4M-COCOS @ Fukuoka 19.10.22

Uncertain stellar evolution: convection, rotation, magnetic field

Koh Takahashi
Max-Planck-Institut für Gravitationsphysik (AEI)

Outline

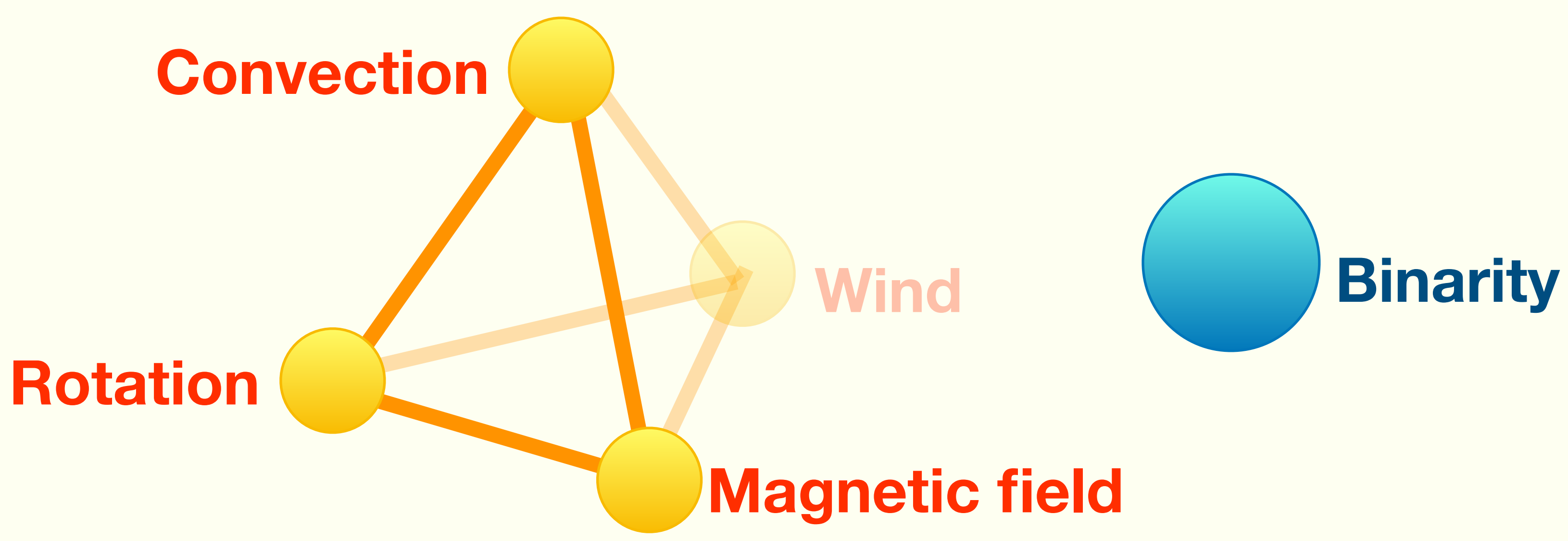
○ **Theory of stellar evolution**

Stars are the fundamental component of the universe.
What are **the robust predictions** and **the uncertainties** involved in the theory?

Because of the long timescale, 1D modeling is inevitable.
Then, how can we include the effects of

- ○ **convection**
- ○ **stellar rotation**
- ○ **stellar magnetism** ?

- ○ **stellar wind** Massive stars lose significant fraction of mass.
- ○ **binarity** High frequency of binary/multiple stellar systems



Non-rotating, non-magnetized & single star

○ Where are uncertainties?

Stellar evolution is described by a set of partial differential equations:

$$\frac{\partial r}{\partial M} = \frac{1}{4\pi r^2 \rho}$$

$$\frac{\partial p}{\partial M} = -\frac{GM}{4\pi r^4} + \frac{1}{4\pi r^2}\frac{\partial v}{\partial t}$$

$$\frac{\partial e}{\partial t} = -p\frac{\partial (1/\rho)}{\partial t} - \frac{\partial (L_{\rm rad} + L_{\rm conv})}{\partial M} + \epsilon$$

$$L_{\rm rad} = \frac{4aT^4/3}{p}\frac{4\pi c G M}{\kappa}\frac{d\ln T}{d\ln p}$$

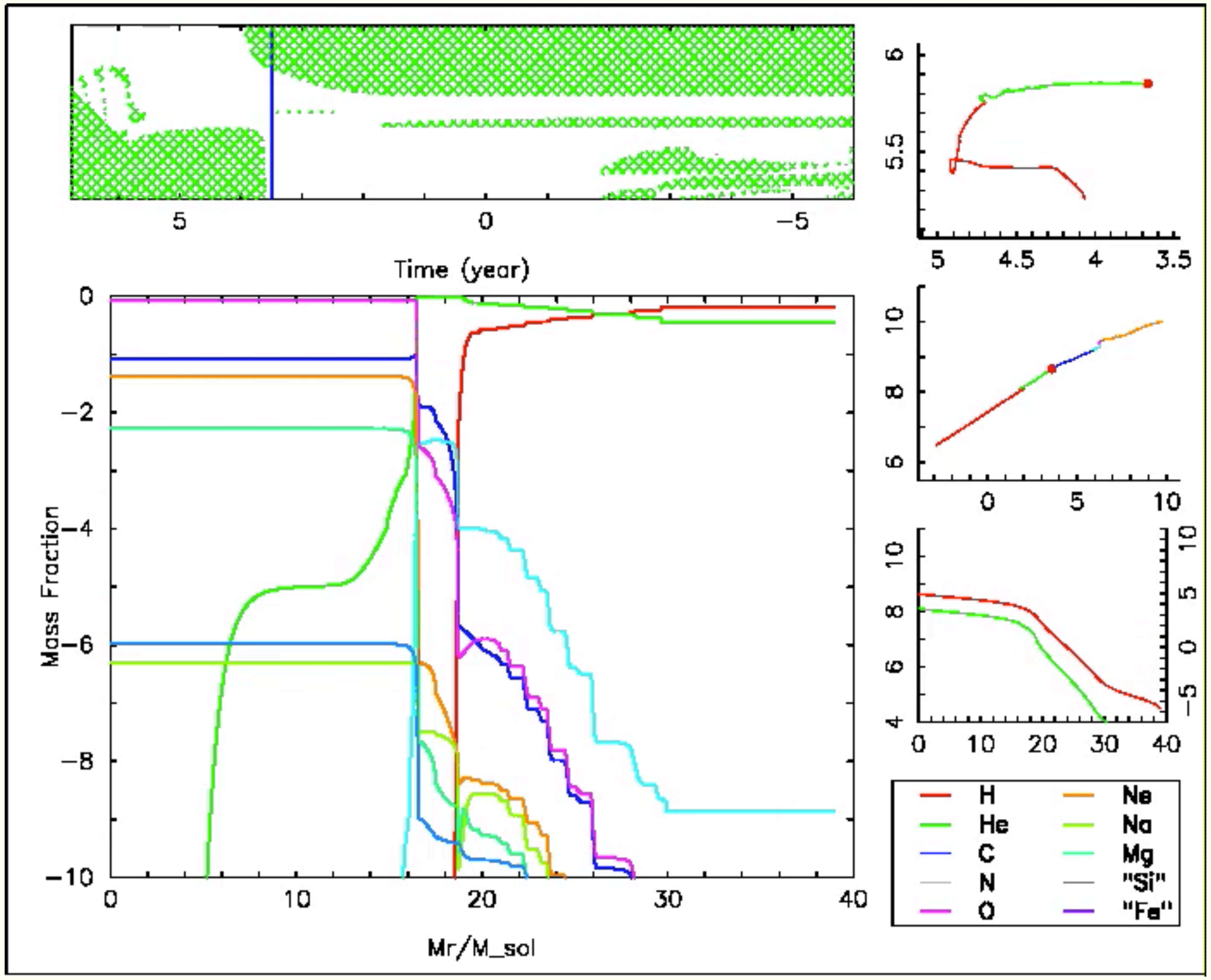
$$\frac{\partial Y_i}{\partial t} = \dot{Y}_{i,{\rm reac}} + \frac{\partial}{\partial M}\left((4\pi r^2 \rho)^2 D \frac{\partial Y_i}{\partial M}\right)$$

independent variables:
ρ, T, Y_i, r, L

microphysics:
$p, e, \kappa, \epsilon, \dot{Y}_{i,{\rm reac}}(\rho, T, Y_i)$

macrophysics:
$L_{\rm conv}, D$ **: Convection**

Rotating pop III 40 M_{sol} model: KT+14



Convection

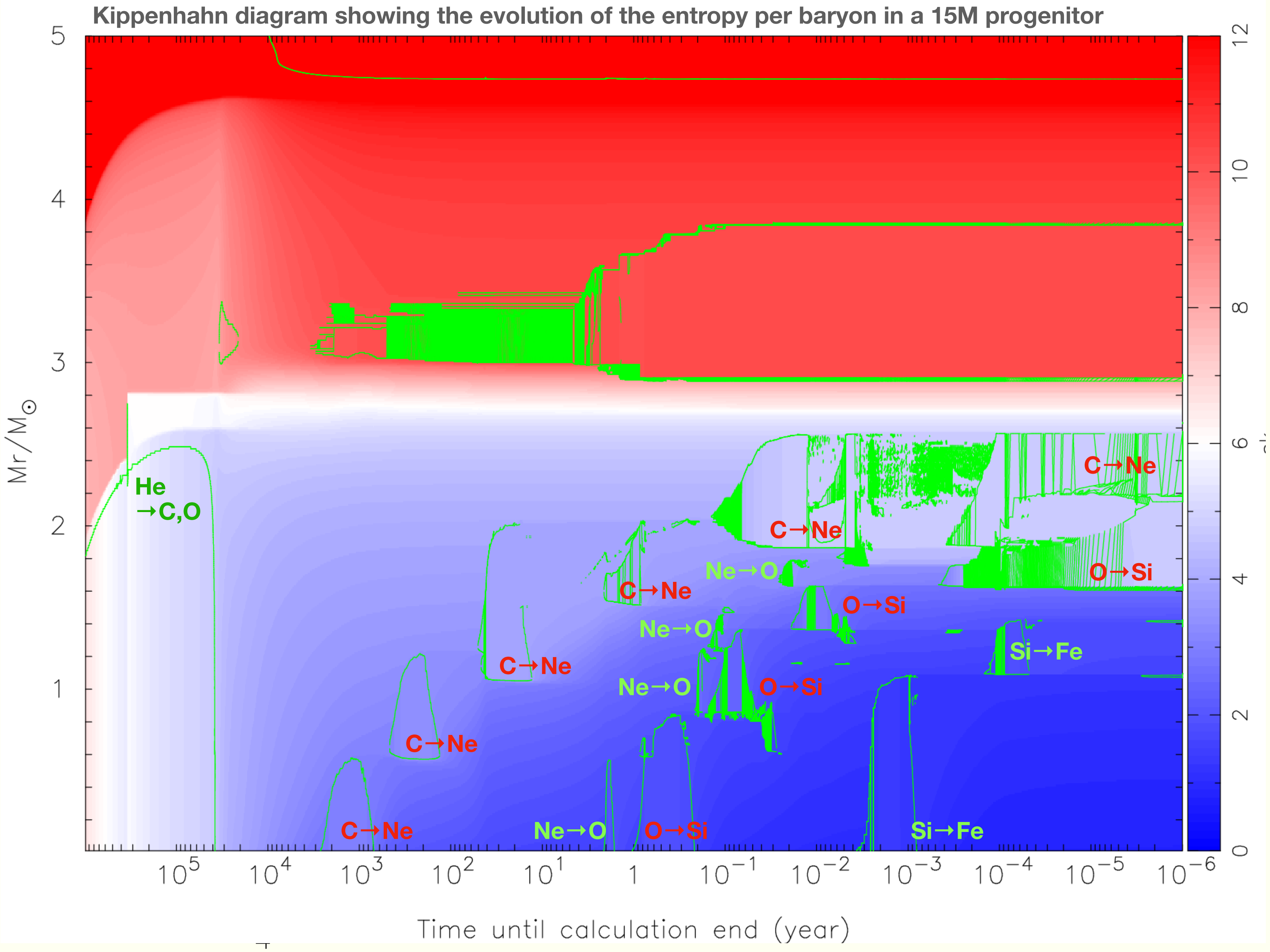
○ Convection

A region becomes convective when the radiative energy transport is not efficient enough to carry the whole energy flux.
(Schwartzschild/Ledoux criterion & Mixing length theory)

→ **reasonably good (~a few %) estimate for the structure of the Sun.**

○ Prediction

The **numbers** and **durations** of **shell convective burning episodes** are important for determining the final progenitor structure.

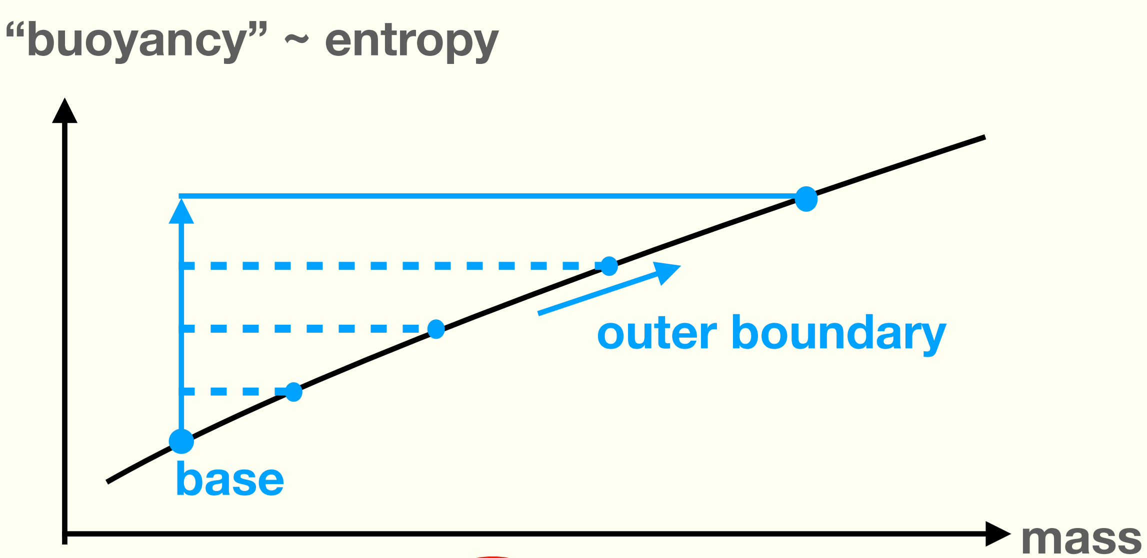


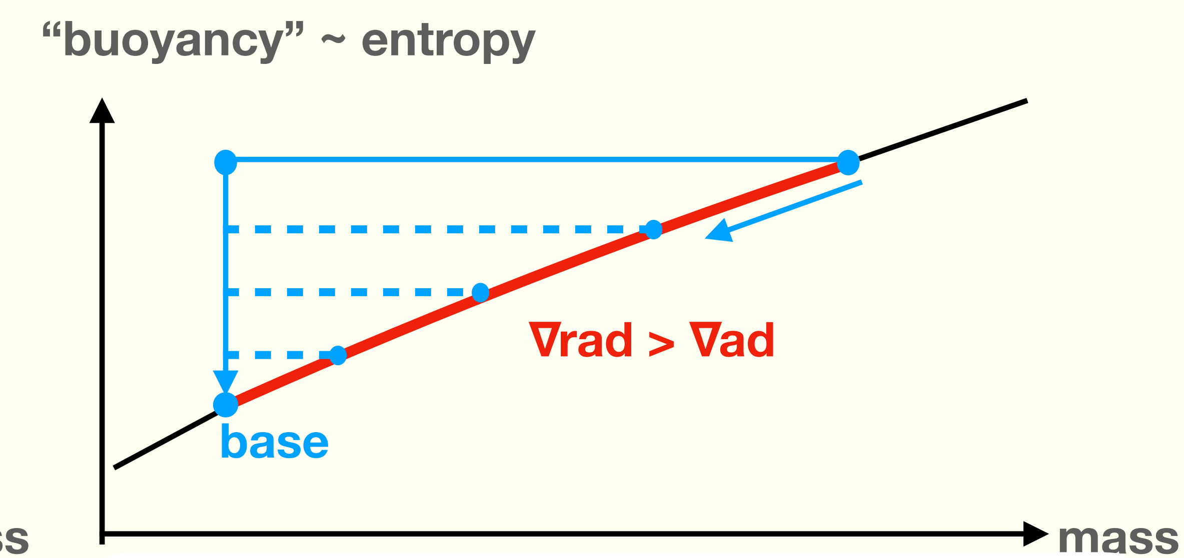
Convection

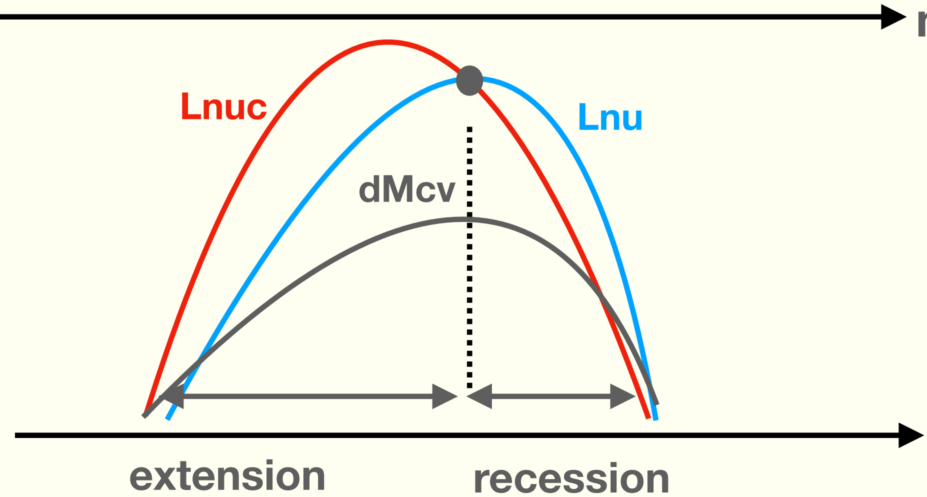
○ **What determines properties of shell convections?**

The important assumptions: “Inside a convective region, the entropy is constant.”
as well as the chemical abundances
“The released energy is compensated by the ν cooling.”

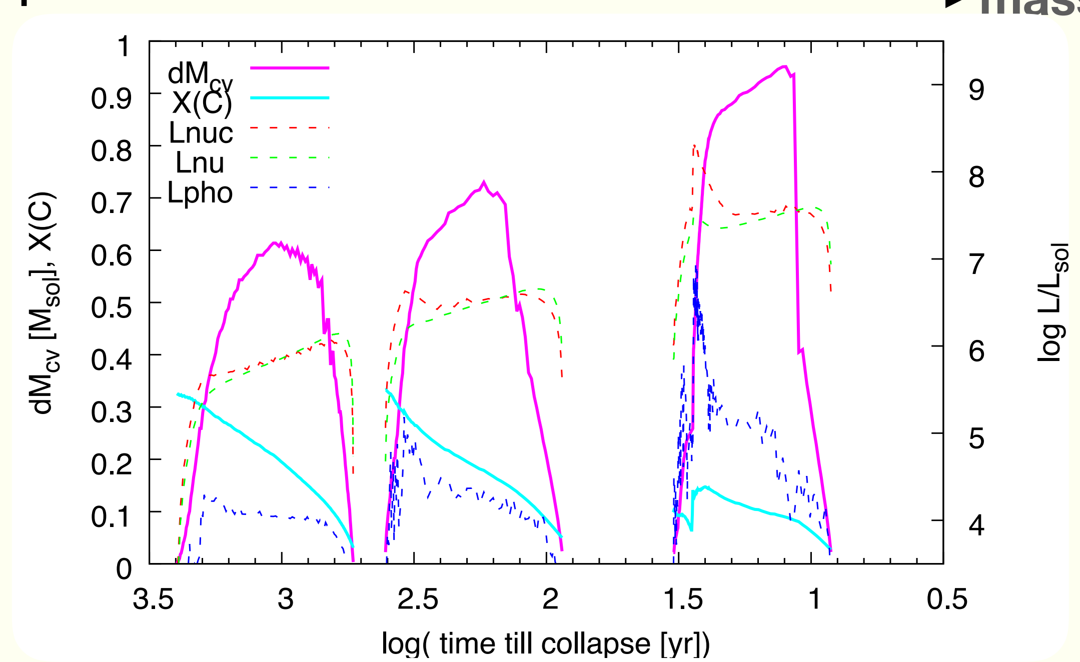
→ extension/recession(, and the lifetime) of a convective region should be solely determined by the net heating/cooling in the region.







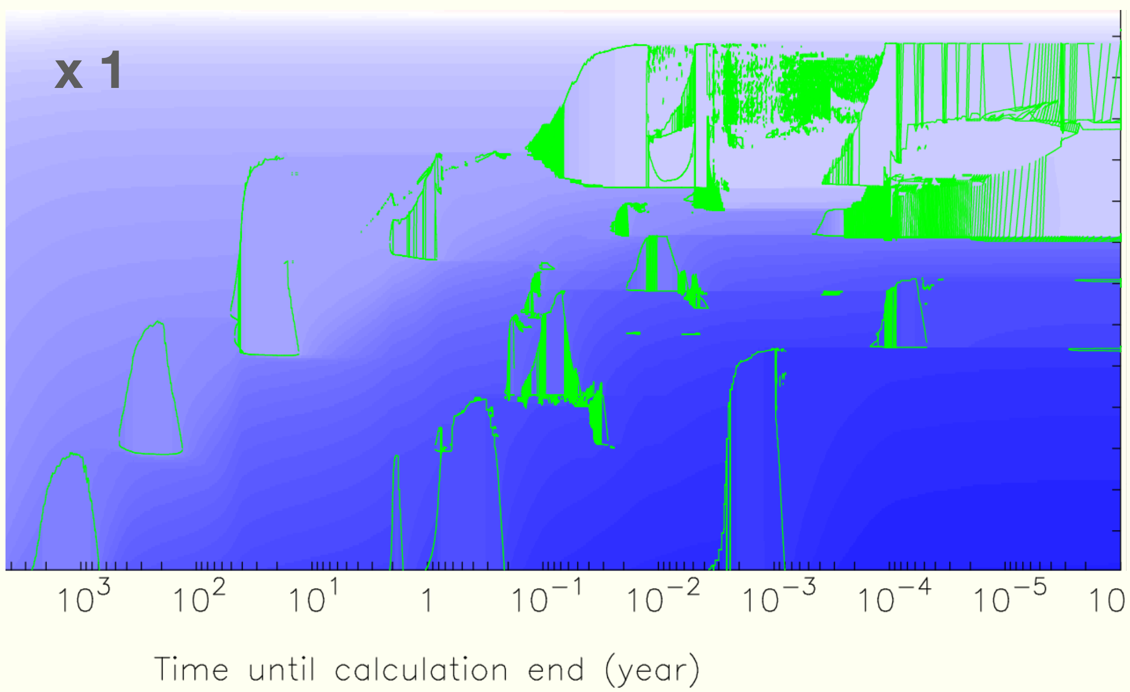
When Lnuc > Lnu, a convective region extends, and when Lnuc < Lnu, a convective region recedes.

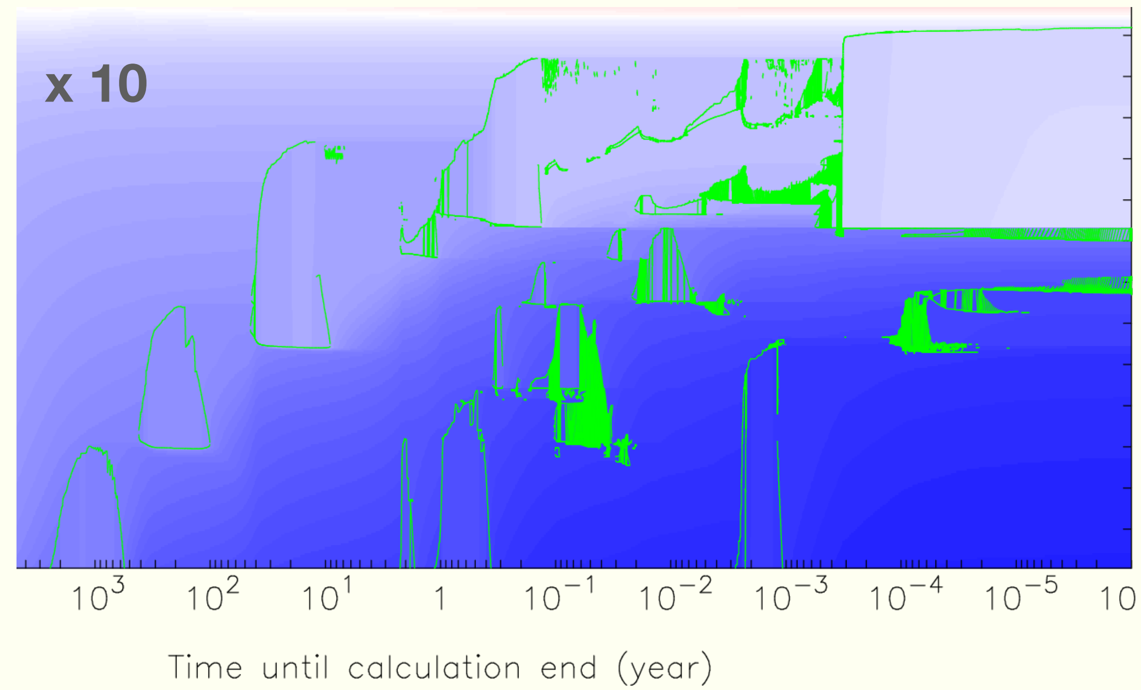


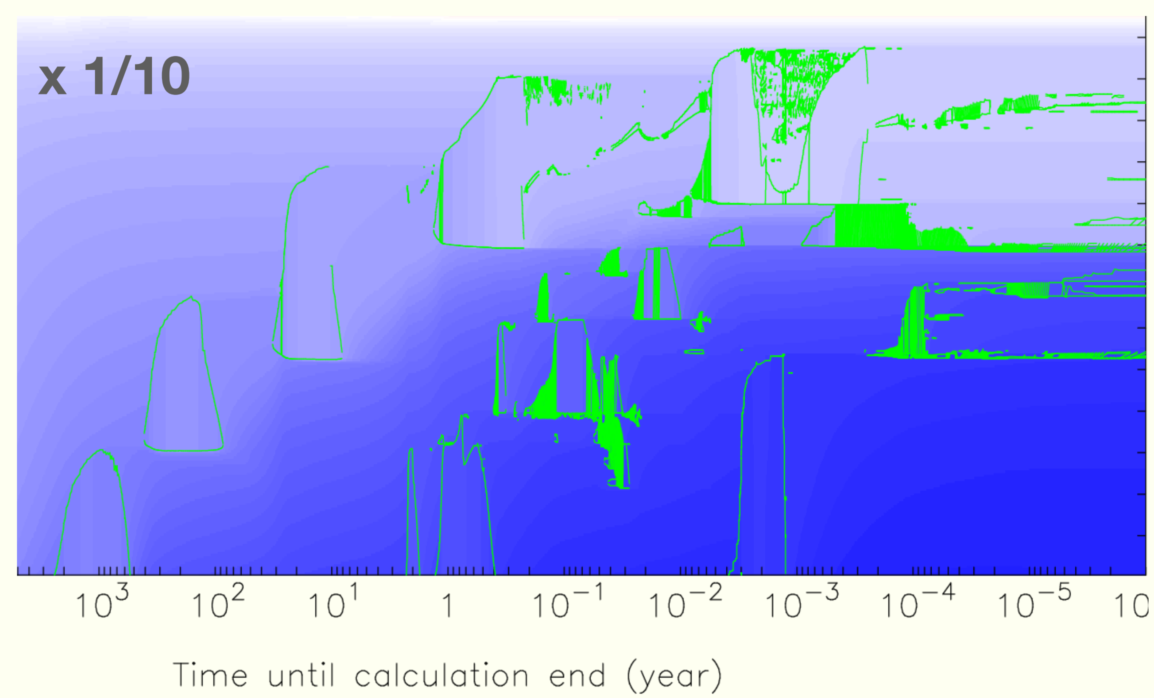
○ **What determines properties of shell convections?**

KT+ in prep.

Changing the mixing coefficient D has negligible effects on the convective properties.





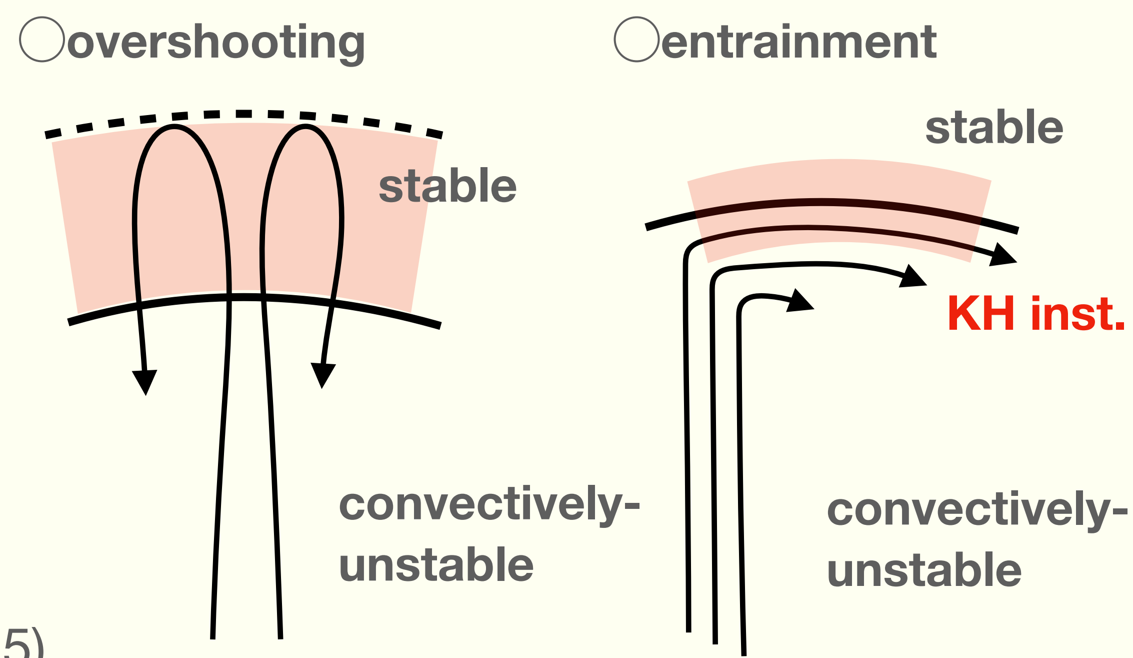


Convection

○ Missing dynamical physics

Obs.: the size of a H burning convective core is larger than the model prediction.

- -main sequence width
  (Maeder 1976, Schaller et al. 1992, etc.)
- -measurements by asteroseismology
  (e.g., Aerts et al. 2018)

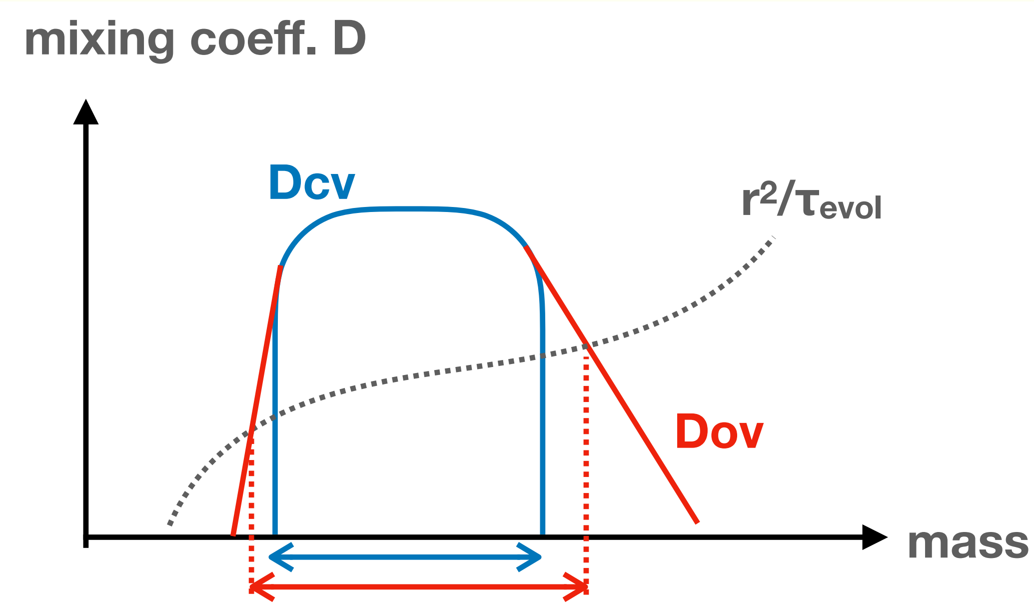


→ **convective boundary mixing (CBM)**

- -convective overshoot (e.g. Freytag et al. 1996)
- -matter entrainment (e.g. Woodward et al. 2015)

○ prescription

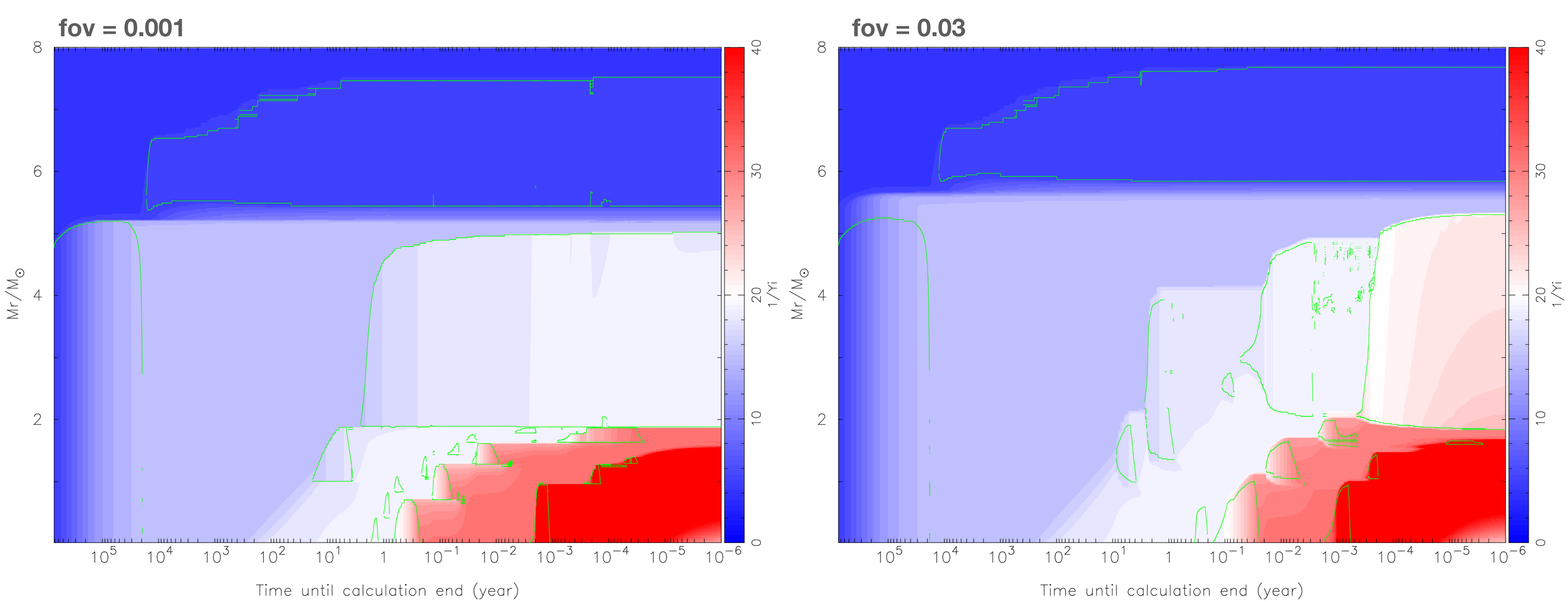
$$D_{\mathrm{cv}}^{\mathrm{ov}} = D_{\mathrm{cv},0} \exp\left(-2\frac{\Delta r}{f_{\mathrm{ov}} H_{p,0}}\right),$$



Convection

KT+ in prep.

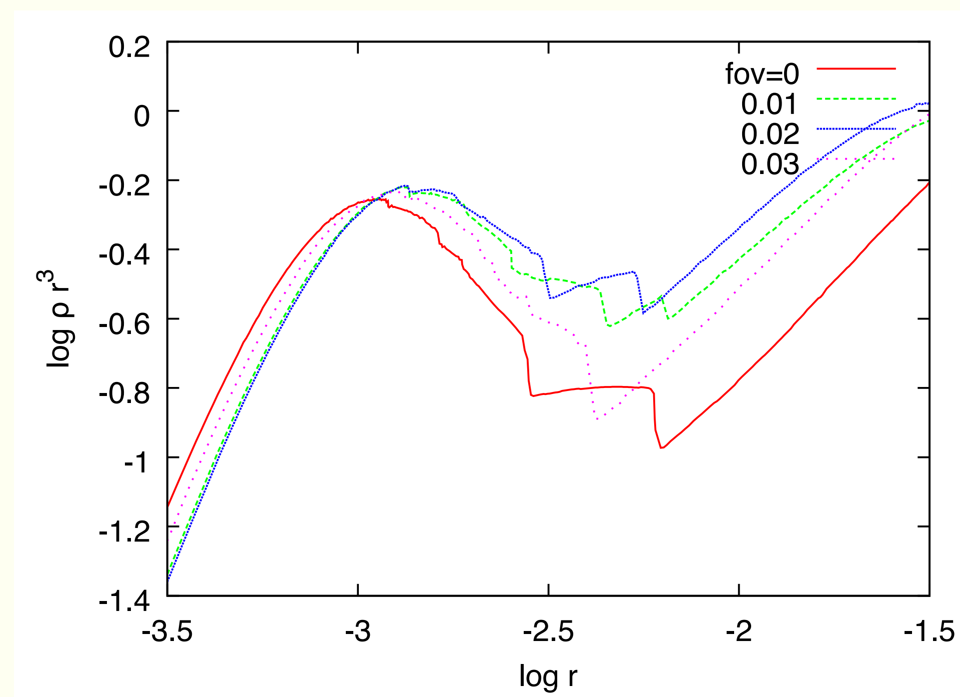
○ **effect of CBM**



Progenitor structure is affected by a large CBM parameter.

-extension enhanced

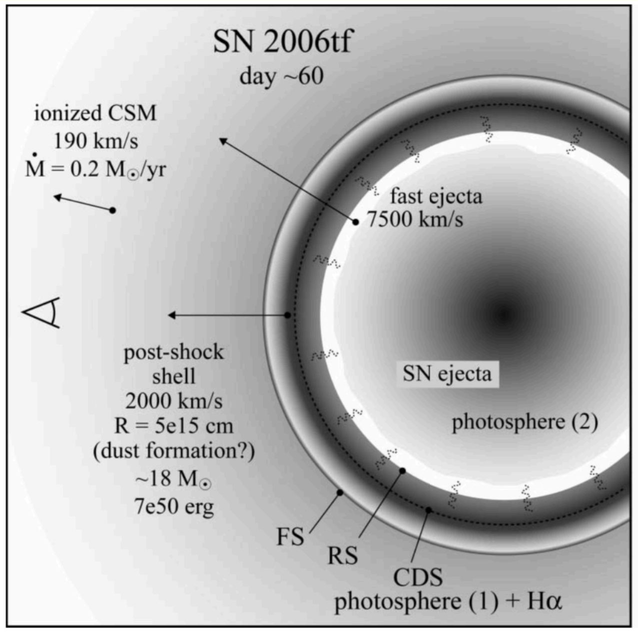
-**convective merger** between O & Ne/C shells



Convection

○ **Indication of active core convection**

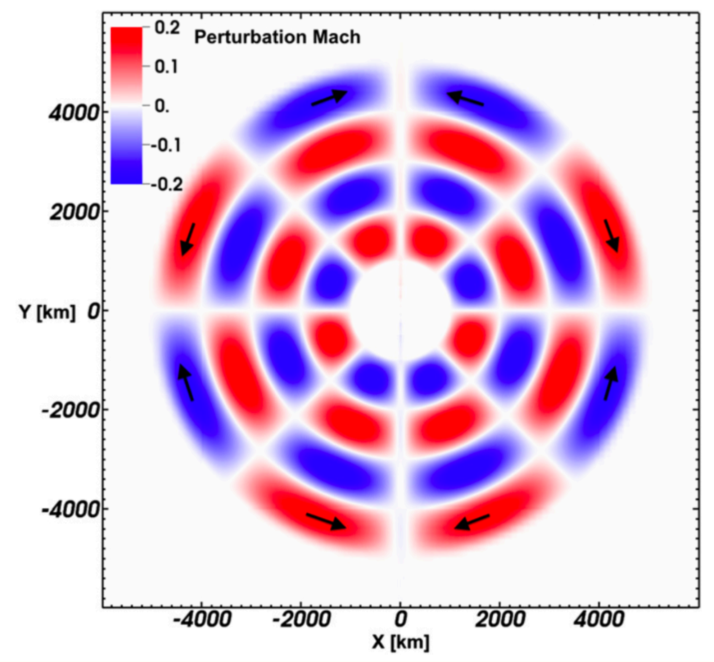
Smith et al. 2008



Obs.: SNe IIn indicate that strong mass ejections happen ~10 yr before the SN happens (e.g., Smith et al. 2007).

→ **Merger of convective regions** may explain the energetic nuclear burning triggering the mass ejection (Quataert & Shiode 2012, Smith & Arnett 2014).

Couch & Ott 2013



Obs.: CCSNe explode with $E_{exp} \sim 10^{51}$ erg.

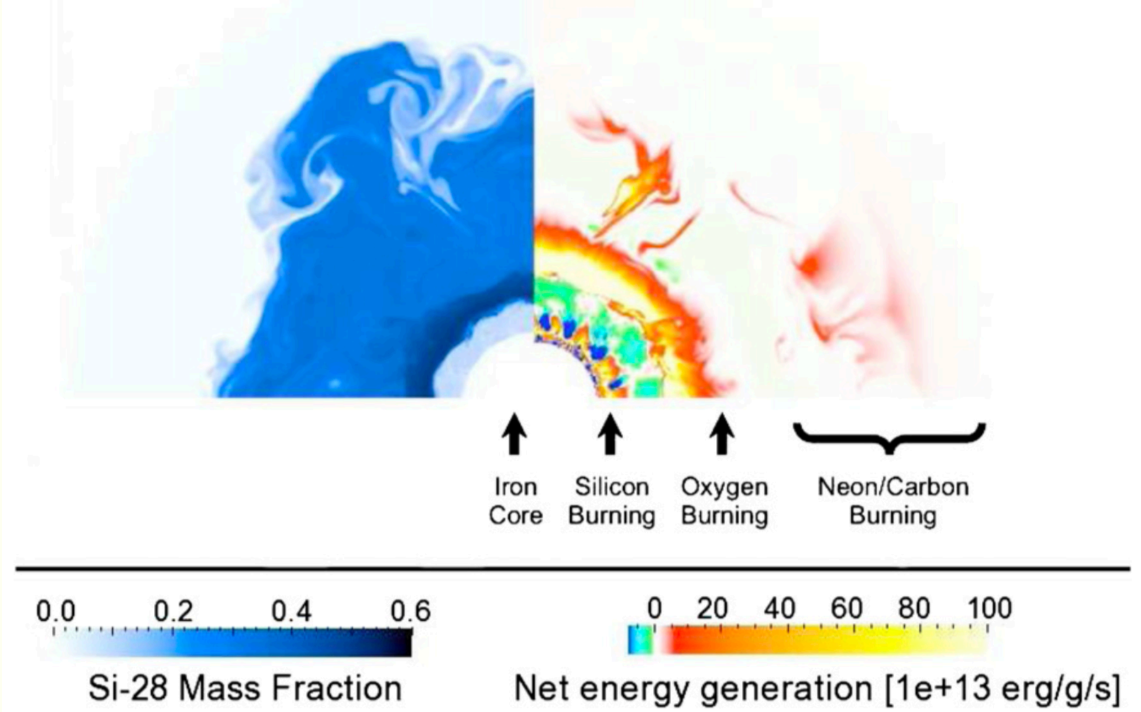
→ Multi-D velocity & density fluctuations formed by convective turbulence can help the CCSN explosion (Couch & Ott 2013, Müller et al. 2015, Takahashi et al. 2016).

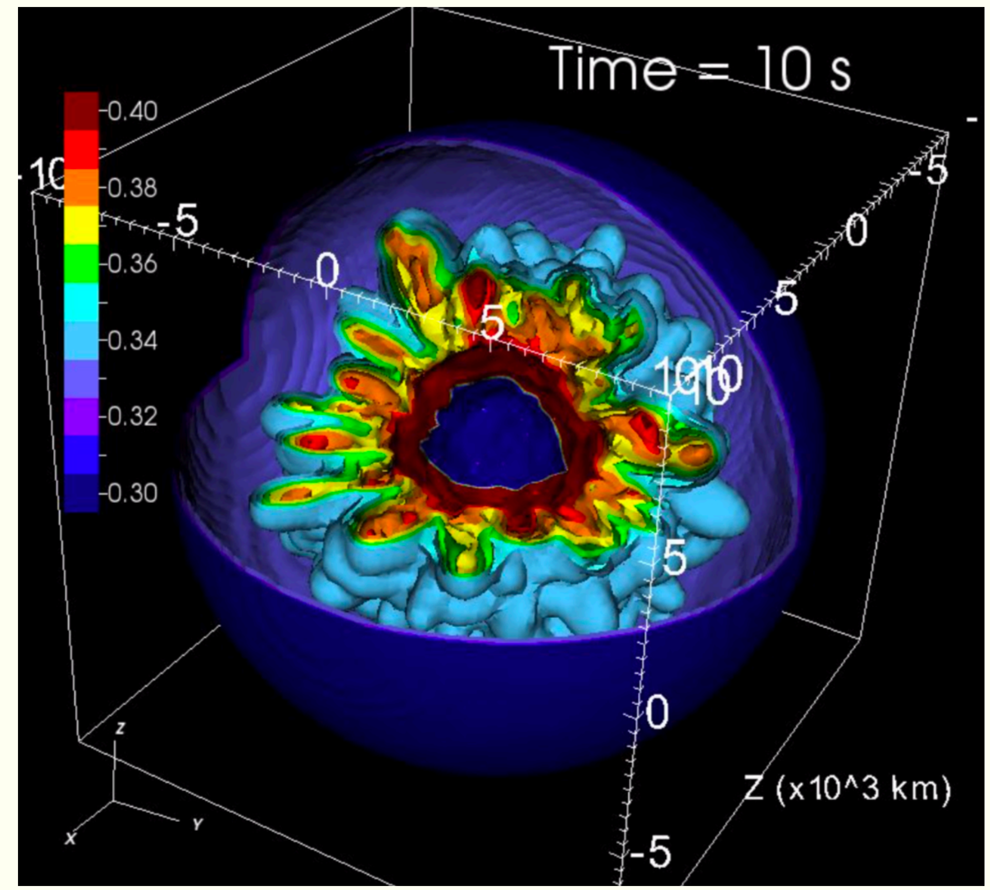
Convection

○ Multi-D hydrodynamical simulations

Yoshida, Kotake, Takiwaki, KT et al. 2019

Arnett & Meakin 2011





Multi-D simulation ⇆ 1D evolution calculation

→ find an alternative treatment of L_{conv}, D_{conv}, and D_{CBM}.

(Arnett & Meakin 2011, Jones et al. 2017, Arnett et al. 2018a, b,,,)

For the CCSN progenitor structure

→ produce more realistic initial conditions.

(Müller et al. 2016, 18, Yadav et al. 2019, Yoshida et al. 2019,,,)

→ Yoshida-san's talk.

Convection

○ **Summary**

1D treatment (MLT) is not so bad.

CBM is the most significant, but highly uncertain.

3D convection may have a key importance for the CCSN explosion.

Multi-D hydro calc is powerful and indispensable.

Furthermore, interplay among rotation, B field, and convection can be important.

Stellar rotation

○ **Stars rotate.**

-varying evolution?
-SN mechanism?
-WD/NS/BH rotation rates?

○ **Expected effects of stellar rotation**

Deformation
Mass-loss rate enhancements

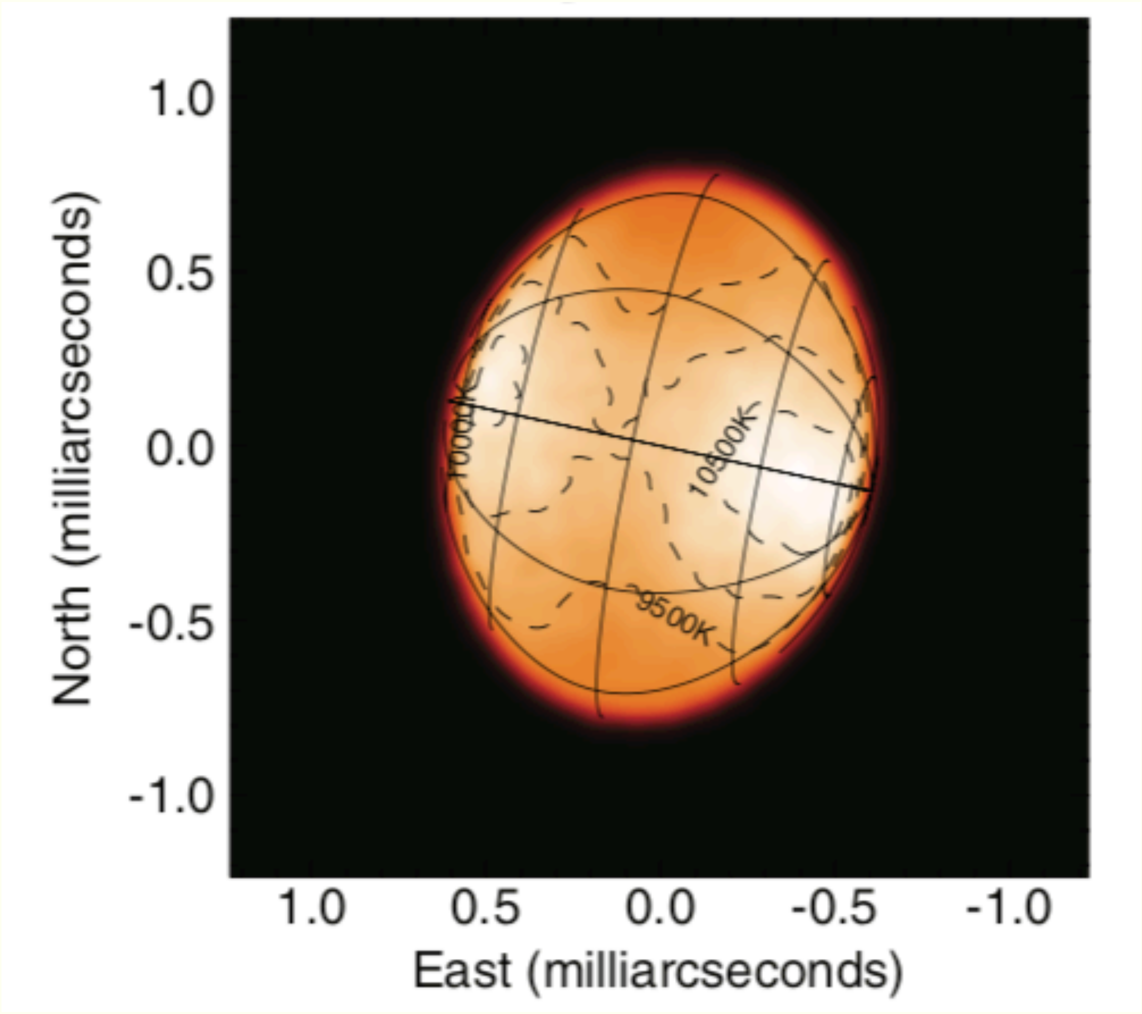
→ Due to the centrifugal force, a fast spinning star is expected to have an elongated shape and an enhanced wind mass-loss rate.

Chemical mixing due to rotation induced instabilities

Obs.:
-**surface N enhancement**
-the size of a H burning convective core

→ Several instabilities, such as Eddington-Sweet circulation Goldreich-Schubert-Fricke instability and shear instability, are proposed, which account for the additional chemical mixing.

Interferometry of α-Leo (Regulus), V_{rot} ~ 300 km s^{-1}, M = 3.8 M_{sol}: Che et al. 2011



Stellar rotation

○ 1D description of a rotating stellar structure

(Endal & Sofia 1976, Pinsonneault et al. 1989, Zahn 1992, Maeder & Zahn 1998)

-Deformation factors are incorporated.

$$\frac{\partial p}{\partial M} = -\frac{GM}{4\pi r^4}\mathbf{f_p} + \frac{1}{4\pi r^2}\frac{\partial v}{\partial t}$$

$$L_{\rm rad} = \frac{4aT^4/3}{p}\frac{4\pi cGM}{\kappa}\frac{d\ln T}{d\ln p}\frac{\mathbf{f_T}}{\mathbf{f_p}}$$

-Mass loss rate is enhanced.

$$\dot{M}(v_{\rm rot}) = \dot{M}(0) \times f_{\dot{M}_{\rm rot}}$$

-Mixing coefficient is modified.

$$D = D_{\rm cv} + D_{\rm ES} + D_{\rm GSF} + D_{\rm SH} + D_{\rm SS} + D_{\rm DS} + \dots$$

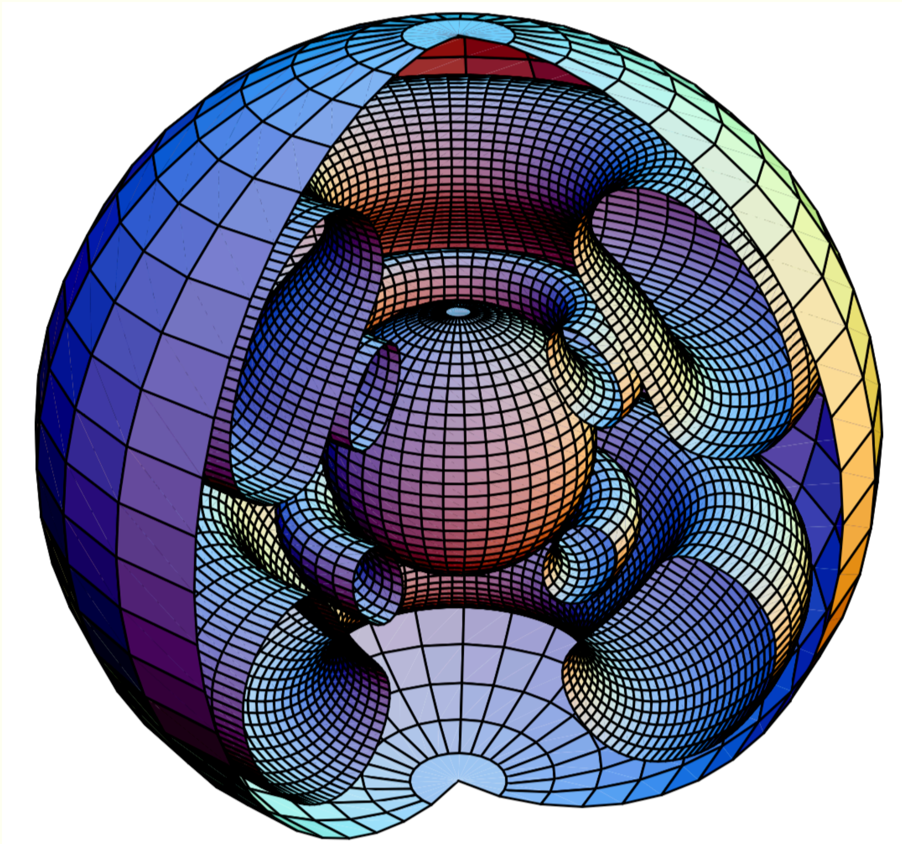
→ **the estimates of Ds are extremely uncertain!**

(semi-)empirical way of the estimate

-construct a phenomenological model

-calibration with observation **assuming N enhancement is due to rot. mixing.**

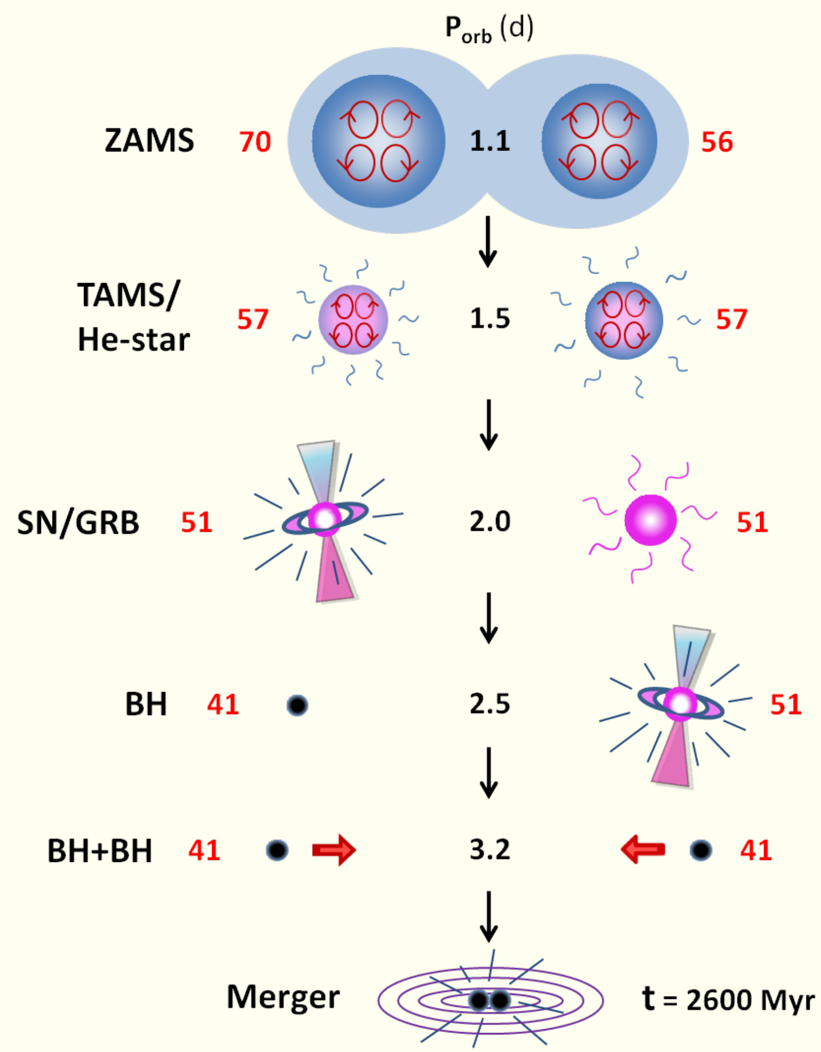
Streamline of the Eddington-Sweet circulation
Maynet & Maeder 2002



Stellar rotation

○ Chemically homogeneous evolution

Fast enough rotation may allow the star to evolve chemically homogeneously.



-retaining angular momentum
→ **GRB/SN Ibc progenitors**

(Yoon & Langer 2005, Woosley & Heger 2005, Aguilera-Dena et al. 2018)

-restrained radius → **Binary BH progenitors**

(Mandel & de Mink 2016, Marchant et al. 2016)

○ Changing nucleosynthesis in the early universe

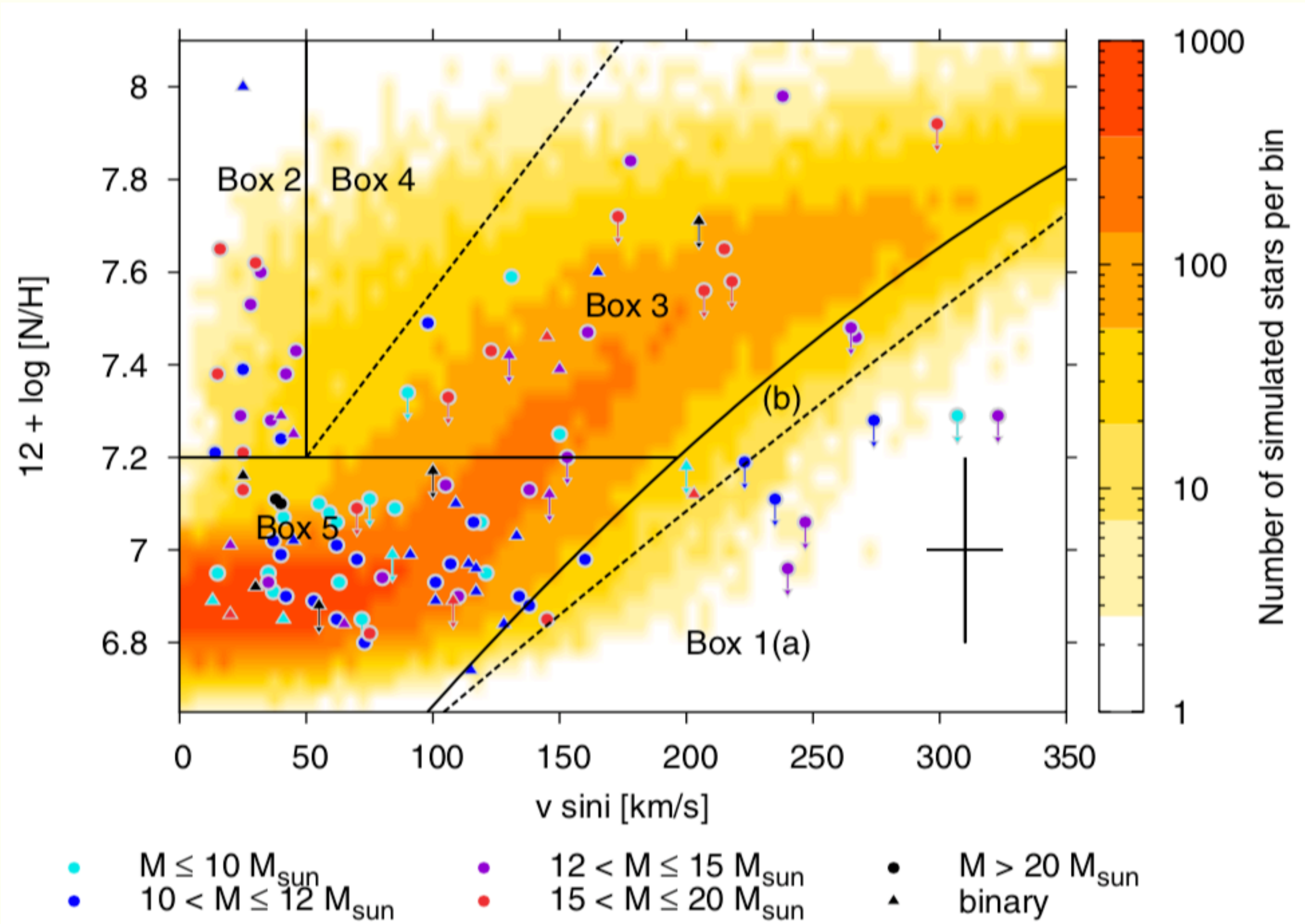
Nucleosynthesis at the H & He burning shells is boosted to yield C, N, O, Na, Mg, Al, as well as s-process elements.

(Meynet et al. 2010, KT+14, Frischknecht et al. 2016, Choplin et al. 2016, 2017)

Stellar rotation

○Rotation induced mixing, or not.

N enhancement vs v sini compared with theoretical models for LMC B/O type stars: Brott et al. 2011, Rivero González et al. 2012



-[N/H] correlates with v sin i (3).

+ N enhancement is stronger for more massive stars

→ comparable with theoretical prediction

Meanwhile, there are other populations.

-slowly rotating N enhanced stars (2)

-fast rotating N normal stars (1).

→ In addition to rotational mixing, other enrichment processes will be decisive.

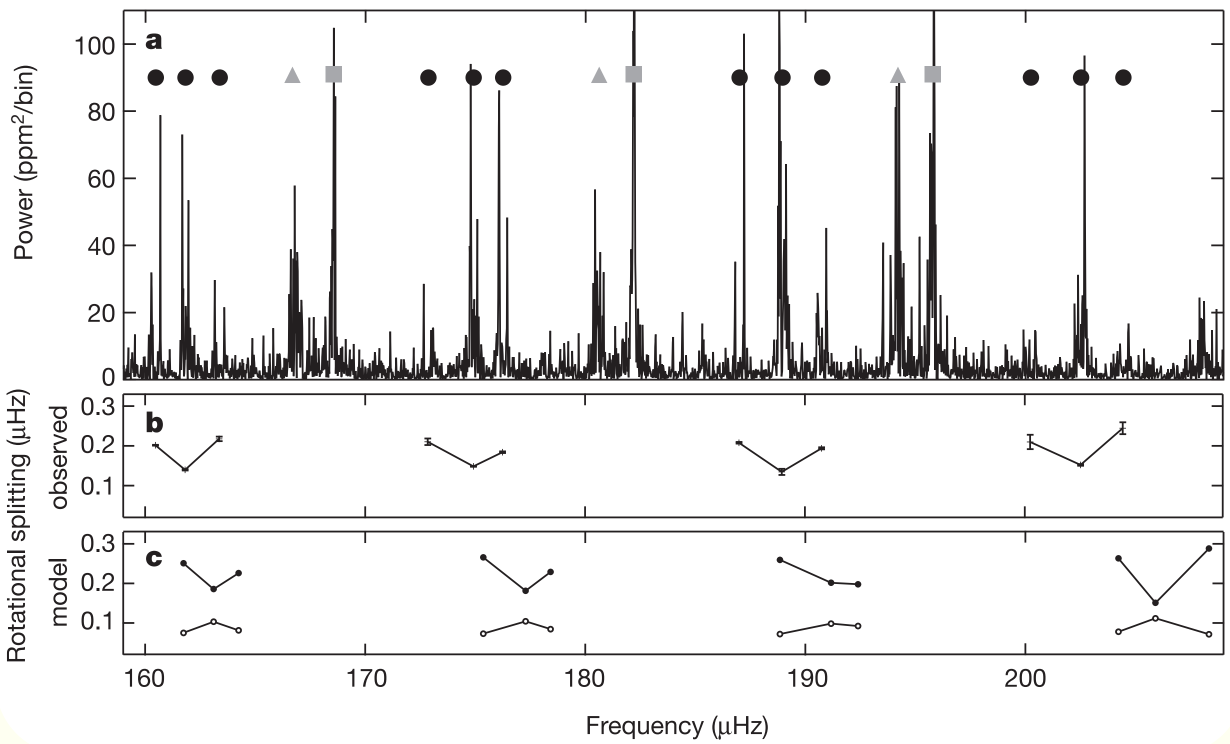
-However, a star can be represented by numbers of parameters… (e.g., Aerts et al. 2014)

Stellar rotation

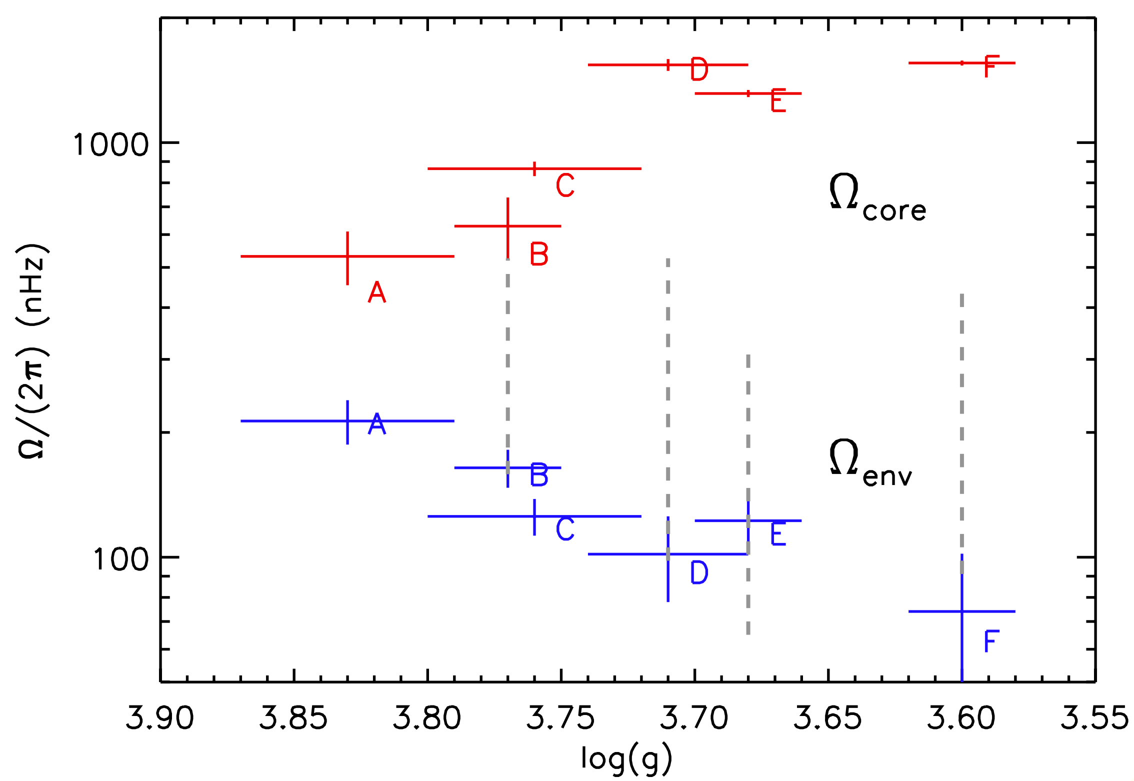
○ **Spin rate of red giant cores**

-RG cores spin up (Beck+12, Mosser+14)
-The rotation periods are far less than predictions (>~100).
-Efficient AM transfer is required. (Cantiello et al. 2014, Eggenberger et al. 2017)

Beck et al. 2012: rot splitting in oscillation spec.



Deheuvels et al. 2014: RG core/surface rotations



→ Possibly **the magnetic stress**?

Or internal gravity wave?

Convection

○ **Summary**

-1D treatment (MLT) is not so bad.

-CBM is significant, but highly uncertain.

-3D convection may have a key importance for the CCSN explosion.

-Multi-D hydro calc is powerful and indispensable.
Furthermore, interplay among rotation, B field, and convection would be important.

Rotation induced mixing is crucial, if exists.

Additional mixing due to other mechanisms would be decisive as well.

Efficient mechanism(s) of angular momentum transfer exists.

Stellar magnetism

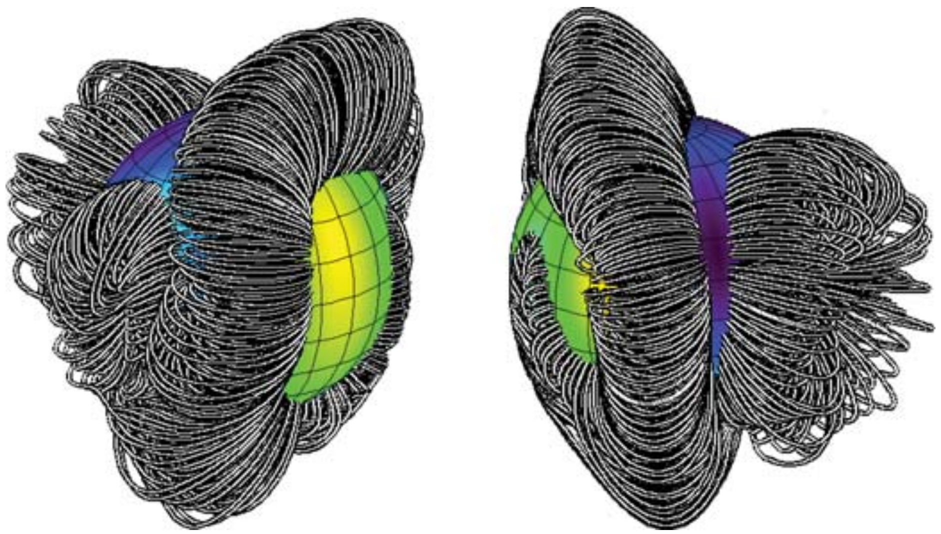
○ **magnetic field of Ap/Bp stars**

-Chemically peculiar A/B type stars
with enhancements in Sr, Cr, Eu, etc.

-**~10%** of all A/B type stars

-**Strong surface magnetic fields** are detected
from nearly all of the Ap stars.
(Badcock 1947,58; Landstreet 1992)

Field geometry of the B0 star τ Sco



(Donati et al. 2006)

Obs: The surface magnetic field in a radiative star is in a stable structure.
-large scale structure ~dipole, quadrupole
-stability with a long timescale ~10 yr
-**Massive O type stars also show similar field properties.**

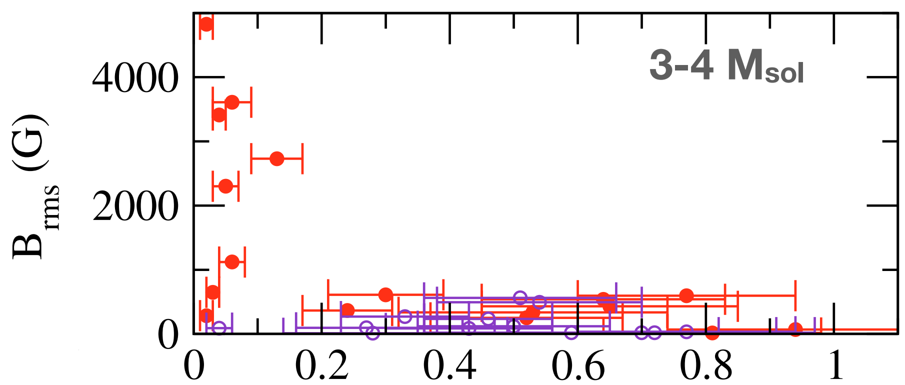
→ progenitor of **magnetars/magnetized WDs** ?

→ origin of **slowly-rotating N-enhanced stars/efficient AM transport** ?

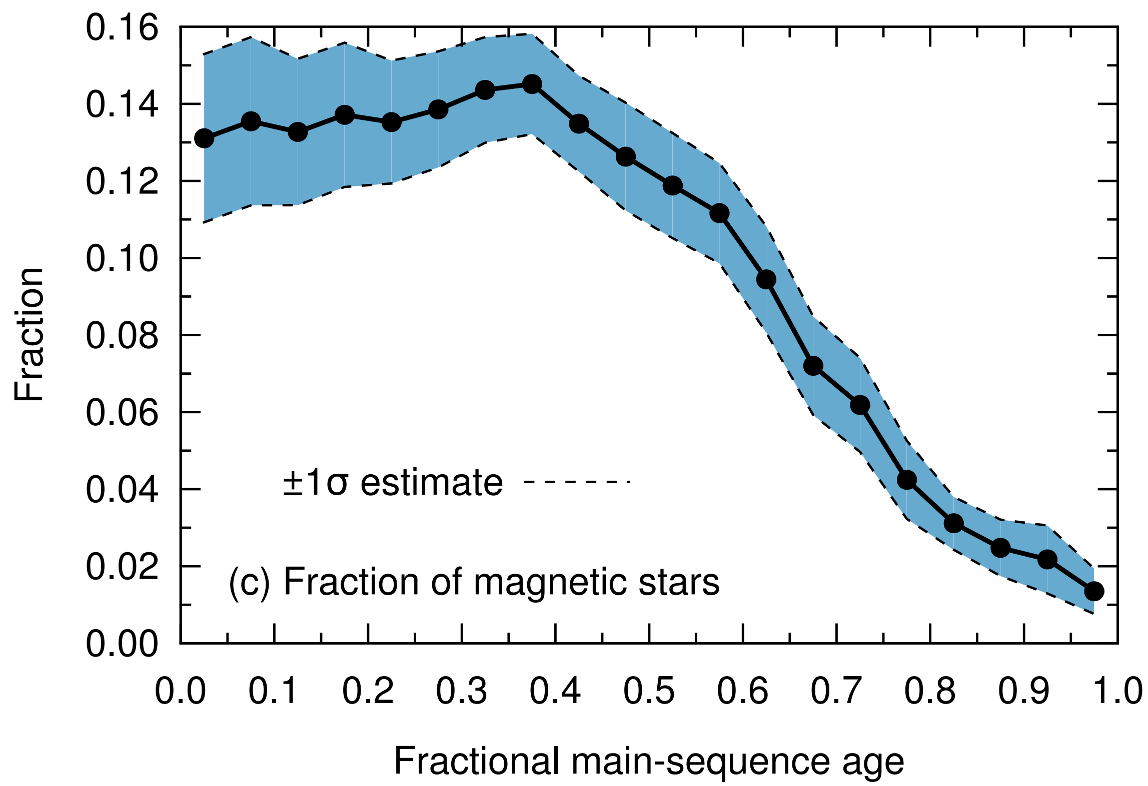
Stellar magnetism

○ **Observations indicating magnetic field evolution**

Rapid decline in the early MS phase?: Landstreet+08



Fraction decrease in OB stars: Fossati et al. 2016



→ **indication of magnetic dissipation?**

○ **Expected effects of stellar magnetism**

Internal AM transfer

by the magnetic stress

Magnetic stress is one of the leading idea
to explain the slow RG core rotation.

Wind-magnetic field interaction

-wind confinement leading to form
a rigidly rotating magnetosphere
-magnetic breaking

○ Requirement for the global theory

Most ‘magnetic’ stellar evolution calculations so far apply **local** **&** **time-independent** **theories** for the description of the magnetic fields.

Tayler-Spruit dynamo:
-Maeder & Meynet 2003,04,05
-Heger et al. 2005
-Denissenkov & Pinsoneault 2007
-Fuller et al. 2019

Convection inhibition:
-Petermann et al. 2015

Magnetic breaking:
-Meynet et al. 2011

Wind confinement:
-Petit et al. 2017
-Georgy et al. 2017
-Keszthelyi et al. 2019

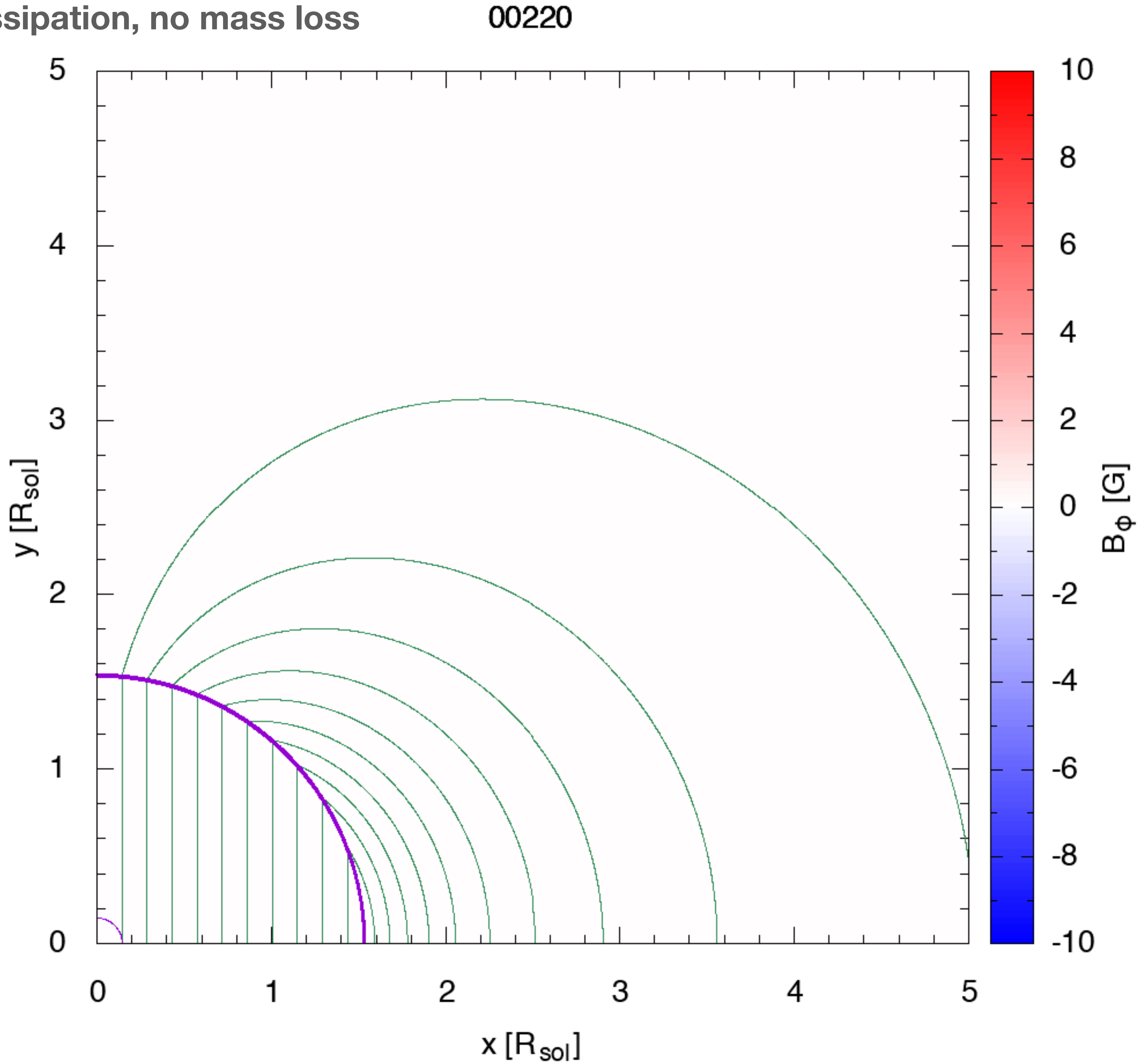
→ **Global & time-dependent prescription is demanded for progenitor evolution calculation.**

cf. Potter et al. 2012

- Field evolution obtained by our code

Reconstructed 2D field evolution of a 1.5 M_{sol} main sequence star

no dissipation, no mass loss



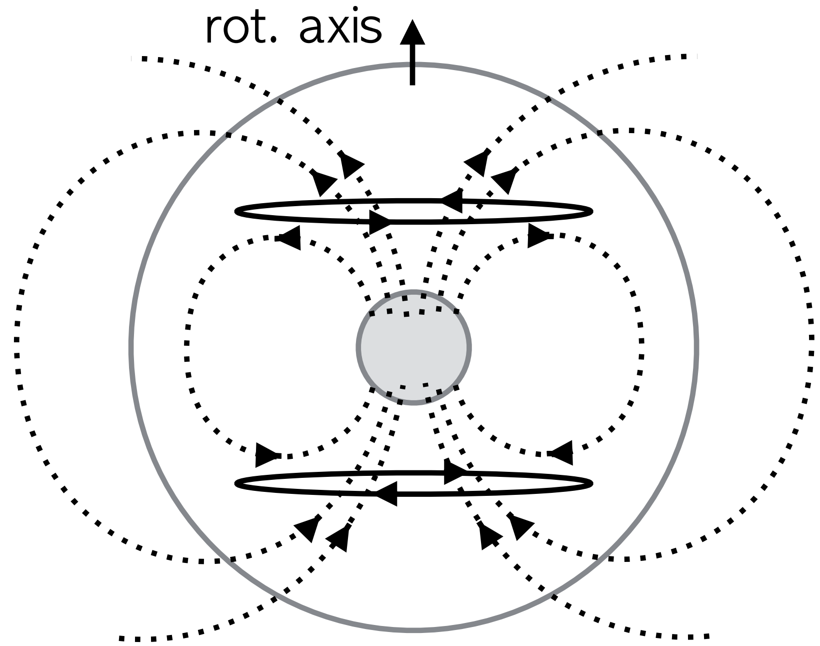
○ A novel modeling of the magneto-rotating stellar evolution

KT & Langer, in prep

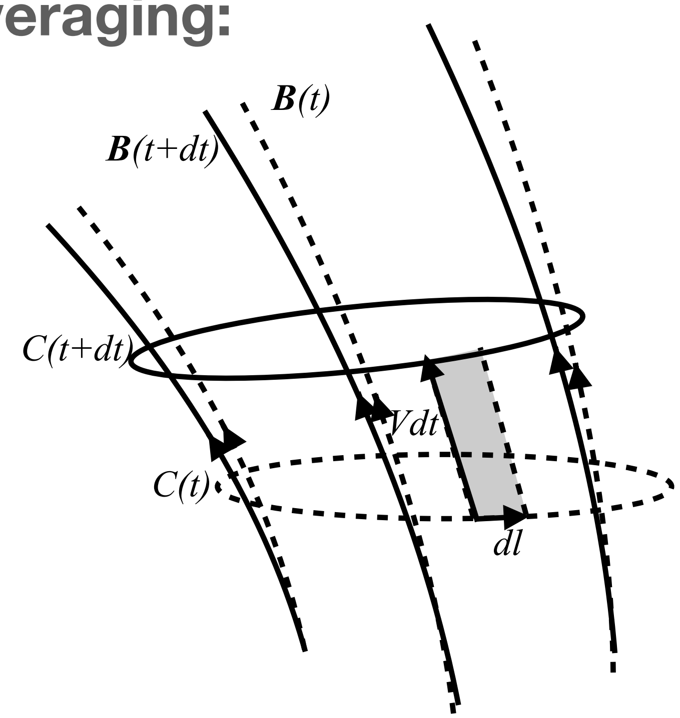
Field configuration:

$$\boldsymbol{B}_{\rm tor} = B_\phi(r,\theta)\boldsymbol{e}_\phi,$$
$$B_\phi(r,\theta) = B(r)\sin 2\theta.$$

$$\boldsymbol{B}_{\rm pol} = \nabla\times\boldsymbol{A}_{\rm tor},$$
$$A_\phi(r,\theta) \equiv A(r)\sin\theta,$$
$$B_r(r,\theta) = \frac{2A}{r}\cos\theta$$
$$B_\theta(r,\theta) = -\frac{\sin\theta}{r}\frac{\partial(Ar)}{\partial r}.$$



1D averaging:



Flux eq. + induction eq.:

$$\frac{\mathrm{d}\Phi_C}{\mathrm{d}t} = \int_C (\nabla\times(\boldsymbol{U}\times\boldsymbol{B}) - \nabla\times(\eta\nabla\times\boldsymbol{B}) + \nabla\times(\alpha\boldsymbol{B}))\cdot\mathrm{d}\boldsymbol{S}$$

For the poloidal component,

$$\frac{d(Ar)}{dt} = \eta r\frac{\partial}{\partial r}\left(\frac{1}{r^2}\frac{\partial}{\partial r}(Ar^2)\right) + r(\alpha\boldsymbol{B})_\phi(\theta=\pi/2).$$

For the toroidal component,

$$\frac{d}{dt}\left(\frac{Br}{r^2\rho}\right) = \frac{1}{r^2\rho}\left(Ar\frac{\partial\Omega}{\partial r} + \eta r\frac{\partial}{\partial r}\left(\frac{1}{r^2}\frac{\partial}{\partial r}(Br^2)\right) + r\frac{\partial\eta}{\partial r}\frac{\partial Br}{\partial r} - \alpha r\frac{\partial}{\partial r}\left(\frac{1}{r^2}\frac{\partial}{\partial r}(Ar^2)\right) - r\frac{\partial\alpha}{\partial r}\frac{\partial Ar}{\partial r}\right)$$

Stellar magnetism

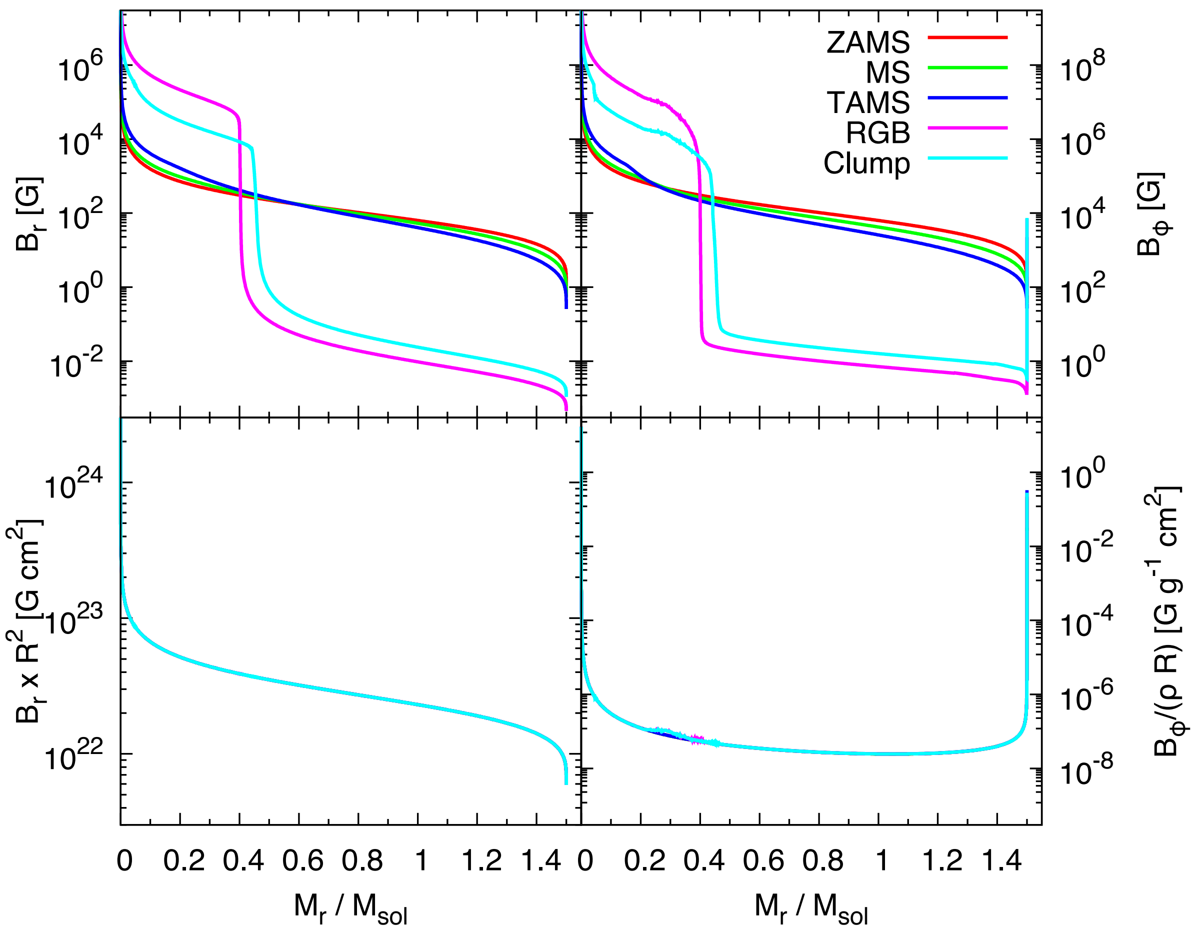
○ code test

→ The code can follow

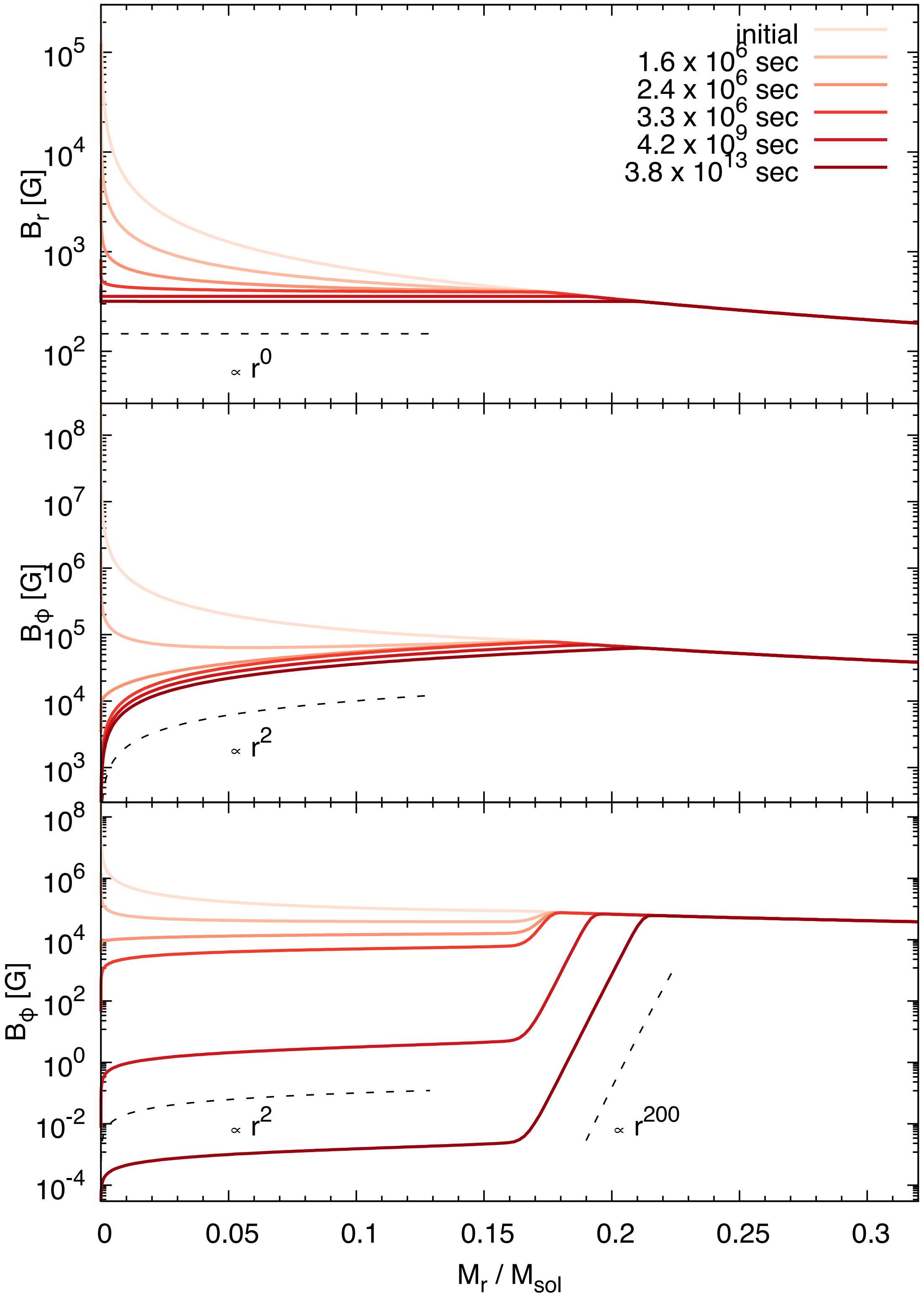
-B flux conservation

-B dissipation

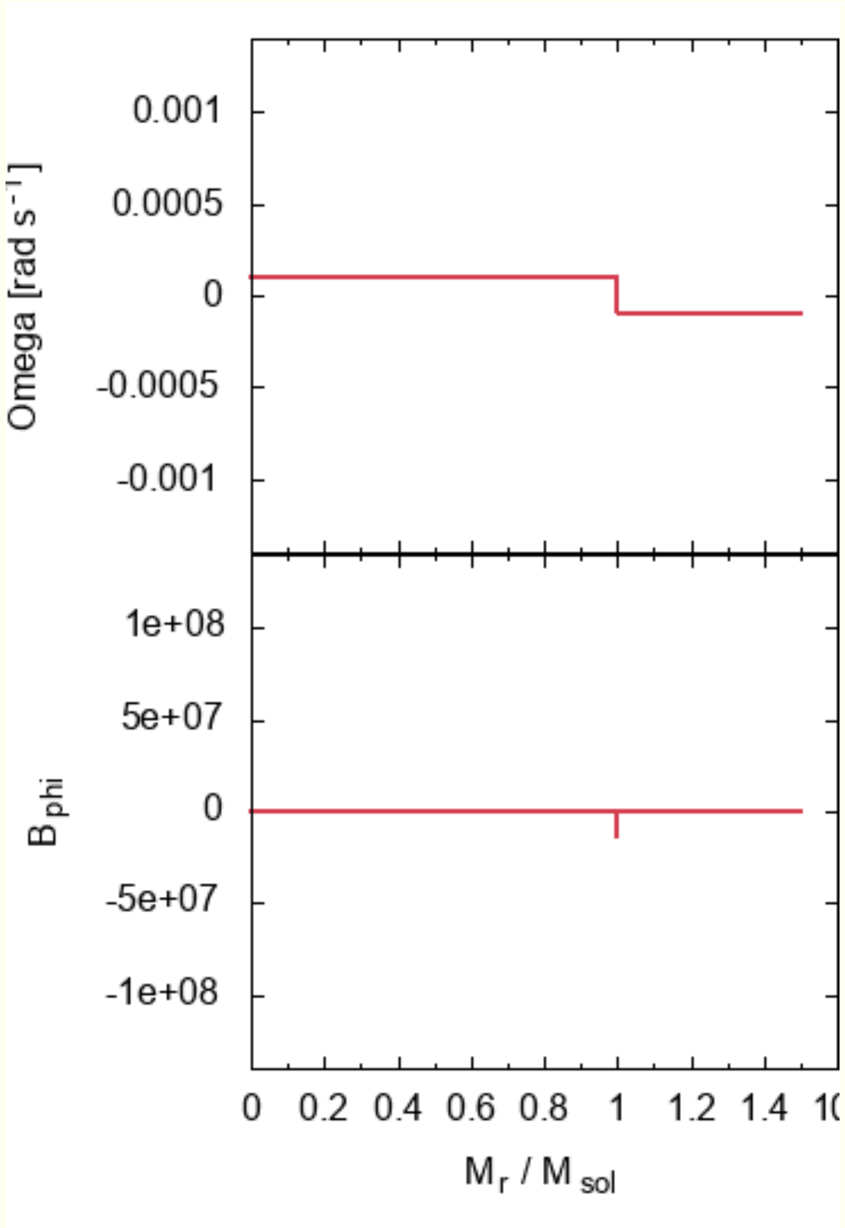
Magnetic flux conservation



Magnetic dissipation KT & Langer, in prep



KT & Langer, in prep



○ **wave solution**

The basic equation can be simplified into a hyperbolic equation of

$$\frac{\partial (Br^3)}{\partial t} = \frac{B_r r^4}{2}\frac{\partial \Omega}{\partial r}$$ **: Ω effect**

$$\frac{\partial \Omega}{\partial t} = \frac{B_r}{10\pi\rho r^4}\frac{\partial (Br^3)}{\partial r},$$ **: Magnetic stress**

which has a set of eigenvalue and eigenvector of

$$\pm c \equiv \frac{1}{\sqrt{5}} v_A \text{ and } \boldsymbol{r}^\pm = (1 \ \ \sqrt{5\pi\rho r^4})^t.$$

Here, $v_A \equiv B_r/\sqrt{4\pi\rho}$ is the Alfvén velocity

→ **Dissipating Alfvén's wave transfers angular momentum efficiently.**

This phenomena can only be acquired by the global & time-dependent modeling of the magneto-rotating star.

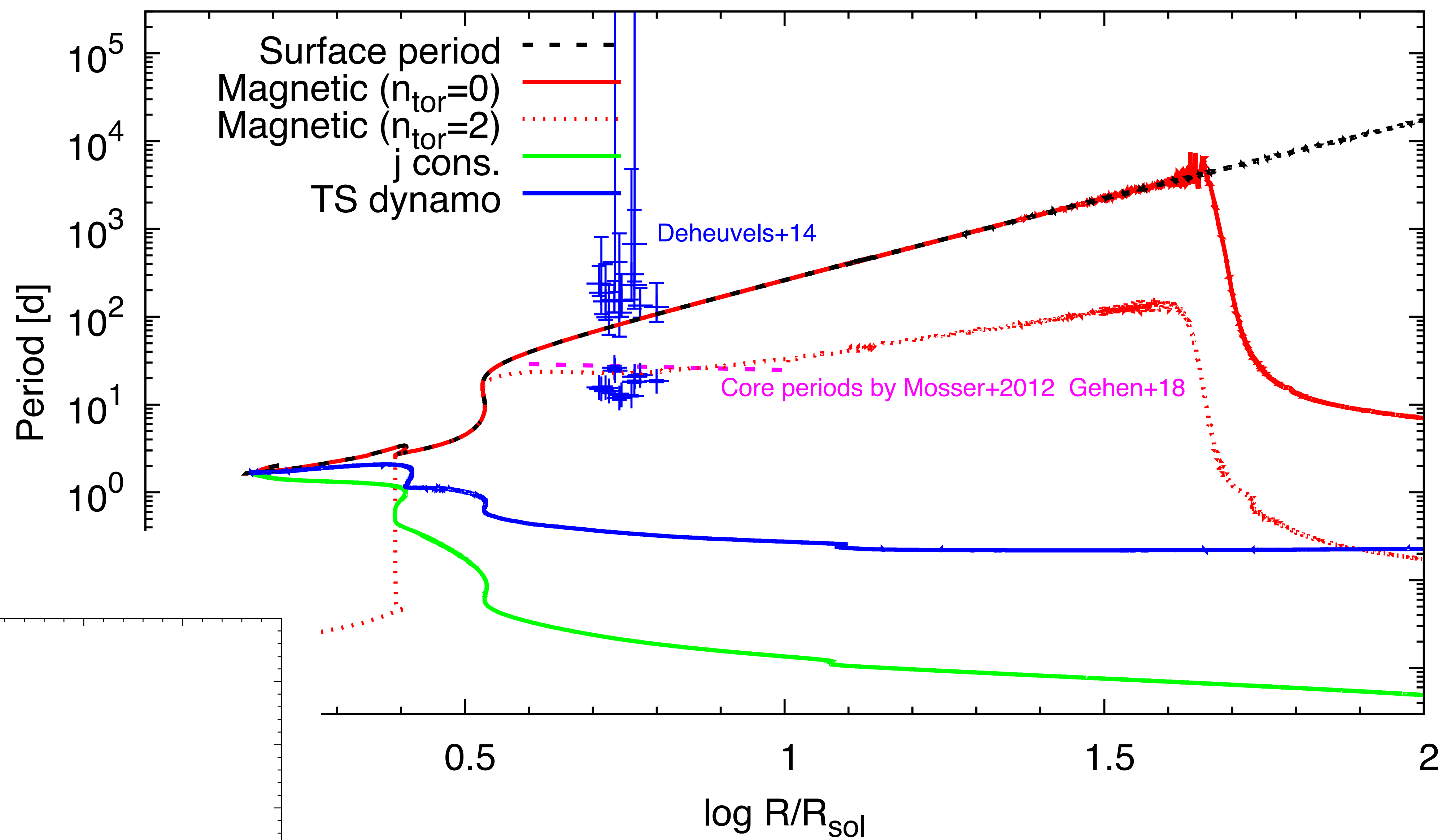
⇆ **Tayler-Spruit dynamo (Spruit 1998, 2002, Fuller et al. 2019)**

Stellar magnetism

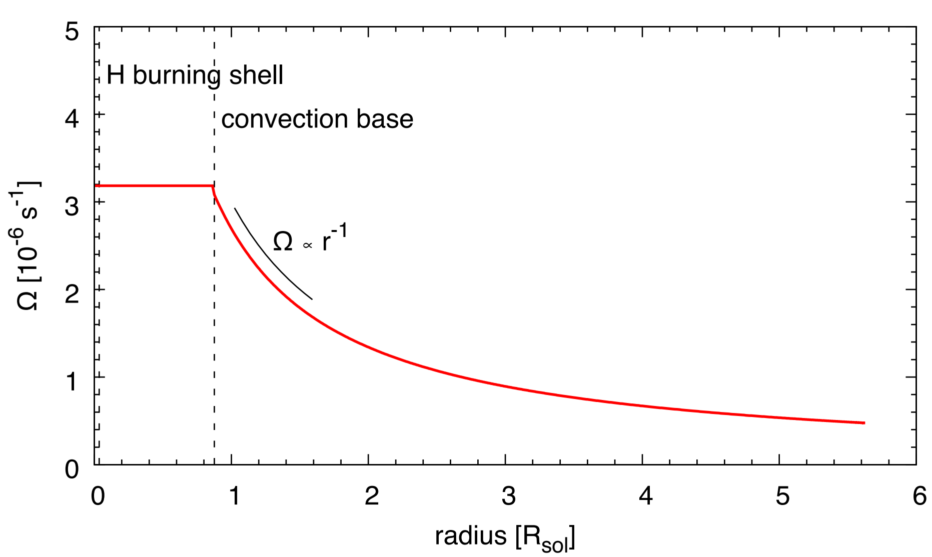
convective AM transport
n_{cv} = **0**: rigid body rotation
= **2**: iso-j

$$\frac{\partial}{\partial t}(i\Omega) = \frac{\partial}{\partial M}\left((4\pi\rho r^2)^2 \nu_{\rm cv} i r^{-n_{\rm cv}} \frac{\partial(\Omega r^{n_{\rm cv}})}{\partial M}\right) + \frac{\partial}{\partial M}\left((4\pi\rho r^2)^2 \nu_{\rm eff} i \frac{\partial\Omega}{\partial M}\right) + \frac{\partial}{\partial M}\left(\frac{8r^2AB}{15}\right)$$

Evolution of surface/core rotation periods



Ω distribution

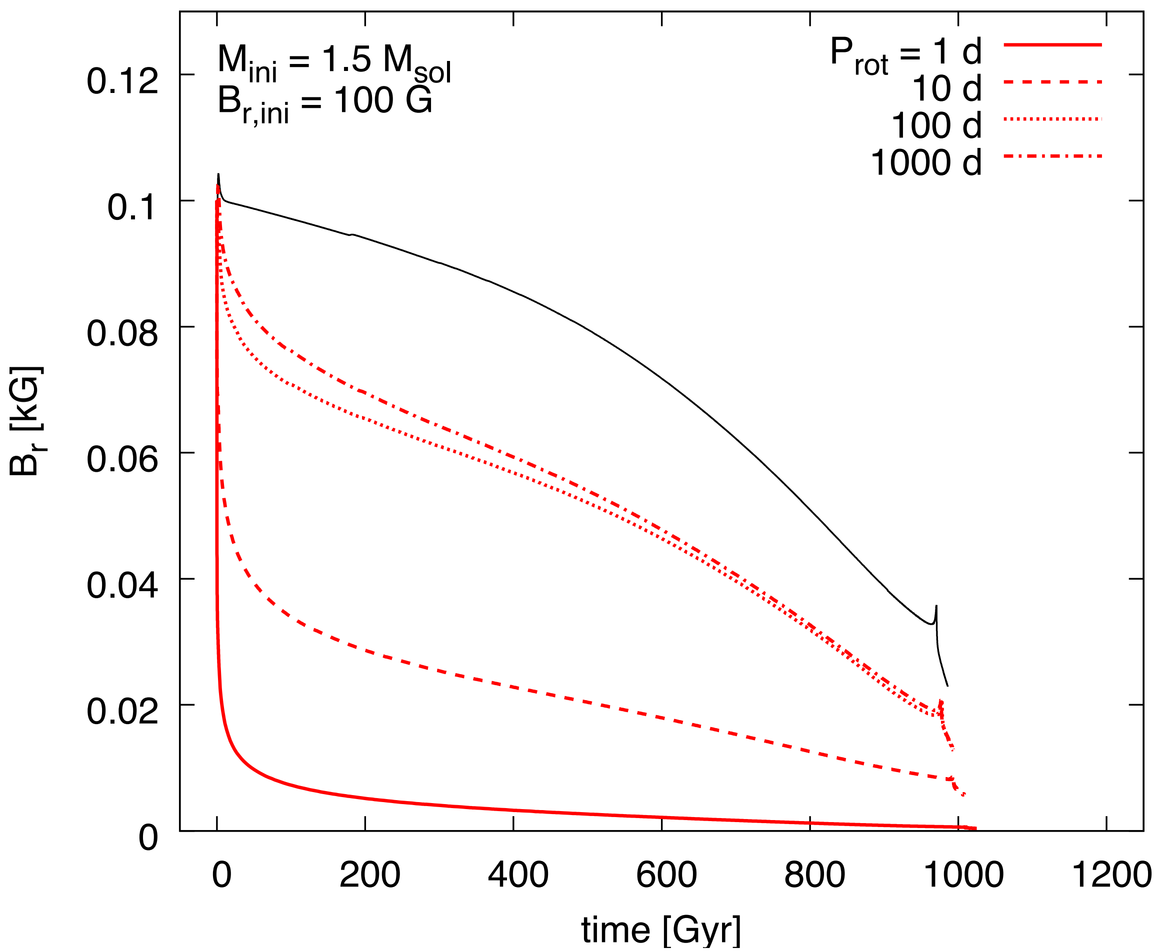


○ Observables

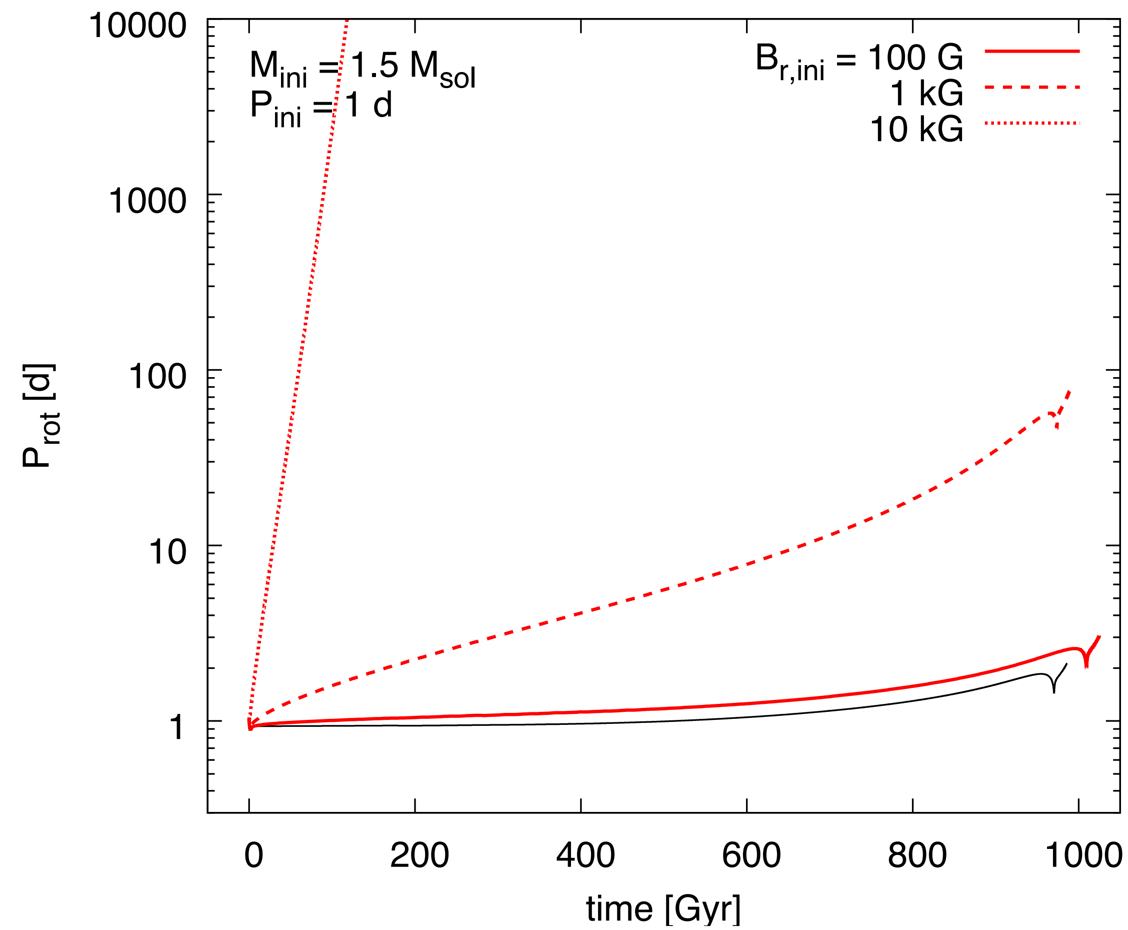
KT & Langer, in prep

First theoretical model comparable to surface magnetic field observations

Surface B field evolution



Rotation period evolution



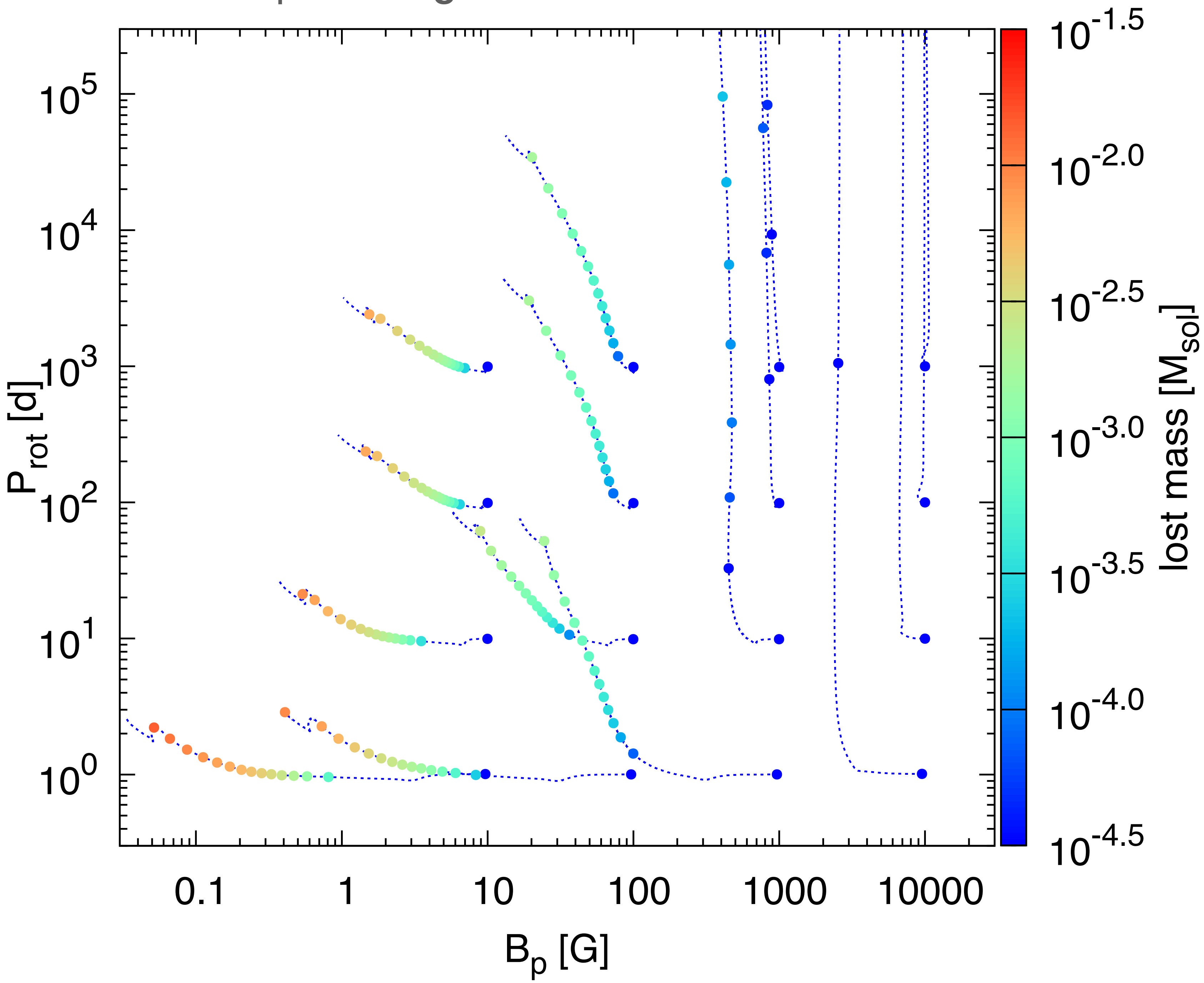
The surface magnetic dissipation rate correlates with the rotation rate.
→ **Magnetic dissipation due to rotation induced turbulence**

The rotation period correlates with the surface magnetic field strength.
→ **Magnetic breaking is also important.**

○ **Observables**

KT & Langer, in prep

Evolution in B_p-P_{rot} diagram for 1.5 M_{sun} model



→ **Magneto-rotating model expects** **divergent evolution** **even with a given single initial mass!**

Stellar magnetism

○ Summary

-1D treatment (MLT) is not so bad.
-CBM is significant, but highly uncertain.
-3D convection may have a key importance for the CCSN explosion.
-Multi-D hydro calc is powerful and indispensable.
Furthermore, interplay among rotation, B field, and convection would be important.

-Rotation induced mixing is crucial, if exists.
-Additional mixing due to other mechanisms would be decisive as well.
-Efficient mechanism(s) of angular momentum transfer exists.

Magnetic effects can be influential for the evolution as well.

Global & time-dependent theory is demanded.

Our new model yields results comparable to many observations.

Soon be applied for massive star evolution.

Conclusion

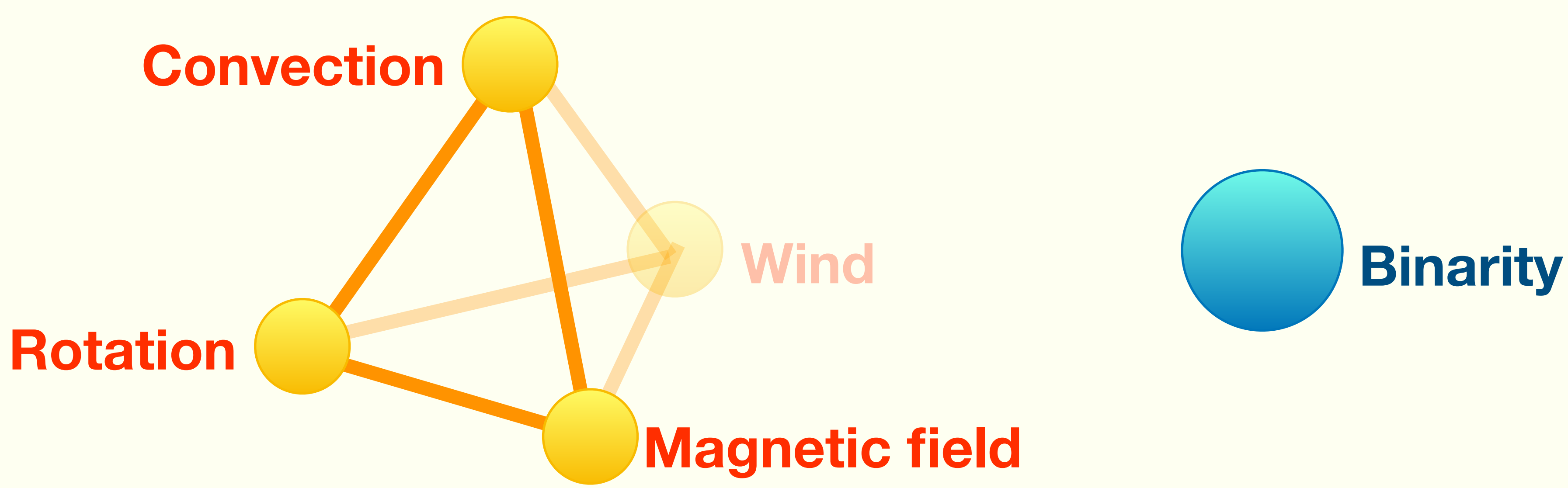
○ **All at once**

Stellar evolution simulation needs to be complex

to account for complicated observations.

-convective boundary mixing … wide MS width, late time activities
-rotation induced mixing … N enhancement
-magnetic field … rigidly rotating magnetosphere, internal AM transfer

Convection, rotation, and magnetic field **affect** and **depend on each other**.



→ **Fit all the data at once to disentangle the complex causality relations!** **Evolution simulations including *everything* is required, and it's coming!**

and don't forget about stellar wind & binary