

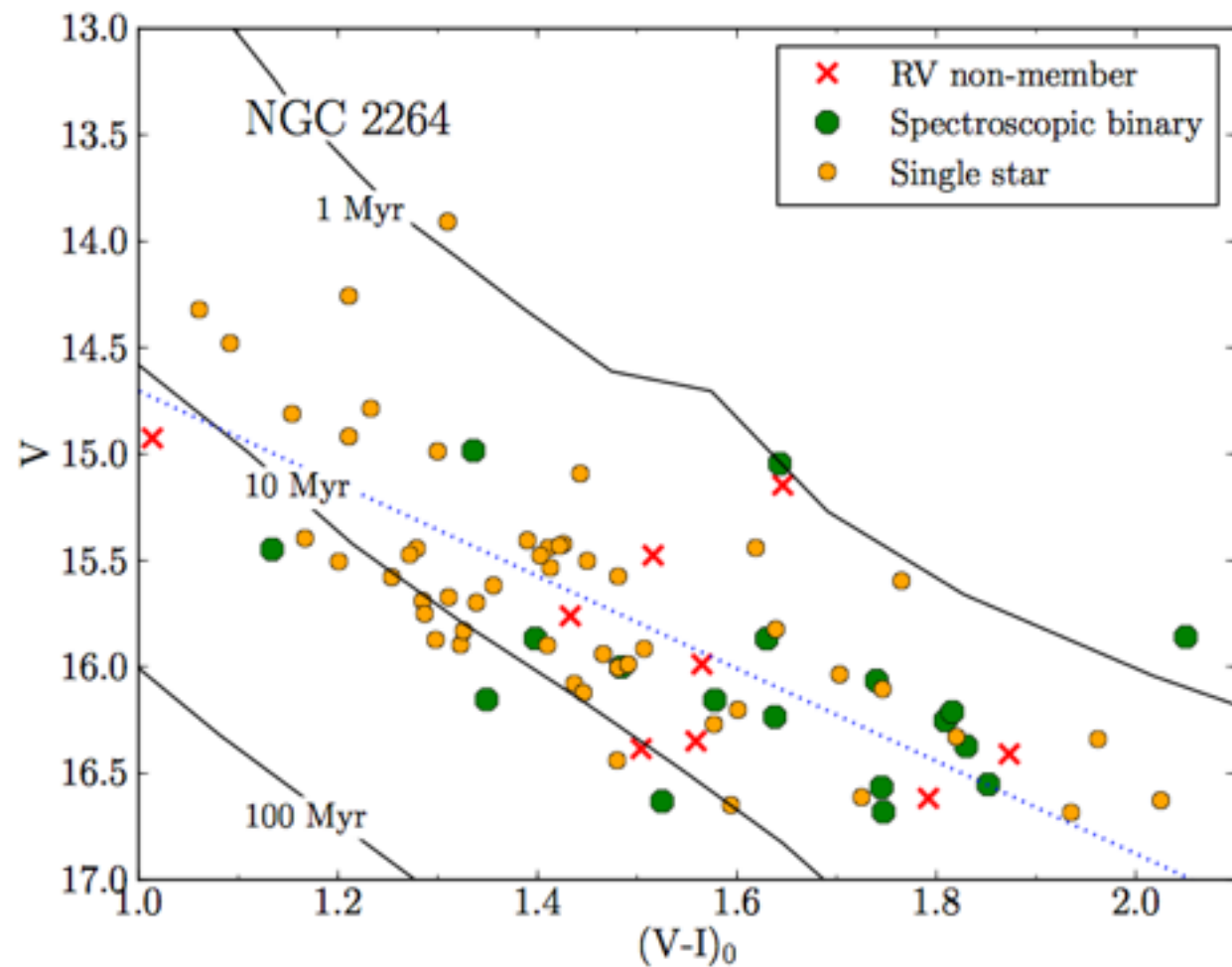
New Approaches to the Evolution of Young Low Mass Stars and Brown Dwarfs:

Consistent Models of Accretion History and Multi-Dimensional Structure of Accreting Young Stars

I. Baraffe
University of Exeter - CRAL Lyon

I) What observations tell us

- Spread in the HRD:



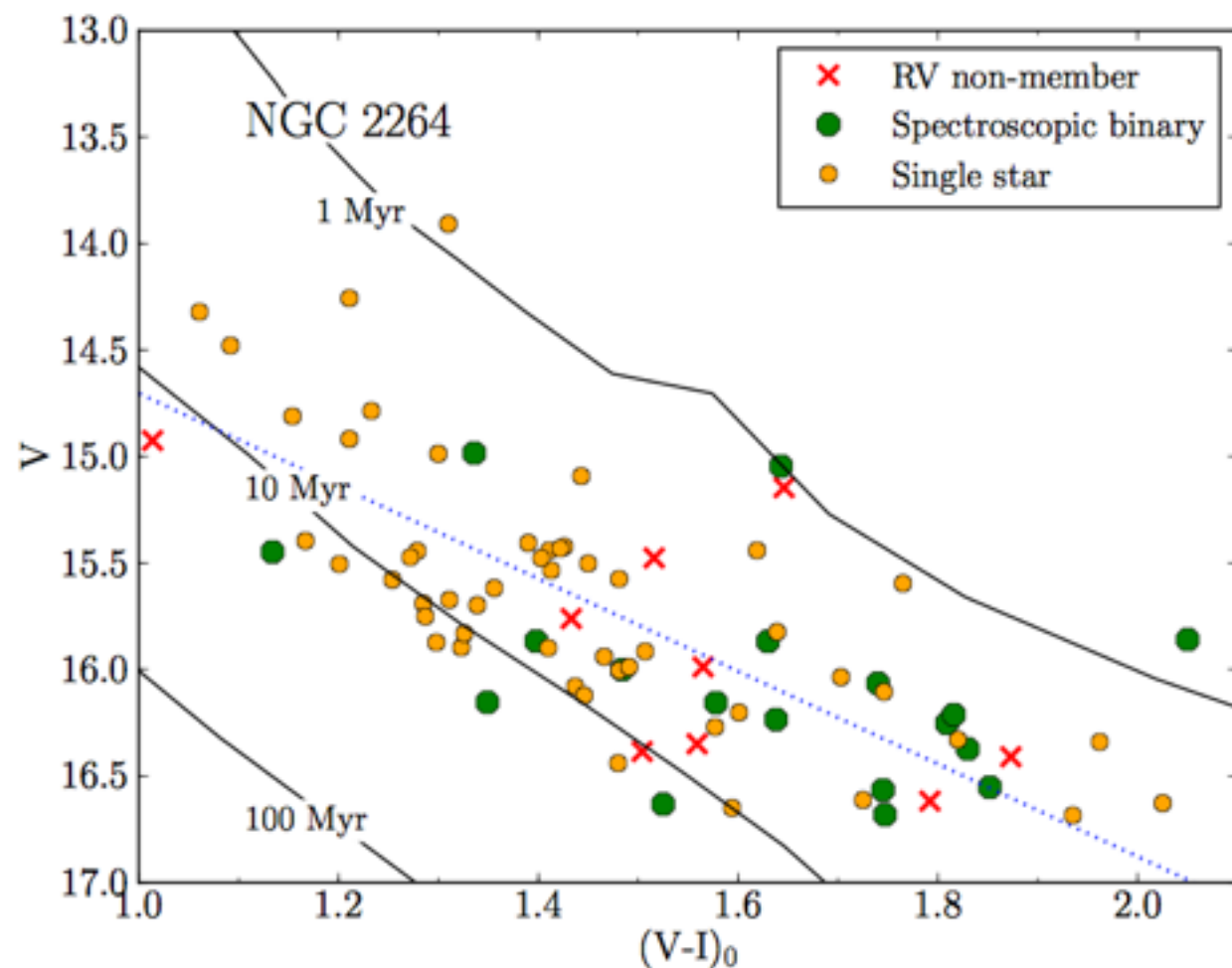
Well known problem: spread in T_{eff} - L or Color-Magnitude diagrams of young cluster members (1-10 Myr)

➔ **Age spread?**

Sergison et al. 2013

I) What observations tell us

• Spread in the HRD:



Well known problem: spread in T_{eff} -L or Color-Magnitude diagrams of young cluster members (1-10 Myr)

➔ **Age spread?**

Sergison et al. 2013

• Lithium depletion

(1) Large lithium scatter and some anomalous Li depletion in young cluster members of a few Myr old

(Kenyon et al. 2005; Sacco et al. 2007, 2008; Prizinsano et al. 2007)

(2) Lithium-rotation connection in NGC2264 (~ 5 Myr) *Bouvier et al. 2016*

Li-excess in fast rotators compared to slow ones!

II) What we (modellers) suggest....

1) Early episodic accretion could explain these observations (and others)
(Baraffe et al. 2009; Baraffe & Chabrier 2010; Baraffe et al. 2012)

II) What we (modellers) suggest....

1) Early episodic accretion could explain these observations (and others) (Baraffe et al. 2009; Baraffe & Chabrier 2010; Baraffe et al. 2012)

- Using accretion rates from collapse simulations of prestellar cores:
 $M_c = 0.061 M_\odot - 1.85 M_\odot$
- Assuming “cold” and “hot” accretion
 $\alpha = 0 - 20\%$
(deposit of accretion energy $\alpha G M \dot{M} / R$)

II) What we (modellers) suggest....

1) Early episodic accretion could explain these observations (and others) (Baraffe et al. 2009; Baraffe & Chabrier 2010; Baraffe et al. 2012)

- Using accretion rates from collapse simulations of prestellar cores:
 $M_c = 0.061 M_\odot - 1.85 M_\odot$
- Assuming “cold” and “hot” accretion
 $\alpha = 0 - 20\%$
(deposit of accretion energy $\propto GM\dot{M}/R$)

→ Early accretion ($\ll 1$ Myr) can produce a **luminosity spread** (not an age spread)
at $t > 1$ Myr

- **More consistent approach: Coupling** between collapse simulations of pre-stellar cores and disk evolution (Vorobyov & Basu) and central object evolution (Baraffe & Chabrier)

- Consistent accretion rates

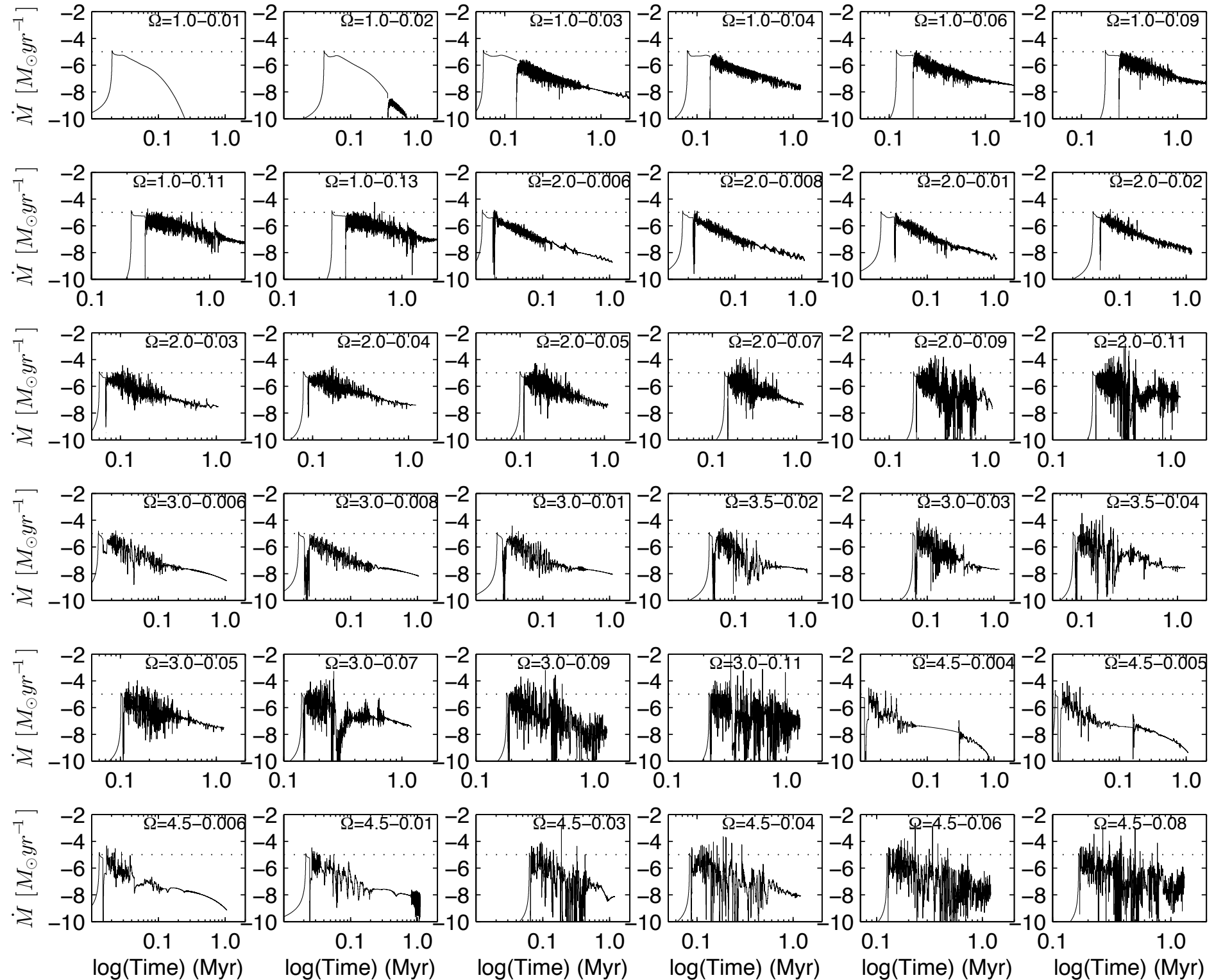
- Consistent feedback of protostar luminosity on disk

- **More consistent approach: Coupling** between collapse simulations of pre-stellar cores and disk evolution (Vorobyov & Basu) and central object evolution (Baraffe & Chabrier)

➡ Consistent accretion rates

➡ Consistent feedback of protostar luminosity on disk

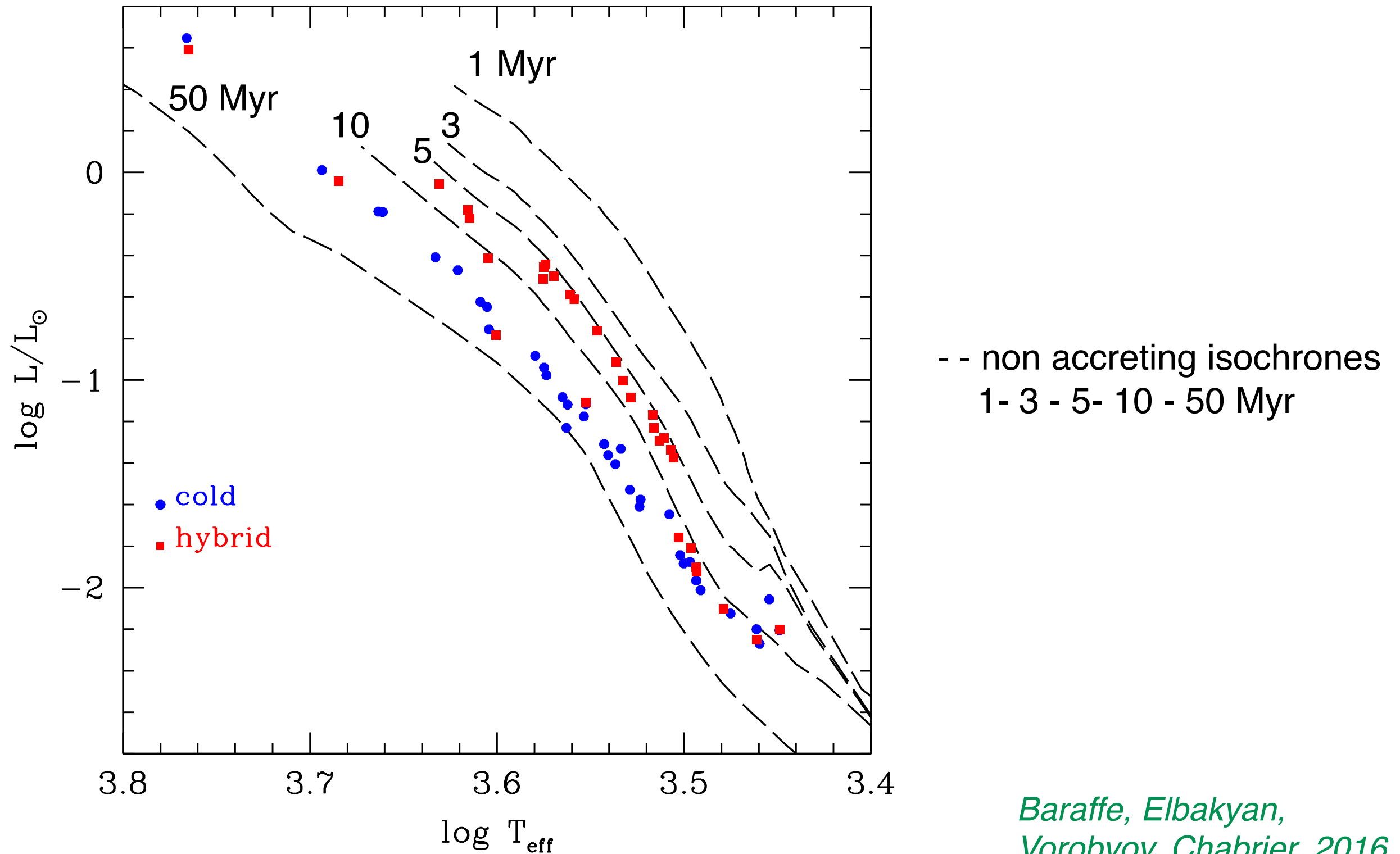
Survey of parameter space to produce objects of final mass
 $\sim 0.04 M_{\odot} - 1.4 M_{\odot}$



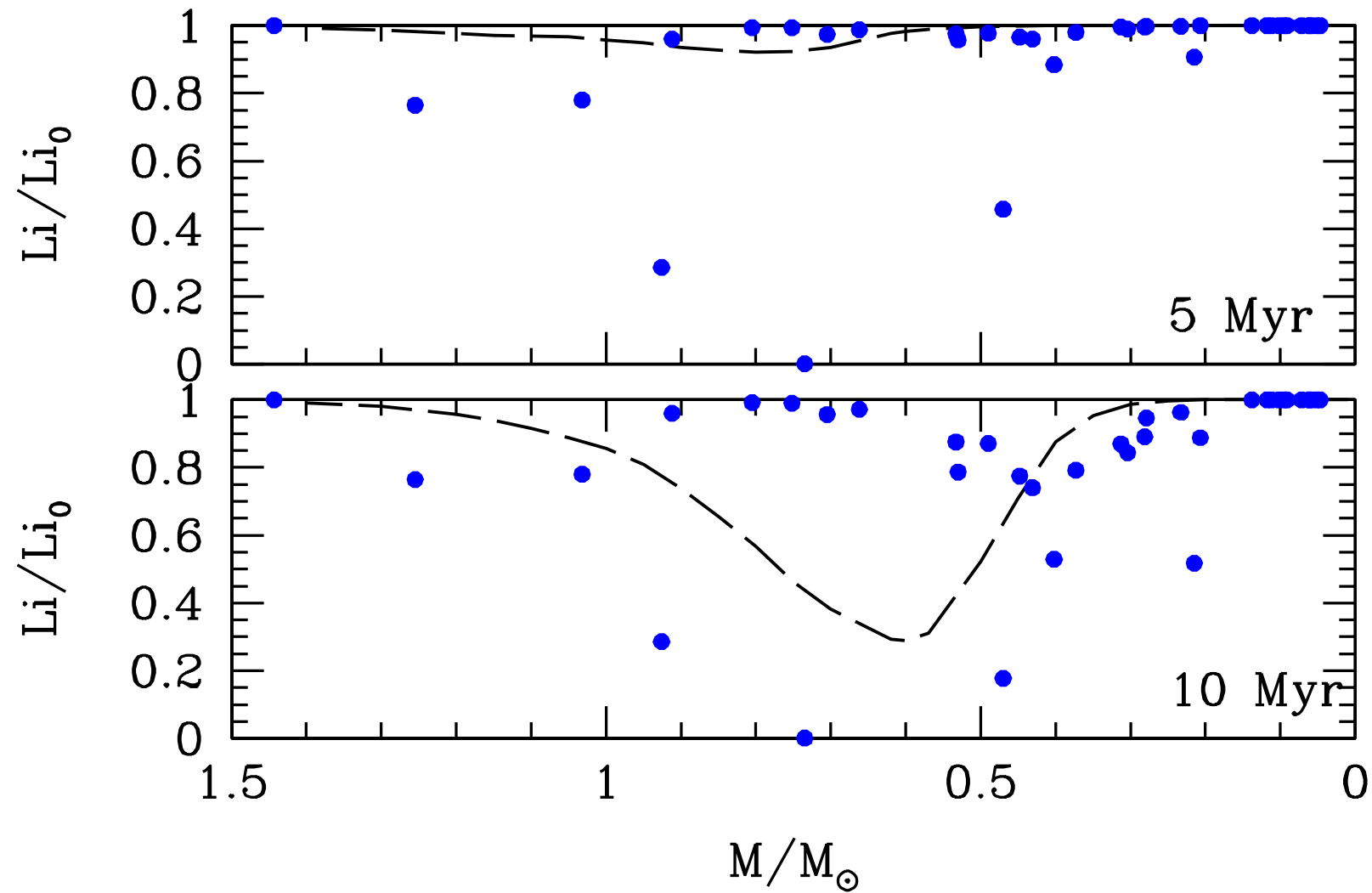
*Baraffe, Elbakyan,
 Vorobyov, Chabrier, 2016*

☞ Confirms spread in the HRD

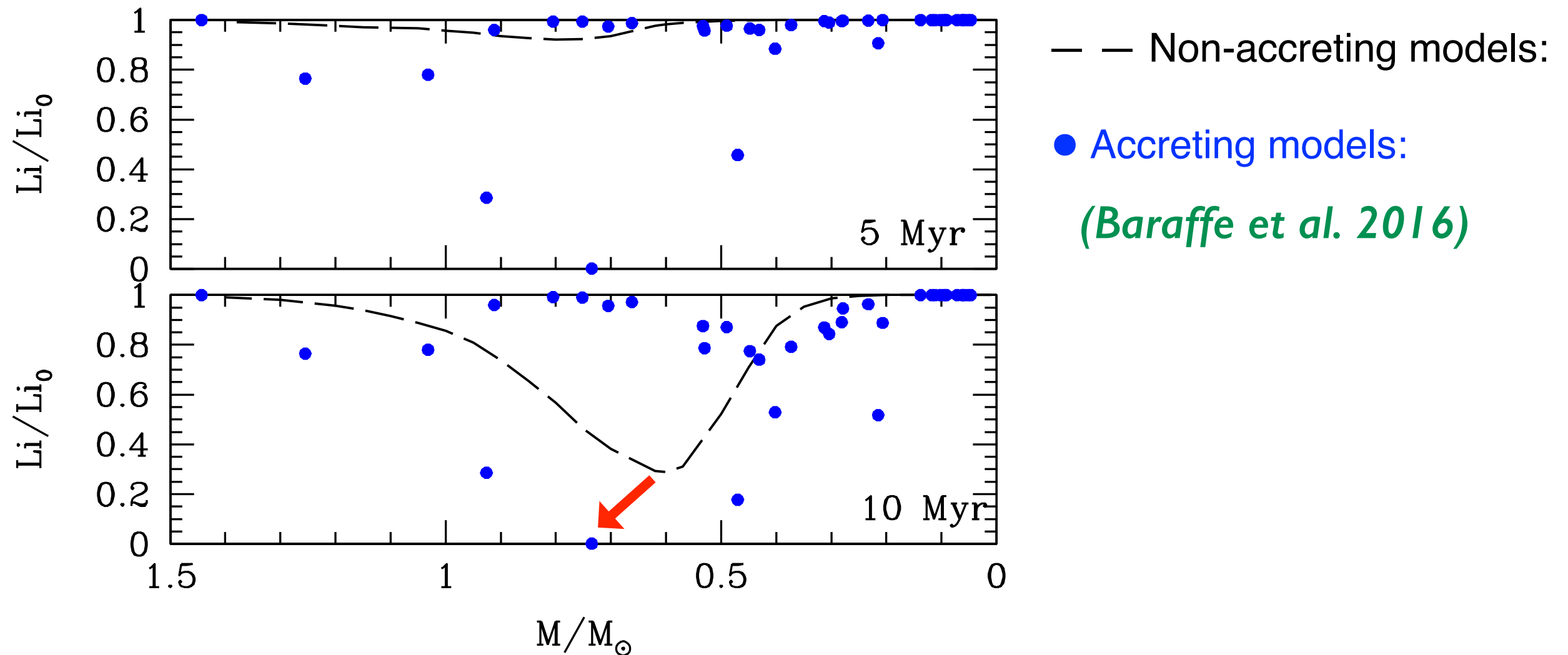
Location of objects with different accretion history at **5 Myr**



➡ Effect of early accretion on lithium depletion



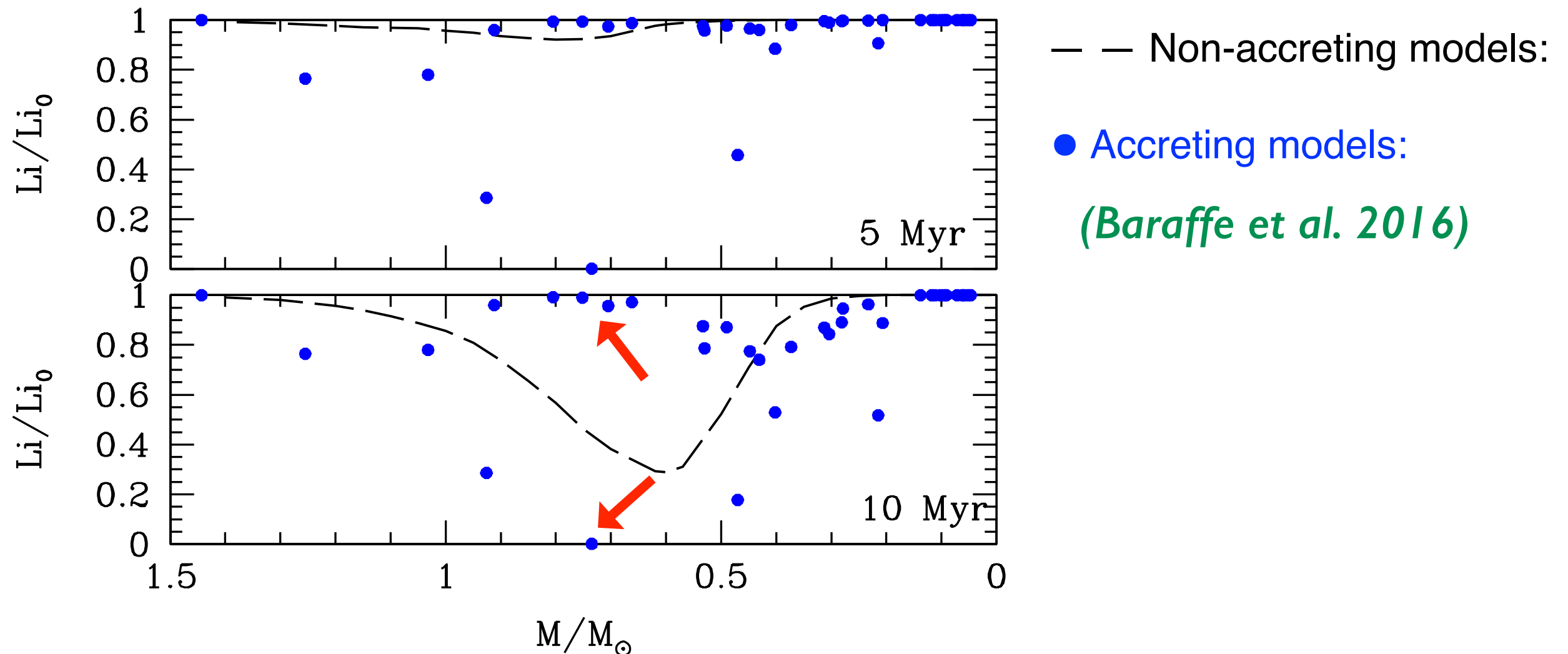
➡ Effect of early accretion on lithium depletion



Interesting effects:

- Confirmation that accretion can produce **abnormal Li depleted** objects for their **age/mass** (conclusions of Baraffe & Chabrier 2010 based on arbitrary rates)

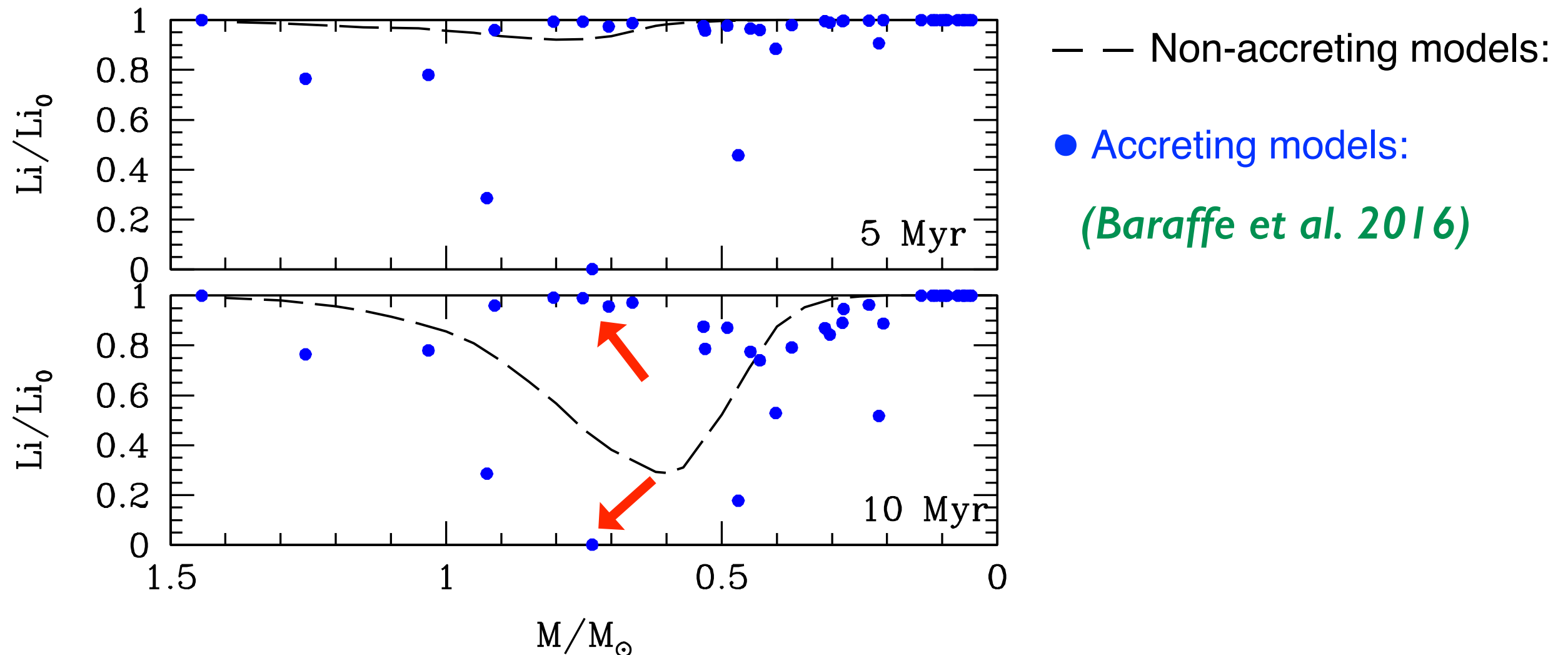
➡ Effect of early accretion on lithium depletion



Interesting effects:

- Confirmation that accretion can produce **abnormal Li depleted** objects for their **age/mass** (*conclusions of Baraffe & Chabrier 2010 based on arbitrary rates*)
- Accretion can produce objects with **Li excess** compared to non accreting counterparts → explanation of Li excess observed by Bouvier et al. (2016)??

➡ Effect of early accretion on lithium depletion



Interesting effects:

- Confirmation that accretion can produce **abnormal Li depleted** objects for their **age/mass** (conclusions of Baraffe & Chabrier 2010 based on arbitrary rates)
- Accretion can produce objects with **Li excess** compared to non accreting counterparts → explanation of Li excess observed by Bouvier et al. (2016)??

Consistent models reveal a **very subtle competition** between high accretion event (burst) + increase of T_{central} + growth of radiative core + accretion of fresh Li from accretion disk

2) A step forward: multi-D structure of accreting objects

➡ Numerical developments: MUSIC (MUlti-dimensional Stellar Implicit Code; ERC adv. grant TOFU)

(Viallet et al. 2011, 2013, 2016; Geroux et al. 2016; Pratt et al. 2016; Goffrey et al. 2016)

- Spherical geometry (2D or 3D)
- Fully compressible hydrodynamics
- **Implicit time integration** (no limitation on the numerical timestep)
- **Realistic equation of state and opacities** for stellar interiors
- Initial model from 1D stellar evolution calculation

2) A step forward: multi-D structure of accreting objects

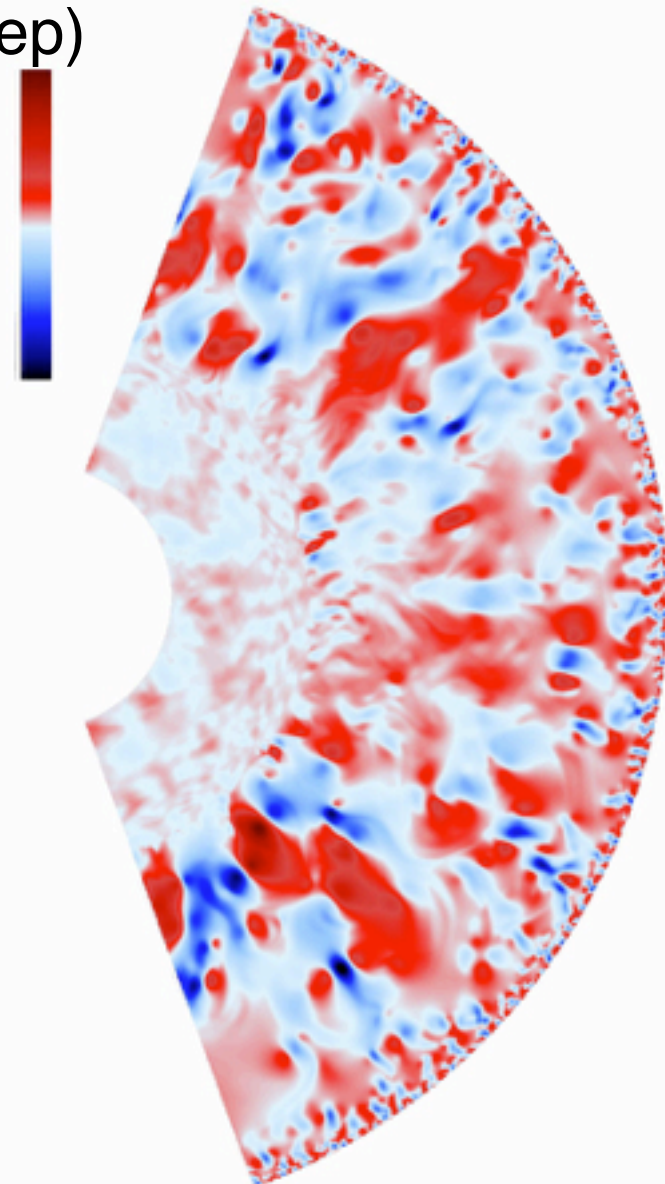
➡ Numerical developments: MUSIC (MULTi-dimensional Stellar Implicit Code; ERC adv. grant TOFU)

(*Viallet et al. 2011, 2013, 2016; Geroux et al. 2016; Pratt et al. 2016; Goffrey et al. 2016*)

- Spherical geometry (2D or 3D)
- Fully compressible hydrodynamics
- **Implicit time integration** (no limitation on the numerical timestep)
- **Realistic equation of state and opacities** for stellar interiors
- Initial model from 1D stellar evolution calculation

➡ Simulations for a young low mass star ($1 M_{\odot}$, $\sim 60\%$ convective envelope)

- 2D simulations up to 1024^2
- 3D simulations up to 512^3



Pratt et al. 2016, A&A, sub.

→ **First application:** Testing the validity of accretion treatment in 1D stellar evolution code (*Geroux et al. A&A, 2016*)

One main assumption: instantaneous redistribution of accretion mass and energy in the interior

Effect of “burst” accretion $\dot{M} = 10^{-4} M_{\odot}/\text{yr}$ on a young, almost fully convective star

- explore a range of values for α (fraction of accretion energy added to the star)

 - $\alpha \sim 0 \rightarrow$ “cold” accretion

 - $\alpha > 0 \rightarrow$ “hot” accretion

➔ **First application:** Testing the validity of accretion treatment in 1D stellar evolution code (*Geroux et al. A&A, 2016*)

One main assumption: instantaneous redistribution of accretion mass and energy in the interior

Effect of “burst” accretion $\dot{M} = 10^{-4} M_{\odot}/\text{yr}$ on a young, almost fully convective star

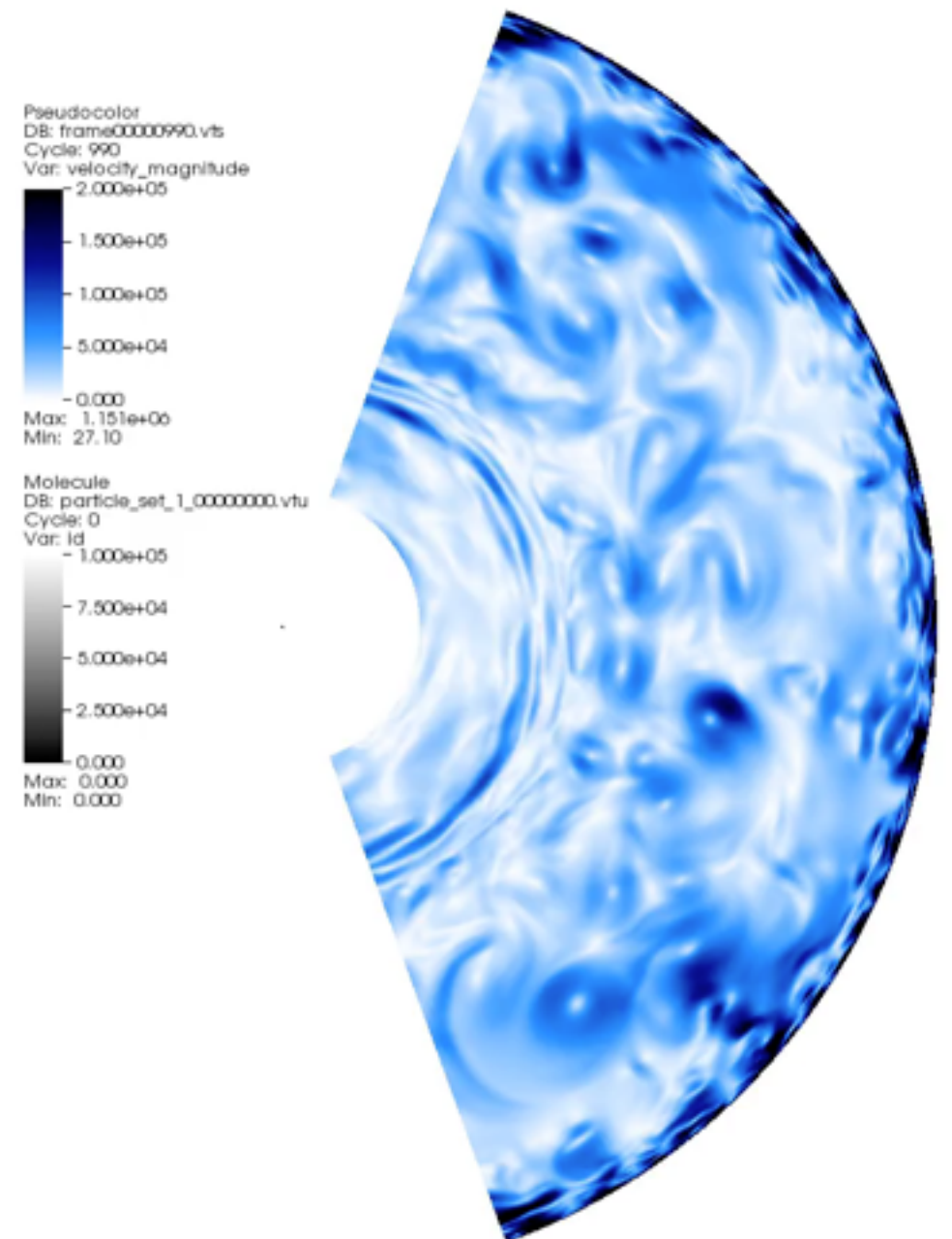
- explore a range of values for α (fraction of accretion energy added to the star)

$\alpha \sim 0 \rightarrow$ “cold” accretion

$\alpha > 0 \rightarrow$ “hot” accretion

First result:

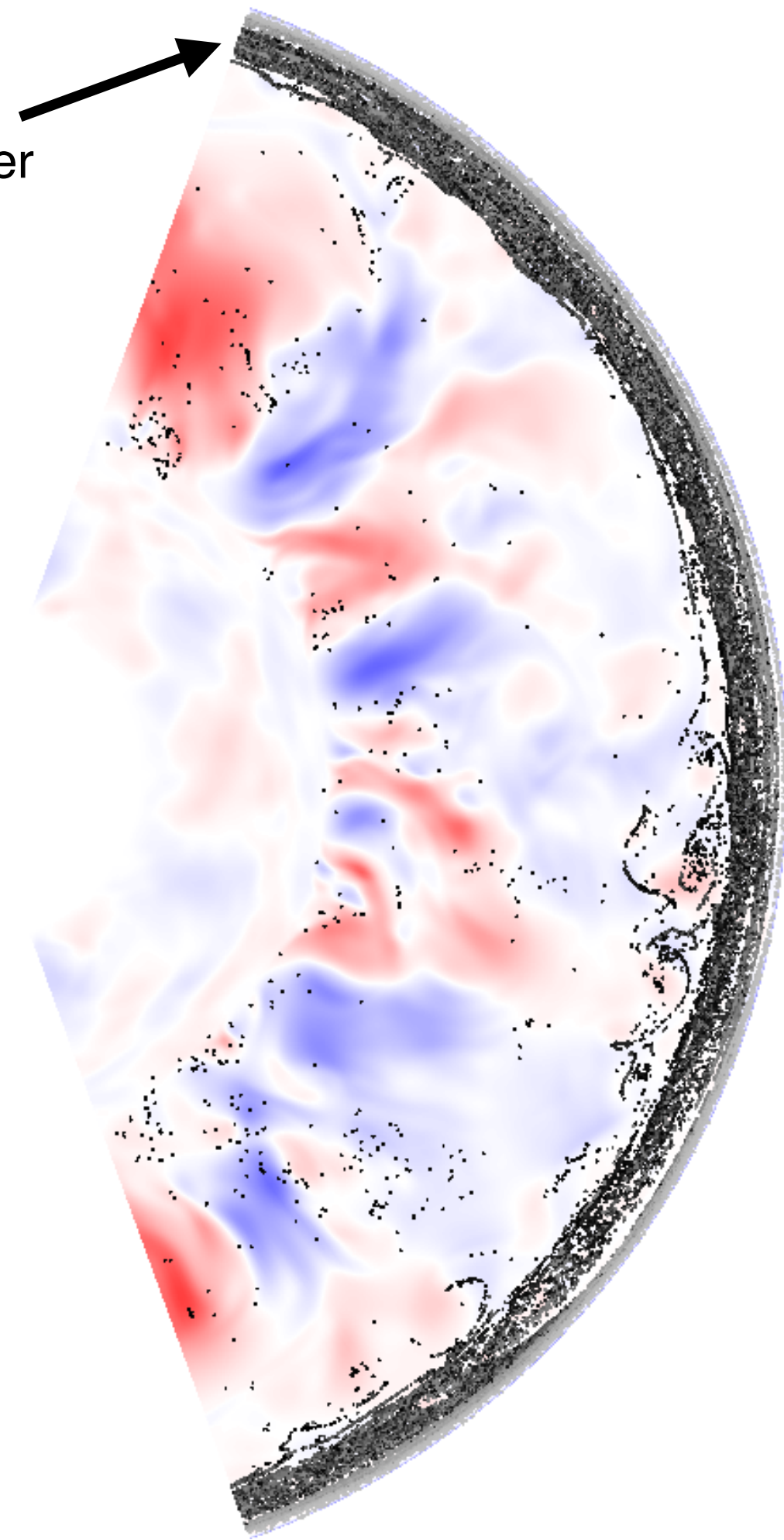
Multi-D simulations confirm assumption in 1D codes of instantaneous and homogeneous redistribution of accreted material for cold/warm accretion ($\alpha \lesssim 0.1$)



Visualization with tracer particles on velocity field

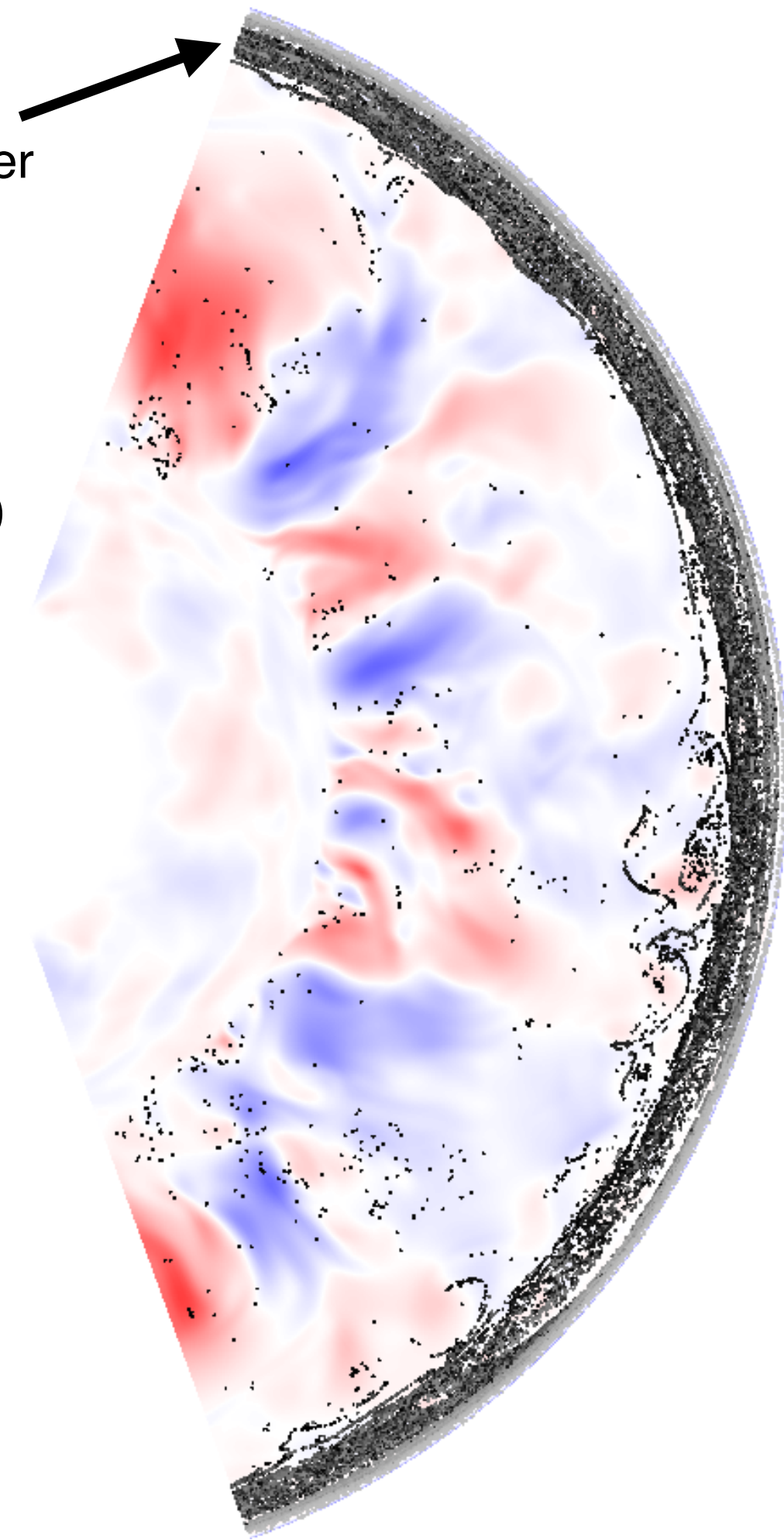
Second result:

- For hot accretion ($\alpha \gtrsim 0.1$), formation of a hot surface layer (no deep mixing of accretion energy)



Second result:

- For hot accretion ($\alpha \gtrsim 0.1$), formation of a hot surface layer (no deep mixing of accretion energy)
- Assumption in 1D codes of redistribution of accretion energy deep in the interior could overestimate the effect on the structure or $\alpha \gtrsim 0.1$ (expansion of accreting object)
- Use of an accretion boundary condition $L_{\text{surf}} = L_{\text{acc}}$ is more realistic in 1D codes

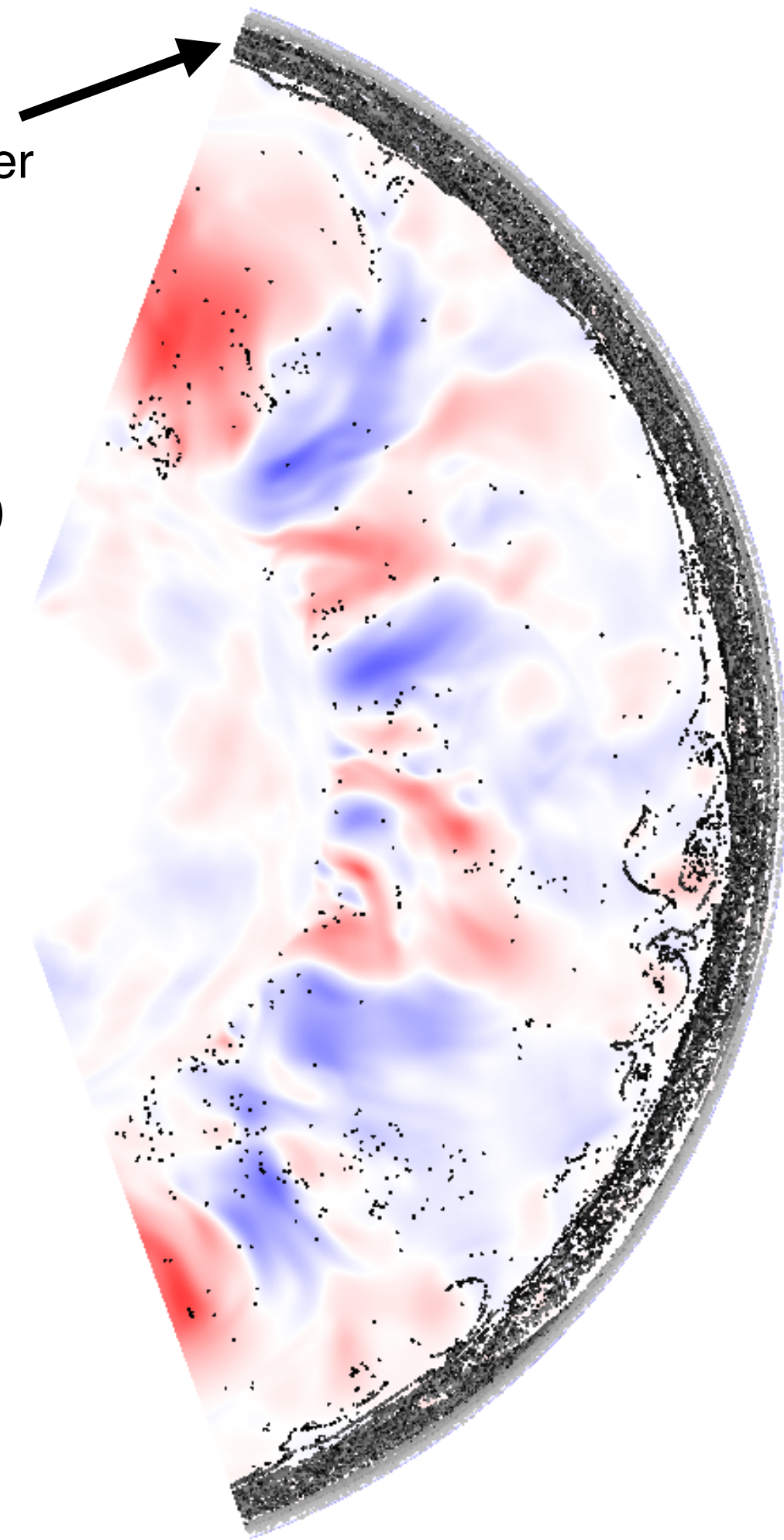


Second result:

- For hot accretion ($\alpha \gtrsim 0.1$), formation of a hot surface layer (no deep mixing of accretion energy)
- Assumption in 1D codes of redistribution of accretion energy deep in the interior could overestimate the effect on the structure or $\alpha \gtrsim 0.1$ (expansion of accreting object)
- Use of an accretion boundary condition $L_{\text{surf}} = L_{\text{acc}}$ is more realistic in 1D codes

➡ But assumption of redistribution of energy can **mimic** the effects described by the multi-D simulations

Reassuring regarding the validity of previous qualitative results from 1D models



Conclusion and perspectives

- Consistent coupling between hydrodynamical disk evolution models and accreting central object evolution
 - ➡ Confirms a spread in HRD
 - ➡ Confirms abnormal Li depletion (though expected to be very rare events)
 - ➡ Predict existence of pre-MS objects with Li-excess
*(due to a subtle competition between burst accretion, impact on T_c , growth or radiative core and accretion of fresh Li that only **consistent models could reveal**)*

Conclusion and perspectives

- **Consistent coupling between hydrodynamical disk evolution models and accreting central object evolution**

- ➡ Confirms a spread in HRD
- ➡ Confirms abnormal Li depletion (though expected to be very rare events)
- ➡ Predict existence of pre-MS objects with Li-excess
*(due to a subtle competition between burst accretion, impact on T_c , growth or radiative core and accretion of fresh Li that only **consistent models could reveal**)*

- **Realistic Multi-D stellar structure models are on their way**

*TOFU team: C. Geroux, T. Goffrey, T. Constantino, J. Pratt (Exeter) - M. Viallet (MPA)
D. Folini, M. Popov, R. Walder (Lyon)*

- ➡ Confirms qualitatively the effects of accretion predicted by 1D evolutionary models
- ➡ “hot” accretion effects in 1D codes may be overestimated
—> work in progress with more realistic accretion boundary condition
- ➡ **Further application to study overshooting and rotation effects**