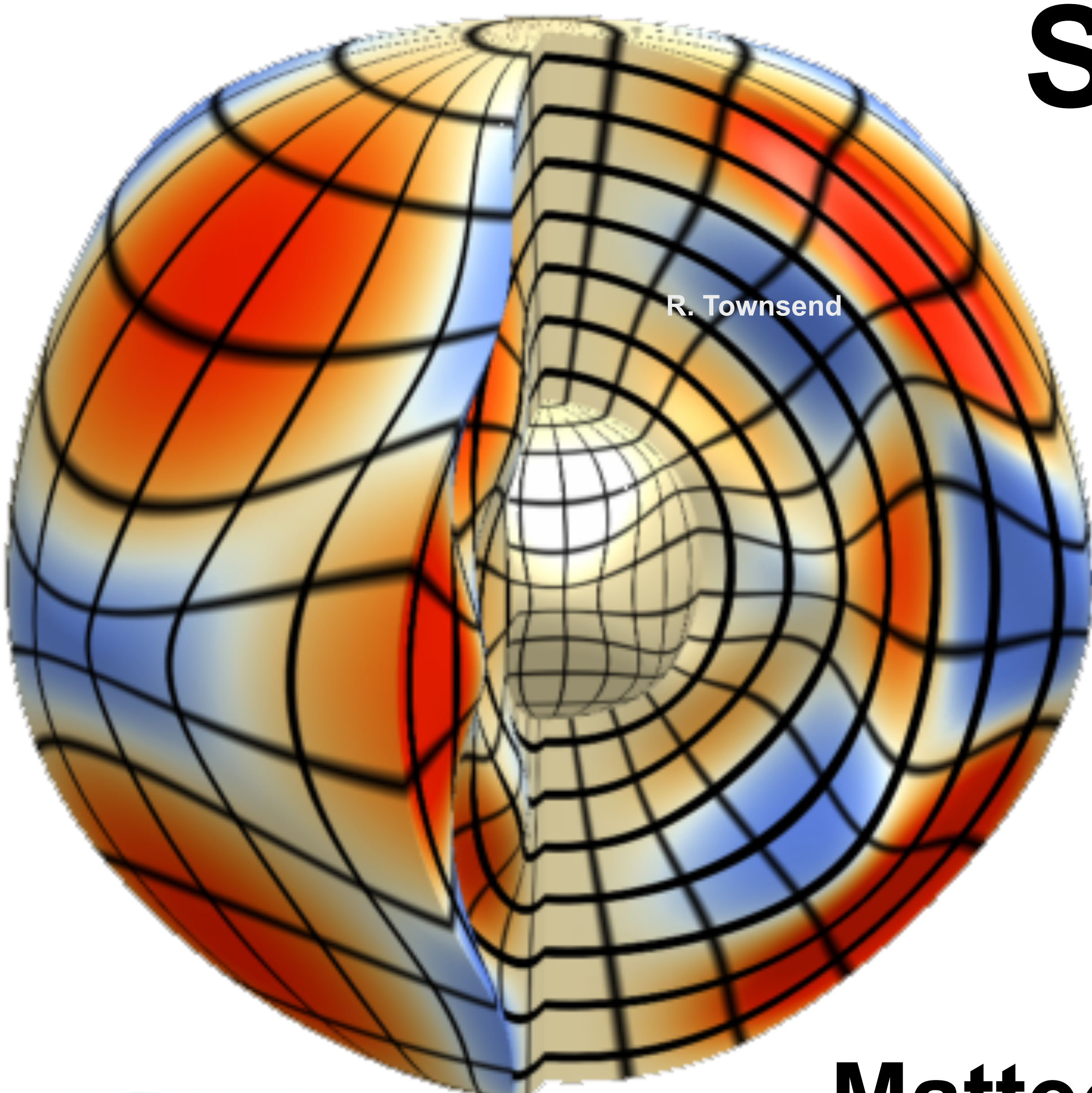
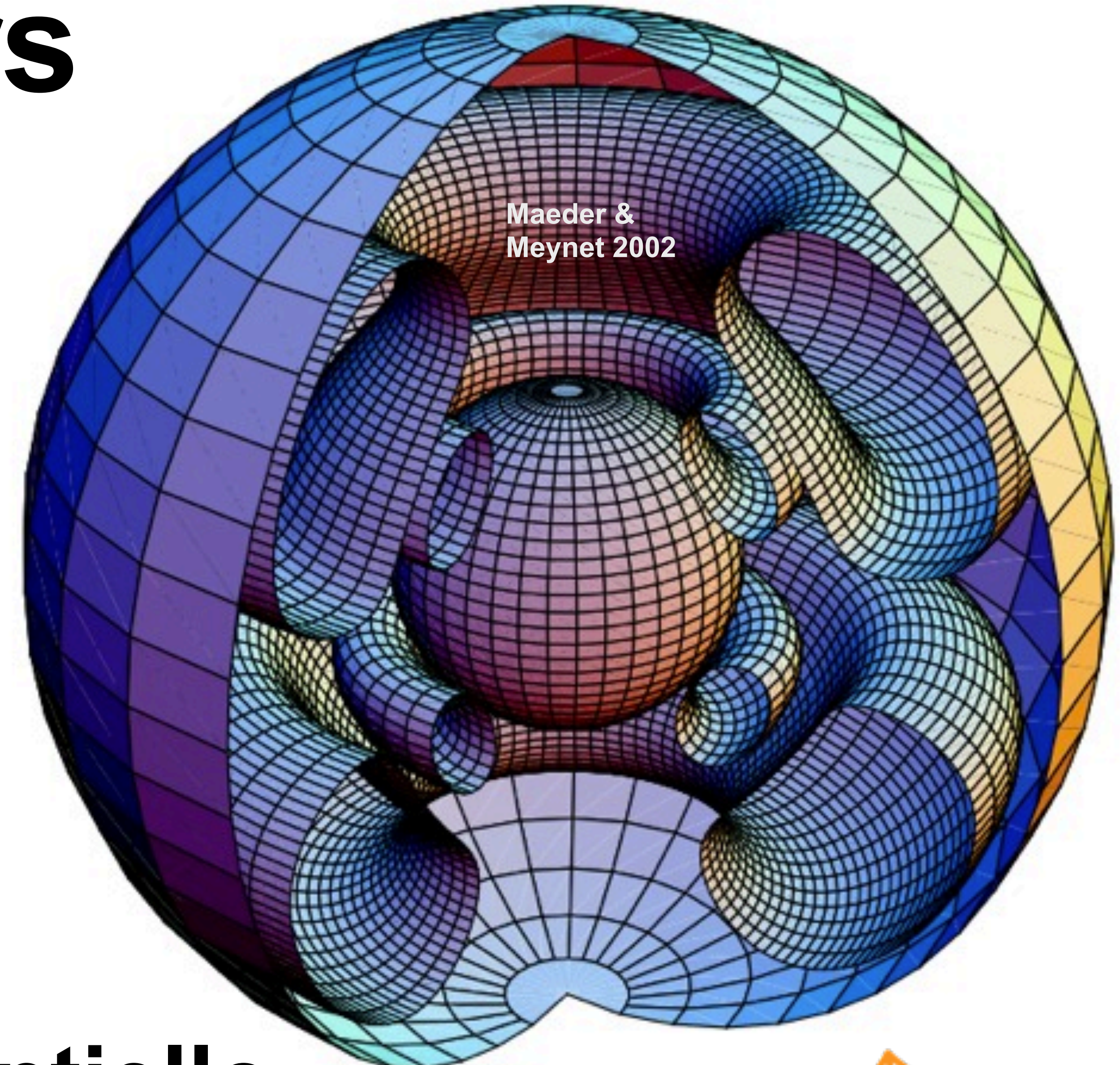
The Physics of Stellar Angular Momentum Transport in Massive Stars





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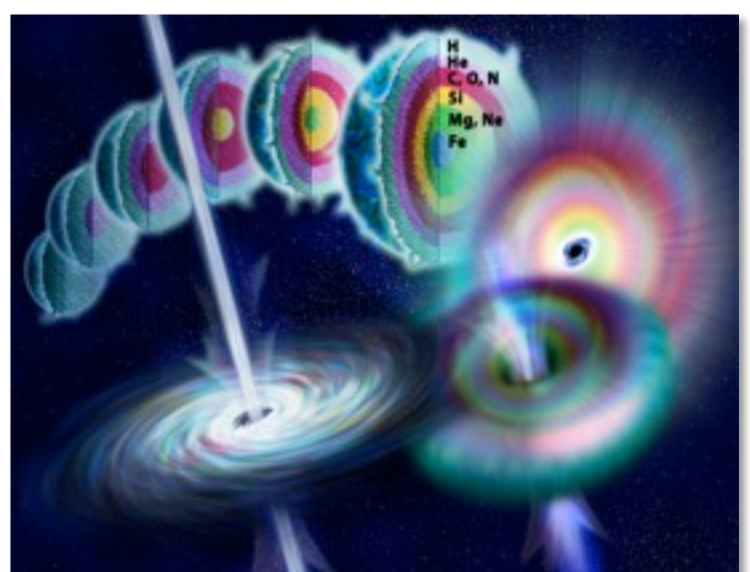
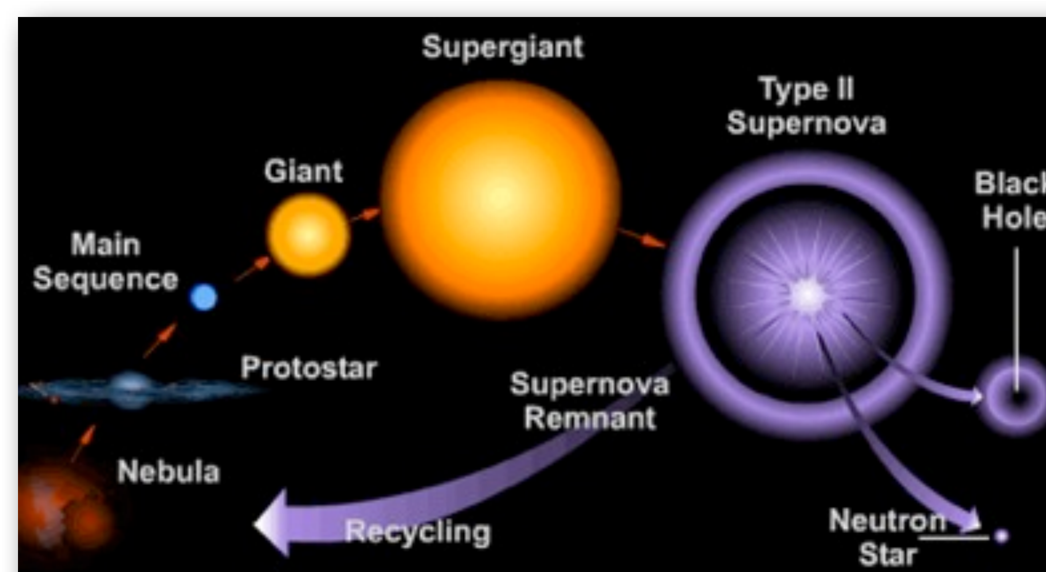
Chris Mankovich, Lars Bildsten, J.Christensen-Dalsgaard, Bill Paxton, Jim Fuller, Daniel Lecoanet, Ben Brown, Eliot Quataert

Massive Stars

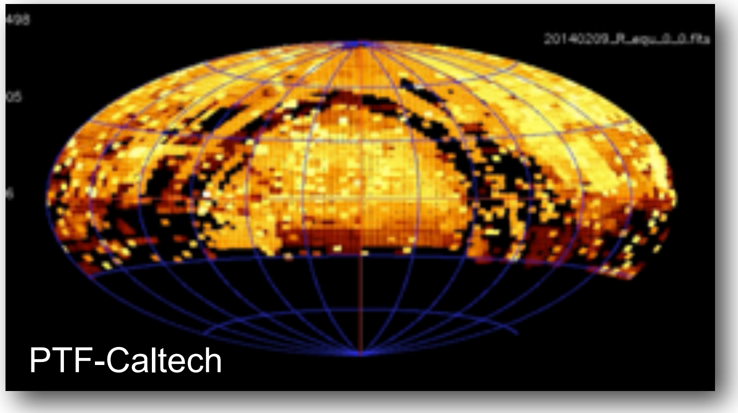
- Energy / Momentum in ISM
- Stellar Winds, SNe
- Nucleosynthesis
- Remnants: NS and BHs
- Magnetars, Pulsars, Long GRBs... Importance of magnetic fields and final angular momentum budget





An Exciting, Rapidly Evolving Field

- Entering the era of high precision stellar astrophysics (CoRoT, Kepler, K2, GAIA,TESS, Plato...)
- Transient surveys revealing unexpected explosions diversity (PTF/ZTF, Pan-STARRS, LSST...)



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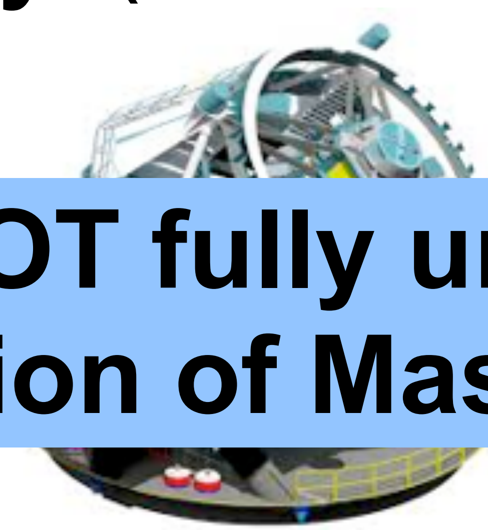
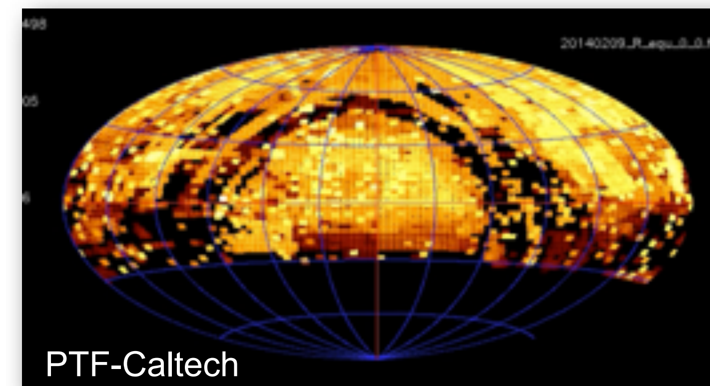


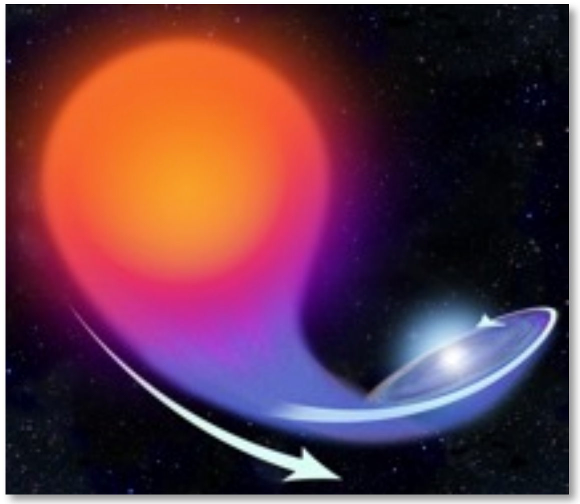
TESS

We do NOT fully understand the evolution of Massive Stars!



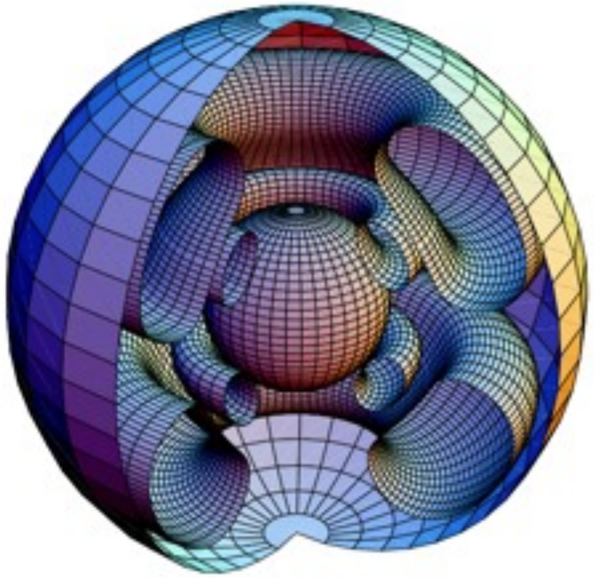
Massive Stars in the 21st Century

Binary Interactions



The presence of a close companion can significantly influence the evolution of massive stars (e.g. Podsiadlowski+ 1992, Cantiello+ 2007, Langer+ 2008, Eldridge+ 2011)

Rotation



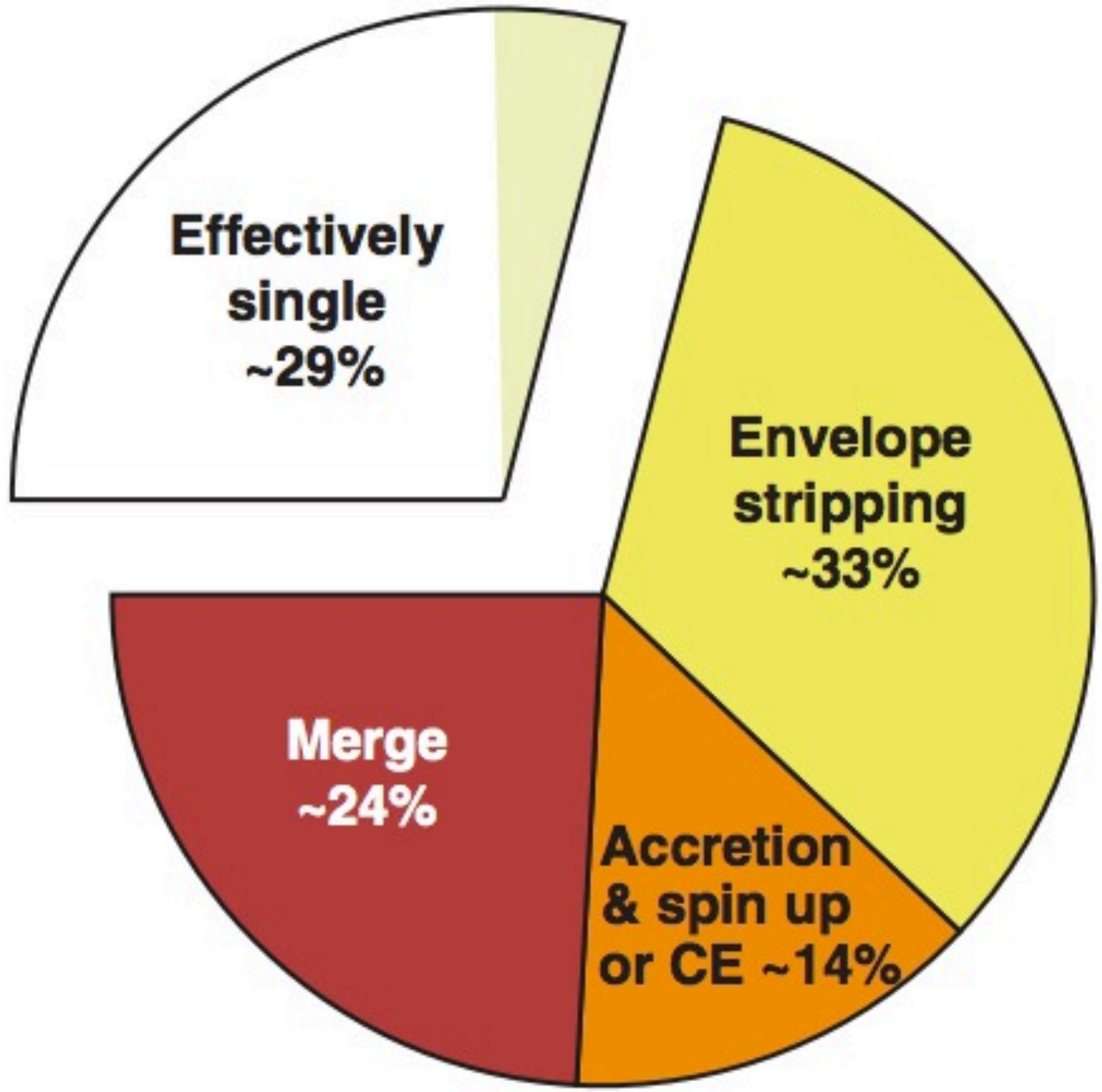
Stellar rotation has also a profound impact on the evolution of massive stars. In particular the final fate of rapidly rotating stars is expected to differ significantly from slowly rotating ones. (e.g. Yoon+ 2006, Woosley+ 2006)

Magnetic Fields

Magnetic fields can potentially affect the evolution of massive stars and their explosive deaths. At this stage little is known about the prevalence and amplitude of (internal) magnetic fields (e.g. Spruit 2002, Heger+ 2005, Cantiello & Braithwaite 2010, MiMES)

Binary Interactions are the norm

"71% of all stars born as O-type interact with a companion, over half of which do so before leaving the main sequence"

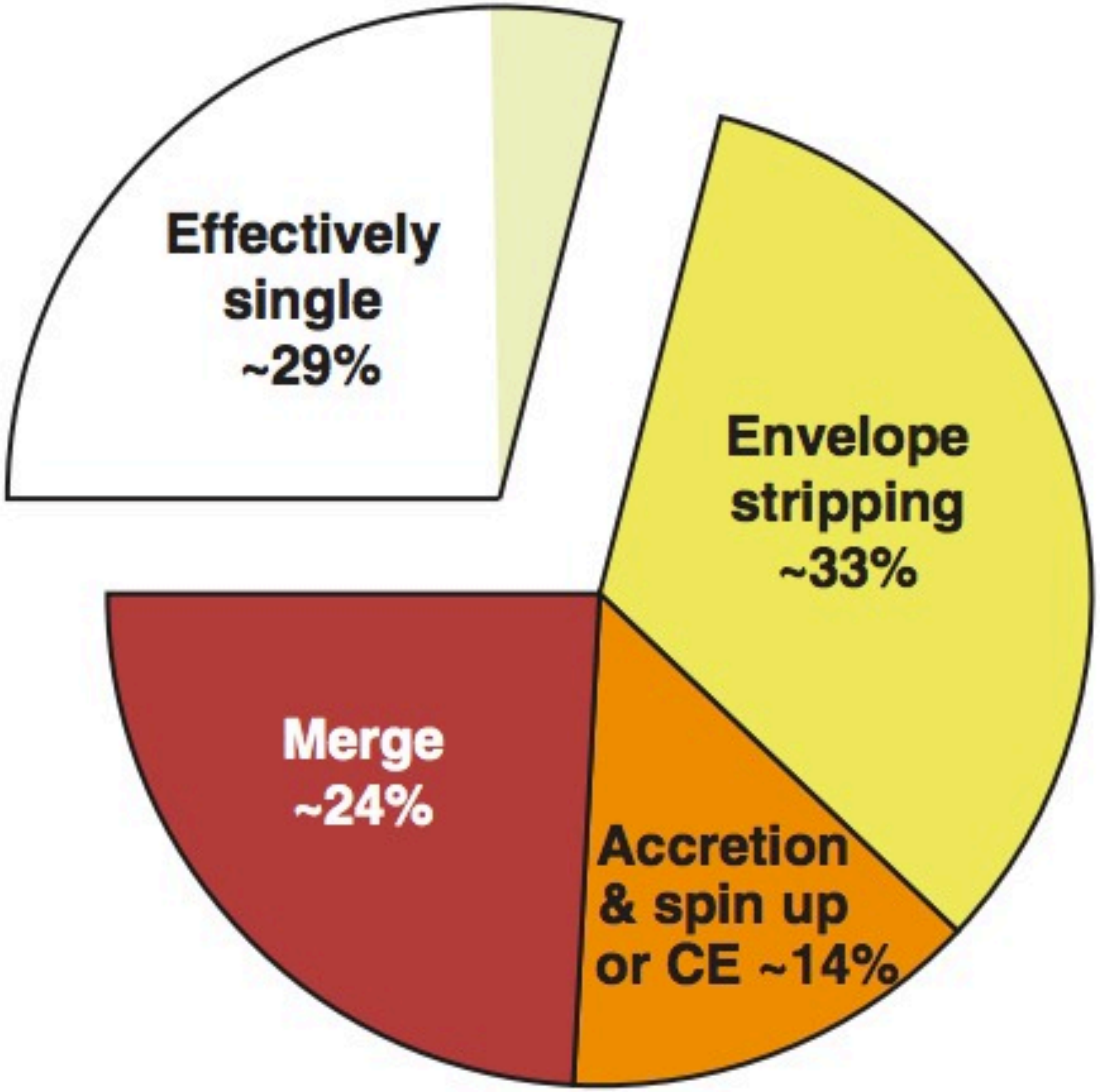


Sana et al. 2012 (Science)

Binary Interactions are the norm

Numbers for B-type stars look similar

Dunstall et al. 2015



A large fraction of CCSN progenitors interacted with a binary companion

Sana et al. 2012 (Science)

Binary Interactions are the norm

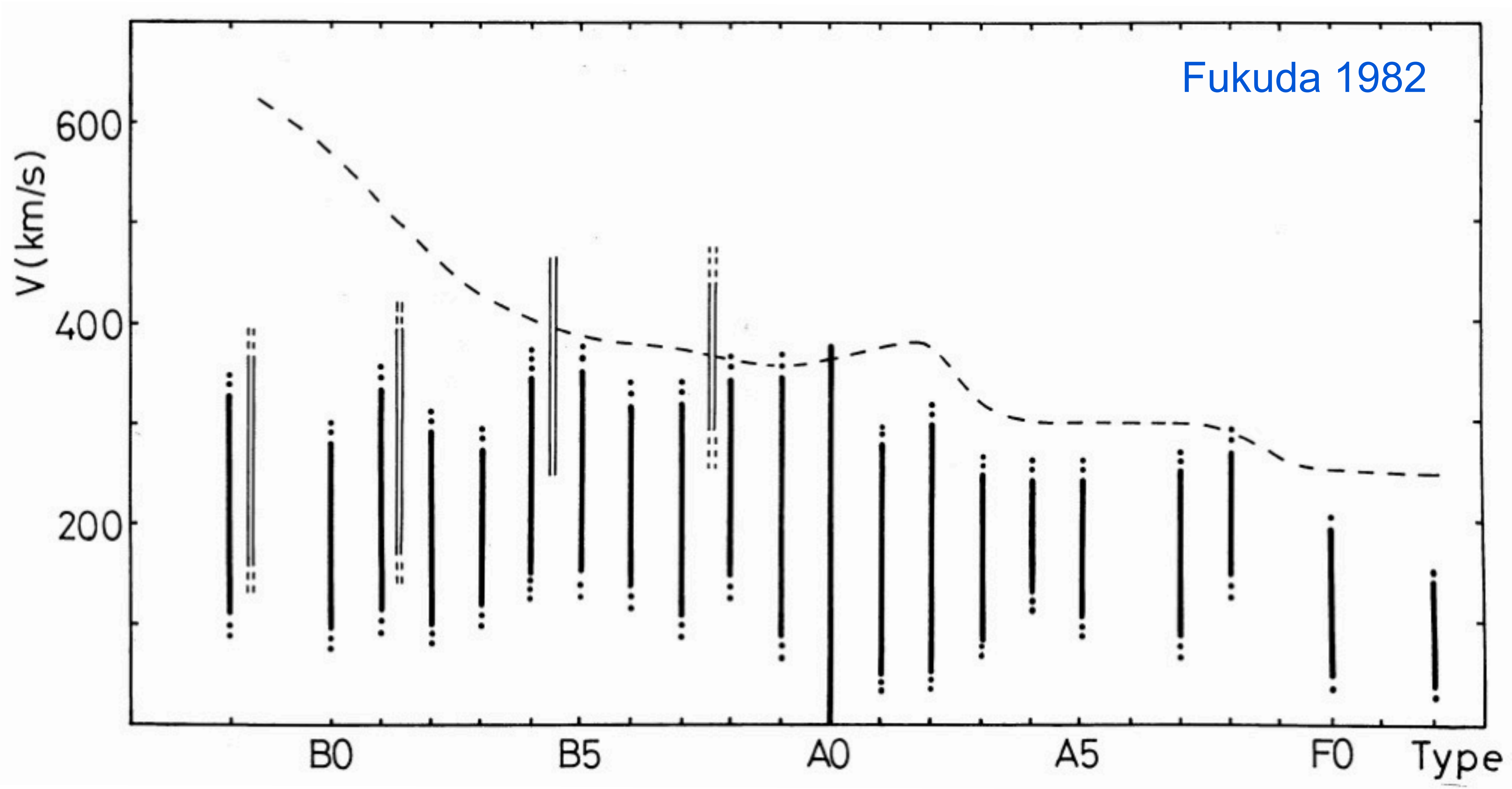
- Tides, mass transfer and stellar mergers are expected to largely change the rotational properties of stars

- To fully understand binary interactions (and SN progenitors) we **first need to understand the physics of stellar rotation** (in single stars)

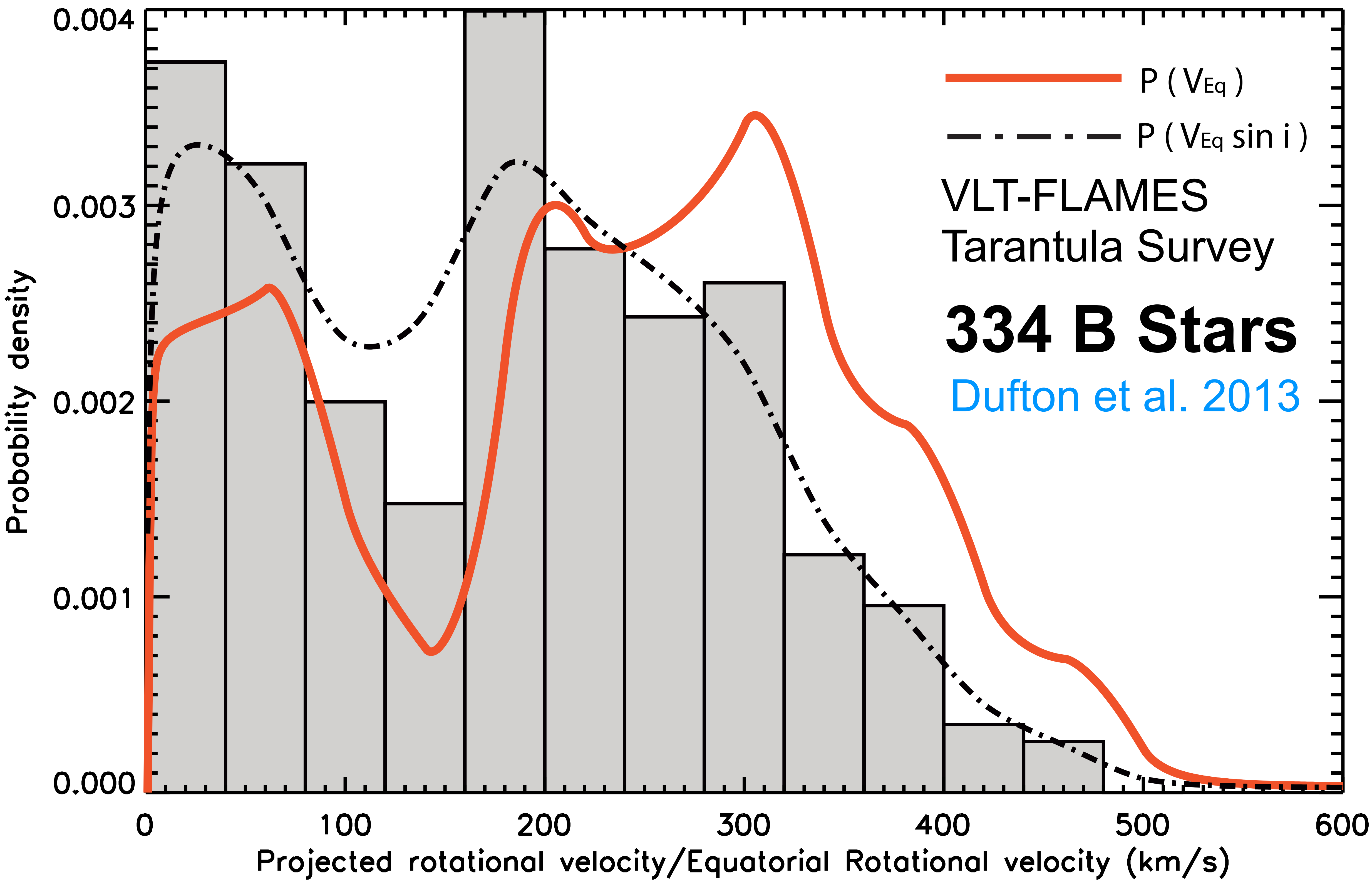
Stars are born rotating

Range of rotational velocity

“In practice **all stars** are rotating around their axis” - Maeder & Meynet



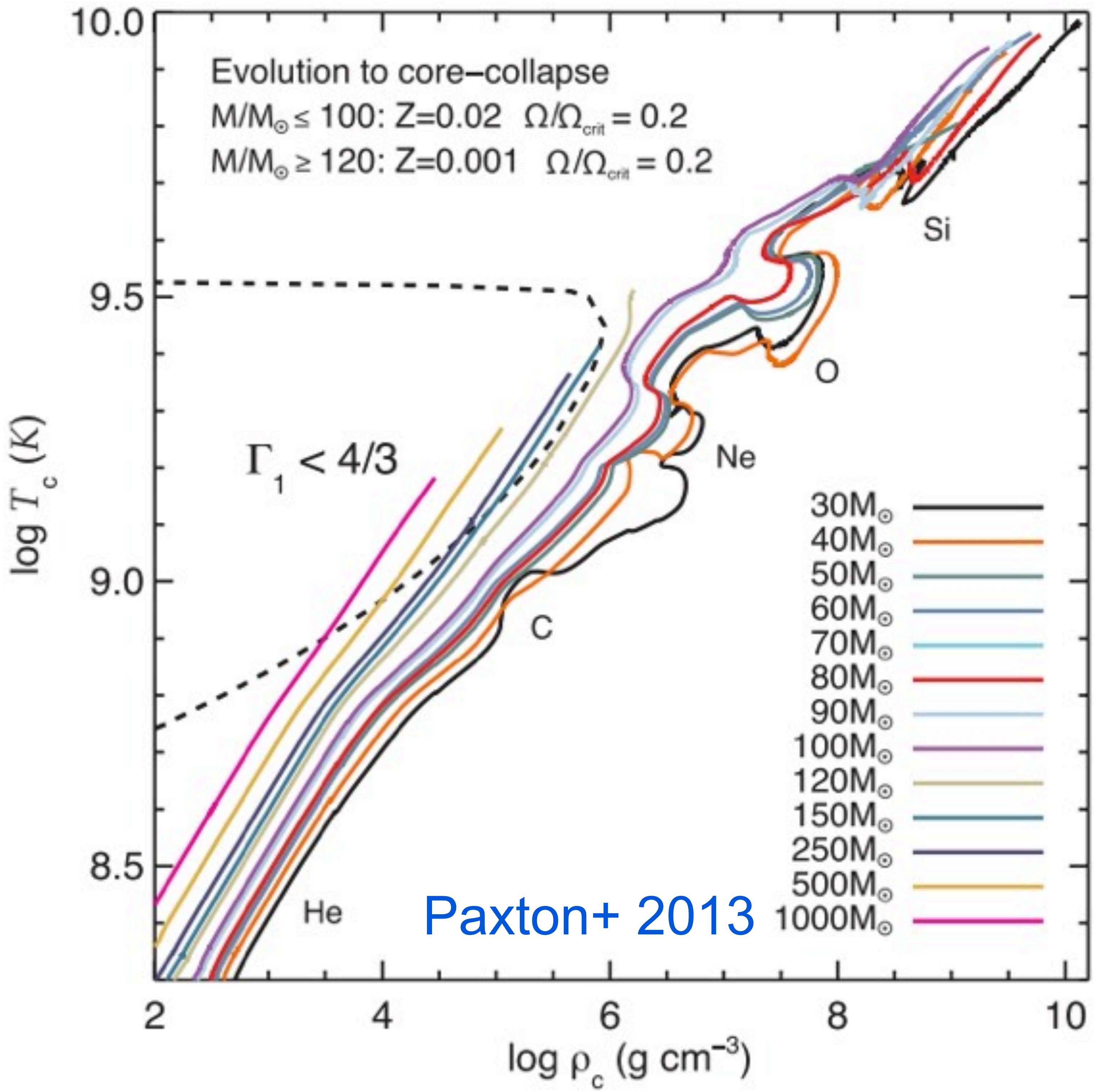
Early type stars in 30 Doradus



Stellar Cores

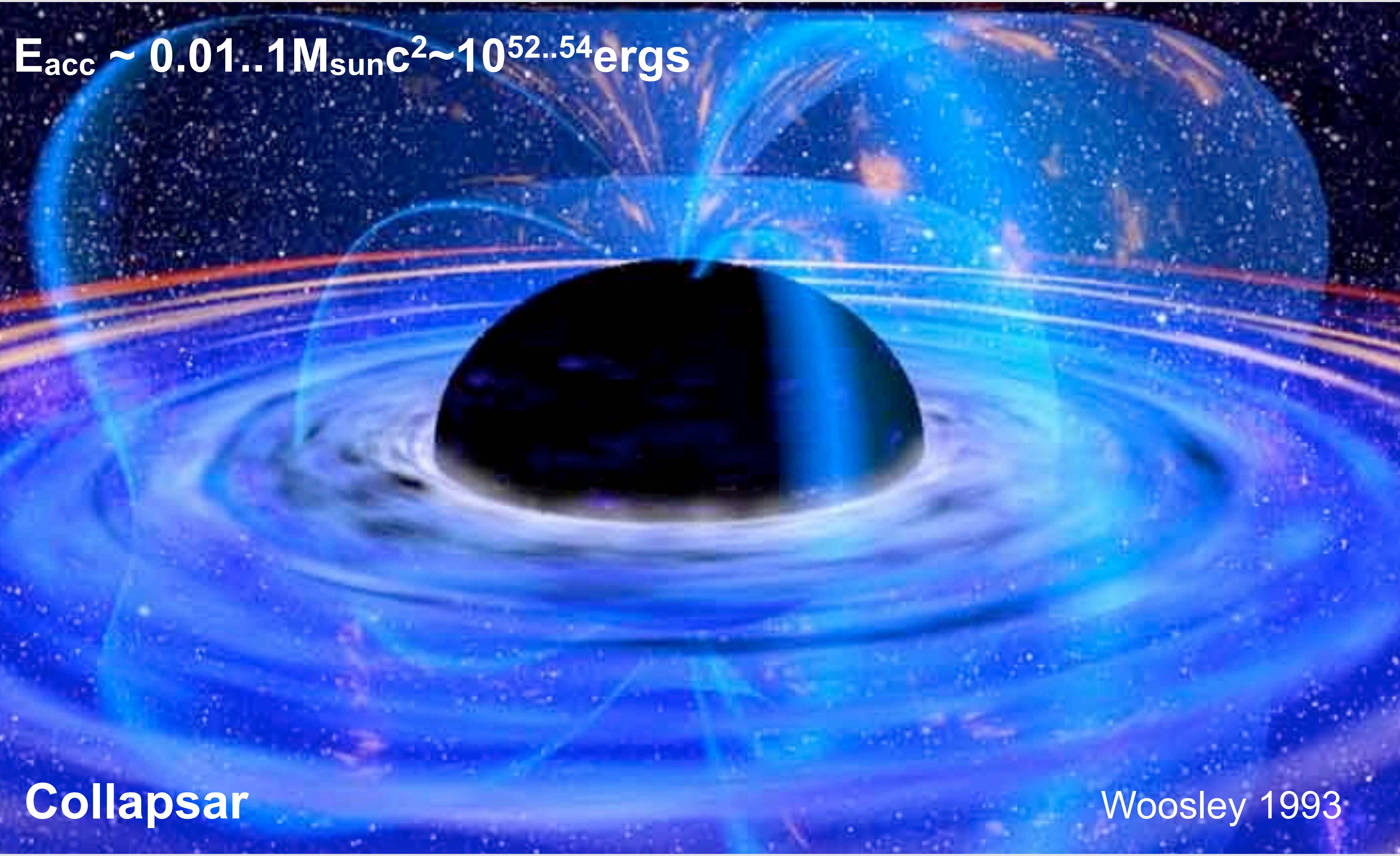
To maintain hydrostatic equilibrium stars need to burn nuclear fuel at higher and higher temperatures. This implies an inexorable **contraction of stellar cores**

In the absence of angular momentum transport mechanisms, stellar cores would **spin up** to very high rotation rates



Paxton+ 2013

Long GRB Central Engine

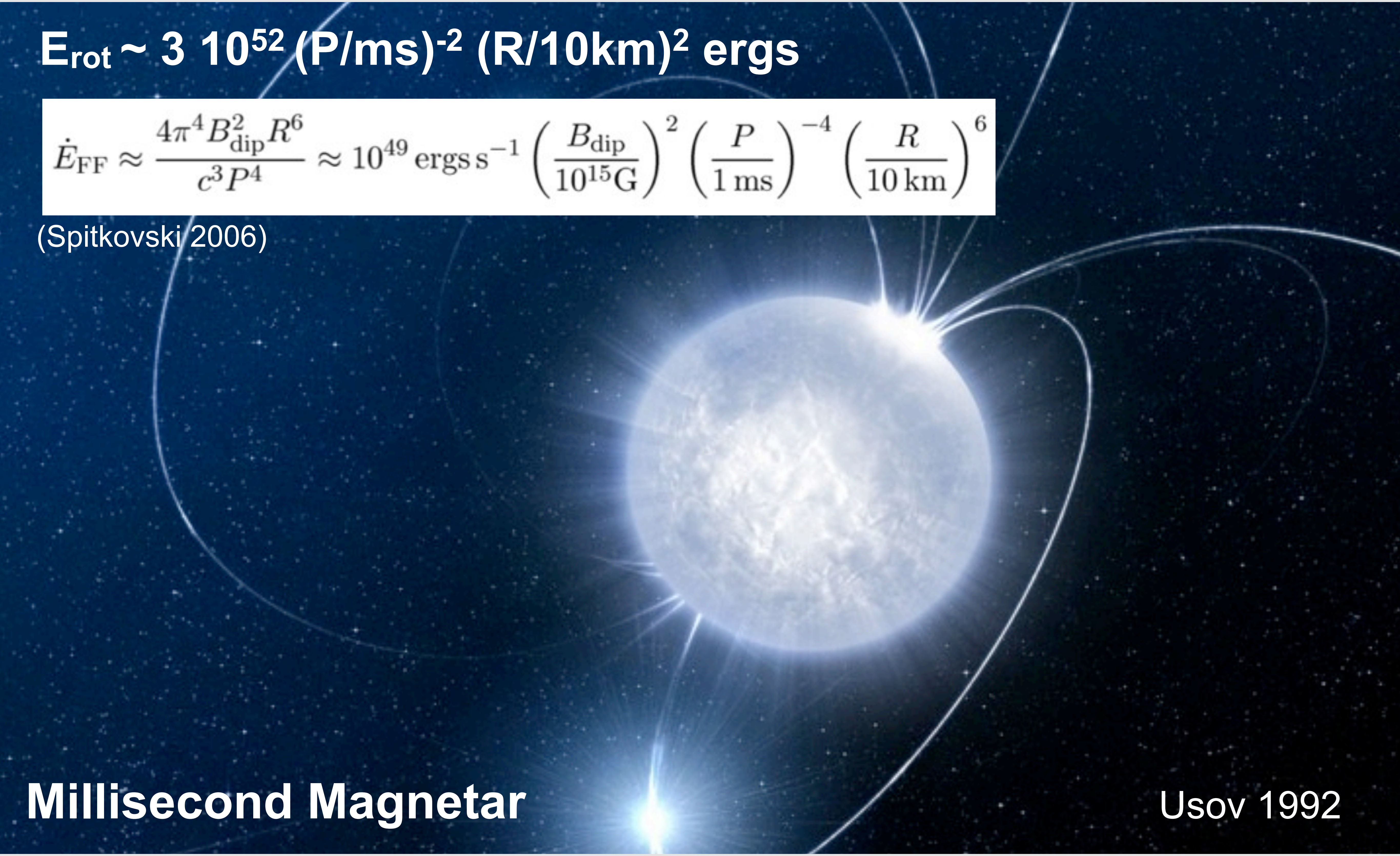


Long GRB Central Engine

$E_{rot} \sim 3\ 10^{52}\ (P/ms)^{-2}\ (R/10km)^{2}$ ergs

$$\dot{E}_{\rm FF} \approx \frac{4\pi^4 B_{\rm dip}^2 R^6}{c^3 P^4} \approx 10^{49}\,{\rm ergs\,s^{-1}} \left(\frac{B_{\rm dip}}{10^{15}{\rm G}}\right)^2 \left(\frac{P}{1\,{\rm ms}}\right)^{-4} \left(\frac{R}{10\,{\rm km}}\right)^6$$

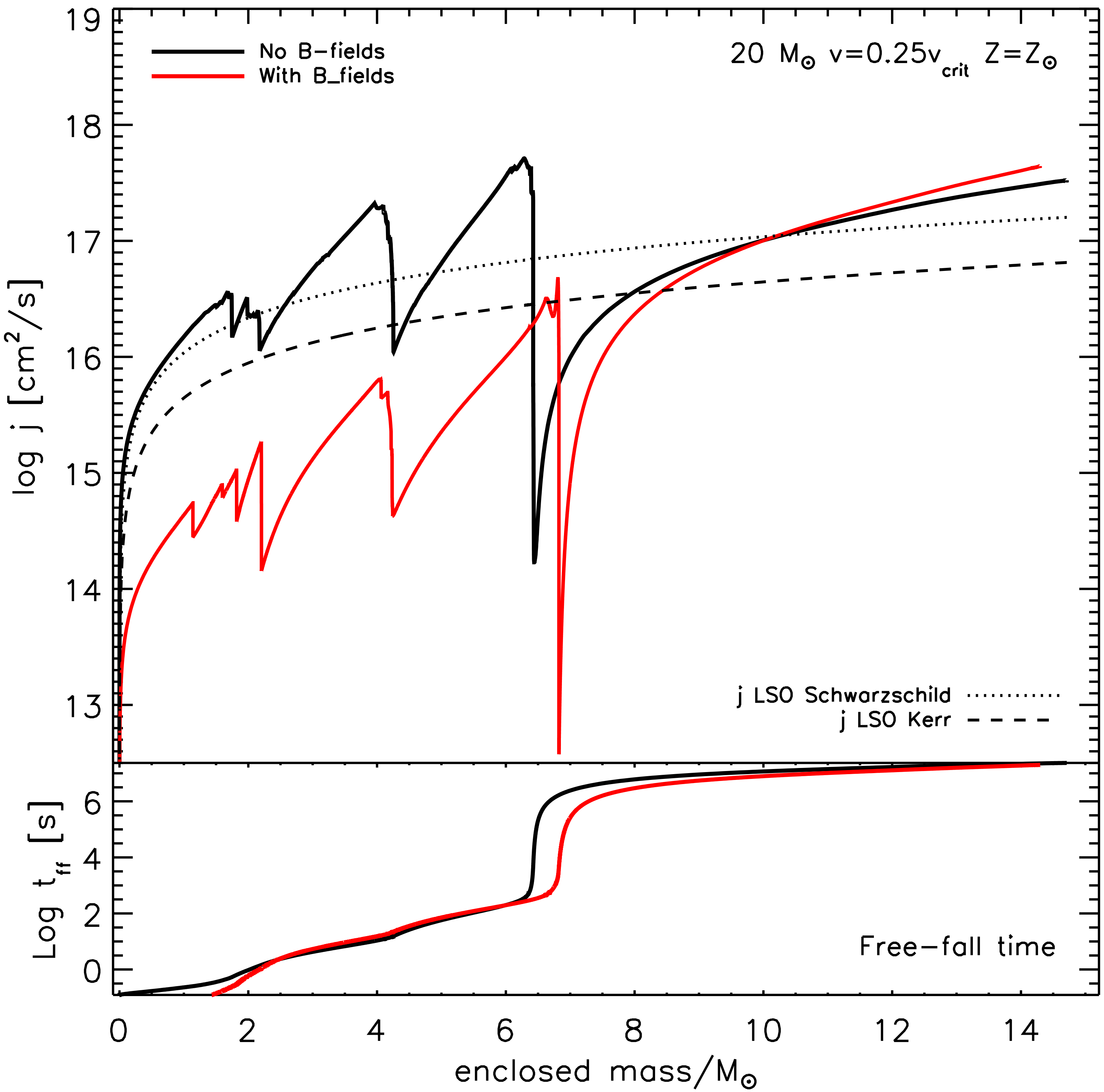
(Spitkovski 2006)



Millisecond Magnetar

Usov 1992

Final j-distribution



GRB (?): enough angular momentum in the core to make an accretion disk during collapse / create a rapidly rotating NS

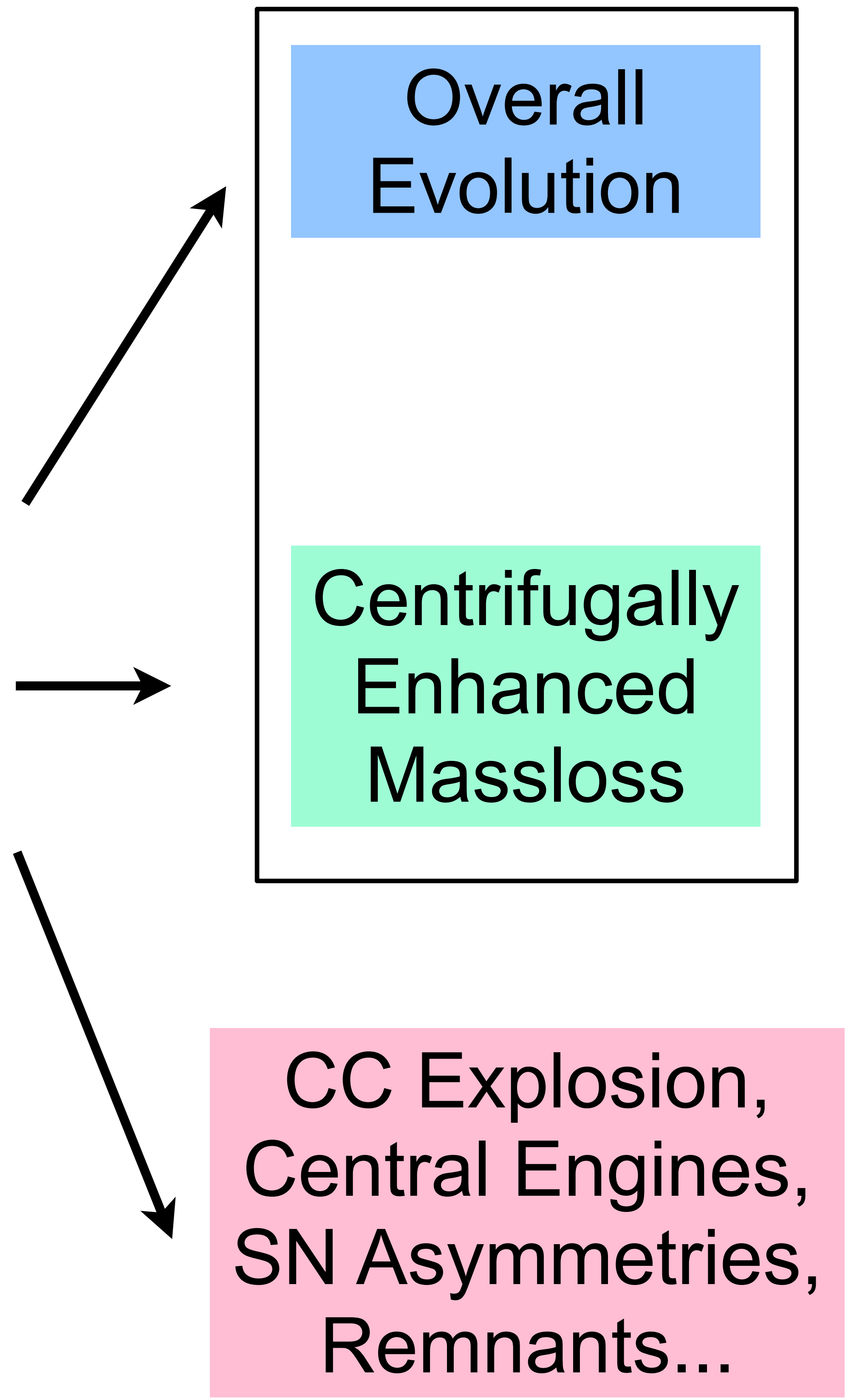
SN: no accretion disk during collapse / no rapidly rotating NS

1D MESA
Stellar evolution calculations

Paxton+ 2011, 2013, 2015

Impact of Stellar Rotation

- Internal Mixing
- Mass Loss
- Core Collapse



Impact of Stellar Rotation

- Internal Mixing
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Overall Evolution

Centrifugally Enhanced Massloss

CC Explosion, Central Engines, SN Asymmetries, Remnants...

See e.g. talks from:

Maria Drout

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Leah Huk

Jeff Silverman

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Raffaella Margutti
Brian Morsony

William Hix
Bernard Mueller
Remi Kazeroni
Grant Williams

Physics of Angular Momentum Transport

Timescales & Approximations

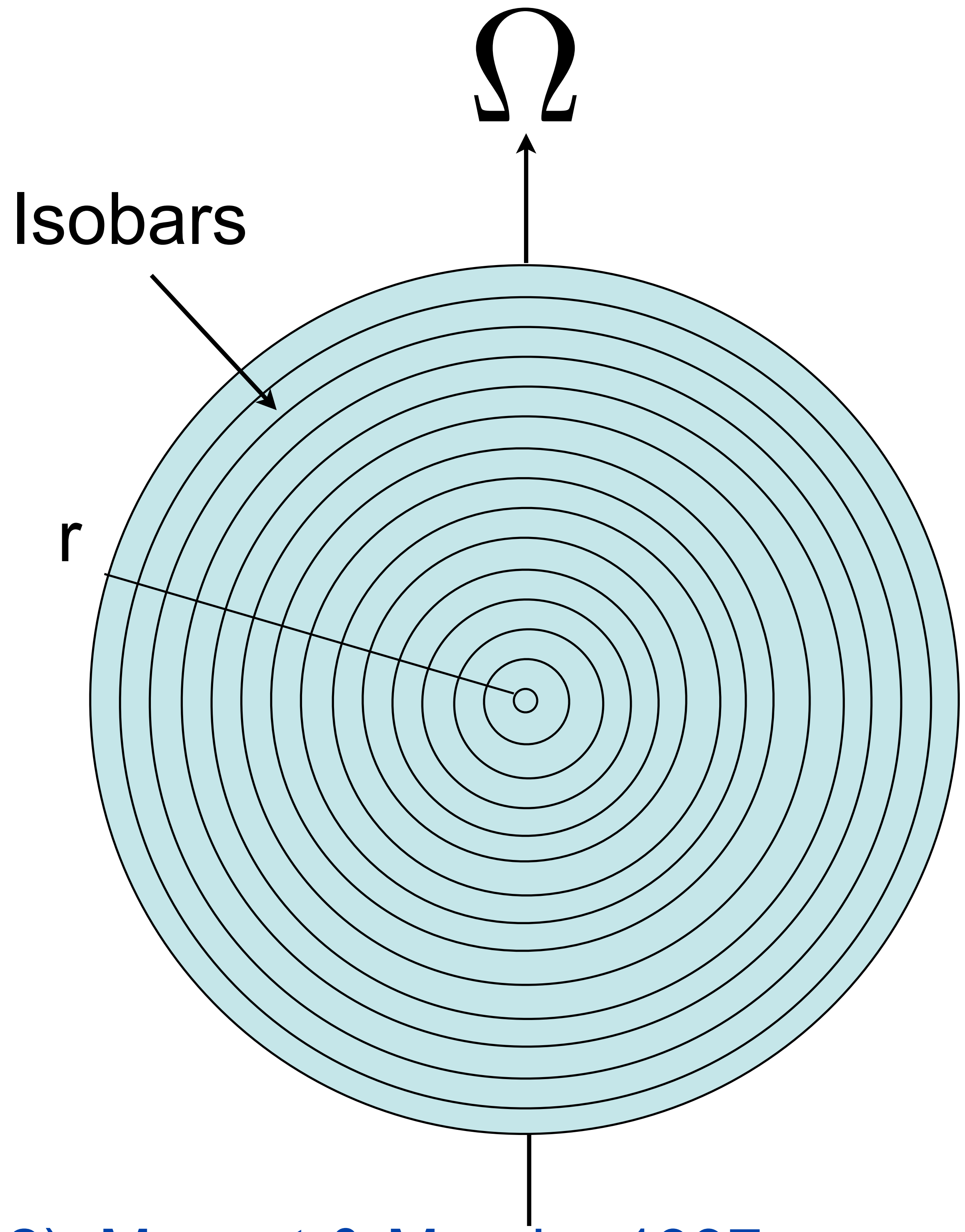
$$\tau_{\rm nuc} \gg \tau_{\rm KH} \gg \tau_{\rm dyn}$$

Main Sequence	t_{nuc}	t_{KH}	t_{dyn}
1 M_{Sun}	10^{10} yr	10^{7} yr	0.02 d
10 M_{Sun}	~10^{7} yr	10^{4} yr	0.1 d
100 M_{Sun}	~10^{6} yr	10^{3} yr	0.5 d

To resolve and include dynamical phenomena one has to take ~10^{11} timesteps. This is beyond current capabilities. Stellar evolution requires **MLT**, **Diffusion approximations** etc.

Rotation in 1D: The Shellular Approximation

$$\omega = \omega(\mathrm{r})$$



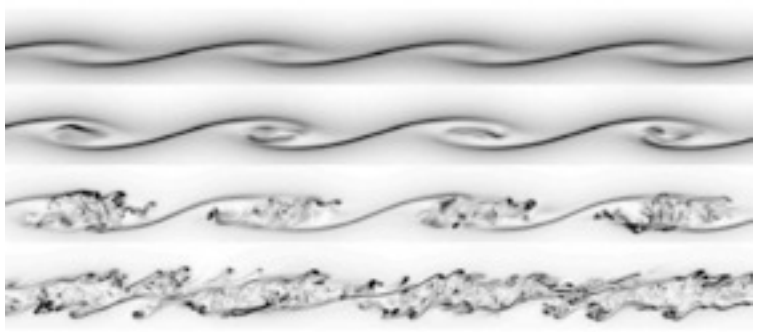
Composition is only function of the r coordinate, as each shell is assumed to be efficiently mixed by strong horizontal turbulence

Zahn (1975), Chaboyer & Zahn (1992), Meynet & Maeder 1997

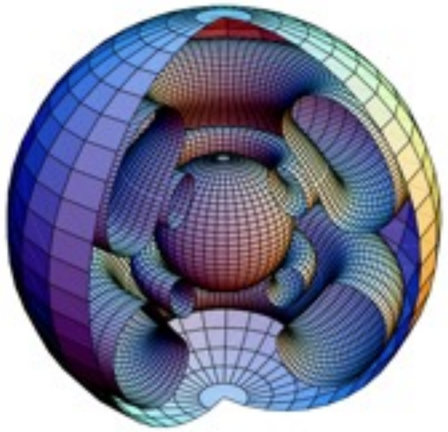
Angular Momentum Transport

Different classes of mechanisms have been proposed:

e.g. Heger et al. 2000



e.g Maeder & Meynet 2002



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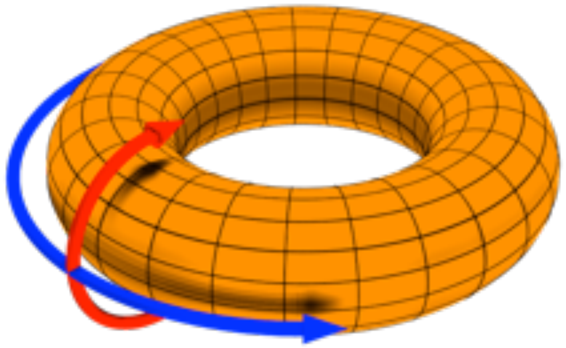

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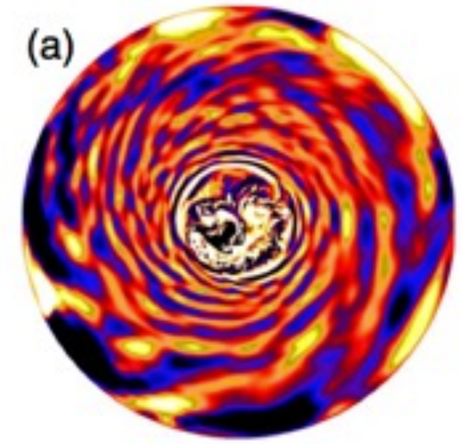


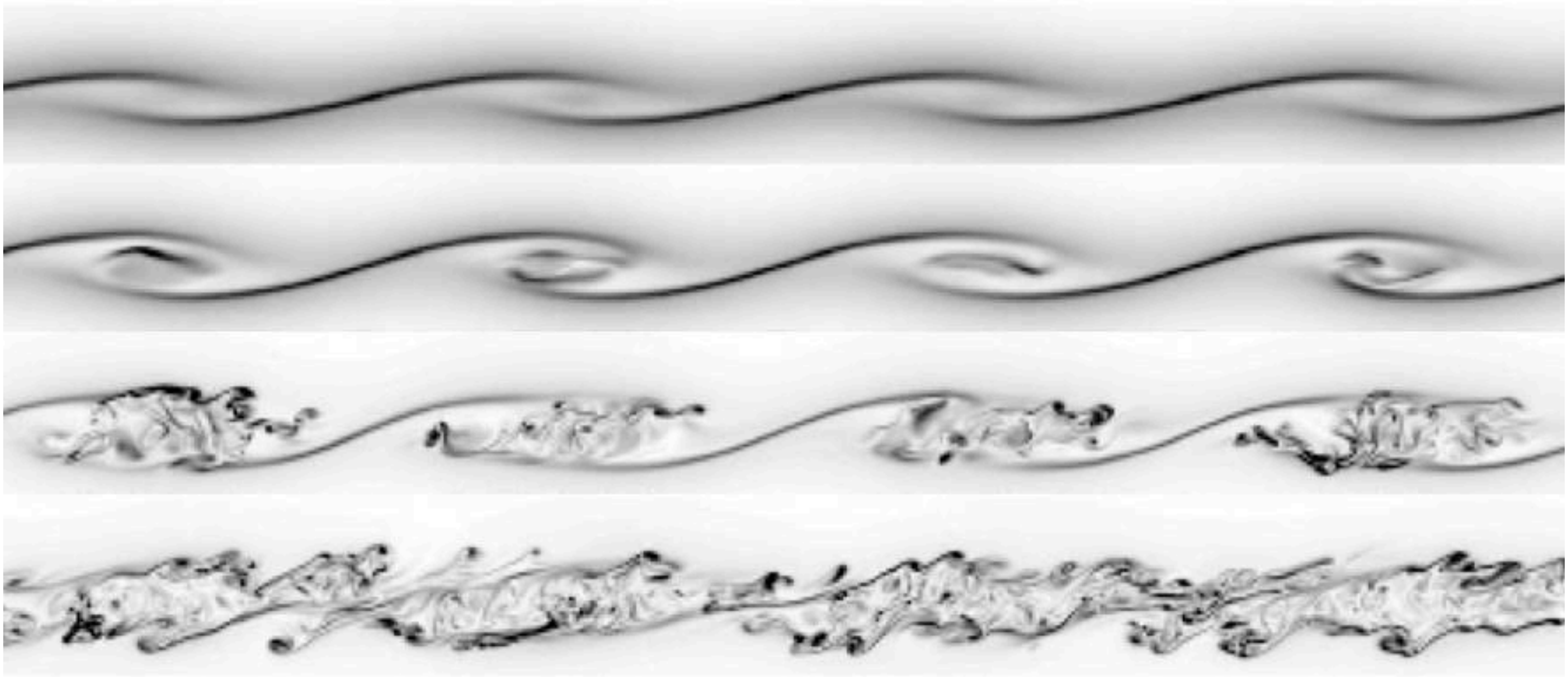
- **Hydrodynamics instabilities**
- Rotationally induced circulations
- Magnetic torques
- Internal gravity waves

Convective Regions usually assumed rigidly rotating

Hydrodynamic Instabilities

- Dynamical Shear

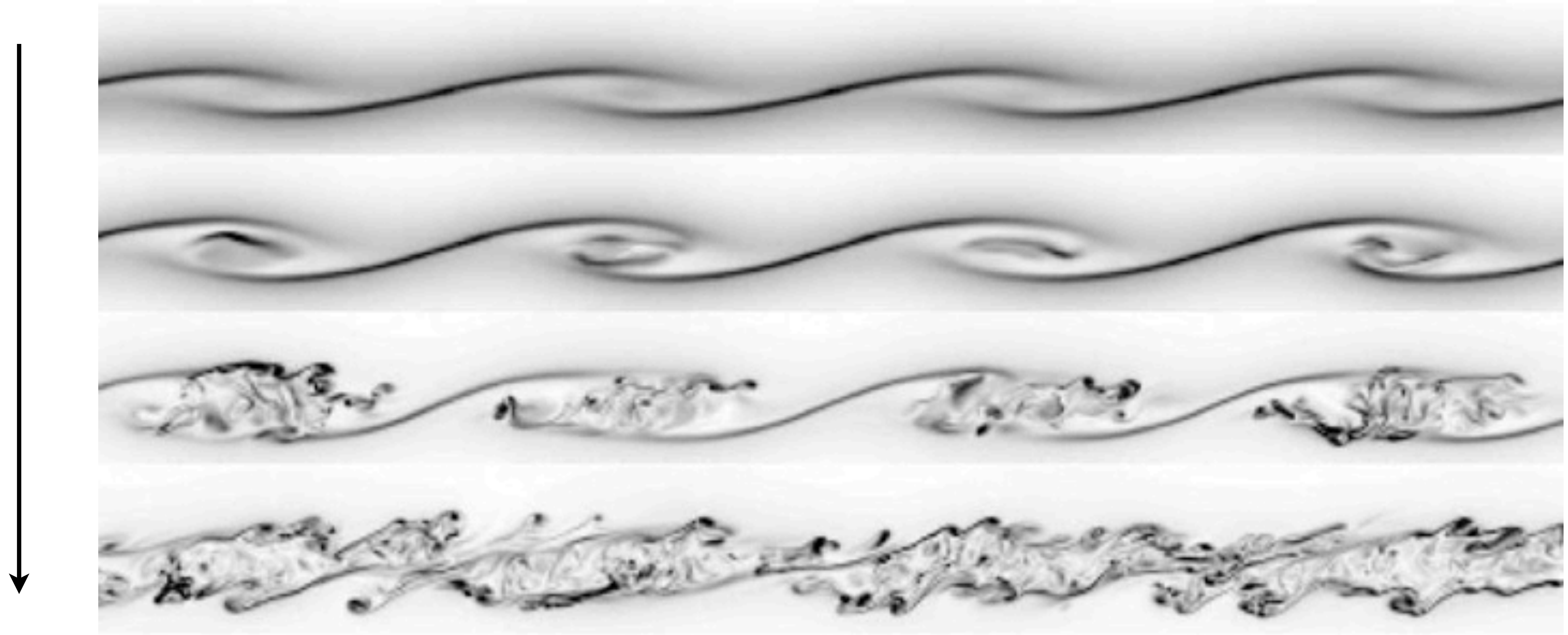
Dynamical shear instability occurs when the energy that can be gained from the shear flow becomes comparable to the work that has to be done against the gravitational potential for the adiabatic turnover of a mass element



Hydrodynamic Instabilities

- Secular Shear

Thermal Timescale



- In the presence of a stabilizing thermal gradient, an eddy might have to wait for heat to diffuse out before an overturn is energetically favorable

- Mixing process on t_{KH}

More Hydro instabilities: see e.g. Heger et al. 2000

Angular Momentum Transport

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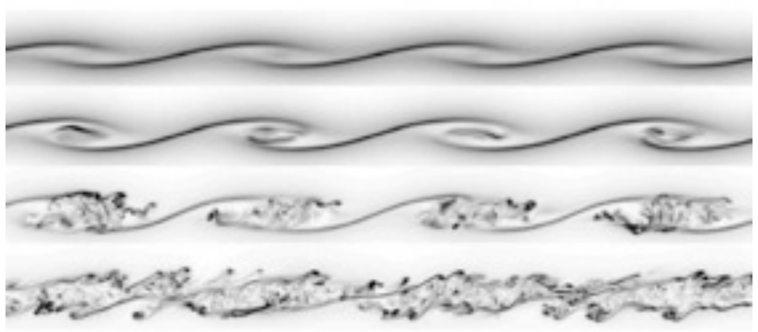

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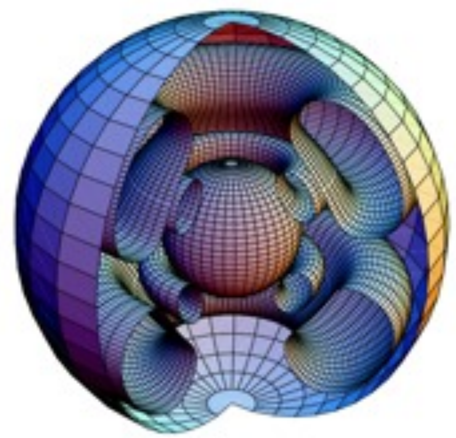

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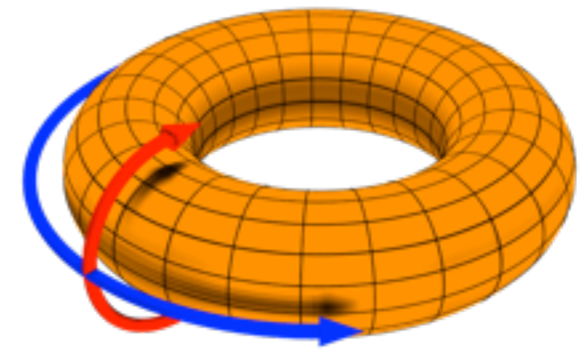

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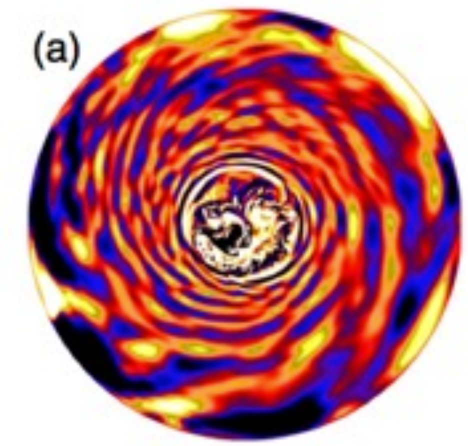
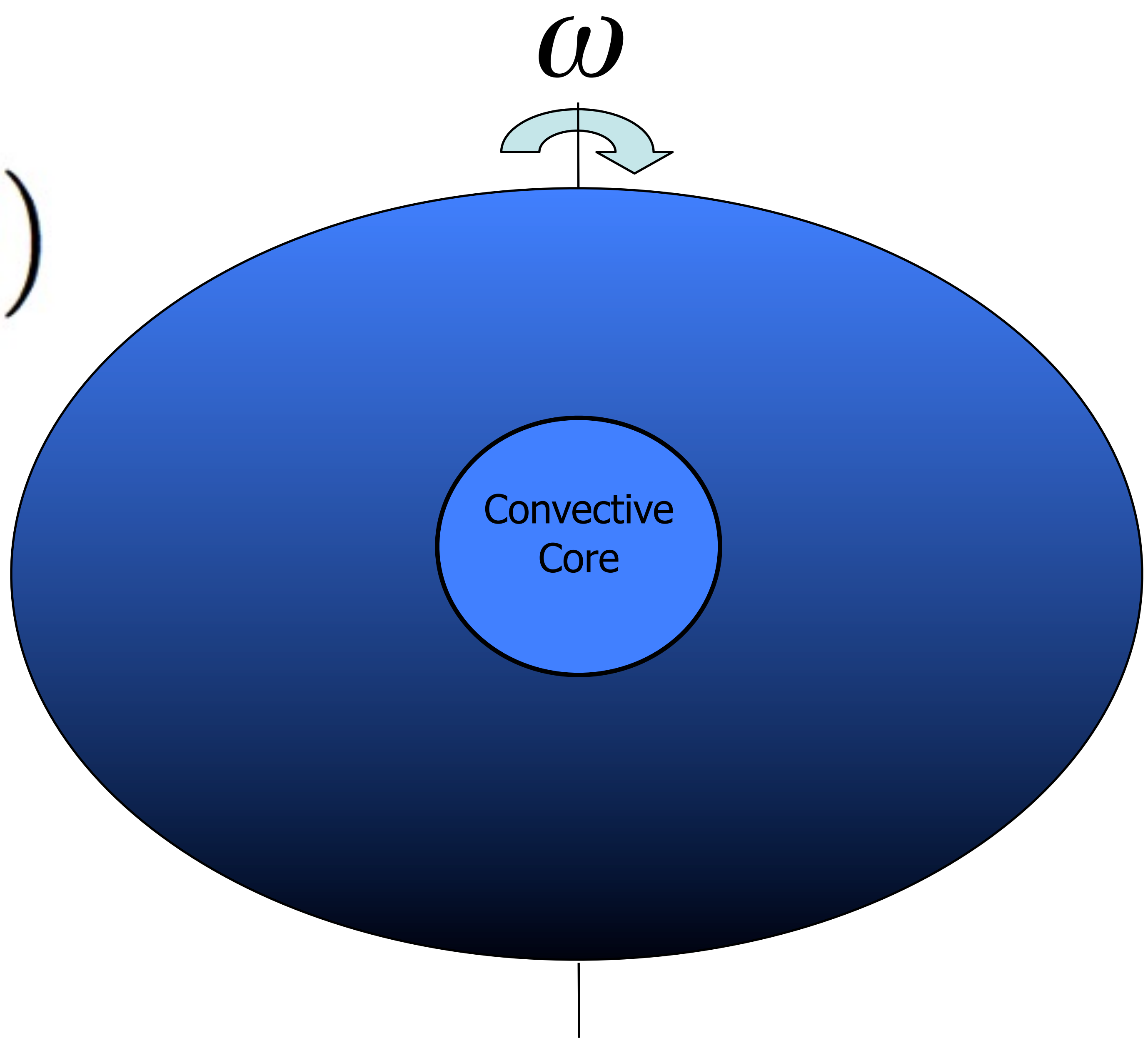


- Hydrodynamics instabilities
- **Rotationally induced circulations**
- Magnetic torques
- Internal gravity waves

Rotationally Induced Circulations

The thermal flux through the surface of a (radiative) rotating star is proportional to the local effective gravity. Since this depends on the co-latitude, one expects a greater radiative flux at the poles than at the equator.

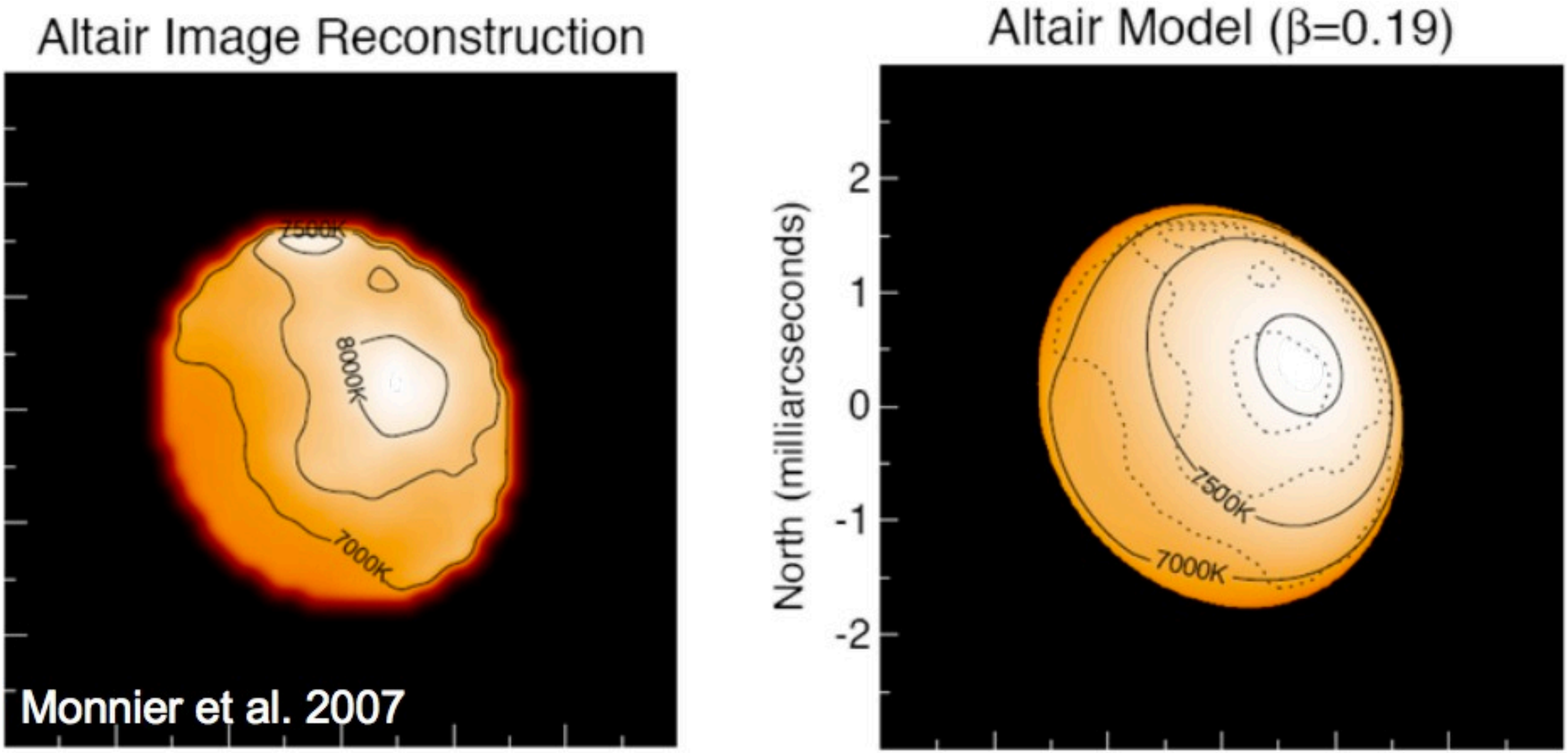
$$T_{\rm eff}(\vartheta) \sim g_{\rm eff}^{1/4}(\vartheta)$$



Von Zeipel Theorem

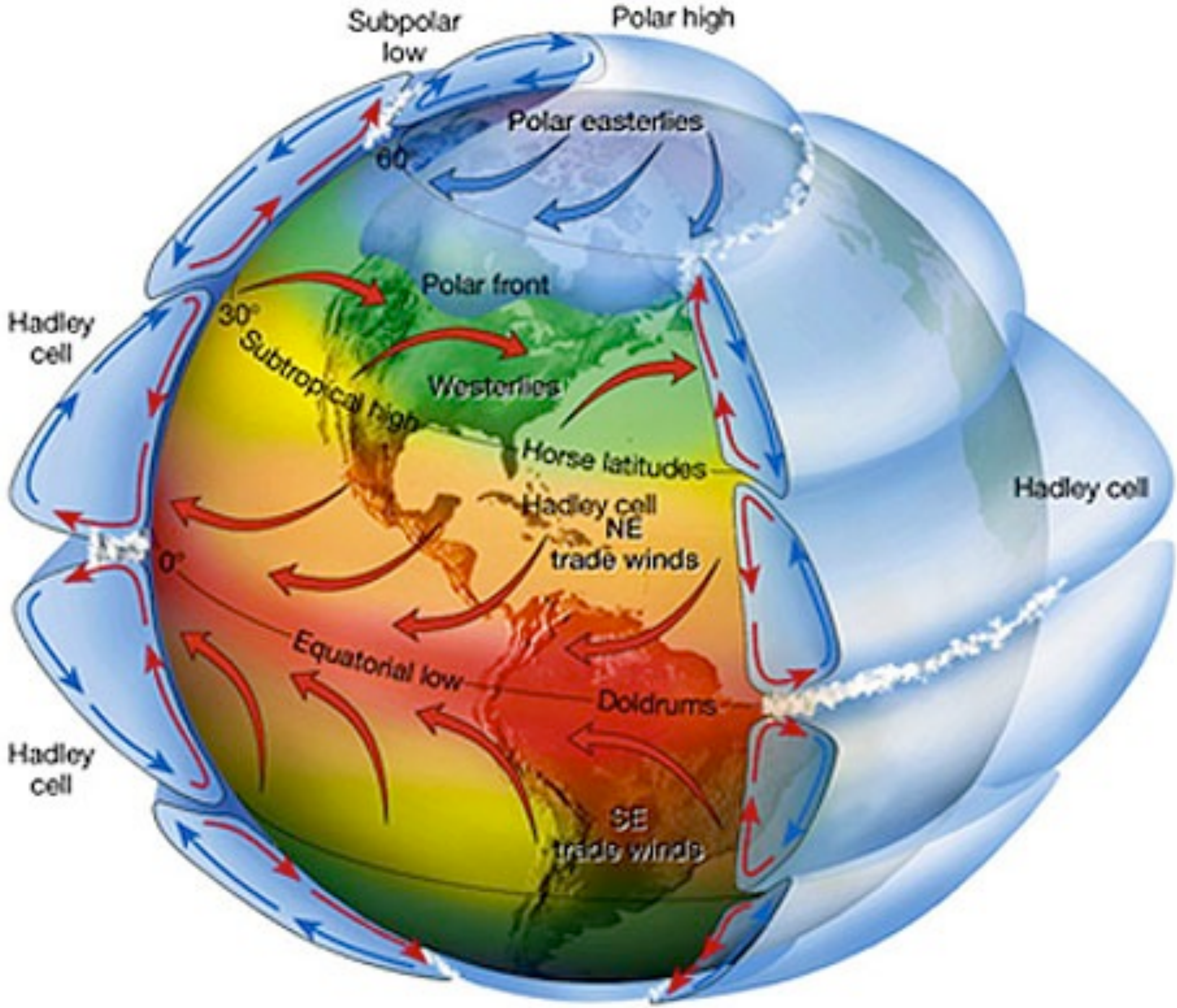
Von Zeipel (1924)

Interferometry of rotating stars



Altair (A7IV-V Star): confirms Von Zeipel ‘gravity darkening’ even if with a slightly different exponent

Thermal imbalance drives circulations



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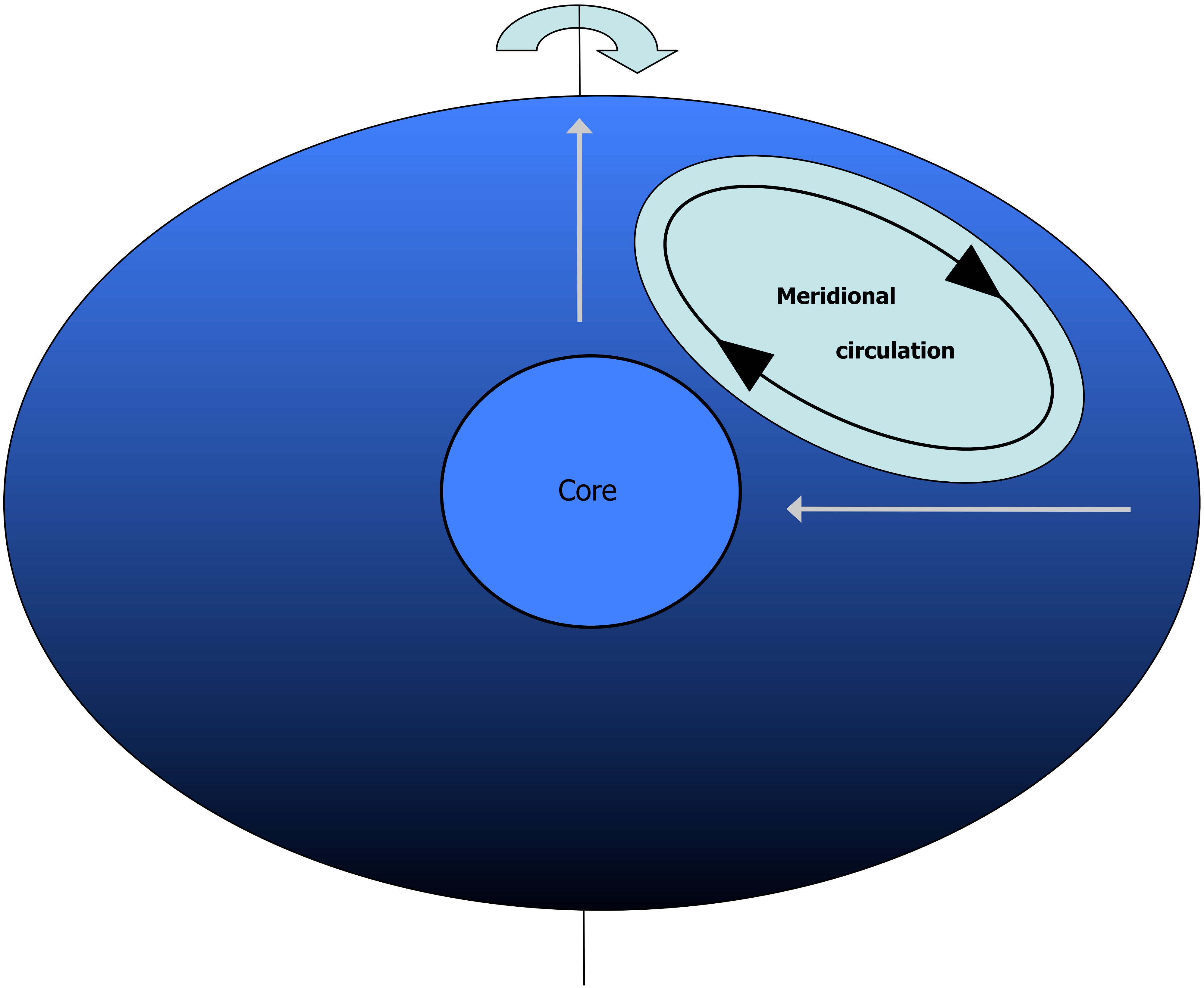
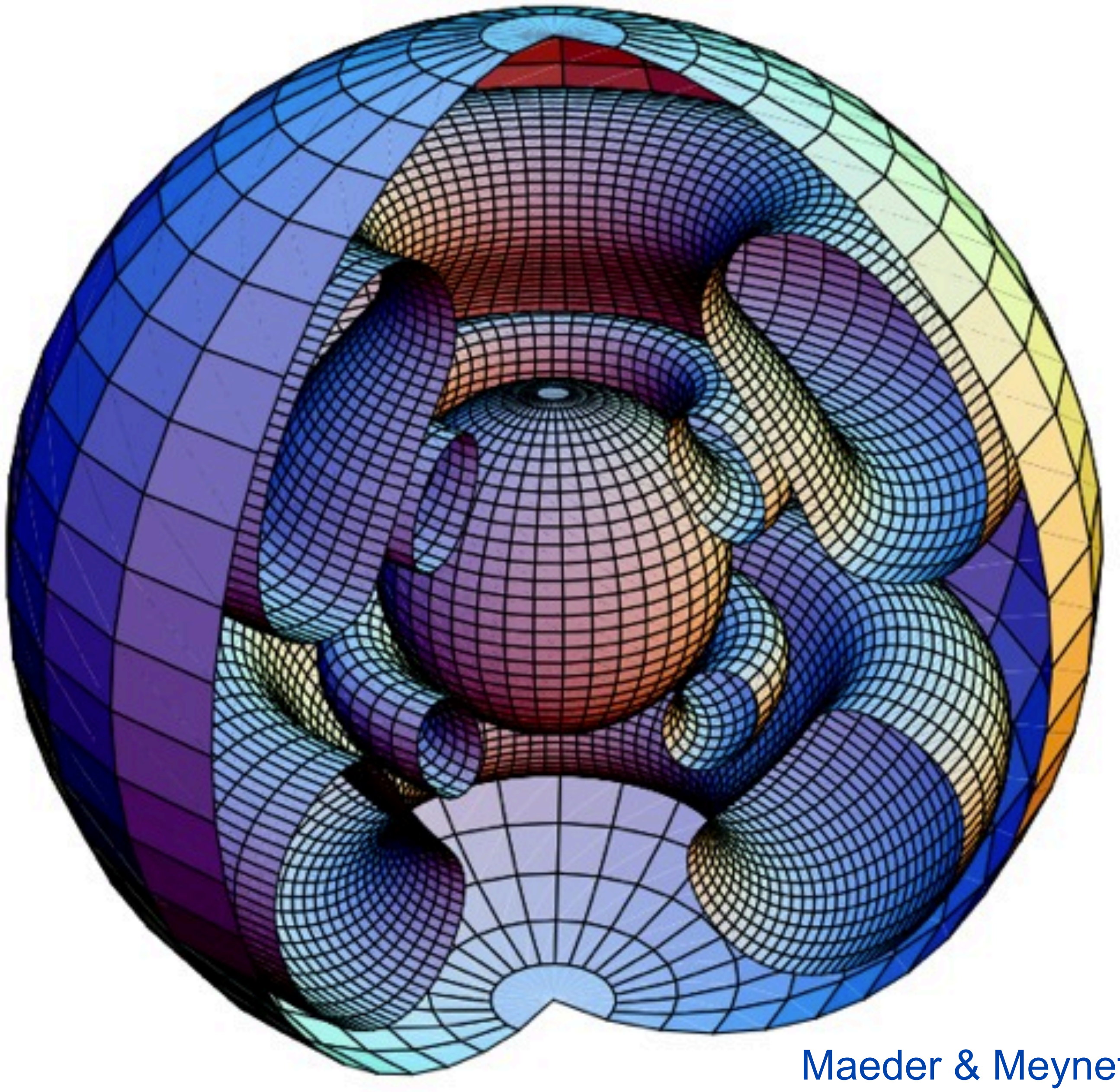


Rotationally Induced Circulations

- **Eddington-Sweet** Circulation
- Is a meridional circulation mixing the stellar interior
- Mixing process on t_{KH}

$$\tau_{ES} \propto \tau_{KH} \left(\frac{\omega_K}{\omega} \right)^2$$



Maeder & Meynet 2002

Angular Momentum Transport

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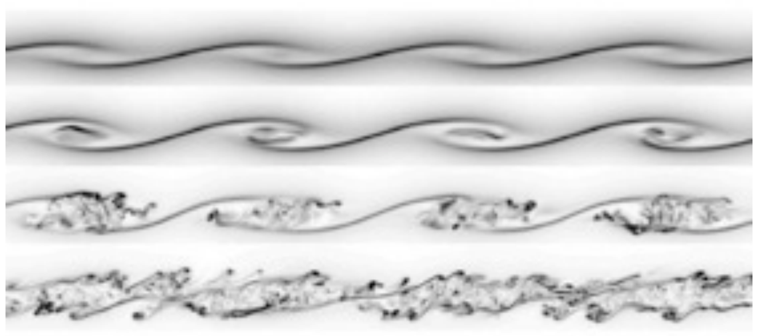

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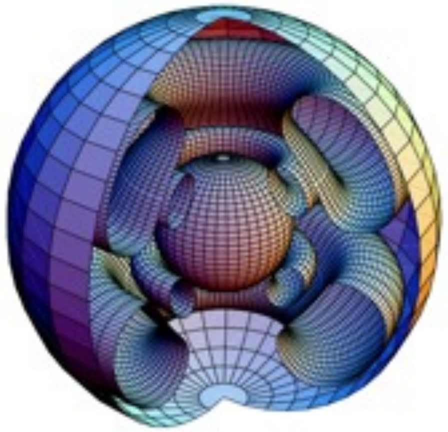

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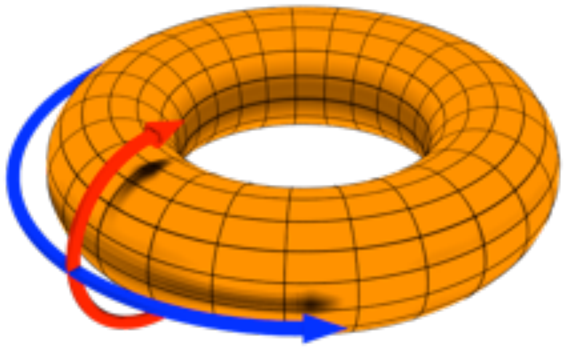

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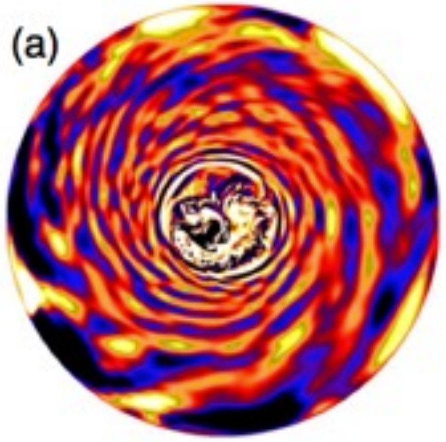
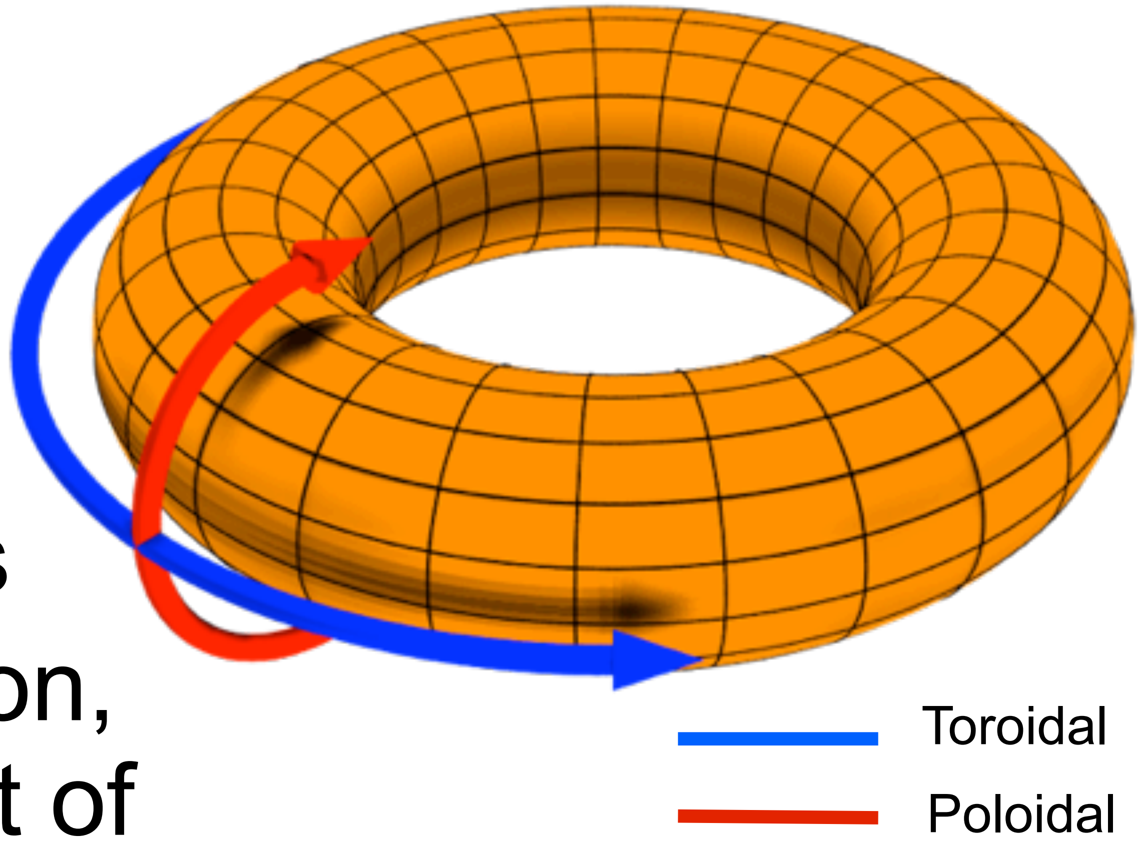
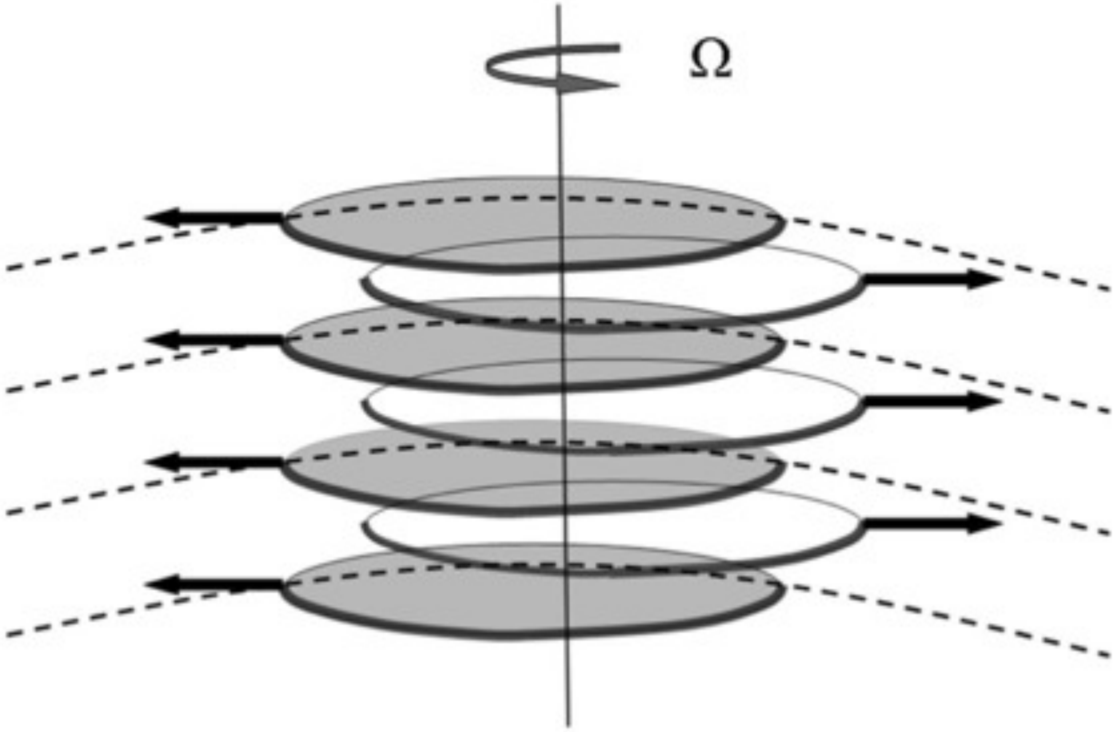


- Hydrodynamics instabilities
- Rotationally induced circulations
- **Magnetic torques**
- Internal gravity waves

Tayler-Spruit Dynamo

- Dynamo in a radiative layer
- Magnetic energy is generated from differential rotation
- Initially a seed magnetic field is stretched by the differential rotation, amplifying the toroidal component of the field
- An instability in the toroidal component of the field (Tayler instability) is used to close the dynamo loop

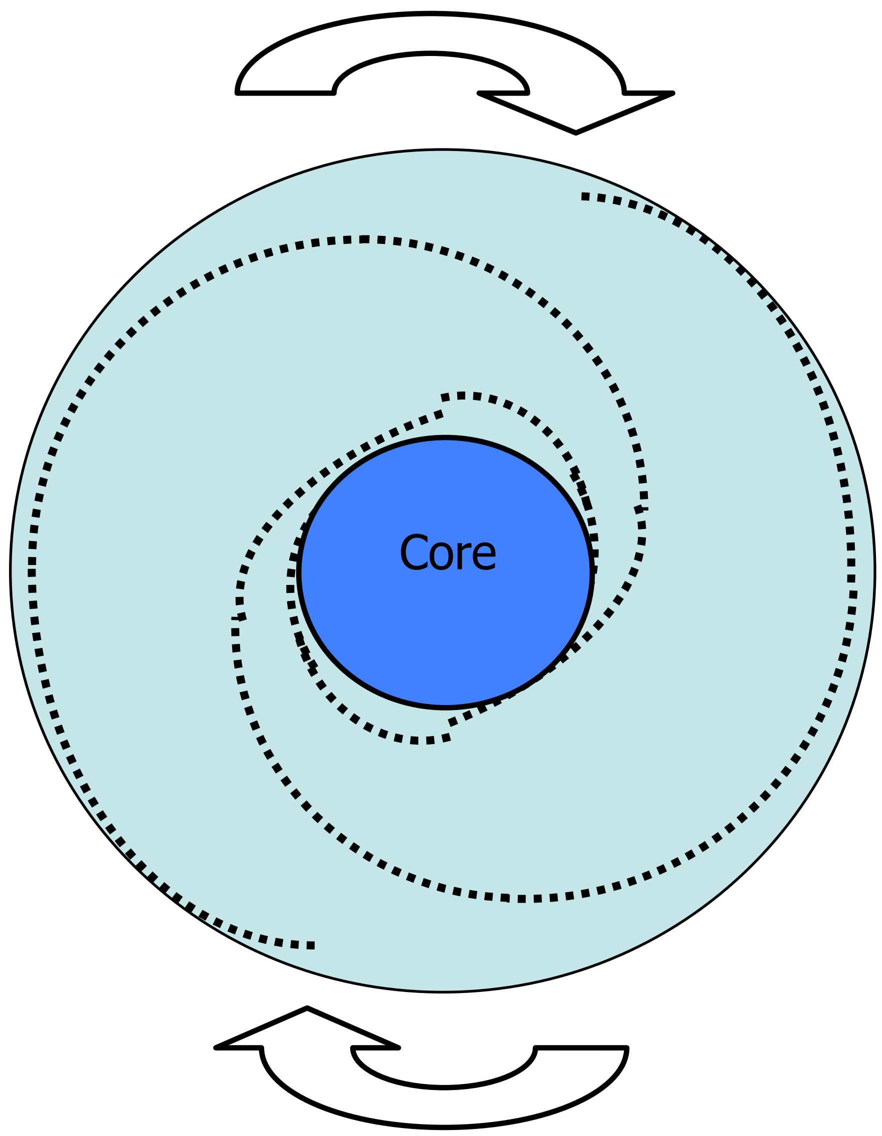




Spruit 2002

Tayler-Spruit Dynamo

- Tayler-Spruit Dynamo (Spruit 2002)
- Core - Envelope coupling



1. Differential rotation winds up toroidal component of B
2. Magnetic torques tend to restore rigid rotation

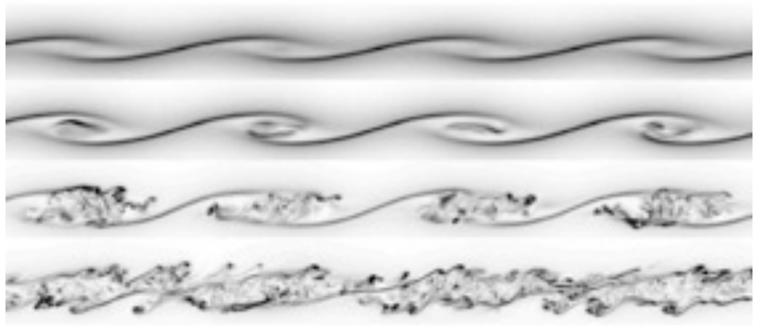
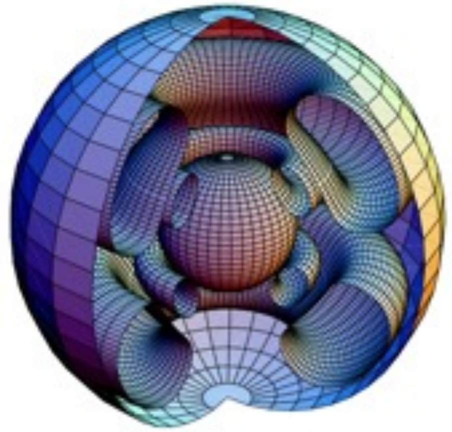
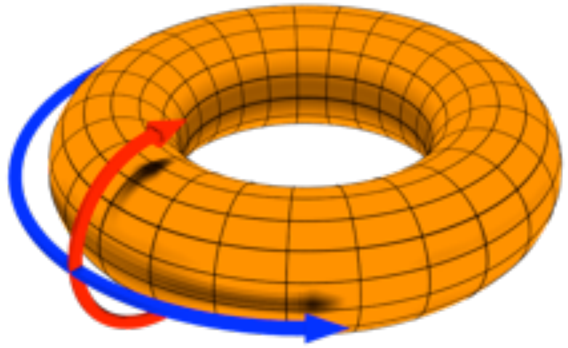
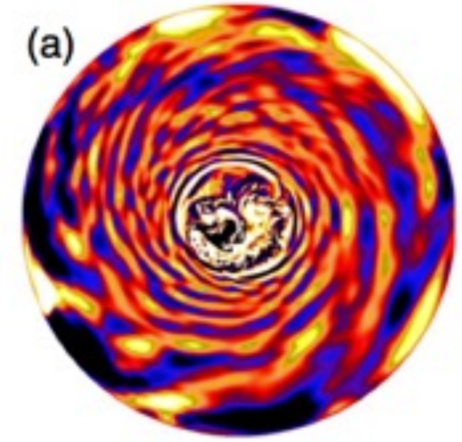
If the envelope slows down angular momentum is also removed from the core

Debate on the TS Dynamo

- The Tayler-Spruit (TS) dynamo is still under review
- While the Tayler instability is sound, the loop proposed by Spruit has been criticized
- Simulations of Zahn et al. 2007 could not find dynamo action
- On the other hand simulations of Braithwaite et al. 2006 showed the TS dynamo
- The jury is still out, but it looks like a j-transport mechanism similar (or even more efficient, see later) than the TS has to work in stars to reproduce some observations (e.g. spin rates of compact remnants, solar rotation profile, Red Giants core rotation) Suijs et al. 2008, Eggenberger et al. 2005, Cantiello et al. 2014

Angular Momentum Transport

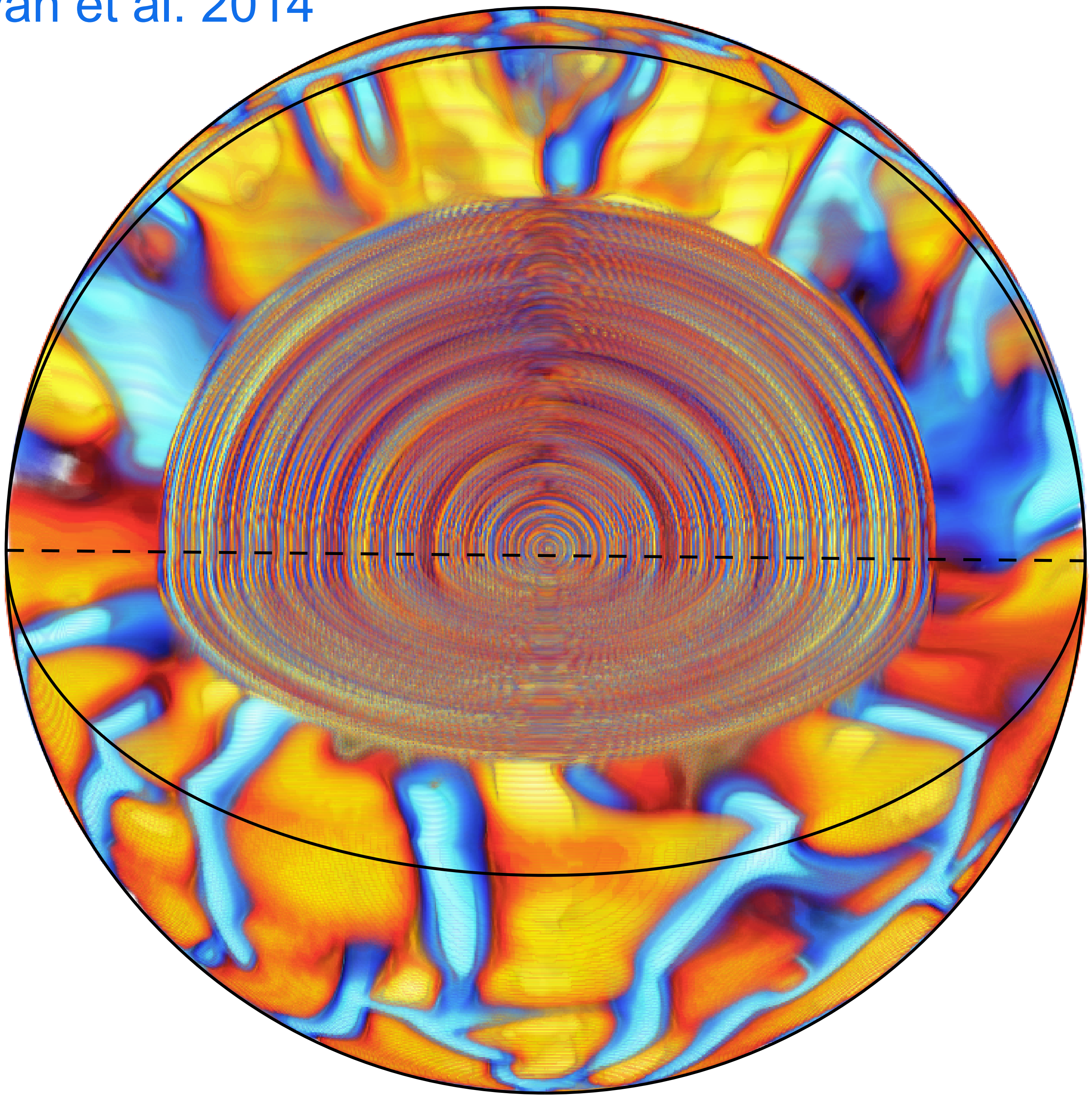
Different classes of mechanisms have been proposed:

- Hydrodynamics instabilities
- Rotationally induced circulations
- Magnetic torques
- **Internal gravity waves**
  - Charbonnel & Talon 2005
  - Rogers et al. 2013
  - Alvan et al. 2014
  - Fuller, Lecoanet, MC et al. 2014
  - Fuller, MC et al. 2015

Internal Gravity Waves

Alvan et al. 2014



IGW: Excited by turbulent convection

They carry angular momentum

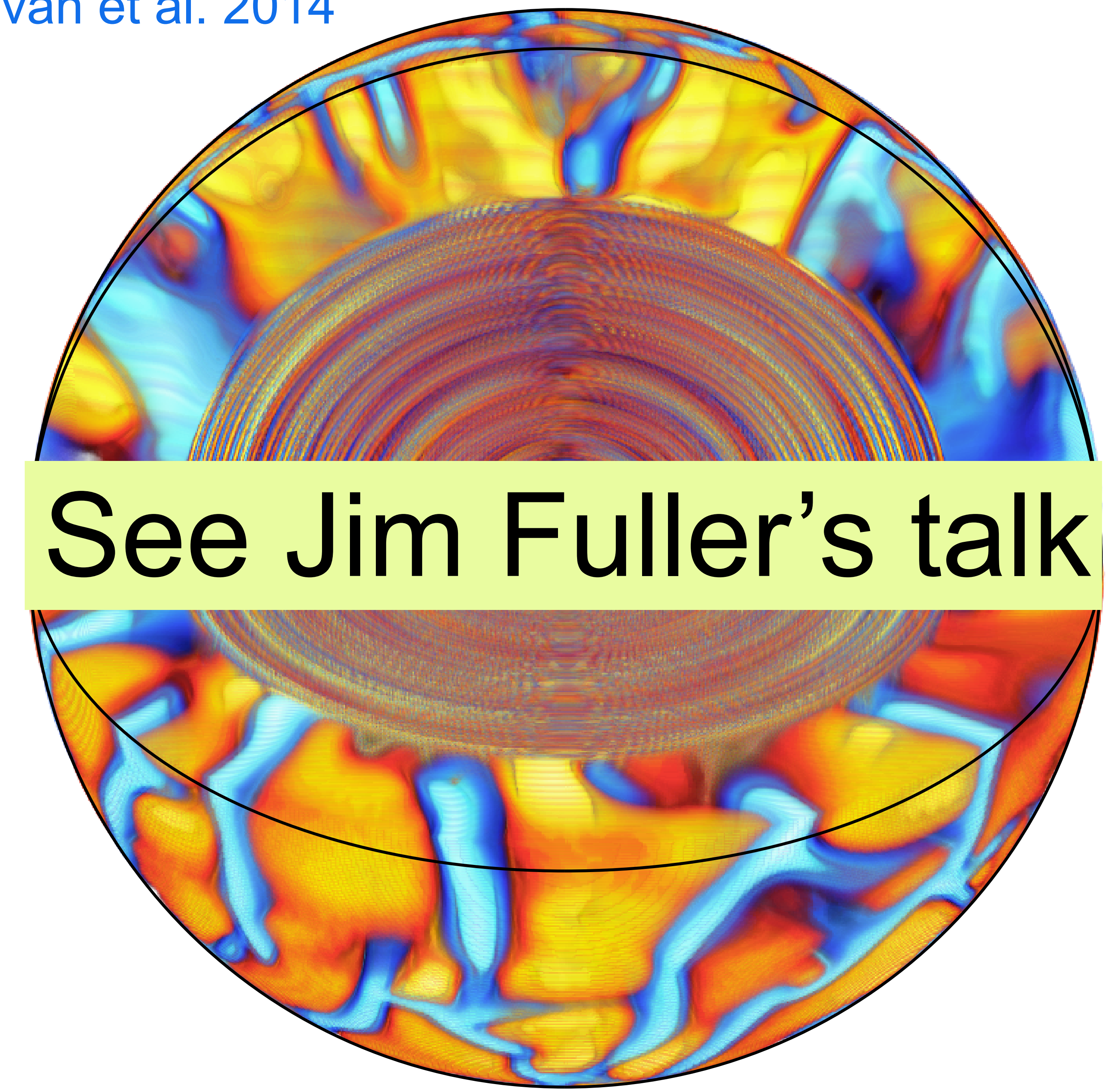
Spectrum: Not well understood. But likely Kolmogorov-like with a steep exponent

Dissipation: Radiative dissipation usually dominates in stellar interiors

See e.g.: Charbonnel & Talon 2005, Goldreich & Kumar 1990, Lecoanet & Quatert 2013, Mathis et al. 2014, Rogers et al. 2013, Fuller, MC et al. 2015

Internal Gravity Waves

Alvan et al. 2014



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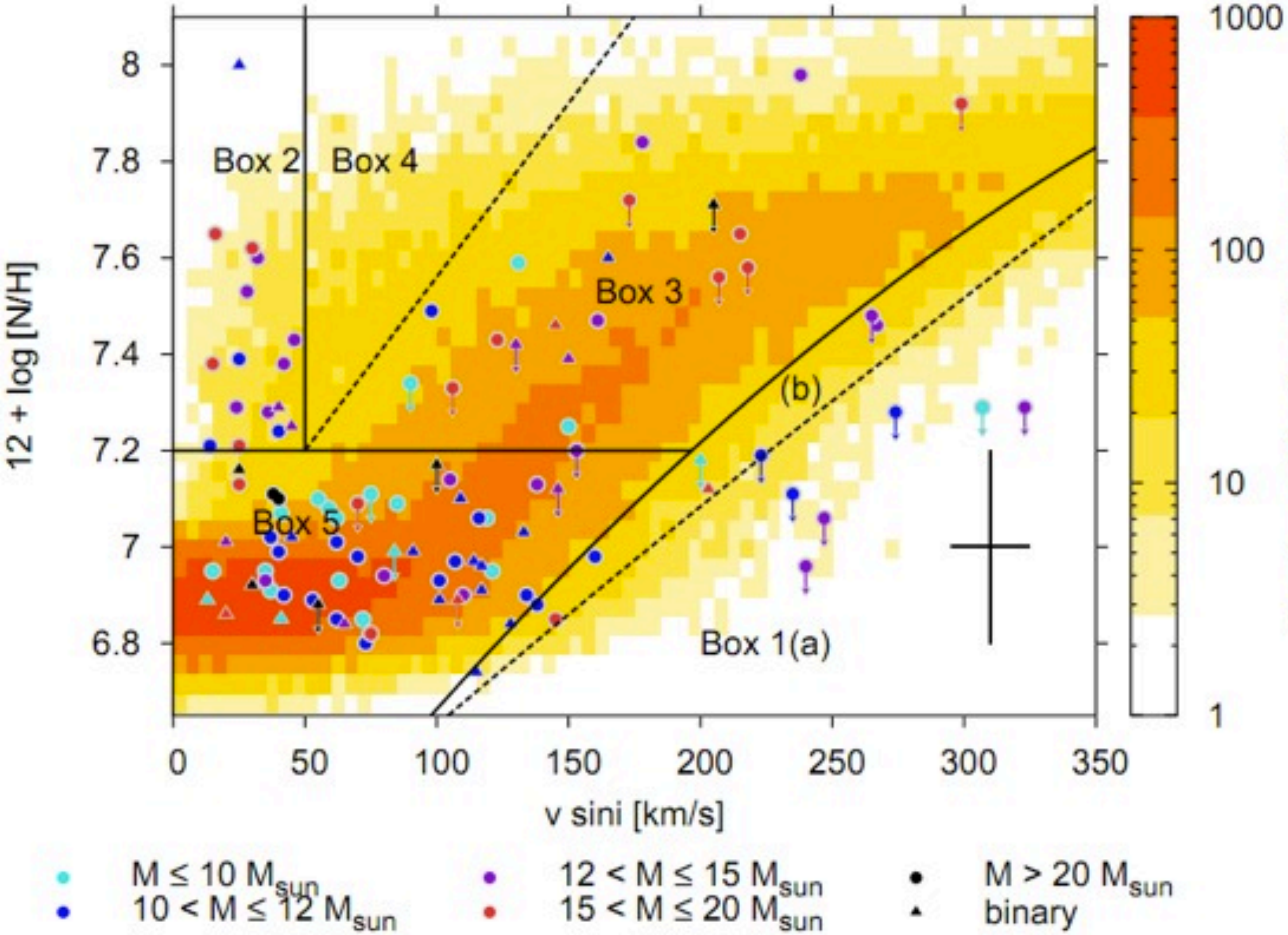
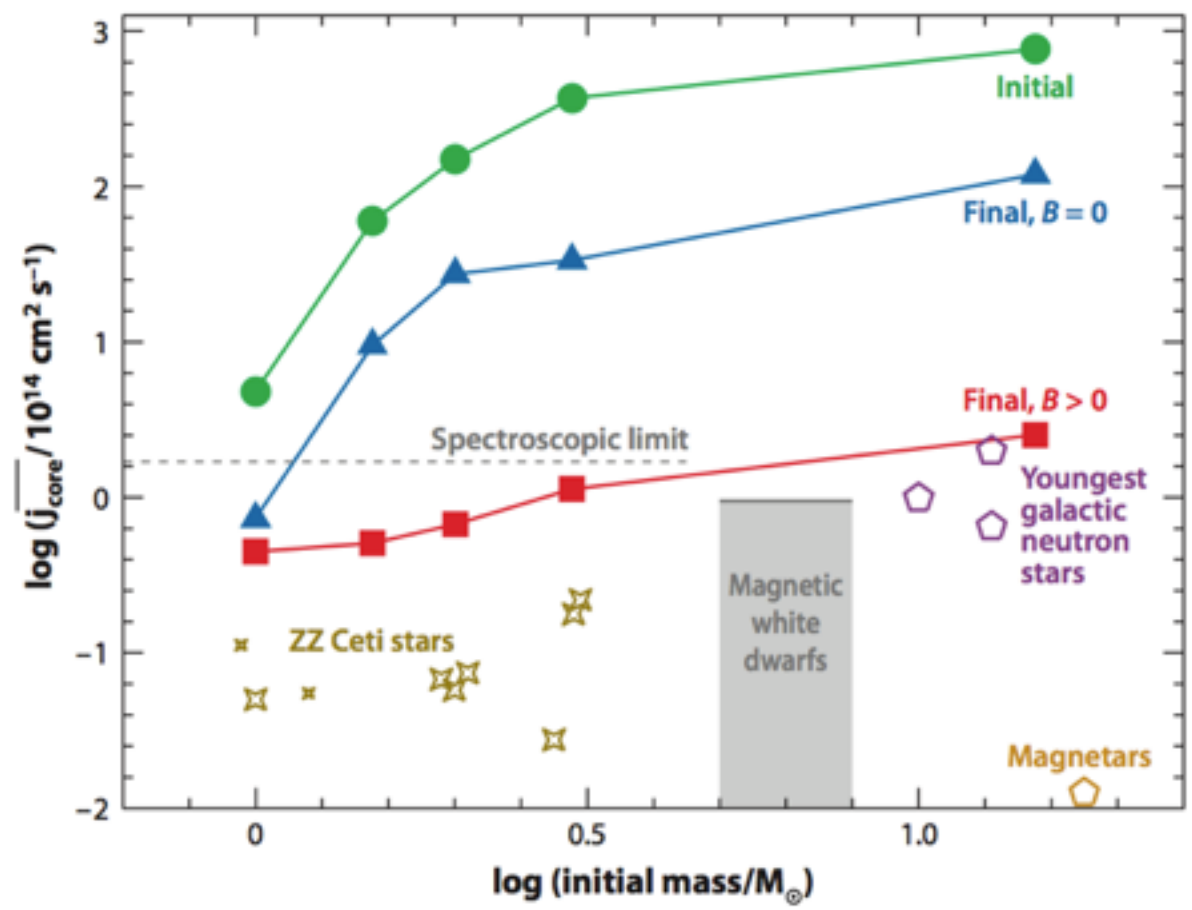
Tests of Angular Momentum Transport

Testing angular momentum transport mechanisms

Brott et al. 2011

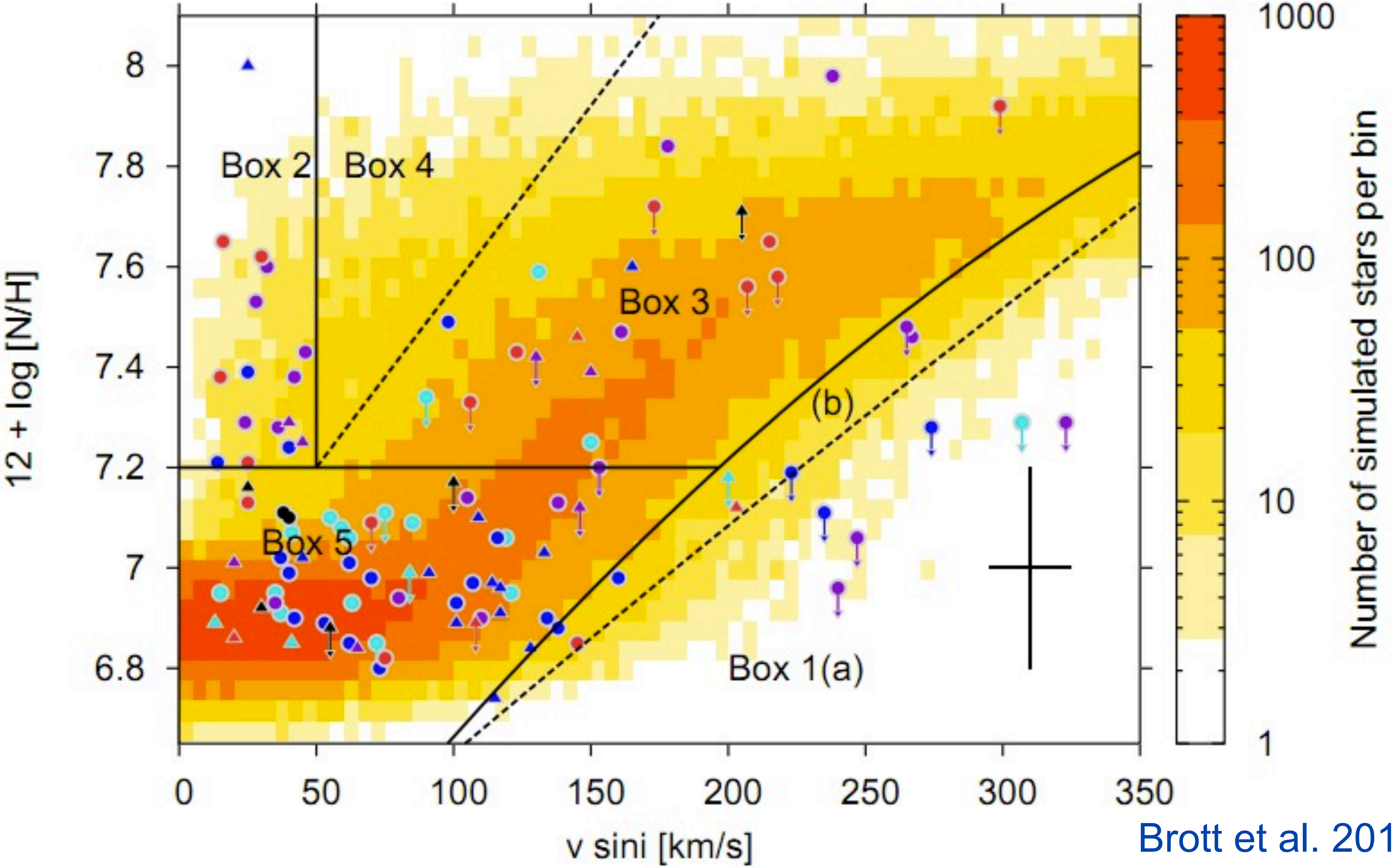


Suijs et al. 2008



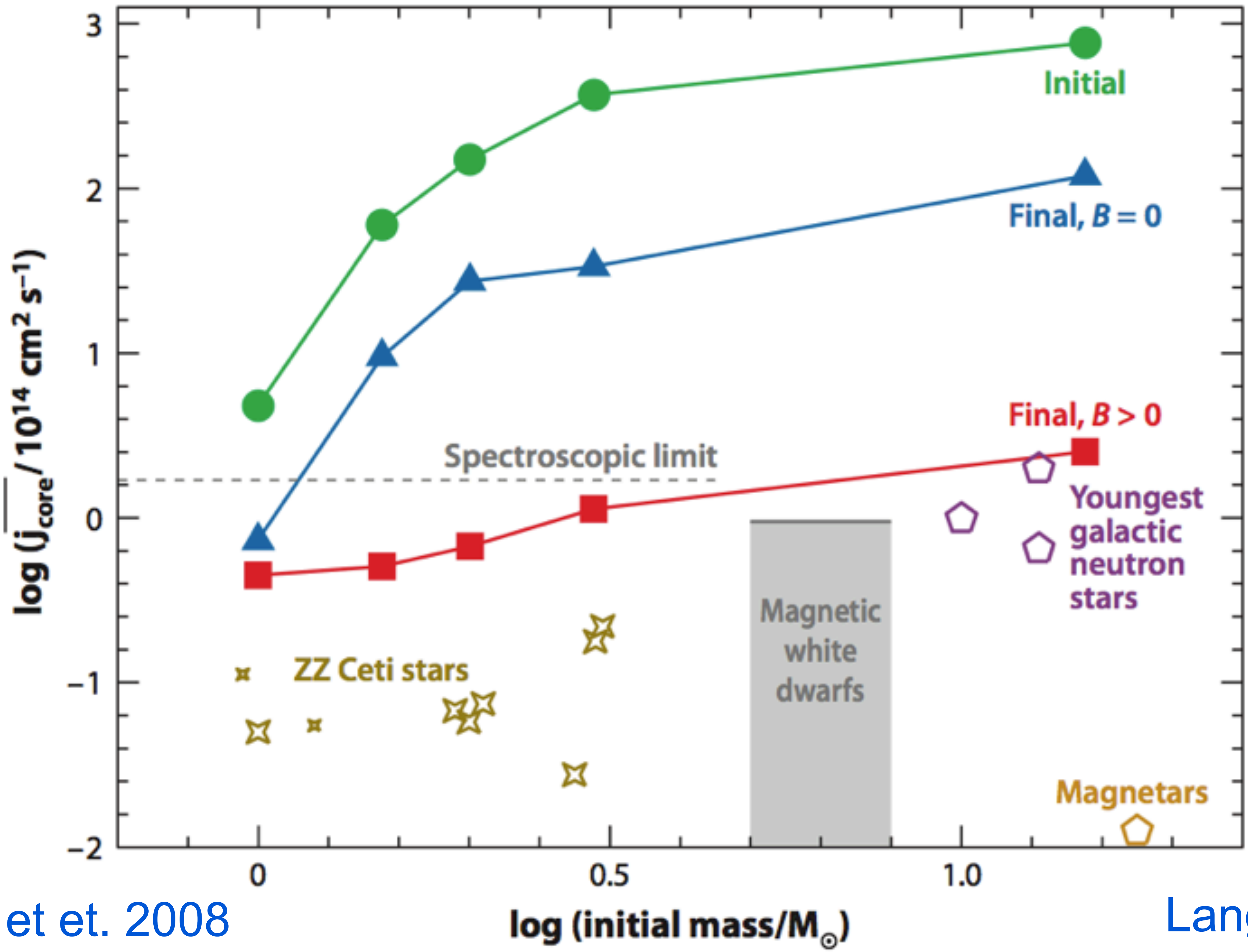
- Surface abundances
- Compact Remnants

Testing angular momentum transport mechanisms



Brott et al. 2011

Testing angular momentum transport mechanisms



Suijs et et. 2008

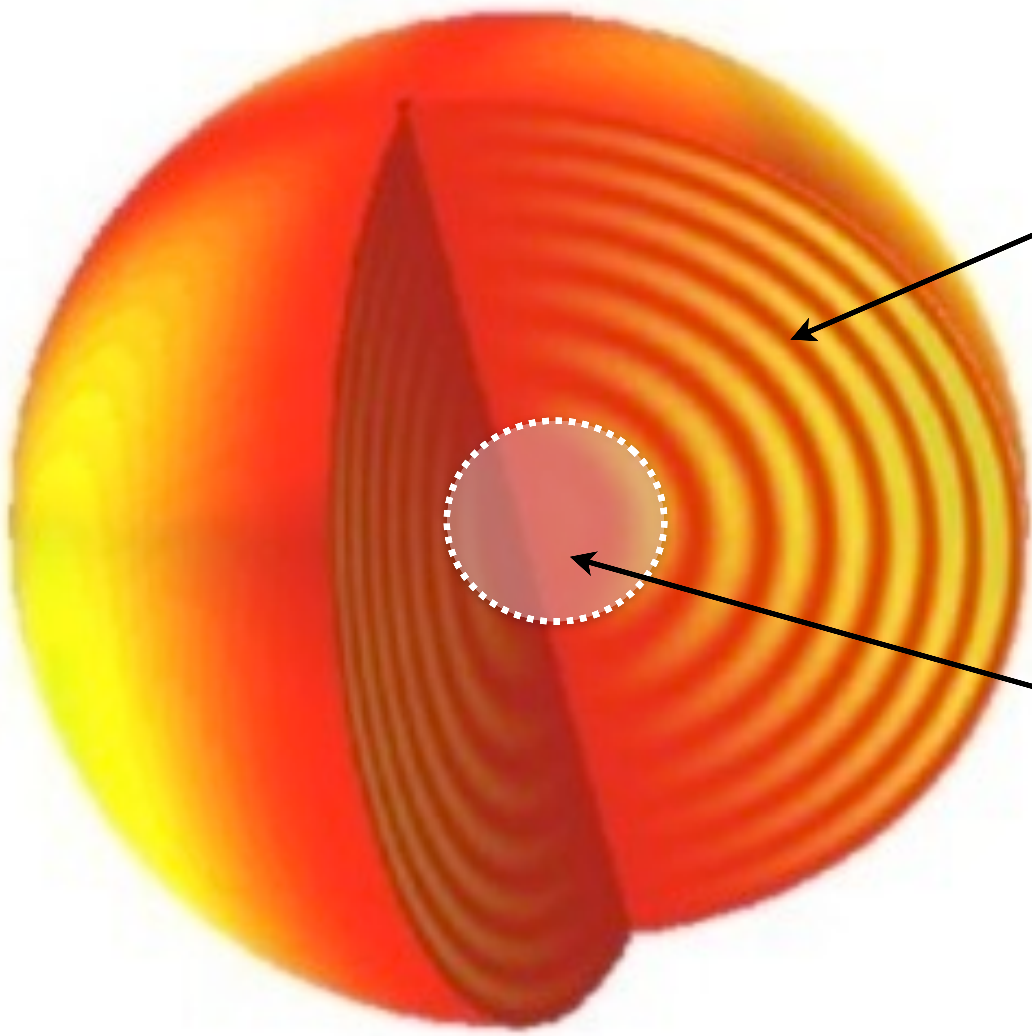
Langer 2012

Testing angular momentum transport mechanisms

- Surface abundances
- Rotation of compact remnants
- **Asteroseismology**

Red giants Asteroseismology

Mixed Modes

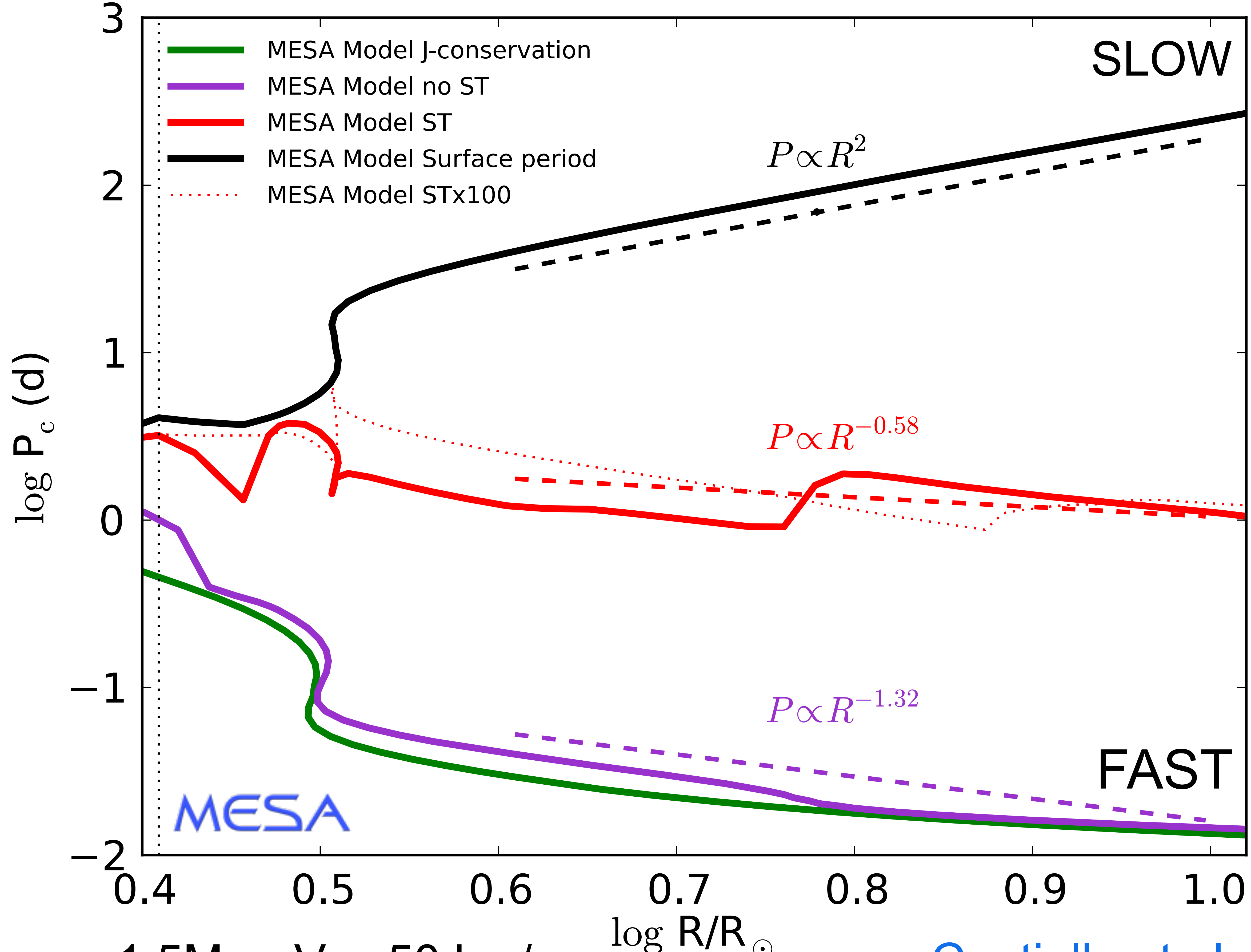


p-mode cavity (envelope)

g-mode cavity (core)

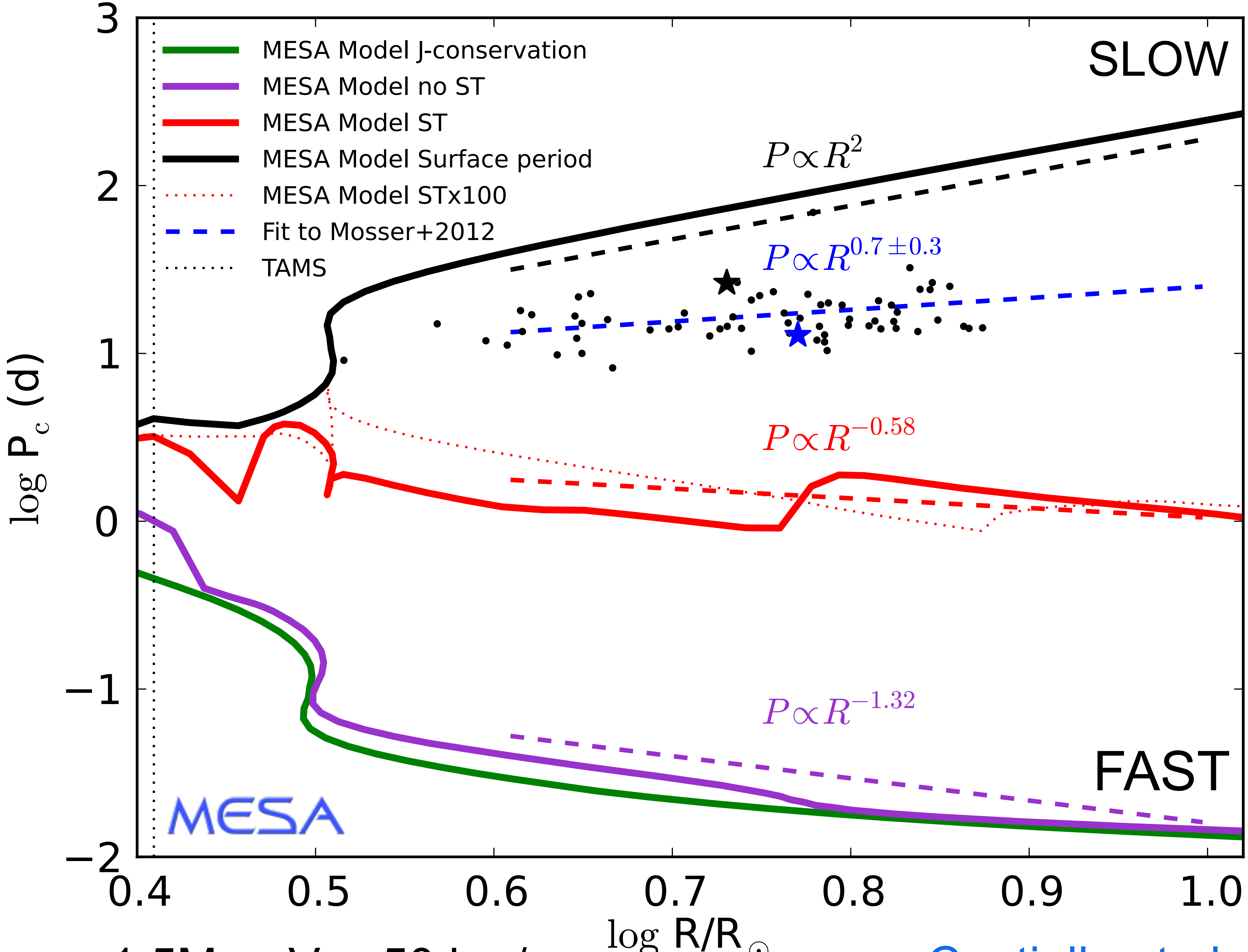
Since a mixed mode lives both as a p-mode (in the envelope) and as a g-mode (in the core), if observed at the surface can give informations about conditions (e.g. **rotation rate**) in different regions of the star!

Beck et al. 2012, Mosser et al. 2012



$1.5 M_{Sun}$ V_{ini}=50 km/s

Cantiello et al. (2014)

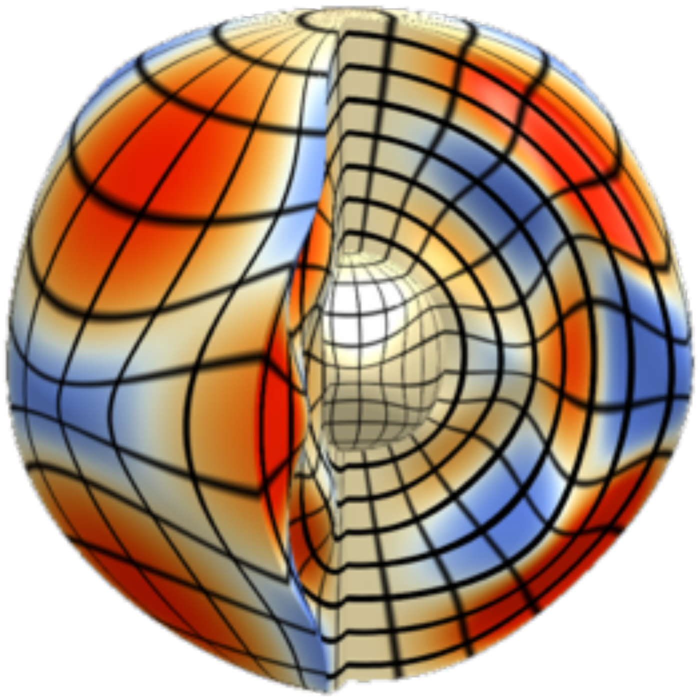


$1.5 M_{Sun}$ V_{ini}=50 km/s

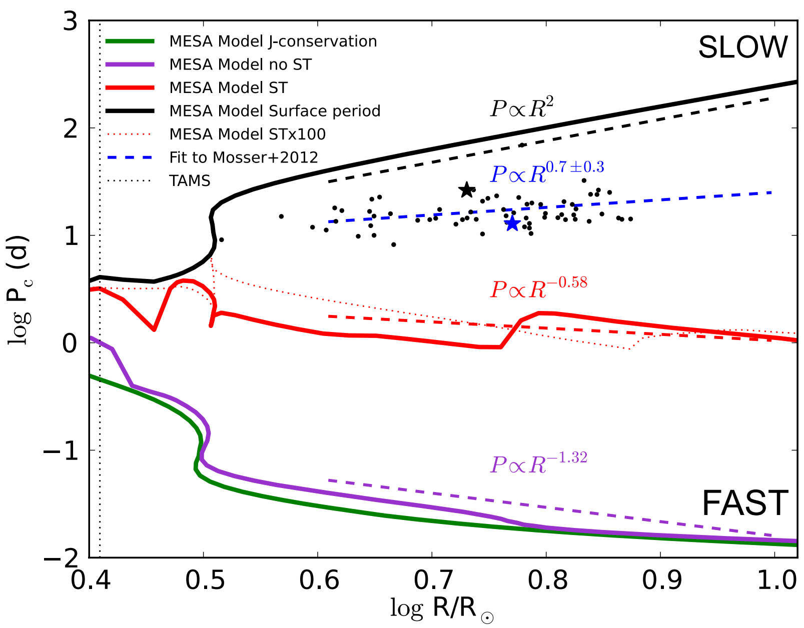
Cantiello et al. (2014)

Take Home Messages

Credits: R. Townsend



- Thanks to space-based asteroseismology it is now possible to **access the internal rotational profile** of stars other than the Sun
- Despite great progress in last few years, the nature of **internal mixing of angular momentum** is still an unsolved problem



Cantiello et al. 2014, Fuller et al. 2014

Conclusions

- Rotation and binarity play an important role for the evolution and final fate of massive stars
- In most codes rotation and the induced transport of angular momentum and chemical species are included in a 1D, diffusion approximation
- A number of physical process are modeled. Indirect tests include surface abundances and remnant rotation rates
- In low-mass stars asteroseismology provides a way to directly probe the rotational evolution of stellar cores
- We still do not fully understand internal angular momentum transport in stars. More to do!