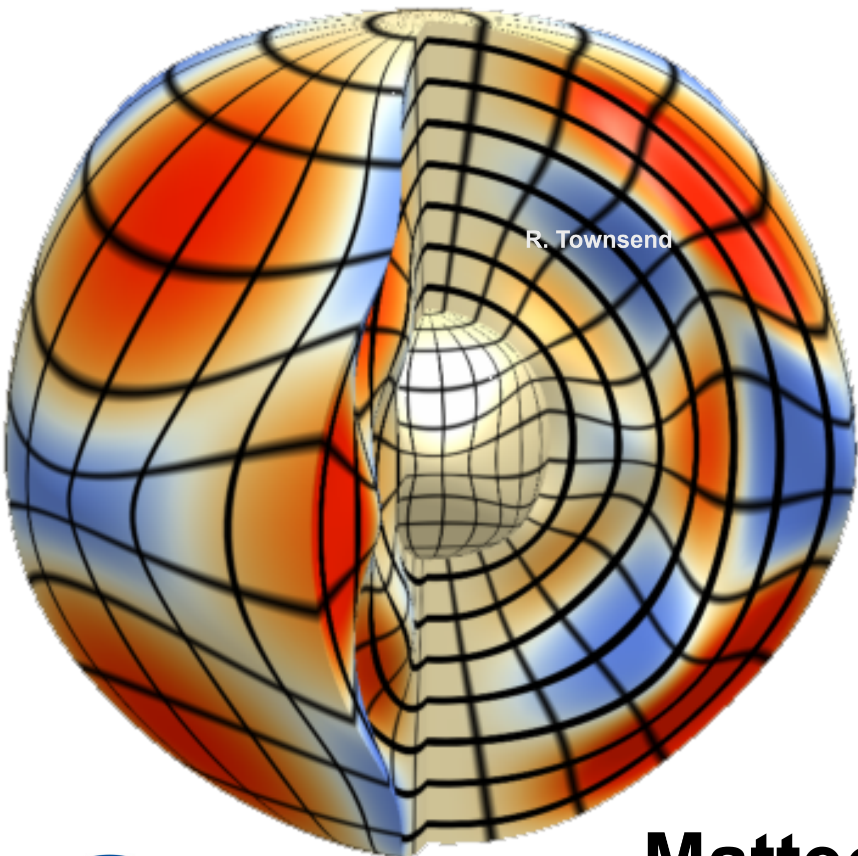
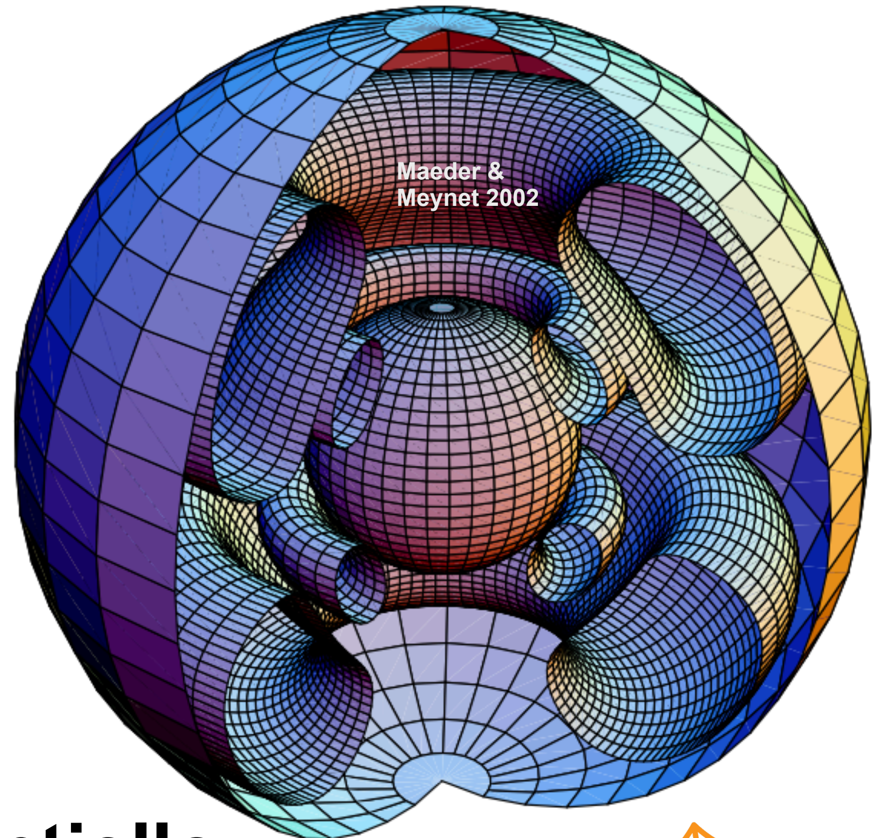
Rotation and Asteroseismology:
Testing Angular Momentum Transport Mechanisms





Matteo Cantiello

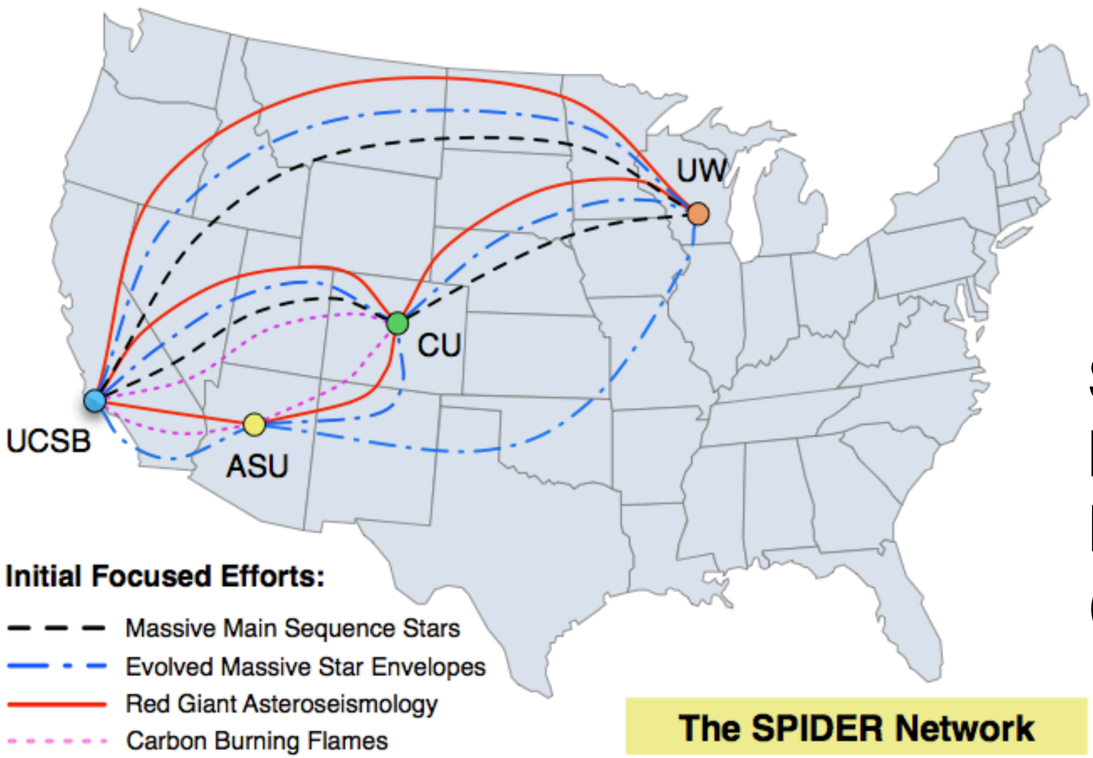
Kavli **I**nstitute for **T**heoretical **P**hysics

(University of California Santa Barbara)

SPIDER

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

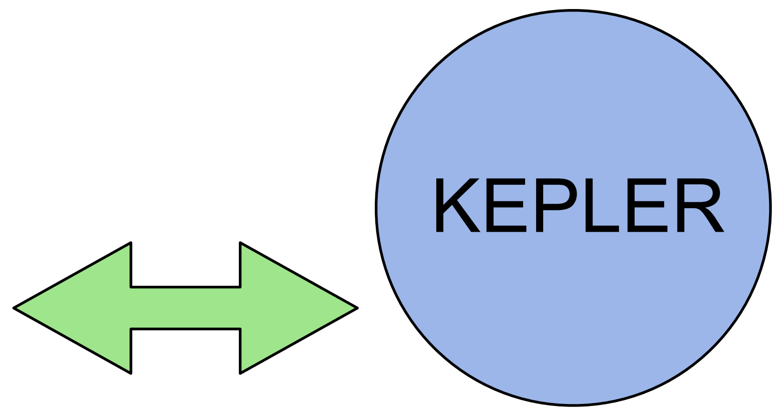
SPIDER Network



SPIDER

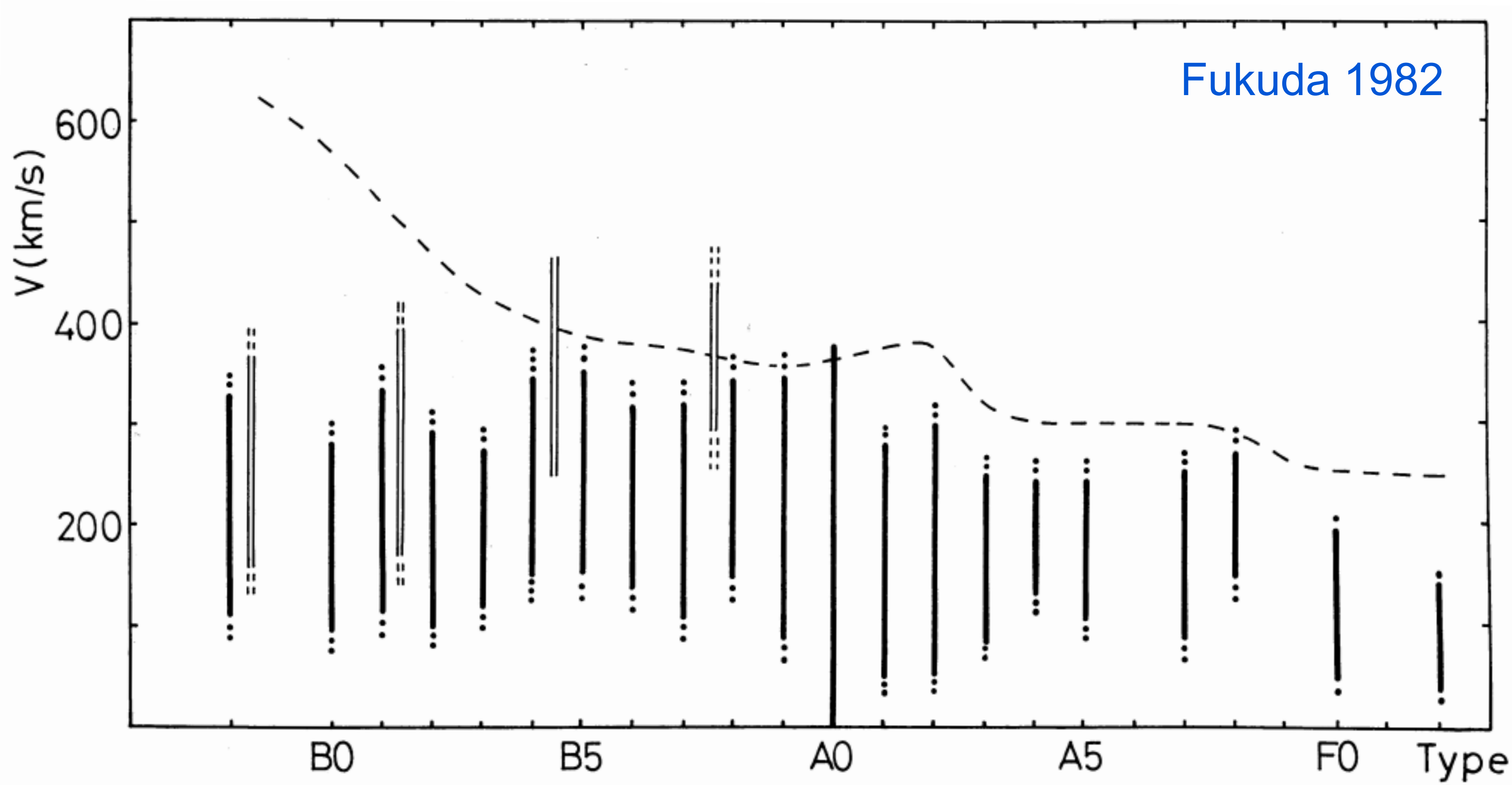
Supernova **P**rogenitors, **I**nternal **D**ynamics and **E**volution **R**esearch (Funded by TCAN / NASA)

Node	**ASU** Arizona State University	**UW** University of Wisconsin	**CU** University of Colorado	**UCSB** University of California Santa Barbara
Fundamental Theory	Stellar Evolution, Flames, Supernovae, Nucleosynthesis	Massive Stars, Asteroseismology, Waves, MHD	Convection, Dynamos MHD, Waves, Helioseismology,	Stellar Evolution, Supernovae, Asteroseismology
Computational Tools	MESA	GYRE	ASH CSS	MESA



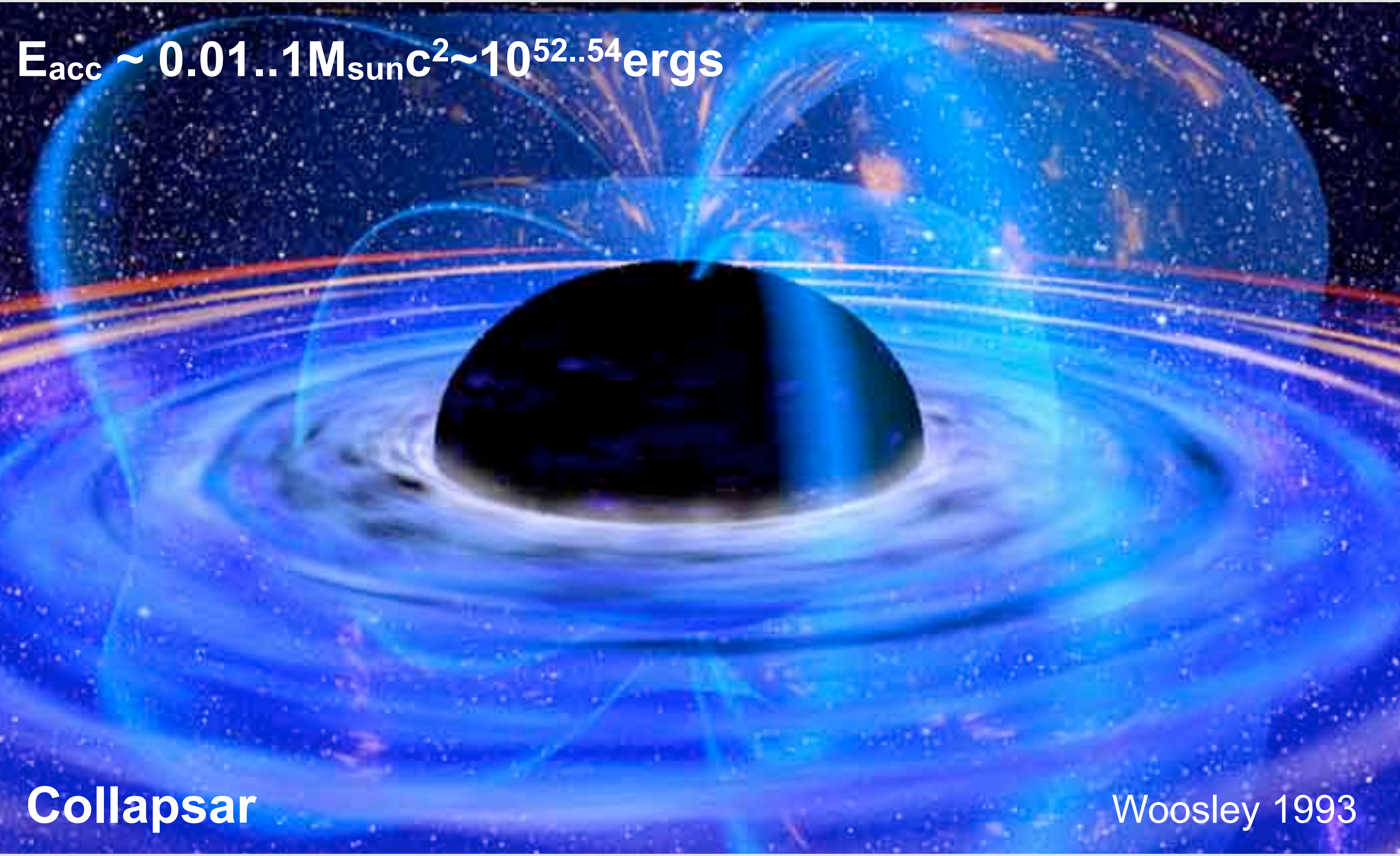
Range of rotational velocity

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



When you wish upon a star... you wish upon a rotating sphere of hot plasma

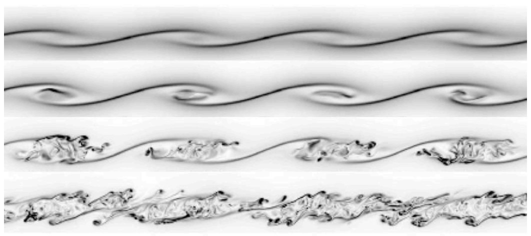
Long GRB Central Engine



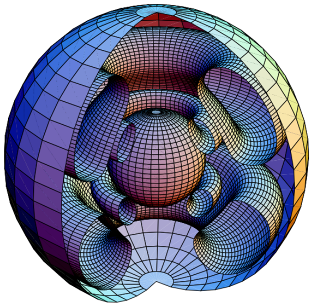
Angular Momentum Transport

Different classes of mechanisms have been proposed:

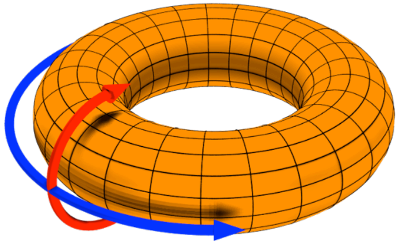
e.g. Heger et al. 2000



e.g Maeder & Meynet 2002



e.g. Spruit 2002



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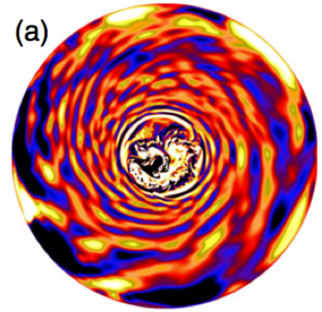

- Hydrodynamics instabilities
- Rotationally induced circulations
- Magnetic torques
- Internal gravity waves

Angular Momentum Transport

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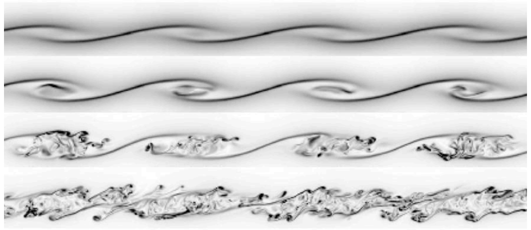
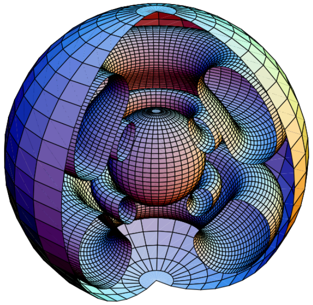


e.g Maeder & Meynet 2002



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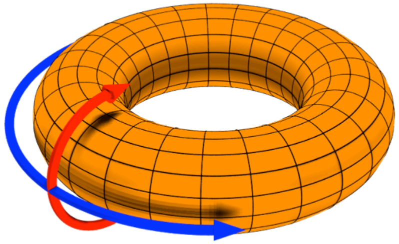

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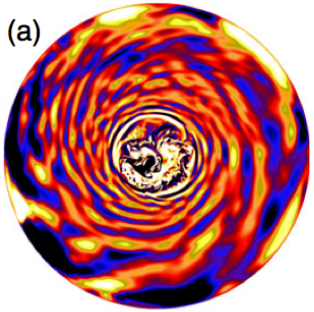

- Hydrodynamics instabilities
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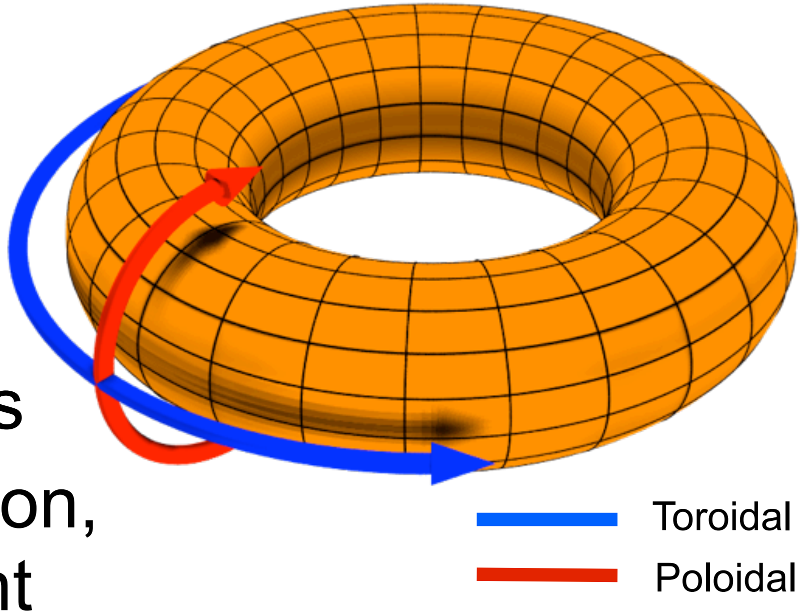
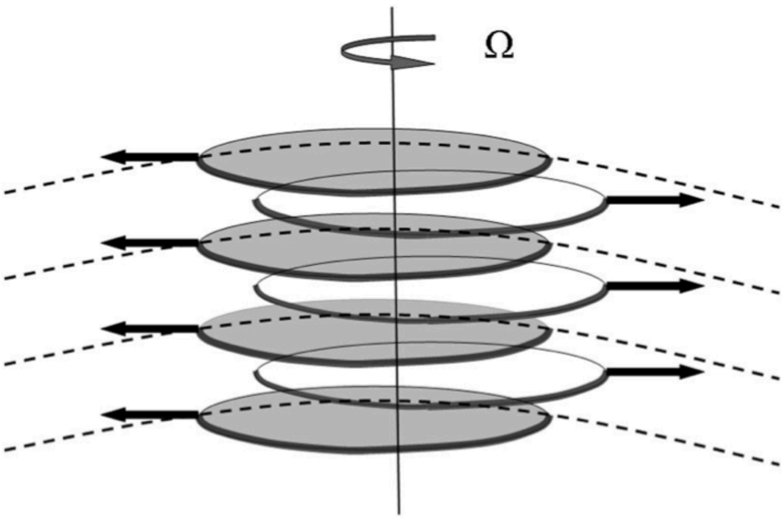
See Ana Palacios' talk

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

Debate on the ST 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 Spruit-Tayler 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) Suijs et al. 2008, Eggenberger et al. 2005

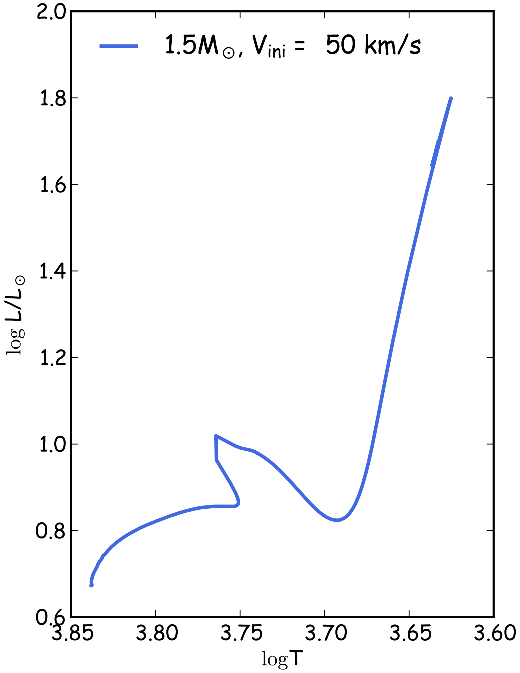
Testing angular momentum transport mechanisms

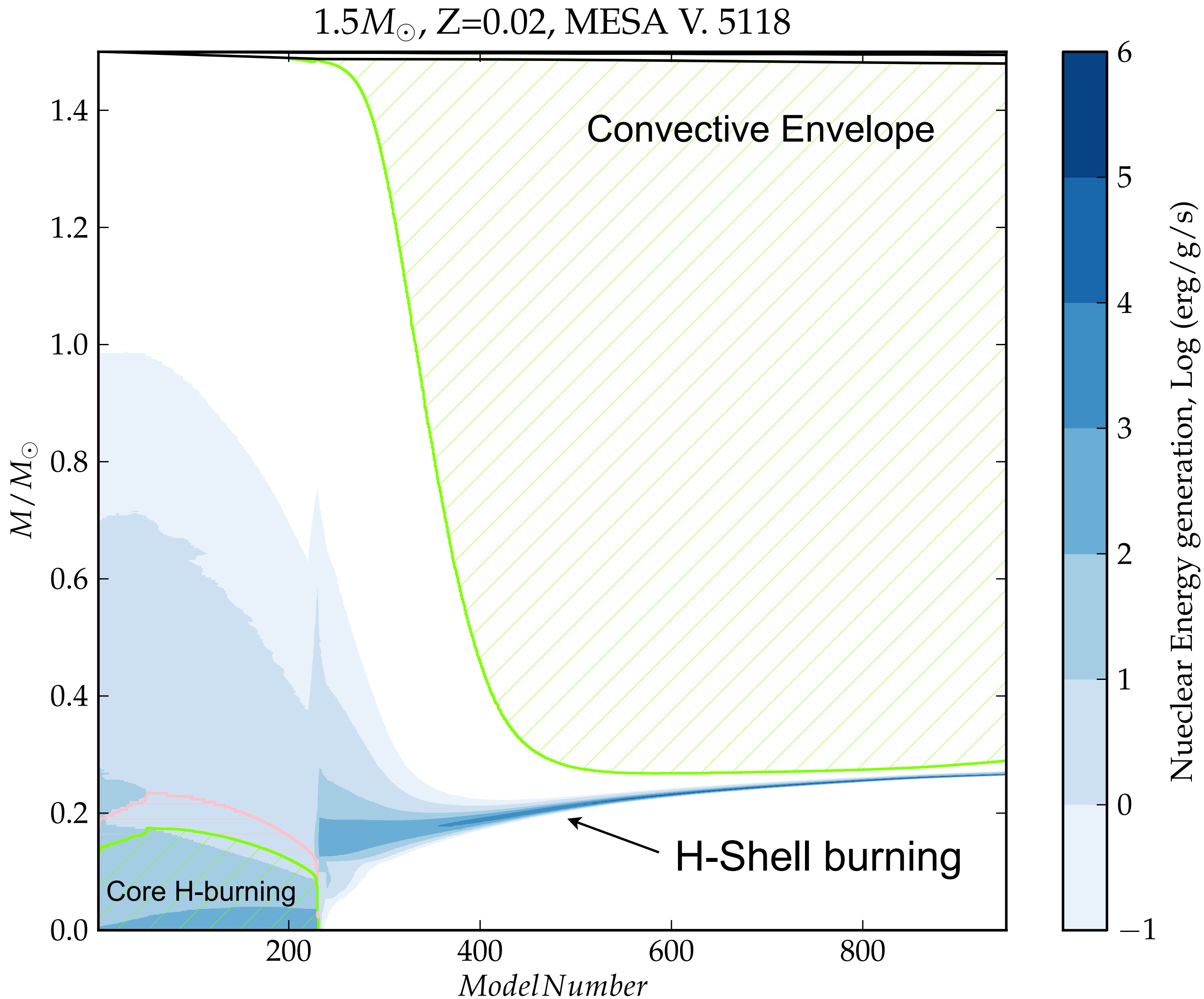
- Surface abundances
- Rotation of compact remnants
- Asteroseismology

Red giants Asteroseismology

Evolution of a 1.5 M_{Sun}

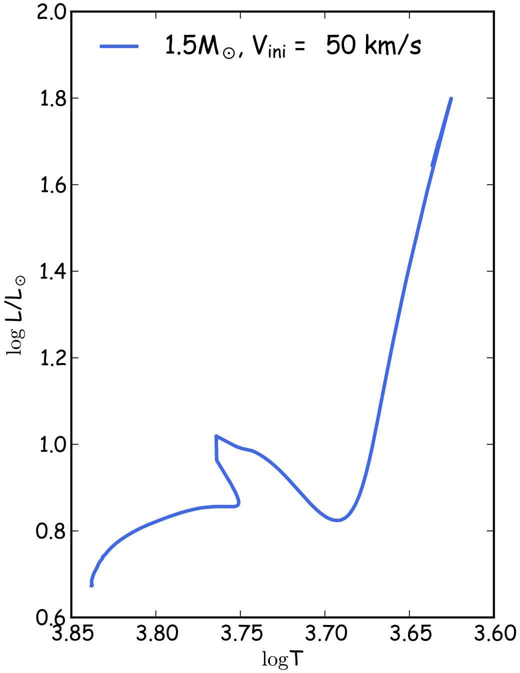
In Mass Coordinate

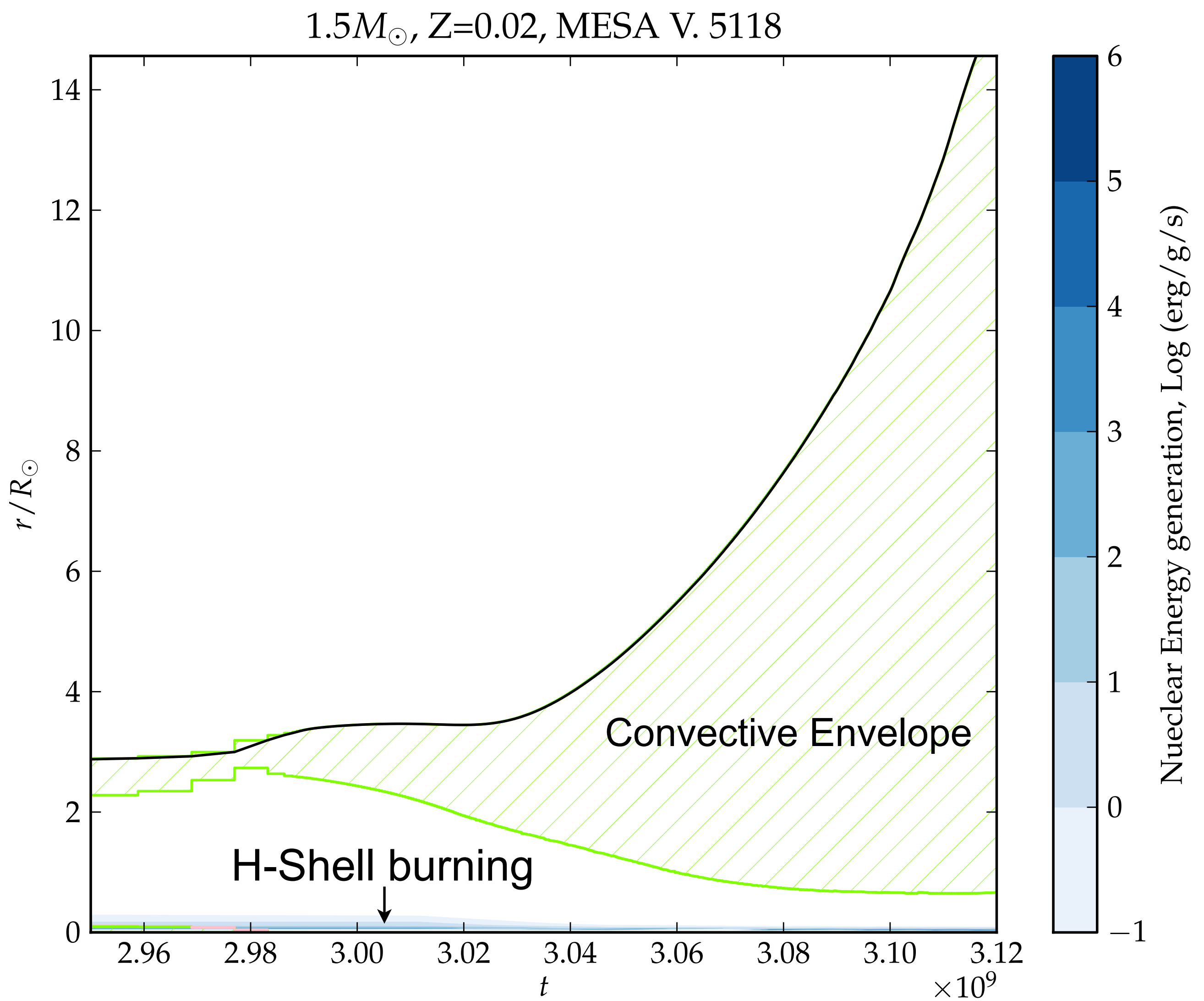




Evolution of a 1.5 M_{Sun}

Zoom
In Radius
Coordinate





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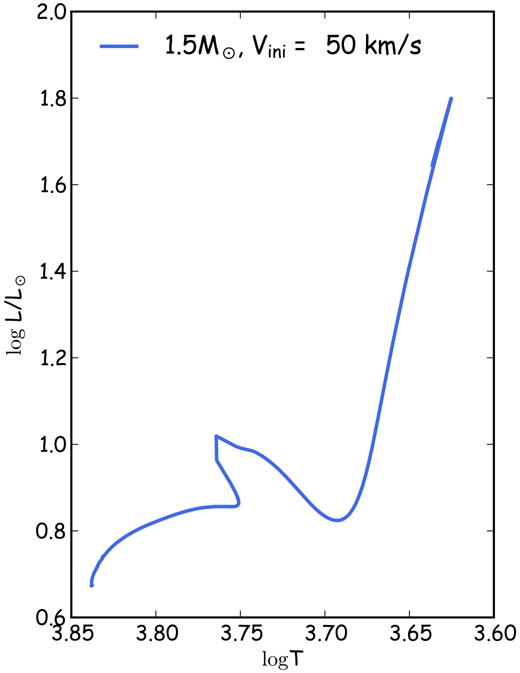

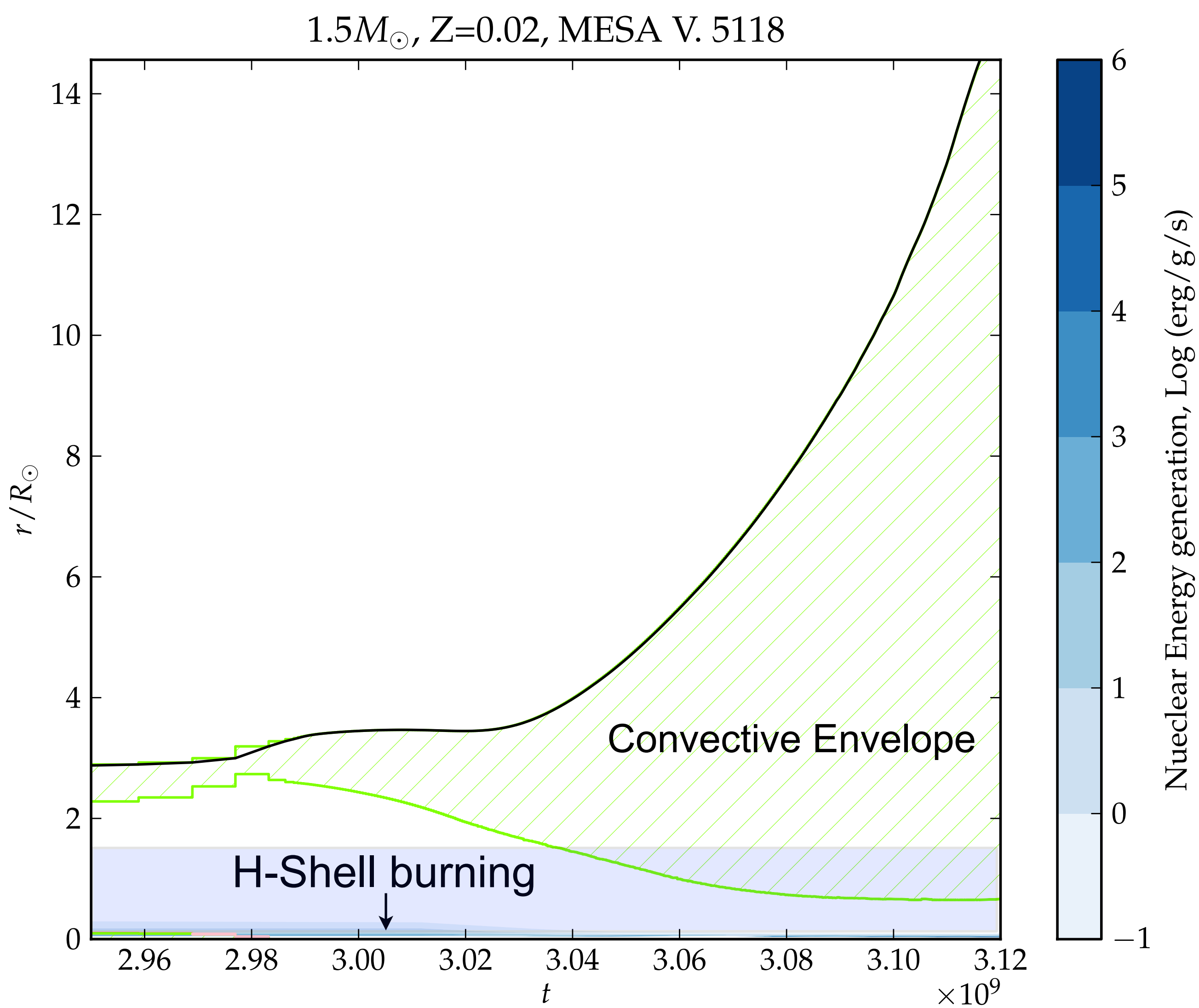

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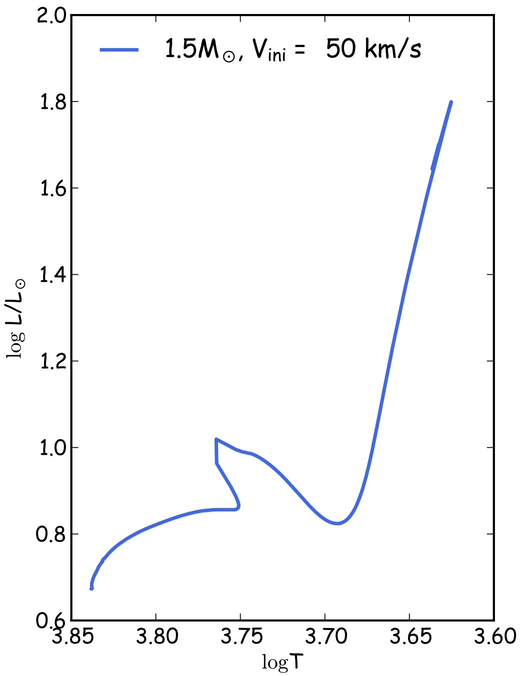
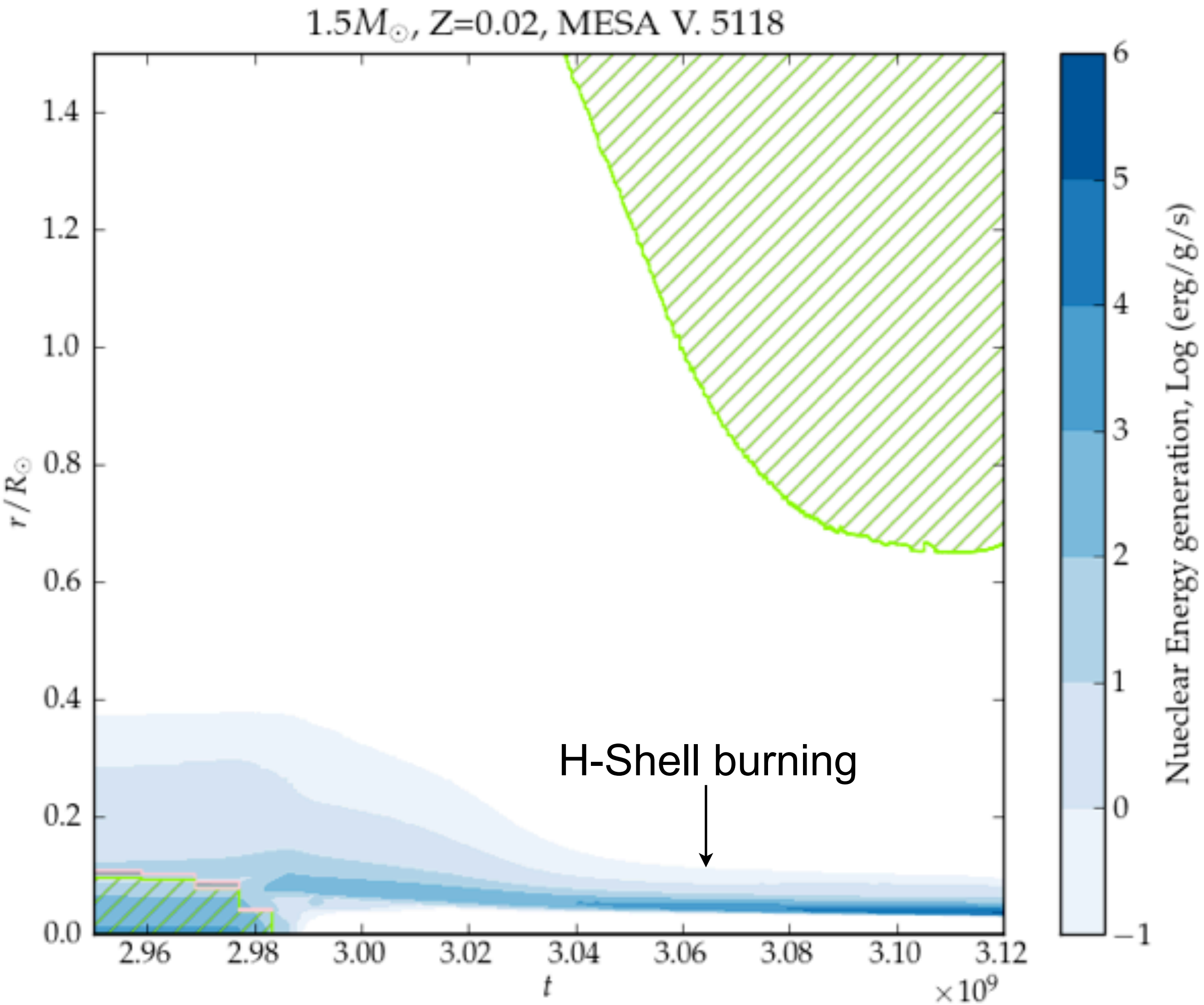
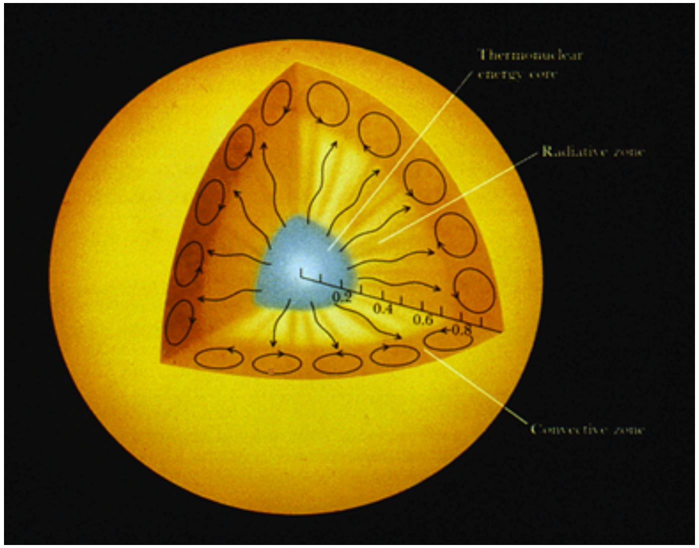


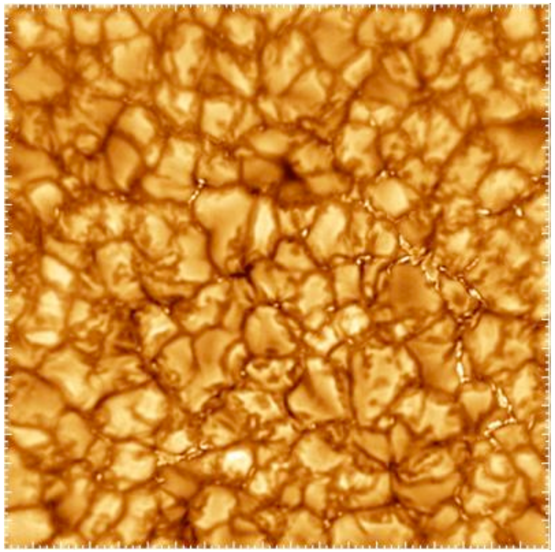


Evolution after H-exhaustion

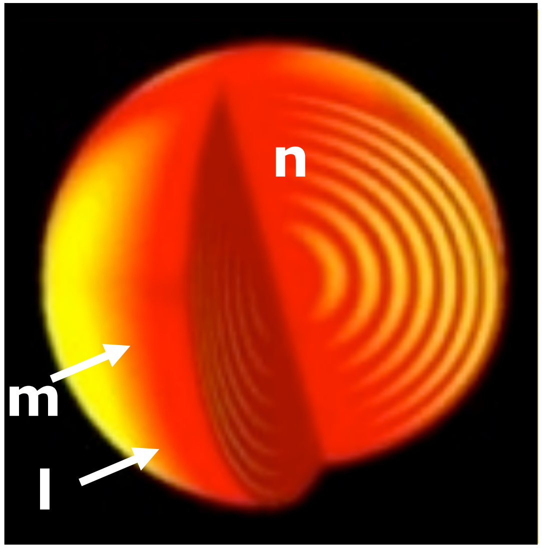
- A dramatic change in the stellar structure
- Huge density contrast between core and envelope
- Assuming simple conservation of angular momentum, core spins up, envelope spins down
- As a star evolves past H-exhaustion angular momentum transport mechanisms determine the rotation rate of the core

Solar-Like Oscillations



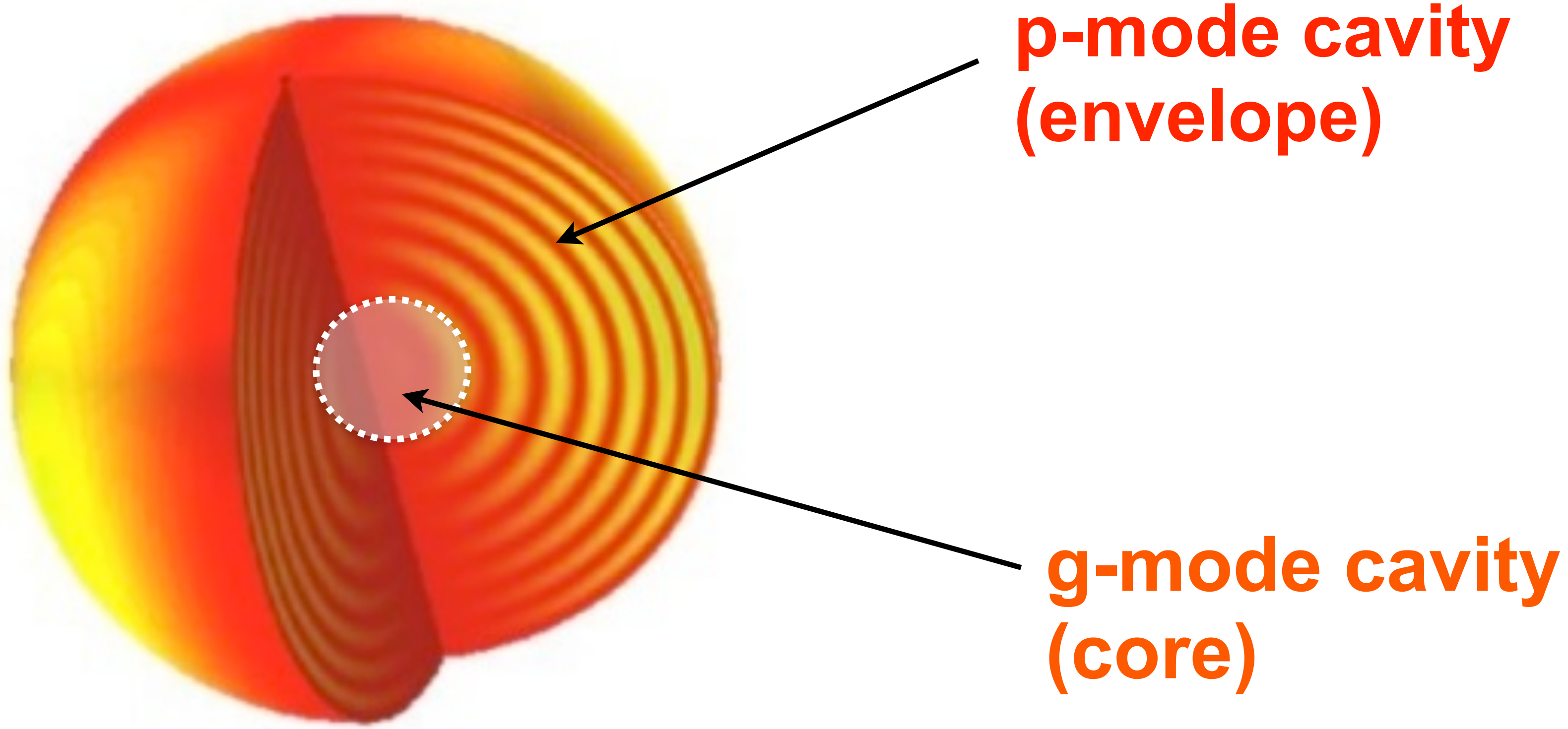


Credit: BBSO/NJIT



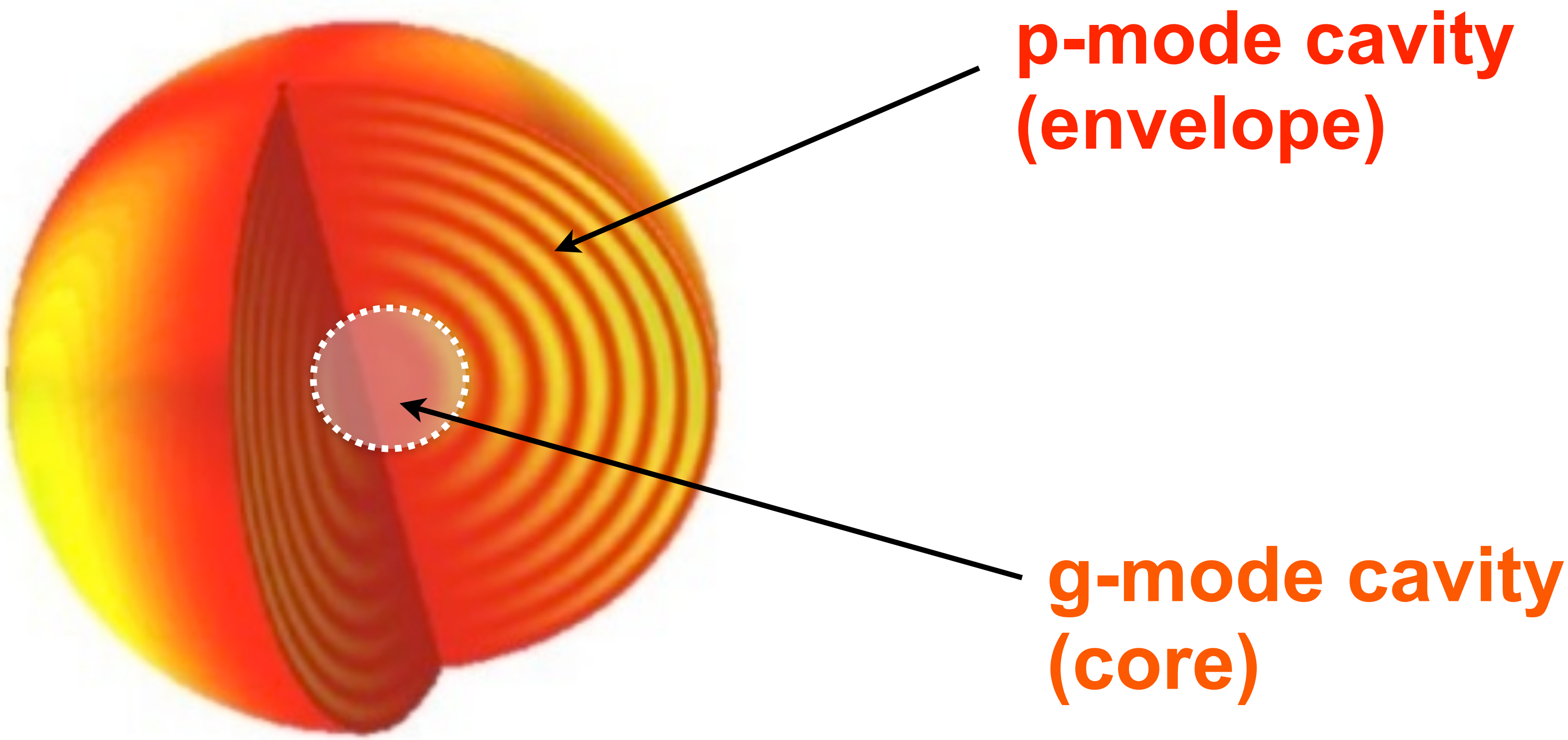
- Turbulent convection causes stochastic excitation of (non-radial) pulsation
- Solar-like oscillations expected and observed in red giants as well (see e.g. Dupret et al. 2009)

Mixed Modes



If the frequencies of the stochastically excited p-modes become comparable to the frequencies of the g-modes, a ‘cross-talk’ between core and envelope is possible (**mixed modes**). This happens in **Red Giant stars** due to the increased core density.

Mixed Modes



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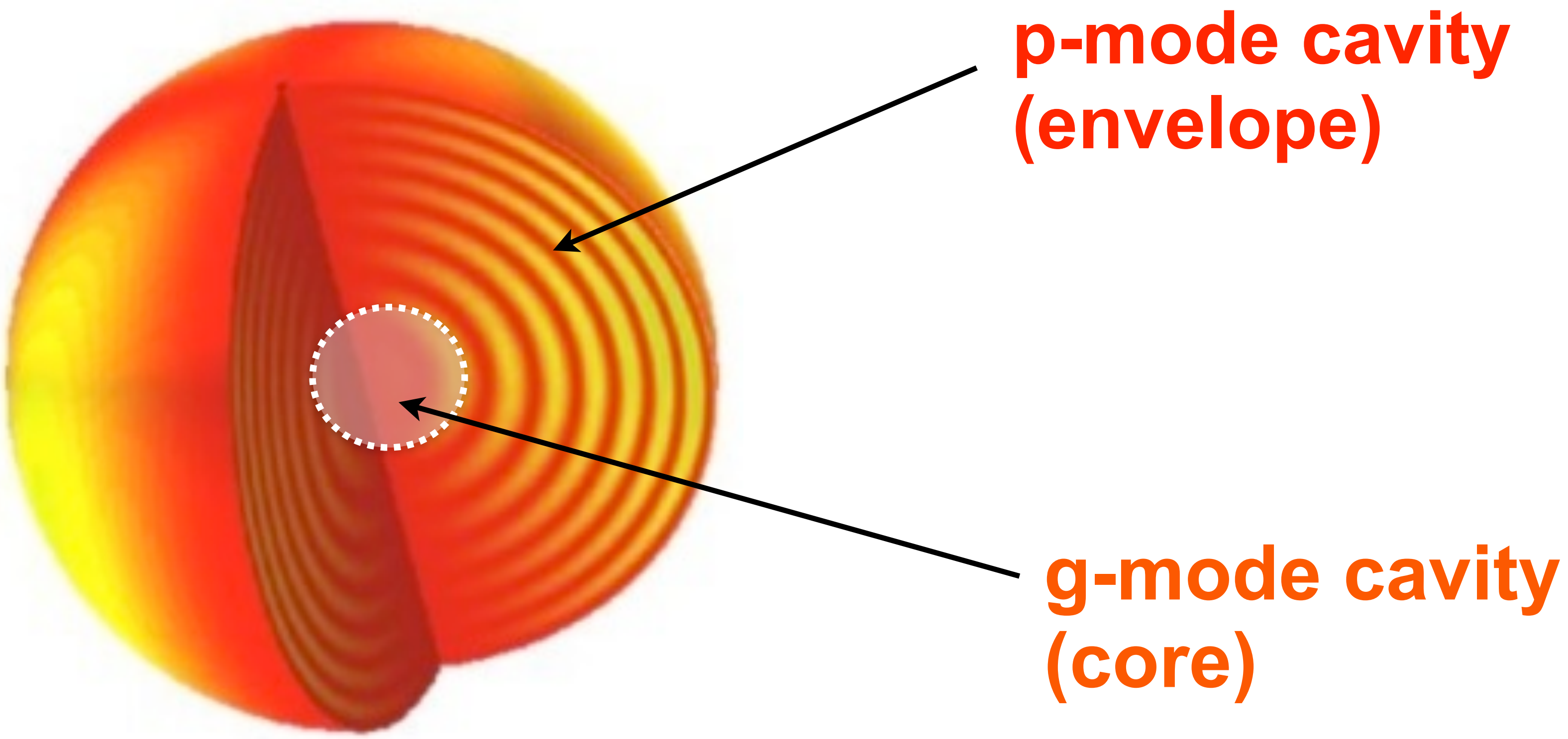
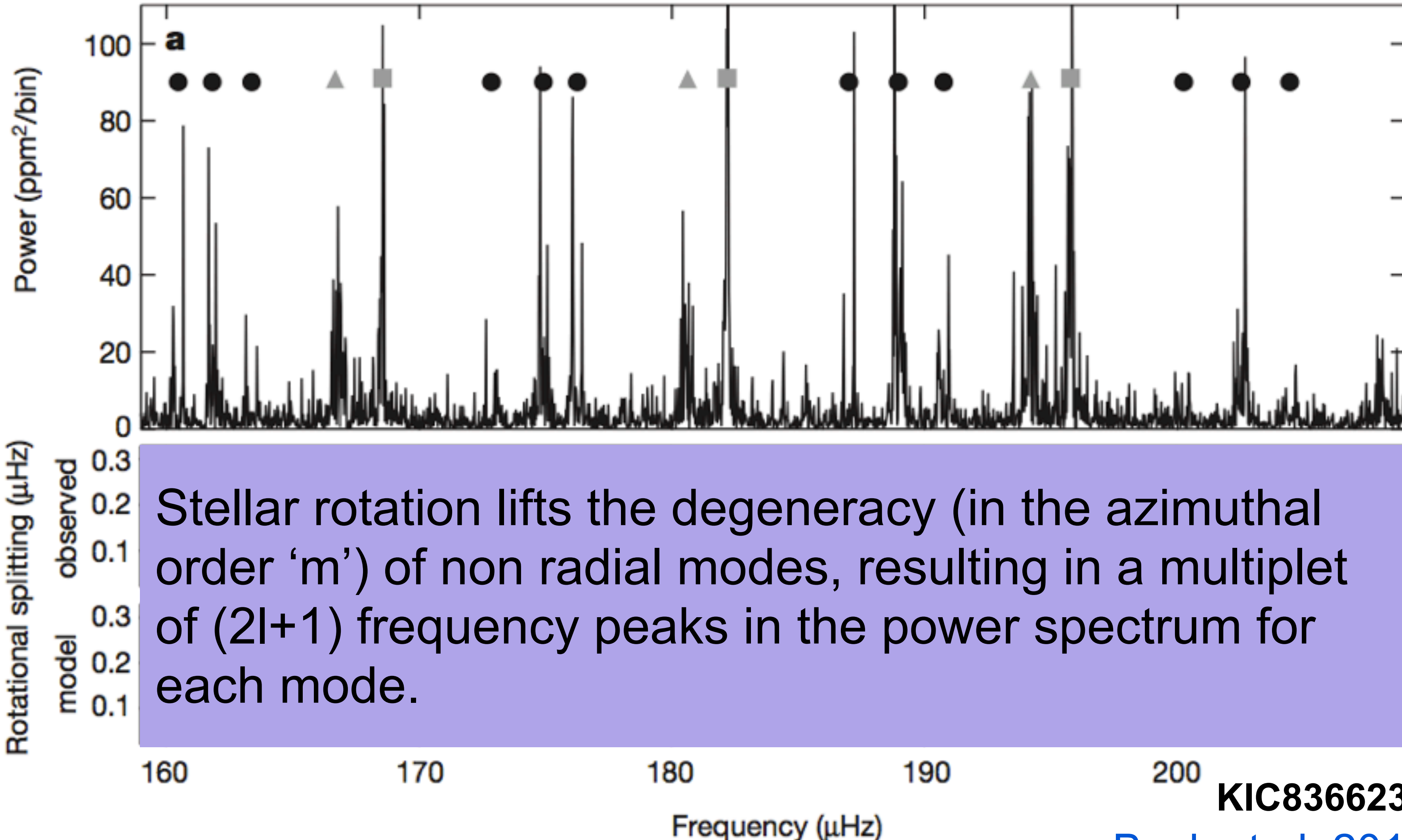
See Benoit Mosser’s talk

Mixed Modes



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!

Splitting of Mixed Modes

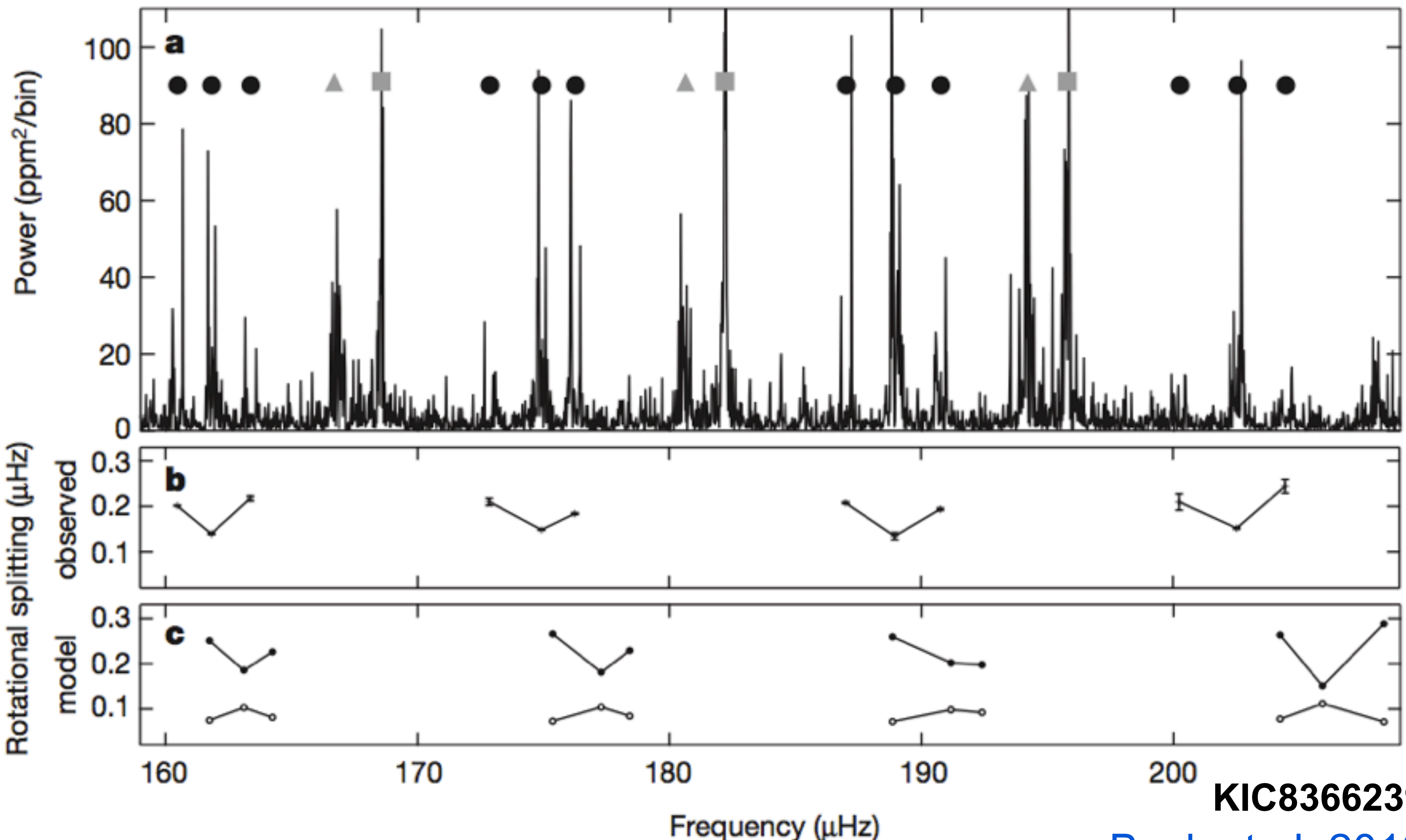


Stellar rotation lifts the degeneracy (in the azimuthal order ‘m’) of non radial modes, resulting in a multiplet of (2l+1) frequency peaks in the power spectrum for each mode.

KIC8366239

Beck et al. 2012

Splitting of Mixed Modes



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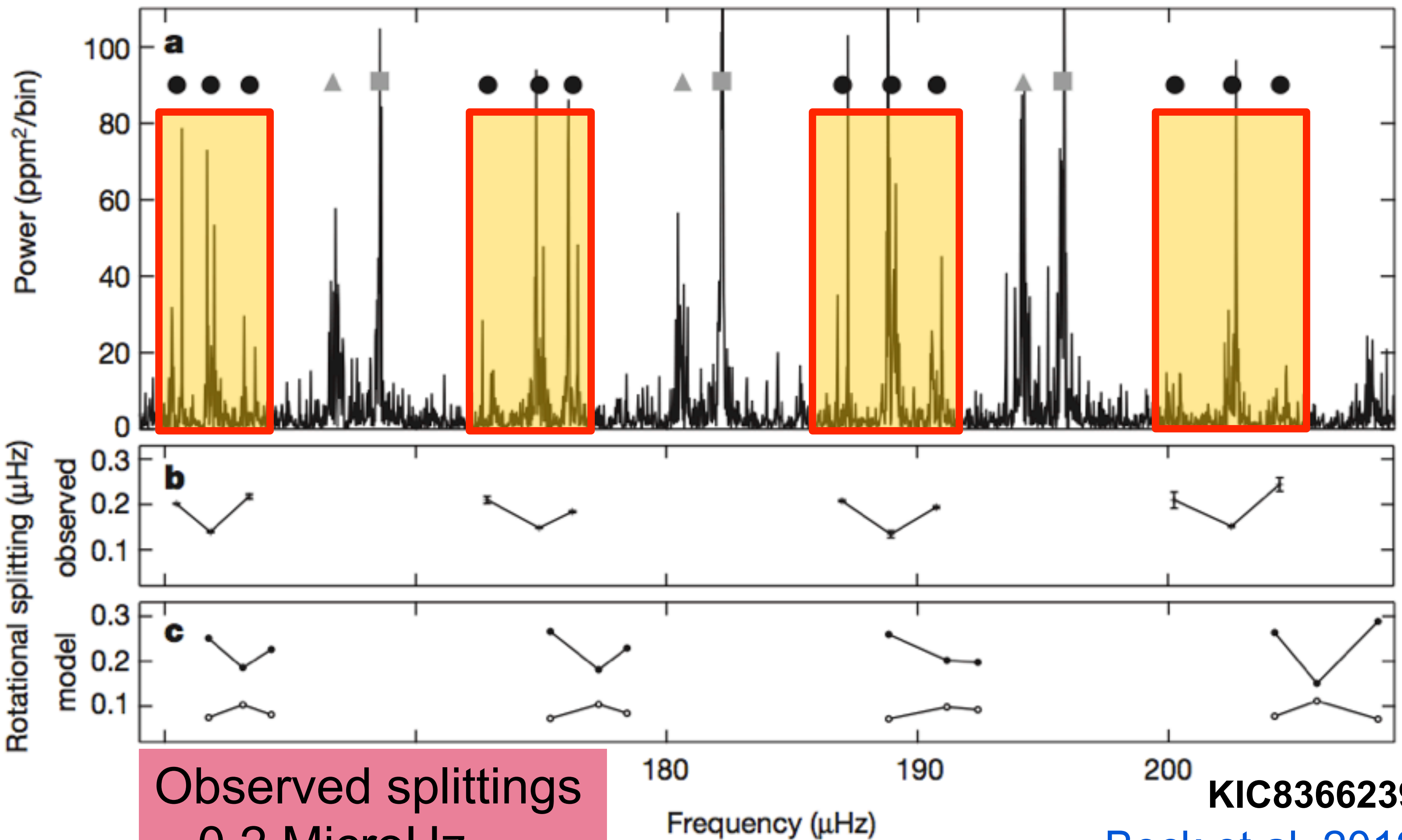


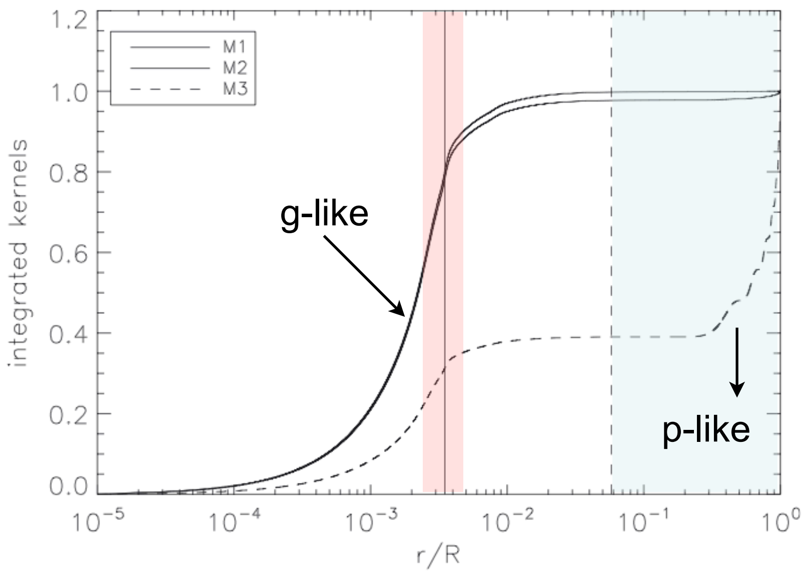
Observed splittings
~ 0.2 MicroHz

KIC8366239

Beck et al. 2012

Core-Envelope Differential Rotation

$$\delta\nu_{\mathrm{rot},n,\ell} = \int_0^1 \mathcal{K}_{n,\ell}(x)\,\frac{\Omega(x)}{2\pi}\,\mathrm{d}x,$$



$$\mathcal{K}_{n,\ell} = \frac{1}{I_{n,\ell}}\left[\xi_{\mathrm{r}}^2 + (\Lambda - 1)\xi_{\mathrm{h}}^2 - 2\xi_{\mathrm{r}}\xi_{\mathrm{h}}\right]_{n,\ell}\rho x^2$$

where $I_{n,\ell}$ is the mode inertia

$$I_{nl} = \int_0^1 \left[\xi_r^2 + \Lambda\,\xi_h^2\right]_{n,\ell}\rho x^2 \mathrm{d}x.$$

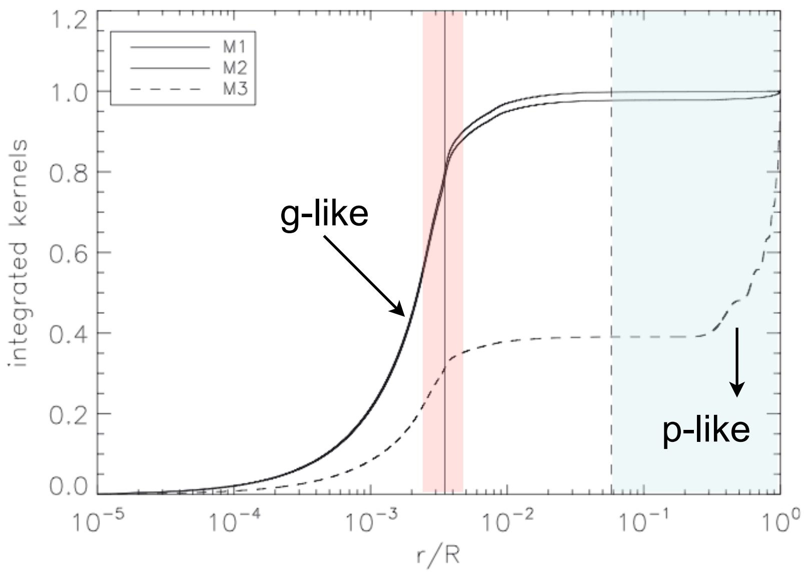
See e.g.

- Beck et al. 2012
- Mosser et al. 2012
- Deheuvels et al. 2012

Core-Envelope Differential Rotation

See Don Kurtz's talk

$$\delta \nu_{\mathrm{rot},n,\ell} = \int_0^1 \mathcal{K}_{n,\ell}(x) \, \frac{\Omega(x)}{2\pi} \, \mathrm{d}x,$$



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Attempts to Reproduce the Observed Rotation Rates

Eggenberger et al. 2012

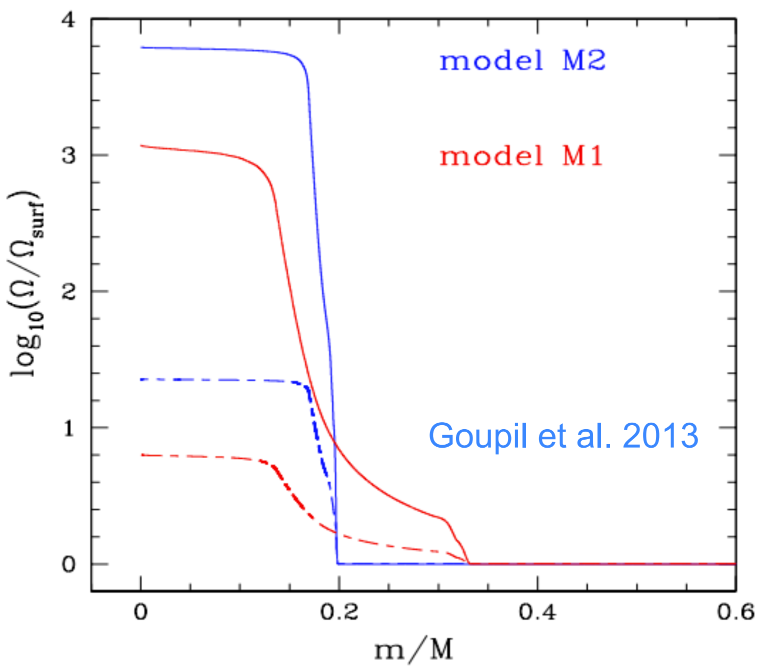
Marques et al. 2013

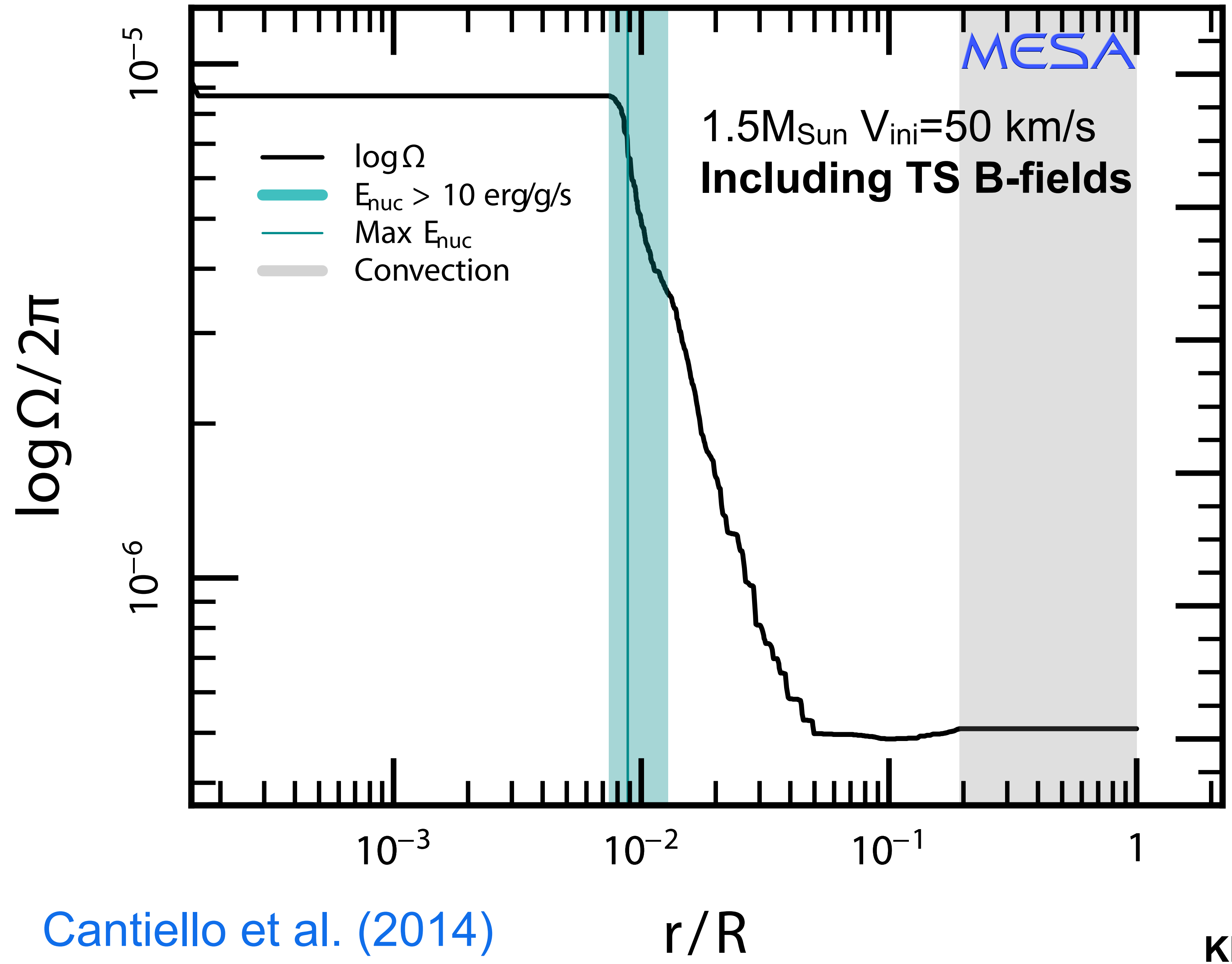
Ceillier et al. 2013

Goupil et al. 2013

Tayar & Pinsonneault 2013

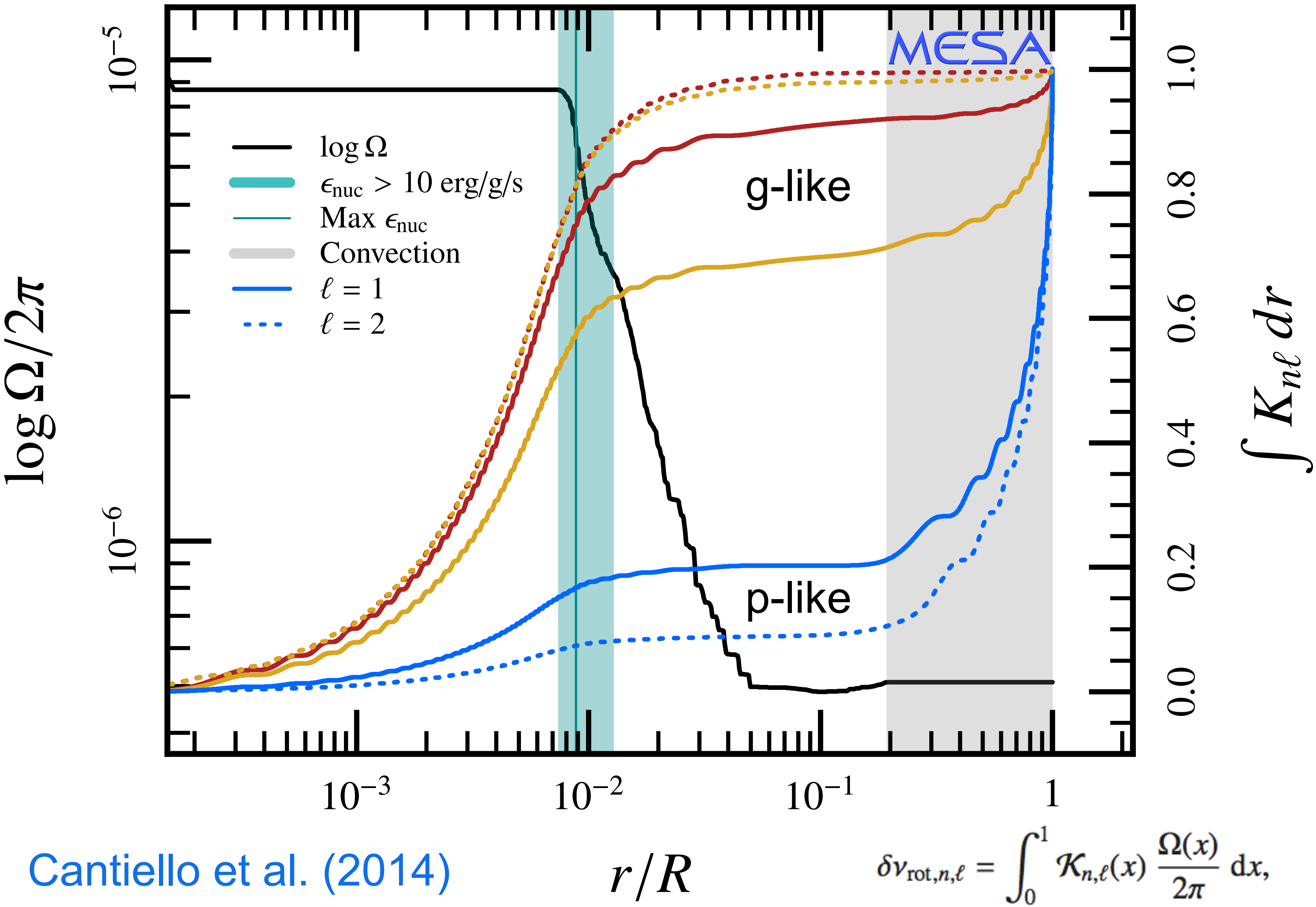
Including the **physics of rotation** (diffusion-advection scheme for angular momentum transport) they obtain cores that are rotating ~100 times or more too fast





Cantiello et al. (2014)

Model of KIC8366239



Cantiello et al. (2014)

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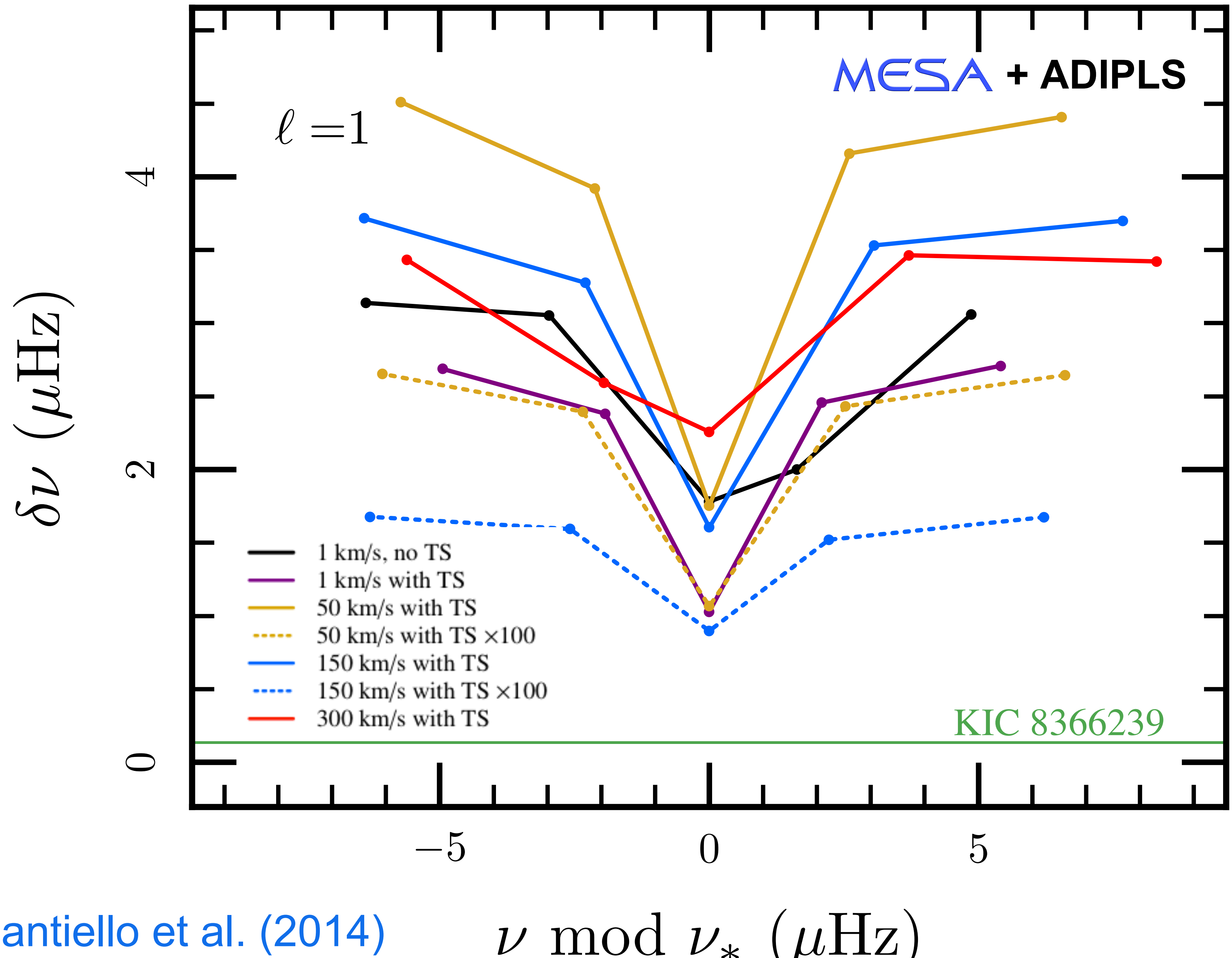
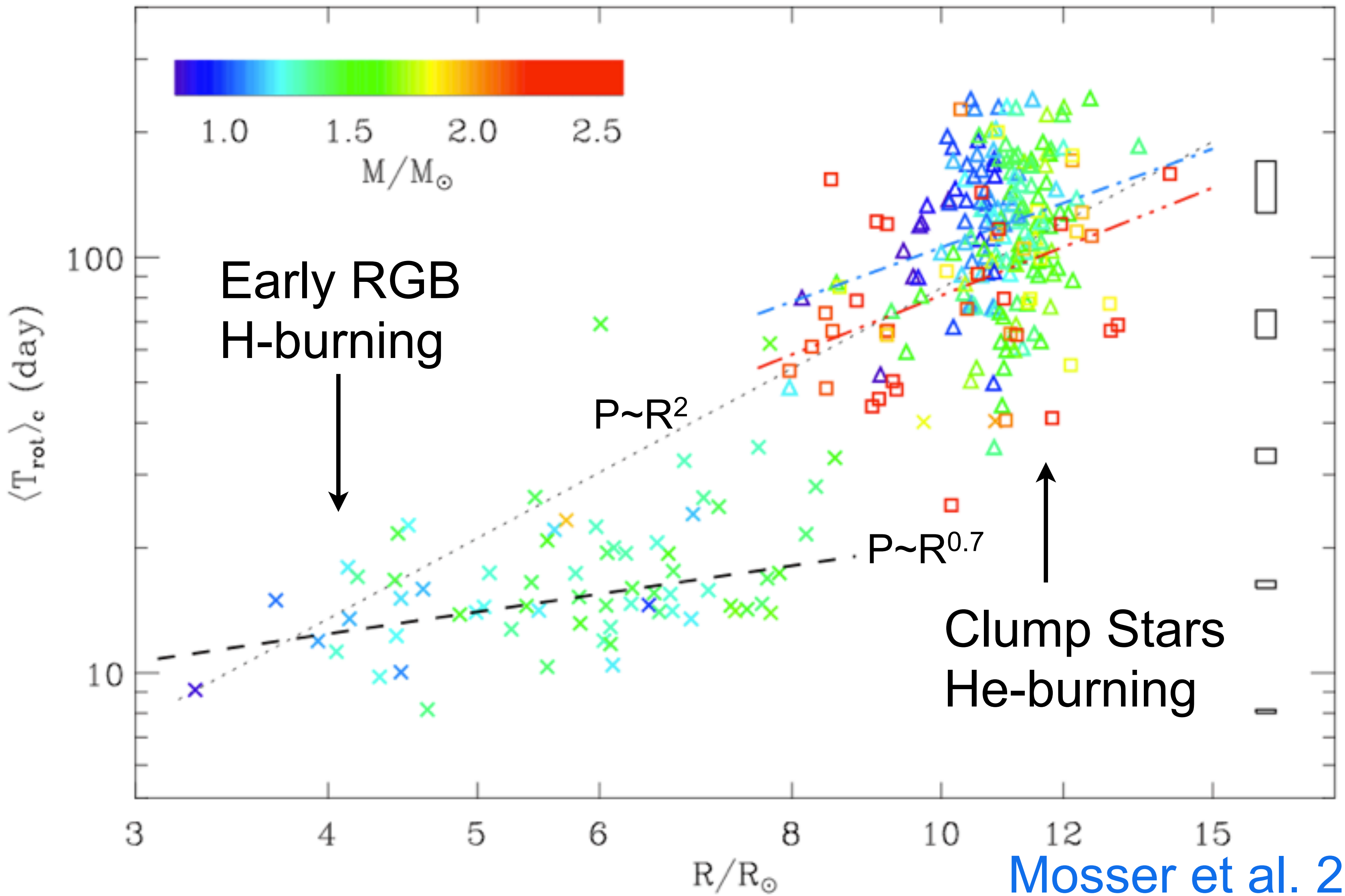
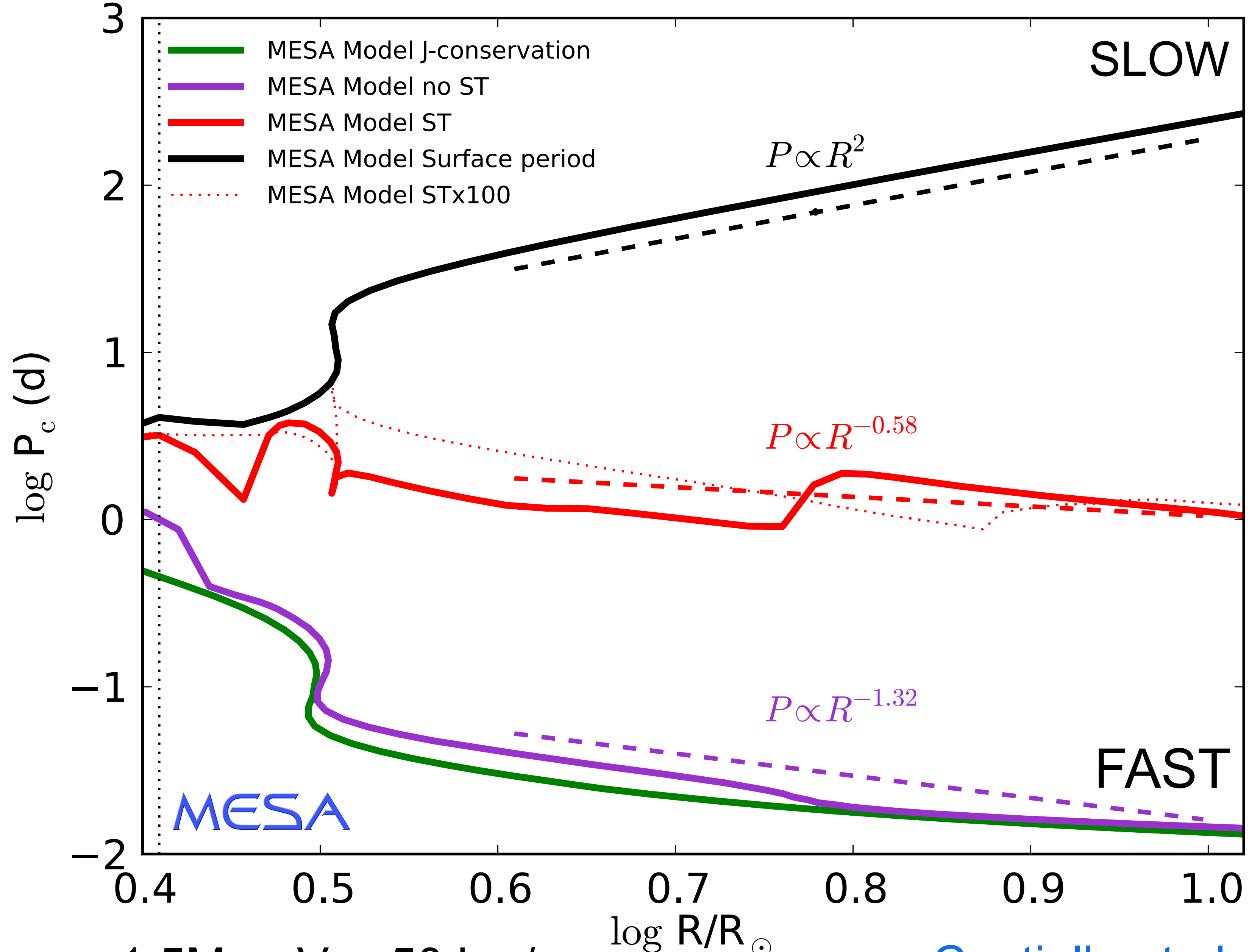


Cantiello et al. (2014)

Evolution of Core Rotation

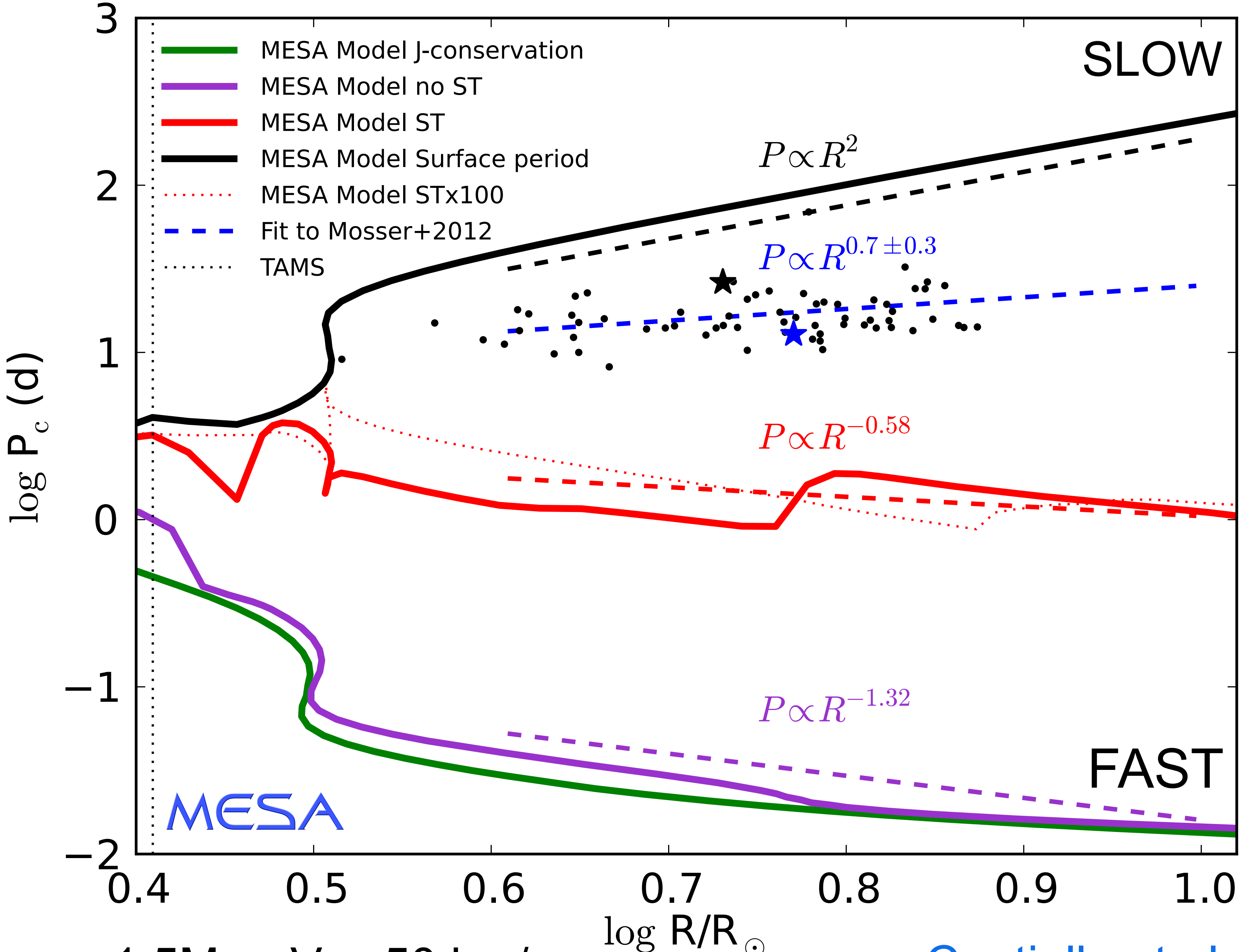


Mosser et al. 2012



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

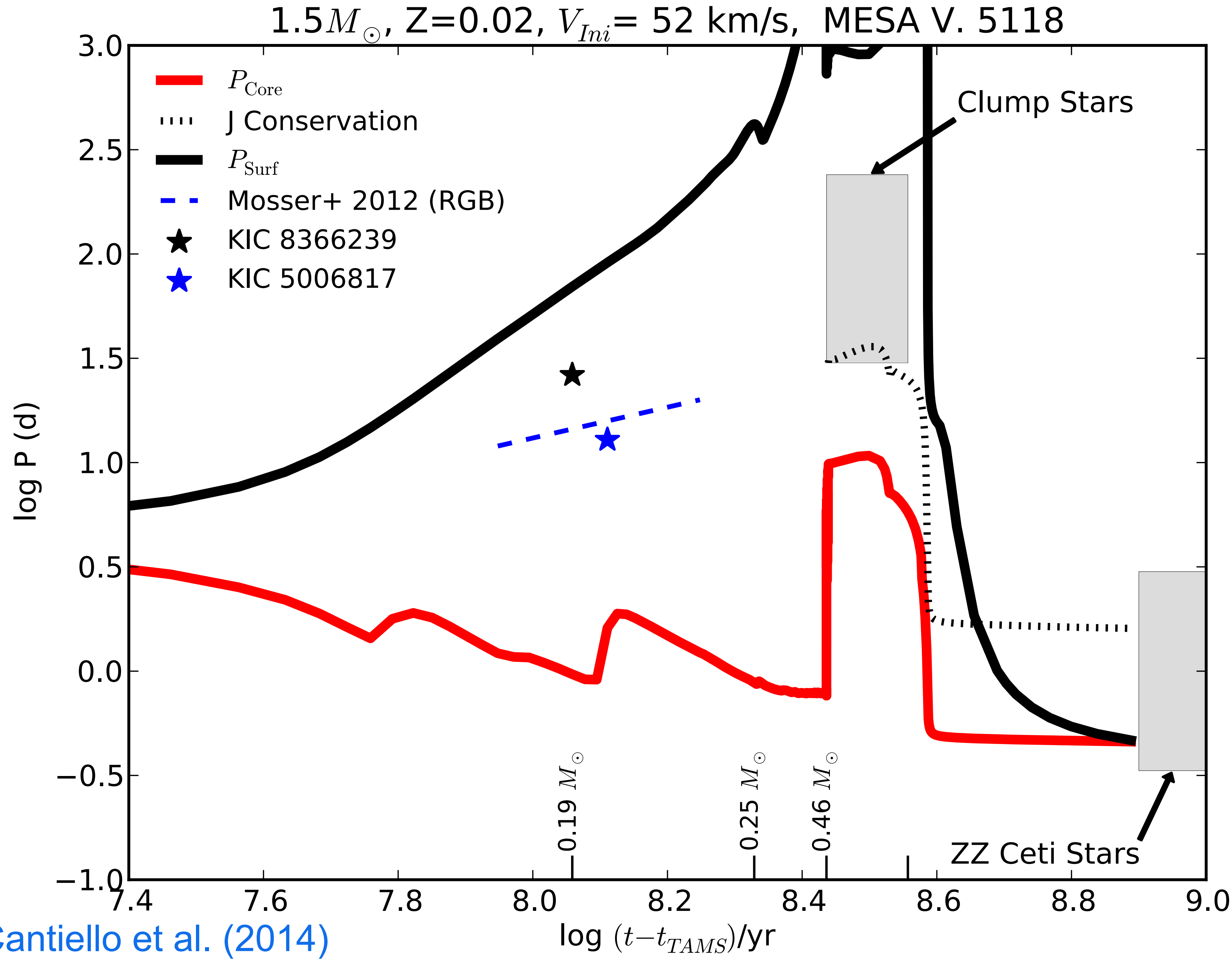
Cantiello et al. (2014)



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

Cantiello et al. (2014)

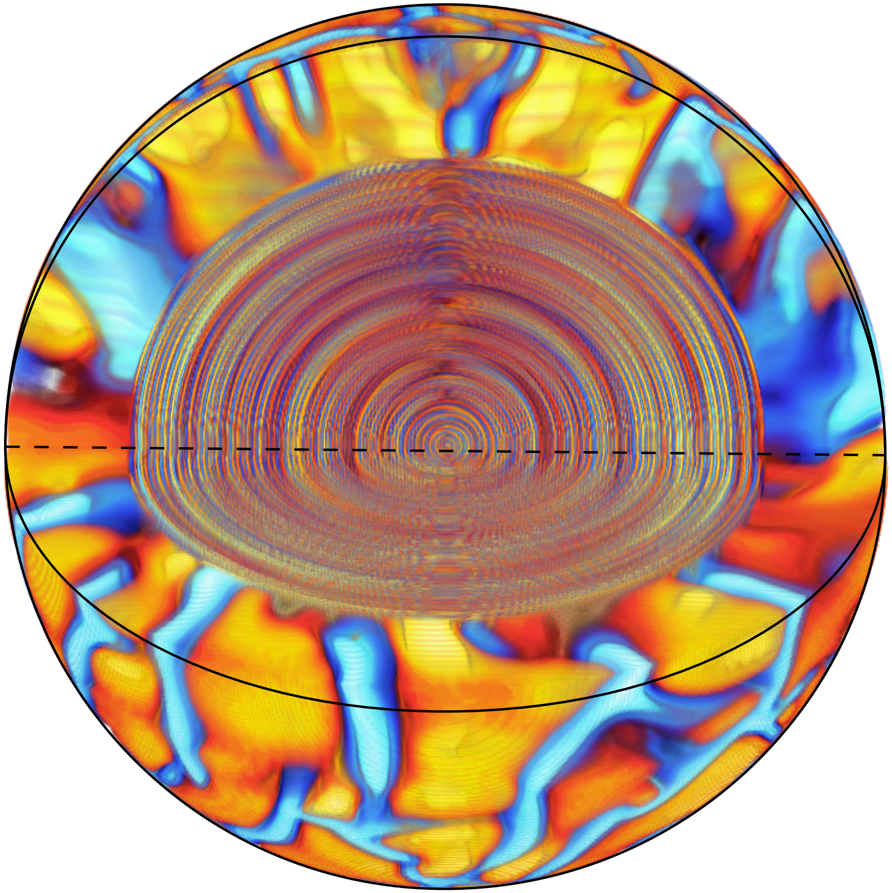
Evolution past the RGB



Cantiello et al. (2014)

Other possible mechanisms?

- Angular momentum transport from **IGW** during the Red Giant Phase
- Magnetic coupling from **fossil** or **convective dynamo generated** magnetic fields

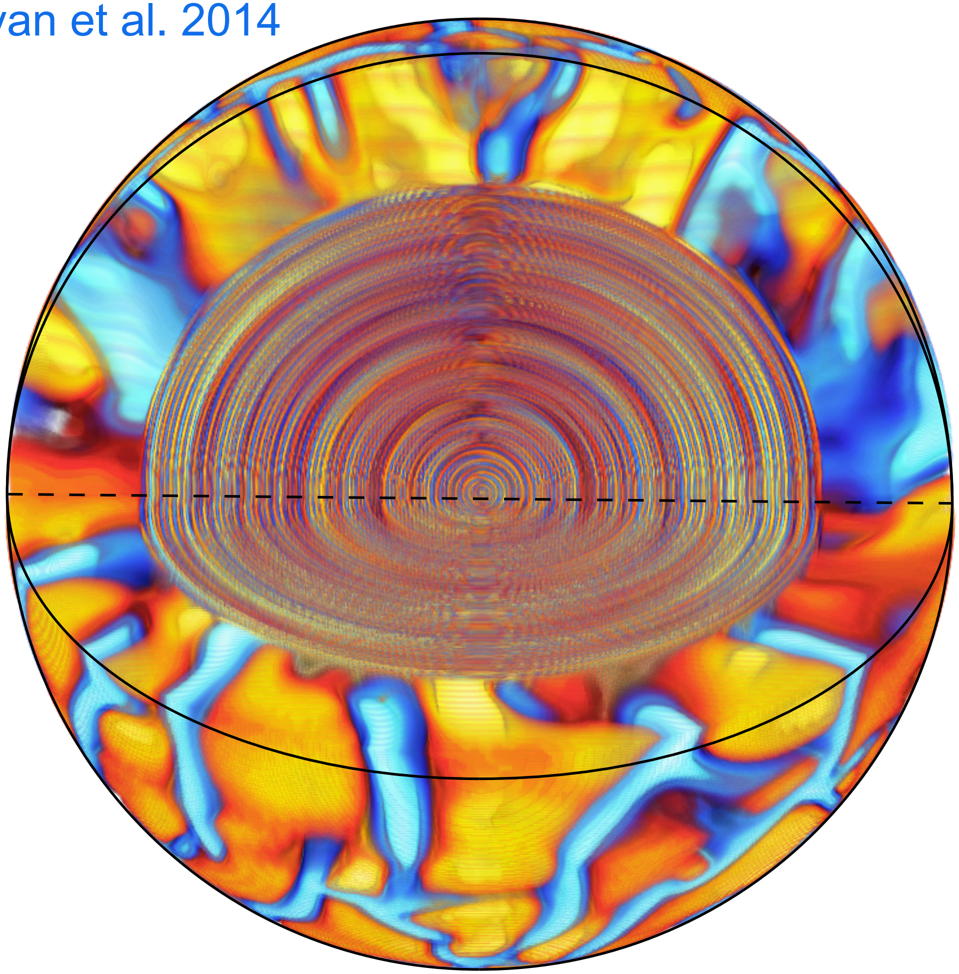


Alvan et al. 2014

See also e.g. Charbonnel & Talon (2007)

Internal Gravity Waves

Alvan et al. 2014



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

IGW: Excited by turbulent convection

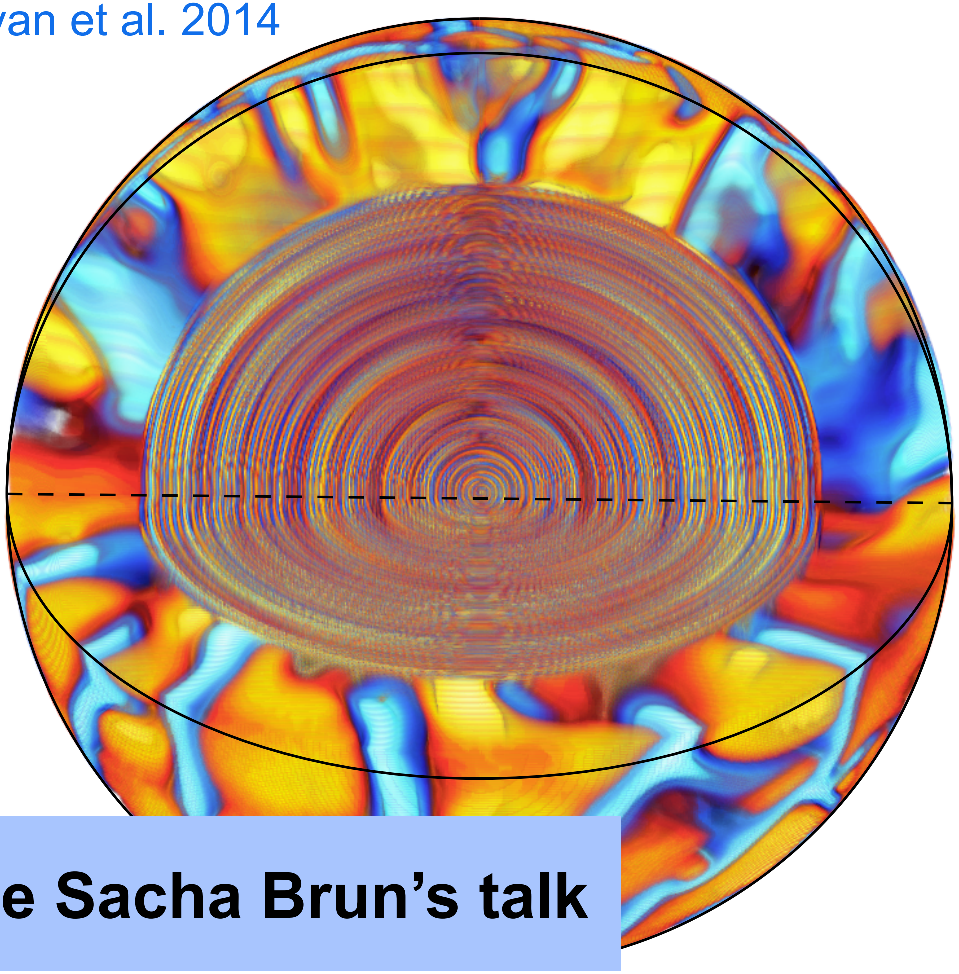
They carry angular momentum

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

Dissipation: Radiative dissipation usually dominates in stellar interiors

Internal Gravity Waves

Alvan et al. 2014



See Sacha Brun's talk

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

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

IGW: Damping Length

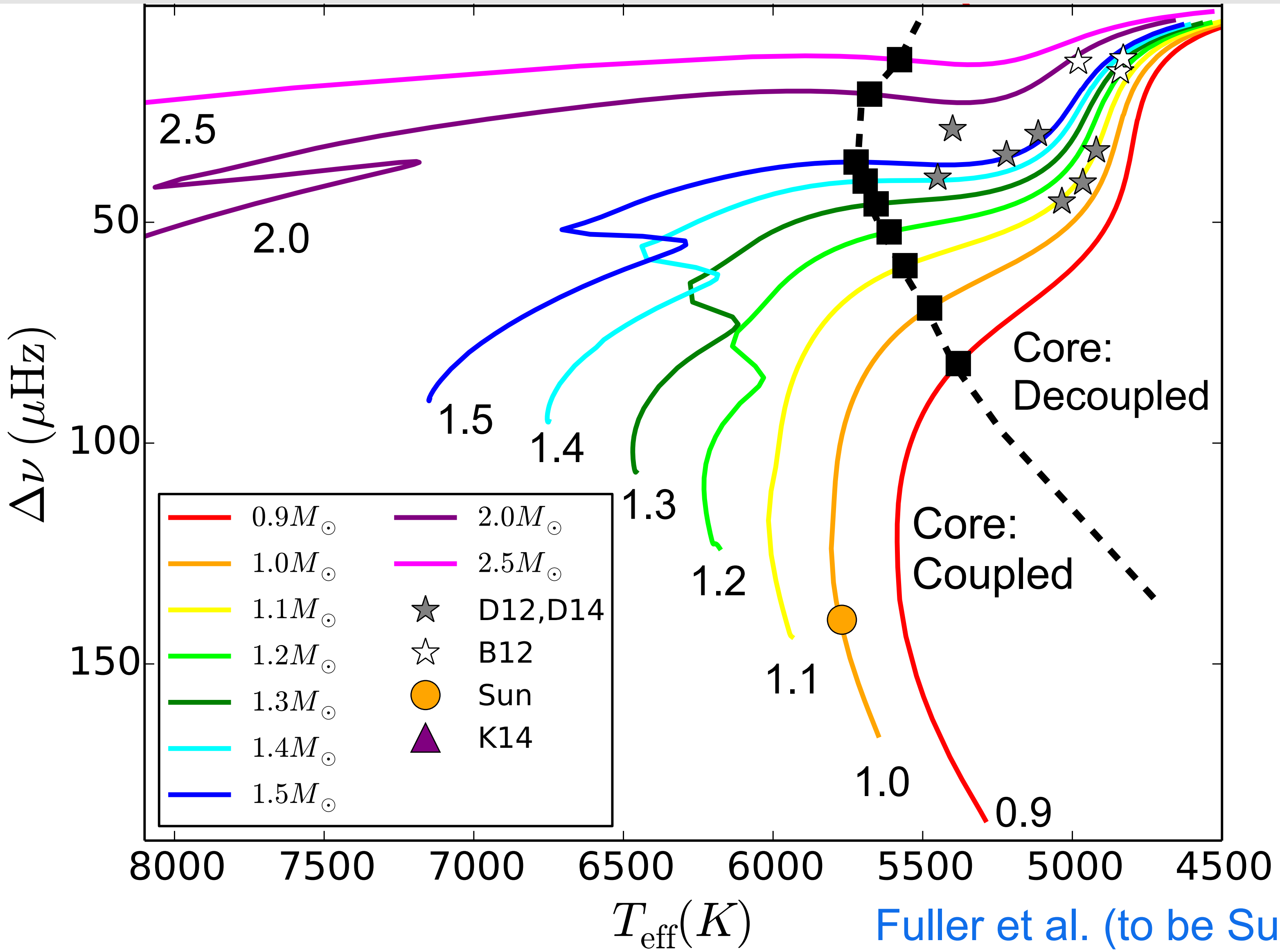
Higher Frequency IGW
propagate further

$$L_d = \frac{2r^3\omega^4}{[l(l+1)]^{3/2} N N_T^2 K}$$

Zahn et al. (1997)

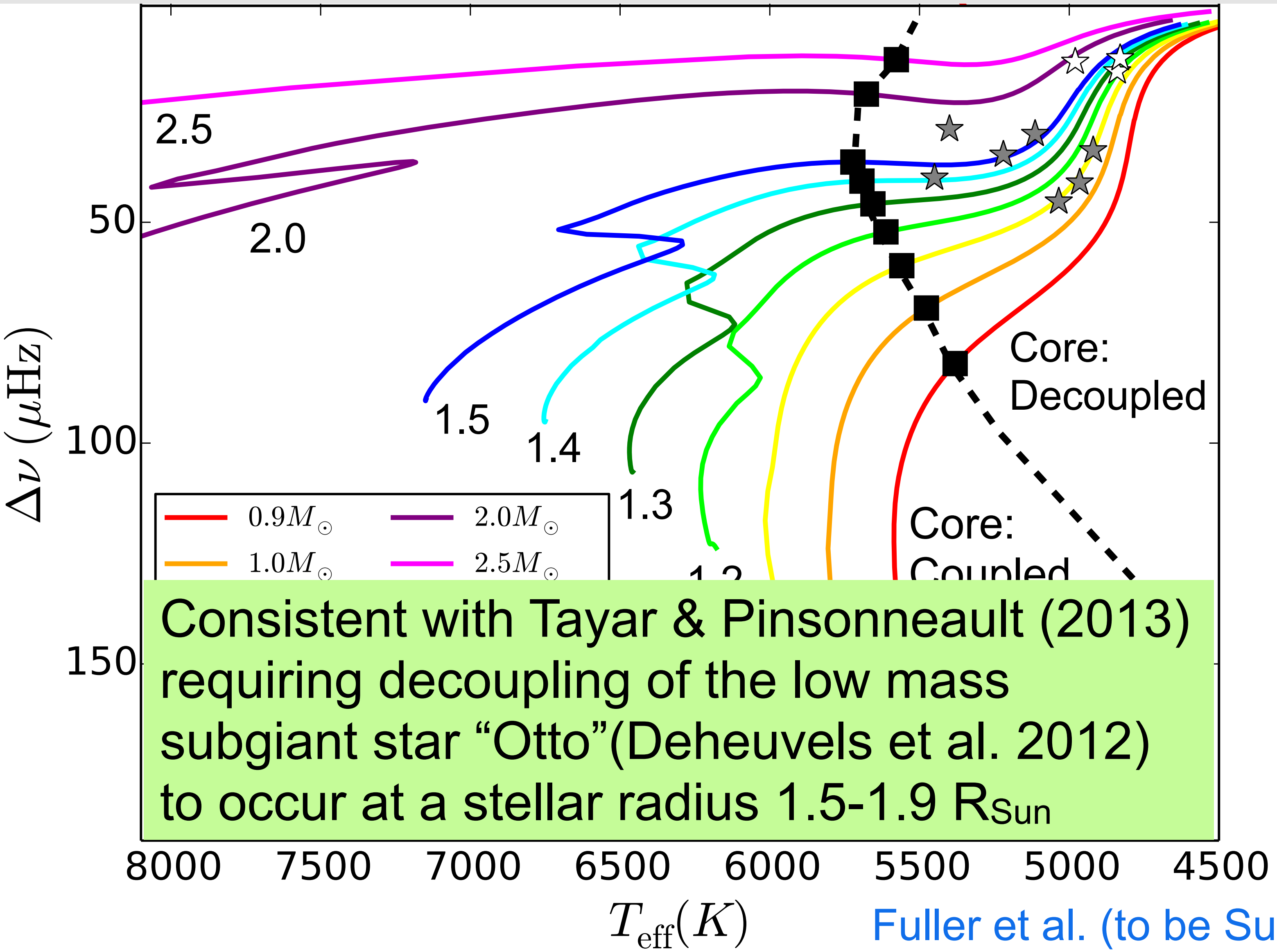
Compositional Gradients
inhibit the propagation

IGW: Wave Decoupling



Fuller et al. (to be Submitted)

IGW: Wave Decoupling



Consistent with Tayar & Pinsonneault (2013) requiring decoupling of the low mass subgiant star “Otto”(Deheuvels et al. 2012) to occur at a stellar radius 1.5-1.9 R_{Sun}

Fuller et al. (to be Submitted)

IGW: Dissipation Length

$$L_d = \frac{2r^3\omega^4}{[l(l+1)]^{3/2} N N_T^2 K}$$

Decoupling of the core occurs due to 3 effects:

1. **Evolution timescale** decreases from 10^9 to 10^7 yr
2. Convection zone deepens, resulting in **smaller turnover frequencies** (hence smaller frequencies of the IGW)
3. As the core contracts the Brunt-Vasaila frequency **N increases** by more than an order of magnitude

The inner core becomes optically thick to the waves, prohibiting efficient core-envelope coupling (due to IGW)

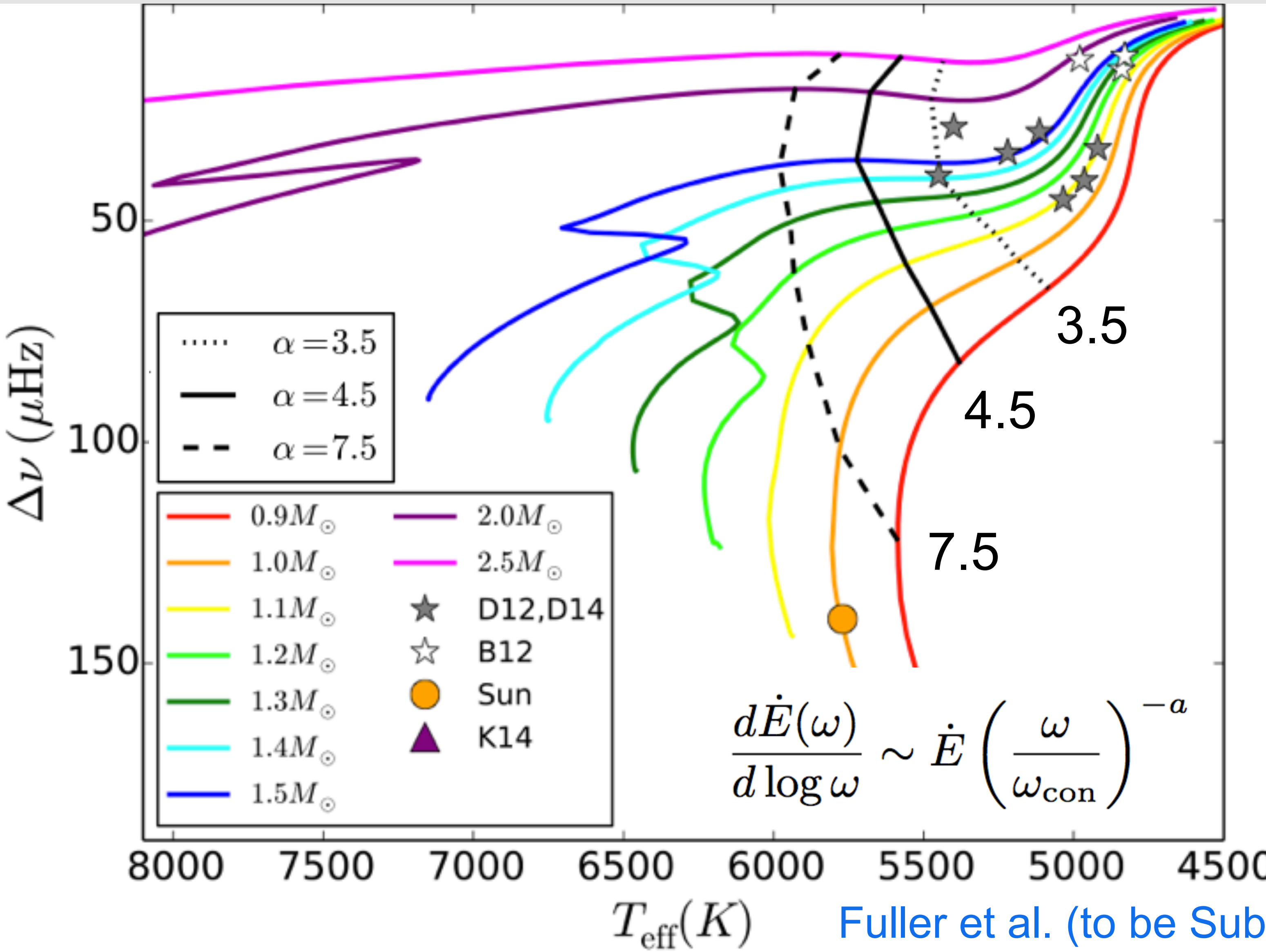
Fuller et al. (to be Submitted)

Conclusions

- Rotational Splitting of mixed modes is a great tool to test internal angular momentum physics
- Rotational mixing alone overpredicts core rotation rate (By a factor of 100 or so) in Red Giants
- Including Tayler-Spruit magnetic torques helps to reduce the discrepancy to a factor of 10 or so. But predicted splittings are still too large
- IGW can couple the core of main sequence and early sub giants. But alone it's unlikely to explain the observed amount of coupling in red giants
- We still do not understand internal angular momentum transport in stars, but asteroseismology provides a direct test. More to do!

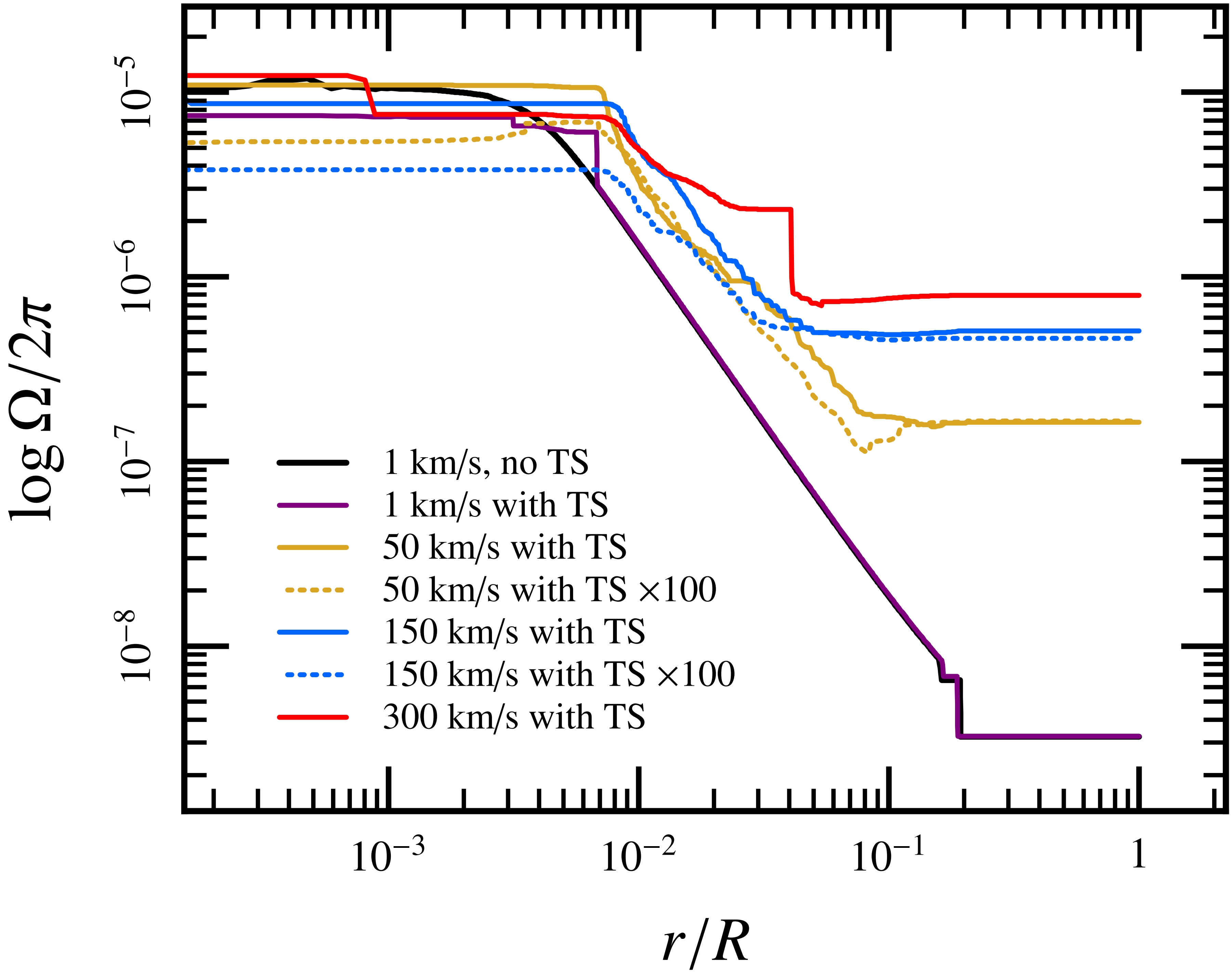
Backup Slides

IGW: Wave Decoupling



$$\frac{d\dot{E}(\omega)}{d\log\omega} \sim \dot{E}\left(\frac{\omega}{\omega_{\rm con}}\right)^{-a}$$

Fuller et al. (to be Submitted)



1 km/s, no TS
1 km/s with TS
50 km/s with TS
50 km/s with TS ×100
150 km/s with TS
150 km/s with TS ×100
300 km/s with TS
$\log \Omega / 2\pi$
r/R
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-3}
10^{-2}
10^{-1}
1

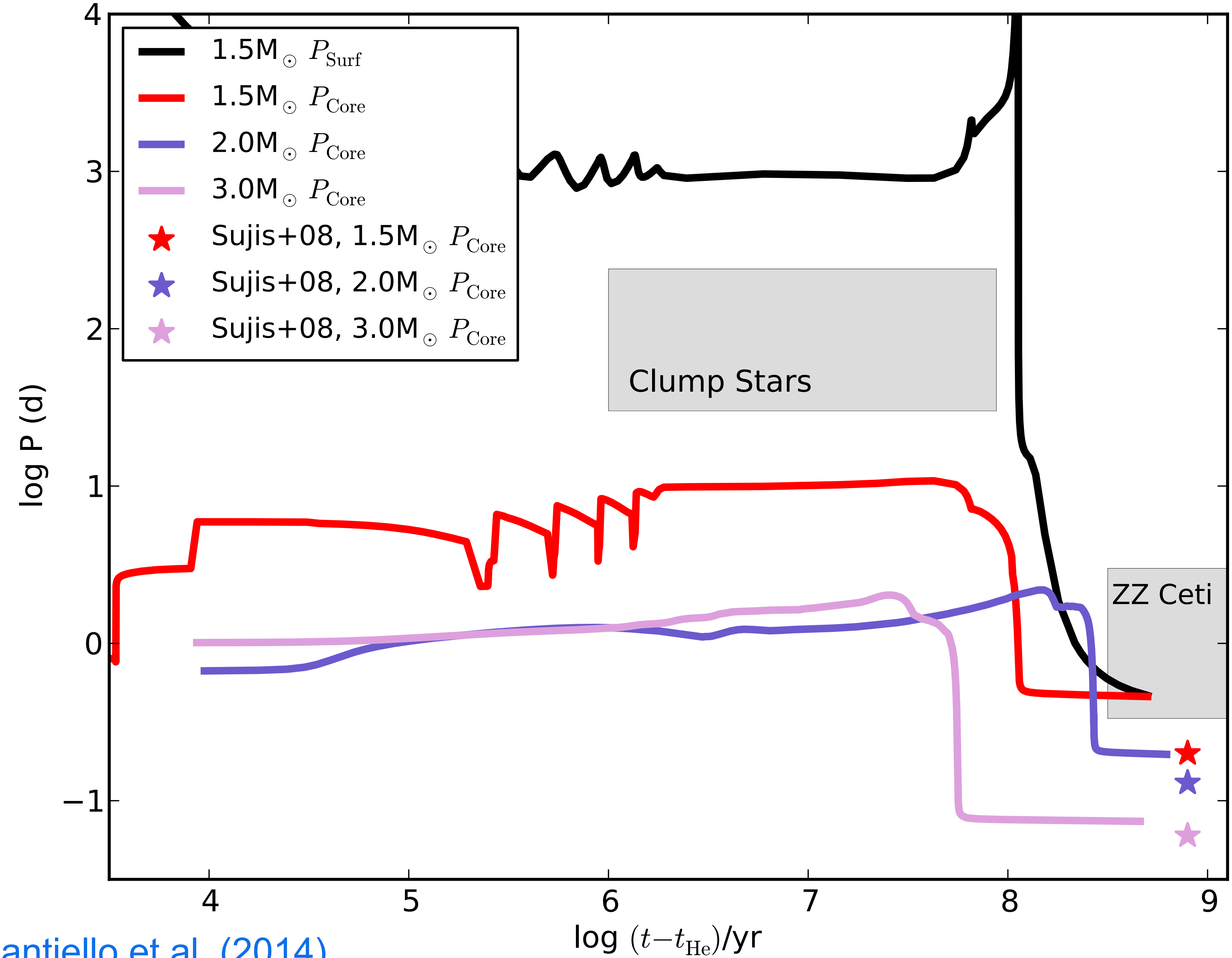
IGW: Damping Length

$$\dot{J}(r) = \dot{J}(r_{\rm con})e^{-\tau}$$

$$\tau = 2\int_r^{r_c} \frac{dr}{L_d}$$

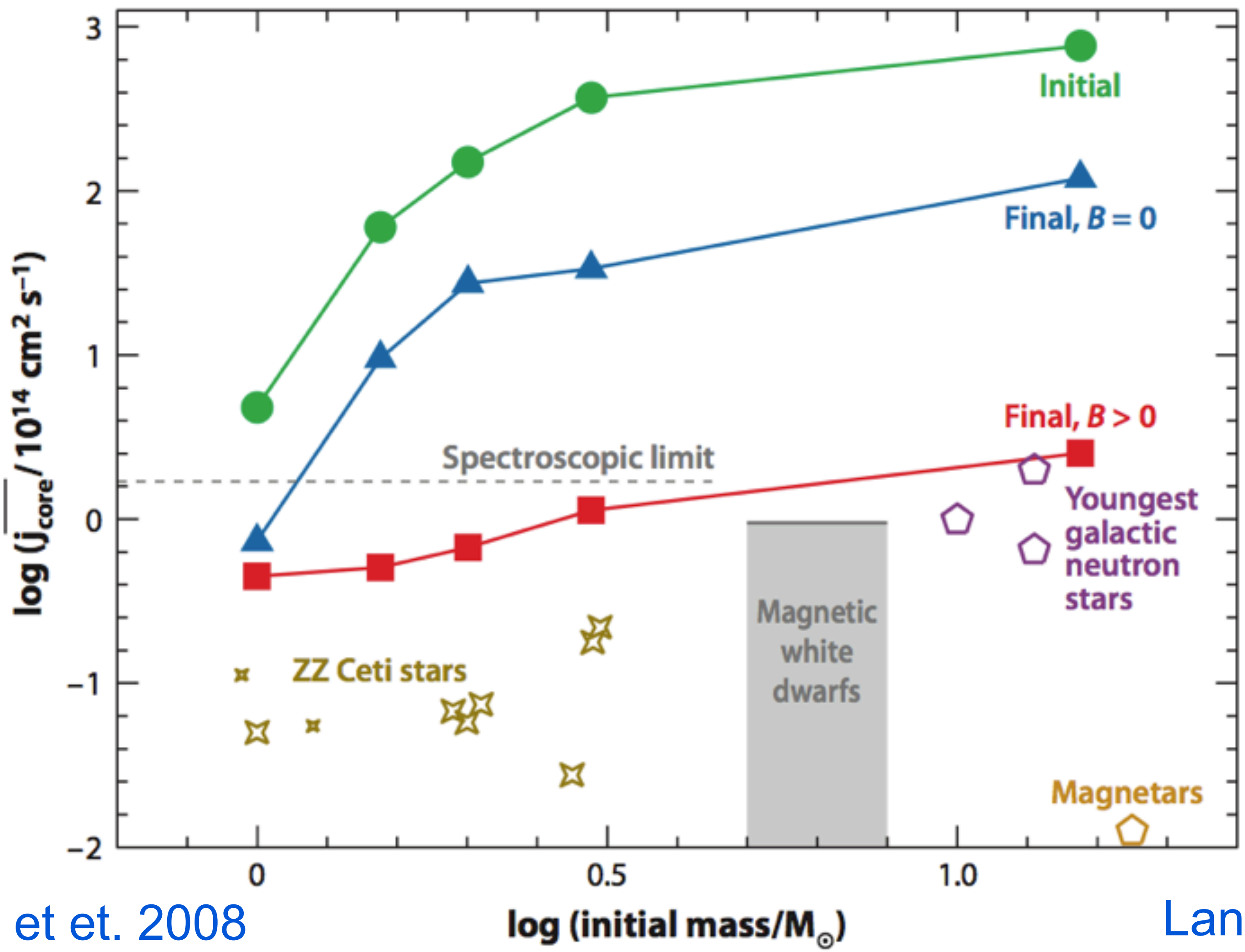
$$= \int_r^{r_c} dr \frac{[l(l+1)]^{3/2} N N_T^2 K}{r^3 \omega^4}$$

Fuller et al. (to be Submitted)



Cantiello et al. (2014)

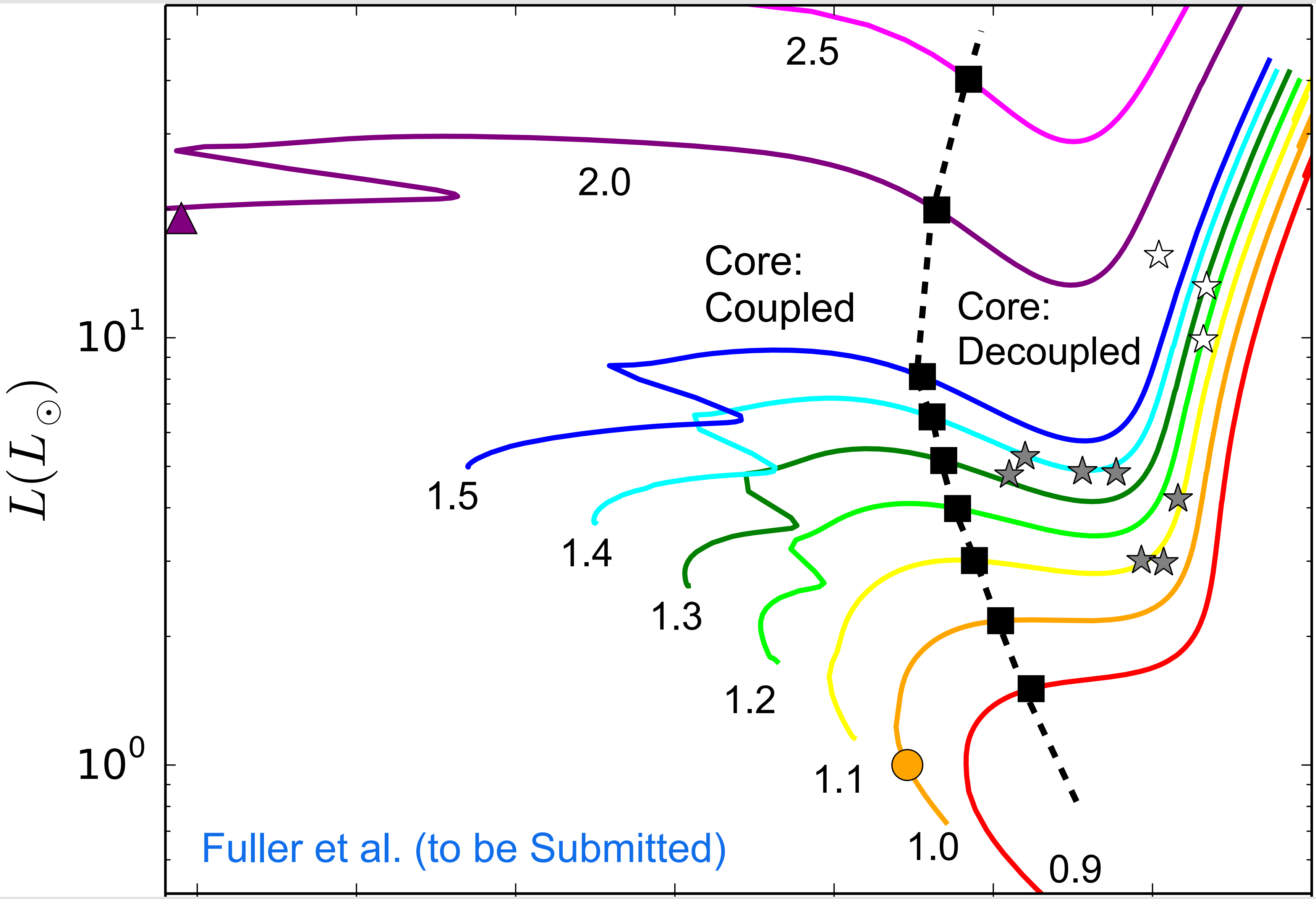
Need for an extra j-transport mechanism?



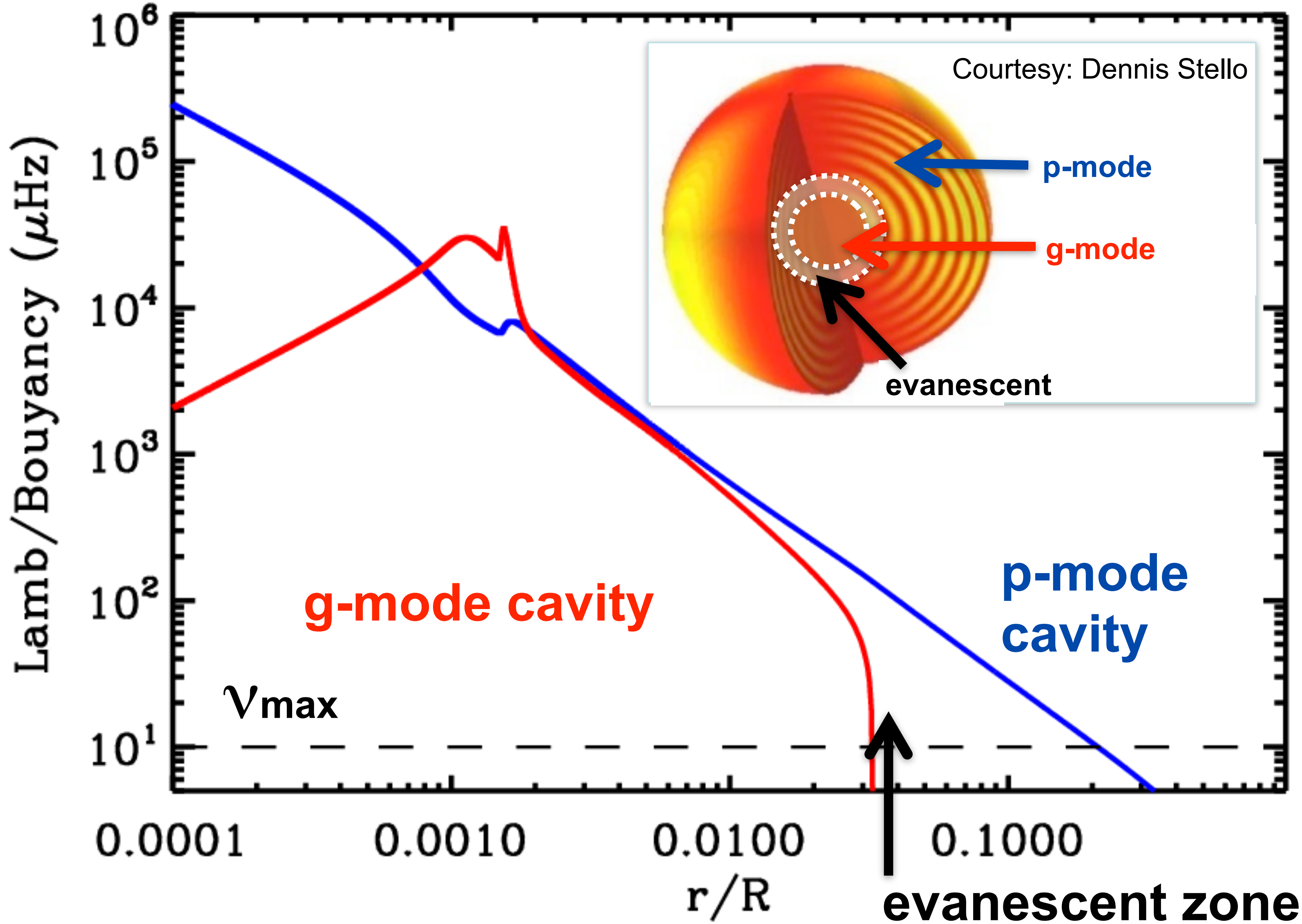
Suijs et et. 2008

Langer 2012

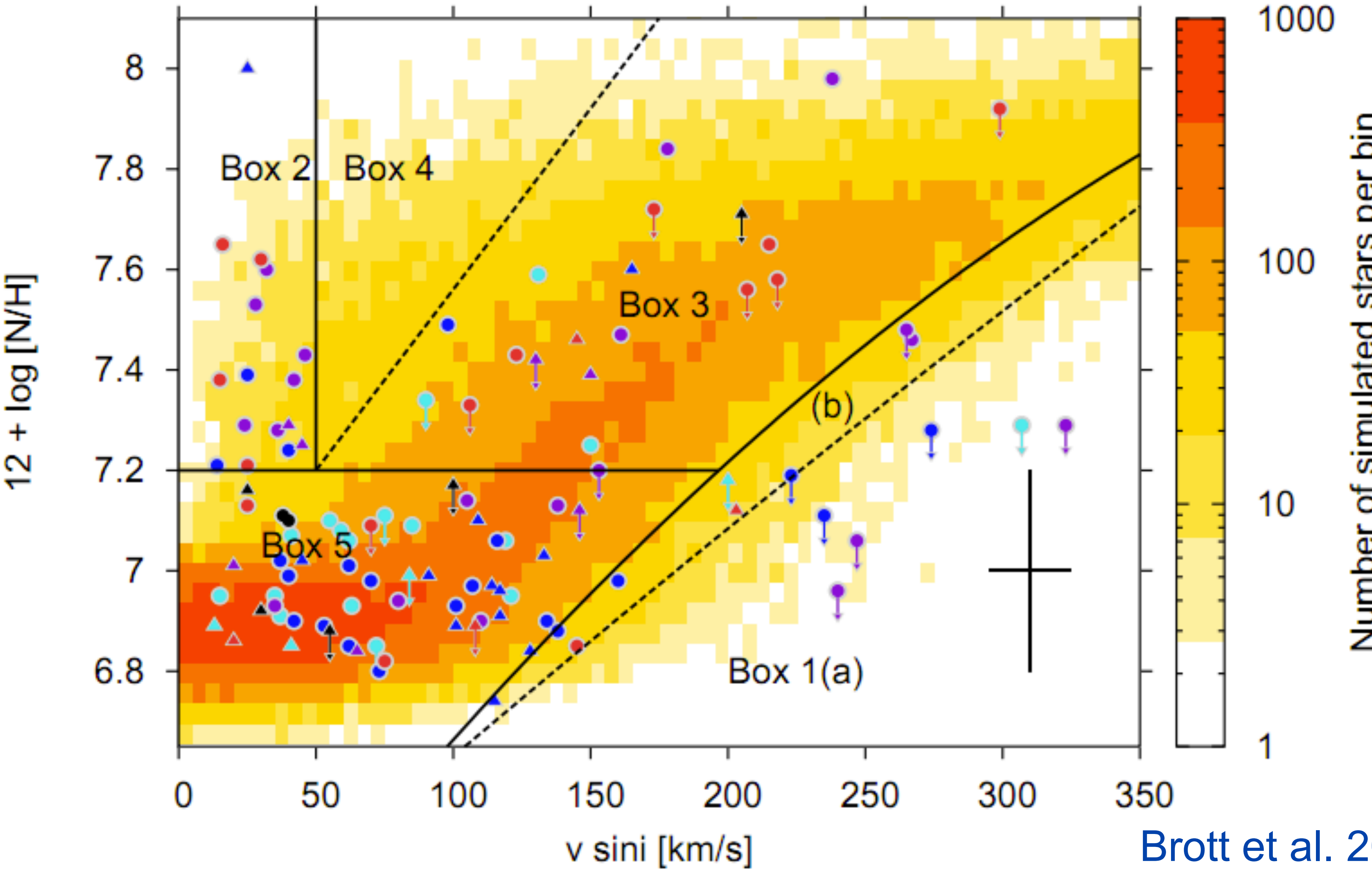
IGW: Wave Decoupling



Asteroseismology in the Space Era



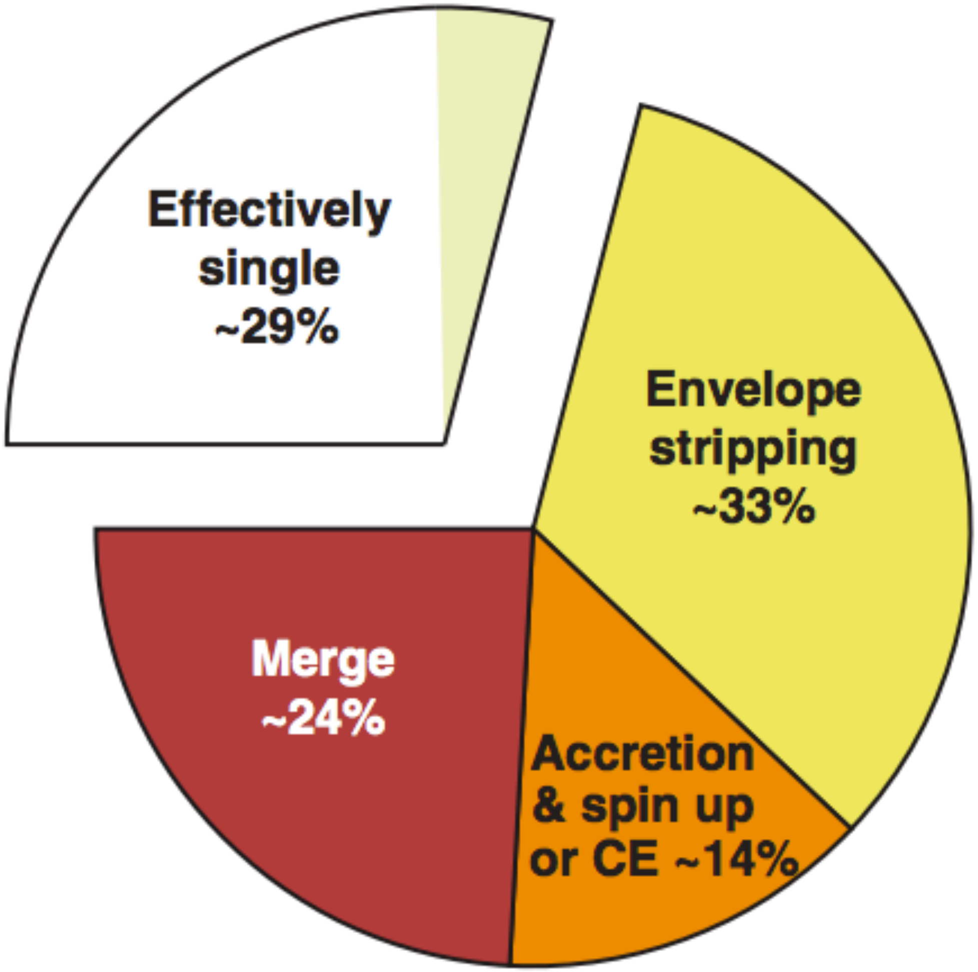
Testing transport mechanisms



Brott et al. 2011

Incidence of binarity

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

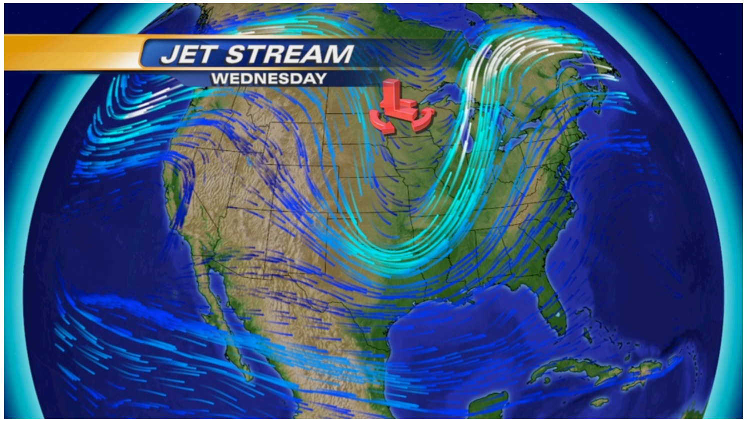


Sana et al. 2012 (Science)

The Shellular Approximation

The Shellular approximation allows to calculate 1D models of rotating stars

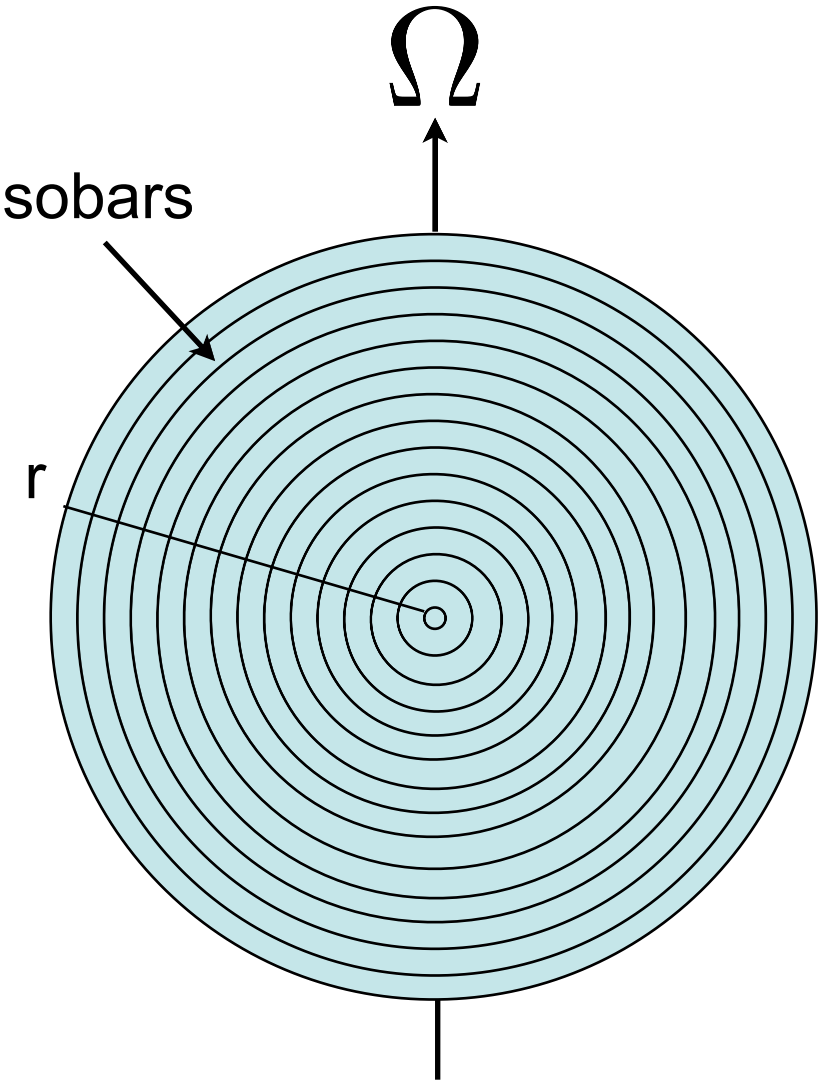
- Rotation and especially differential rotation generates turbulent motions. On Earth, we have the example of west winds and jet streams.



- According to Zahn (1975), Chaboyer & Zahn (1992), and Zahn (1992), in a star anisotropic turbulence acts much stronger on isobars than in the perpendicular direction. This enforces a shellular rotation law (Meynet & Maeder 1997), and it sweeps out compositional differences on isobars. Therefore it can be assumed that matter on isobars is approximately chemically homogeneous and that angular momentum is quickly mixed along isobars. This allows to retain a **one-dimensional approximation** with mass shells corresponding to isobars instead of spherical shells.

The Shellular Approximation

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



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

The structure equations of rotating stars

For a star in **shellular** rotation it is possible to modify the eqs of stellar structure to include the effect of the centrifugal force while keeping the form of the equations very close to that of the non-rotating case. Basically all quantities are redefined on isobars.

Mass conservation

$$\frac{dm_P}{dr_P} = 4\pi r_P^2 \rho$$

Hydrostatic Eq.

$$\frac{dP}{dm_P} = -\frac{Gm_P}{4\pi r_P^4} f_P$$

Energy transport

$$\frac{d\ln T}{d\ln P} = \frac{3\kappa P L_P}{16\pi a c G m_P T^4} \frac{f_T}{f_P}$$

...

$$V_P = 4\pi r_P^3/3$$

$$\langle q \rangle \equiv \frac{1}{S_P} \oint_{S_P} q \, d\sigma$$

$$f_P = \frac{4\pi r_P^4}{G m_P S_P} \left\langle g_{\text{eff}}^{-1} \right\rangle^{-1}$$

$$f_T \equiv \left(\frac{4\pi r_P^2}{S_P} \right) \left(\langle g_{\text{eff}} \rangle \langle g_{\text{eff}}^{-1} \rangle \right)^{-1}$$

Endal & Sofia 1978

Diffusion Equations

Transport of chemical species:

$$\left(\frac{\partial X_n}{\partial t}\right)_m = \left(\frac{\partial}{\partial m}\right)_t \left[(4\pi r^2 \rho)^2 D \left(\frac{\partial X_n}{\partial m}\right)_t\right] + \left(\frac{\mathrm{d}X_n}{\mathrm{d}t}\right)_{\mathrm{nuc}}$$

$$t_{\mathrm{diff}} \simeq \frac{R^2}{D}$$

Transport of angular momentum:

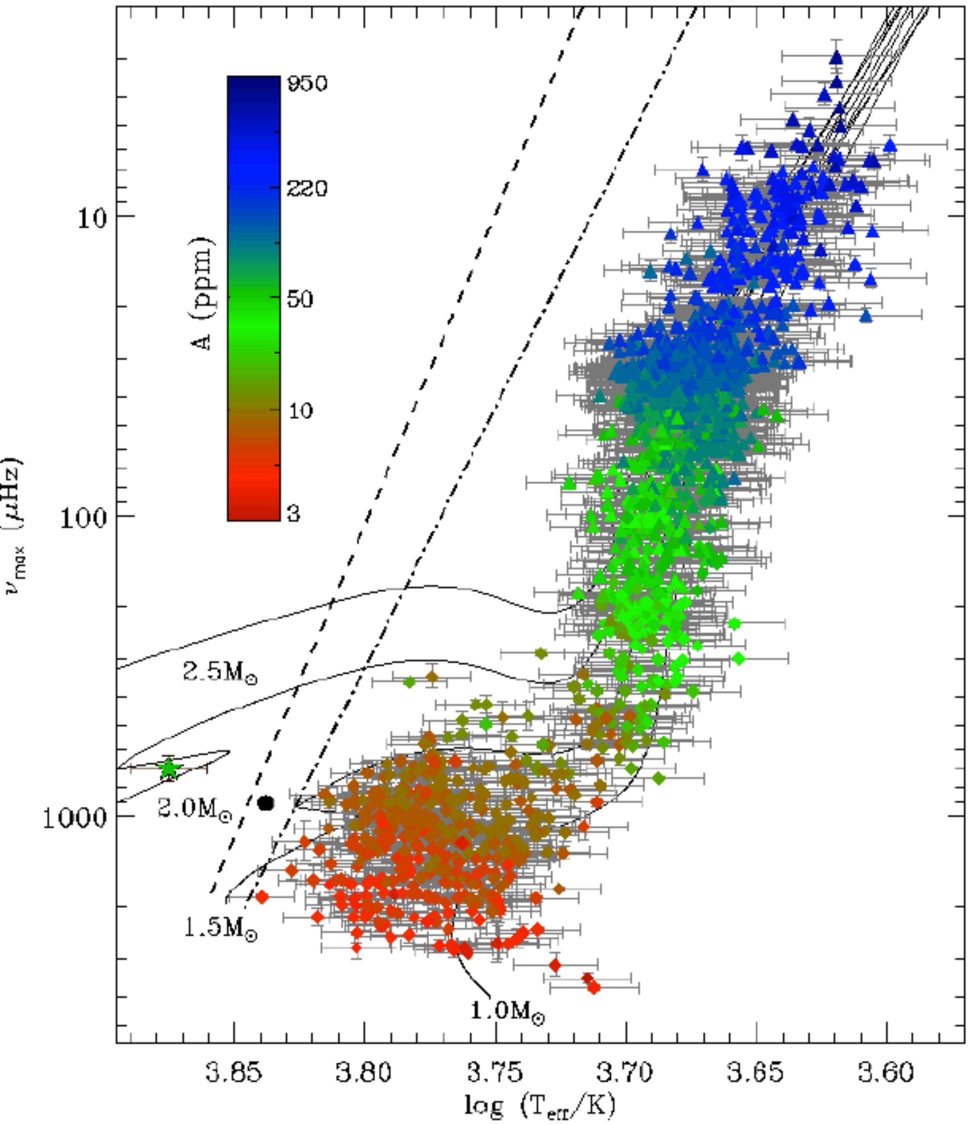
$$\left(\frac{\partial \omega}{\partial t}\right)_m = \frac{1}{i}\left(\frac{\partial}{\partial m}\right)_t \left[(4\pi r^2 \rho)^2 i v \left(\frac{\partial \omega}{\partial m}\right)_t\right] - \frac{2\omega}{r}\left(\frac{\partial r}{\partial t}\right)_m \left(\frac{1}{2}\frac{d\ln i}{d\ln r}\right)$$

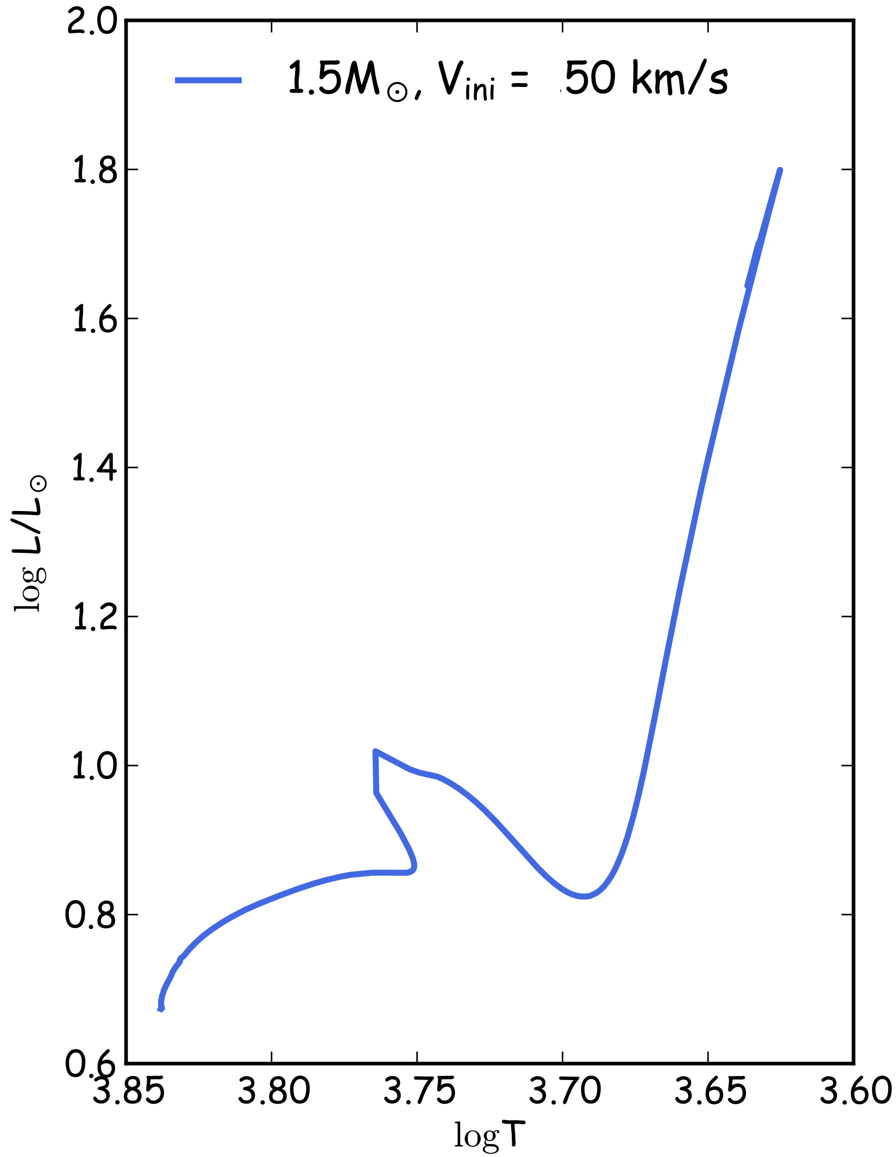
Advection- Diffusion Scheme

MESA adopts the diffusion approximation (like e.g. KEPLER and STERN). An alternative approach is to solve an advection-diffusion equation for the transport of angular momentum (e.g. in the GENEVA, Maeder & Meynet 2000, 2012).

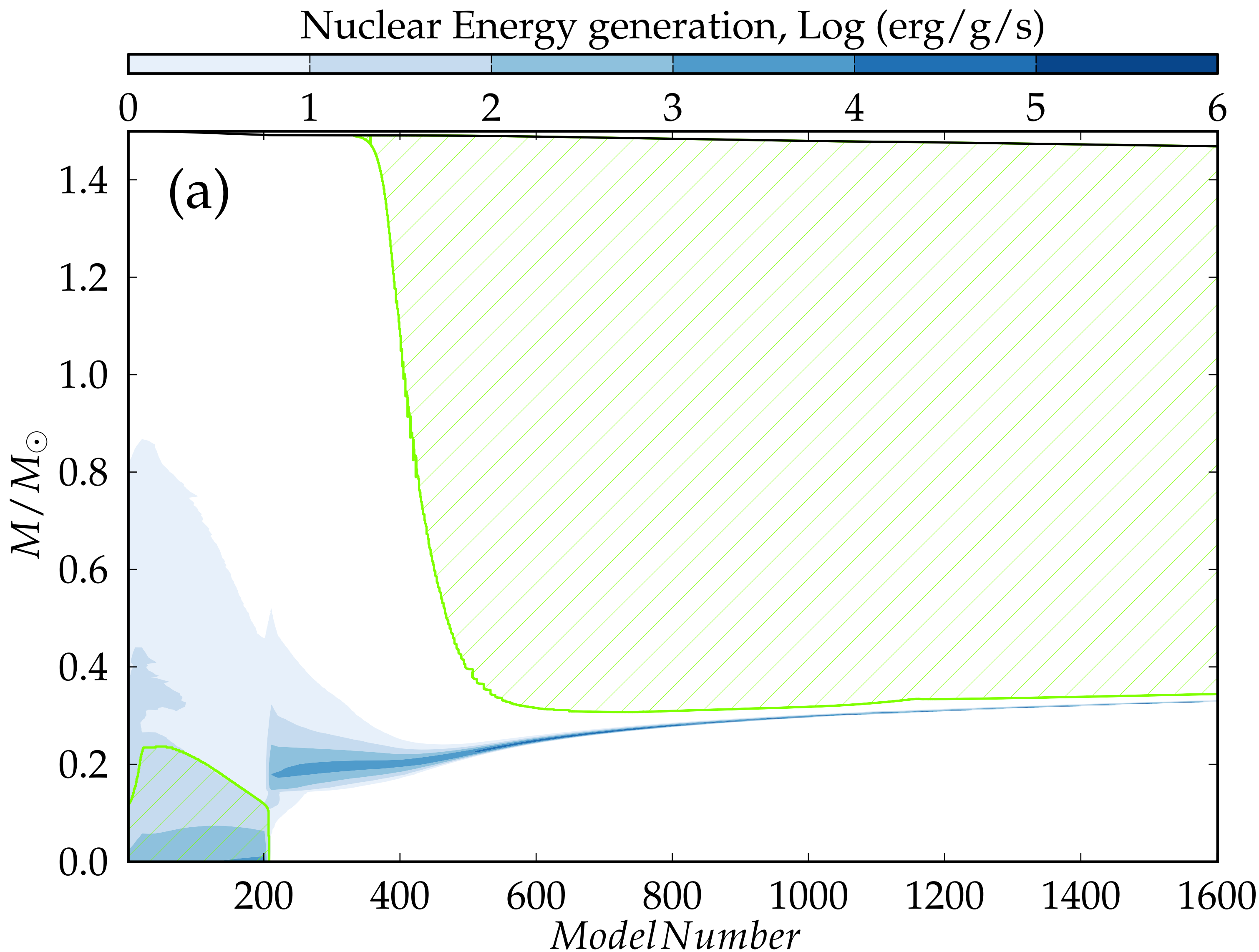
A very interesting work comparing the different implementations has been published by Potter et al. 2012 (ROSE code). While the advection-diffusion scheme is more physically sound, a key result of Potter's work is that is not yet possible to prefer one of the two implementations, given the available observational constraints.

Huber et al. 2011





Evolution of a 1.5 MSun



Evolution of a 1.5 M_{Sun}