Evolution of rotating magnetized stars

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+
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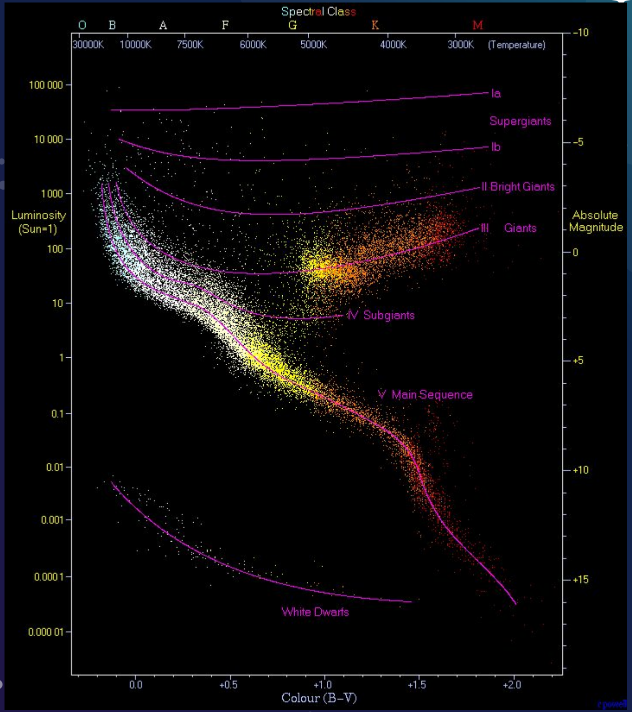
Before we begin: How do (massive) stars normally evolve??

Main sequence massive stars

- Stars are in hydrostatic & thermal equilibrium
- More massive stars evolve faster, roughly

$$\tau_{nuc} = \frac{E_{nuc}}{L} = \phi f_{nuc} \frac{Mc^2}{L} \approx 10^{10} \frac{M}{M_\odot} \frac{L_\odot}{L} yr$$

- More massive stars are also more luminous
- They are also rare!



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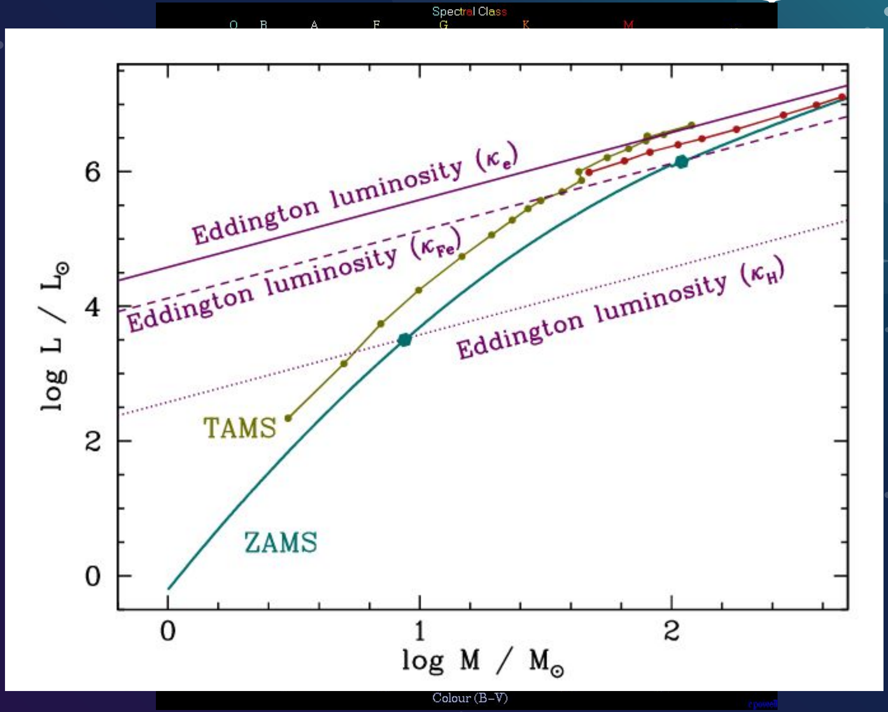
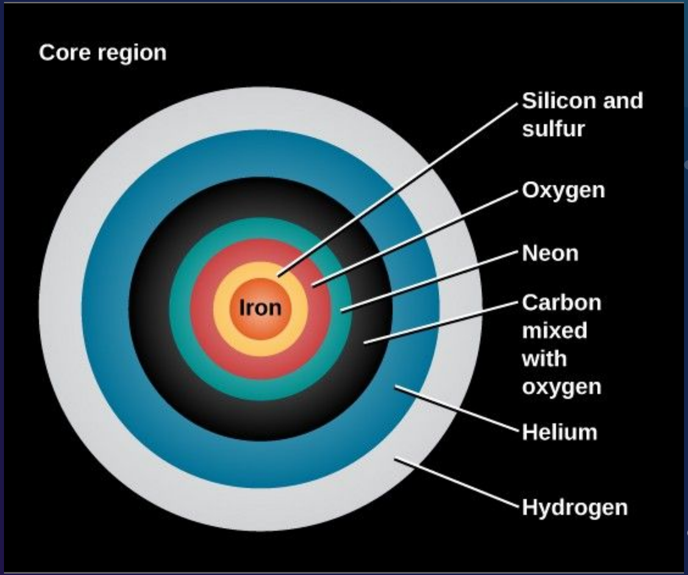


Late evolution of massive stars

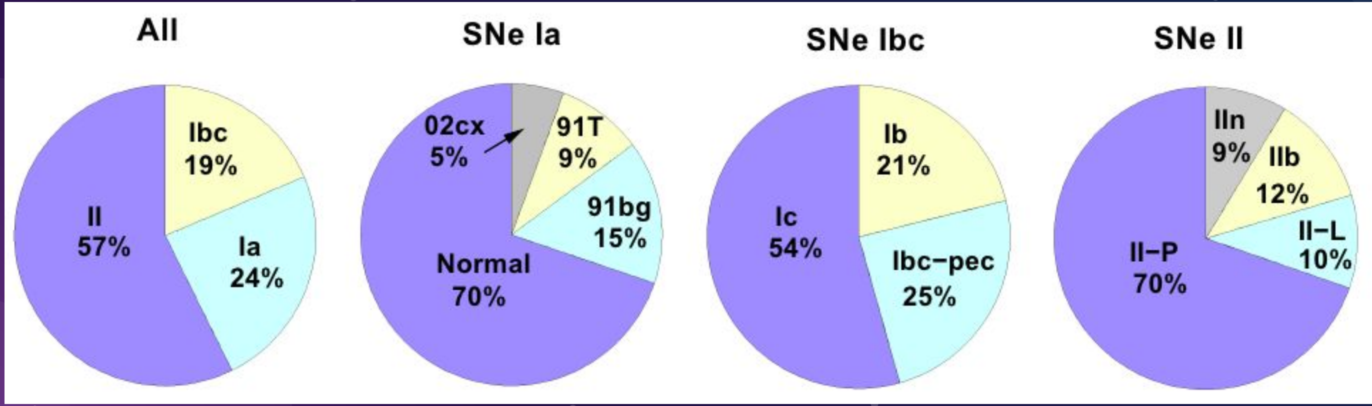
- Stars burn heavier metals until they form an iron core
- Neutrino emission from thermal and nuclear processes becomes more important
- Evolution is accelerated
- Iron core formation leads to core collapse!

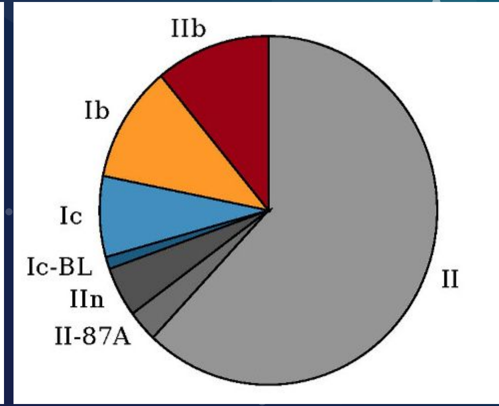


Not the whole story: The SN Zoo!

- SNe
  - Type I
    - Ia (thermonuclear)
    - Ib
    - Ic
      - Type I SLSN
      - Ic-BL
      - GRB-SN
      - Ultrastripped
    - etc!
  - Type II
    - IIP
    - IIL
    - IIn
    - IIb
    - Type II SLSN
    - etc!

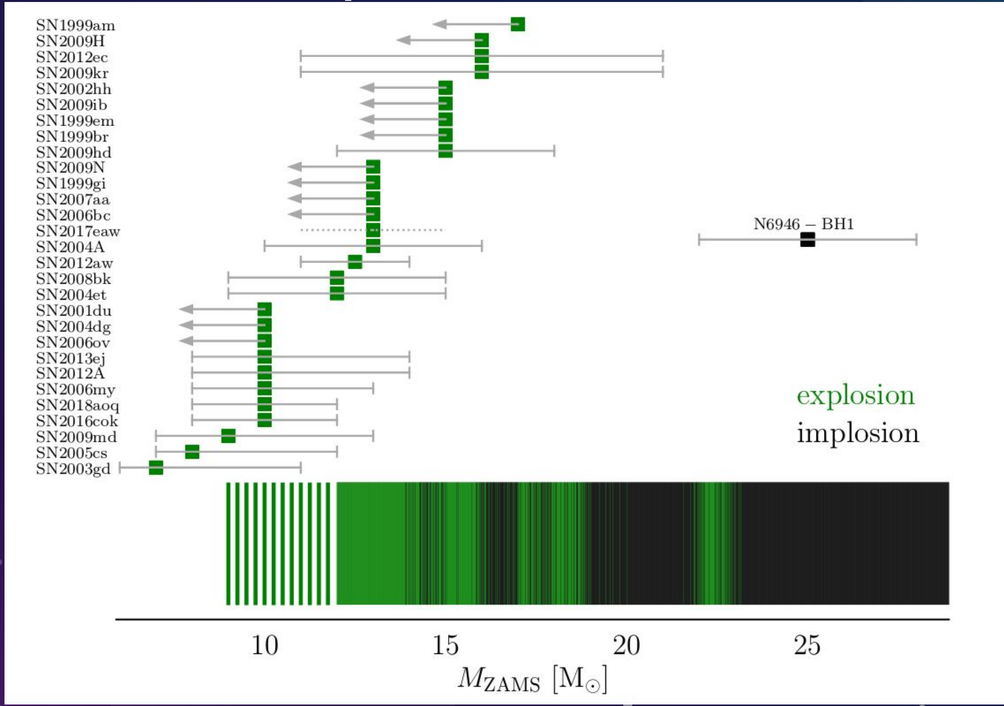
Progenitors: What we know so far...





Relative rates from volume-limited samples (Li et al. 2010, Shivvers et al. 2017)

Type II Progenitors: the RSG problem



Masses of observed SN progenitors and KEPLER model ZAMS masses, Sukhbold & Adams 2019

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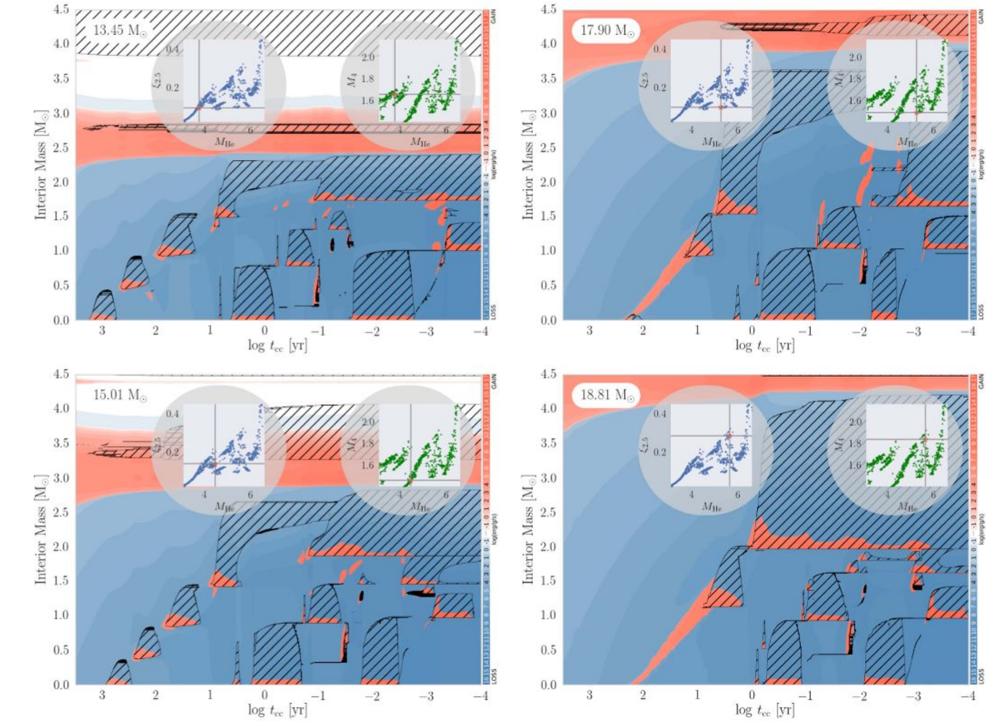
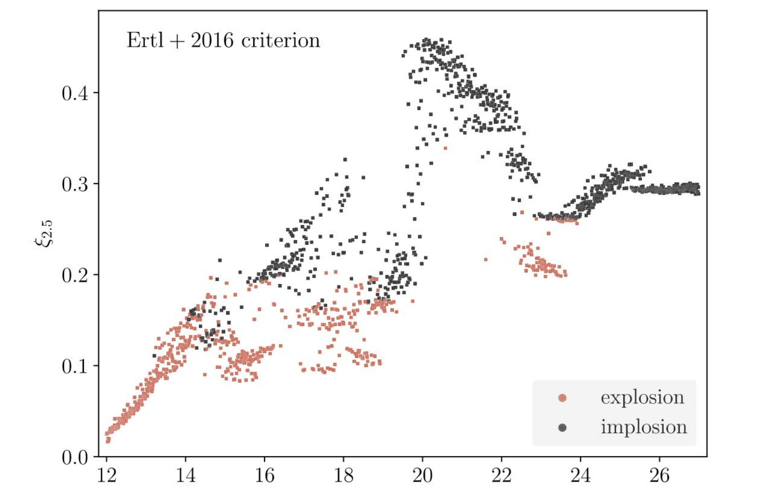
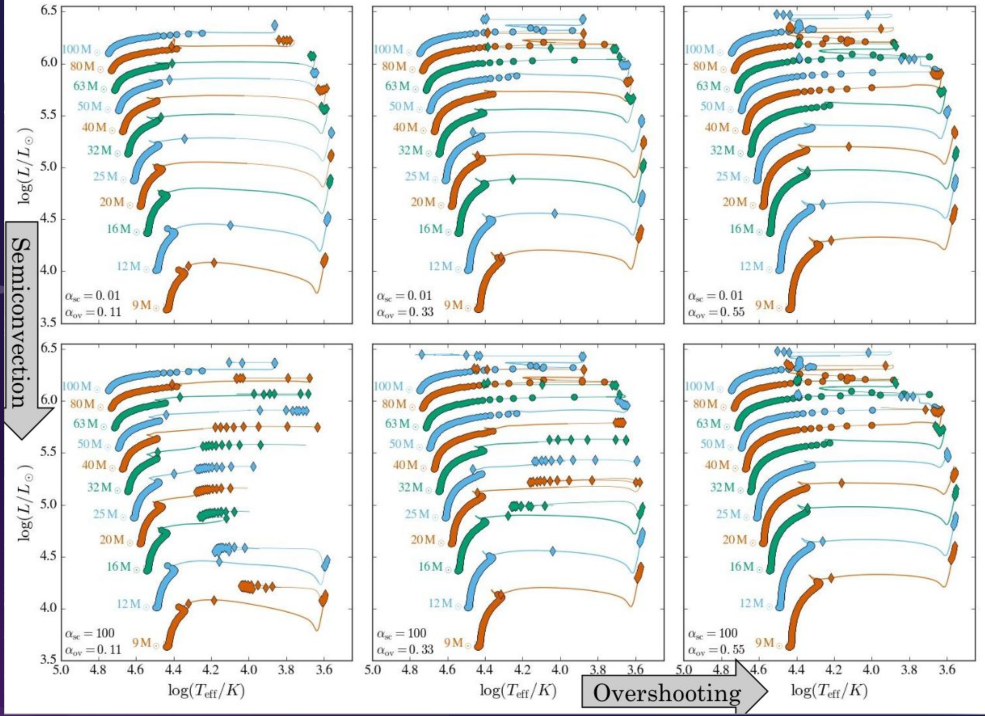




$$\xi_{2.5} = \frac{M/M_\odot}{R/1000km}$$

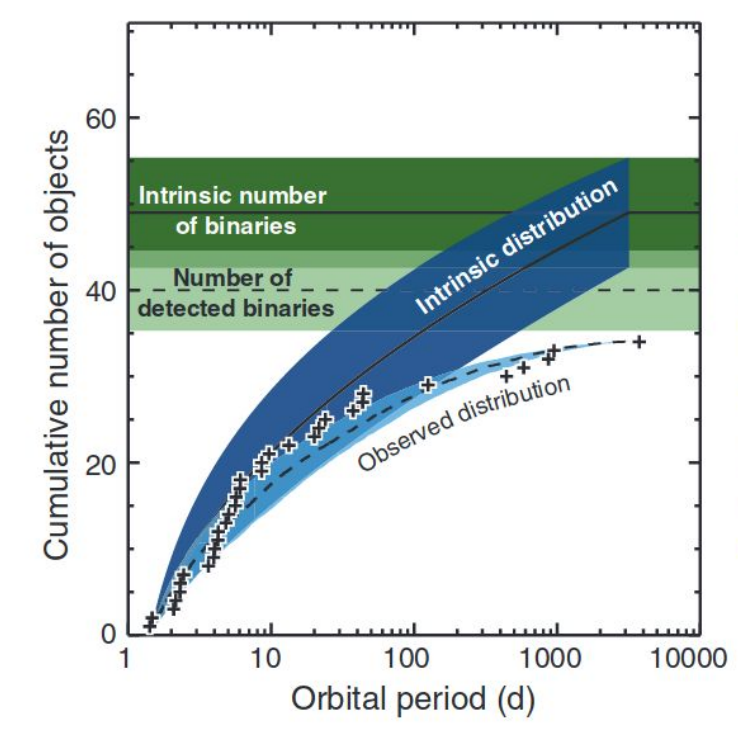
Kippenhahn diagrams of presupernova models from and their compactness, from Sukhbold et al. 2018

Other uncertainties in massive star evolution



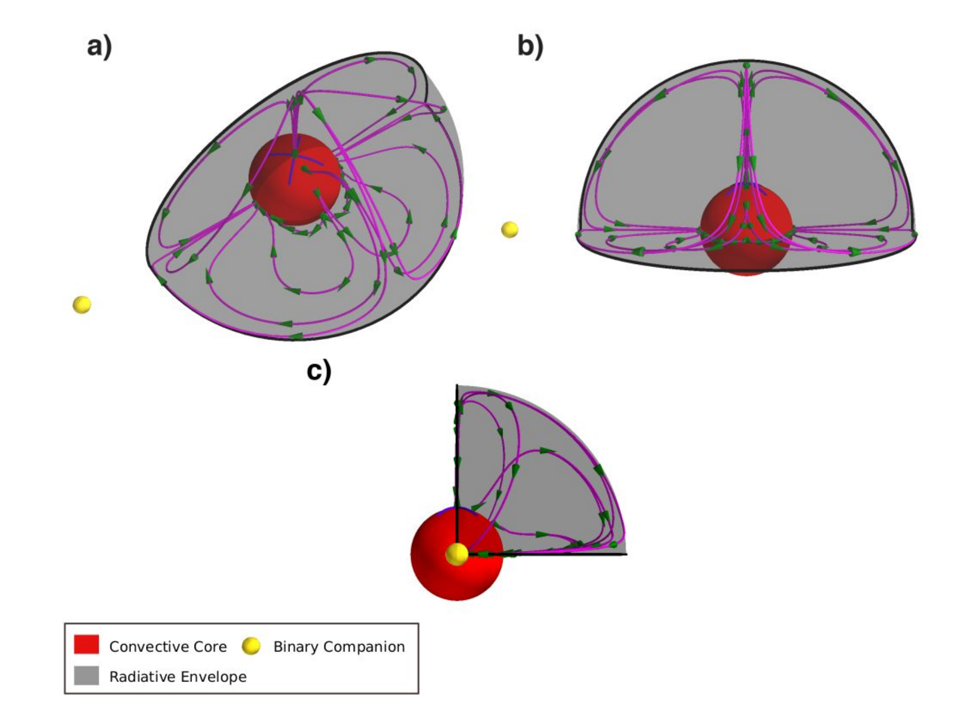
HR diagrams of evolutionary tracks with SMC metallicity, with different overshooting and semiconvection parameters, Schootemeijer et al. 2019

Other uncertainties in massive star evolution



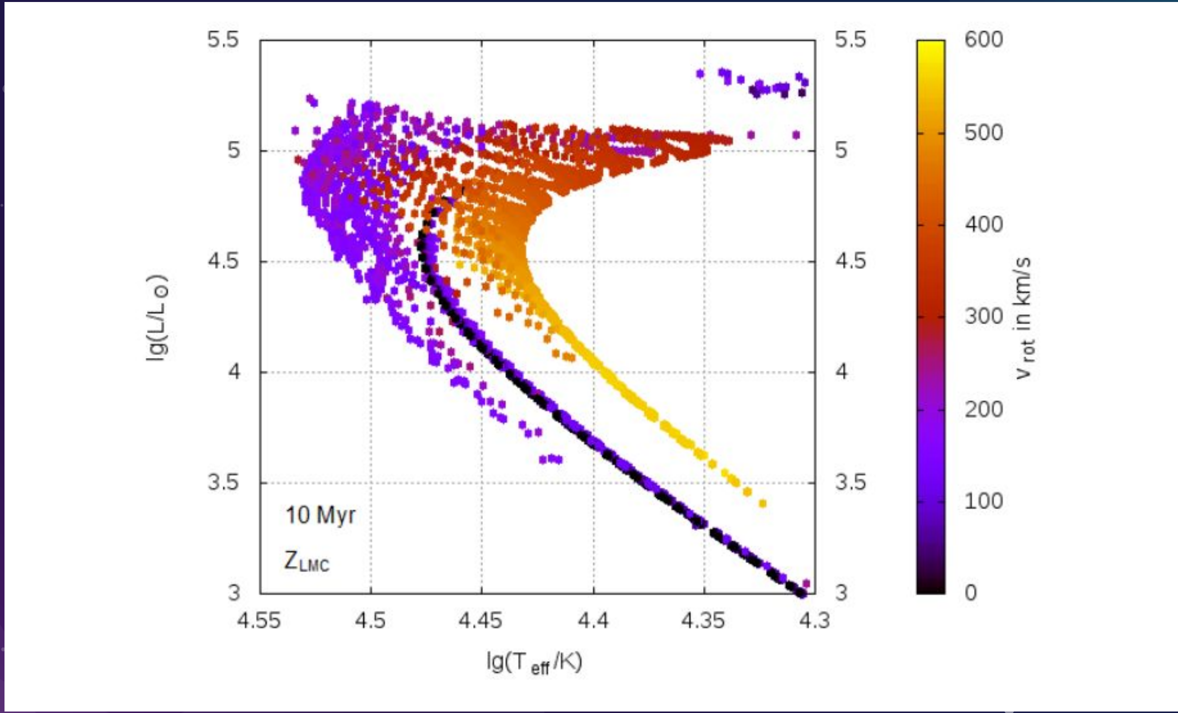
Observed and inferred distributions of massive binary periods, Sana et al. 2012

Other uncertainties in massive star evolution



Circulation patterns in binary stars, Hastings et al. in prep.

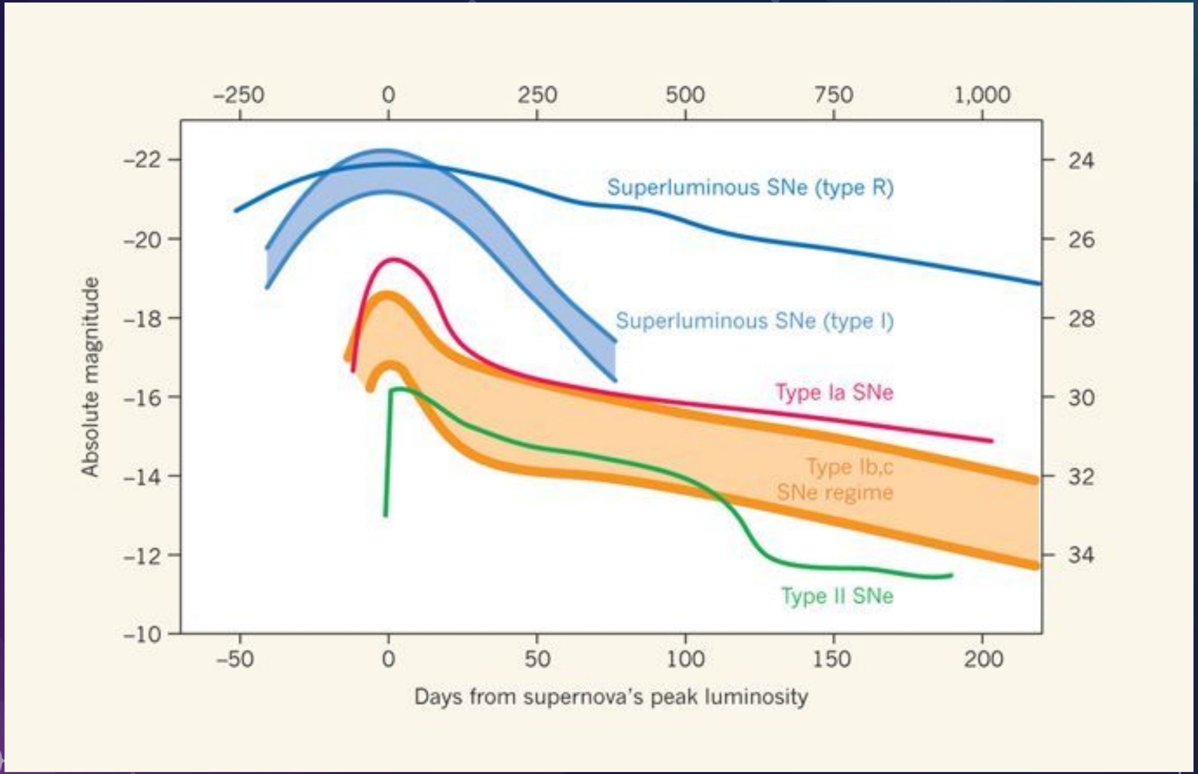
Other uncertainties in massive star evolution



HR diagram of a binary population in the LMC after 10 Myr, Bachelor thesis of S. Adscheid, see also the work by C. Wang

Moving on to the very energetic explosions...

Type I SLSNe



Example light curves from Smartt 2012

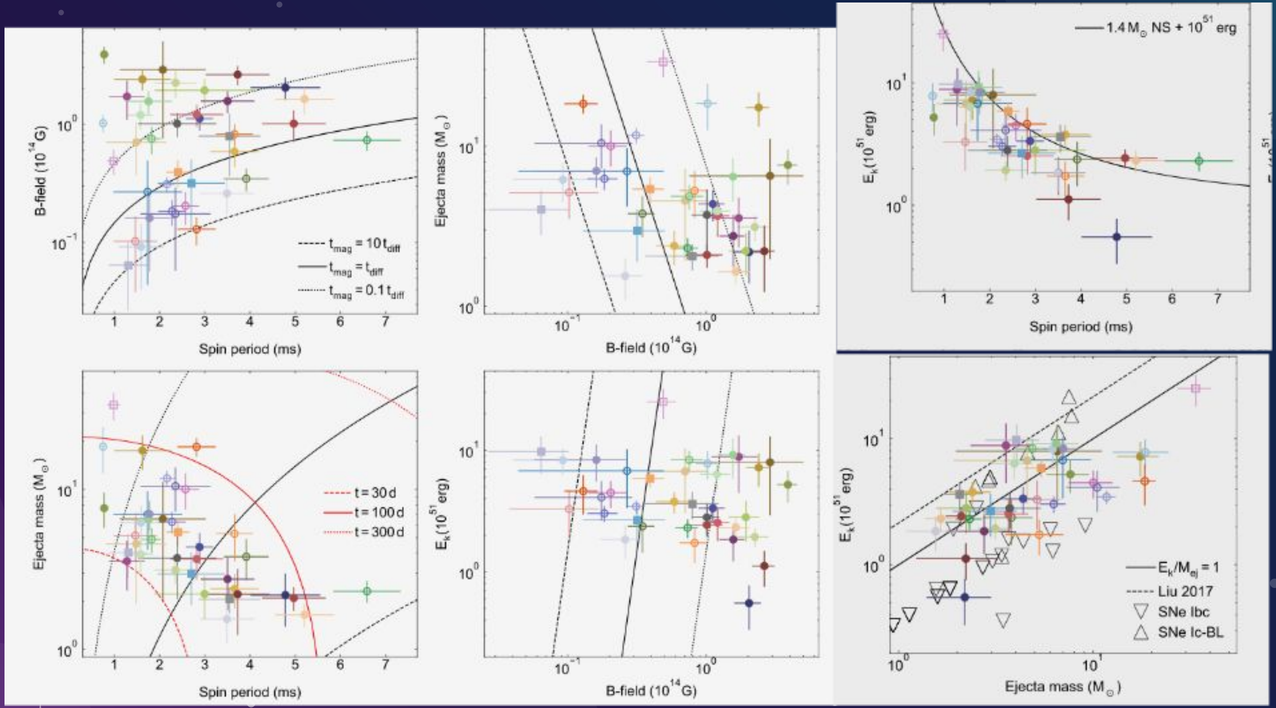
Type I SLSNe

- ★ Have no hydrogen or helium in their spectra (this probably means they have almost no H and He, see Hachinger et al. 2012)
- ★ They have very high energies
- ★ Their spectra show mostly O lines and are very hot
- ★ Found preferably in low metallicity environments (e.g. Lunnan et al. 2015)

Type I SLSNe

- ★ Powered by a central magnetar (Kasen & Bildsten 2010, Nicholl et al. 2017)
- ★ Powered by interaction with the CSM (Chevalier 1982, Chevalier & Fransson 1994)
- ★ They're actually PISNe! (see, e.g. Chatzopoulos et al. 2015)
- ★ Powered by fallback accretion (Moriya et al. 2018)

The magnetar model



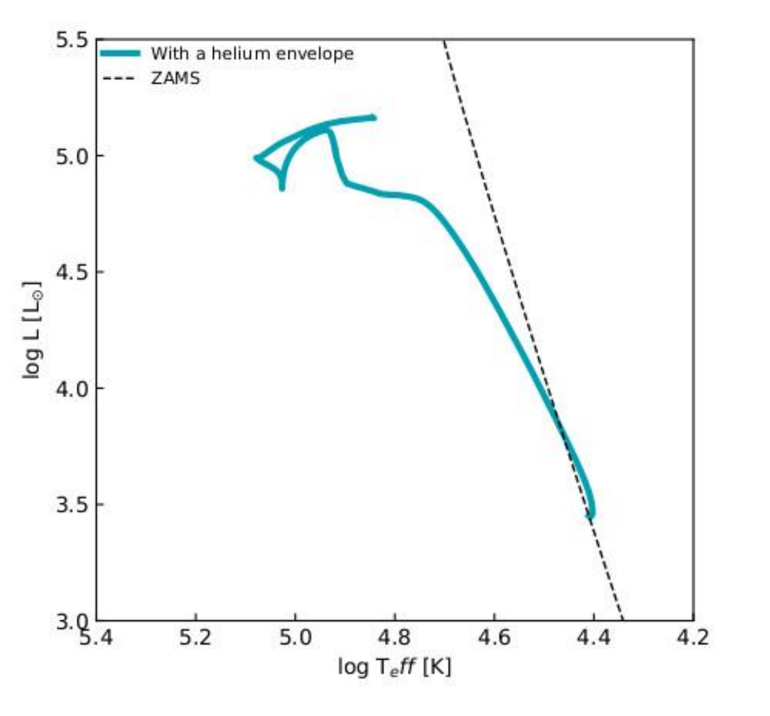
Inferred properties of SLSNe in the magnetar model, from Nicholl et al. 2017

Gamma ray bursts (and their SNe)

- ★ They are related to massive stars and to Ic-BL SNe (Hjorth et al. 2003, Levan et al. 2016)
- ★ They form collimated relativistic jets (e.g. Piran 2004)
- ★ Their host galaxies are generally at low Z (Levan et al. 2016)
- ★ Most favored progenitor model is the collapsar model (Woosley 1993)

Fast rotation
&
Low metallicity

Not the first time it's been done



Similar to Yoon et al. 2006, Szécsi et al. 2015

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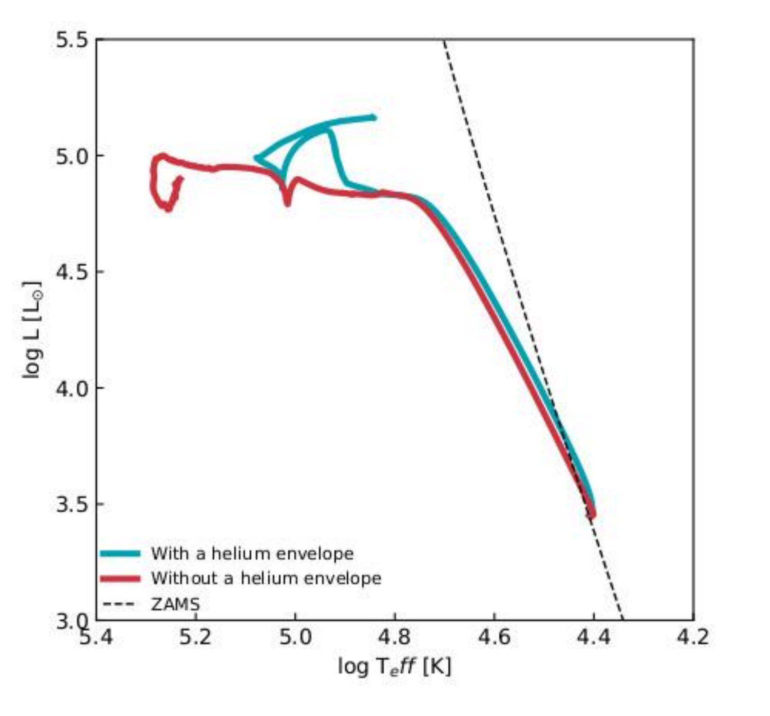
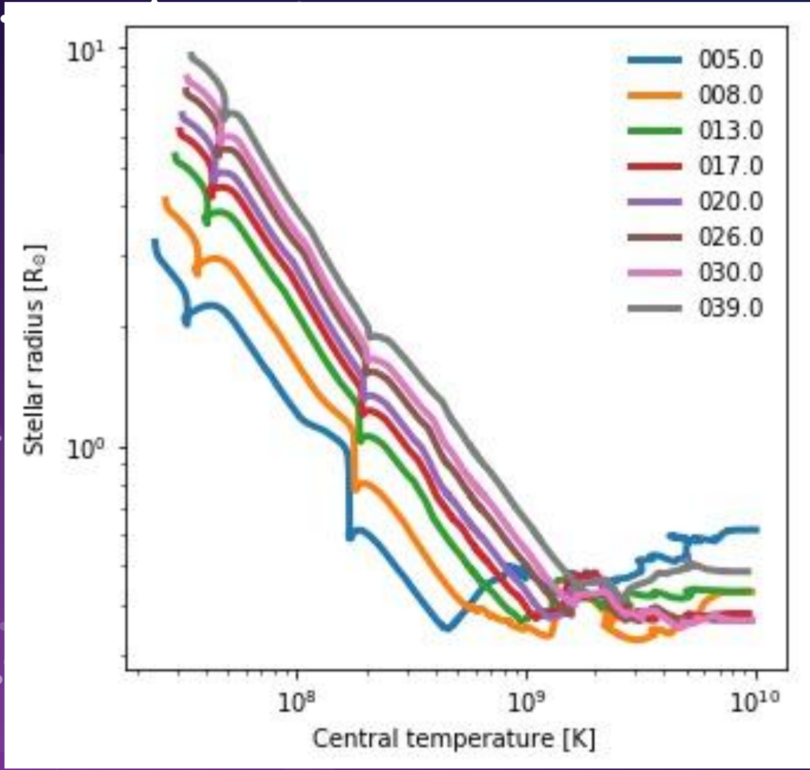


- Rotational mixing has been enhanced by a factor 10, from Aguilera-Dena & Langer, in prep.

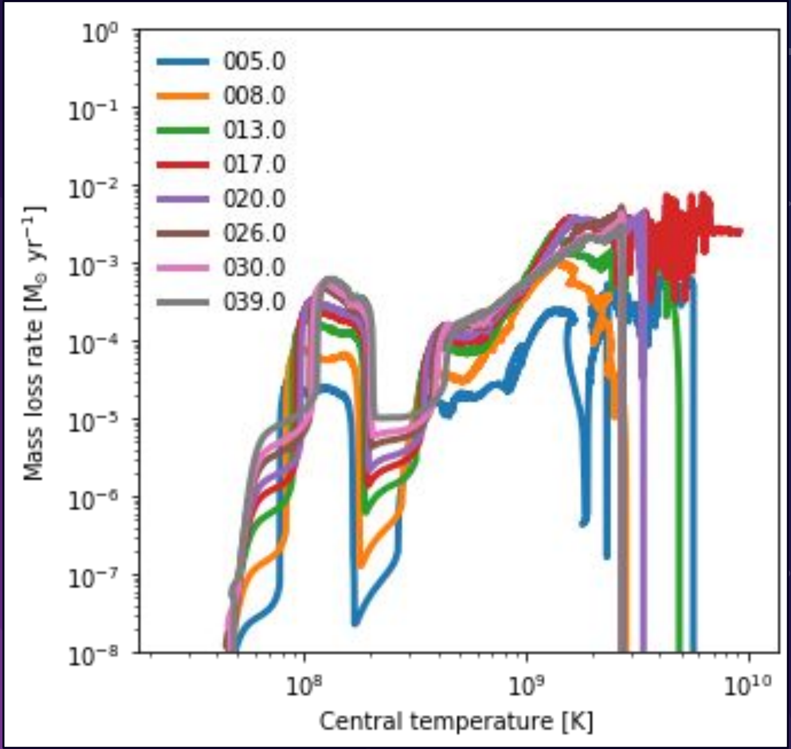
Evolution with extreme rotation



- ★ Mixing leads to CHE
- ★ Lack of H/He shell leads to contraction
- ★ Contraction accelerates due to neutrinos
- ★

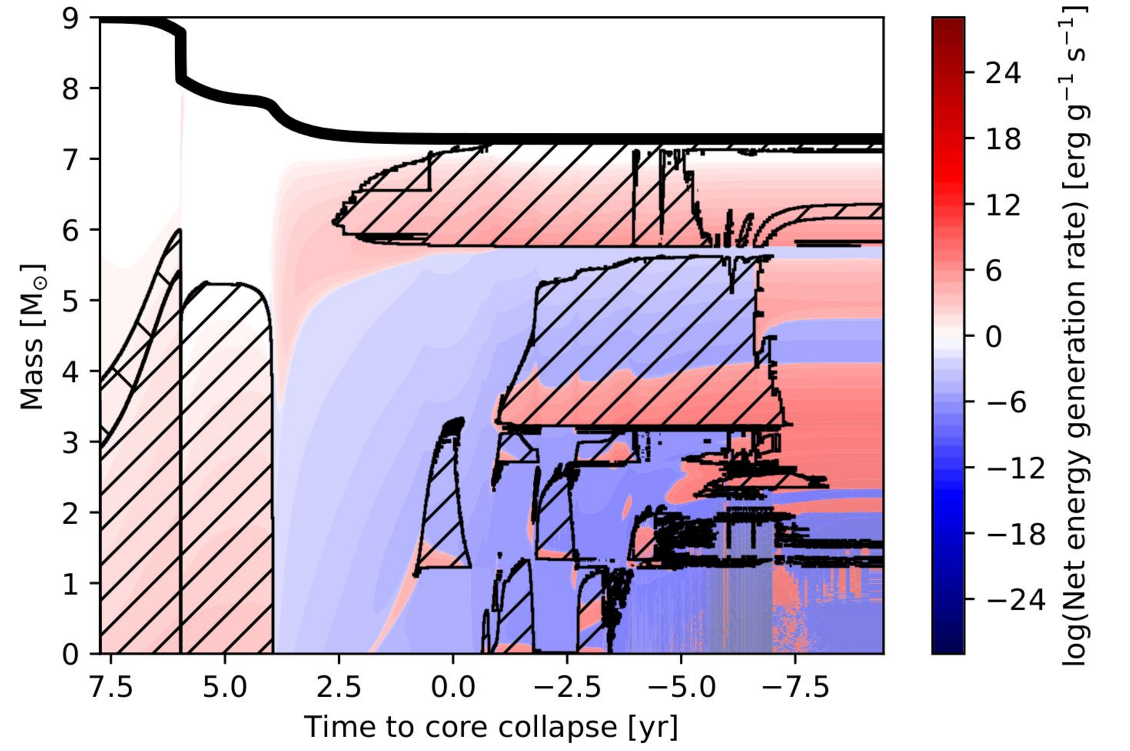
$$\tau_{KH,\nu} = \frac{GM^2}{R(L + L_\nu)}$$

Evolution with extreme rotation



- ★ Contraction leads to differential rotation (mostly small)
- ★ Angular momentum is transported to the surface (by magnetic fields)
- ★ Critical rotation very likely!

Evolution with extreme rotation



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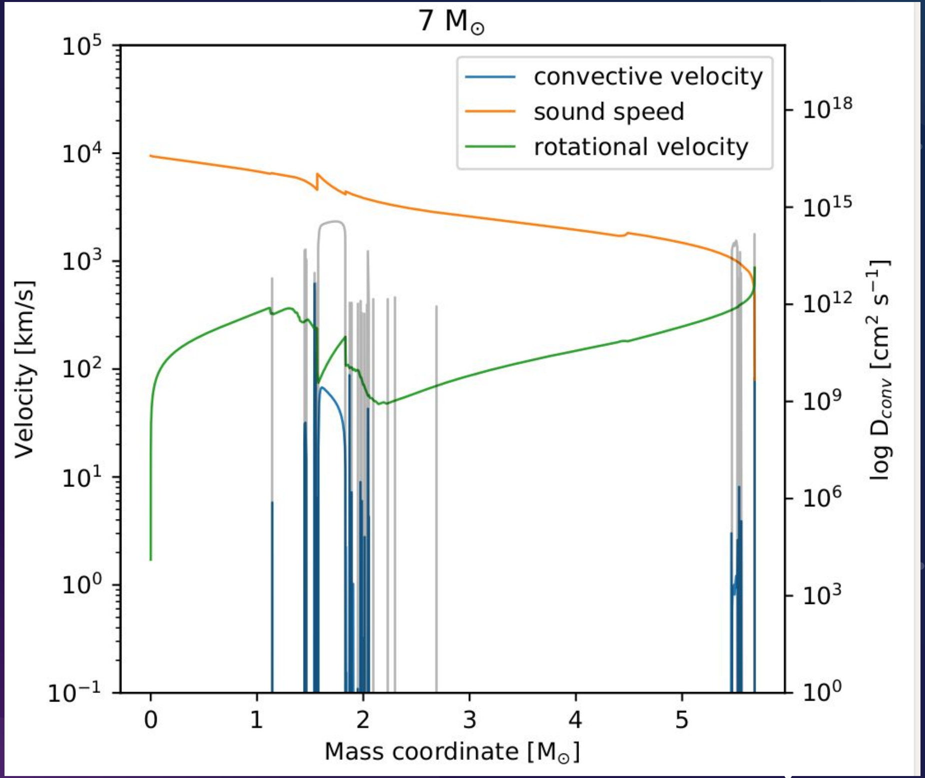

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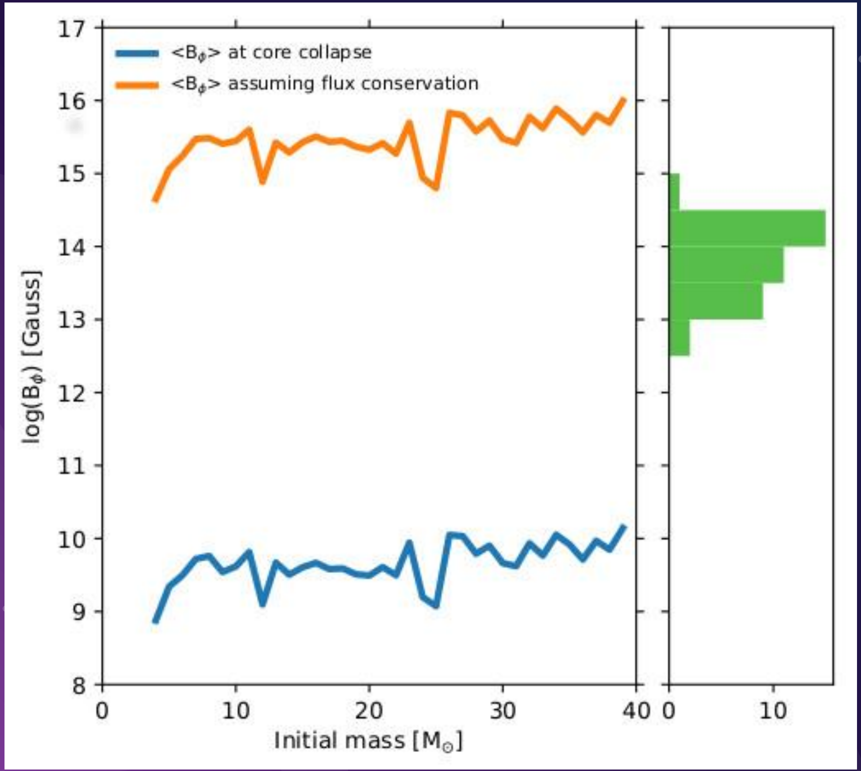
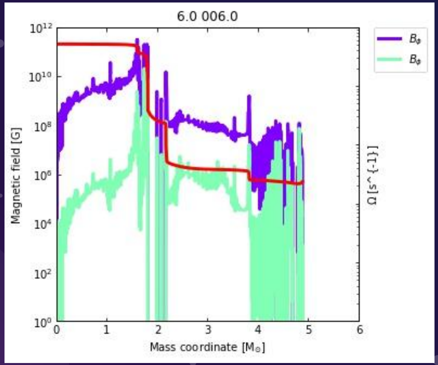
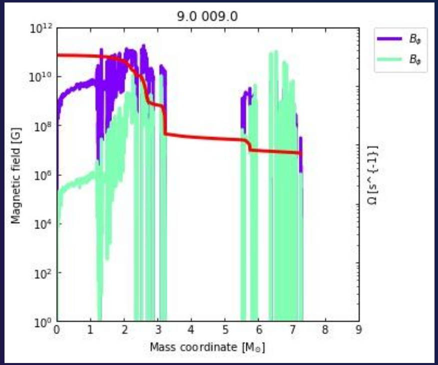
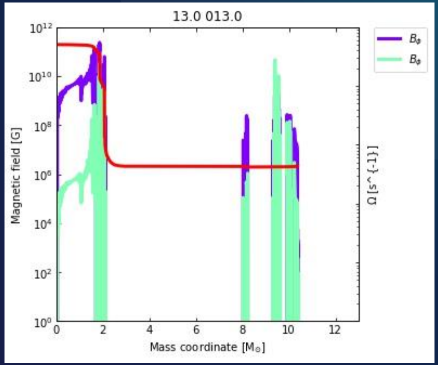


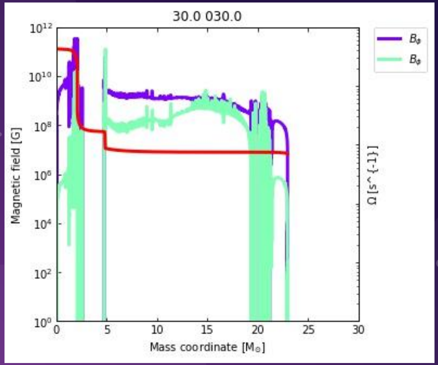
- ★ Differential rotation leads to formation of magnetic fields
- ★ Magnetic fields can be strong enough to power SLSNe!

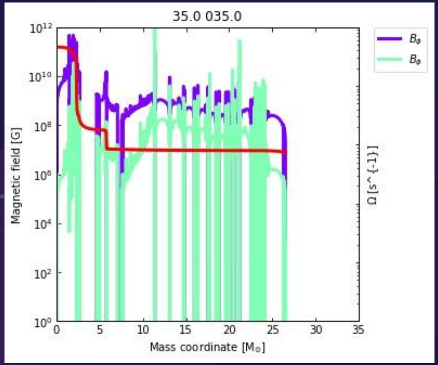
Variety in magnetic fields!

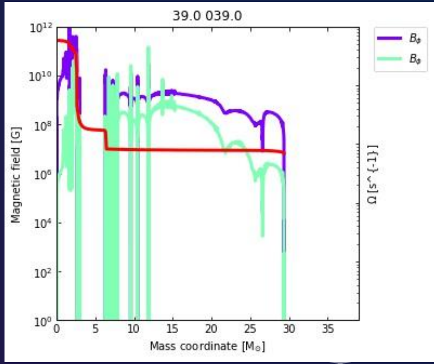




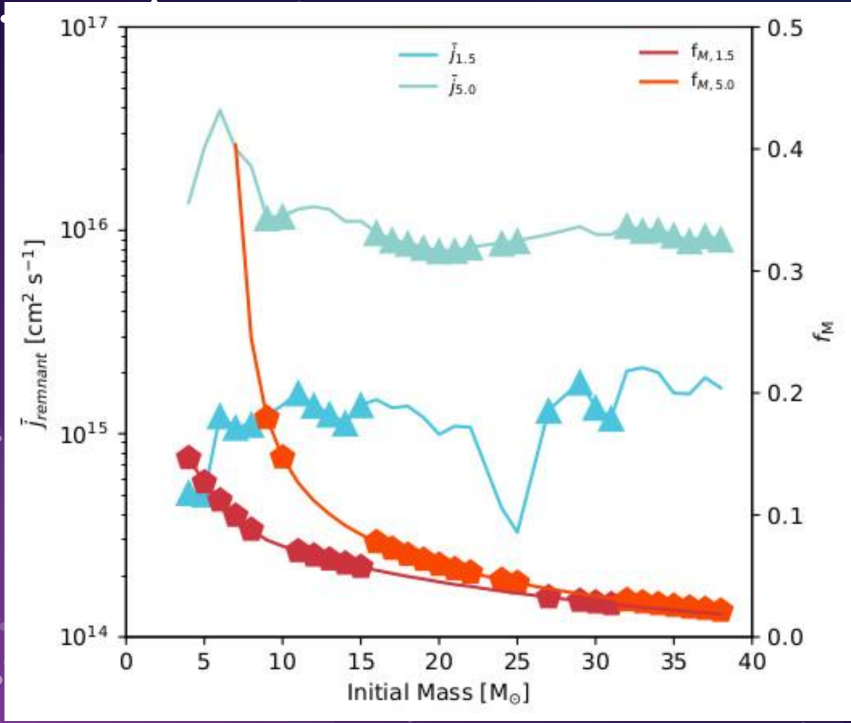








Evolution with extreme rotation

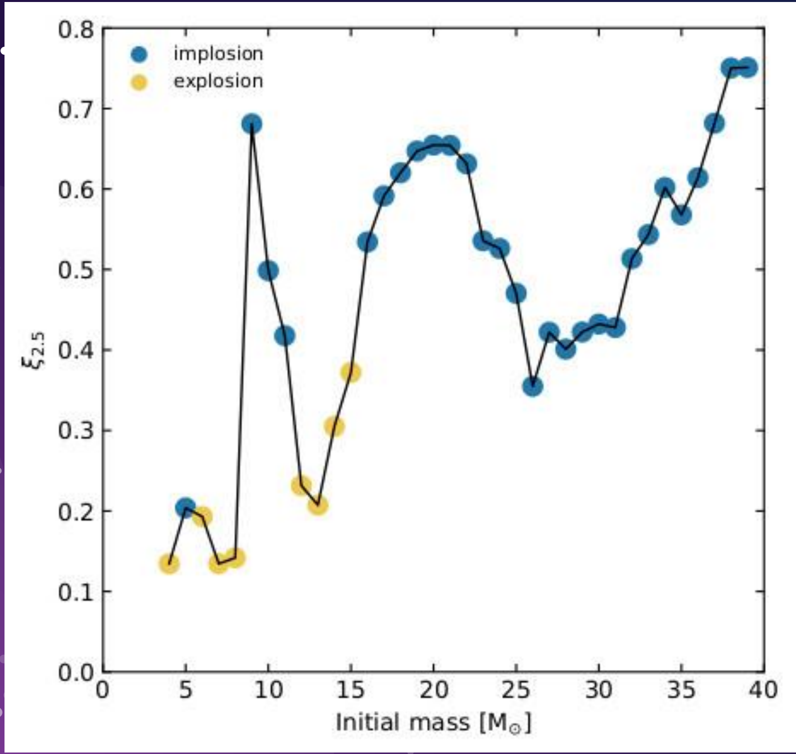


★ Expected observable features

- Interaction with dense CSM
- Fast rotating remnant
- Power from rotation being deposited into explosion

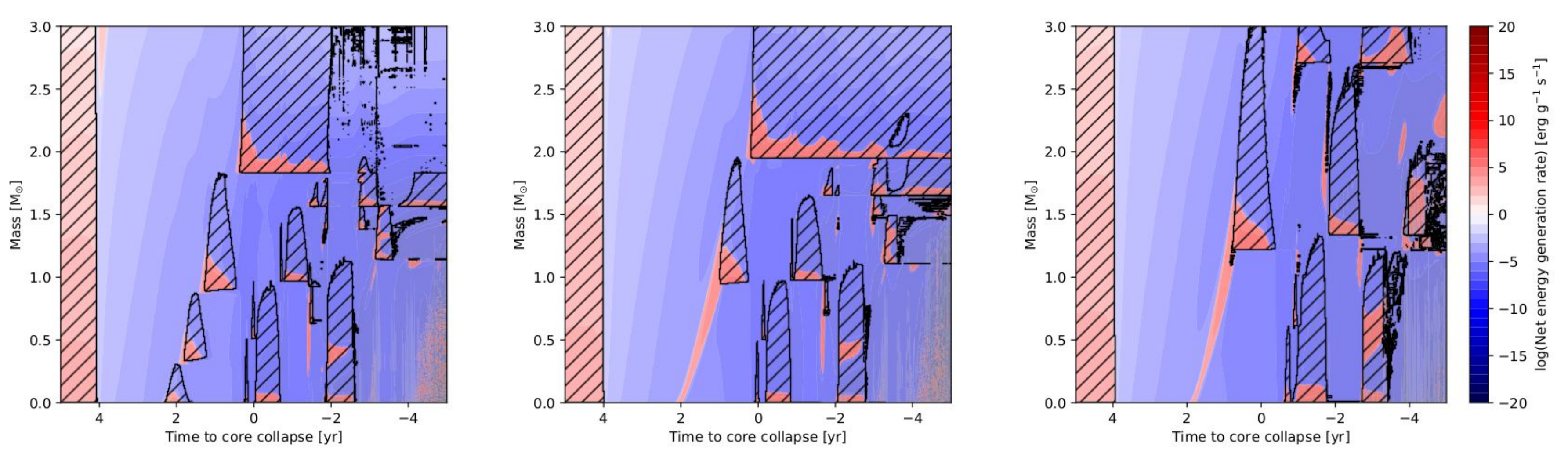
★ Enough angular momentum in the core to produce a GRB if black hole forms

Evolution with extreme rotation



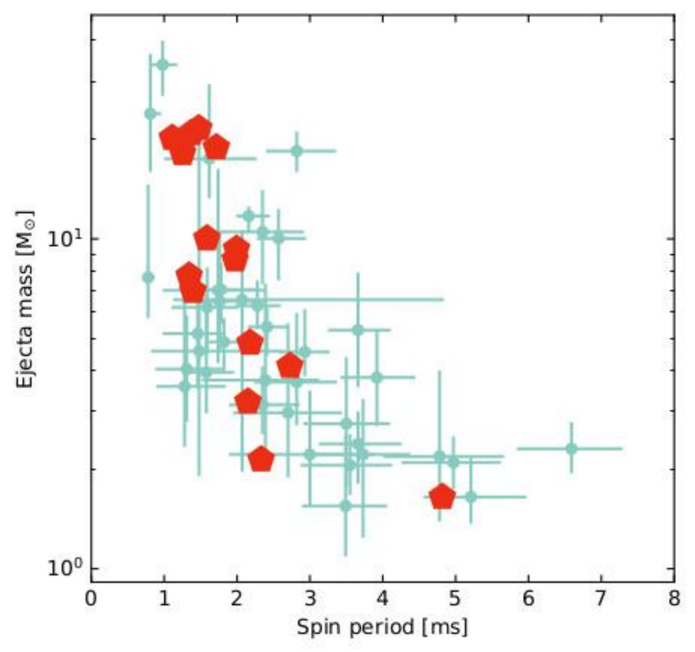
- How to know if they form a magnetar (and a SLSN) or a black hole (and a long GRB)?
  - Compactness parameter
  - Core properties (mass gradient, core mass)
  - Stellar structure
- We need 2D/3D to see the impact of structure, rotation and magnetic fields!

Evolution with extreme rotation



7, 8 and 9 Msun

Evolution with extreme rotation



Comparison with the values obtained through the magnetar model by Nicholl et al. 2017

Conclusions

- ★ Massive star evolution is complicated! Many uncertainties go into characterizing the progenitors of the observed SN population
- ★ We discovered a new evolutionary channel where fast rotation and neutrino emission get together to form extreme conditions
- ★ It could lead to SLSNe or GRBs depending on explosion physics and late evolution, needs to be studied in 2D and 3D!
- ★ Core evolution has similarities to non-rotators, but explosions are different due to rotation and CSM
- ★ Important to consider rotation and magnetic fields in more detail since they appear in many extreme astrophysical situations