# Gravitational Collapse of Population III Stars

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YS et al., PASJ 59, 771 (2007a)
YS et al., ApJ 665, L43 (2007b)
YS et al., submitted (2008)

Collaboration with
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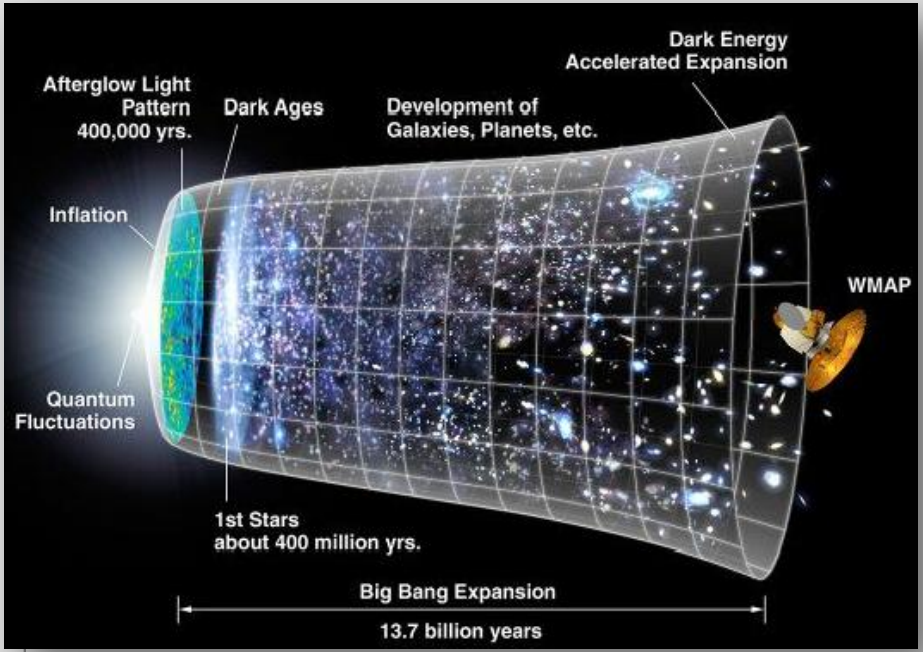
# Outline

- Population III stars
- Gravitational Collapse of Population III stars
- Neutrinos from Population III stars
- Gravitational Waves from Population III  stars
- Conclusions

# Population III Stars

# What are Population III Stars?

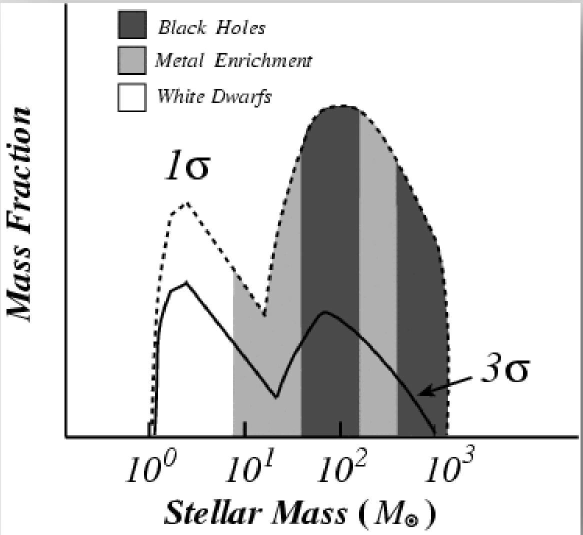



WMAP team (http://map.gsfc.nasa.gov/)

- First stars in the Universe
- Metal free material
- Stars formed within $\sim 10^8$ years of the Big Bang
- Stars no longer exist, but affected the environment
- Relations with GRB? IMBH? IRB?

# Properties of Pop III Stars

Nakamura & Umemura 01




- Pop III stars are thought to have been very massive (~O(100)$M_\odot$)

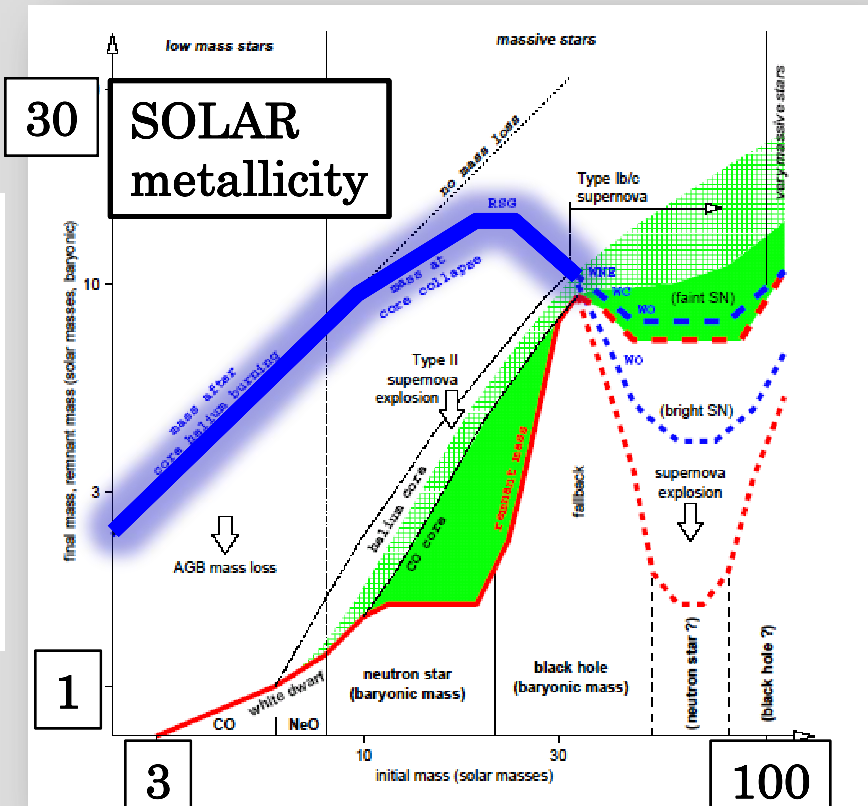
  Nakamura & Umemura 01, Abel+ 02, Bromm+ 02, Yoshida+ 06, O'Shea & Norman 07 …

- Initial Mass Function might be very different from modern stellar populations

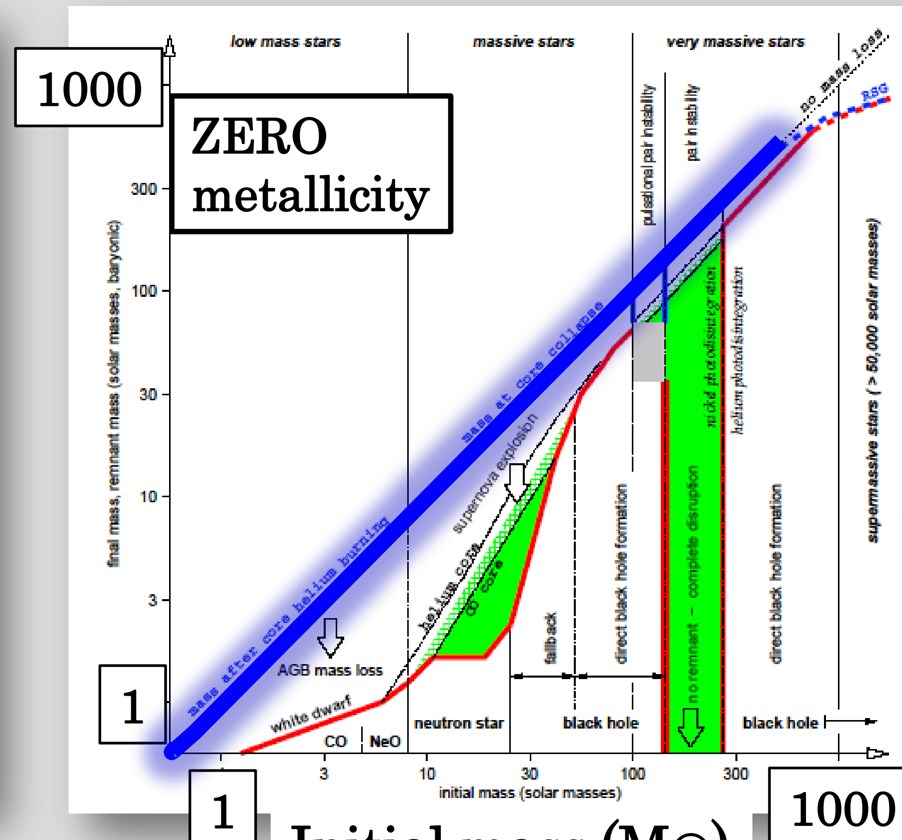
# The Fate of Pop III Stars

Heger+ 03

Final mass (M⊙)

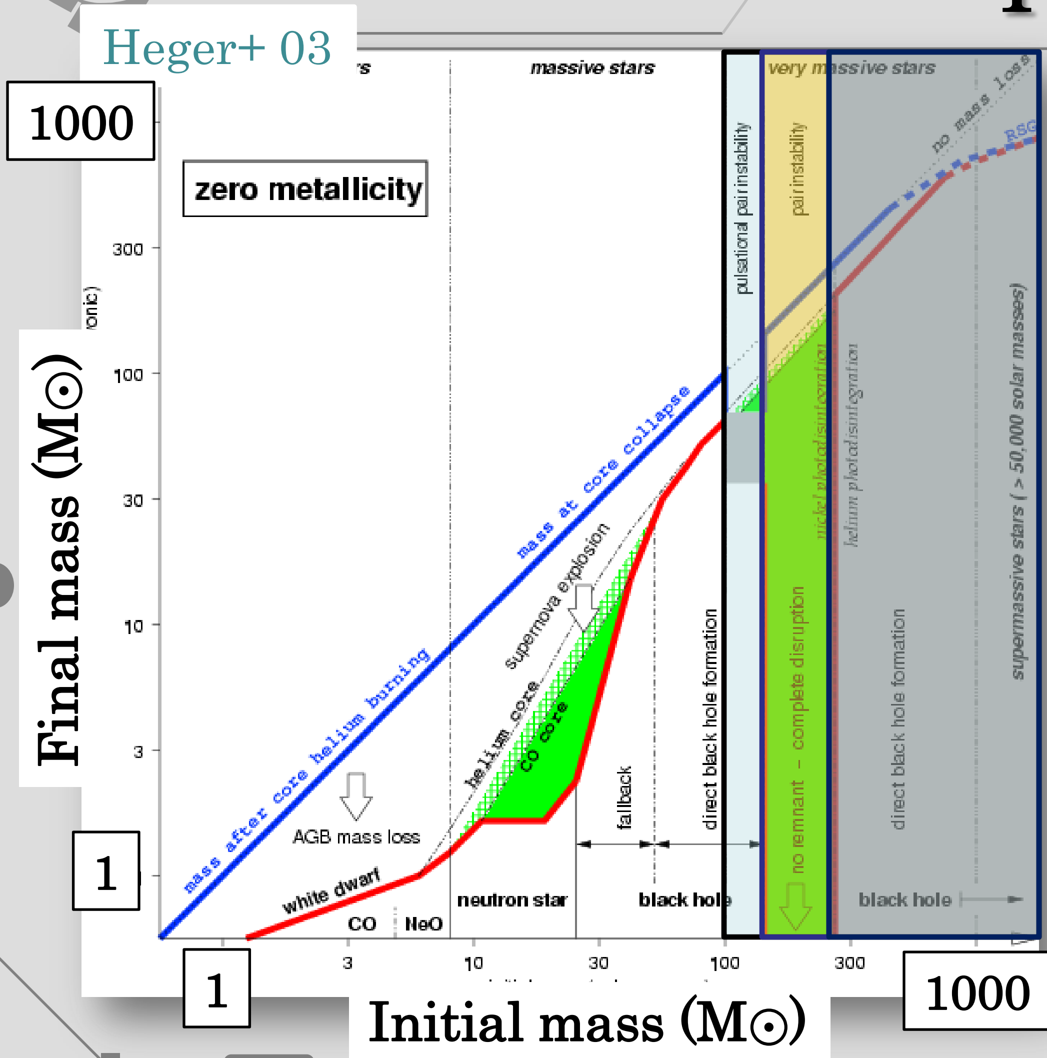



Initial mass (M⊙)




Initial mass (M⊙)

# The Fate of Pop III Stars




- Pop III stars have less metals so that the mass loss is insufficient
  ➔ very large core just before collapse
- $M \gtrsim 100\ M_\odot$ becomes unstable by $e^+e^-$ pair creation
  - $M \lesssim 260\ M_\odot$ ➔ PISN
  - $M \gtrsim 260\ M_\odot$ ➔ BH

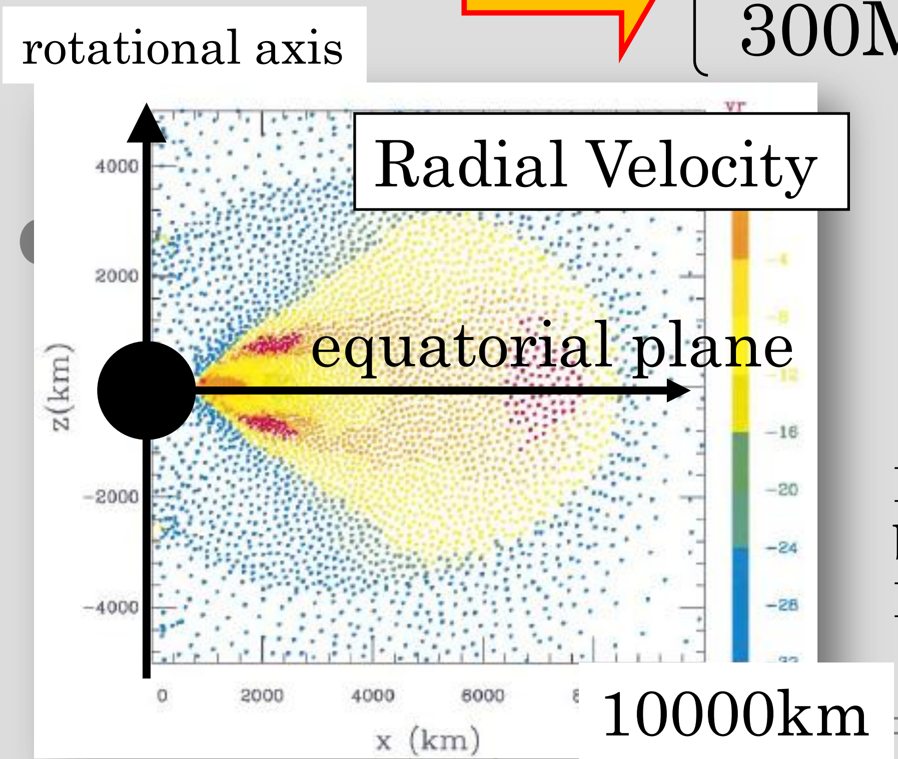
# Gravitational Collapse of Population III Stars

# Gravitational Collapse Simulation

Numerical Simulation by Fryer et al.(2001)

They calculated the evolution of 250$M_\odot$ and 300$M_\odot$ Pop III Stars(1D).

250$M_\odot$ → PISN
300$M_\odot$ → BH




They also simulated the collapse of 300$M_\odot$ star with 2D-SPH code.

BH-disk system forms (collapsar?)
but not enough neutrino density to explode
How about magnetic fields?

# Numerical Method

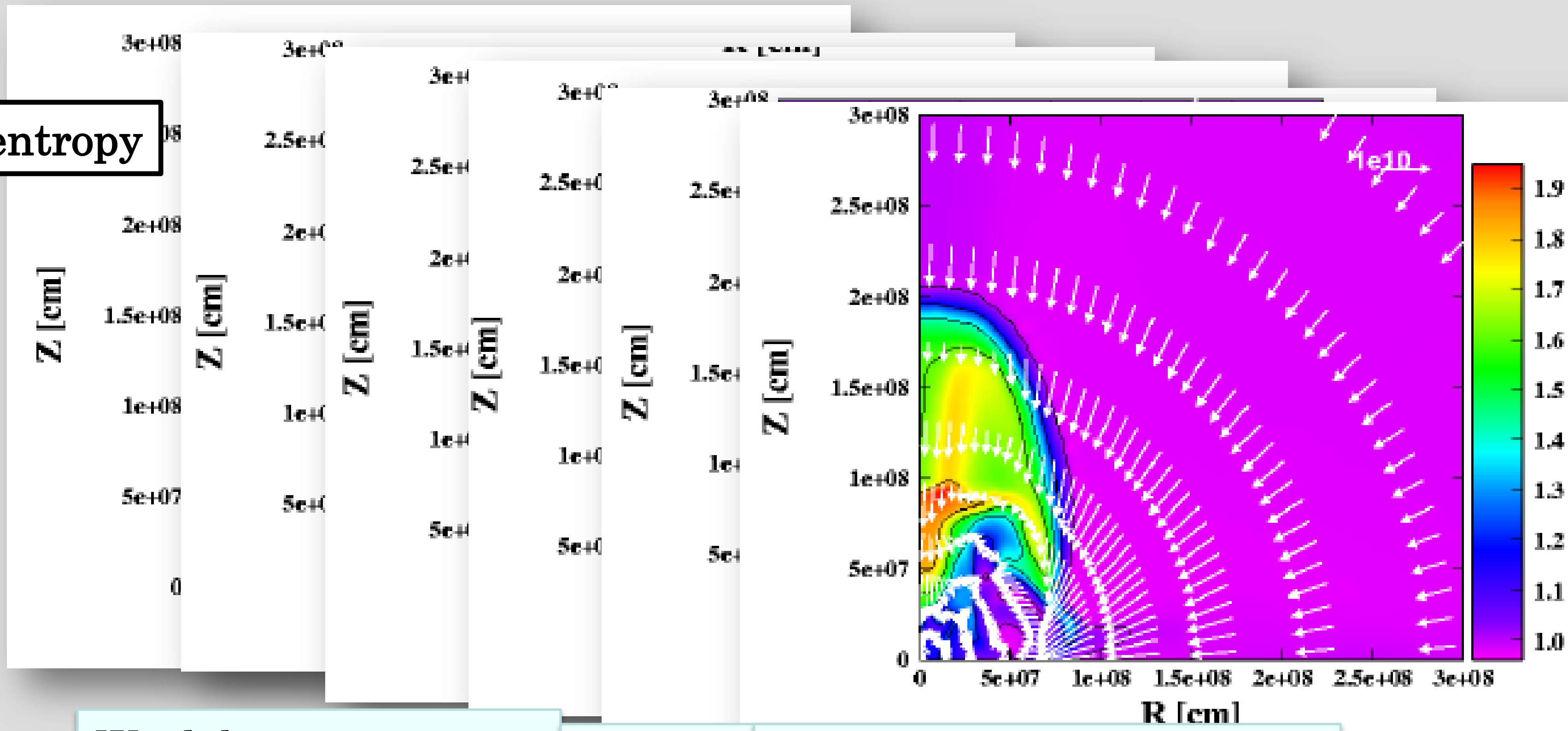
- 2D-axial symmetry
- Hydrodynamics ➔ ZEUS2D (Stone & Norman 92)
- Shen's EOS (Shen+ 98)
- Leakage scheme with all species (Epstein 78)

- Initial model
  - Progenitor ➔ 180 $M_\odot$ core of 300 $M_\odot$ star with s~10 $k_B$ (Fryer+ 01)
  - Magnetic fields ➔ $10^{10}$, $10^{11}$, $10^{12}$ G

# Weak Magnetic Field model

$B_{initial}$ <~ $10^{11}$ G

entropy



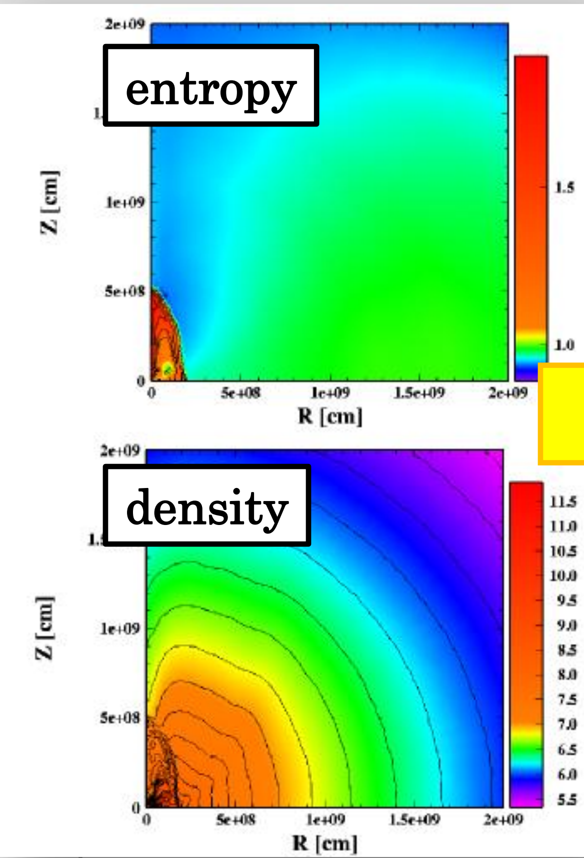

Weak bounce (by *thermal* pressure)

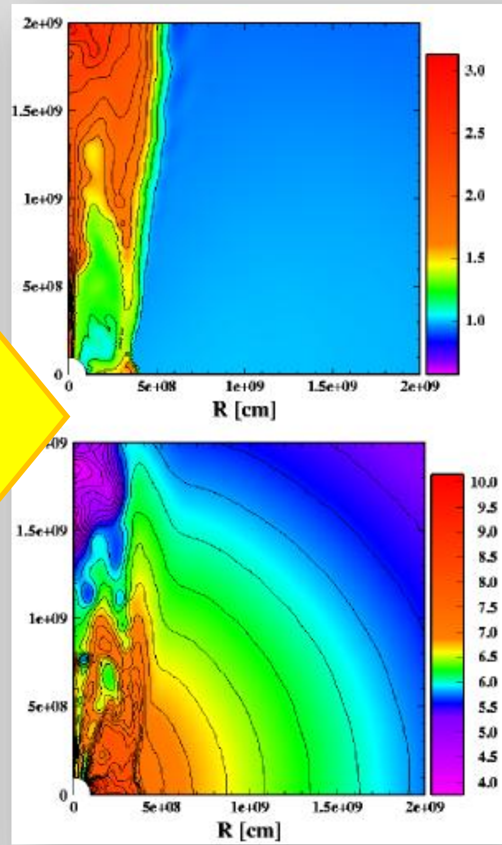
Outward

Shock stall and re-collapse

# Strong Magnetic Field model

$B_{initial} = 10^{12}$ G




Magnetic field driven jet is launched before black hole formation.

affect the chemical evolution of environment?
Ohkubo+ 06

# Neutrino Emission from Population III Stars

# Neutrino and Gravitational Wave

Population III stars are very massive and form BHs

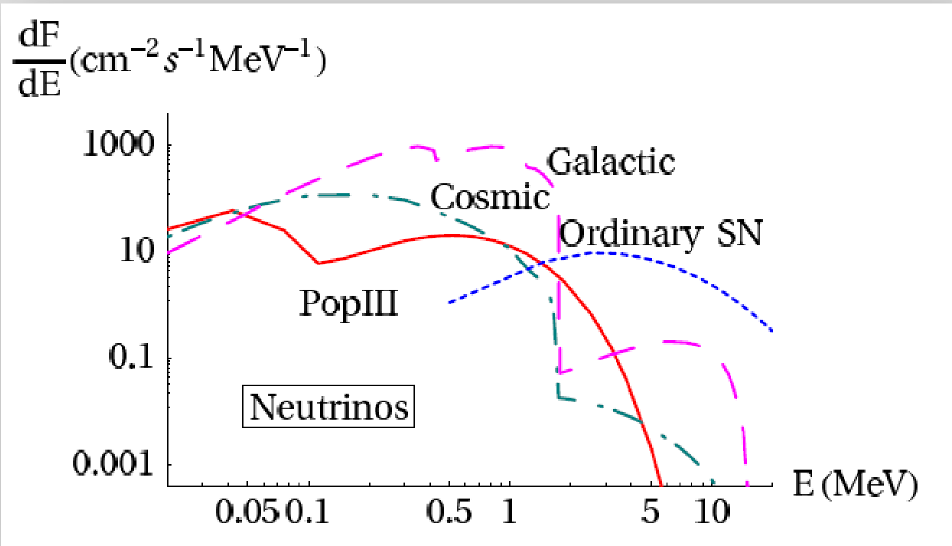
⇒ Large amount of gravitational energy are emitted by neutrinos and gravitational waves.

| Neutrino | Gravitational Wave |
|---|---|
| Ordinary SNe<br>$L_\nu \sim 10^{53}$ erg/sec | Ordinary SNe<br>$E_{GW} \sim 10^{-7} M_\odot c^2$ |
| Population III<br>$L_\nu \sim 10^{55}$ erg/sec  Fryer+ 01, Nakazato+ 06, YS+ 07a | Population III<br>$E_{GW} \sim 10^{-3} M_\odot c^2$  Fryer+ 01 |

Population III stars are too far to detect directly
➔ How about summing up contributions from all stars?

# Neutrino Background

Iocco+ 05




- The expected diffuse cosmic neutrino flux produced by Pop III stars during their nuclear burning and their core-collapse phases
- Estimated flux is comparable to the diffuse neutrino fluxes produced by ordinary SNe. However, due to the large cosmological redshift, the typical energies are MeV and sub-MeV, where the other components dominate.

**No window for observation of Population III stars ??**

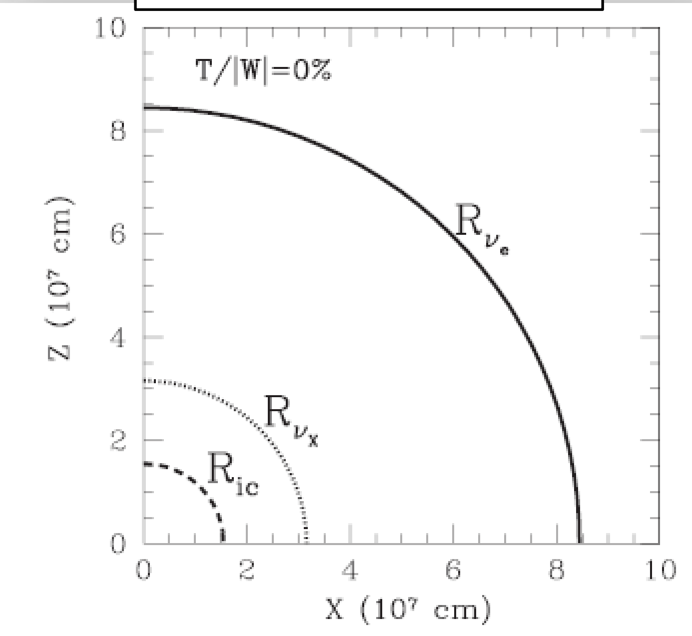
# Numerical Method

- 2D-axial symmetry
- Hydrodynamics ➔ ZEUS2D (Stone & Norman 92)
- Shen's EOS (Shen+ 98)
- Leakage scheme with all species (Epstein 78)

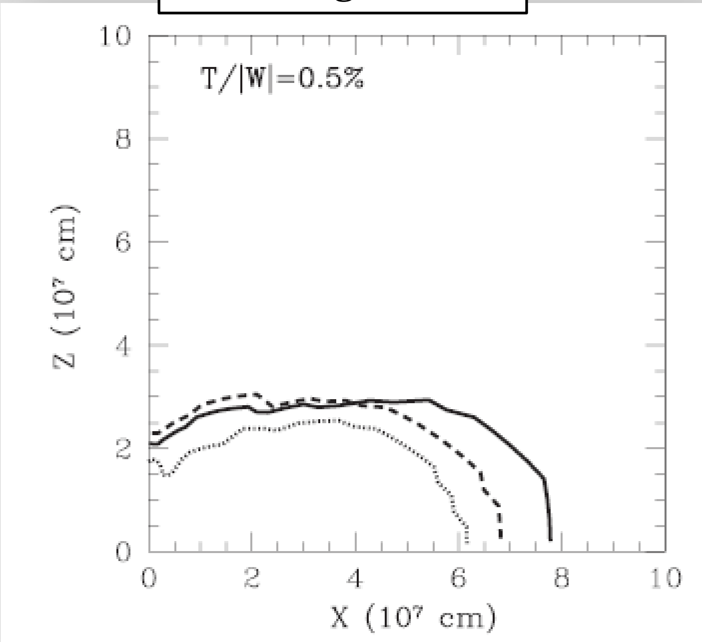
- Initial model ➔ 300 $M_\odot$ w/o rotation ($T/|W|$=0.5%, 2%)

# Neutrinosphere and Inner core

non-rotating model



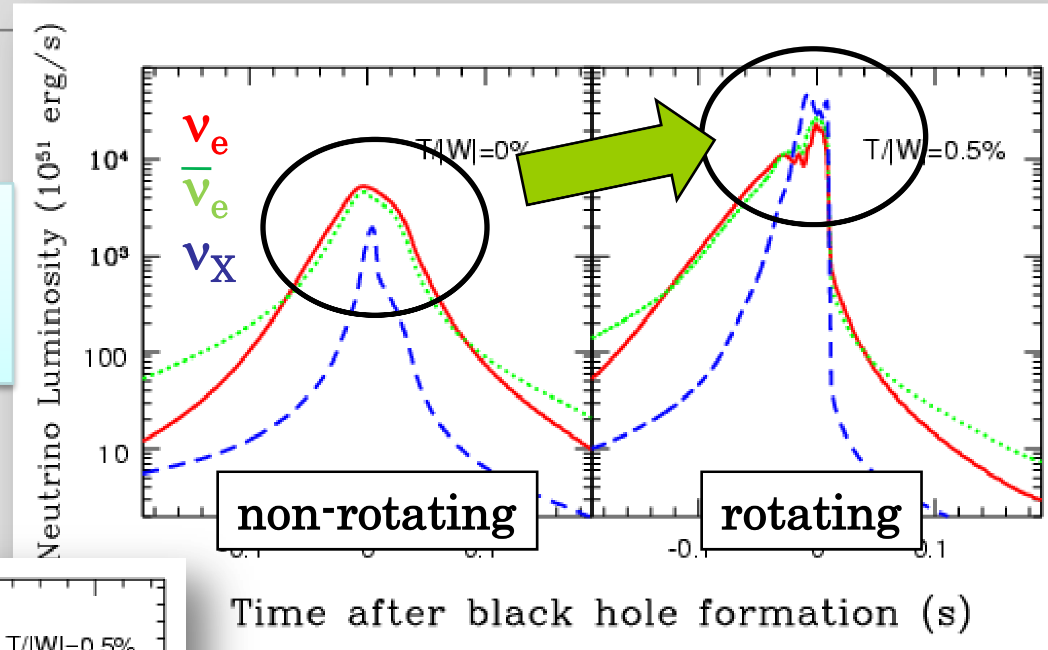

rotating model

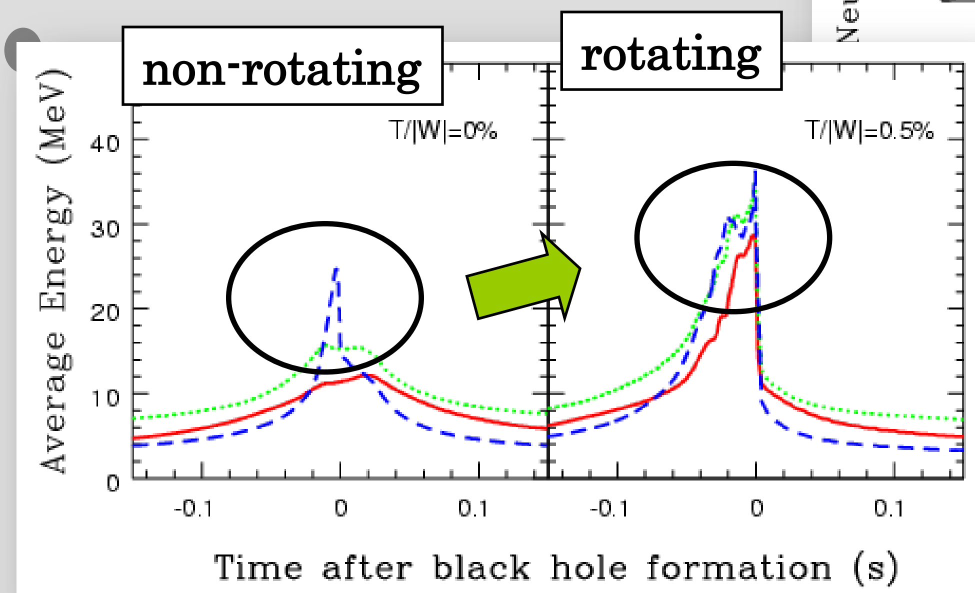



Rotation makes the inner core oblate and larger.
Collapse to BH is delayed by rotation and neutrinospheres shrink smaller.

# Rotation Effect

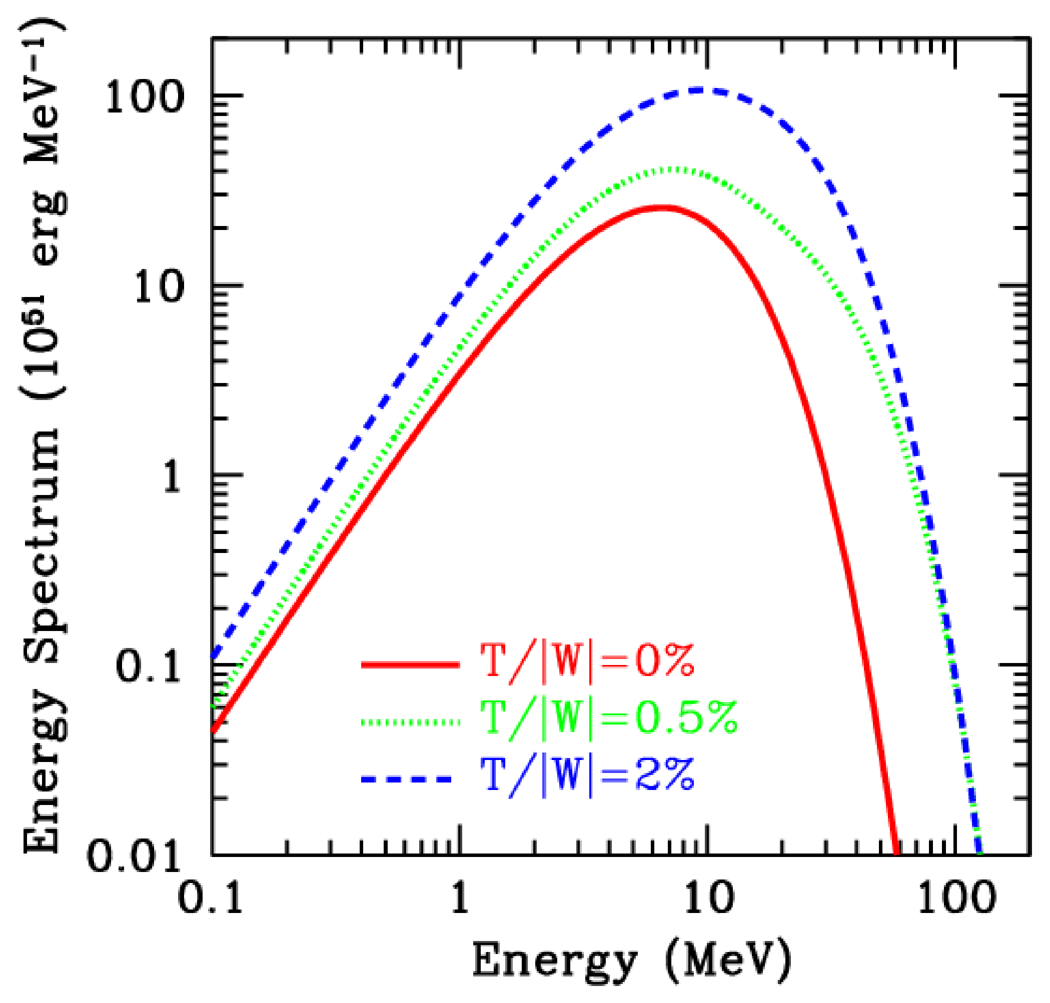
Luminosity gets larger




Average energy also gets larger

# Neutrino Spectrum




Luminosity spectrum

$$\frac{dL_\nu}{d\varepsilon'}(t) = \int dV Q_\nu \frac{dP_\nu}{d\varepsilon'}$$

$Q_\nu$ : emissivity
ε' : ν energy at local frame

(local) Fermi-Dirac distribution

$$\frac{dP_\nu}{d\varepsilon'} = \frac{2}{3\zeta_3 T_\nu^3} \frac{\varepsilon'^2}{e^{\varepsilon'/T_\nu} + 1}$$

$T_\nu$ : effective temperature of ν

# Relic Neutrino Background

Differential flux at Earth

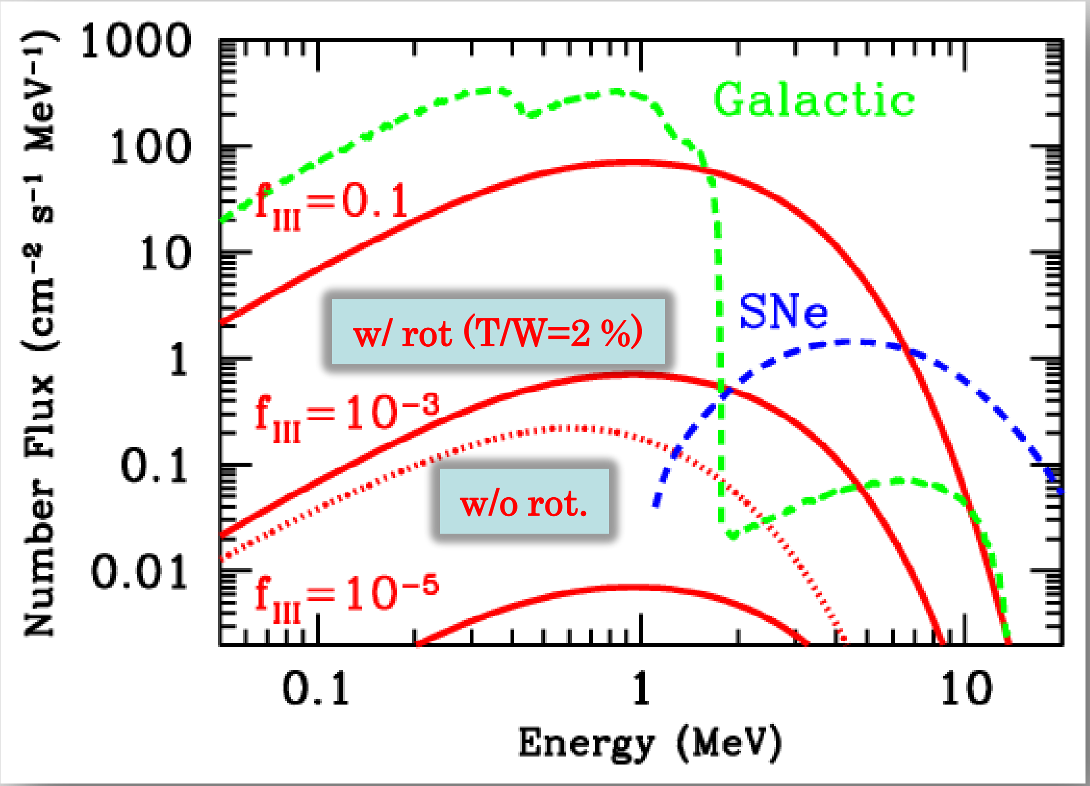
$$\frac{dF_\nu}{d\varepsilon} = c f_{III} n_\gamma \eta \frac{m_N}{m_{III}} \int_0^\infty dz (1+z) \psi(z) \frac{dN_\nu}{d\varepsilon'}$$

z: redshift
ε: ν energy observed at Earth (ε=ε'/(1+z))
$f_{III}$: baryon fraction of all baryons going through Pop III
$n_\gamma$: CMB photon density at z=0 (~ 410 $cm^{-3}$)
η: cosmic baryon-photon ratio (~ $6.3\times 10^{-10}$)
$m_N$: nucleon mass
$m_{III}$: mass of Pop III
ψ(z): star formation rate
dN/dε' : number spectra at the source frame

Assumptions

$f_{III} = 0.1, 10^{-3}, 10^{-5}$  $m_{III} = 300 M_\odot$  $\psi(z) = \delta(z-10)$

# Relic Neutrino Background




If we adopt the largest value for $f_{III}$, the contribution of Pop III dominate the ordinary core-collapse SNe below ~ 7 MeV.

# Gravitational Wave from Population III Stars

# Sources of Gravitational Wave

## matter

quadruple formula

Distance between observer and source

$$h_{ij}^{\mathrm{TT}} = \frac{2G}{c^4}\frac{1}{R}\frac{\mathrm{d}^2}{\mathrm{d}t^2}\left(I_{ij}^{\mathrm{TT}}\left(t-\frac{R}{c}\right)\right)$$

$$I_{ij}^{\mathrm{TT}} = \int \mathrm{d}V\,\rho\,(x,t)\left(x_i x_j - \frac{1}{3}x^2\delta_{ij}\right)$$

## neutrino

Epstein 78, Mueller & Janka 97

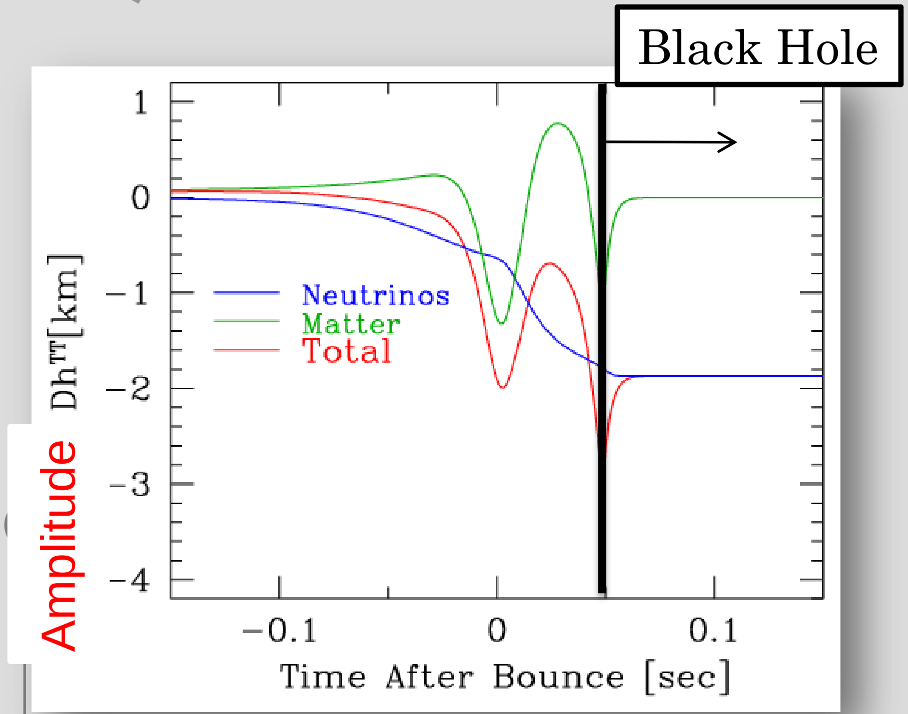
$$h_{\nu}^{\mathrm{TT}} = \frac{2G}{c^4}\frac{1}{R}\int_{-\infty}^{t} dt' L_{\nu}(t')\alpha(t')$$

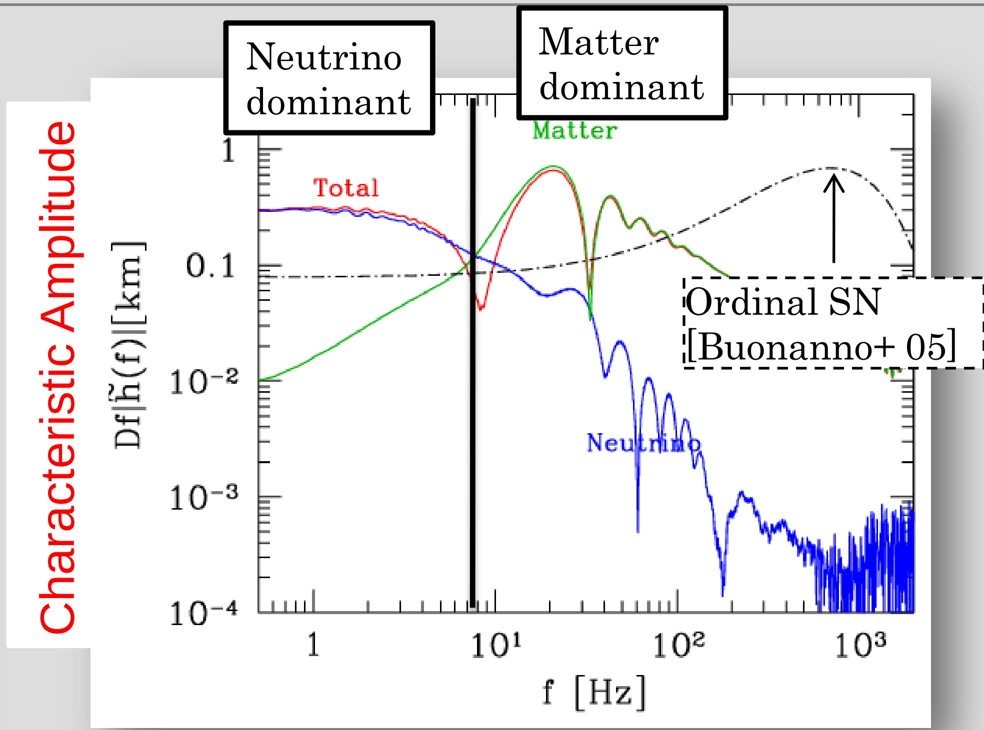
Neutrino luminosity

anisototropy

$$\alpha(t) \propto \frac{1}{L_{\nu}(t)}\frac{dL_{\nu}(t)}{d\Omega}$$

# GW from a single star




- Initially, the contribution of matter dominate the wave form.
- The GW from neutrinos gradually deform the signal from GW of the matter motion.
- Finally, the neutrino's GW dominate.

- The low frequency ➔ neutrino
- The high frequency ➔ matter

# Gravitational Wave Background

## Density parameter of GWB

Phinney 01

$$\Omega_{GW} = \frac{1}{\rho_c}\frac{d\rho_{GW}}{d\log f} = \frac{16\pi^2 c D^2}{15 G \rho_c}\int \frac{dz}{1+z}\left|\frac{dt}{dz}\right| \underbrace{\psi(z)}_{\text{SFR}} \int_{M_{min}}^{M_{max}} dm \underbrace{\phi(m)}_{\text{IMF}} f'^3 |\tilde{h}(f')|^2$$

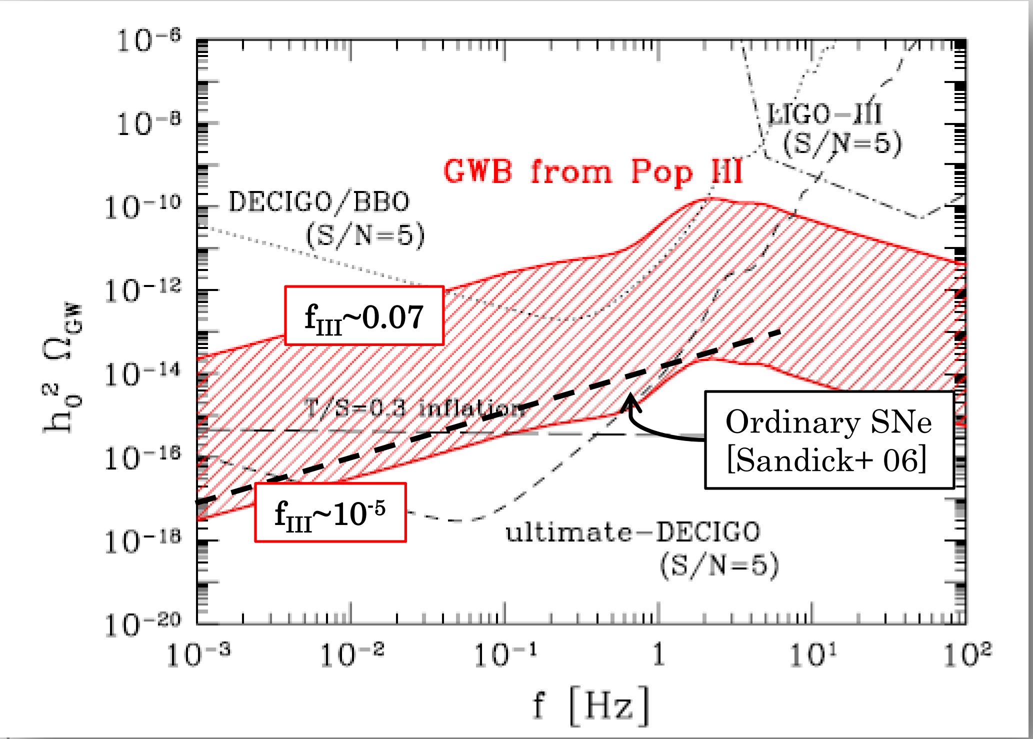
critical density: $\frac{3H_0^2}{8\pi G}$

GW signal from single star

## Assumption

- SFR ➔ Sandick *et al.*(2006)
- IMF ➔ Salpeter type: $\phi(m) \propto m^{-2.3}$ (300-1000$M_\odot$)
- Cosmology ➔ WMAP parameters

# Gravitational Wave Background




The GWB from Pop III stars can be detectable by future planning interferometers BBO and DECIGO. (It is hard for ground-based interferometers such as LIGO)

# Conclusion

- MHD simulation for core-collapse of Population III stars
  - Magnetic field driven jet before black hole formation.
- Effects of rotation on neutrino emission.
  - Rotation enhances the luminosity and energy of emitted neutrinos
  - Possibility of observational window at range of sub-MeV
- Gravitational wave emission
  - Neutrino contribution dominates low frequency regime
  - Detectability of gravitational wave background

*Thank you for attention!*