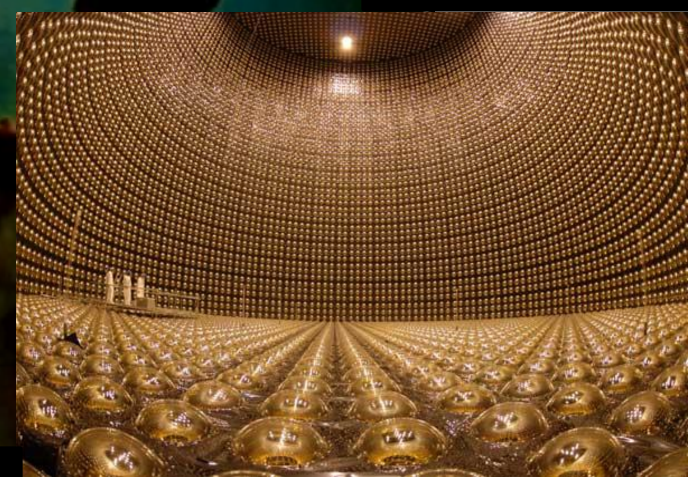
Neutrino Probes of Supernovae

Shunsaku Horiuchi (Uni of Tokyo, IPMU)



IPMU ACP Seminar, 14th May 2009

- Introduction

- Thermal neutrinos from supernovae
  - Detecting the diffuse supernova neutrino background

- Non-thermal neutrinos from supernovae
  - Gamma-ray burst context
  - (Magnetic stars)

- Summary

The Dream of Neutrino Astronomy

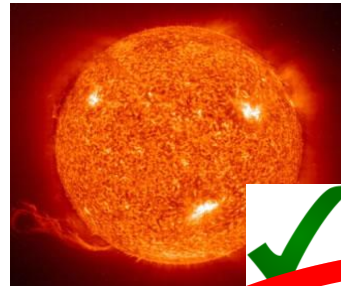
- *"If [there are no new forces] -- one can conclude that there is no practically possible way of observing the neutrino."* **Bethe&Peierls, Nature (1934)**
- *"The title is more of an expression of hope than a description of the book's contents....the observational horizon of neutrino astrophysics may grow...perhaps in a time as short as one or two decades."* **Bahcall, Neutrino Astrophysics (1989)**

- **We now have the technology to detect neutrinos!**
- **And we know neutrino sources exist.**
- **Neutrinos are unique messengers in astrophysics.**

It is timely to study astrophysical neutrinos

Some neutrino sources

Radioactive decay



Sun (x1)

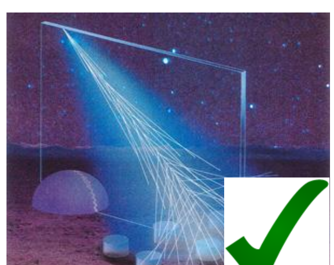
Nuclear reactors

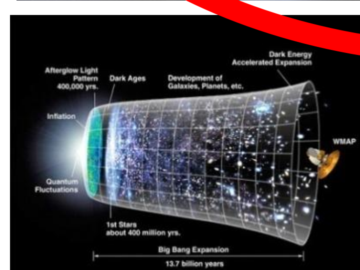
Supernova (x1)

Particle accelerator

Astrophysical accelerator

Atmospheric





Cosmic background

Supernova neutrinos are Many

- **MeV neutrinos [thermal]**
  - **Core-collapse of massive star**
  - **How are neutron stars and black holes formed?**

(x1)

- **GeV – TeV neutrinos [non-thermal]**
  - **Supernova, supernova remnants, and gamma-ray bursts**
  - **Particle acceleration and hadronic interactions?**

- **> TeV neutrinos [non-thermal]**
  - **Gamma-ray bursts?**
  - **What are the origins of high-energy cosmic rays?**

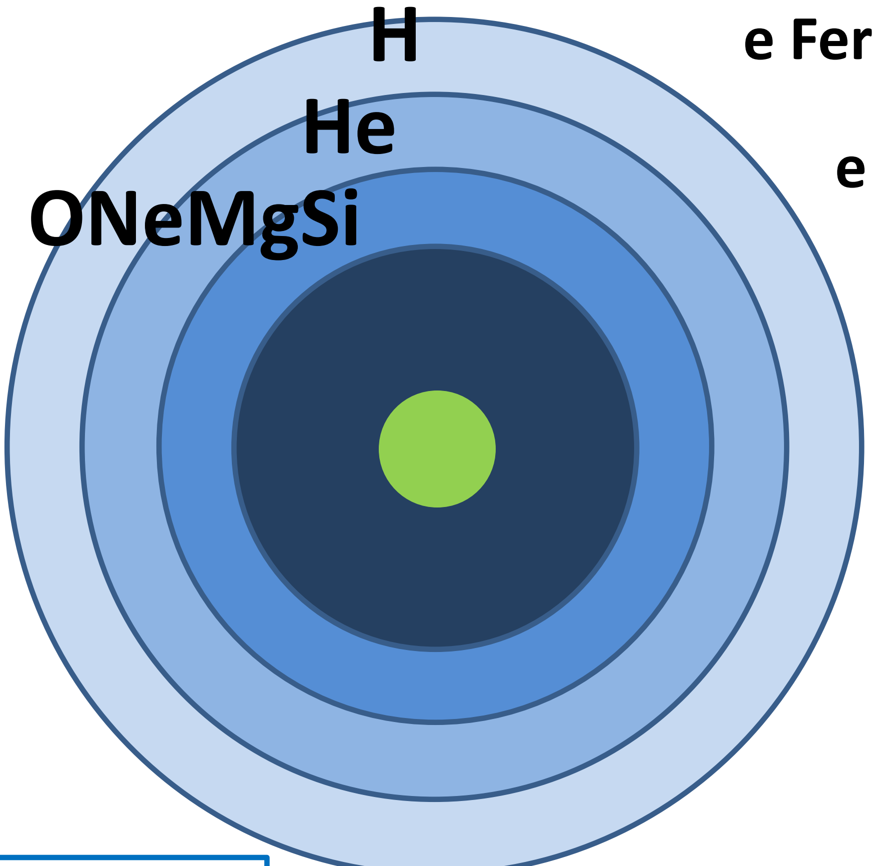
Each gives us valuable information

Supernova classifications

Spectral type	Ia	Ib	Ic	II
Spectrum	No Hydrogen			Hydrogen
	Silicon	No Silicon		
		Helium	No Helium	
Mechanism	Nuclear (low-mass star)	Core-collapse (massive-star)		
Thermal Neutrinos	Insignificant	Copious		
Compact remnant	None	Neutron star (typically pulsar, sometimes magnetar) or black hole		
Light curve	~ reproducible	Large variations		
		Gamma-ray burst link		

Initiation of core-collapse

onion structure | core collapse | neutrinosphere formation



0 – 0.1 sec

e Fermi energy: $\mu_e = (3\pi^2 n_e)^{1/3} \hbar c$

e capture: ${}^{56}\mathrm{Fe} + e^- \rightarrow {}^{56}\mathrm{Mn} + \nu_e$

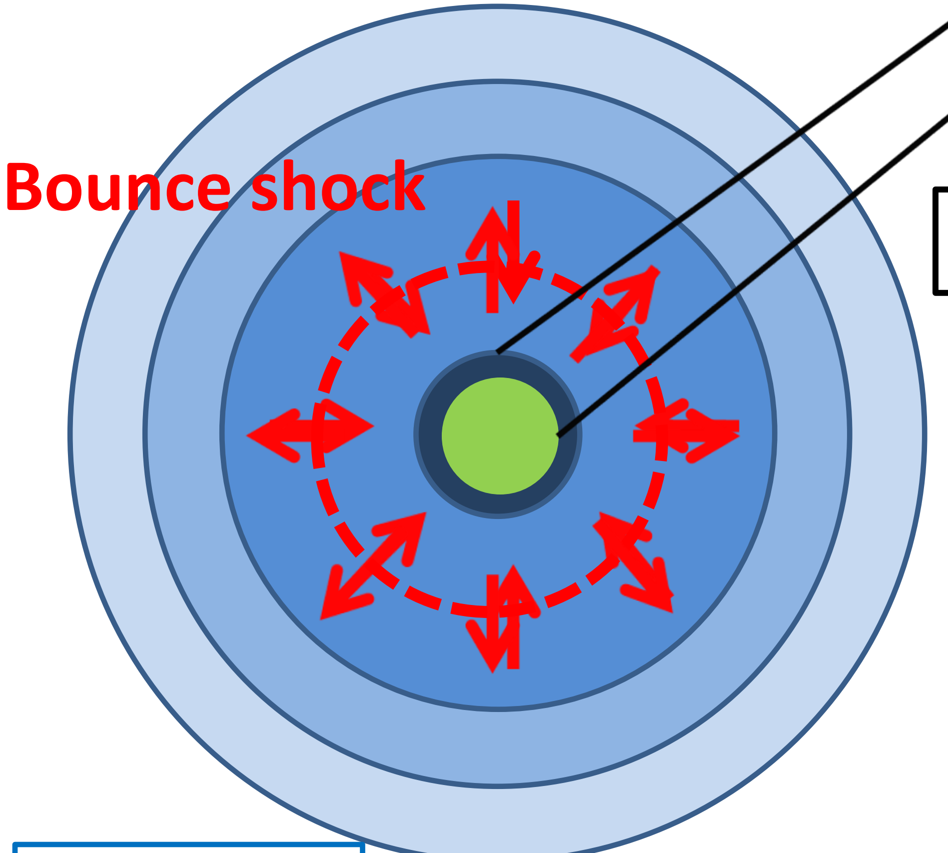
Degeneracy pressure:

$$P_e = \frac{1}{4}(3\pi^2)^{1/3}\hbar c \left(\frac{\rho}{m_u}\right)^{4/3} Y_e^{4/3}$$

When M_{Fe} > $M_{chandra}$
it starts to collapse:
R : 10^3 → 30 [km]
ρ : 10^9 → 10^{14} [g/cc]
T : 1 → 30 [MeV]

Core-collapse (2)

Shock formation | **Explosion** | **Proto neutron star formation**



0.1 – 10 sec

Energy budget:

Total energy ~ binding energy

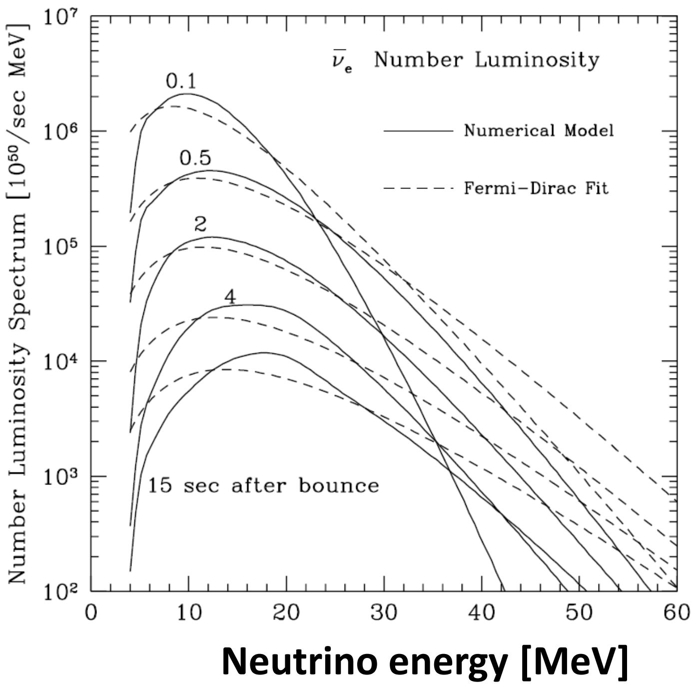
$$E_{bind} = \frac{3}{5}\frac{GM_{NS}^2}{R_{NS}} \sim 3\times10^{53}\,\mathrm{ergs}$$

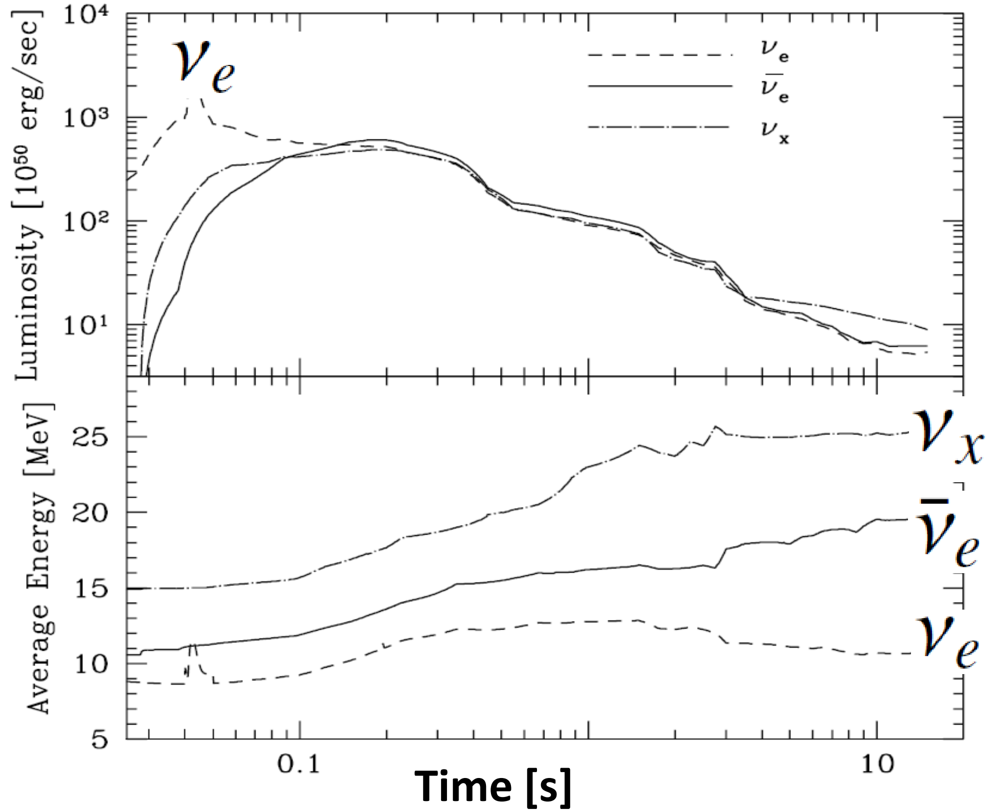
99% into neutrino
1% into shock
0.01% into photons

Simulation by Lawrence Livermore group

Delayed explosion by the LL group (1D, "neutron-finger" convection)

[from Totani et al. (1998)]



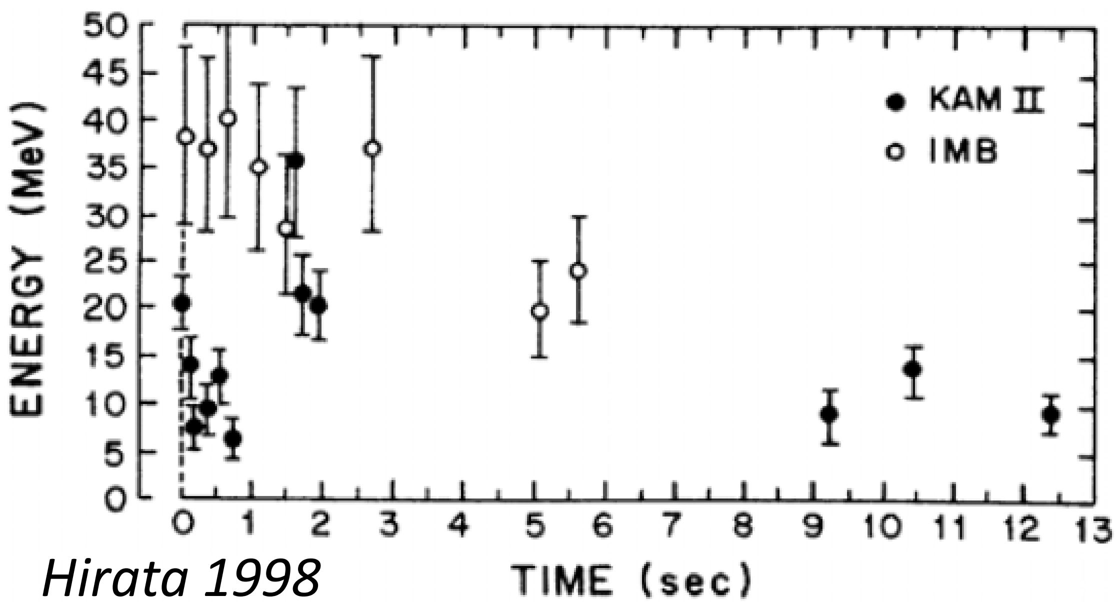


- **Broad characteristics:**
  - **Thermal spectrum (few MeV) & energy hierarchy - neutrinosphere**
  - **Long duration - neutrino trapping and diffusion** *[Sato (1975)]*
  - **Close to total energy equipartition**

SN 1987A

- SN 1987A: successful detection of neutrinos
- dawn of extrasolar neutrino astronomy!
- Confirmation of basic theoretical predictions:
  - Duration: ~10 sec
  - Neutrino energies: T_{eff} ~ 3-6 MeV
  - Energetics: E_{tot} ~3-6 x 10^{52} ergs

  [e.g., Sato&Suzuki (1987), many others]



Hirata 1998

Shunsaku Horiuchi (IPMU)

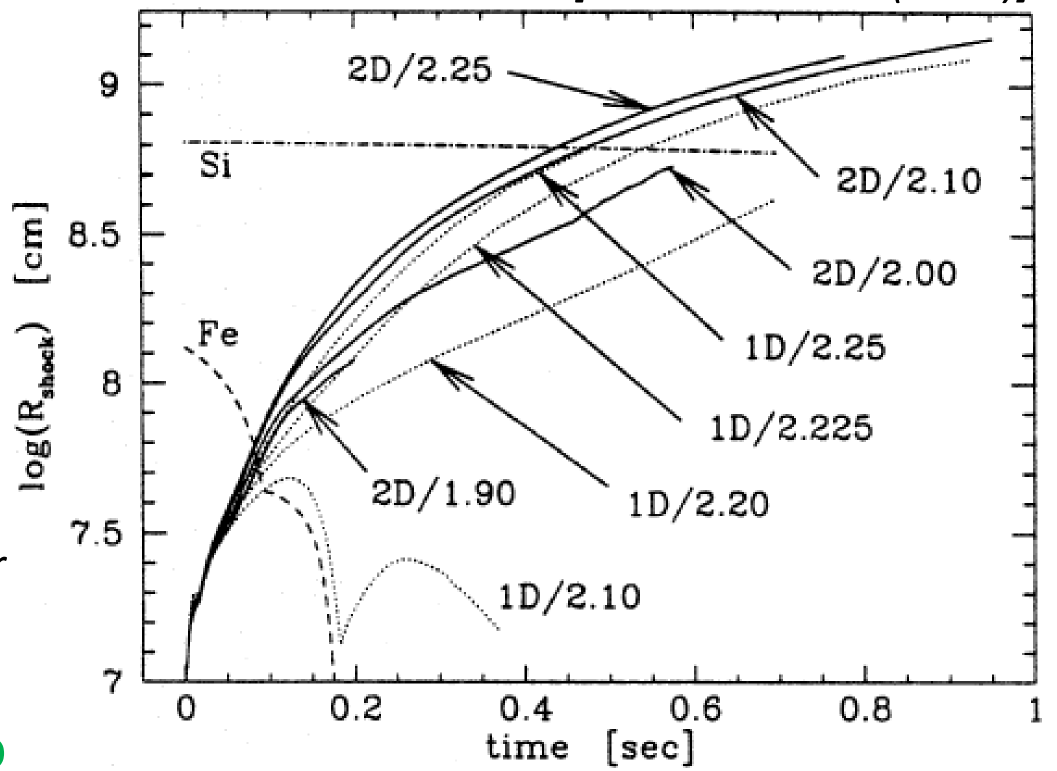
But the shock stalls in robust simulations

- **When detailed neutrino interactions, neutrino transport, and GR effects are included, simulations (1D) fail to explode...**

$$\gamma + {}^{56}\mathrm{Fe} \rightarrow 13\alpha + 4n$$

[Arnett (1982), Rampp (2000), Mezzacappa (2001), Leibendorfer (2001,2004), Thompson (2003)]

[Janka&Mueller (1996)]



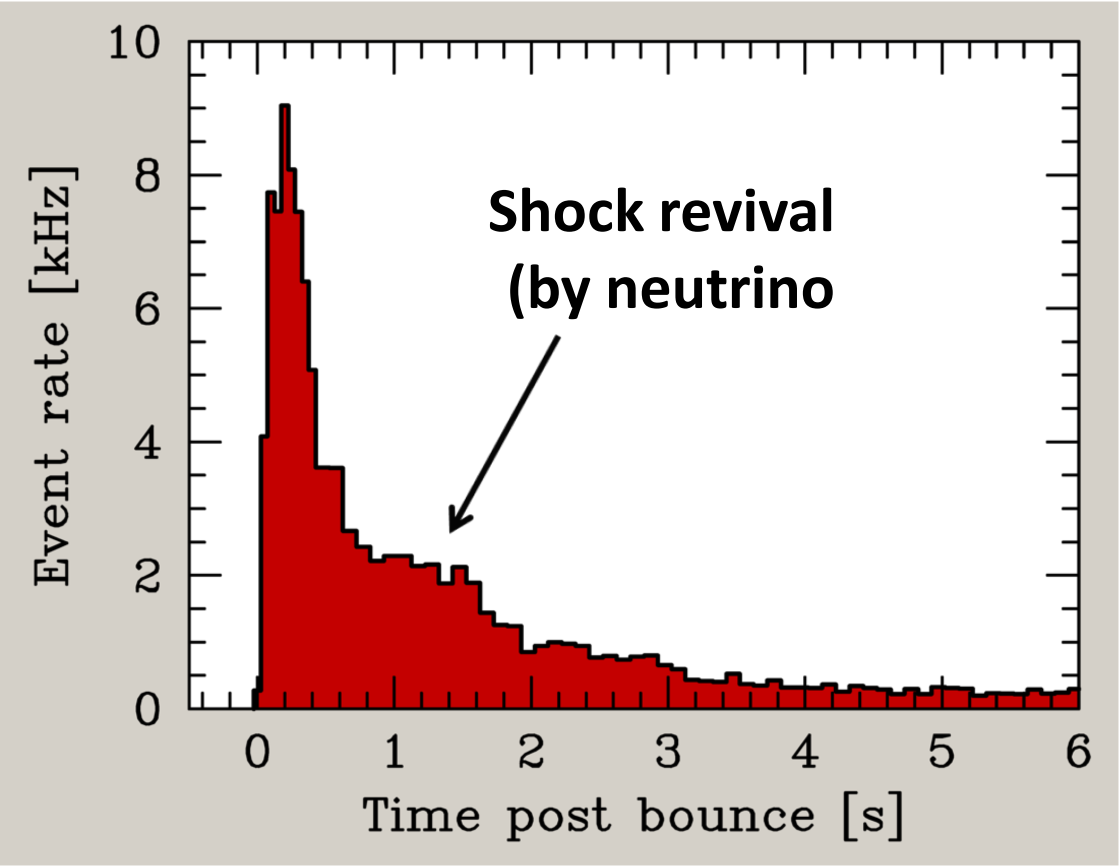
- **Delayed explosion scenario**
- **Only a small (a few %) increase in neutrino luminosity needed!**
  - **Multi-D effects (jets, convections, instabilities, …)**
  - **Equation of state of dense matter, pasta structures, …**

[e.g., review by Kotake, Sato, Takahashi (2006)]

Neutrino Probes

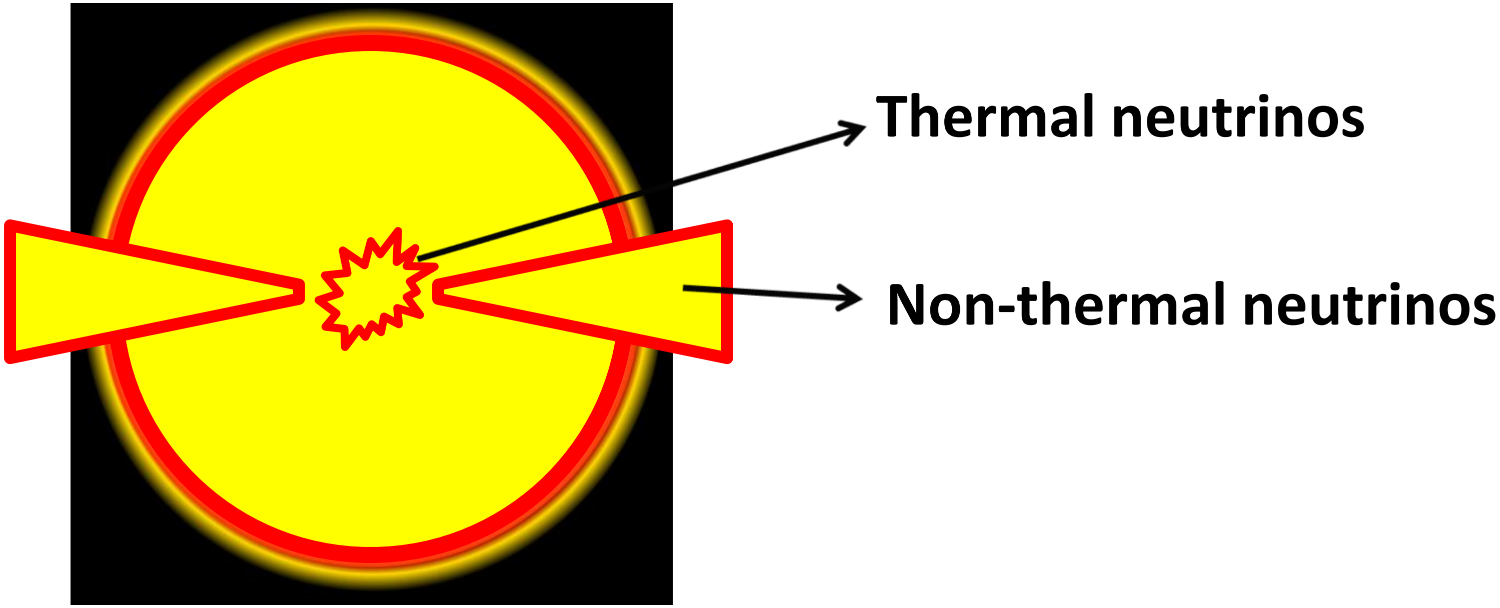
- Neutrinos are one of very few probes of the most inner processes during core-collapse

- For example, the simulated supernova signal at Super-Kamiokande (for a supernova at 10kpc, based on LL group)



[from Totani et al. (1998)]

Non-thermal neutrinos



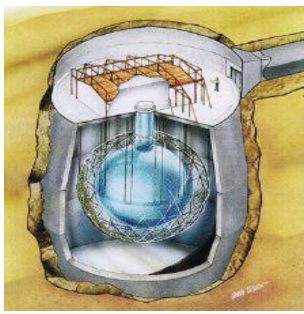
- **Core-collapse supernova have structures, e.g.**
  - **JETS: Gamma-ray bursts, late time radio**

    [e.g., Stanek et al. (2003), Soderberg et al. (2004)]
  - **Asymmetric: SN 1987A, spectropolarimetry, pulsar kicks**

    [e.g., by HST, Maeda et al (2008)]
- **Structures can be studied by neutrinos?**

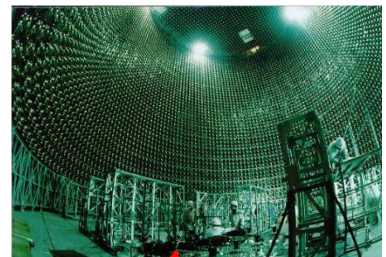
Some modern neutrino detectors

SNO+
(1kton liq.sci.)

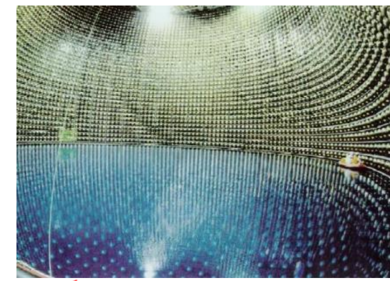


LVD (kton liq.sci.)

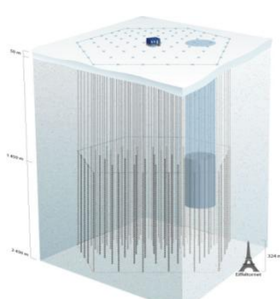
BAKSAN
(330t liq.sci.)



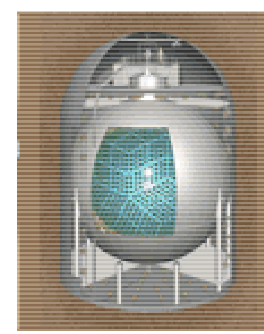
Super-K
(32kton water)



+ Gd

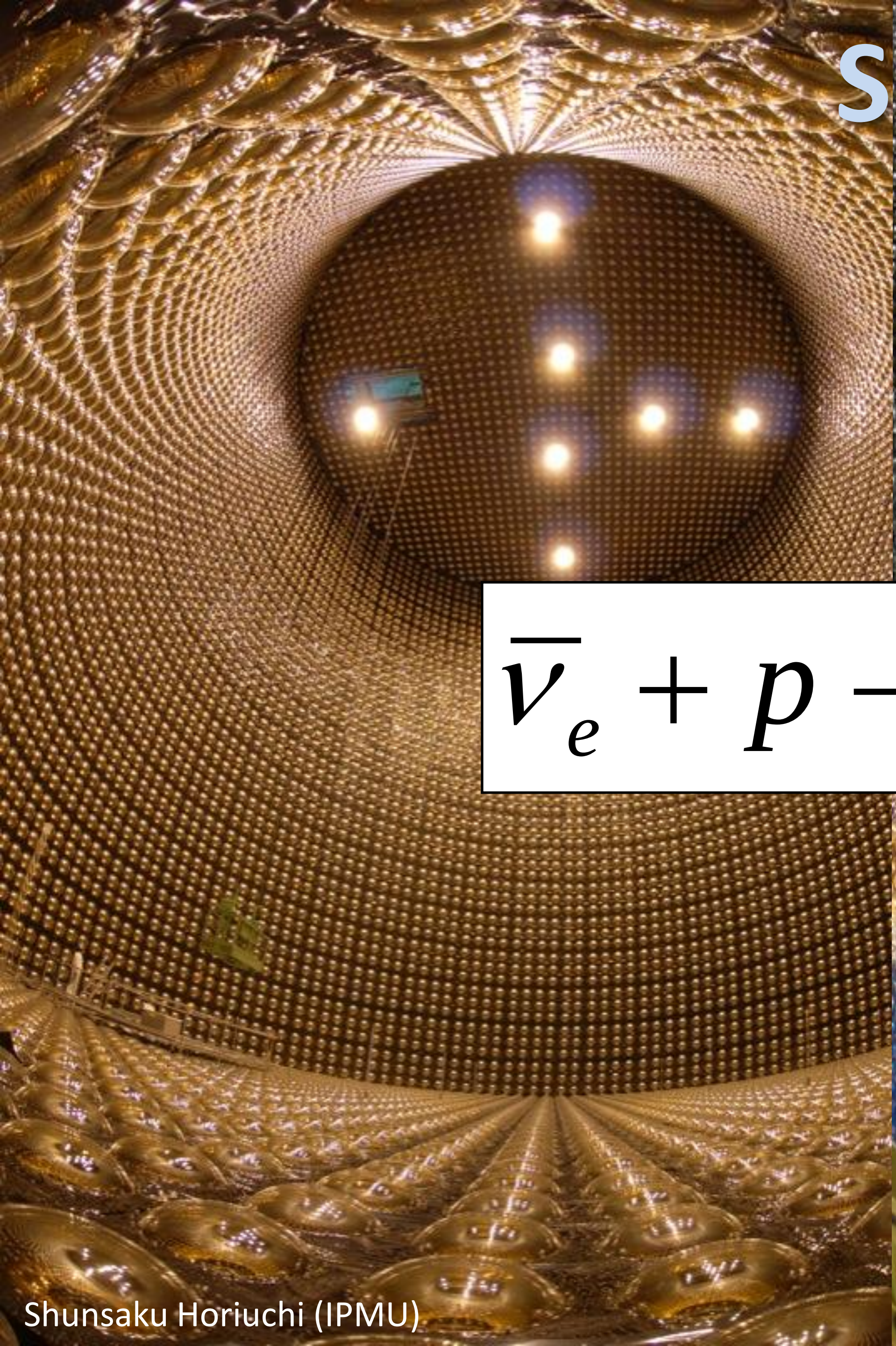


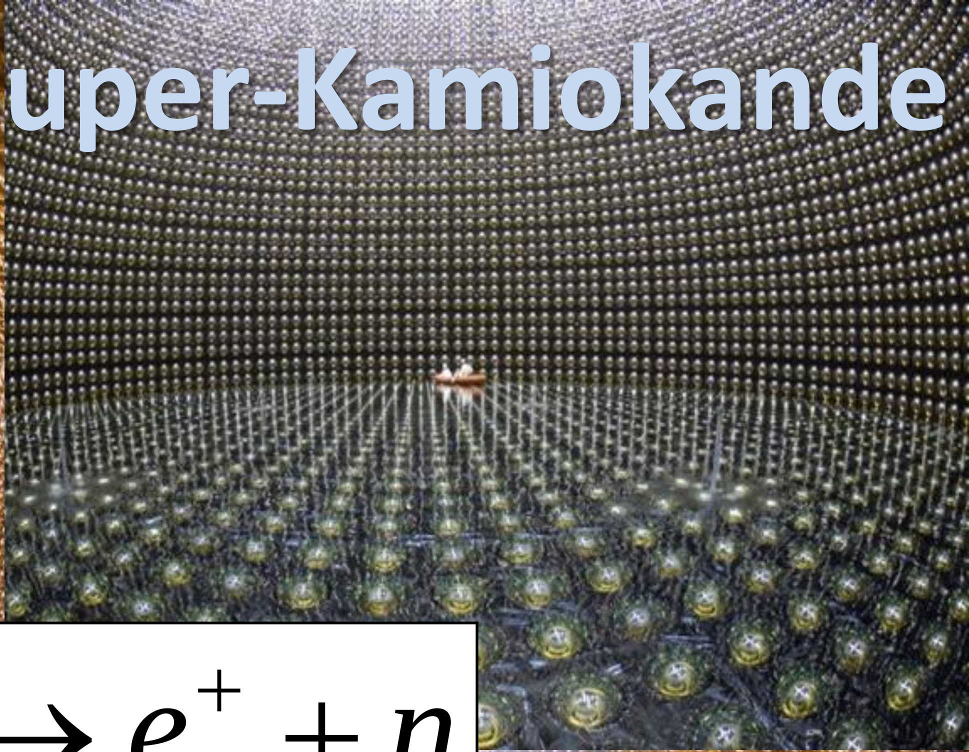
IceCube (Gton ice)

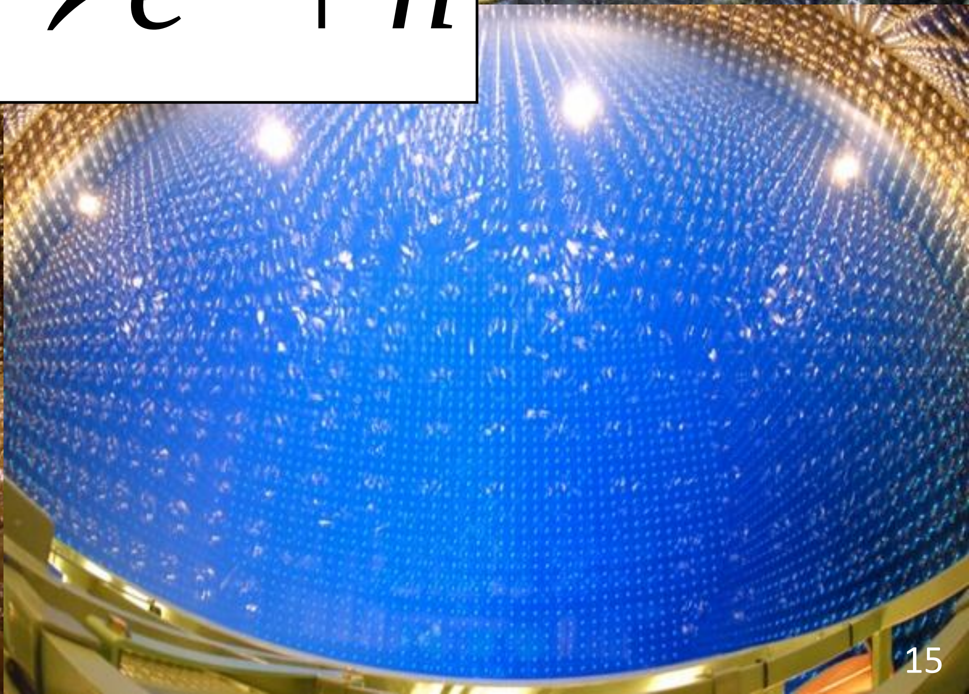


KamLAND (1kt liq.sci.)

Super-Kamiokande







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

Summary - why supernova neutrinos?

- **Basics of supernova are understood & confirmed.**
- **But, simulations fail to explode**

  [Arnett (1982), Rampp (2000), Mezzacappa (2001), Leibendorfer (2001,2004), …]

  HOW can the shock be revived?

  - **Neutrino emission & interactions**
  - **Multi-dimensional effects (e.g., rotation, instabilities, jets)**

    [e.g., review by Kotake, Sato, Takahashi (2006)]

- **Supernovae are by observation not really symmetrical**

  [e.g., SN1987A, Stanek et al. (2003), Soderberg et al. (2004), Maeda et al (2008)]

  What hidden structures are there inside the supernovae?

→ We can study these effects by neutrinos from supernova interiors

- Introduction
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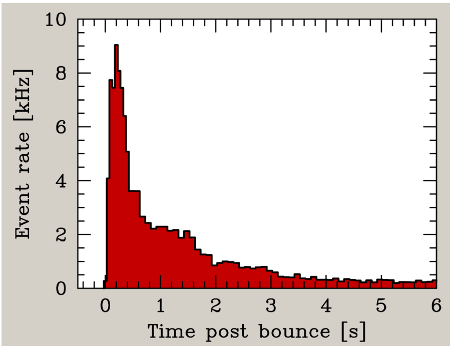
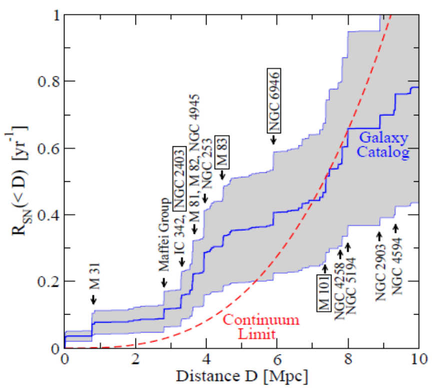
Neutrino Detection Methods



1. Milky Way Supernova

Excellent statistics (10^4 events for 10kpc), high sensitivity to explosion scenarios [*e.g. Totani et al. (1998)*] and e.g. neutrino oscillation parameters [*e.g. Takahashi et al. (2003)*].

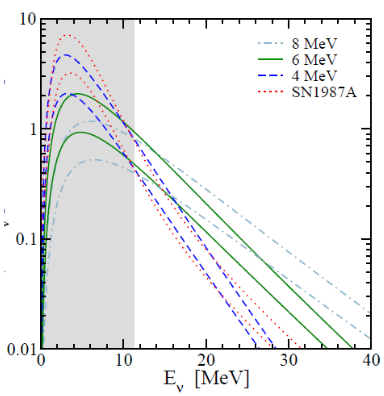
1 supernova per ~40 years



2. Supernova in nearby galaxies

Few to 10 neutrinos per supernova, but requires a ~1 Mton volume (SK x30) detector. *[Ando et al. (2005), Kistler et al. (2008)]*

1 supernova per ~year



3. Diffuse Supernova Neutrino Background (DSNB)

Neutrinos from all past core-collapse; emission is averaged, no timing or direction.

[e.g., Bisnovatyi-Kogan (1984), many others]

(faint) signal is always there

Diffuse SN Neutrino Background (DSNB)

- **Inputs for the DSNB (positron flux from DSNB anti-ν_e)**
  - **Neutrino emission per supernova**
  - **Rate of Supernovae**
  - **Detector capabilities**

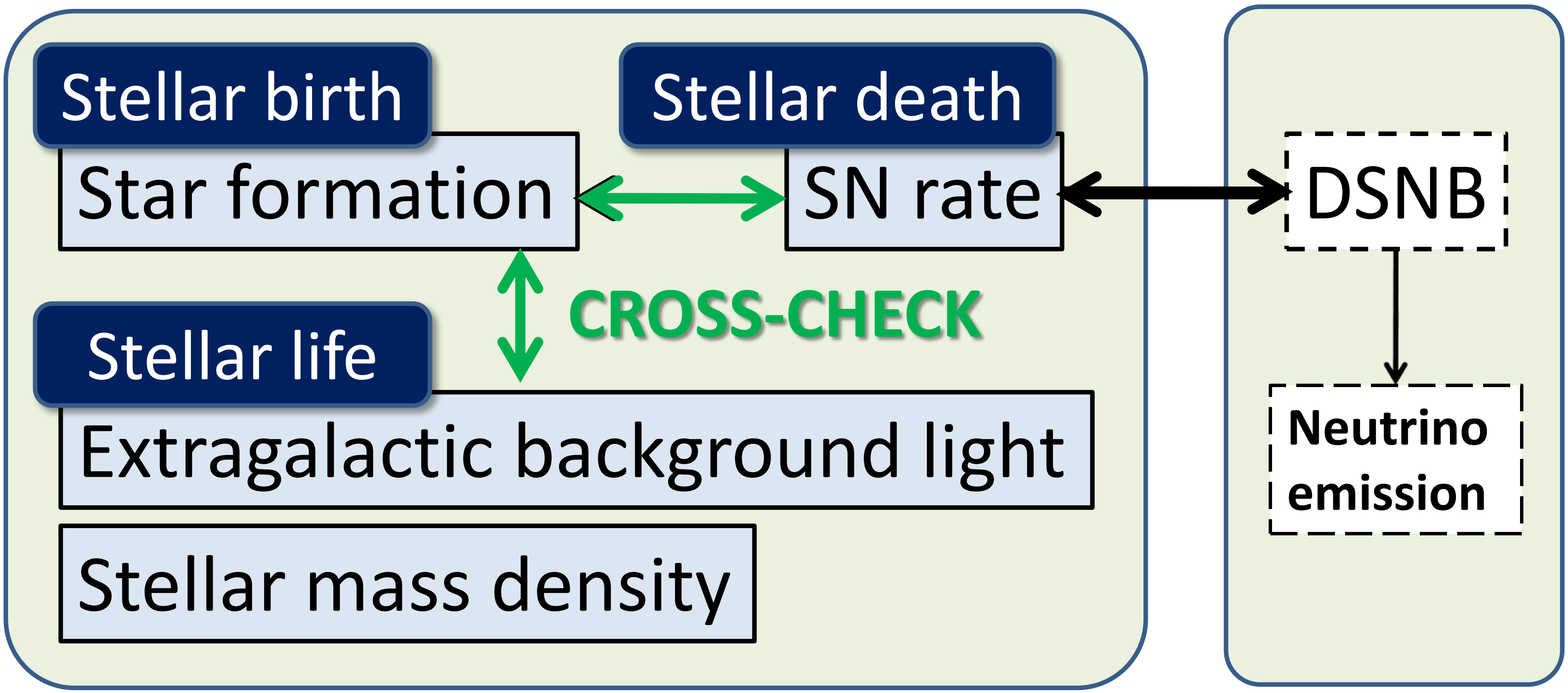
$$\psi\left(E_{e^+}\right) = c\,\boxed{\sigma\left(E_\nu\right)N_t}\int \boxed{R_{CCSN}\left(z\right)}\,\boxed{\frac{dN\left(E_\nu^{'}\right)}{dE^{'}}}\left(1+z\right)\frac{dt}{dz}\,dz$$

want to study

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

Information Flow

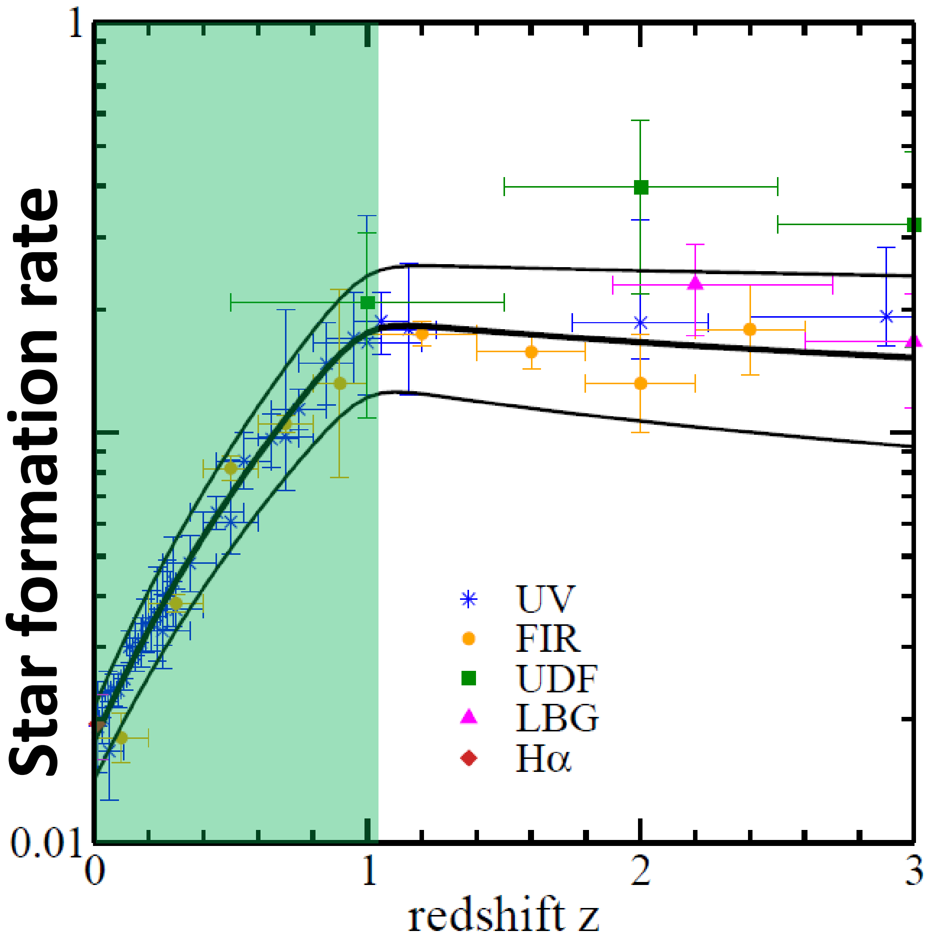
[Totani et al. (1998), Fukugita&Kawasaki (2003), Ando (2004), Hopkins&Beacom (2006)]



- **QUESTIONS**:
  1. **When can we detect the DSNB?**
  2. **Can the DSNB be used to study stellar/neutrino physics?**

Star Formation Rate

[Horiuchi et al. (2008)]



- ☐ **Determination**
  1. **Observe luminosity**
  2. **Calibration: stellar pop. code**
- ☐ **Sources of uncertainty**
  - ➢ **Dust correction**
  - ➢ **Stellar pop. code inputs**
    - **Star formation duration, metallicity, …**
  - ➢ **Initial mass function**
- ☐ **Different indicators are consistent to ~ 20% (at z < 1, which yields 90% of DSNB events)**

[Hopkins (2004), Hopkins&Beacom (2006), Yuksel et al. (2008)]

Extragalactic Background Light: Prediction

- **Non-nucleosynthesis sources (e.g., AGNs) are negligible** *[Hopkins et al. (2006)]*, **i.e., the background light acts as a calorimetric test of the star formation history.**
- **Predictions from the star formation rate:**

$$\boxed{I(\nu)} = \frac{c}{4\pi}\int_0^{z_*} \epsilon(\nu', z)\left|\frac{\mathrm{d}t}{\mathrm{d}z}\right| \mathrm{d}z,$$

$$\epsilon(\nu, z) = \int_{t_*}^{t_z} \underbrace{\boxed{\dot{\rho}_*(t)}}_{\text{Star formation rate}} \mathrm{d}t \int_{0.1}^{M(t')} L(\nu, M, t') \underbrace{\boxed{\psi(M)}}_{\text{Initial mass function}} \mathrm{d}M,$$

Numerical values:

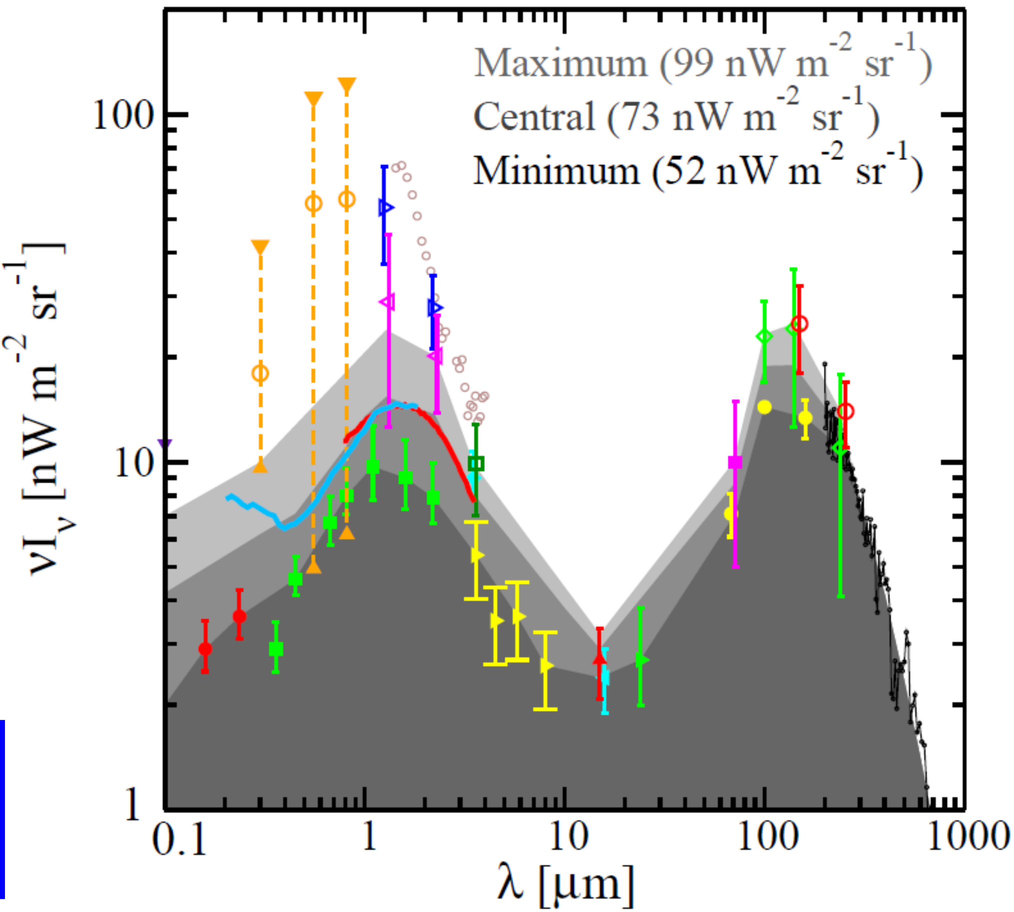
- **Salpeter IMF (-2.35, 1995) : $I_{tot} \sim 95$ nW m^{-2} sr^{-1}**
- **Kroupa IMF (-2.3, 2001) : $I_{tot} \sim 88$ nW m^{-2} sr^{-1}**
- **Baldry-Glazebrook (-2.1, 2003) IMF : $I_{tot} \sim 78$ nW m^{-2} sr^{-1}**

Extragalactic Background Light: Obs

- **Background light observations:**
  - **<u>Upper</u>: goes through data error bars**
    [Bernstein 2002, 2005, 2007, etc]
  - **<u>Nominal</u>: respects gamma-ray constraints**
    [by HESS (2006), MAGIC (2008)]
  - **<u>Lower</u>: galaxy counts**
    [Madau&Pozzetti (2000), etc]
- **Total background light:**

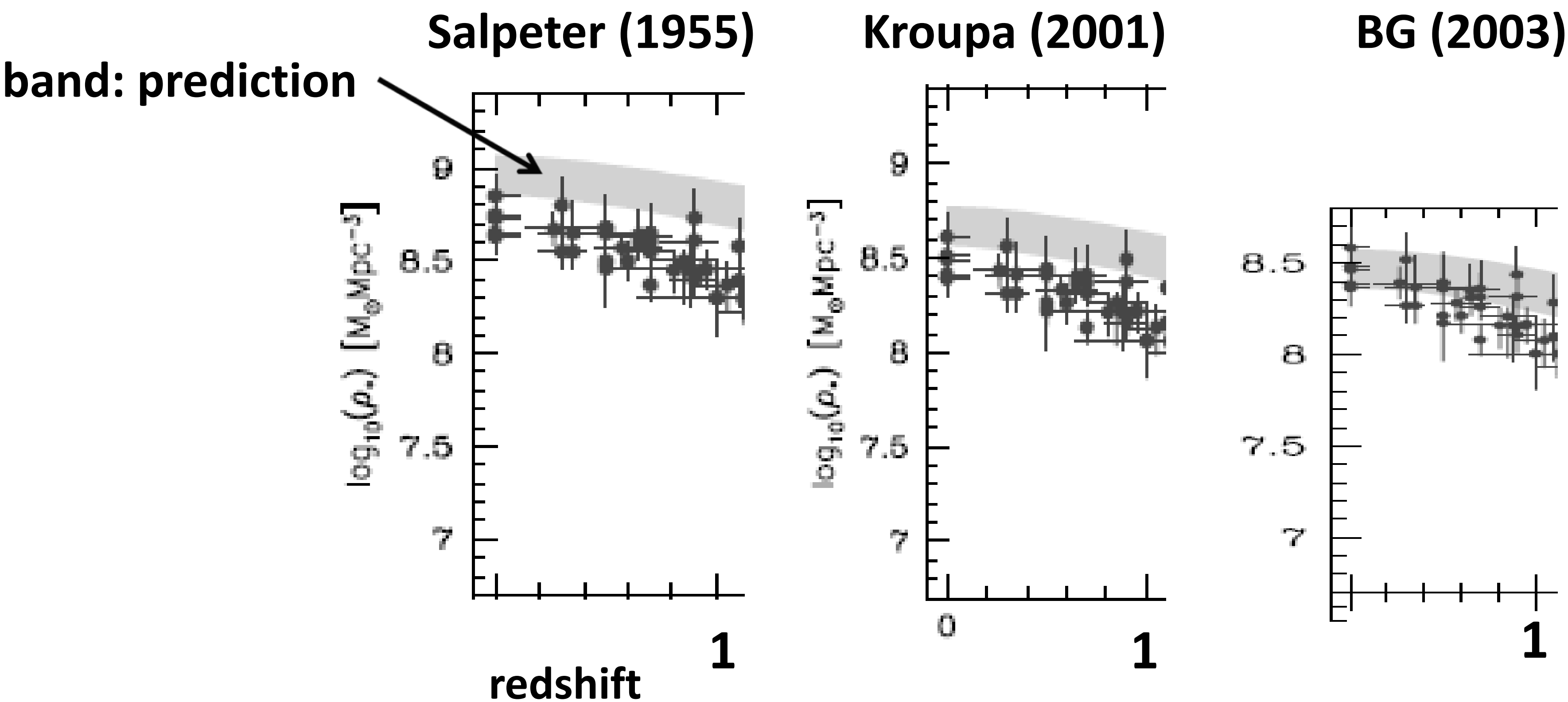
$$\boxed{73^{+26}_{-21}\ \mathrm{nWm^{-2}sr^{-1}}}$$

[Horiuchi et al. (2008)]



Choice of IMF

- **Baldry-Glazebrook IMF (2003) is a modern IMF, suggested to be the average IMF by stellar mass density studies** *[e.g., Wilkins et al. (2008)]*



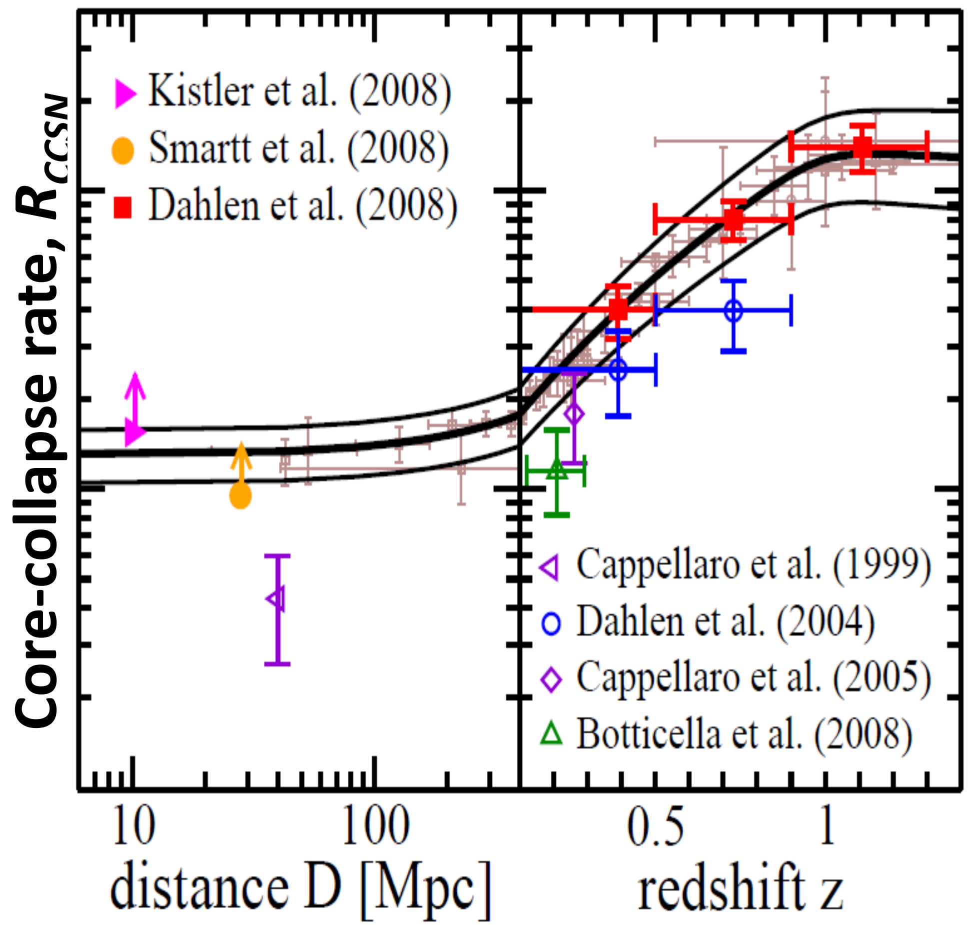
Core-Collapse Supernova Rate

- **Prediction: follows from the star formation rate**

$$\dot{\rho}_{\rm SNII}(z) = \dot{\rho}_*(z)\frac{\int_8^{50}\psi(M)dM}{\int_{0.1}^{100}M\psi(M)dM}$$

  - **M_{min}: 8.5 M_{sun} for Type II-P** *[Smartt et al. (2008)]*
  - **Almost independent of the initial mass function**
- **Observed: most likely low limits**
  - **Incompleteness**
  - **Host galaxy dust**
  - **Type Ia / CCSN ratio**

[Horiuchi et al. (2008)]



Predictions in the Literature

- **Studies of neutrino emission at the core ("production"). Many works:**

Author	time[a]	T_{ν_e} [b]	$T_{\bar{\nu}_e}$ [b]	T_{ν_x} [b]
Myra & Burrows (1990)	0.2	3.3	4.0	8.0
Totani et al. (1998)	0.5	3.9	4.9	6.3
	10	3.5	6.3	7.9
Rampp & Janka (2000)	0.5	2.3	3.4	
Liebendoerfer et al. (2001)	0.5	4.2	4.6	5.3
Mezzacappa et al. (2001)	0.5	3.6	4.2	5.2
Keil et al. (2003)		3.7	4.0	5.2
Thompson et al. (2003)	0.2	2.9	3.8	4.6
Liebendoerfer et al. (2004)	0.5	3.7	4.2	4.5
	0.5[c]	4.5	4.8	7.5
Sumiyoshi et al. (2007)	1.4[c]	6.6	7.0	10

- **Collective effects and neutrino oscillation → flavor mixing in stellar matter** *[MSW; Takahashi et al. (2001, 2003), DasguptaDighe (2008)]*

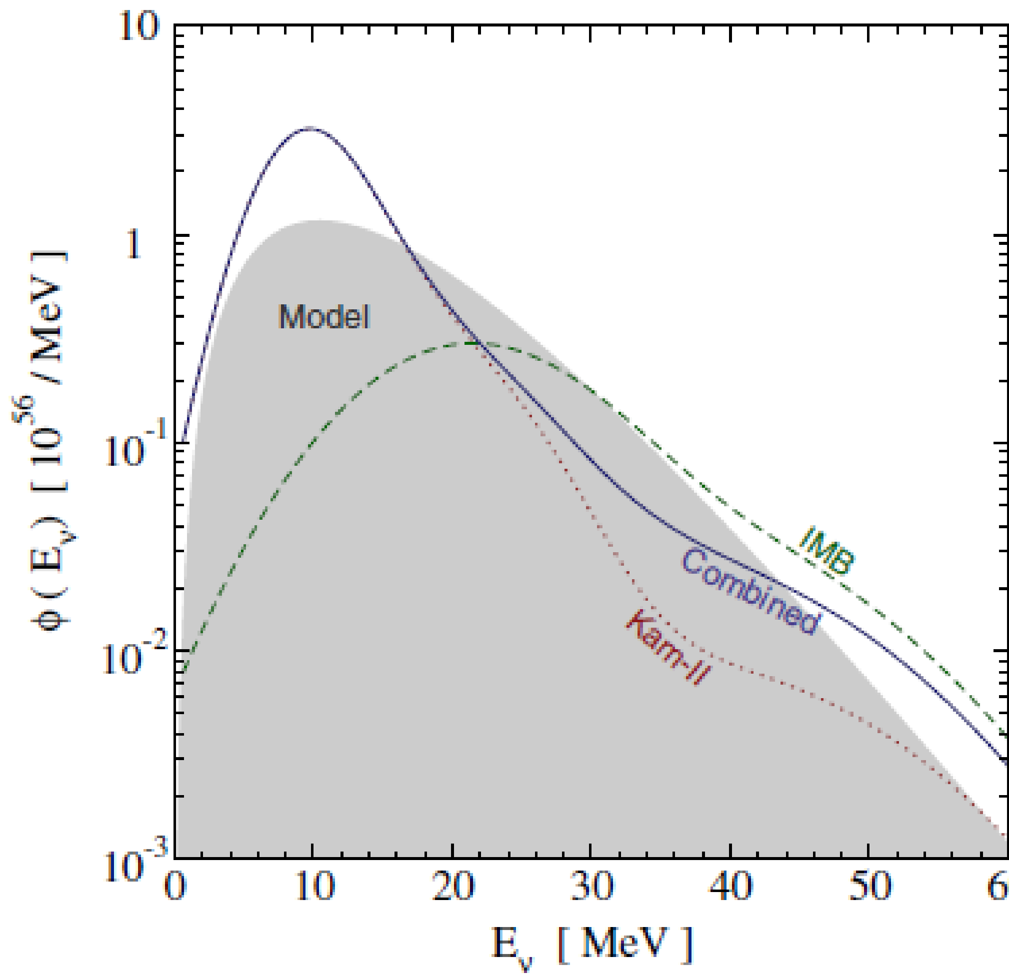
➔ **the "effective" $\bar{\nu}_e$ temperature is a mix of $\bar{\nu}_e$ and $\bar{\nu}_x$ at production**

➔ ***T_{eff}* ~ 4-8 MeV**

SN 1987A Spectrum Reconstruction

Reconstruction of the neutrino spectrum from SN 1987A neutrino data ***[Fukugita&Kawasaki 2003, Lunadini 2006]***

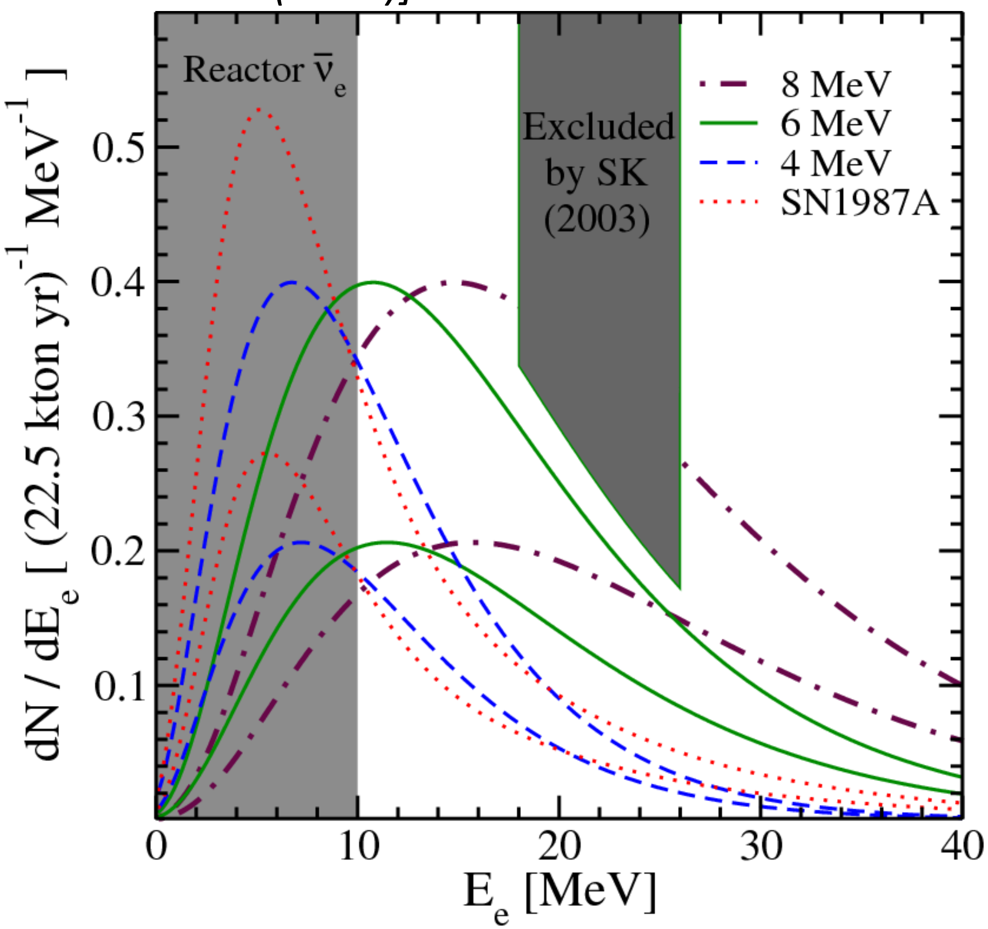
Model-independent reconstruction ***[Yuksel Beacom 2007]*** **yields a slightly pinched spectrum.**



[Yuksel Beacom 2007]

DSNB event spectrum @SK

[Horiuchi et al. (2008)]



- **Thermal spectra (T_{eff}) + uncertainty bands for R_{CCSN}**
- **SK limit:** *[Malek et al. (2003)]*
  - **Int. flux < 1.2 cm^{-2} s^{-1}**
  - **Int. event < 2 event yr^{-1}**
- **Results:**
  - **SK partially constraints T_{eff} = 8 MeV**
  - **Uncertainty band due to R_{CCSN} is not large (smaller than T_{eff} uncertainty).**

One last issue : background

Background limited search @19-30 MeV because of neutrino (reactor, atmospheric) and positron (spallation, invisible μ) backgrounds.

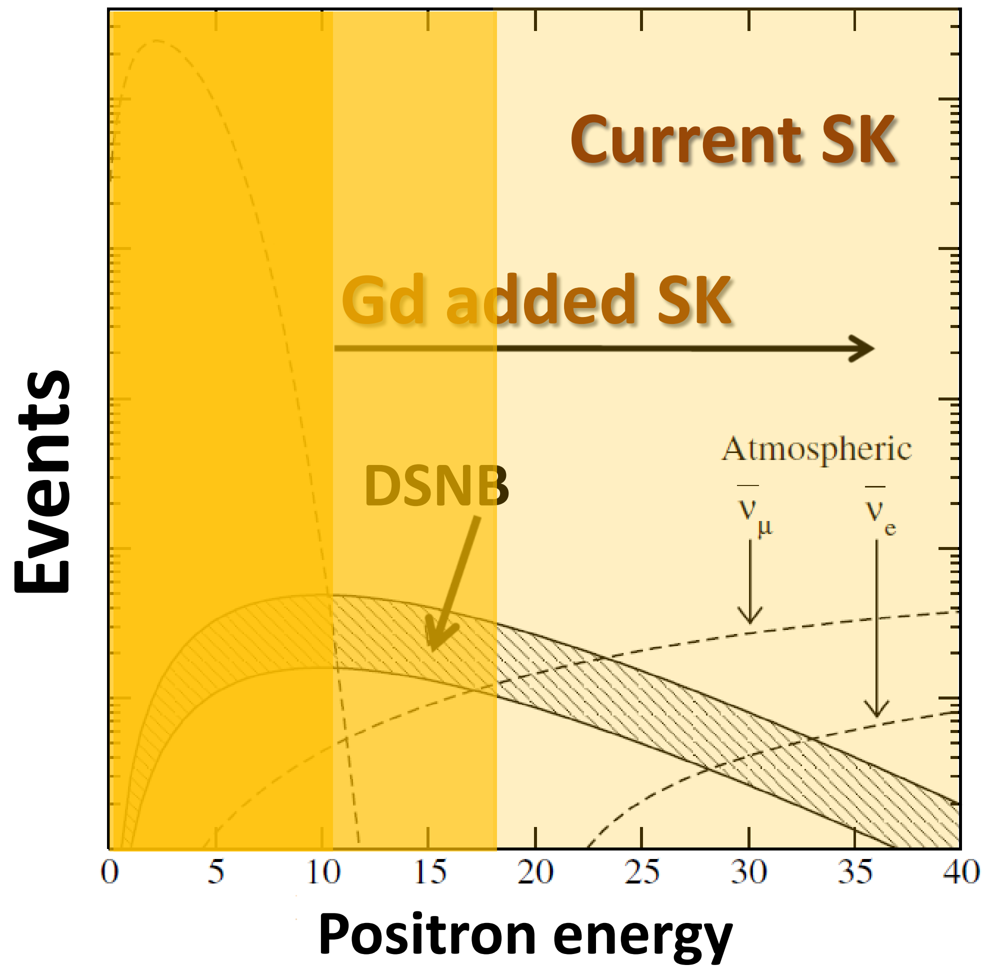
Addition of Gd in SK water enables *n* to be tagged:

$$\overline{\upsilon}_e + p \rightarrow e^+ + n$$

Gd + *n* → 8 MeV photon

$\overline{\nu}_e$ can be identified by delayed coincidence.

Beacom, Vagins PRL (2004)



Test tank being built now in Kamioka mine.

Event Rates @SK

$\bar{\nu}_e$ spectrum	events $[(22.5\ \text{kton yr})^{-1}]$	
(effective $T_{\bar{\nu}_e}$)	$10 < E_e/\text{MeV} < 26$	$18 < E_e/\text{MeV} < 26$
8 MeV	4.2 ± 1.4	2.0 ± 0.7
6 MeV	3.5 ± 1.1	1.3 ± 0.4
4 MeV	1.8 ± 0.5	0.4 ± 0.1
SN 1987A	1.7 ± 0.5	0.5 ± 0.1

- **Compatible with literature**
  - **Theoretical range (Ando&Sato)**
  - **SN1987A analysis (Lunardini, FukugitaKawasaki)**
- **Importantly, we are able to set the normalization to within +/- 40%**
- **Addition of Gadolinium big boost!**

Author	Event / yr
Ando, Sato (2005)	(0.25–2.3) *f*
Lunardini (2006)	0.1 – 0.7
Fukugita, Kawasaki (2003)	0.2–1.2

Summary of DSNB

- **Star formation rate → *DSNB detectability***
- **The QUESTIONS:**

  Q1. When can we detect the DSNB?

  Q2. Can the DSNB be used to study stellar/neutrino physics?
- **The ANSWERS :**

  A1. There are many past core-collapse supernovae

  DSNB event > 1 /yr @Gd-enhanced SK

  A2. Uncertainty in R_{CCSN} is small

  DSNB temperature can be probed eventually

- **In the future:**
  - **Uncertainty in R_{CCSN} will continue to decrease**
  - **Galactic CCSN → generic properties, distances, BH population**

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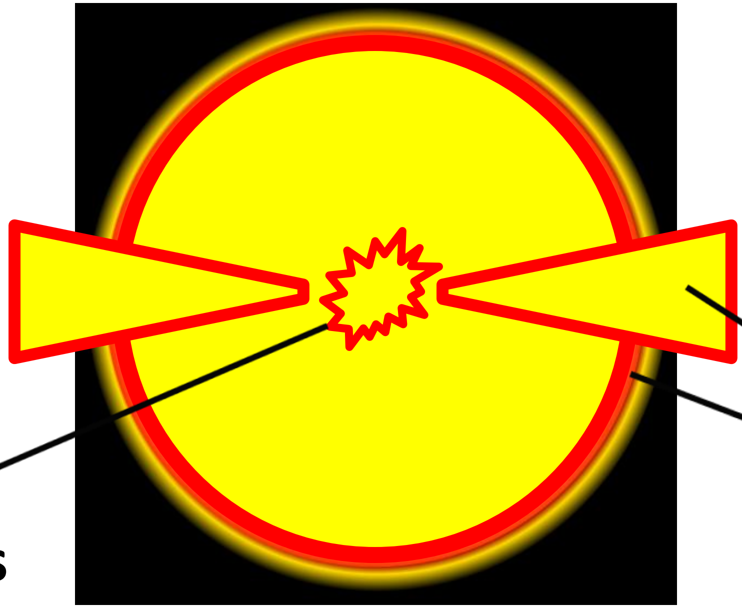
Production processes & sites



Thermal neutrinos

Non-thermal neutrinos

e.g.

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

and then thermalized

Acceleration + nuclear interactions

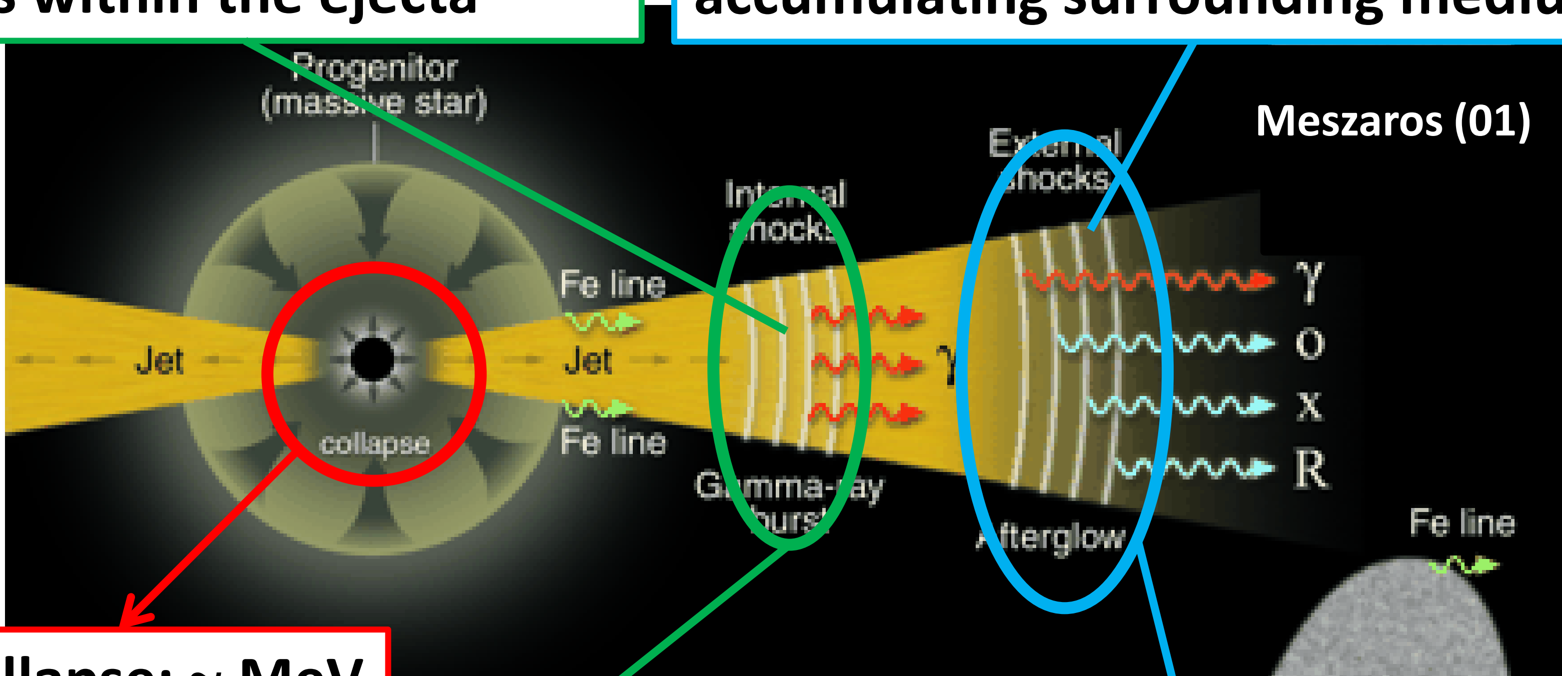
$$pp \longrightarrow pn\pi^+ \quad p\gamma \longrightarrow \Delta \longrightarrow n\pi^+$$

$$\pi^+ \longrightarrow \boxed{\nu_\mu}\mu^+ \qquad \mu^+ \longrightarrow \boxed{\bar{\nu}_\mu \nu_e} e^+$$

Gamma-ray bursts

Gamma rays: collisions of shells within the ejecta

Afterglow: ejecta decelerated by accumulating surrounding medium



At collapse; ~ MeV

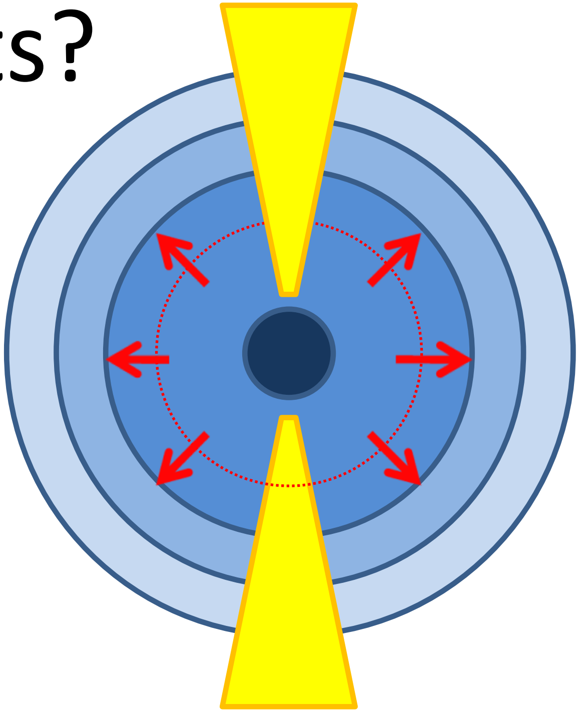
With prompt; ~ 10^9 MeV
[Waxman Bahcall 1997, etc]

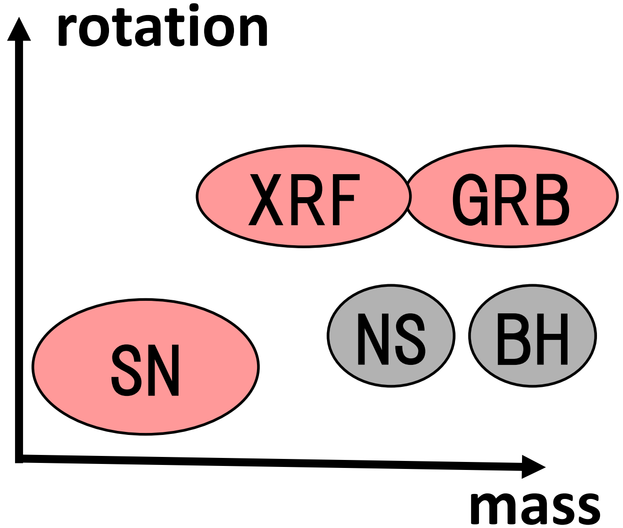
With afterglow; ~ 10^{12} MeV
[Waxman Bahcall 2000, etc]

How about gamma-dark jets?

- Supernovae are typically not symmetric (late time radio, gamma-ray bursts, neutron star kicks, etc)

- a JET can be "hidden" or "choked"
  - **Choked:** stalls inside the star (depends on the progenitor, jet energetics, collimation, central engine activity, etc)
  - **Hidden:** heavy baryon-load jets (also called failed-GRB jets)





[courtesy Takiwaki]

Can Neutrinos Escape?

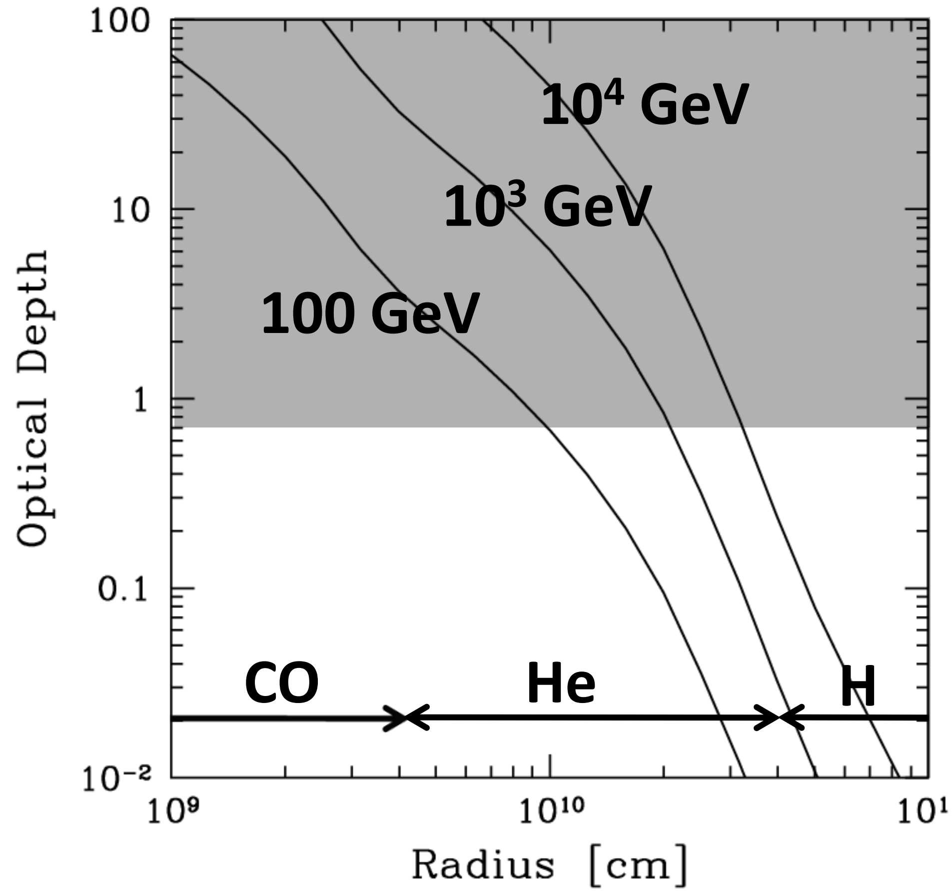
- **Opacity for high-energy neutrinos**

$$\nu + p \rightarrow \mu + p$$

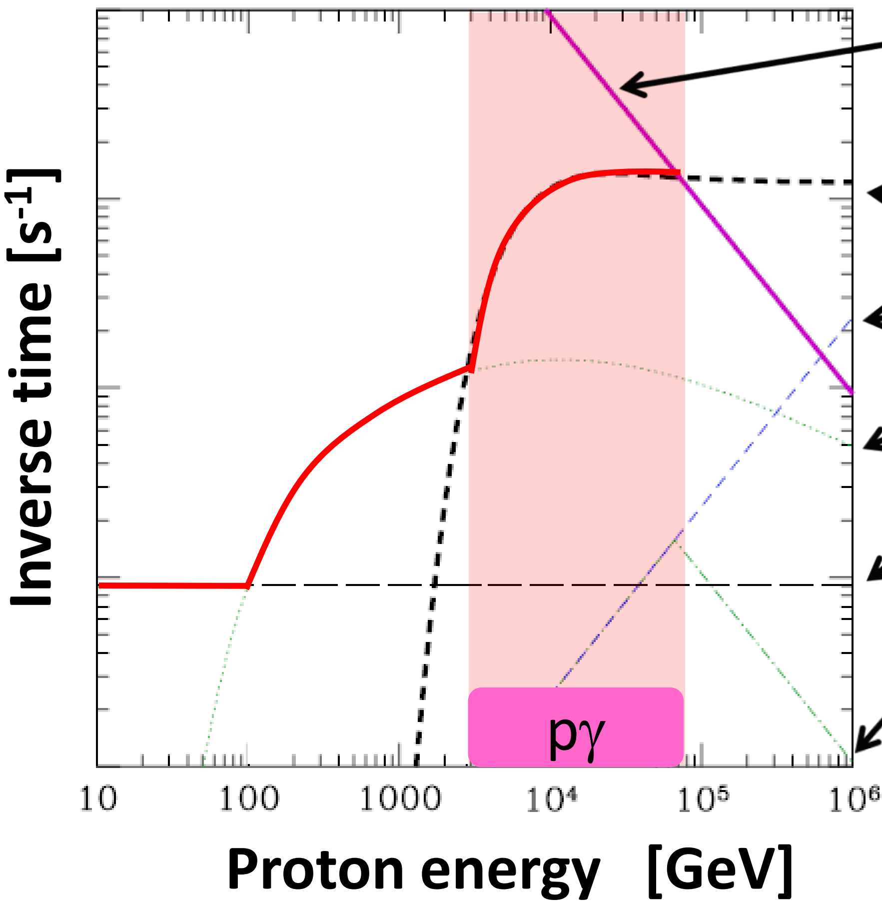
is > 1 inside the star

- **For typical supernova progenitors:**
  - **CO core : no neutrino emission**
  - **He : up to ~ 10^3 GeV neutrinos**
  - **H envelope : optically thin**

- **We consider He envelope region**



Neutrino Production (2)



Acceleration $(t_{acc} \propto EB^{-1})$

Energy loss mechanisms:

- **Photomeson production**
- **Synchrotron**
- **Pair-production**
- **pp collisions**
- **Inverse Compton**

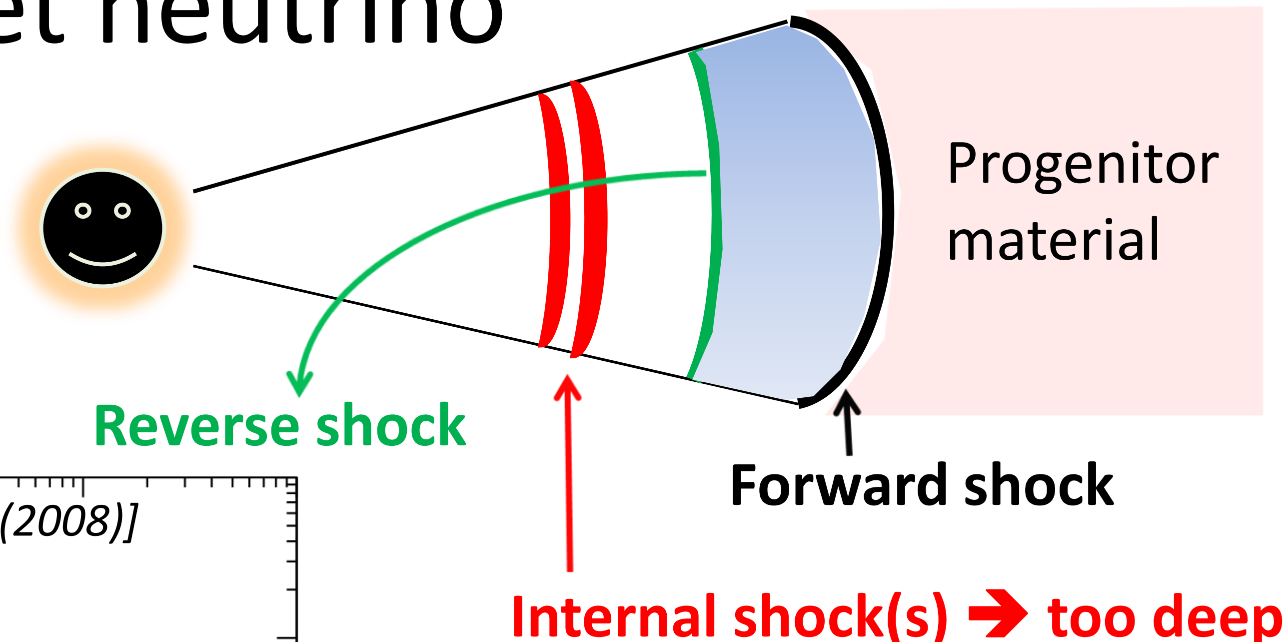
Acceleration condition:

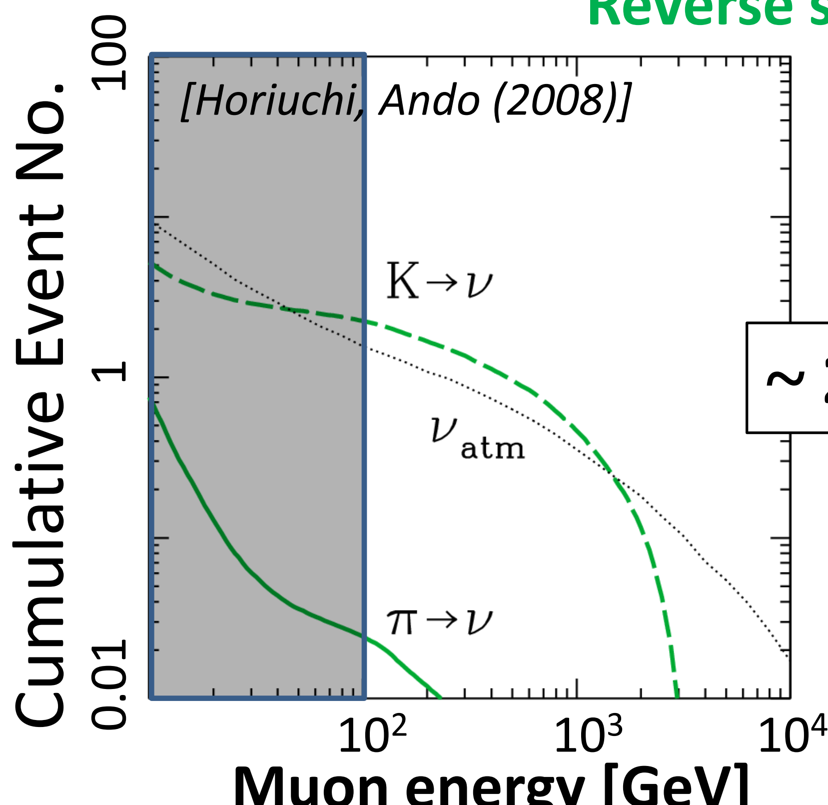
$$t_{acc}^{-1} > t_{cool}^{-1}$$

Shown for r = 5 10^{10} cm: $E_{p,max}$ ~ 10^5 GeV ➔ $E_{\nu,max}$ ~ 10^3 GeV

Choked jet neutrino

E_{iso}= 3 10^{53} ergs
T = 34 s
→ R = 5 10^{10} cm
D = 5 Mpc





~ 2 events @IceCube

- **Suppression due to proton energy loss**
- **<u>Suppression due to meson energy losses</u>**
- **Neutrino oscillation in vacuum**
- **Earth effects**

Choked jet neutrino

E_{iso}= 3 10^{53} ergs
T = 34 s
→ R = 5 10^{10} cm
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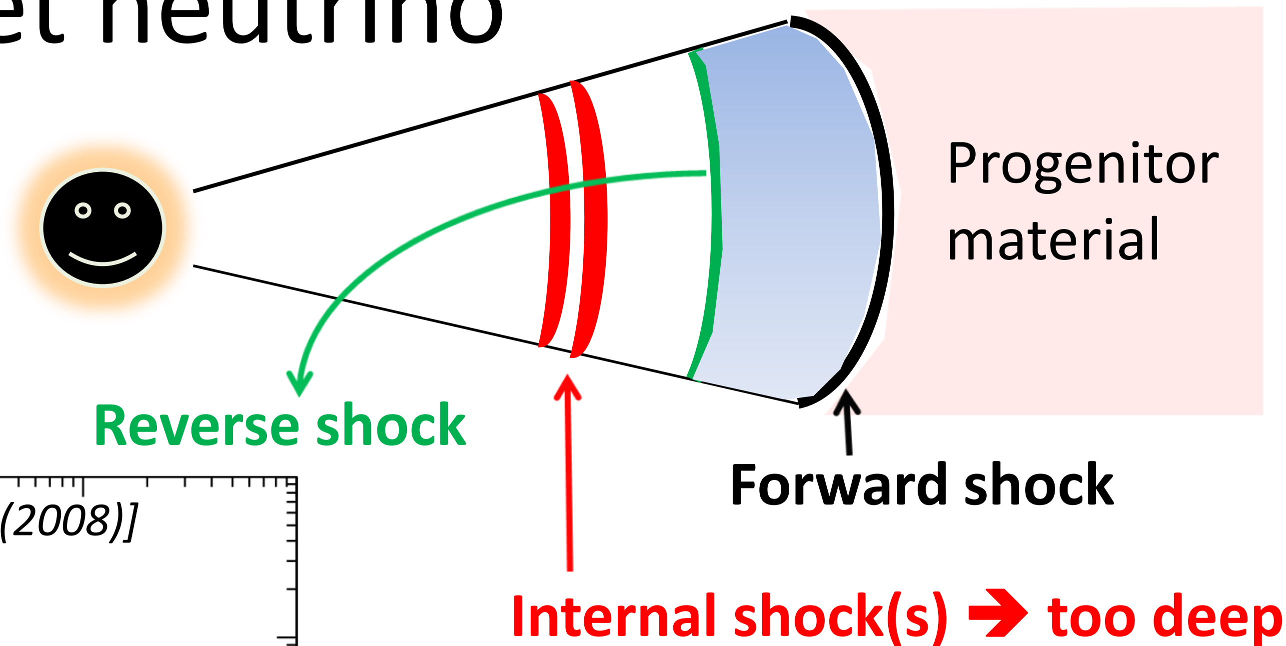
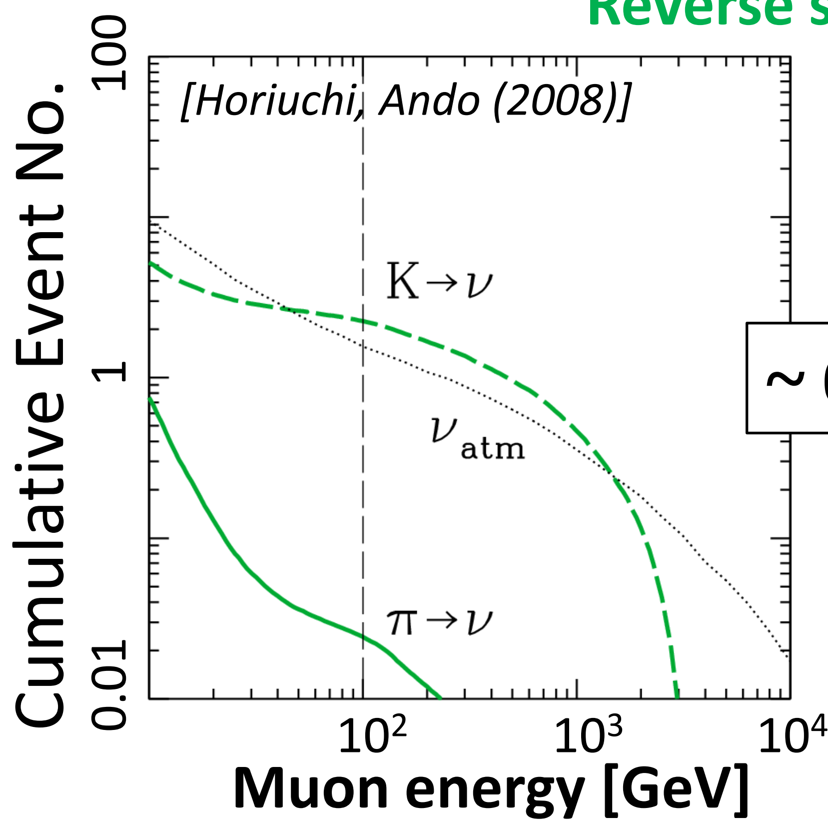


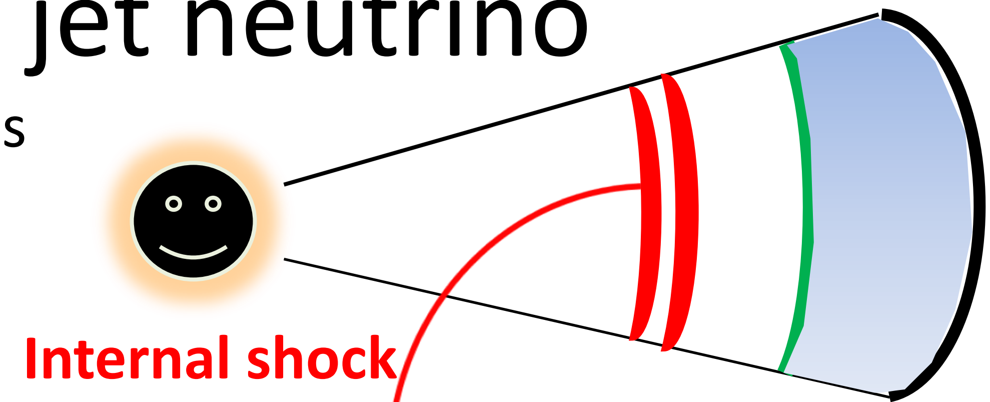


~ 6 events @IceCube

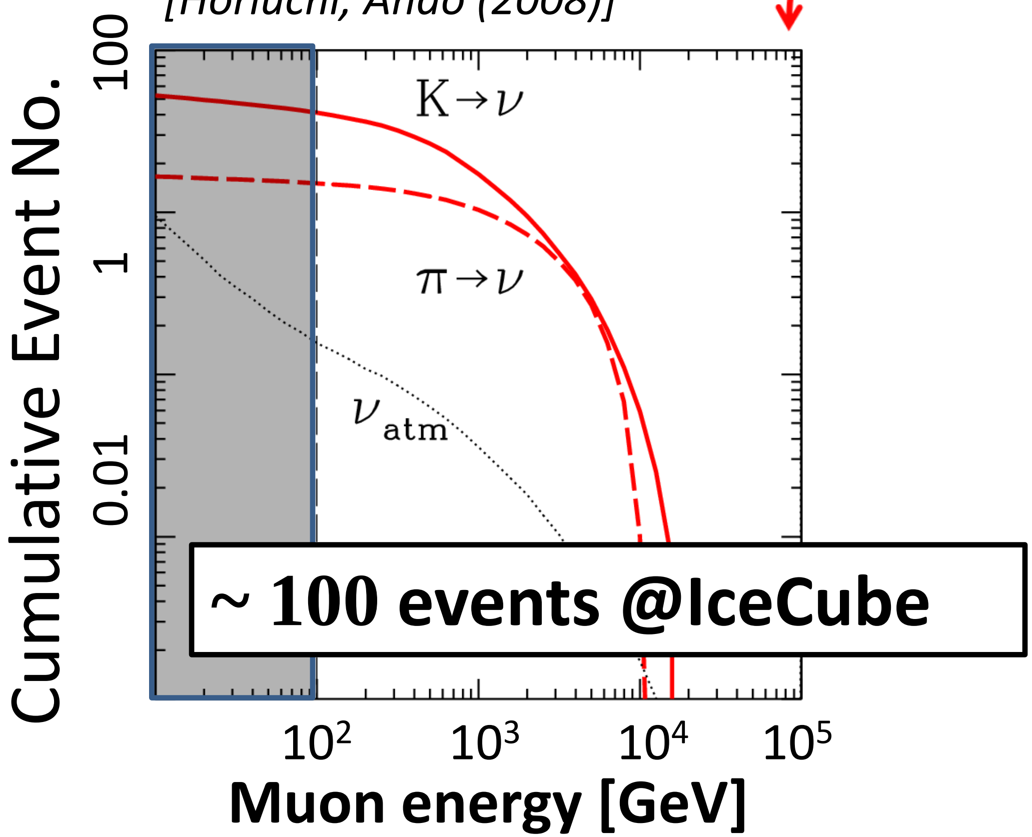
- **Suppression due to proton energy loss**
- **<u>Suppression due to meson energy losses</u>**
- **Neutrino oscillation in vacuum**
- **Earth effects**

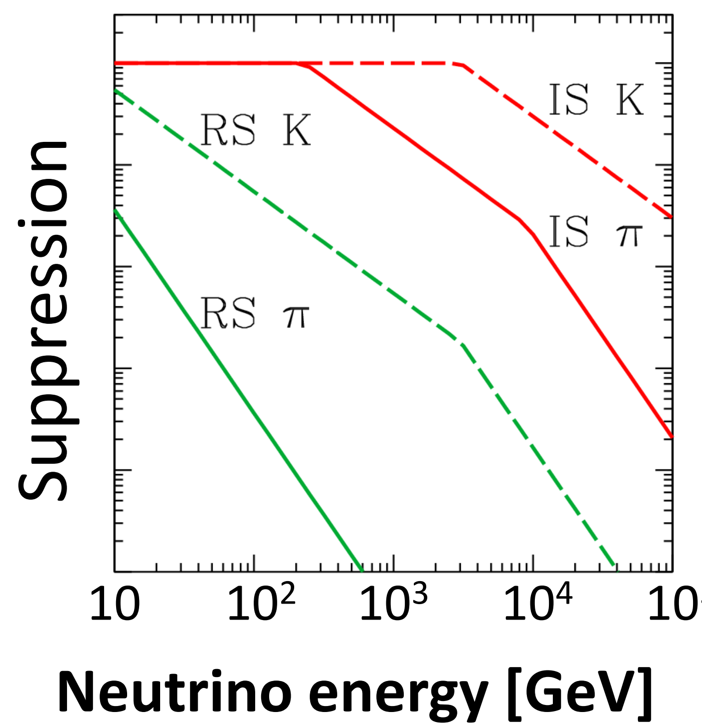
Hidden jet neutrino

E_{iso}= 3 10^{53} ergs
T = 100 s
D = 5 Mpc
R = 6 10^{10} cm



[Horiuchi, Ando (2008)]





Conclusion

	Choked		Successful	
	$\Gamma_j = 10$	$\Gamma_j = 100$	$\Gamma_j = 10$	$\Gamma_j = 100$
γ rays	dark	dark	typically dark	bright
ν	our work	our work	our work	well studied

- **Investigated neutrino emission from gamma-dark jets**
  - **Kaons important**
- **Detectability @IceCube:**
  - **Choked jet: detectable up to 5 Mpc**
  - **"hidden" jet: detectable out to ~ 20 Mpc**

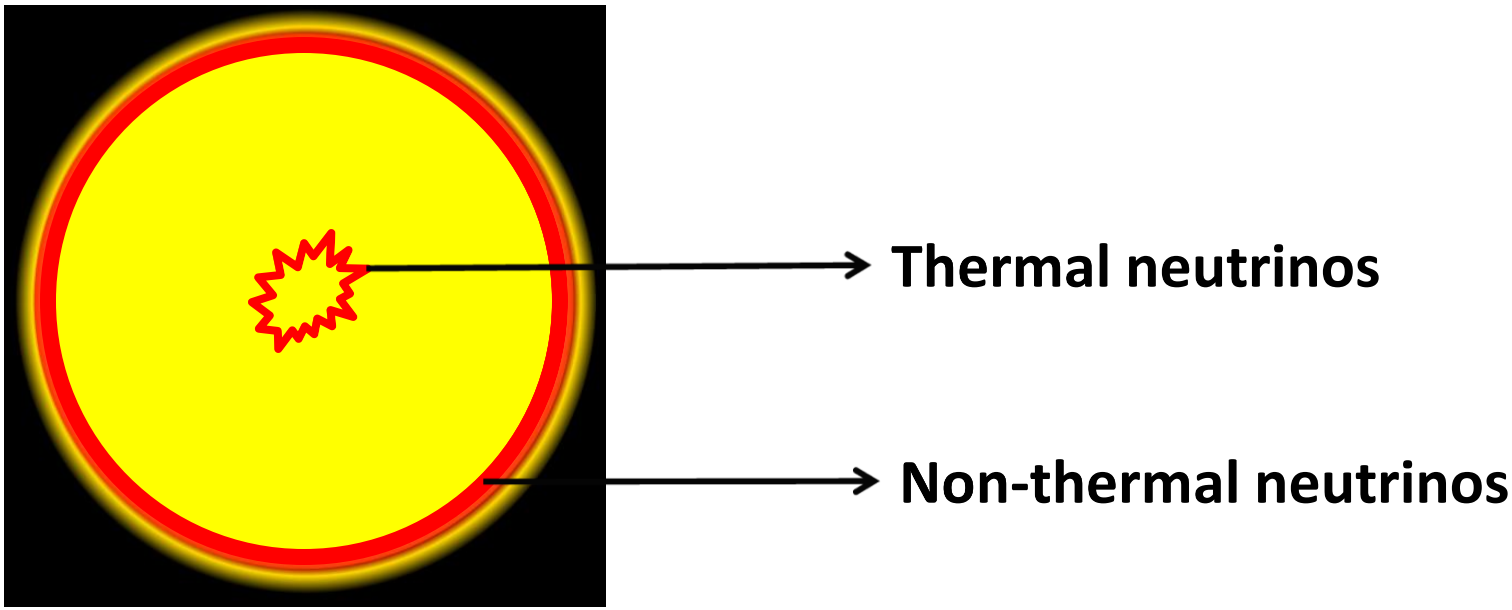
(Rate of core-collapse ~ 0.5 per year within 5 Mpc; w/out beaming)

- **Implications**
  - **Jet distribution can be studied**
  - **Information for jet production timing (→ mechanism)**

- Introduction
- Thermal neutrinos from supernovae
  - Detecting the diffuse supernova neutrino background
- Non-thermal neutrinos from supernovae
  - Gamma-ray burst context
  - (Magnetic stars)
- Summary

Where are we looking?

Non-thermal neutrinos from the supernovae of strongly magnetic stars. Emission is possible near the surface of the star.



$$pp \rightarrow pn\pi^{+}$$
$$p\gamma \rightarrow \Delta \rightarrow n\pi^{+}$$

$$\pi^{+} \rightarrow \boxed{\nu_{\mu}}\mu^{+}$$
$$\mu^{+} \rightarrow \boxed{\bar{\nu}_{\mu}\nu_{e}}e^{+}$$

Motivation: origin of magnetic field

- **We know of strong magnetic fields in neutron stars**
  - **B ~ $10^{11} – 10^{15}$ G**
- **Origin is yet unknown. Ideas:**
  - **Dynamo** *[Thompson&Duncan1993]*
  - **Fossil** *[Ruderman1972,Ferario2006]*

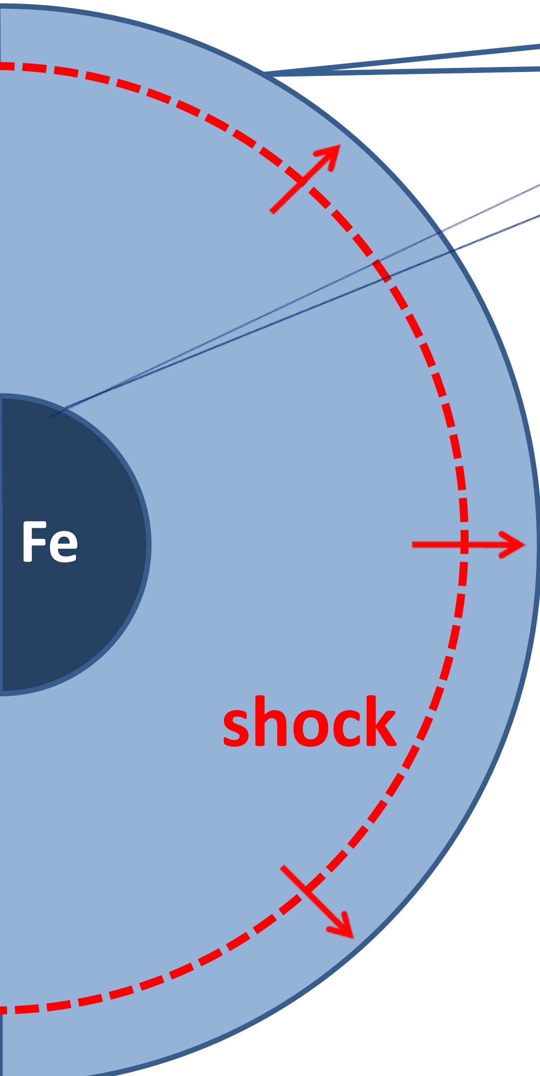
supernova

- **Surface magnetic fields in massive stars:**
  - **OB stars: 10^3 G** *[Donati et al. 2006, etc]*
- **Origin is thought to be fossil**

Source	B-field /G	Radius /cm	B-flux /G cm^2
Ap, Bp stars	100 – 10^4	10^{11}	< 10^{27}
White dwarfs	10^6-10^9	5 10^8	< 10^{27}

So we want to probe the magnetic field inside the star.

Supernova of a Magnetic star



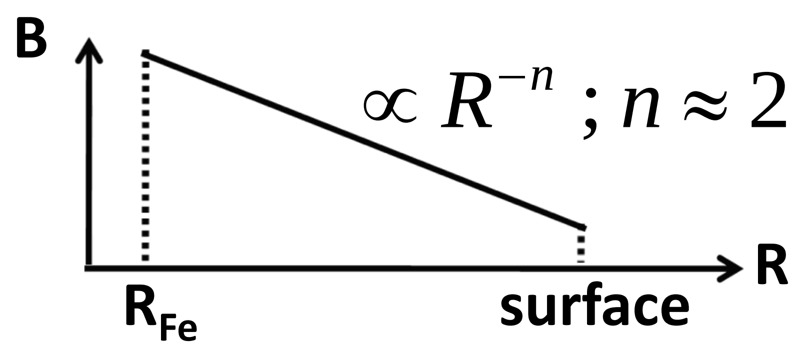
Surface B-field: use observed value

Require the production of a magnetar

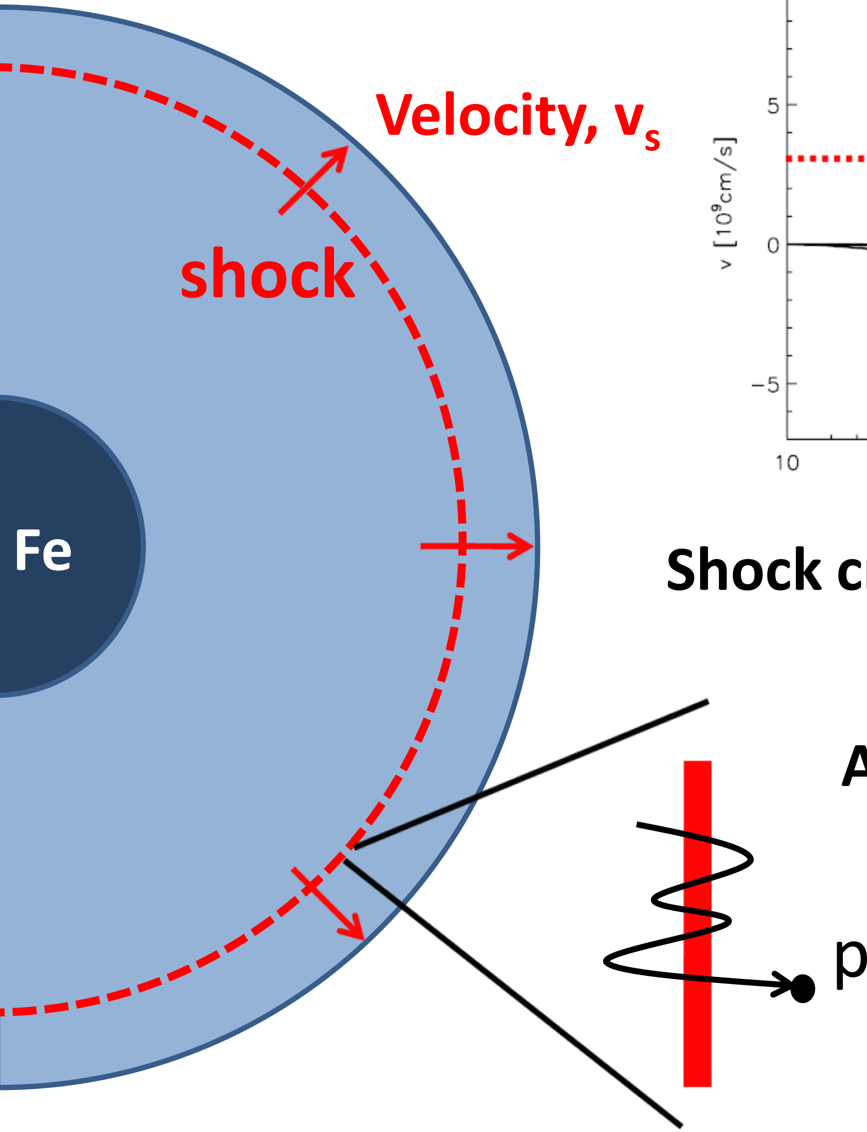
Assuming fossil field hypothesis, the Fe core B-field is given by conservation of Br^2 :

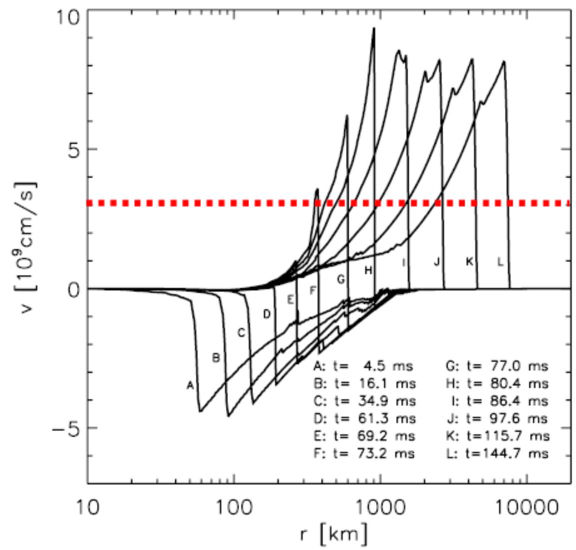
$$B_{\rm core} = 10^{15} \left(\frac{R_{\rm Fe}}{10^6 \,{\rm cm}} \right)^{-2} = 10^{11}\,{\rm G}$$

Assume a power-law B-field strength:



Acceleration time scale





$v_s = 10^{9.5}$ cm/s

Kitaura et al. A&A (2006)

Shock crossing time : $\dfrac{R}{v_s} \approx$ **seconds – hours**

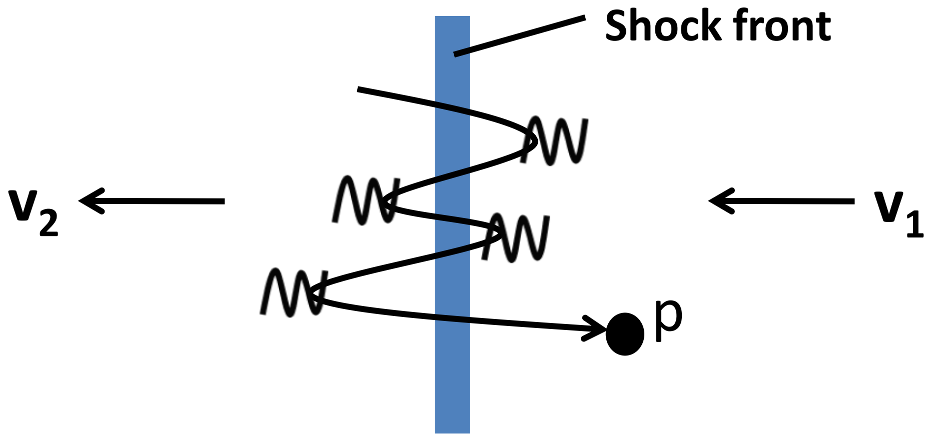
Acceleration time (Bohm limit $\eta \to 1$) :

$$t_{acc} \approx \frac{10}{3}\eta\frac{r_g c}{v_s^2} \approx 10^{-5}\,\mathrm{sec}$$

Particle Acceleration

First order Fermi acceleration is a favourite. Shocks are efficient proton accelerators.

Drury, PhyRep (1983)
Blandford, Eichler ,PhyRep (1987)



The energy gain in each cycle is: $\frac{\Delta E}{E} = \frac{4\Delta v}{3v} \sim 0.15$

Important distance scales:

- **Acceleration:** $vt_{acc} \sim 0.1 E_3 B_{4.5}^{-1}\, cm$
- **Collisions with: protons (ionized)** $l_{pp} \sim 10^6 \rho_{-5}^{-1}\, cm$

  nuclei (partially ionized): $l_{pN} \sim 1 \rho_{-5}^{-1}\, cm$

As E increases, acceleration < collisions ← is this a problem?

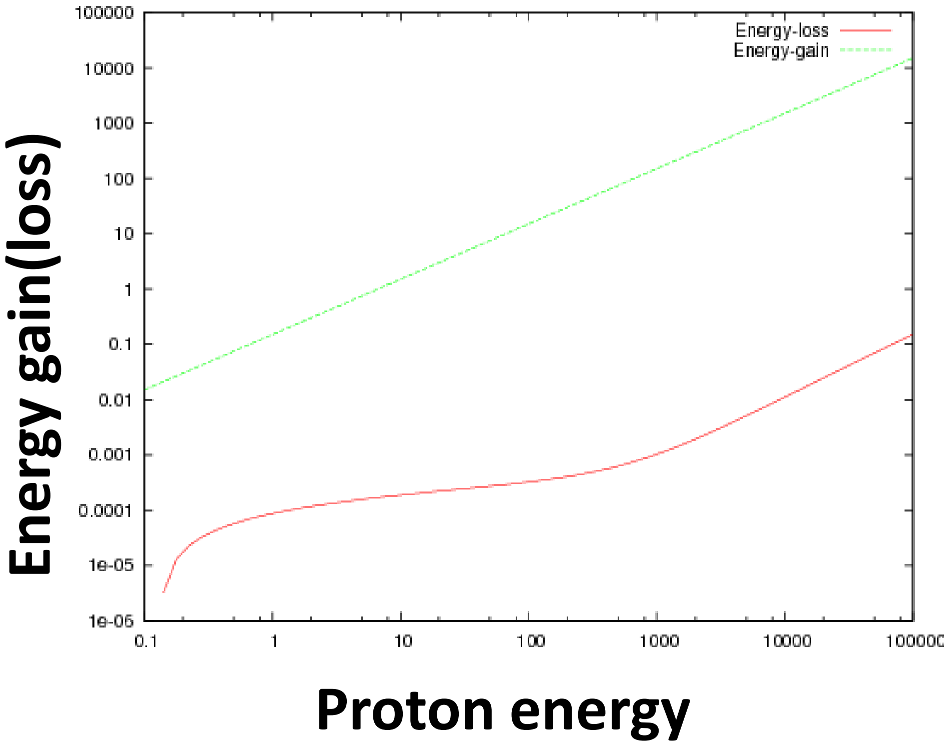
Acceleration vs. energy loss

Protons must be accelerated faster than the lose energy.

- **Energy-loss by collisions with heavy nuclei:**
  “stopping power” is max ~ 300 MeV/(g cm^{-2})   @ ~ 1 MeV

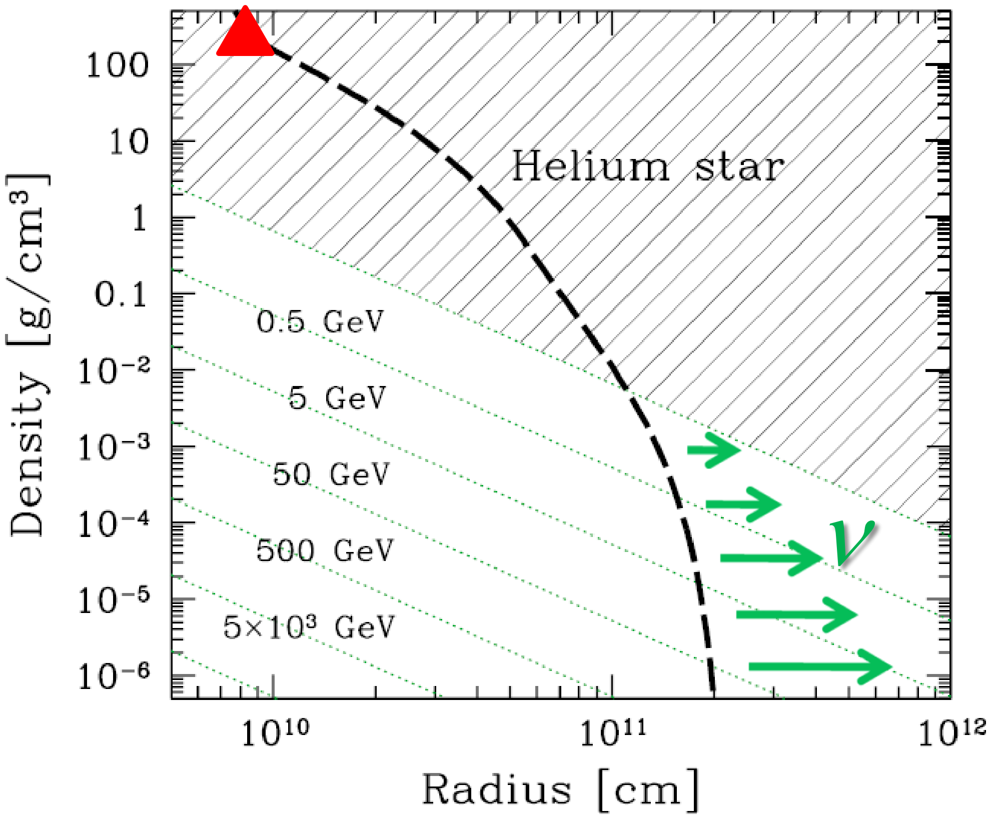
- **Energy loss by synchrotron, inverse-Compton (includeng feedback from electron synchrotron), pair-production are all negligible small.**

- **Energy-loss by collisions with target protons is fastest**



Acceleration Limit

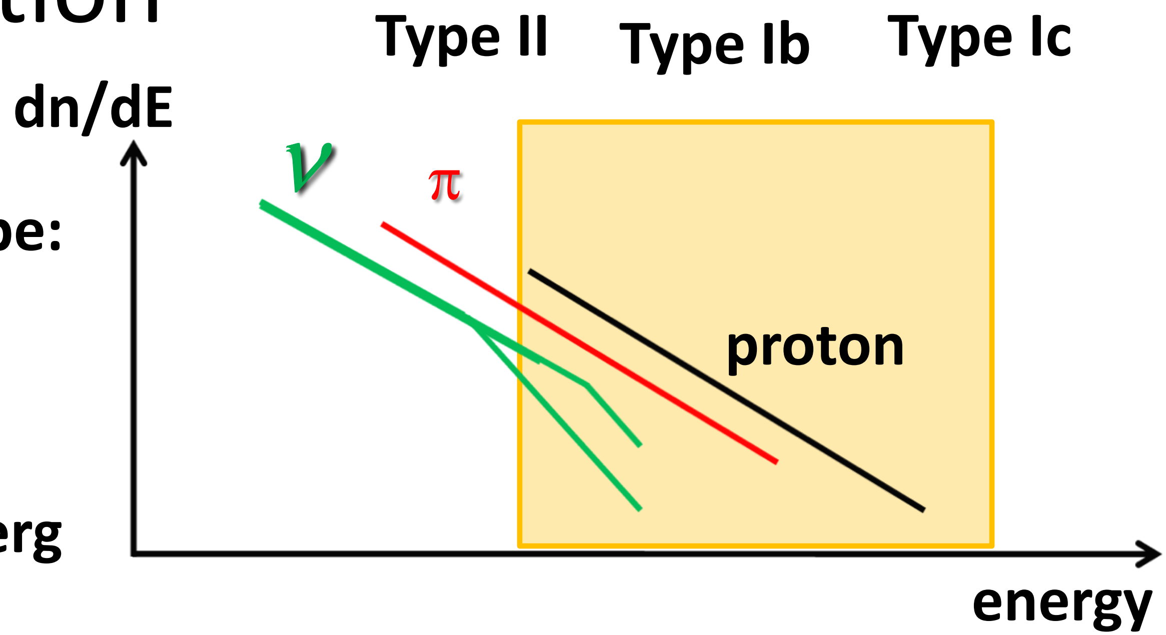
$\boxed{t_{acc} = t_{cool,pp}}$ **yields** $\epsilon_{\nu,\max} \propto \left[\left(\frac{v_s^2 qB}{0.2c\sigma_{pp}\kappa\rho_u/m_p} \right)^2 + m_p^2 c^4 \right]^{1/2}$



Horiuchi et al. MNRAS (2008)

Neutrino Detection

Neutrino spectrum shape:



Event number, for 10^{51} erg supernova at 10 kpc :

Source	@ Super-K	@ IceCube
type II	130	200
type Ib	160	6000
type Ic	70	600

due to low maximum energy

due to energy loss of pions

Background ~ 10 /day

Background ~ 100 /day

- ☐ Introduction
- ☐ Thermal neutrinos from supernovae
  - ➢ Detecting the diffuse supernova neutrino background
- ☐ Non-thermal neutrinos from supernovae
  - ➢ Gamma-ray burst context
  - ➢ (Magnetic stars)
- ☐ Summary

Summary of Neutrinos from Supernovae

Neutrinos provide unique information on supernova interiors.

- ☐ On thermal neutrino detectability
  - ➢ Plenty of past supernovae:
    - ➔ DSNB is not small
    - ➔ DSNB can probe neutrino emission models
  - ➢ Implications for dark-collapses
- ☐ On non-thermal neutrinos emission
  - ➢ Neutrinos reveal hidden jets, up to a few Mpc away
    - ➔ constraints on jets
  - ➢ Strong stellar magnetic fields can produce neutrinos
    - ➔ info for origin of B-field

Neutrino Emission Processes

① **Collapse phase**

$$e^- + A \to \nu_e + A'$$

② **Burst phase**

$$e^- + p \to n + \nu_e$$

"Neutronization burst"

③ **Accretion phase**

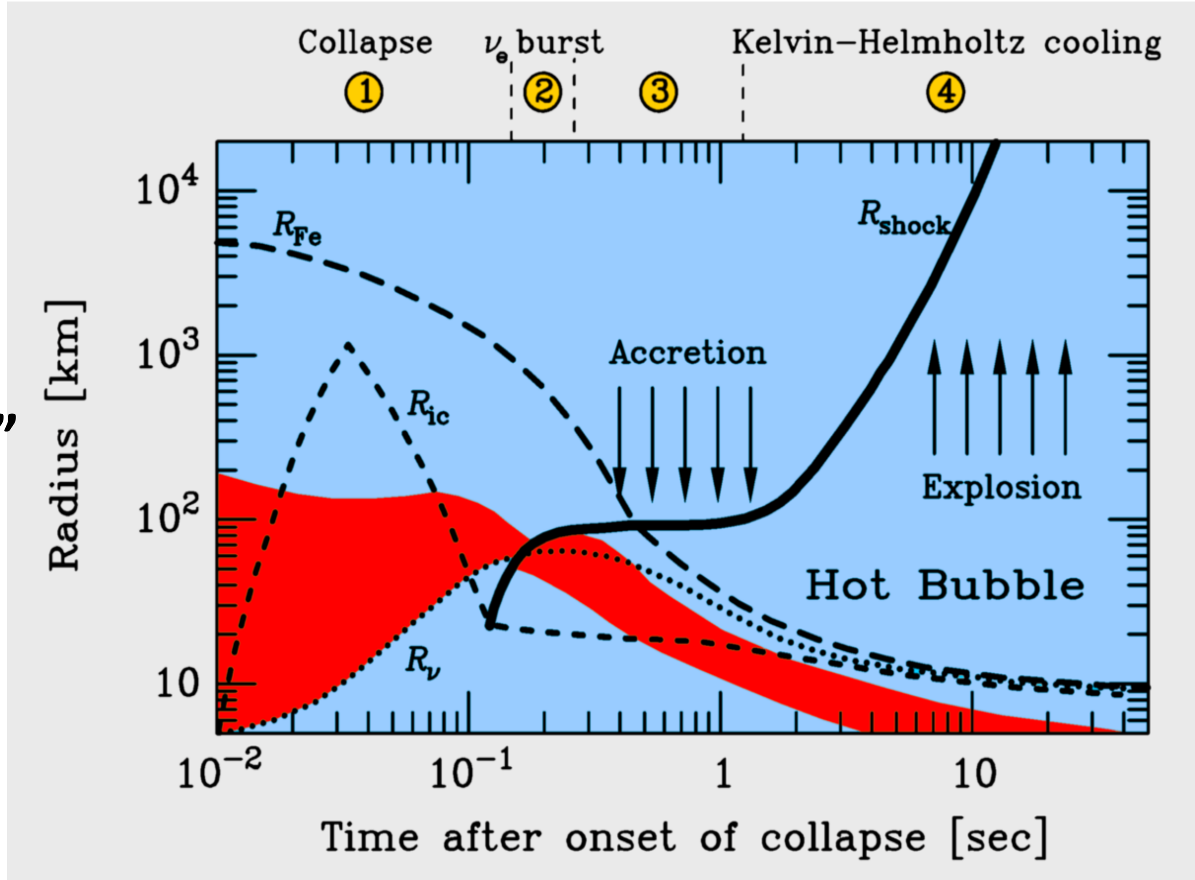
$$\gamma + \gamma \to e^+ + e^-$$

$$e^+ + e^- \to \nu + \bar{\nu}$$

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

④ **Cooling phase**

$$N + N' \to N + N' + \nu + \bar{\nu}$$



Simulation details

1D simulations		Neutrino transport	Notes
Myra 1990	GR	MGFLD	
Totani 1998	GR	MGFLD	neutron finger convection
Rampp 2000	Newton	Accurate Boltzmann	15Msun
Lieben 2001	GR/New	Boltzmann	13 Msun
Mezzacappa 2001	Newton	Accurate Boltzmann	13 Msun
Keil 2003	(GR)	(MC)	solved on background
Thompson 2003	Newton	Boltzmann solver	11, 15, 20 Msun
Lieben 2004	GR	MGFLD / Boltzmann	13, 40 Msun
Sumiyoshi 2007	GR	Boltzmann solver	BH formation

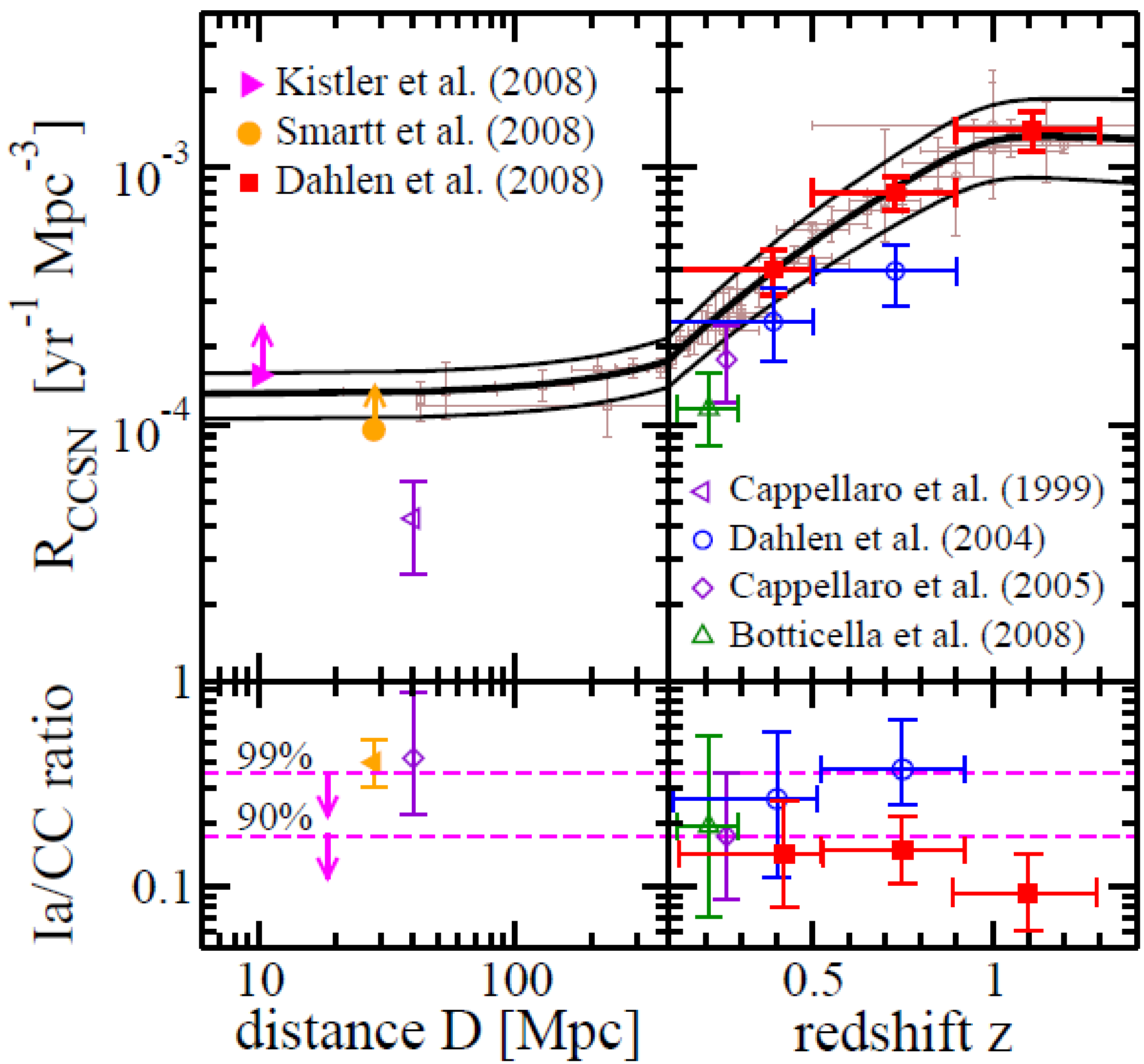
Keil (2003) neutrino interactions:

scattering (elastic) on electrons and neutrinos

scattering (elastic) on nucleons + recoil

Nuclear bremsstrahlung

Pair annihilation processes (e+e- & n n-bar)



Kistler et al. (2008)
Smartt et al. (2008)
Dahlen et al. (2008)
Cappellaro et al. (1999)
Dahlen et al. (2004)
Cappellaro et al. (2005)
Botticella et al. (2008)
R_{CCSN} [yr^{-1} Mpc^{-3}]
10^{-3}
10^{-4}
1
0.1
Ia/CC ratio
99%
90%
10
100
0.5
1
distance D [Mpc]
redshift z

One last issue : background

- **Background neutrinos**
  - **Solar** → **directional**
  - **Reactor** → **problem E < 10 MeV**
  - **Atmospheric** → **problem E > 40 MeV**
- **Background positrons**
  - **Spallation products** → **problem E < 19 MeV**
  - **Invisible muons** → **problem 19-60 MeV**

  → **window is 19-40 MeV, but background limited!**
- **Addition of Gd in SK water enables *n* to be tagged:**

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

Gd + *n* → 8 MeV photon ; $\bar{\nu}_e$ **can be identified by delayed coincidence.**

Test tank being built now in Kamioka mine.