Australian National University

ASTR2013 – *Foundations of Astrophysics*

Week 5: Stellar Evolution

Following Dan Maoz – Astrophysics in a Nutshell

Mike Ireland

Field Trip!!!

- This is a compulsory part of the course comprising 30% of the assessment.
- Payment and pre-departure form due this week.
- Next week, rooms will be assigned for those who haven’t chosen to share with friends.
- Week 6 Lecture and tutorial is prep for field trip.

Revision - Stellar Evolution

- A 1 M_{sun} star goes through the following stages. Lets see who remembers their key features:
  – Pre-main sequence contraction
  – Main sequence
  – Sub-giant phase
  – First ascent giant branch
  – Red clump
  – Asymptotic Giant Branch
  – White Dwarf

Revision - White Dwarfs

- Electron degeneracy pressure can be derived from simple quantum particle-in-a-box considerations. In the non-relativistic case and relativistic cases respectively, this is:

$$P_e = \left(\frac{3}{\pi}\right)^{2/3} \frac{h^2}{20 m_e m_p^{5/3}} \left(\frac{Z}{A}\right)^{5/3} \rho^{5/3}.$$

$$P_e = \left(\frac{3}{8\pi}\right)^{1/3} \frac{hc}{4 m_p^{4/3}} \left(\frac{Z}{A}\right)^{4/3} \rho^{4/3}.$$

- As the electrons approach relativistic speeds throughout the white dwarf, the star approaches the limiting mass called the Chandrasekhar mass.

What happens if a Fe core white dwarf reaches this limit?

$$M_{\mathrm{ch}} = 0.21 \left(\frac{Z}{A}\right)^2 \left(\frac{hc}{G m_p^2}\right)^{3/2} m_p.$$

Week 5 Summary

Textbook: Sections 4.3, 4.4, 4.5.

1. End states of massive stars.
2. Neutron Stars and Black Holes.
3. Supernovae Ia – exploding white dwarfs
4. Accretion disk brief intro.

The End of a Massive Star

- As the inert Fe core approaches the Chandrasekhar mass and collapses, it compresses and the nuclear reactions go backwards.
- Total energy available in complete collapse to a black hole is *much* larger than that available from nuclear reactions [exercise for board – derive that the radius at which collapse to release 0.65% of the mass energy is ~160 km]
- When electrons are absorbed in *neutronization* processes, the electron degeneracy pressure goes away.

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

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

$$e^- + {}^{56}\mathrm{Mn} \rightarrow {}^{56}\mathrm{Cr} + \nu_e.$$

- Collapse continues until a neutron star is formed.

Neutron Stars

- We can find the radius of an object supported by *neutron degeneracy pressure* rather than electron degeneracy pressure by the EOS of a nonrelativistic electron gas (4.27) and the virial theorem, to get a relationship between degenerate particle mass *m* and radius:

$$R \propto \frac{1}{m}\left(\frac{Z}{A}\right)^{5/3}$$

- This implies neutron stars are 574 times smaller than a white dwarf at the same mass in the non-relativistic limit, giving a mass (see textbook) of:

$$r_{\rm ns} \approx 2.3 \times 10^9 \text{ cm } \frac{m_e}{m_n}\left(\frac{Z}{A}\right)^{5/3}\left(\frac{M}{M_\odot}\right)^{-1/3} \approx 11 \text{ km}\left(\frac{M}{1.4M_\odot}\right)^{-1/3}.$$

Neutron Stars

- Just like the Chandrasekhar limit for white dwarfs, there is an equivalent limit for Neutron stars:

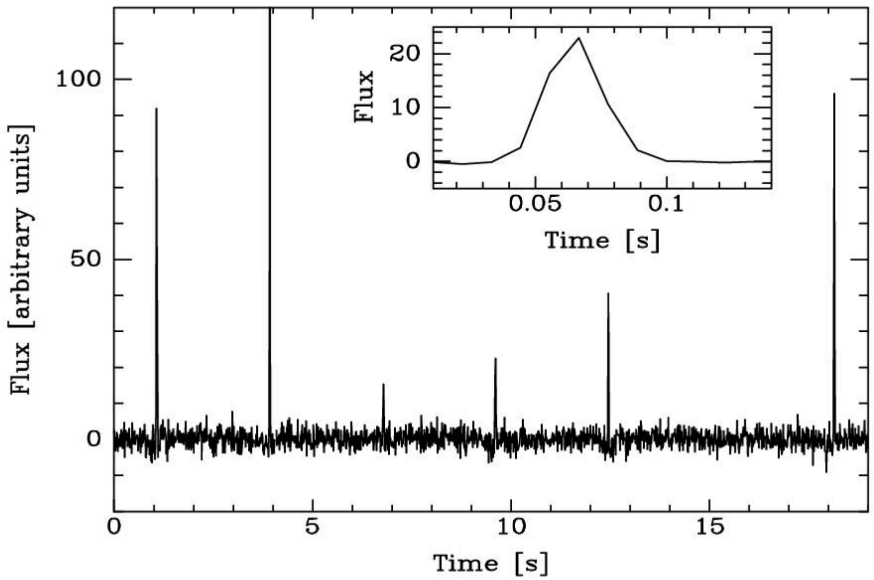
$$M_{\mathrm{ch}} = 0.21 \left(\frac{Z}{A}\right)^2 \left(\frac{hc}{Gm_p^2}\right)^{3/2} m_p$$

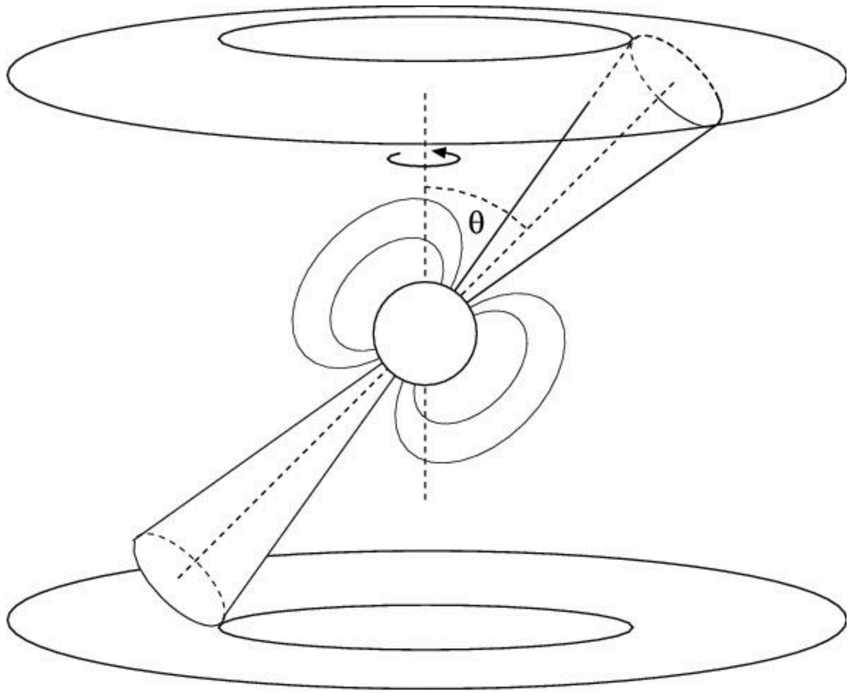
Replace this with 1.0, and get 4 times the mass?

- However, general relativity becomes important (GM/R close to c^2), really complicating this scenario.
- Neutrons are also *not* point masses – the strong nuclear force comes into play, and the equation of state is a subject of active research.
- The maximum mass of a neutron star is agreed to be around $2M_{sun}$.

Pulsars

- The dynamical timescale of a neutron star is ~1ms.
- Most of the neutron stars we observe are as *pulsars*, with periods of a few ms to many seconds.
- Interpreted as where electrons caught in the magnetic field of a neutron star emit radio waves brightly whenever the N or S pole points in our direction.





Black Holes

- This isn't a General Relativity course, so we'll only introduce black holes roughly.
- If the potential energy of a compact object GM/R approaches c^2, then Newtonian gravity has to be replaced with general relativity.
- Once an object can no longer support itself, it collapses to a point-like object with an apparent radius of the Schwarzschild radius:

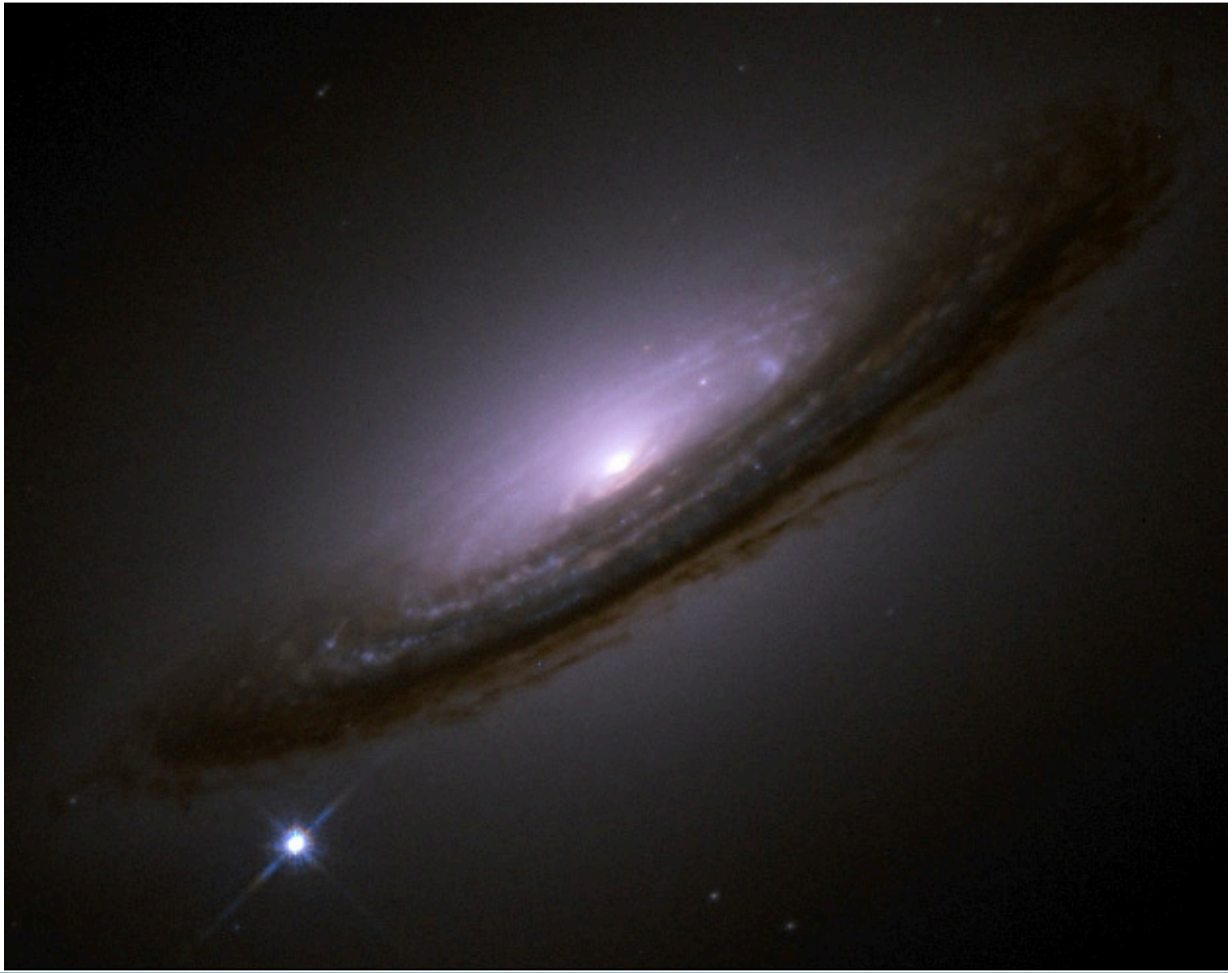
$$r_s = \frac{2GM}{c^2} = 3\,\mathrm{km}\frac{M}{M_\odot}.$$

- Photons can not escape inside this radius, and approach infinite redshift (and infinite time dilation) as radius approaches this value.

Supernova Explosions

Textbook pic:

Actually a SNIa… not the kind we're talking about yet.

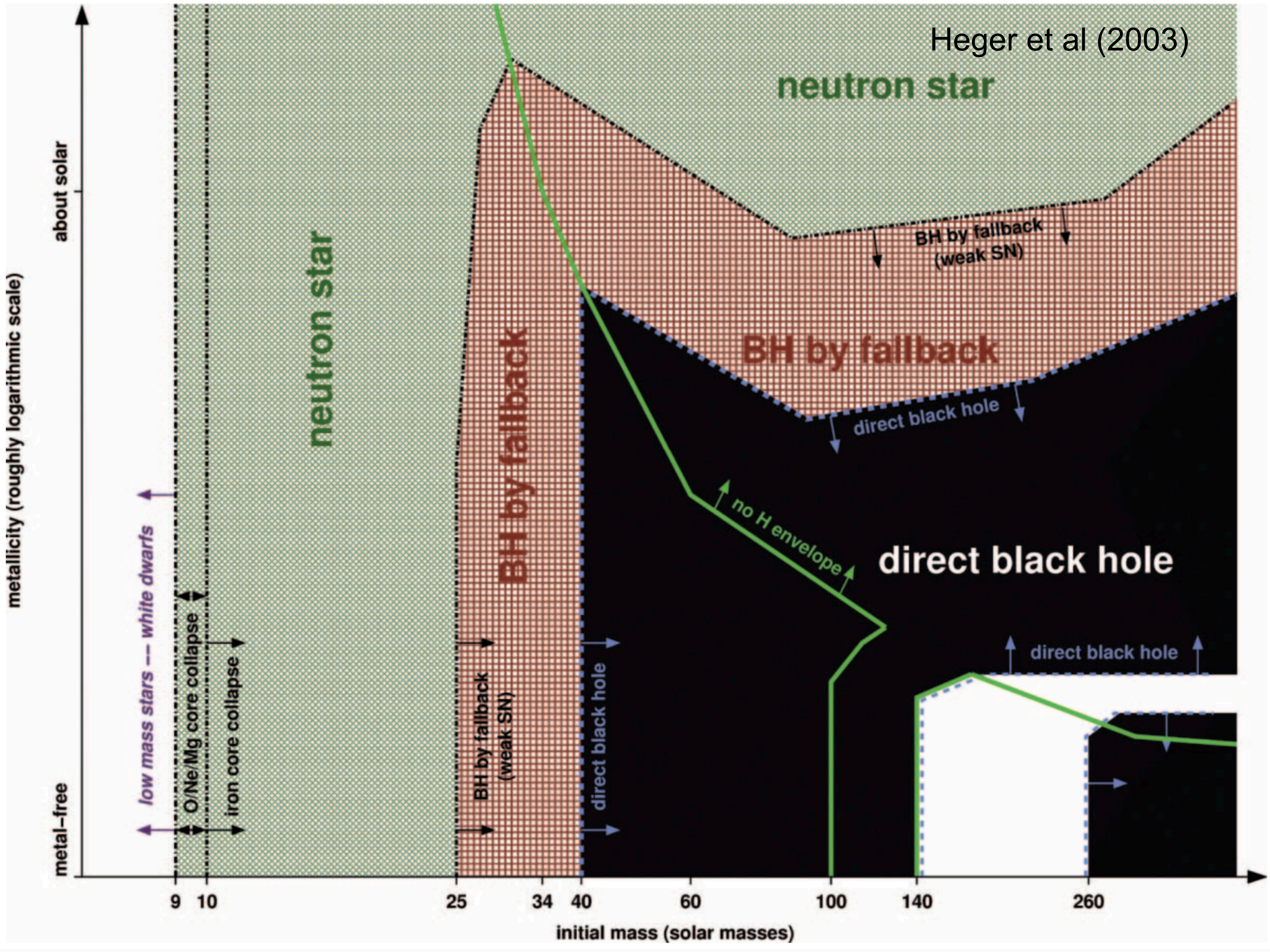


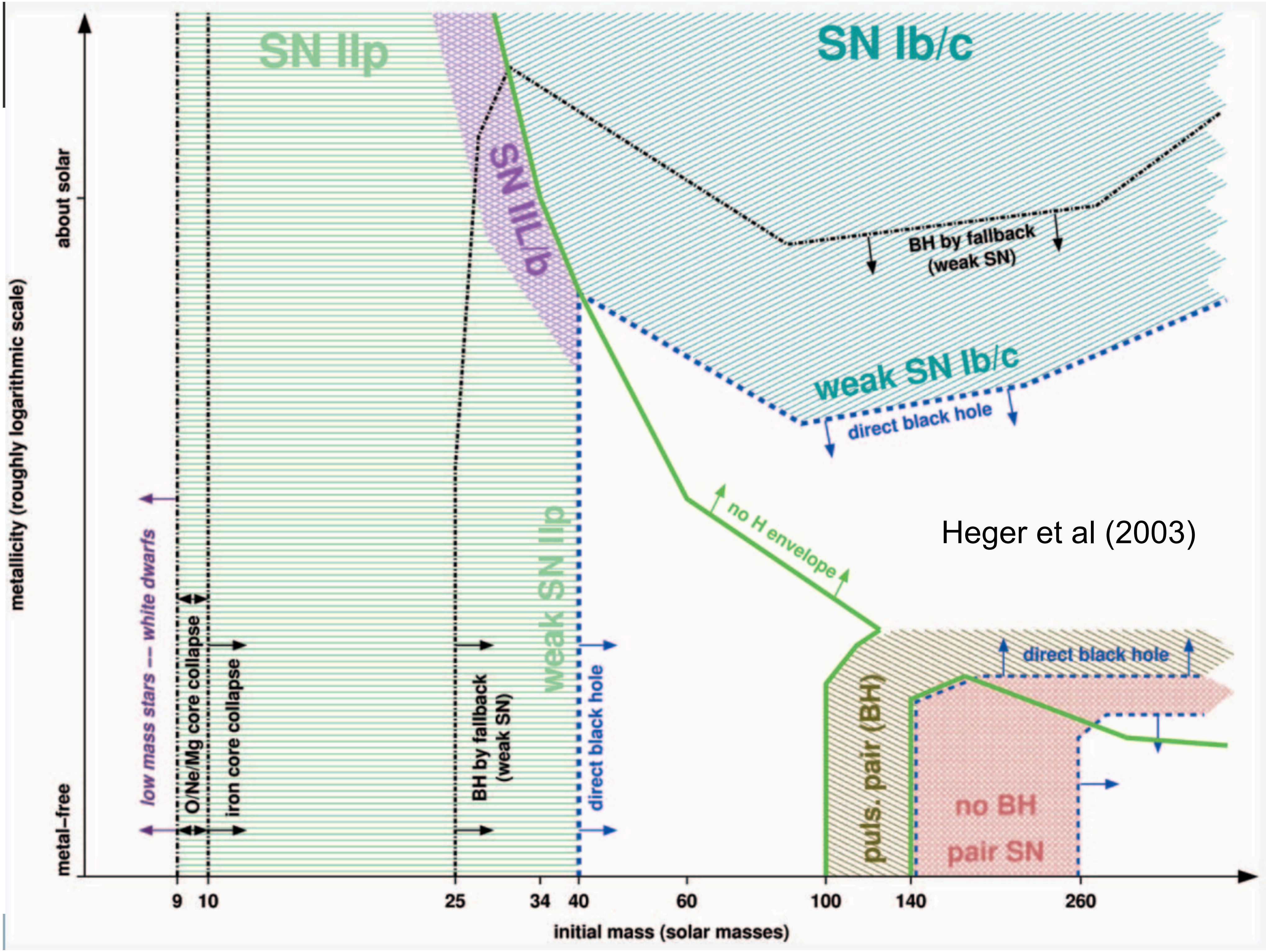
Supernova Explosions

- Supernova 1987A: an exploding massive star.

Supernova Explosions

- It only takes a fraction of the energy released in the collapse to a neutron star ($\sim GM_{core}/R_{ns}$) to unbind the rest of a massive ($\sim 10M_{sun}$) star.
- This energetic argument led bright explosions, called supernovae, to be attributed to the end of massive stars.
- Energy leaves the collapsing core primarily via neutrinos, which can couple to the layers immediately outside the core.
- Neutrino luminosity was *directly observed* in the case of 1987A – supporting the accepted theory that this sort of explosion was due to a collapsing massive star core.
- However, there are many different kinds of supernovae and end states of massive stars…


Heger et al (2003)
neutron star
neutron star
BH by fallback
BH by fallback
BH by fallback (weak SN)
BH by fallback (weak SN)
direct black hole
direct black hole
direct black hole
direct black hole
no H envelope
low mass stars — white dwarfs
O/Ne/Mg core collapse
iron core collapse
metallicity (roughly logarithmic scale)
about solar
metal-free
9
10
25
34
40
60
100
140
260
initial mass (solar masses)



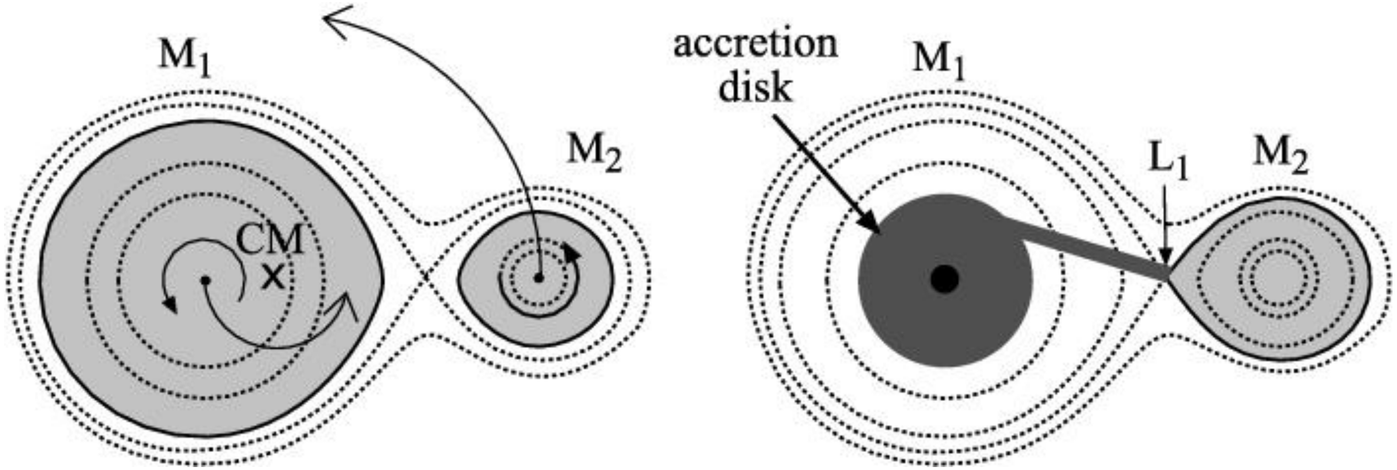
Heger et al (2003)

Type Ia Supernovae

- Of the many, many kinds of supernovae, one type stands out – the SN Ia class. These have a characteristic spectrum which has no Hydrogen, and a characteristic maximum luminosity.
- It is generally accepted that this class come from a white dwarf that has reached the Chandrasekhar mass.
- Models predict that the energy released in fusing CNO to Fe is typically enough to unbind the white dwarf (Q: what does this depend on?)
- The key question is whether two smaller white dwarfs merge to exceed the Chandrasekhar mass (double degenerate scenario) or whether a single white dwarf can gradually accrete mass from a companion (made tricky by “novae” explosions).
- Textbook author (Dan Maoz) is a leading researcher in this area, and has published in support of the double degenerate scenario being dominant.

Accretion

- After starting with individual stars, we've also mentioned objects like white dwarfs that grow.
- Growth of old stellar mass objects typically occurs by overflow of mass from one star to another, in what is called an *interacting binary*.
- The overflow occurs through the 1st Lagrange point, where in the rotating reference frame, the gravity from the two stars balance.



Accretion

- One key limiting factor for accretion is called the *Eddington limit.* This will come up later in the course as well (quasars).
- We equate the radiative force on electrons from Thomson scattering:

$$F_{\mathrm{rad}} = \frac{L\sigma_{\mathrm{T}}}{4\pi r^2 c}$$

Derive this on board…

- … to the gravitational force:

$$F_{\mathrm{grav}} = \frac{GMm_p}{r^2}.$$

- Arriving at a maximum possible accretion luminosity for a given mass:

$$L_{\mathrm{E}} = \frac{4\pi c G M m_p}{\sigma_{\mathrm{T}}}$$

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