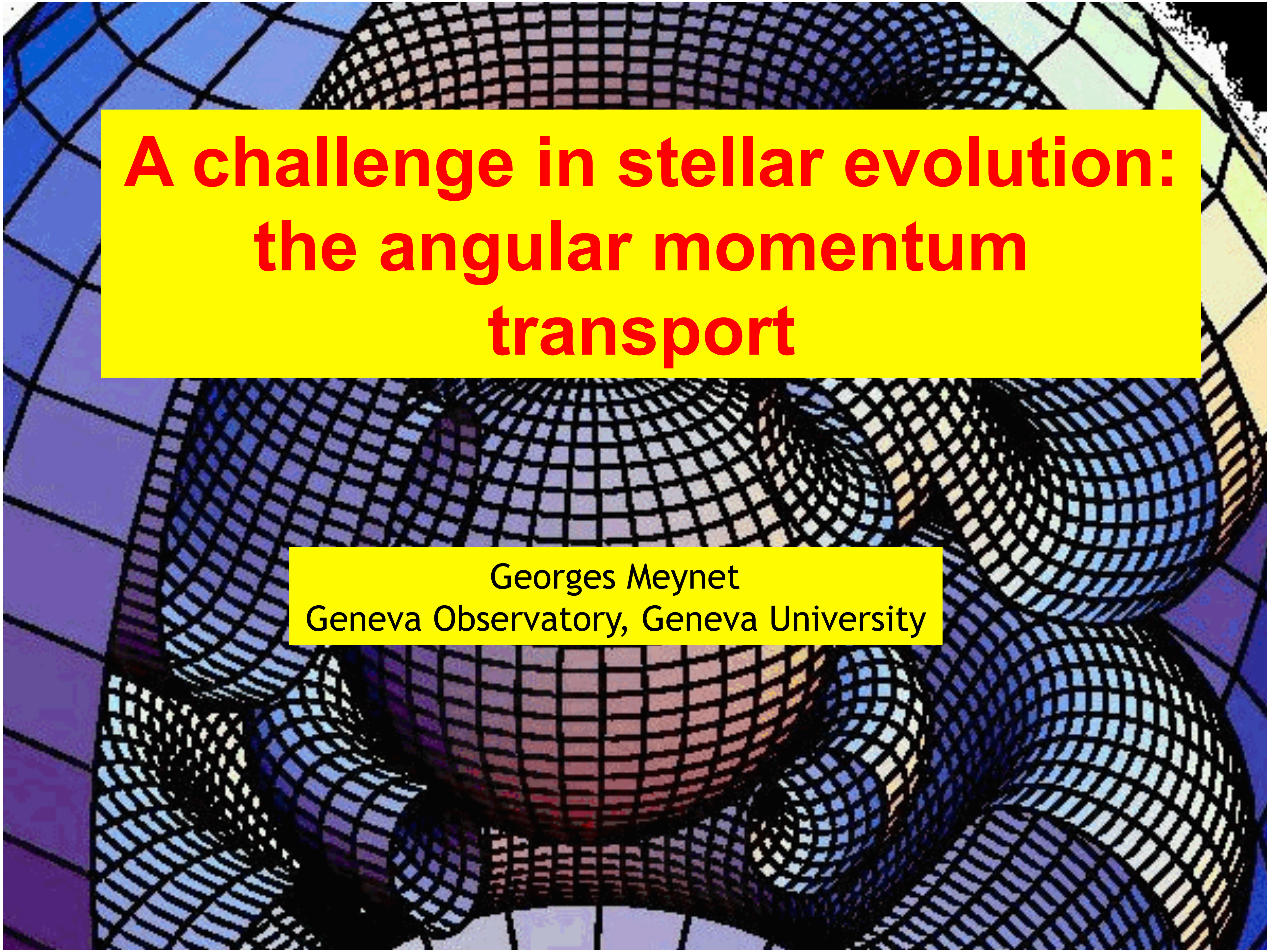

A challenge in stellar evolution: the angular momentum transport

Georges Meynet
Geneva Observatory, Geneva University

Ying Qin
Lionel Haemmerlé
Arthur Choplin
José Groh
Anahi Granada
Cyril Georgy
Raphael Hirschi
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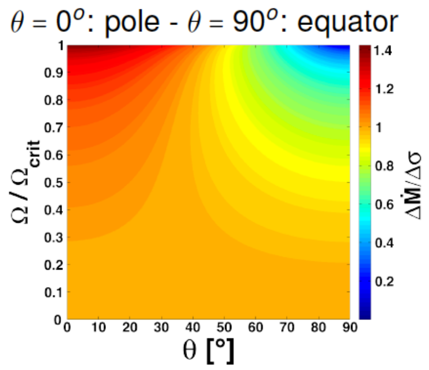
WHY TO CARE DURING THIS 51 ergs CONFERENCE?

→ 1) Impact on mass-losses
→ 2) Impact on the way the CC occurs (GRBs, PISNe)
→ 3) Impact on stellar yields
→ 4) Impact on the stellar remnant properties

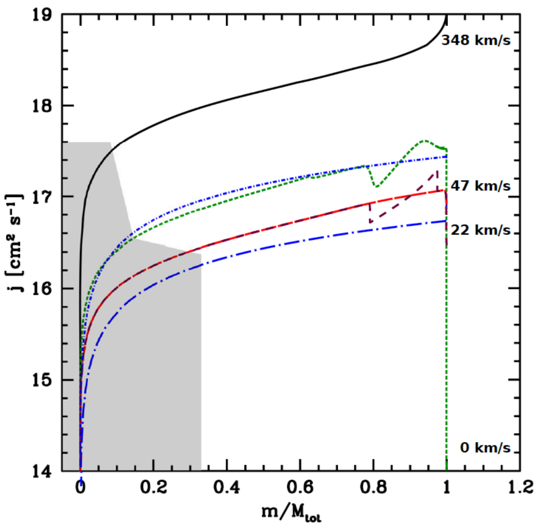
Georgy+ 2011

1)

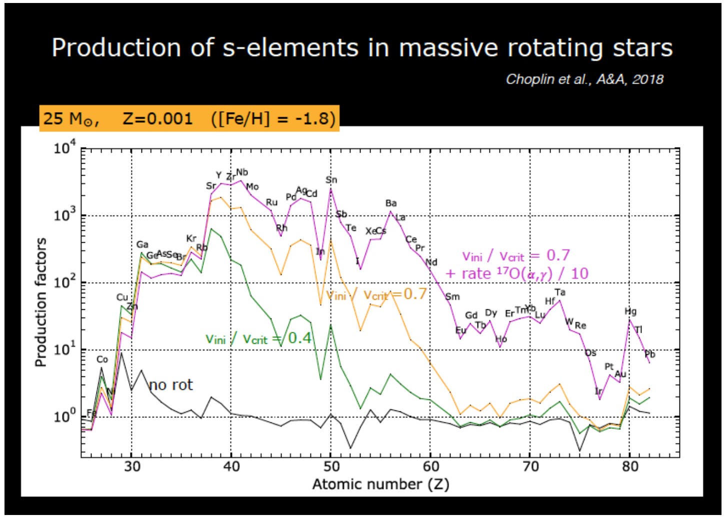


at $\Omega/\Omega_{crit} = 0.95$:
$\dot{M}(\text{pole}) = 3.25\, \dot{M}(\text{eq})$

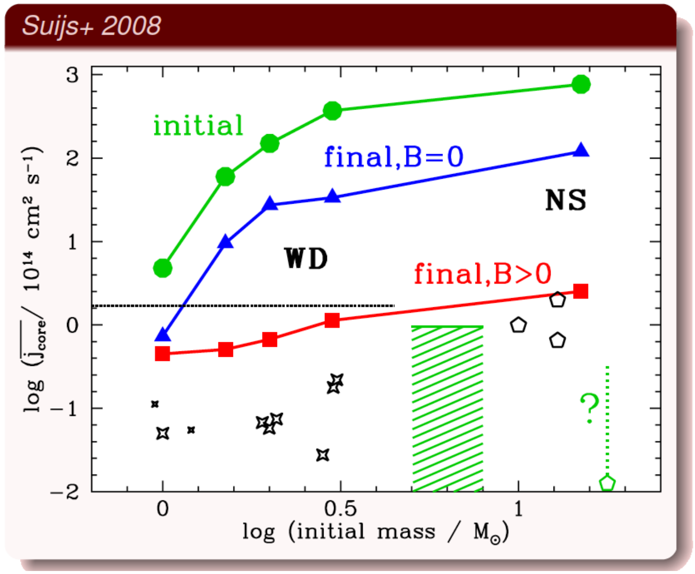
2)



3)



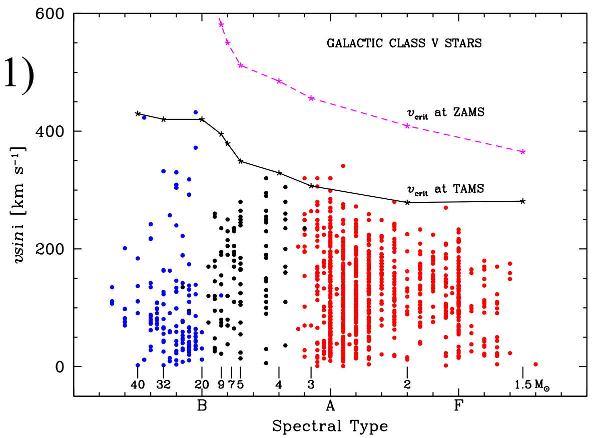
4)



WHAT ARE THE OBSERVATIONAL CONSTRAINTS?

- 1) EVOLUTION OF THE SURFACE ROTATION-SURFACE ABUNDANCES
- 2) HELIOSEISMOLOGY & ASTEROSEISMOLOGY
- 3) YOUNG PULSAR ROTATION RATES-WHITE DWARF SPIN
- 4) SPIN OF MERGING BLACK HOLES
- 5) SPIN OF BH IN X-Ray Binaries

1)



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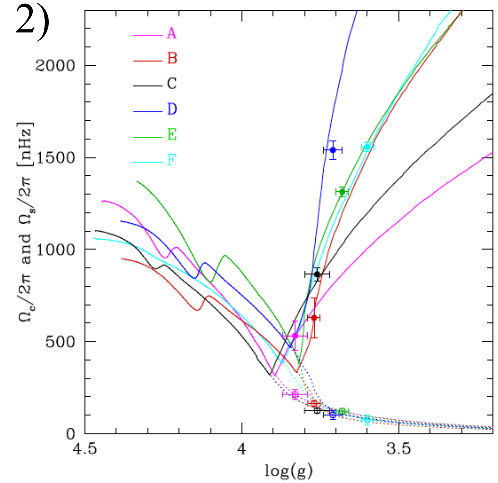

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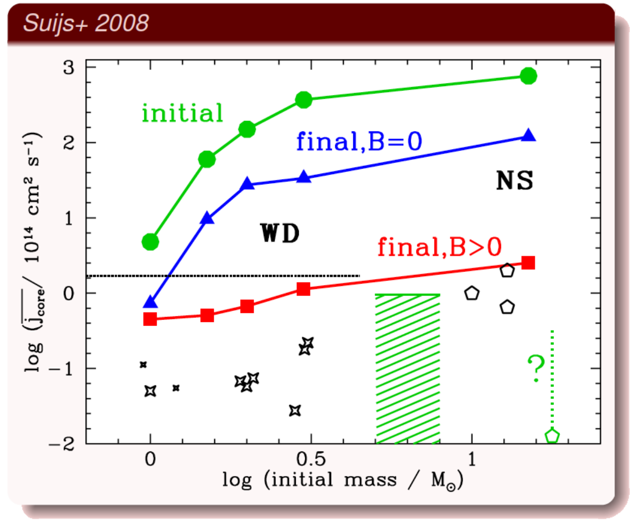

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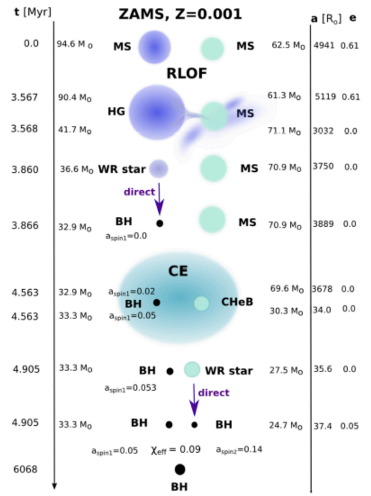


5)

Table 1: BH spins via Continuum Fitting method

Sources	a_*	$M/M_\odot$	P_{orb}/days	References
HMXBs				
Cyg X-1	>0.983	14.8 ± 1.0	5.60	Gou et al. (2014)
LMC X-1	$0.92^{+0.05}_{-0.07}$	10.9 ± 1.4	3.91	Gou et al. (2009)
M33 X-7	0.84 ± 0.05	15.65 ± 1.45	3.45	Liu et al. (2008, 2010)
LMXBs				
GRS 1915+105	>0.98	10.1 ± 0.6	33.9	McClintock et al. (2006)
4U 1543–47	0.80 ± 0.05	9.4 ± 1.0	1.12	Shafee et al. (2006)
GRO J1655–40	0.70±0.05	6.3 ± 0.5	2.26	Shafee et al. (2006)
XTE J1550–564	$0.34^{+0.20}_{-0.5}$	9.1 ± 0.6	1.54	Steiner et al. (2011)
LMC X-3	$0.25^{+0.13}_{-0.16}$	7.6 ± 2.6	1.70	Steiner et al. (2014a)
A0620-00	0.12 ± 0.19	6.6 ± 0.25	0.32	Gou et al. (2010)

WHAT IS THE PHYSICS OF ANGULAR MOMENTUM?

→ TOTAL ANGULAR MOMENTUM
→ ANGULAR MOMENTUM DISTRIBUTION

Single and close binary stars

- INTERNAL ANGULAR MOMENTUM TRANSPORT (internal magnetic field)
- MASS LOSSES BY LINE DRIVEN WINDS (surface magnetic field)
- MECHANICAL MASS LOSSES

Close binary stars

- TIDAL INTERACTIONS
- MASS TRANSFER IN CLOSE BINARIES
- COMMON ENVELOPE PHASE
- MERGING

Not a collection of additive processes, rather processes whose interaction should ideally be accounted for

WHAT IS THE PHYSICS OF ANGULAR MOMENTUM?

→ TOTAL ANGULAR MOMENTUM
→ ANGULAR MOMENTUM DISTRIBUTION

Single and close binary stars

- INTERNAL ANGULAR MOMENTUM TRANSPORT

TWO FLAVOURS OF ROTATING MODELS

WEAK COUPLING MODELS

Zahn 1992

Differential rotation

Mixing of the elements due to shear

Efficiency of mixing $\div$ $d\Omega/dr$

STRONG COUPLING MODELS

Spruit 1999, 2002

Solid body rotation

Mixing of the elements due to meridional circulation

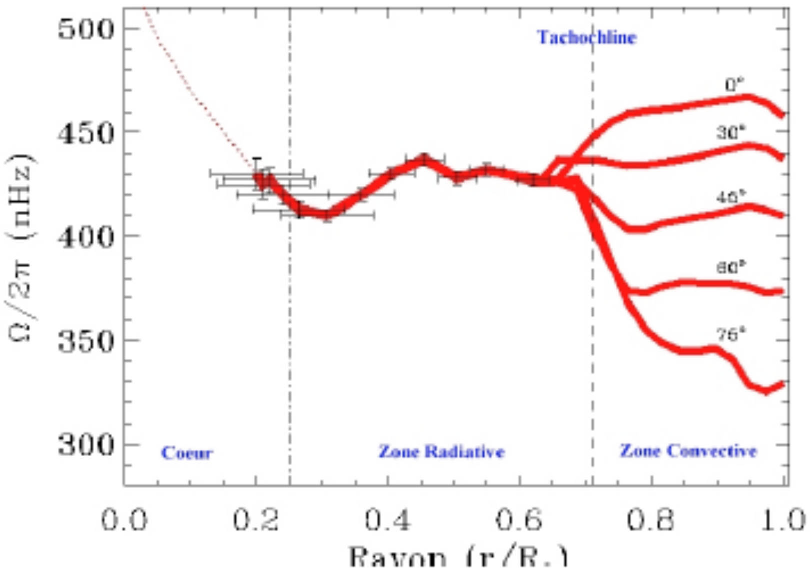
Efficiency of mixing $\div$ Ω

→ CONSEQUENCES FOR THE EVOLUTION OF THE ANGULAR MOMENTUM

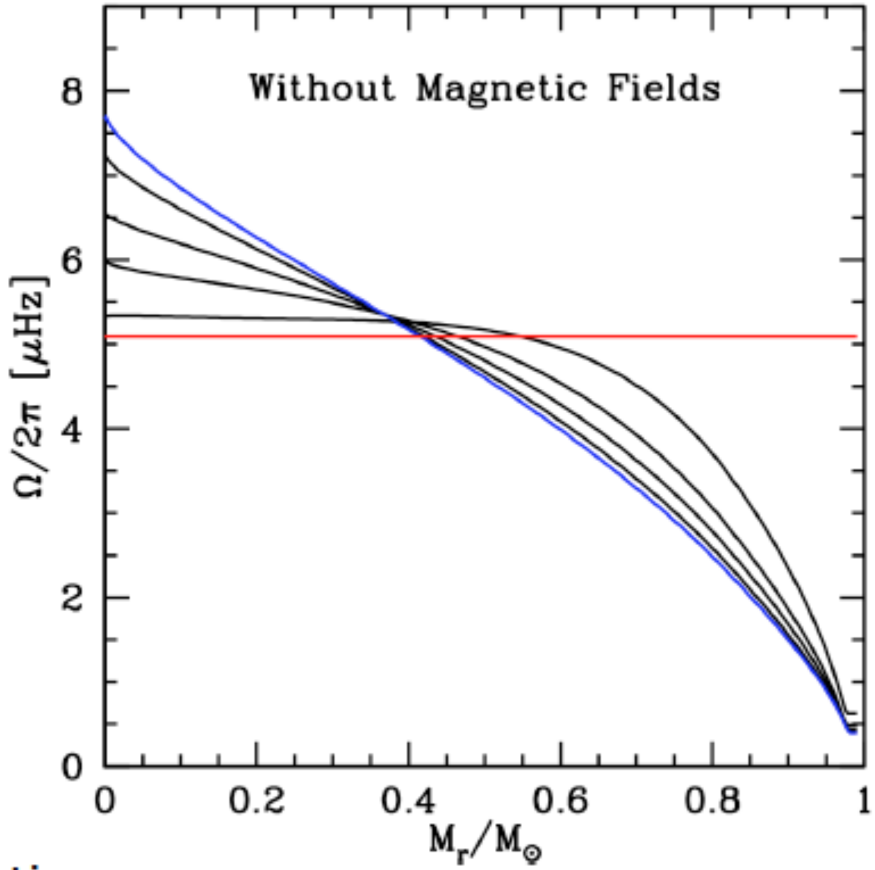
The solar rotation profile

- Helioseismic measurements
  - Rotational splittings:

$$\delta\omega_{n\ell m} = m\beta_{n\ell}\int_0^R K_{n\ell}(r)\Omega(r)\mathrm{d}r$$



Garcia et al. 2007



  - Problem with shellular rotation

Pinsonneault et al. 1989; Chaboyer et al. 1995; Talon et al. 1997; Eggenberger et al. 2005; Turck-Chièze et al. 2010

An approach to The PHYSICS behind the Tayler-Spruit dynamo in one slides

To propose prescriptions for the transport processes, you need

1) Identify a source of energy that can be tapped to drive the instability
2) Determine the length scale over which the instability develop
3) Determine how this instability transport the angular momentum and the chemical species
4) Determine the timescale over which the instability develop

In the Tayler-Spruit theory:

1)The excess of energy in differential rotation is the energy to be tapped for driving the instability.
2) The instability has to overcome the stabilizng gradients in radiative zones
3) Moments on are due to the Lorentz force applied to stellar layers
4) The timescale of the instability is the one of the Tayler instability in a rotating star

Two general equations

$$\sigma_B = \frac{\omega_A \Omega q}{N} \qquad \eta = r^2 \Omega q \left(\frac{\omega_A}{N}\right)^3$$

One specific equation

$$\sigma_B = \frac{\omega_A^2}{\Omega}$$

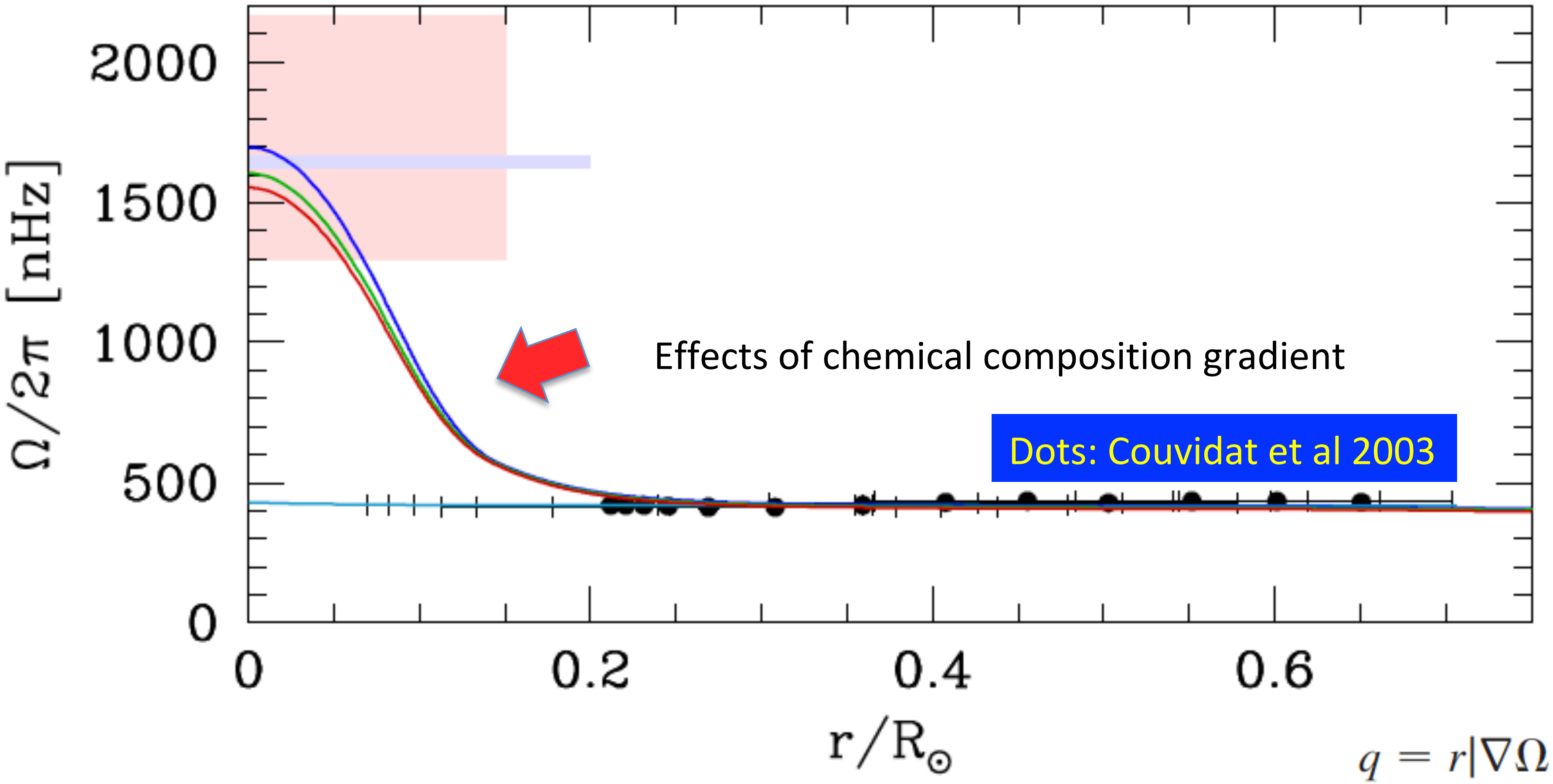
Tayler 1973; Spruit 1999, 2002, Maeder and GM 2012

Three unknows:
ω_A (Alven frequency/magnetic field),
η (magnetic diffusivity),
σ_B (growth rate of the instability)

Rotation rate of the solar core as a key constraint to magnetic angular momentum transport in stellar interiors

P. Eggenberger[1], G. Buldgen[1], and S.J.A.J. Salmon[2]

Letter in press for A&A



$q = r|\nabla\Omega|/\Omega$

$$\nu_{TS} = r^2\Omega q^2 \left(\frac{\Omega}{N_\mu}\right)^4 ; \; q_{\min} = \left(\frac{N_\mu}{\Omega}\right)^{7/4} \left(\frac{\eta}{r^2 N_\mu}\right)^{1/4}$$

ν_{TS} prop to N_μ^{-1}

Slowing the spins of stellar cores

MNRAS 2019

Jim Fuller,[1★] Anthony L. Piro[2] and Adam S. Jermyn[3]

Magnetic Tayler instability saturates when turbulent dissipation of the perturbed magnetic field energy is equal to magnetic energy generation via winding.

According to Fuller et al 2019, the damping rate is much smaller than in the original Spruit theory

This allows stronger magnetic field to be reached and hence stronger coupling.

$$\nu_{\mathrm{T}} = \alpha^3 r^2 \Omega \left(\frac{\Omega}{N_{\mathrm{eff}}} \right)^2$$

$$q_{\mathrm{min}} = \alpha^{-3} \left(\frac{N_{\mathrm{eff}}}{\Omega} \right)^{5/2} \left(\frac{\eta}{r^2 \Omega} \right)^{3/4}$$

$$N_{\mathrm{eff}}^2 = \frac{\eta}{K} N_T^2 + N_\mu^2$$

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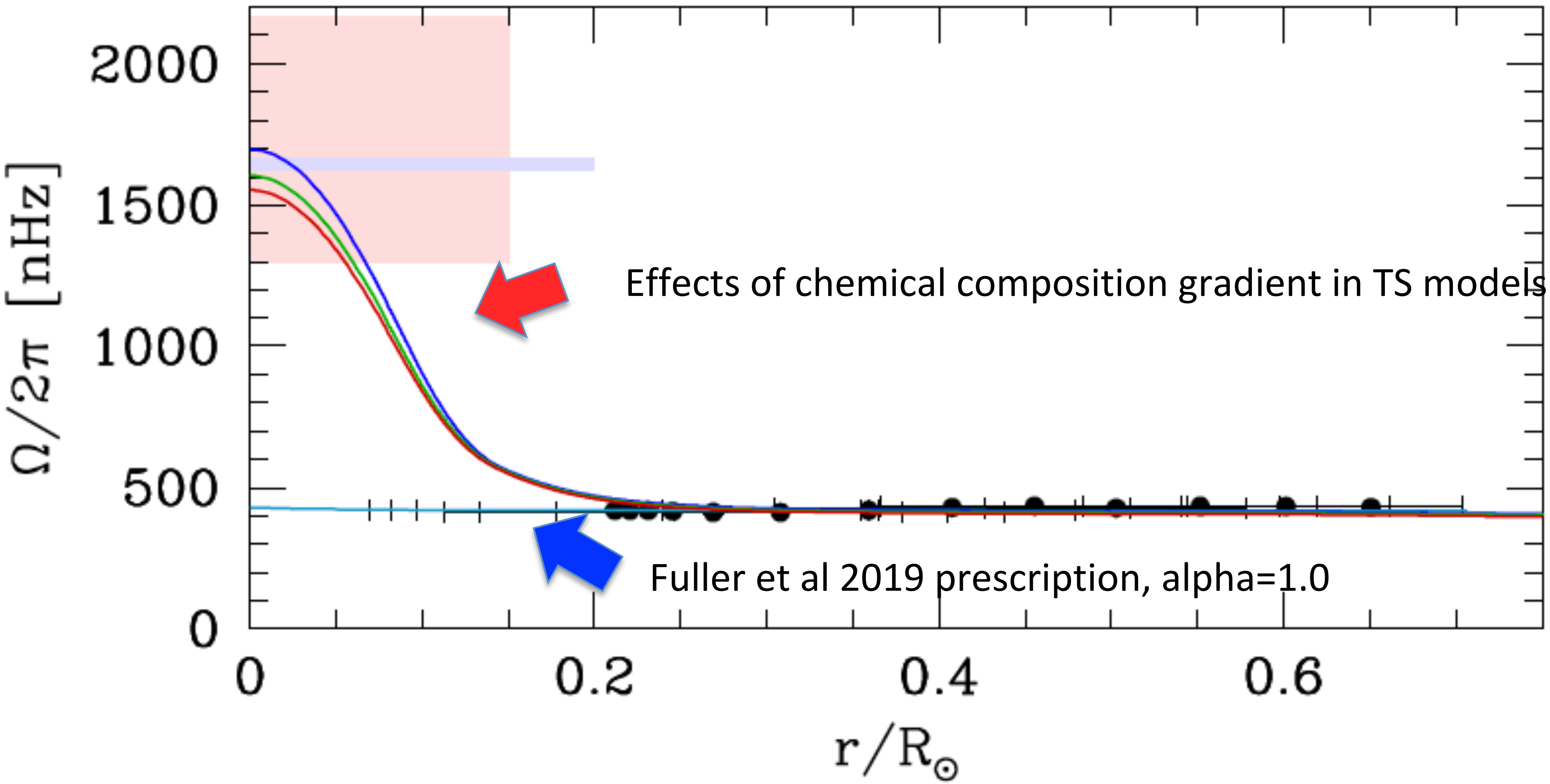

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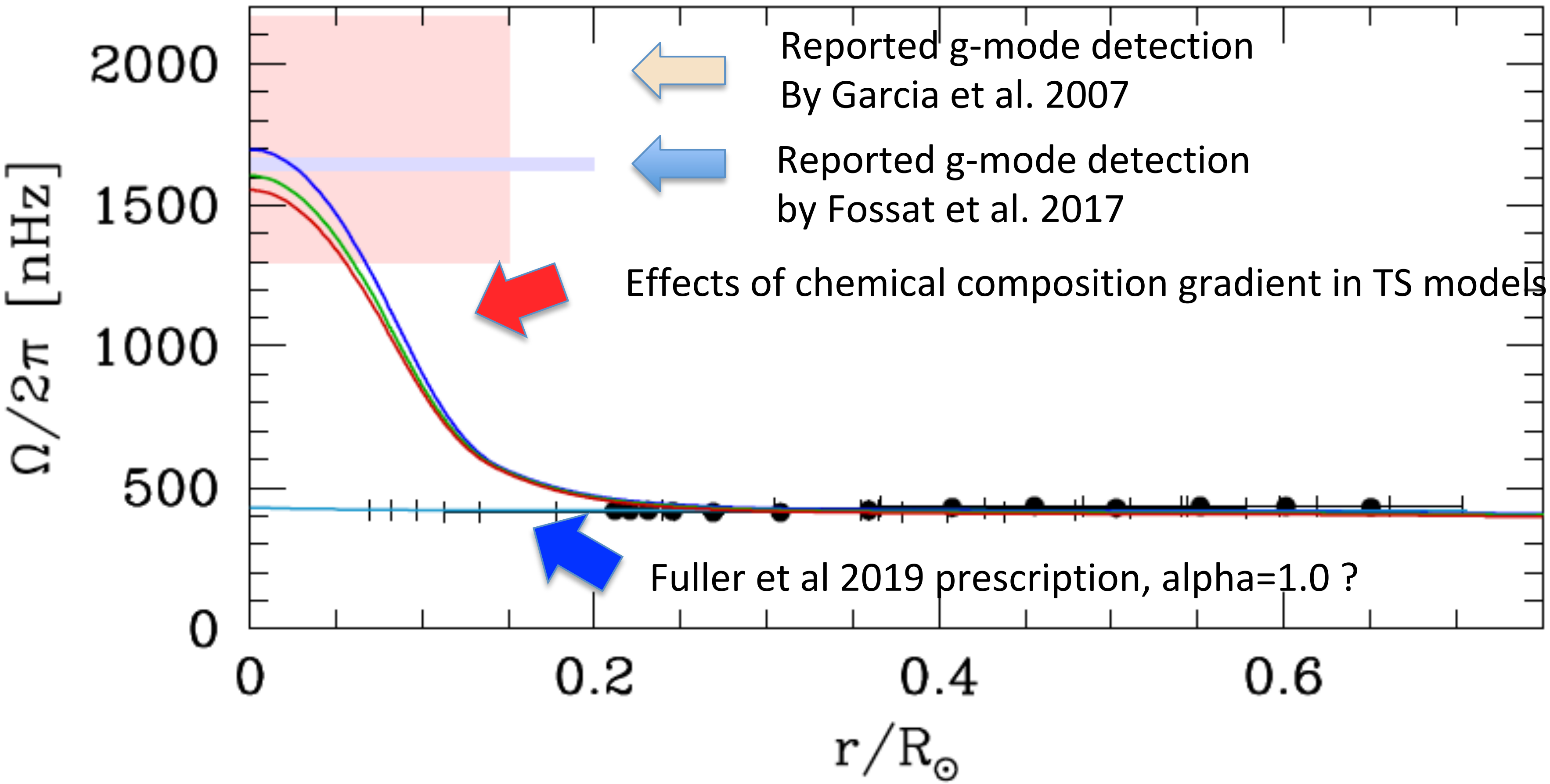
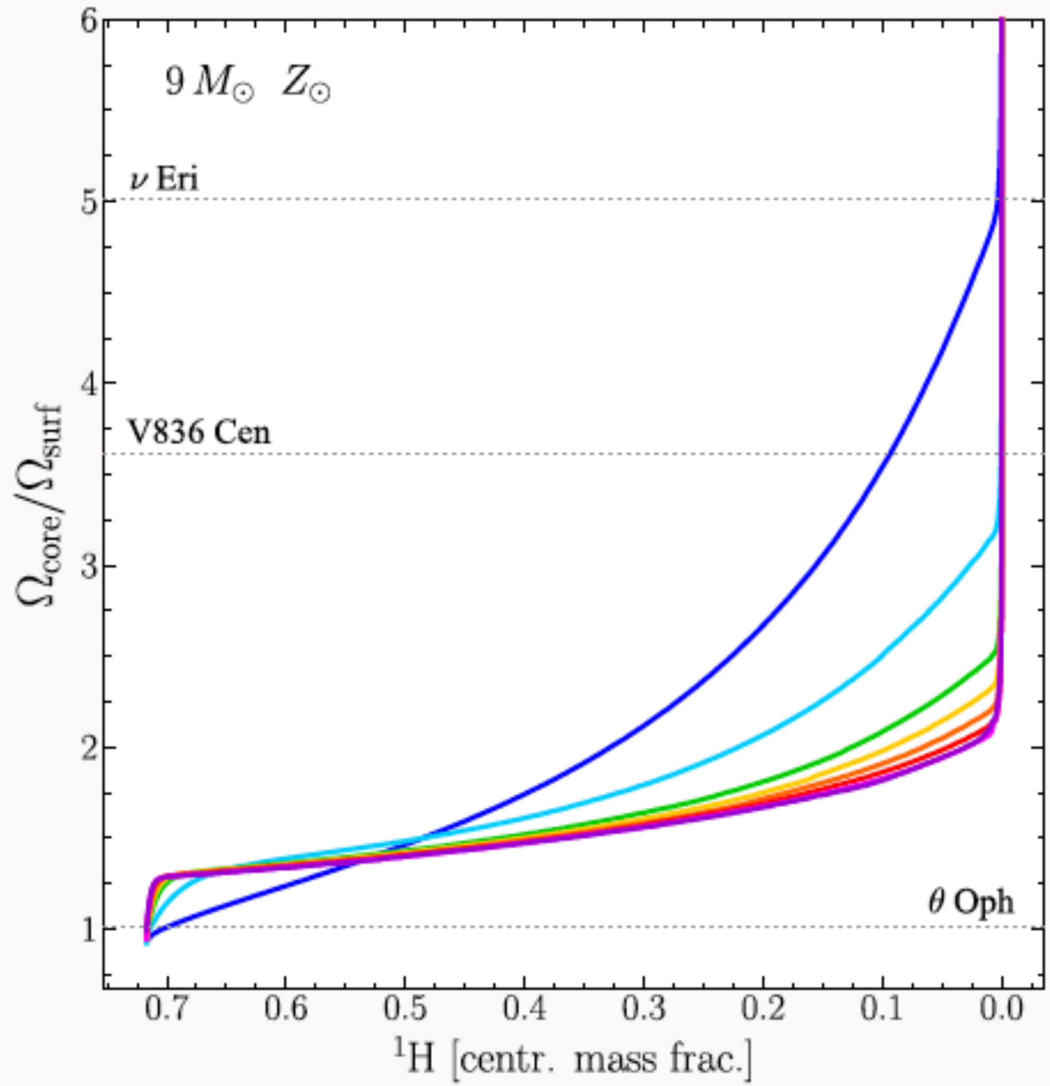
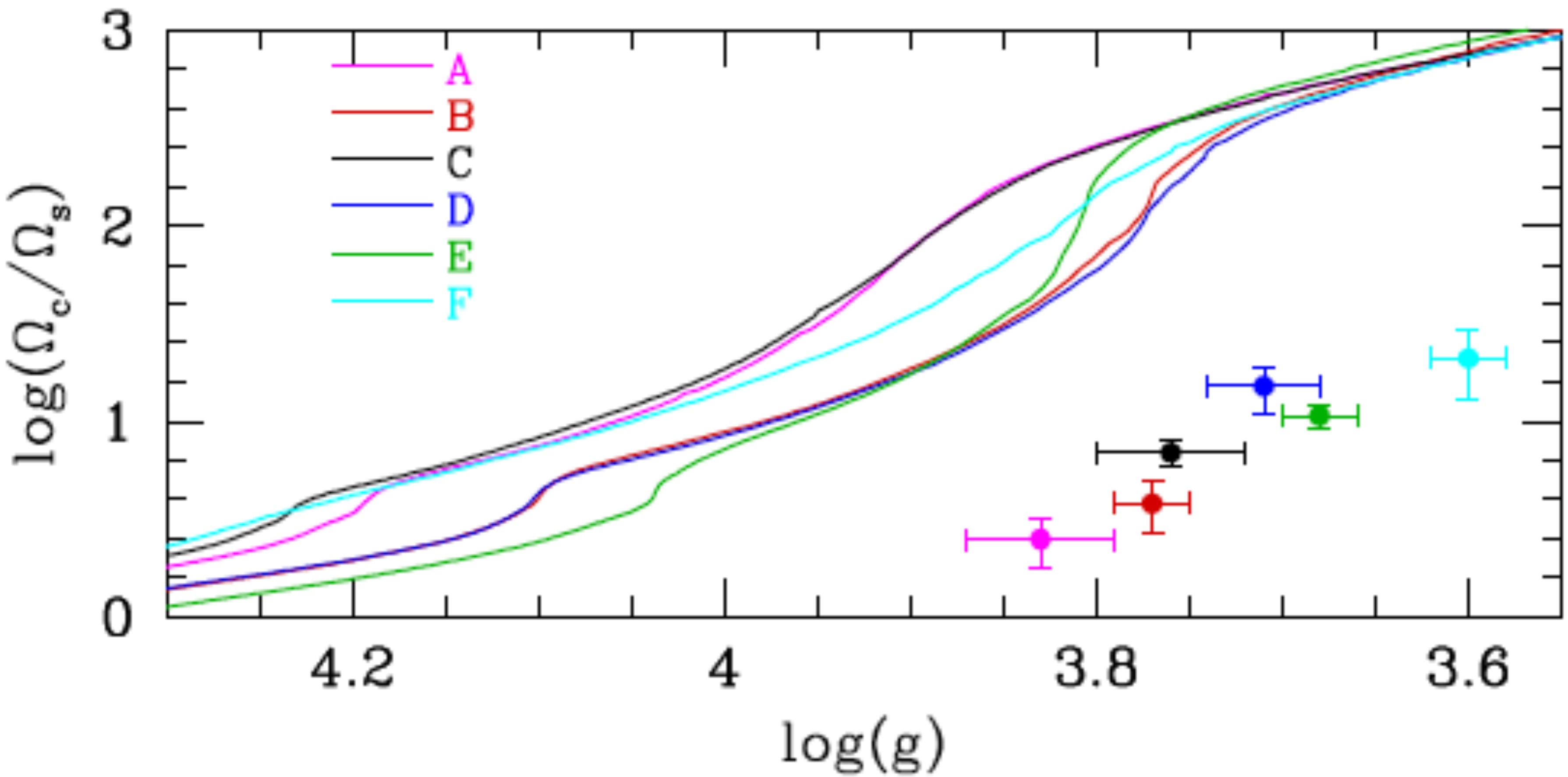


Models from Georgy+ 2013b, obs. values from Aerts 2008



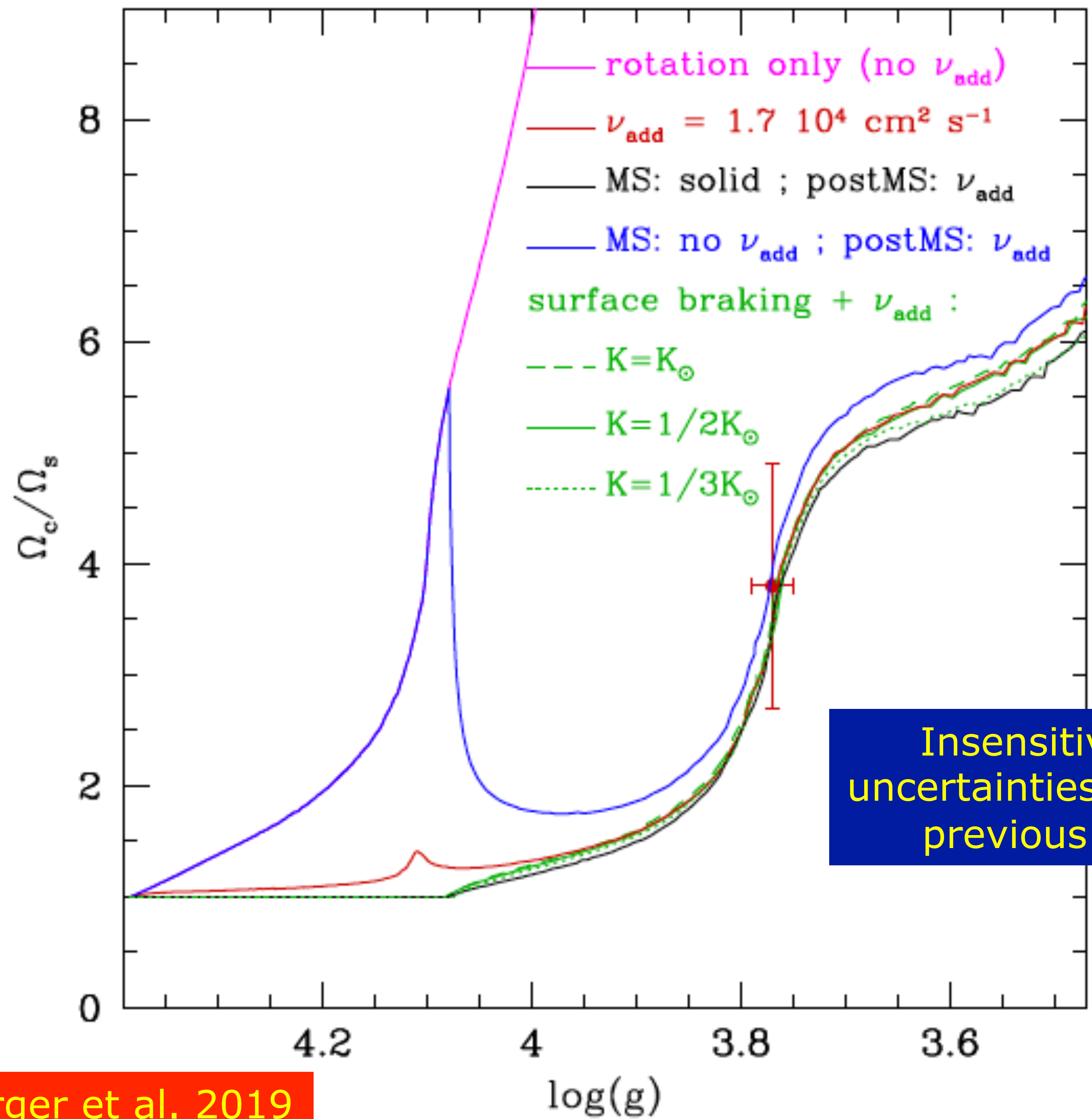
Aerts 2008, Goupil 2011

star	$\Omega_{core}/\Omega_{env}$
ν Eri	~ 5
V836 Cen	3.6
θ Oph	~ 1
12 Lac	1.8 – 5



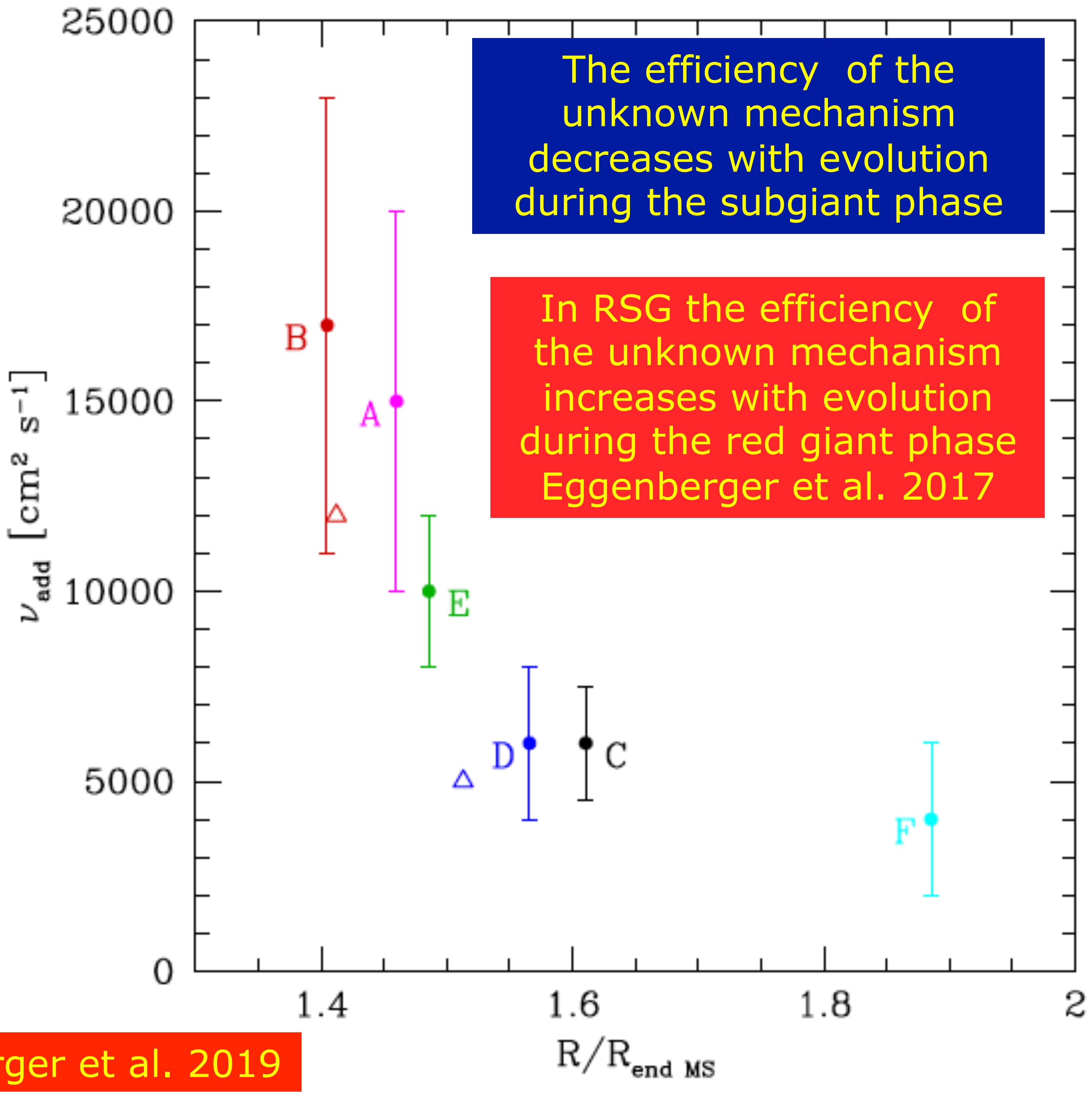
Shellular models: Eggenberger et al. 2019→Masses : 1.15-1.4 M_{sol},
V_{rot}(ZAMS): 4-8 km s^{-1}

Observations: Deheuvels et al 2014



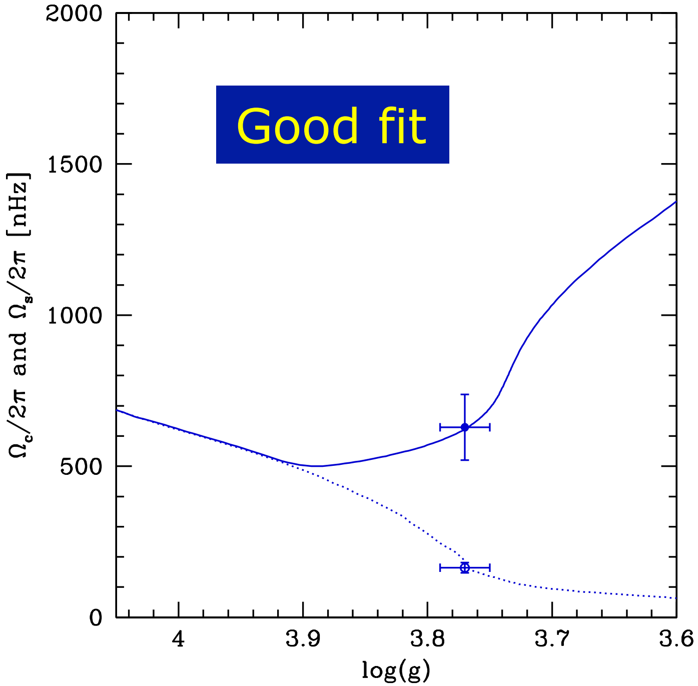
Insensitive to all uncertainties during the previous phases

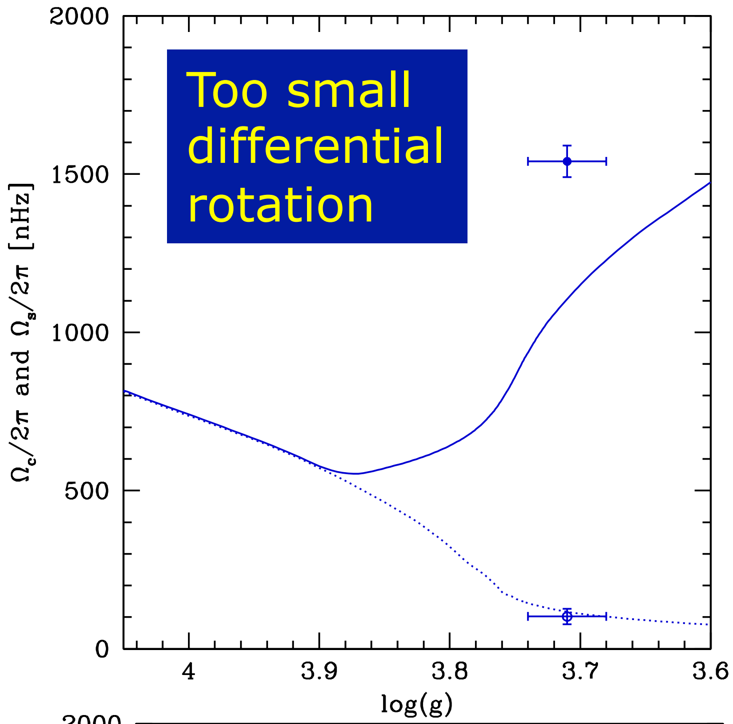
Eggenberger et al. 2019

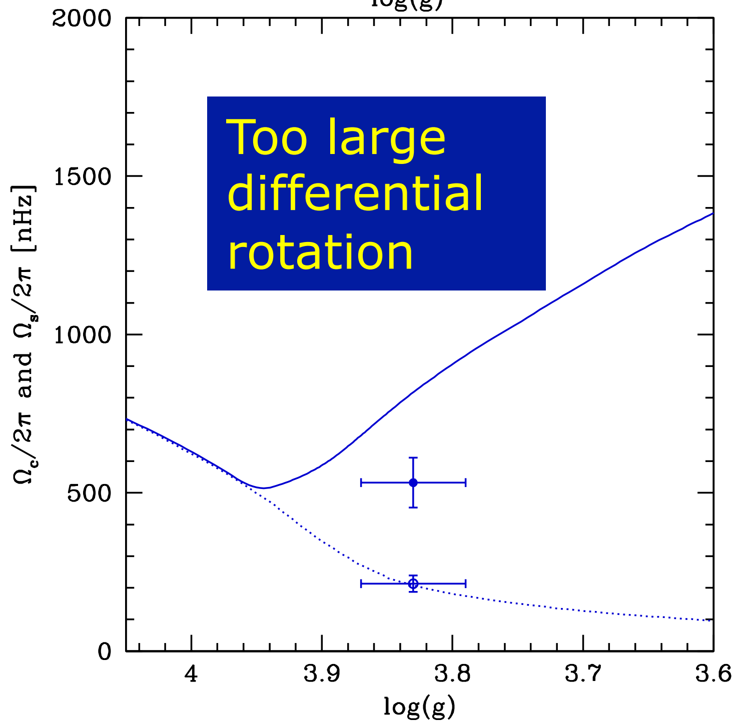


Eggenberger et al. 2019

Comparisons with subgiants Using the Fuller's et al prescription







2 stars over 6 correctly reproduced

Observations: Deheuvels et al 2014

Eggenberger et al. In preparation

CONCLUSIONS

- Angular momentum of stars is only one aspect, but one that can be of importance in some circumstance for the consequence of core collapses.

- Helioseismology and asteroseismology have brought new key constraints

- Still some work to be done for finding the physics of the angular momentum transport in stars, but progresses are presently made.

- Only an understanding of the physical processes will allow to apply to massive stars what we have learned from low mass star asteroseismology

THE CHALLENGES

CONVECTION	→ physics of the boundaries of the convective zones? → how to go beyond the mixing length theory?
MASS LOSSES	→ impact of pulsation, dusts? → origin/frequency/conditions for outbursts?
ROTATION	→ transport processes? → origin of fast rotators?
MAGNETIC FIELDS	→impact of wind magnetic braking? →impact on the core rotation at the pre-SN stage?
MULTIPLICITY	→ Is mass transfer/CE phase the sole significant effects? → How to handle with the numerous parameters?


The details are making the perfection and the perfection is not a detail.
Léonard de Vinci
Extrait des carnets