The physical mechanism behind normal and peculiar SN Ia

YOSSEF ZENATI

AND

Hagai B. Perets, Silvia Toonen, Robert T. Fisher, Alexey Bobrick, and Rediger Pakmor.

Supernovae are classified according to their spectra

Observations

Type I (no hydrogen)

Ia (Si, no He)
Ib (He, no Si)
Ic (no Si; no He)

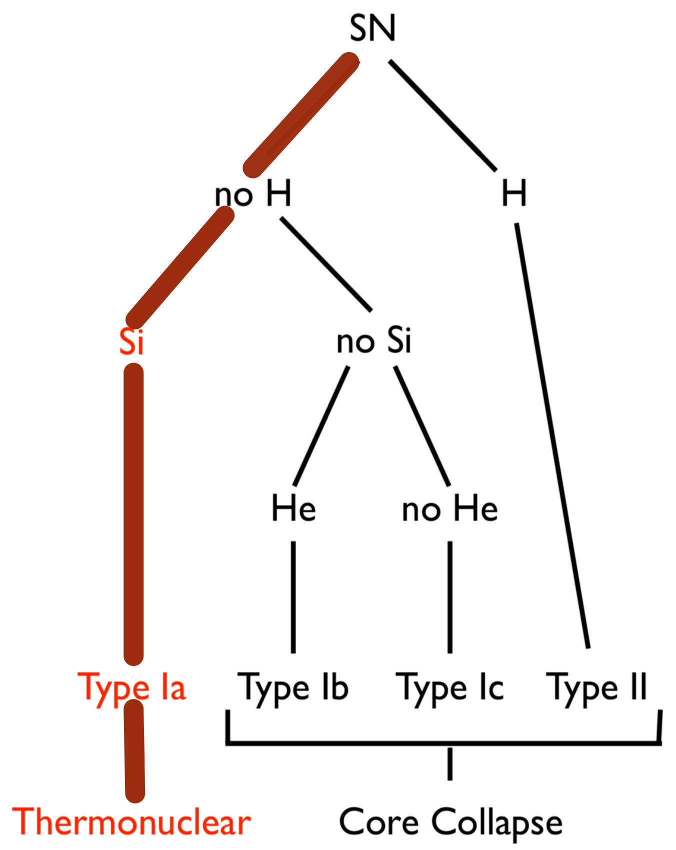


Figure 1.1: SN classification decision tree. Classification of SNe is based on the presence of elements in SN spectra observed near maximum light.

Theory

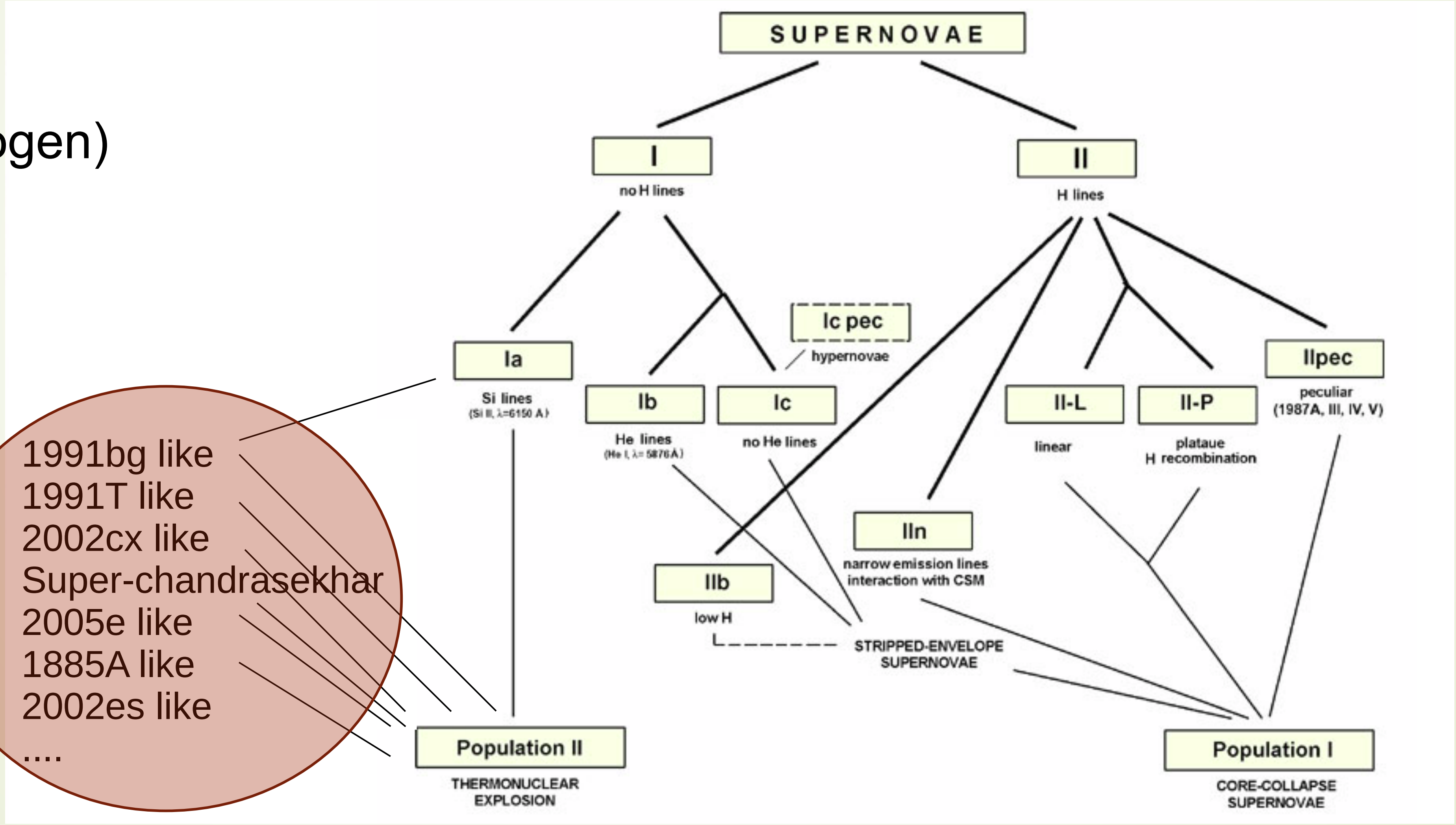
Thermonuclear explosion

Carbon-Oxygen WD
Hybrid-CO WD?

There are many sub-types of SNe

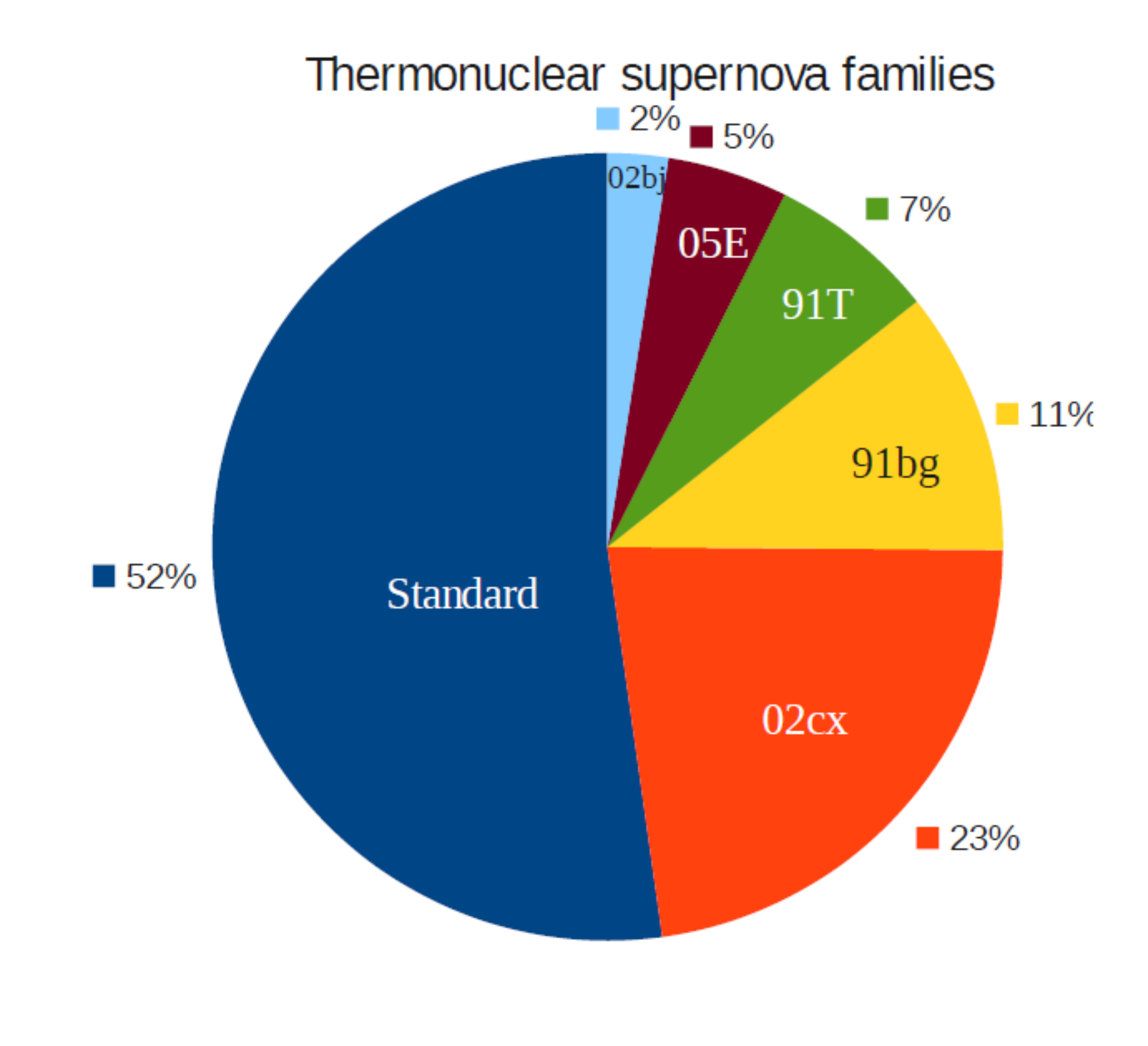
Type I (no hydrogen)

- Ia (Si, no He)
- Ib (He, no Si)
- Ic (no Si; no He)



1991bg like
1991T like
2002cx like
Super-chandrasekhar
2005e like
1885A like
2002es like
....

Non "standard" SNe might even be the norm among WD SNe



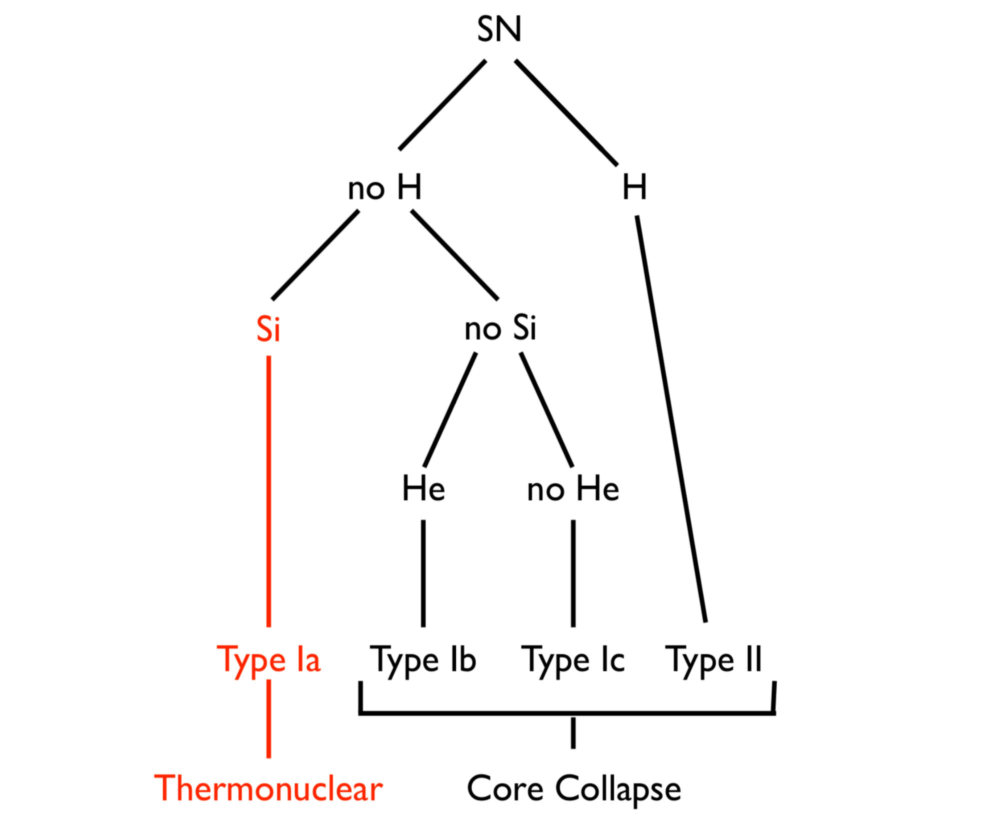
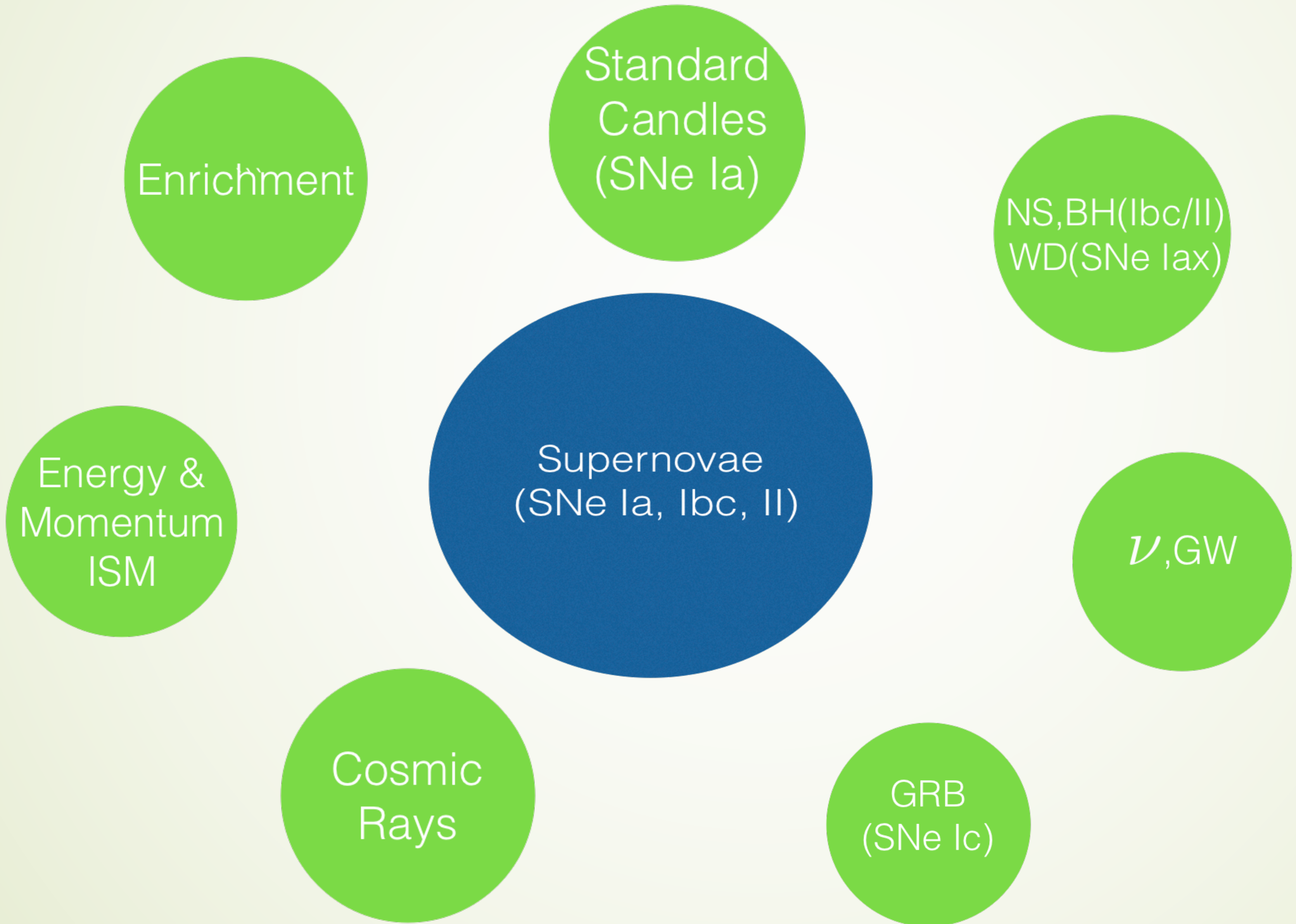
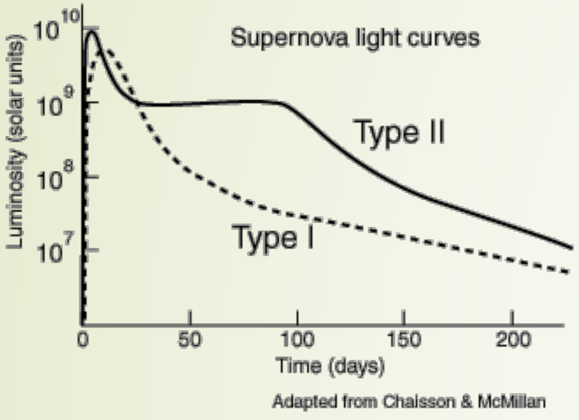


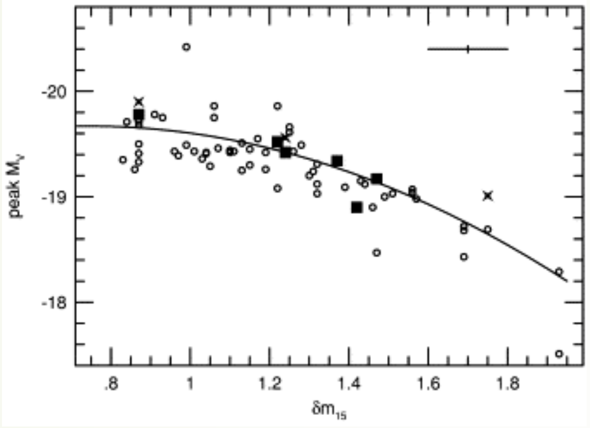
Figure 1.1: SN classification decision tree. Classification of SNe is based on the presence of elements in SN spectra observed near maximum light.

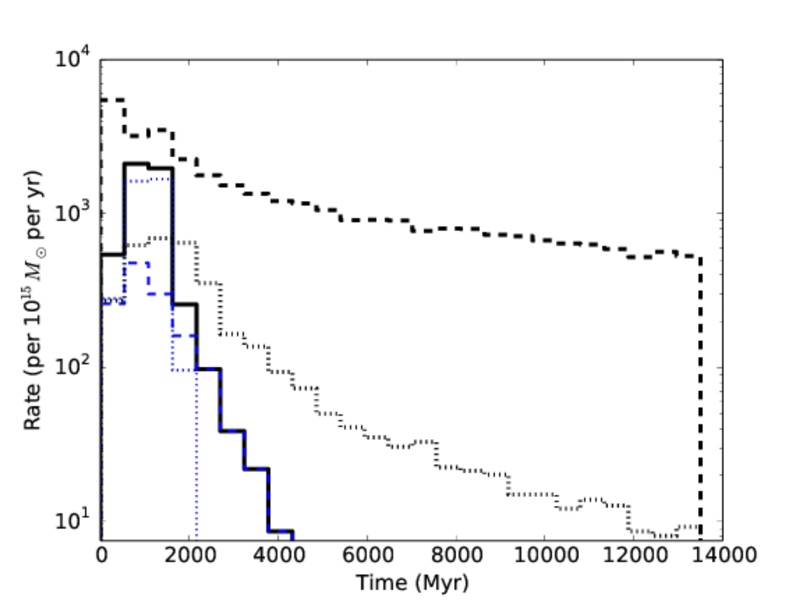
Importance of Supernovae

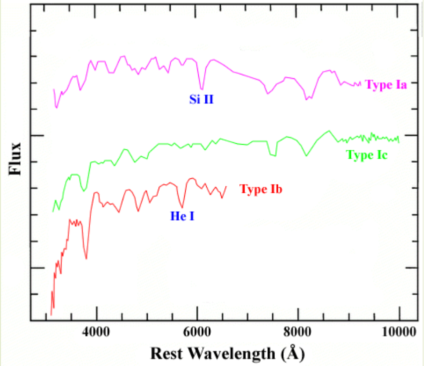


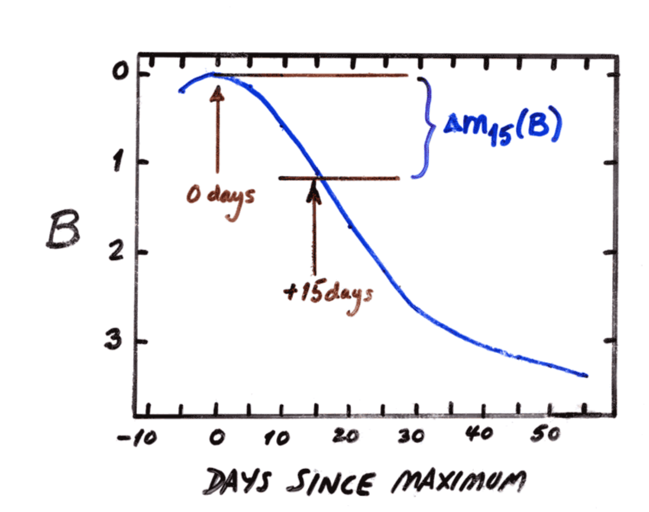
Observational expectations











Pinto et al. 2001
Gal-Yam 2016
Kushnir et al. 2013
Maoz, Mannucci & Nelemans 2014
Maoz et al. 2014

White Dwarf Nuclear Energetics

- Total kinetic energy = energy released - binding ~ 10^{51} erg

  Implying a typical expansion velocity ~ 10^4 km/s

- Light curve is powered by radioactive decay of ^{56}Ni to ^{56}Co to ^{56}Fe, ~6 MeV / nucleus,

$$L_{\rm SNIa} \sim E_{\rm SNIa}/t_{\rm decay} \sim 10^{10} L_\odot$$

$$M_{\rm SNIa} \sim -20$$

Single Degenerates

.
.
Whelan & Iben 1973
Nomoto 1982a
Livne 1990
Woosley & Weaver 1994
Livne & Arnett 1995
Garc ´ıasenz, Bravo & Woosley 1999
Fink, Hillebrandt & Ropke 2007
Fisher et al. 2018
Townsley et al. 2018
.
.

- C/O WD + MS or sub-giant star, mass transfer of H/He via RLOF/winds
- Accrete to near Chandra limit:
  - central detonation
  - central pure deflagration
  - deflagration to detonation transition
- Light curve is powered by radioactive decay of ^{56}Ni to ^{56}Co to ^{56}Fe, ~6 MeV / nucleus,
- The B15 lies in specific regime.

$$L_{\mathrm{SNIa}} \sim E_{\mathrm{SNIa}}/t_{\mathrm{decay}} \sim 10^{10} L_{\odot}$$

Double Degenerates

Seitenzahl et al. 2009
Pakmor et al. 2009
Soker Noam 2011
Marius et al 2012
Jordan et al. 2012
Markus et al. 2010-2016
Kushnir et al. 2013
Shen & Bildsten 2014
Kashyap et al. 2015
Sato et al. 2015
Perets et al.2020

- CO + CO merger with total M >= $1.4M_{\odot}$
  - "Slow" merger --- DDT
  - Violent ("Fast") merger --- Detonation
  - Direct collision --- Detonation
  - Super slow ---**D6**
- CO + CO merger with total M <$1.4M_{\odot}$
- The primary mass at explosion is more important than total mass at explosion.

- Core degenerate (AGB core + C/O WD)
- Collision of DWD.

Outstanding Problems

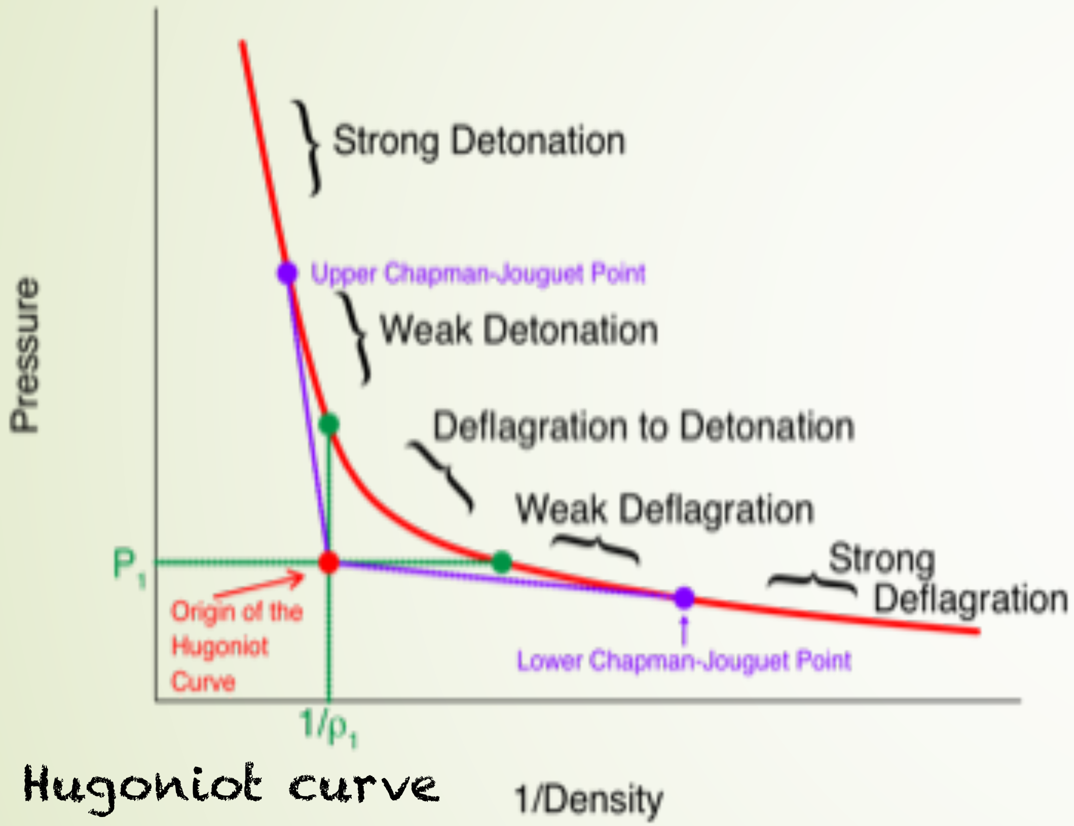
Single-Degenerates (SD)	Double-Degenerates (DD)
Rates	Rates ✓
Absence of companion	Absence of companion ✓
Absence of nebular H-alpha	Absence of nebular H-alpha ✓
Delay-time distribution	Delay-time distribution ✓
✓ Stable IGE Isotopes	Stable IGE Isotopes
✓ Explosion mechanism	Explosion mechanism
✓ Light curve/ Spectra	Light curve/ Spectra ✓

$$\frac{^{55}\mathrm{Fe}}{^{57}\mathrm{Co}} = 0.68$$

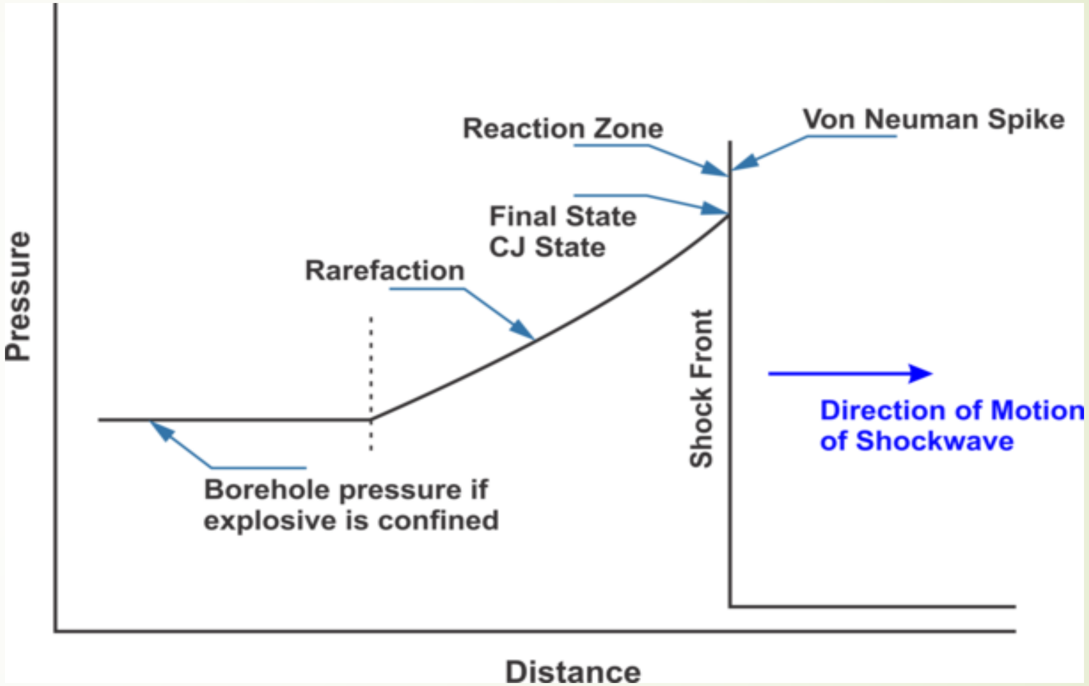
$$\frac{^{55}\mathrm{Fe}}{^{57}\mathrm{Co}} = 0.27$$

Röpke et al., 2012
Graur et al., 2016
Shappee et al. 2016

Deflagration - Detonation



Hugoniot curve

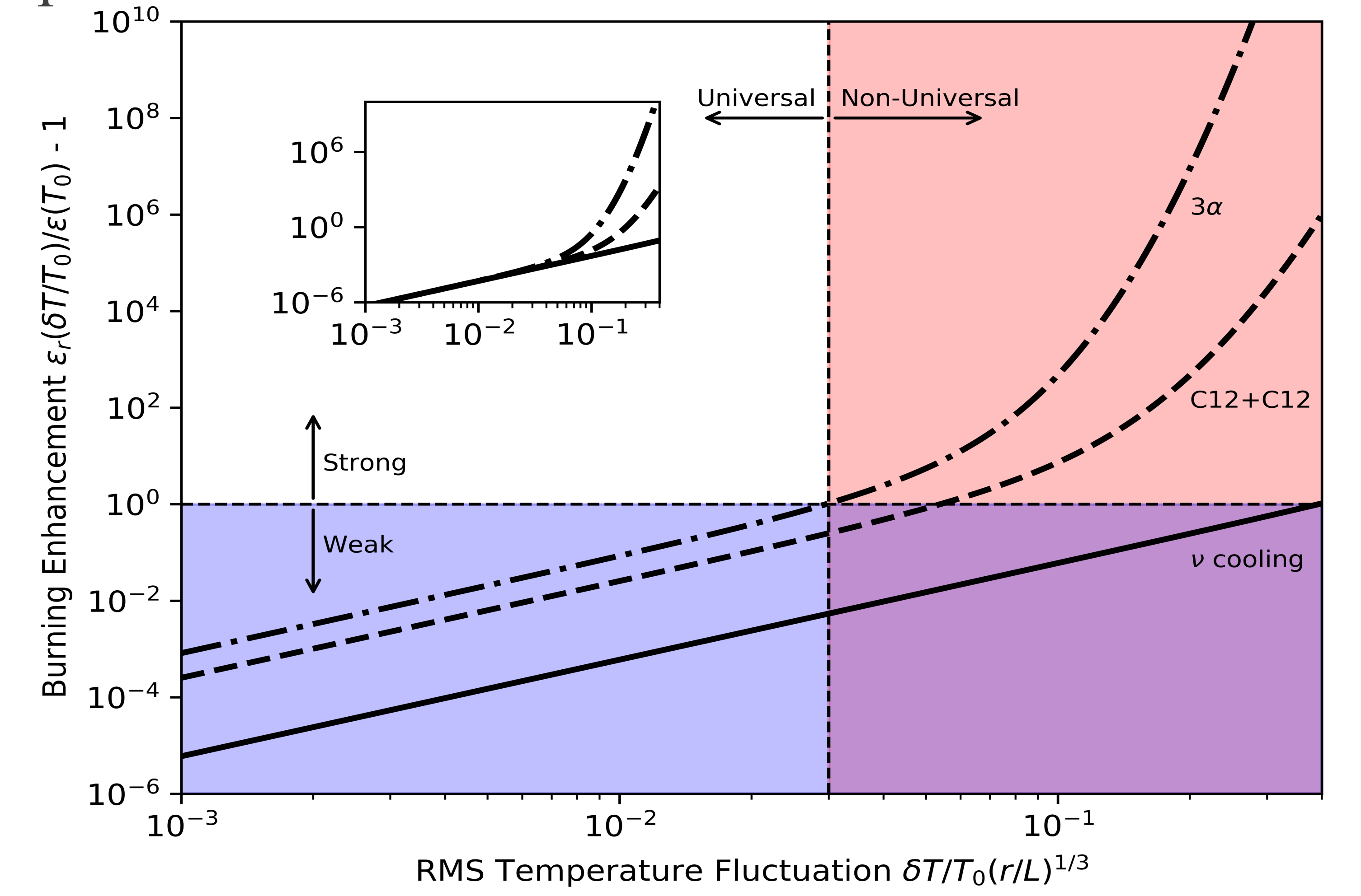


ZND detonation model

Website FXT, Detonation textbook 73

Turbulent Combustion Modeling

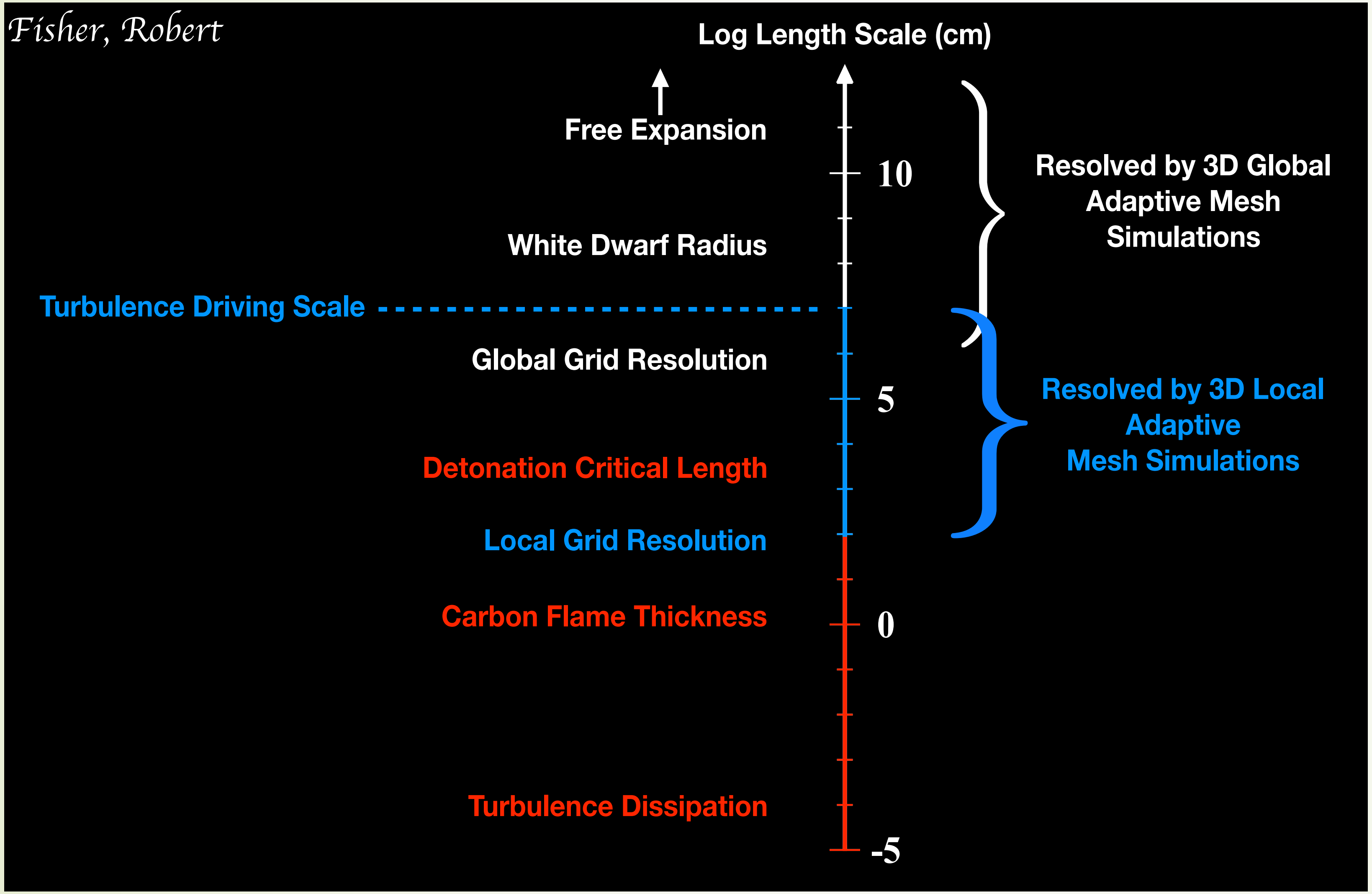
Burning rate on scale r determined by integration over the joint PDF $P_r(X, \rho, T)$ of composition, density, & temperature



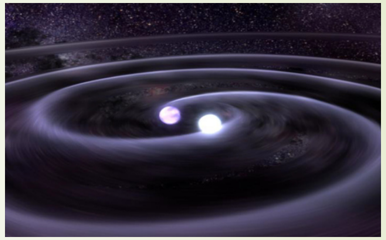
Nordita
12/16/20

YZ & Fisher (PRL)

The Ia SN are Multiscale, which is a real challenge



DD



SD

Implies a large dynamic range down to Kolmogorov scale :

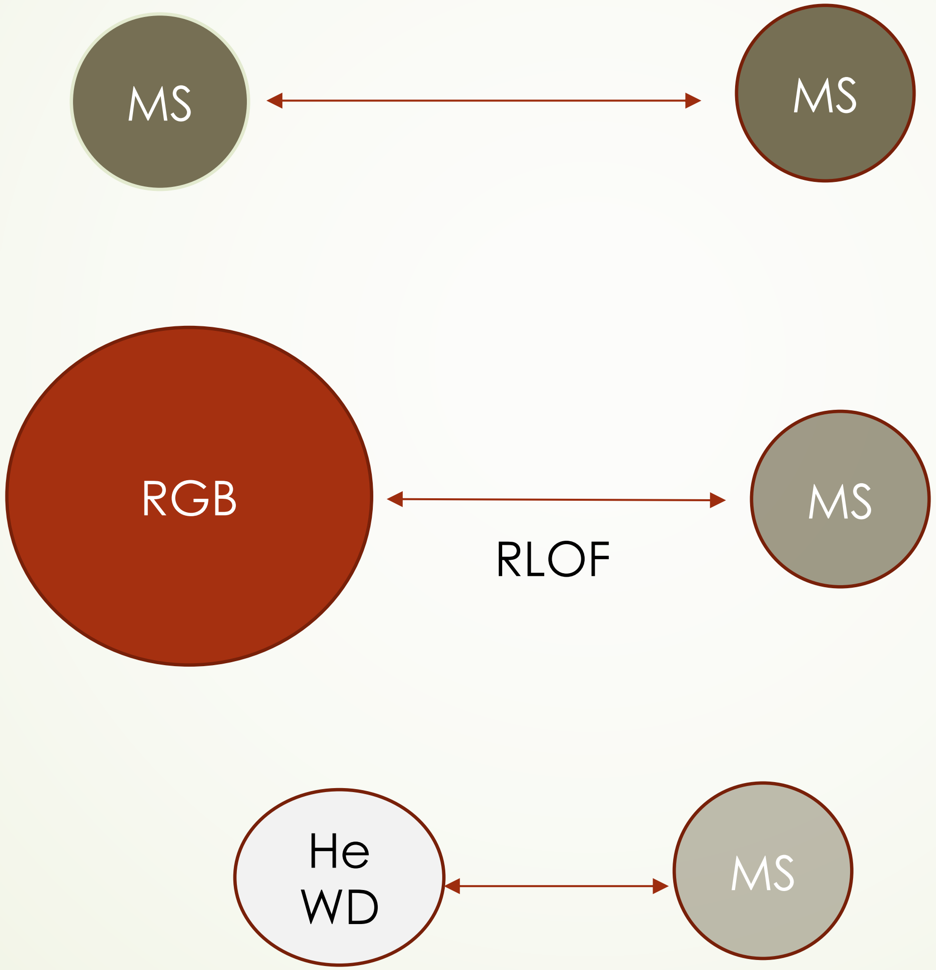
$$\frac{L}{\eta_K} = \mathrm{Re}^{3/4} \sim 10^{11}$$

Nordita
12/16/20

Binary evolution can produce other types of WD

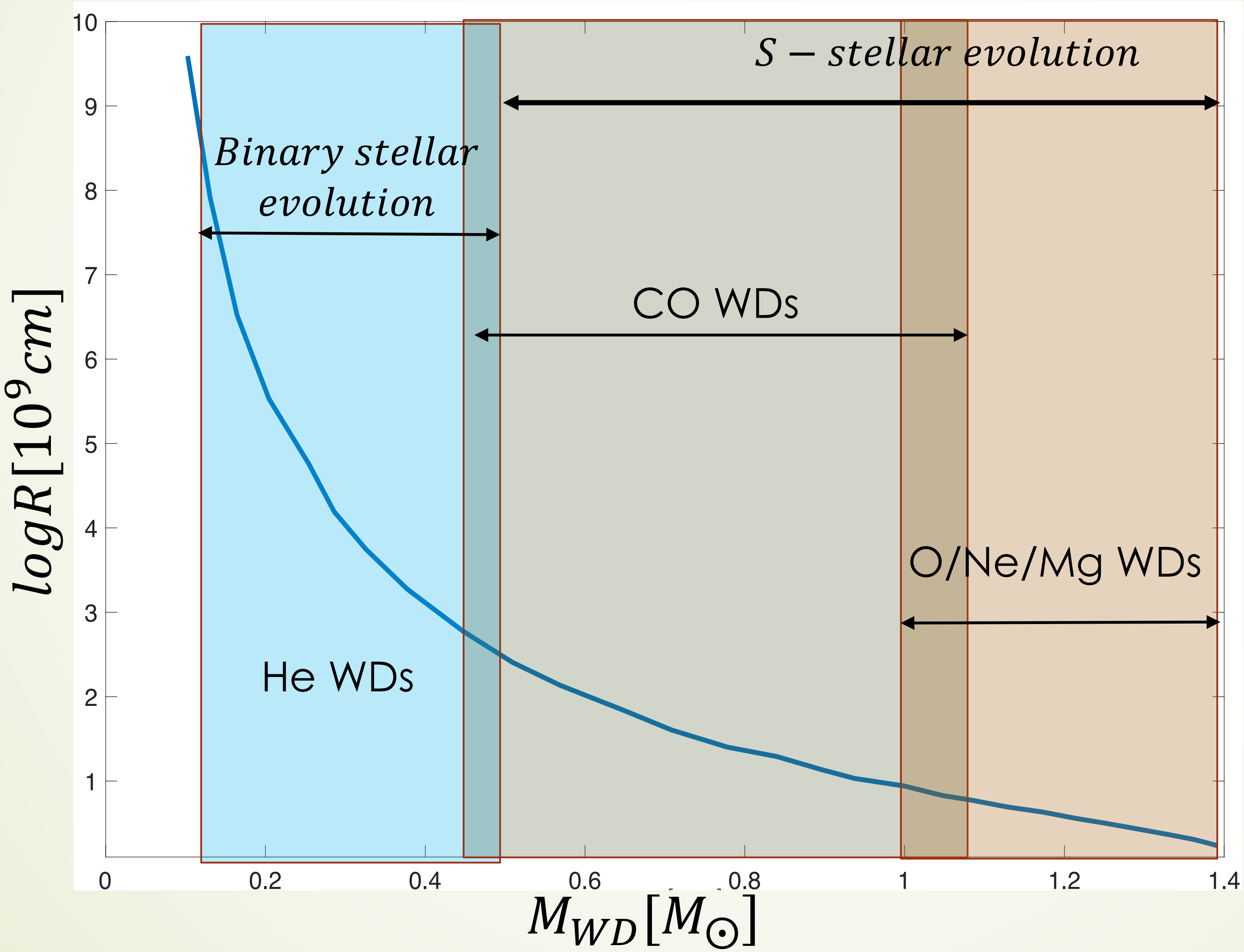
Low mass binary

$Z_\odot$



In binaries $M_{HeCO\,WD} \gtrsim 0.33\ M_\odot$
(Prada Moroni & Straniero 09)

S/Binary evolution can produce other types of WD



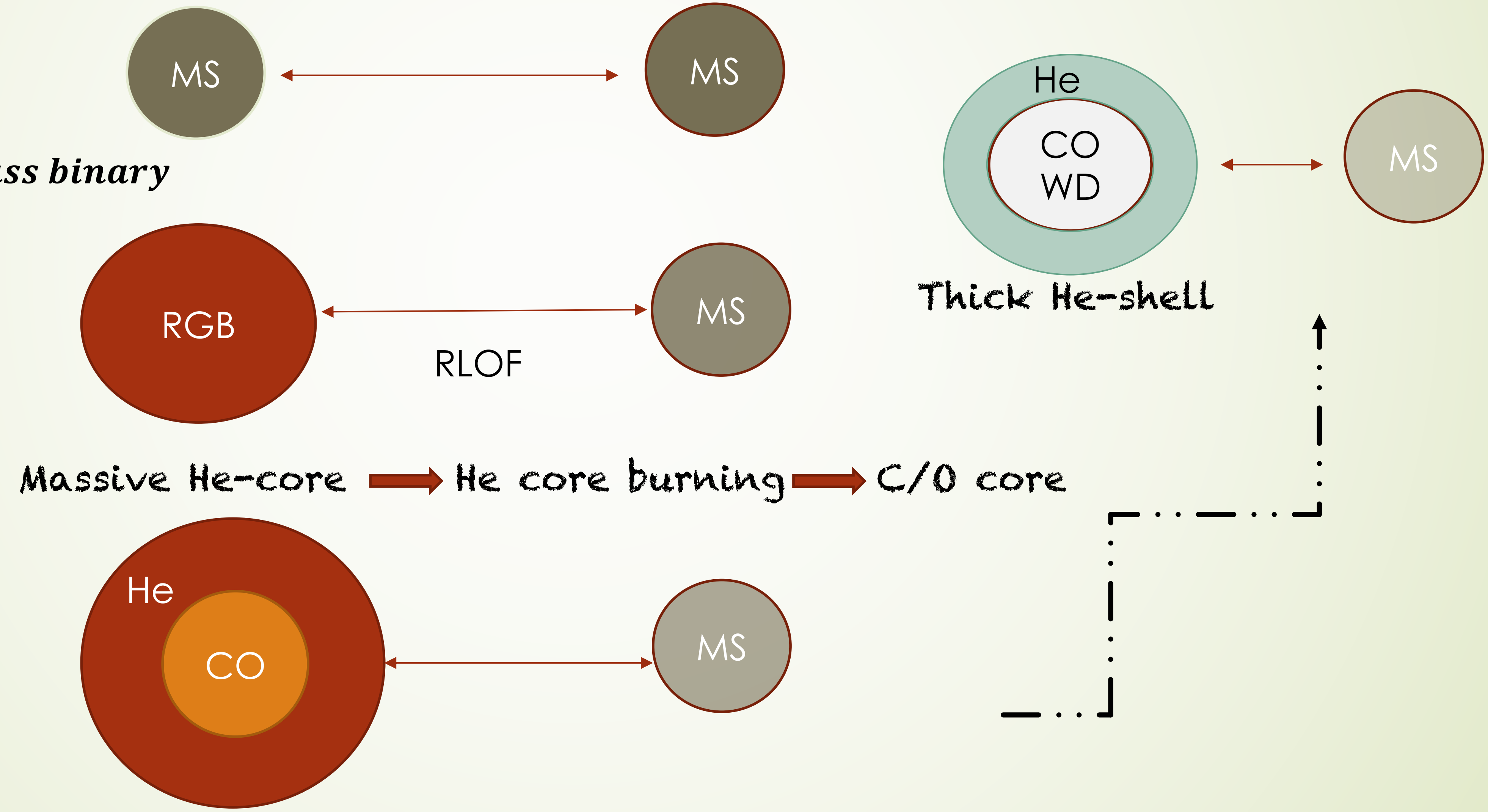
$M_{CO\,WD} \gtrsim 0.53\ M_\odot$

$M_{He\,WD} \lesssim 0.45\ M_\odot$

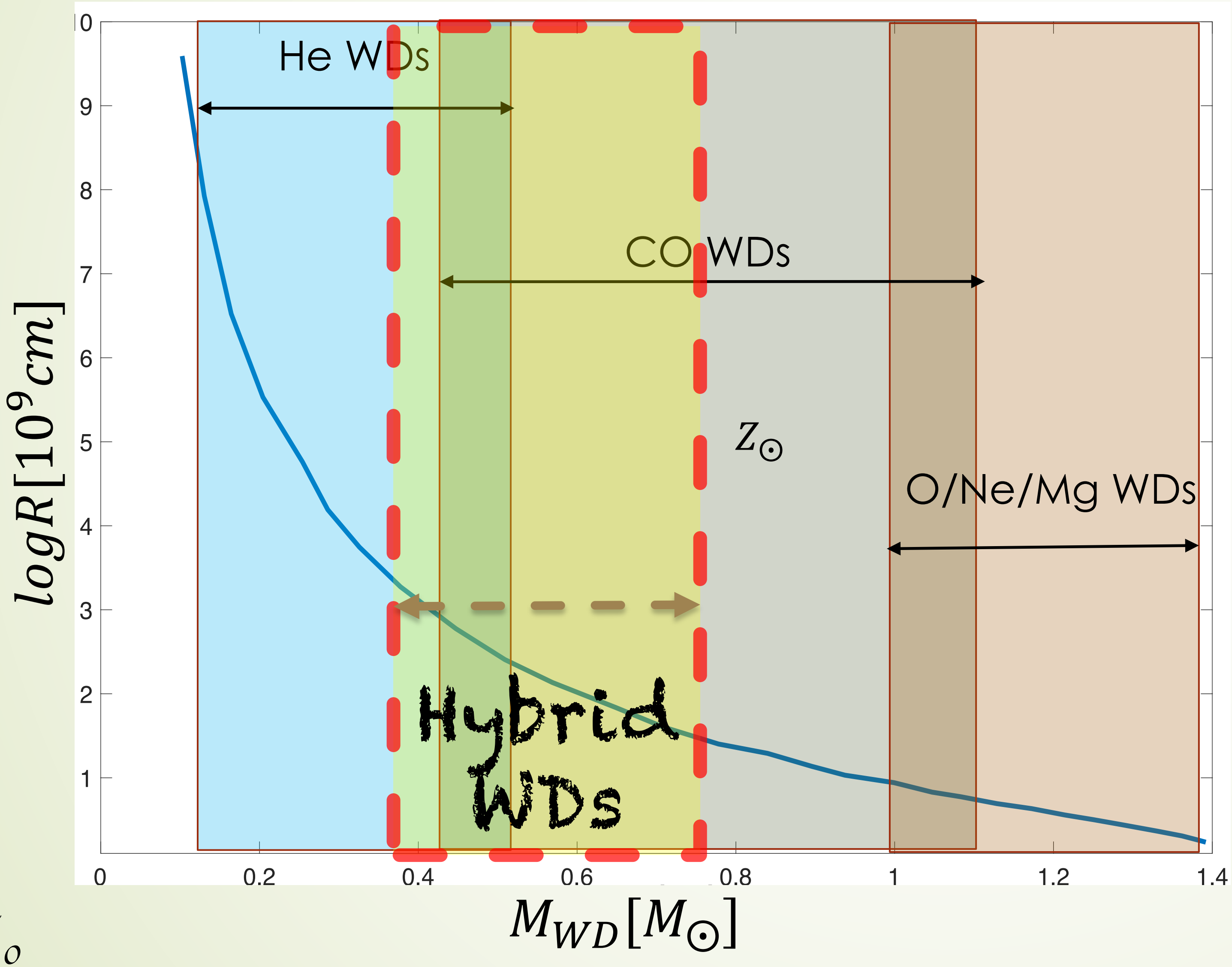
Binary evolution could produce a hybrid type of He-CO WDs

Intermediate − mass binary

$Z_\odot$



The masses of hybrid-WDs overlap with both He and CO WDs



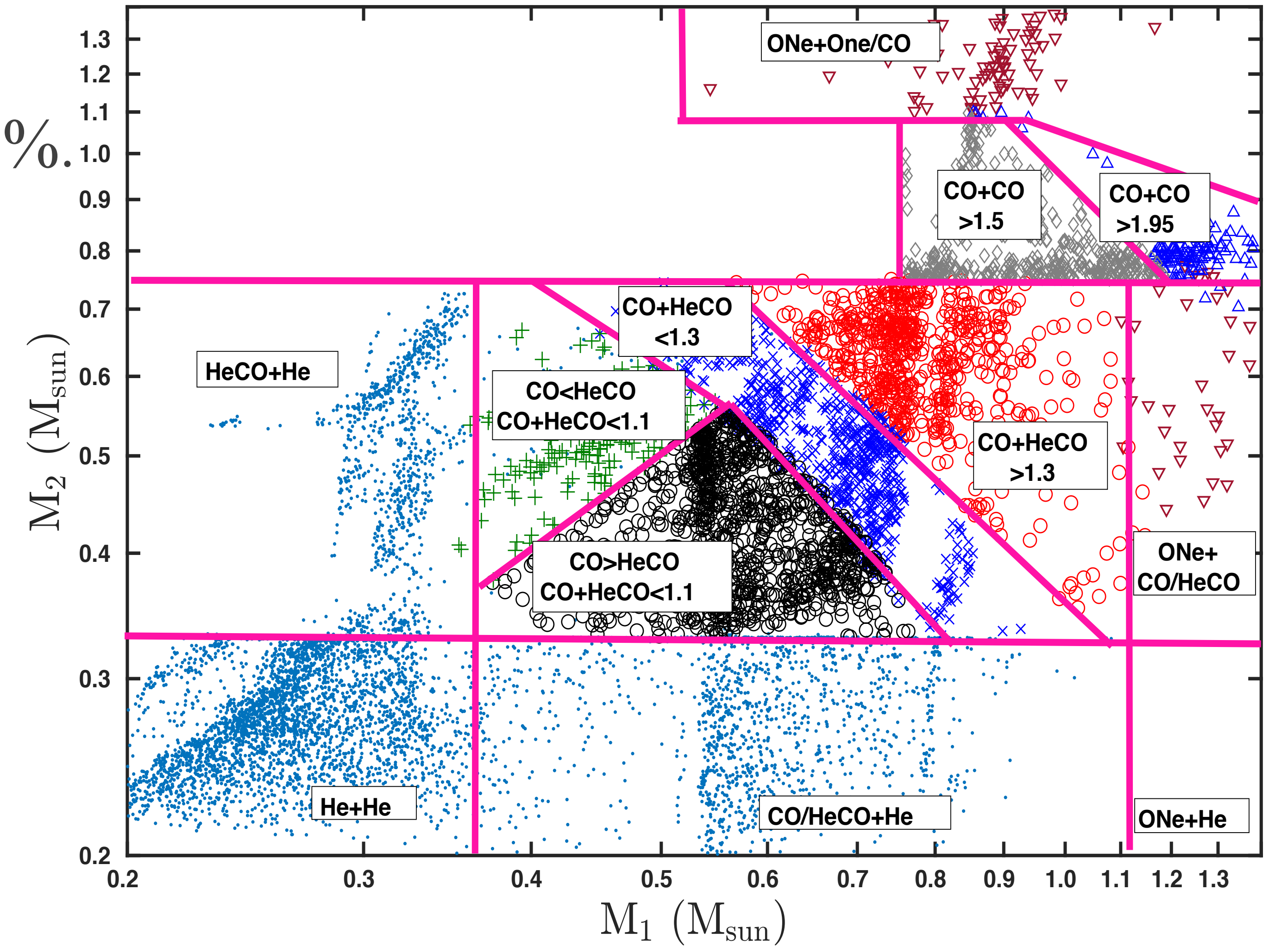
Hybrid-WDs are composed of significant fractions of both CO and He.

In binaries $M_{HeCO\,WD} \gtrsim 0.33\ M_\odot$
(Prada Moroni & Straniero 2009)

Iben & Tutukuv 1985
Tutukov & Yugelson 1992
Drirble et al. 1998
YZ+18

Wide range of possible mergers

- Hybrid WD's masses range
  $0.36 \leq M_{WD} \leq 0.74 M_{\odot}$
- He mass fractions in the range 5-25%.
- 15-30% of all hybrid cases will merge with another WD.

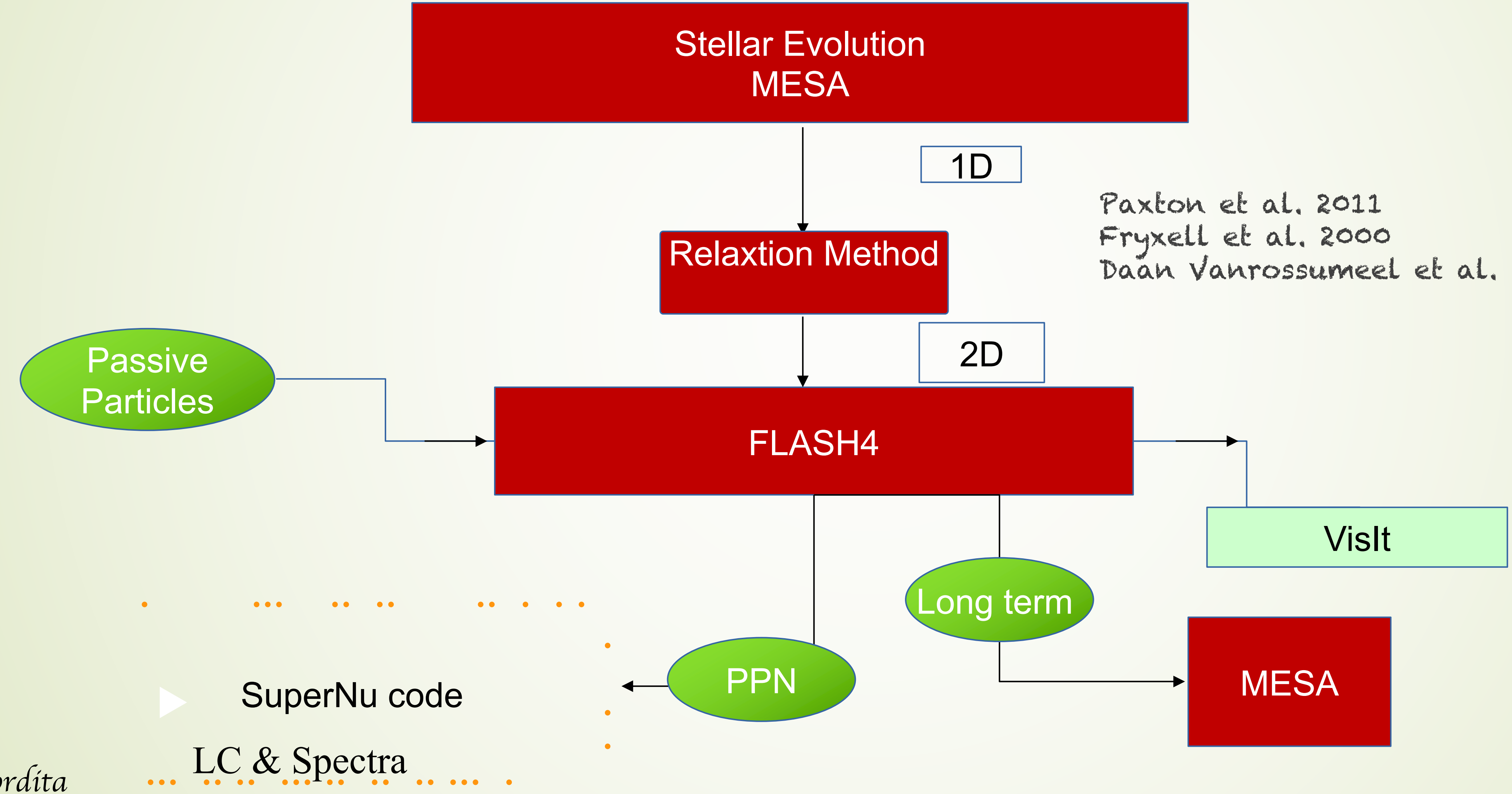


Possible discovery of Hybrid HeCO WD

- First ultracompact Roche lobe-filling hot subdwarf binary
  - Period of $P = 39.3401$ min, $M_{Donor,sdOB} \sim 0.337 M_{\odot}$, $M_{accretor} \sim 0.545 M_{\odot}$
  - Thick helium layer of $\approx 0.1 M_{\odot}$
- First known pulsating Eclipsing double WD binary
  - SDSS J115219.99+024814.4, Period of $P = 2.4$ hour, $M_1 \sim 0.362 M_{\odot}$, $M_2 \sim 0.325 M_{\odot}$.
- X-ray observations of the eclipsing polar HY Eri (RX J0501–0359)
  - Period of $P = 2.855$ hour, $M_{WD} = 0.42\ M_{\odot}$. The secondary is a MS of $M_2 = 0.24\ M_{\odot}$.

Kupfer et al. 2020
Parsons et al. 2020
K.Beuermann et al. 2020

Work- flow



Paxton et al. 2011
Fryxell et al. 2000
Daan Vanrossumeel et al. 2015

Simulations should include both hydrodynamics and thermonuclear reactions

- BH-WD merger –during the merger, the WD is tidally disrupted and sheared into accretion disk. (Papaloizou et al 83,Fryer et al 1998 and Metzger 2012).
- Also Paschalidis et al. (2011) & Bobrick et al. (2017) have explored the disruption and the disk formation process with time-dependent simulations.
- Thermonuclear processes can also play an important role on the dynamics of accretion following the TD of WD. (Metzger12, Fernandes&Metzger13, YZ+19).
- NS-WD mergers could be modeled in 2D using accretion disk. (Fernandes&Metzger13, Bobrick et al 2016, Margalit&Metzger16, and YZ+19, 20).

$$t_{\rm visc} \simeq \alpha^{-1}\left(\frac{R_0^3}{GM_c}\right)^{1/2}\left(\frac{H_0}{R_0}\right)^{-2}$$

$$\sim 2600\,{\rm s}\left(\frac{0.01}{\alpha}\right)\left(\frac{R_0}{10^{9.3}{\rm cm}}\right)^{3/2}\left(\frac{1.4M_\odot}{M_c}\right)^{1/2}\left(\frac{H_0}{0.5R_0}\right)^{-2}$$

$$\rho_{\rm disk} = \rho_{\rm max}\left[\left(\frac{\rm 2H}{\rm R_0}\right)\frac{\rm 2d}{\rm d-1}\left(\frac{\rm R_0}{r} - \frac{1}{2}\left(\frac{\rm R_0}{\rm r\sin\theta}\right)^2 - \frac{1}{\rm 2d}\right)\right]^{7/2} \quad (3)$$

$$\frac{\rm P}{\rho} = \frac{\rm 2GM}{\rm 5R_0}\left[\frac{\rm R_0}{\rm r} - \frac{1}{2}\left(\frac{\rm R_0}{\rm r\sin\theta}\right)^2 - \frac{1}{\rm 2d}\right] \quad (4)$$

CO WD-hybrid WDs could merge and lead to DD type Ia SN

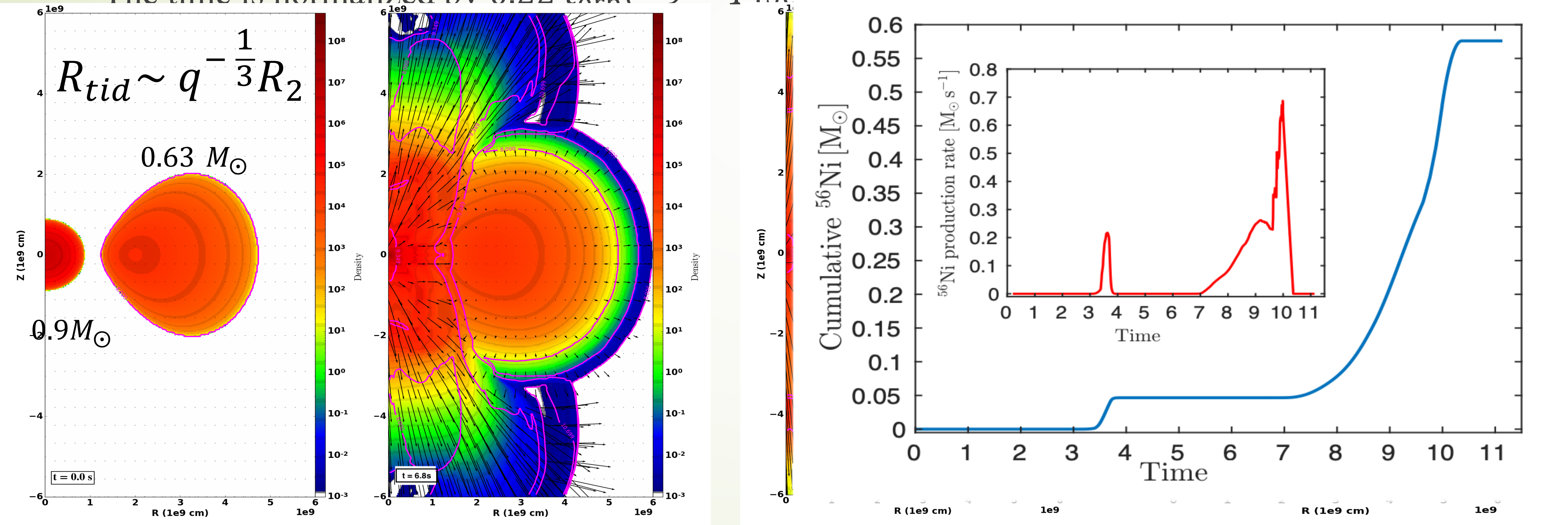
- A He envelope can ignite and lead to the detonation.
- Merger of low mass double WDs could explode as well.
- The time is normalized by 0.22 t_{orb} $(\sim 9-14 sec)$

Virial Temperature

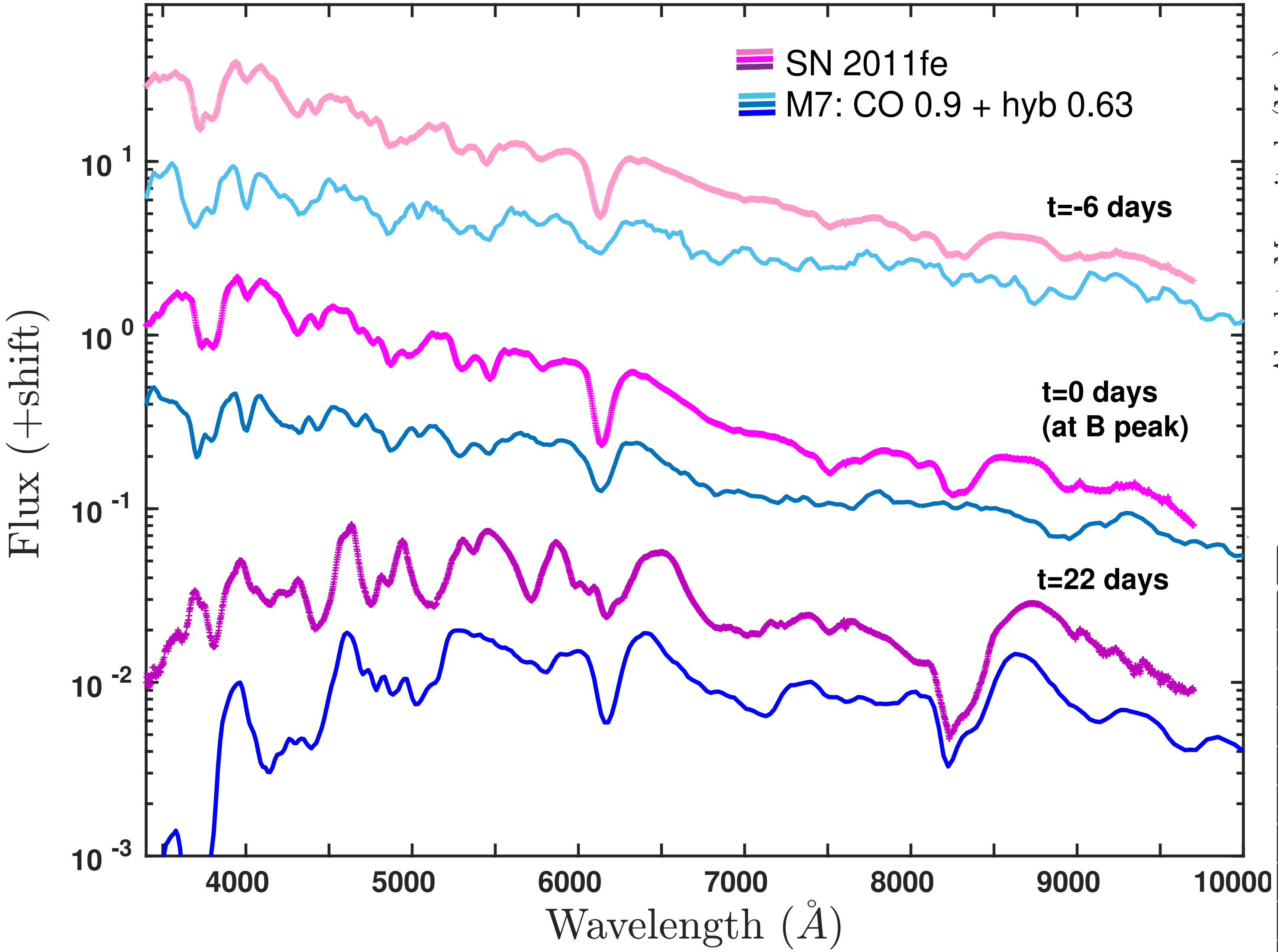
$$T(R_{tid}) \geq 6\times10^8 K$$

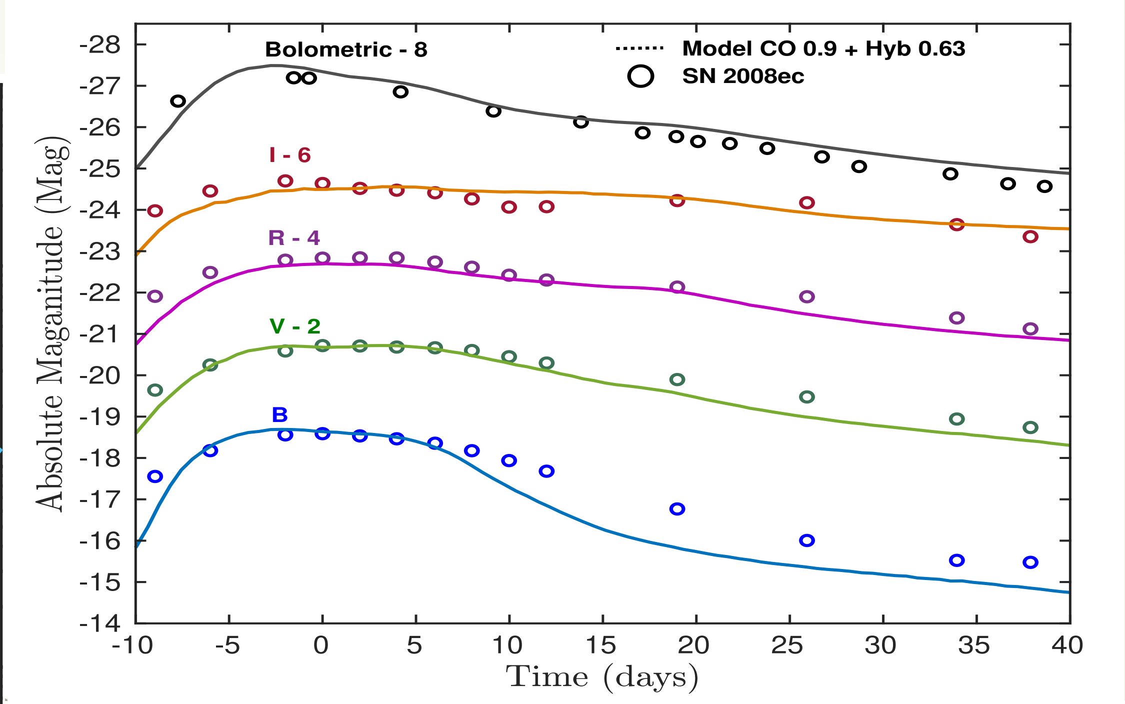
Midplane Density

$$\rho(R_{tid}) \approx 10^7 gcm^{-1}$$



Light curves & Spectra

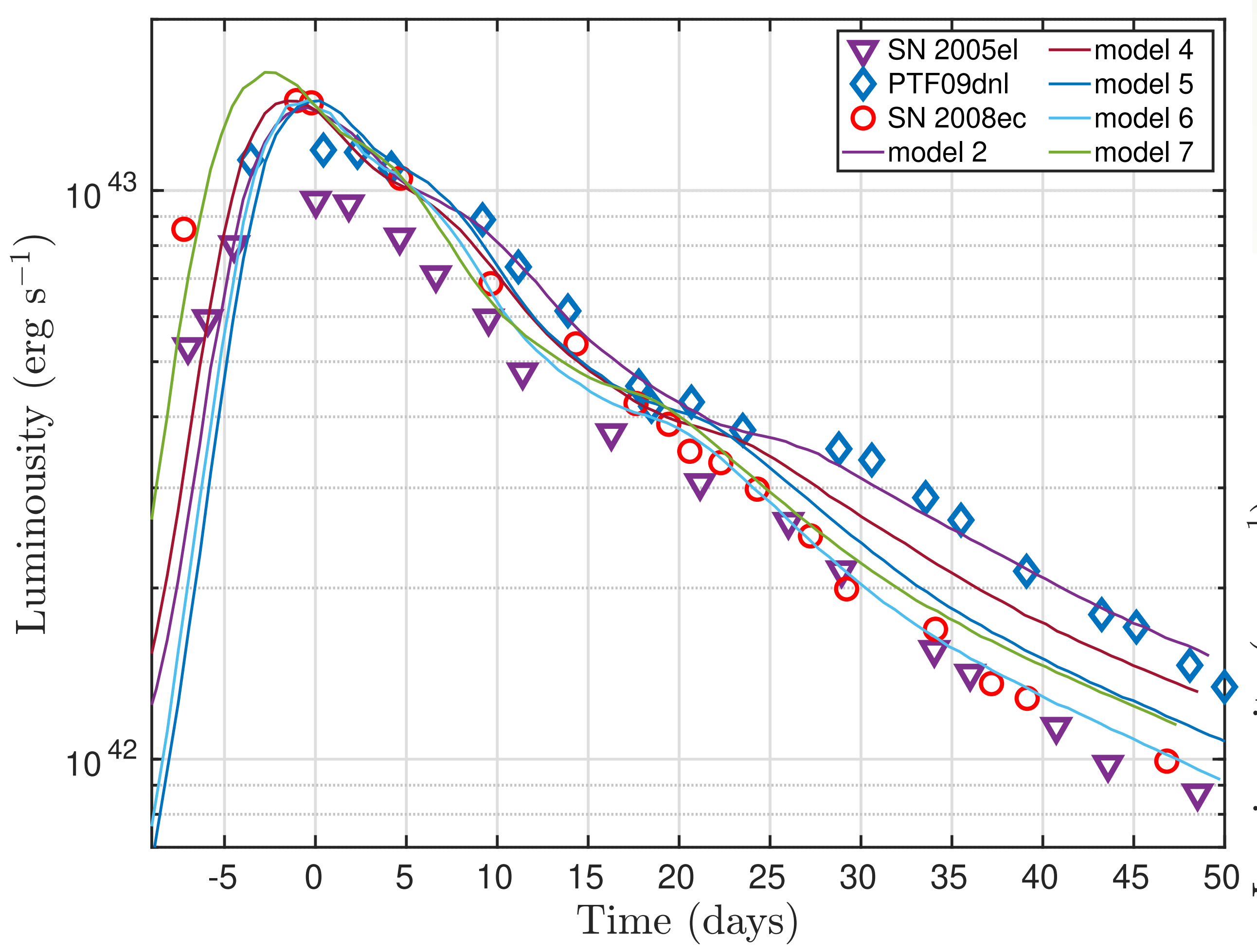


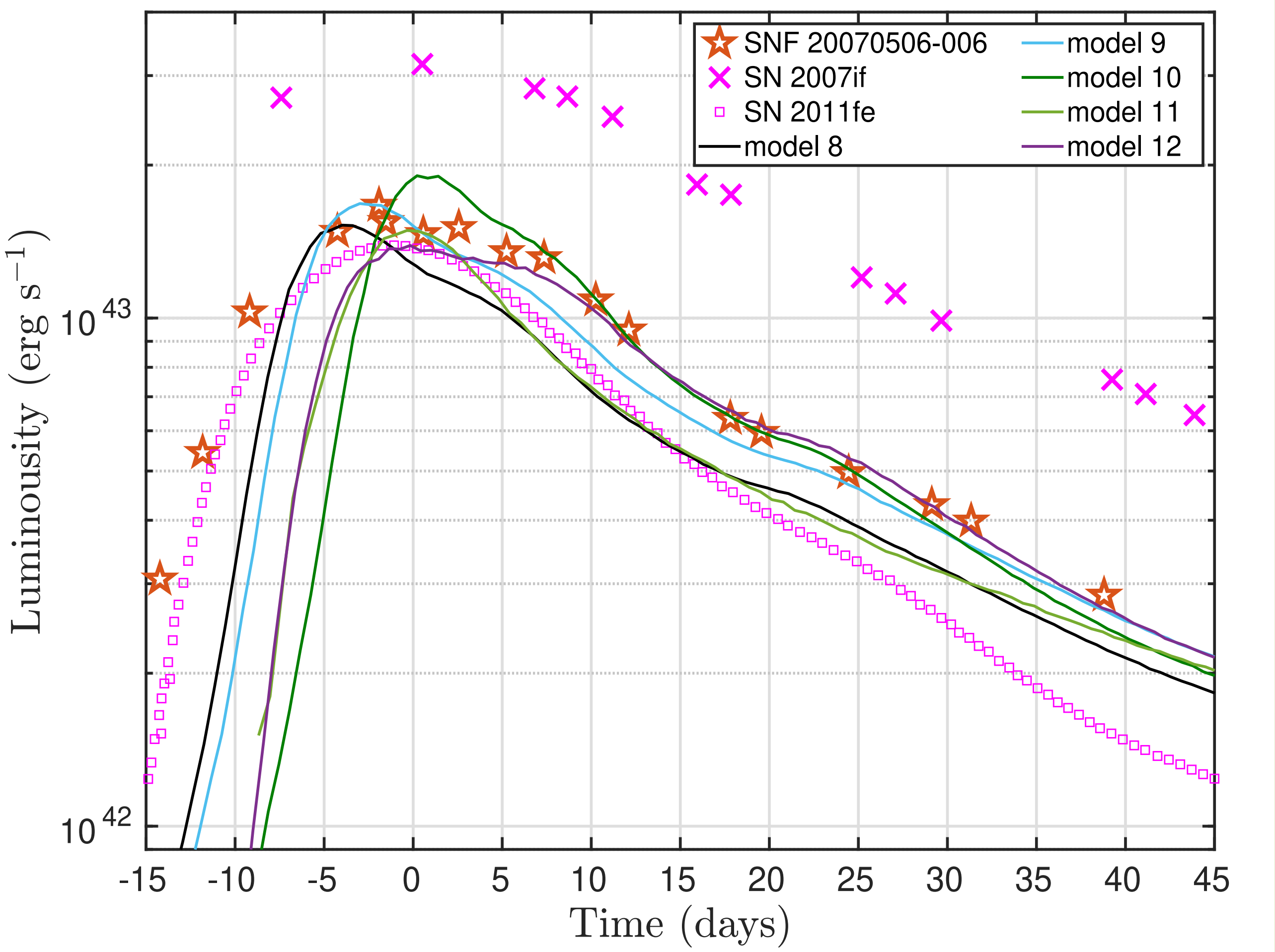


#	$M^{Hyb}(M_{He4}[M_\odot])$	$M_{CO}[M_\odot]$	$M_{tot}[M_\odot]$	$M_{Ni56}[M_\odot]$
1	0.53 (0.074)	0.7	1.23	0.512
2	0.53 (0.074)	0.75	1.28	0.533
3	0.53 (0.074)	0.8	1.33	0.530
4	0.53 (0.074)	0.9	1.43	0.549
5	0.63 (0.03)	0.75	1.38	0.538
6	0.63 (0.03)	0.8	1.43	0.556
7	0.63 (0.03)	0.9	1.53	0.562
8	0.63 (0.03)	1.0	1.63	0.564
9	0.68 (0.015)	1	1.68	0.569
10	0.68 (0.015)	1	1.68	0.574
11	0.74 (0.01)	0.9	1.64	0.589
12	0.74 (0.01)	1.0	1.74	0.592

YZ+ 20

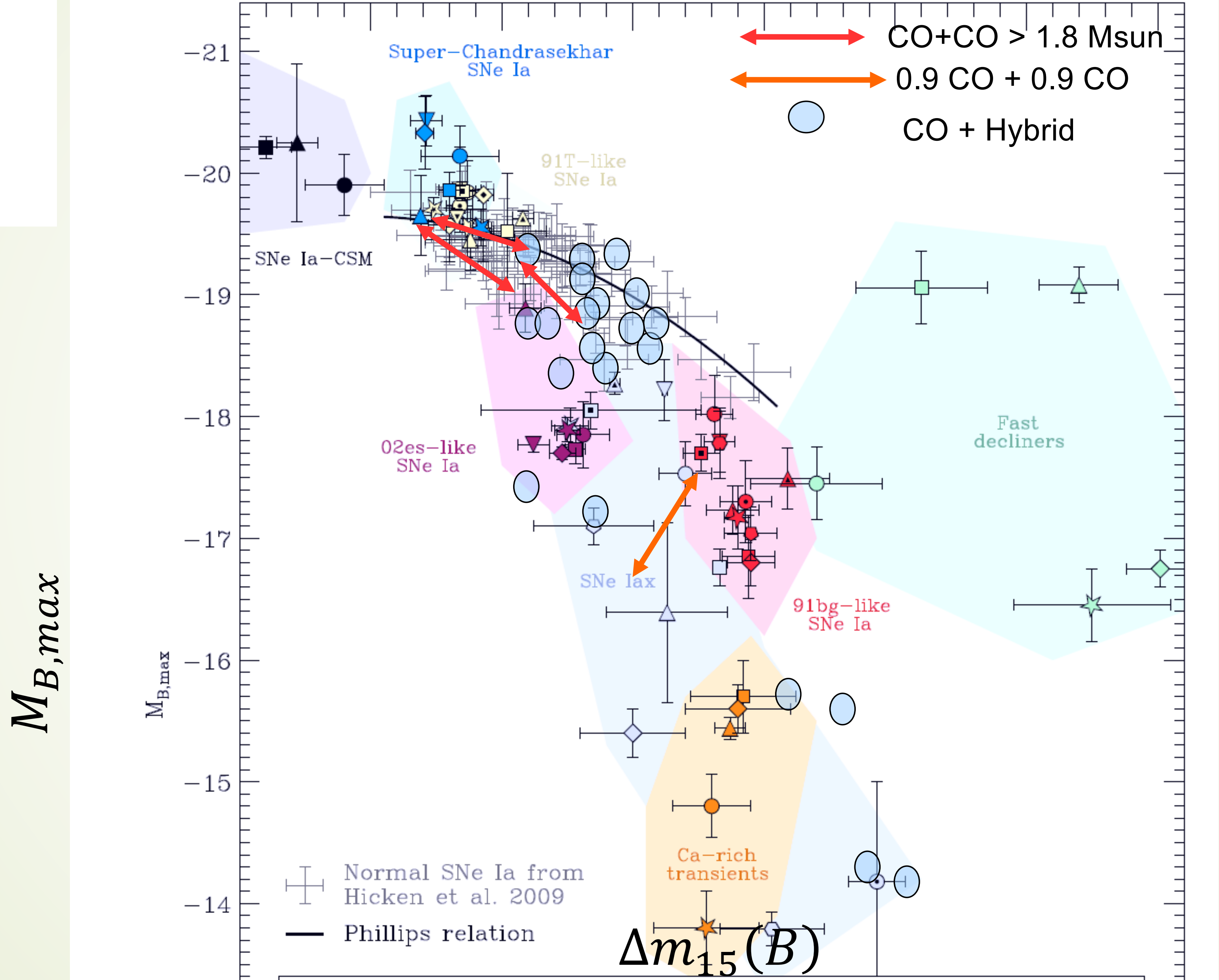
Light curves & Spectra



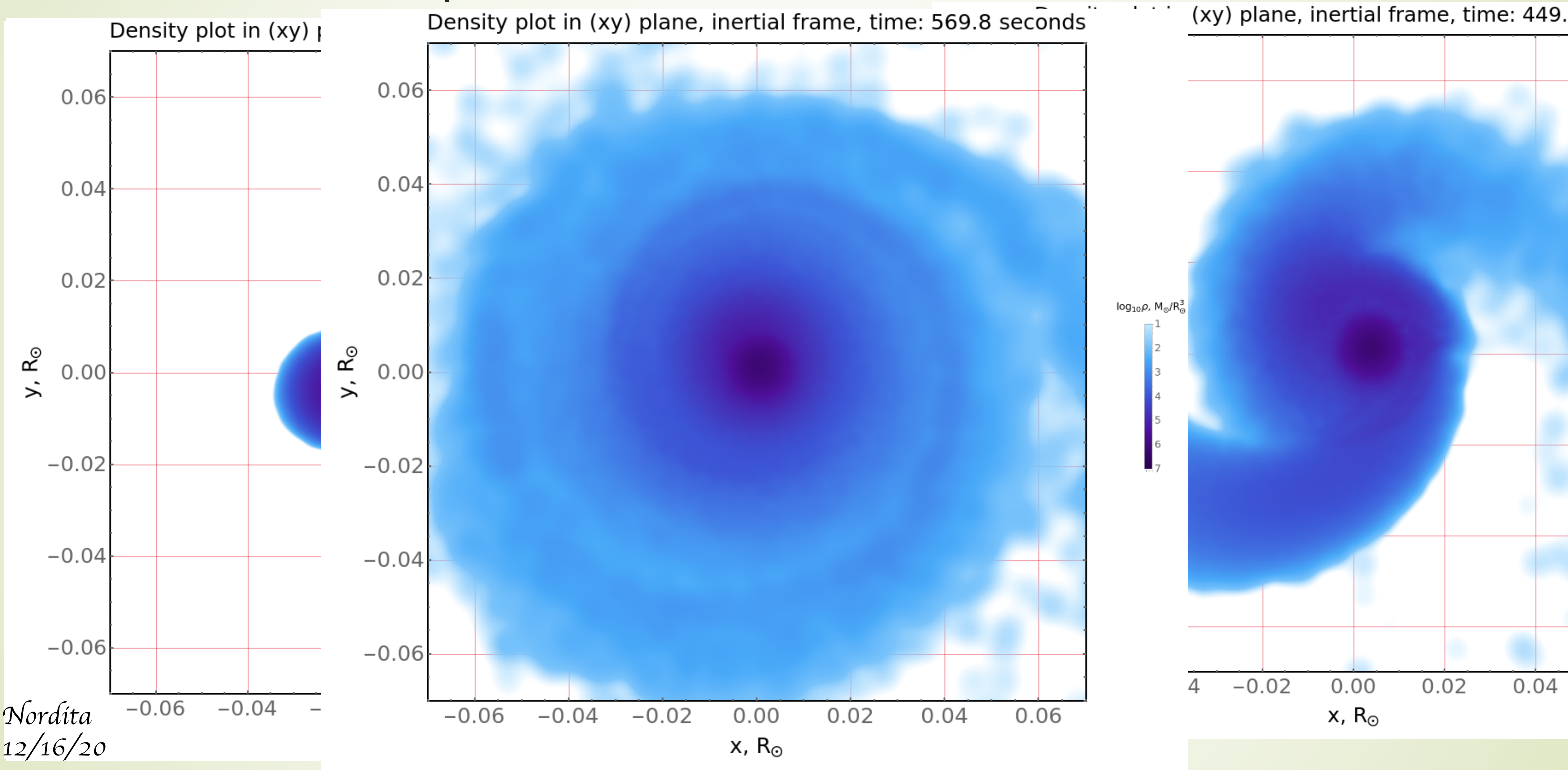


YZ+20

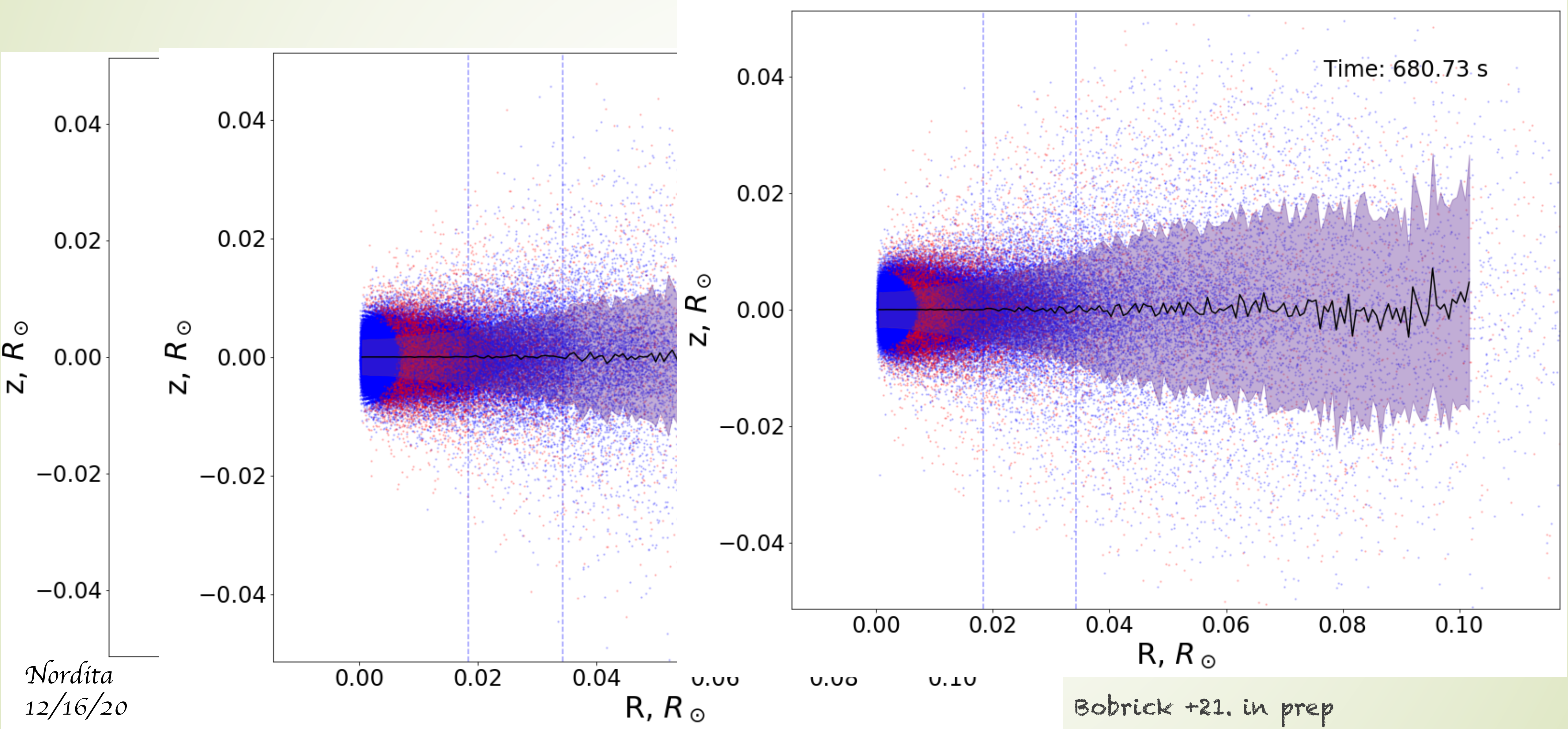
Peak width relation



Our assumptions could be more realistic



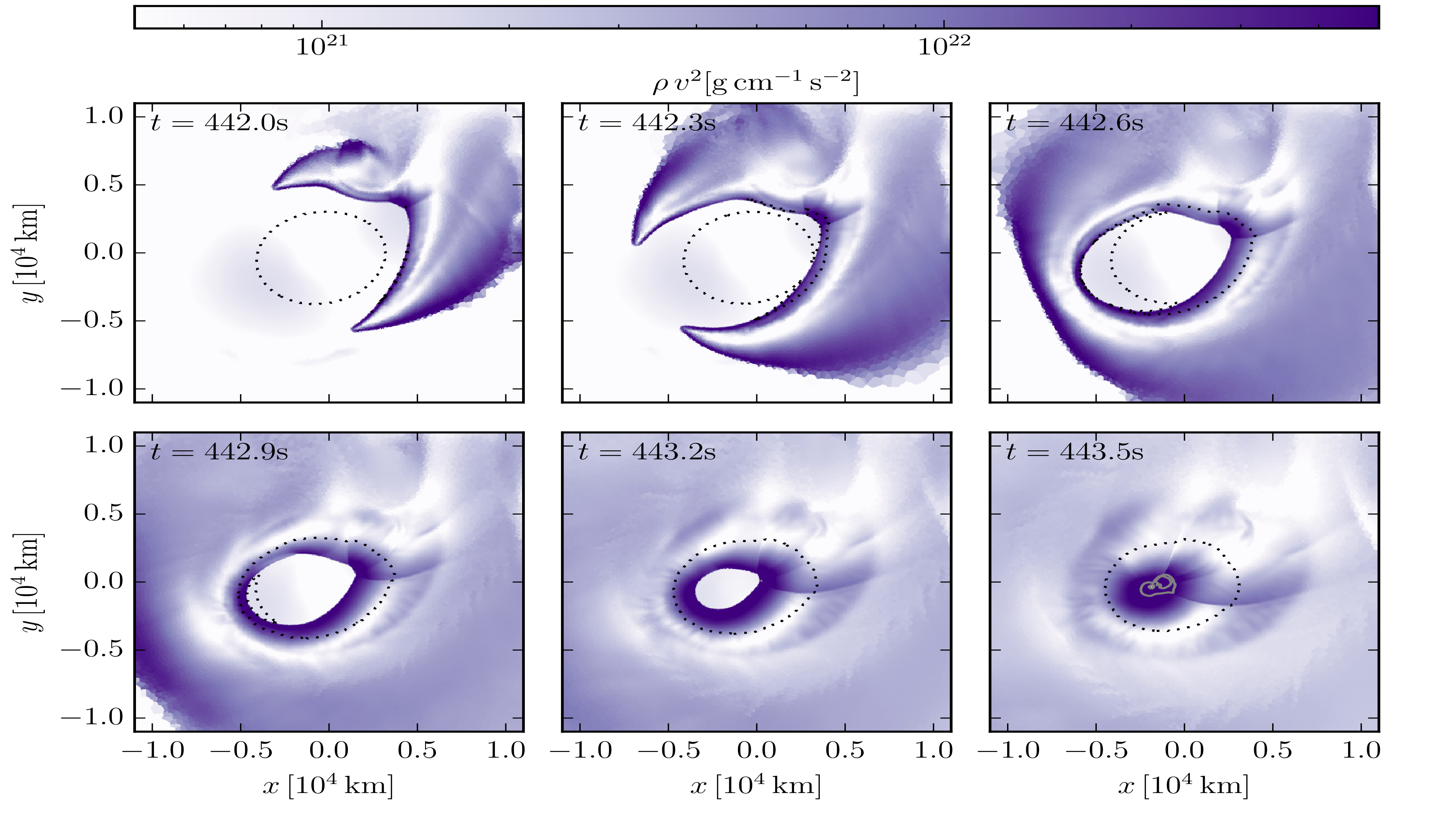
Our assumptions could be more realistic



Nordita
12/16/20

Bobrick +21, in prep

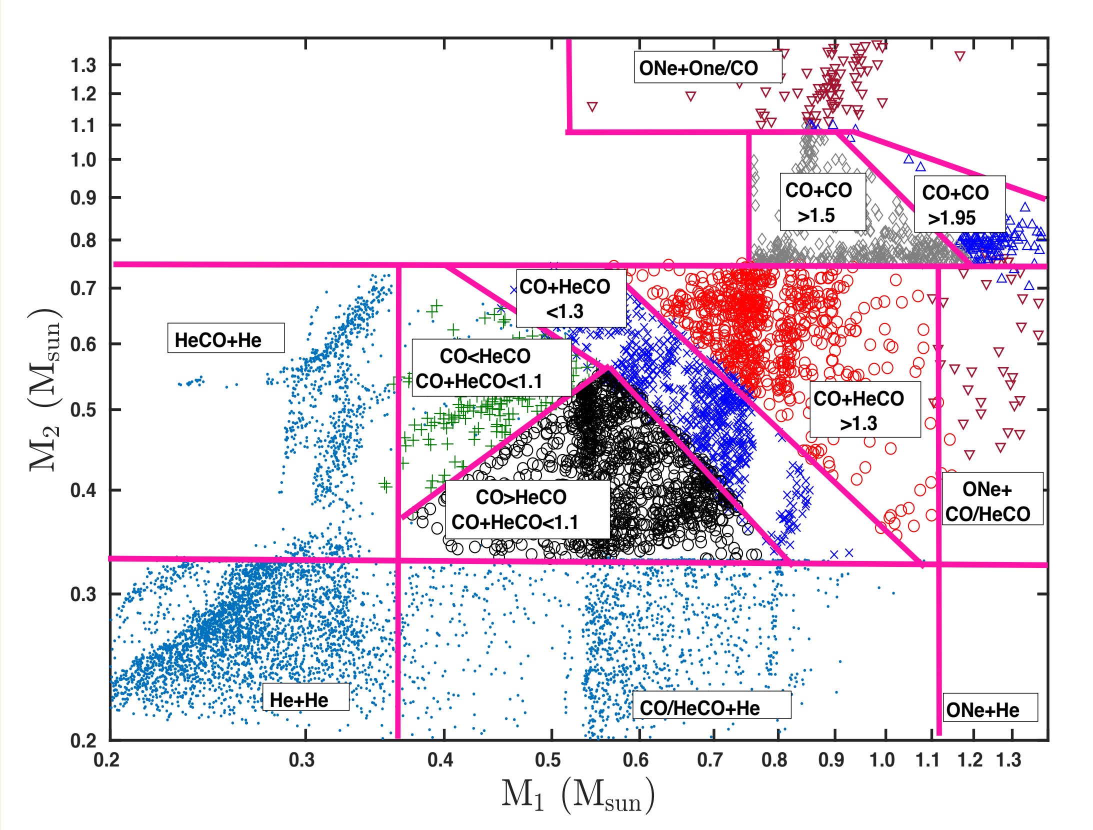
CO WD-hybrid WDs could merge and lead to DD type Ia SN

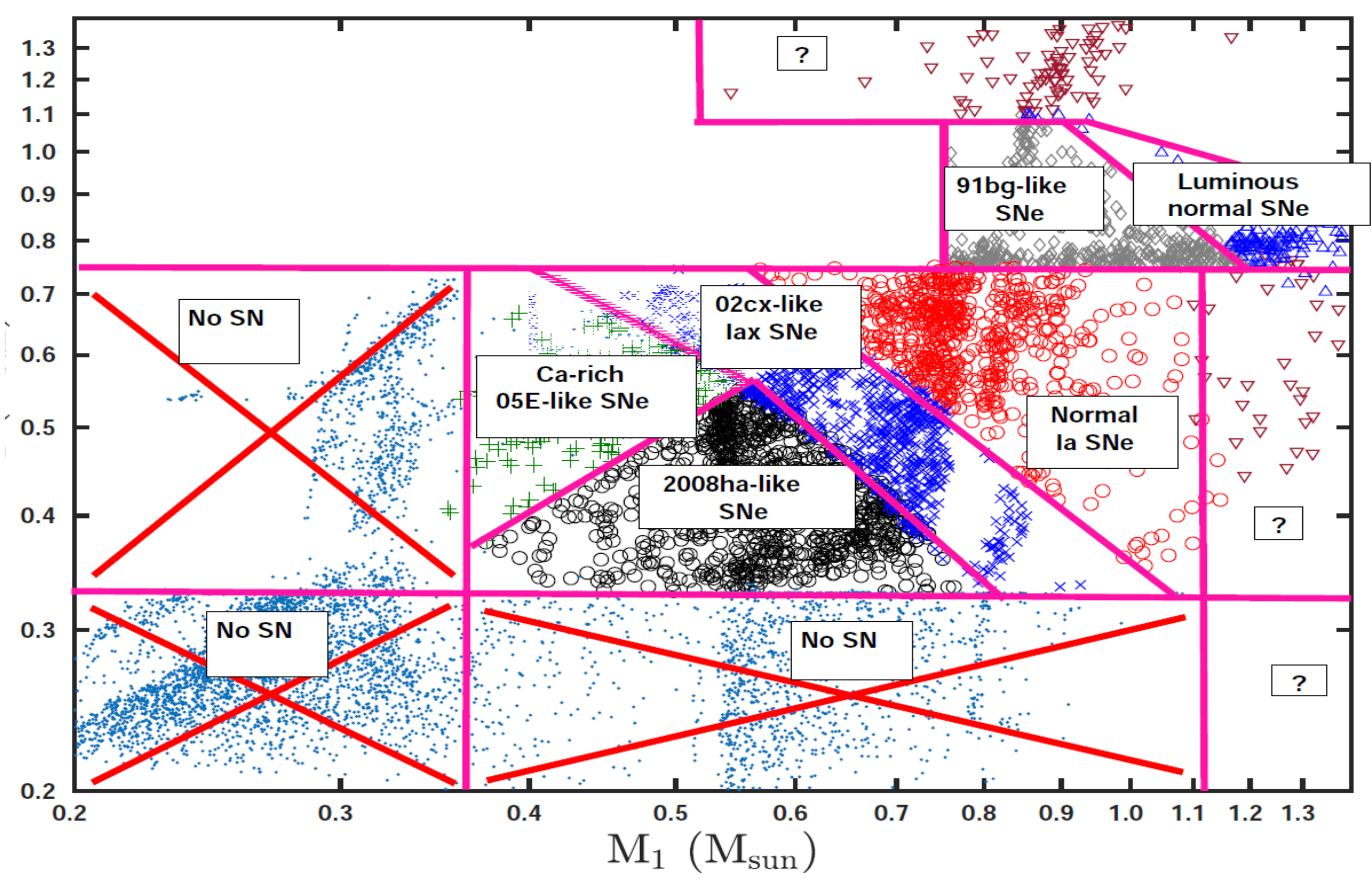


Nordita
12/16/20

Pakmor, YZ, Perets, Toonen 2020

The hybrid WD - CO WD merger give rise to normal and peculiar SN





Nordita
12/16/20

Summary- SNe Ia

- Hybrid HeCO WDs can form robustly.
- Turbulent enhancement formalism we present provides a promising basis for an approach for sub-grid modeling of turbulent nuclear burning and detonation initiation.
- Mergers with Hybrids could potentially give rise to explosive thermonuclear events.
- Our models can only reproduce the somewhat faster evolving and somewhat fainter normal type Ia SNe. ($M_B \gtrsim -19.2$).
- Our models can generally reproduce the detailed light-curves and spectra of normal but fainter ($M_B \sim -18.4$ - -19.2, $M_R \sim -18.5$ - -19.4) type Ia SNe.