Tokyo Time Machine 2018

[Massive & Very Massive] Star Evolution @ low Z & Z=0

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Plan

- Standard picture & expectations

- Uncertainties and open questions:

- - Are PISNe just theoreticians pets?

- - Internal mixing due to rotation & shell mergers

- Summary & outlook

Standard Picture & Expectations

Low/zero metallicity (Z) for single non-rotating stars means:

- less cooling → top-heavy IMF? [Monday session]

- Low opacities → stars are more compact

- Low/negligible mass loss:

More massive remnants

VMS → PISNe

(VMS = Very Massive Stars for $M > 100\ M_\odot$)

- Primordial initial abundances (or close to it)

Primary elements unaffected (e.g. O, Mg, Fe)

Little/no secondary elements (e.g. N, ***weak*** s process)

First Generations: Fate of Non-Rotating Stars

Heger, Fryer et al 2003

Z~0:

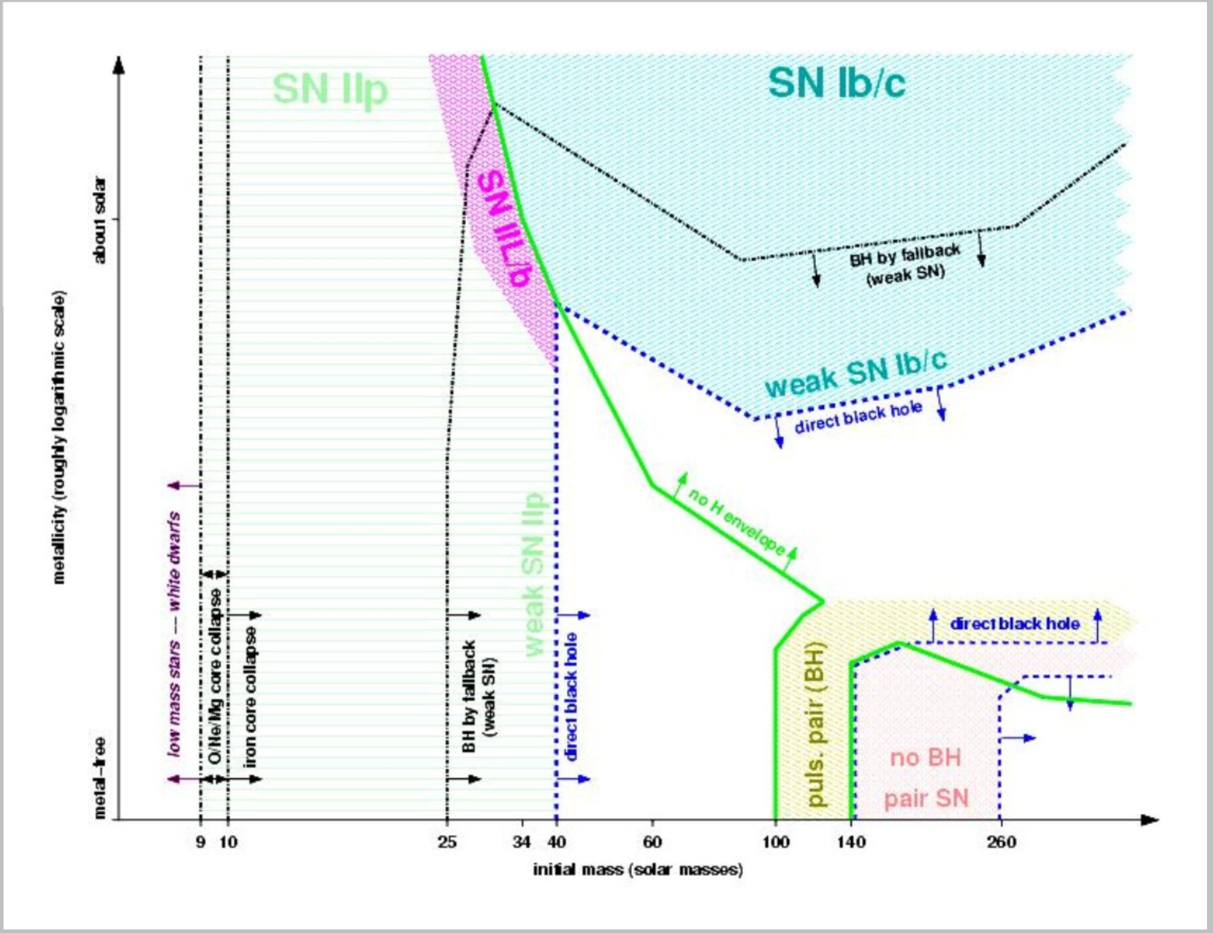
M<25 Mo: SNII

25-40: weak SNII

40-140:BH, no SN

140-260: PISN

260-?: BH, no SN



Talks this morning

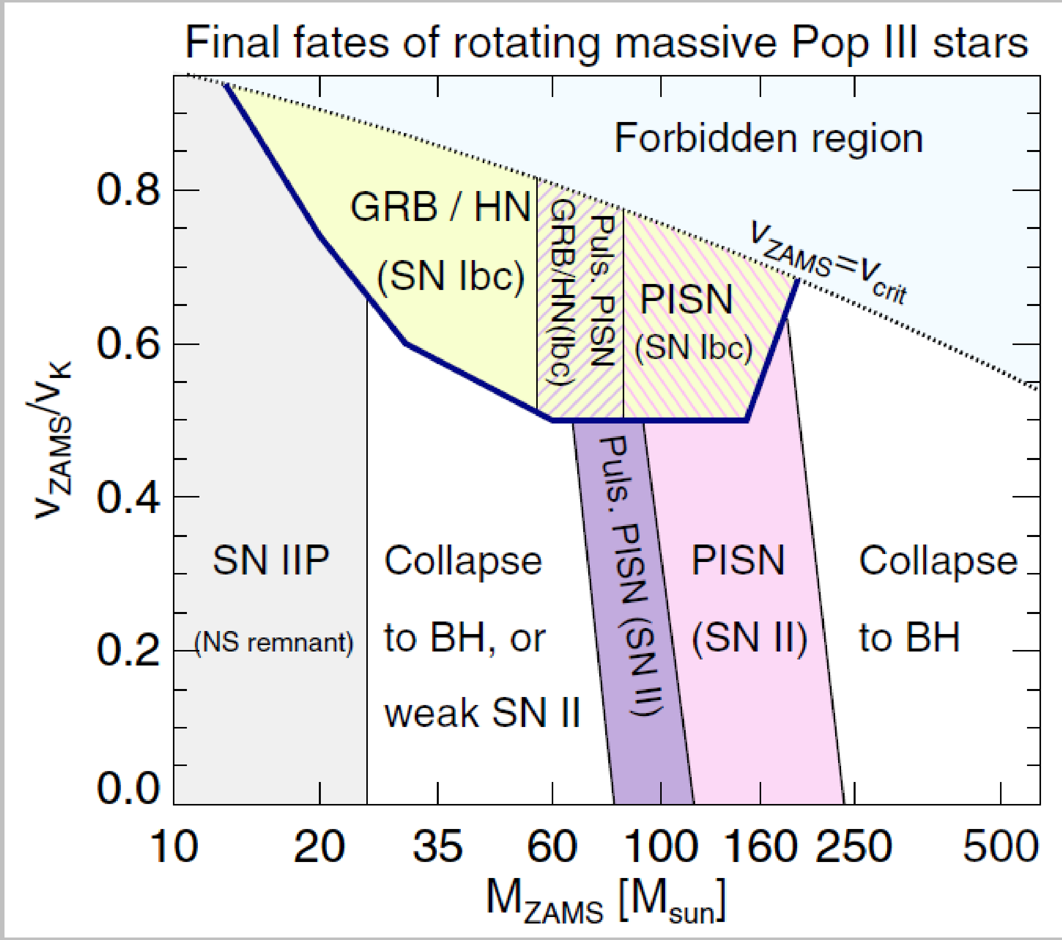
The fate of VMS @ Z=0

Yoon et al 2012 (see also Chatzopoulos, & Wheeler 2012 and Heger & Woosley 2012, Heger & Woosley 2002)

Z= 0:
Models including Mdot, rotation & B-fields

Rotation lowers mass range for PISN

Mechanical Mdot important



Pair instability SN (M:140-260 $M_\odot$) (Heger and Woosley 02, Scannapieco et al 05):

- Chemical signature of PISN not observed in EMP stars (Umeda and Nomoto 02,03,05, Chieffi and Limongi 00,02,04)
- Due to strong mass loss? Hirschi 2007, Ekström et al 2008
- Only PISN candidates found (PTF12dam), no standard PISN observed

Why are PISNe not observed?

Maybe PISNe only occur in models because

- the IMF stops around 150 $M_\odot$

- VMS lose too much mass

- PISNe are not as we expect them (e.g. rarer or fainter)? JWST coming soon

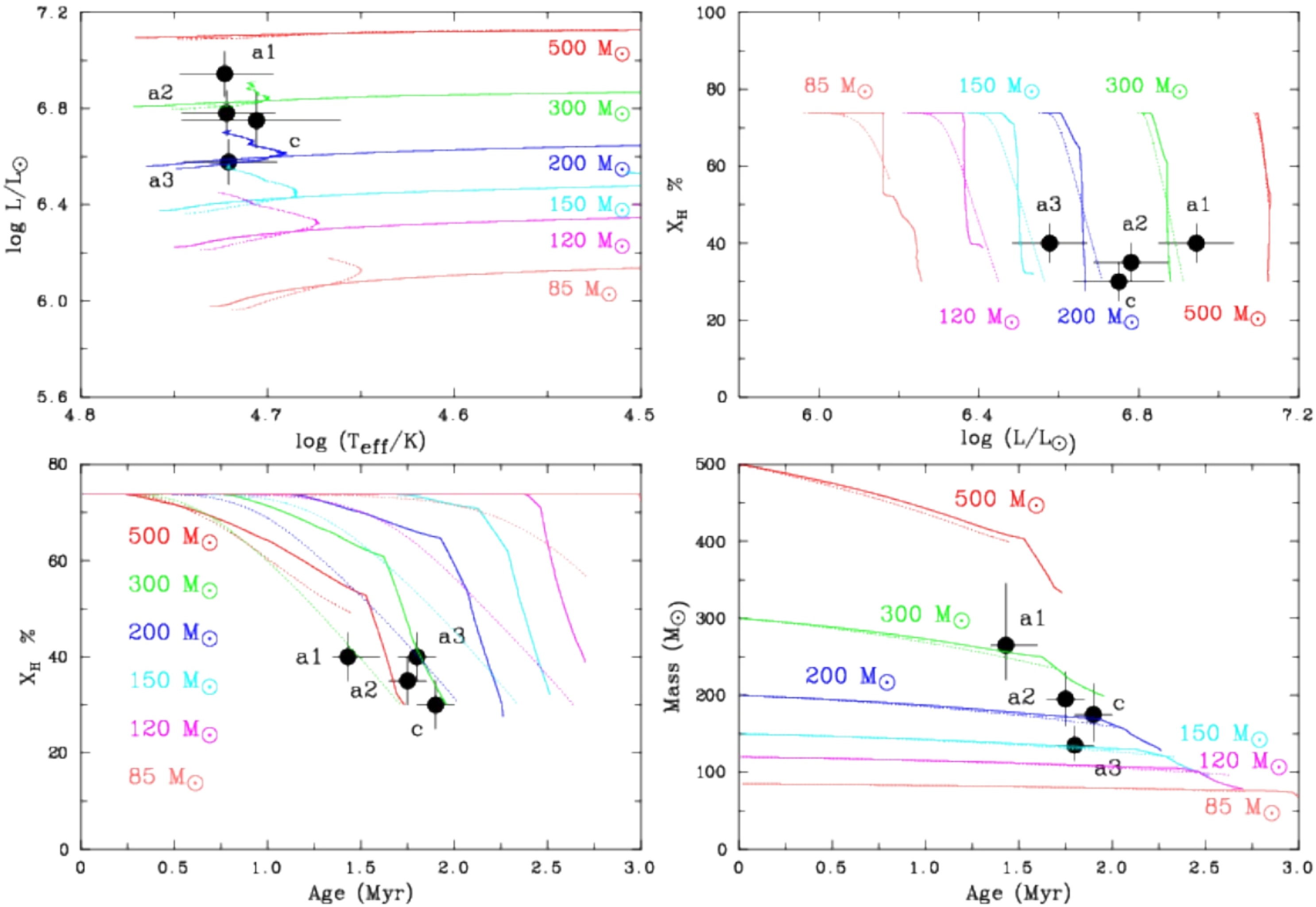
Whether or not (P)PISNe occur, we want to know why

→ Black-hole mass function & gravitational waves

VMS are Found in Nature: R136 (30 Dor)

Cluster in the LMC with about 5×10^4 M_o so we expect a few stars more massive than 150 M_o.

Crowther et al 10, MNRAS



Results:
age: 1.7+/-0.2 Myr

Initial masses:
a1: 320 +100-40 M_o
a2: 240 +/-45 M_o
c: 220 +55-45 M_o
a3: 165 +/-30 M_o

Checks: clumped mass loss rates derived: $2\text{-}5 \times 10^{-5}$ M_o/yr match Vink et al predictions

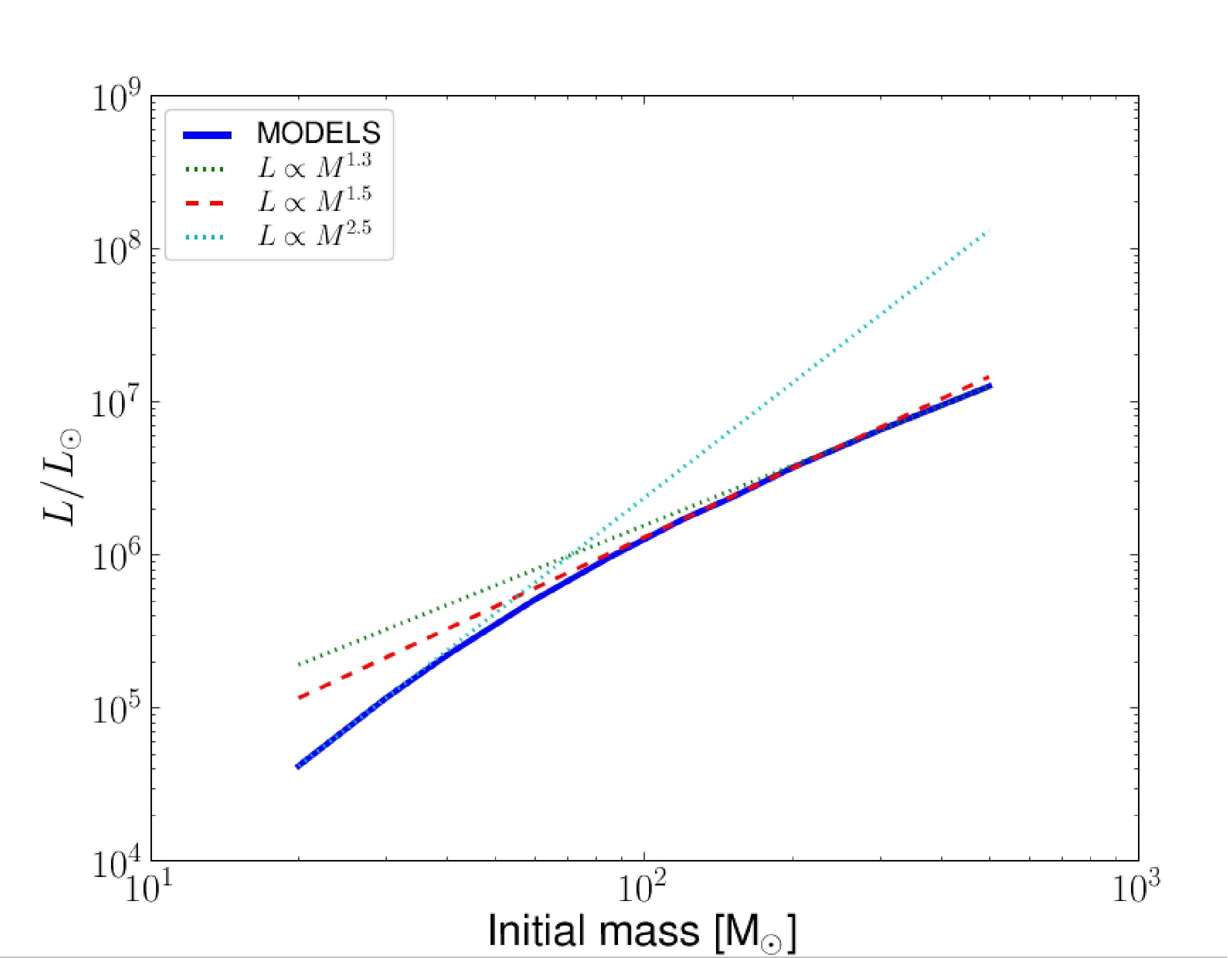
Very Massive Stars are Very Luminous (~10^7 $L_\odot$)

R136a1 ($10^7 L_\odot$) alone supplies 7% of the ionizing flux of the entire 30 Doradus region!

What is the shape of the luminosity vs mass relation in this mass range?

Textbooks: $L \sim M^3$ for stars in the solar mass range

Above 100 $M_\odot$: $L \sim M^{1-1.5}$



Yusof et al 13 MNRAS, aph1305.2099

Classical Eddington limit around 100 $M_\odot$ assumes $L \sim M^{2\sim3}$

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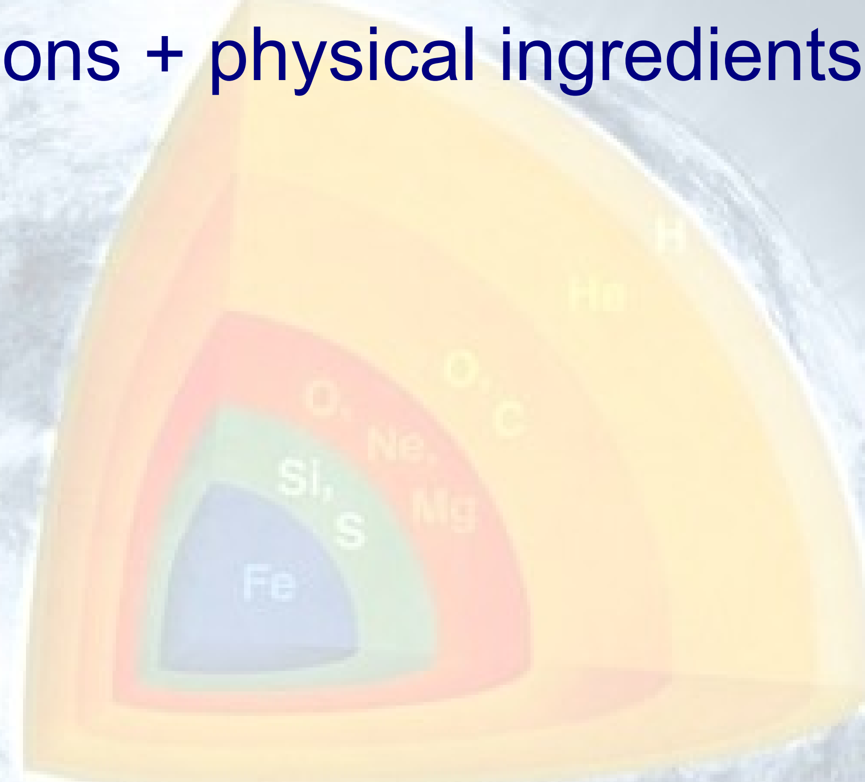
Stellar Models

Stellar structure equations + physical ingredients:



- Nuclear reactions

- Mass loss

- Convection

- Rotation

- Magnetic fields

- Binary interactions

- Equation of state, opacities & neutrino losses

including metallicity dependence

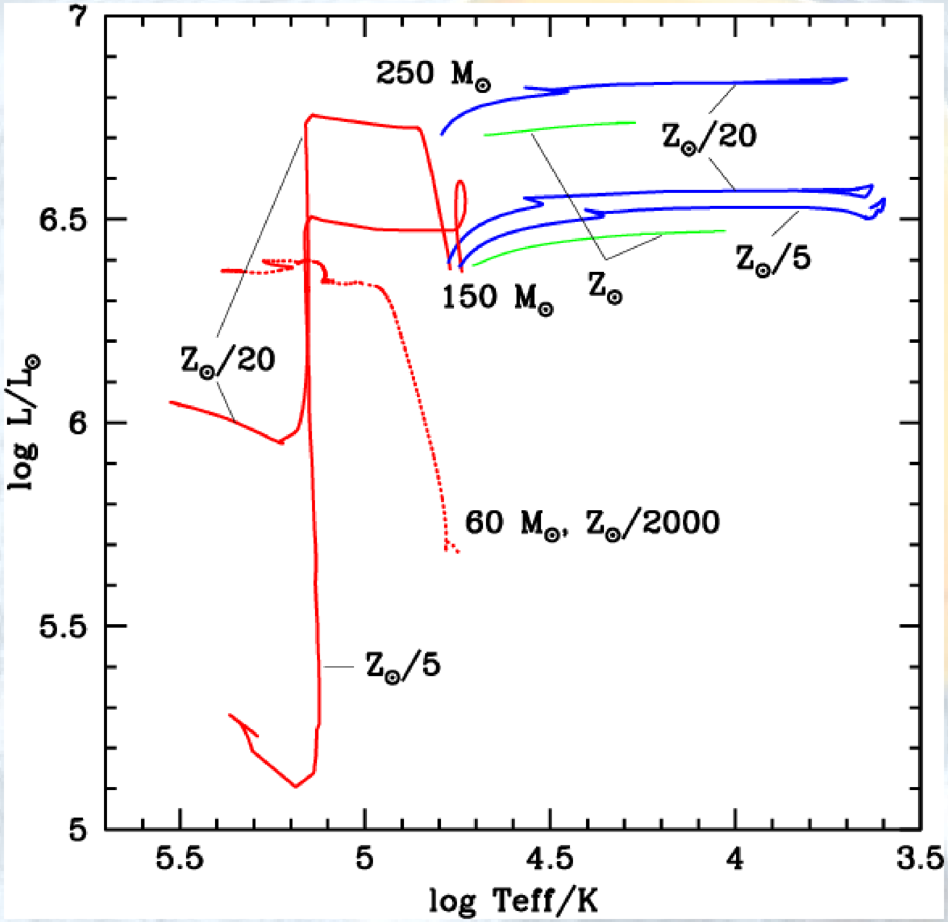
Mass Loss: Types, Driving & Recipes

Mass loss driving mechanism and prescriptions for different stages:

- O-type & "LBV" stars (bi-stab.): line-driven Vink et al 2000, 2001
- WR stars (clumping effect): line-driven Nugis & Lamers 2000, Gräfener & Hamann (2008)
- RSG: Pulsation/dust? de Jager et al 1988
- RG: Pulsation/dust? Reimers 1975,78, with η=~0.5
- AGB: Super winds? Dust Bloecker et al 1995, with η=~0.05
- LBV eruptions: continuous driven winds? Owocki et al
- Binary interactions also lead to loss (or gain)

Evolution of VMS across HRD: role of rotation/Mdot

Langer et al 07 (see also Yusof et al 2013)



Fast rotation → stars stay hot
Slow rotation → stars become cool
Different mass loss driving, Z dep.?

What changes at low Z?

- Stars are more compact: $R \sim R(Z_o)/4$ (lower opacities) at $Z=10^{-8}$
- Rotation at low Z: stronger shear, weaker mer. circ.
- Mass loss weaker at low Z: → faster rotation

$$\dot{M}(Z)=\dot{M}(Z_0)(Z/Z_0)^{\alpha}$$

- α = 0.5-0.6 (Kudritzki & Puls 00, Ku02) (Nugis & Lamers, Evans et al 05)
- α = 0.7-0.86 (Vink et al 00,01,05)

Z(LMC)~Z_o/2.3 => Mdot/1.5 – Mdot/2

Z(SMC)~Z_o/7 => Mdot/2.6 - Mdot/5

Mass loss at low Z still possible?

RSG (and LBV?): no Z-dep.; CNO? (Van Loon 05, Owocky et al)

Mechanical mass loss ← critical rotation/ Eddington limit

(e.g. Hirschi 2007, Ekstroem et al 2008, Yoon et al 2012)

The fate of VMS: PCSN/BH/CCSN?

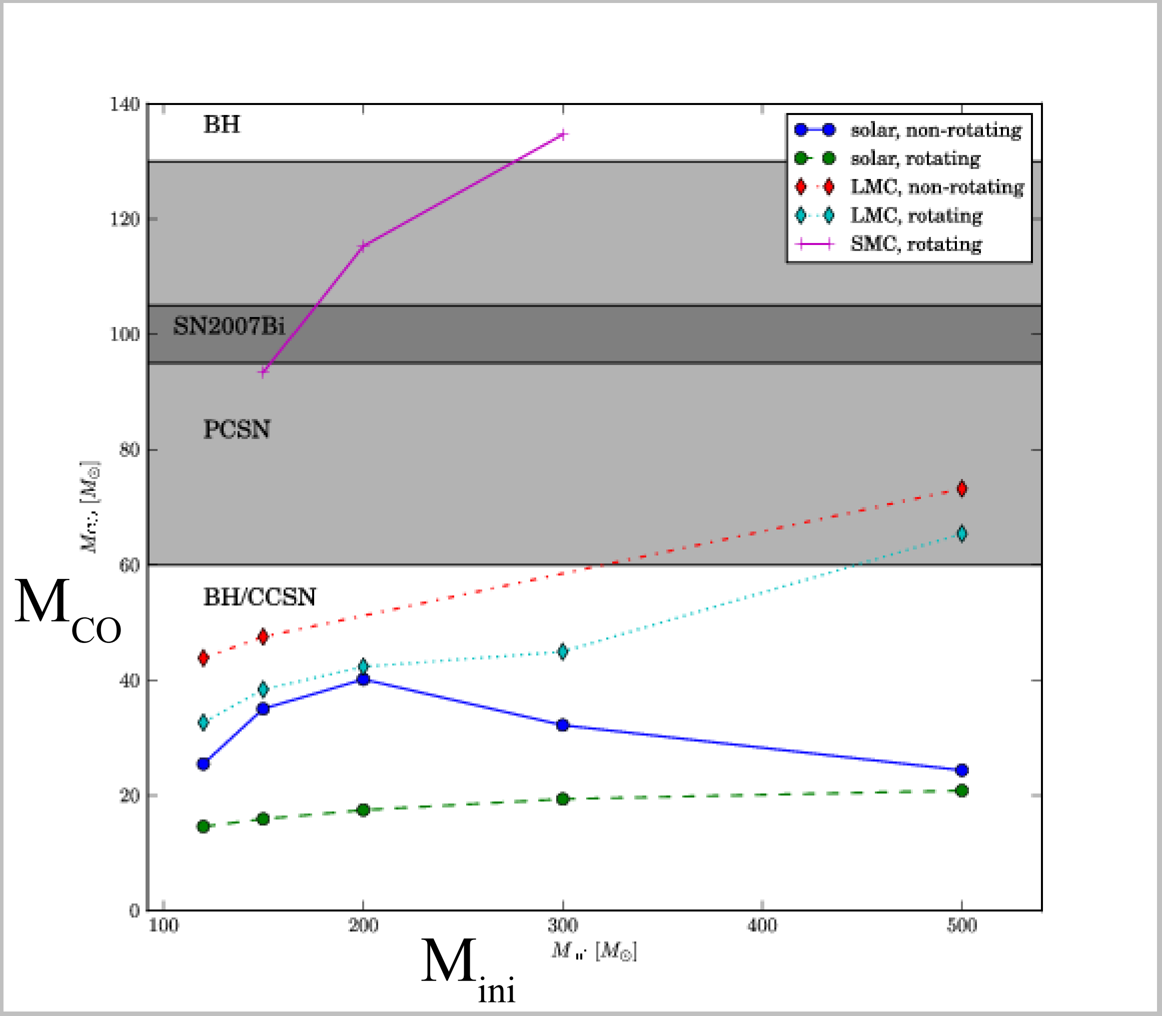
(Yusof et al 13 MNRAS, aph1305.2099)

Z_{solar}: no PISN

(Rotating) models with Z<Z(LMC) lose less mass,

and enter the PISN instability region!

BUT mass loss uncertain!



PISN M_{CO} range from Heger & Woosley (2002)

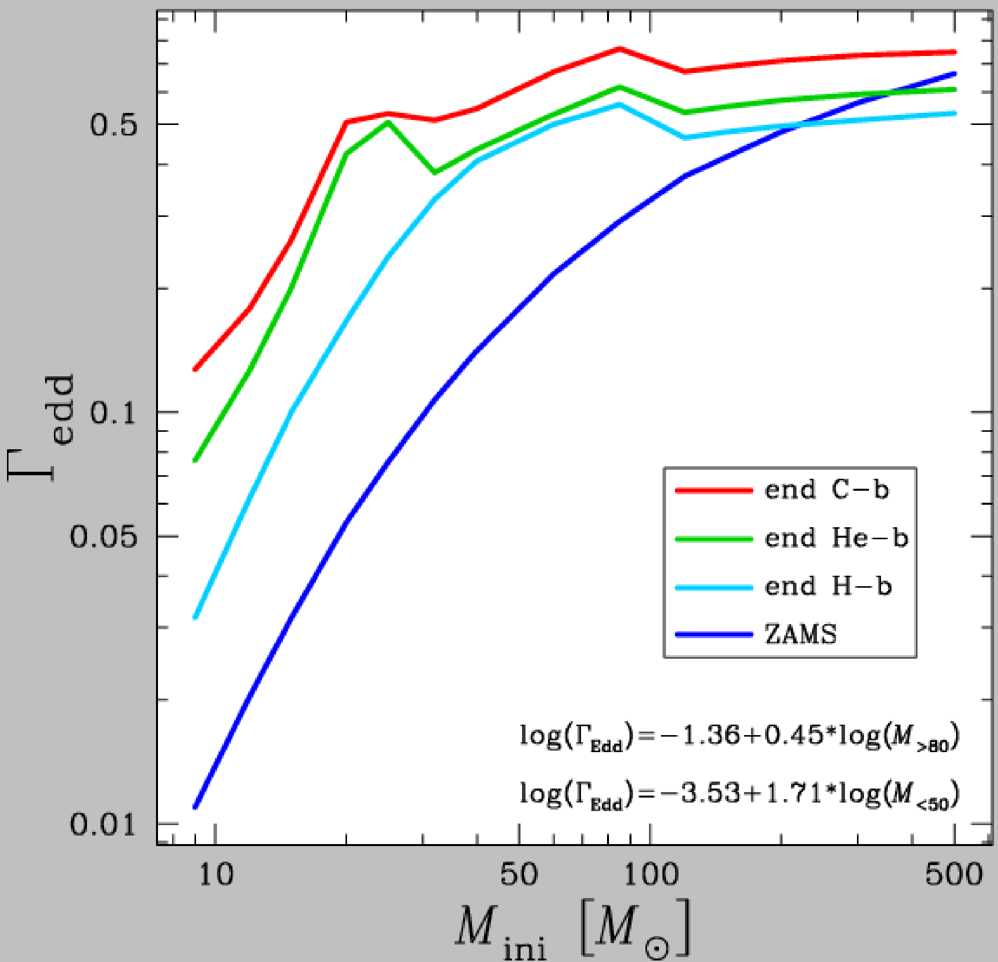
Consistent with Langer et al (2007): PCSN for $Z<Z_{\odot}/3$

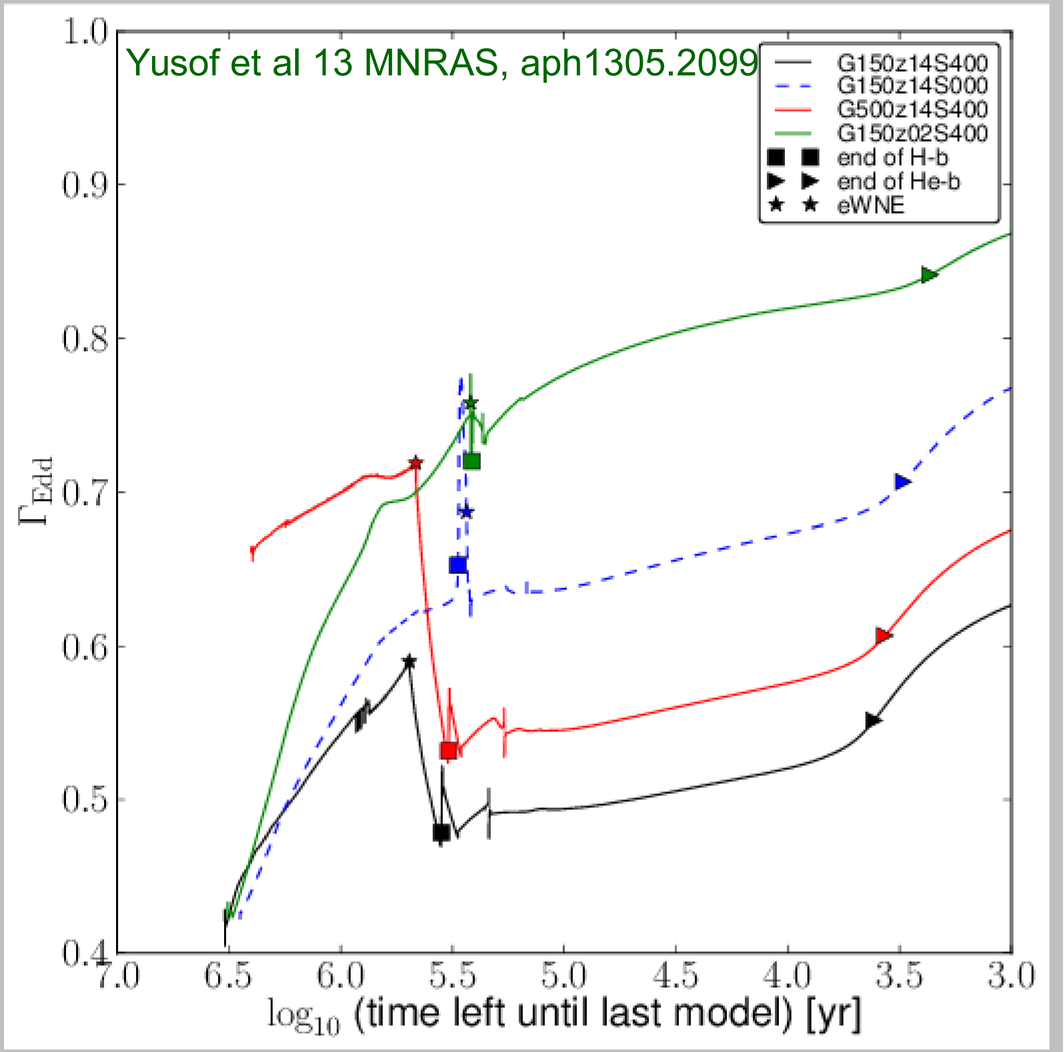
Key Open Questions Concerning Mass Loss

- **Mass loss in cool parts of HRD**: LBV & RSG, especially at low Z
- Position in & evolution across HRD: effects of rotation-induced mixing, feedback from mass loss Yusof et al 13, Langer 07, Sanyal et al 15, Kohler et al 15...
- **Mass loss near Eddington limit** Graefener & Hamann 08, Vink et al 11, ...
- Importance of clumping, porosity, inflation Fullerton et al 06, Graefener et al. 12, Vink et al, ...
- Which stars may explode in the LBV phase? Smith et al 11, ... ,Vink et al, ...
- Look of WR stars: radius, spectra Graefener et al. 2012, Groh et al 2013-...
- Additional mass loss mechanisms? Critical rotation at low Z? Shell mergers in late phases of evolution? ... Hirschi 2007, Meynet et al 2006, … , Smith & Arnett 2014, ...
- …

Evolution of Eddington Factor

$\Gamma_{Edd} < 1$ but Γ_{Edd} close to 1 if mass loss is low





Γ_{Edd} may be larger than one below surface, see Sanyal et al. (2015).

Mass Loss near the Eddington Limit

Vink et al A&A 531, A132 (2011)

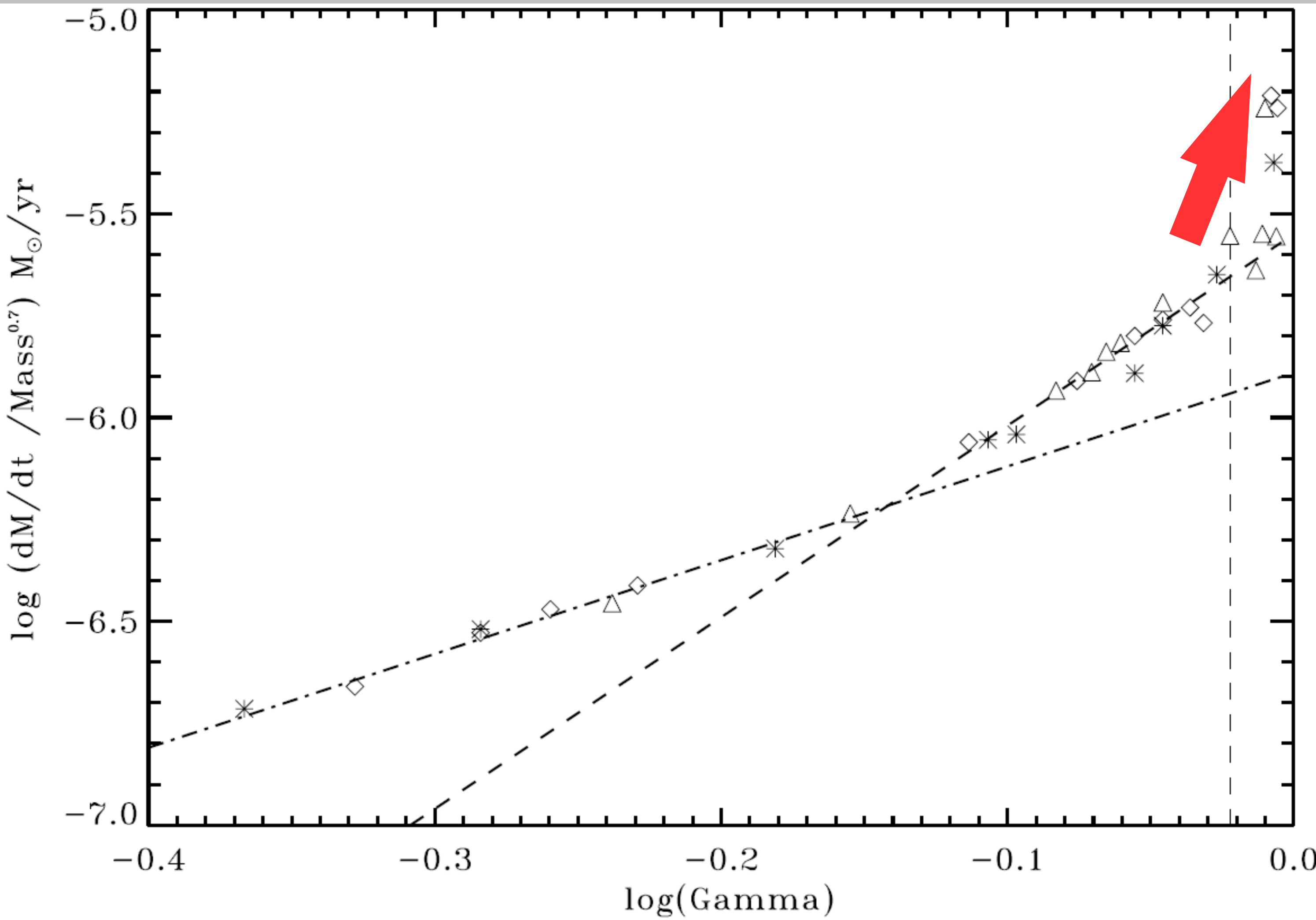


Fig. 5. The predicted mass-loss rates divided by $M^{0.7}$ versus Γ_e for models approaching the Eddington limit. The dashed-dotted line represents the best linear fit for the range $0.4 < \Gamma_e < 0.7$. The dashed line represents the higher $0.7 < \Gamma_e < 0.95$ range. Symbols are the same as in Fig. 1.

Why are PISNe not observed?

Maybe PISNe only occur in models because

- the IMF stops around 150 $M_\odot$

- VMS lose too much mass

- PISNe are not as we expect them (e.g. rarer or fainter)?

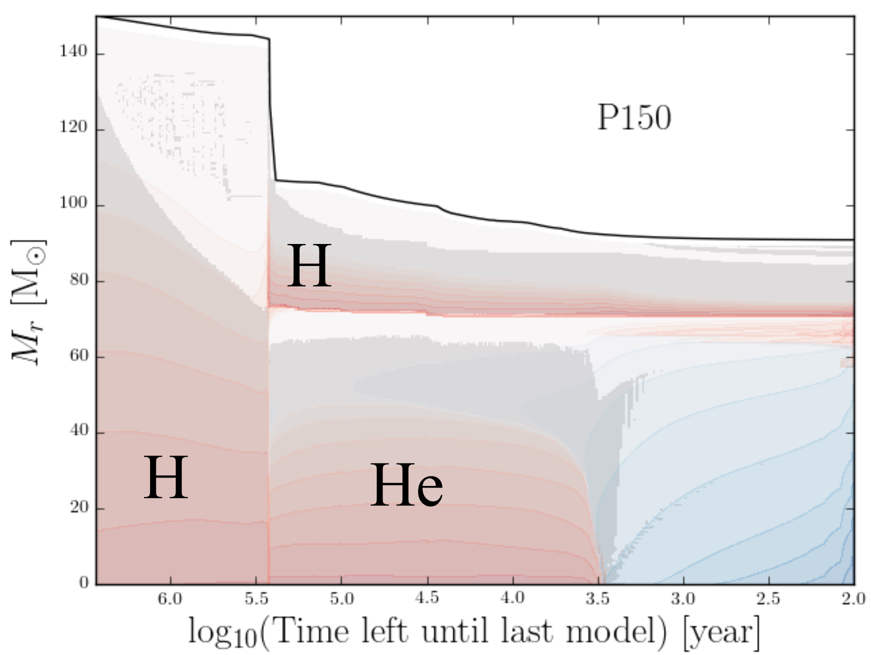
See also talks by

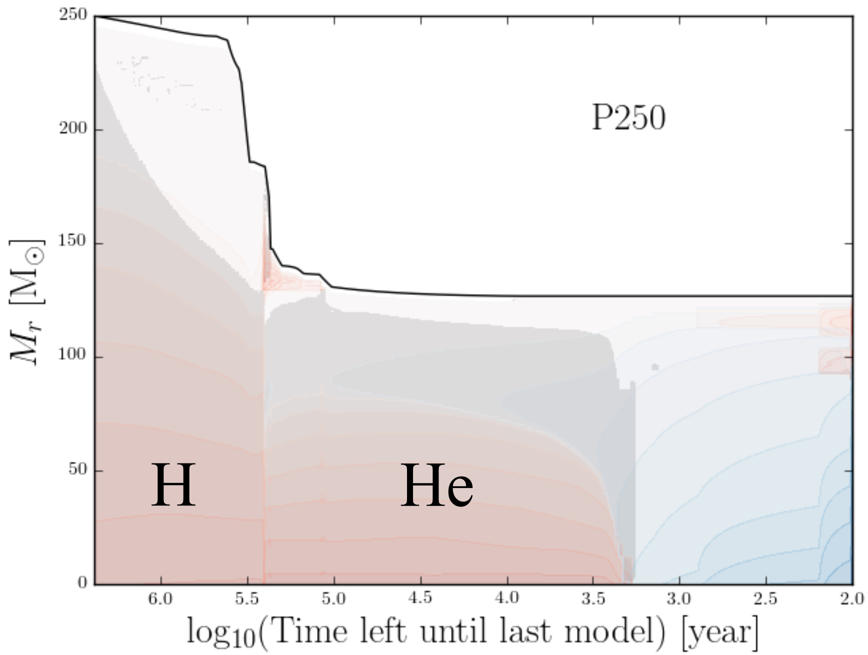
K. Nomoto & A. Tolstov

PISN Model Grid at Z=0.001

(Kozyreva+RH+ 2017MNRAS.464.2854K, Gilmer+RH+ 2017ApJ.846.100, ArXiV170607454G)

- New GENEC progenitor models at Z=0.001 (non-rotating):
- M_{ini}=150,175, 200, 250 $M_\odot$
- Exploded with FLASH in 1D, 2D and 3D + Light curves with STELLA

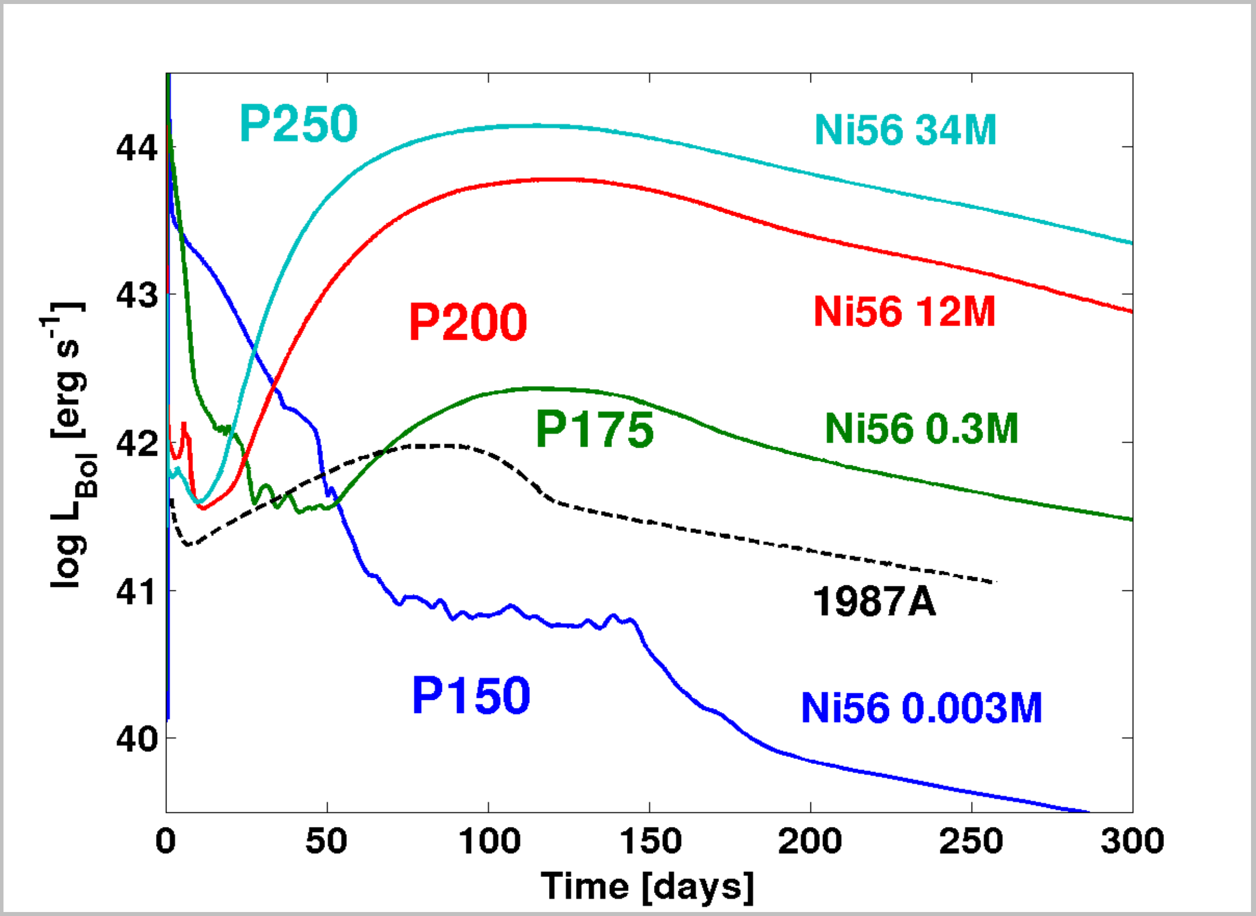




Pre-SN: H-rich, extended envelope (1267$R_\odot$) H-poor, compact env. (2.4$R_\odot$)

Light Curves of PISNe at Z=0.001

(Kozyreva+RH+ 2017MNRAS.464.2854K, Gilmer+RH+ 2017ApJ.846.100, ArXiV170607454G)



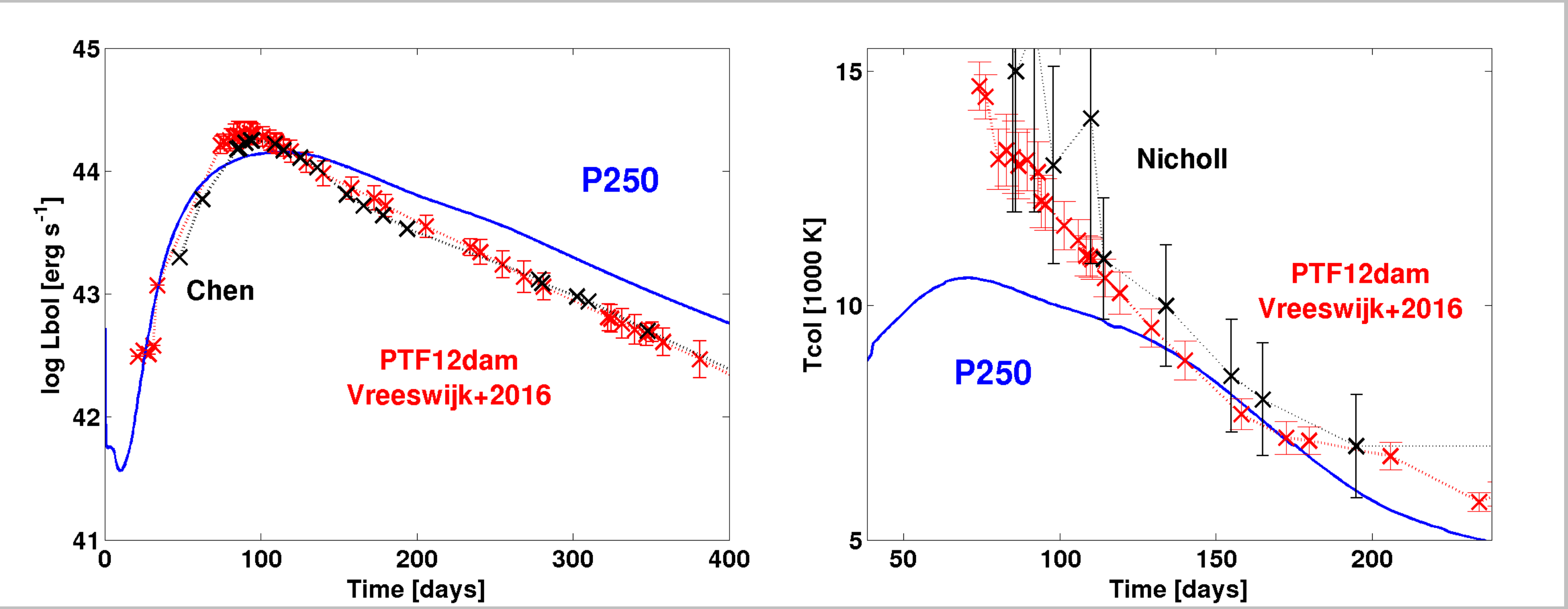
Some (many?) PISNe and most PPISNe are faint!!

Comparison to PTF12dam

(Kozyreva+RH+ 2017MNRAS.464.2854K, Gilmer+RH+ 2017ApJ.846.100, ArXiV170607454G)

- Exploded with FLASH in 1D, 2D and 3D + Light curves with STELLA

Bolometric | Colour temperature



GENEC high-mass PISNe look as *relatively* fast SLSNe!

250 $M_\odot$ GENEC PISN – might be a candidate for PTF12dam!?

See also Jerkstrand et al & Dessart et al for the look of PISNe

Mixing found in 3D models might change the spectrum!

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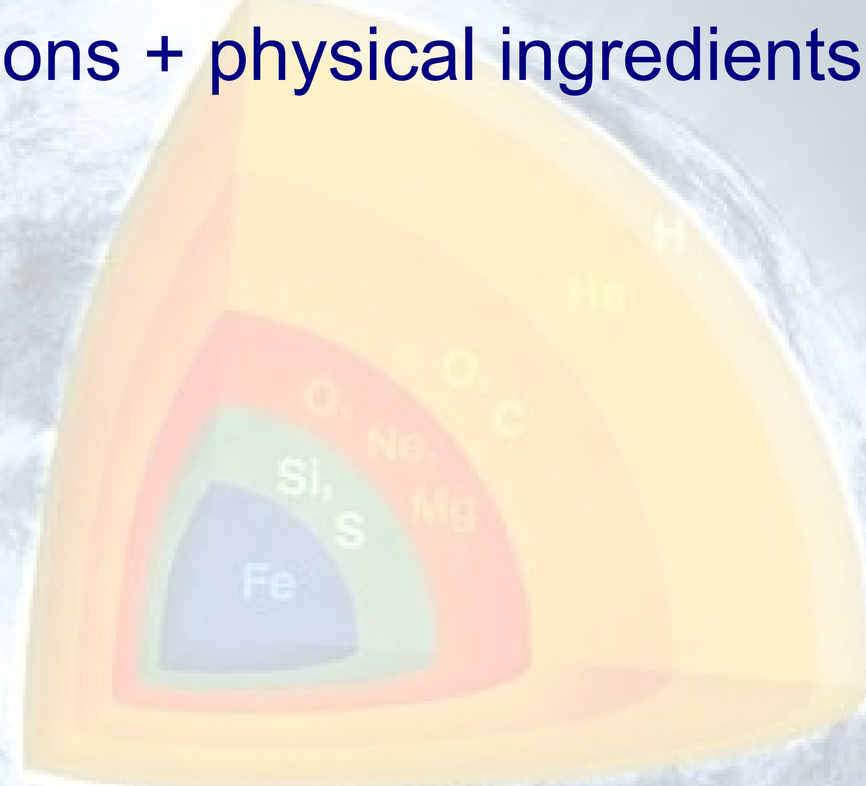


Stellar Evolution with Rotation: Geneva Code

1.5D hydrostatic code (Eggenberger et al 2008)

Rotation: (Maeder & Meynet 1990s-2010s)

Centrifugal force: KEY FOR GRB prog.

$$\vec{g}_{\rm eff} = \vec{g}_{\rm eff}(\Omega,\theta) = \left(-\frac{GM}{r^2} + \Omega^2 r \sin^2\theta\right)\vec{e}_r + \Omega^2 r \sin\theta\cos\theta\,\vec{e}_\theta$$

Shellular rotation → still 1D: (Zahn 1992)

- Energy conservation:

$$\frac{\partial L_P}{\partial M_P} = \epsilon_{nucl} - \epsilon_\nu + \epsilon_{grav} = \epsilon_{nucl} - \epsilon_\nu - c_P\frac{\partial T}{\partial t} + \frac{\delta}{\rho}\frac{\partial P}{\partial t} \qquad (2.9)$$

- Momentum equation:

$$\frac{\partial P}{\partial M_P} = -\frac{GM_P}{4\pi r_P^4} f_P \qquad (2.10)$$

- Mass conservation (or continuity equation):

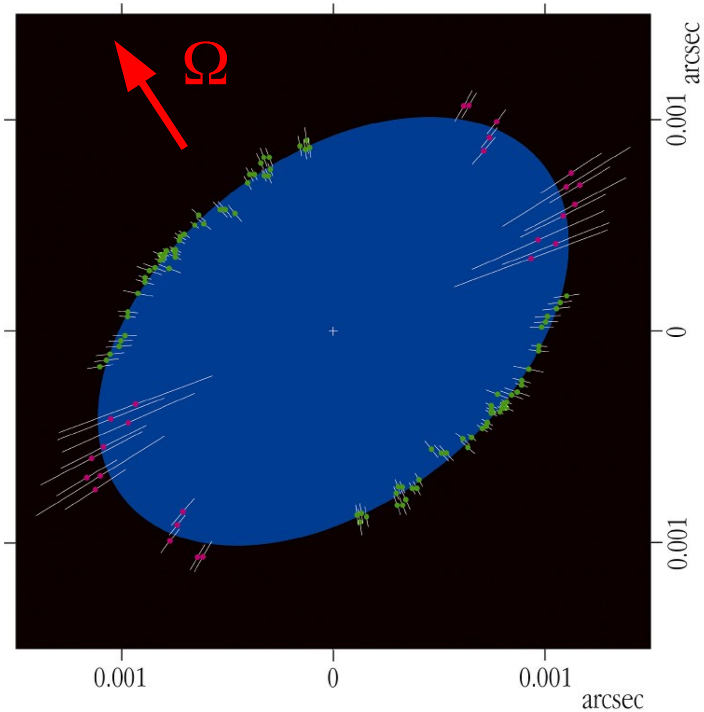
$$\frac{\partial r_P}{\partial M_P} = \frac{1}{4\pi r_P^2 \overline{\rho}} \qquad (2.11)$$

- Energy transport equation:

$$\frac{\partial \ln \overline{T}}{\partial M_P} = -\frac{GM_P}{4\pi r_P^4} f_P \min[\nabla_{\rm ad}, \nabla_{\rm rad}\frac{f_T}{f_P}] \qquad (2.12)$$

where

$$\nabla_{\rm ad} = \frac{P\delta}{\overline{T}\overline{\rho}c_P} \quad \text{(convective zones)},$$
$$\nabla_{\rm rad} = \frac{3}{16\pi acG}\frac{\kappa l P}{m\overline{T}^4} \quad \text{(radiative zones)},$$



The Shape of Achernar
(VLTI + VINCI)
ESO PR Photo 15b/03 (11 June 2003)

$$f_P = \frac{4\pi r_P^4}{GM_P S_P}\frac{1}{<g^{-1}>},$$
$$f_T = \left(\frac{4\pi r_P^2}{S_P}\right)^2 \frac{1}{<g><g^{-1}>},$$

(Meynet and Meynet 97)

Rotation-Induced Transport

Zahn 1992: strong horizontal turbulence

Transport of angular momentum:

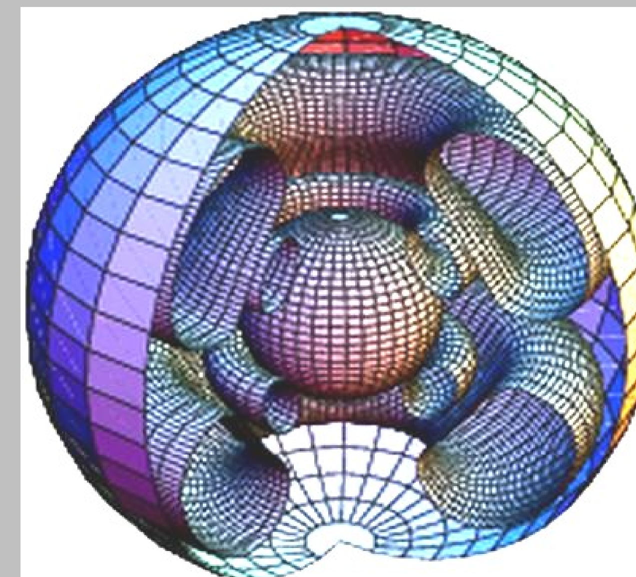
$$\rho \frac{\mathrm{d}}{\mathrm{d}t}\left(r^2\bar{\Omega}\right)_{M_r} = \underbrace{\frac{1}{5r^2}\frac{\partial}{\partial r}\left(\rho r^4 \bar{\Omega} U(r)\right)}_{\text{advection term}} + \underbrace{\frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho D r^4 \frac{\partial \bar{\Omega}}{\partial r}\right)}_{\text{diffusion term}}$$

Transport of chemical elements:

$$\rho \frac{\mathrm{d}X_i}{\mathrm{d}t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho r^2 \left[D + D_{eff}\right] \frac{\partial X_i}{\partial r}\right) + \left(\frac{\mathrm{d}X_i}{\mathrm{d}t}\right)_{\mathrm{nucl}}$$

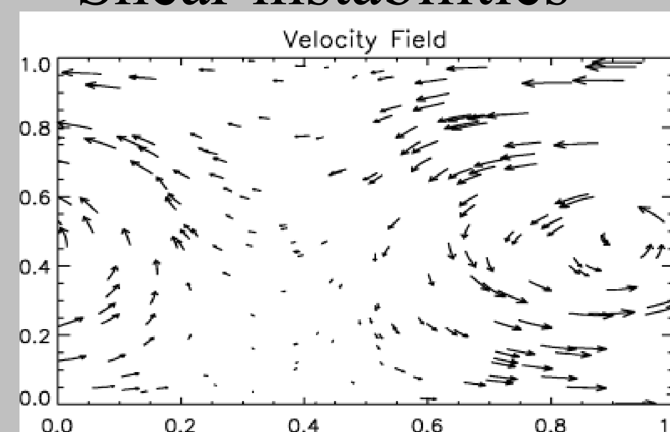
D: diffusion coeff. due to various transport mechanisms (convection, shear)

D_{eff}: diffusion coeff. due to meridional circulation + horizontal turbulence



Meynet & Maeder 2000

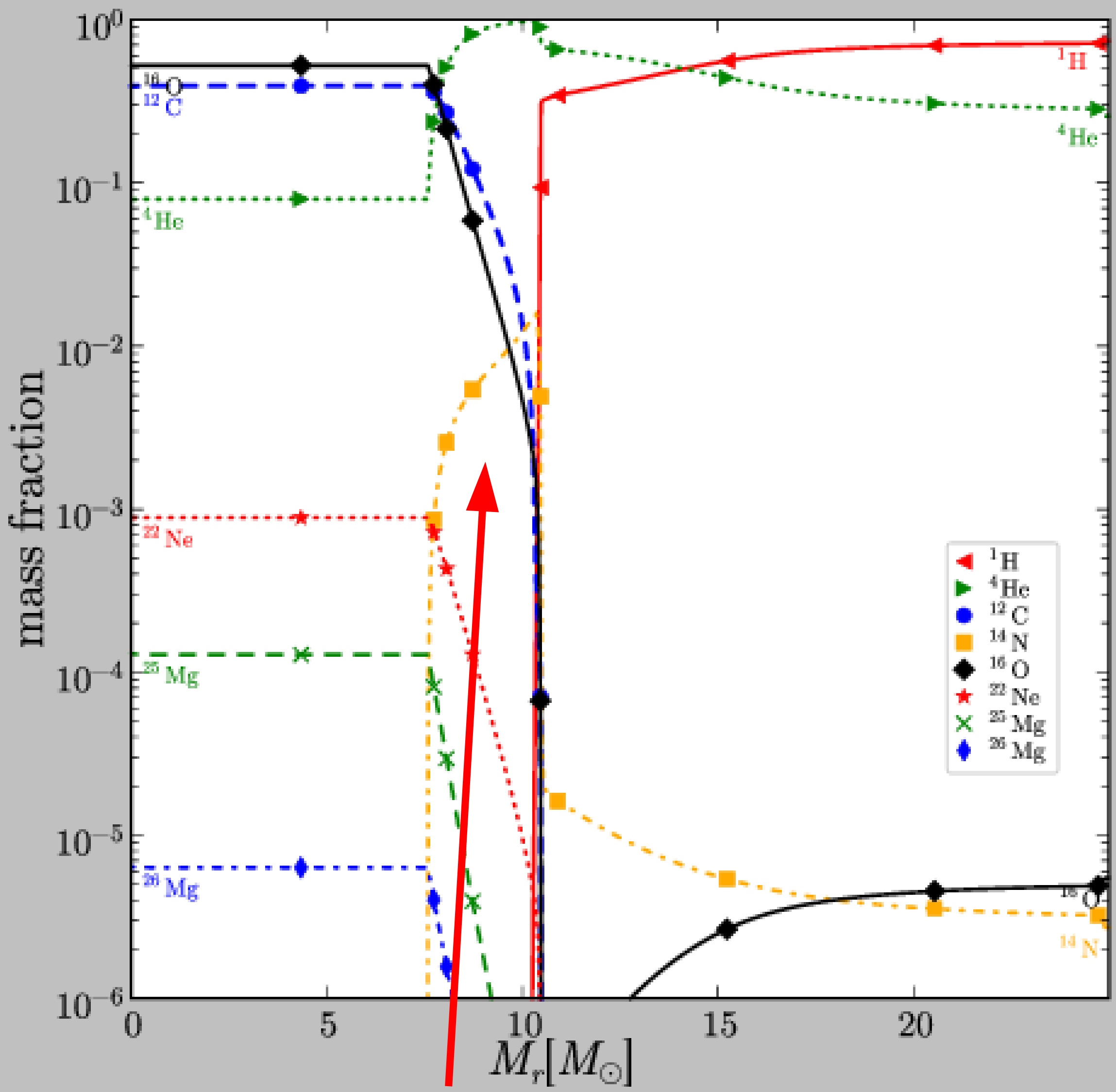
Shear instabilities



Brueggen & Hillebrandt 2000

Rotation-Induced Mixing → Primary ^{14}N & ^{22}Ne

Frischknecht, Hirschi et al, MNRAS, 2016, 456, 1803



Mixing between He and H-burning layers

Galactic Chemical Evolution: Primary ^{14}N

1) Evolution of [N/O] reproduced

← using $Z=10^{-8}$ yields

Hirschi 07: - - - - - - - -

2) Upturn of [C/O]

Observations:

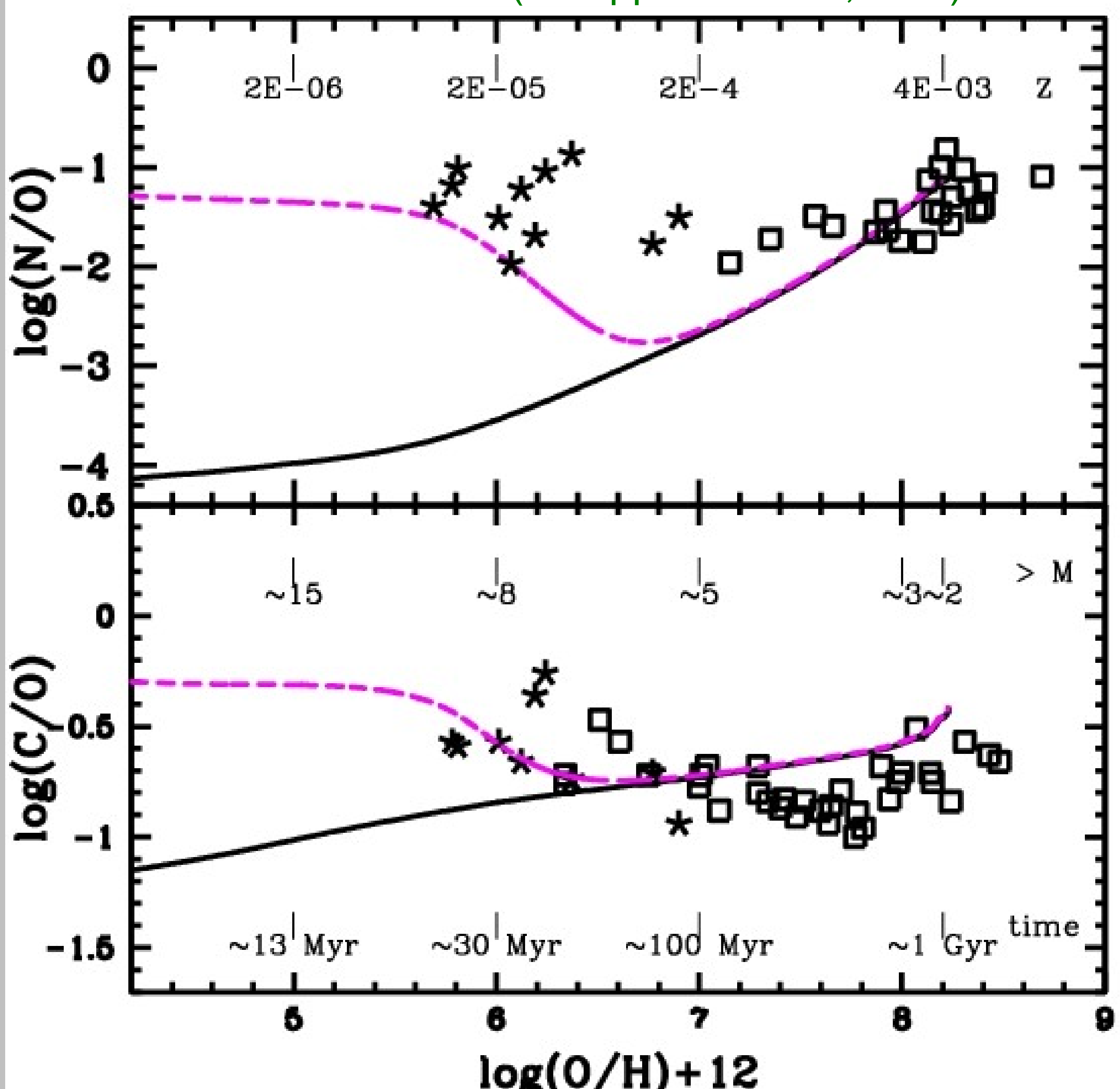
Spite et al 2004 (asterisks)

Israelian et al 2004 (squares)

DLAs : Fabbian et al 2009

Pettini et al 2008

(Chiappini et al 06, A&A)



S Process in Massive Stars

Kaeppeler, et al, 2011, RvMP, 83, 157, ...

Weak s process: (slow neutron capture process) during core He- and shell C-burning

He: T > 0.25 GK

(~ 21.6keV)

C: T ~ 1GK

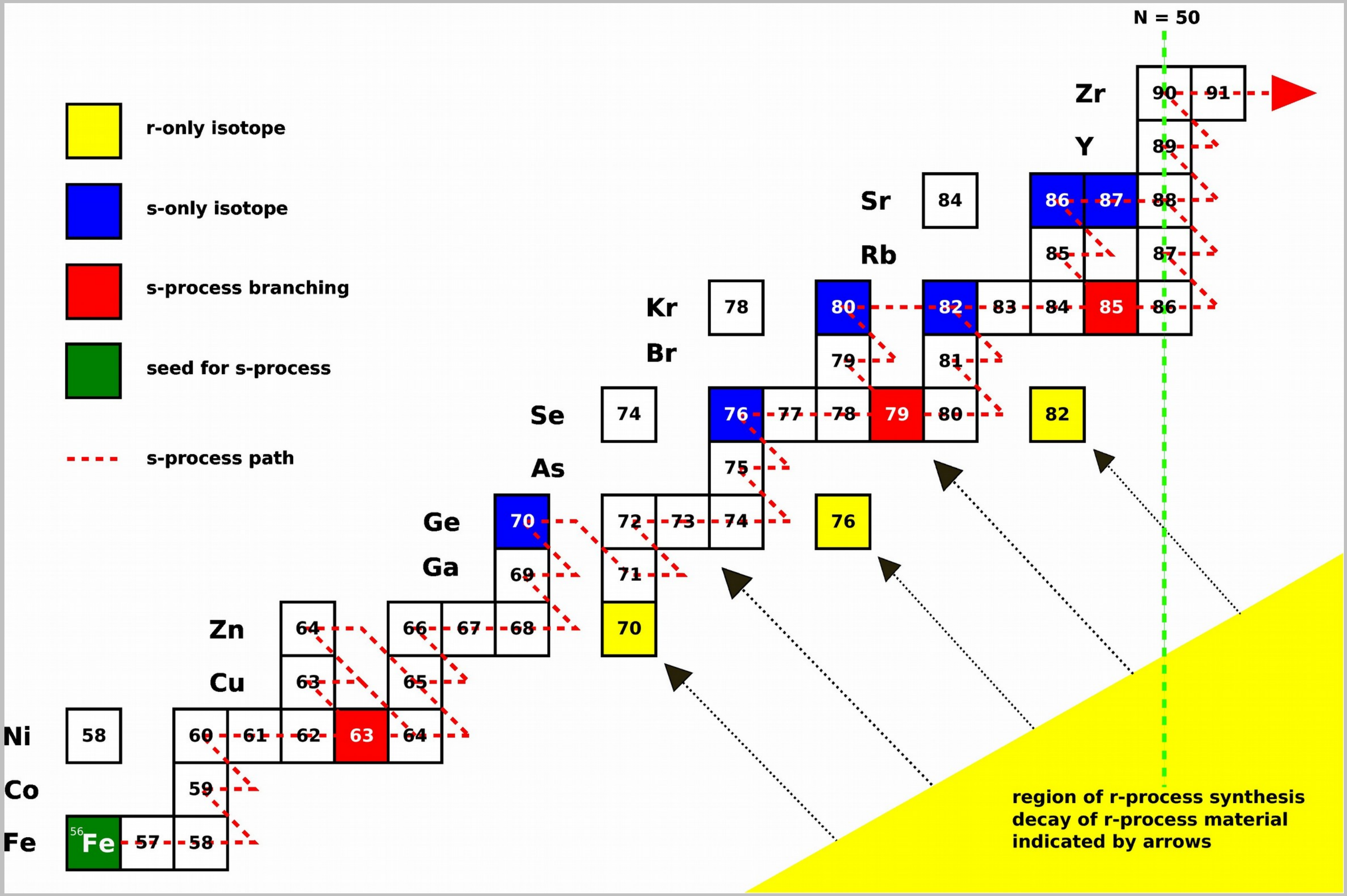
N-source: ^{22}Ne(a,n)

Seed: iron

Poisons:

- He-b.: ^{22}Ne, ^{25}Mg, ^{16}O, ^{12}C

- C-b.: ^{24}Mg, ^{25}Mg, ^{16}O, ^{20}Ne



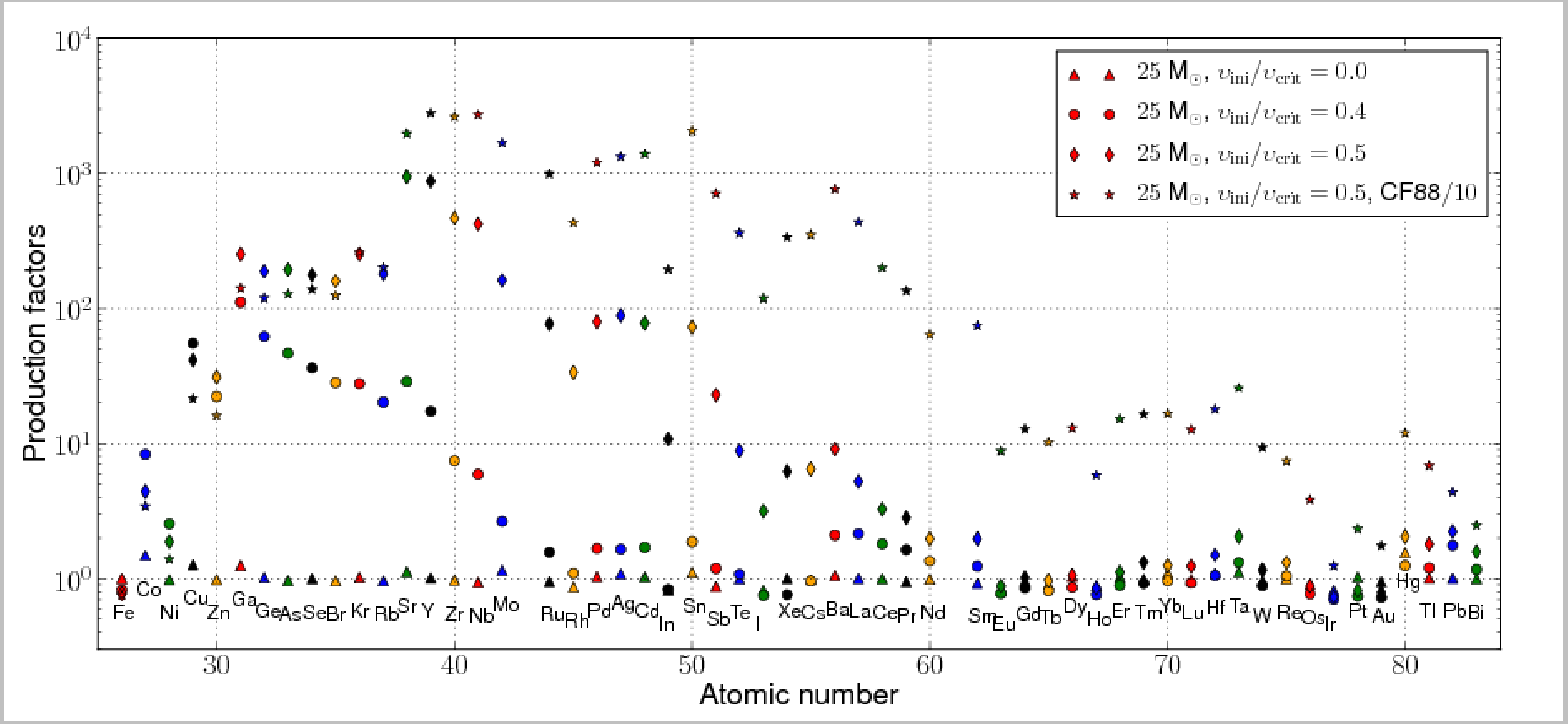
At solar Z: rotating models may produce up to 3x more s process

(See also Chieffi, Limongi, 2012ApJS..199...38L)

How much s process do massive rotating stars produce at low Z?

S-Process Models of Massive Rotating Stars

$Z=10^{-5}$, rotating models with different $^{17}O(a,g)$ rates; V_{ini}



Frischknecht et al, A&A letter 2012, 2016

- Stellar evolution calculations with **600/700-ISOTOPE NETWORK!**

- **^{22}Ne production almost primary but still varies with Z & especially V_{ini}. M_{ini}**
- Secondary seeds (Fe) limit production (^{22}Ne cannot act as seed)
- Strong variations in [Sr,Y/Ba] up to 2 dex depending on Z, V_{ini}, and $^{17}O(a,g)$

See also Choplin et al. (2017, 2018), Chieffi & Limongi (2018), Prantzos et al (2018)

*New S-Process Models Compared to EMP * & Bulge GC*

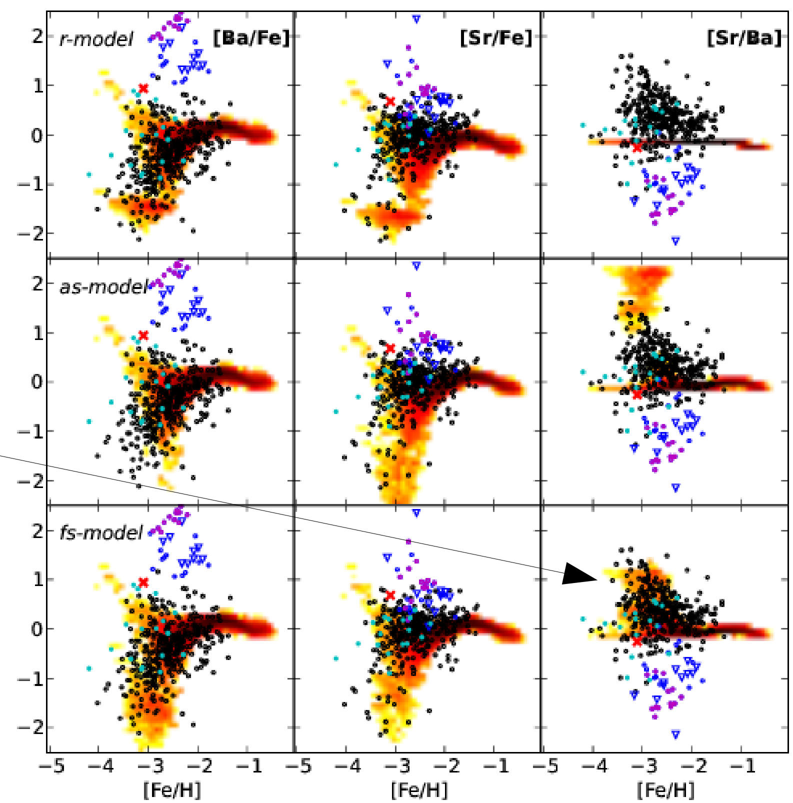
* 5 signatures of rotation at low Z Cescutti,..., Hirschi et al, 2013, A&A, 553, A51
rise of N/O and C/O, low 12C/13C, and a primary-like evolution of Be and B, s process

* Models explain abundances in one of the oldest clusters in galactic bulge Chiappini et al, Nature Letter, 2011

Inhomogeneous GCE models by
Cescutti et al 2013 A&A,553,51,
2015 A&A, 577, 139

- Strong variations in [Sr/Ba] > 1 dex matches well observed range for EMP stars (black circles)!

(no main s process included so cannot explain CEMP-s stars in blue)



Model name	panels in Fig. 5	s-process	r-process
r-	Upper	No s-process from massive stars	standard + extended r-process site (8 - 30 $M_\odot$)
as-	middle	average rotators (v_{ini}/v_{critic} = 0.4)	standard r-process site (8 - 10 $M_\odot$)
fs-	lower	fast rotators (v_{ini}/v_{critic} = 0.5) and 1/10 for $^{17}O(\alpha,\gamma)$ reaction rate	standard r-process site (8 - 10 $M_\odot$)

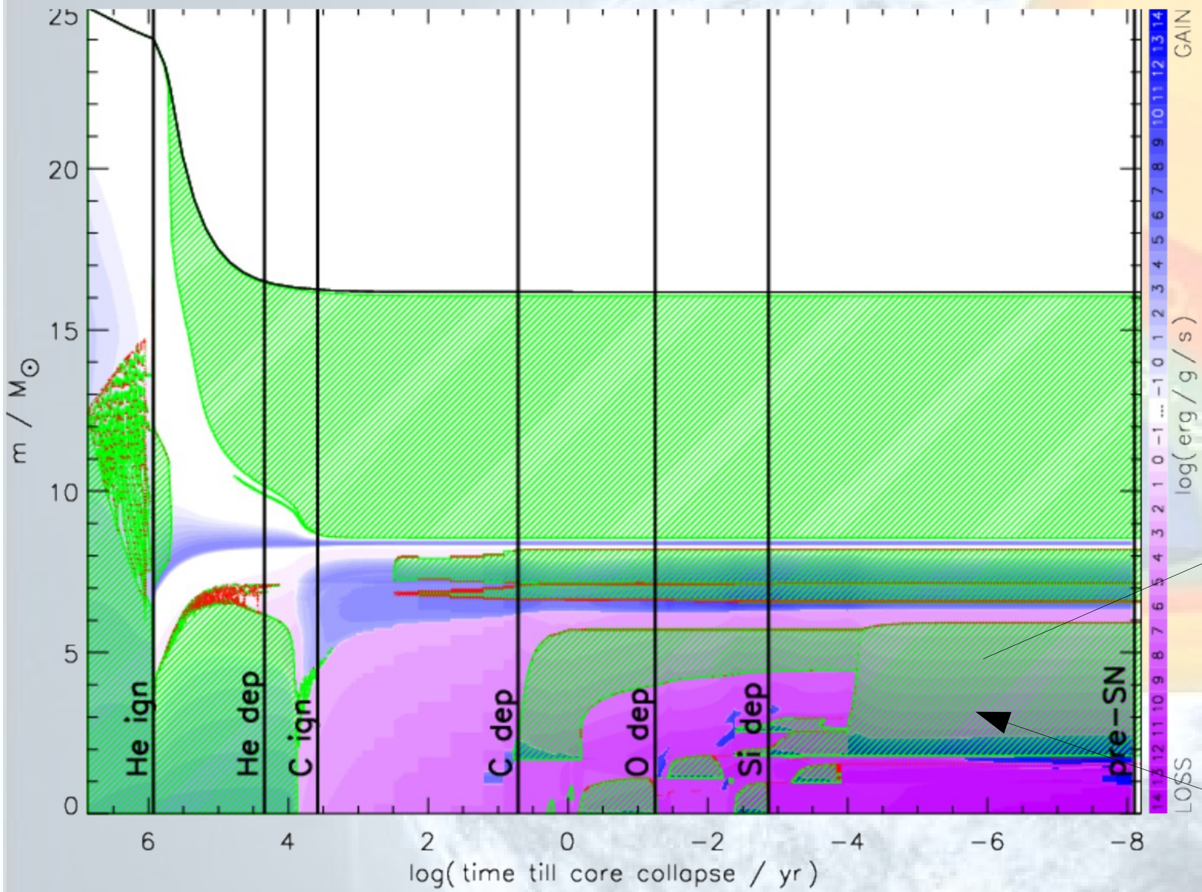
(EMP *: Frebel et al 2010)

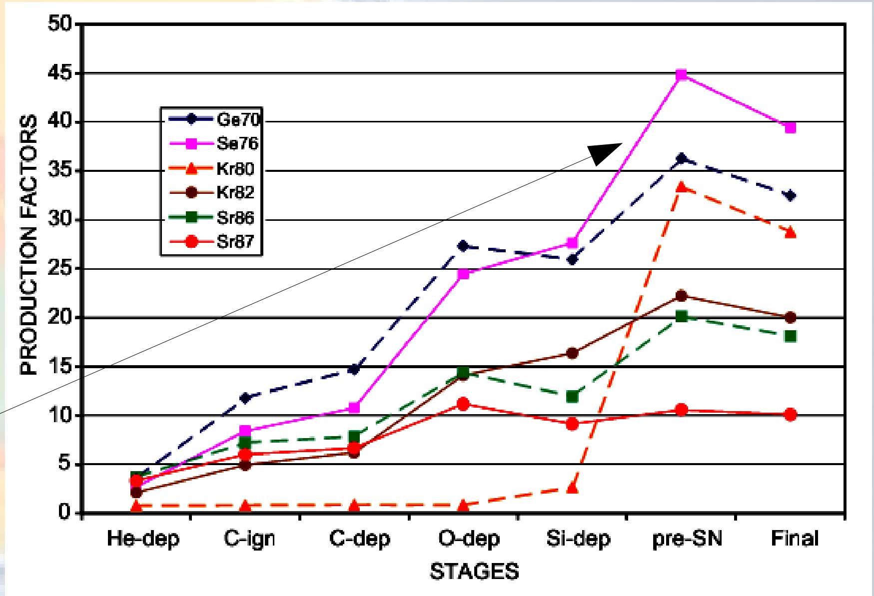
Key Open Questions Concerning Rotation

- Uncertainties in strength of rotation-induced mixing Hunter et al 07/08, Maeder et al 07, …
- Importance/impact of diff. prescriptions & their implementations (advective vs diffusive) Meynet et al LNP, 13, Meynet/Maeder et al ..., Chieffi & Limongi et al 13, Heger et al 2000, Paxton et al 13 (MESA), Martins & Palacios, 13
- Interaction between magnetic fields and rotation: Solid body rotation? More or less mixing? Spruit 02, Heger et al 05-..., Yoon et al 06-... Maeder et al 2005-..., Potter et al 12, ...
- Impact of binary interactions on distribution of rotation velocities
  Langer et al 2012, de Mink et al 2013, ...
- Additional transport mechanism for Ω needed ←asteroseismology
  Cantiello et al. 14, Eggenberger 15; Spada et al. 16, Eggenberger et al 16, den Hartogh et al 2019
- De/coupling between angular momentum and chemical composition transport …

1D Model Uncertainties: Possible Shell Mergers

Tur, Heger et al 07/09/10





C/Ne/O shell mergers

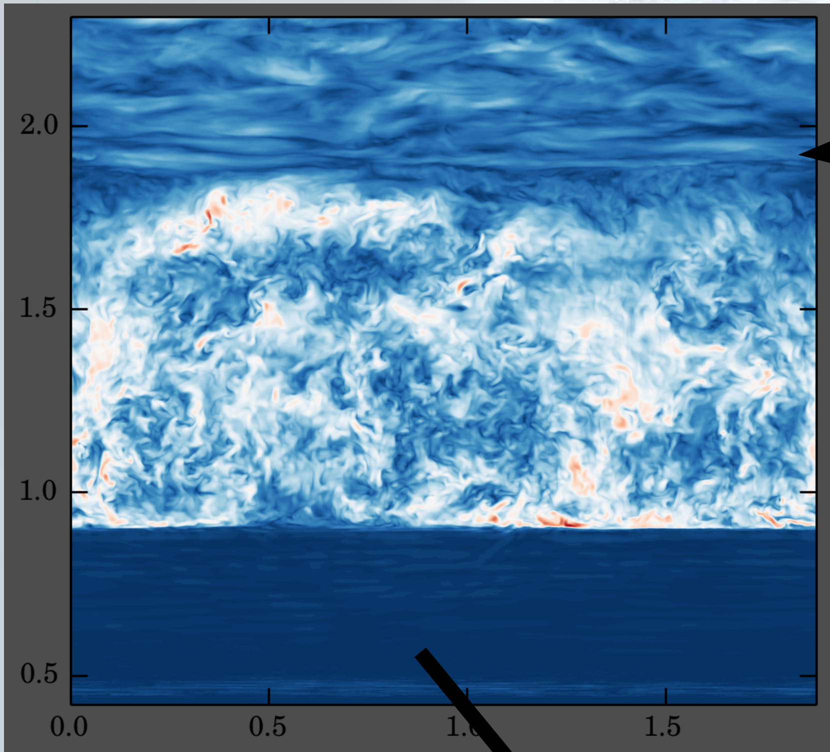
Rauscher, Heger and Woosley 2002: "Interesting and unusual nucleosynthetic results are found for one particular 20M model as a result of its special stellar structure."

Shell mergers also affect explodability (e.g. compactness)

Convection physics uncertainties affect fate of models: strong/weak/failed explosions!!!

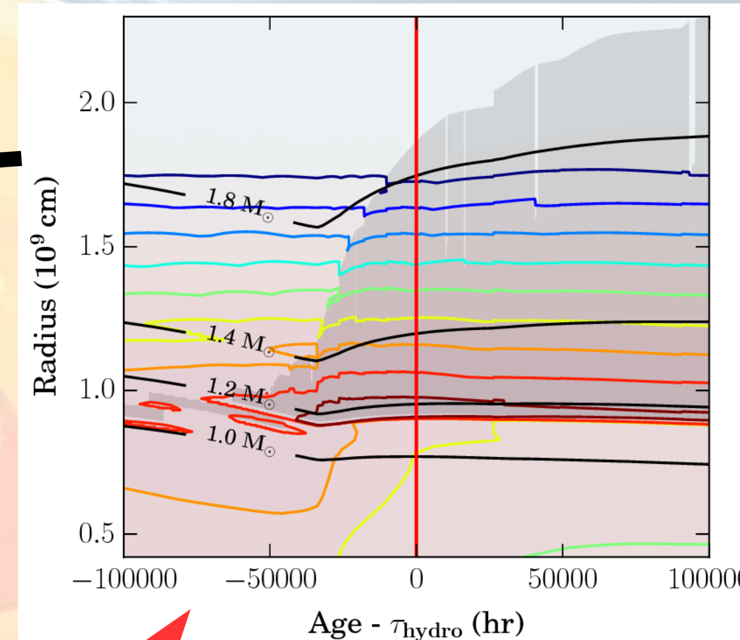
Way Forward: 1 to 3 to 1D link

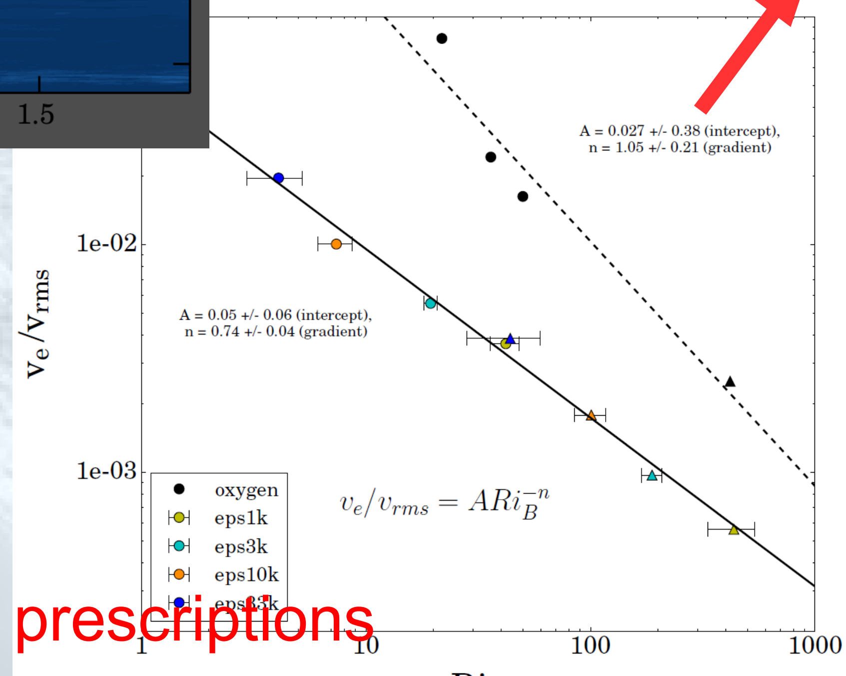
Targeted 3D simulations



Cristini+2017, MNRAS

Uncertainties in 1D





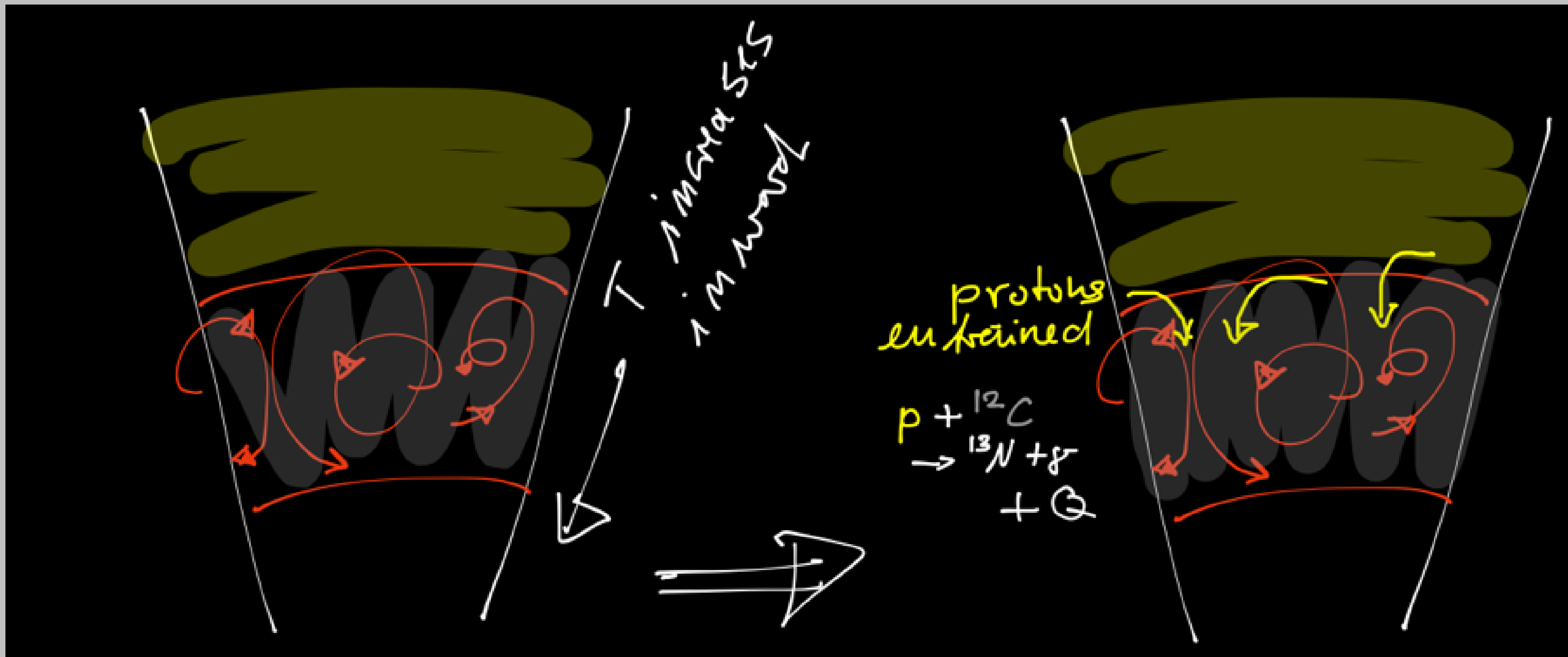
Cristini+2019, MNRAS

→ Improve theoretical prescriptions

3D Hydro Efforts/Priority List

* Convective boundary mixing during core hydrogen burning:
• +: many constraints (HRD, astero, ...)
• -: difficult to model due to important thermal/radiative effects
• -: long time-scale
•
•* Silicon burning:
• +: important to determine impact on SNe of multi-D structure in progenitor (Couch et al 2015a,b, Mueller & Janka aph1409.4783, Mueller et al ArXiV1605.01393)
• +: possible shell mergers occurring after core Si-burning (e.g. Tur et al 2009ApJ702.1068; Sukhbold & Woosley 2014ApJ783.105) strongly affect core compactness
• +: radiative effects small/negl.
• -: ~ 10^9 CPU hours needed for full silicon burning phase will be ok soon;
• -: might be affected by convective shell history
•
•* AGB thermal pulses/H-ingestion:
• +: already doable (e.g. Herwig et al 2014ApJ729.3, 2011ApJ727.89, Mocak et al 2010A&A520.114, Woodward et al 2015)
• +: thermal/radiative effects not dominant
• ?: applicable to other phases?
•
•* Oxygen shell: (Meakin & Arnett 2007ApJ667.448/665.448, Viallet et al 2013ApJ769.1, Jones et al ArXiV1605.03766)
• +: similar to silicon burning but smaller reaction network needed
• -: might be affected by convective shell history
•
•* Carbon shell: (PhD A. Cristini)
• +: not affected by prior shell history
• +: first stage for which thermal effects become negligible
•
•* Envelope of RSG (e.g. Viallet et al. 2013, Chiavassa et al 2009-2013),
•* Solar-type stars (e.g. Magic et al. 2013A&A557.26, ...)
•

"Simulation" from F. Herwig



N13 and/or C13 are mixed <u>for hours</u> in regions with typical He-burning temperatures (T9 ~ 0.25-0.3 GK), <u>together with Fe-seed rich material.</u>

Main source of neutrons: C13(α,n)O16

Possible sites: low-Z LMS & MS; RAWD

Challenge: requires multi-D hydro simulations

CEMP-i stars?

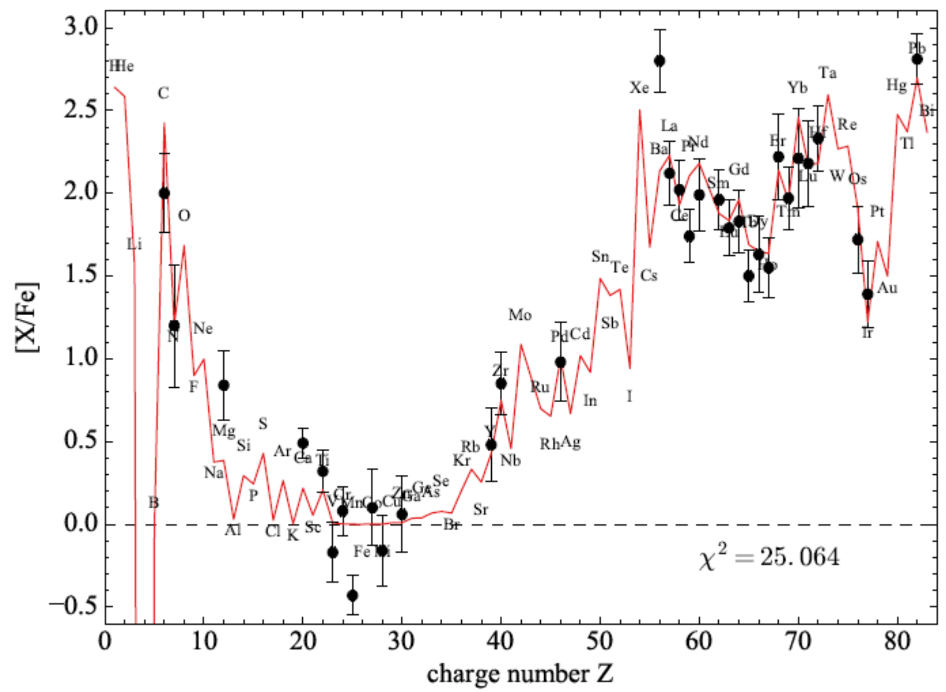
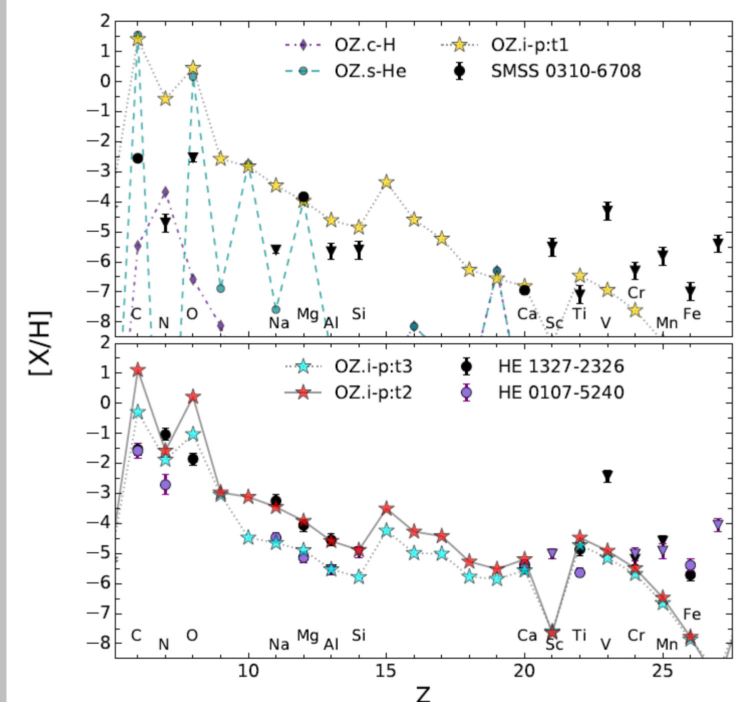


Figure 12. Abundances of heavy elements observed in the CEMP-r/s star CS31062-050 (Aoki et al. 2002; Johnson & Bolte 2004) and the best-fit abundance distribution from the time evolution of the RAWD model G diluted with 99.58% of the initial abundances.



Clarkson+2018 MNRAS:

- H-ingestion in massive star at Z=0
- Neutron density ~ 10^{13} n cm^{-3}
- The i-process does not reach Fe

Talk by S. Campbell

See also Ritter et al,
Choplin et al. (2017, 2018)

For GCE impact, see Cote + 2018ApJ...854..105C

Advert for Recent Activities

- Main & weak s processes:

Large grid of massive star models + weak s proc (Frischknecht+2016, MNRAS):

Nugrid: set 1 (Pignatari+2016, ApJS), set1extension (Ritter+in 2018, MNRAS),

s process with new convective boundary mixing (CBM): (Battino+ ApJ 2016)

- Nuclear uncertainties: MC-based sensitivity studies for gamma-process (CCSNe: Rauscher+ 2016, MNRAS, SNIa: Nishimura+2018, MNRAS), weak s process (Nishimura+2017, MNRAS), main s process (Cescutti+in 2018)

- Stellar uncertainties:

Multi-D tests of convection (Cristini+ 2017, MNRAS) and rotation (Edelmann+2017, A&A)

- Reviews/book chapters: Springer Handbook of Supernovae

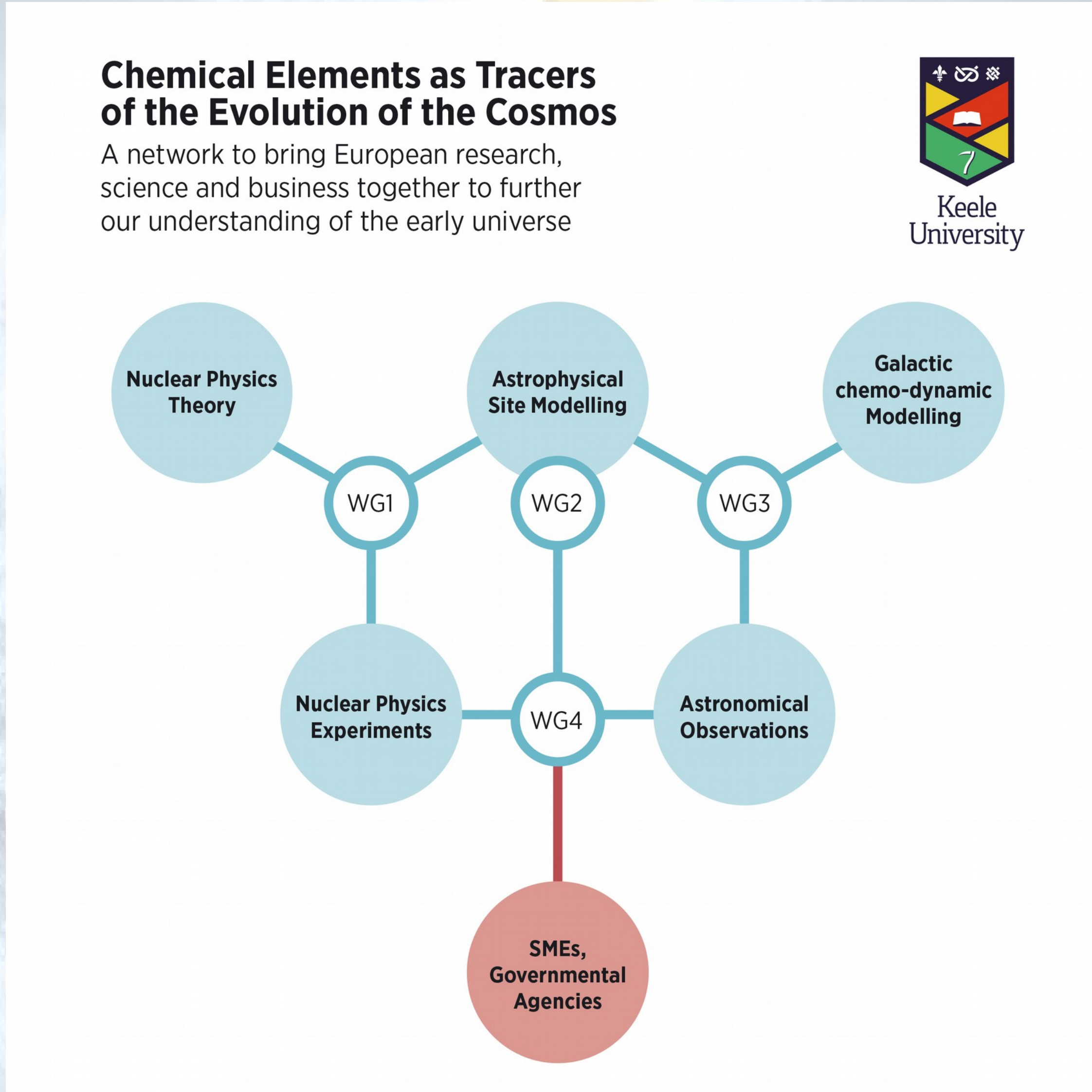
"Pre-supernova Evolution and Nucleosynthesis in Massive Stars and Their Stellar Wind Contribution" (doi:10.1007/978-3-319-20794-0_82-1)

"Very Massive and Supermassive Stars: Evolution and Fate" (doi:10.1007/978-3-319-20794-0_120-1)

- ChETEC COST Action 2017-2021: see www.chetec.eu for details

ChETEC COST Action (2017-2021) www.chetec.eu

Funding for collaboration visits: STSMs!!



Formal cooperation with JINA-CEE underway!!

30 countries joined ChETEC to coordinate research efforts in Nuclear Astrophysics:

Austria, Belgium, Bulgaria, Czech Rep., Croatia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Israel, Italy, Lithuania, Malta, The Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and United Kingdom

Standard Picture & Expectations

- Low/negligible mass loss: Not so small!

PISNe look different or VMS lose too much mass

Symptom: Γ_{Edd} close to 1 (or critical rotation)

- Little/no secondary elements (e.g. N, ***weak*** s process):

More secondary elements observed than expected!

→ important internal mixing taking place in stars!

← rotation, convection, possibly both?

Symptoms: rotation rates of remnants;

shell mergers in 1D models

Conclusions & Outlook

- **Physical ingredients still uncertain**: nuclear reactions, convection, rotation, mass loss, B-fields, atomic diffusion

I like to see problems as an opportunity for change!

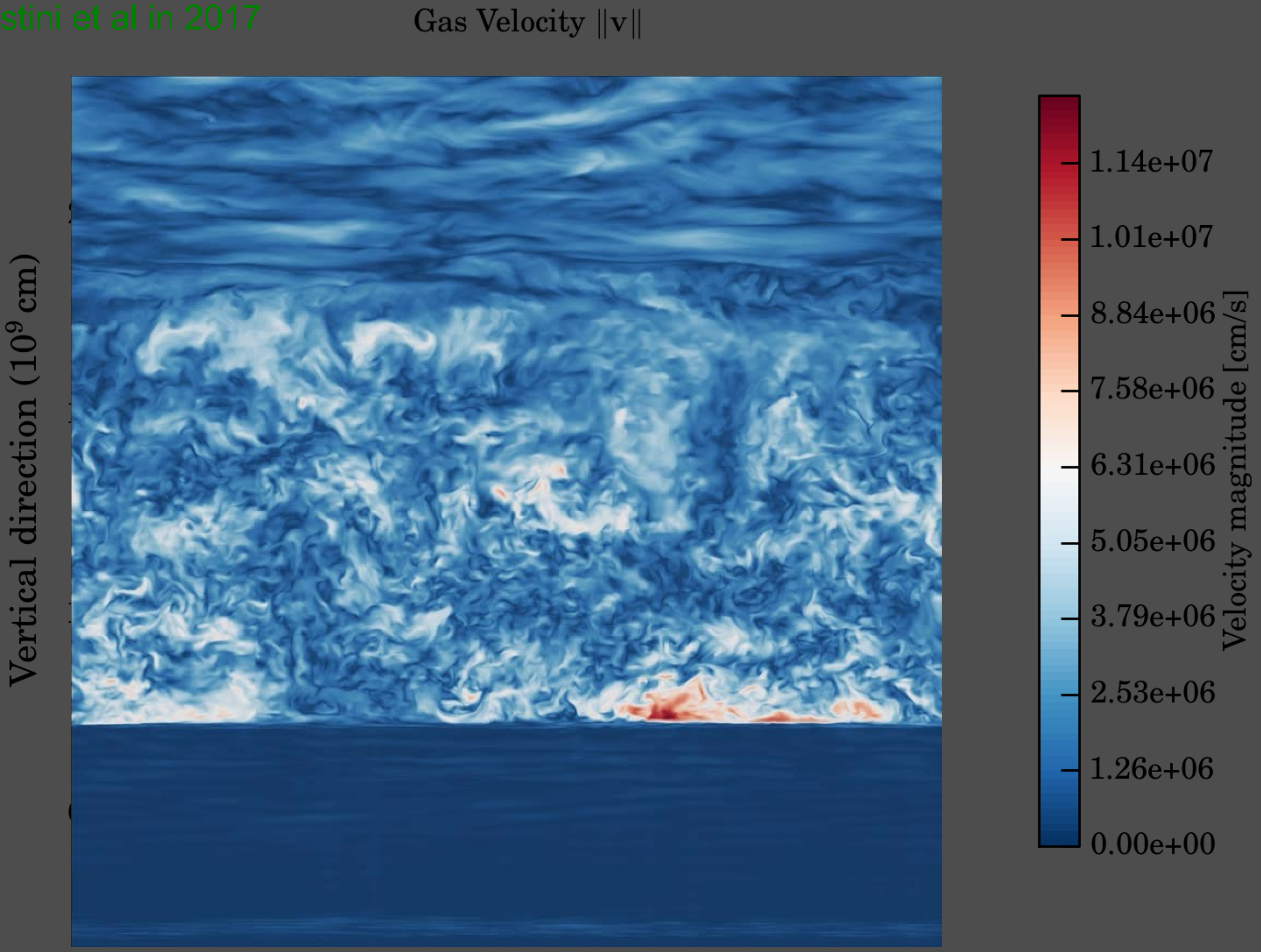
- 1D to 3D to 1D work underway: **new CBM prescriptions** under development!

- Exciting times ahead: **complex physics & large data sets**

Large consorted effort needed!

C-shell Simulations: $|v|$ movie

Cristini et al in 2017



http://www.astro.keele.ac.uk/shyne/321D/convection-and-convective-boundary-mixing/visualisations

Keele is Not Kiel (Germany) But Where is it?

West Midlands:

Keele area

is famous for pottery: Wedgwood, ...

Exciting HyDeploy.co.uk / SEND projects