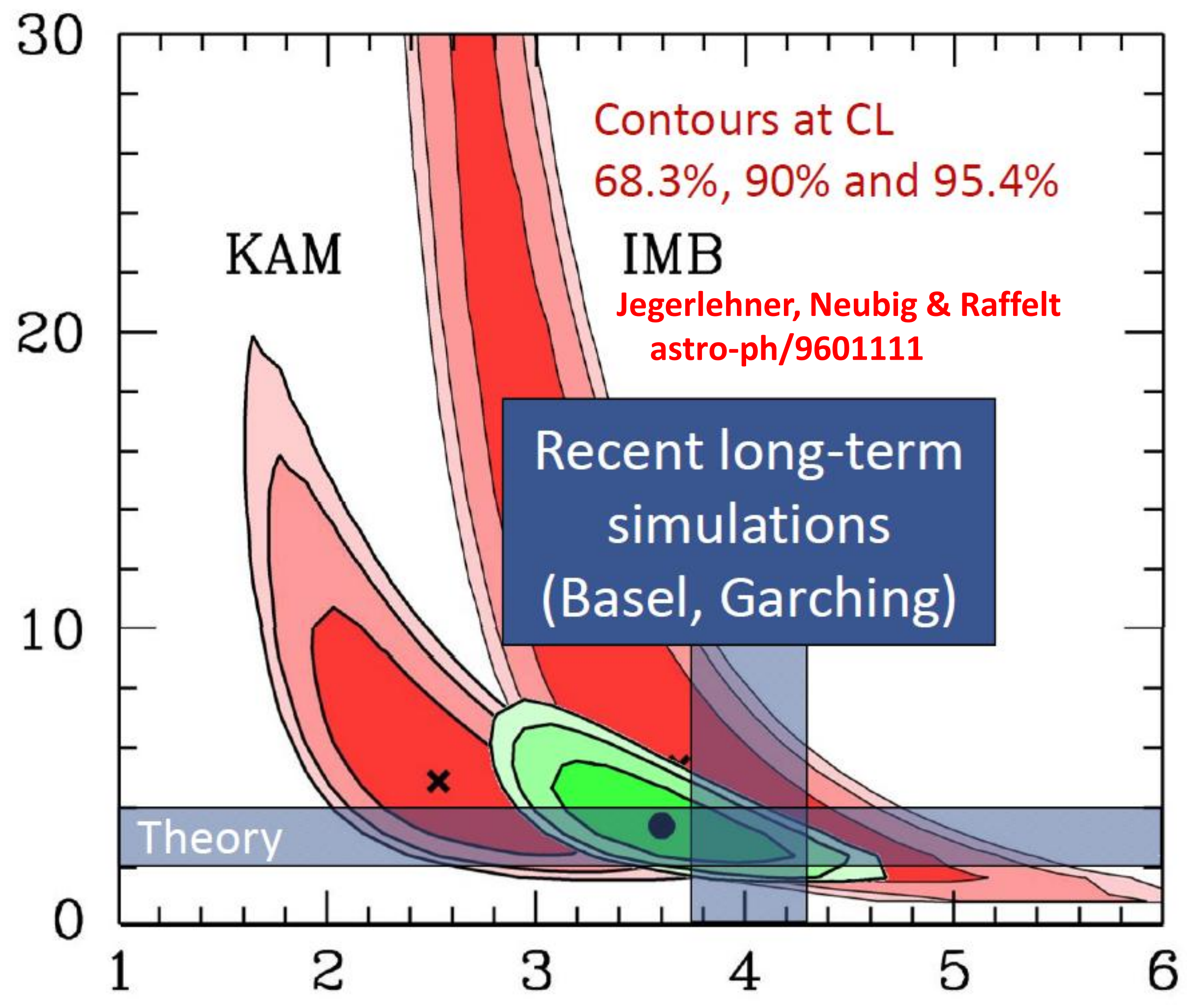
Baksan LST (Soviet Union):

- Liquid Scintillator (200 ton)
- Clock Uncertainty +2/-54 s

Mont Blanc: 5 events, 5 h earlier



Supernova Neutrinos: SN 1987A



E_b [10^{53} ergs]

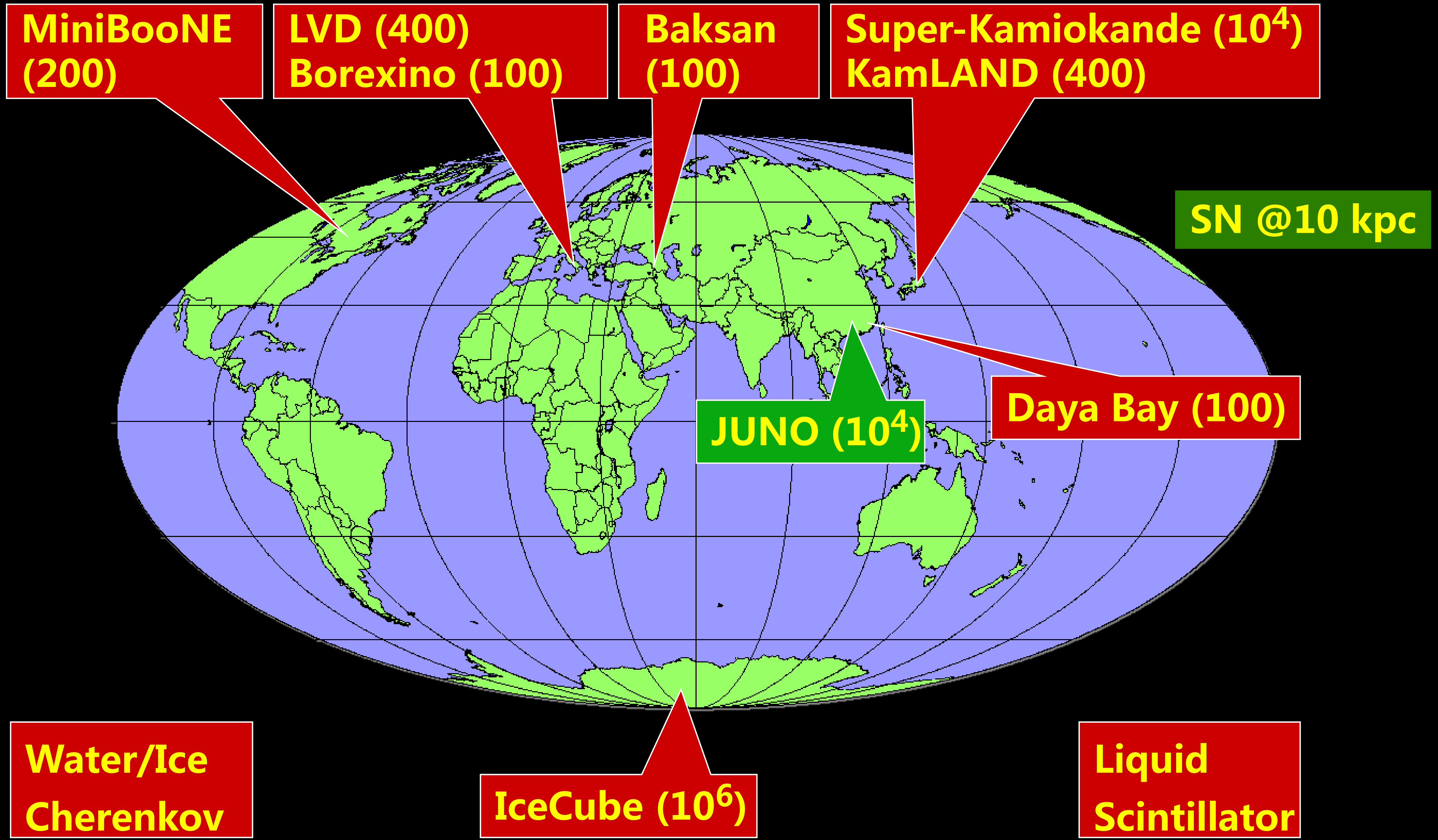
Spectral anti-ν_e Temperature [MeV]

Assumptions:
- ☐ Thermal
- ☐ Equipart.

Conclusions:
- ■ Collapse
- ■ Ave.Ener.
- ■ Duration

Problems:
- ☐ 24 events
- ☐ Just once

SN ν Detection: present and future experiments

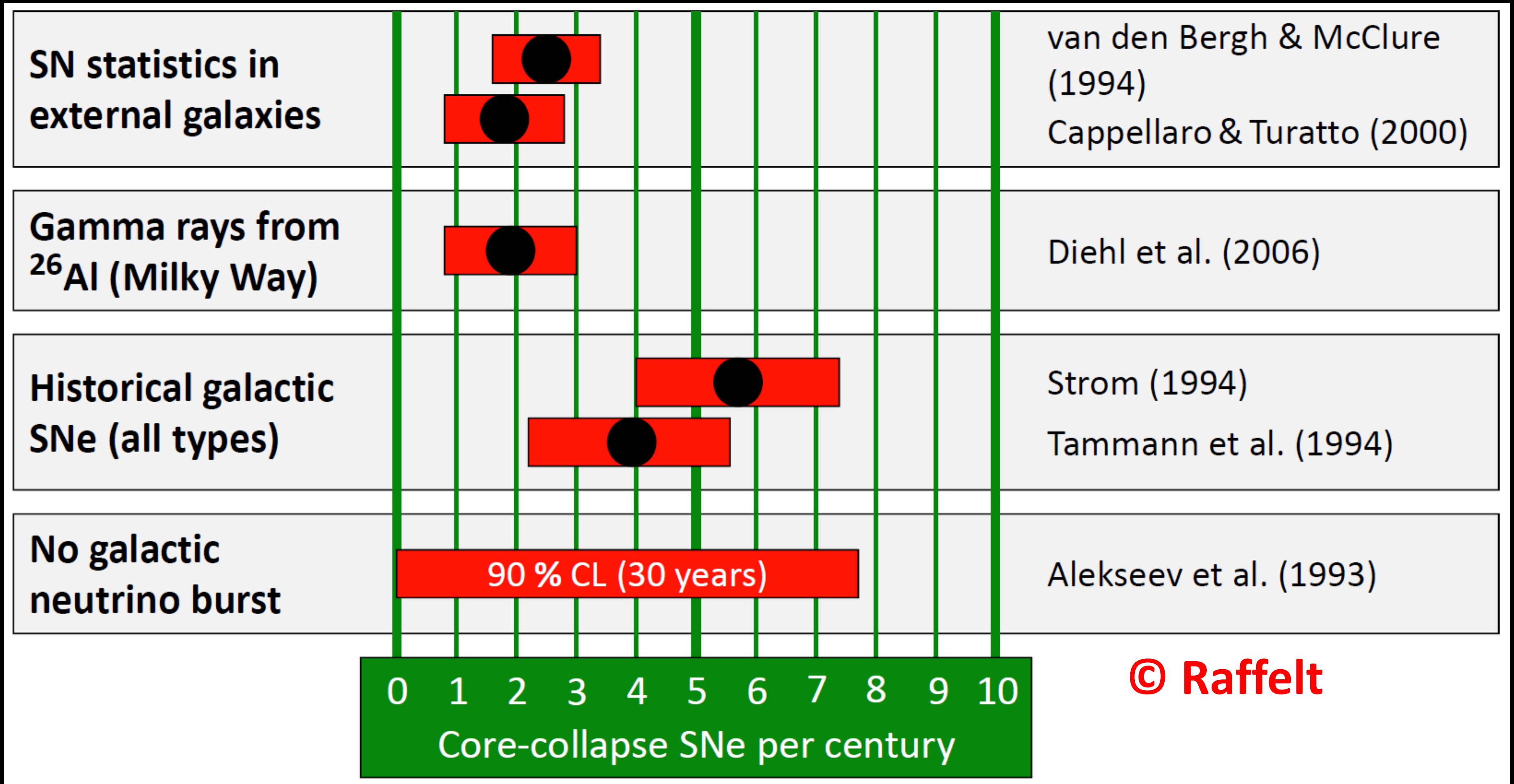


supernova neutrino detectors

Detector	Type	Location	Mass (kton)	Events @ 10 kpc	Status
Super-K	Water	Japan	32	8000	Running (SK IV)
LVD	Scintillator	Italy	1	300	Running
KamLAND	Scintillator	Japan	1	300	Running
Borexino	Scintillator	Italy	0.3	100	Running
IceCube	Long string	South Pole	(600)	(10^6)	Running
Baksan	Scintillator	Russia	0.33	50	Running
Mini-BooNE	Scintillator	USA	0.7	200	(Running)
HALO	Lead	Canada	0.079	20	Running
Daya Bay	Scintillator	China	0.33	100	Running
NOvA	Scintillator	USA	15	3000	Turning on
SNO+	Scintillator	Canada	1	300	Under construction
MicroBooNE	Liquid argon	USA	0.17	17	Under construction
DUNE	Liquid argon	USA	34	3000	Proposed
Hyper-K	Water	Japan	540	110,000	Proposed
JUNO	Scintillator	China	20	6000	Under construction
RENO-50	Scintillator	South Korea	18	5400	Proposed
PINGU	Long string	South pole	(600)	(10^6)	Proposed

Adapted from Scholberg @ Neutrino 14

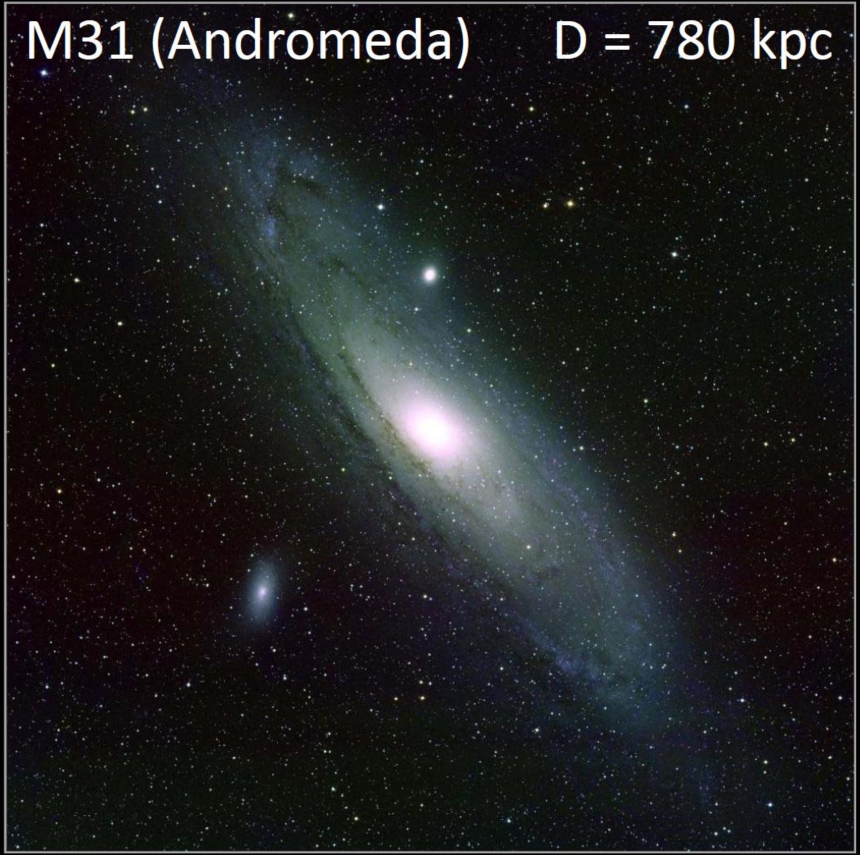
Key Problem: where and when?



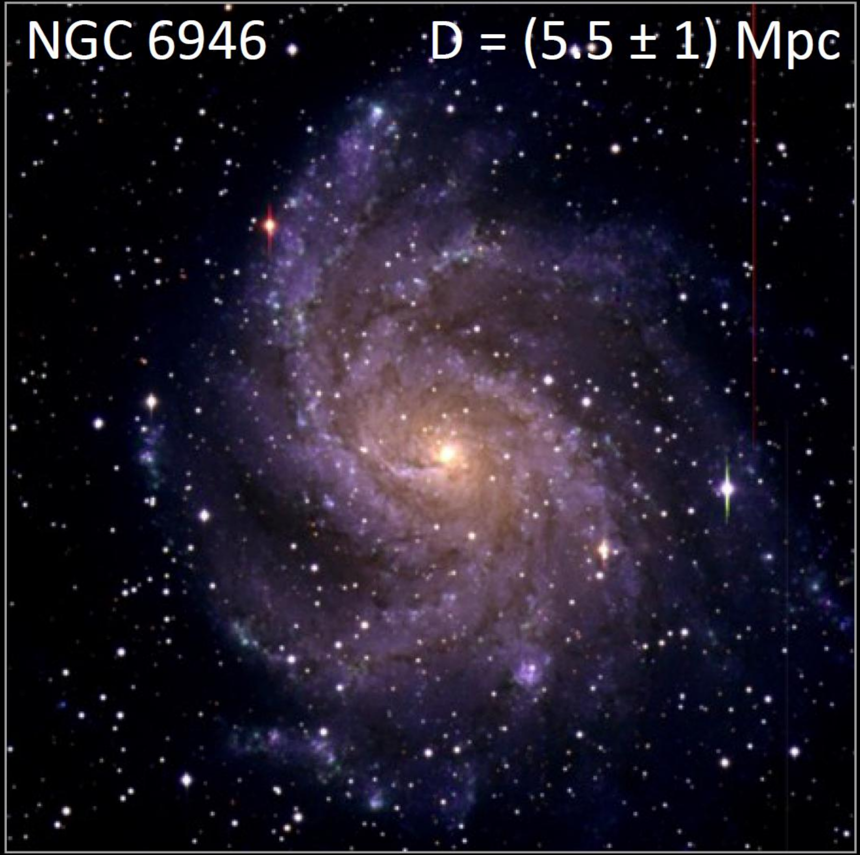
(1) Estimate from SN statistics in other galaxies; (2) Only massive stars produce ^{26}Al (with a half-life 7.2×10^5 years); (3) Historical SNe in the Milky Way; (4) No neutrino bursts observed by Baksan since June 1980

Key Problem: where and when?

High and Low Supernova Rates in Nearby Galaxies

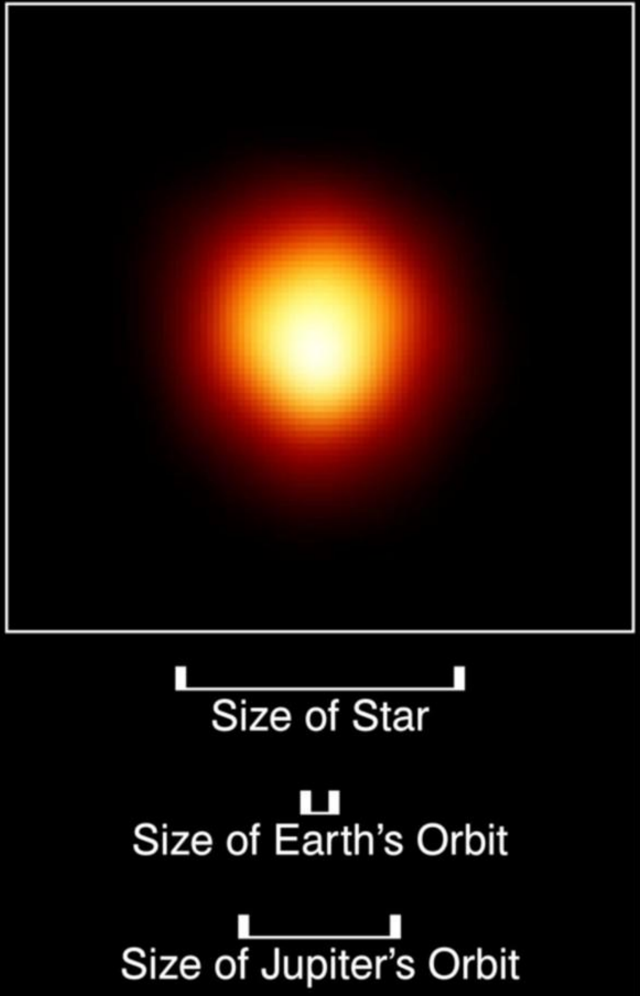


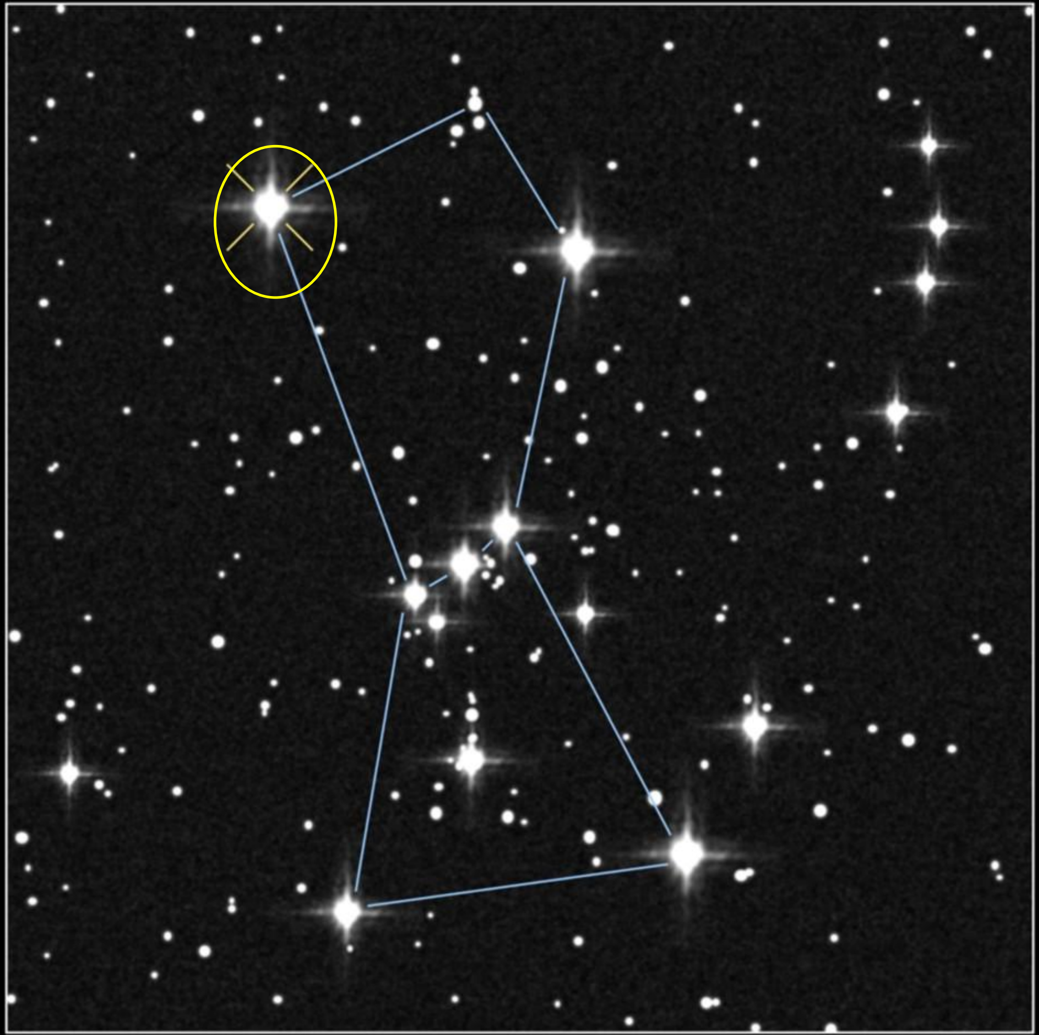
Last observed supernova: 1885A



Observed supernovae:
1917A, 1939C, 1948B, 1968D, 1969P,
1980K, 2002hh, 2004et, 2008S

SN Candidate: The Red Supergiant Betelgeuse (Alpha Orionis)

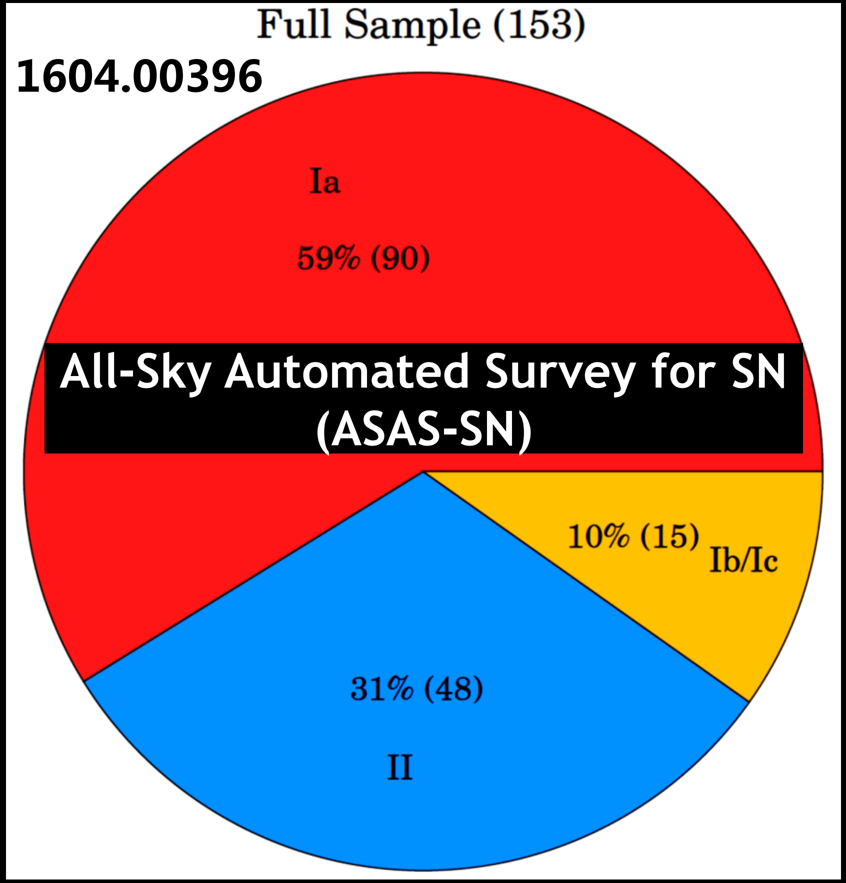




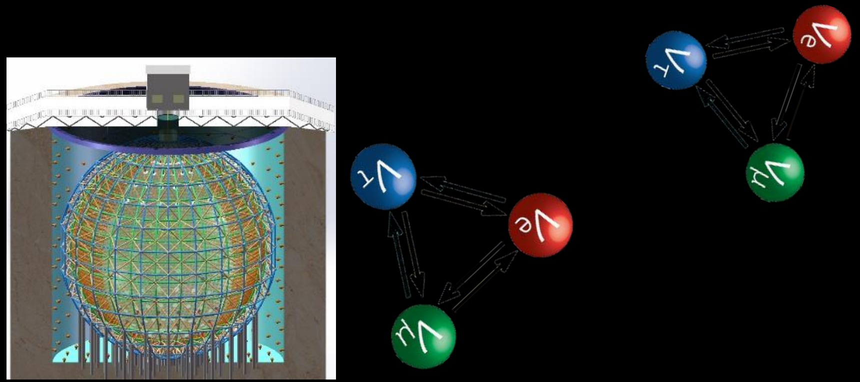
Distance: 642 ly (197 pc)
Type: Red Supergiant
Mass: ~ 18 solar masses

Expected to end its life as SN explosion
@ JUNO: 2 $\times 10^7$ events

ASAS-SN Bright Supernova Catalog I: 2013-2014



SN 2020a



Good Luck to JUNO!