Internal Gravity Waves in Massive Stars

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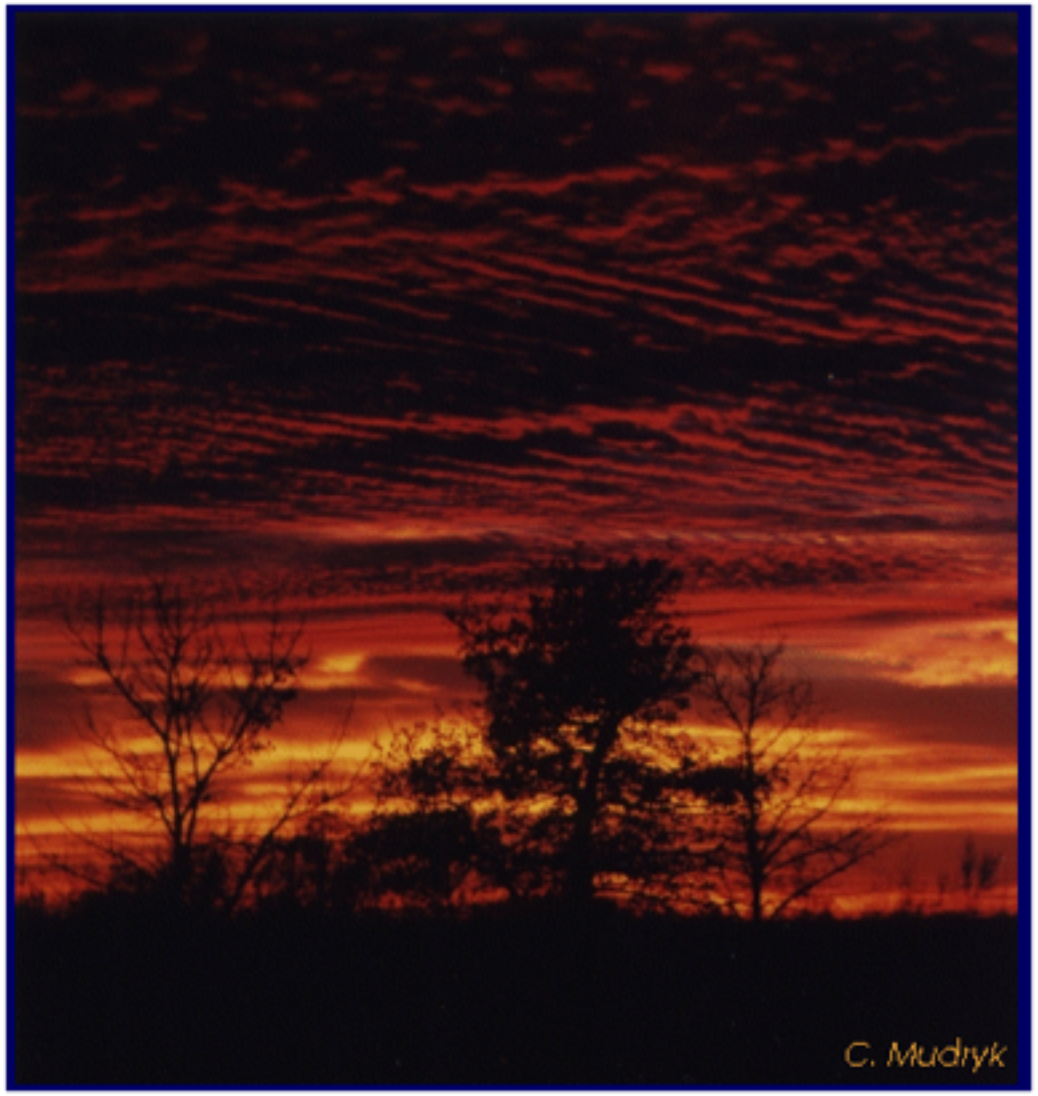
20 March 2017

Internal Gravity Waves

(not gravitational waves)

- Waves for which the restoring force is gravity
- Occur in any stably-stratified (radiative) region



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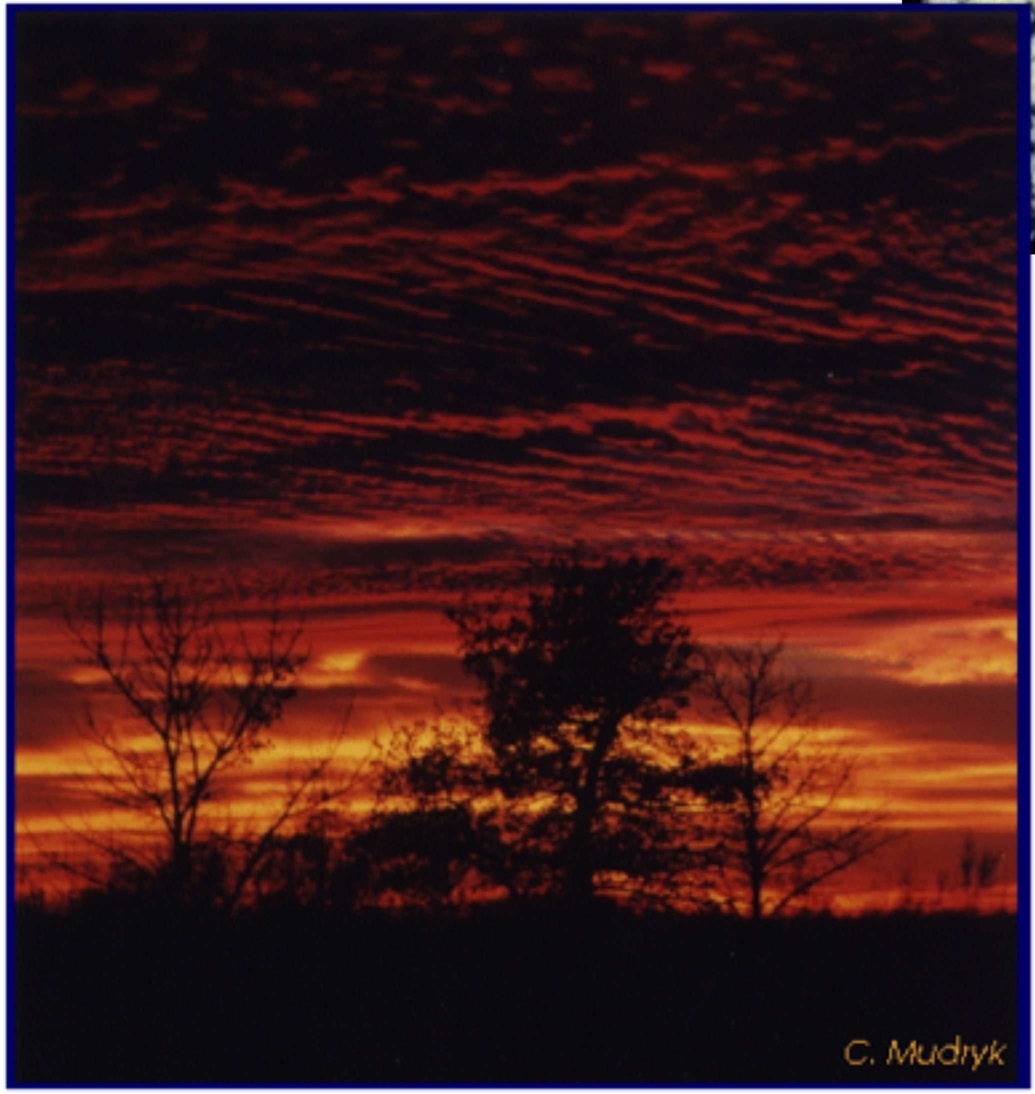
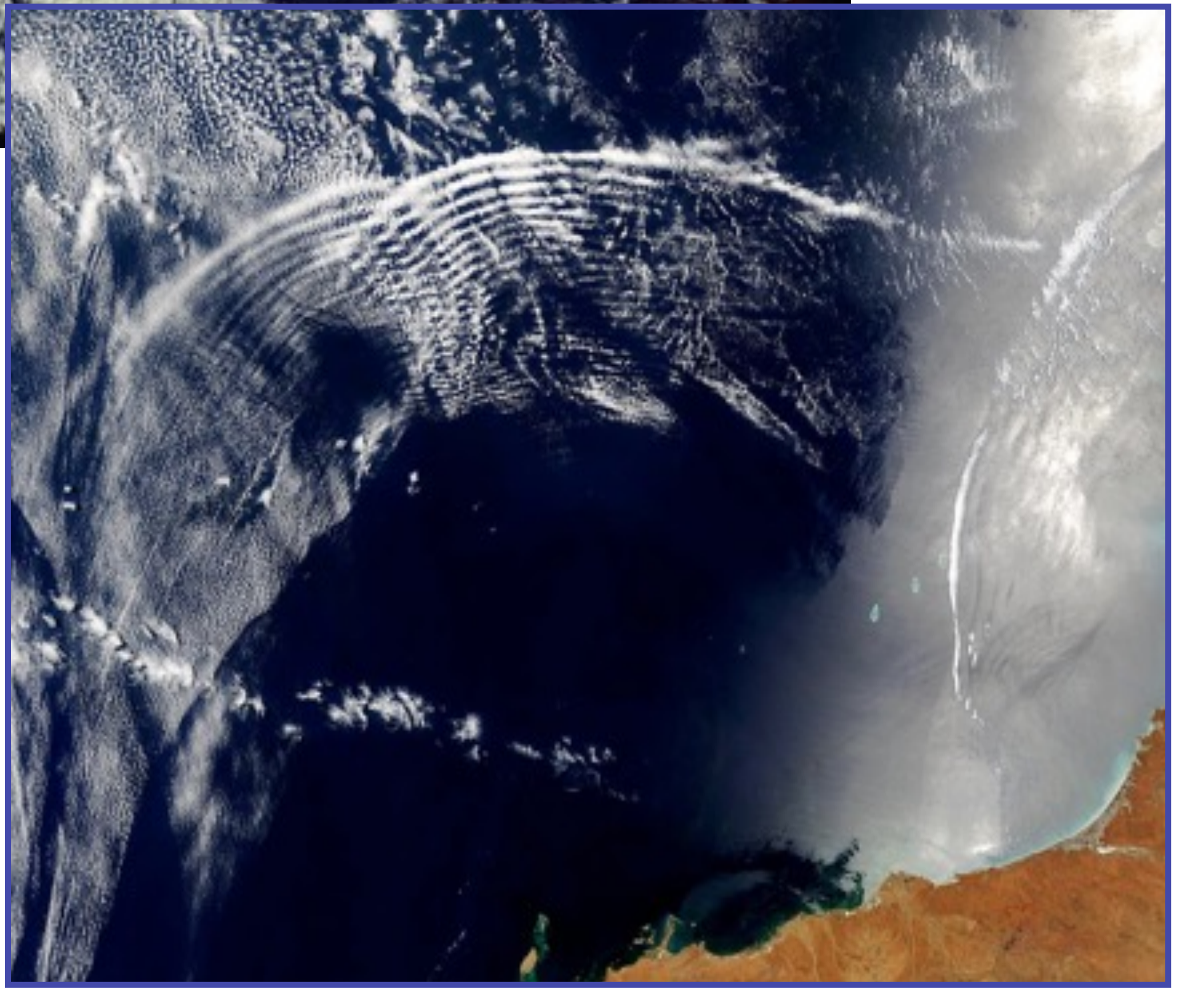
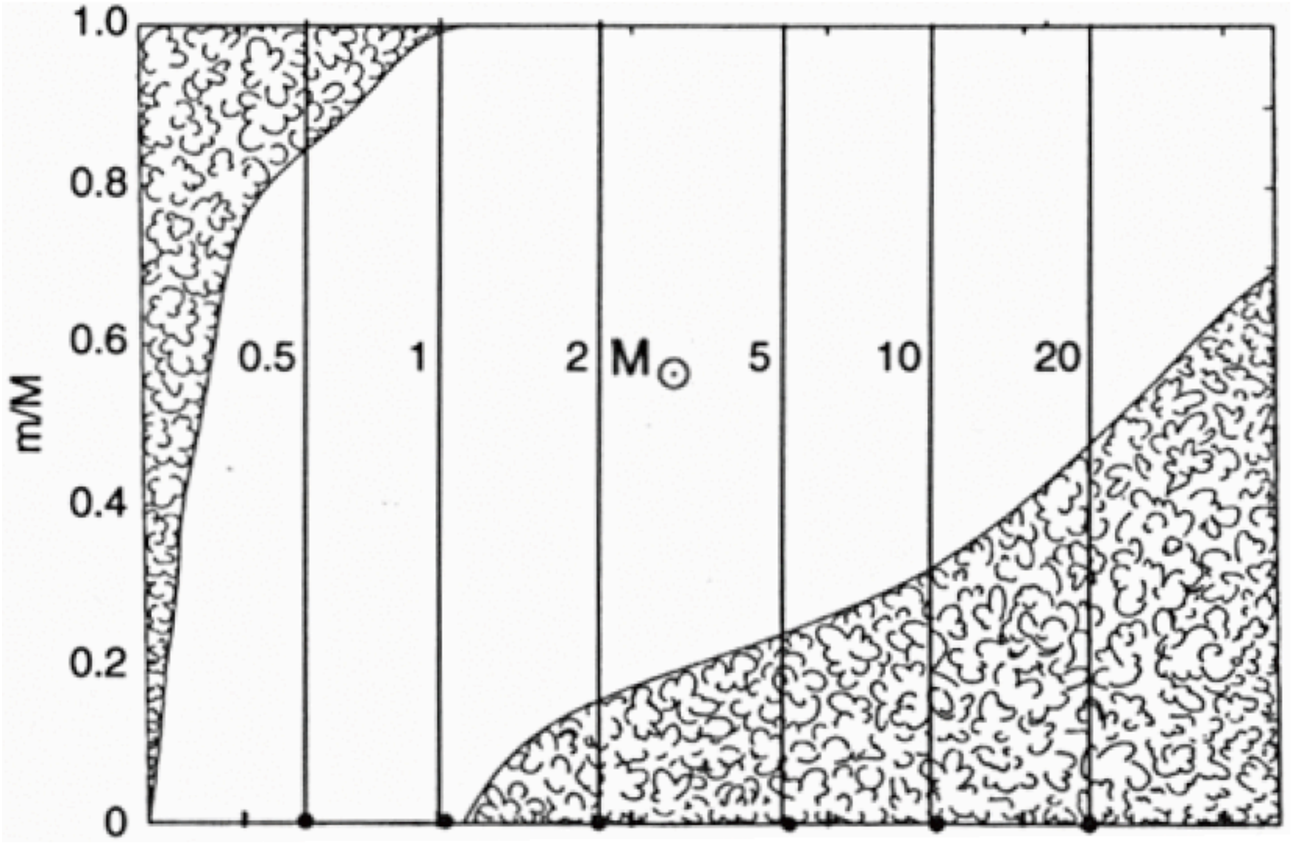


C. Mudryk

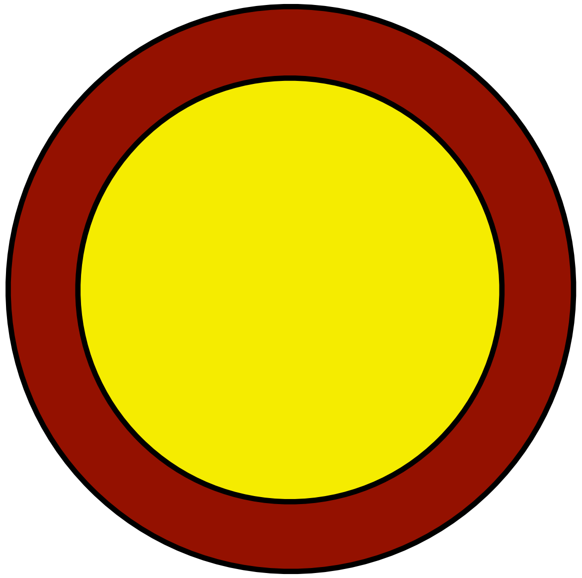


Massive Stars

- Solar type stars have convective envelopes and radiative (stably-stratified) interiors
- Intermediate and Massive stars have convective cores and extended radiative envelopes
- Some massive stars have additional tenuous convective envelopes

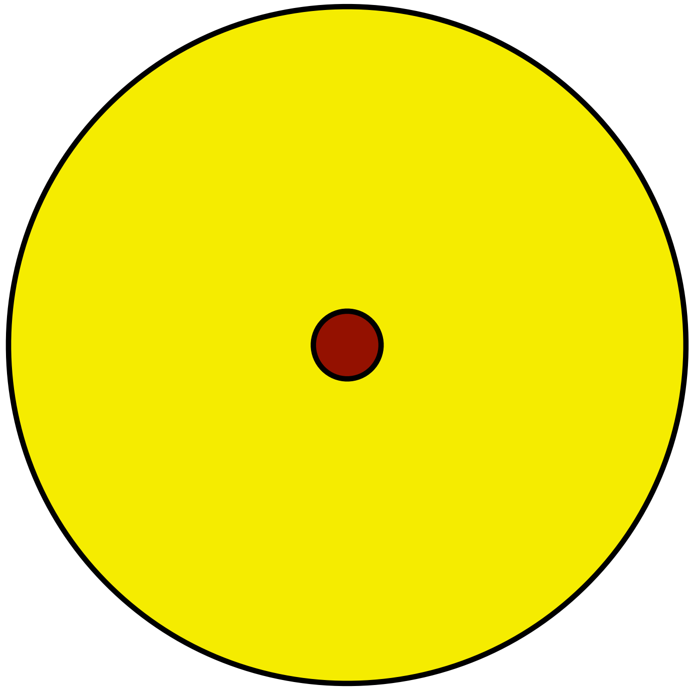


Sun



A star

4Msun



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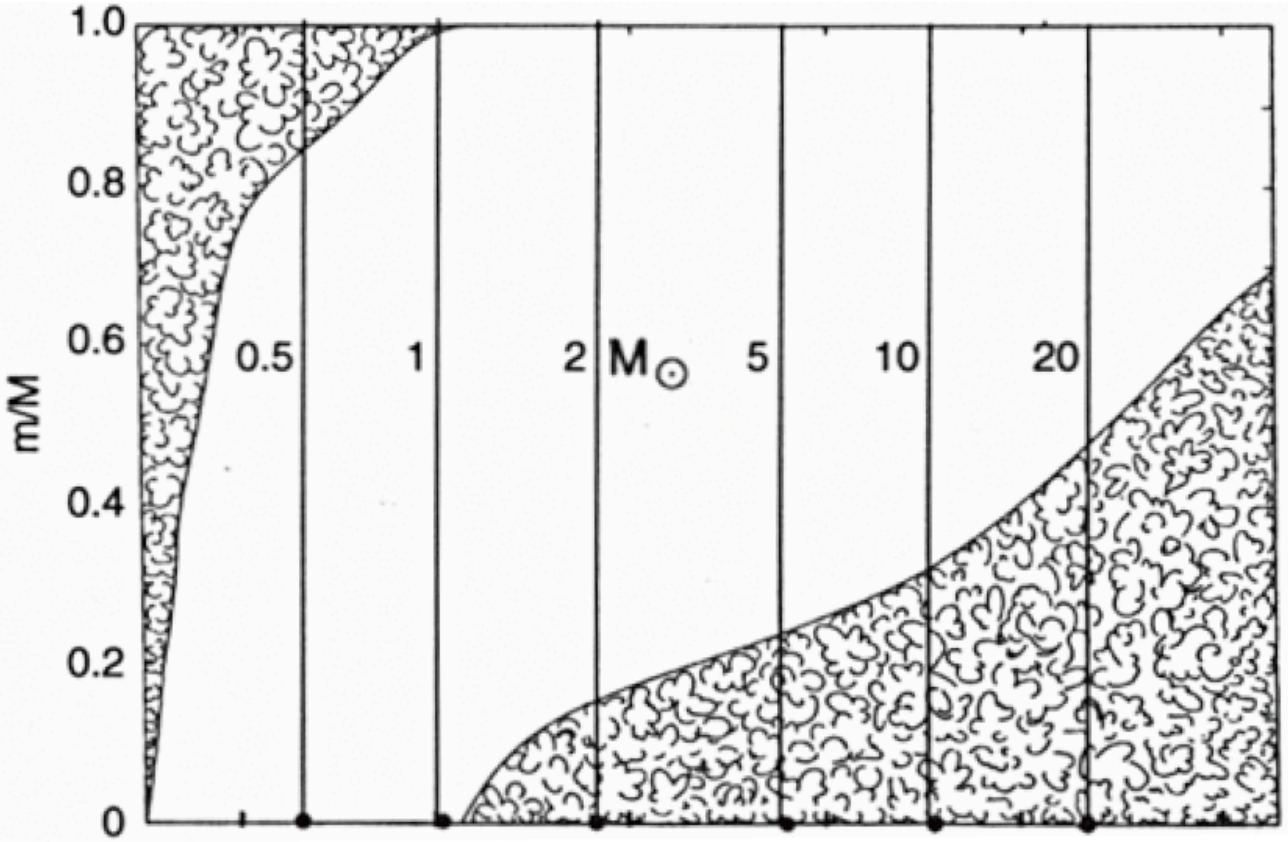
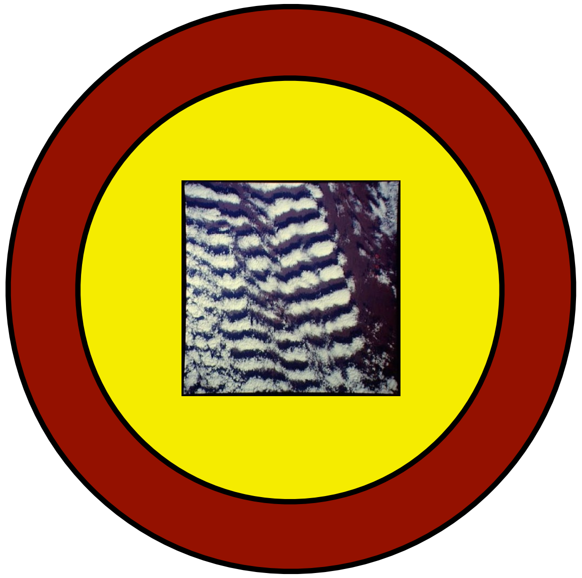
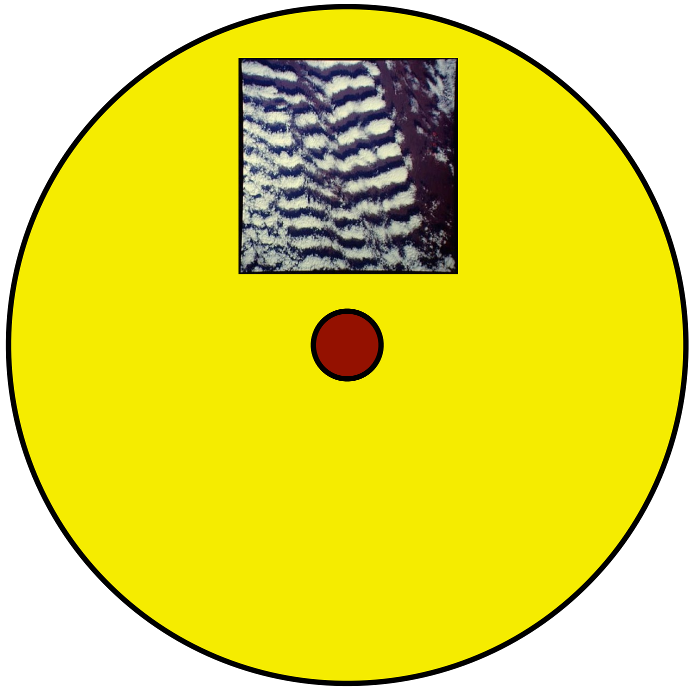


Sun



A star

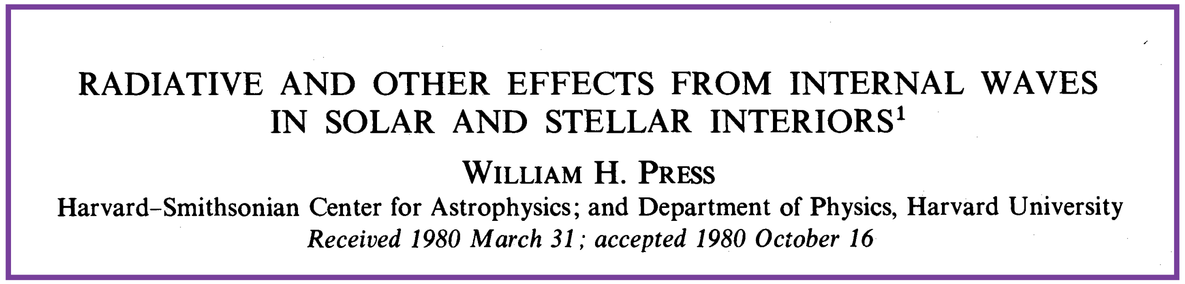
4M$_{sun}$



Why We Care

Gravity Waves Transport Angular Momentum and Mix Species which leads to Rotational and Chemical Evolution of the Star

Solar Neutrinos

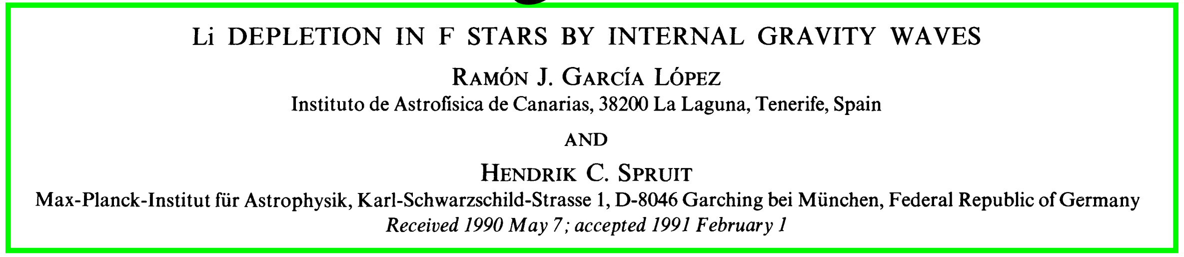

RADIATIVE AND OTHER EFFECTS FROM INTERNAL WAVES IN SOLAR AND STELLAR INTERIORS[1]

William H. Press

Harvard–Smithsonian Center for Astrophysics; and Department of Physics, Harvard University

Received 1980 March 31; accepted 1980 October 16

Mixing in Stars


Li DEPLETION IN F STARS BY INTERNAL GRAVITY WAVES

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Instituto de Astrofísica de Canarias, 38200 La Laguna, Tenerife, Spain

and

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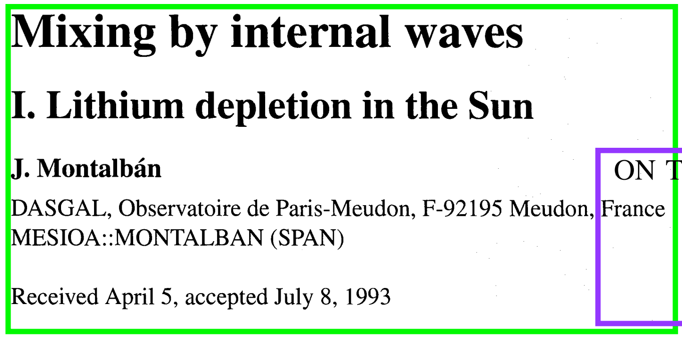
Received 1990 May 7; accepted 1991 February 1


Mixing by internal waves

I. Lithium depletion in the Sun

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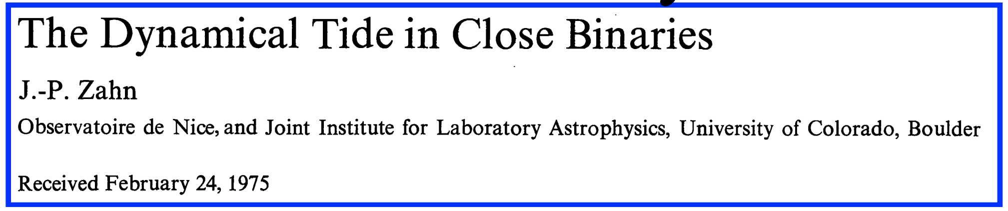
MESIOA::MONTALBAN (SPAN)

Received April 5, accepted July 8, 1993

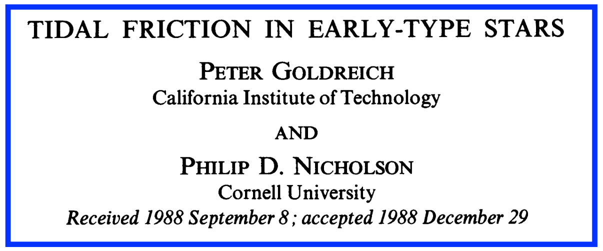
Orbits of Binary Stars


The Dynamical Tide in Close Binaries

J.-P. Zahn

Observatoire de Nice, and Joint Institute for Laboratory Astrophysics, University of Colorado, Boulder

Received February 24, 1975


TIDAL FRICTION IN EARLY-TYPE STARS

Peter Goldreich

California Institute of Technology

and

Philip D. Nicholson

Cornell University

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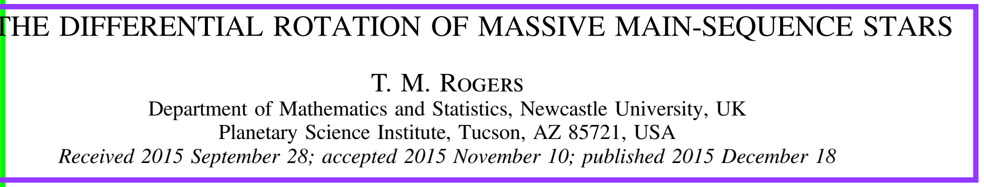
Differential Rotation


ON THE DIFFERENTIAL ROTATION OF MASSIVE MAIN-SEQUENCE STARS

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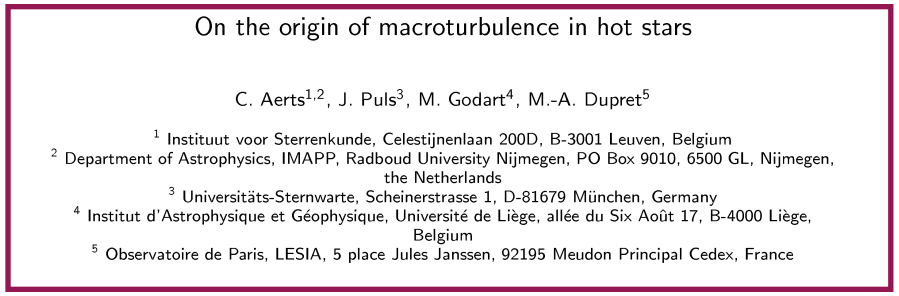
Macroturbulence


On the origin of macroturbulence in hot stars

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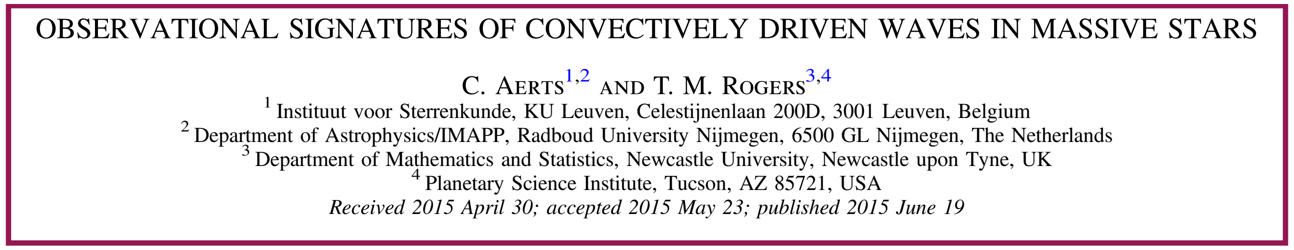
OBSERVATIONAL SIGNATURES OF CONVECTIVELY DRIVEN WAVES IN MASSIVE STARS

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[1] Instituut voor Sterrenkunde, KU Leuven, Celestijnenlaan 200D, 3001 Leuven, Belgium

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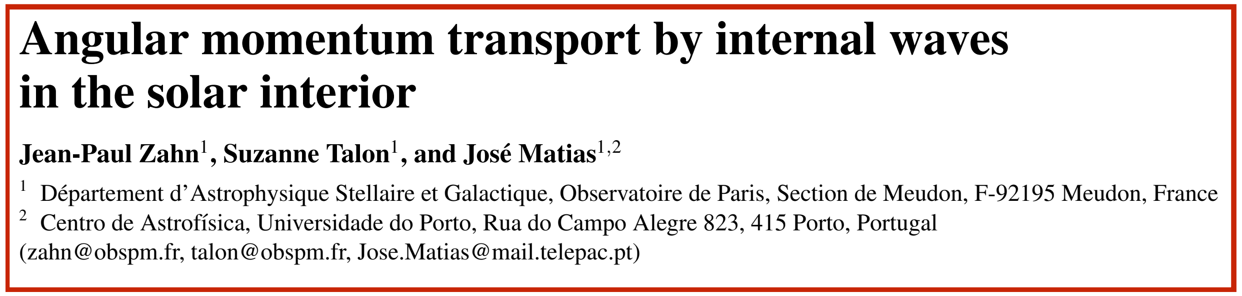
Uniform Rotation of Solar Interior


Angular momentum transport by internal waves in the solar interior

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[1] Département d'Astrophysique Stellaire et Galactique, Observatoire de Paris, Section de Meudon, F-92195 Meudon, France

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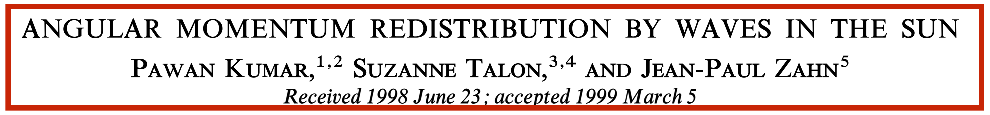
ANGULAR MOMENTUM REDISTRIBUTION BY WAVES IN THE SUN

Pawan Kumar,[1,2] Suzanne Talon,[3,4] and Jean-Paul Zahn[5]

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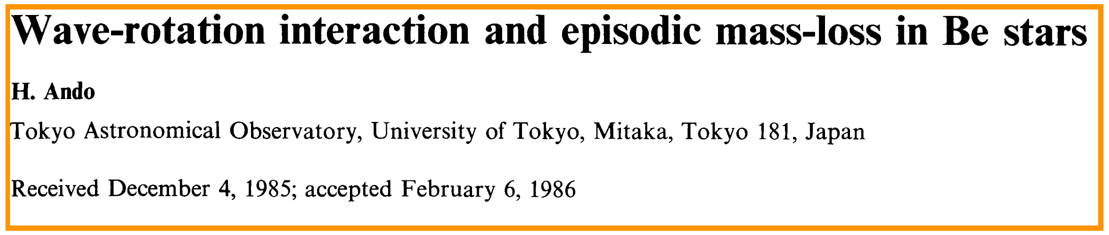
Be Stars


Wave-rotation interaction and episodic mass-loss in Be stars

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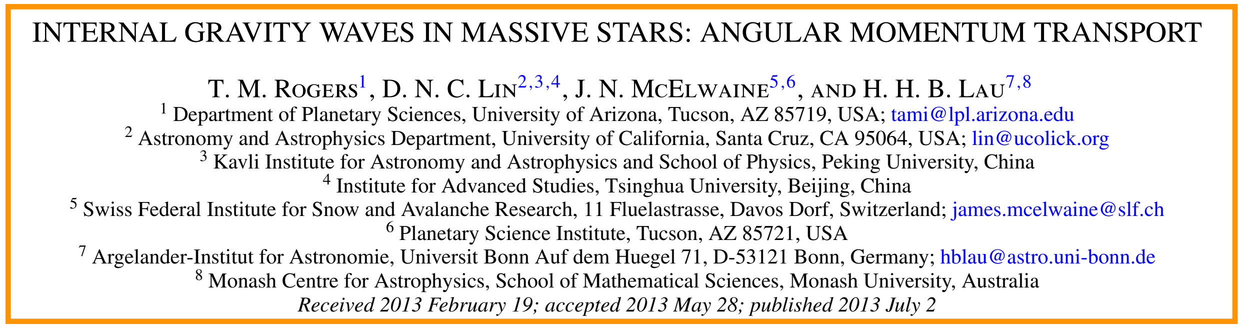
Received December 4, 1985; accepted February 6, 1986


INTERNAL GRAVITY WAVES IN MASSIVE STARS: ANGULAR MOMENTUM TRANSPORT

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[8] Monash Centre for Astrophysics, School of Mathematical Sciences, Monash University, Australia

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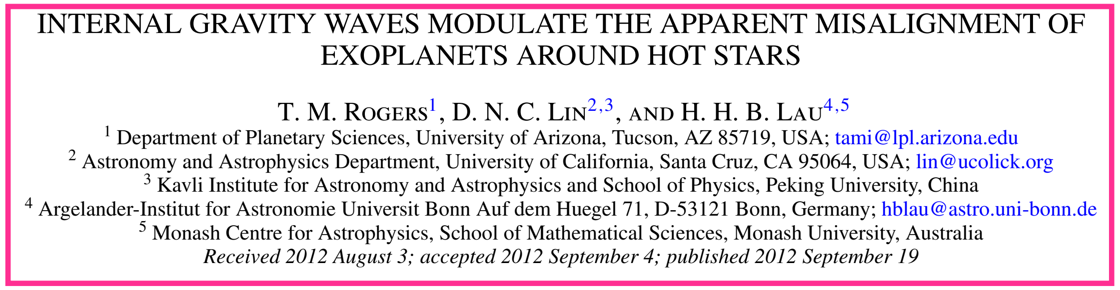
Obliquities of Hot Jupiters


INTERNAL GRAVITY WAVES MODULATE THE APPARENT MISALIGNMENT OF EXOPLANETS AROUND HOT STARS

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[4] Argelander-Institut for Astronomie Universit Bonn Auf dem Huegel 71, D-53121 Bonn, Germany; hblau@astro.uni-bonn.de

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Simulations of IGW

IGW dynamics depend strongly on the spectrum generated by convection, therefore we need to simulate both convection and wave propagation simultaneously. Furthermore in massive star conditions some waves may break, again requiring simulation for adequate modeling. ***Simulations are required but are difficult because of vast range of length and timescales.***

Numerical Model

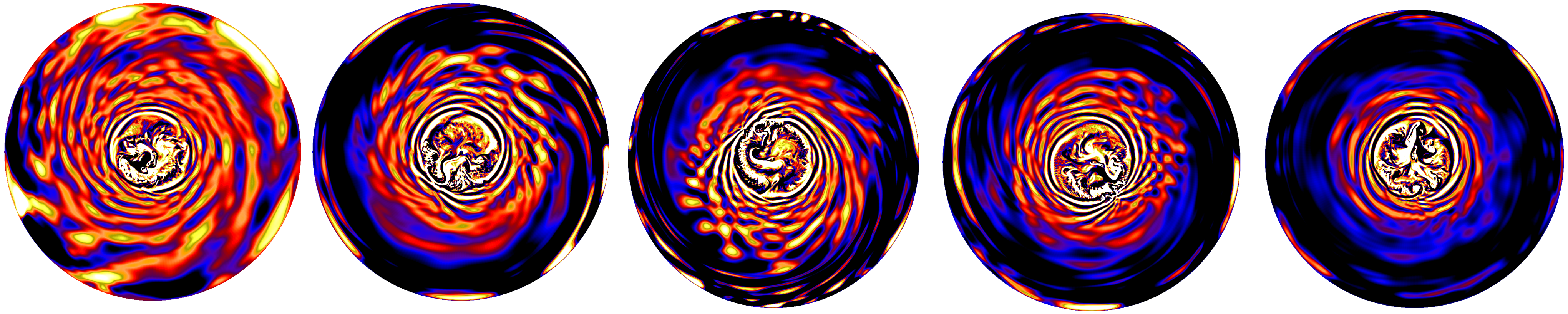
- We solve the full set of hydrodynamic equations in the anelastic approximation in 2D representing an equatorial slice of the star
- Our reference state model is taken from the Cambridge STARS 1D stellar evolution code for a $3M_{sun}$ star: ~inner 15% convection+radiative envelope
- **The Basic Physical Picture**
- Turbulent convection generates IGW at the convective-radiative interface: get ***spectrum*** of waves
- As waves propagate outward toward the surface, their amplitudes are affected by two main effects:
    - wave amplitude increases because of decreasing density
    - wave amplitude decreases because of radiative dissipation
- *Some* waves make it to the surface with sufficient amplitude to break
- Wave breaking is accompanied by angular momentum transport
- Angular momentum transport causes surface rotation to change
- Leads to enhanced mixing

CAVEATS

- Since we have a realistic temperature gradient and our diffusion coefficients are too large: **in some we force the convection harder - higher luminosity than $3M_{sun}$ star**
- Our convective velocities are ~10 x larger than mixing-length theory would predict, however surface amplitude not larger

Convectively driven waves in massive stars (sometimes) cause surface to spin ***retrograde***

Vorticity is shown:
White-prograde flow
Black-retrograde flow



Rogers et al (2013)

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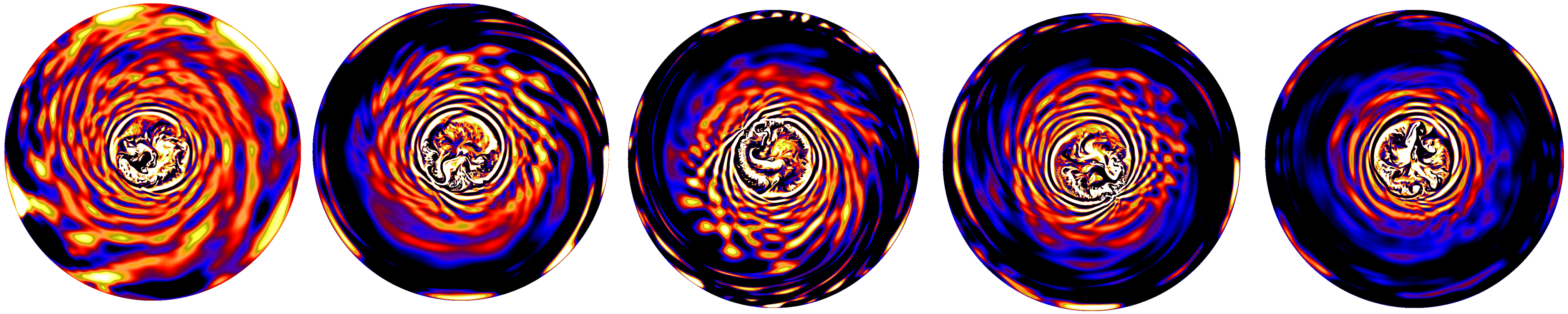
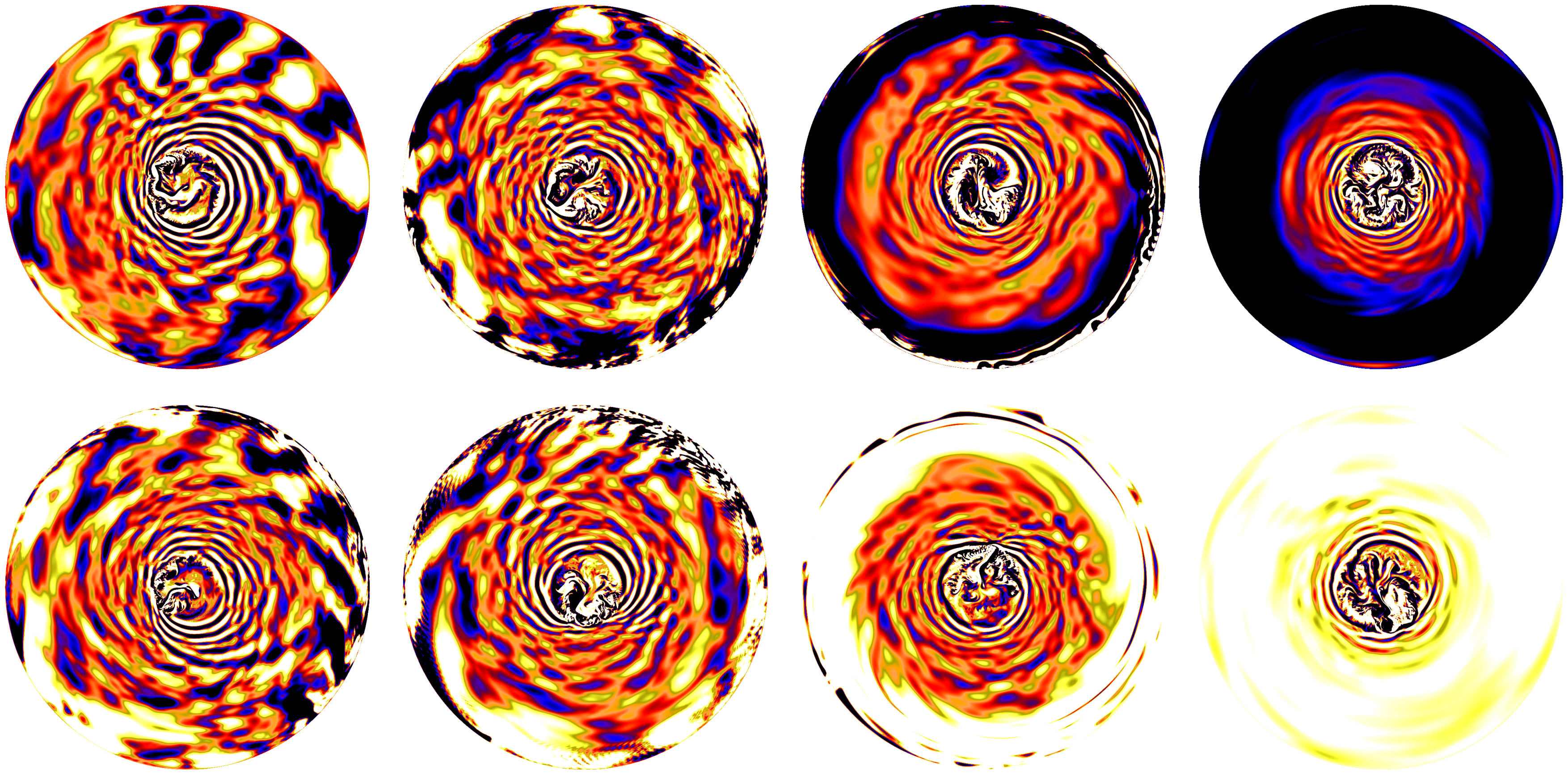


Rogers et al (2013)

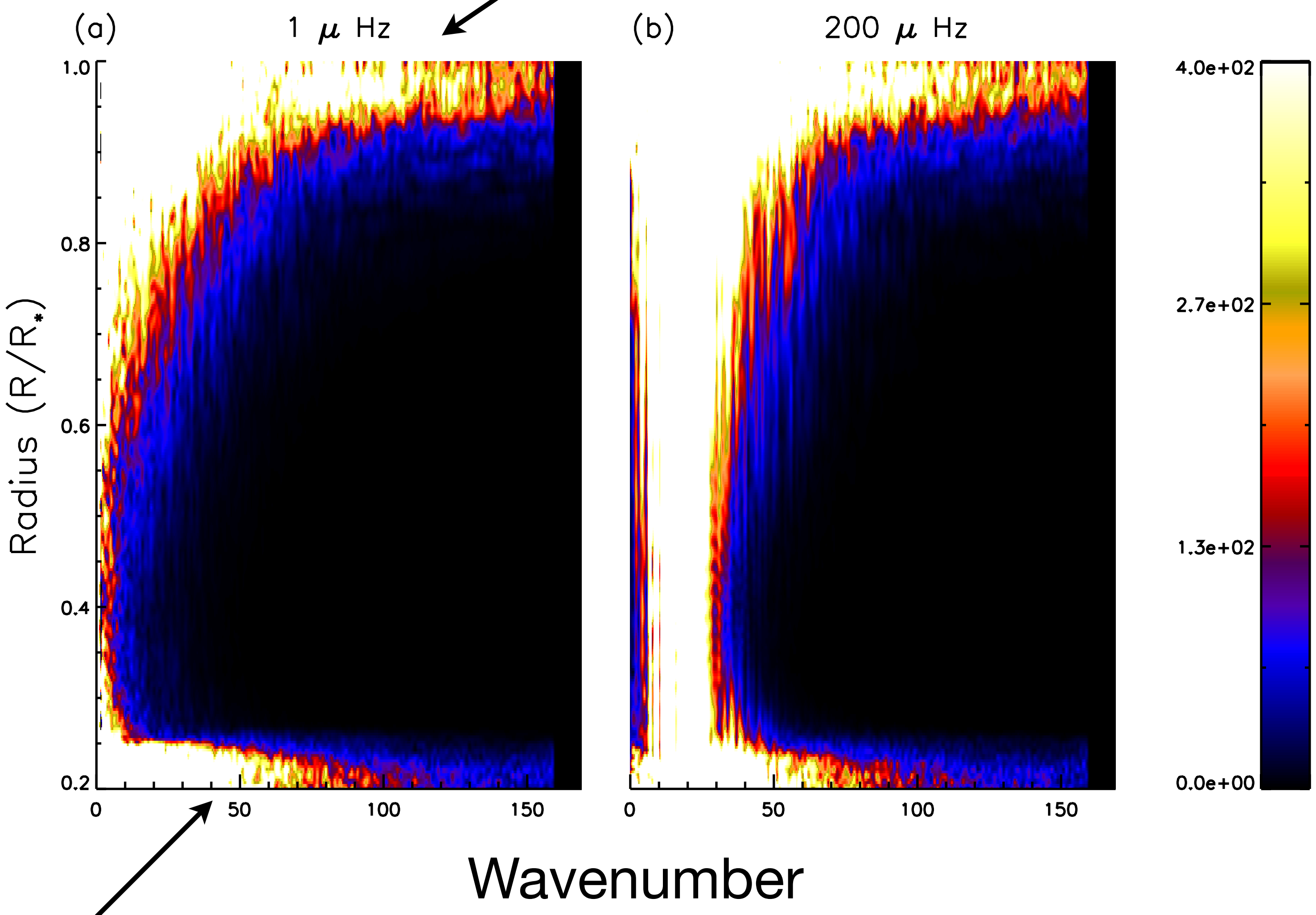
Results:
Angular Momentum Transport by IGW



Wave Amplification and Breaking at Surface

- Large scale waves generated at the convective-radiative interface
- Only the largest scale survive through the bulk of the interior (depending on frequency)
- At surface, smaller scales are generated-> indicative of wave breaking

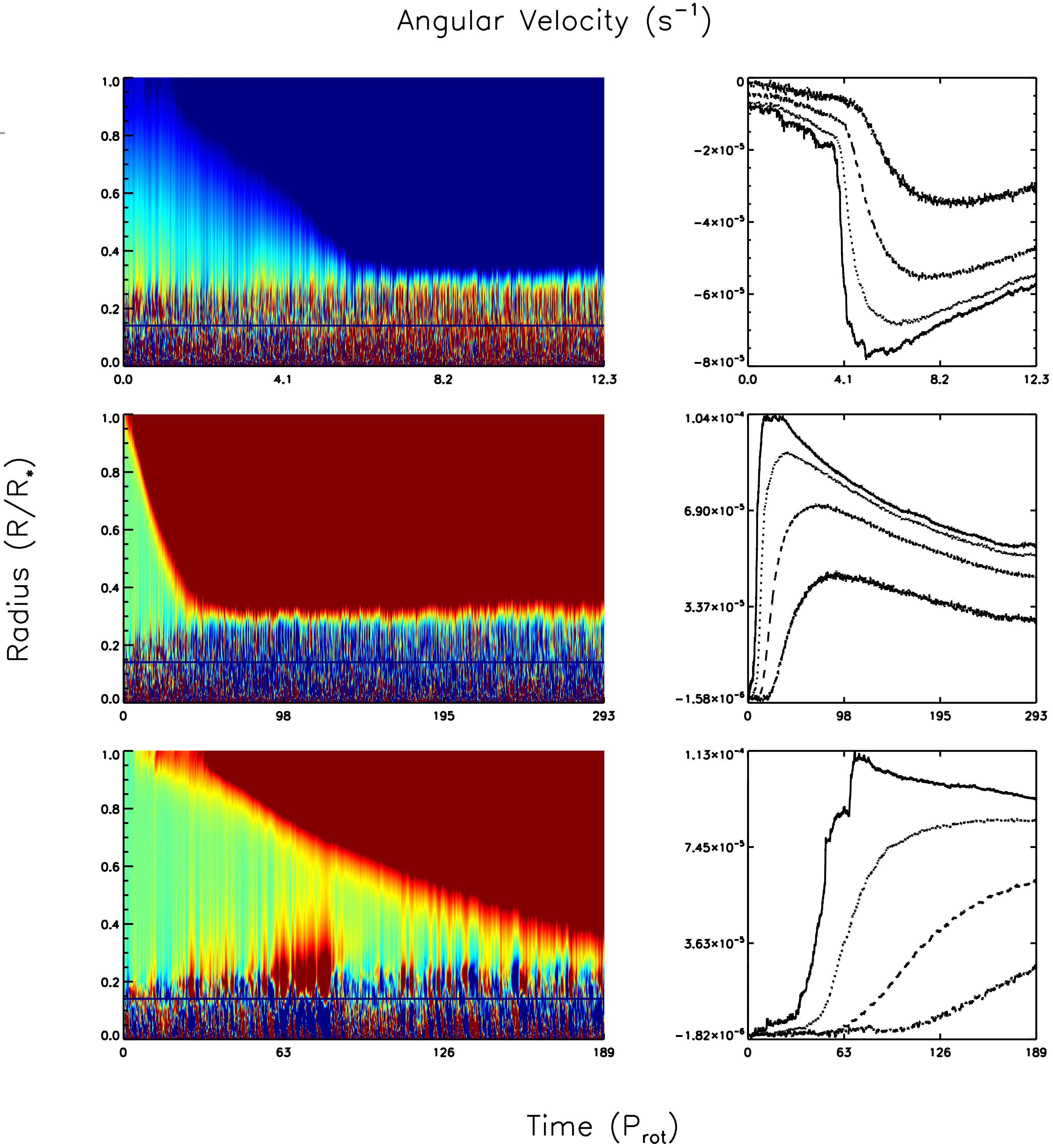
Waves generated at surface by breaking



Waves generated at convective-radiative interface

Angular Velocity Evolution

- Shear layer develops first at the surface then migrates toward the source in time
  - Initial development is due to wave breaking, followed by critical layer formation and absorption
- Convection zone starts to spin (predominantly) with the opposite sense as radiative envelope (to conserve AM)
- Rapid AV variation in short time, conservative extrapolation ~10^3-10^4 rotation period
- However, it is unclear whether this will reverse (as in QBO) or tend toward a steady differential rotation



Rogers et al. 2013

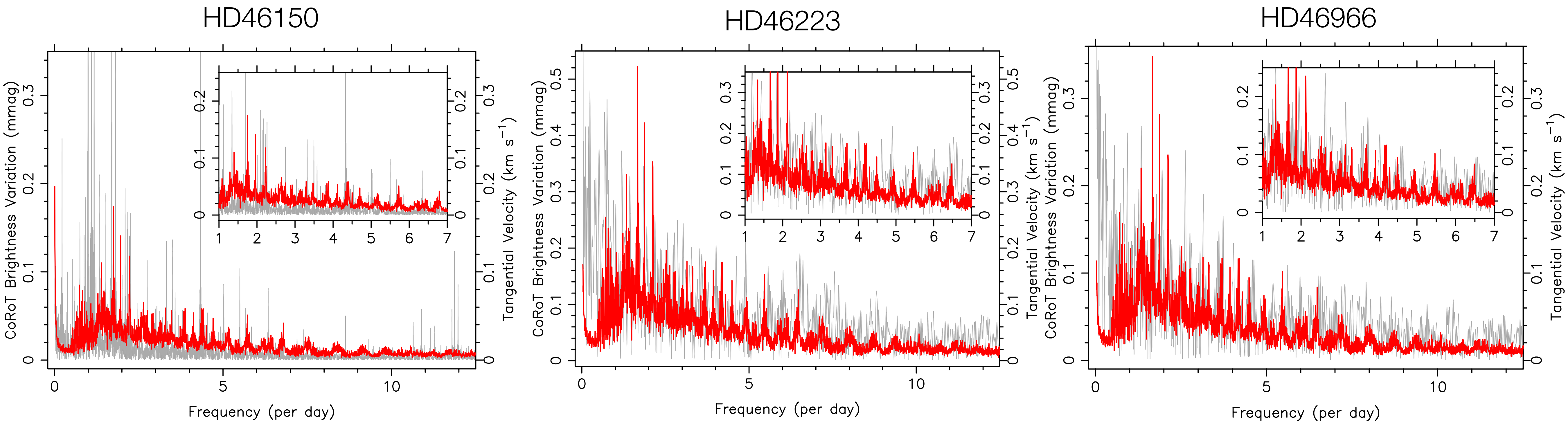
Results:
Direct Comparisons to Observations

Although standing wave *modes* are readily observed in stars we have very few observational constraints on propagating (and dissipating) waves, i.e. the ones responsible for angular momentum transport and mixing. This is changing with recent asteroseismic detections.

Brightness Variations in O-stars

🟥 Simulations
▬ Observations

Aerts & Rogers 2015

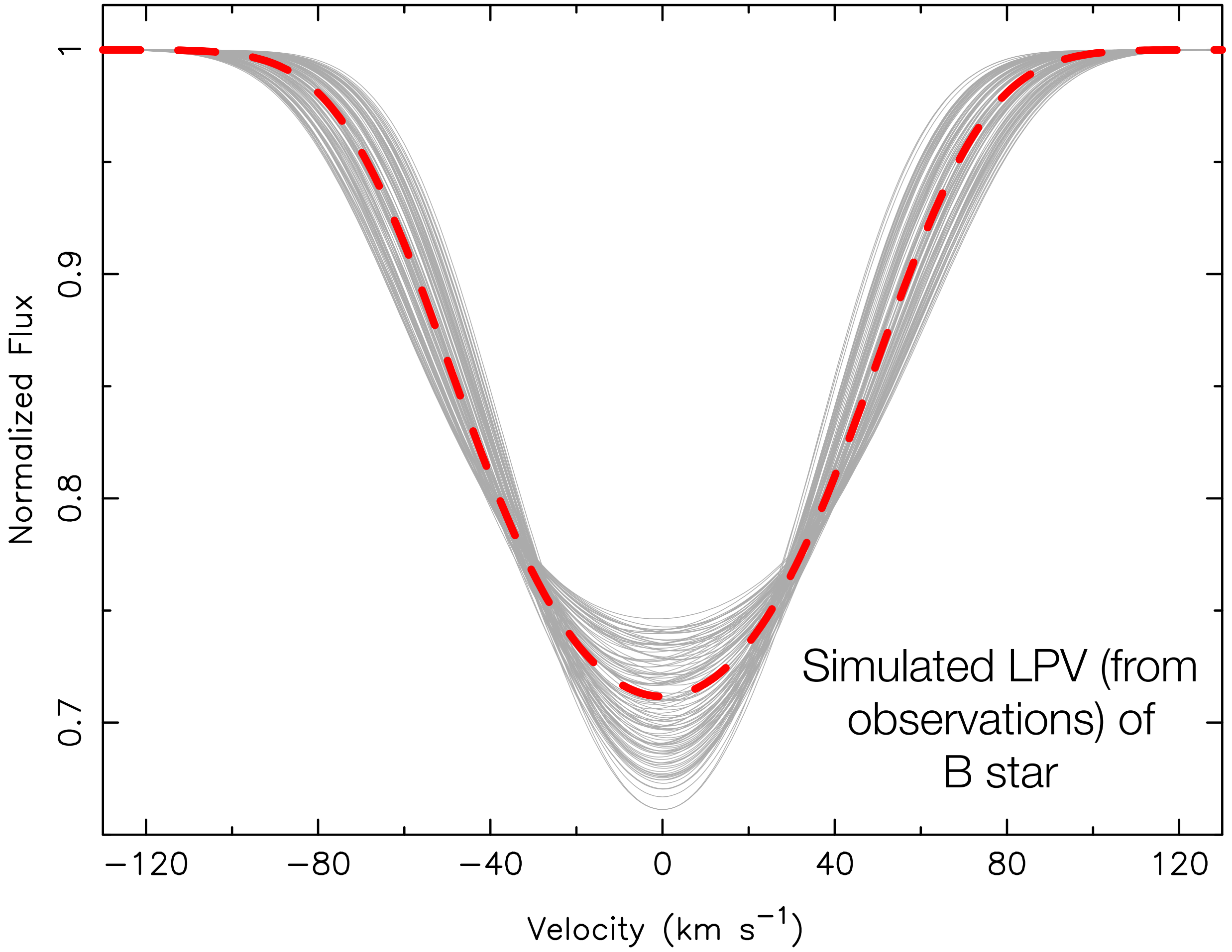


- The most observed massive stars are B stars, which are dominated by heat driven g-modes, difficult to pull out IGW signature.
- O stars do not show heat driven g-modes, but show power excess at high frequencies
- Accounting for variation in mass and conversion between observed brightness fluctuations and velocity, spectra match well (except at lowest frequencies)
- We found that numerical models which were differentially rotating (core-envelope) matched observations better than uniformly rotating models

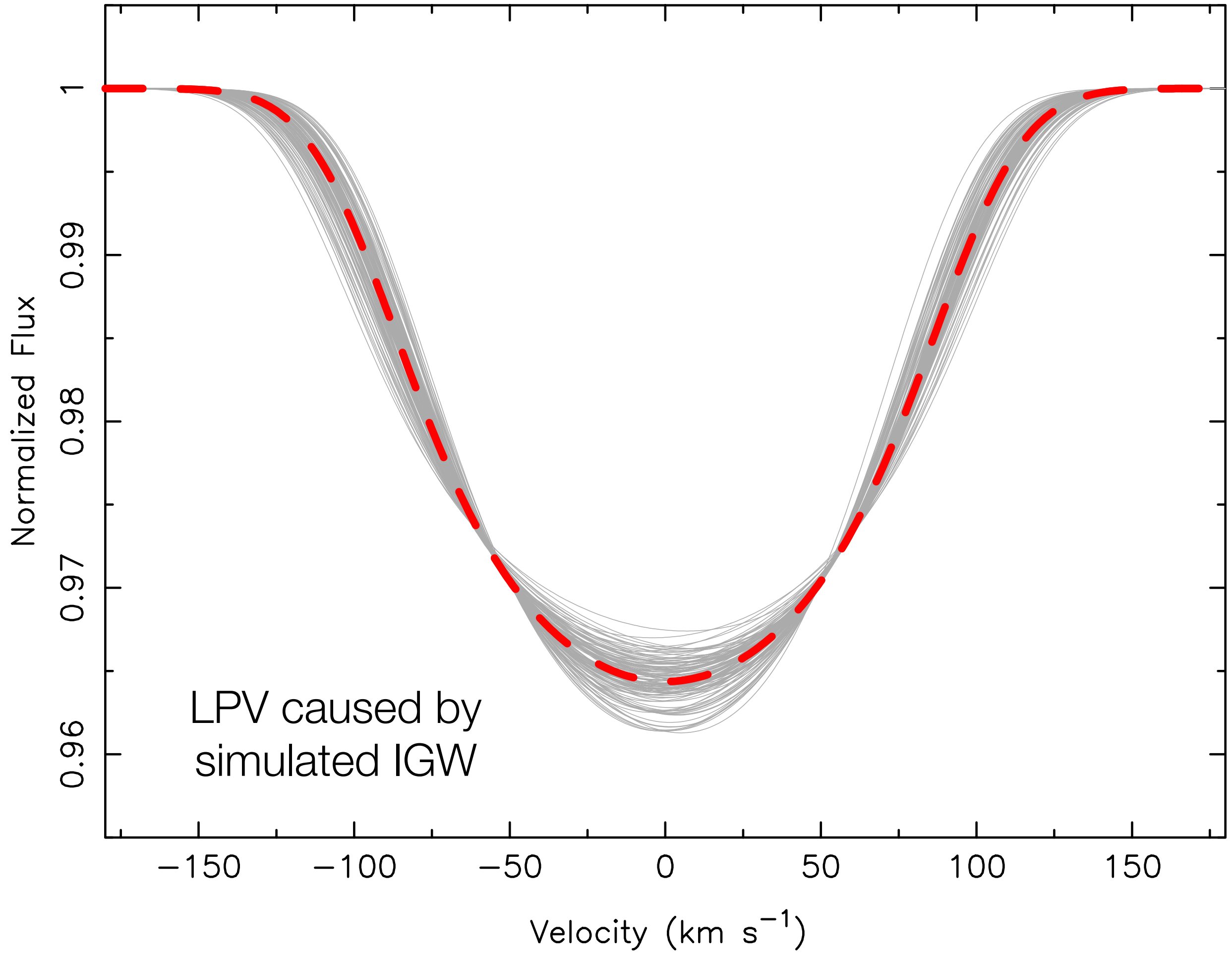
Macroturbulence

- Upper main sequence shows evidence of time dependent, non-doppler line broadening and variations in that broadening (LPV)
- Broadening has been referred to as “macroturbulence”. Expected in low mass stars, but hard to reconcile with expected quiescent envelope of higher mass stars. Could be surface convection zone (Cantiello), heat driven g-modes (Aerts)
- The same IGW that explain spectra, also show LPV similar to what is expected in O stars

Aerts & Rogers 2015



Simulated LPV (from observations) of B star



LPV caused by simulated IGW

Differential Rotation in Massive Main Sequence Stars

Using multiplets of g-modes which probe convective-radiative boundary and multiplets of p-modes which probe surface conditions, can get a measure of core-envelope differential rotation

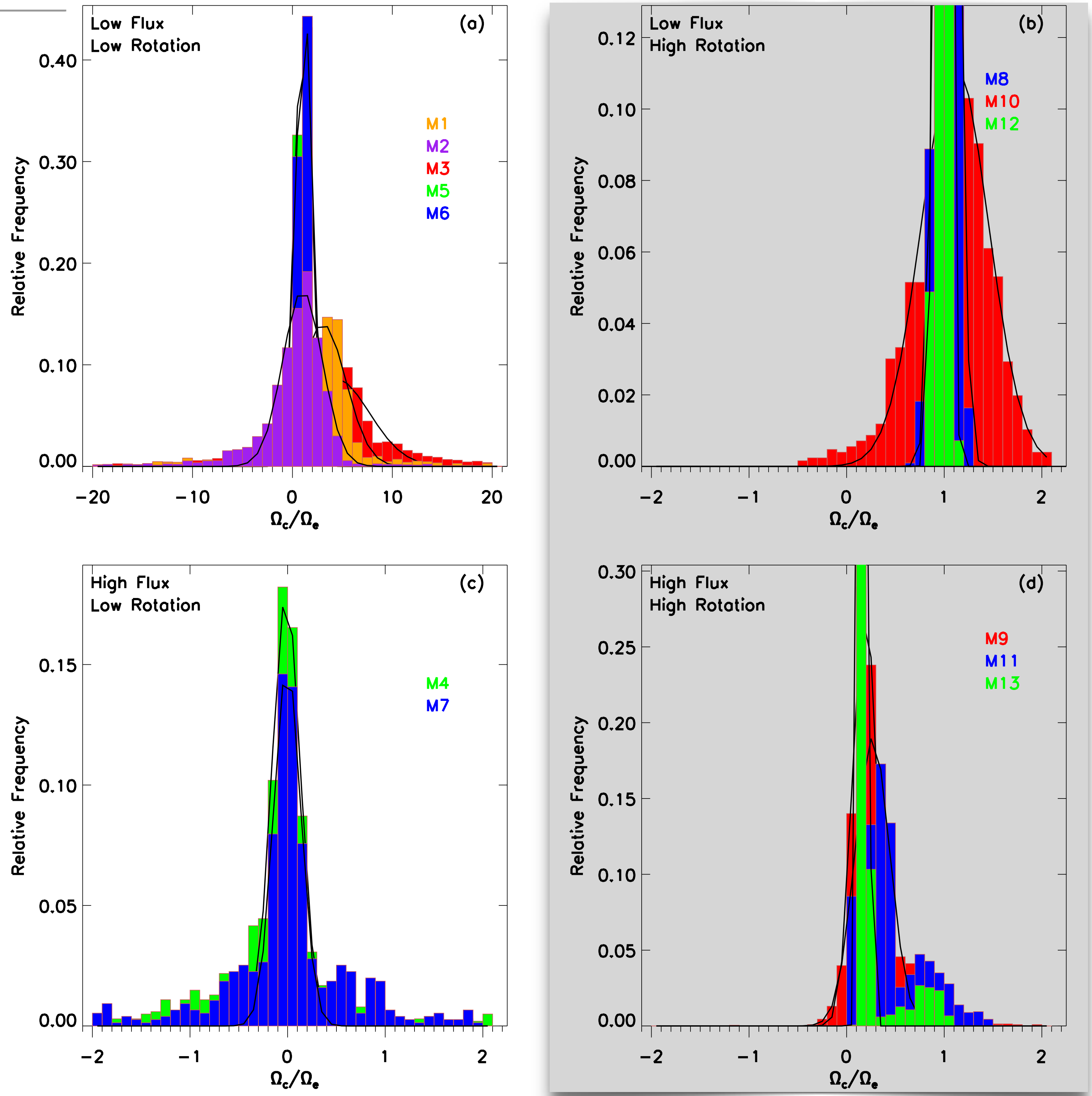
Star	Ω_c/Ω_e
HD 129929, B (Aerts et al. 2003)	3.6
HD 29248, B (Ausseloos et al. 2004)	5.0
HD 157056, B (Briquet et al. 2007)	~1
KIC 9244992, F (Saio et al. 2015)	0.97
KIC 11145123, A/F (Kurtz et al. 2014)	1.03
KIC 10080943a, F (Schmid et al. 2015)	tentative but slightly larger than 1
KIC 10080943b, F (Schmid et al. 2015)	tentative but slightly less than 1
KIC 10526294, B (Triana et al. 2015)	-0.3

Note: these are all slow rotators

Observations of core-envelope differential rotation in Intermediate and Massive Main Sequence Stars

Rogers 2015

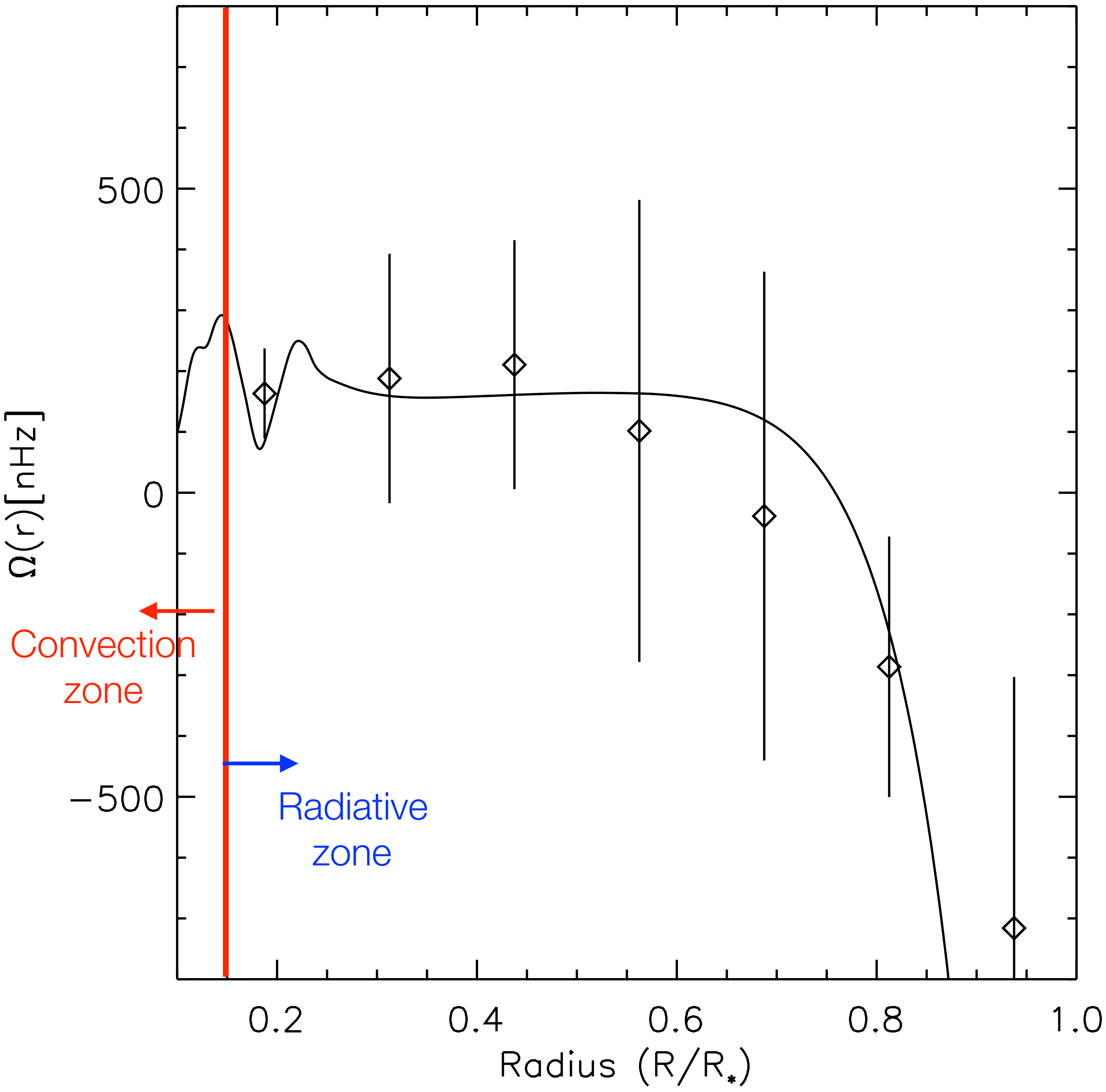
- Simulation suite which had a single fiducial ($3M_{sun}$) model, varying initial rotation rate and convective flux
- Low Flux/Low Rotation models give $\Omega_c/\Omega_e \approx 1-5$ similar to most of the observations
- Low Flux/High Rotation models (not yet observed) have $\Omega_c/\Omega_e \approx 1$ but notably, not exactly 1
- High Flux/Low Rotation models show retrograde surface flows which are larger than core (KIC 10526294)
- High Flux/High Rotation models (not yet observed) show prograde surface flows which are larger than core



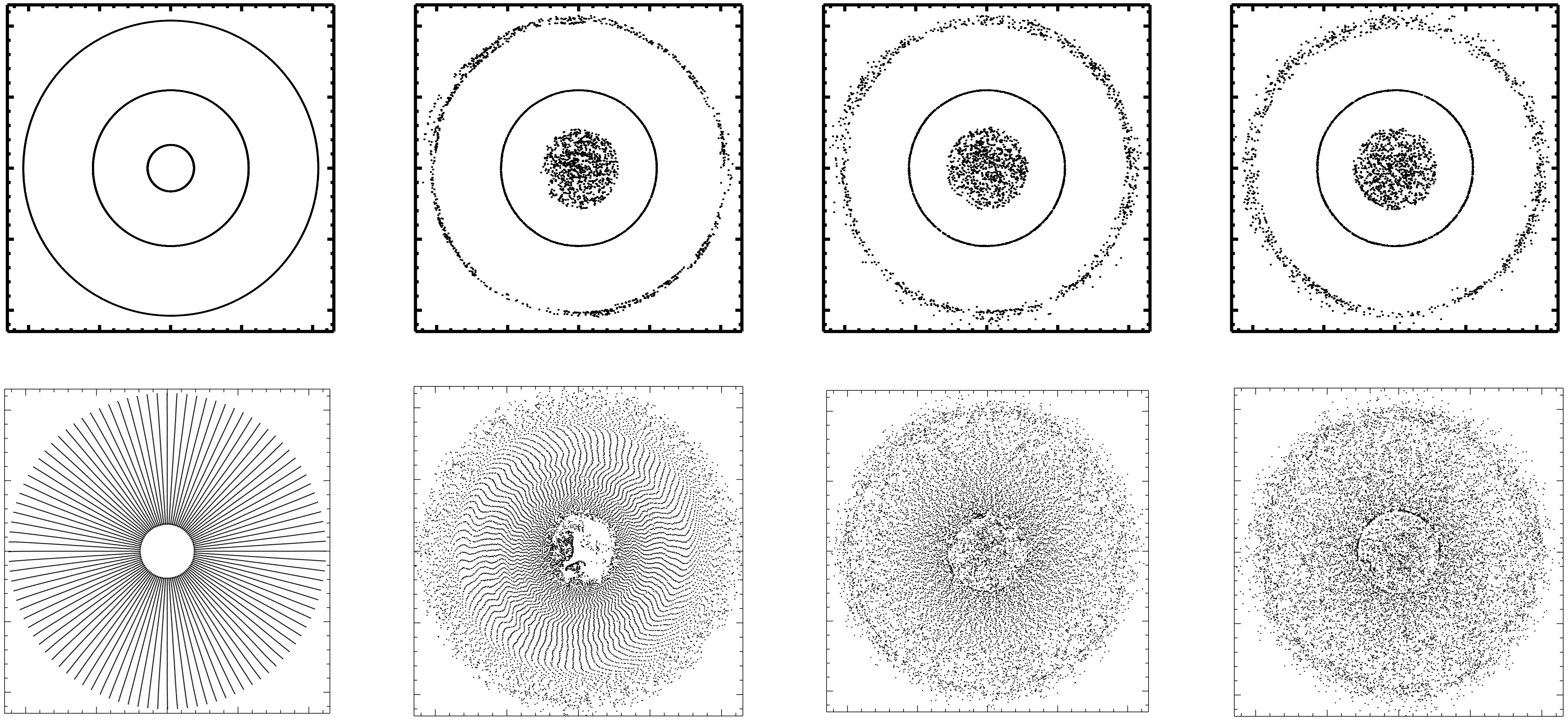
Differential Rotation in KIC 10526294

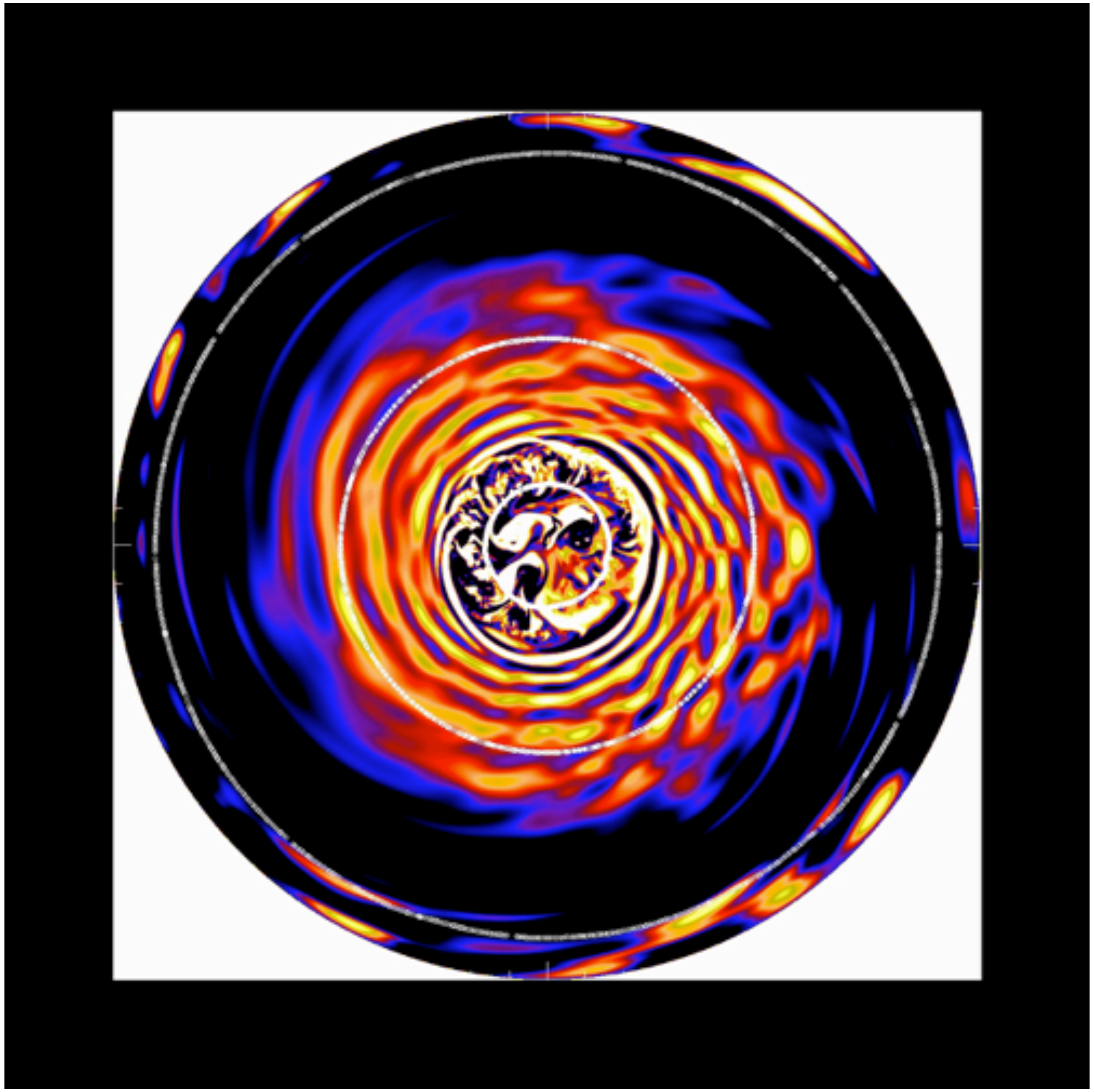
- Used 19 g-mode multiplets, 3.25 M_{sun} star did full inversion to recover differential rotation, ***first time done in a star other than the Sun***
- Found that the envelope is spinning faster than the core and *in the opposite direction*

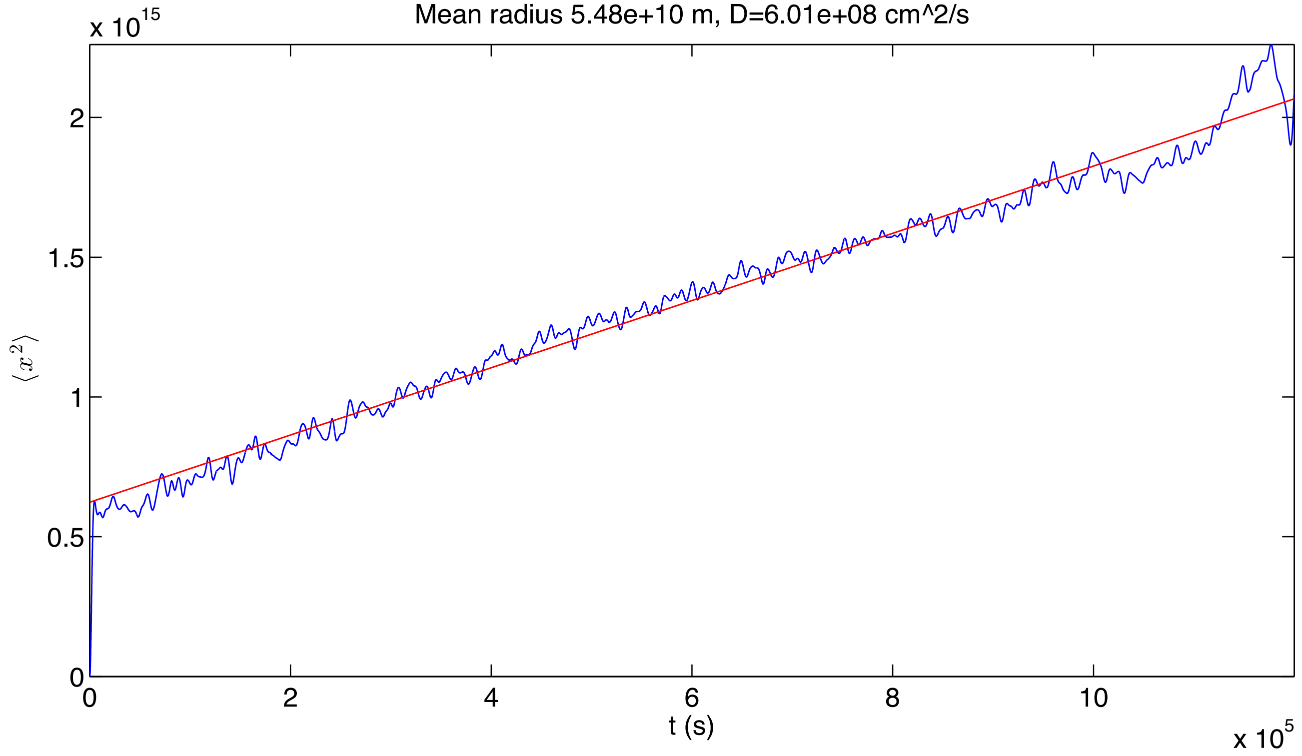
Triana et al. 2015

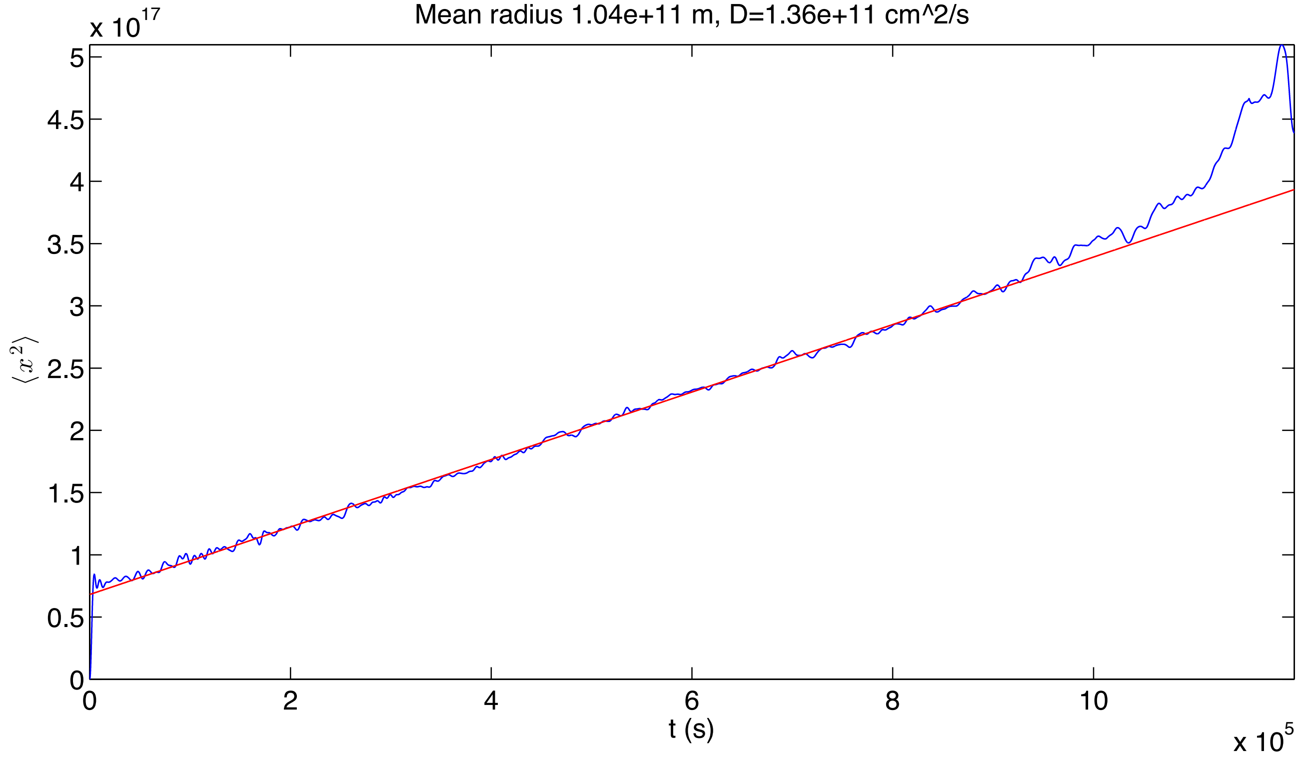


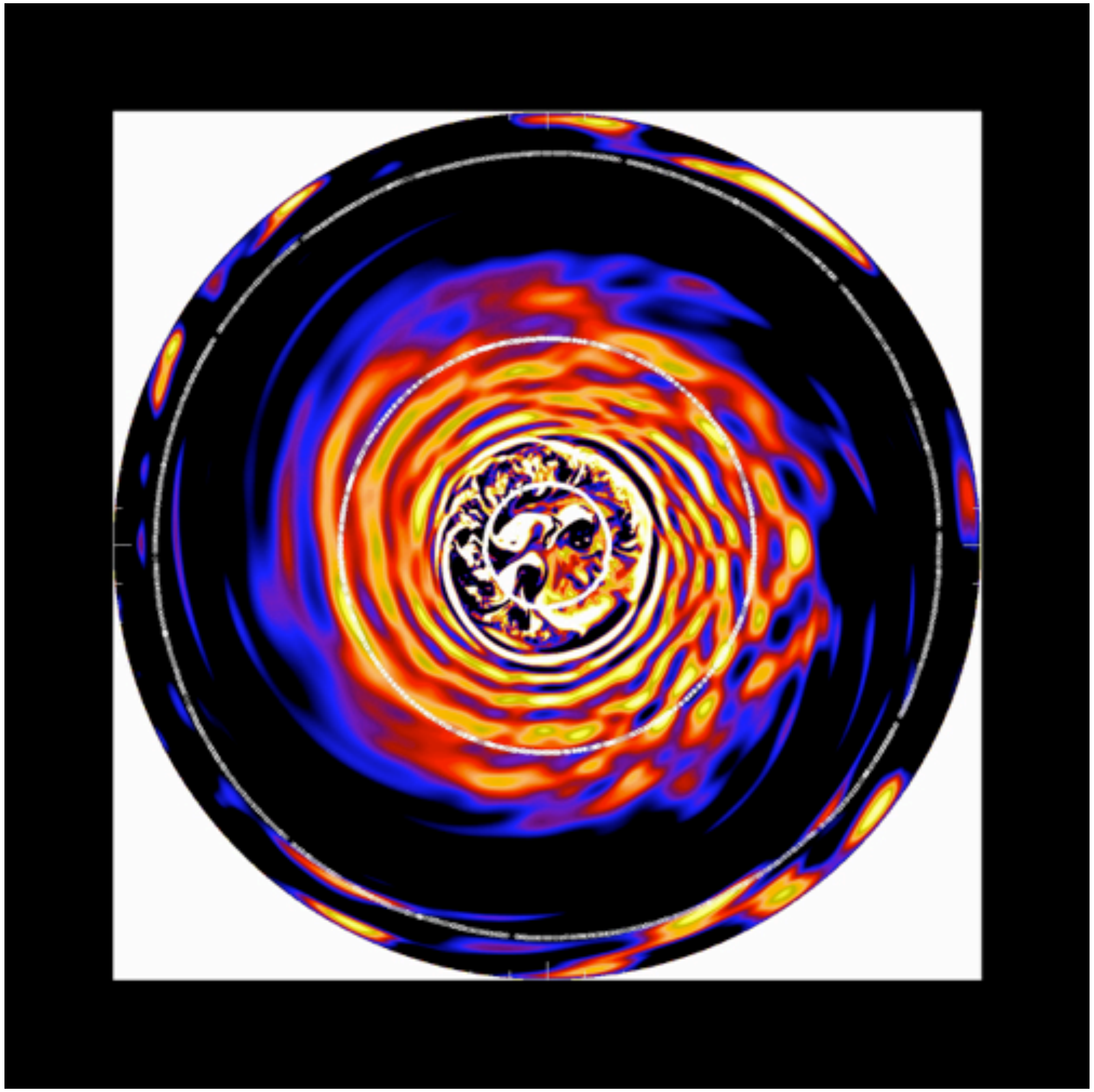
Results:
Chemical mixing by Waves

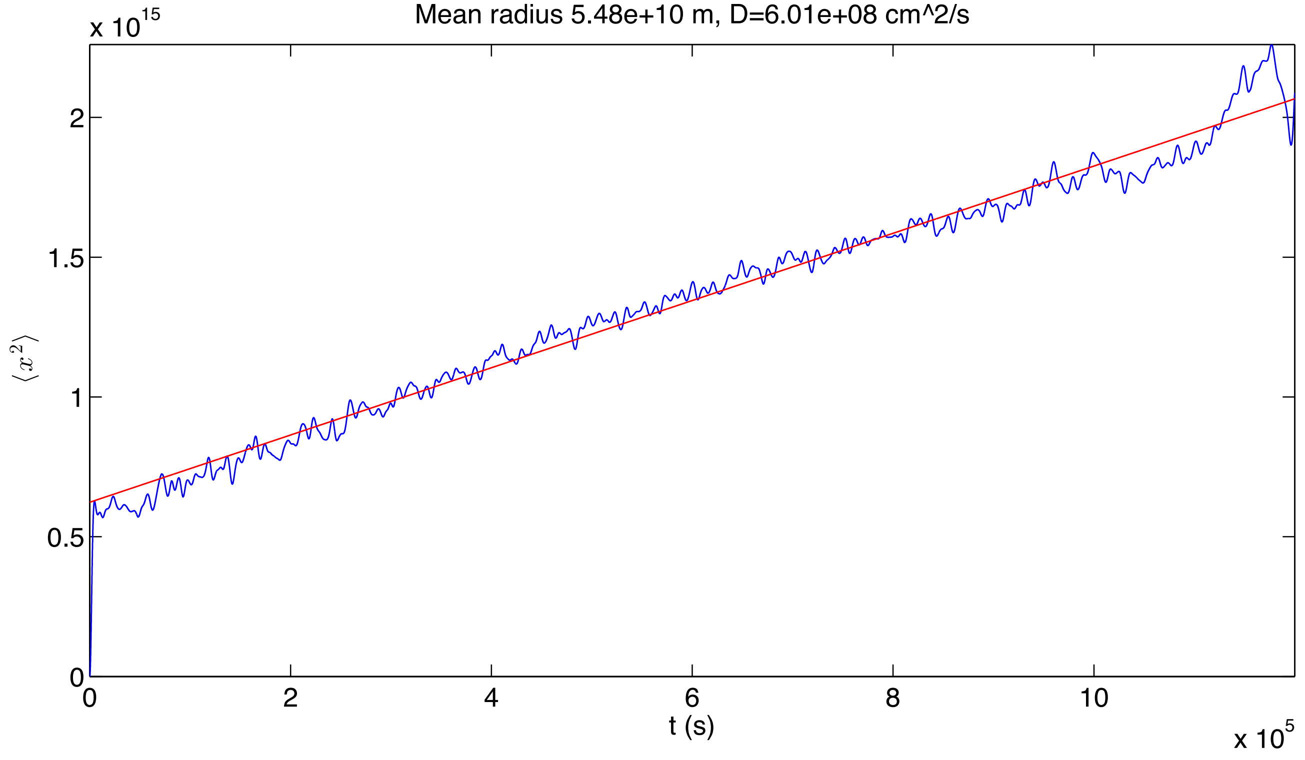





Mean radius 5.48e+10 m, D=6.01e+08 cm^2/s


Mean radius 1.04e+11 m, D=1.36e+11 cm^2/s

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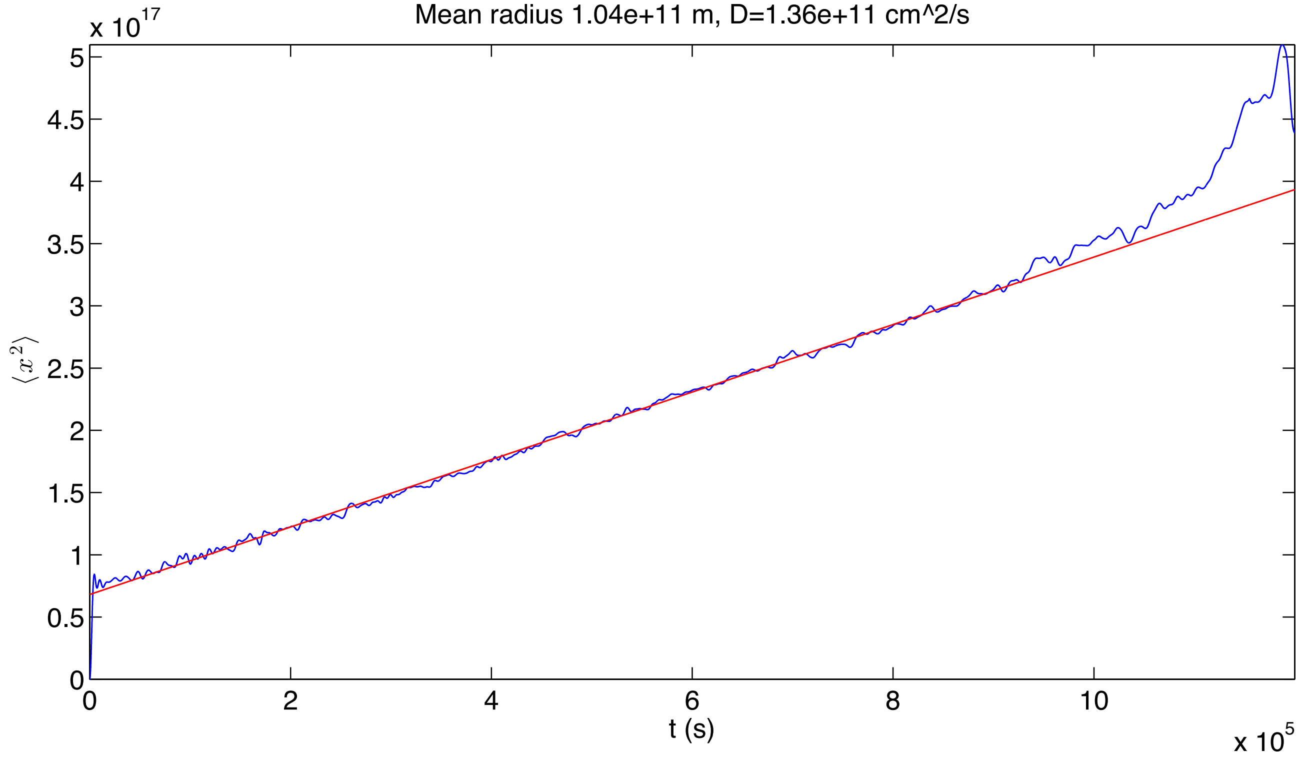
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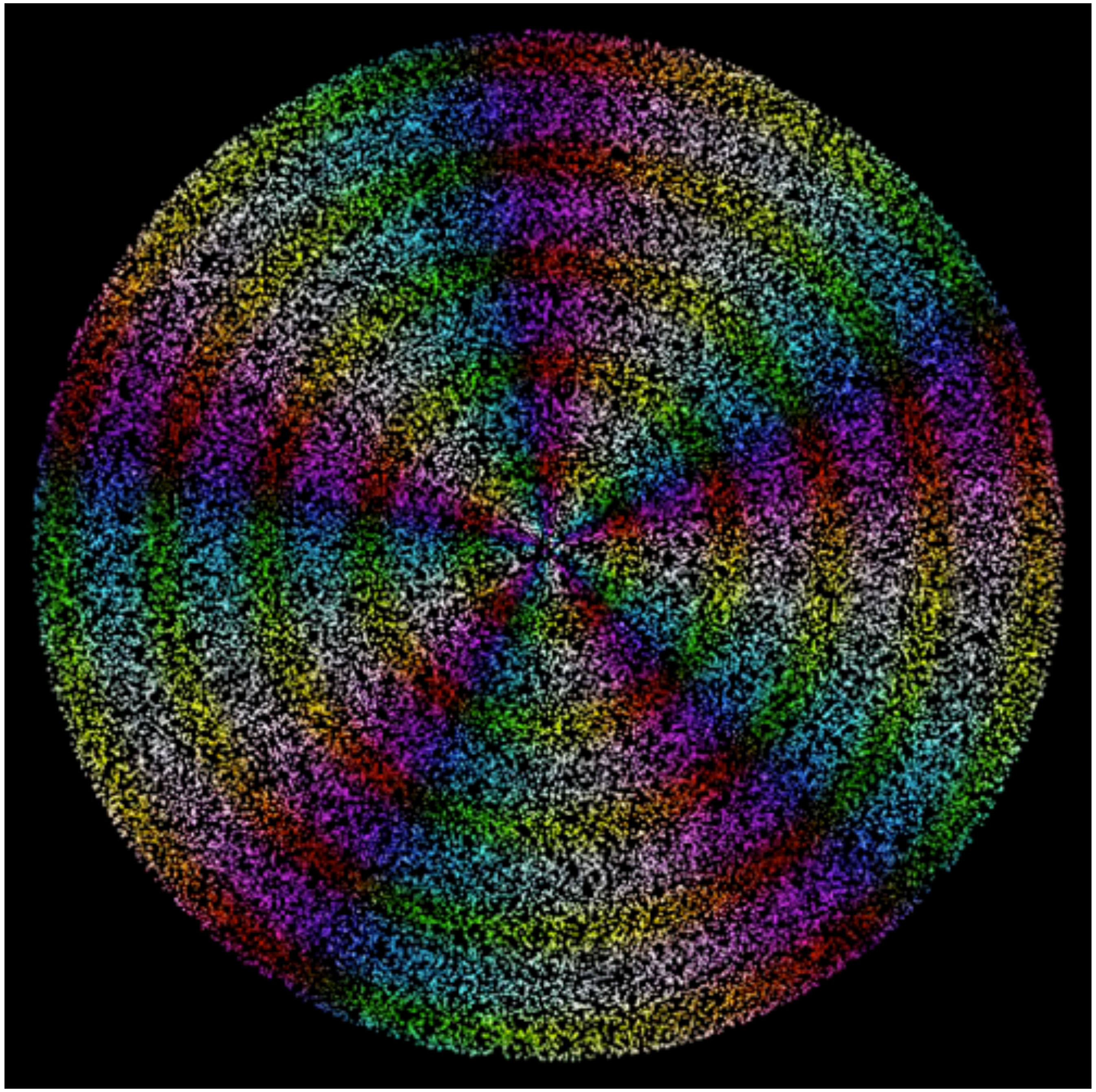
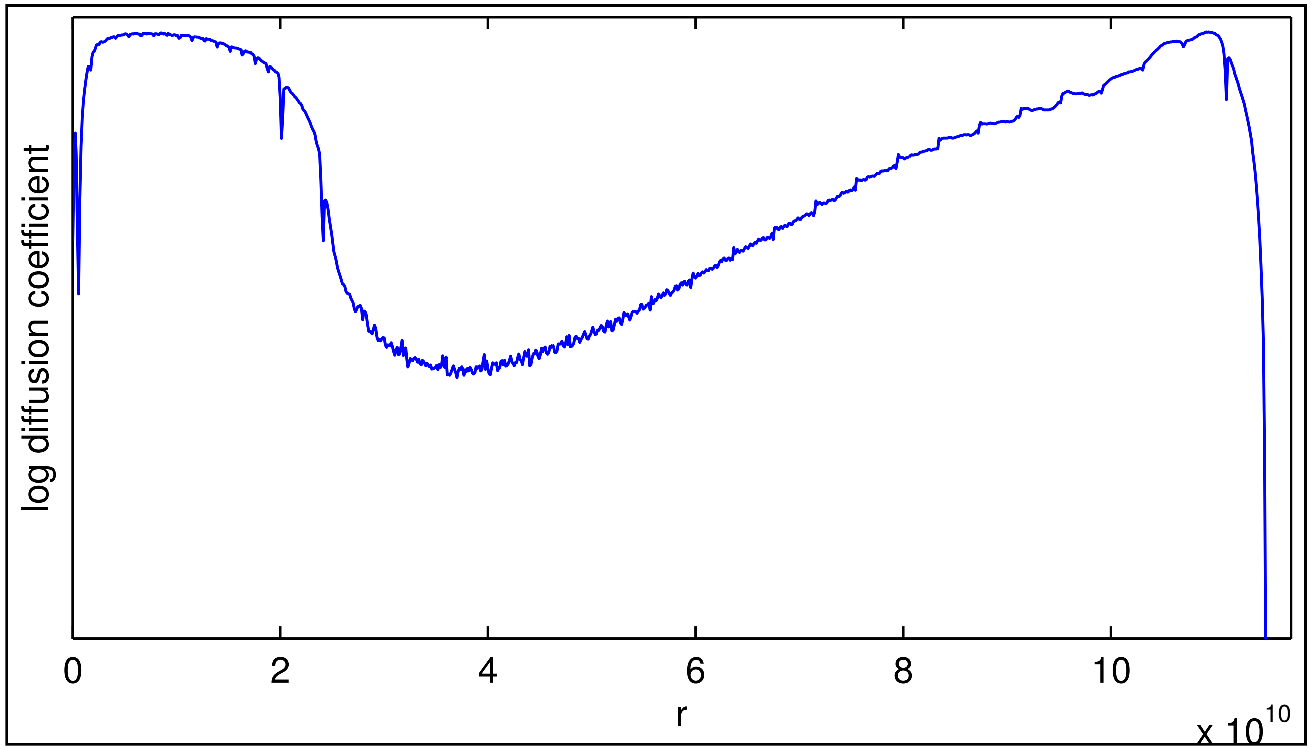
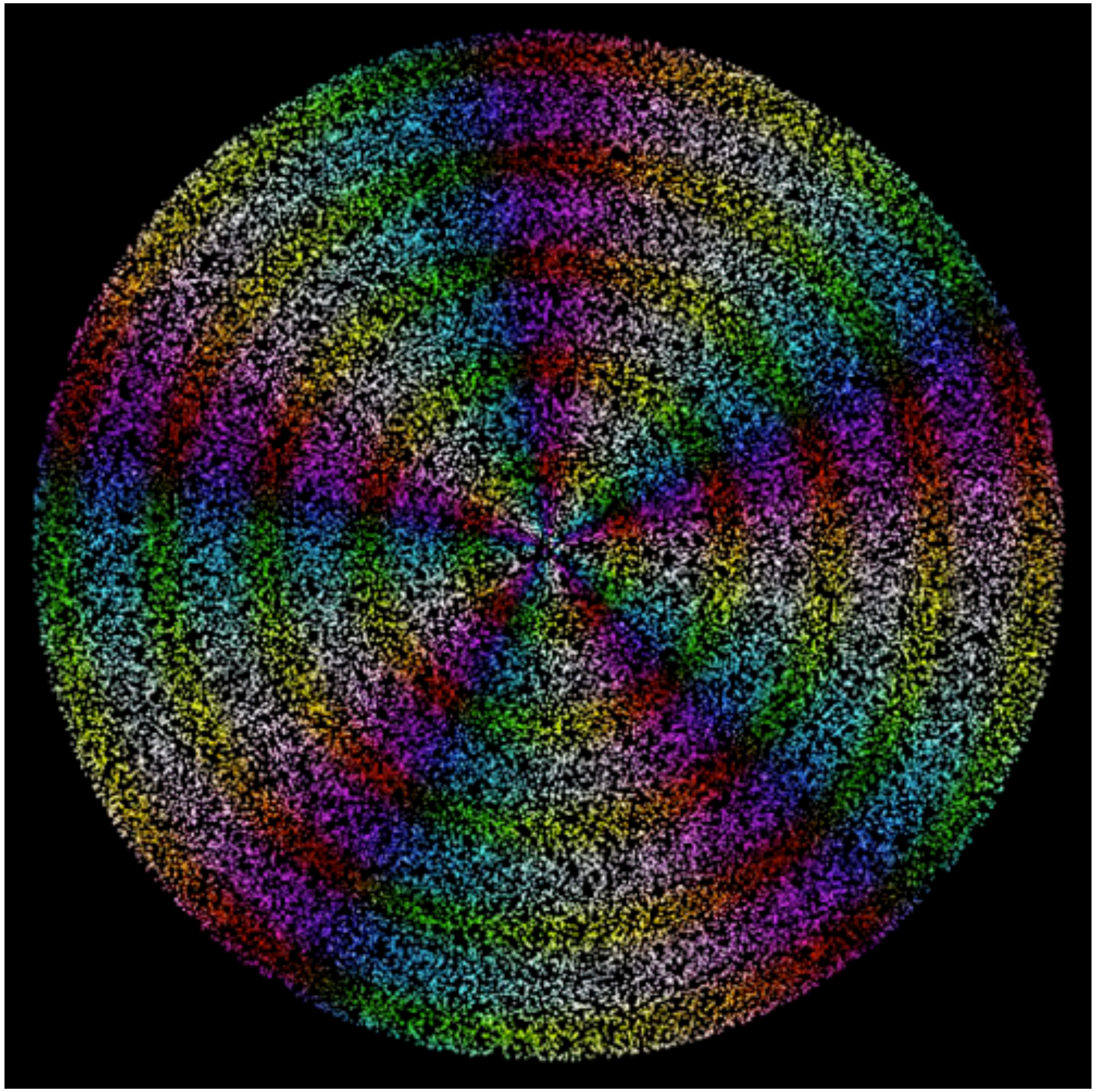
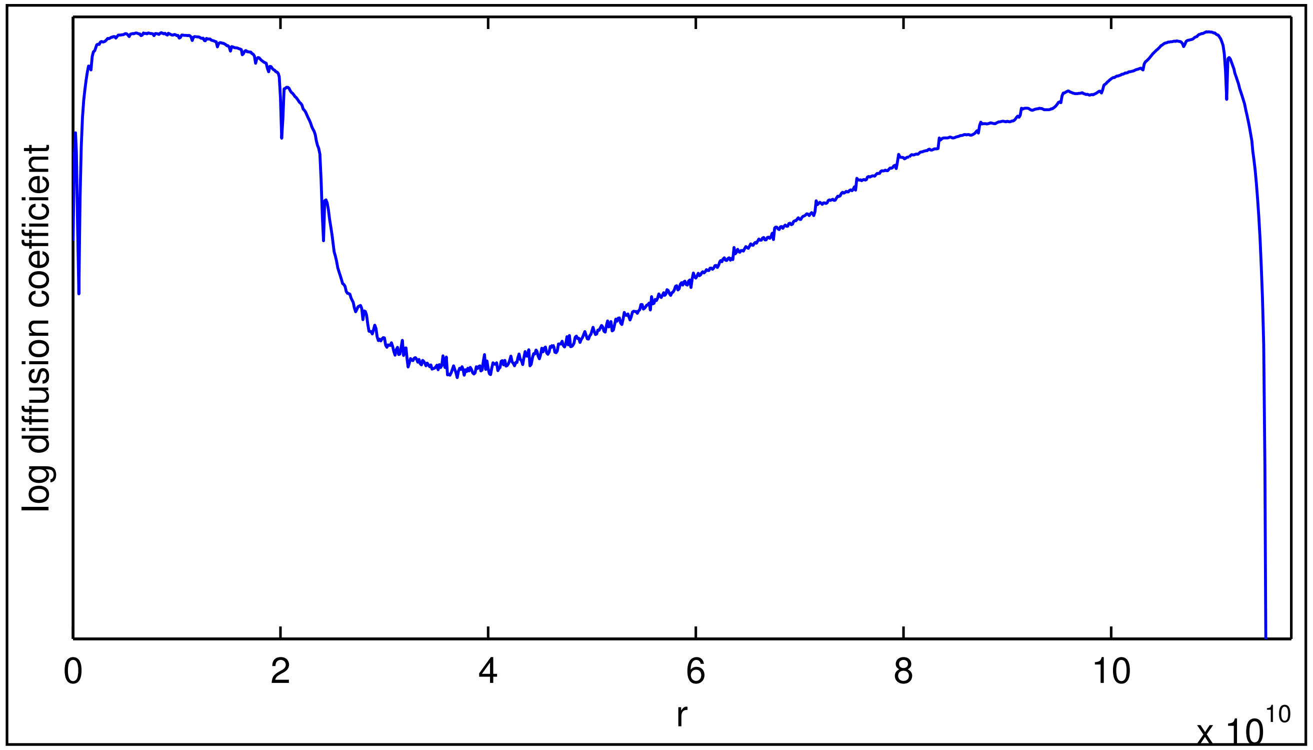




Asteroseismology can now place constraints on mixing within the radiation zone





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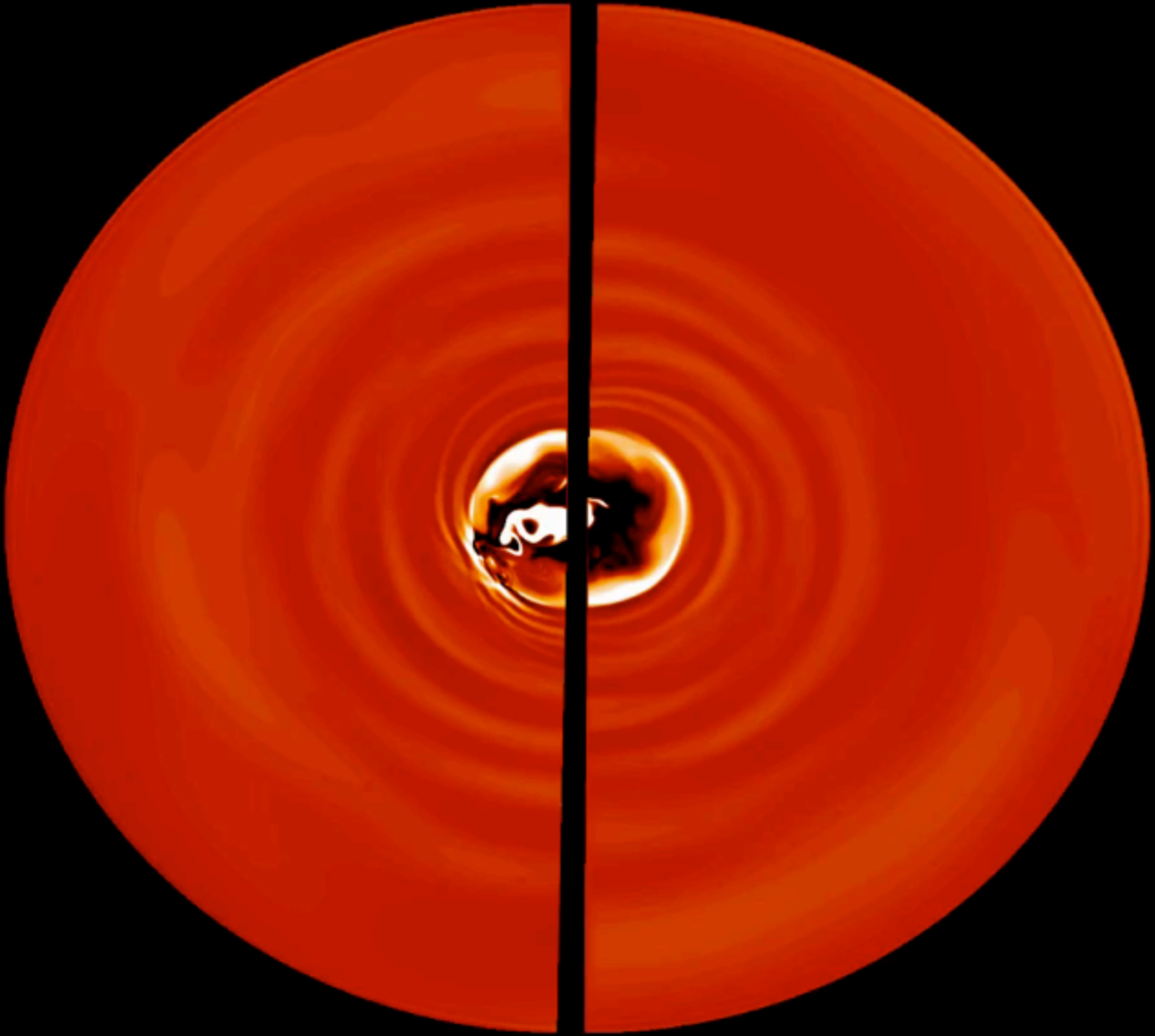
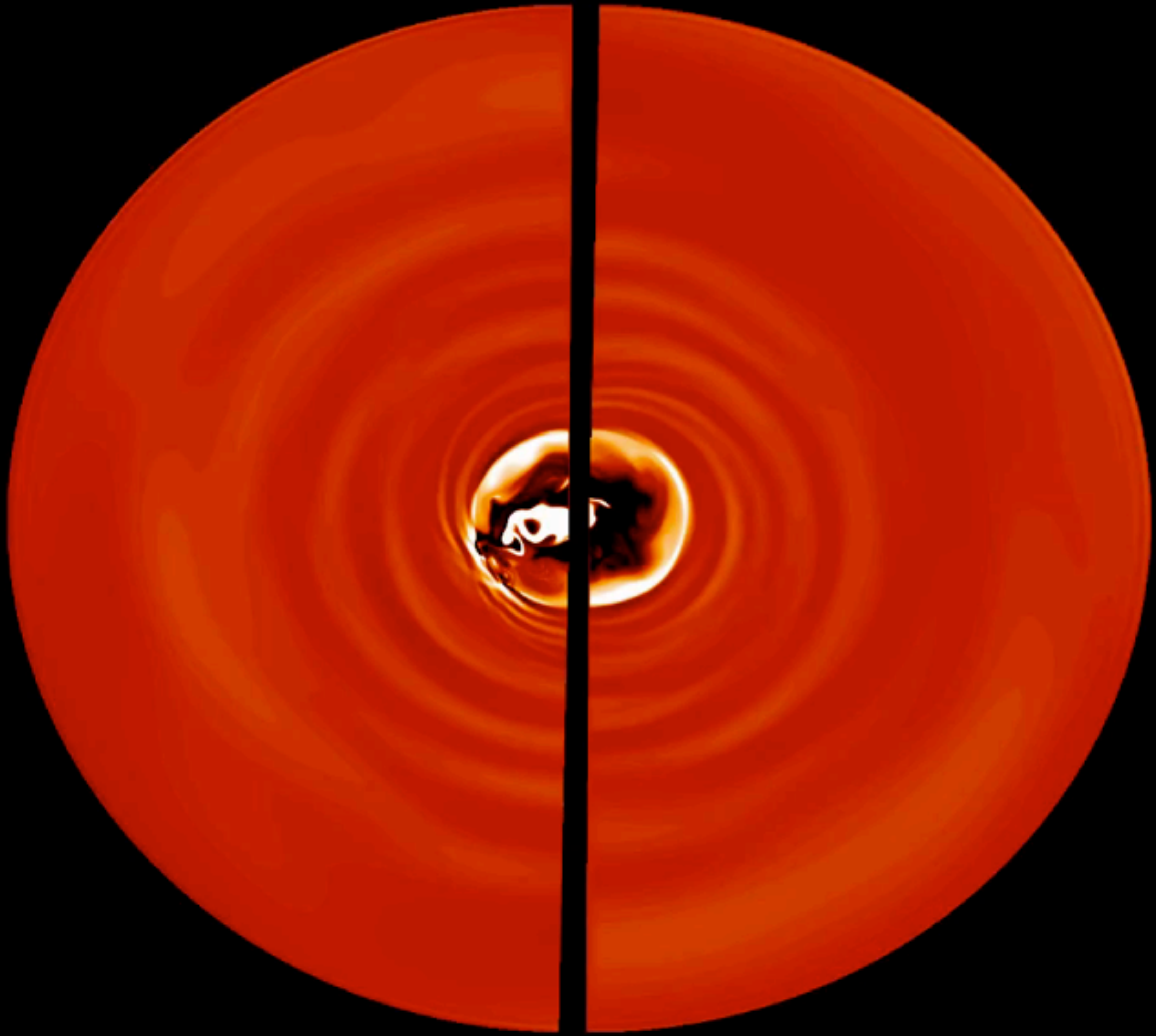
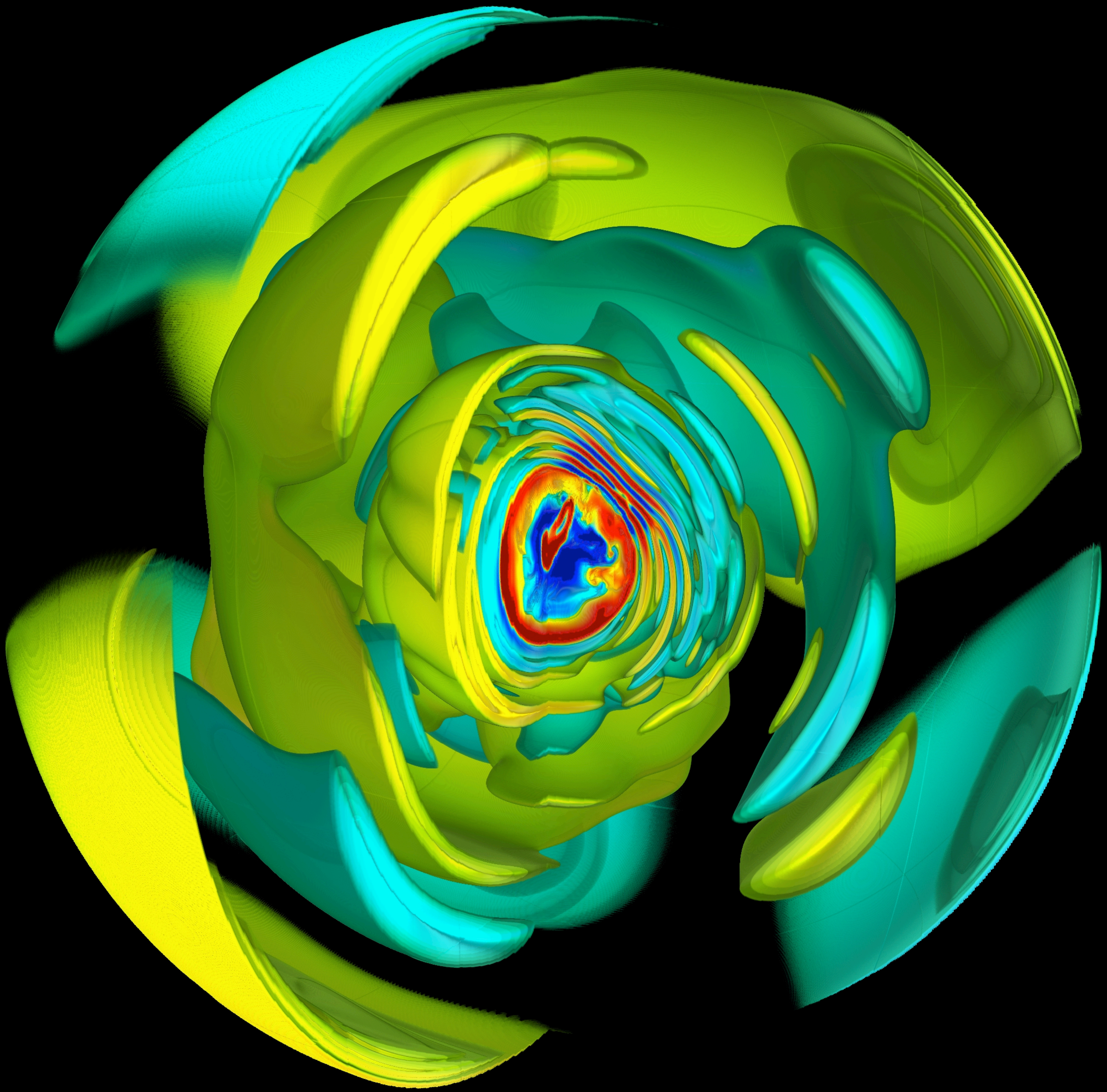
3D Simulations





Future:



More 2D simulations of different masses/ larger parameter space to better constrain spectra, surface spectra, angular momentum transport and mixing as a function of stellar mass and age (Rathish Ratnasingham)

More direct comparisons to observations - currently trying to do more sophisticated line profile calculations (Tkachenko), pre-whiten B-stars to look for IGW signature and combing Kepler data base for more stars (Bowman) with multiple multiplets to measure internal differential rotation (Aerts group)

3D simulations sparingly to confirm/test important results, understand latitudinal structure (Philipp Edelmann)