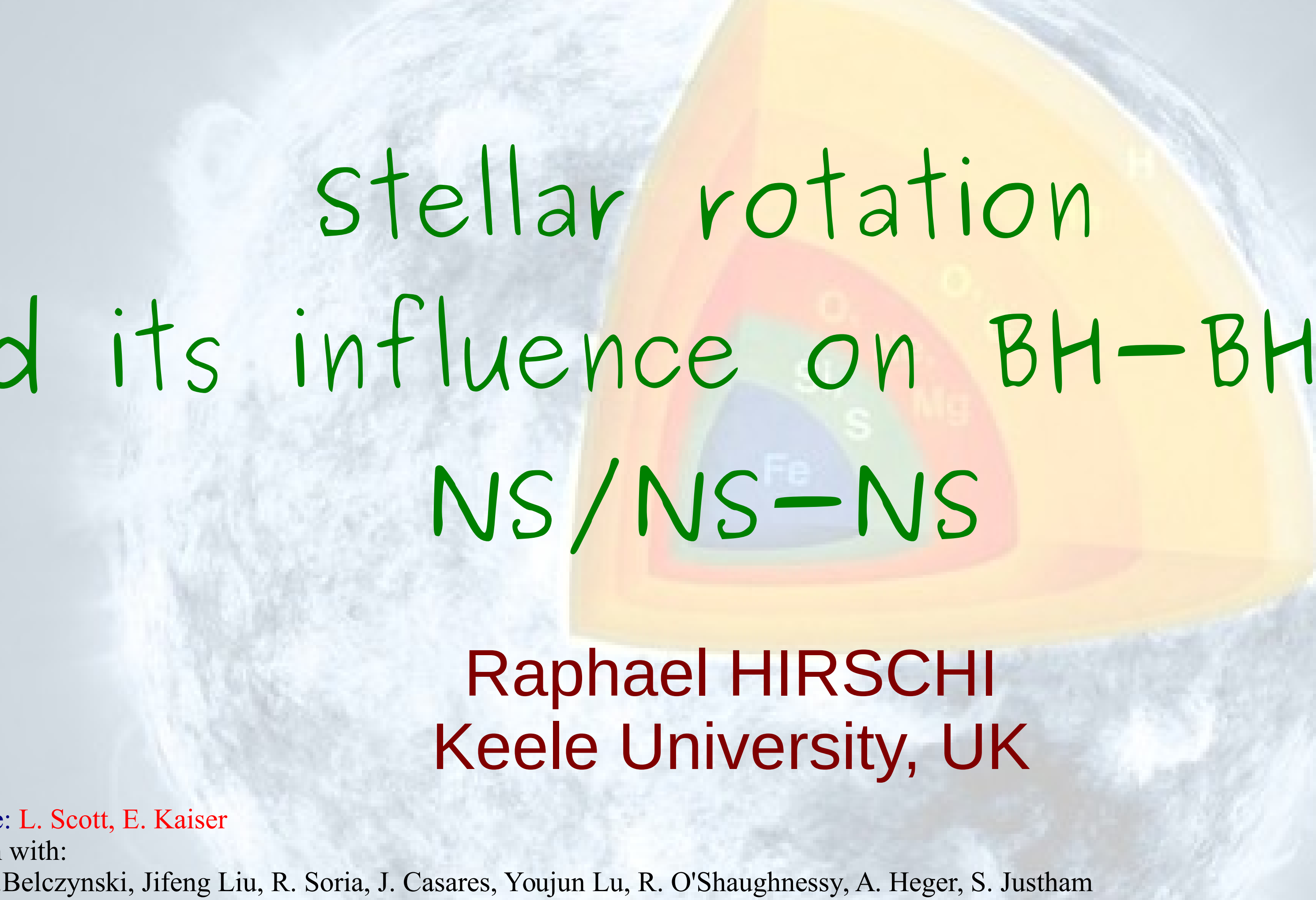
IPMU, January 2020

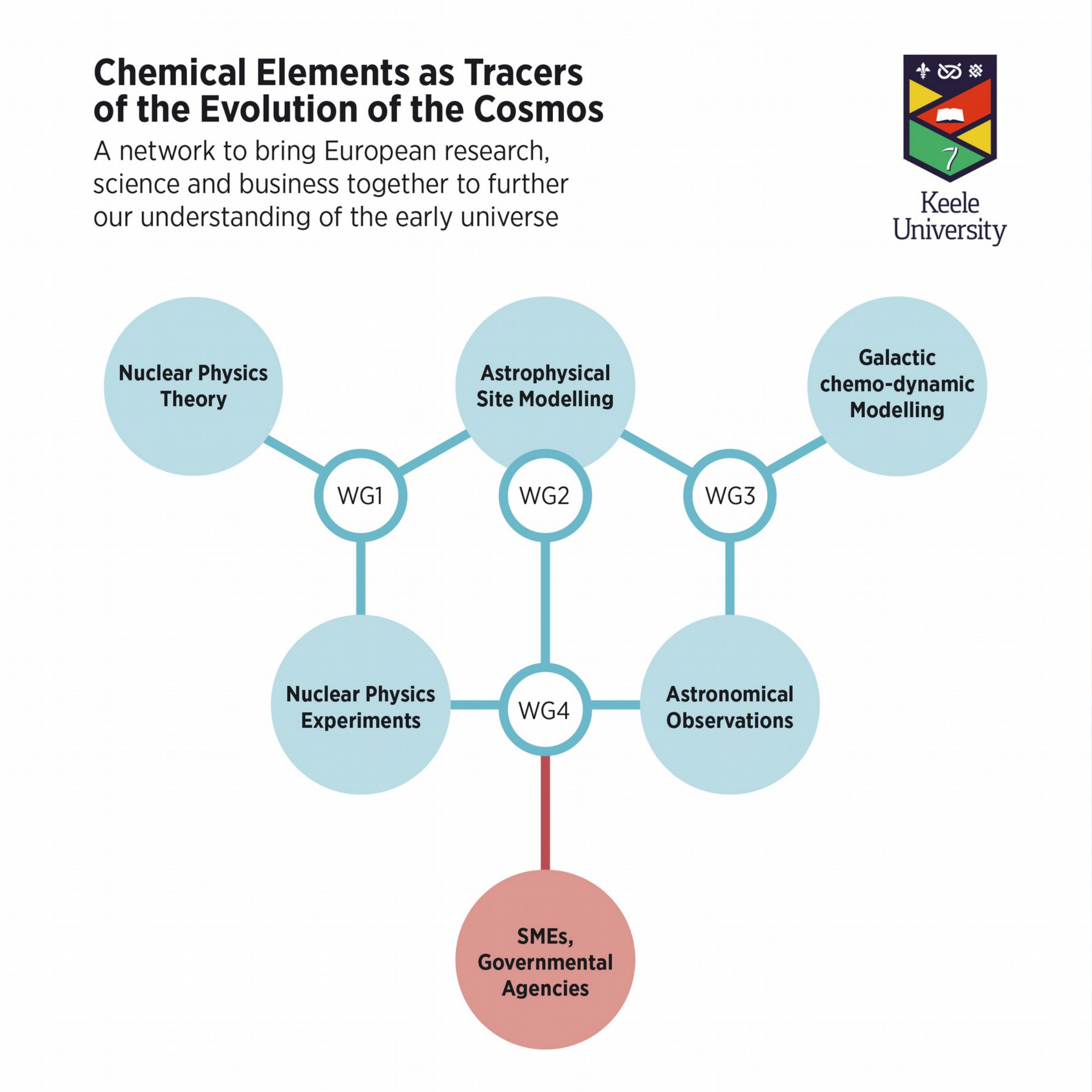


Stellar rotation and its influence on BH-BH/BH-NS/NS-NS

Raphael HIRSCHI
Keele University, UK

SHEN @ Keele: L. Scott, E. Kaiser
in collaboration with:
BHs (LB-1): K.Belczynski, Jifeng Liu, R. Soria, J. Casares, Youjun Lu, R. O'Shaughnessy, A. Heger, S. Justham
GVA code: G. Meynet, A. Maeder, C. Georgy, S. Ekström, P. Eggenberger, A. Choplin and C. Chiappini (IAP, D)
VMS: N. Yusof, H. Kassim (UM, KL, Malaysia), P. Crowther (Sheffield), O. Schnurr (IAP)
Nucleo: F.-K. Thielemann, U. Frischknecht, T. Rauscher (Basel, CH/Herts, UK) N. Nishimura
NUGRID: F. Herwig (Victoria, Canada), M. Pignatari (Hull), C. Fryer, S. Jones (LANL),
J. den Hartogh (Konkoly Obs., H), Laird (York), UChicago, UFrankfurt, …
MESA: B. Paxton (KITP), F. X. Timmes, (UArizona, US)
SNe: K. Nomoto (IPMU, J), C. Frohlich, M. Gilmer (NCSU), A. Kozyreva (Tel Aviv,Il), T. Fischer (W.,P)
HYDRO: C. Meakin, D. Arnett (UArizona), C. Georgy (GVA), M. Viallet (MPA),
F. Roepke, L. Horst (HITS, D), S. Jones (LANL), P. Edelmann (Newcastle, UK), A. Cristini (Uoklahoma,US)

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



Chemical Elements as Tracers of the Evolution of the Cosmos

A network to bring European research, science and business together to further our understanding of the early universe

Keele University

Nuclear Physics Theory

Astrophysical Site Modelling

Galactic chemo-dynamic Modelling

WG1

WG2

WG3

Nuclear Physics Experiments

WG4

Astronomical Observations

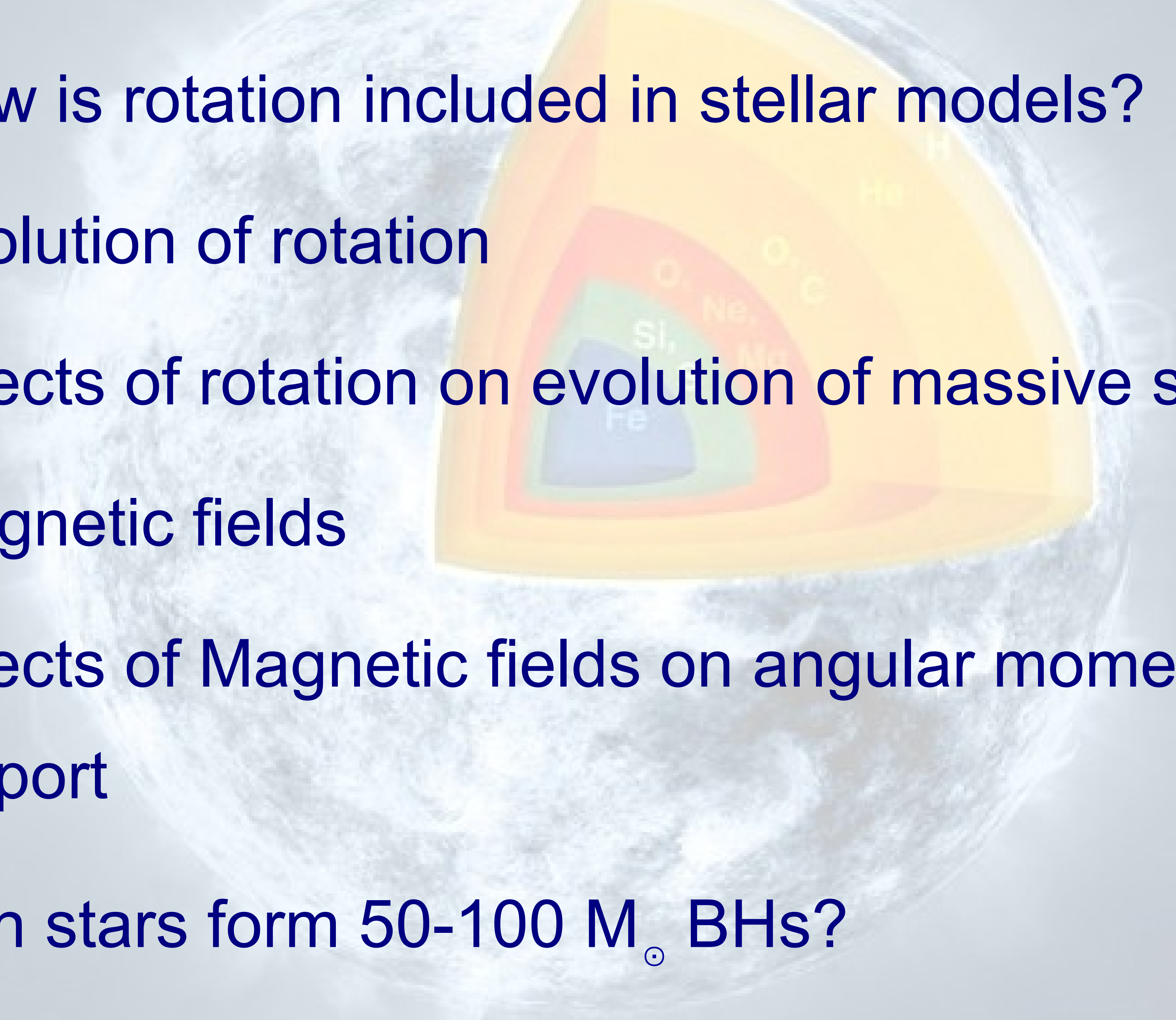
SMEs, Governmental Agencies

Funding for collaboration visits: STSMs!!

30 countries joined ChETEC to coordinate research efforts in Nuclear Astrophysics

Now world-wide cooperation with IReNA: https://www.irenaweb.org/ 2019-2024

Plan



- How is rotation included in stellar models?

- Evolution of rotation

- Effects of rotation on evolution of massive stars

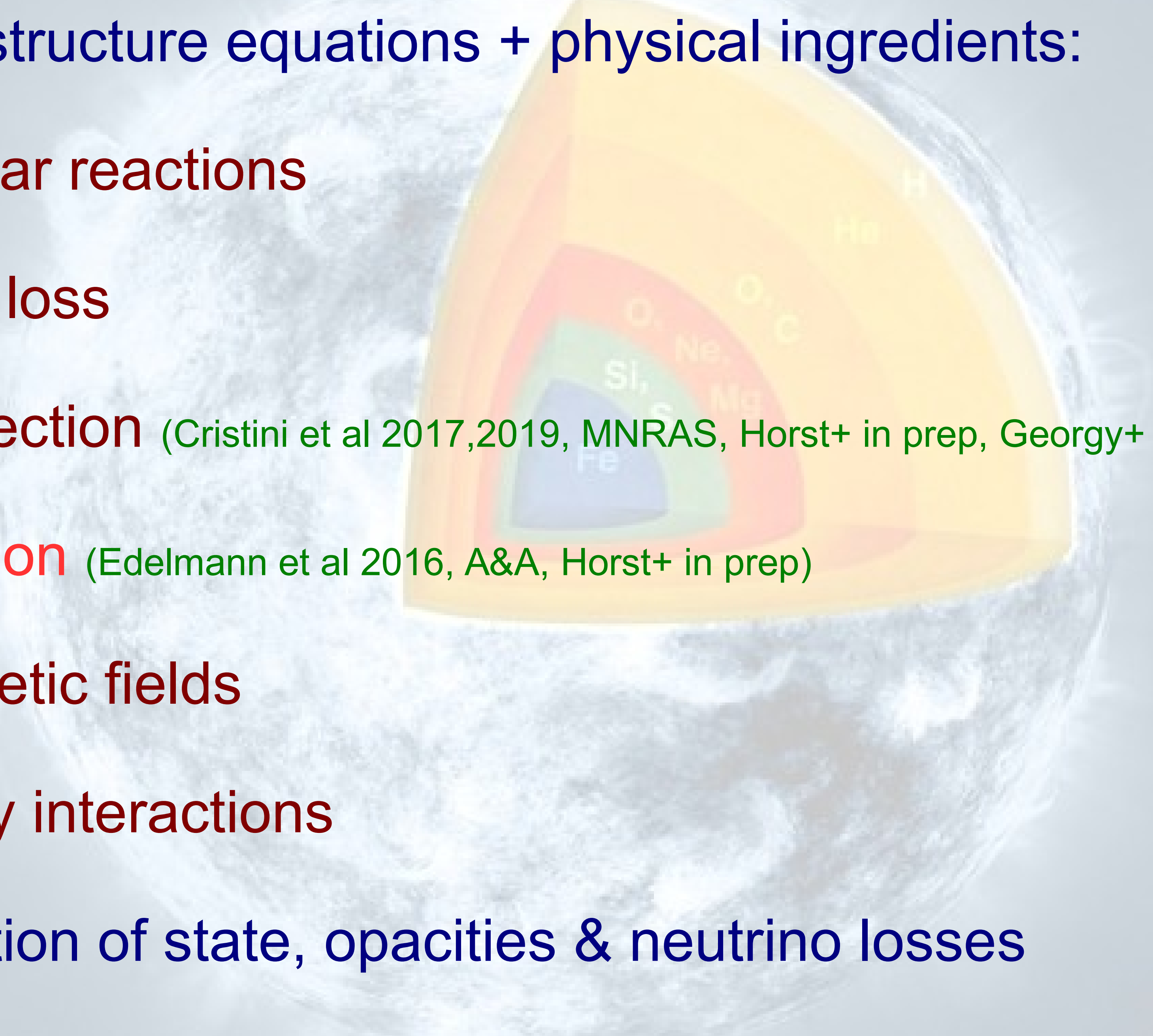
- Magnetic fields

- Effects of Magnetic fields on angular momentum transport

- Can stars form 50-100 $M_\odot$ BHs?

Stellar Evolution Models

Stellar structure equations + physical ingredients:



- Nuclear reactions

- Mass loss

- Convection (Cristini et al 2017,2019, MNRAS, Horst+ in prep, Georgy+ in prep)

- Rotation (Edelmann et al 2016, A&A, Horst+ in prep)

- Magnetic fields

- Binary interactions

- Equation of state, opacities & neutrino losses

including metallicity dependence

Stellar Evolution with Rotation: Geneva Code

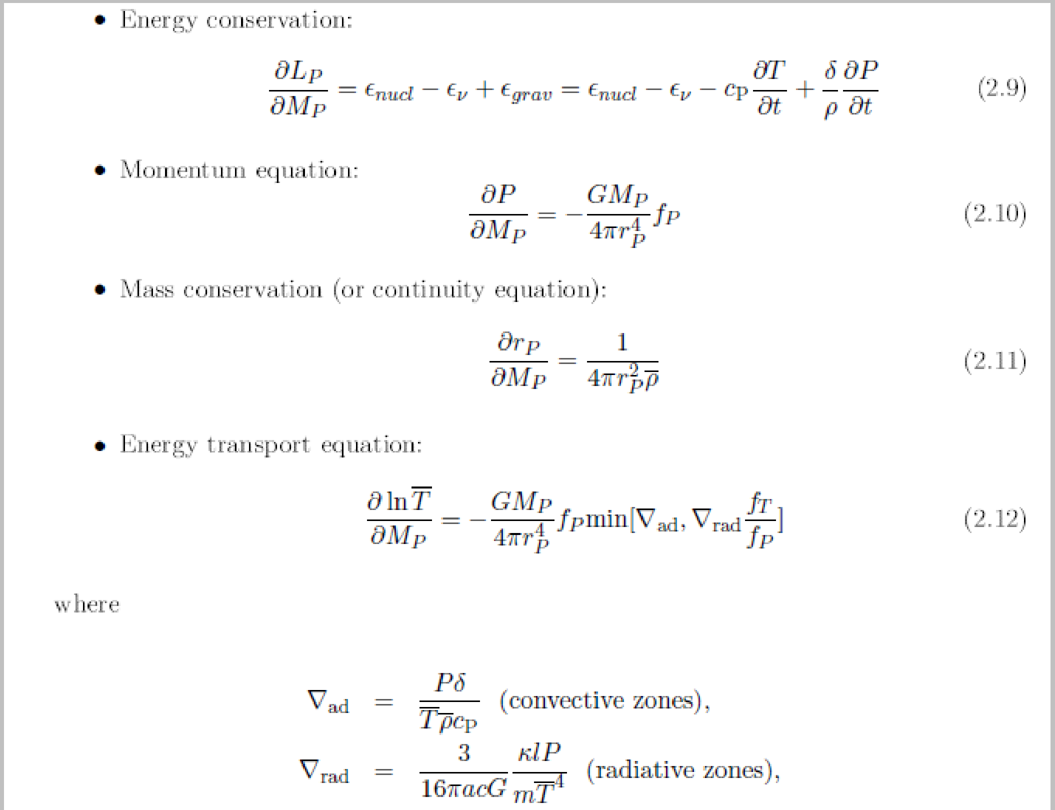
1.5D hydrostatic code (Eggenberger et al 2008)

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):

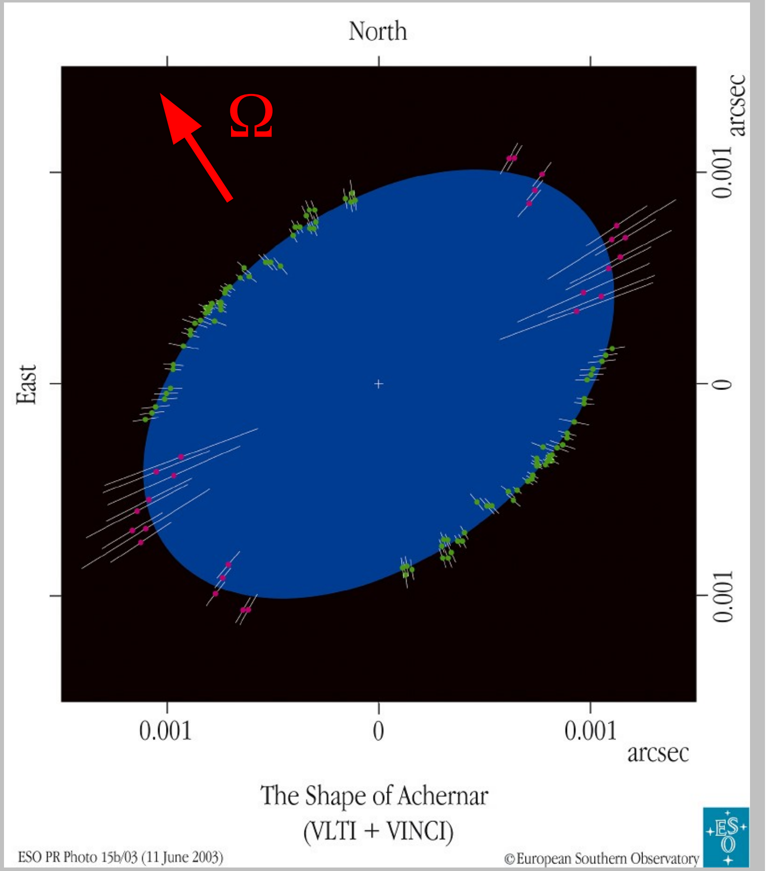
$$\frac{\partial r_P}{\partial M_P} = \frac{1}{4\pi r_P^2 \bar{\rho}} \qquad (2.11)$$

- 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

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



The Shape of Achernar
(VLTI + VINCI)

ESO PR Photo 15b/03 (11 June 2003)

©European Southern Observatory

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

(Meynet and Meynet 97)

Rotation Induced Transport

Zahn 1992: strong horizontal turbulence

Transport of angular momentum:

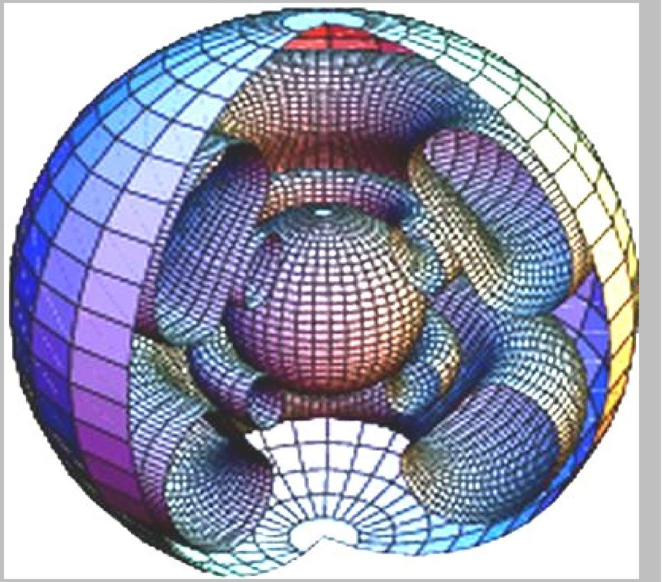
$$\rho\frac{\mathrm{d}}{\mathrm{d}t}\left(r^2\bar{\Omega}\right)_{M_r} = \underbrace{\frac{1}{5r^2}\frac{\partial}{\partial r}\left(\rho r^4\bar{\Omega}U(r)\right)}_{\text{advection term}} + \underbrace{\frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho D r^4\frac{\partial\bar{\Omega}}{\partial r}\right)}_{\text{diffusion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

Transport of chemical

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

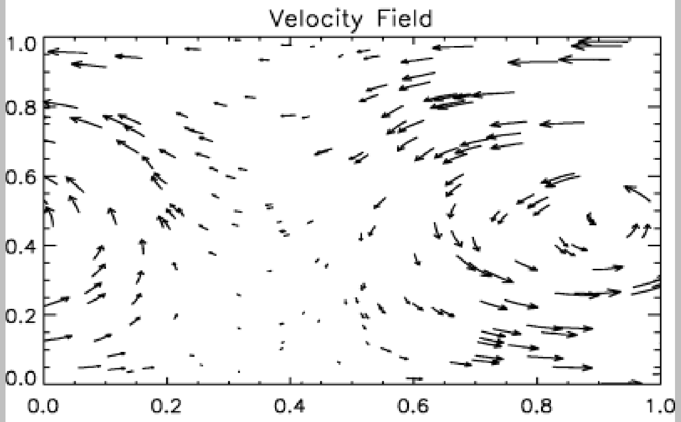
D: diffusion coeff. due to various transport mechanisms (convection, shear)

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



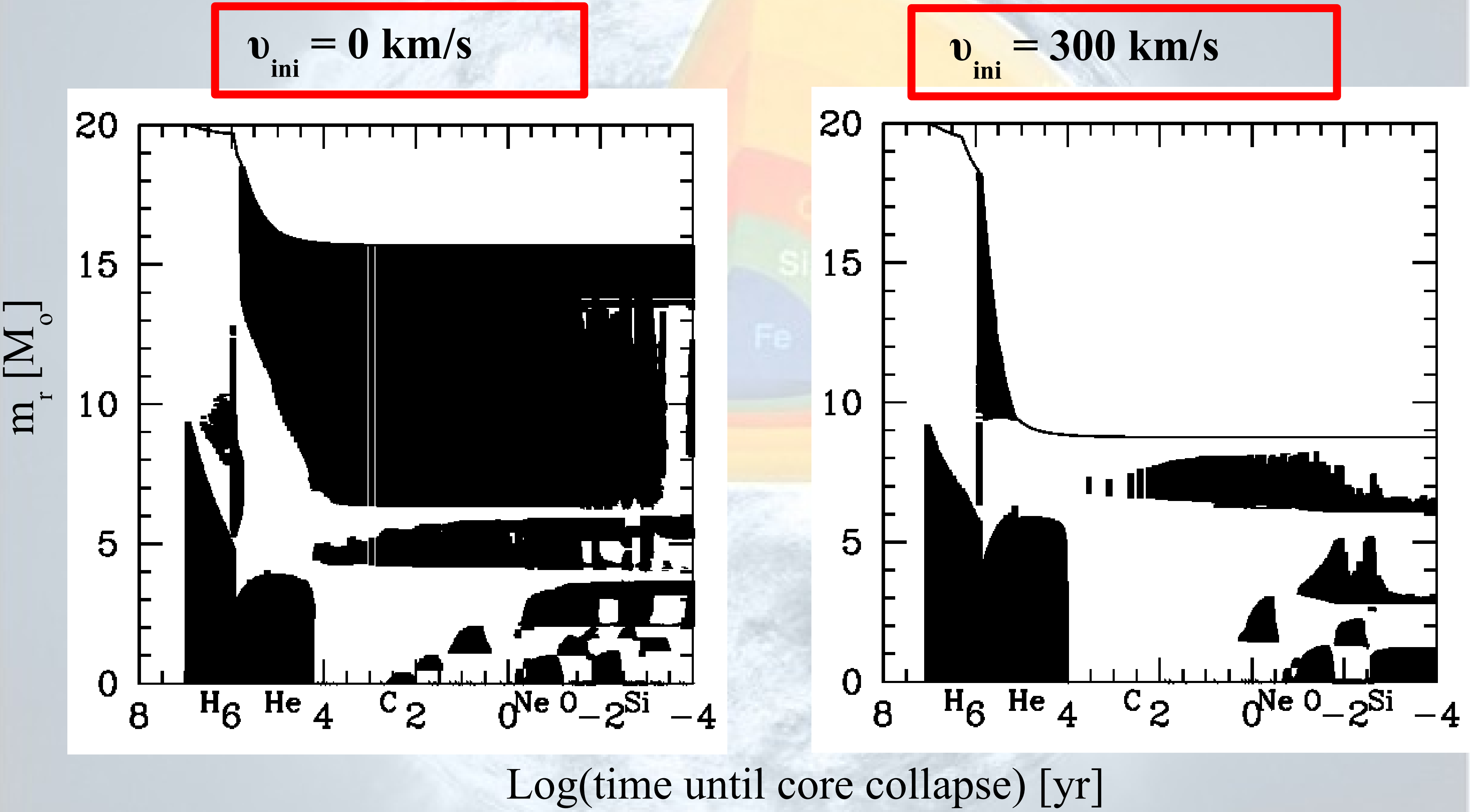
Meynet & Maeder 2000

Shear instabilities



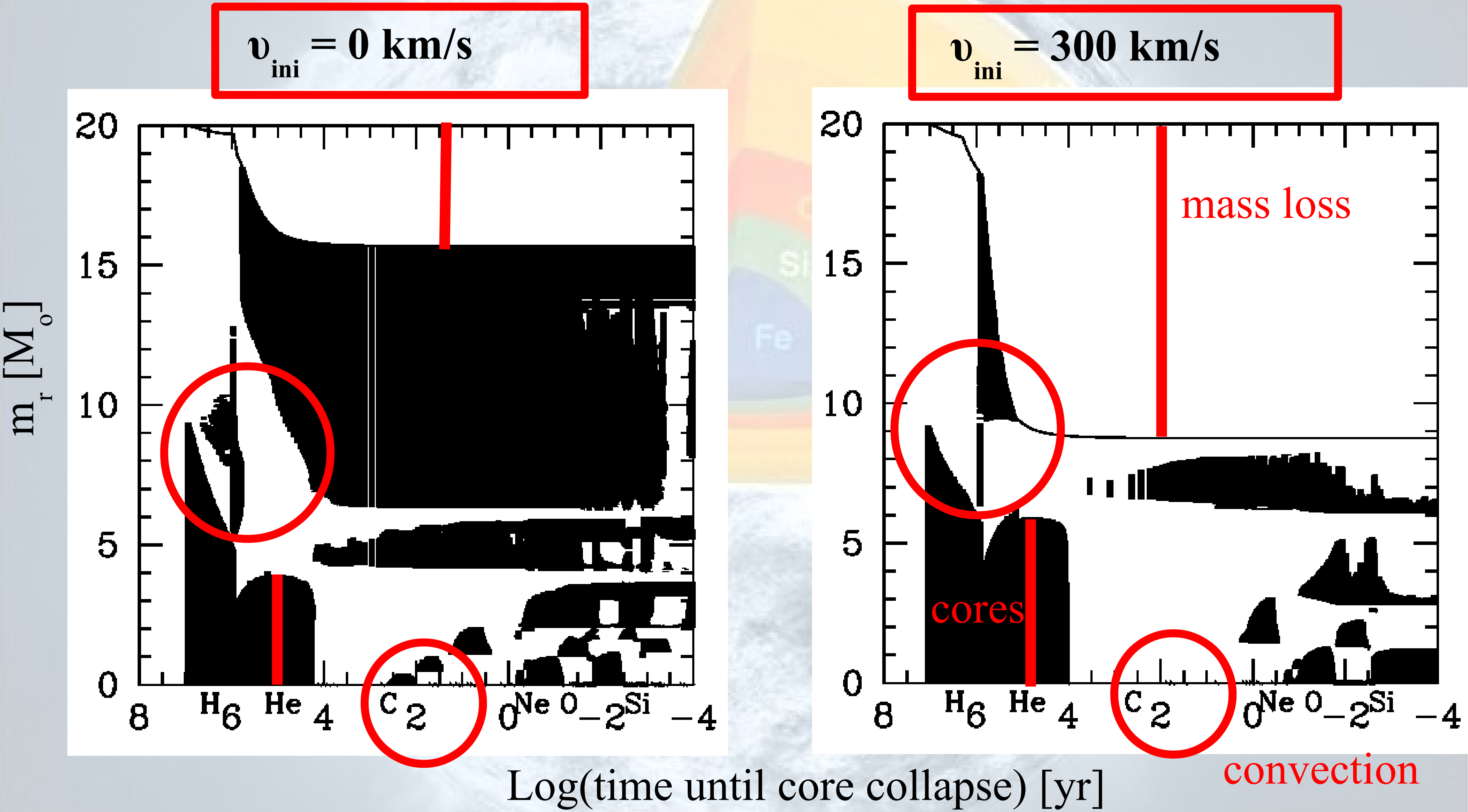
Brueggen & Hillebrandt 2000

Effects of Rotation on Evolution



Hirschi+ 2004, A&A

Effects of Rotation on Evolution

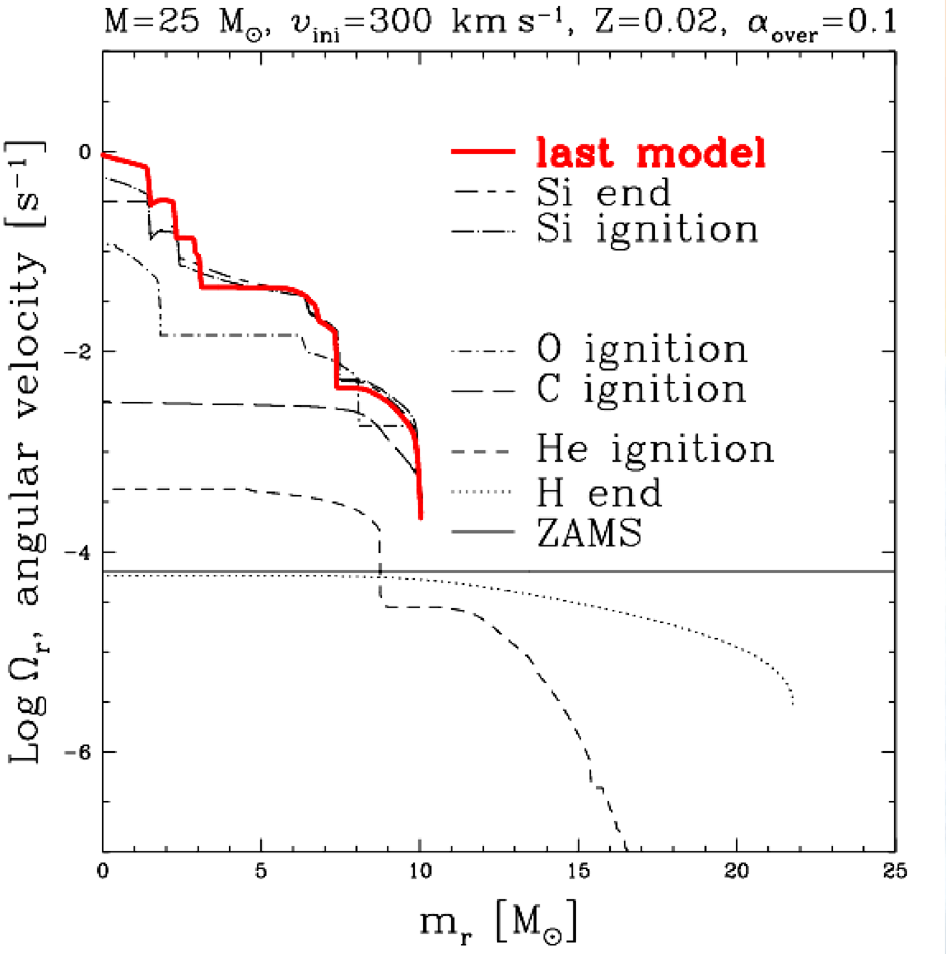


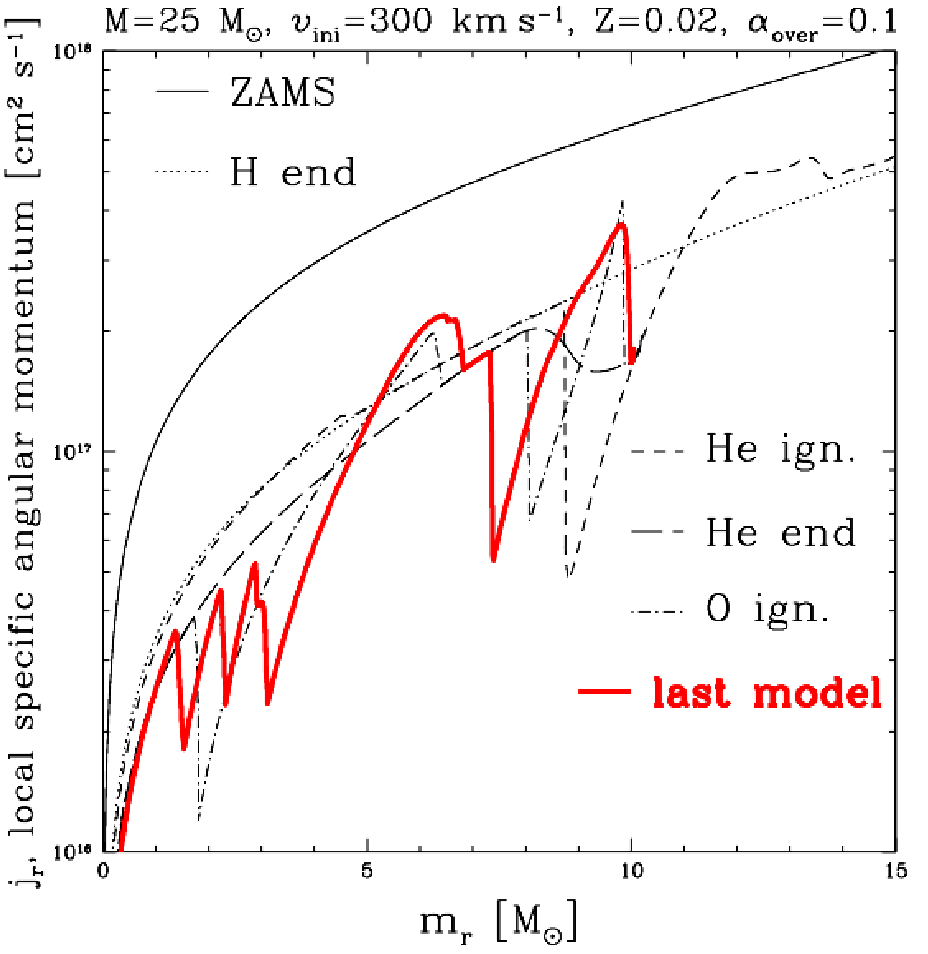
Hirschi+ 2004, A&A

Evolution of Rotation

Angular velocity: Ω↑
end Si: Ω~ 1 s^{-1}

Angular momentum, j↓
j(end Si) ~ j(end He)

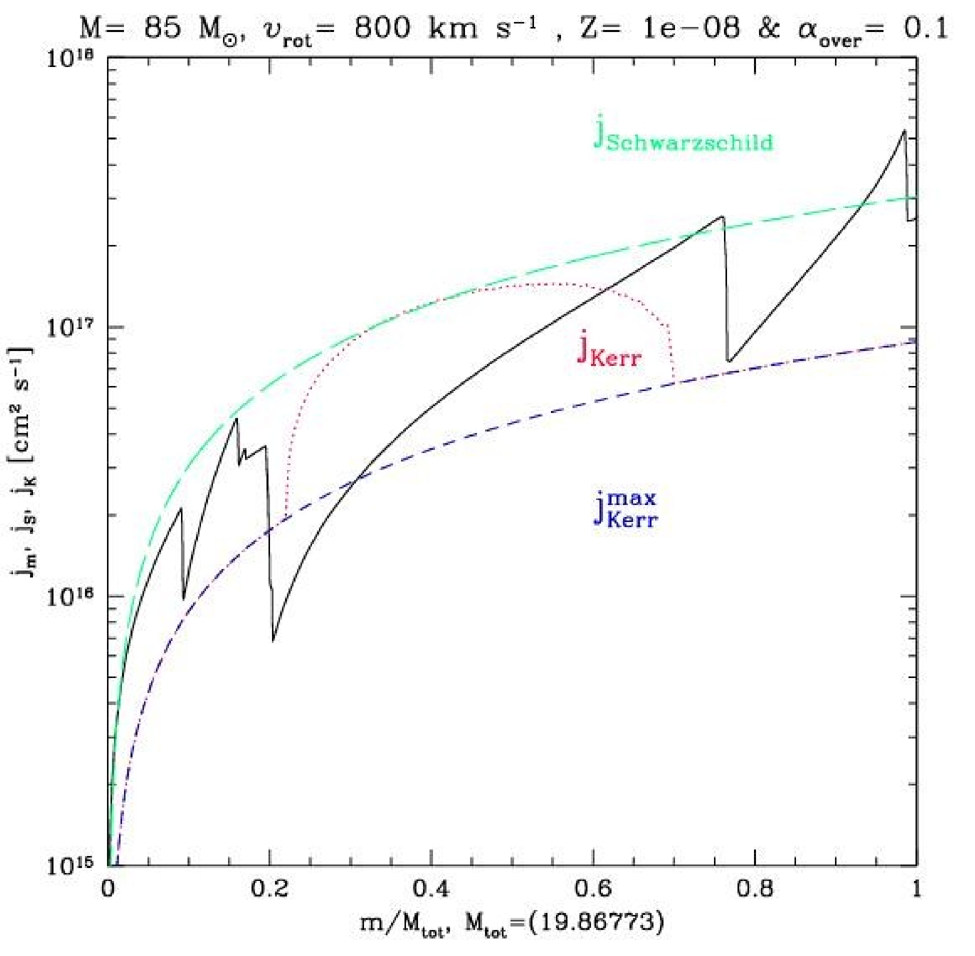




Hirschi+ 2004, A&A; Similar results in Chieffi & Limongi 2013

Pre-SN Angular Momentum (no-B)

High j_{final} → GRB

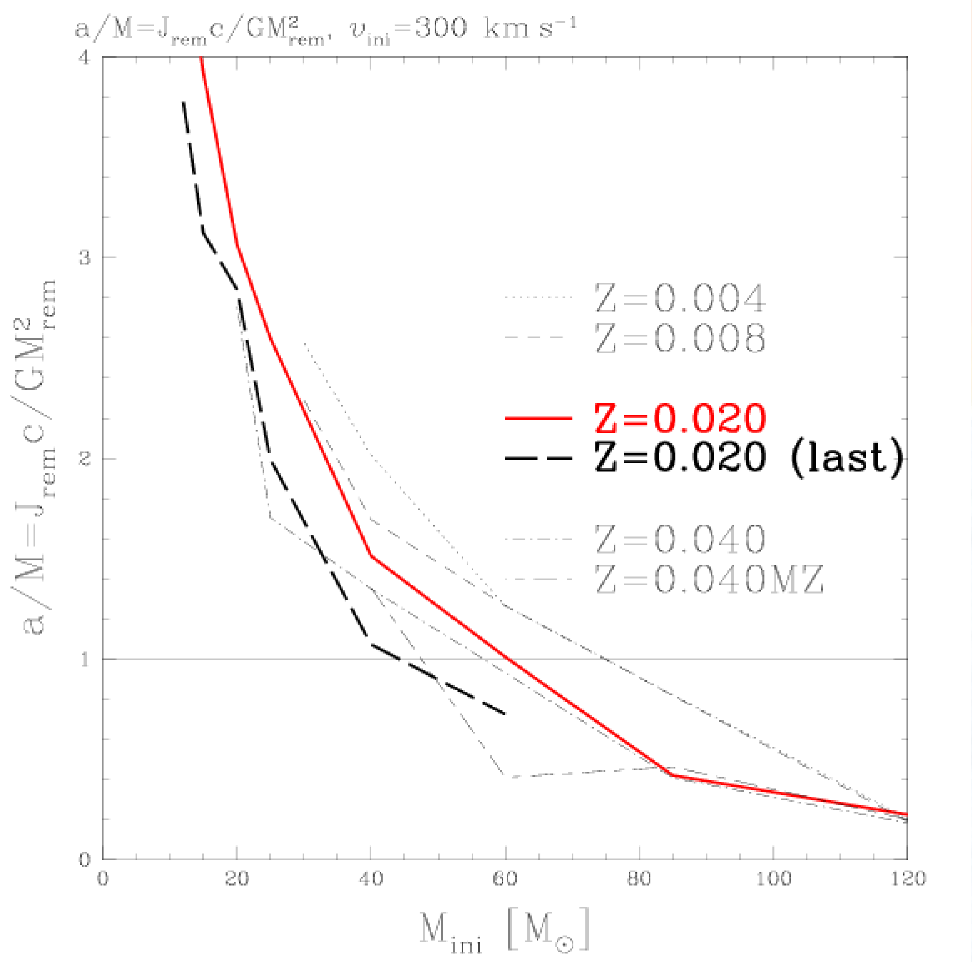


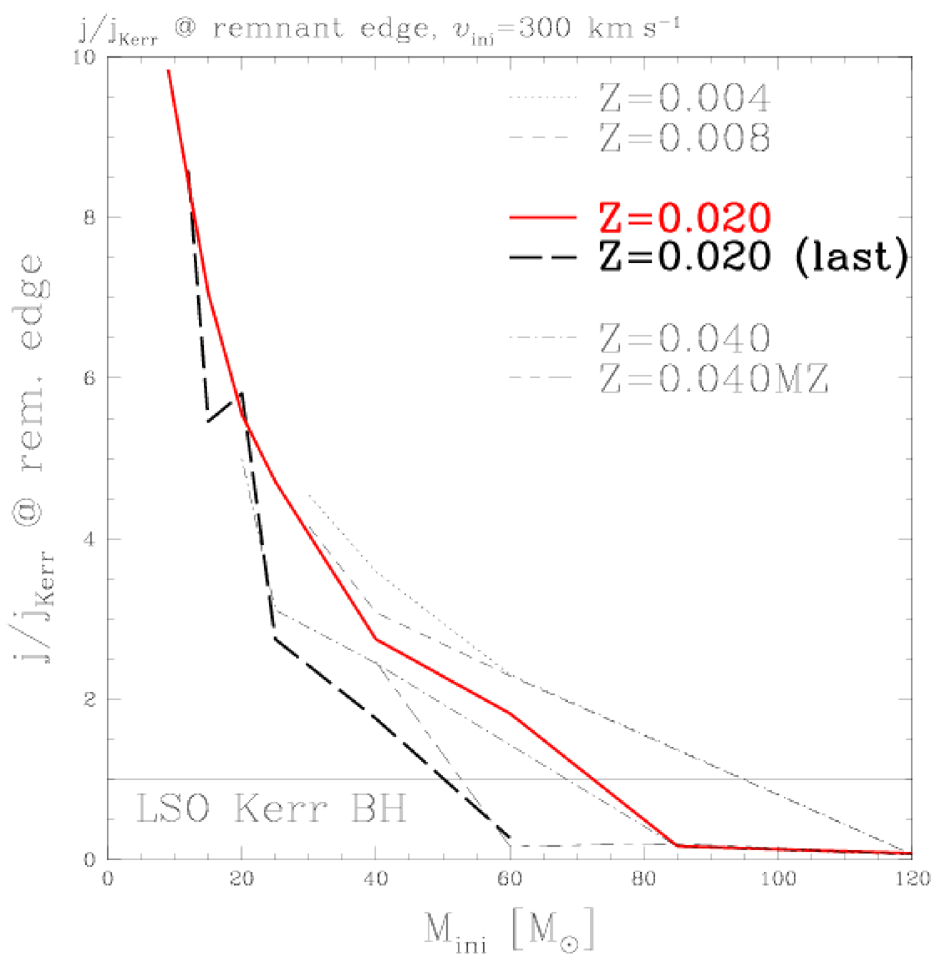
Hirschi+ 2005, A&A

Pre-SN Angular Momentum (no-B)

Many models with
supercritically rot. NS

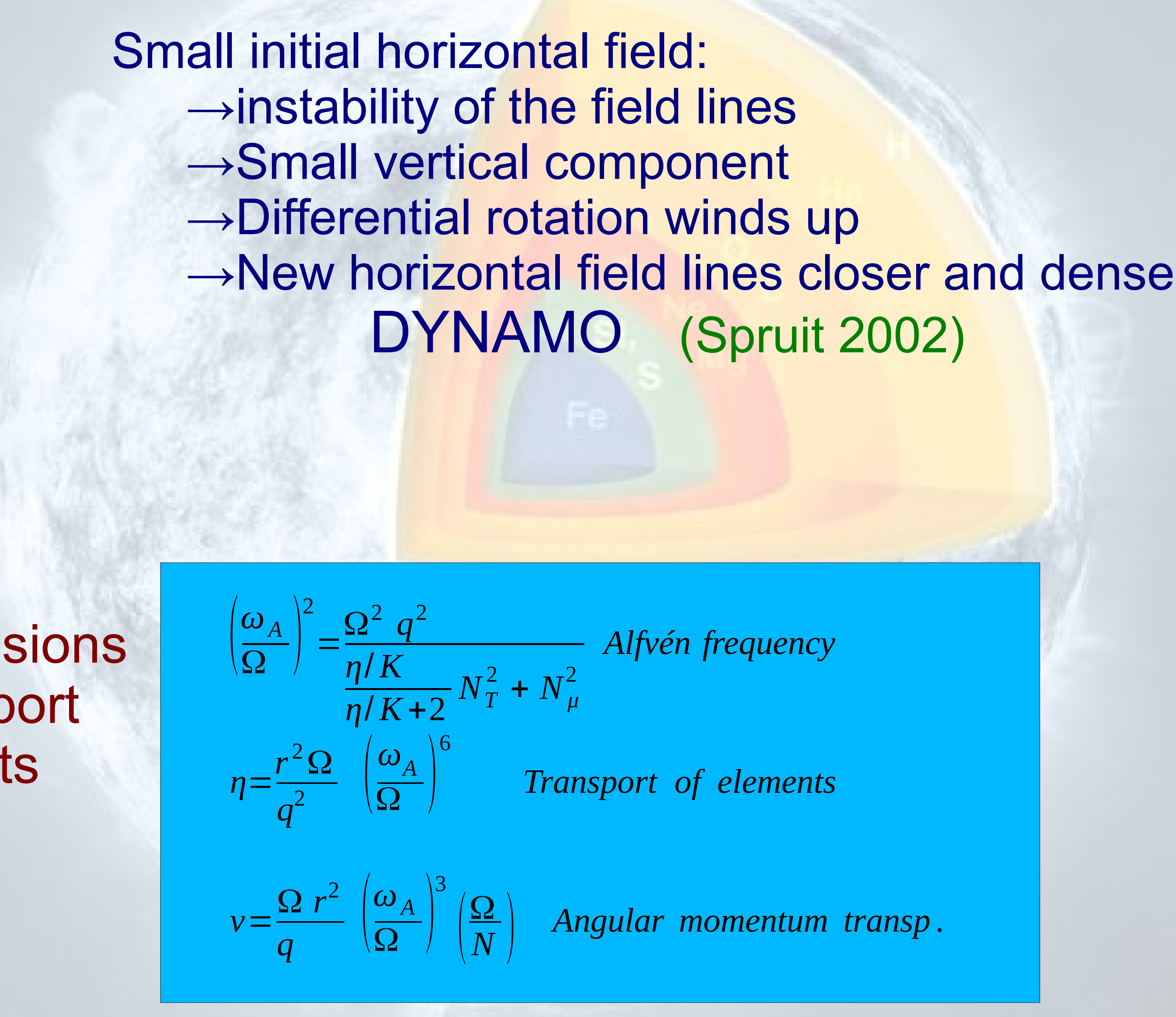
Condition for disk formation:
(too) often fullfilled





Hirschi+ 2005, A&A

Magnetic Field Theory



Taylor Instability (1973)

Small initial horizontal field:

→instability of the field lines
→Small vertical component
→Differential rotation winds up
→New horizontal field lines closer and denser:

DYNAMO (Spruit 2002)

→ expressions For transport coefficients (Maeder & Meynet 2005)

$$\left(\frac{\omega_A}{\Omega}\right)^2 = \frac{\Omega^2\, q^2}{\frac{\eta/K}{\eta/K+2} N_T^2 + N_\mu^2} \quad \textit{Alfvén frequency}$$

$$\eta = \frac{r^2\Omega}{q^2} \left(\frac{\omega_A}{\Omega}\right)^6 \quad \textit{Transport of elements}$$

$$\nu = \frac{\Omega\, r^2}{q} \left(\frac{\omega_A}{\Omega}\right)^3 \left(\frac{\Omega}{N}\right) \quad \textit{Angular momentum transp.}$$

Magnetic Fields in Massive Stars

Taylor-Spruit dynamo (Spruit 2002) : better for NS (Heger et al 2005) (Yoon et al 2006)

No $A_{BH}>1$ in Fe-core @ pre-SN stage with B-fields (Petrovic et al 2005, ...)

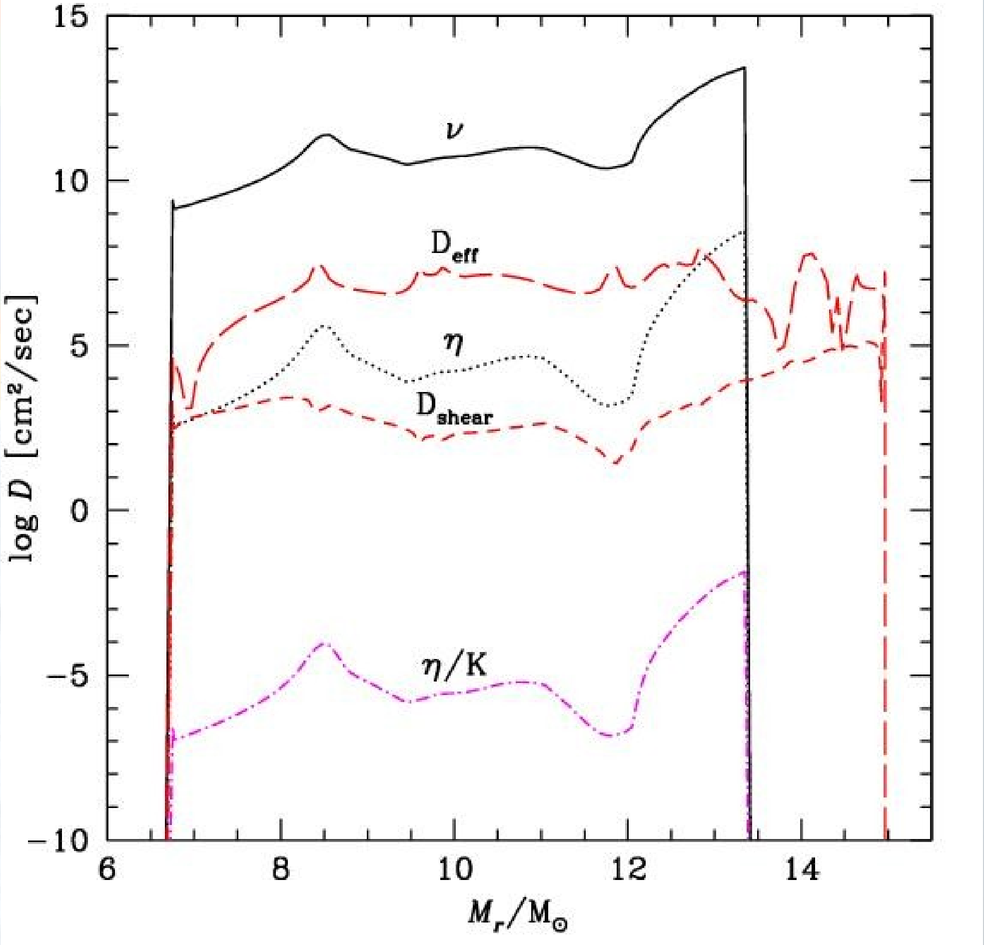
Transport of Ω:

- dominated by B-fields (ν)
- Flatter Ω profiles

Transport of X_i:

- Dominated by meridional circulation (D_{eff})
- Stronger mixing

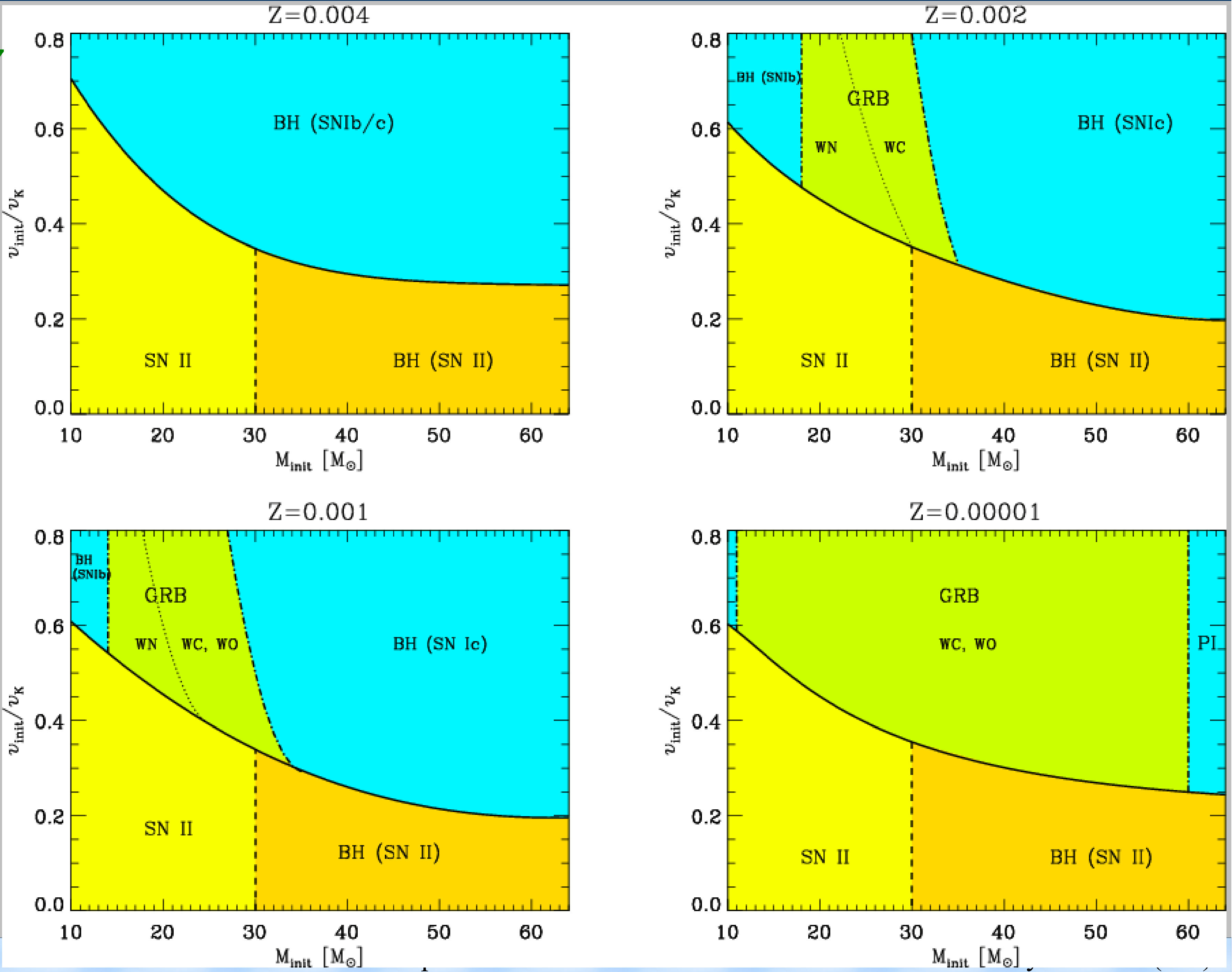
15 M_o, Z=0.02 & v_{ini} =300 km/s



(Maeder & Meynet 2005)

GRB progenitors with B-Fields

Yoon et al 07



Binary Mass Gainer Spin-Up

Cantiello+ 2007 A&A

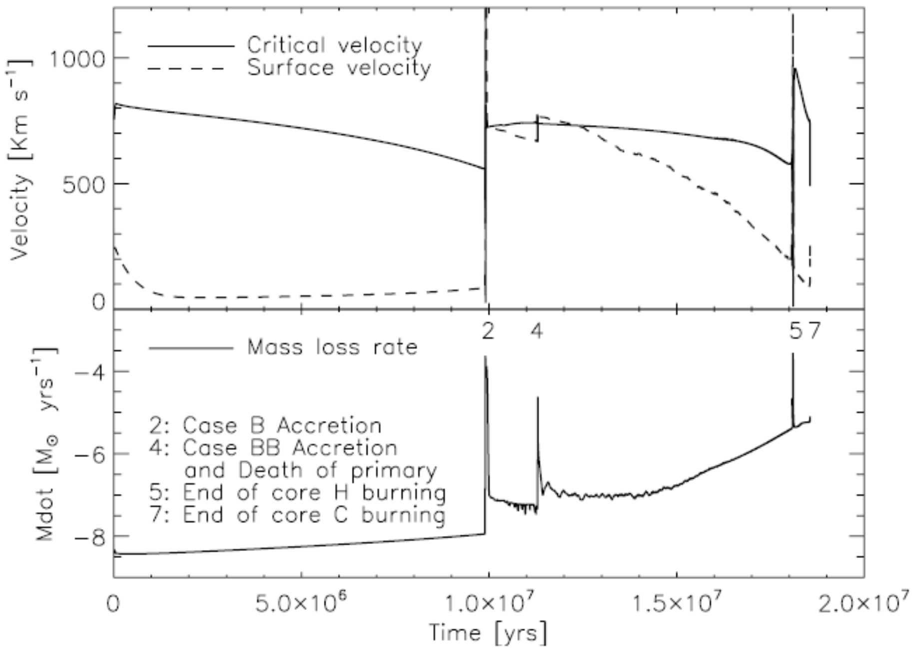


Fig. 2. *Upper panel*: equatorial rotation velocity (dashed line) and critical rotation velocity (solid line) of the mass gainer of the computed $16\,M_\odot + 15\,M_\odot$ early Case B binary sequence, as function of time, from the zero-age main sequence until core carbon exhaustion. *Lower panel*: mass loss rate of the same stellar model, as function of time. The numbered evolutionary stages correspond to those given in Fig. 1 and Table 1.

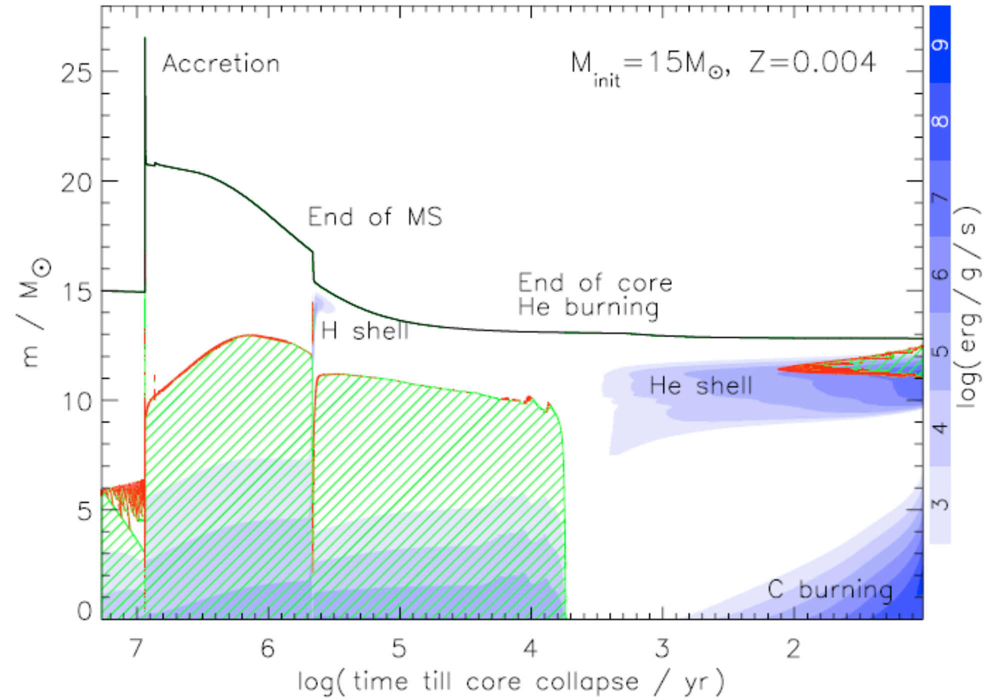


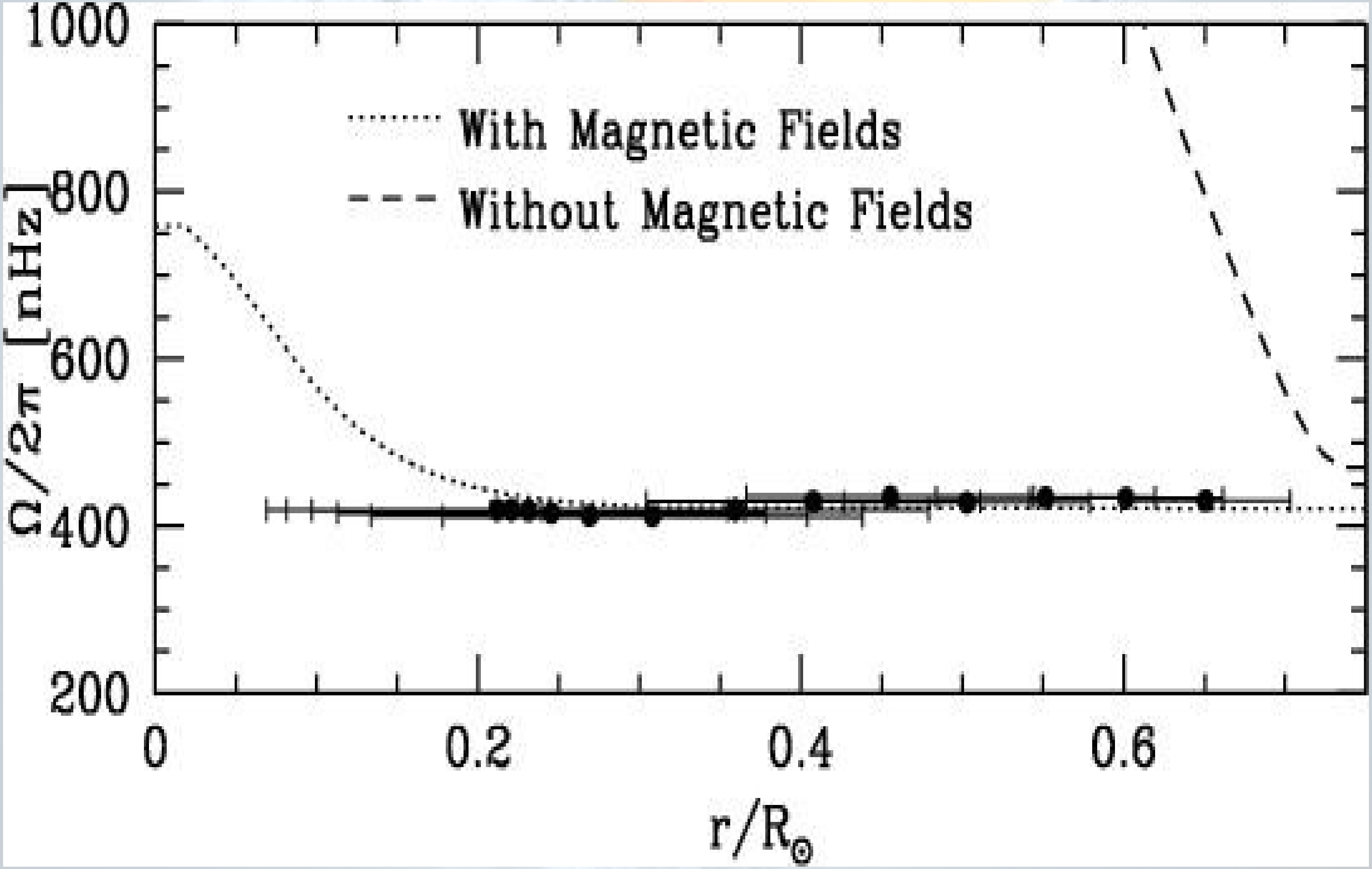
Fig. 3. Evolution of the internal structure of the mass gainer of the computed $16\,M_\odot + 15\,M_\odot$ early Case B binary sequence, as function of time, from the zero-age main sequence to core carbon exhaustion. The time axis is logarithmic, with the time of core collapse as zero point. Convective layers are hatched. Semiconvective layers are marked by dots (red dots in the electronic version). Gray (blue) shading indicates nuclear energy generation (color bar to the right of the figure). The topmost solid line denotes the surface of the star.

Mass gainer behaves as initially very fast spinning single star

Rotation of the Sun & Magnetic Fields

Sun rotation profile compatible with helioseismology

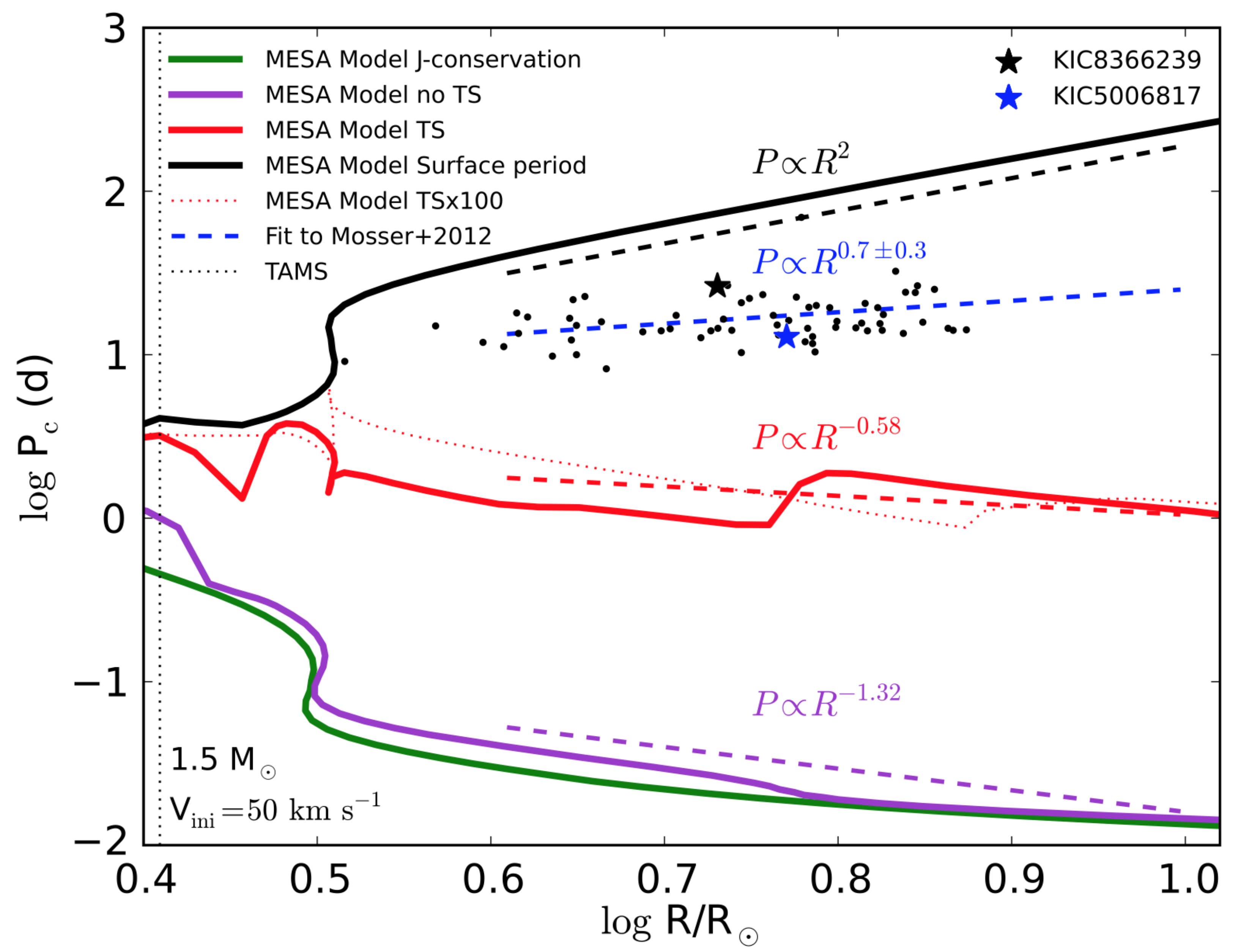
(e.g. Eggenberger et al 2005)



Gravity waves can also help (e.g. Charbonnel & Talon 2005, Arnett & Maekin 2006)

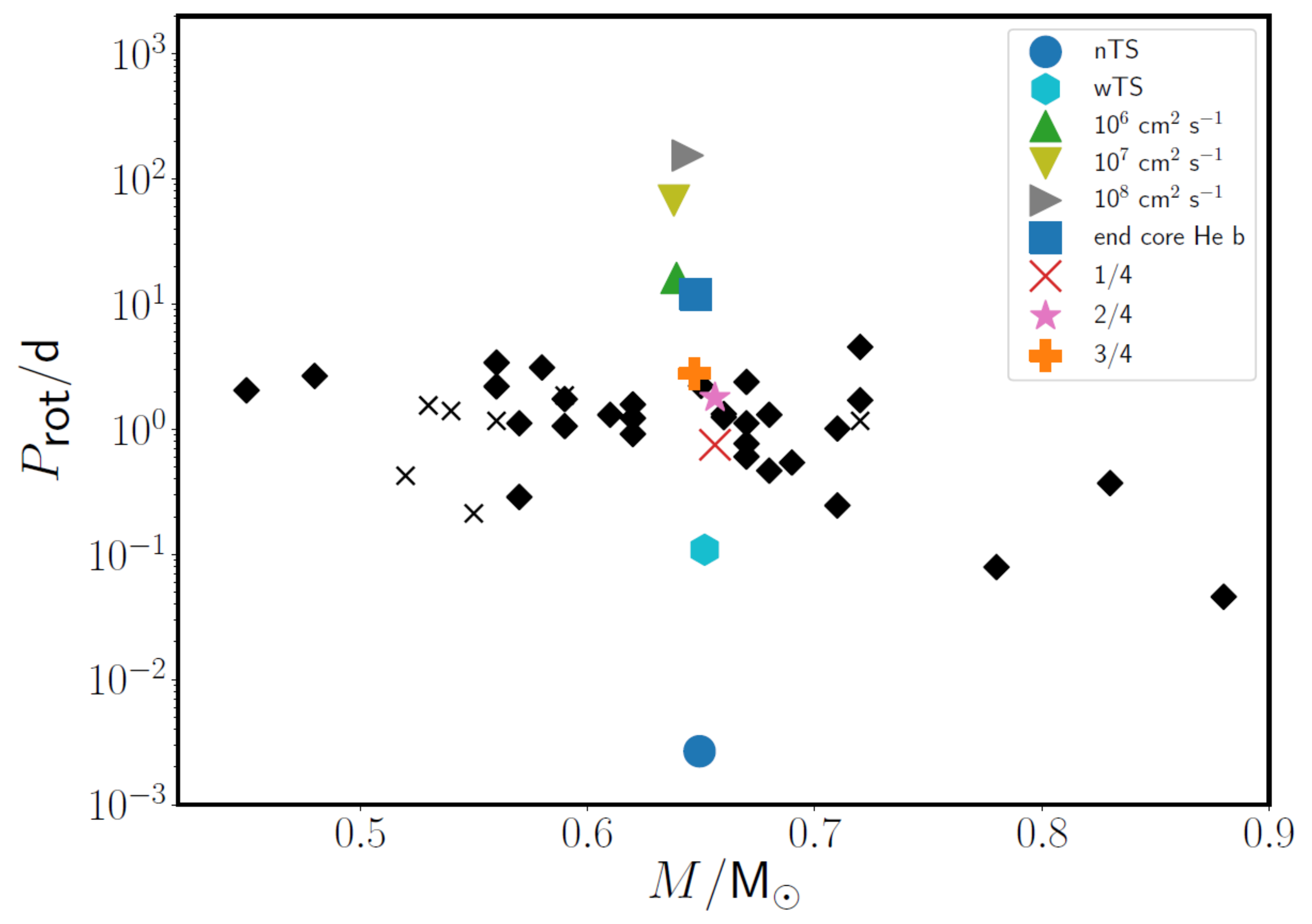
TS Dynamo still not enough

Rotation of low-mass stars on RGB (e.g. Cantiello+ 2014)



WD Rotation Periods

den Hartogh, Eggenberger, Hirschi 2019, A&A



Stronger transport needed during early (up to start He-b.) than during late (He-b. and beyond) evolution

Fuller-Modified TS-Dynamo (TSF)

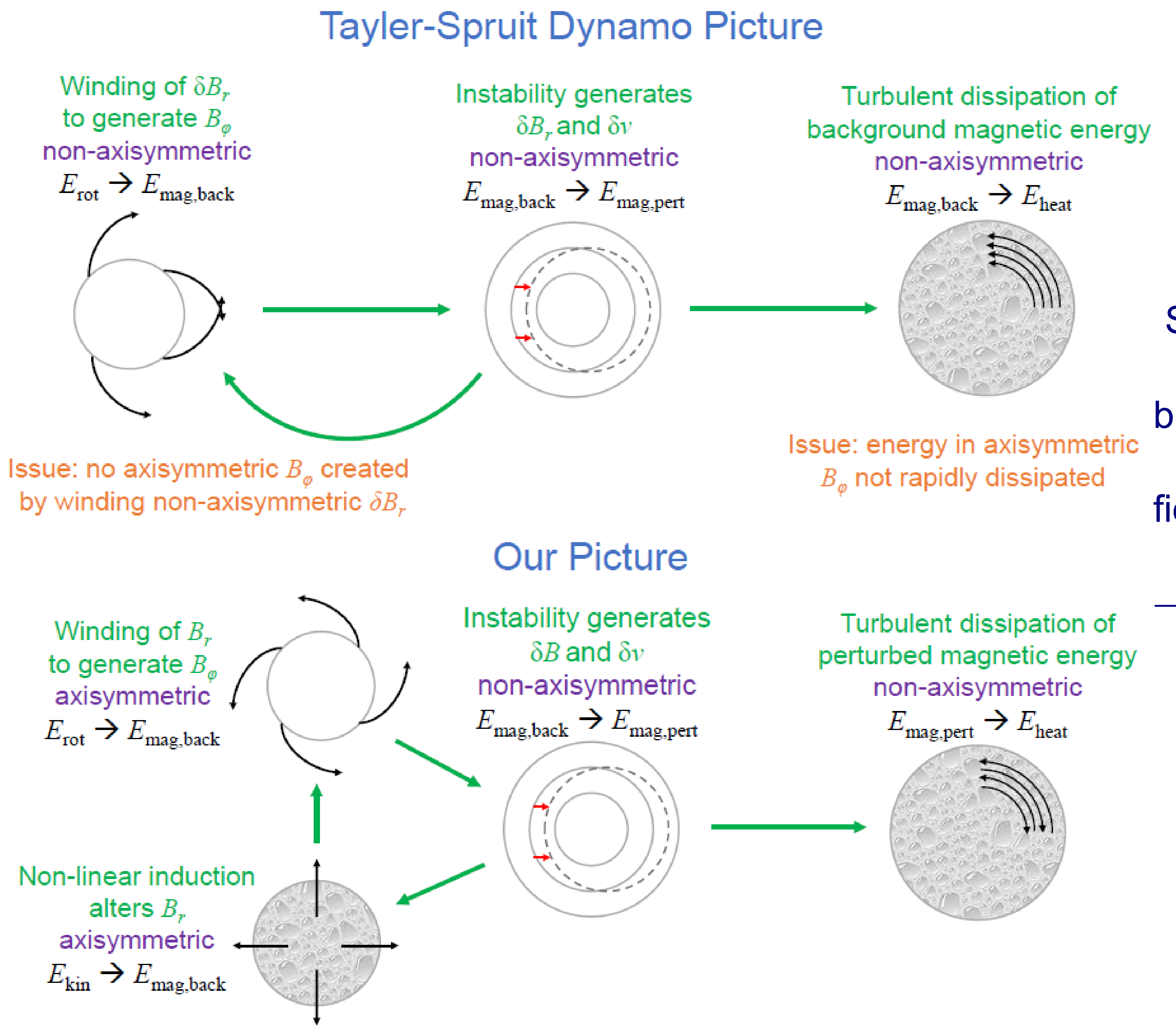


Figure 1. Schematic showing the physical processes at work in stars undergoing Tayler instability, according to the Tayler-Spruit dynamo

Fuller, Piro, Jermyn,

2019, MNRAS

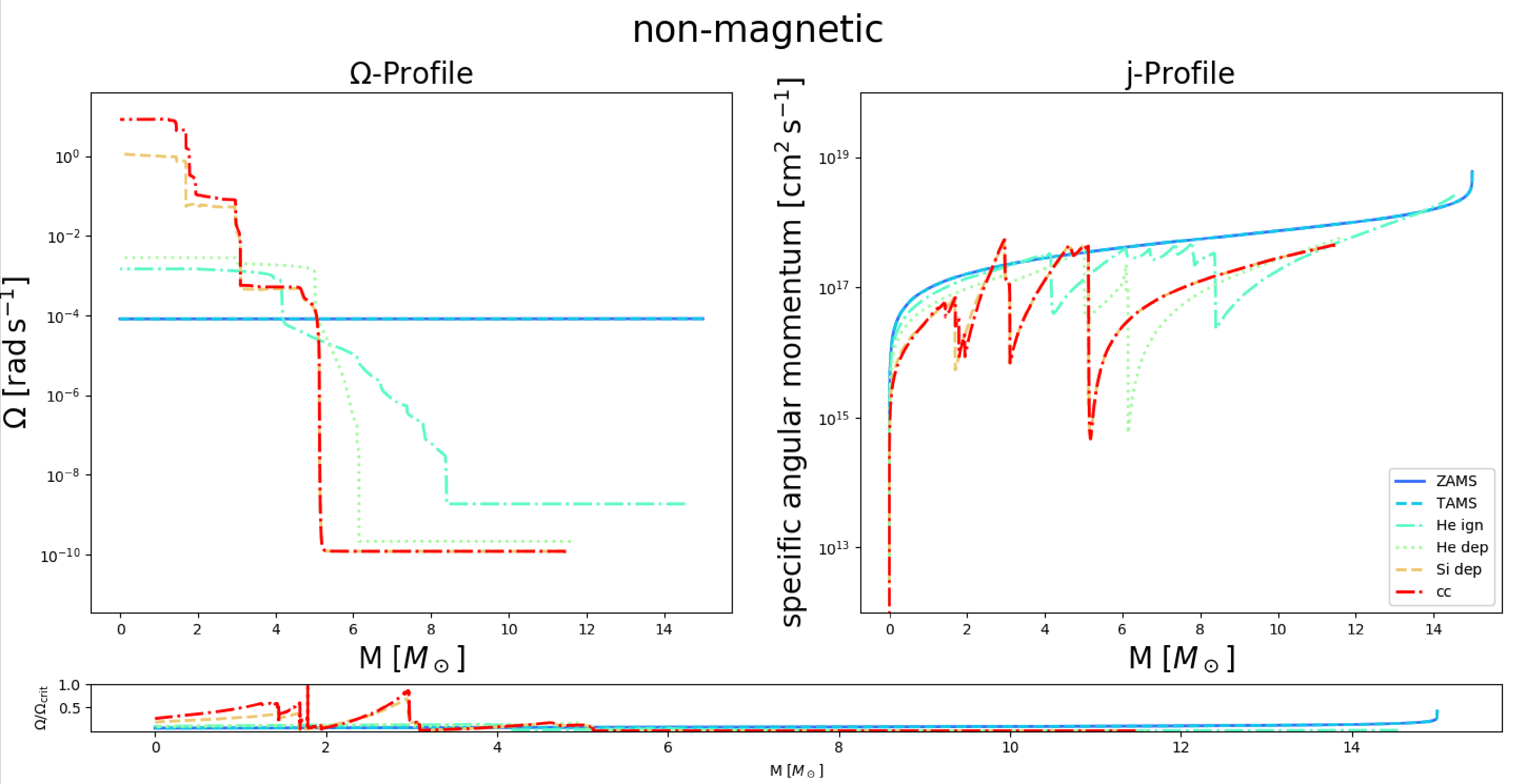
Similar to TS dynamo

but with higher saturation

field magnetic magnitude

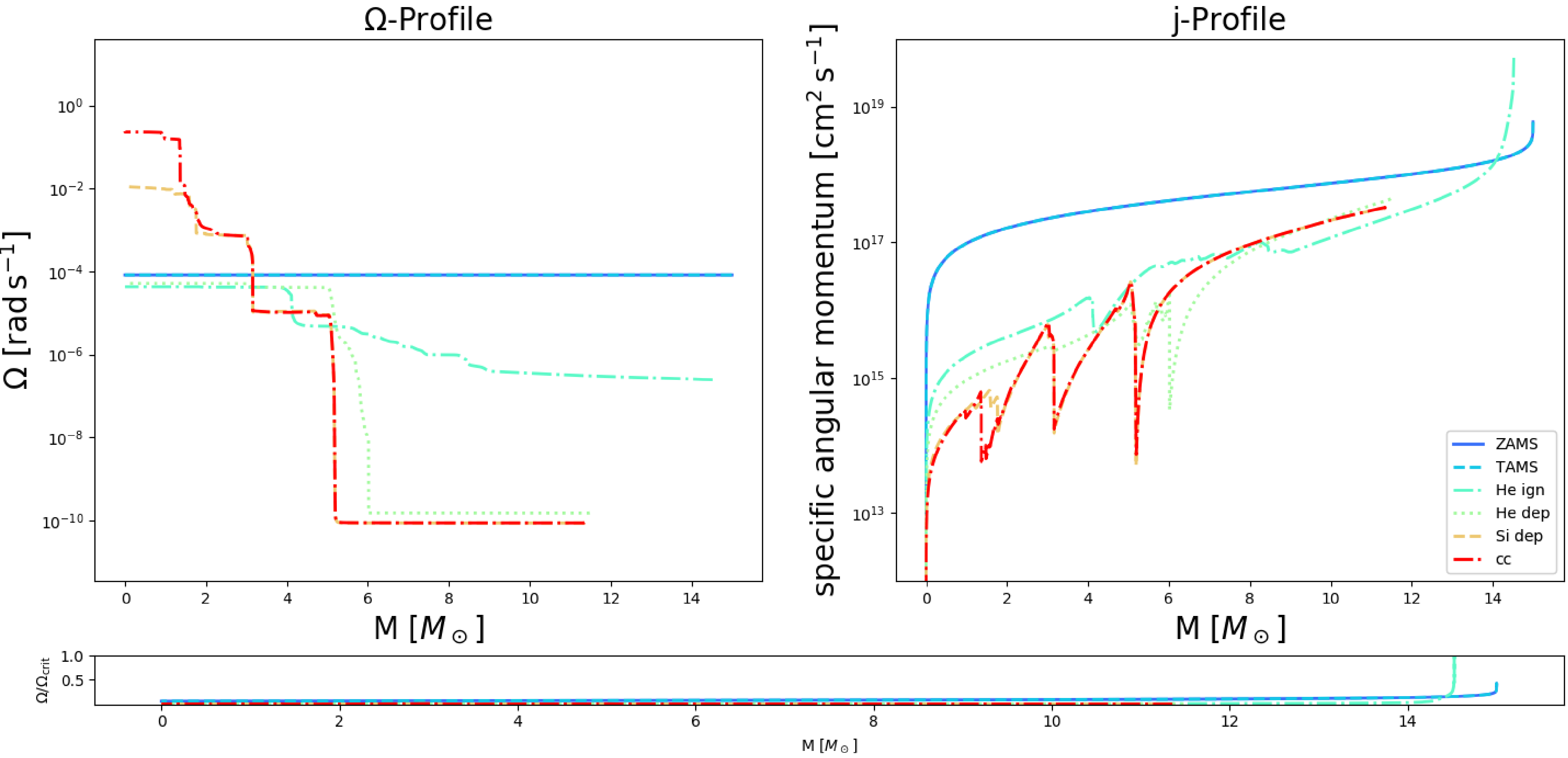
→ Stronger coupling

MESA: $15\,M_\odot$, $Z = 0.014$, $\dfrac{\Omega_{\mathrm{ini}}}{\Omega_{\mathrm{crit}}} = 0.4$

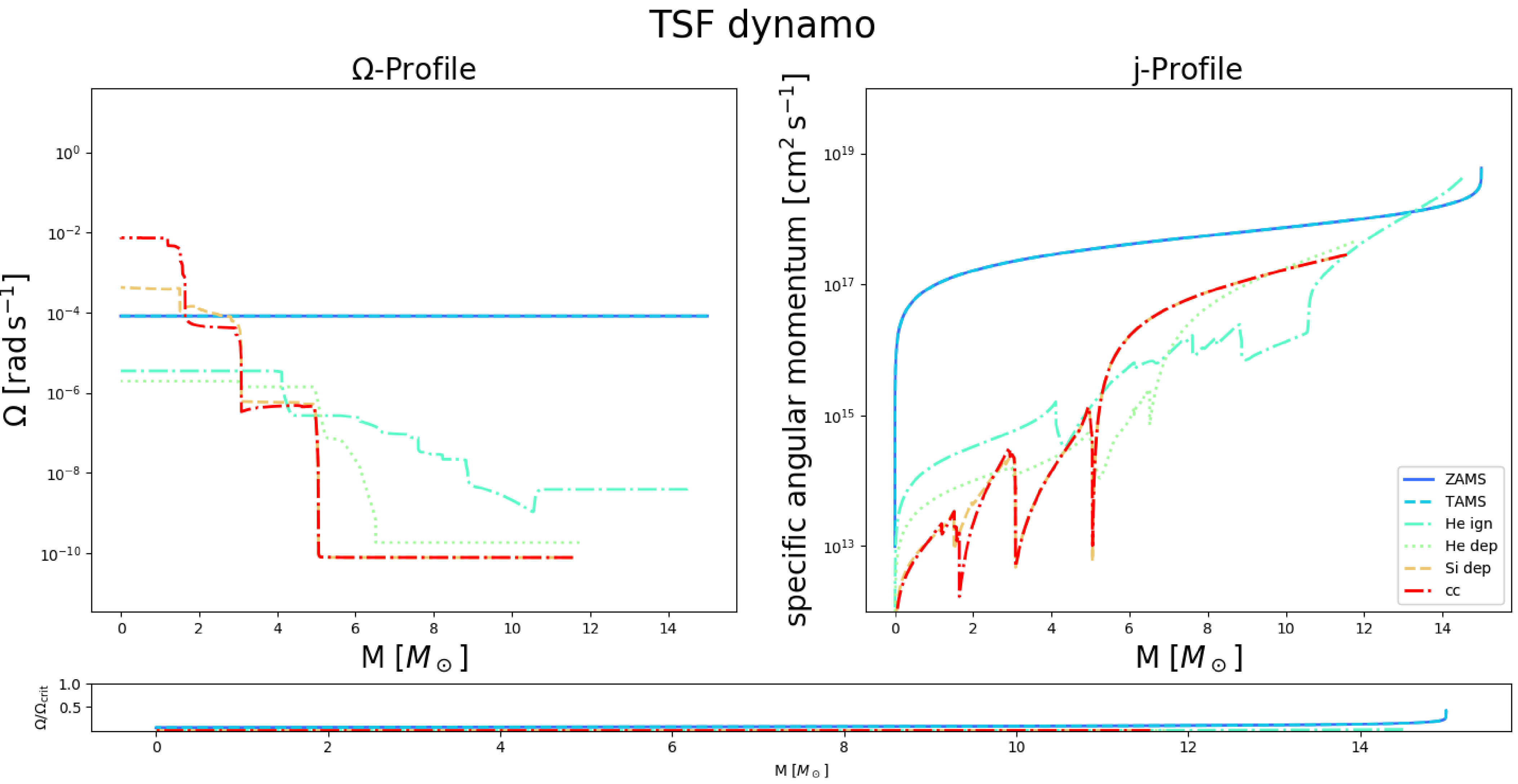


$$\text{MESA: } 15\,M_\odot,\, Z = 0.014,\, \frac{\Omega_{\rm ini}}{\Omega_{\rm crit}} = 0.4$$

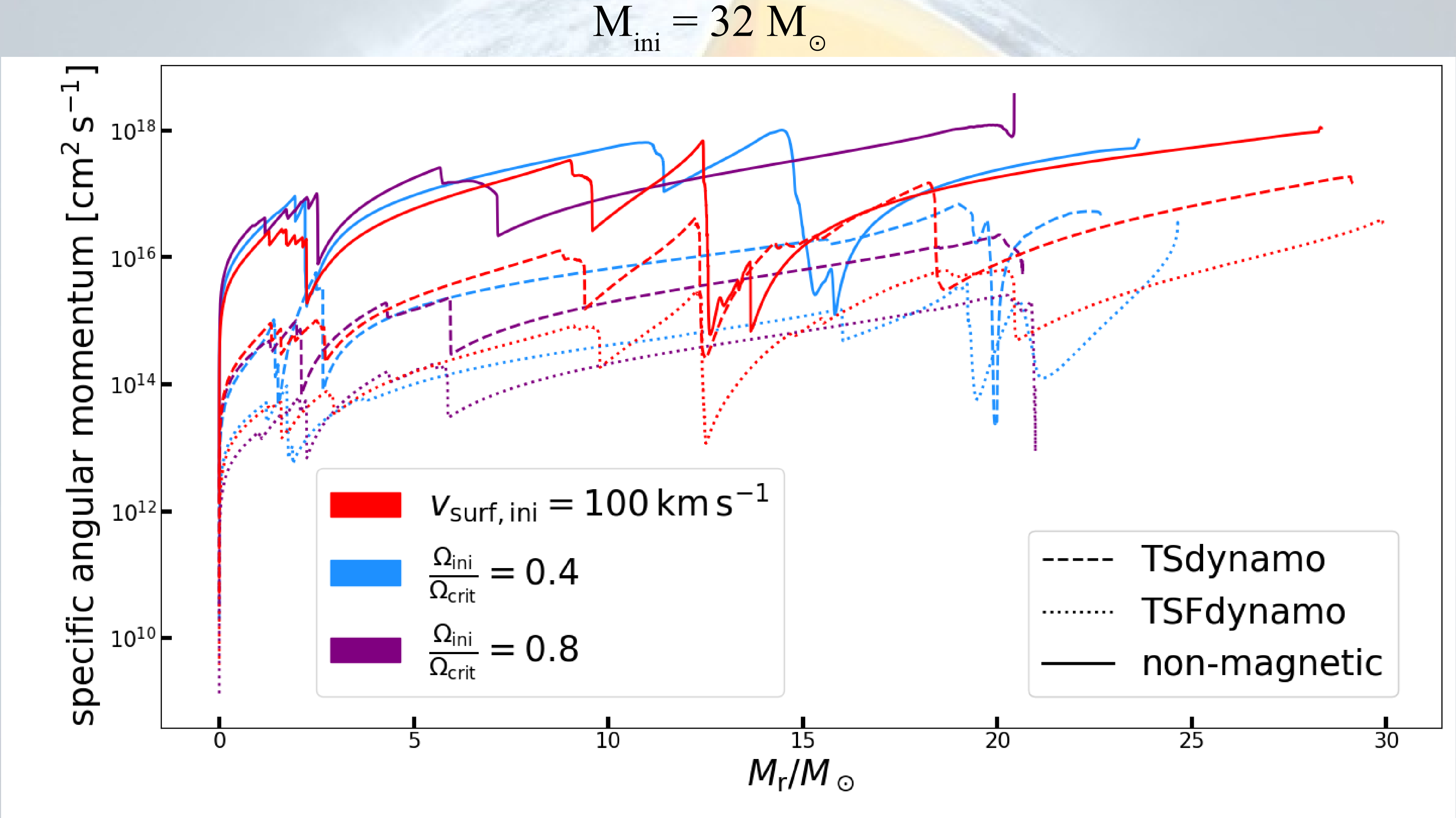
TS dynamo



$\text{MESA: } 15\,M_\odot,\ Z = 0.014,\ \frac{\Omega_{\rm ini}}{\Omega_{\rm crit}} = 0.4$



Pre-SN Angular Momentum (with B)

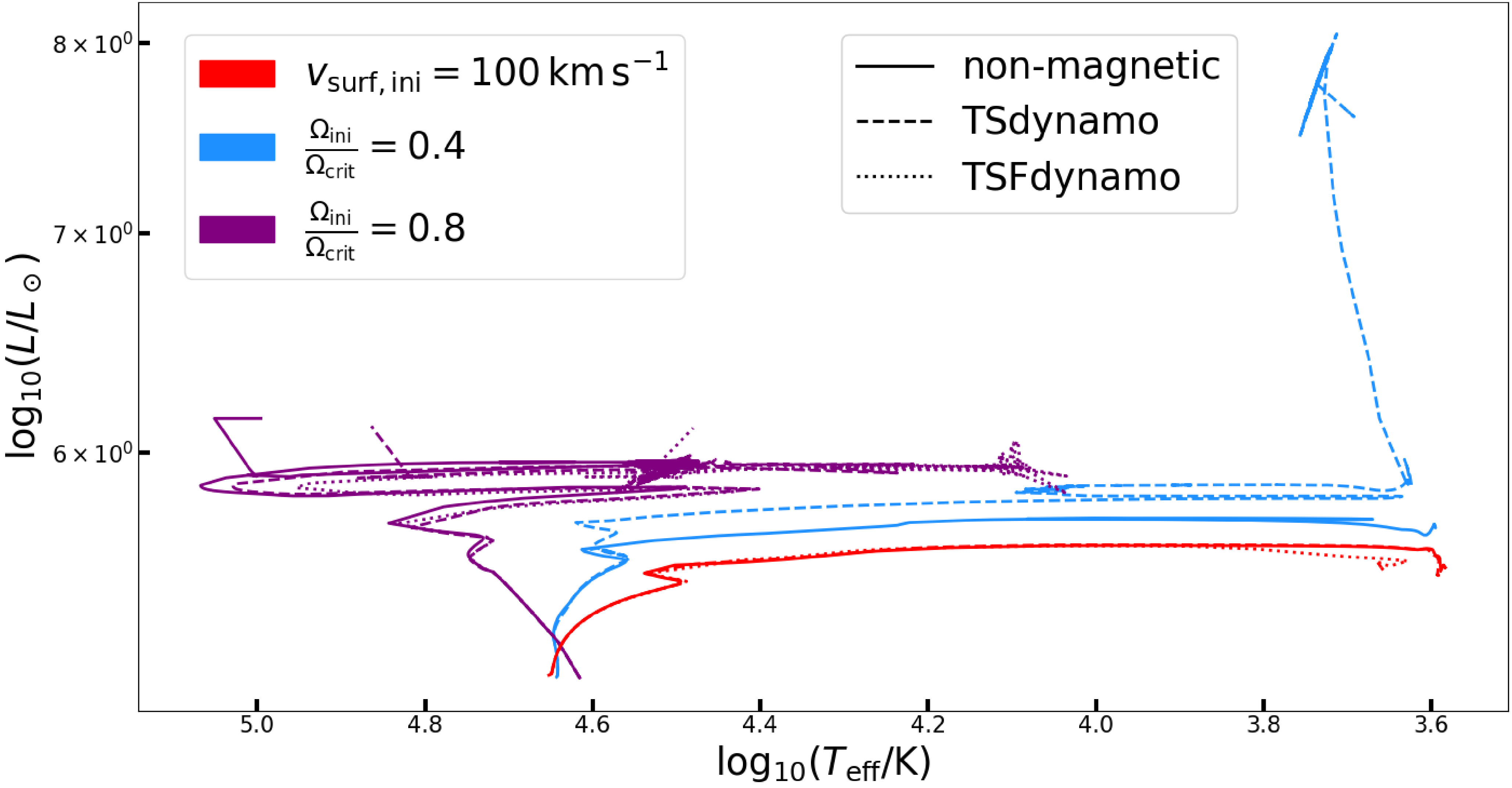


The specific angular momentum in the interior at core-collapse depends on the AM transport mechanism rather than initial rotation rate.

Kaiser+ 2020, in prep

Pre-SN Angular Momentum (with B)

$M_{ini} = 32\ M_\odot$



The specific angular momentum in the interior at core-collapse depends on the AM transport mechanism rather than initial rotation rate.

Kaiser+ 2020, in prep

Comparison to GW BHs

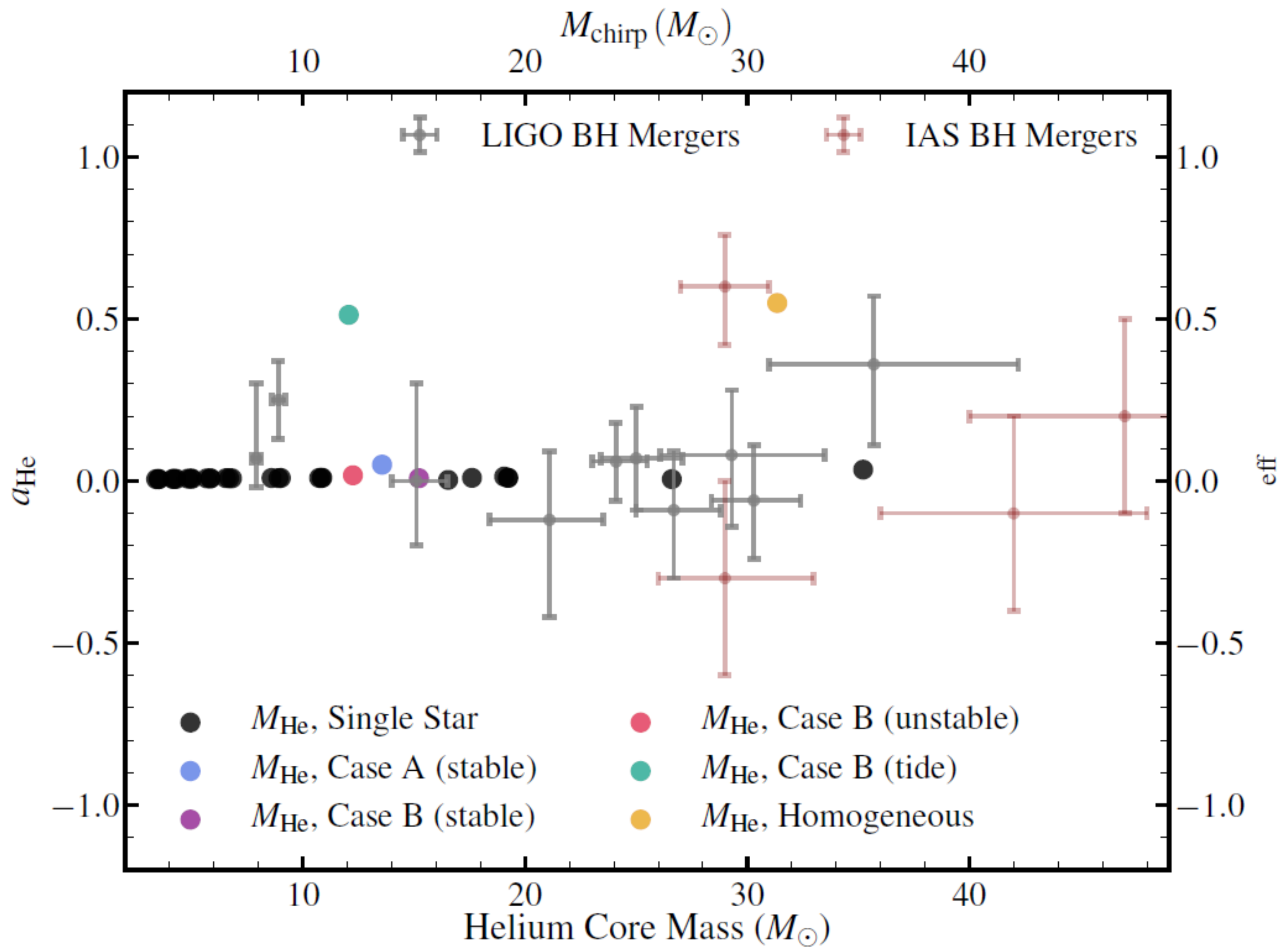
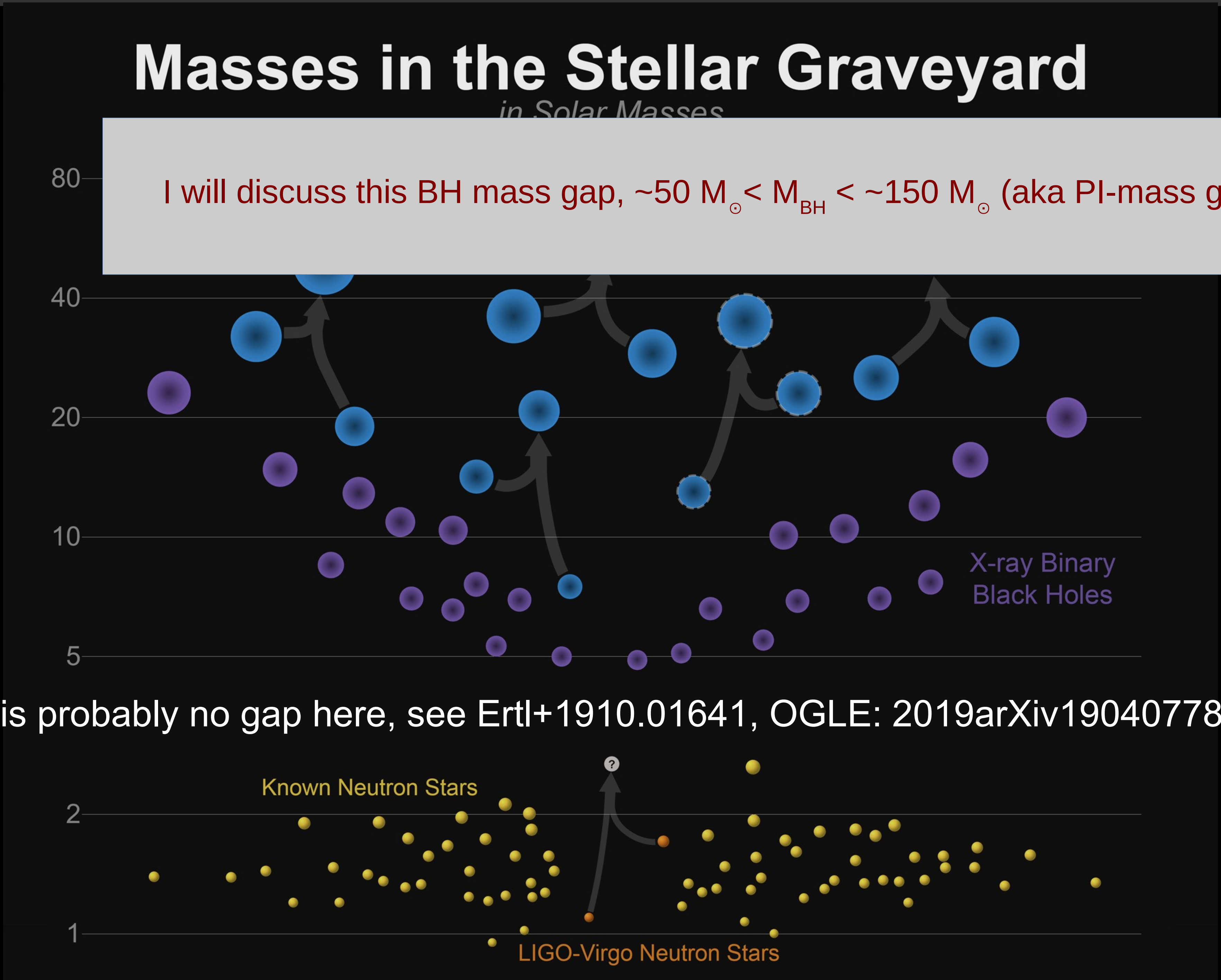


Figure 2. The dimensionless spin, $a_{\rm He}$, of the helium core just before core-collapse as a function final helium core mass, with

Fuller & Ma 2019 ApJ   open questions: - Predicted spin of NS too low?

- Interplay between B-fields & E.-S./M.C. chemical mixing?

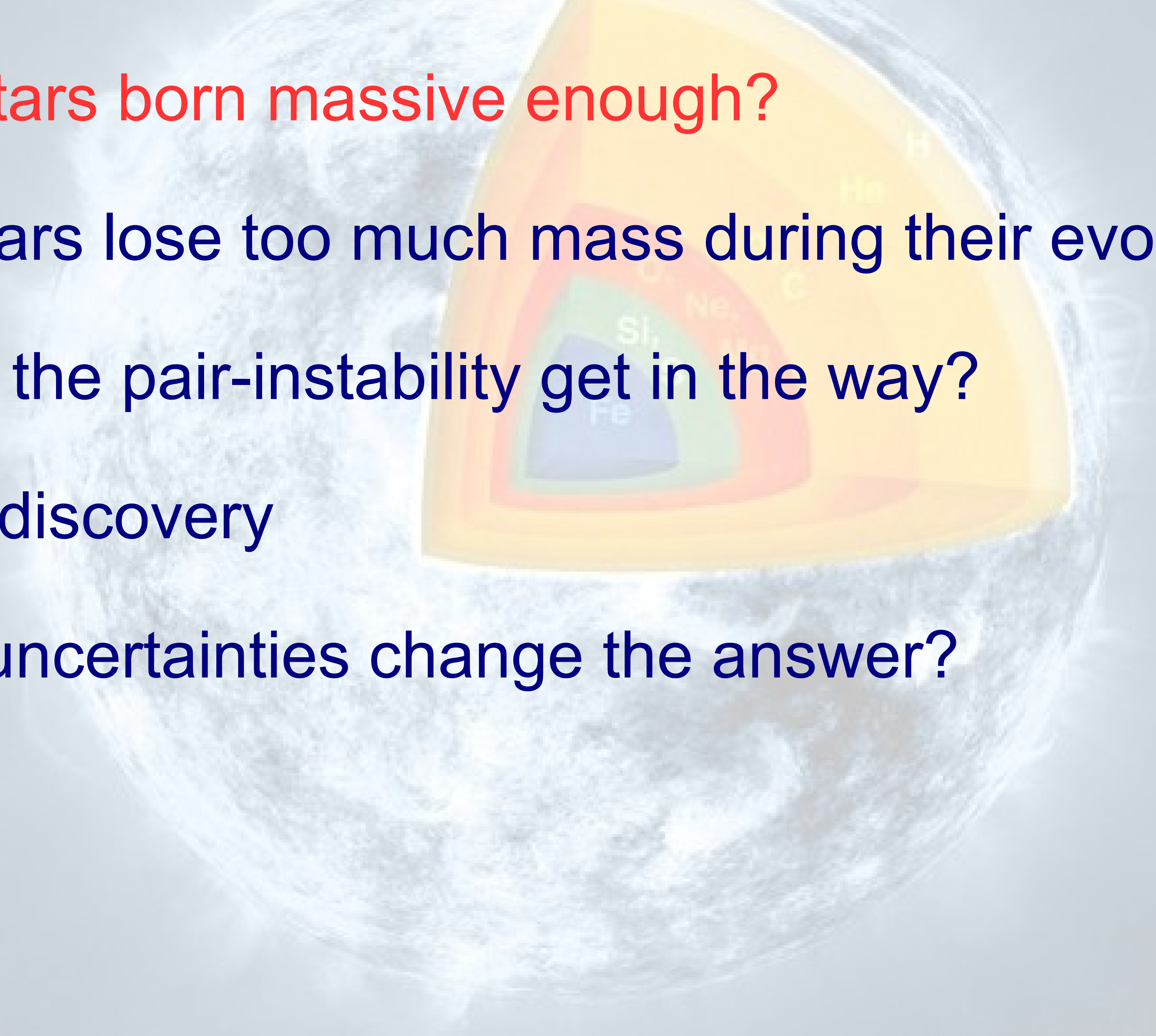
Are there BH Mass Gaps?



I will discuss this BH mass gap, ~50 $M_\odot$ < M_{BH} < ~150 $M_\odot$ (aka PI-mass gap)

There is probably no gap here, see Ertl+1910.01641, OGLE: 2019arXiv190407789W

Can Stars Form 50-100 $M_\odot$ BHs?



- Are stars born massive enough?
- Do stars lose too much mass during their evolution?
- Does the pair-instability get in the way?
- LB-1 discovery
- Can uncertainties change the answer?

Most Massive Stars Observed (so far): R136 (30 Dor)

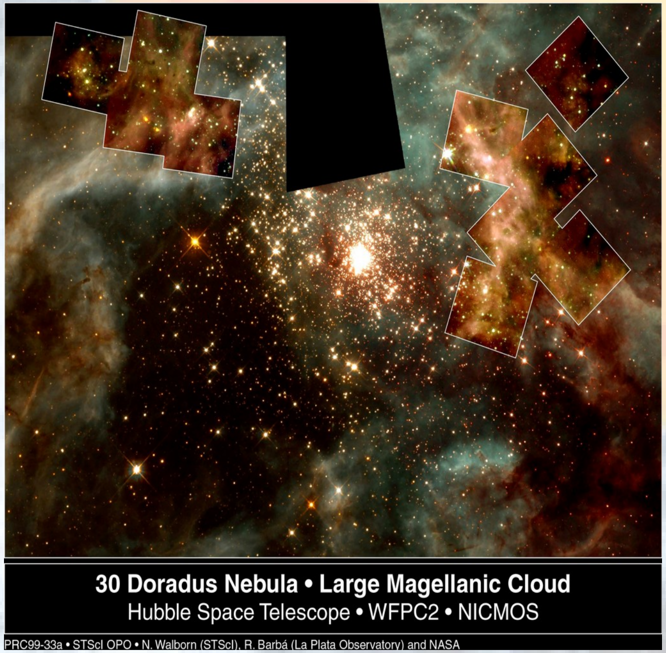
Crowther et al 10, MNRAS

NGC 3603 @ Our Galaxy

$92\ M_\odot$ $113\ M_\odot$

$120\ M_\odot$ $132\ M_\odot$

Tarantula @ LMC



30 Doradus Nebula • Large Magellanic Cloud

Hubble Space Telescope • WFPC2 • NICMOS

PRC99-33a • STScI OPO • N. Walborn (STScI), R. Barbá (La Plata Observatory) and NASA

R136 cluster:

$135\ M_\odot$ $175\ M_\odot$

$195\ M_\odot$ $265\ M_\odot$

Results:

age: 1.7+/-0.2 Myr

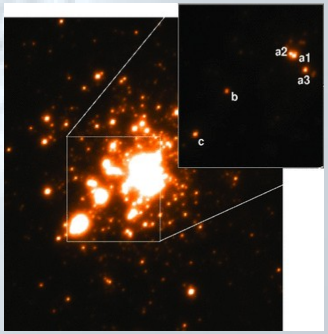
Initial masses:

a1: 320 +100-40 $M_\odot$

a2: 240 +/-45 $M_\odot$

c: 220 +55-45 $M_\odot$

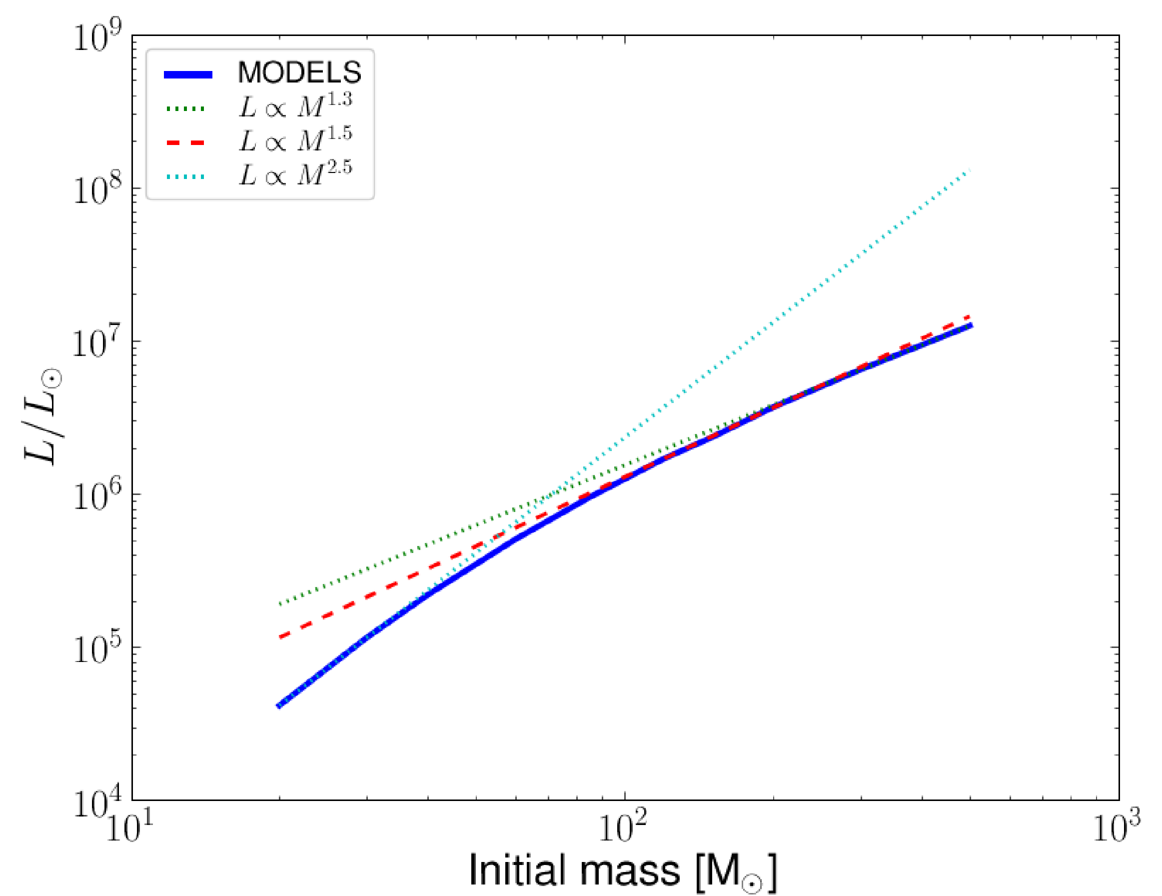
a3: 165 +/-30 $M_\odot$



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?



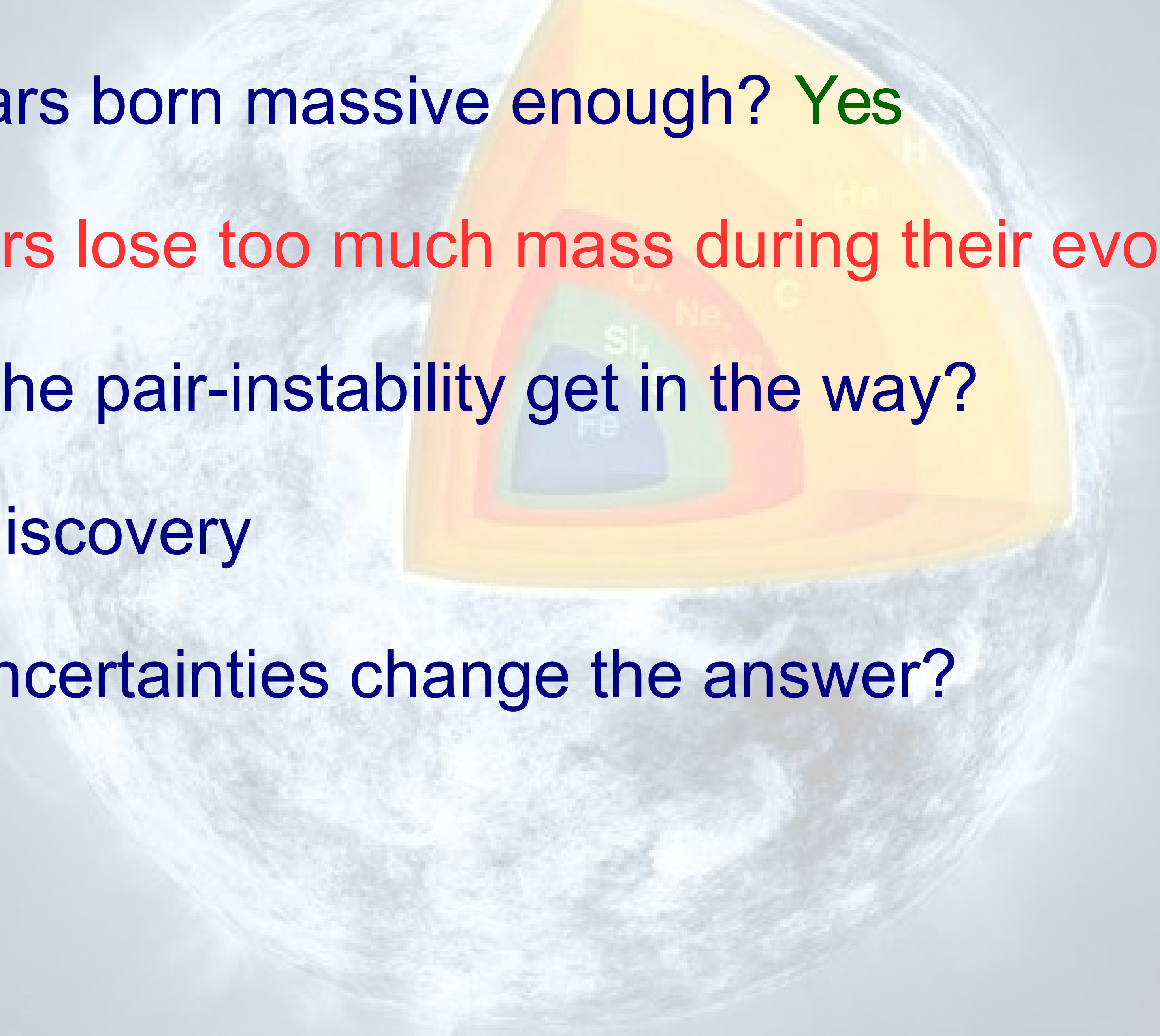
Yusof et al 13 MNRAS, aph1305.2099

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

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

Classical Eddington limit around 150 $M_\odot$ assumes $L \sim M^{2\sim3}$

Can Stars Form 50-100 $M_\odot$ BHs?



- Are stars born massive enough? Yes
- Do stars lose too much mass during their evolution?
- Does the pair-instability get in the way?
- LB-1 discovery
- Can uncertainties change the answer?

Evolution of Surface Properties

Main sequence:

hydrogen burning

After Main Sequence:

Helium burning

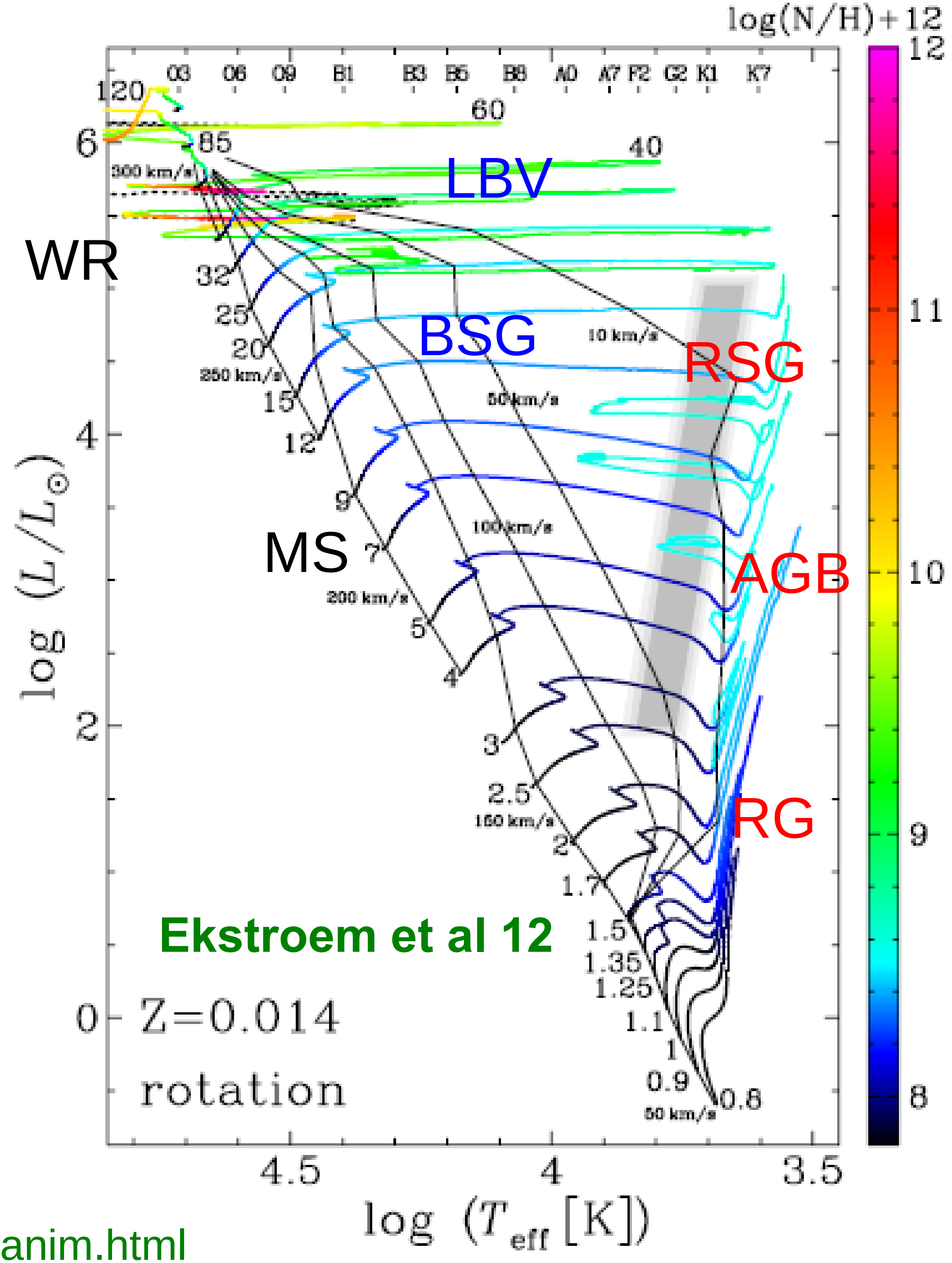
Supergiant stage (red or blue)

Wolf-Rayet (WR): $M > 20\text{-}25\ M_\odot$

WR without RSG: $M > 40\ M_\odot$

Advanced stages: C,Ne,O,Si

→ iron core → SN/NS/BH



Ekstroem et al 12

http://www.astro.keele.ac.uk/~hirschi/animation/anim.html

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
- LBV eruptions: continuous driven winds? Owocki et al
- Binary interactions also lead to mass loss (or gain)

Mass Loss Dependence on Metallicity?

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

- 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)~$Z_\odot$/2.3 => Mdot/1.5 – Mdot/2

Z(SMC)~$Z_\odot$/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)

Rotation Impact on Stellar Winds

Mass loss prescription without rotation:

O-type & LBV stars (bi-stab.): Vink et al 2000, 2001 and de Jager et al 1988

WR stars (clumping effect): Nugis & Lamers 2000

Effect of rotation:

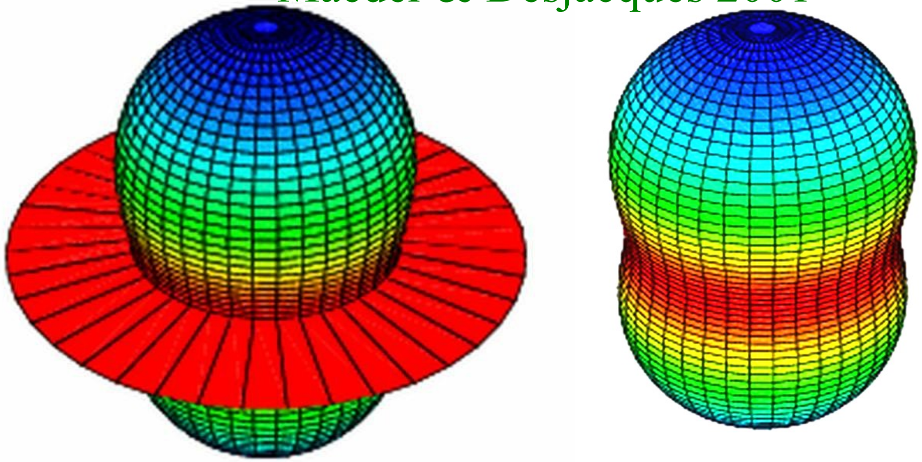
Enhancement: Maeder & Meynet 2000

$$\frac{\dot{M}(\Omega)}{\dot{M}(0)} \approx \frac{(1-\Gamma)^{\frac{1}{\alpha}-1}}{\left[1-\frac{4}{9}\frac{v^2}{v^2_{crit,1}}-\Gamma\right]^{\frac{1}{\alpha}-1}}$$

& anisotropy:

$F_{rad} \sim g_{eff}$: Von Zeipel, 1924

Maeder & Desjacques 2001



T_{eff} =25 000 K

T_{eff} =30 000 K

→ affects angular momentum loss

Going to Low Metallicity Helps

e.g. Groh et al 19, A&A (see also Yusof et al 2013, ...)

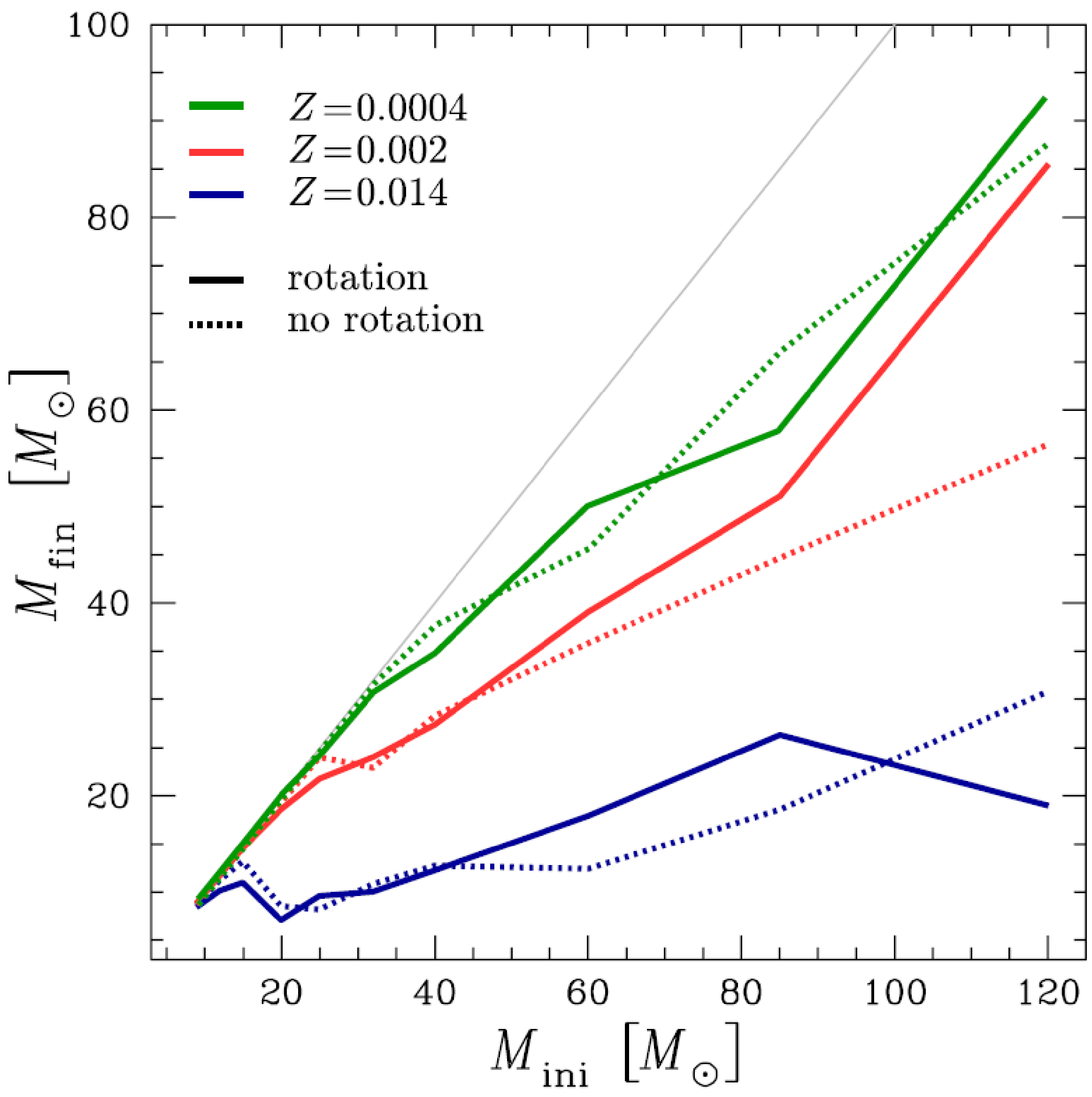
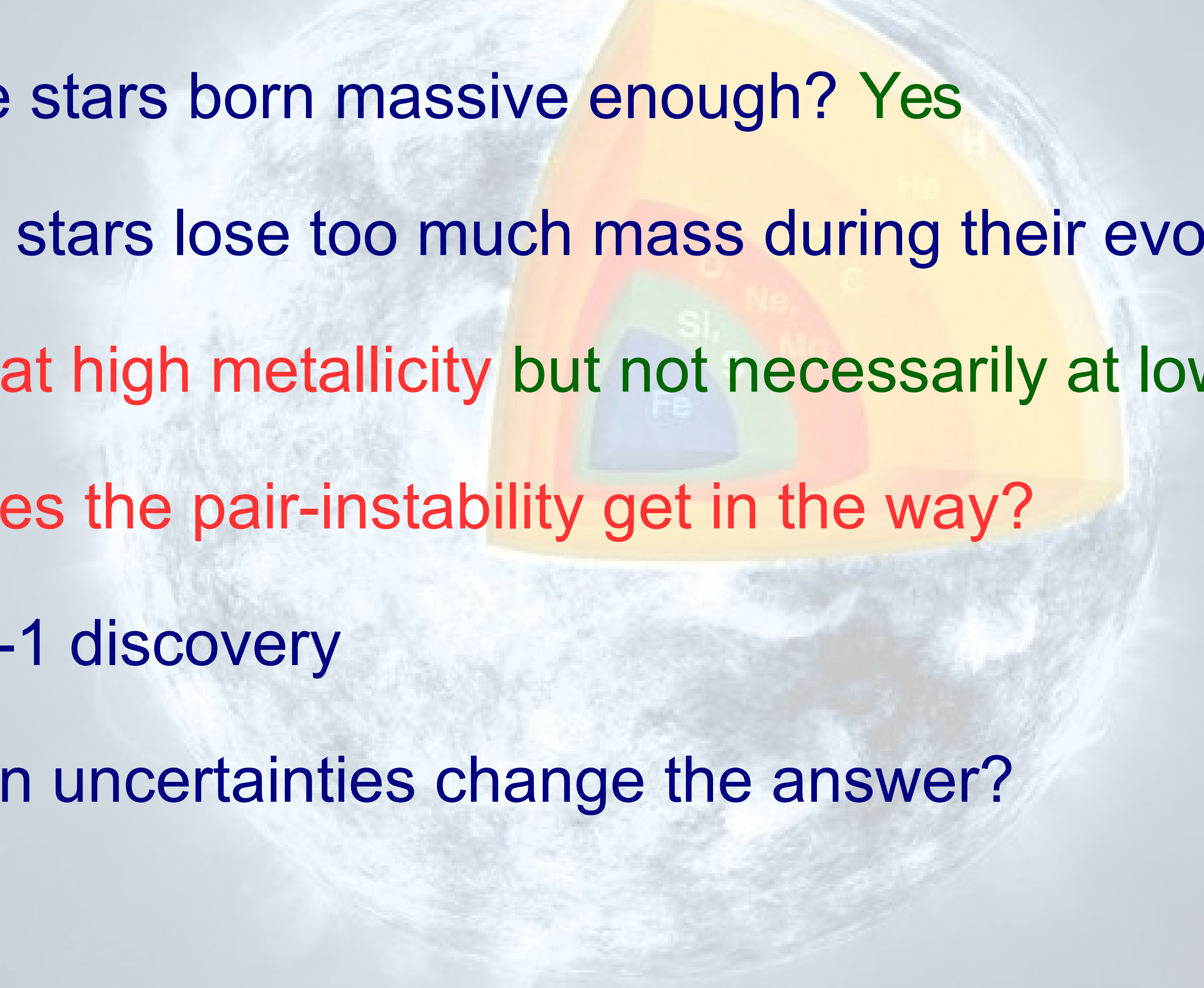


Fig. 6. Final mass ($M_{\rm fin}$) of the models as a function of the initial mass

Can Stars Form 50-100 $M_\odot$ BHs?



- Are stars born massive enough? Yes

- Do stars lose too much mass during their evolution?

Yes at high metallicity but not necessarily at low Z

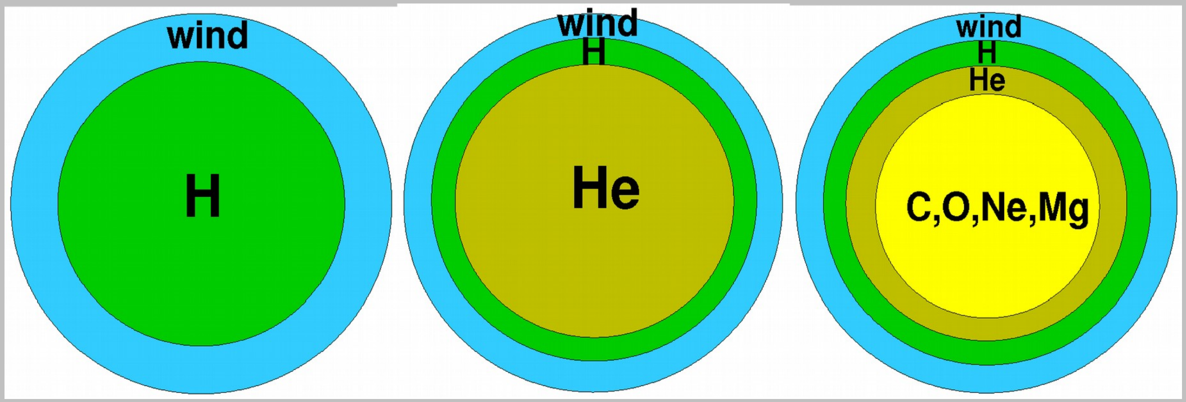
- Does the pair-instability get in the way?

- LB-1 discovery

- Can uncertainties change the answer?

Pair-Instability Supernovae (PISN)

[slide from Sasha Kozyreva]



Electron-positron pair creation

Instability ($\Gamma_1 < 4/3$):

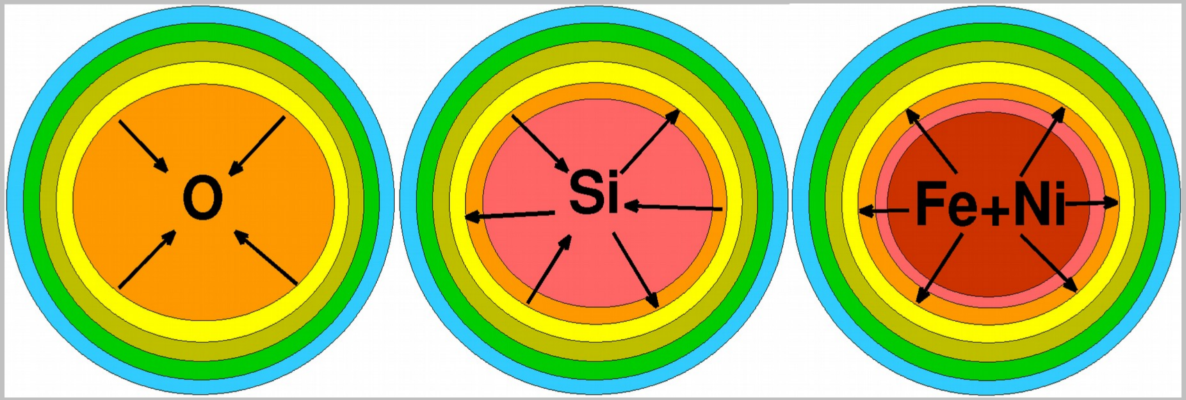
→ $2\gamma \rightarrow e^- + e^+$ pair creation

→ dynamical collapse

(e.g. Pinaeva 1964, Zel'dovich & Novikov 1971, Blinnikov, Dunina-Barkovskaya, Nadezhin 1996)

Explosive O-Si-burning exceeds binding energy

→ Complete disruption!



Occurs before iron core-collapse as long as CO core is massive enough!

$\sim 60\ M_\odot < M_{CO} < \sim 140\ M_\odot$

(in both single and binary stars)

See e.g. El Eid et al 1983; Ober et al 1983; Bond et al 1984; Klapp 1984; Arnett 1996; Heger & Woosley 2002

Pulsation Pair-Instability (P-PISN)

See Woosley 2017, Farmer et al 2019, Leung et al 2019

from Farmer et al 2019

Max BH mass predicted

$\sim 50\ M_\odot$!!

Note: $M_{BH} > \sim$**150 $M_\odot$**, i.e. above the PI mass gap also possible

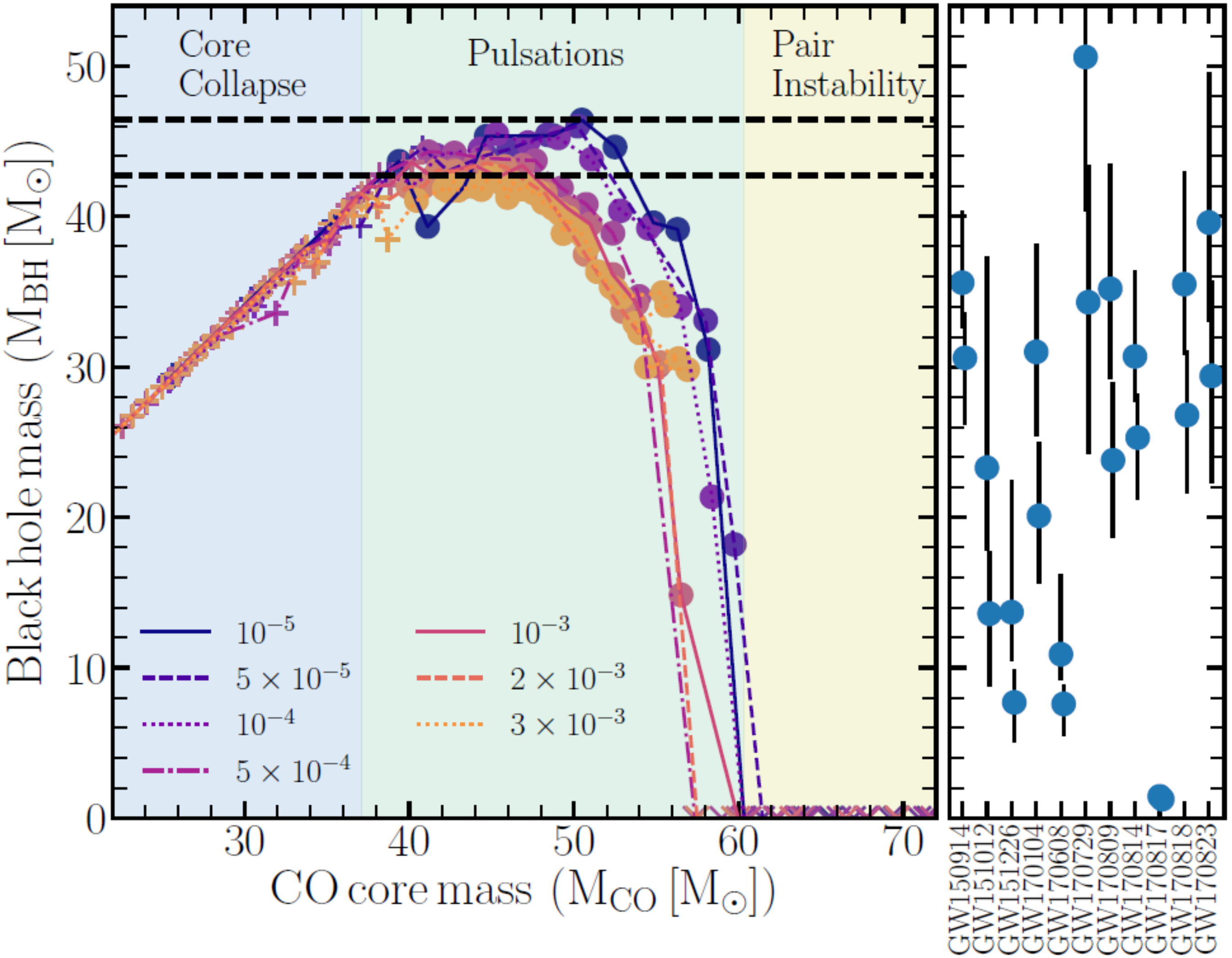
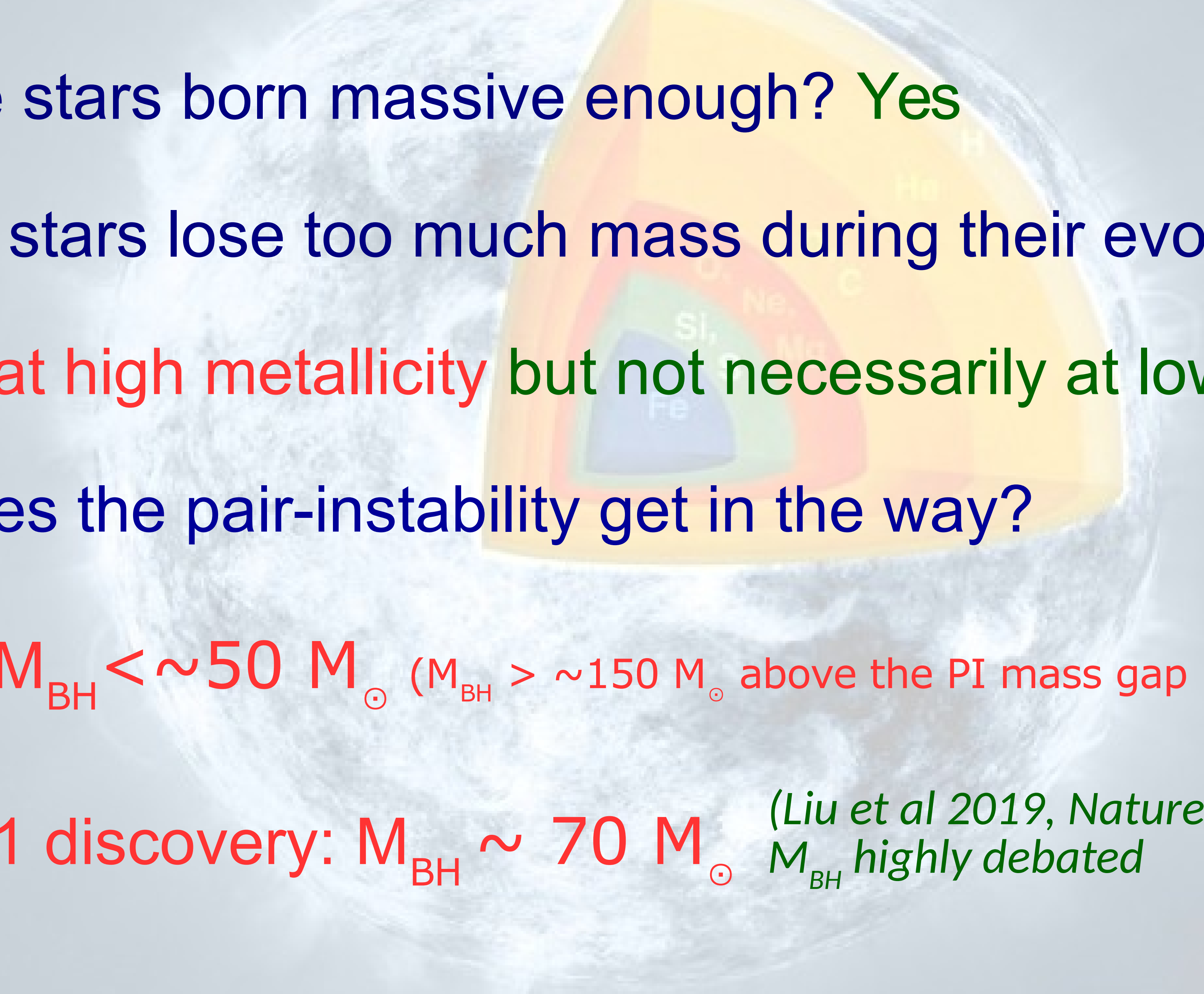


Figure 2. Mass of final BH as a function of the CO core mass, for different metallicities. Circles denote models that underwent

Caveat: these models use helium stars (hydrogen assumed to be lost by stellar winds or binary interaction)

Can Stars Form 50-100 $M_\odot$ BHs?



- Are stars born massive enough? Yes

- Do stars lose too much mass during their evolution?

Yes at high metallicity but not necessarily at low Z

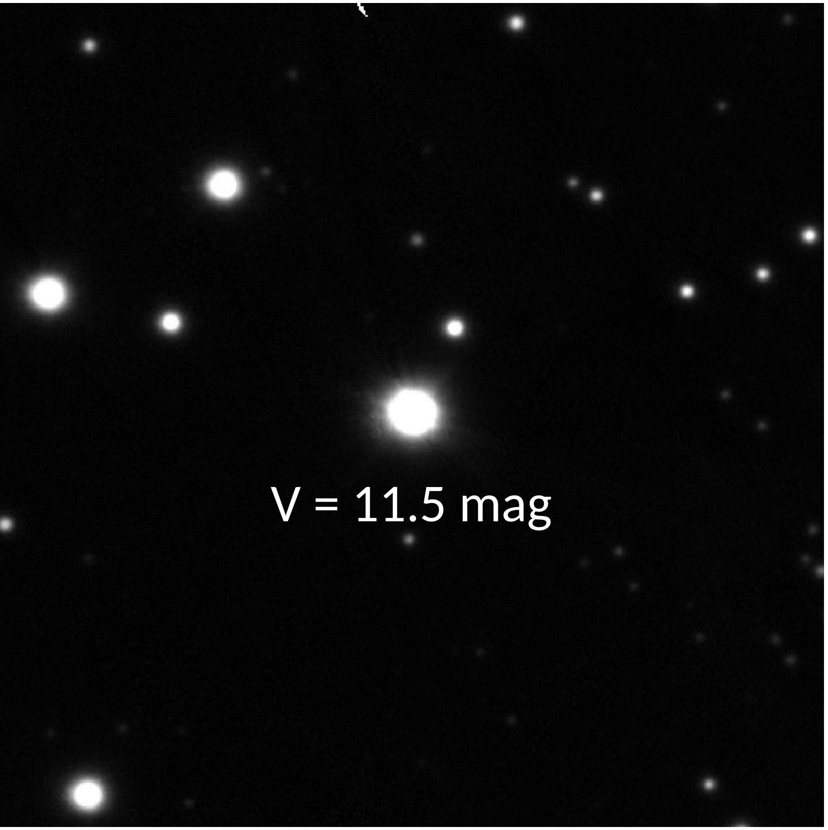
- Does the pair-instability get in the way?

Yes: $M_{BH} < \sim 50\ M_\odot$ ($M_{BH} > \sim 150\ M_\odot$ above the PI mass gap possible)

- LB-1 discovery: $M_{BH} \sim 70\ M_\odot$ *(Liu et al 2019, Nature, 575, 618)* *M_{BH} highly debated*

Optical Search for massive stellar BHs with LAMOST

Project led by Jifeng Liu at NAOC



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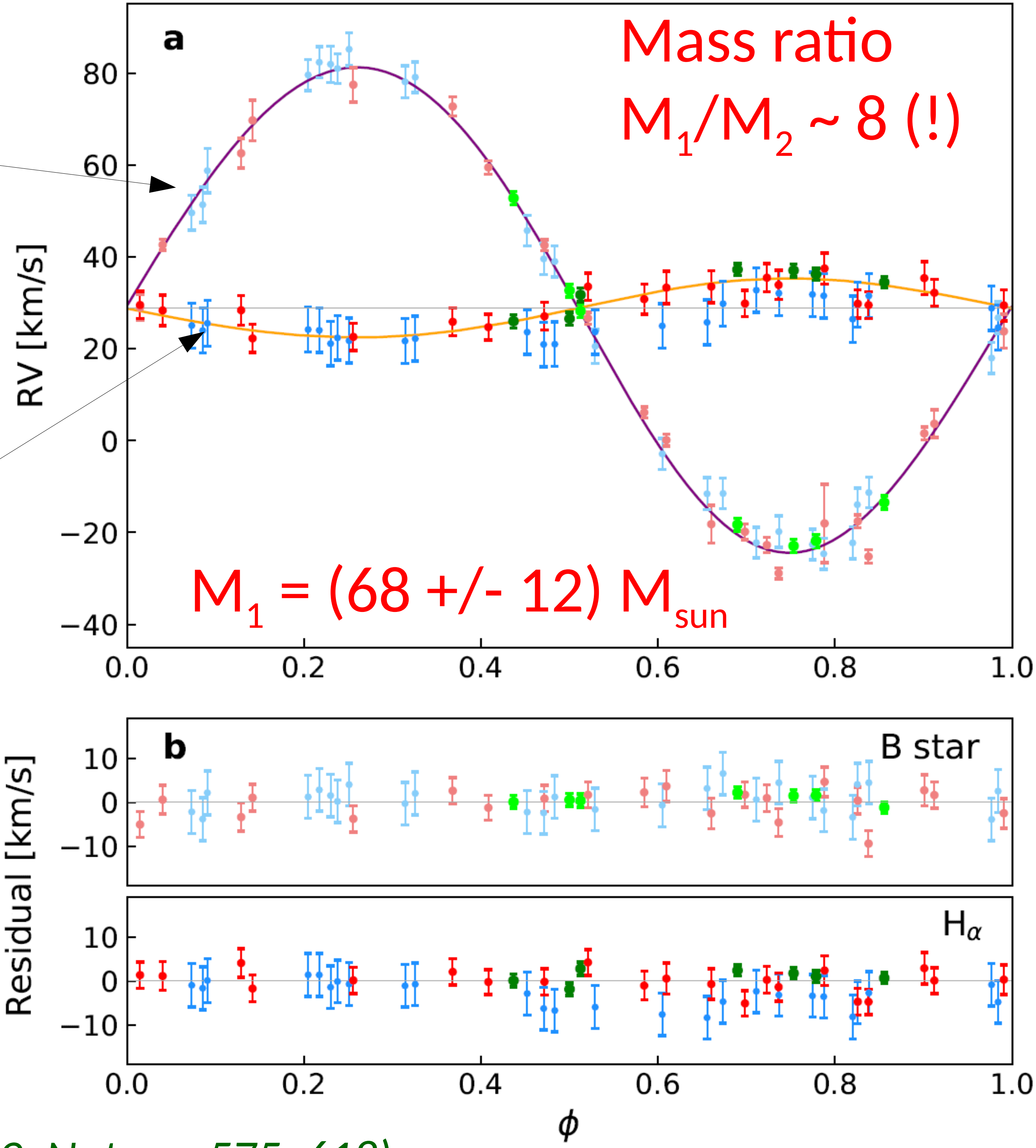
4-m Guo Shoujing Telescope at Xinglong

Companion
B-star
RV curve

BH Disk
Hα
RV curve



Mass ratio
$M_1/M_2 \sim 8$ (!)

$M_1 = (68 +/- 12)\ M_{sun}$

(Liu et al 2019, Nature, 575, 618)

Uncertainties in LB-1 Mass Determination

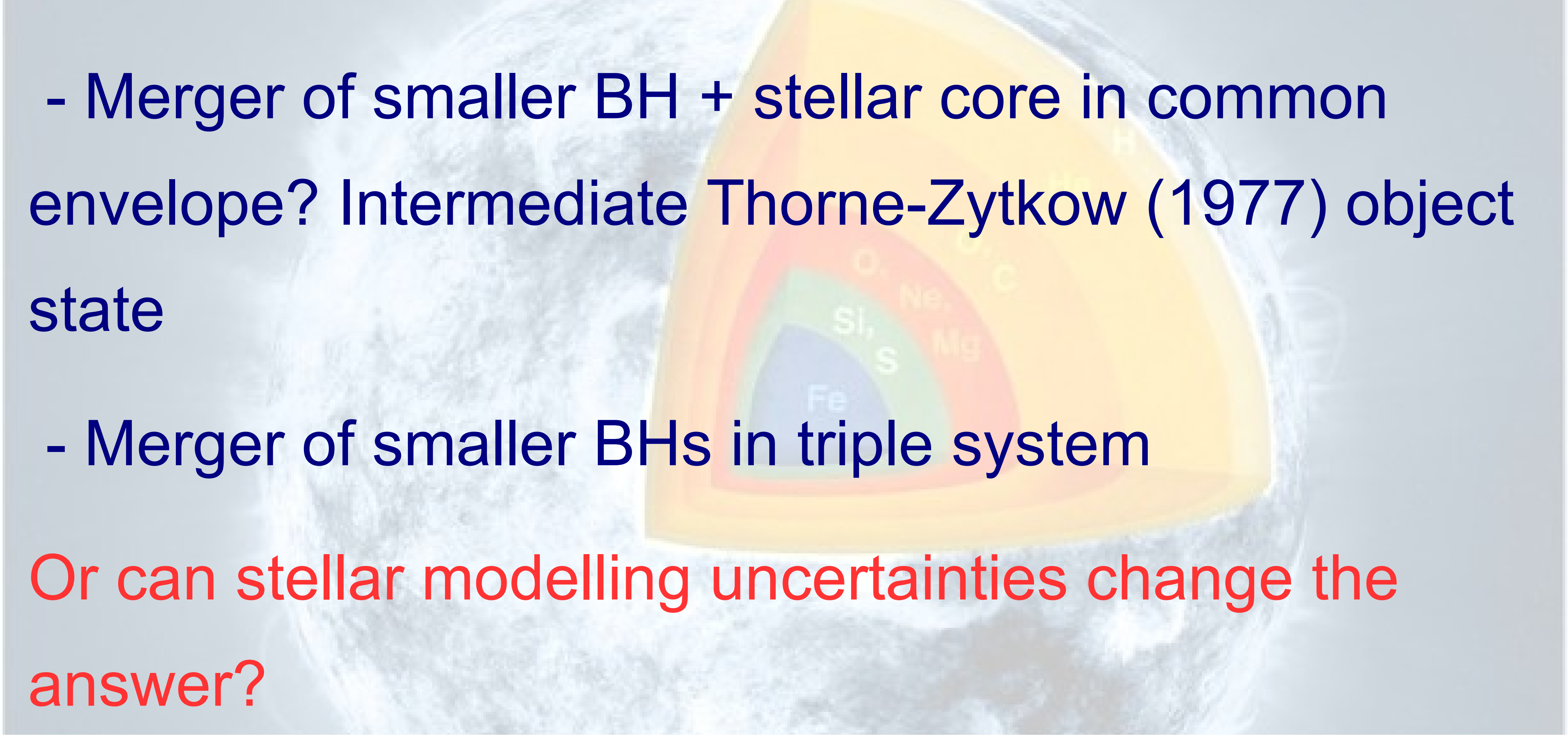
- Distance to LB-1: 4kpc or 2kpc? See Eldridge+2019

- Stellar temperature and mass of companion overestimated? See Simon-Diaz+2019; Eldridge+2019

- Emission lines not from BH disk? Paschen β lines will help settle this point

Further work needed to confirm discovery and LB-1 BH mass

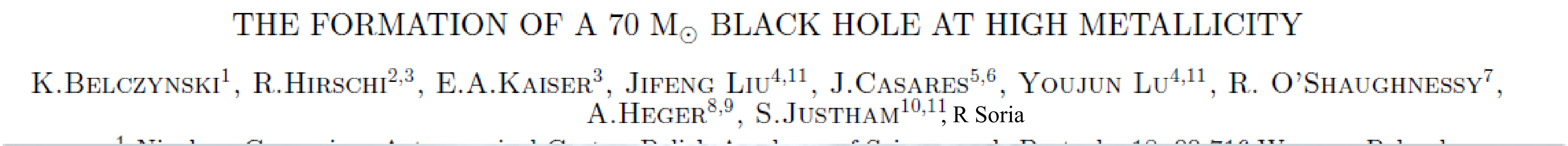
Origin of LB-1 and 50-100 $M_\odot$ BHs?



- Merger of smaller BH + stellar core in common envelope? Intermediate Thorne-Zytkow (1977) object state

- Merger of smaller BHs in triple system

Or can stellar modelling uncertainties change the answer?

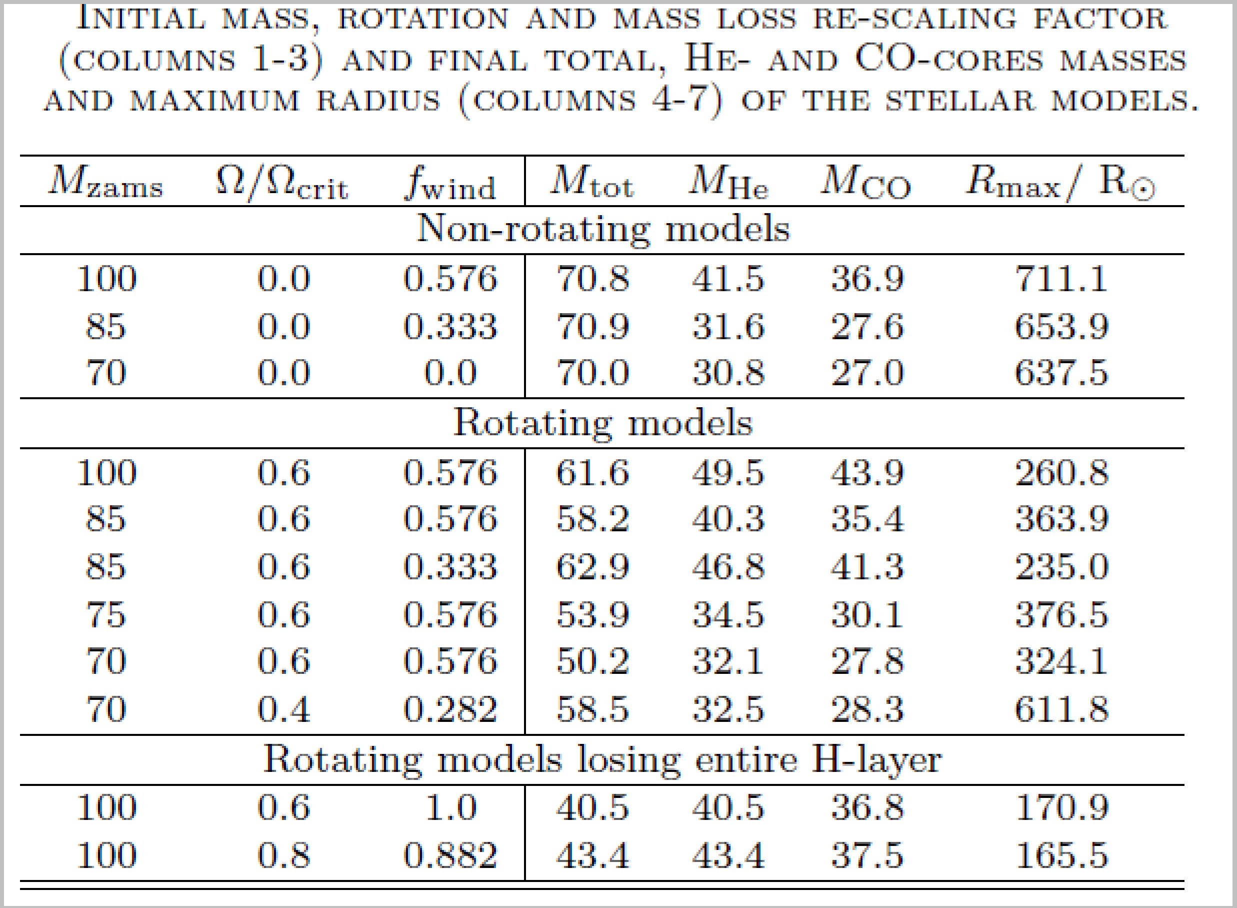


THE FORMATION OF A 70 $M_\odot$ BLACK HOLE AT HIGH METALLICITY

K.Belczynski[1], R.Hirschi[2,3], E.A.Kaiser[3], Jifeng Liu[4,11], J.Casares[5,6], Youjun Lu[4,11], R. O'Shaughnessy[7], A.Heger[8,9], S.Justham[10,11], R Soria

ApJ subm.; https://arxiv.org/abs/1911.12357

Lower Mass Loss Enables to Keep Enough Mass

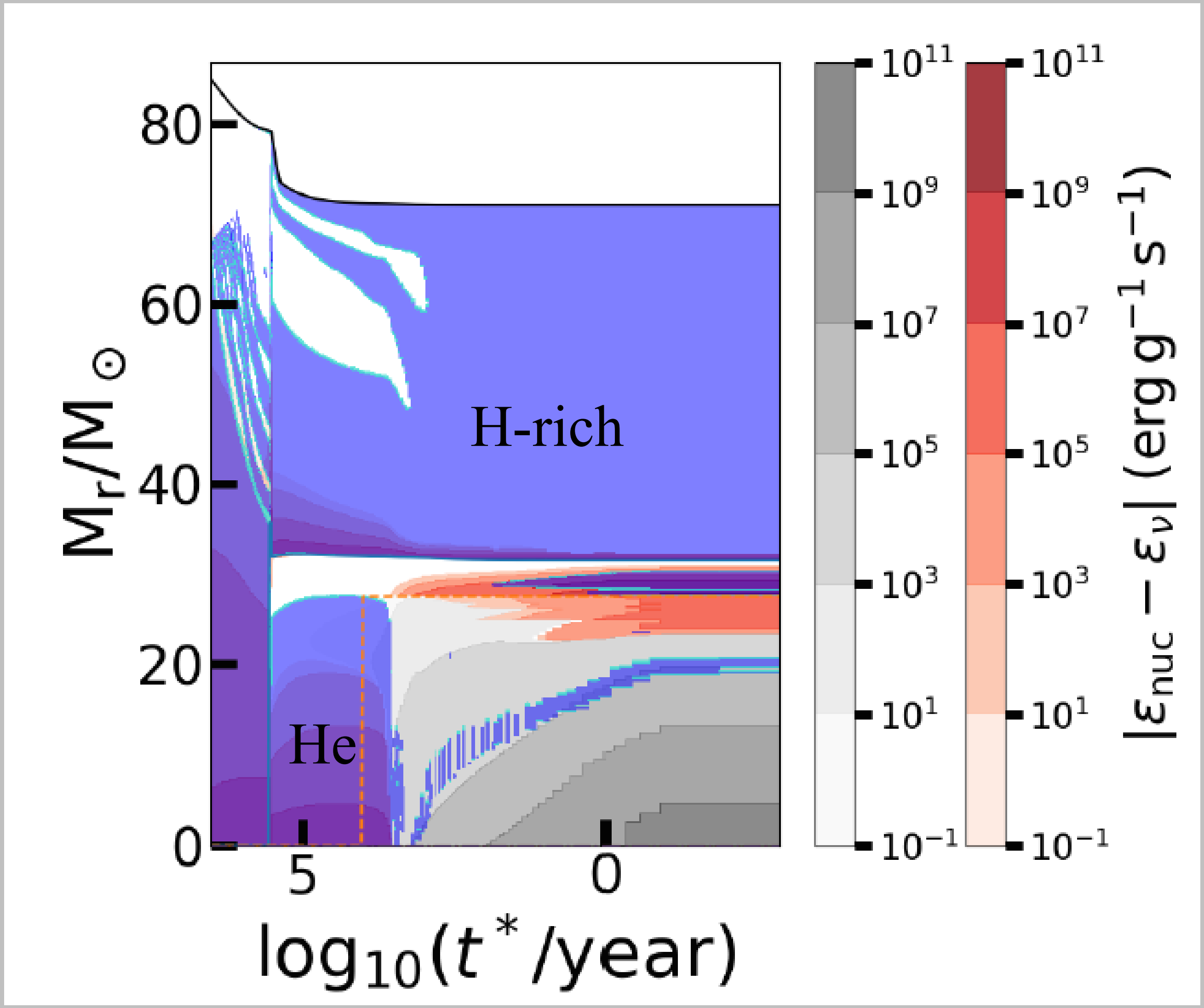


Initial mass, rotation and mass loss re-scaling factor (columns 1-3) and final total, He- and CO-cores masses and maximum radius (columns 4-7) of the stellar models.

$M_{\rm zams}$	$\Omega/\Omega_{\rm crit}$	$f_{\rm wind}$	$M_{\rm tot}$	$M_{\rm He}$	$M_{\rm CO}$	$R_{\rm max}/ R_\odot$
Non-rotating models						
100	0.0	0.576	70.8	41.5	36.9	711.1
85	0.0	0.333	70.9	31.6	27.6	653.9
70	0.0	0.0	70.0	30.8	27.0	637.5
Rotating models						
100	0.6	0.576	61.6	49.5	43.9	260.8
85	0.6	0.576	58.2	40.3	35.4	363.9
85	0.6	0.333	62.9	46.8	41.3	235.0
75	0.6	0.576	53.9	34.5	30.1	376.5
70	0.6	0.576	50.2	32.1	27.8	324.1
70	0.4	0.282	58.5	32.5	28.3	611.8
Rotating models losing entire H-layer						
100	0.6	1.0	40.5	40.5	36.8	170.9
100	0.8	0.882	43.4	43.4	37.5	165.5

- Mass loss reduction might be explained by magnetic fields
  See e.g. Georgy et al 2017A&A...599L...5G, Petit et al MNRAS, 2017
- Can we avoid (P-)PISN? Woosley 2017: no PPISN below $M_{CO}=28\ M_\odot$

Hydrogen-Rich Models May Avoid P/PISN



- Large hydrogen-rich layer means lower core mass so no PPISN predicted (Most previous studies considered only He-cores/stars)

Hydrogen-Rich Models May Avoid P/PISN

- Radius of model too large to fit in LB-1 orbit: $R_{max} \sim 300\ R_\odot$ (note that fast rotating models do remain very compact, see table above)

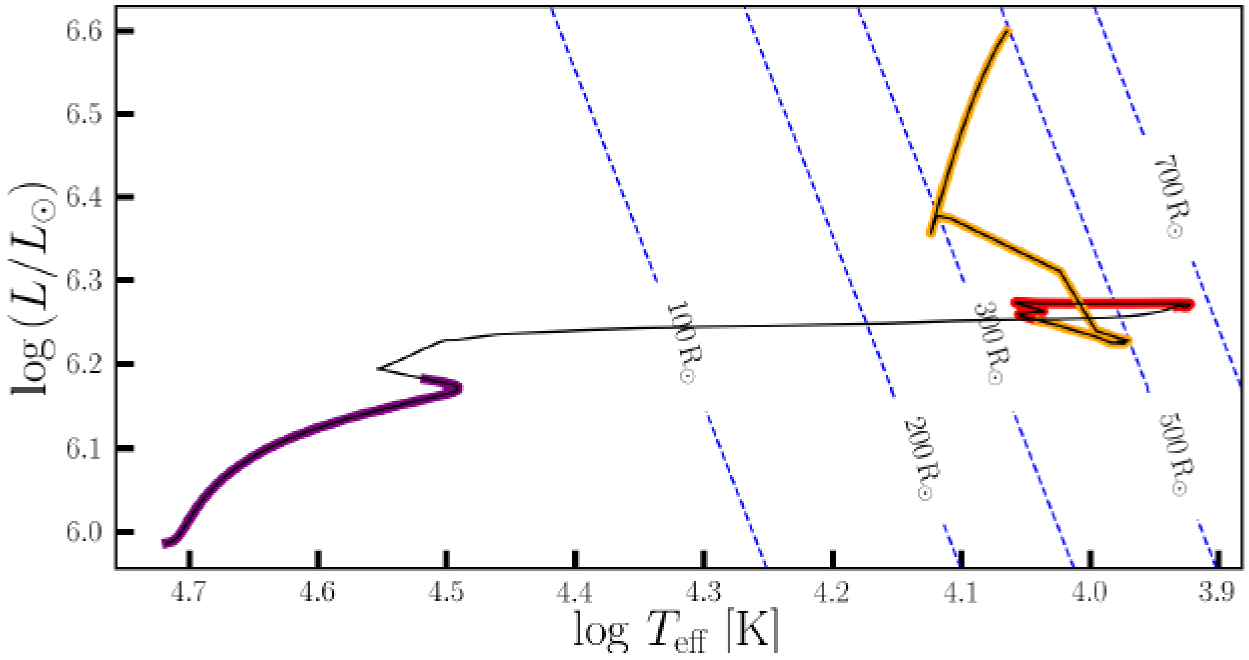
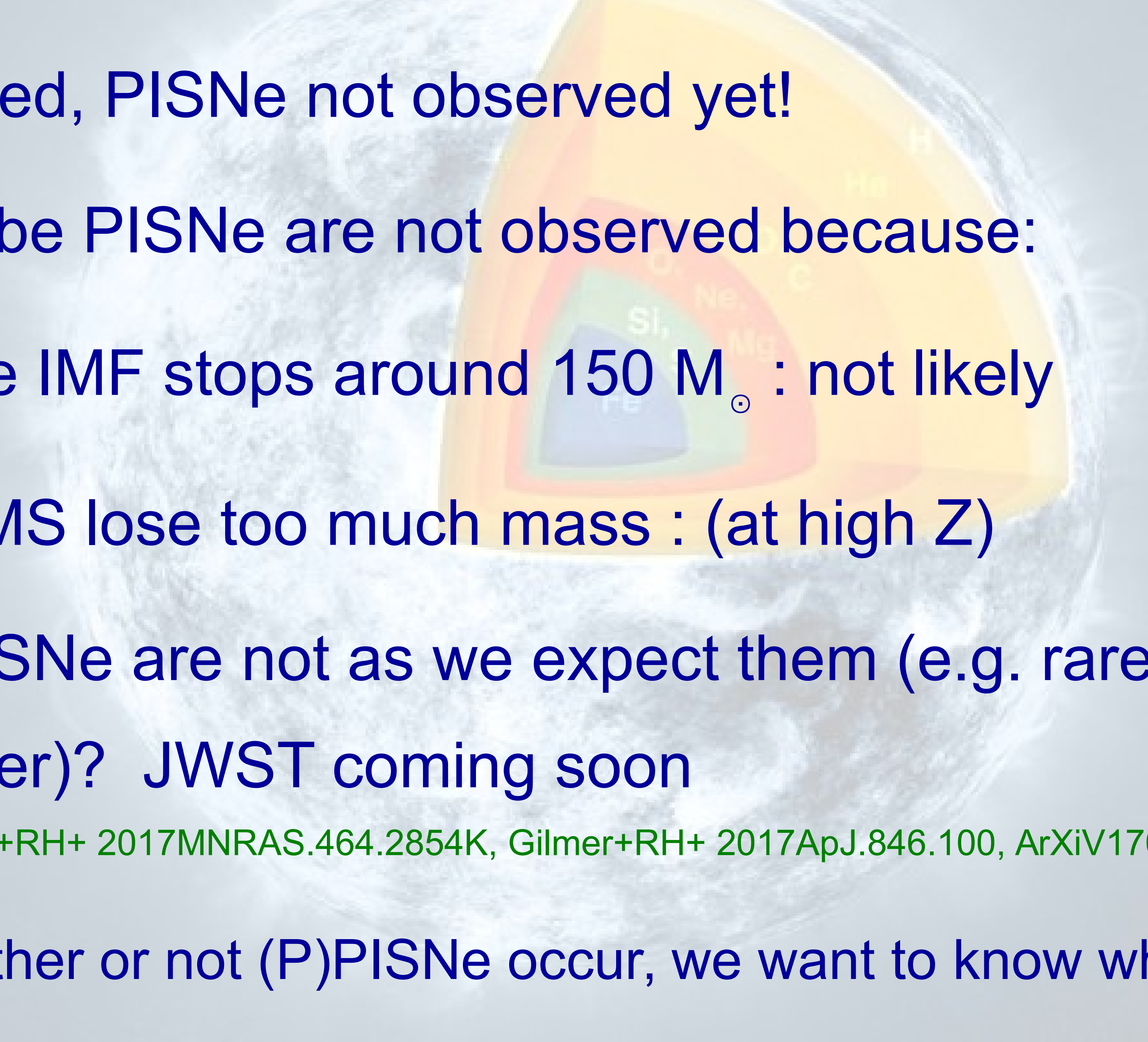


FIG. 3.— Hertzsprung-Russell diagram of the $M_{zams} = 85\ M_\odot$

- Mass loss rates remains key uncertainty: LBV mass loss & Humphreys & Davidson (1979) limit; see also Groh et al 2019arXiv191200994G

Maybe Pair-Instability does not Exist?



Indeed, PISNe not observed yet!

Maybe PISNe are not observed because:

- the IMF stops around 150 $M_\odot$: not likely

- VMS lose too much mass : (at high Z)

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

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

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

Can Stars Form 50-100 $M_\odot$ BHs?

Conclusions:

- Are stars born massive enough? Yes, definitely

- Do stars lose too much mass during their evolution?

Yes at high Z but not necessarily at low Z

- Does the pair-instability get in the way? Probably (M_{BH}<~50 $M_\odot$)

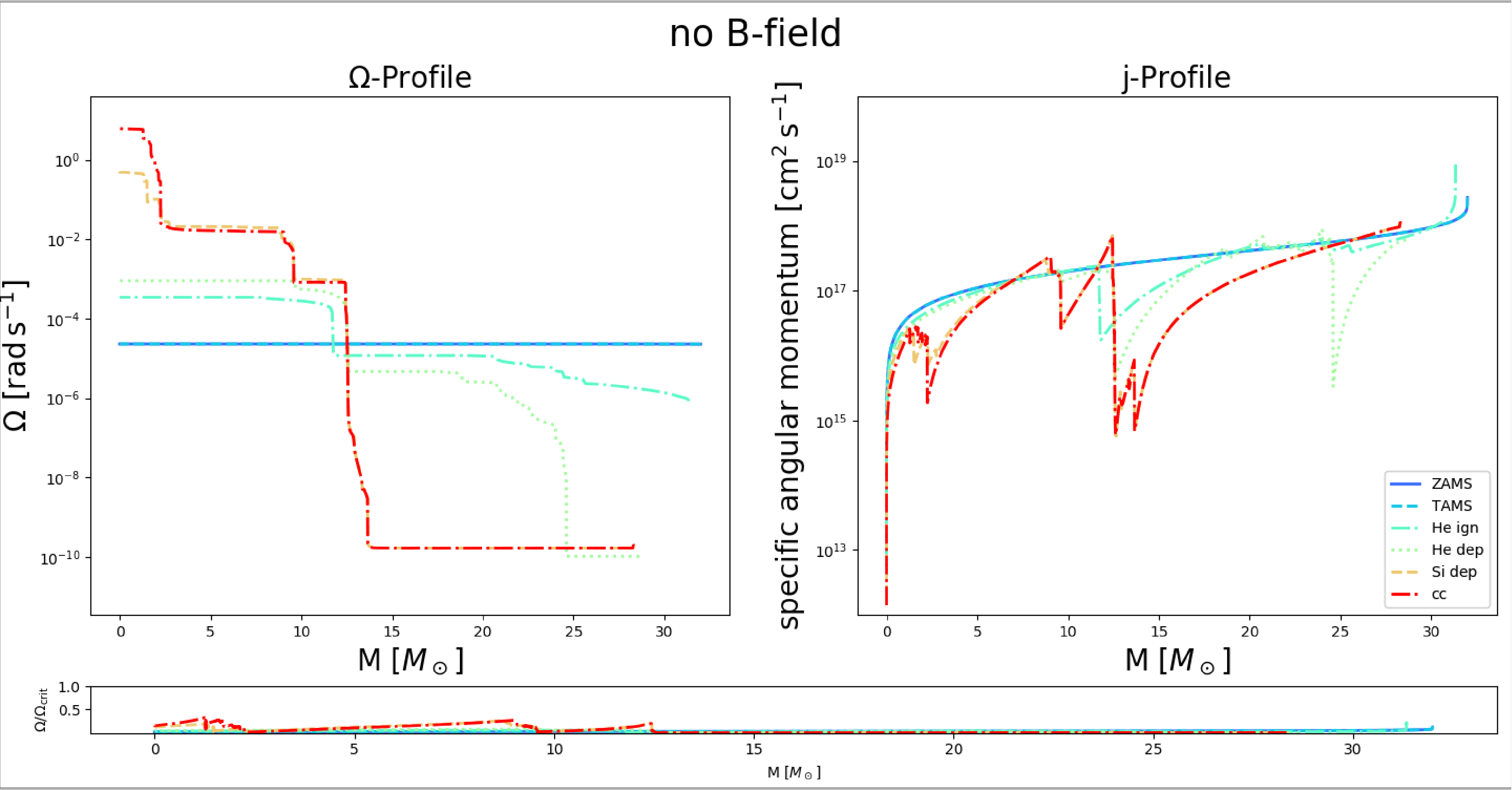
(M_{BH} > ~**150 $M_\odot$** above the PI mass gap possible)

Hydrogen-rich models may work (https://arxiv.org/abs/1911.12357)

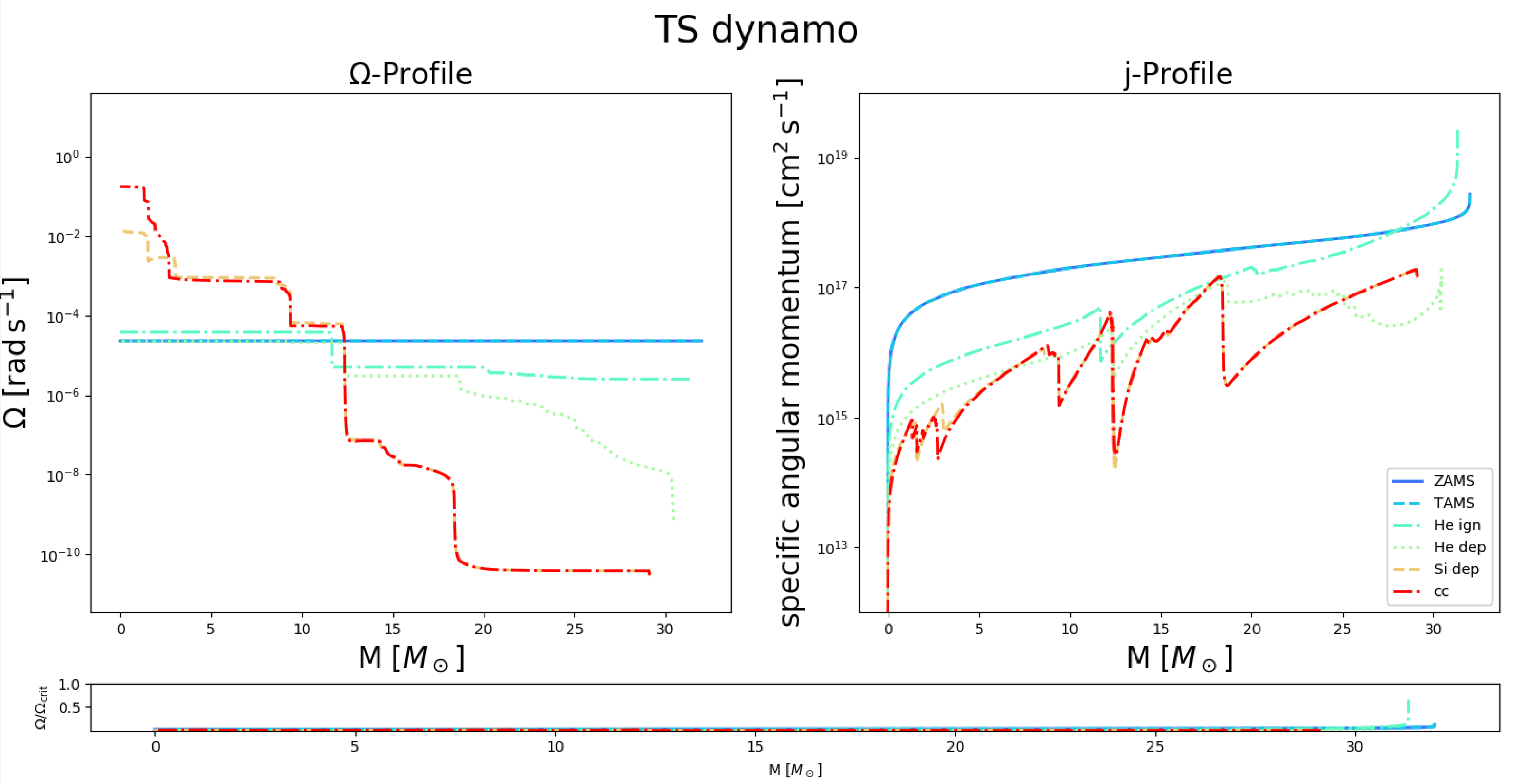
- LB-1 discovery: mass determination still needs confirmation

- Can uncertainties change the answer? Mass loss uncertain, other physics to explore: convection, ...?

MESA: $32\,M_\odot, Z = 0.002, v_{\rm surf,ini} = 100\,{\rm km\,s^{-1}}$

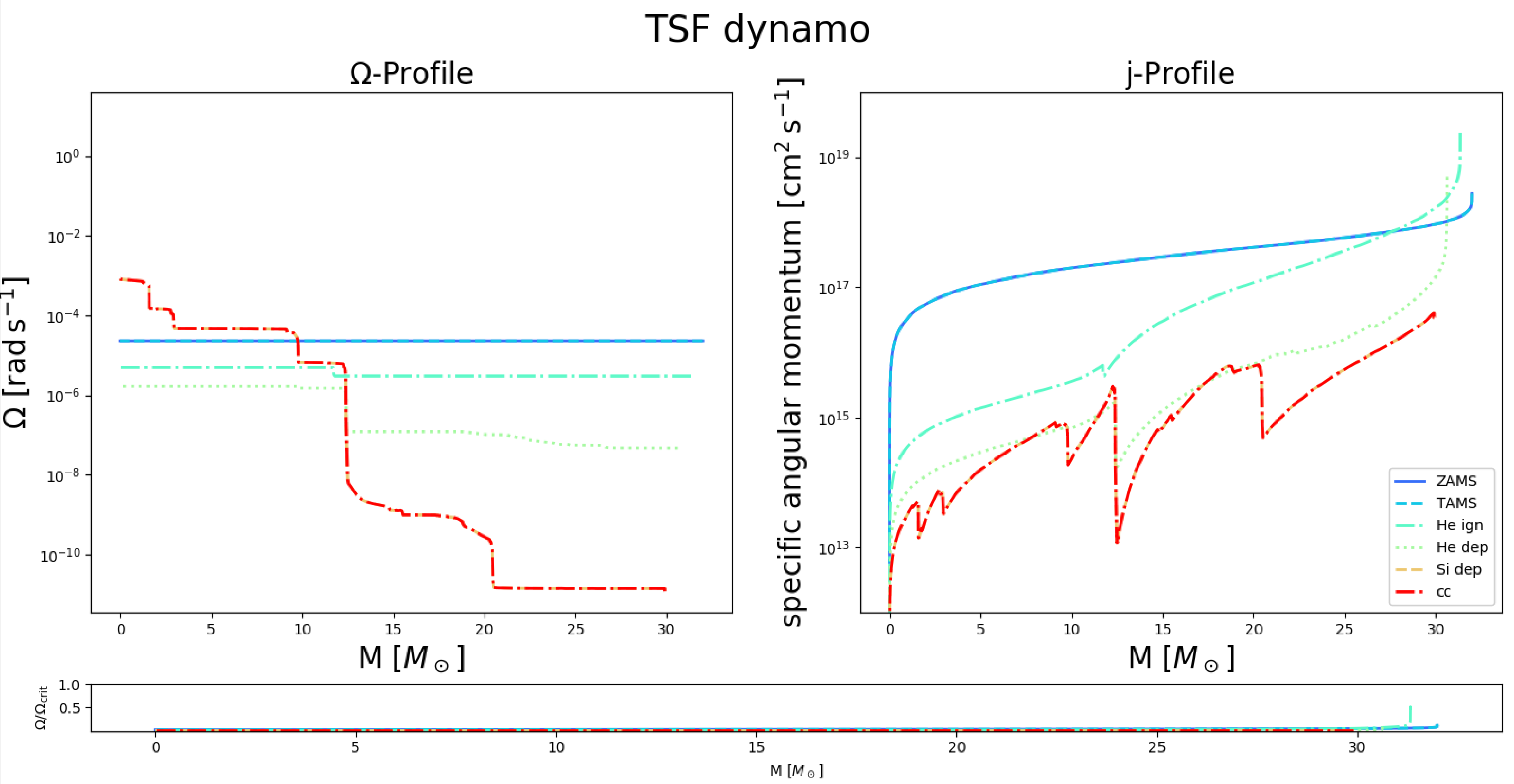


MESA: $32\,M_\odot, Z = 0.002, v_{\mathrm{surf,ini}} = 100\,\mathrm{km\,s^{-1}}$

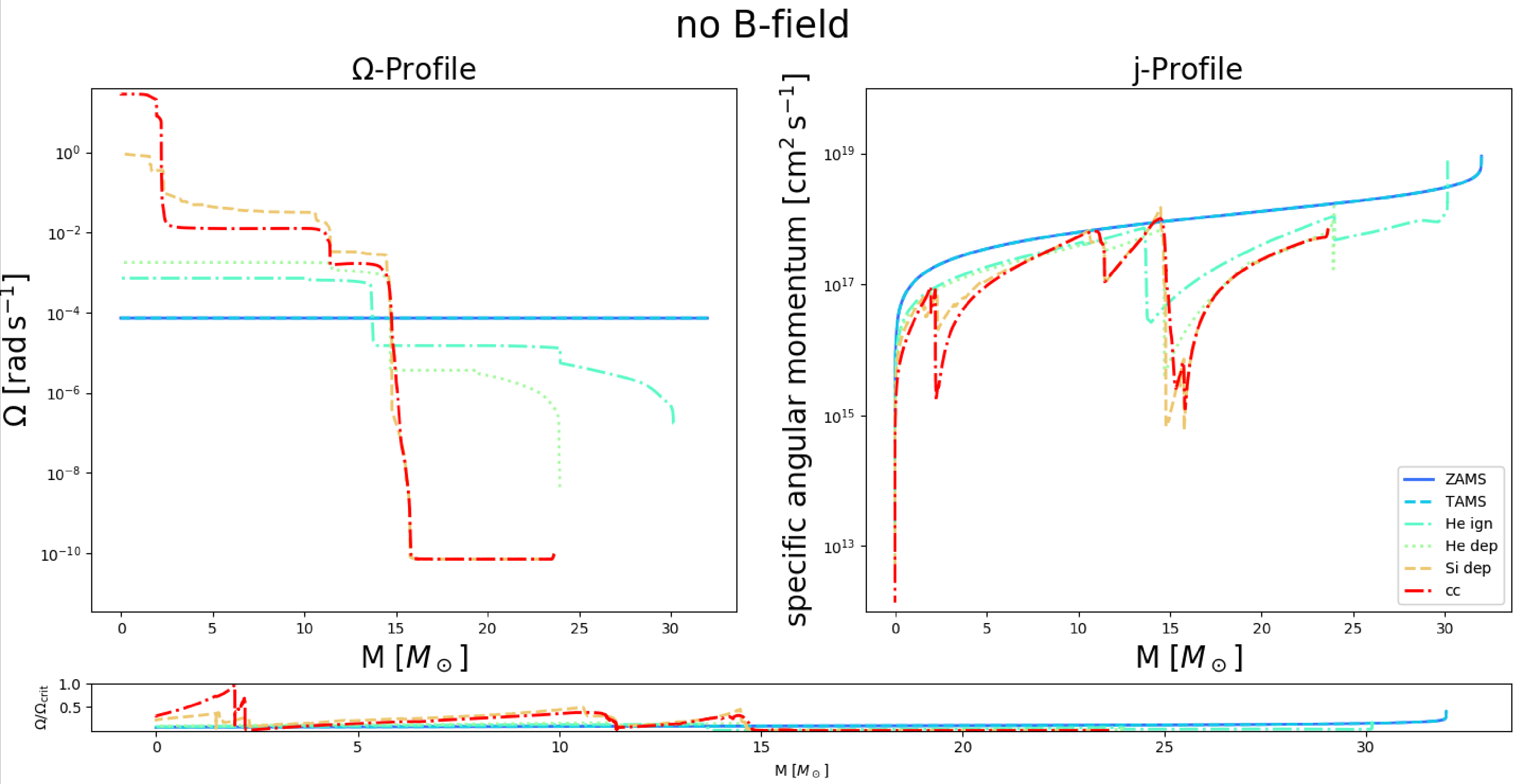


TS dynamo

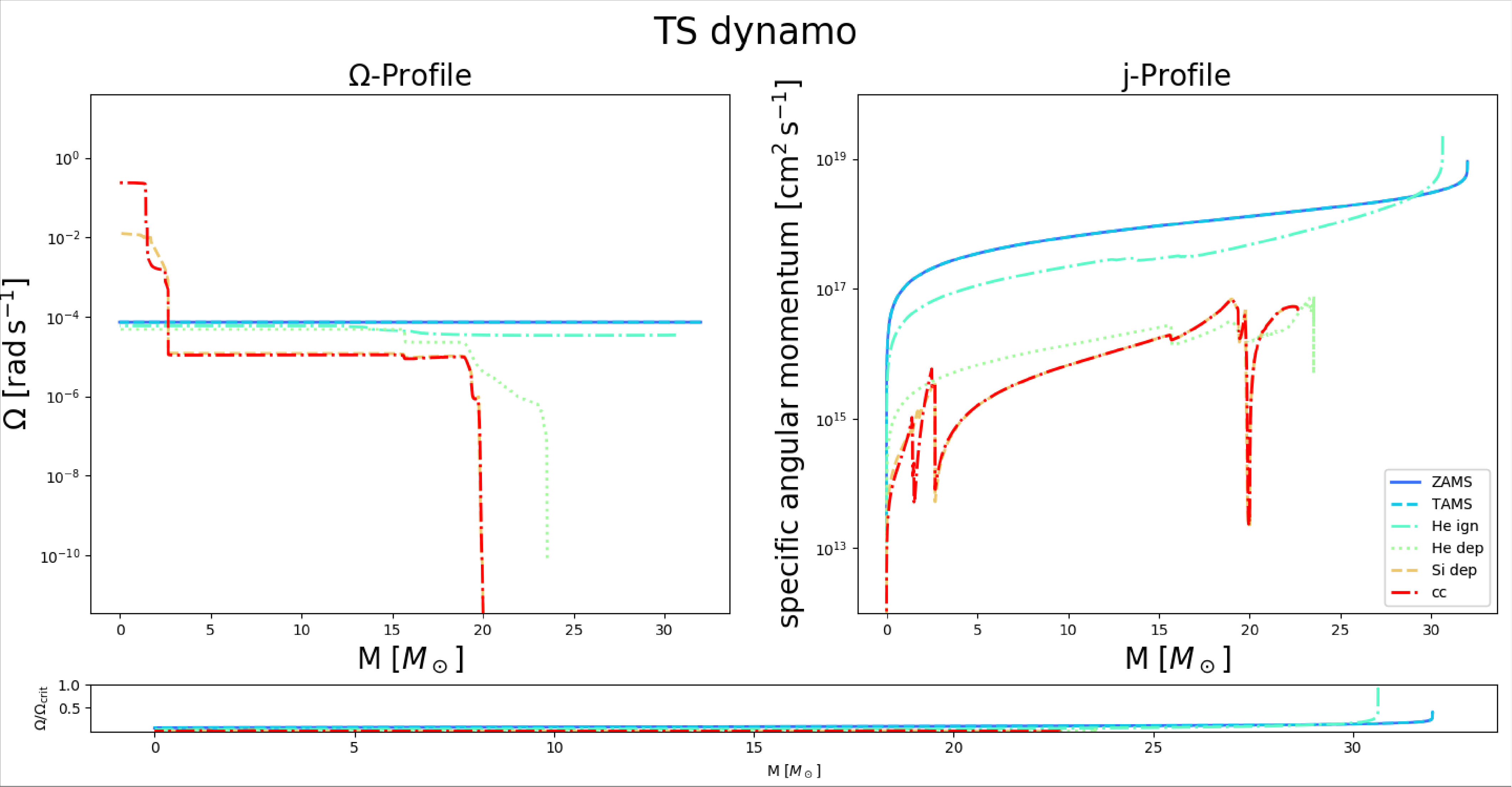
MESA: $32\,M_\odot, Z = 0.002, v_{\rm surf,ini} = 100\,{\rm km\,s^{-1}}$



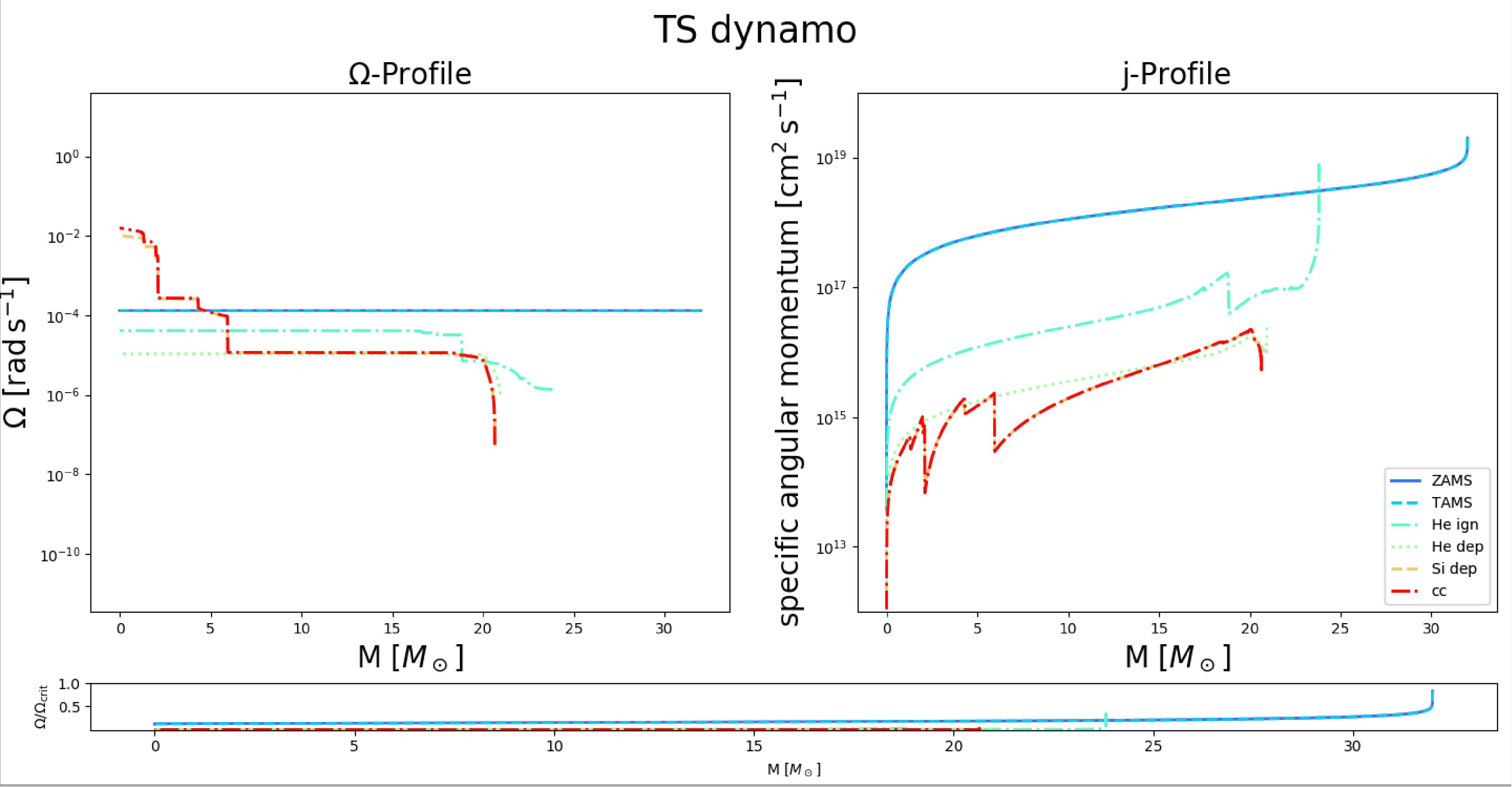
$$\text{MESA: } 32\,M_\odot,\, Z = 0.002,\, \frac{\Omega_{\rm ini}}{\Omega_{\rm crit}} = 0.4$$


no B-field

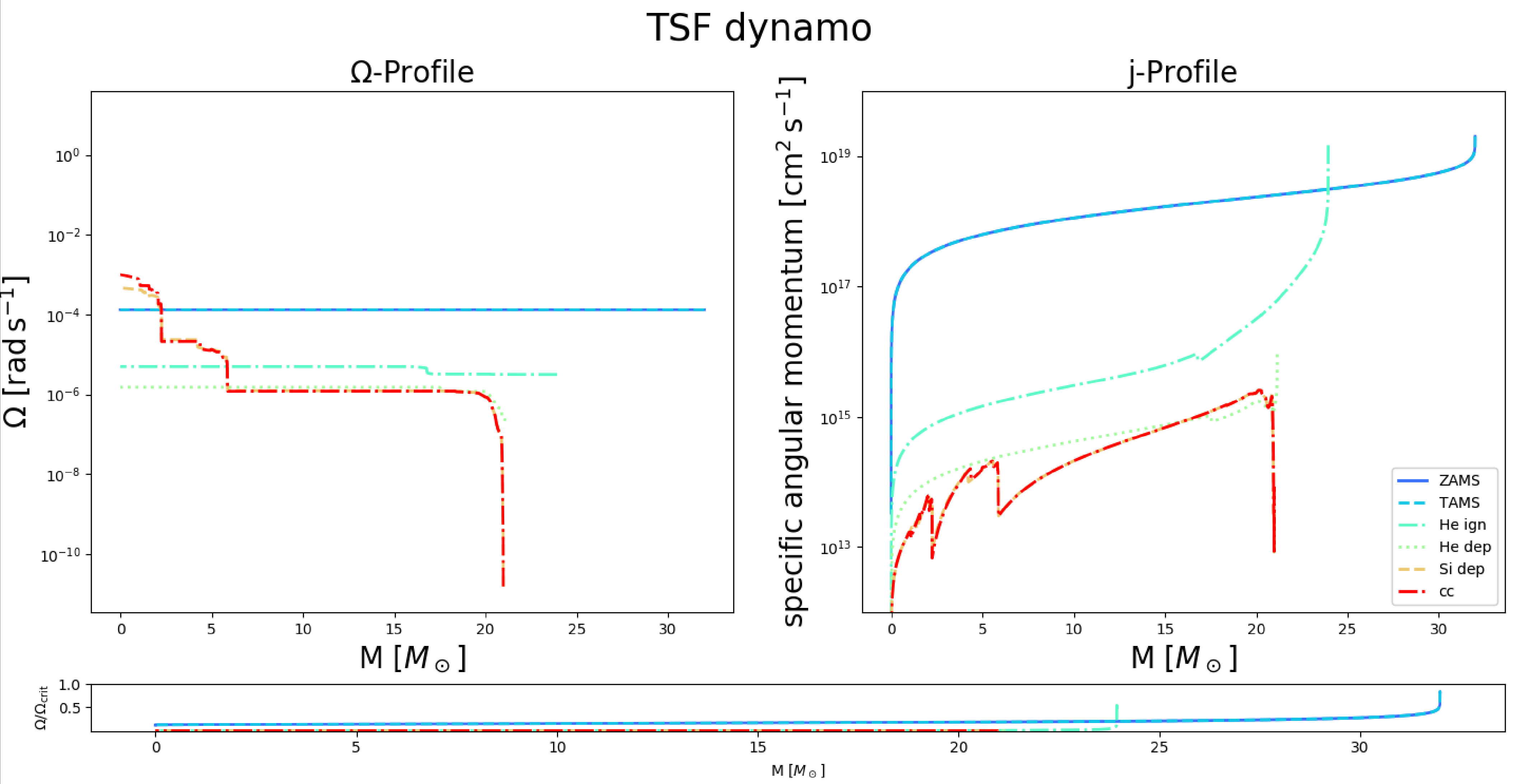
MESA: $32\,M_\odot$, $Z = 0.002$, $\frac{\Omega_\mathrm{ini}}{\Omega_\mathrm{crit}} = 0.4$



MESA: $32\,M_\odot, Z = 0.002, \frac{\Omega_{\rm ini}}{\Omega_{\rm crit}} = 0.8$



MESA: $32\,M_\odot, Z = 0.002, \dfrac{\Omega_{\mathrm{ini}}}{\Omega_{\mathrm{crit}}} = 0.8$



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

West Midlands:

Keele area

is famous for pottery: Wedgwood, ...

Exciting HyDeploy.co.uk / SEND projects