DSNB:
Diffuse Supernova Neutrino Background

(& H.E. Diff. Bkg. from HNe and/or GRBs)

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JUNO Workshop, Nanjing, April 2016

(Slides credit: J. Beacom, I. Tamborra, etc.)

What would the DSNB look like?

What we have to go on is:

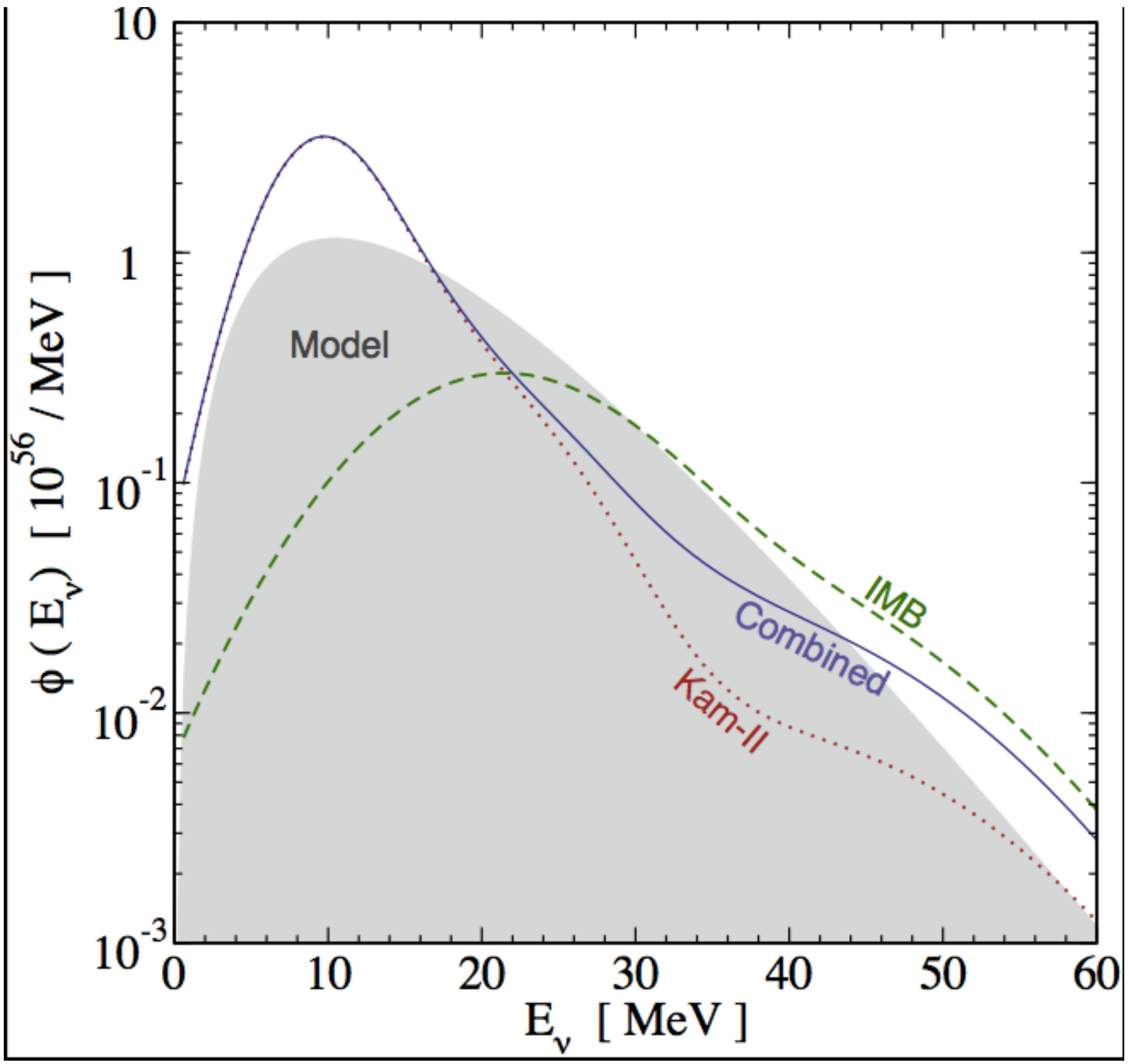
Supernova 1987A

Feb 1984

Mar 8, 1987

On Feb 23, 1987 a supernova was observed optically in the Large Magellanic Cloud at a distance of 170 000 light years (50 kpc)

DSNB

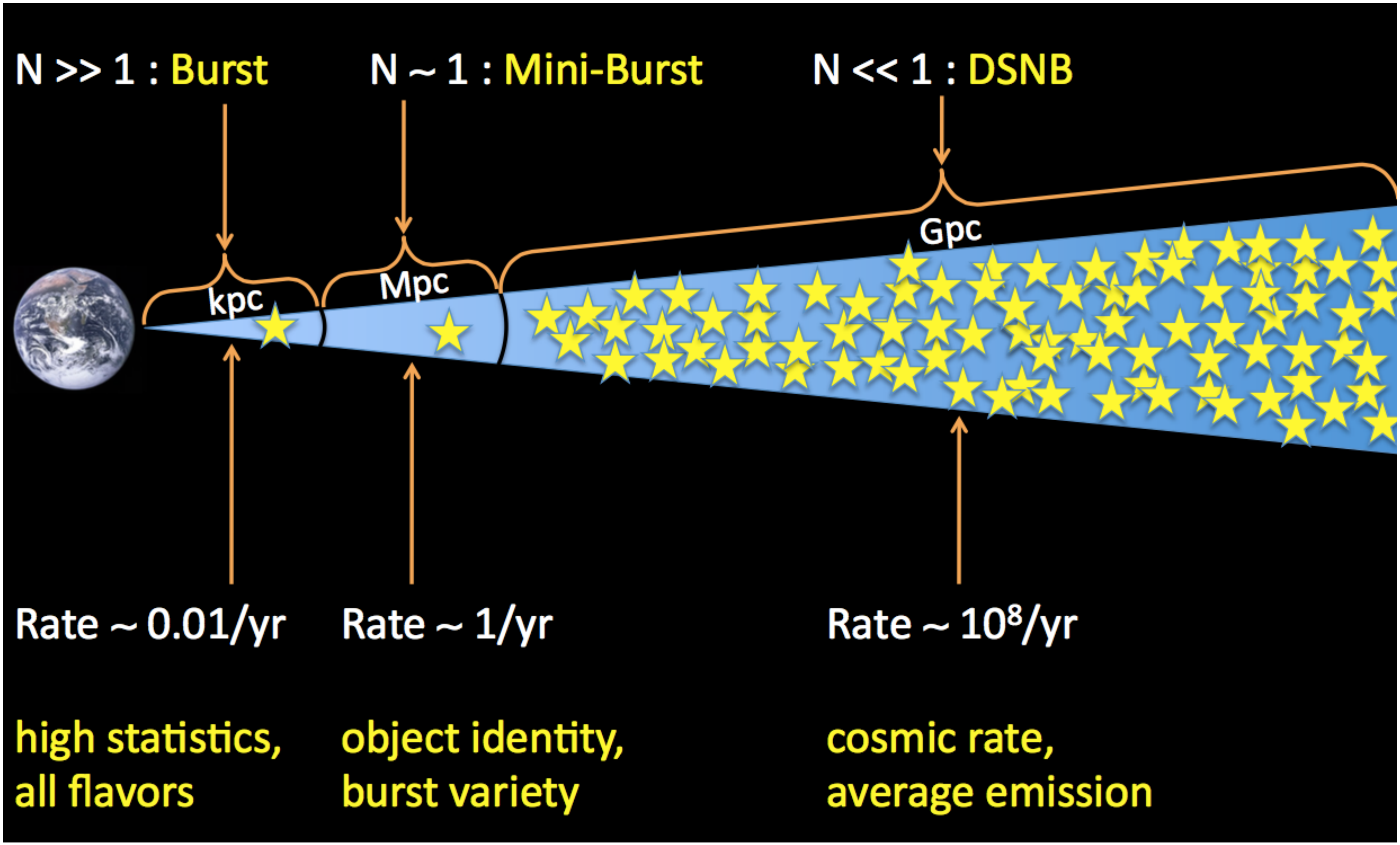


- Based on ***one*** object, SN1987a,
- it might look

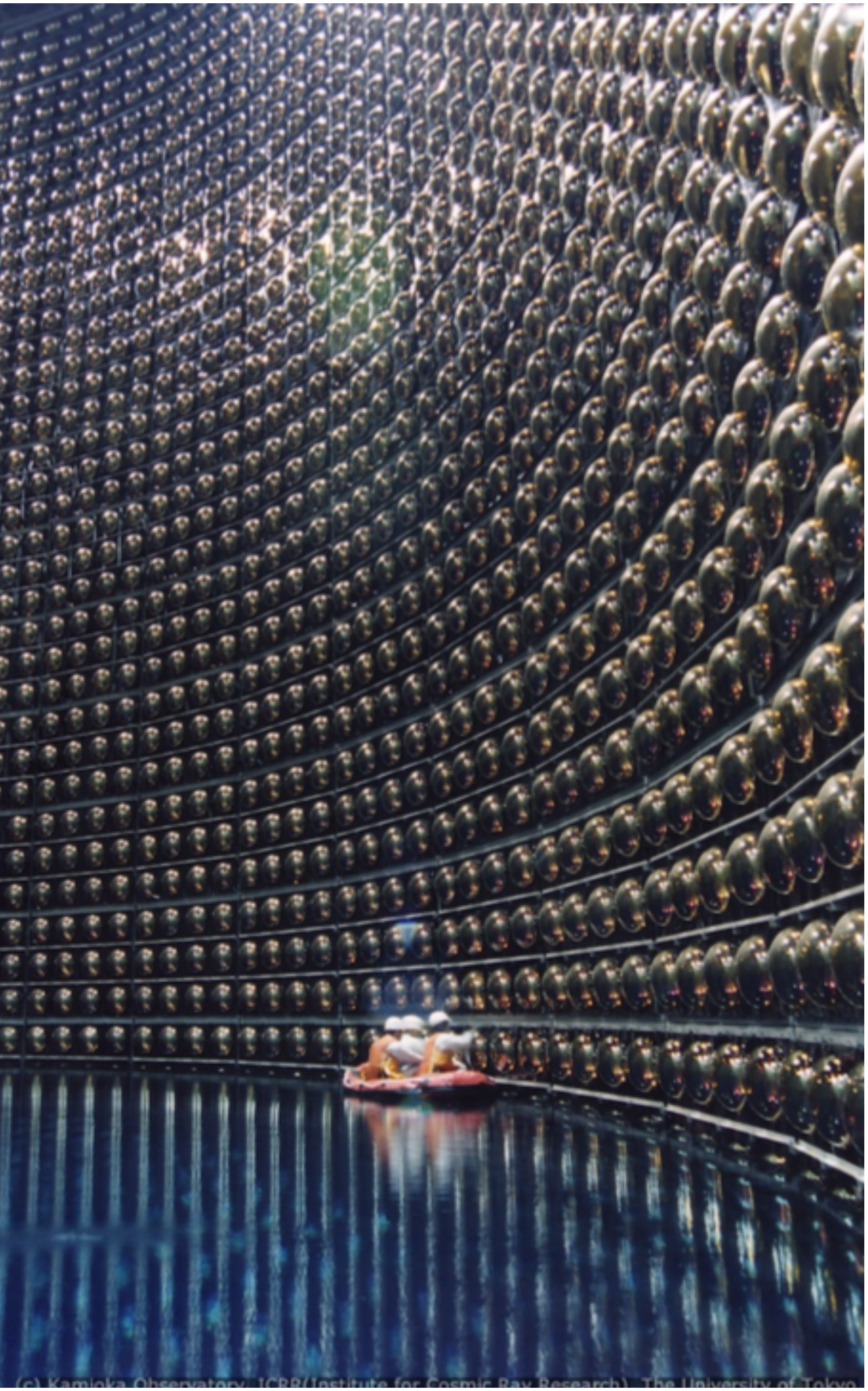
like this !

(or approximately)

How much, from how far?



(from Beacom, 2011)



How it has been detected so far (mainly with SK)

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

inverse beta decay
(charged current)

- electron neutrino hits free proton targets (water)
- cross section $\sigma \sim E^2$
- $e^+ \rightarrow$ Cherenkov $\rightarrow$ PMT

Current SK rate estimate

(without Gadolinium in water)

$$\left[\frac{dN_\nu}{dt}\right]_{\mathrm{DSNB}} \sim \left[\frac{dN_\nu}{dt}\right]_{87\mathrm{A}} \frac{\left[\frac{N_{SN}\, M_{det}}{4\pi D^2}\right]_{\mathrm{DSNB}}}{\left[\frac{N_{SN}\, M_{det}}{4\pi D^2}\right]_{87\mathrm{A}}}$$

The detection rate in Kam-II during the burst was $\sim 1\ \mathrm{s}^{-1}$. How are the inputs for the dimensionless product of conversion factors related? For SN 1987A, $N_{SN} = 1$, while there are $N_{SN} \sim 100$ neutrino bursts in the universe starting within any 10-second interval; this accounts for the supernova rate of the Milky Way, $\sim 10^{-2}$ year^{-1}, the space density of comparable galaxies, $\sim 10^{-2}$ Mpc^{-3}, and the fact that the supernova rate per galaxy was ~ 10 times higher in the past. The detector mass M_{det} of Kam-II was ~ 10 times smaller than that of SK, which is 22.5 kton (22.5×10^9 g). The distance D of SN 1987A was 0.050 Mpc, whereas for a typical supernova contributing the DSNB, at $z \sim 1$, it is $c/H_0 \sim 4000$ Mpc, $\sim 10^5$ times farther. Then the time-averaged DSNB detection rate in SK, noting changes in N_{SN}, M_{det}, and $1/D^2$, respectively, is

$$\left[\frac{dN_\nu}{dt}\right]_{DSNB} \sim (1\ \mathrm{s}^{-1}) \times 100 \times 10 \times 10^{-10} \sim 10^{-7}\ \mathrm{s}^{-1} \sim 3\ \mathrm{year}^{-1}$$

(with SK)

(e.g. Beacom 2010)

Approximate Energy & Spectral characteristics

$$\Delta(P.E.) \simeq \left(\frac{3G_N M^2}{5R}\right)_{NS} - \left(\frac{3G_N M^2}{5R}\right)_{core} \simeq 3 \times 10^{53}\ \text{erg}\,,$$

(homogeneous)

$$\varphi(E_\nu) = E_{\bar{\nu}_e,tot}\,\frac{120}{7\pi^4}\,\frac{E_\nu^2}{T^4}\,\frac{1}{(e^{E_\nu/T}+1)}$$

(Ferm-Dirac)

$$E_{\bar{\nu}_e,avg} = 3.15\,T.$$

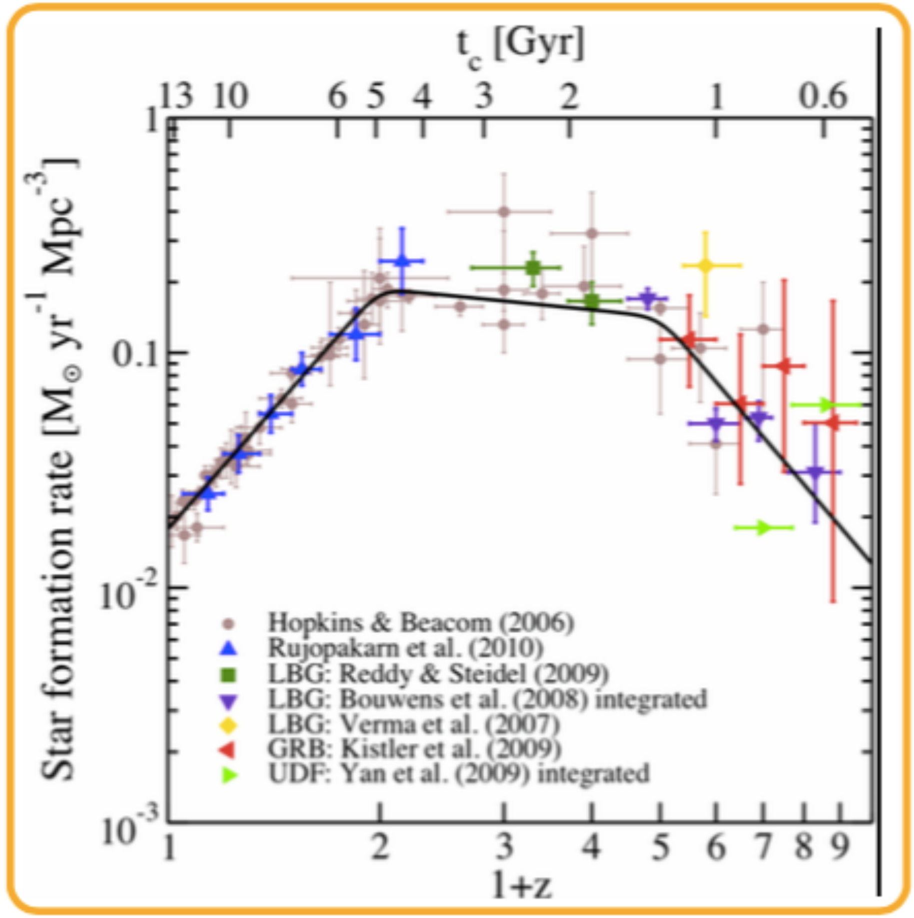
E.g. for SN 1987a, parameters are:

$E_{\bar{\nu}_e,tot} \sim 5 \times 10^{52}$ erg and $E_{\bar{\nu}_e,avg} \sim 15$ MeV.

SNR Predictions from Star Formation Rate

SNR proportional to star formation rate (SFR):

$$\dot{\rho}_\star \propto \begin{cases} (1+z)^\delta & z < 1 \\ (1+z)^\alpha & 1 < z < 4.5 \\ (1+z)^\gamma & 4.5 < z \end{cases}$$



Most precise way to measure SNR is from SFR

$$\psi(M) = dn/dM \propto M^{-2.35}$$

$$R_{SN}(z) = R_{SF}(z)\, \frac{\int_8^{50} \psi(M)dM}{\int_{0.1}^{100} M\psi(M)dM} \simeq \frac{R_{SF}(z)}{143 M_\odot},$$

See for details Horiuchi, Beacom, arXiv: 1006.5751; Hopkins, Beacom, arXiv: astro-ph/0601463.

Progenitor MASS effect ⇒

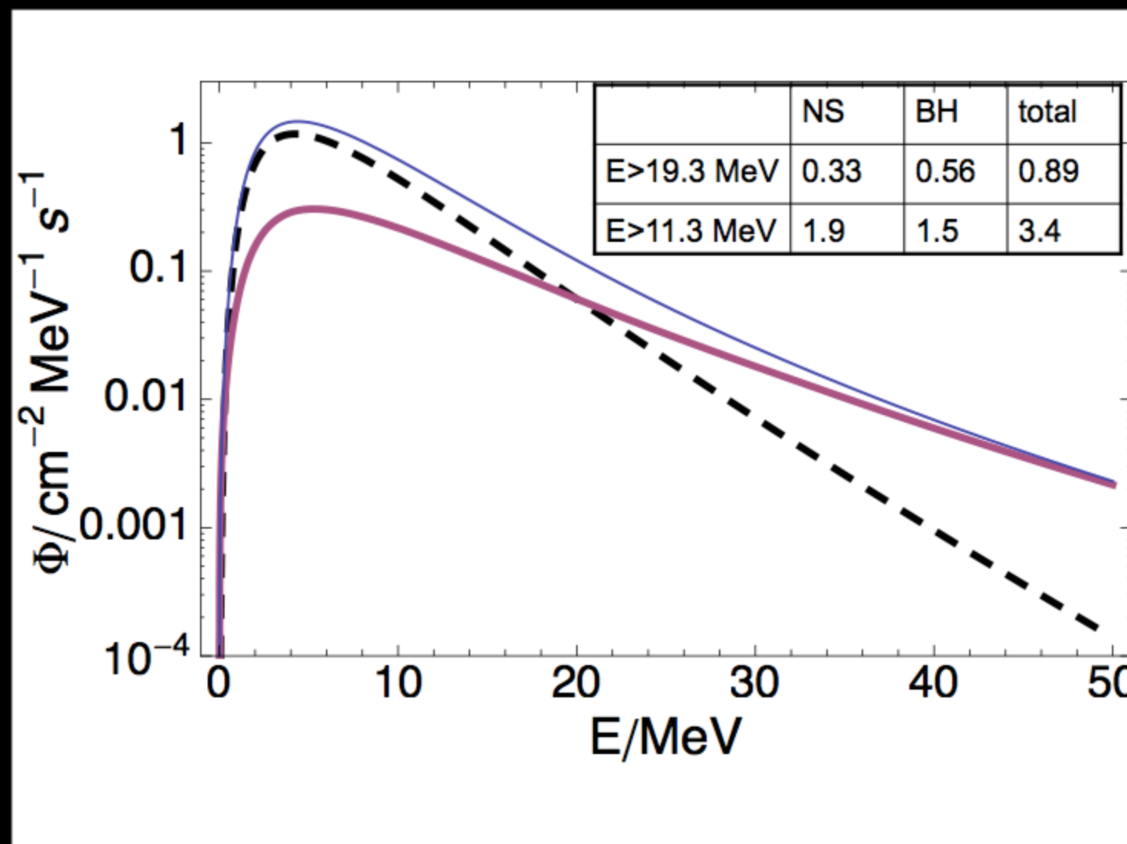
- For $M \gtrsim 8\ M_\odot$ → NS remnant
- For $M \gtrsim 28\ M_\odot$ → BH remnant

When core collapse fails (no optical supernova), the neutrino emission can be *larger* in total and average energy

The collapse goes *farther* and *faster*, but must shed its thermal energy by neutrino emission

Sumiyoshi et al. (2007)
Nakazato et al. (2008)
Fischer et al. (2008)
O'Connor, Ott (2011)

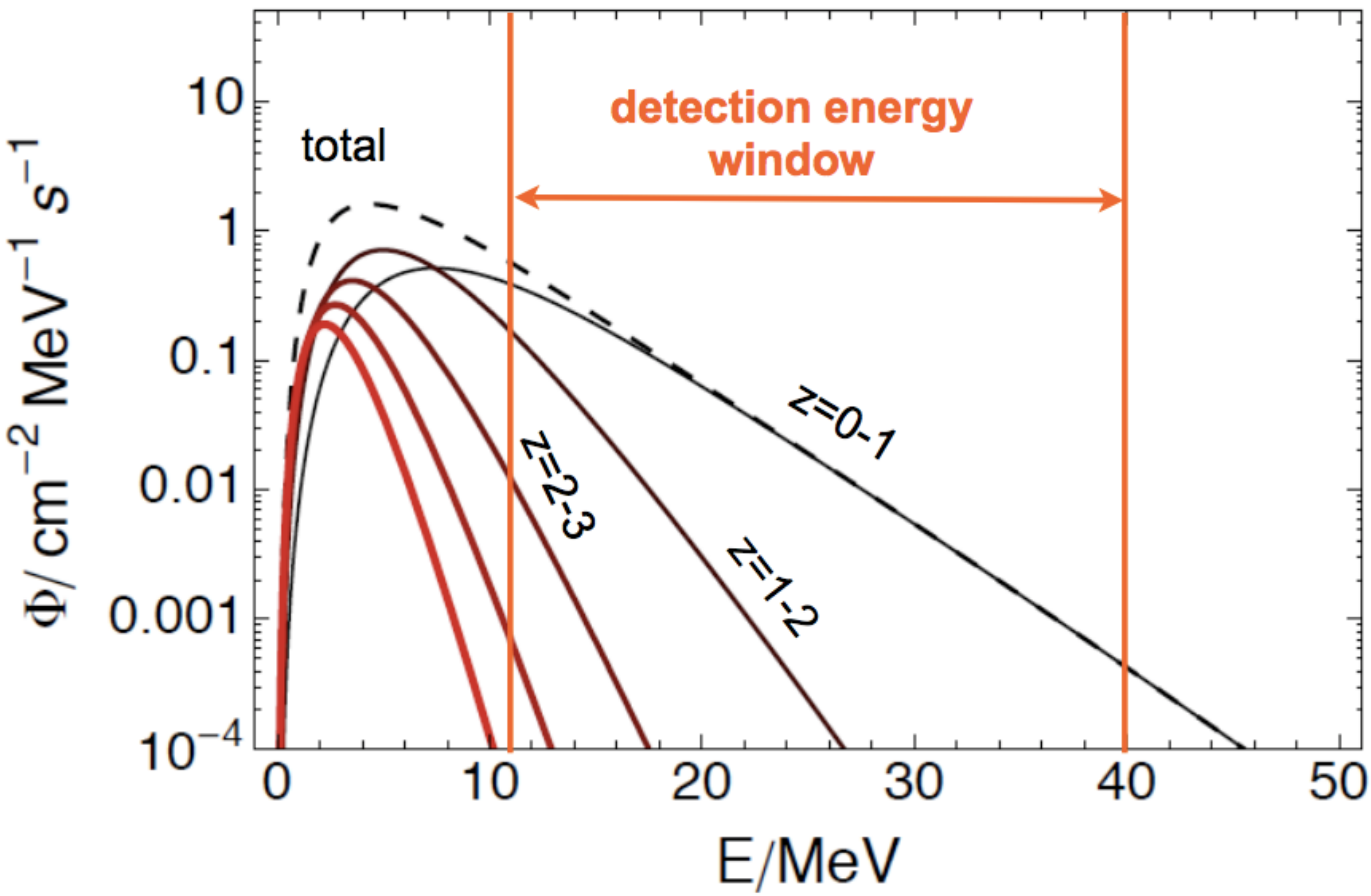
DSNB spectrum would be *more* detectable



Lunardini (2009)

Resdhift effect:

The energy redshift correction accumulates neutrinos of higher redshift at lower energies.



Calculation: from diffuse neutrino flux to signal

$$\Phi(E) = \frac{c}{H_0}\int_0^{z_{max}} R_{SN}(z)\frac{dN(E')}{dE'}\frac{dz}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}$$

Neutrino spectral flux

cosmological supernova rate

cosmology

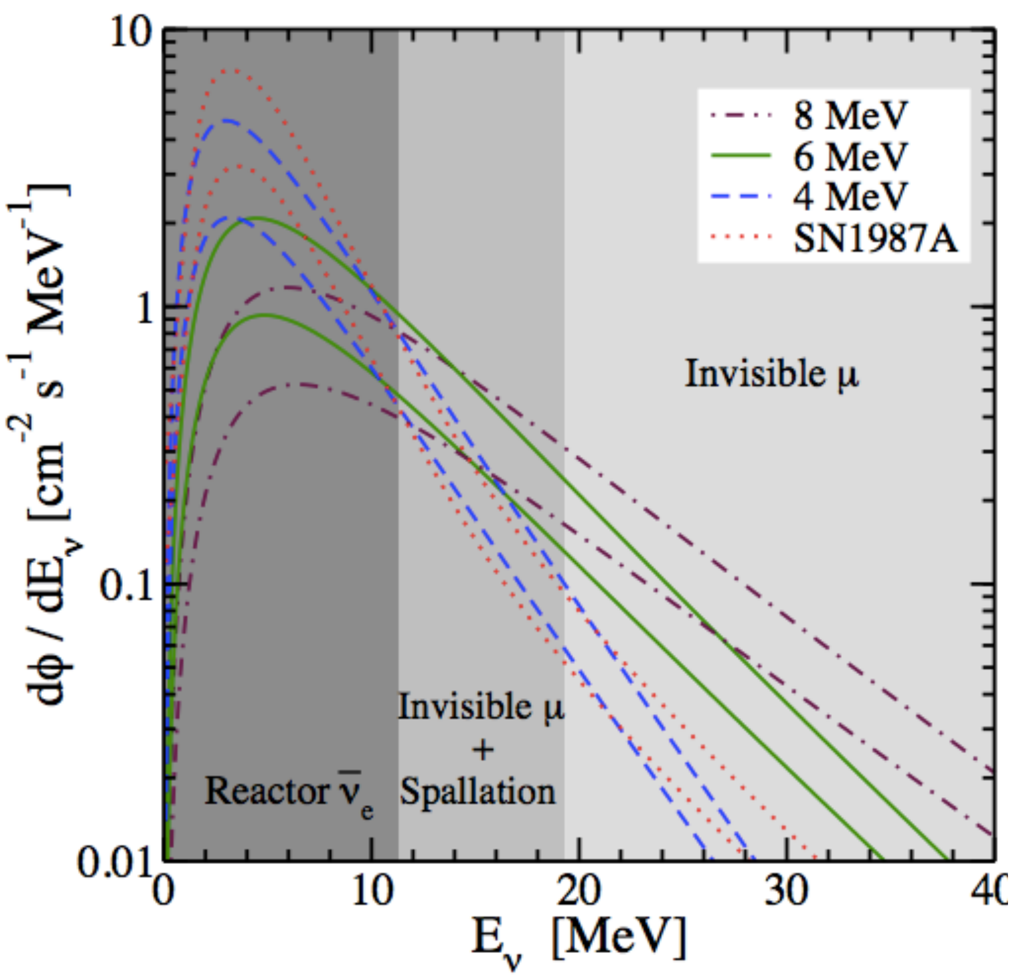
oscillated neutrino flux
$[E' = E(1+z)]$

$$\frac{dN_e}{dE_e}(E_e) = N_p\,\sigma(E_\nu)\int_0^\infty \Big[(1+z)\,\varphi[E_\nu(1+z)]\Big]\Big[R_{SN}(z)\Big]\left[\left|\frac{c\,dt}{dz}\right| dz\right]$$

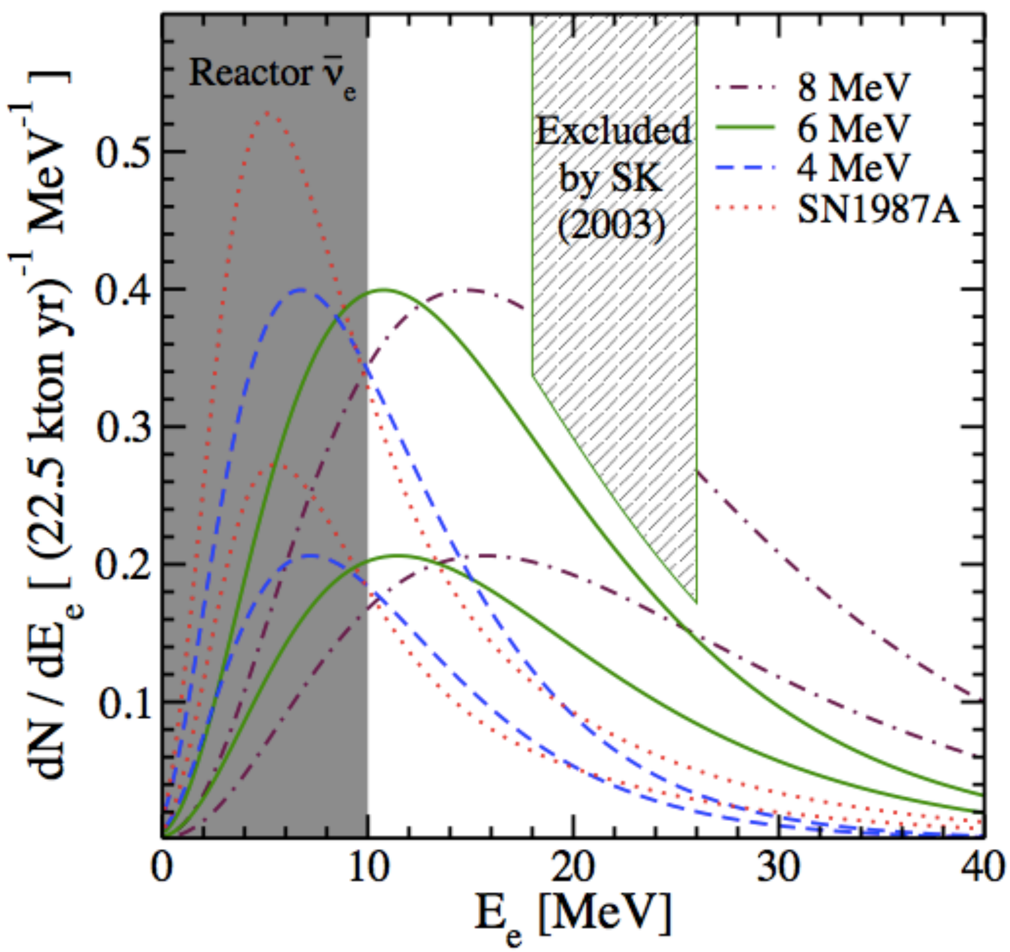
Signal (e^+) spectral flux

DSNB SPECTRA for various T_{avg} & the SK 2003 CONSTRAINTS (no Gd)

nu-spectrum



e^+-spectrum (↓ no detection)



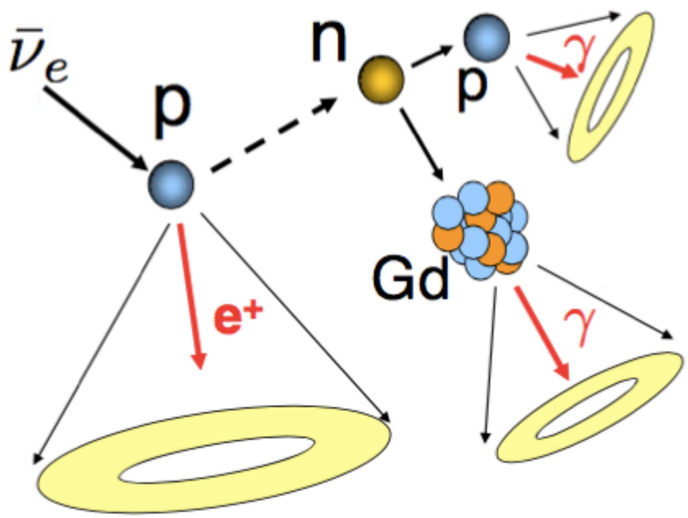
Improvement to SK/HK:

put Gadolinium in the water

Neutron tagging in Gd-enriched WC detector (Super-K with 100 tons Gd to trap neutrons)

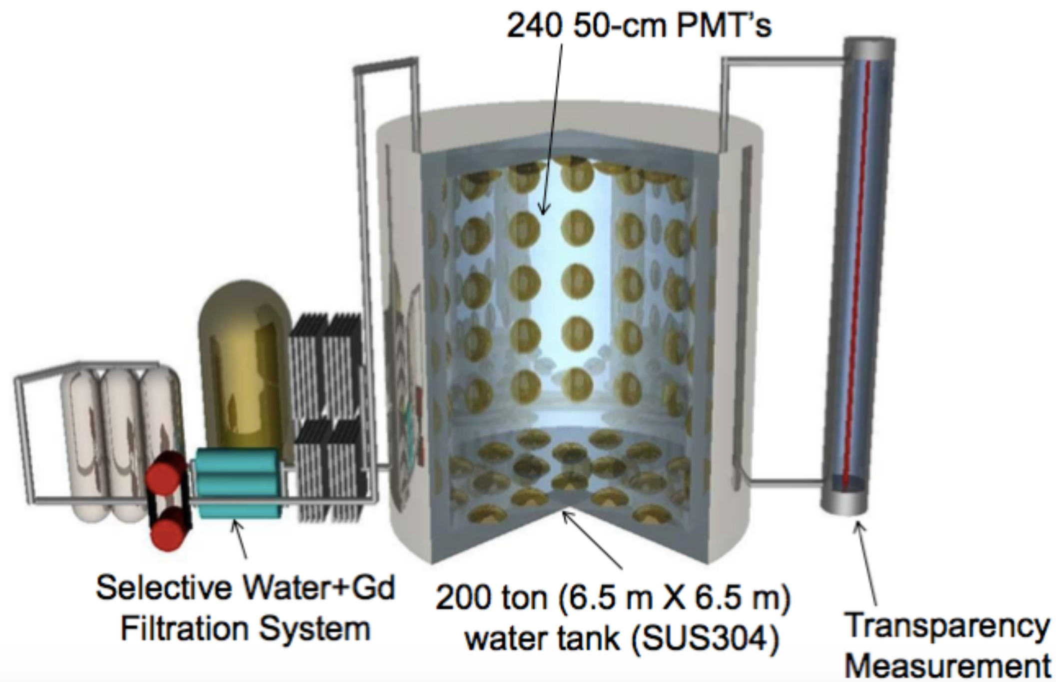
$$\bar{\nu}_e + p \rightarrow n + e^+$$

0.1% concentration of Gd

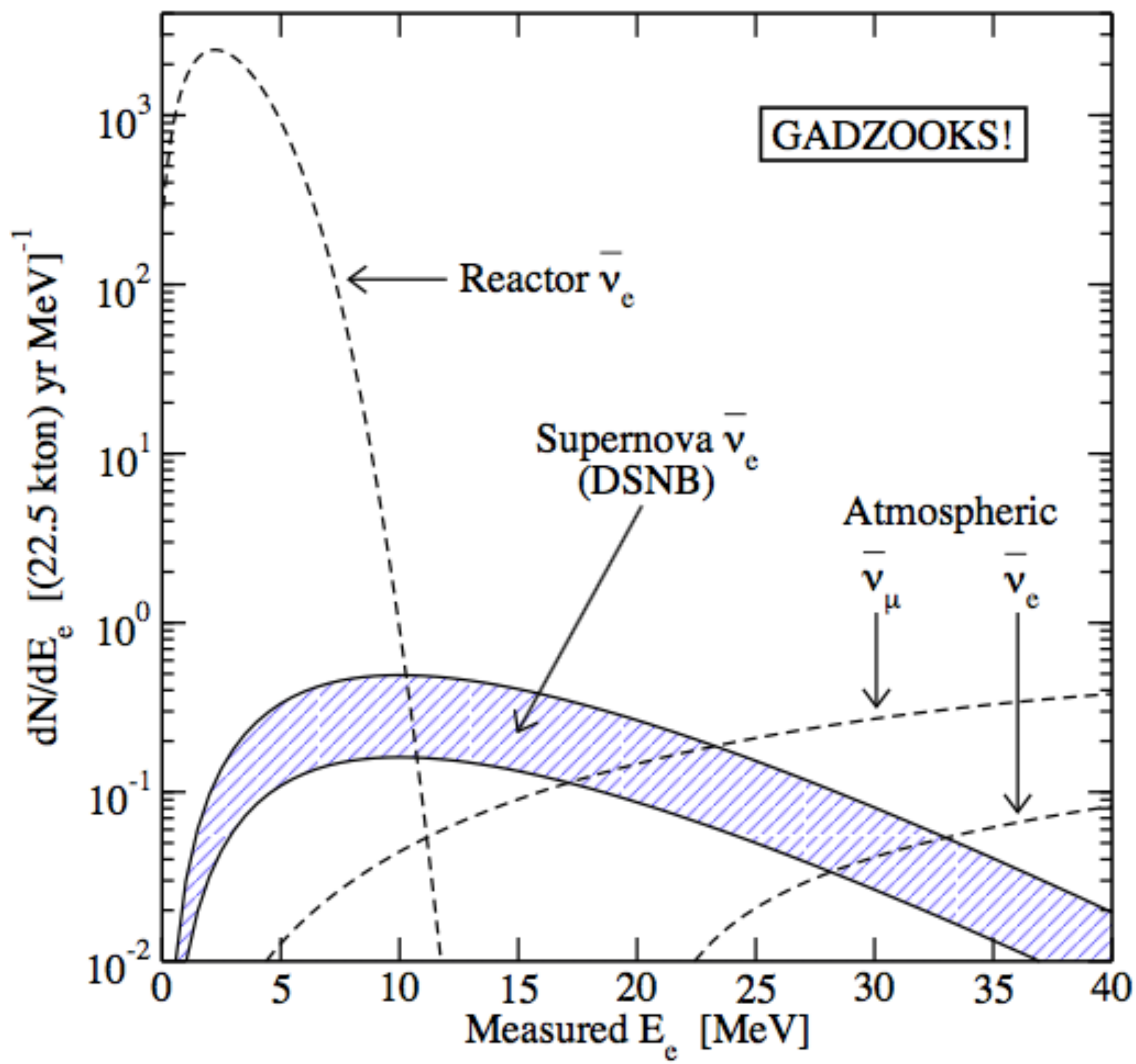


Positron and gamma ray vertices are within ~50cm.

$\bar{\nu}_e$ identified by delayed coincidence



Expected SK+Gd sensitivity improvement



Beacom, Vagins

Recent BH spectral calculations

THE ASTROPHYSICAL JOURNAL, 804:75 (15pp), 2015 May 1 NAKAZATO ET AL.

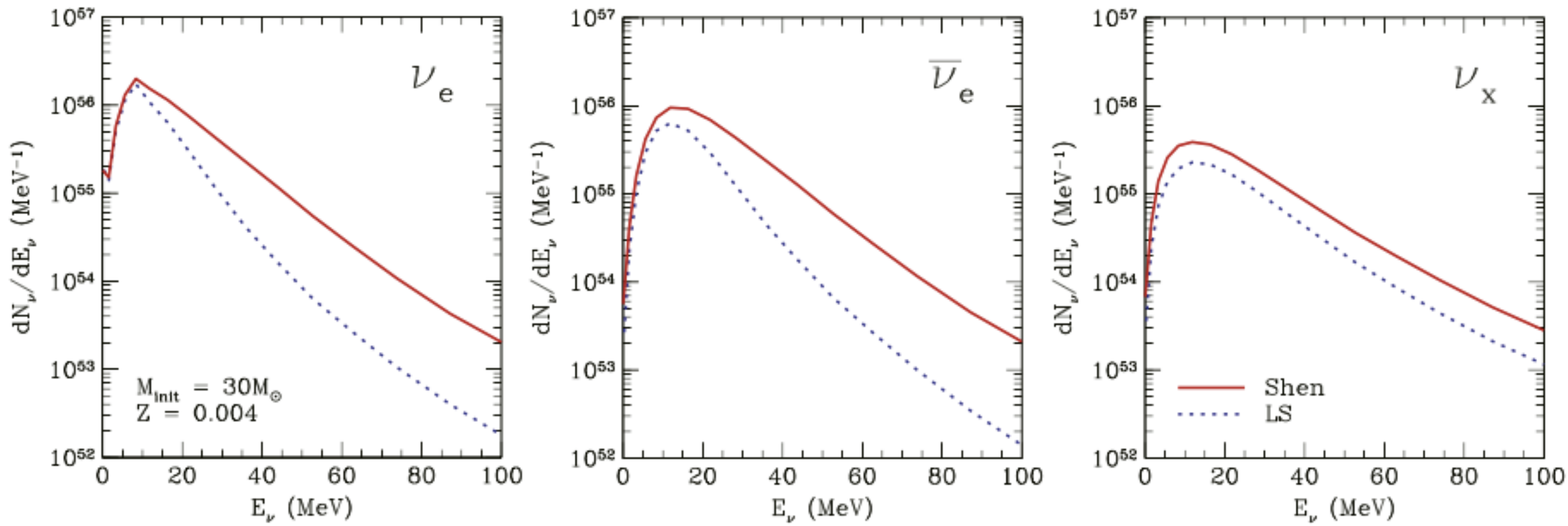


Figure 6. Neutrino number spectra for black hole formation with $30M_\odot$, $Z = 0.004$ and Shen EOS (solid) and LS EOS (dotted). The left, central, and right panels correspond to ν_e, $\bar{\nu}_e$, and ν_x ($=\nu_\mu = \bar{\nu}_\mu = \nu_\tau = \bar{\nu}_\tau$), respectively.

Table 1
Numerical Results for Black Hole Formation of Progenitor With $(M, Z) = (30\,M_\odot, 0.004)$

EOS	t_{BH} (ms)	$\langle E_{\nu_e}\rangle$ (MeV)	$\langle E_{\bar{\nu}_e}\rangle$ (MeV)	$\langle E_{\nu_x}\rangle$ (MeV)	$E_{\nu_e,tot}$ (10^{52} erg)	$E_{\bar{\nu}_e,tot}$ (10^{52} erg)	$E_{\nu_x,tot}$ (10^{52} erg)	$E_{\nu all,tot}$ (10^{53} erg)
Shen	842	17.5	21.7	23.4	9.49	8.10	4.00	3.36
LS(220 MeV)	342	12.5	16.4	22.3	4.03	2.87	2.11	1.53

Note. t_{BH} is the time to black hole formation measured from the core bounce. The mean energy of the emitted ν_i until black hole formation is denoted as $\langle E_{\nu_i}\rangle \equiv E_{\nu_i,tot}/N_{\nu_i,tot}$, where $E_{\nu_i,tot}$ and $N_{\nu_i,tot}$ are the total energy and number of neutrinos, respectively. ν_x stands for μ- and τ-neutrinos and their anti-particles: $E_{\nu_x} = E_{\nu_\mu} = E_{\bar{\nu}_\mu} = E_{\nu_\tau} = E_{\bar{\nu}_\tau}$. $E_{\nu all,tot}$ is the total neutrino energy summed over all species.

Nakazato et al, 2015

Current Upper Limits

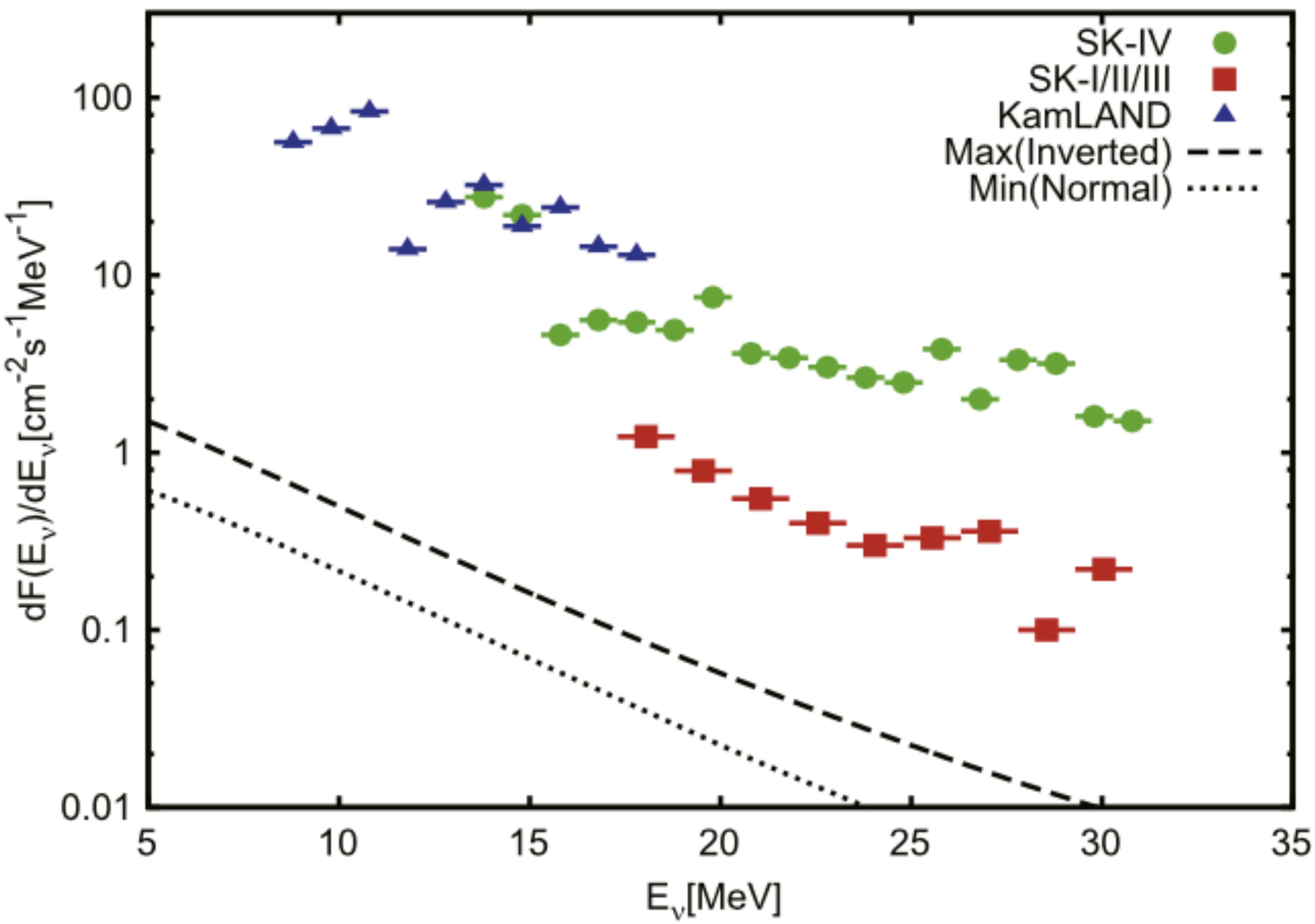


Figure 1. 90% C.L. differential upper limits on $\bar{\nu}_e$ flux of SRNs. The squares, circles and triangles are results for Super-Kamiokande (SK-I/II/III, Bays et al. 2012), Super-Kamiokande with a neutron-tagging (SK-IV, Zhang et al. 2015) and KamLAND (Gando et al. 2012). Dashed and dotted lines correspond to our theoretical models with maximum and minimum values of SRN event rate, respectively (see also Table 3).

Nakazato+15

Detectors, old and new

Concept	window (MeV)	Detection process	Experiment	Fiducial mass (kt)	event/yr
H_2O	19.3-30	$\bar{\nu}_e(p,n)e^+$	SK	22.5	0.25-1.40
H_2O	"	$\nu_x(e^-,e^-)\nu_x$	HK	500	5.5-31.2
H_2O+Gd	11.3-30	$\bar{\nu}_e(p,n)e^+$	SK +Gd	22.5	0.97-2.8
H_2O+Gd	"	$\nu_x(e^-,e^-)\nu_x$	HK +Gd	500	21.5-62.0
Liqu. scintill.		$\bar{\nu}_e(p,n)e^+$ $\nu_x(e^-,e^-)\nu_x$	JUNO	20	
(linear alkylbenzene)		$\nu_x(p,p)\nu_x$ $\nu_x(^{12}C,X)\nu_x$	JUNO		
(+H_20 Cherenkov +muon tracker)		$\nu_x(^{12}C,X)e^{\pm}$	JUNO		

JUNO if det. SN @ 10 kpc

↓***Huge rates!***

Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	0.6×10^3	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	CC	0.5×10^2	0.9×10^2	1.6×10^2
$\overline{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	CC	0.6×10^2	1.1×10^2	1.6×10^2

Table 4-1: Numbers of neutrino events in JUNO for a SN at a typical distance of 10 kpc, where ν collectively stands for neutrinos and antineutrinos of all three flavors and their contributions are summed over. Three representative values of the average neutrino energy $\langle E_\nu \rangle = 12$ MeV, 14 MeV and 16 MeV are taken for illustration, where in each case the same average energy is assumed for all flavors and neutrino flavor conversions are not considered. For the elastic neutrino-proton scattering, a threshold of 0.2 MeV for the proton recoil energy is chosen.

JUNO, DSNB discovery potential

(An+15)

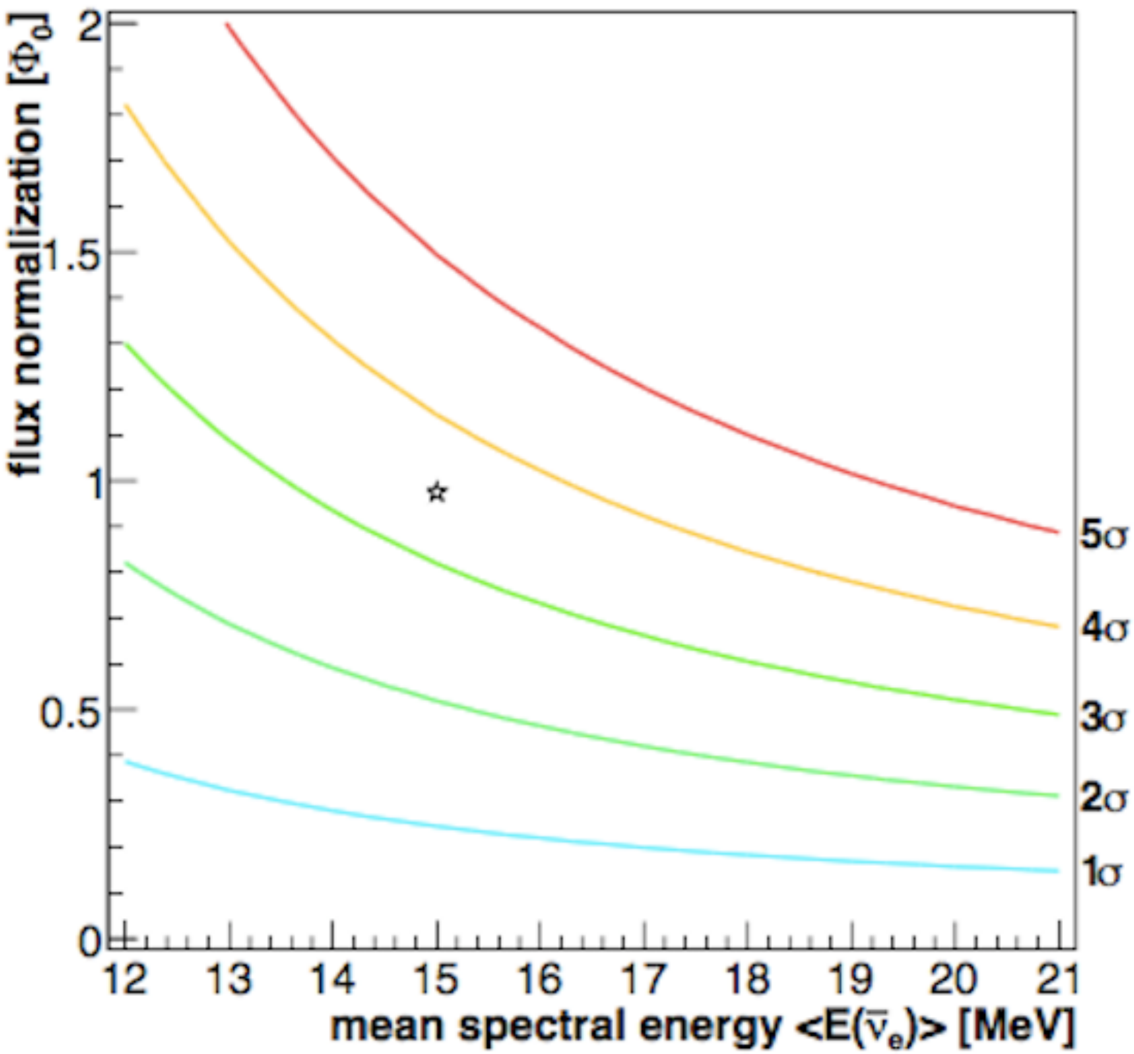
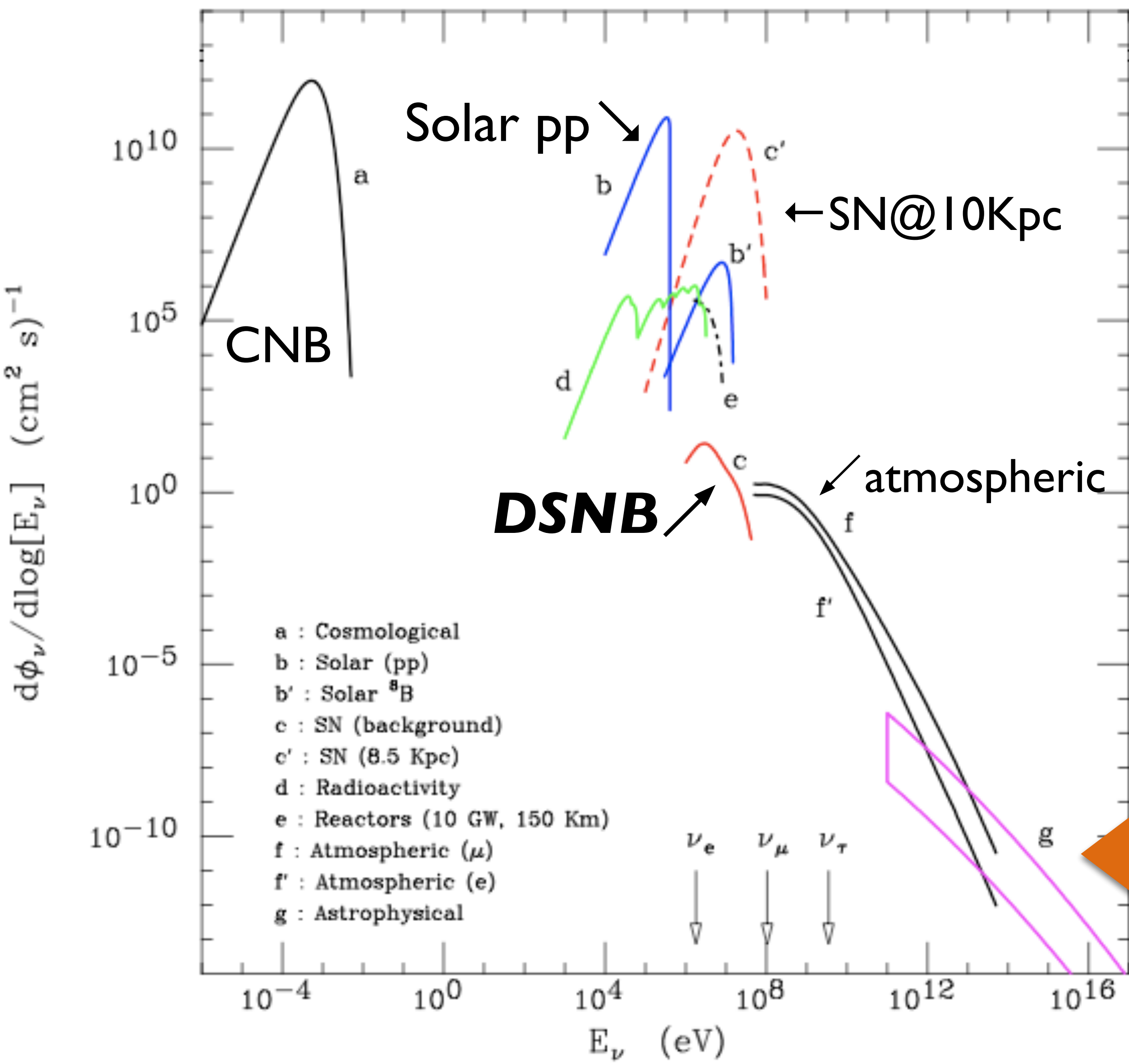


Figure 5-3: JUNO's discovery potential for the DSNB as a function of the mean energy of the SN spectrum $\langle E_{\bar{\nu}_e} \rangle$ and the DSNB flux normalization Φ (cf. section 5.2). We assume 10 yrs measuring time, 5% background uncertainty and a detected event spectrum corresponding to the sum of signal and background predictions. The significance is derived from a likelihood fit to the data. The star marks a theoretically well-motivated combination of DSNB parameters (cf. section 5.2).

i.e., for nominal parameters, detect DSNB at 5σ level in 10 years ops.

What other ν-bkgs?



IceCube:

↓

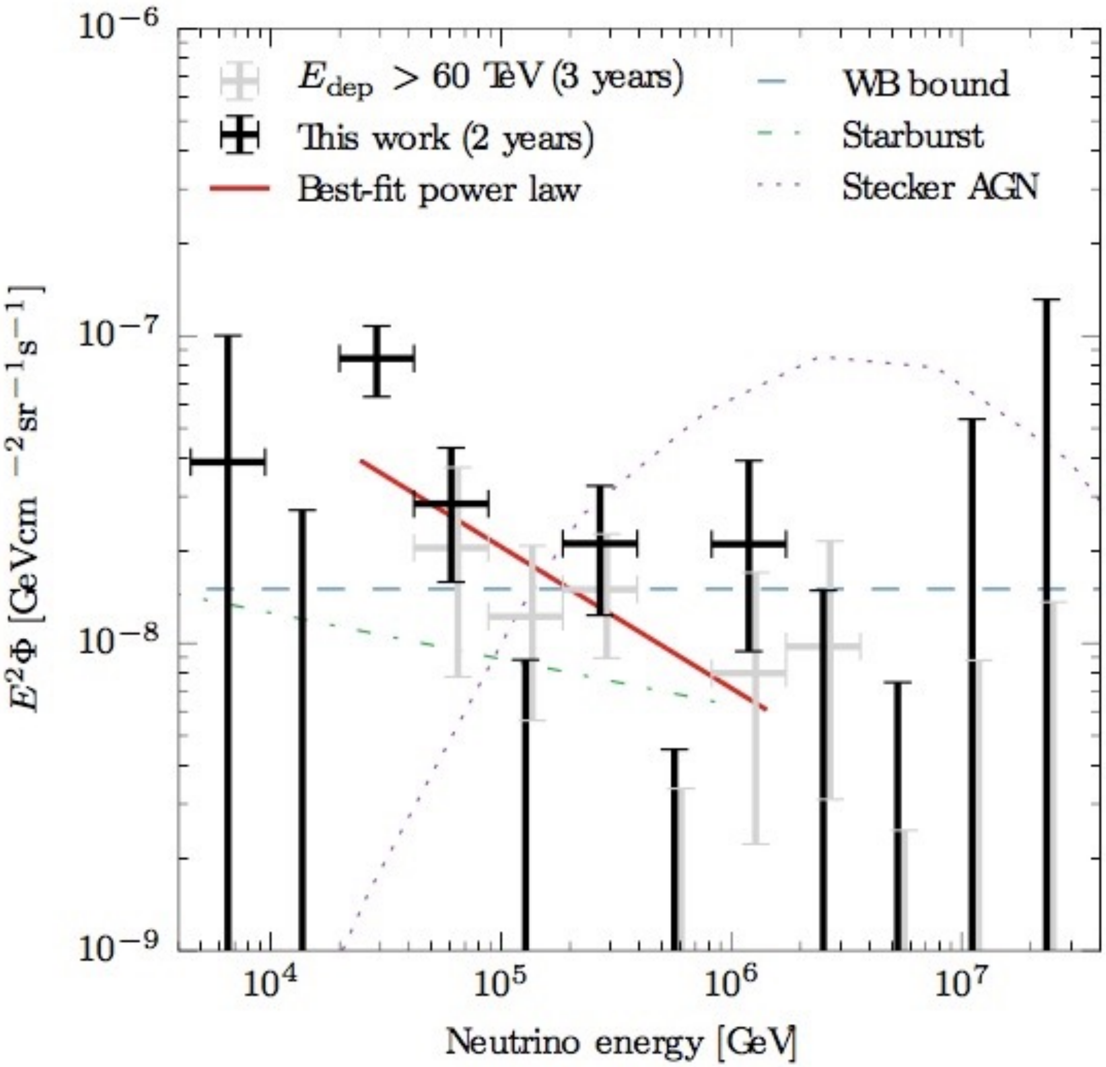
diffuse extragalactic TeV-PeV ν-bkg

The PeV ν-γ Bkg Connection:

GRBs? AGNs? SFGs? HNe? GMSs?

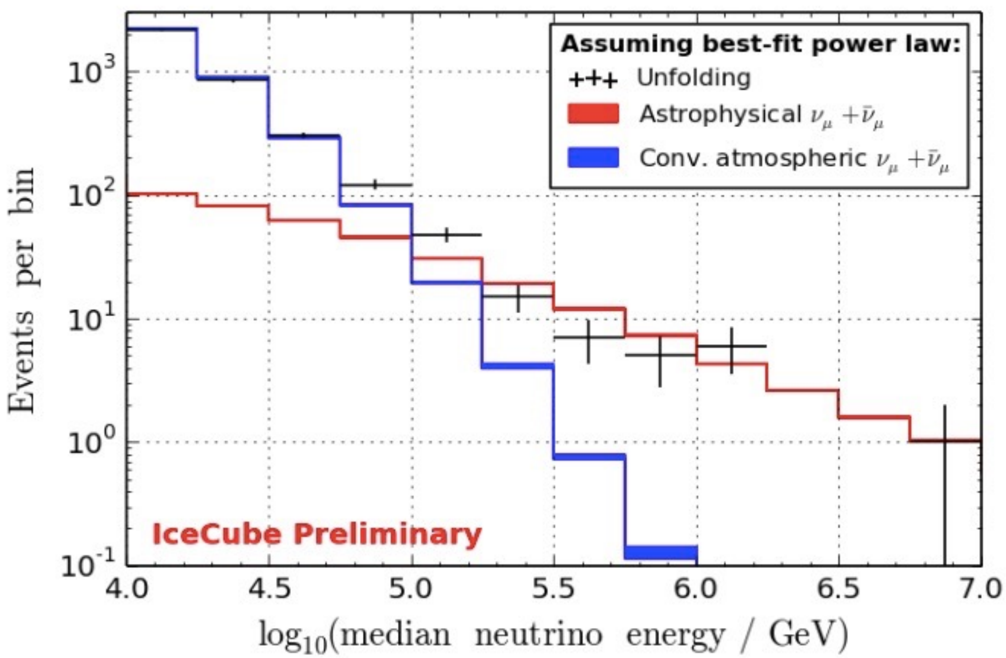
- ***PeV nu bkg (INB)*** obs. by IC3 is ~10^{-8} GeV/cm^2/s/sr, but ***IC3 limit*** on GRBs is factor ~10 below "standard" IS or phot.osph models- ICRC13) → could be ***EM dim/nu-bright GRBs***? (Liu,Wang 13, ApJ 766:73, Murase,Ioka, 13, PRL 111:121102)
- ***PeV nu INB*** from hadronic ***low lum. AGNs ?***: scaling L_p from L_e via L_{phot}, , argue that ***FR1 RG***s (higher density knots) ~ reproduce via ***pp*** the PeV nu bkg (Becker Tjus+15, PRD 89:123005) → ***and also IGB?***
- ***PeV nus*** from individual ***bright*** radio-gamma ***AGNs?*** (***blazars*** in TANAMI sample), if X-γ flux due to ***p***γ , 6 of these blazars within 1σ of 3 PeV events could account for ***INB*** (Krauss+14, A&A, 566:L7; also arXiv:1502.02147), but →***IGB?***
- Starburst galaxies (***SBGs***)***?*** if responsible for PeV nu ***INB*** via ***pp,*** may contribute ~***20%*** of the gamma background (***IGB***) (Chang+14, ApJ, 793:131; but see Bechtol+16)
- **Galaxy-galaxy** collisions → **INB** via **pp** ✓ (<20%, Kashiyama & Mészáros '14 ApJ, 790:L14)
- **Hypernovae** & **SNe** in SFG/SBGs → **INB & IGB** ✓ (<20%, Senno et al '15, ApJ 806:24)

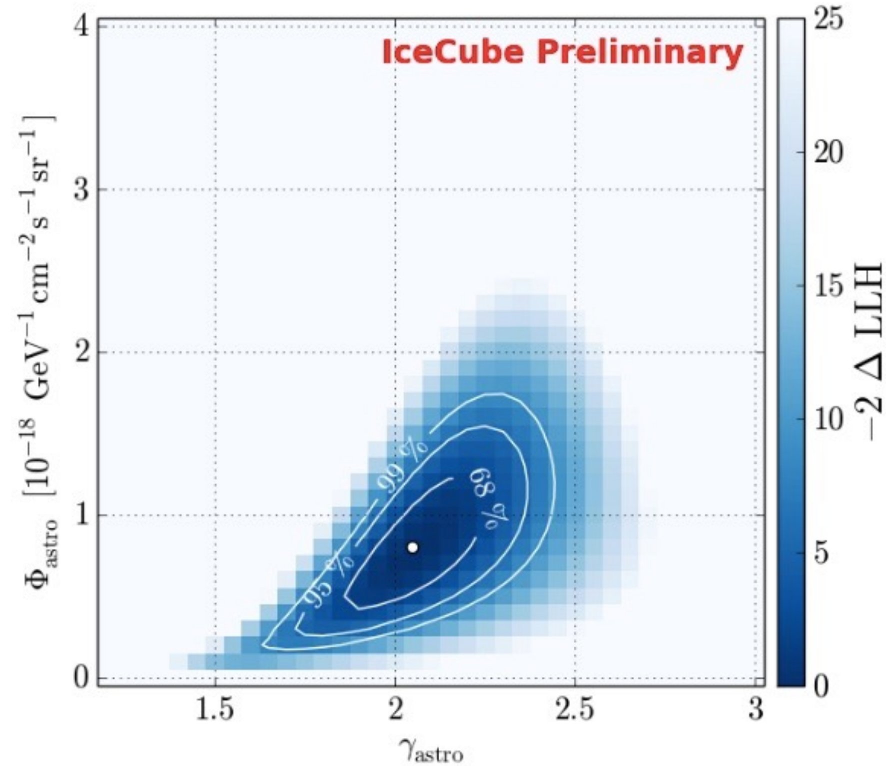
IceCube TeV-PeV spectrum



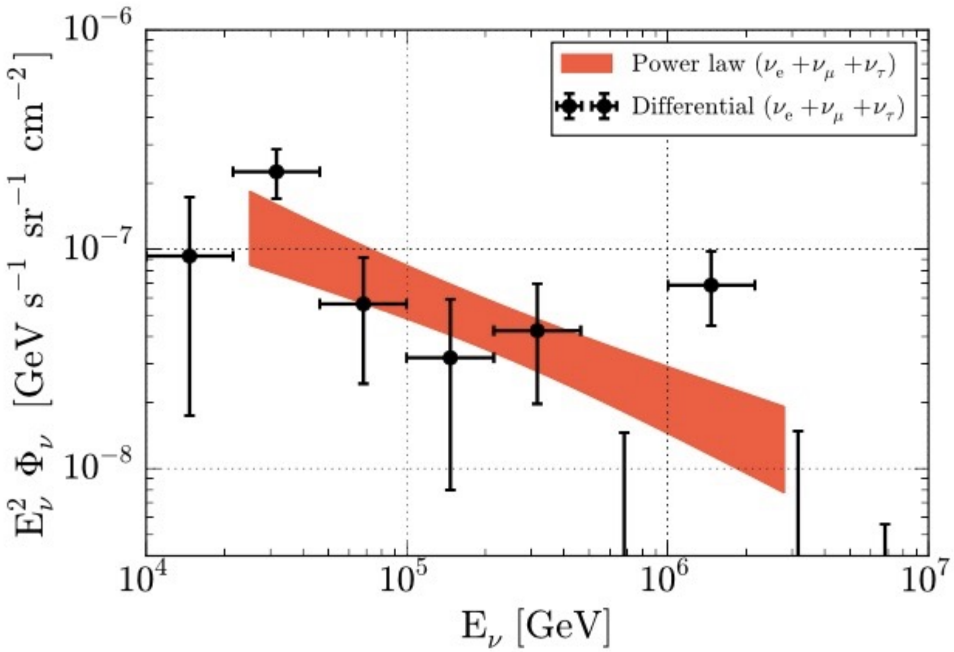
C. Wiebusch & IC3, 1602.00239
C. Kopper & IC3, 1501.05223
M. Aartsen & IC3, PRD 91, 022001

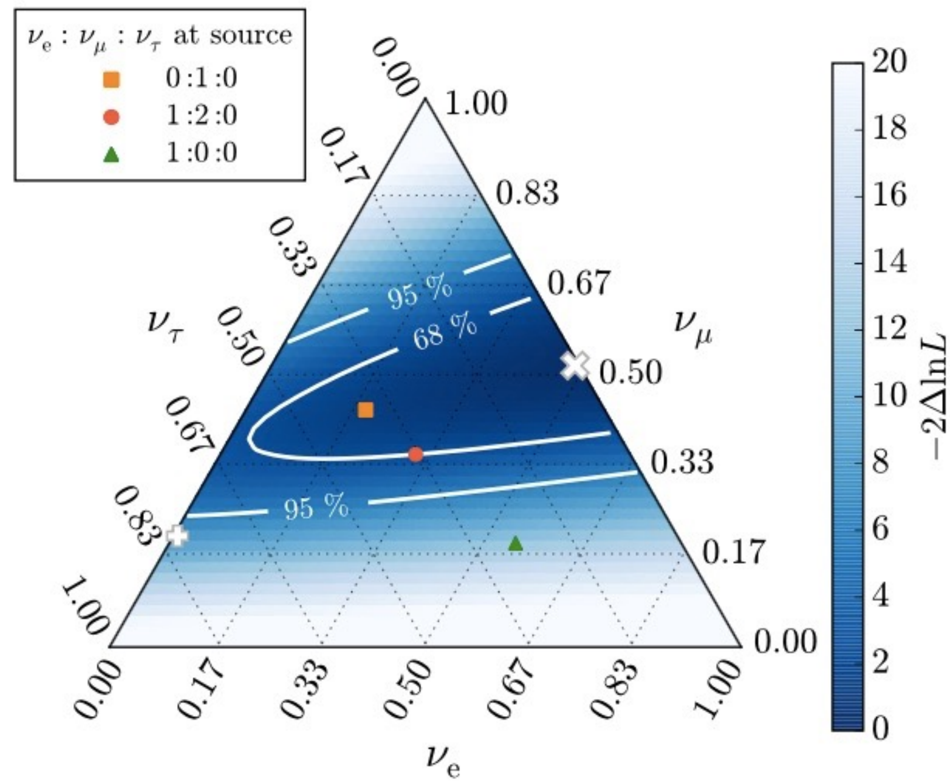
Astrophysical ν, assuming best fit single power law





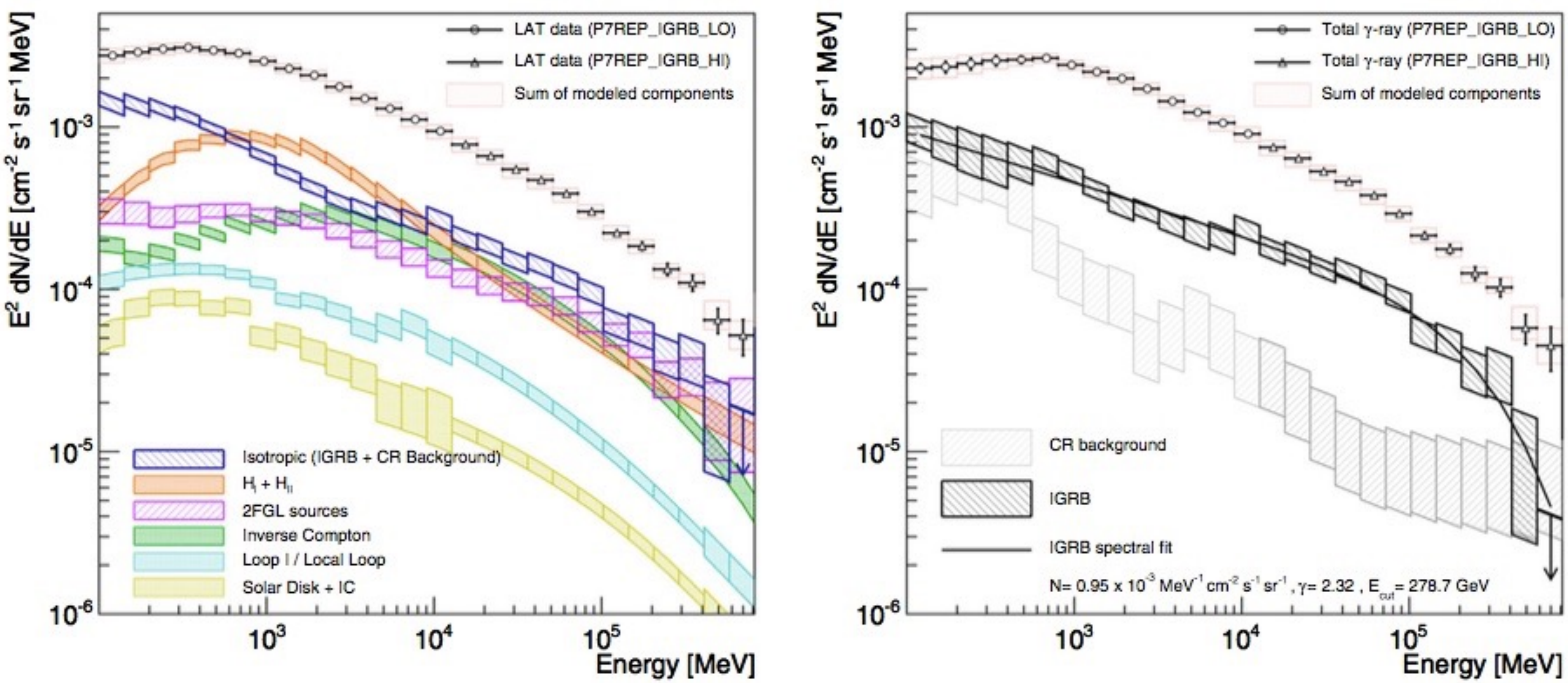
ν-single power law (?) & ν-flavor mix





Unavoidable constraint: the Isotropic Gamma Background

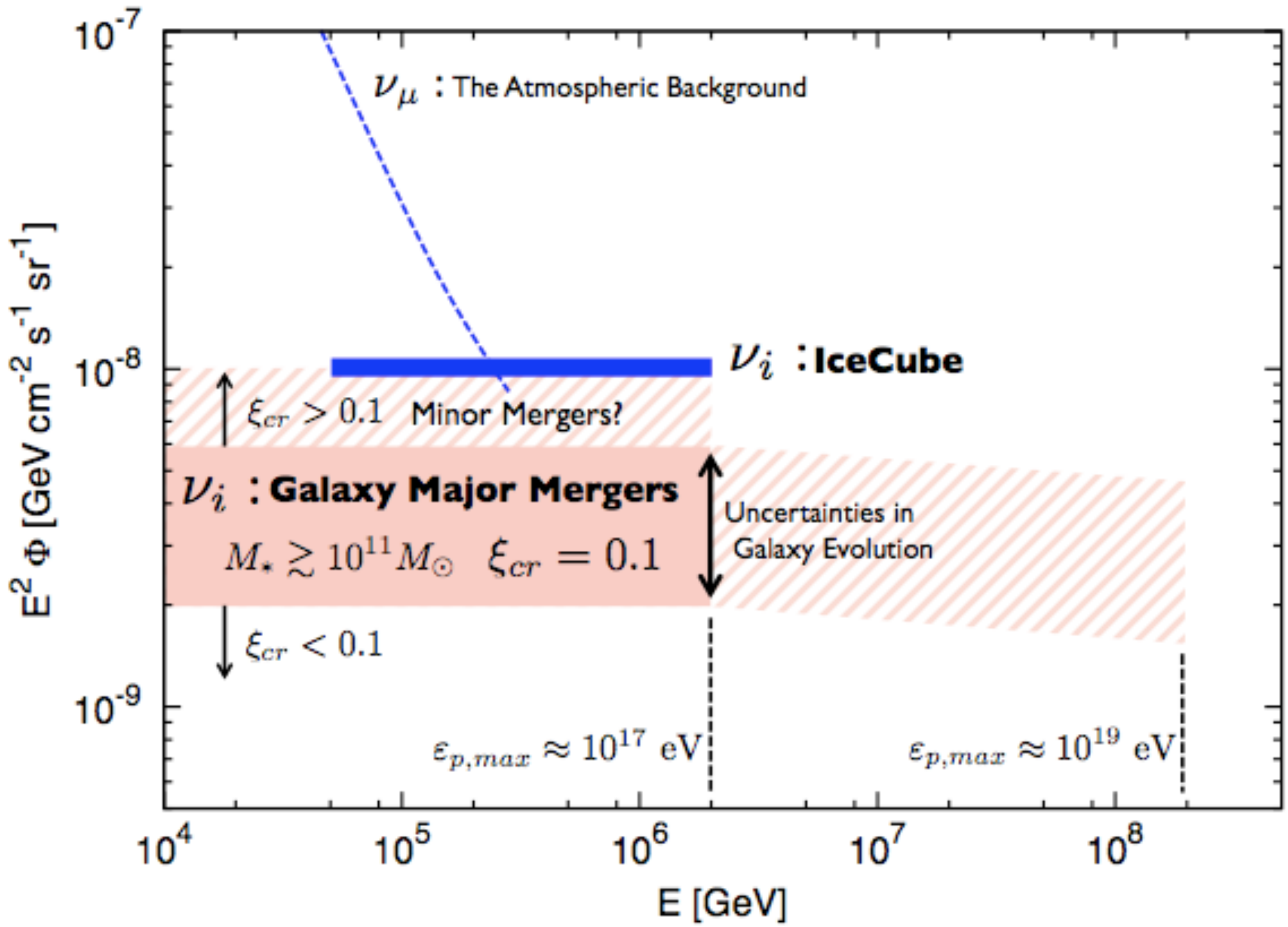
IGB minus pt. src. contribs.



Ackermann, M, 2015, ApJ 799:86

Galaxy mergers, INB & IGB

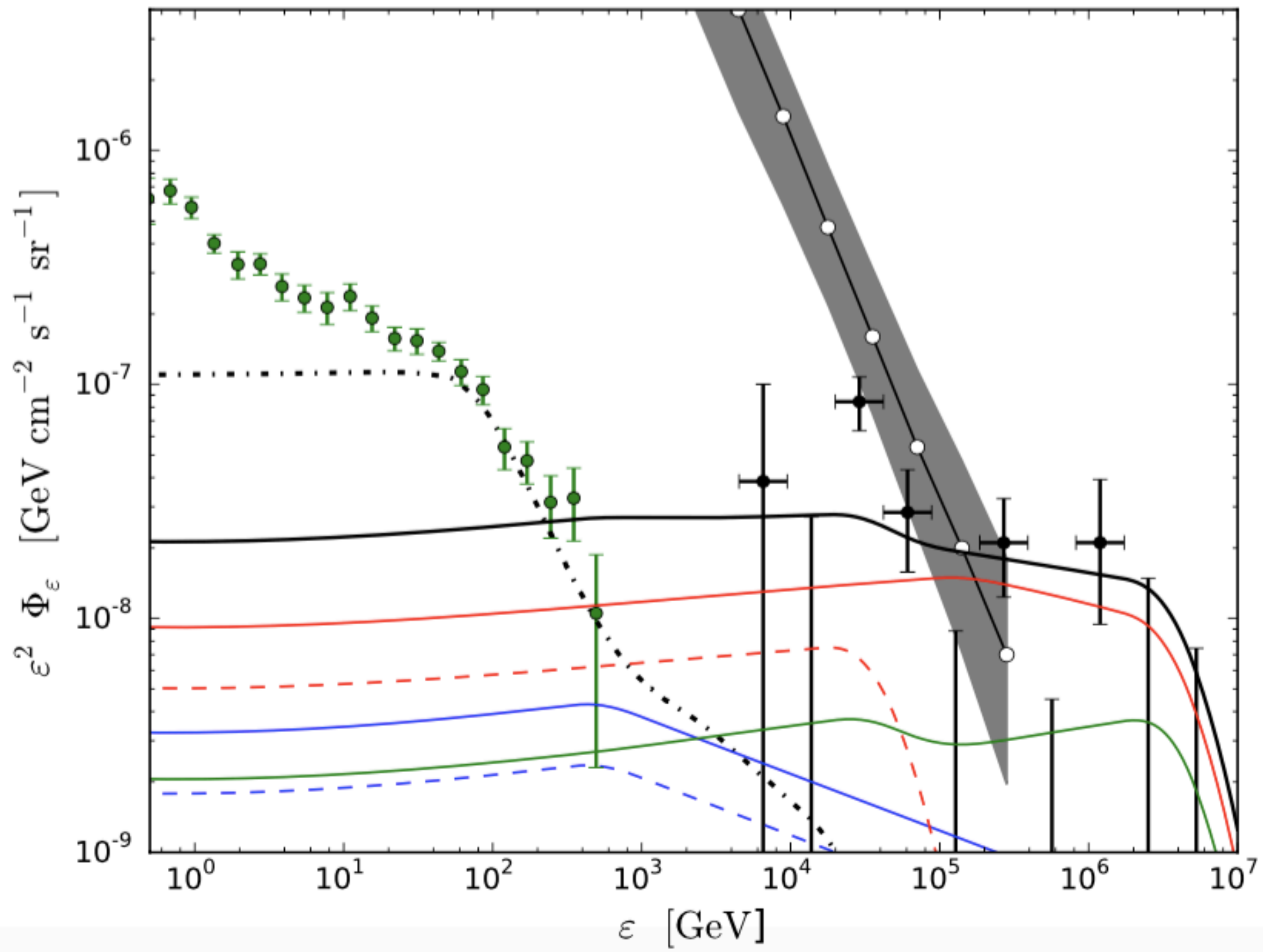
Kashiyama & Mészáros '14, ApJL 790:L14



- ***Every galaxy*** merged at least ***once*** in the last ***Hubble time***
- ***Major mergers*** → E_{gms}~$10^{58.5}$ erg, R~10^{-4} Mpc^{-3} Gyr^{-1} v_s~$10^{7.7}$ cm/s $Q_{cr,gms}$~3x10^{44} erg Mpc^{-3} yr^{-1} $\varepsilon_{cr,max}$ ~$10^{18.5}$ Z eV
- ***pp*** → PeV **ν**s, 100 GeV **γ**s
- **ν:** Individual GMS: 10^{-2} μ/yr, INB: ***20-60%*** IC3 obs.flux
- **γ**: Individual GMS flux: ~3.10^{-13} erg/cm2/s→CTA? ***IGB*** ~10^{-8} GeV/cm^2/s/sr , about ***10-30%*** Fermi IGB
- Minor mergers: uncertain, could add up to 70-100%

HNe & SNe in SBG, SFG

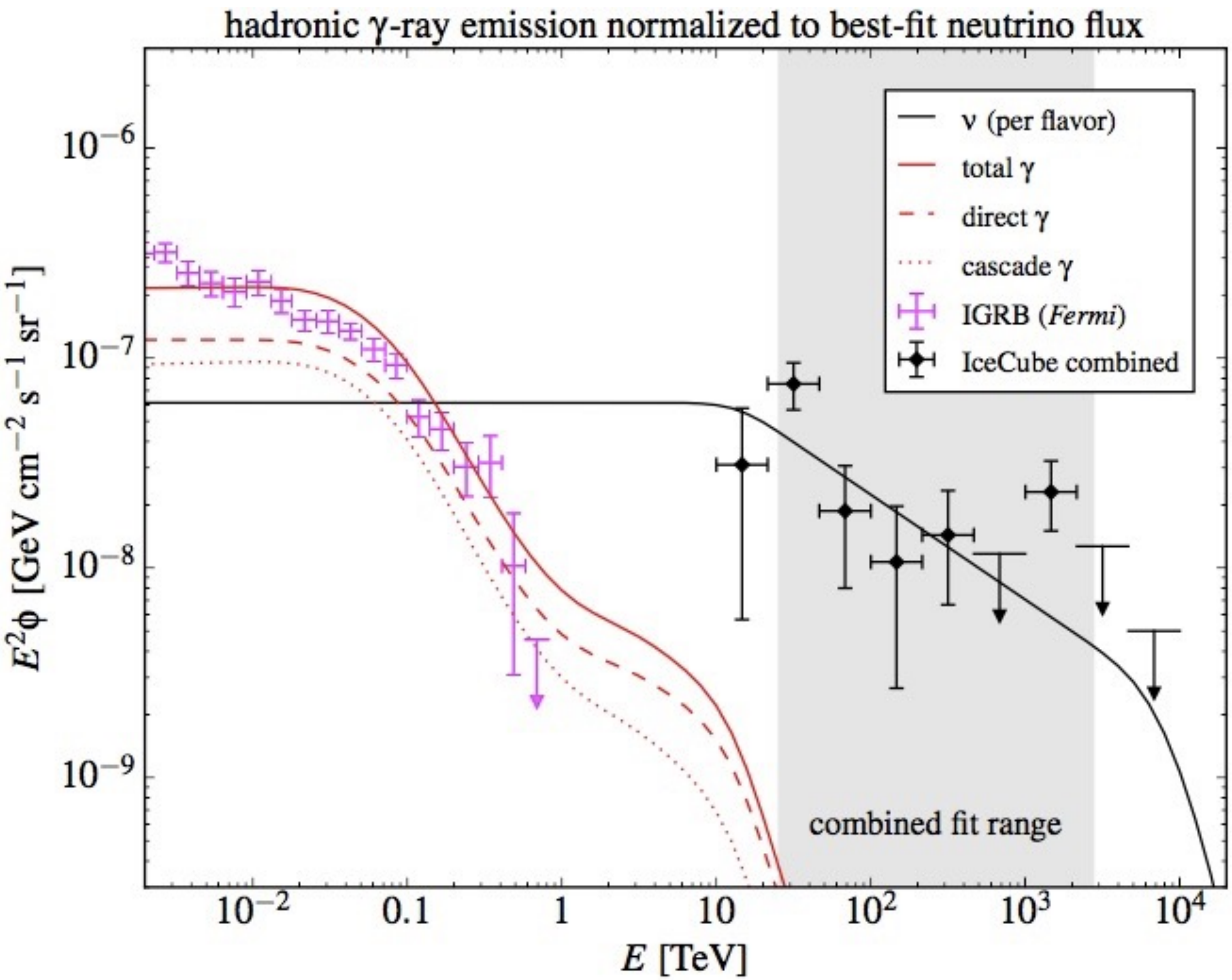
Senno, Mészáros, Murase, Baerwald & Rees,
2015, ApJ, 806:24



- HNe, SNe accelerate CRs with spectrum N(E)~E^{-2}, Emax ~1015 eV (SNe) Emax ~1017 eV (HNe)
- CRs diffuse and pp in both in the host galaxy & cluster
- the t_{diff} at low energies is limited by t_{esc}, t_{wind} , t_{Hubble} → spectrum flattens at low E
- include the σ_{pp} ~ln(E) dep.

Blue: SFG, HN solid, SN dashed;
Red: SBG, HN solid, SN dashed;
Green solid: Cluster total contrib
Black crosses: IceCube neutrinos
Green points: Fermi diff. gammas
Shaded: atmospheric nu-backgr'd

But, SBGs may make too many γs?



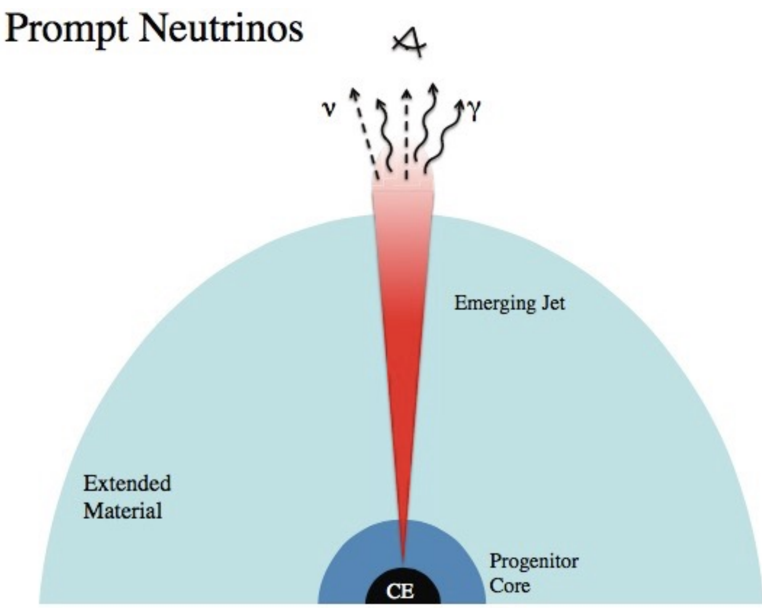
Bechtol, K., 1511.00688

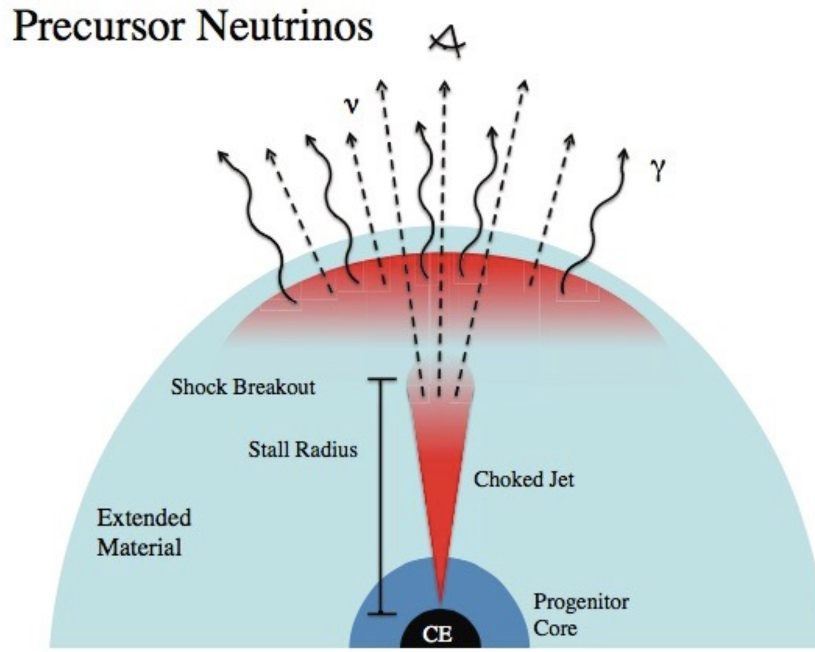
(IGRB based on Ackermann et al 2016, to be pub.)

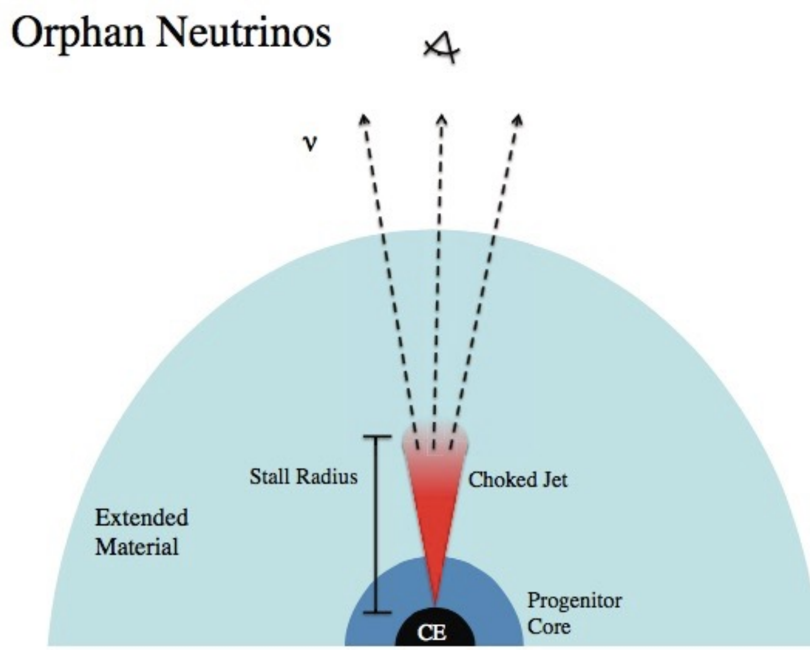
Need "hidden" neutrino sources

- Hidden in the sense of "low or no EM"
- At high optical depth (Thomson kills)?
- At high distances (redshift kills)?

Choked Jets & hidden neutrino sources



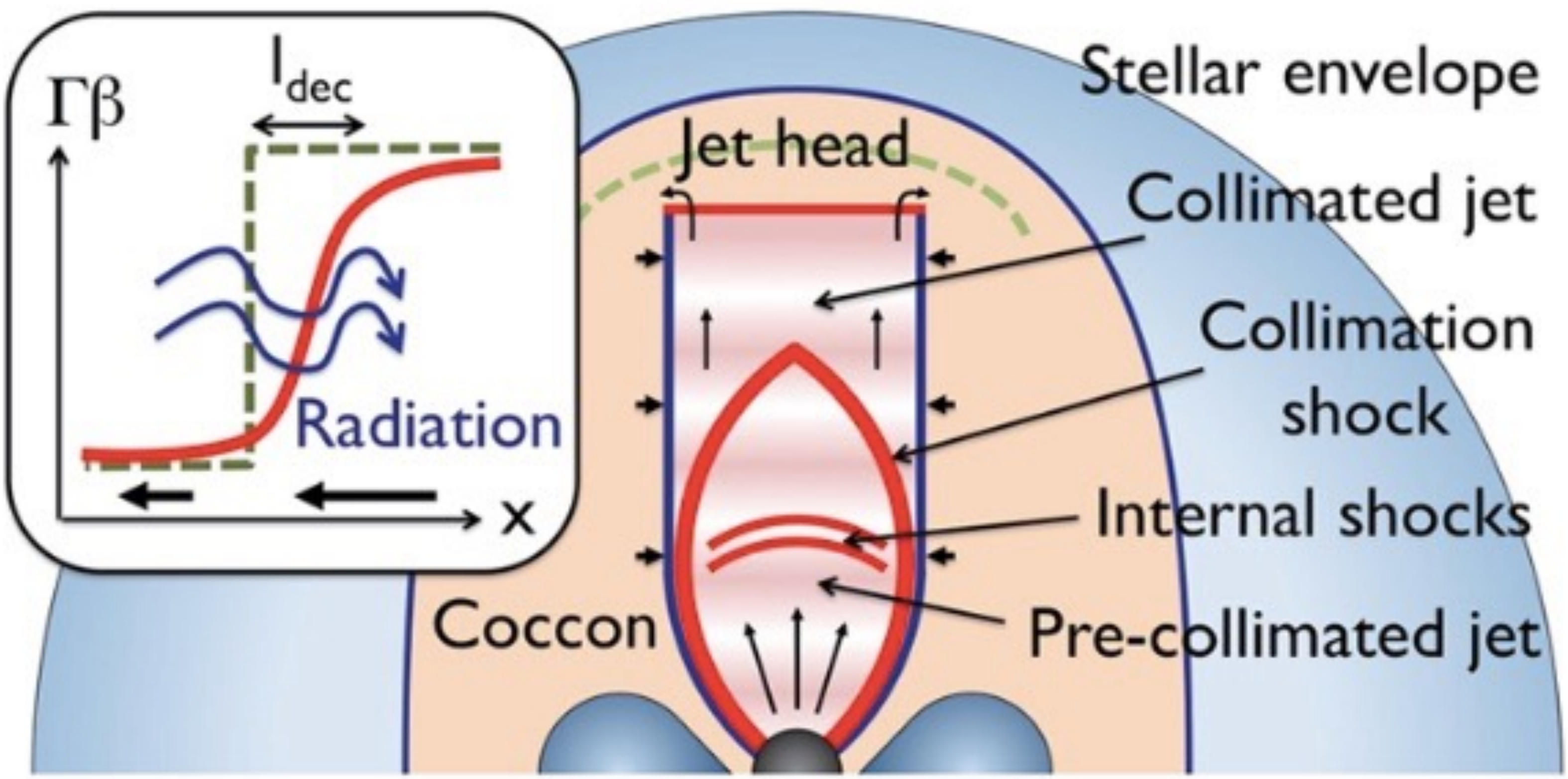




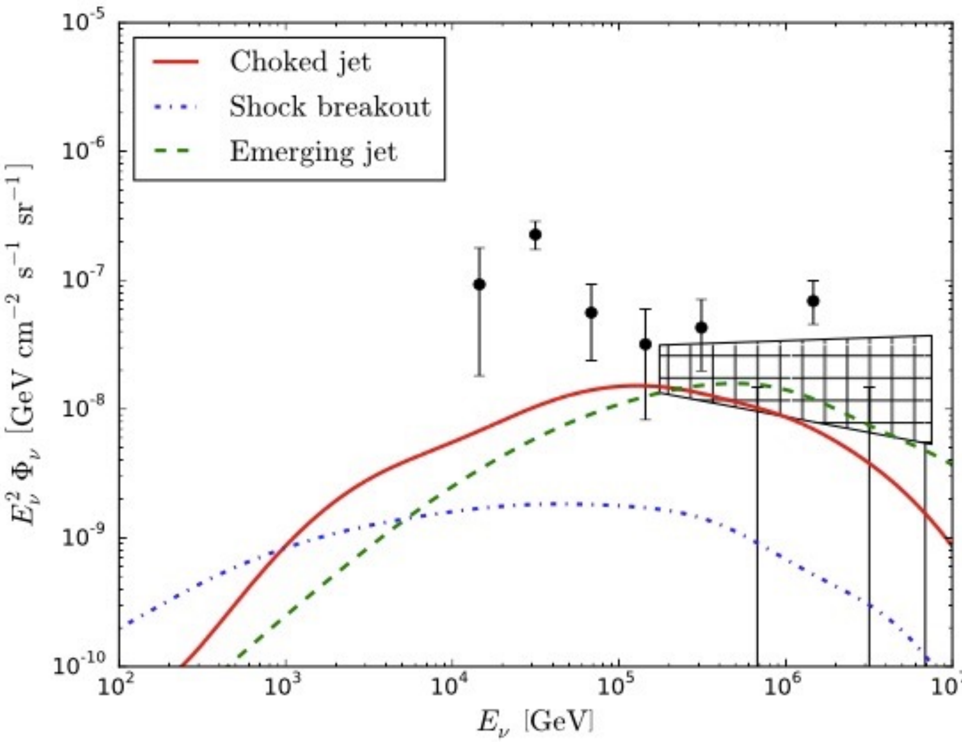
Senno, Murase, Mészáros,
PRD, 93, 083003 (2016)

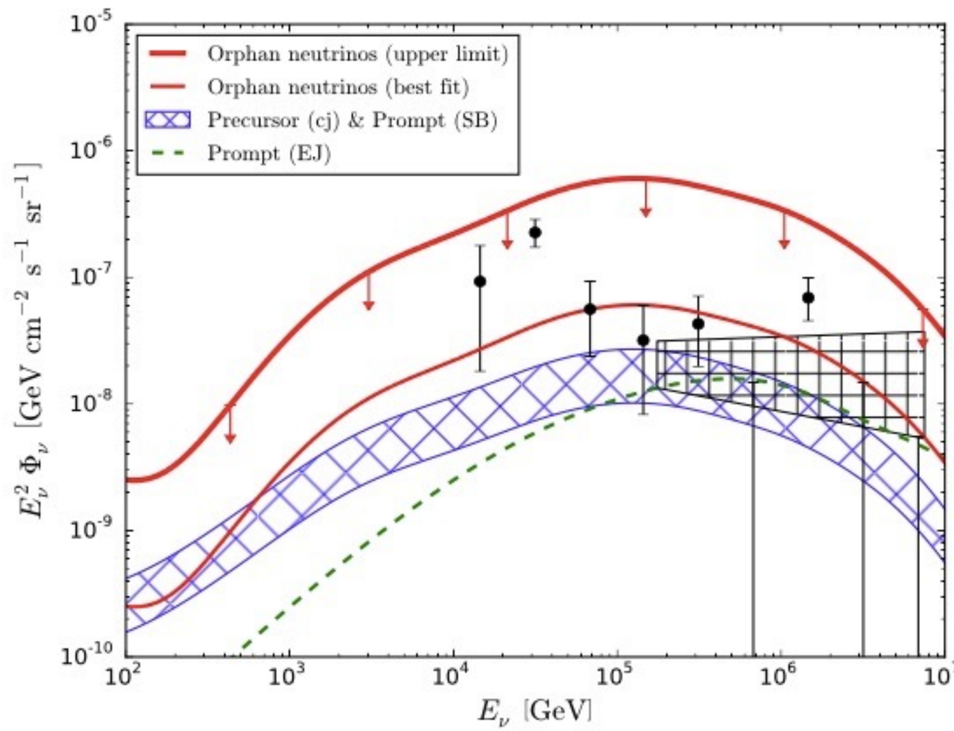
Star-penetrating jets

Mizuta & Ioka '13, etc.



Choked jet, shock breakout & emergent jet ν-spectra



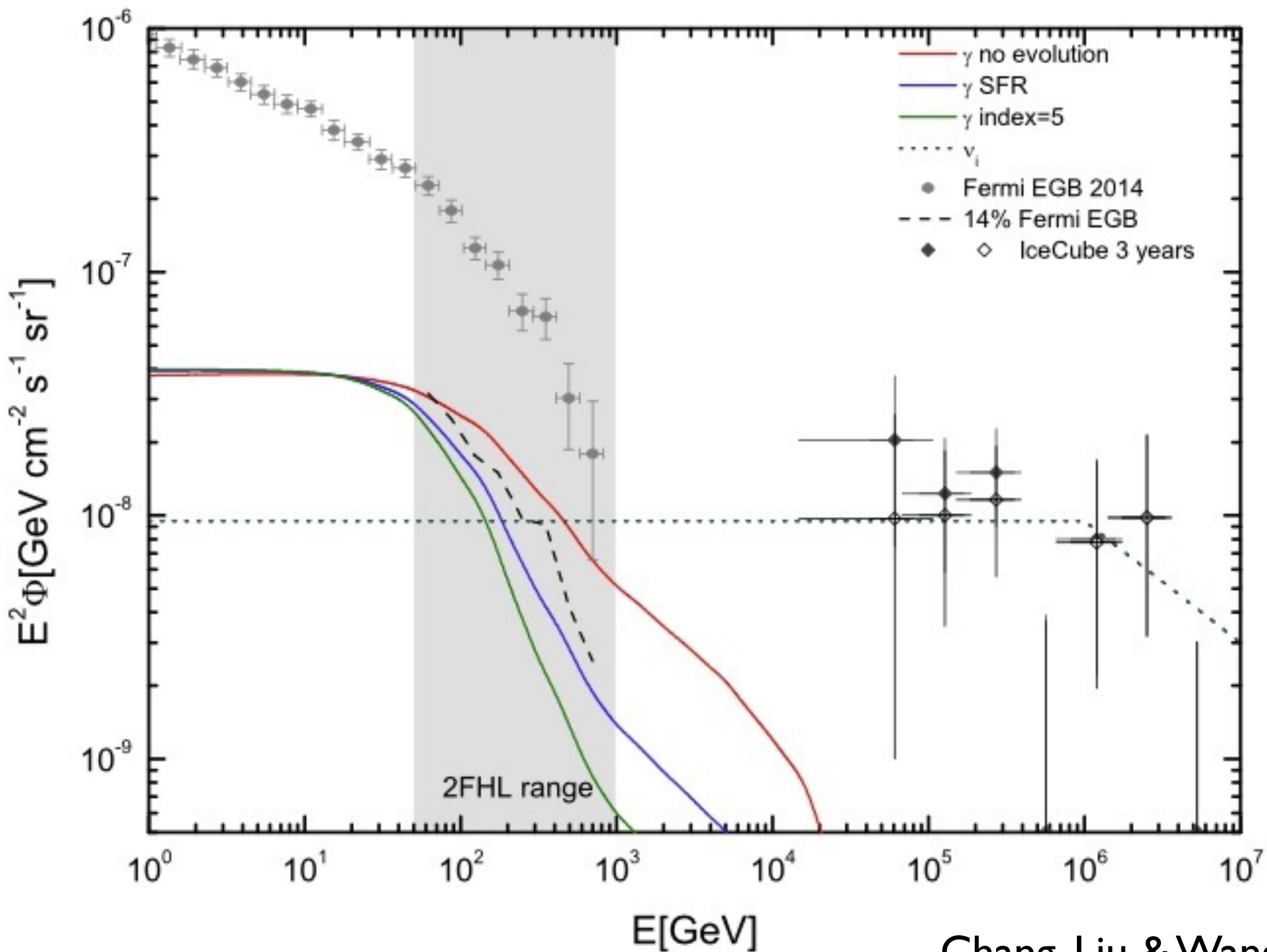


May do the job! (LLGRBs, practically no IGB = hidden)

Senno, Murase, Mészáros, PRD, 93, 083003

Other way to hide:

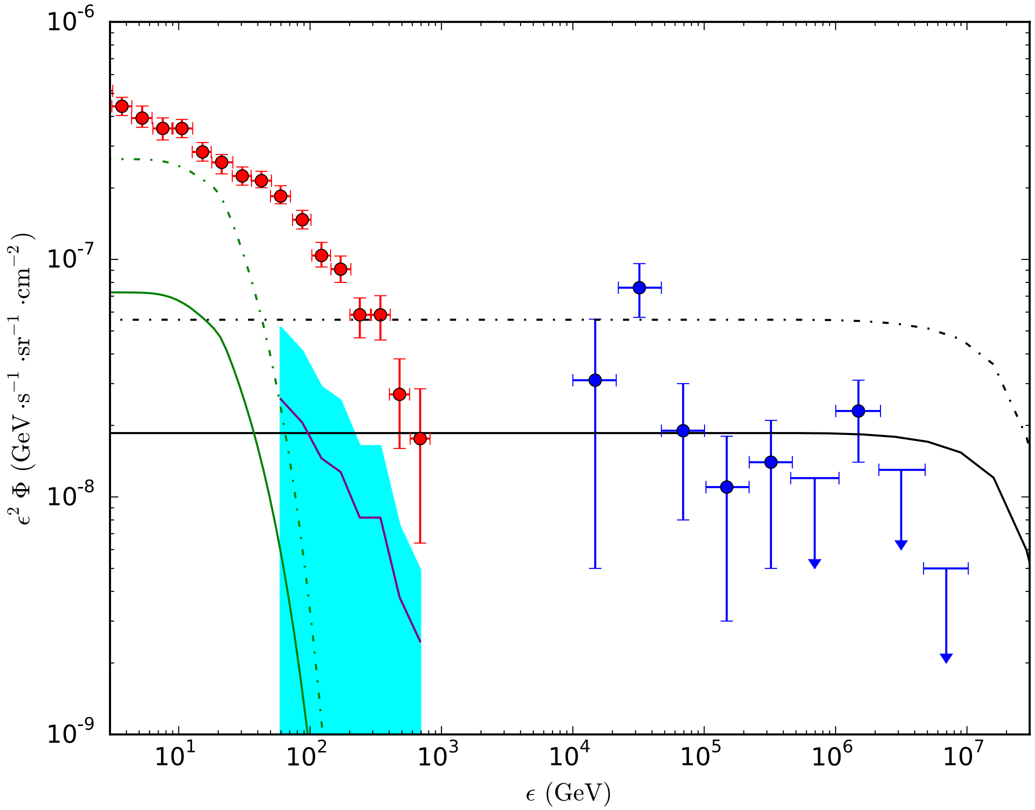
High redshift sources



Chang, Liu & Wang, 1602.06625

For instance:

Pop. III SNe (only)

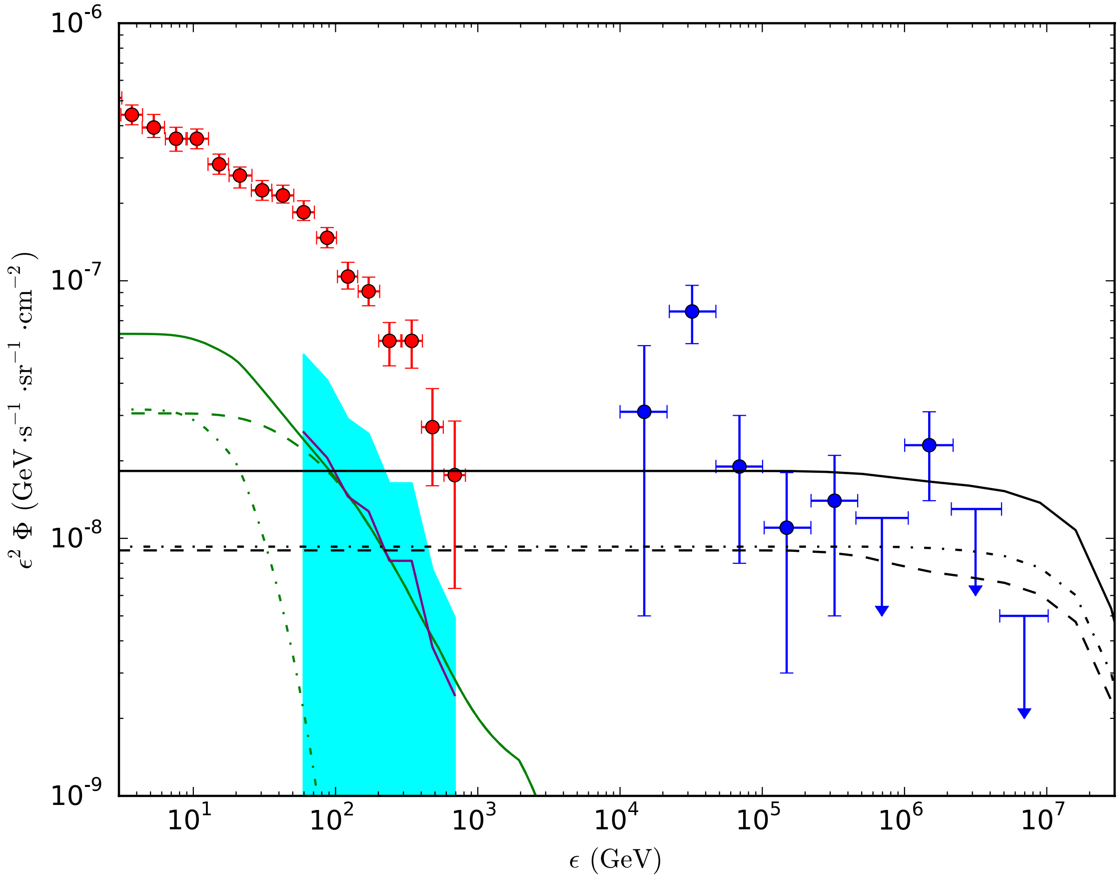


Xiao, Mészáros, Murase, Dai, in prep.

more realistically:

Pop. I-II SNe/HNe + Pop. III SNe

Xiao, Mészáros, Murase, Dai, in prep.



Does the job ✔

Thanks!

Extra slides DSNB

dsnb & hierarchy

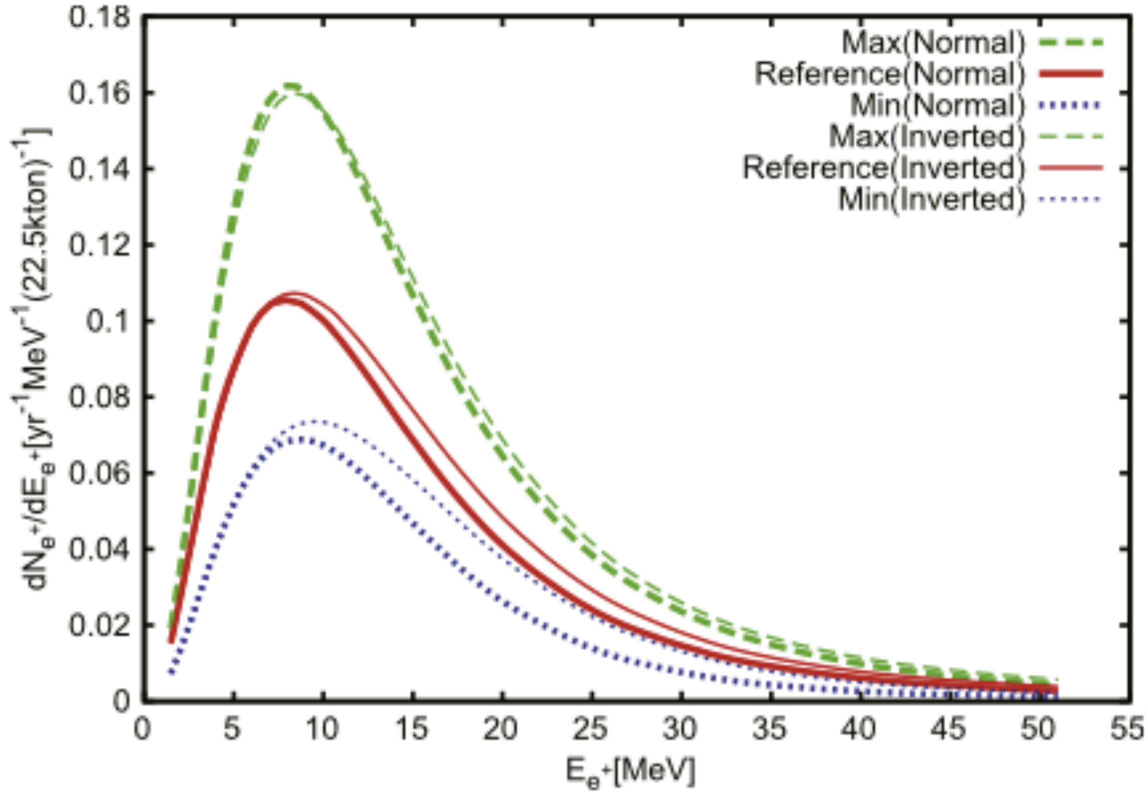
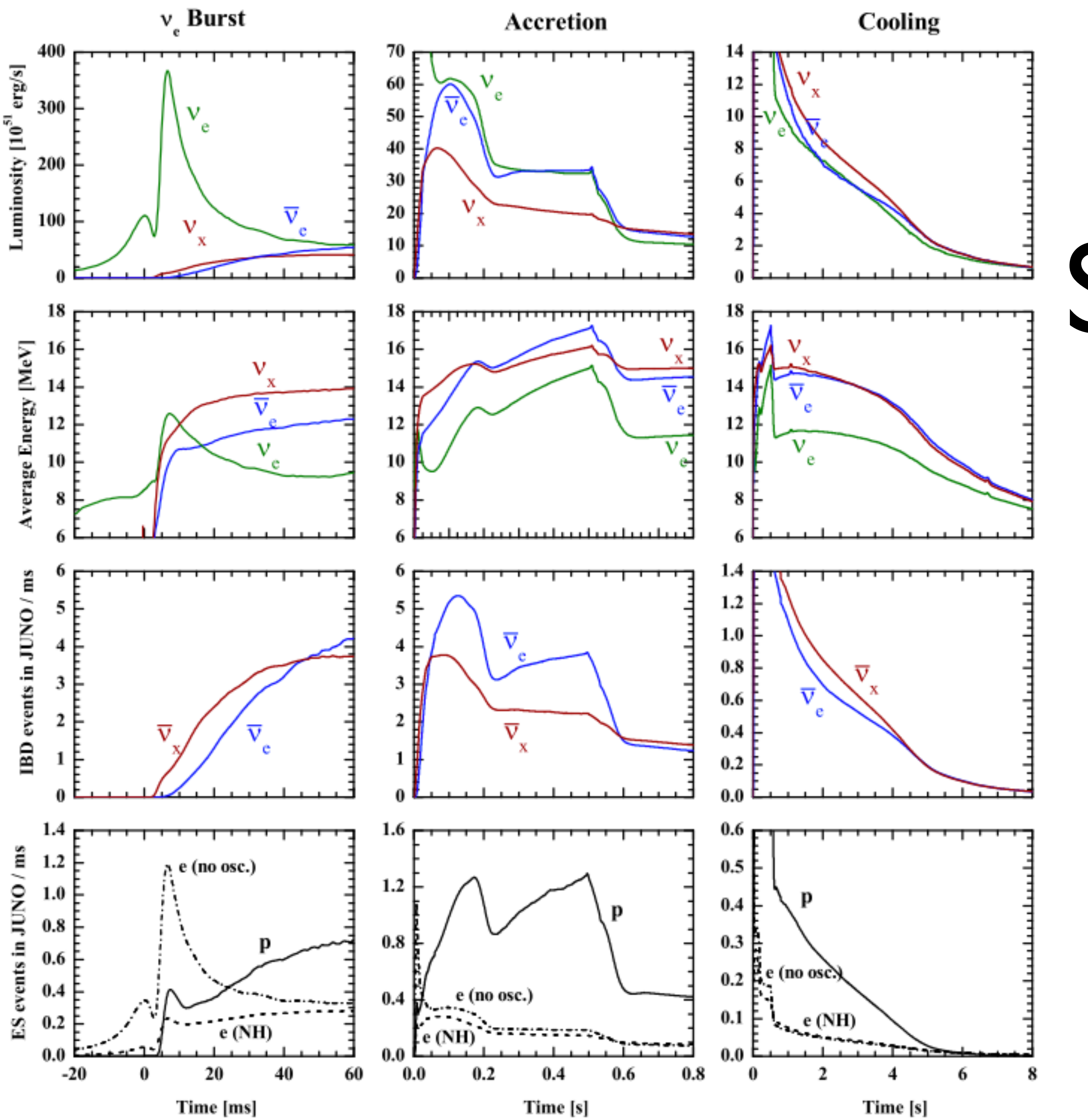


Figure 13. Event rate spectra in Super-Kamiokande over 1 yr obtained using reference model (solid) and models with maximum (dashed) and minimum (dotted) values of SRN event rate among models with metallicity evolution of DA08+M08. Thick and thin lines correspond to the results for the normal and inverted mass hierarchies, respectively.

Nakazato+15



JUNO, SN@10 kpc

- time development, single SN,

JUNO, SN@10kpc

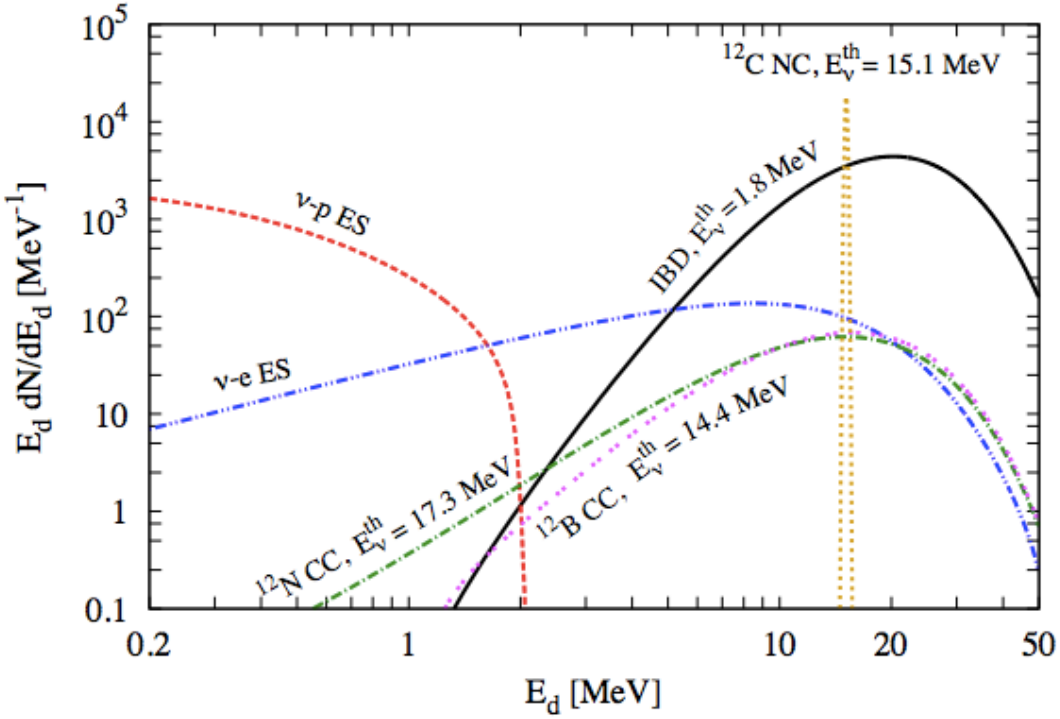


Figure 4-2: The neutrino event spectra with respect to the visible energy $E_{\rm d}$ in the JUNO detector for a SN at 10 kpc, where no neutrino flavor conversions are assumed for illustration and the average neutrino energies are $\langle E_{\nu_e} \rangle = 12$ MeV, $\langle E_{\overline{\nu}_e} \rangle = 14$ MeV and $\langle E_{\nu_x} \rangle = 16$ MeV. The main reaction channels are shown together with the threshold of neutrino energies: (1) IBD (black and solid curve), $E_{\rm d} = E_\nu - 0.8$ MeV; (2) Elastic ν-p scattering (red and dashed curve), $E_{\rm d}$ stands for the recoil energy of proton; (3) Elastic ν-e scattering (blue and double-dotted-dashed curve), $E_{\rm d}$ denotes the recoil energy of electron; (4) Neutral-current reaction $^{12}{\rm C}(\nu, \nu')^{12}{\rm C}^*$ (orange and dotted curve), $E_{\rm d} \approx 15.1$ MeV; (5) Charged-current reaction $^{12}{\rm C}(\nu_e, e^-)^{12}{\rm N}$ (green and dotted-dashed curve), $E_{\rm d} = E_\nu - 17.3$ MeV; (6) Charged-current reaction $^{12}{\rm C}(\overline{\nu}_e, e^+)^{12}{\rm B}$ (magenta and double-dotted curve), $E_{\rm d} = E_\nu - 13.9$ MeV.