Modeling intrinsic luminosity variations induced by internal magnetic field in the Sun and solar-like stars

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Focus of this talk: intrinsic structure changes due to magnetic fields

WHAT: Change of equilibrium stellar structure in response to time-varying magnetic fields in the Sun and solar-like stars

HOW: Include magnetic perturbation in stellar evolution code
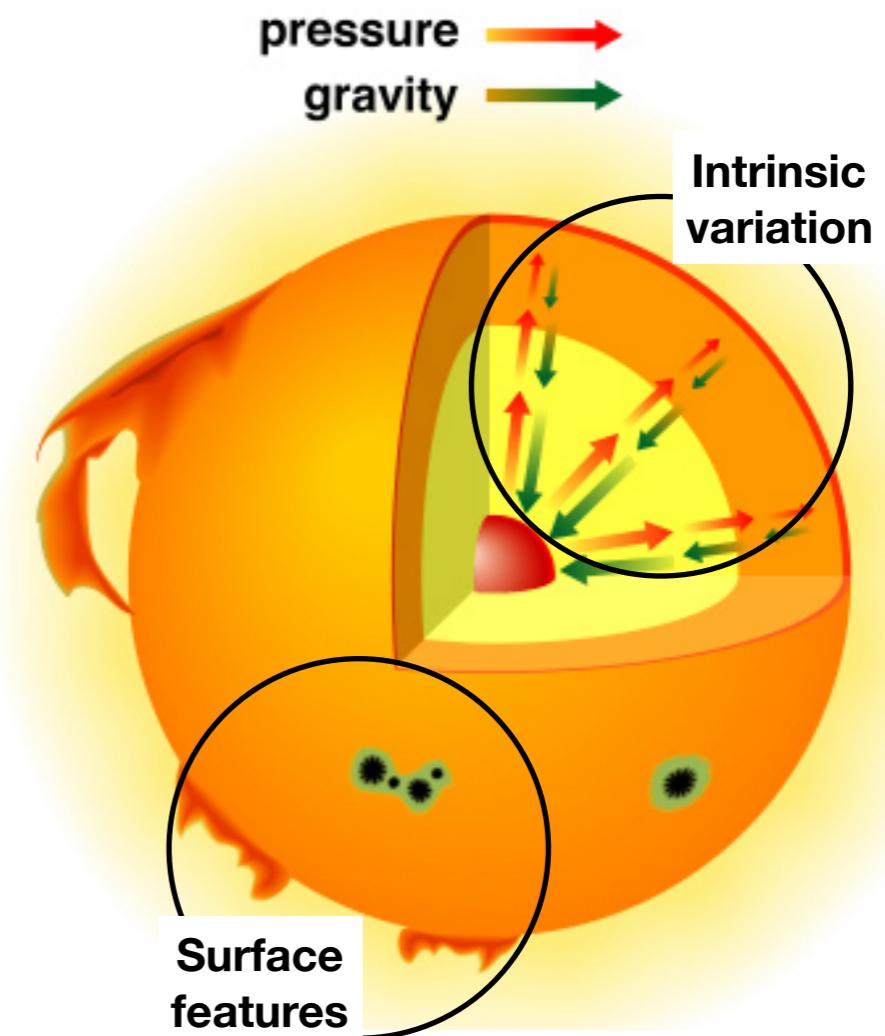
WHY:
- Cumulative effects on climate on decades to millennia
- Constrain and improve solar dynamo theory
- Solar-stellar connection: Sun in time, habitability of exoplanets

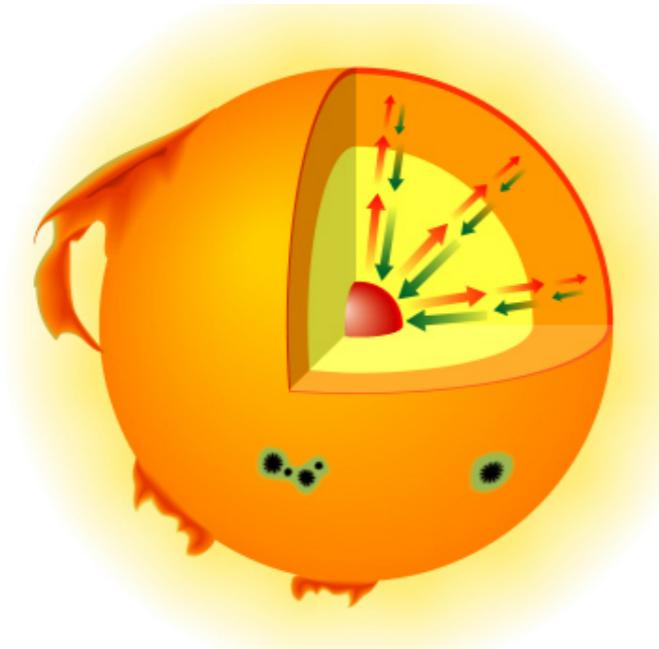# Mechanisms for magnetic variability in solar-like stars

1. **Surface features**

   timescales: days to a decade
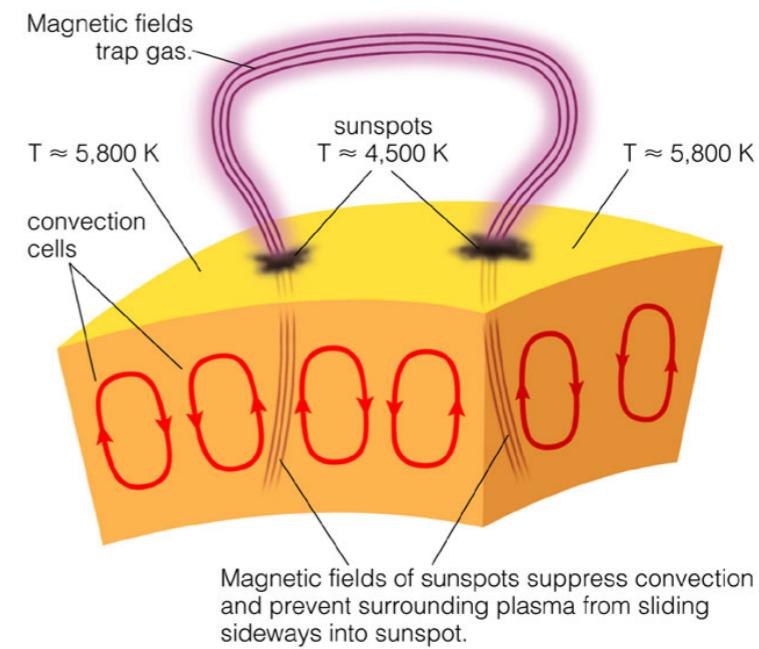
2. **Intrinsic structural changes**

   timescales: decades and longer

pressure →
gravity →

Intrinsic variation

Surface features

Physical mechanisms for intrinsic variations

Magnetic fields trap gas.

T ≈ 5,800 K

sunspots
T ≈ 4,500 K

T ≈ 5,800 K

convection cells

Magnetic fields of sunspots suppress convection and prevent surrounding plasma from sliding sideways into sunspot.

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Direct dynamical effects

Energy budget effects
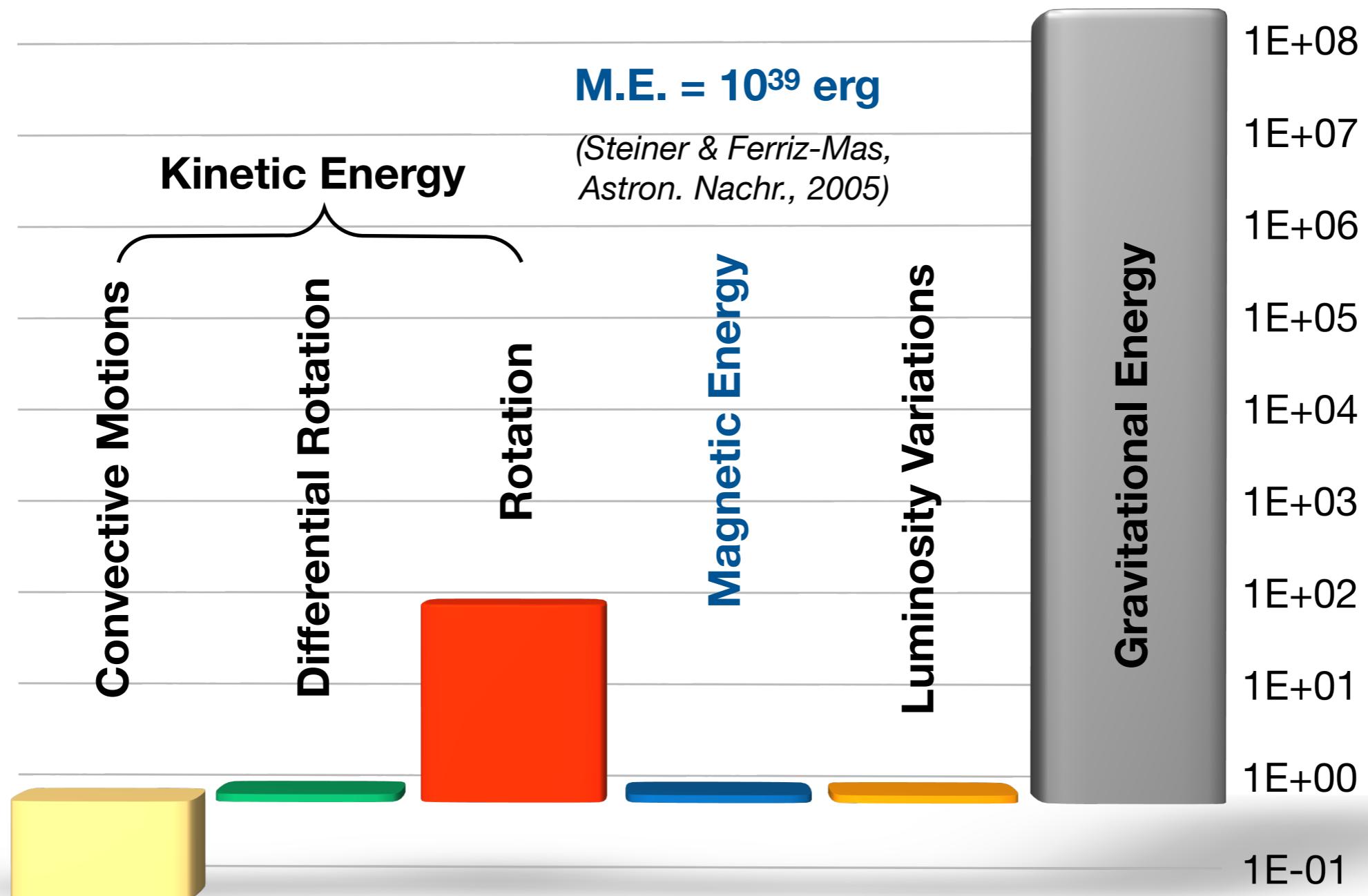
Magnetic pressure contribution
to hydrostatic equilibrium,
changes to equation of state

Inhibition of convective motions
and convective energy transport,
energy source/sink term

Energy considerations

M.E. = 10^{39} erg

(Steiner & Ferriz-Mas, Astron. Nachr., 2005)

Kinetic Energy

Convective Motions

Differential Rotation

Rotation

Magnetic Energy

Luminosity Variations

Gravitational Energy

1E+08
1E+07
1E+06
1E+05
1E+04
1E+03
1E+02
1E+01
1E+00
1E-01

Modeling magnetic variability: methods and challenges

- Magnetic fields introduced as perturbations in a standard 1D stellar evolution code (Yale code, YREC)

- Increased precision requirements:

    1. The effects are small (10^{-3} luminosity, $\sim 10^{-5}$ in radius)

    2. The stellar code must run with time steps $\lesssim 1$ yr

- All stellar structure equations are affected, both directly (i.e., new terms) and indirectly (changes to microphysics)

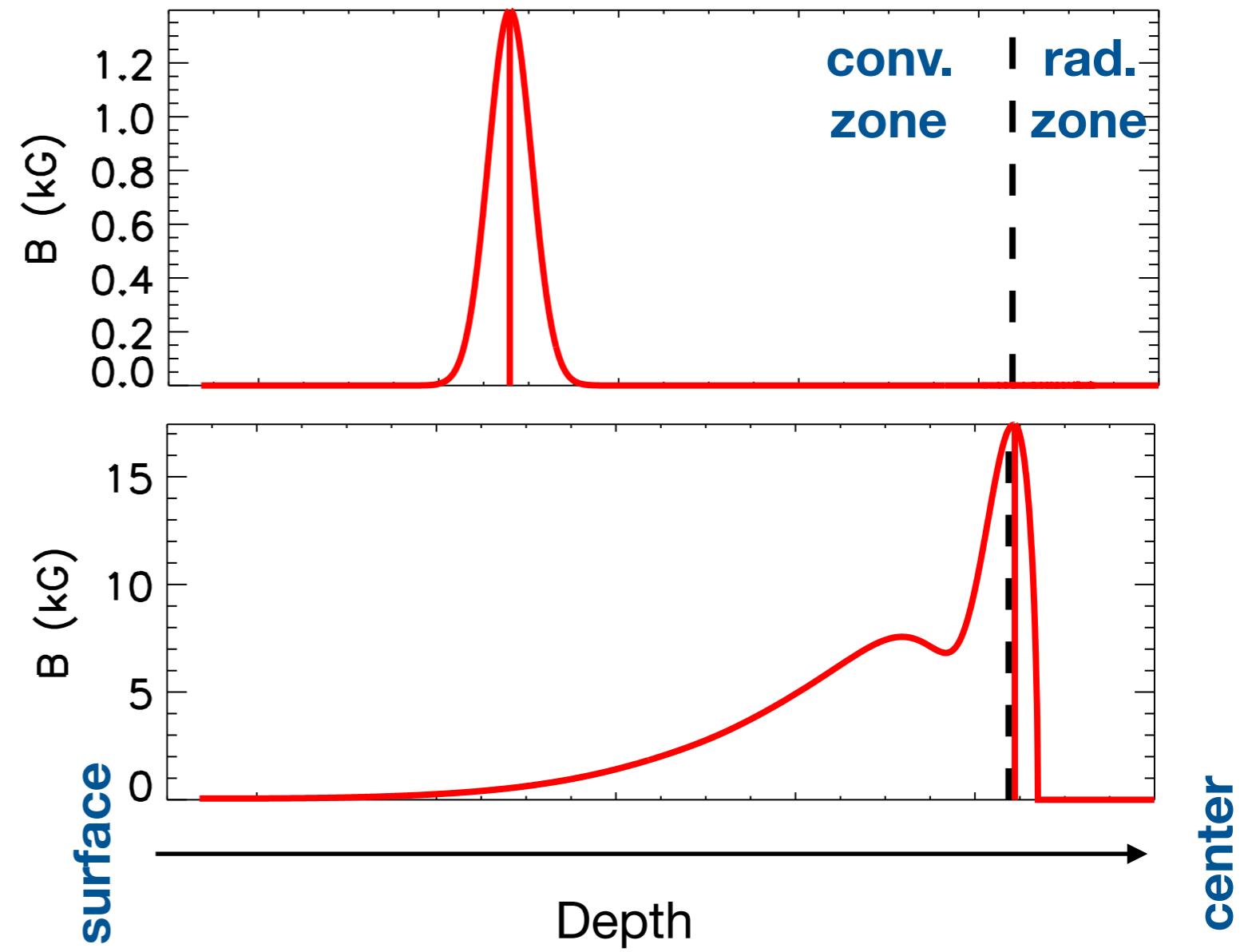# Magnetic perturbation components

- **Hydrostatic equilibrium:** contribution of magnetic pressure

- **Equation of state:** density correction; modified thermodynamic derivatives

- **Convective energy transport:** modified convective instability criterion, convective temperature gradient

- **Source/sink energy term:** energy added/removed by time-varying magnetic fields

Spada et al., A&A (under review)

Radial profile of the magnetic field

Gaussian-shaped profile

Profile extracted from mean-field dynamo model
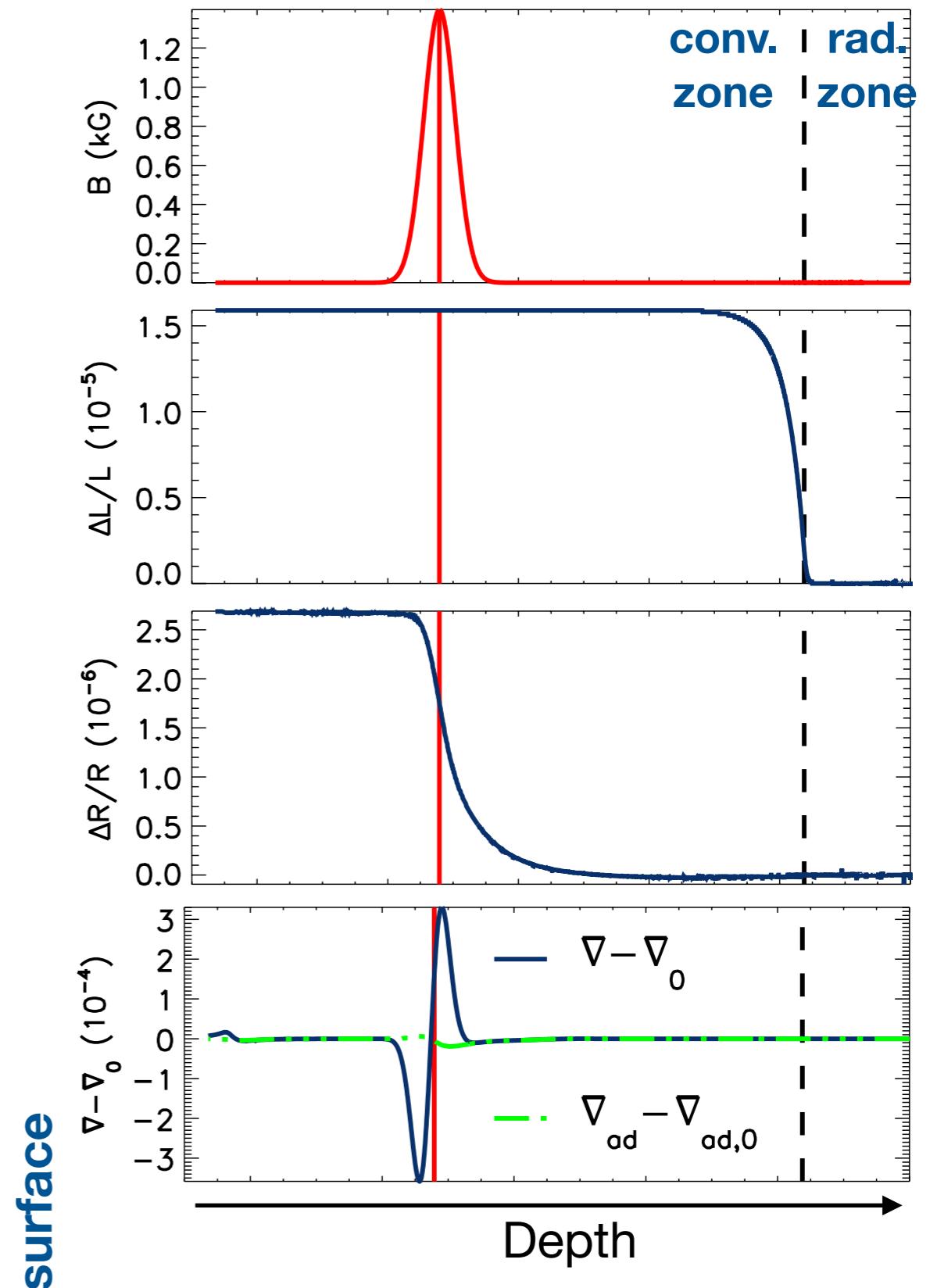

Spada et al., A&A (under review)

Interior structure perturbation

Gaussian-shaped magnetic field profile

Luminosity perturbation (rel.)

Radius perturbation (rel.)

Temperature gradient and
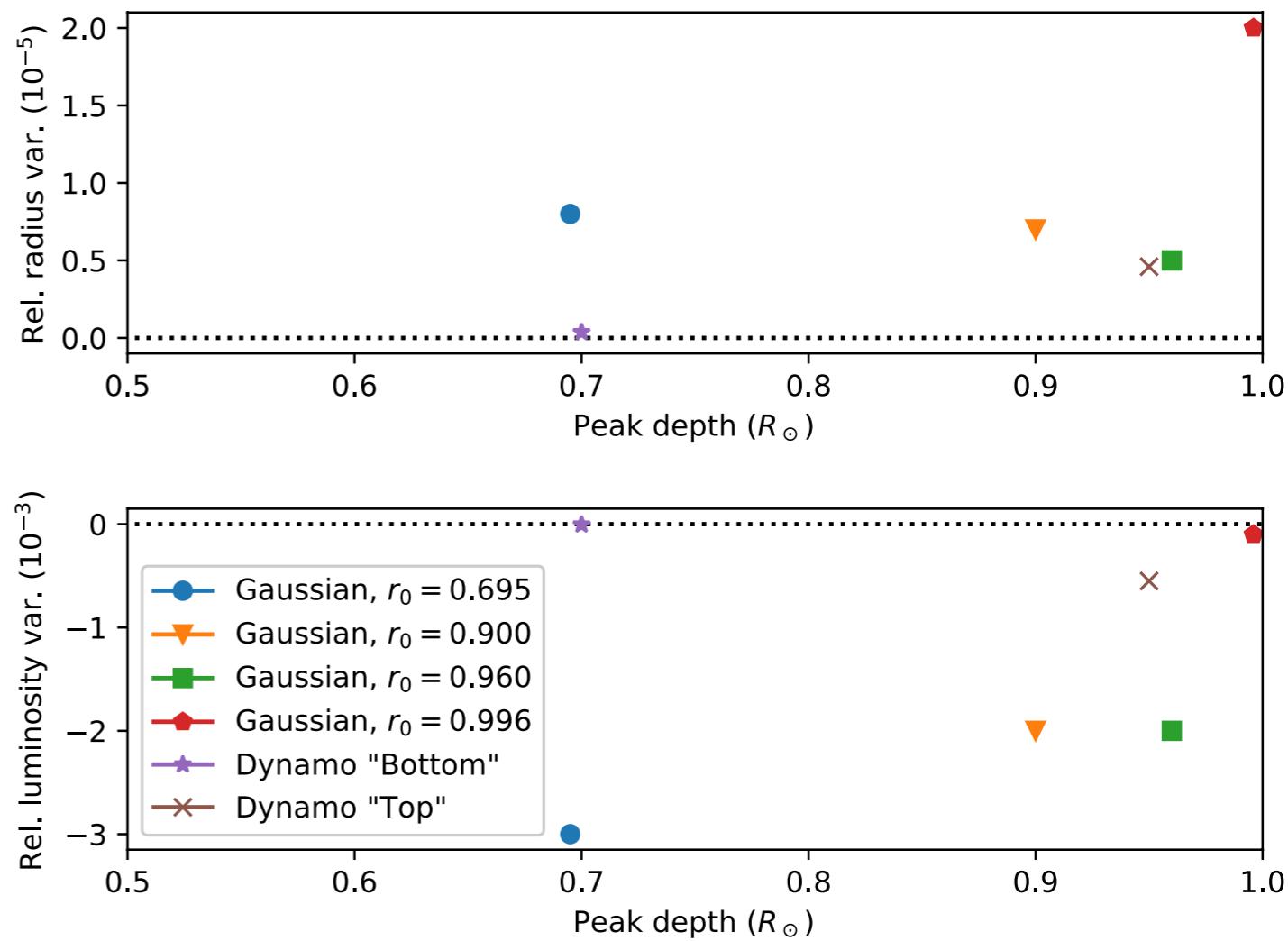**adiabatic temperature gradient**
perturbation

Federico Spada   -   2018 Sun-Climate Symposium, Lake Arrowhead, CA, March 19-23 2018

Radius and luminosity variations

- Peak field strength ~ 10s kG

- Total mag. energy ~ 10^{35}-10^{39} erg

- **Radius variations ~ 10^{-5}**

- **Luminosity variations ~ 10^{-3}**

- Results sensitive to **depth** of the magnetic layer

- Radius and luminosity variations mostly have opposite phases

Spada et al., A&A (under review)

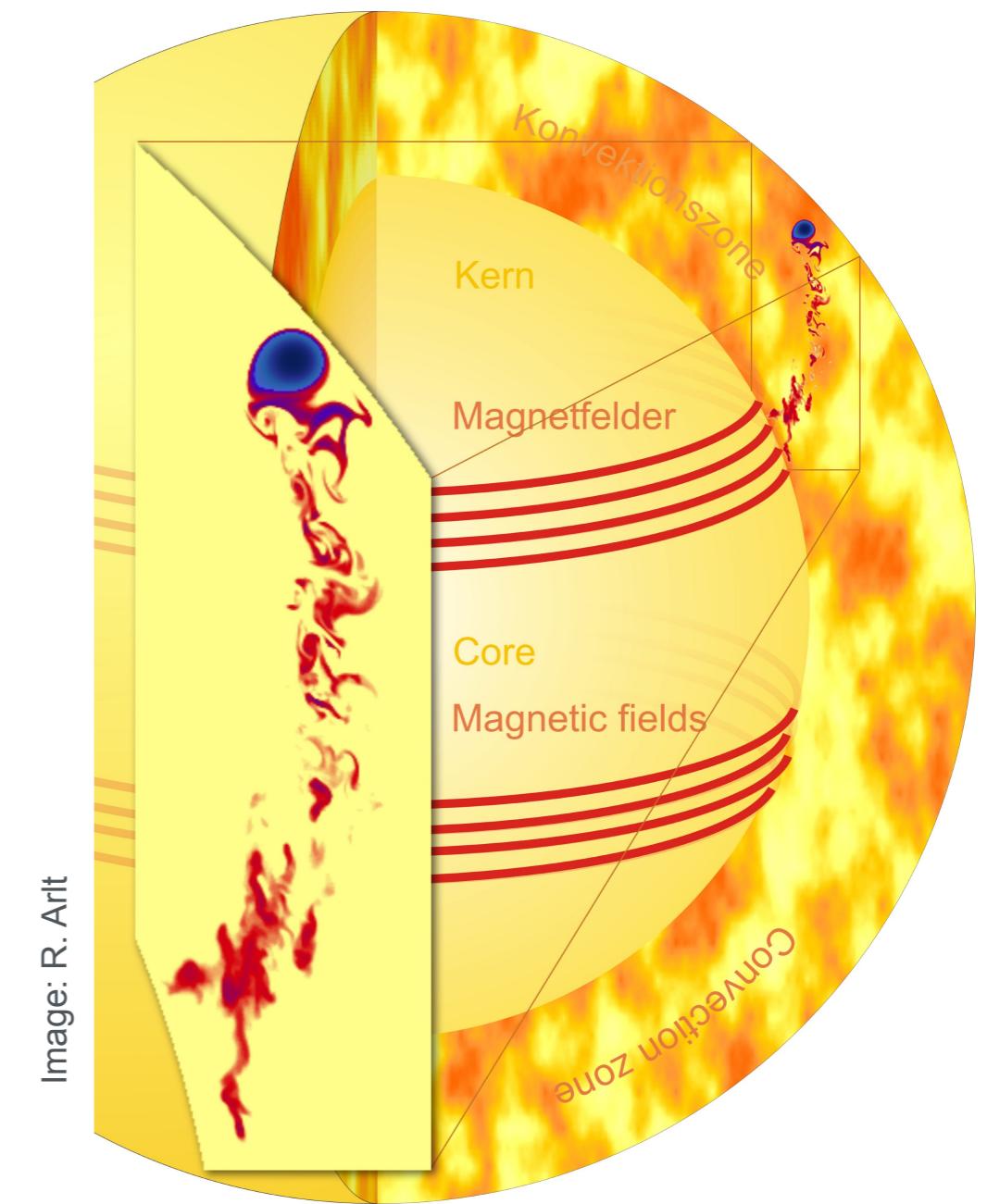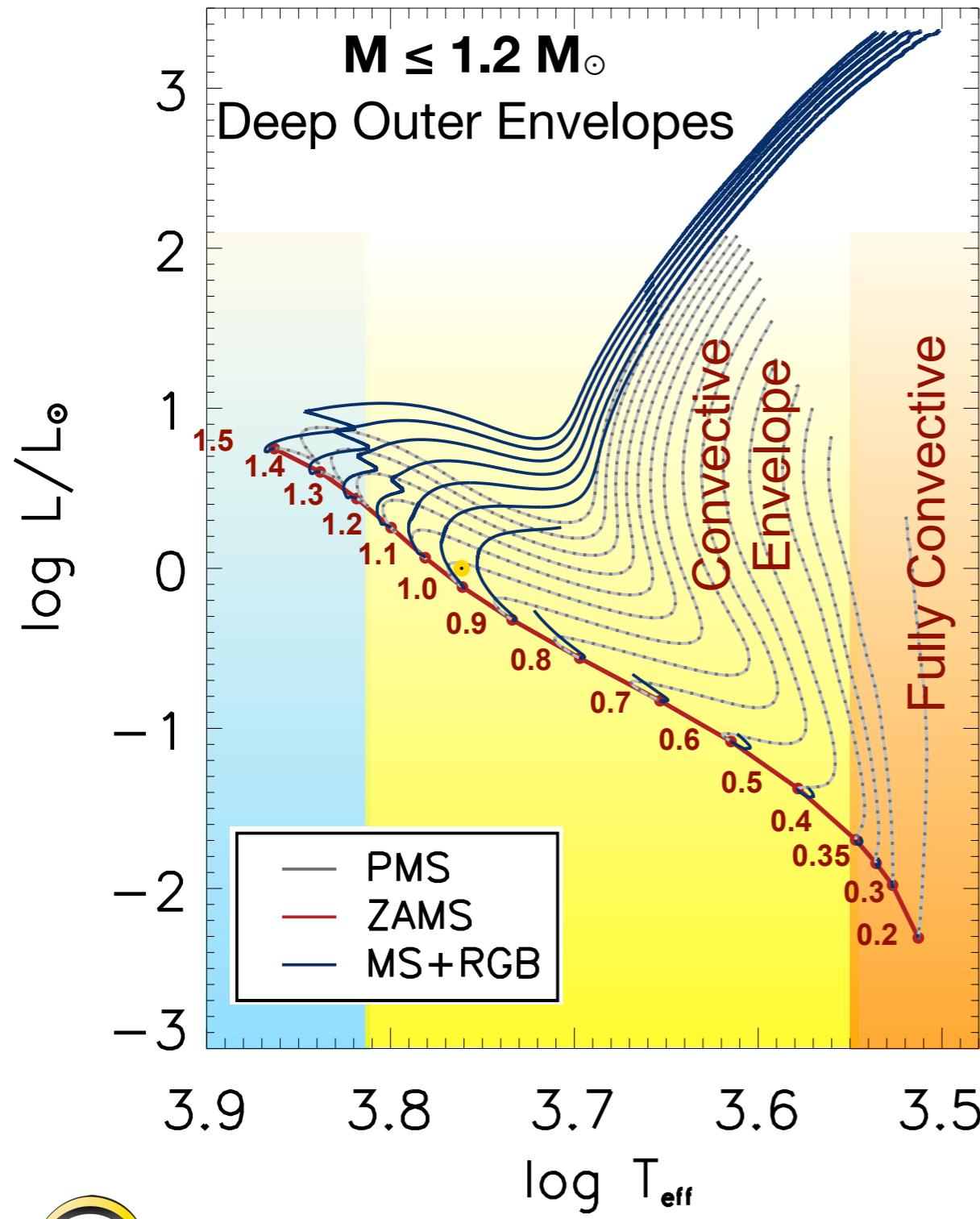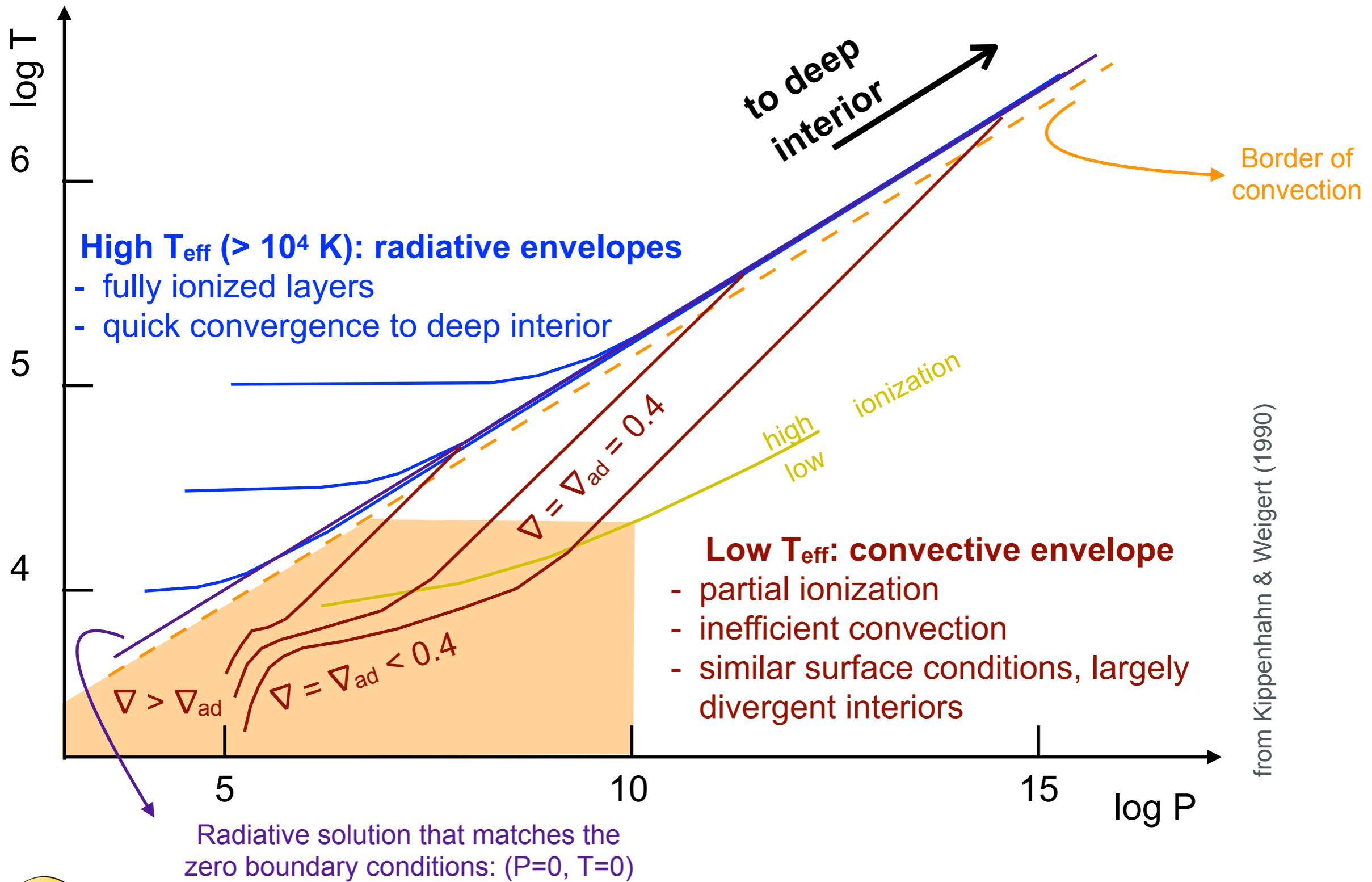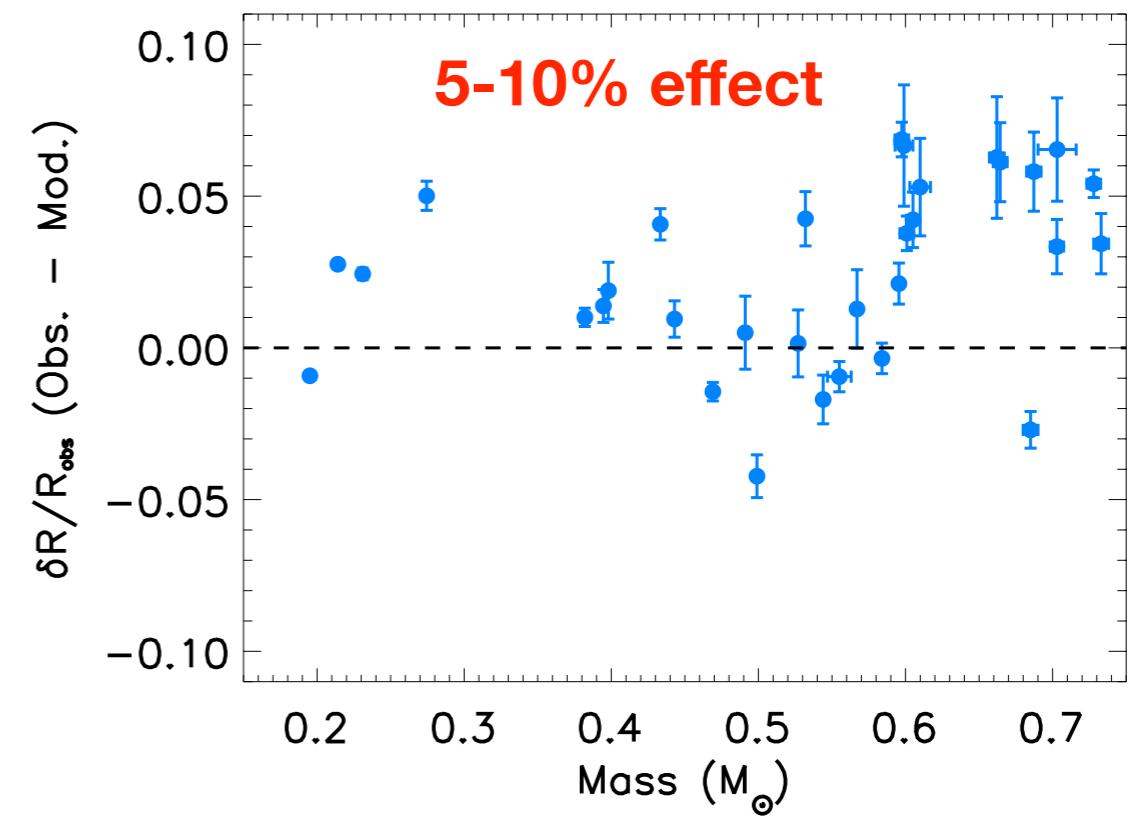# Magnetic variability of solar-like stars

M ≤ 1.2 M$_\odot$
Deep Outer Envelopes

Convective Envelope

Fully Convective

PMS
ZAMS
MS+RGB

Image: R. Arlt

Konvektionszone
Kern
Magnetfelder
Core
Magnetic fields
Convection zone

CE controls the interior structure

High T_{eff} (> 10^4 K): radiative envelopes
- fully ionized layers
- quick convergence to deep interior

to deep interior

Border of convection

high / low ionization

$\nabla = \nabla_{ad} = 0.4$

Low T_{eff}: convective envelope
- partial ionization
- inefficient convection
- similar surface conditions, largely divergent interiors

$\nabla > \nabla_{ad}$

$\nabla = \nabla_{ad} < 0.4$

Radiative solution that matches the zero boundary conditions: (P=0, T=0)

from Kippenhahn & Weigert (1990)

log T

log P

6

5

4

5

10

15

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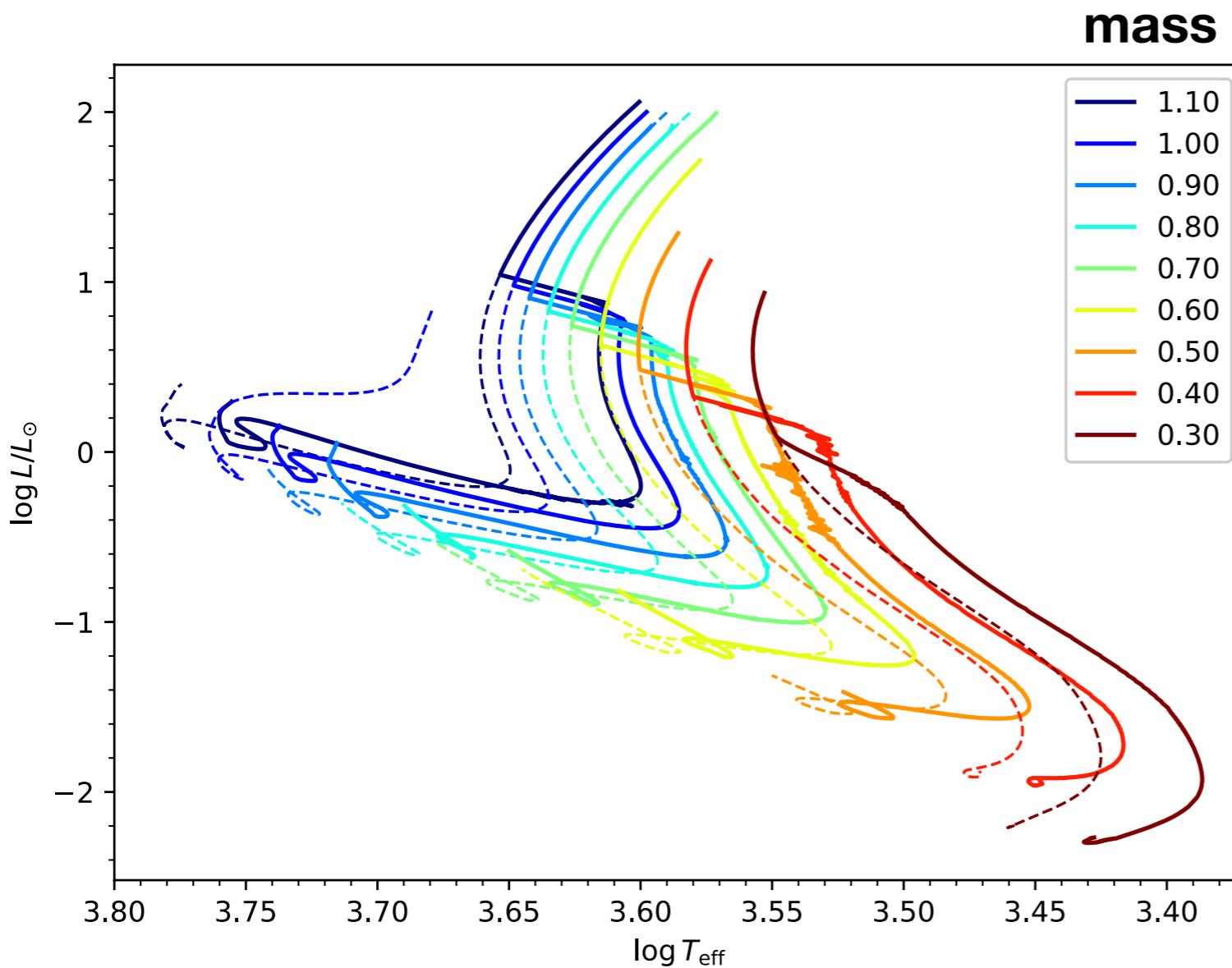
Radius discrepancy in solar-like stars

- Linked to fast rotation, strong magnetic activity, lithium depletion

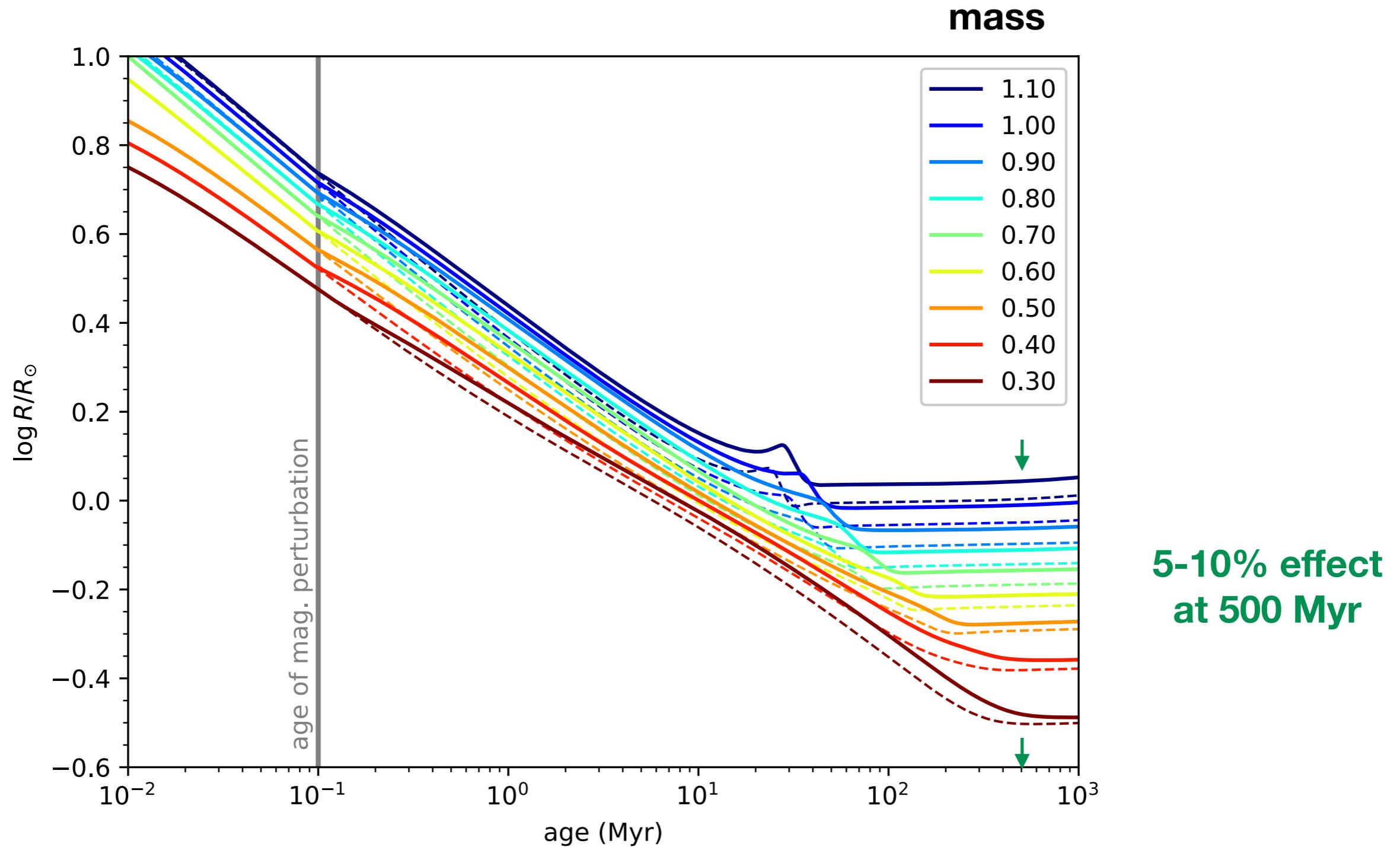- Structural effects of magnetic fields natural explanation
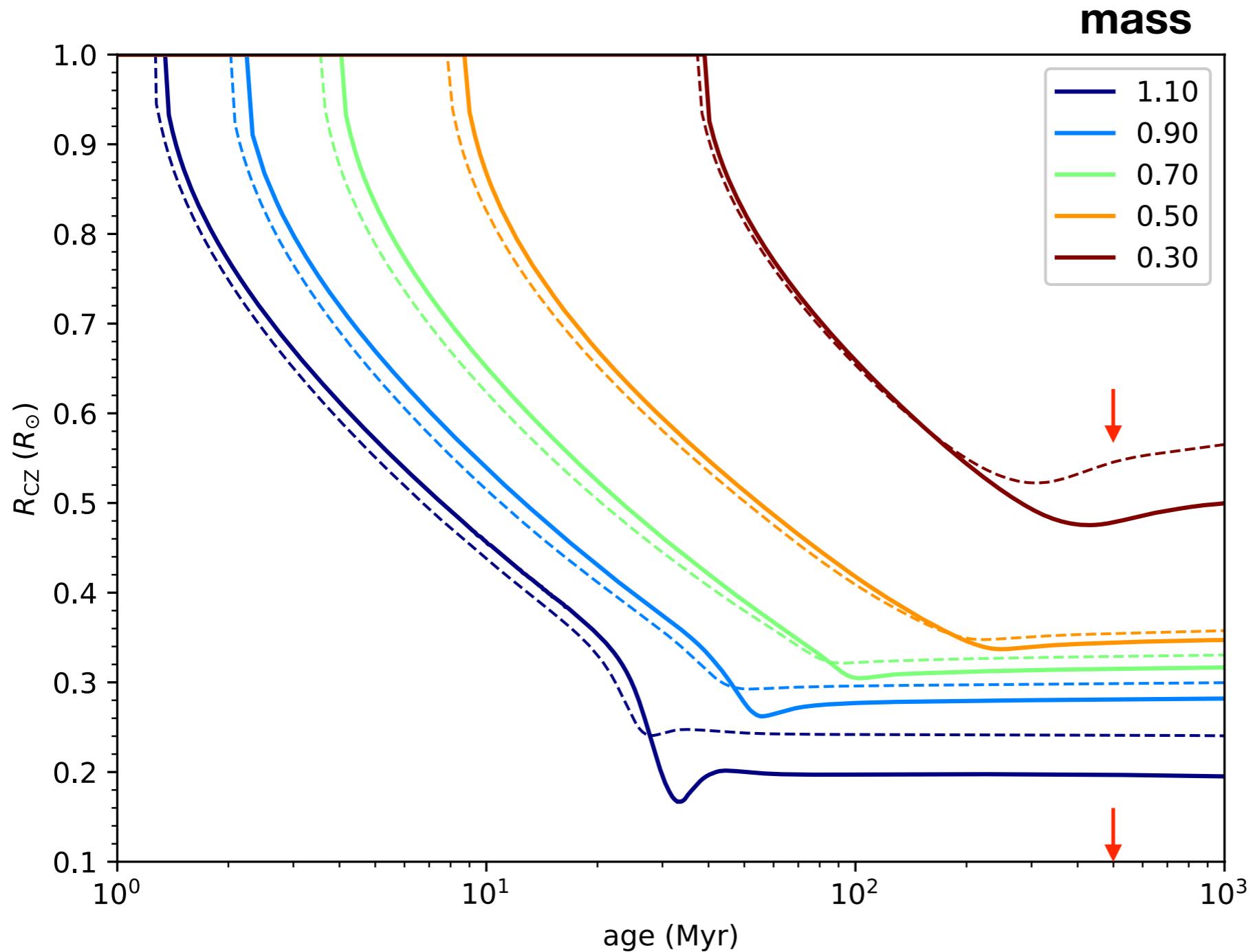
Magnetic vs. non-magnetic tracks

- Gaussian magnetic field profile

- Surface magnetic field intensity in equipartition with surface pressure

- Perturbation added in early pre-main sequence

Feiden, A&A, 2016
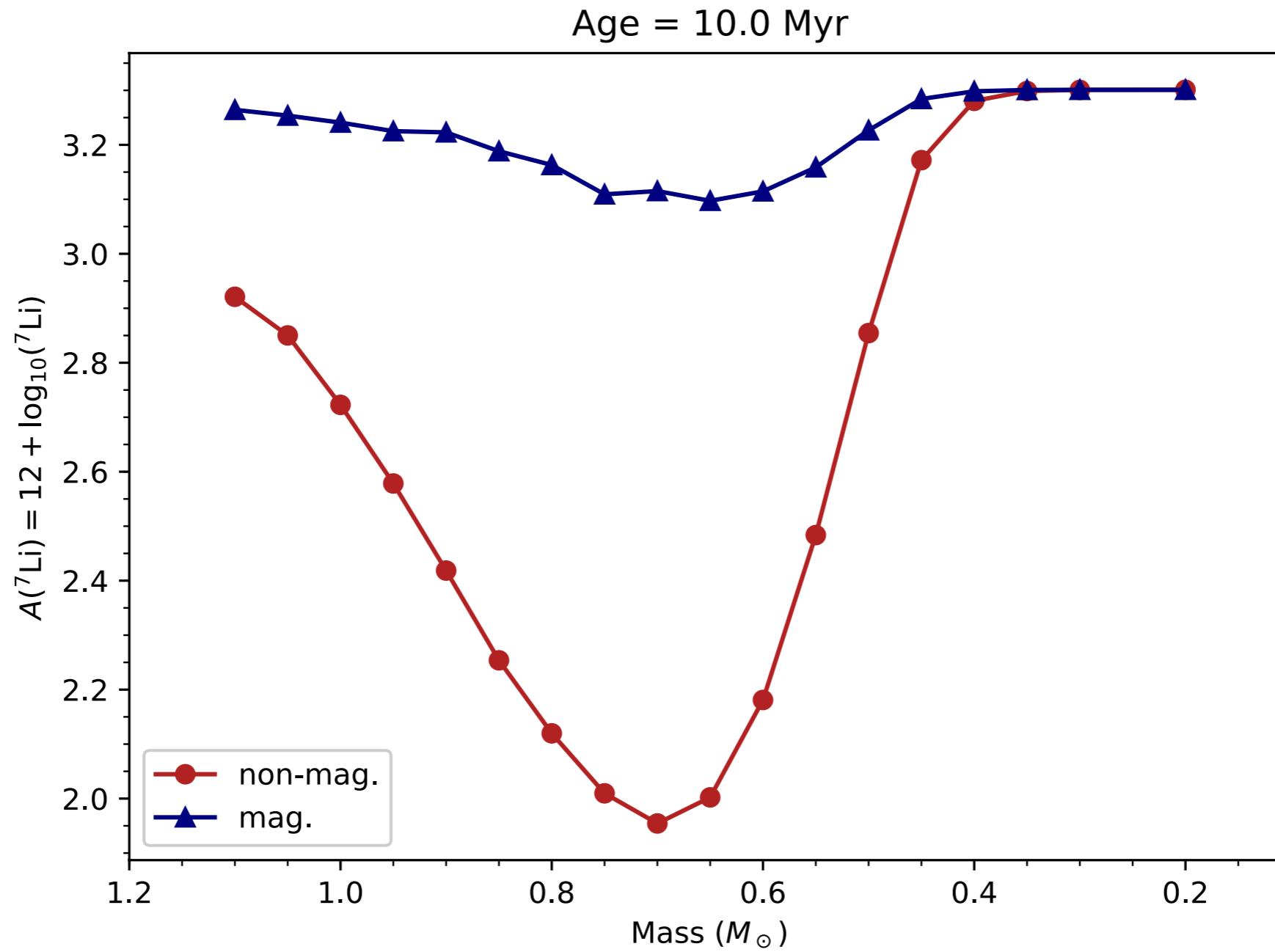
Radius perturbation in PMS

5-10% effect at 500 Myr

Depth of the CZ

2-5% effect
at 500 Myr
(15% for 0.3 $M_\odot$)

Lithium depletion pattern

Age = 10.0 Myr

Conclusions

- Non-trivial radius changes are compatible with available constraints (e.g., magnetic energy, luminosity variations)

- Solar models with magnetic fields can independently test predictions of dynamo theory (e.g., magnetic layer depth)

- Models including magnetic fields can explain features observed in young active stars: inflated radii, suppressed lithium depletion