Theoretical study of supernova relic neutrinos

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Outline

1. Introduction
2. What does SRN spectrum depend on?
   involving metallicity evolution of galaxies
   （K. Nakazato et al. 2015, ApJ 804, 75）
3. Comparison with noise BG
4. Summary

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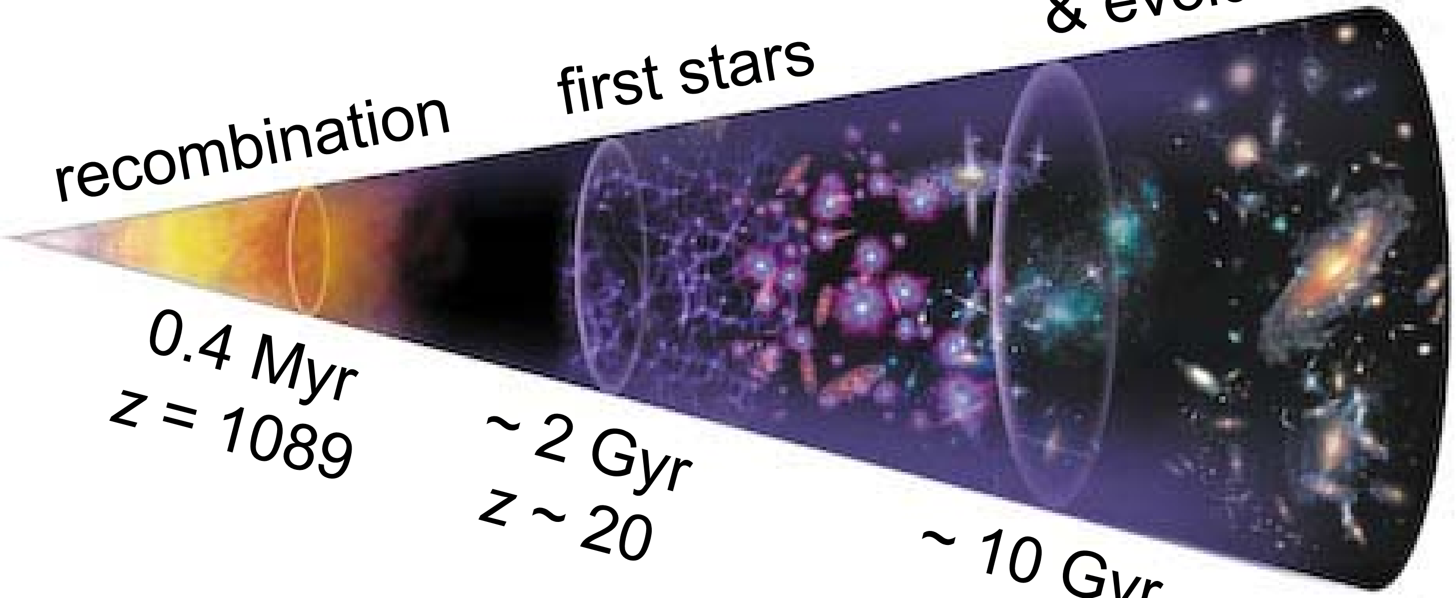
History of Universe



Big Bang

recombination

first stars

galaxy formation & evolution

Now

0.4 Myr
$z = 1089$

~ 2 Gyr
$z \sim 20$

~ 10 Gyr
$z \sim 5$

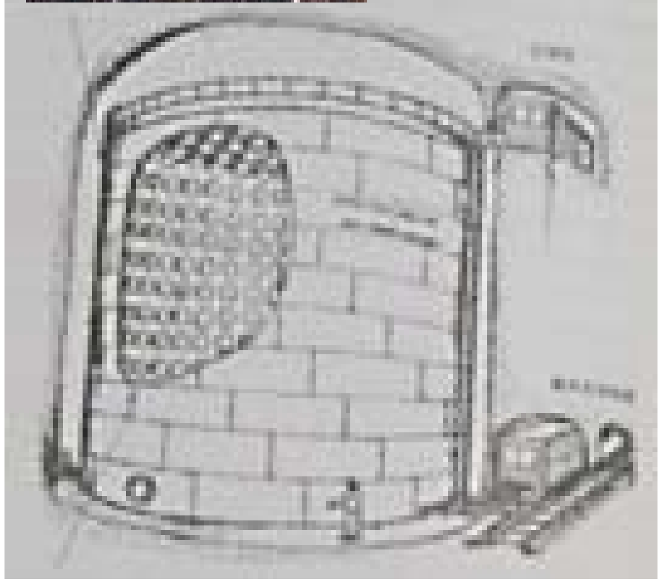
140 Gyr
$z = 0$

- The Universe is expanding!
- Cosmological redshift *z* denotes ``time''.

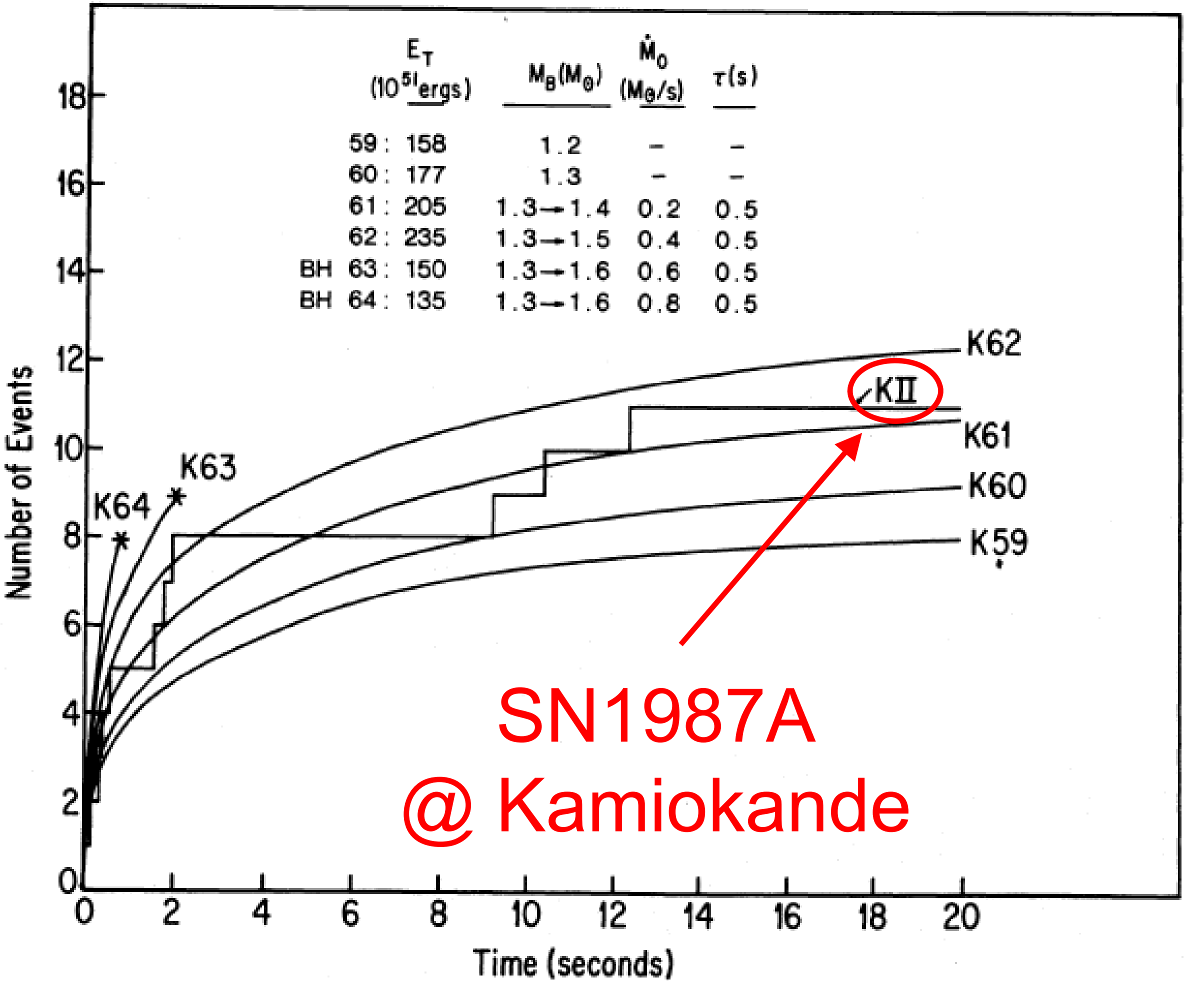
Many generations of stars have exploded!

Supernova neutrinos

- Clue for puzzle in supernova physics.



Burrows（1988）

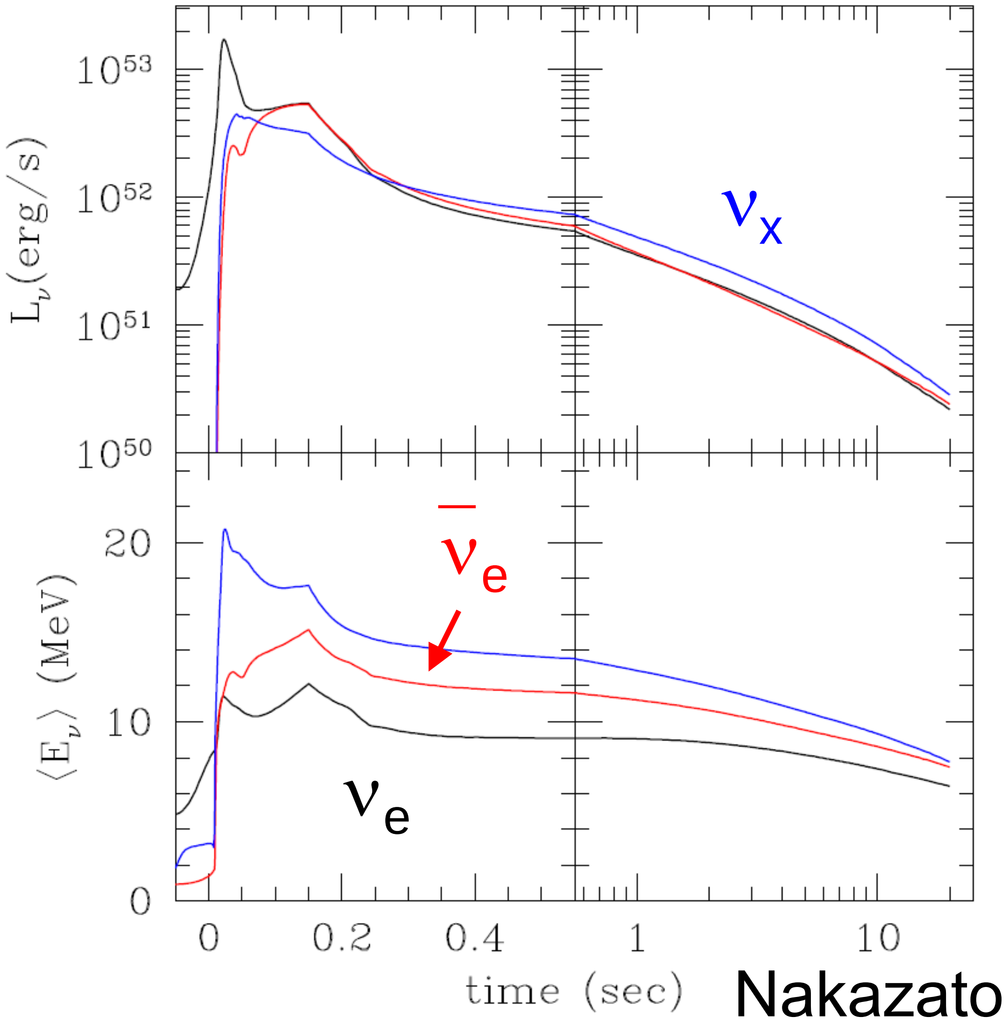


	E_T (10^{51}ergs)	$M_B(M_\odot)$	$\dot{M}_0$ ($M_\odot$/s)	τ(s)
59 :	158	1.2	–	–
60 :	177	1.3	–	–
61 :	205	1.3→1.4	0.2	0.5
62 :	235	1.3→1.5	0.4	0.5
BH 63 :	150	1.3→1.6	0.6	0.5
BH 64 :	135	1.3→1.6	0.8	0.5

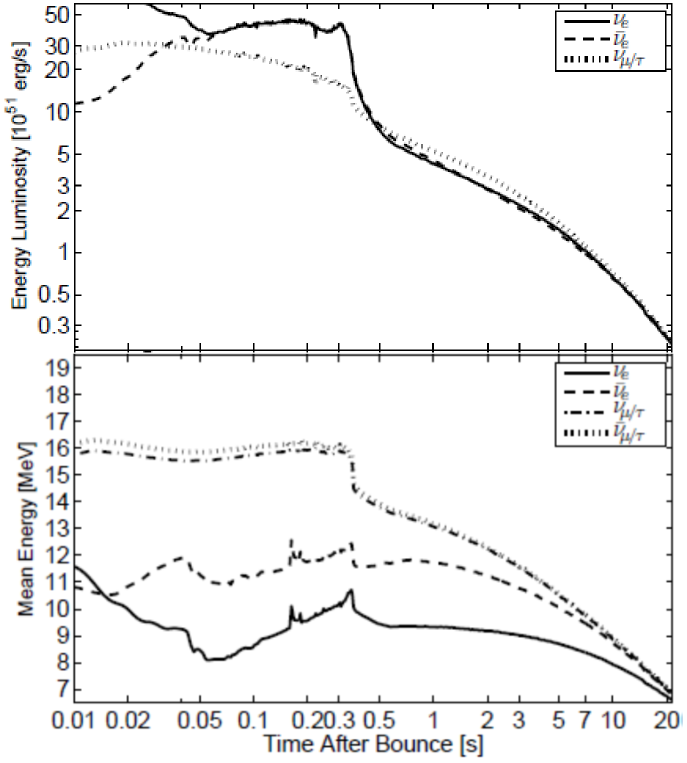
Light curves and spectra

- Neutrino emission continues for 10 seconds.

（diffusion time scale）



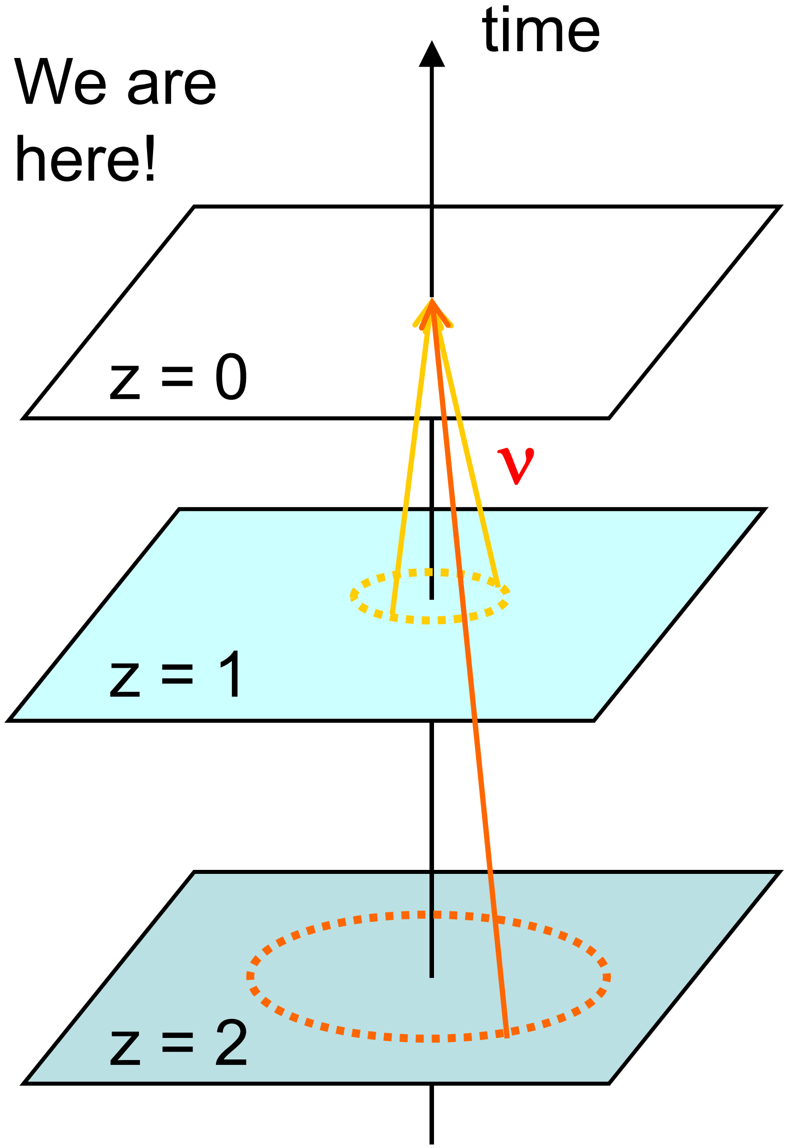
Nakazato+（2013）



Fischer+（2012）

Supernova relic neutrinos

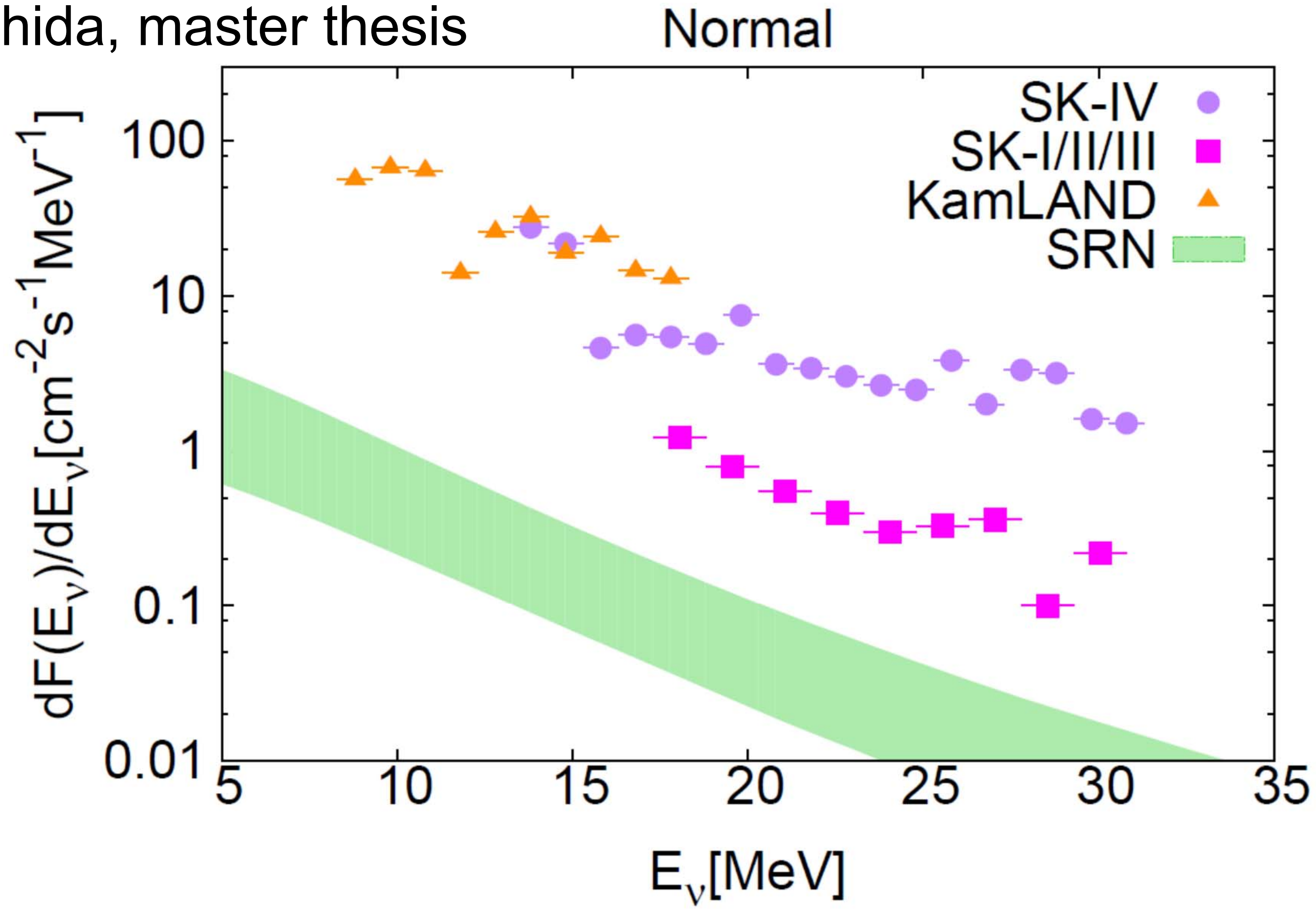
- The flux of neutrinos and antineutrinos emitted by all core-collapse supernovae in the causally-reachable universe.
- Is it possible to study something from supernova relic neutrinos?



Detection status

- The upper limit is near theoretical predictions.

E. Mochida, master thesis



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What determines BG luminosity?

⇓

supernova relic neutrinos

- luminosity of a source → supernova physics
- the source number
- distance to sources
  - cosmological redshift for the expanding universe

} star formation history

- Also neutrino oscillation parameters

Formulation

$$\left(\frac{dE'_\nu}{dE_\nu}=1+z\right)$$

$$\frac{\mathrm{d}F(E_\nu)}{\mathrm{d}E_\nu} = c\int_0^{z_{\max}} \frac{\mathrm{d}z}{\enclose{circle}{H_0}\sqrt{\enclose{circle}{\Omega_m}(1+z)^3+\enclose{circle}{\Omega_\Lambda}}} \times \left[R_{\mathrm{CC}}(z)\int_0^{Z_{\max}}\psi_{\mathrm{ZF}}(z,Z)\left\{\int_{M_{\min}}^{M_{\max}} \underline{\underline{\psi_{\mathrm{IMF}}(M)}}\,\boxed{\frac{\mathrm{d}N(M,Z,E'_\nu)}{\mathrm{d}E'_\nu}}\,\mathrm{d}M\right\}\mathrm{d}Z\right]$$

- Supernova neutrino spectrum: $\frac{\mathrm{d}N(M,Z,E'_\nu)}{\mathrm{d}E'_\nu}$
- Cosmological parameters

  $$H_0 = 70\ \mathrm{km/s/Mpc},\ \Omega_m = 0.3\ \mathrm{and}\ \Omega_\Lambda = 0.7$$

- Initial mass function: $\psi_{\mathrm{IMF}}(M) \propto M^{-2.35}$ （Salpeter）

Formulation

$$\left(\frac{dE'_\nu}{dE_\nu} = 1 + z \right)$$

$$\frac{\mathrm{d}F(E_\nu)}{\mathrm{d}E_\nu} = c \int_0^{z_{\max}} \frac{\mathrm{d}z}{H_0\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}} \times \left[\boxed{R_{\mathrm{CC}}(z)} \int_0^{Z_{\max}} \psi_{\mathrm{ZF}}(z,Z) \left\{ \int_{M_{\min}}^{M_{\max}} \psi_{\mathrm{IMF}}(M) \frac{\mathrm{d}N(M,Z,E'_\nu)}{\mathrm{d}E'_\nu} \mathrm{d}M \right\} \mathrm{d}Z \right]$$

- Core collapse rate: $R_{\mathrm{CC}}(z) = \dot{\rho}_*(z) \times \frac{\int_{M_{\min}}^{M_{\max}} \psi_{\mathrm{IMF}}(M)\,\mathrm{d}M}{\int_{0.1M_\odot}^{100M_\odot} M\psi_{\mathrm{IMF}}(M)\,\mathrm{d}M}$

cosmic star formation rate

related to stellar mass distribution of galaxies

（Drory & Alvarez, 2008）

$$\dot{\rho}_*(z) = \int_0^\infty \underline{\underline{\dot{M}_*(M_*,z)}}\,\underline{\underline{\phi_{\mathrm{SMF}}(M_*,z)}}\,\mathrm{d}M_*$$

SFR of galaxy stellar mass function

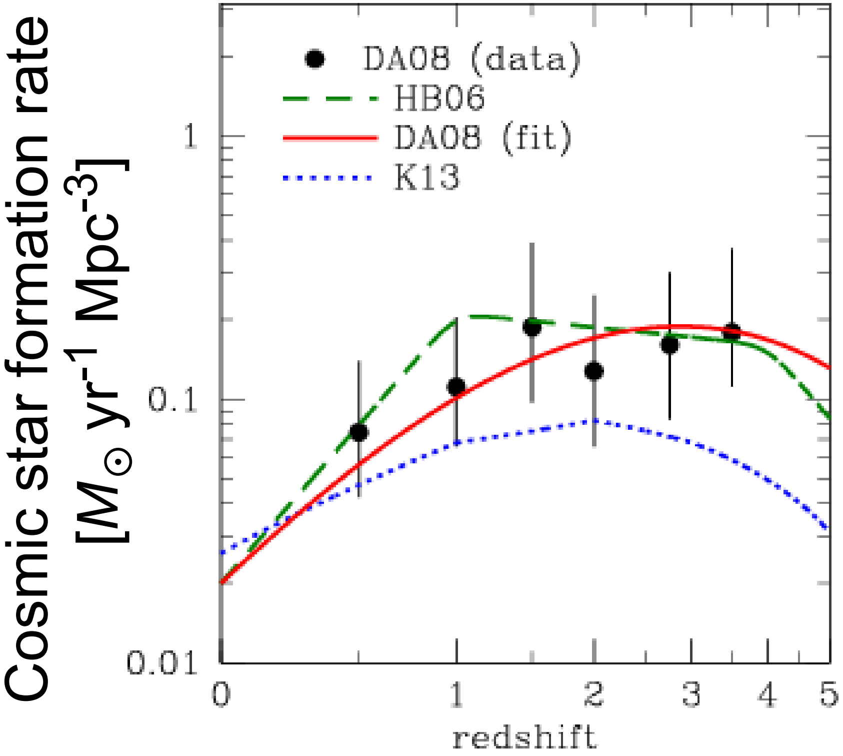
Cosmic star formation rate

- It has a peak at redshift z ~ 1-2, but uncertainty is large.

→ conversion from UV luminosity to star formation rate of galaxy

→ dust obscuration correction

Note: Contribution from stars in $z > 2$ is small.



Observation of galaxies

Hopkins & Beacom（2006）

Drory & Alvarez（2008）

Theoretical model

Kobayashi et al.（2013）

Formulation

$$\left(\frac{dE'_\nu}{dE_\nu} = 1 + z\right)$$

$$\frac{\mathrm{d}F(E_\nu)}{\mathrm{d}E_\nu} = c\int_0^{z_{\max}} \frac{\mathrm{d}z}{H_0\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}} \times \left[R_{\mathrm{CC}}(z)\int_0^{Z_{\max}} \boxed{\psi_{\mathrm{ZF}}(z,Z)}\left\{\int_{M_{\min}}^{M_{\max}} \psi_{\mathrm{IMF}}(M)\frac{\mathrm{d}N(M,Z,E'_\nu)}{\mathrm{d}E'_\nu}\,\mathrm{d}M\right\}\mathrm{d}Z\right]$$

- Metallicity distribution function of progenitors

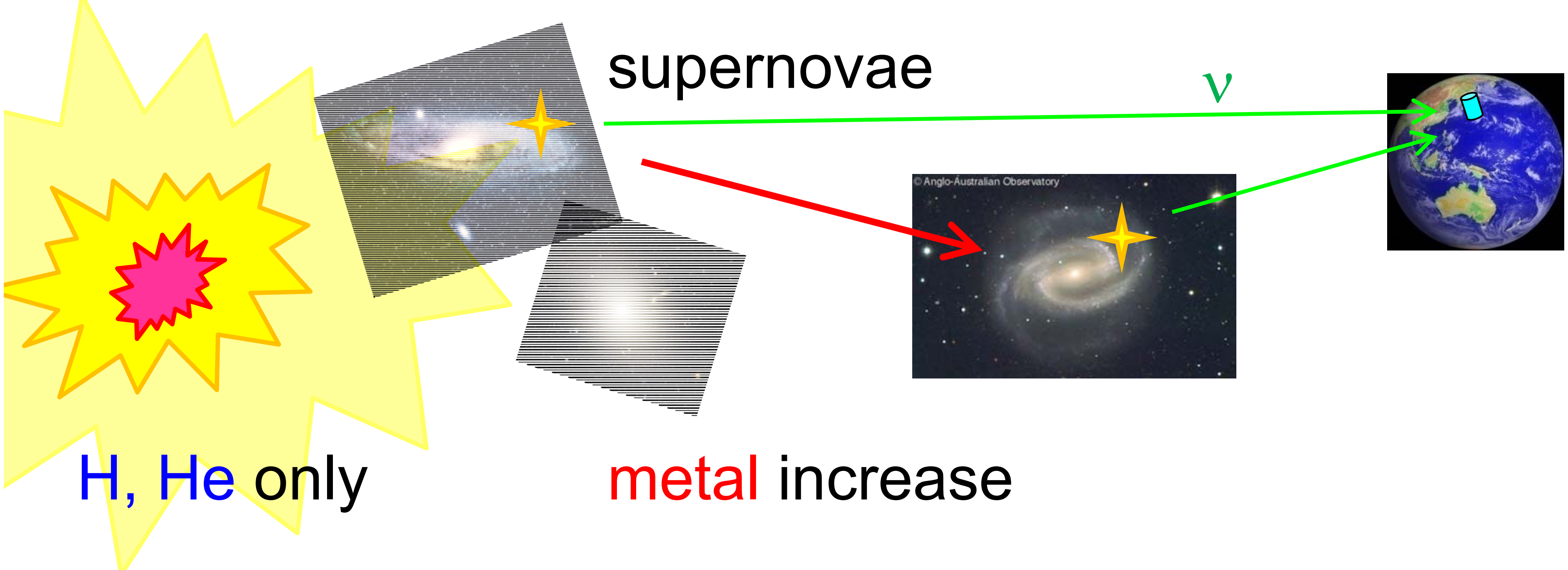
mass metallicity relation（Maiolino+, 2008）

$$\int_0^Z \psi_{\mathrm{ZF}}(z,Z')\ \mathrm{d}Z' = \frac{\int_0^{M_*(z,Z)} \dot{M}_*(M'_*,z)\phi_{\mathrm{SMF}}(M'_*,z)\ \mathrm{d}M'_*}{\int_0^{\infty} \underline{\underline{\dot{M}_*(M'_*,z)}}\,\underline{\underline{\phi_{\mathrm{SMF}}(M'_*,z)}}\ \mathrm{d}M'_*}$$

SFR of galaxy　stellar mass function

（Drory & Alvarez, 2008）

Cosmic chemical evolution



Big Bang galaxy formation, evolution Now

supernovae

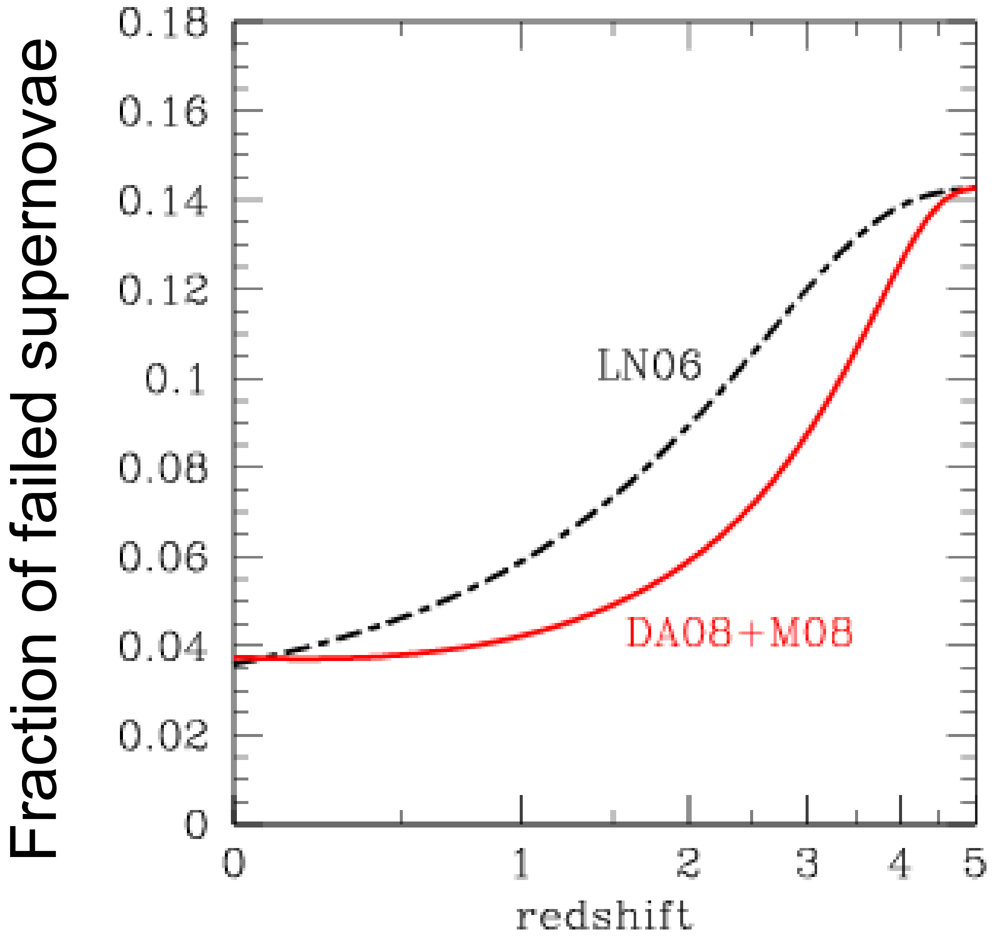
ν

H, He only

metal increase

- Old stars are low metallicity.
- Low metallicity stars have massive cores.
  → Failed supernova progenitors are included.

Fraction of failed supernovae



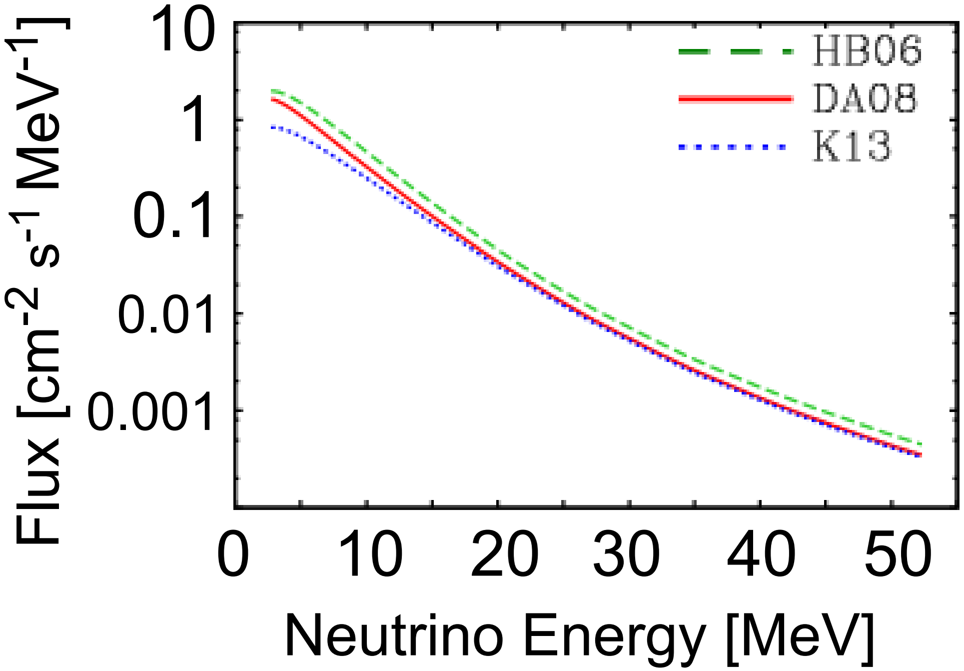
M	Z	
	0.02	0.004
$13M_\odot$	SN	SN
$20M_\odot$	SN	SN
$30M_\odot$	SN	BH
$50M_\odot$	SN	SN

Nakazato+（2015）

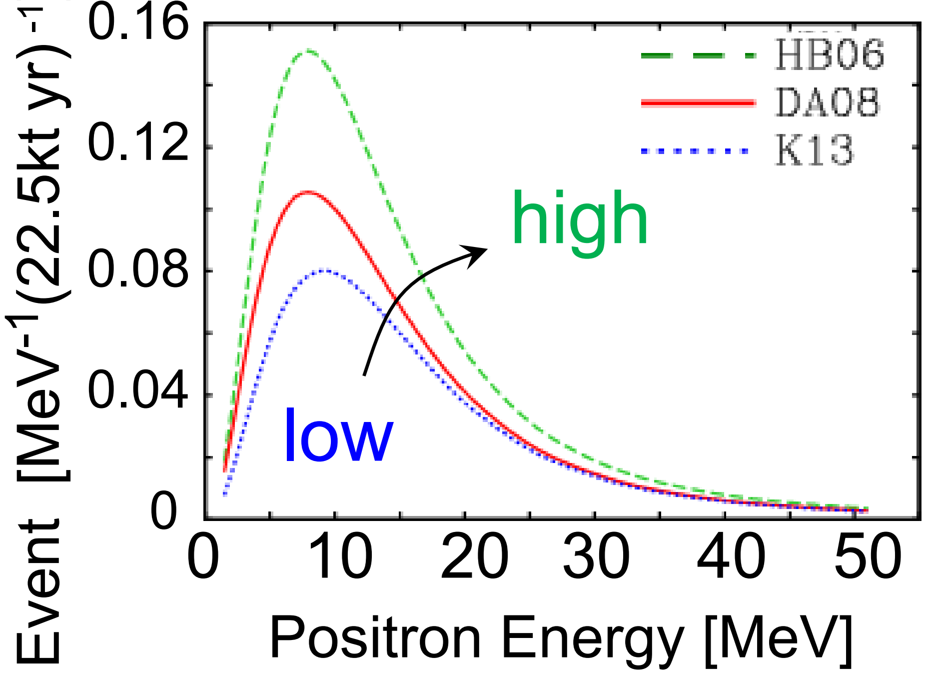
- It increases with redshift because metal poor stars are abundant in high redshift universe.

Spectra of SN relic neutrinos

difference of SFR

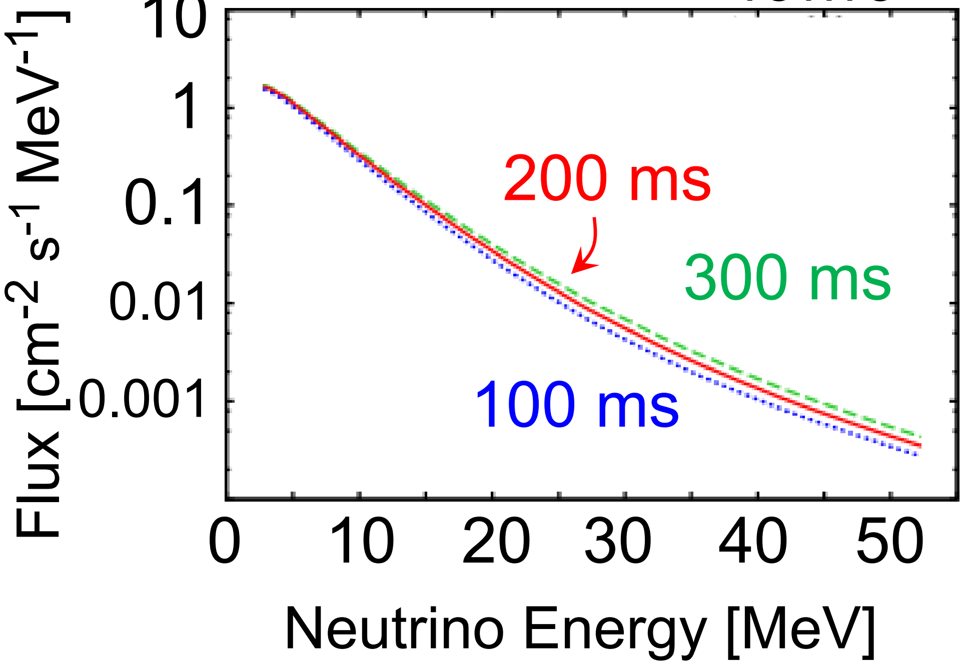


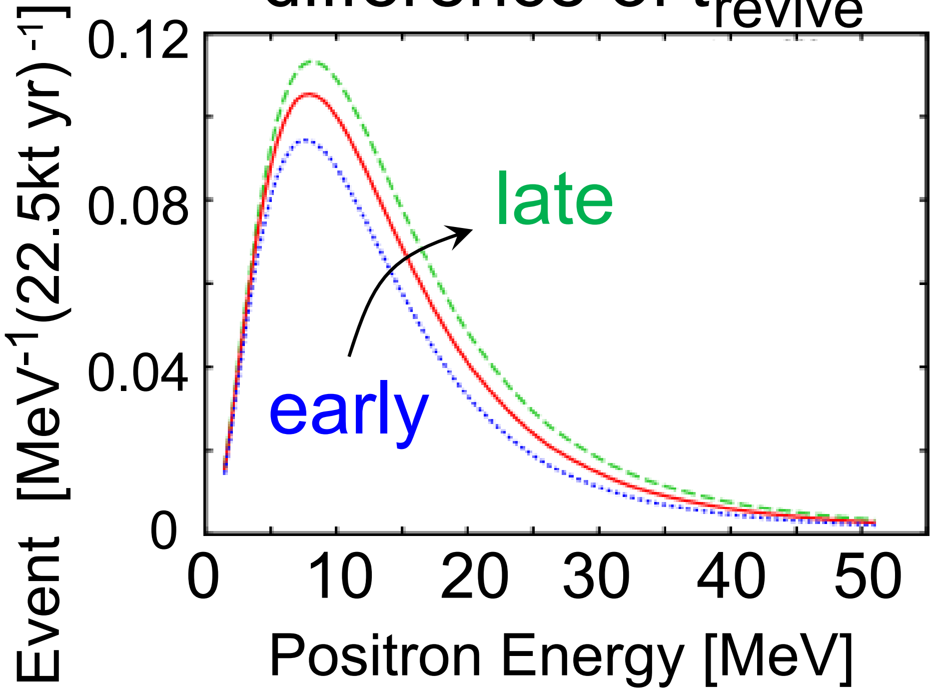
difference of SFR



- Uncertainty is large in low energy region.
- Reflecting large uncertainty of cosmic star formation rate in high redshift universe

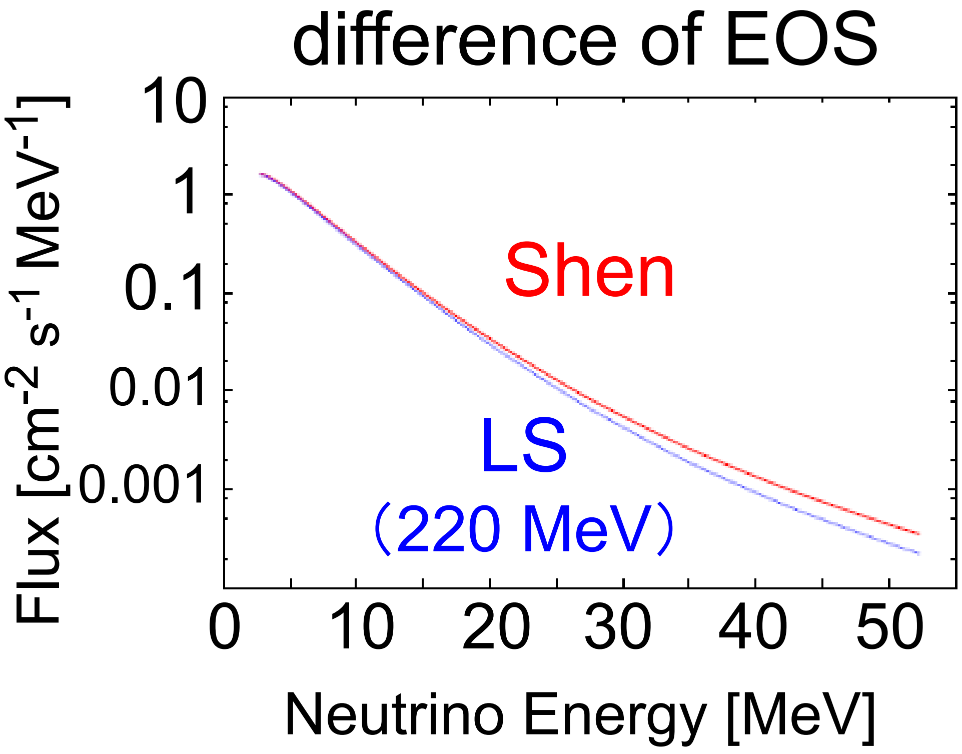
Spectra of SN relic neutrinos

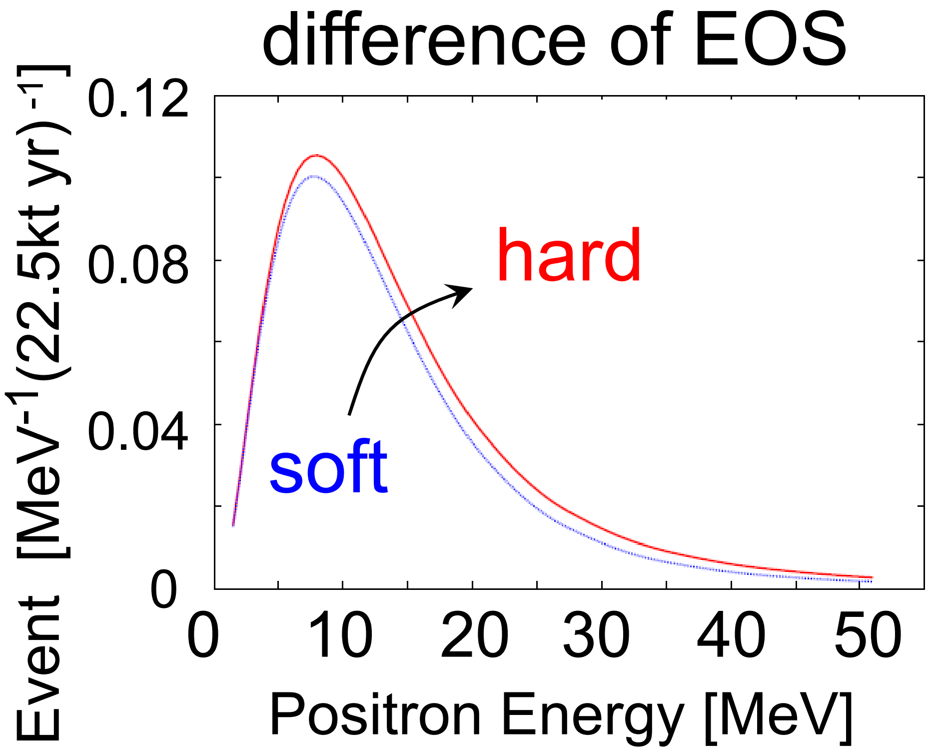

difference of t_{revive}


difference of t_{revive}

- Uncertainty is large in high energy region.
- If the shock revival is late, proto-neutron star is heated and neutrino spectrum gets hard.

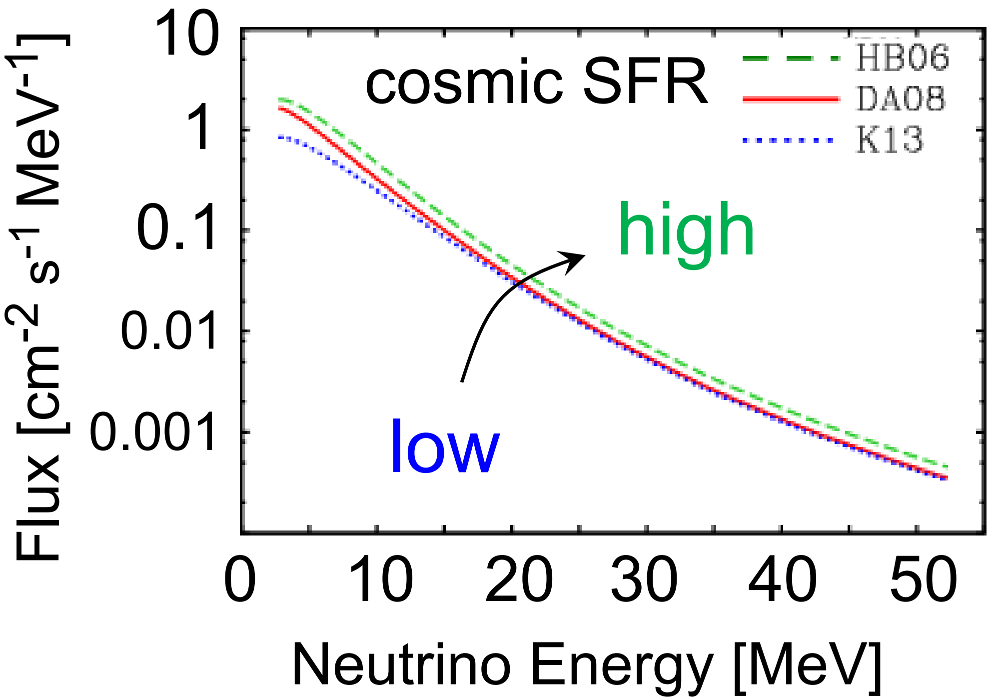
Spectra of SN relic neutrinos

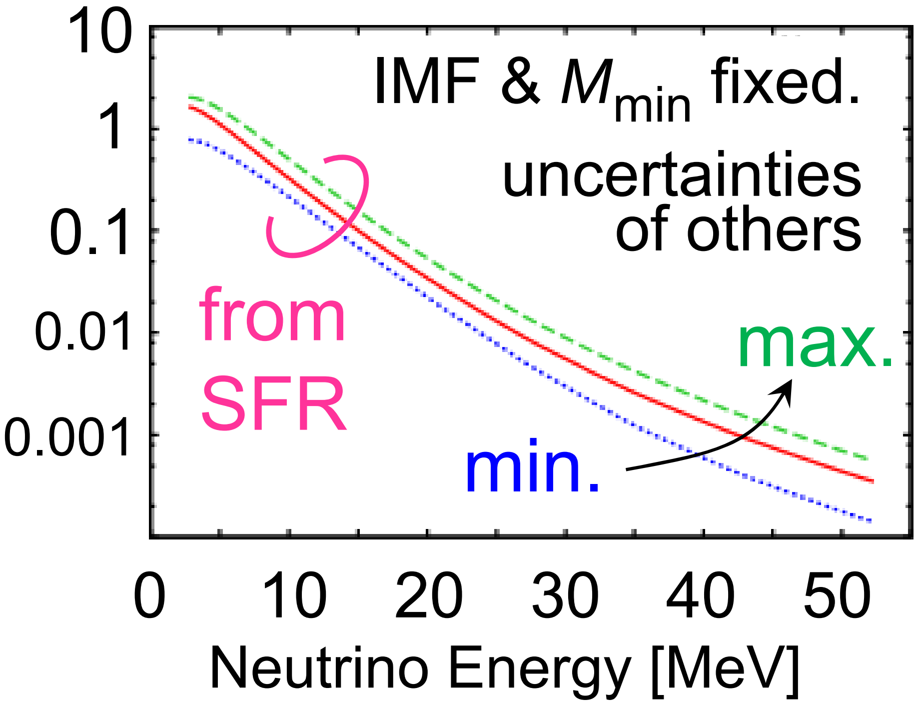

difference of EOS


difference of EOS

- Uncertainty is large in high energy region.
- If the EOS is hard, the black hole formation is delayed and neutrino spectrum gets hard.

Uncertainties on SRN spectrum





- Uncertainty on SRN spectrum in low energies is mainly from cosmic star formation rate.
- To investigate star formation history, low energy is better and SK-Gd is promising.

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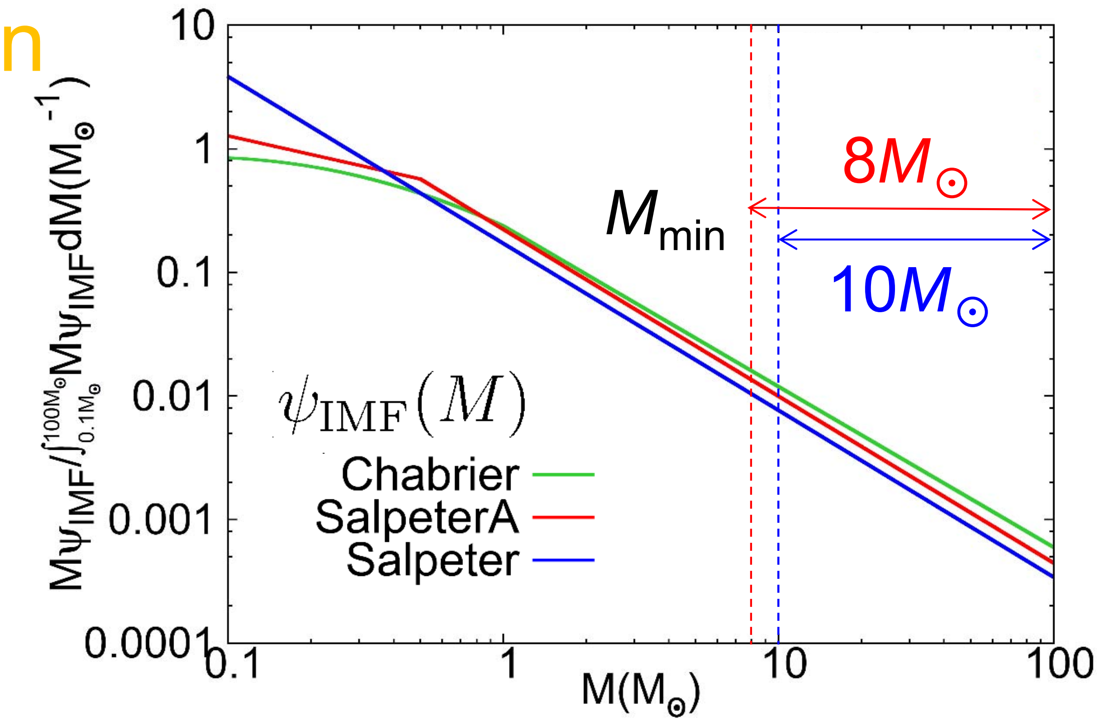
- Min. mass of SN progenitors: $M_{\min} = 8$ or $10 M_\odot$
- Initial mass function

$\psi_{\mathrm{IMF}}(M)$

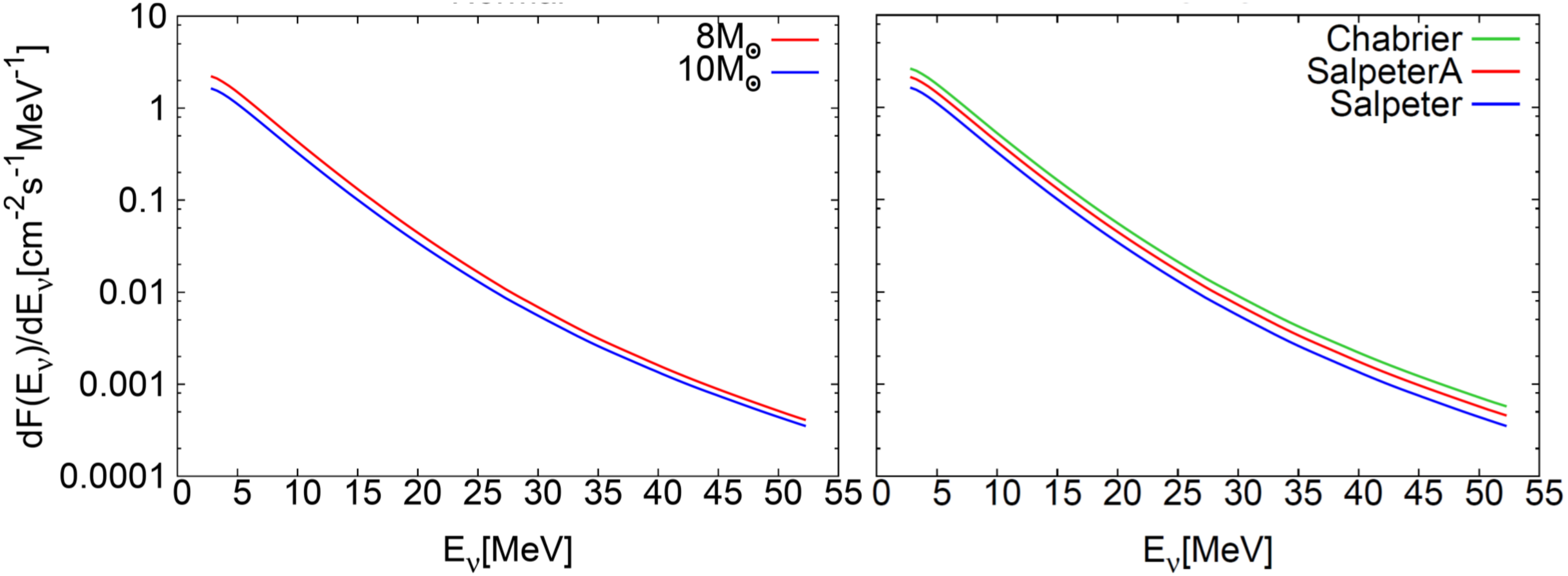
Chabrier (2003);

Baldry, & Glazebrook (2003, SalpeterA);

Salpeter (1955)

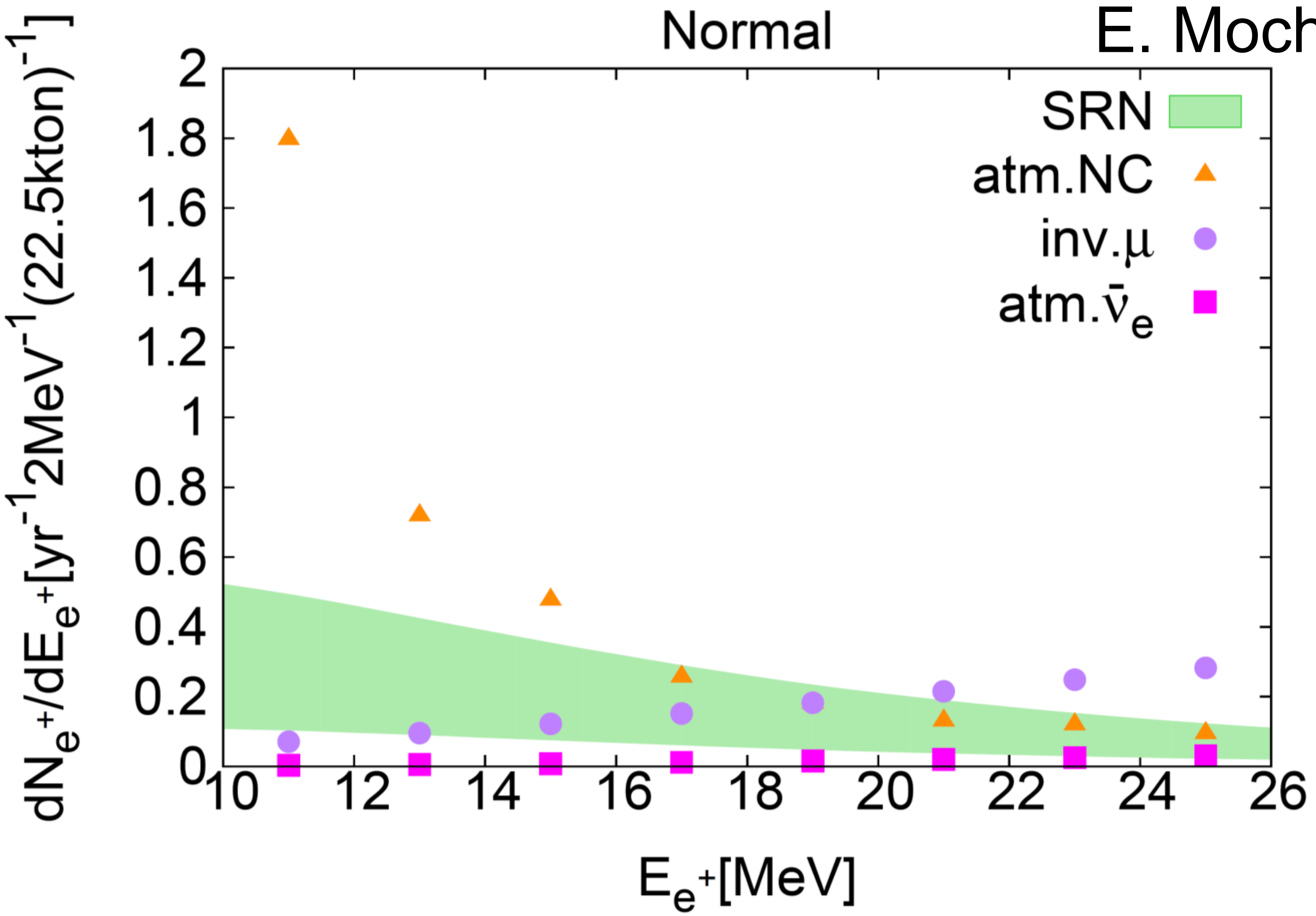


Uncertainties of $M_{\rm min}$ and IMF


difference of $M_{\rm min}$ difference of IMF

- These uncertainties are energy-independent.
- Uncertainty of IMF is largest at high energies, and as large as that of SFR at low energies.

Comparison with noise BG



E. Mochida, master thesis

@ SK-Gd

atmospheric NC
Ueno (2012)

invisible μ &
atmospheric $\bar{\nu}_e$
Abe et al. (2011)

- Detectability highly depends on uncertainties.
- Reduction of atmospheric NC is important.

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Summary

- Uncertainties

	low energy	high energy
SFR	large	middle
t_{revive}	small	middle
EOS（BH）	small	middle
IMF	large	large
M_{min}	middle	middle

- To investigate the star formation history, low energy is better and SK-Gd is promising, but reduction of atmospheric NC is important.