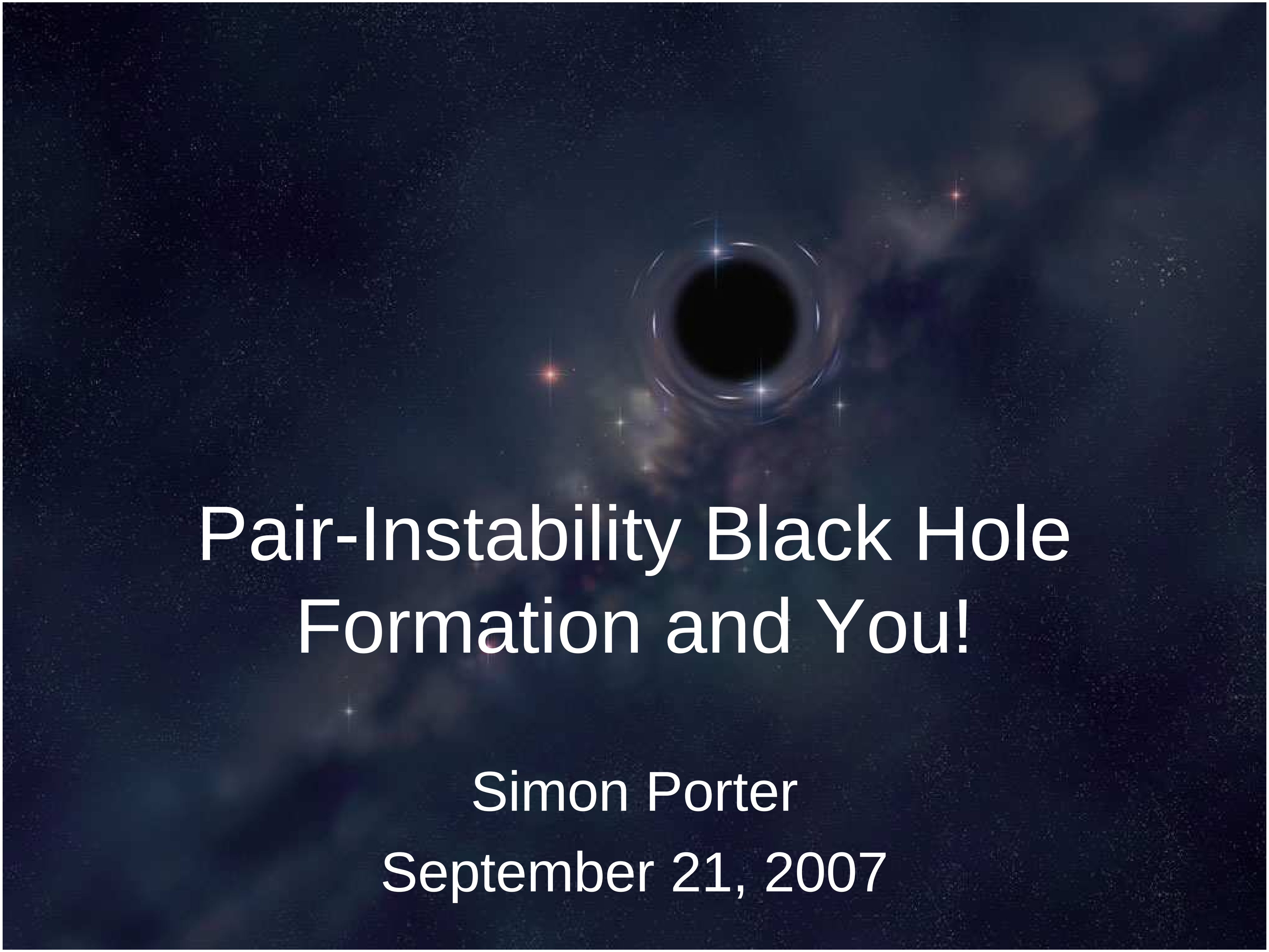


Pair-Instability Black Hole Formation and You!

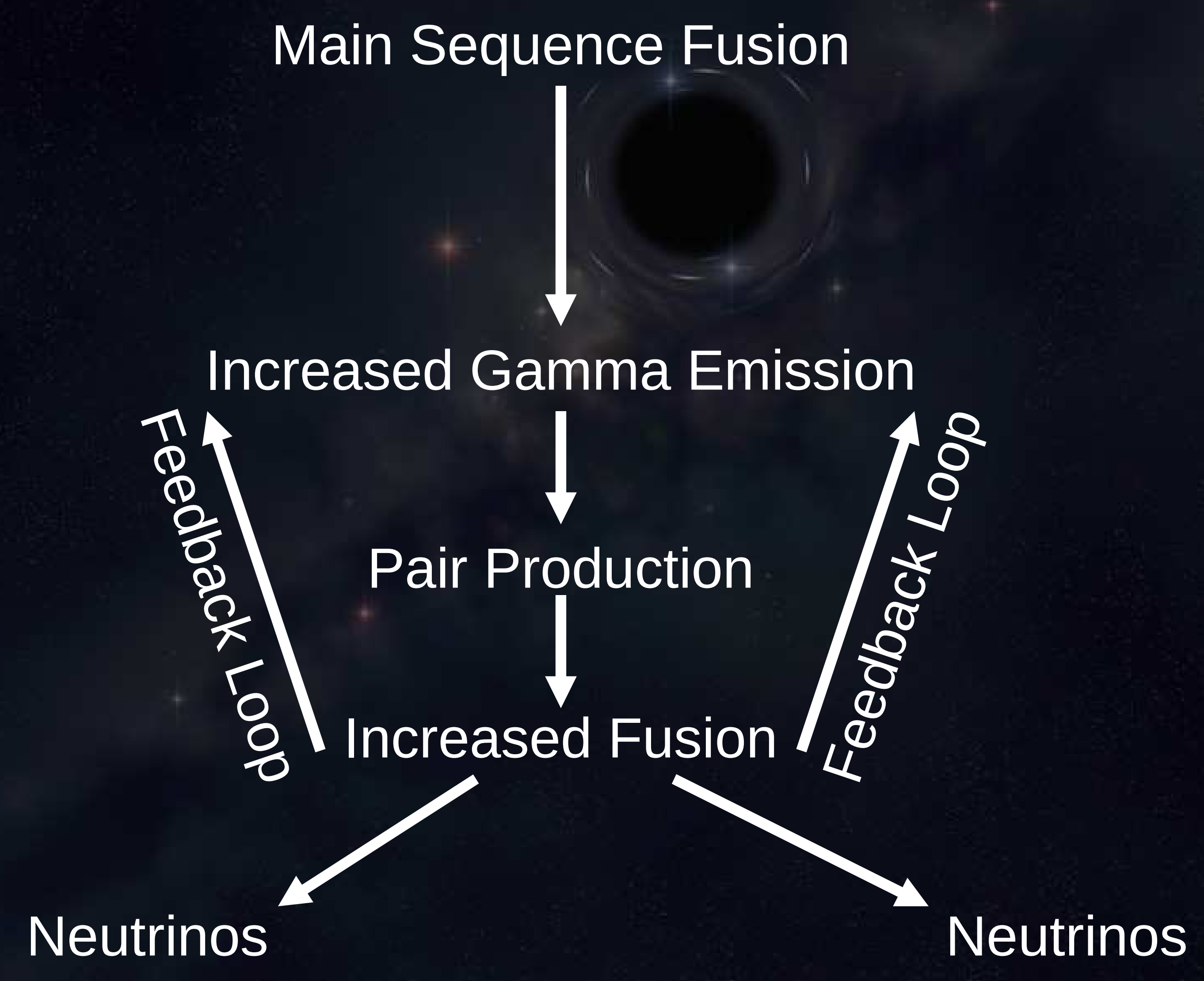
Simon Porter

September 21, 2007

Hyper-Large Pop III Stars

- Population III may have been home to a number of ridiculously large stars (100-10,000 $M_\odot$)
- Such stars would have practically zero metallicity, and thus loose little mass during main sequence
- Internal pressures high enough to create pair-instability

Pair Instability



Main Sequence Fusion

Increased Gamma Emission

Feedback Loop

Pair Production

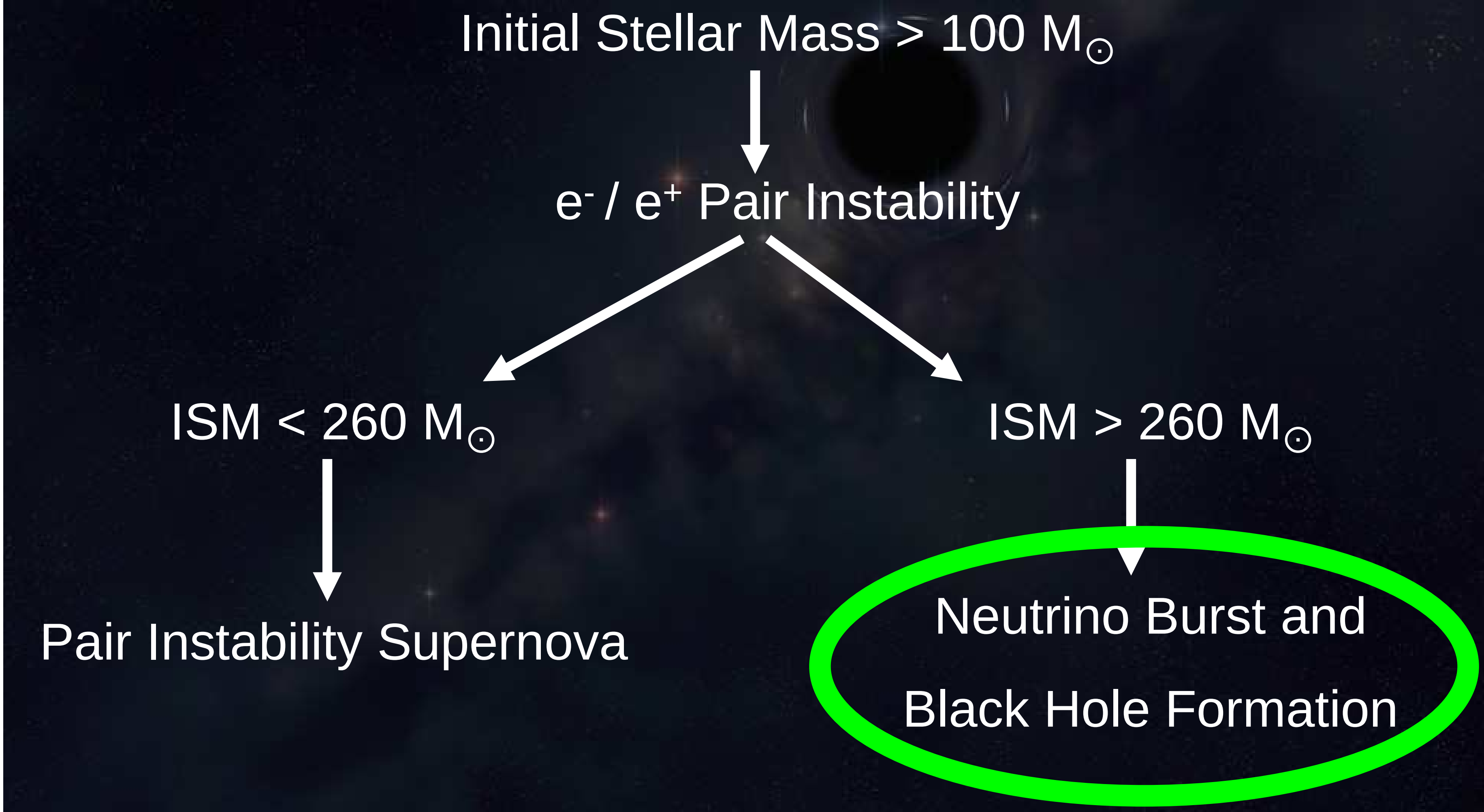
Feedback Loop

Increased Fusion

Neutrinos

Neutrinos

Pair Instability



Initial Stellar Mass > 100 $M_\odot$

e^- / e^+ Pair Instability

ISM < 260 $M_\odot$

Pair Instability Supernova

ISM > 260 $M_\odot$

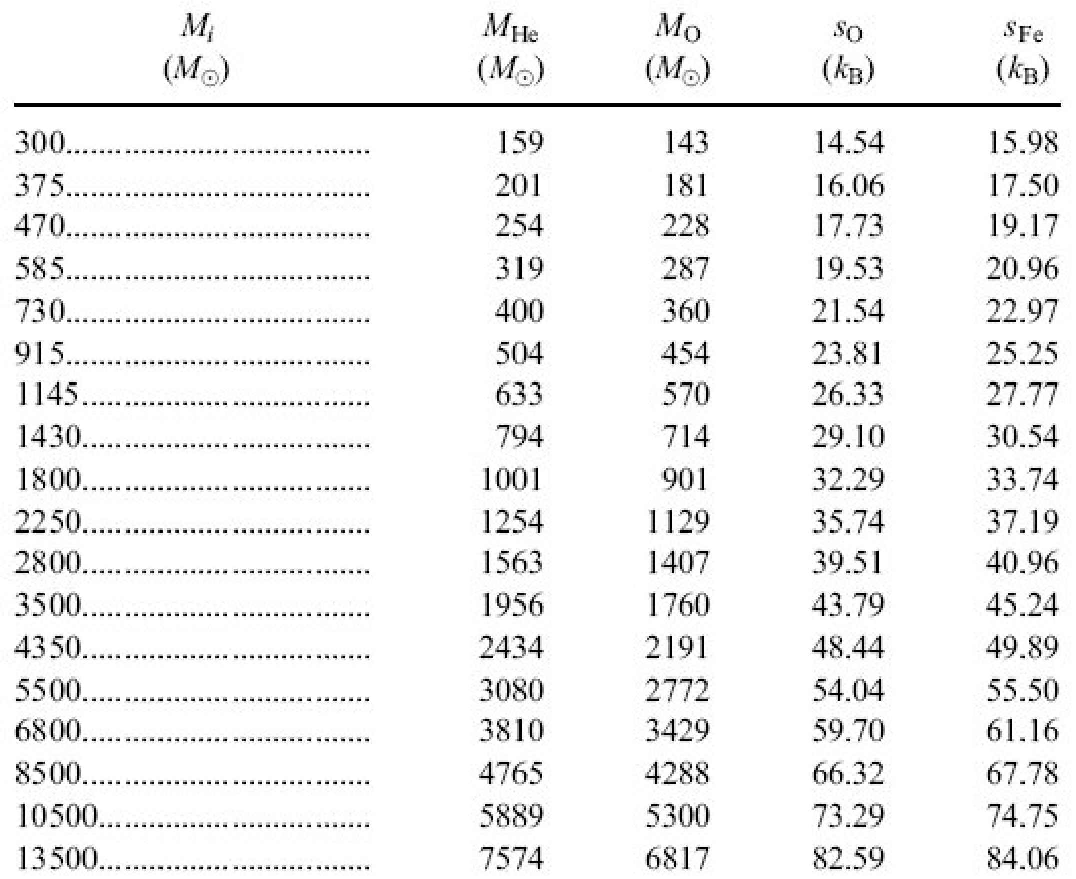
Neutrino Burst and Black Hole Formation

Science Objective

- Goal of Nakazato et al. was to model the spherically symmetric gravitation collapse of Pop III massive stars
- From this, a relic neutrino background flux can estimated, providing a direct measurement of Population III

Pop III Stars Modeled

- 18 ISMs modeled
- ISM > 260 $M_\odot$ (Black hole formation)
- ISM < 1600 $M_\odot$ (GR < Pair Instability)



M_i ($M_\odot$)	M_{He} ($M_\odot$)	M_{O} ($M_\odot$)	s_{O} (k_{B})	s_{Fe} (k_{B})
300	159	143	14.54	15.98
375	201	181	16.06	17.50
470	254	228	17.73	19.17
585	319	287	19.53	20.96
730	400	360	21.54	22.97
915	504	454	23.81	25.25
1145	633	570	26.33	27.77
1430	794	714	29.10	30.54
1800	1001	901	32.29	33.74
2250	1254	1129	35.74	37.19
2800	1563	1407	39.51	40.96
3500	1956	1760	43.79	45.24
4350	2434	2191	48.44	49.89
5500	3080	2772	54.04	55.50
6800	3810	3429	59.70	61.16
8500	4765	4288	66.32	67.78
10500	5889	5300	73.29	74.75
13500	7574	6817	82.59	84.06

The Numerical Model

- Model uses spacetime metric from Misner & Sharp (1964):

$$ds^2 = e^{2\phi(t,m)}c^2dt^2 - e^{2\lambda(t,m)}\left(\frac{G}{c^2}\right)^2 dm^2 - r^2(t,m)\left(d\theta^2 + \sin^2\theta d\phi^2\right),$$

- Energy equation:

$$e^{-\phi}\left(\frac{\partial\varepsilon}{\partial t}\right)_m = -\frac{p}{\Gamma}\frac{\partial}{\partial m}(4\pi r^2 U),$$

$$U = e^{-\phi}\frac{\partial r}{\partial t},$$

$$\Gamma = e^{-\lambda}\frac{\partial r}{\partial m},$$

Neutrino Reactions

$$\nu_e + n \longleftrightarrow e^- + p,$$

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

$$\nu + N \longleftrightarrow \nu + N,$$

$$\nu + e^- \longleftrightarrow \nu + e^-,$$

$$N + N' \longleftrightarrow N + N' + \nu + \bar{\nu}.$$

$$\gamma^* \longleftrightarrow \nu + \bar{\nu},$$

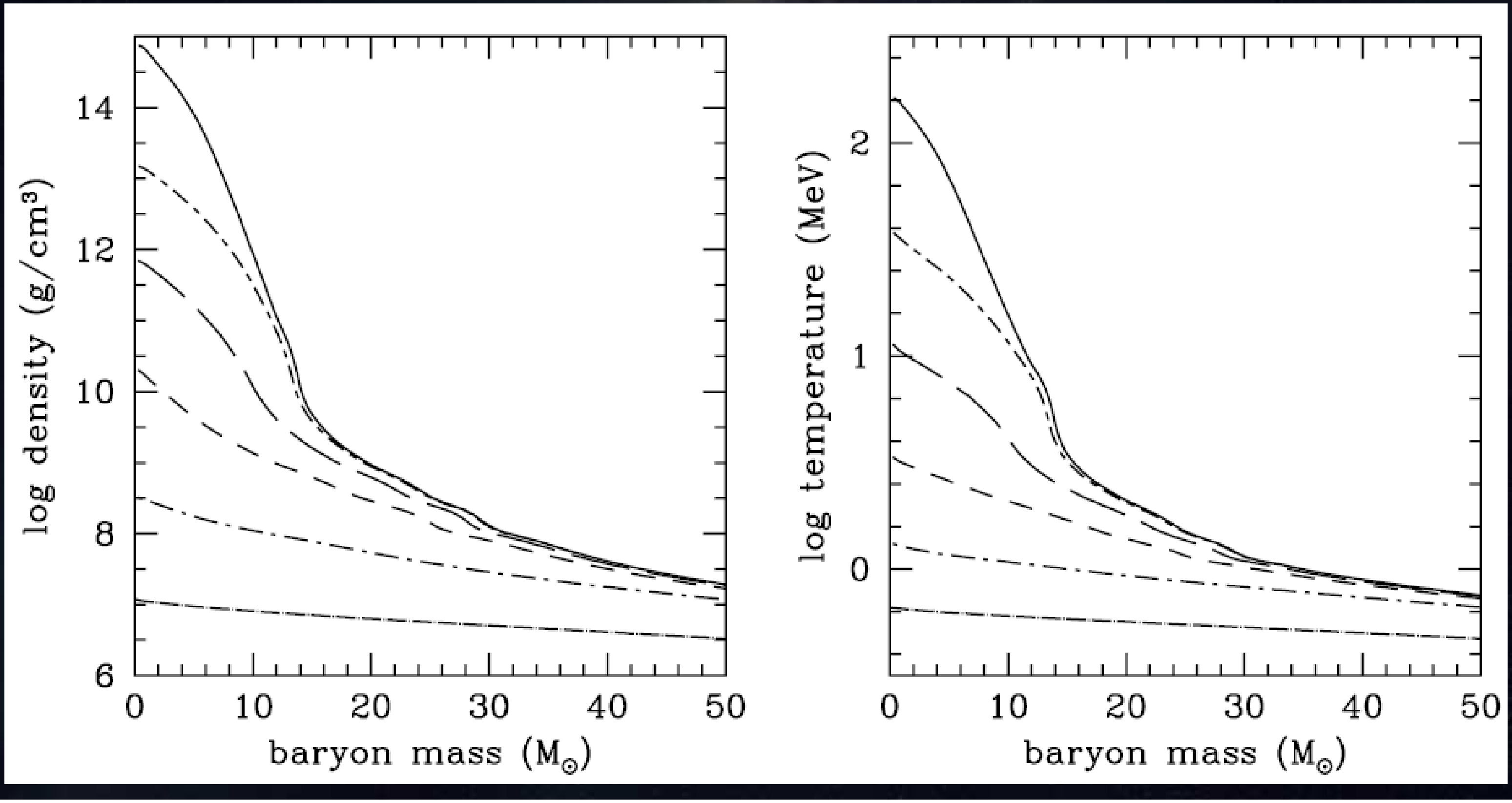
$$e^- + e^+ \longleftrightarrow \nu + \bar{\nu},$$

$$\nu + A \longleftrightarrow \nu + A,$$

$$\nu_e + A \longleftrightarrow A + e^-,$$

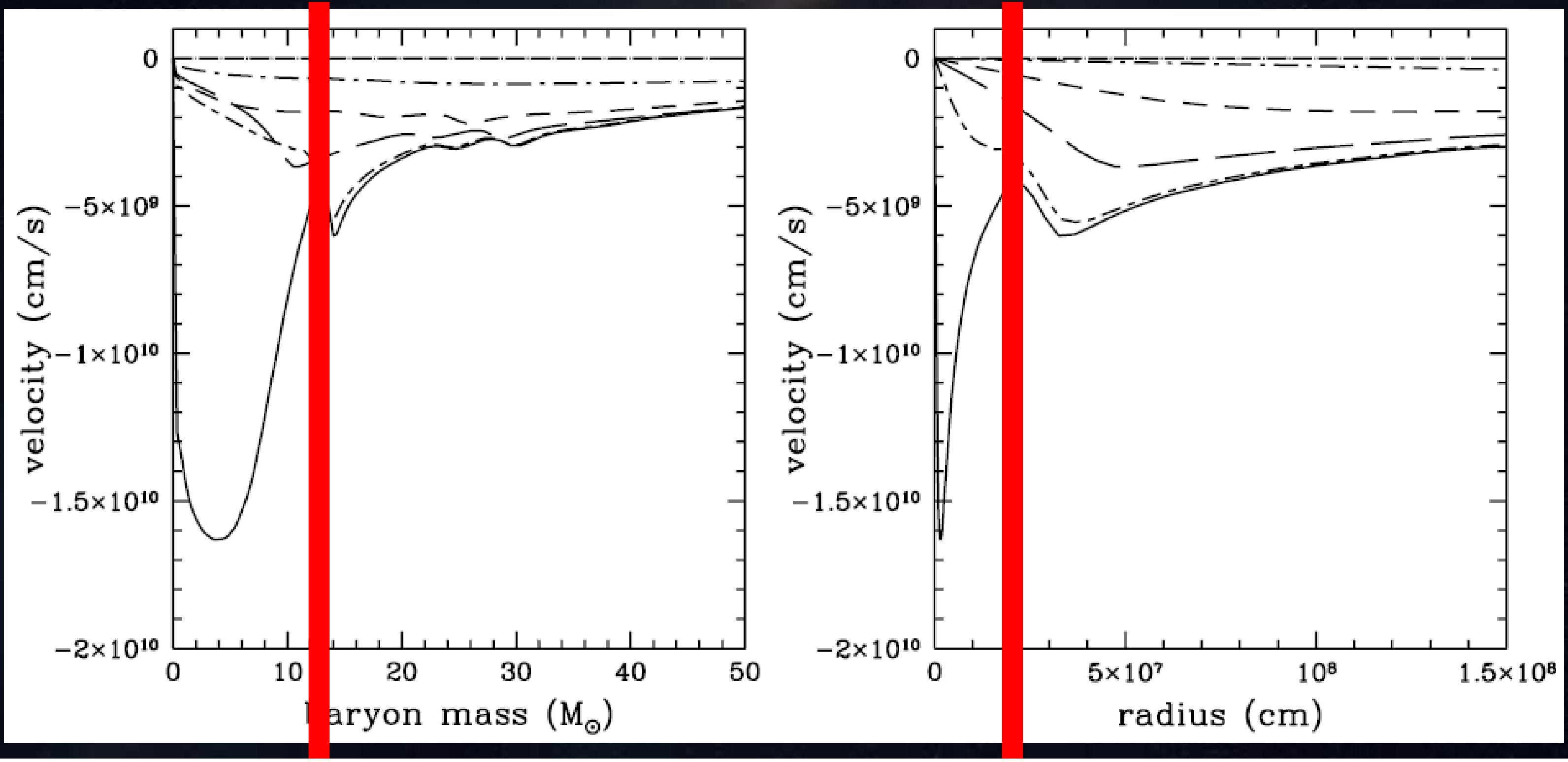
Core Collapse

- Start with a reference hydrodynamic/GR model for density and temperature



Core Collapse

- Core is divided into two parts:
  - Subsonic inner core (U ~ r)
  - Supersonic outer core (U ~ r $^{-1/2}$)



Apparent Horizon

- To chart black hole formation, the model tracks the trapped surfaces described by:

$$U + \Gamma < 0,$$

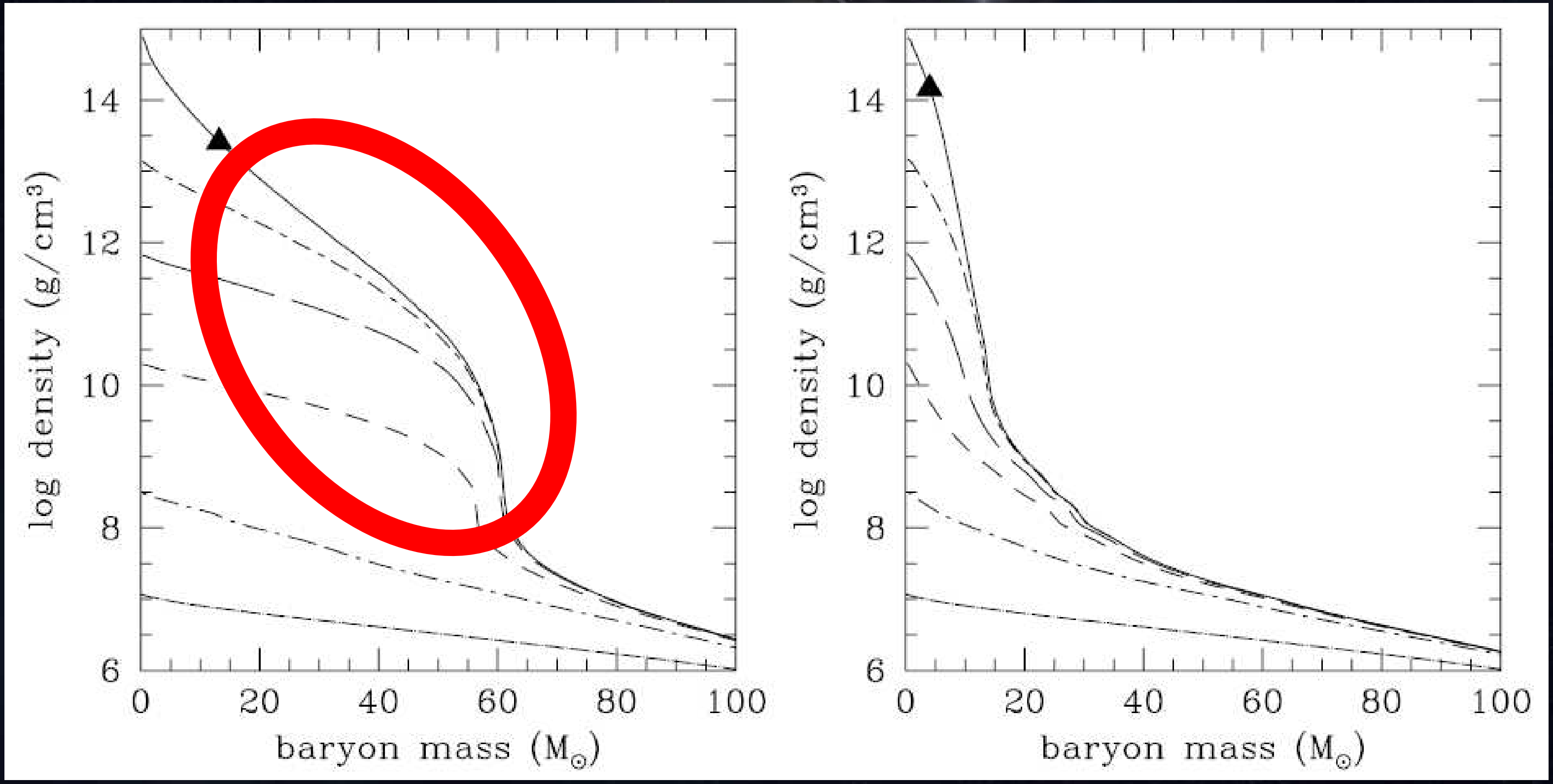
- Which is satisfied by:

$$r < r_g \equiv 2\tilde{m},$$

$$\Gamma^2 = 1 + U^2 - \frac{2\tilde{m}}{r}.$$

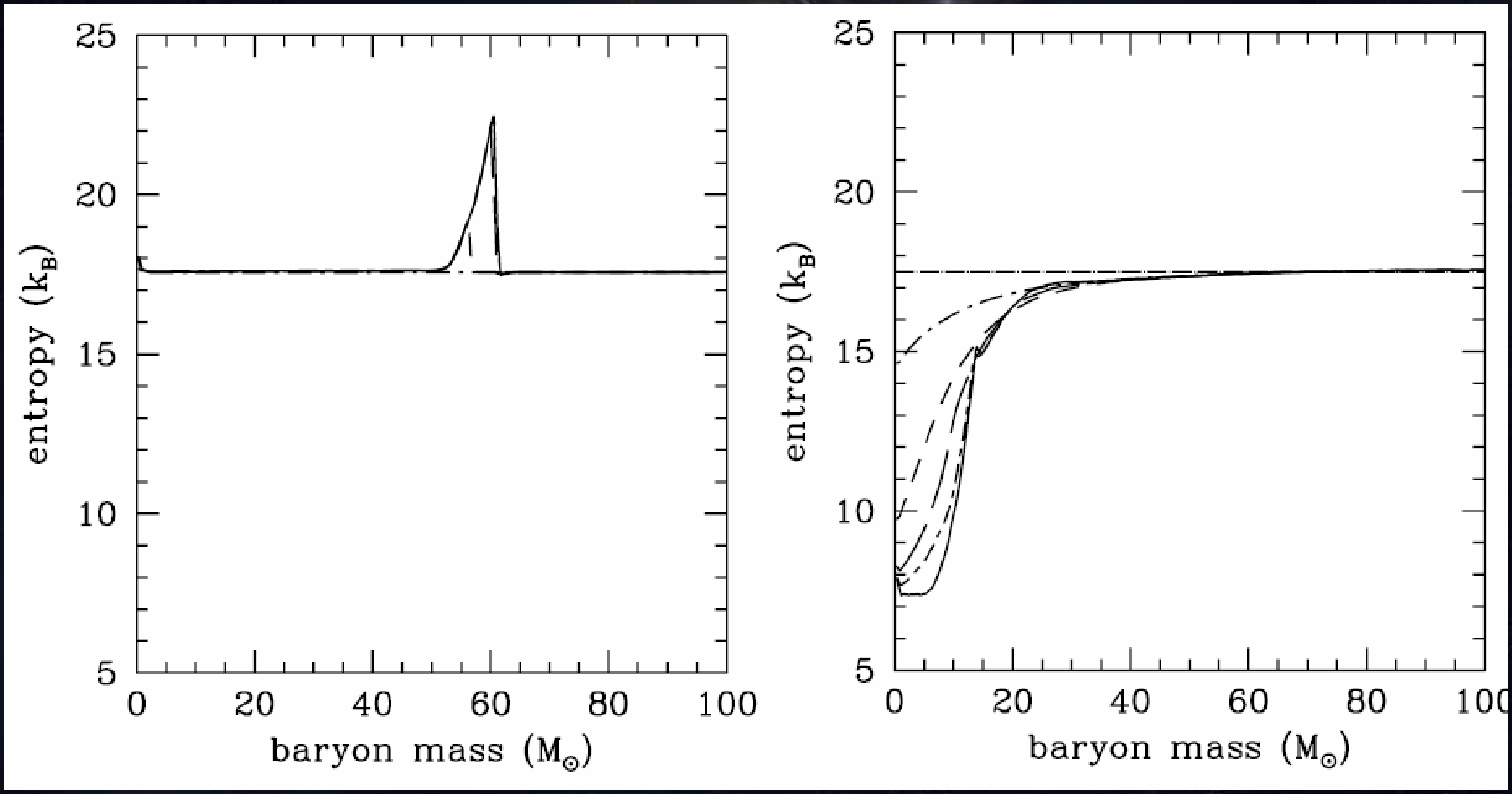
Importance of Neutrino Cooling

- Neutrino cooling has a massive effect on core collapse



Importance of Neutrino Cooling

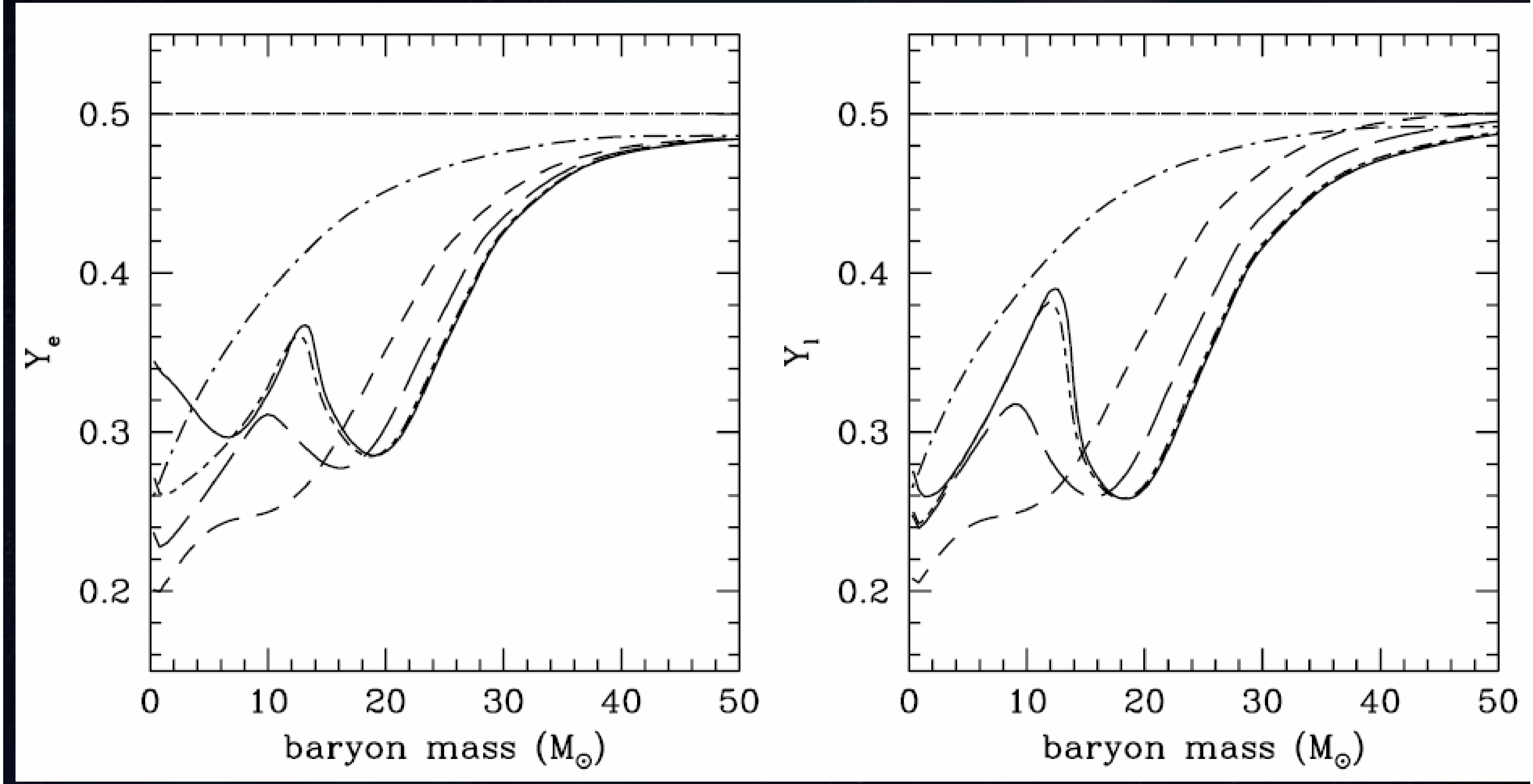
- With neutrino cooling, core shock disappears and entropy drops



Electron Fraction

- The high entropy in the core prevents the core from reaching electron degeneracy pressure.
- The positron capture rate is slower than electrons.
- Equilibrium is reached where β / inverse β reaction rates equal out

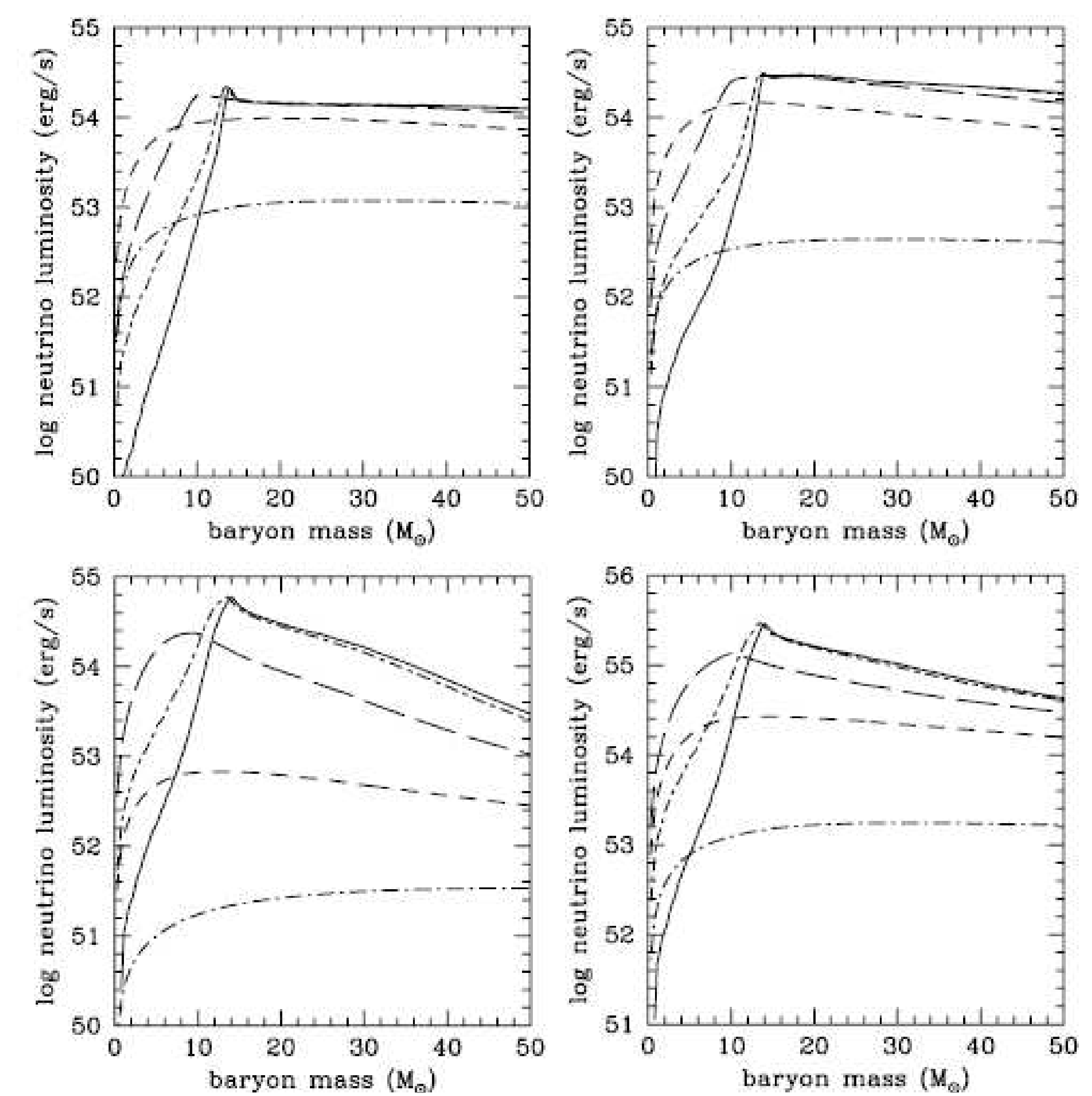
Electron Fraction



Neutrino Luminosity

- Because of the high reaction rates, the neutrino luminosity peaks near ~10^{54} erg/s, 10 times higher than a normal supernova
- But the apparent horizon closes within 100 ms, so total energy emitted is only ~10^{53} erg, comparable to a supernova

Neutrino Luminosity



e^- neutrino

e^+ neutrino

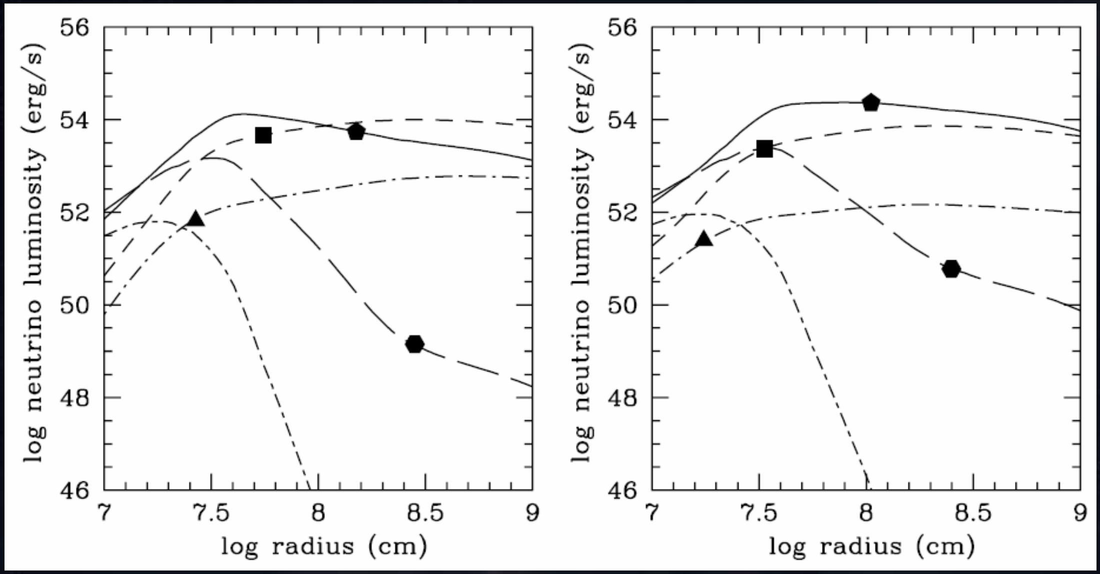
τ, μ neutrino

Total neutrino

Neutrino Luminosity

e^- neutrino,

t = -12.3 ms

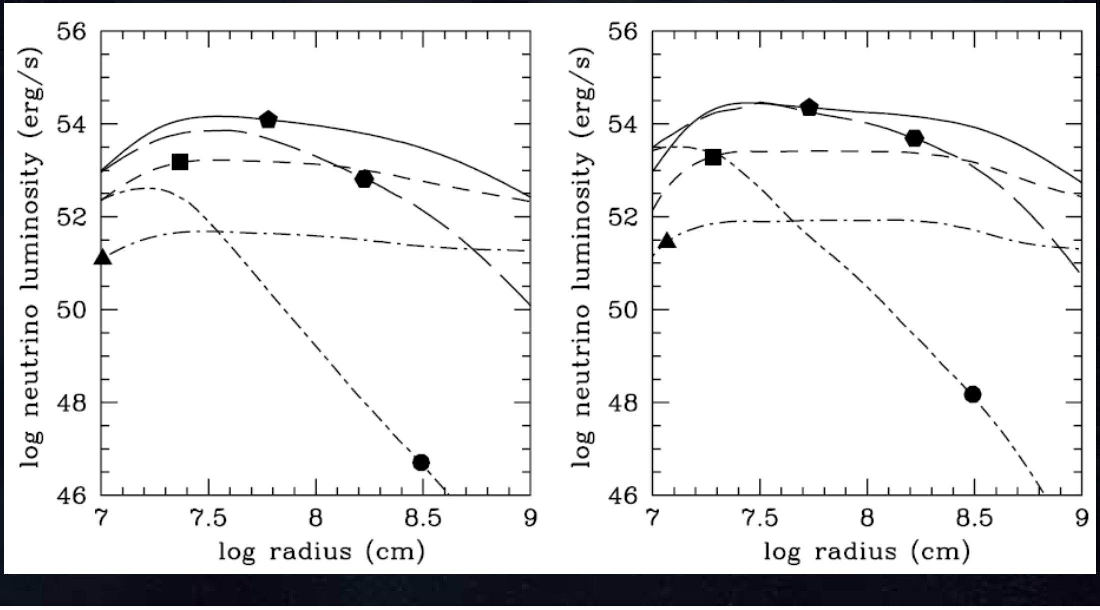


e^+ neutrino,

t = -12.3 ms

τ, μ neutrino,

t = -12.3 ms



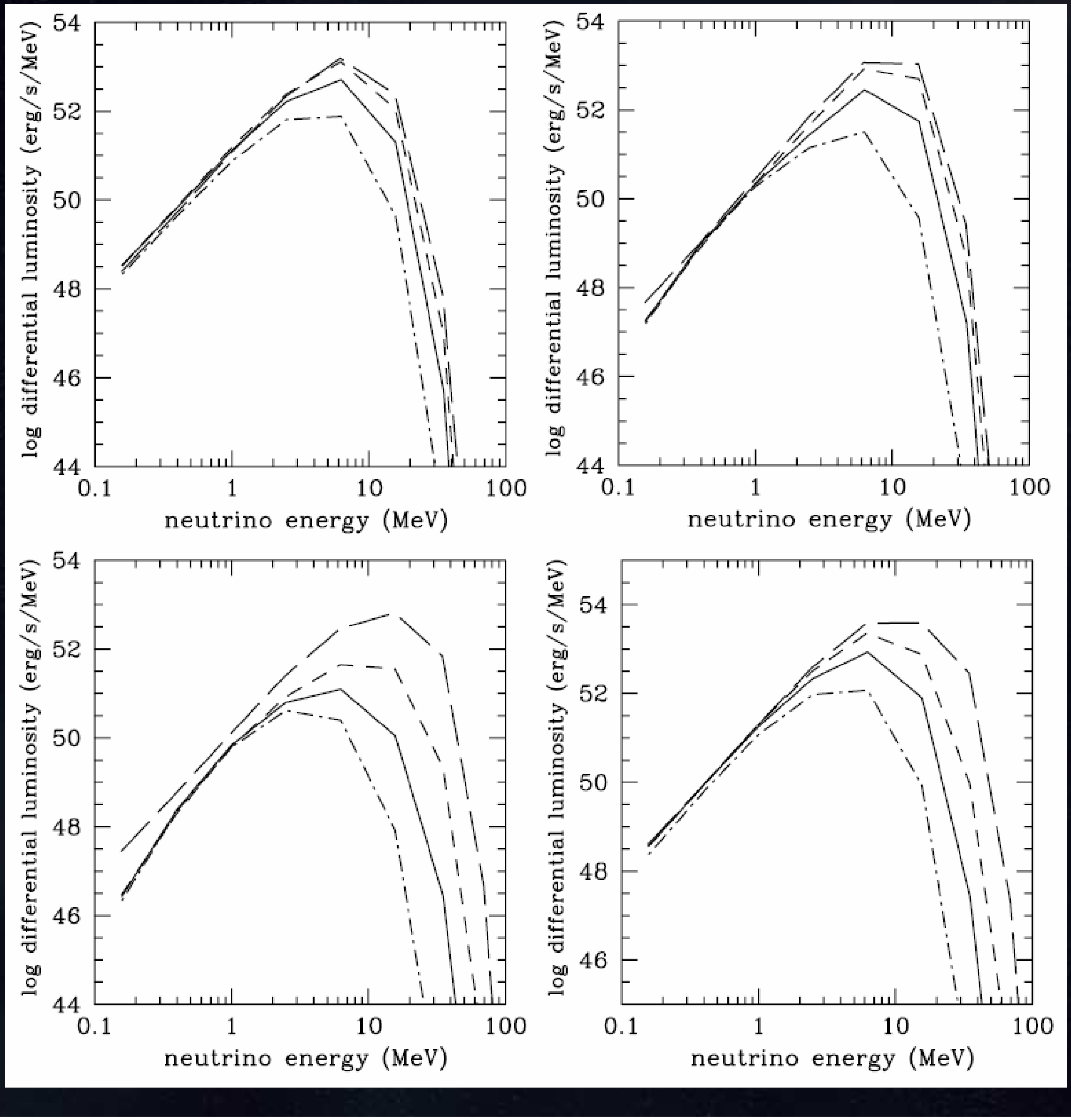
τ, μ neutrino,

t = -1.52 ms

Neutrino Spectrum

- Because of the high reaction rates, the neutrino luminosity peaks near ~10^{54} erg/s, 10 times higher than a normal supernova
- But the apparent horizon closes within 100 ms, so total energy emitted is only ~10^{53} erg, comparable to a supernova

Neutrino Energy Spectrum



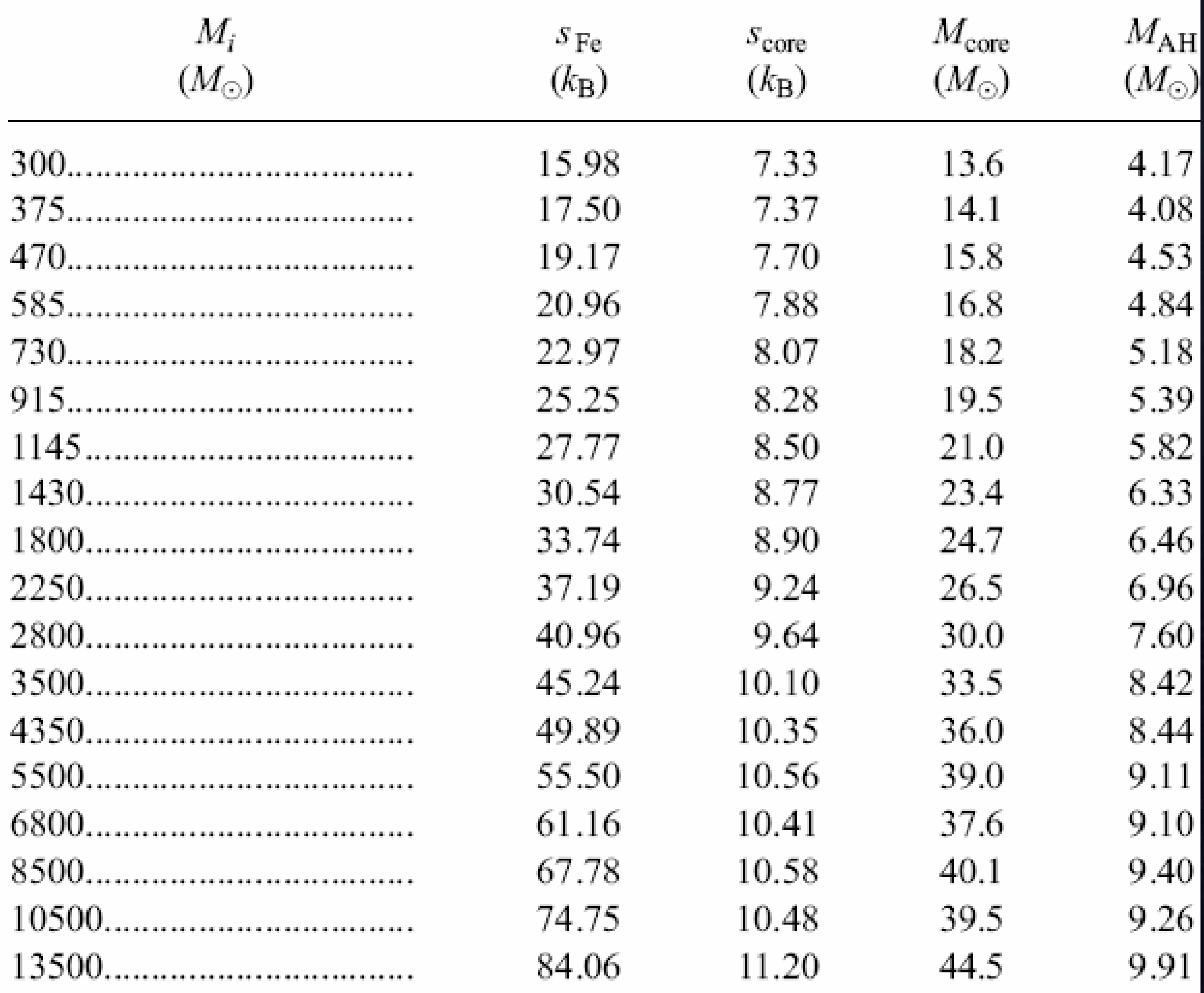
e^-
neutrino

e^+
neutrino

τ, μ
neutrino

Total
neutrino

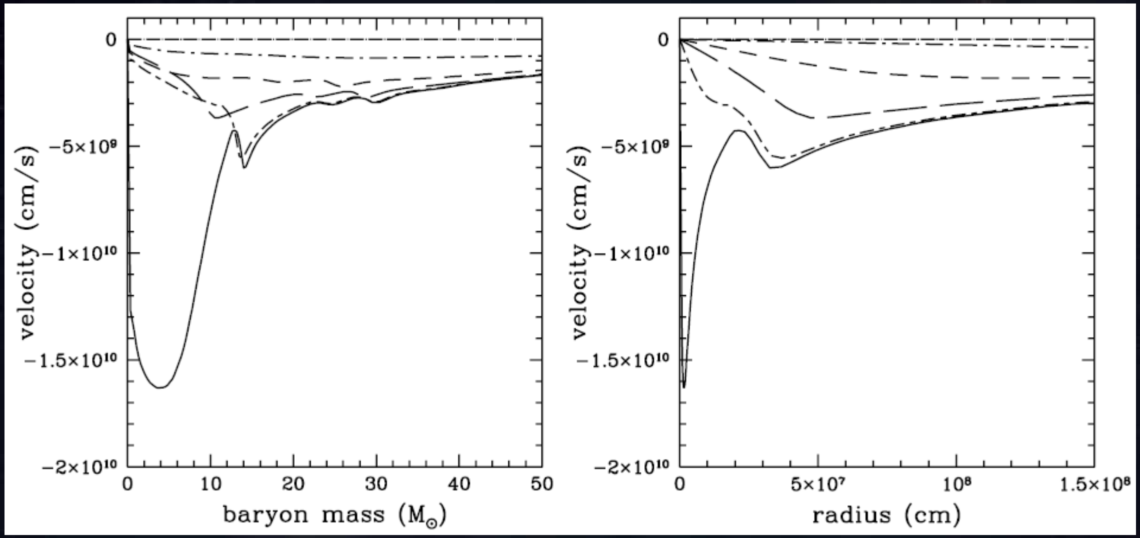
Initial Mass Dependence
(or lack thereof)



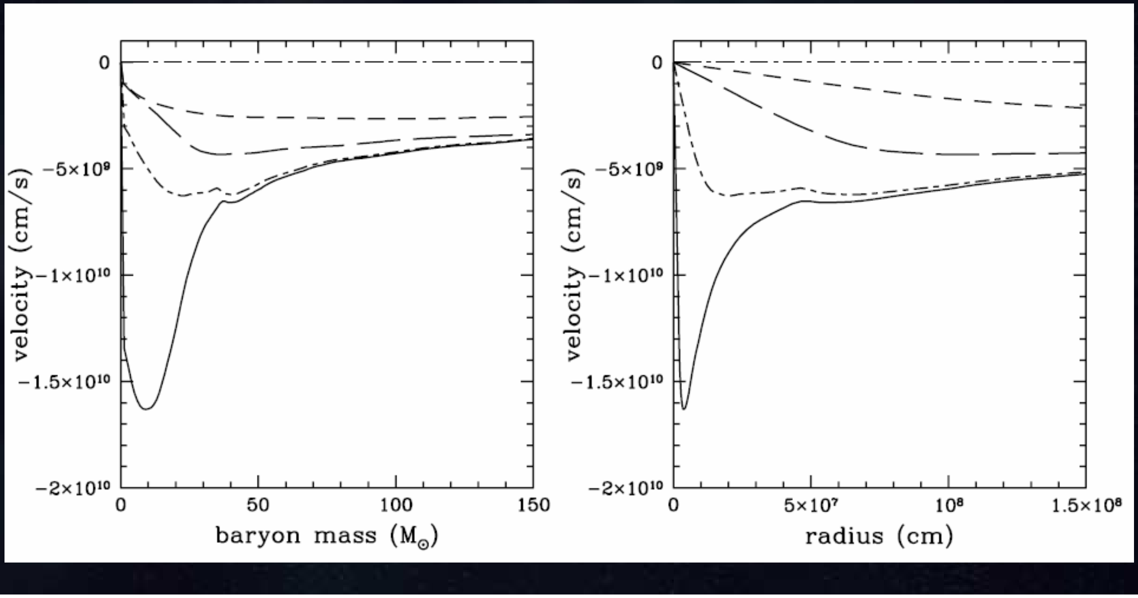
M_i ($M_\odot$)	$s_{\rm Fe}$ ($k_{\rm B}$)	$s_{\rm core}$ ($k_{\rm B}$)	$M_{\rm core}$ ($M_\odot$)	$M_{\rm AH}$ ($M_\odot$)
300	15.98	7.33	13.6	4.17
375	17.50	7.37	14.1	4.08
470	19.17	7.70	15.8	4.53
585	20.96	7.88	16.8	4.84
730	22.97	8.07	18.2	5.18
915	25.25	8.28	19.5	5.39
1145	27.77	8.50	21.0	5.82
1430	30.54	8.77	23.4	6.33
1800	33.74	8.90	24.7	6.46
2250	37.19	9.24	26.5	6.96
2800	40.96	9.64	30.0	7.60
3500	45.24	10.10	33.5	8.42
4350	49.89	10.35	36.0	8.44
5500	55.50	10.56	39.0	9.11
6800	61.16	10.41	37.6	9.10
8500	67.78	10.58	40.1	9.40
10500	74.75	10.48	39.5	9.26
13500	84.06	11.20	44.5	9.91

Initial Mass Dependence (or lack thereof)

375 $M_\odot$

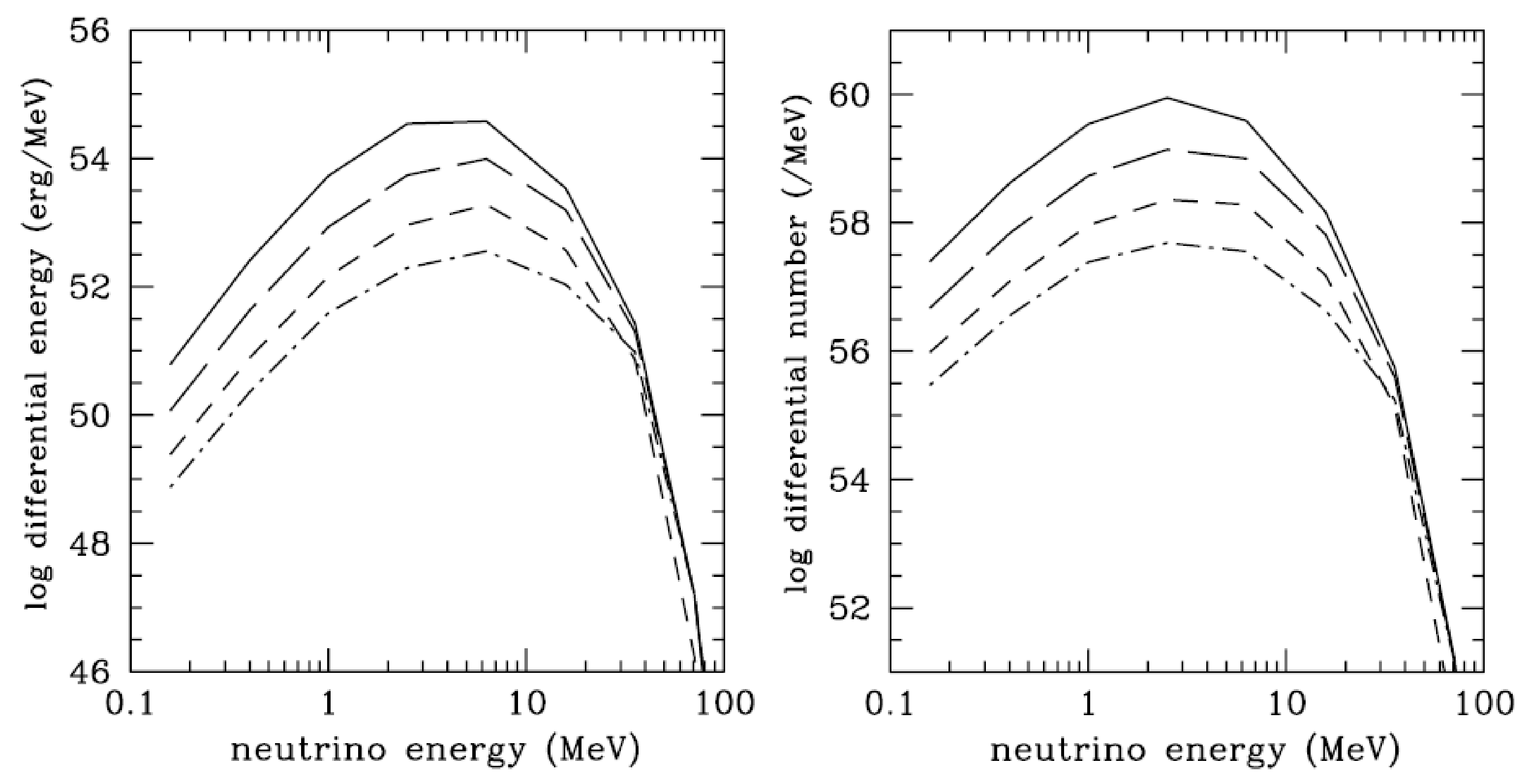


10,500 $M_\odot$



Initial Mass Dependence (or lack thereof)

- The spectrum does not change drastically over the mass range



Relic Neutrino Flux

- The net flux is an integral over the number density of Pop III stars and their redshift:

$$\frac{dF_\nu}{dE_\nu} = c \int_{z_i}^{z_f} \int_{M_0}^{M_N} \frac{dN(m, E'_\nu)}{dE'_\nu} (1+z) R_{\mathrm{PopIII}}(z, m)\, dm\, \frac{dt}{dz}\, dz,$$

- Substituting for redshift and adding a normalizing factor Ψ(z):

$$\begin{aligned} \frac{dF_\nu}{dE_\nu} = c \int_{M_0}^{M_N} dm\, \frac{dn(m)}{dm} \\ \times \int_{z_f}^{z_i} dz\, \frac{\psi(z)}{H_0(1+z)\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}} \frac{dN(m, E'_\nu)}{dE'_\nu}(1+z). \end{aligned}$$

Relic Neutrino Flux

- Using a Pop III mass distribution from Nakamura & Umemura (2001)

$$\begin{cases} \dfrac{dn}{dm} = Bm^{-\beta-1}, & m \geq M_{\min}, \\ n = 0, & m < M_{\min}, \end{cases}$$

$$B = (\beta - 1) M_{\min}^{\beta-1} n_b m_N \epsilon (1 - \kappa).$$

- So,

$$\int_{M_{k-1}}^{M_k} dm \, \frac{dn(m)}{dm} = \frac{\beta - 1}{\beta} n_b m_N \epsilon (1 - \kappa) M_{\min}^{\beta-1} \left(M_{k-1}^{-\beta} - M_k^{-\beta} \right),$$

Relic Neutrino Flux

- Putting it all together:

$$\frac{dF_\nu}{dE_\nu} = \frac{\beta - 1}{\beta} c n_b m_N \epsilon (1 - \kappa) M_{\rm min}^{\beta - 1} \sum_{k=1}^{N} \left(M_{k-1}^{-\beta} - M_k^{-\beta} \right)$$
$$\times \int_{z_f}^{z_i} dz \, \frac{\psi(z)}{H_0 (1+z) \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}} \frac{dN(\widetilde{M}_k, E'_\nu)}{dE'_\nu} (1+z),$$

- But we still need a Ψ(z)!

Relic Neutrino Flux

- Model A assumes reionization at z = 17 ± 5 based on WMAP data (Spergel 2003)

$$\psi(z) = \psi_A(z) \equiv \frac{1}{5\sqrt{2\pi}} \exp\left[-\frac{(z-17)^2}{20}\right] H_0(1+z)\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}.$$

- Model B assumes reionization at z ~ 10 (Scannapieco et al., 2003)

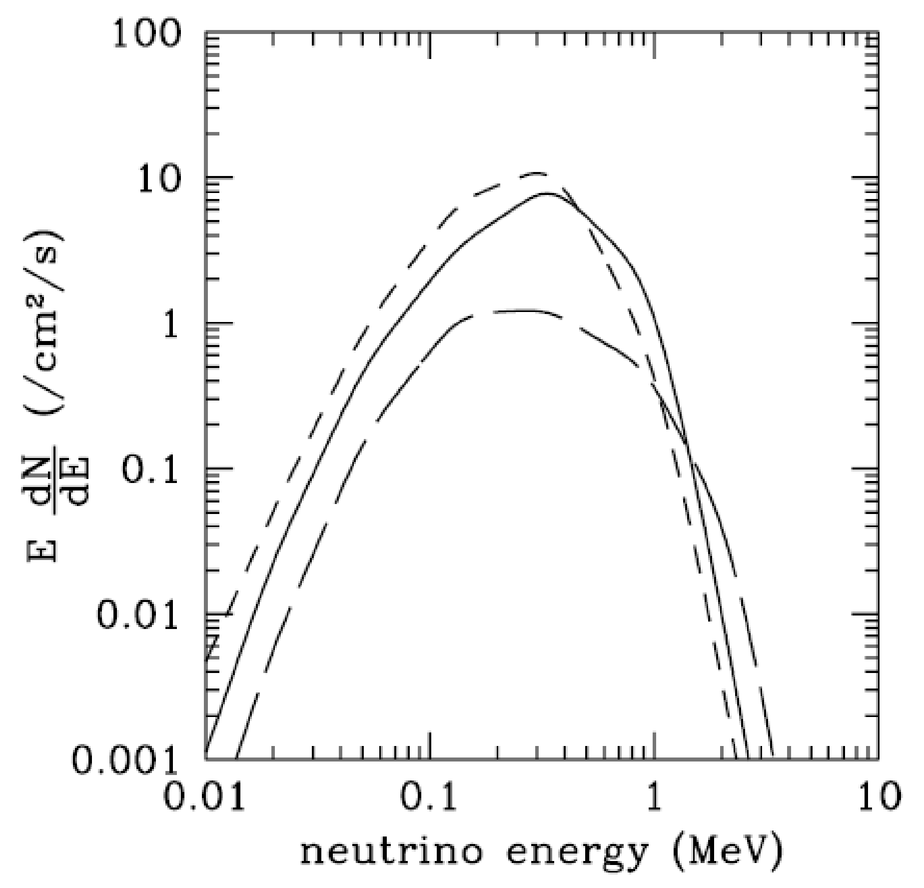
$$\psi(z) = \psi_B(z) \equiv \delta(z-10) H_0(1+z)\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}.$$

- Model C just assumes continuous Pop III formation across z = 4-12 (Yonetoku, 2004)

$$\psi(z) = \psi_C(z) \propto (1+z)^{1.7} \qquad \text{for} \quad 4 < z < 12,$$

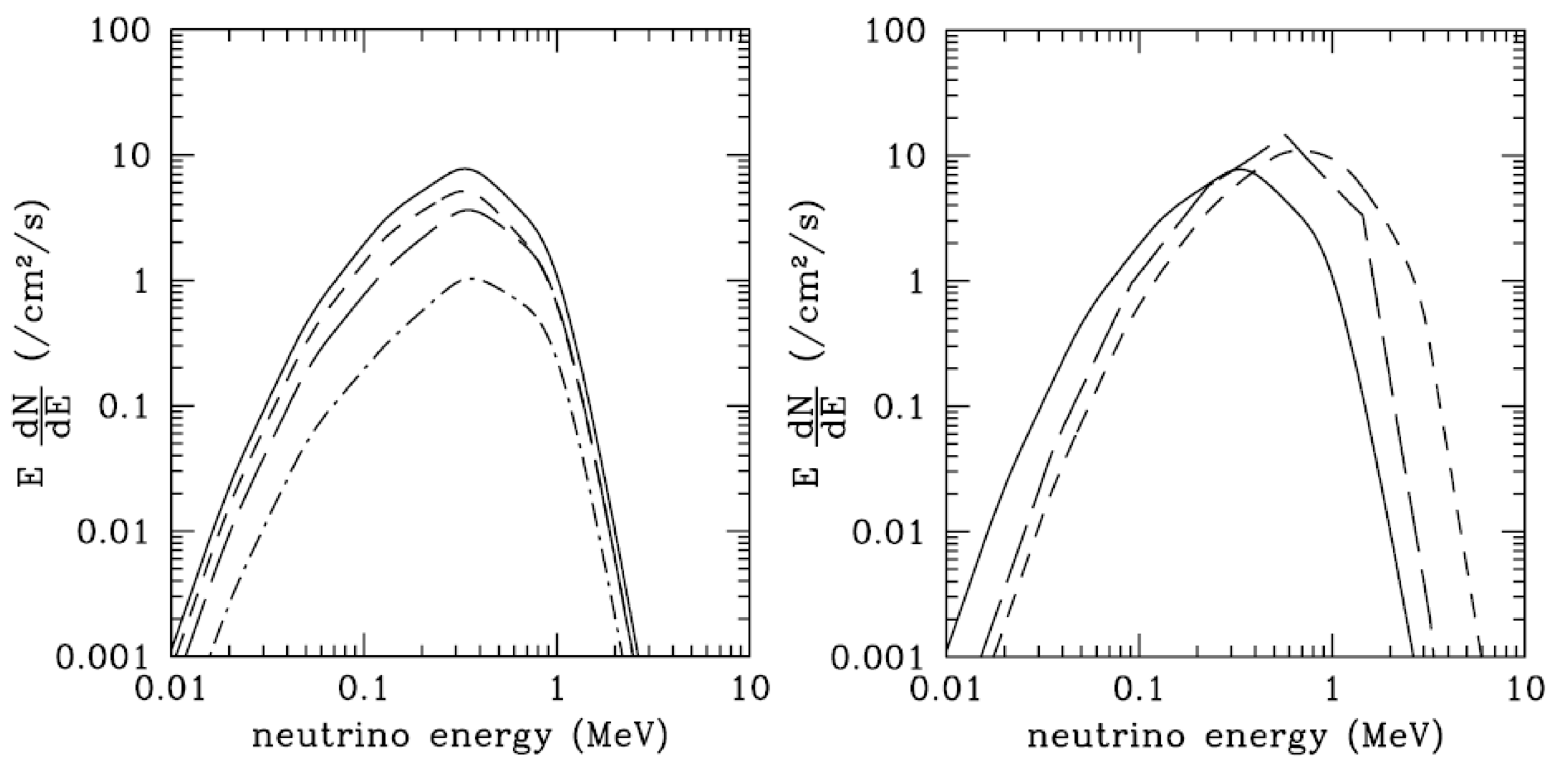
Results!

- Assuming Model A (WMAP):



Results!

- Anti-electron neutrino flux is relatively high!



Detection?

- Solar neutrinos will overwhelm electron neutrinos below 18 MeV, and ordinary supernovas above 10 MeV
- Terrestrial nuclear reactors will dominate anti-electron neutrinos below 10 Mev
- So, no possible detection, *yet…*

Summary

- Pop III stars greater than 260 $M_{\odot}$ would form black holes due to pair instability
- Such a process would produce an intense neutrino burst, with an energy distribution independent of initial mass
- These neutrinos would create a relic background source
- But which is below current limits of detection