magnetic effects

on M dwarf evolution

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2 – 3% accuracy in mass

1% accuracy in radius

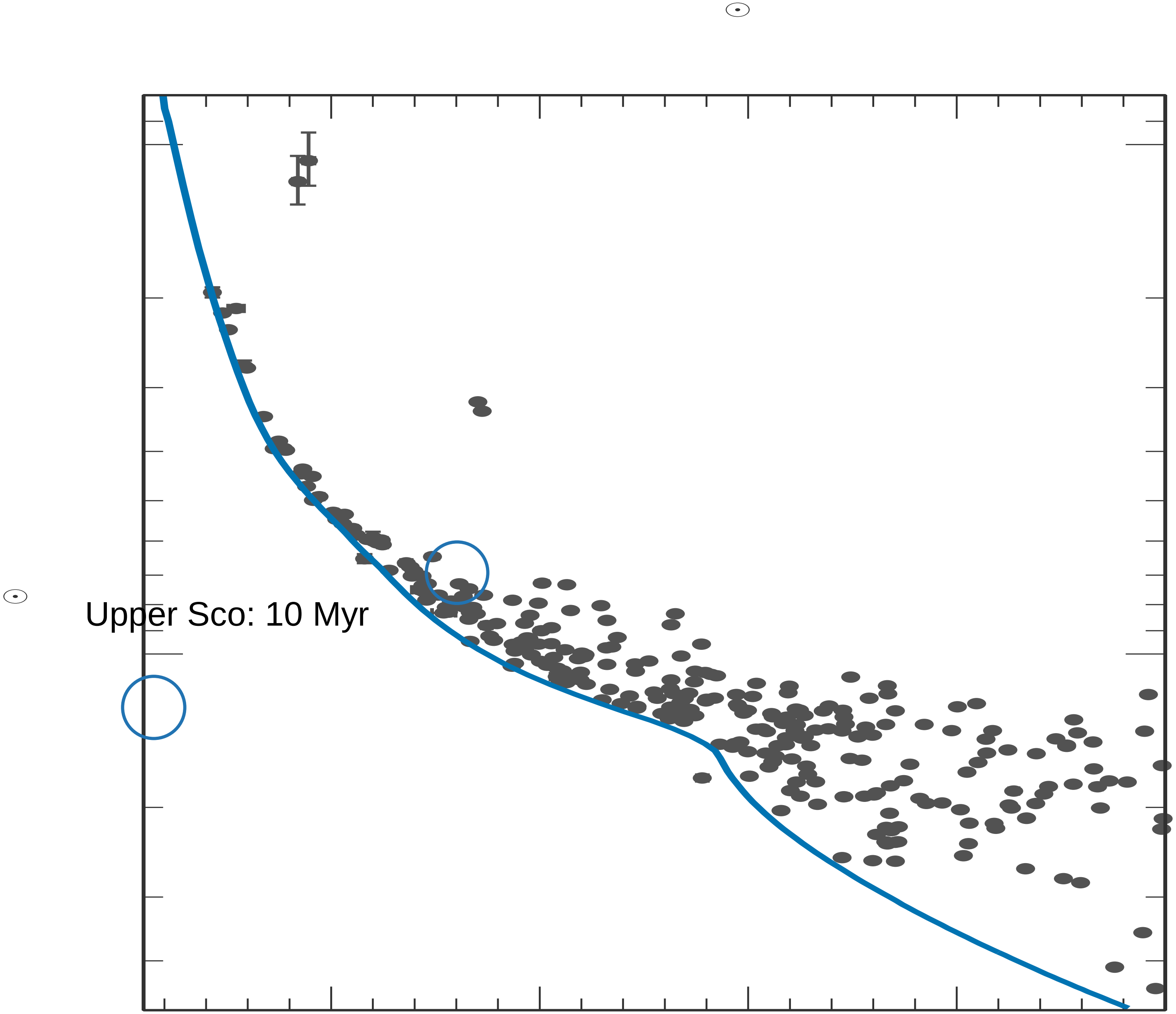
X% accuracy in age

5 – 10% → 2 – 3% precision in mass

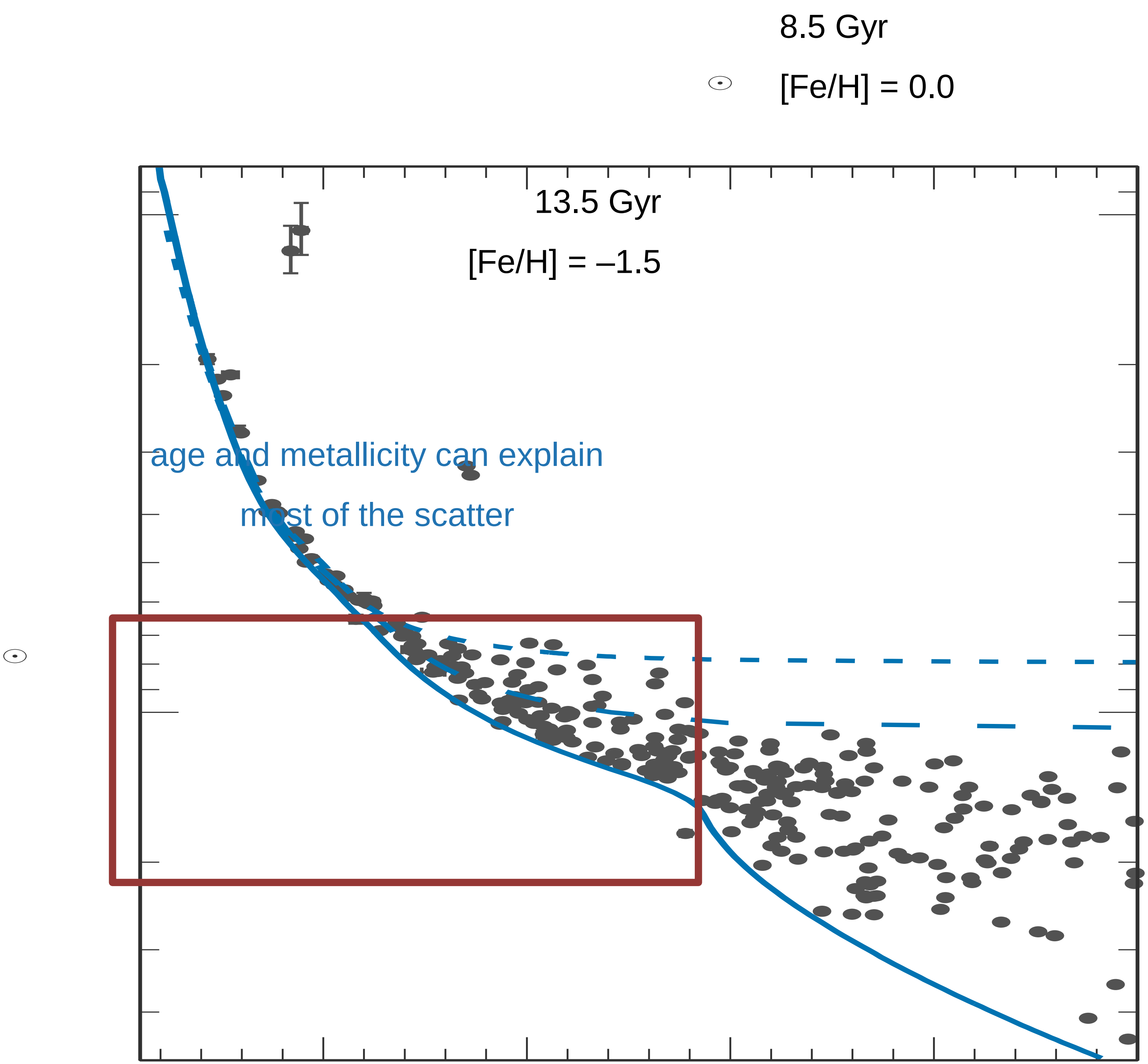
5% → 1% precision in radius

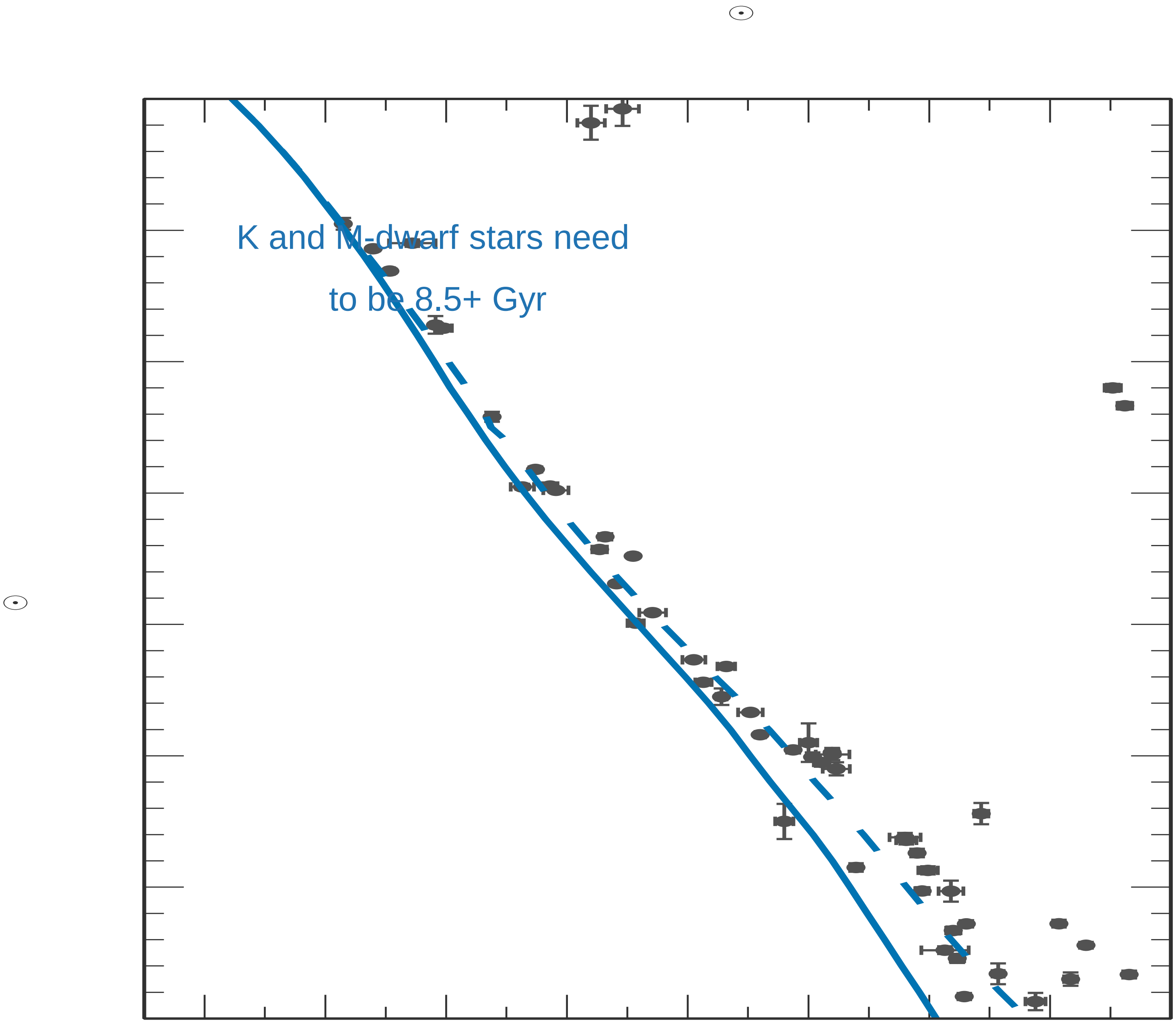
??% → X% precision in age

for the vast majority of M dwarfs, using empirical relations



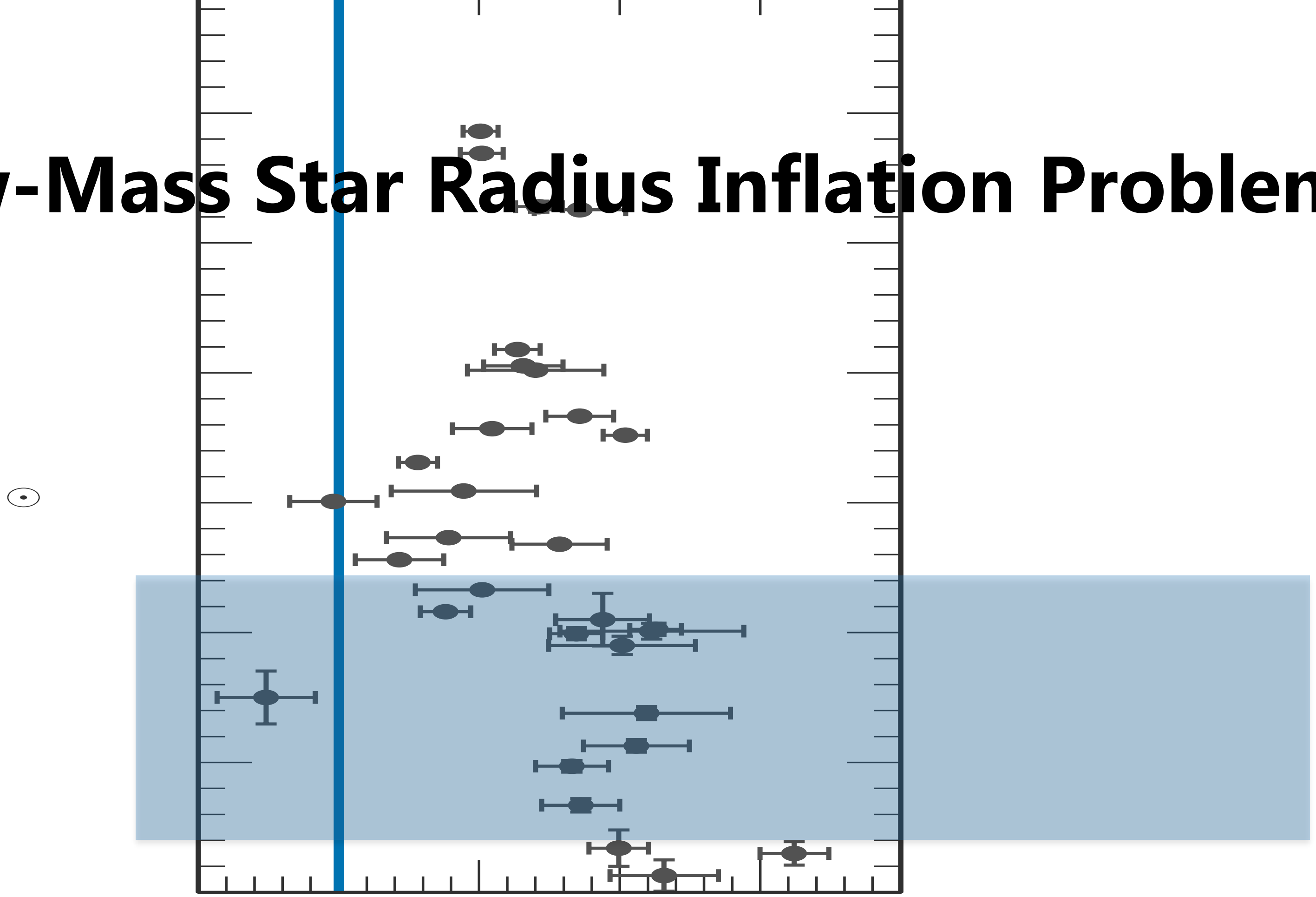
Upper Sco: 10 Myr


8.5 Gyr
[Fe/H] = 0.0
13.5 Gyr
[Fe/H] = –1.5
age and metallicity can explain
most of the scatter



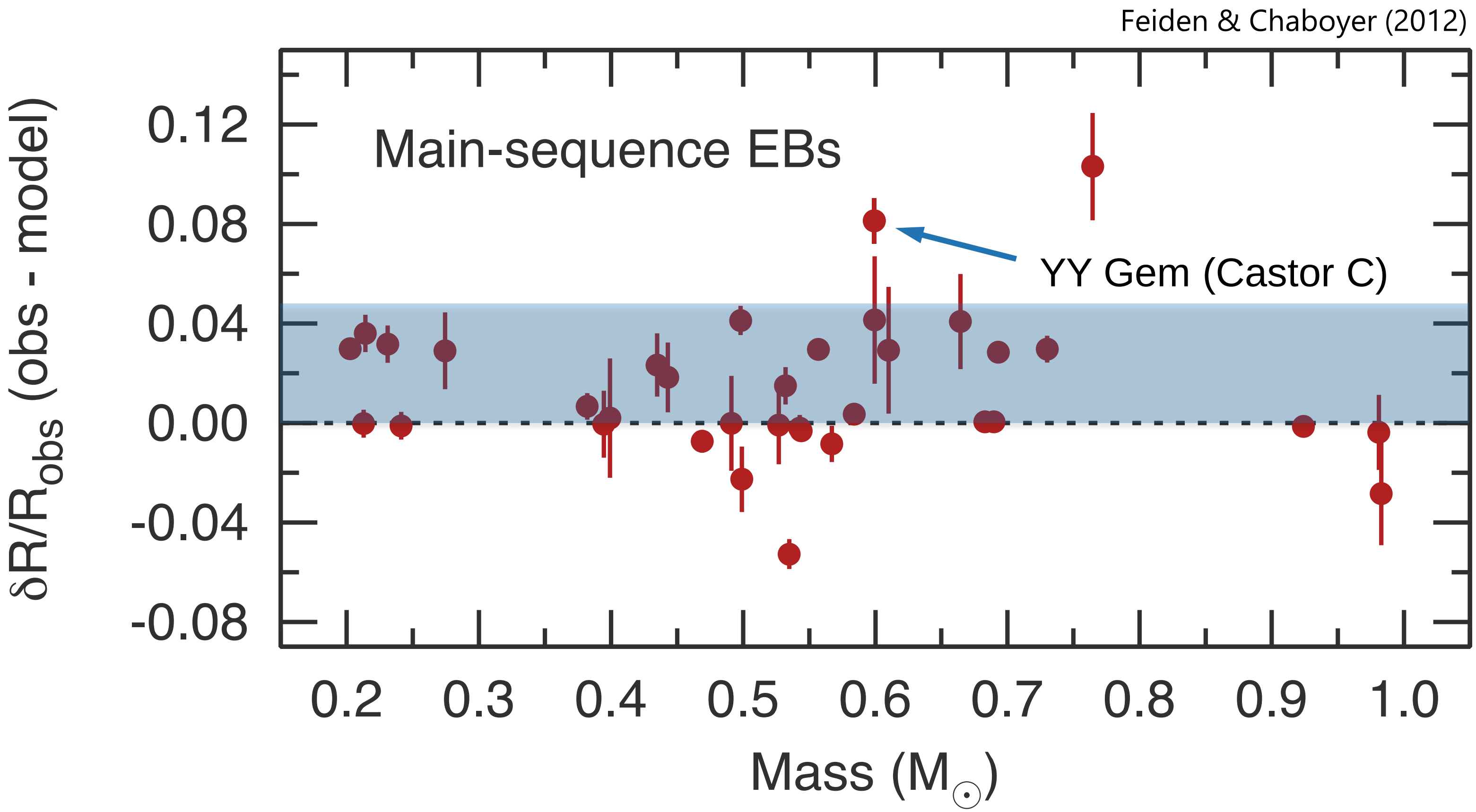
K and M-dwarf stars need
to be 8.5+ Gyr

Low-Mass Star Radius Inflation Problem



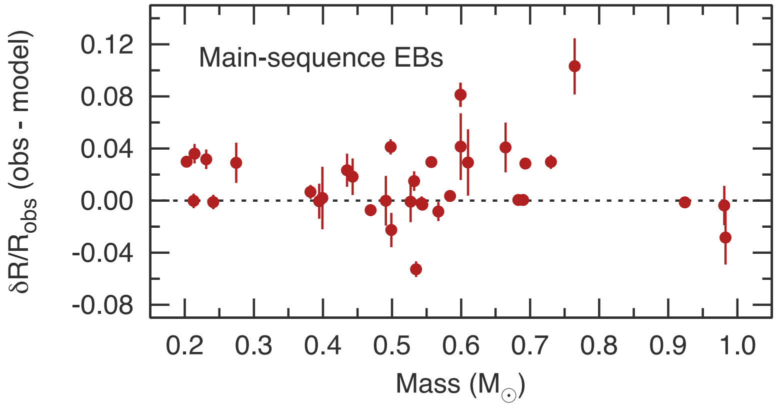
compared to ZAMS models

Low-Mass Star Radius Inflation Problem



fitting for age and [Fe/H]

EBs Feiden & Chaboyer (2012)



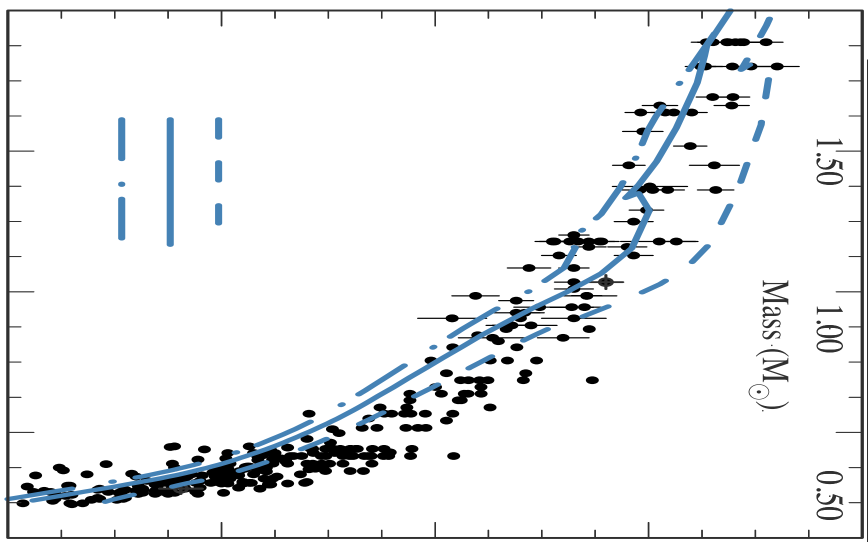
Spectrophotometry Mann et al. (2015)

Interferometry Spada et al. (2013)

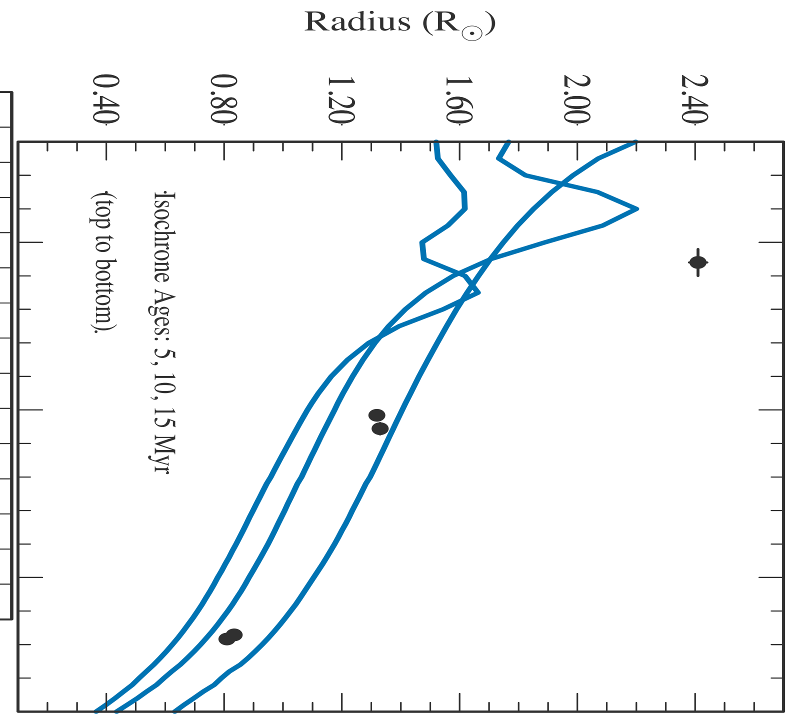
typical error (5%)

Problem is Ubiquitous

Young Stars, Too...



Lodieu et al. (2015), Kraus et al. (2015), David et al. (2016)



Lower mass stars appear

YOUNGER

Higher mass stars appear

OLDER

Lower mass stars appear

OLDER

Higher mass stars appear

YOUNGER

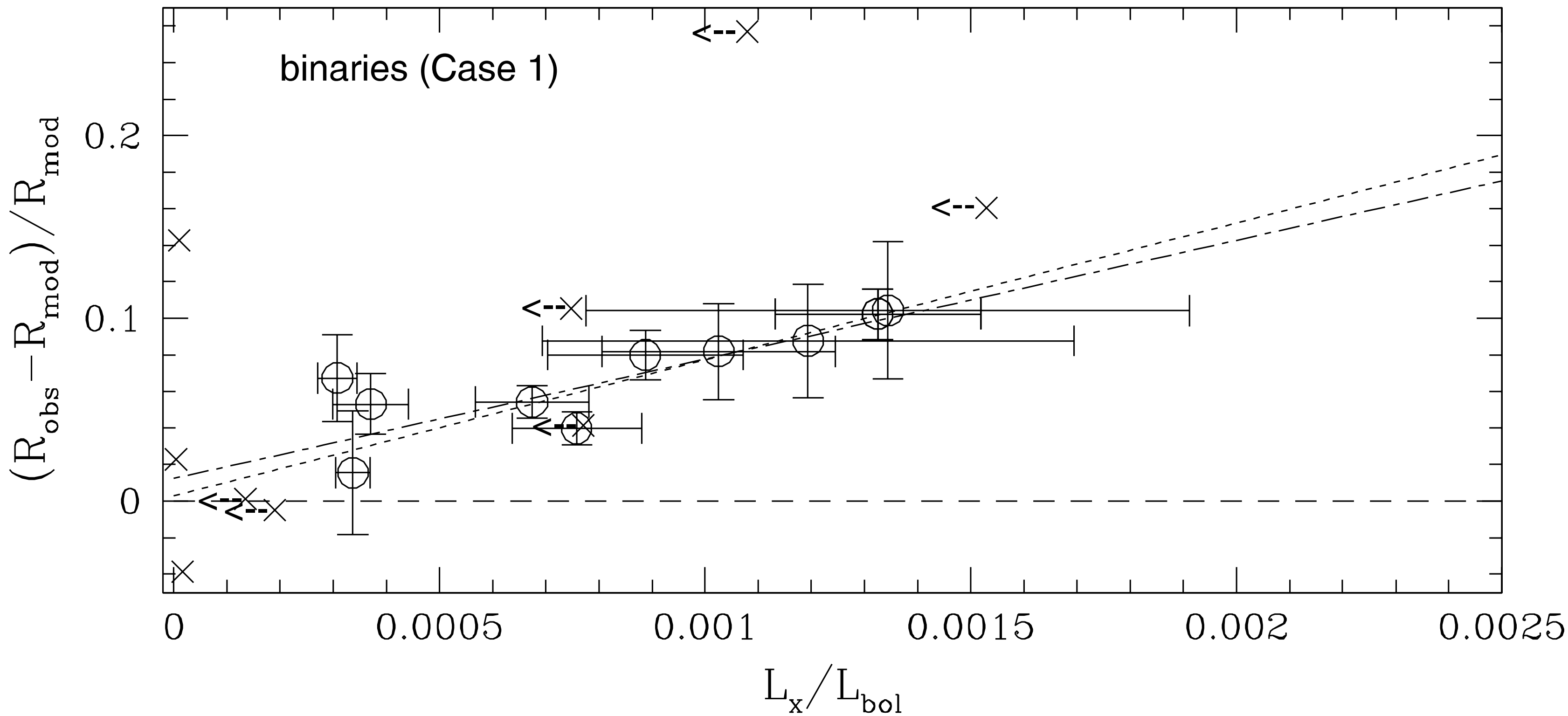
Empirical correction to T(tau) relation

Chen et al. 2014

T_{eff} dependent changes to T(tau) relation hint at required modifications to fundamental physics. Convection properties? Atmospheric opacity?

magnetic activity

López-Morales (2007)



magnetic fields

do they inflate low-mass stars?

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yes

well...

maybe ?

Flavors of Magnetic Models

1. **magnetic inhibition of convection**

   Lydon & Sofia (1995), D'Antona et al. (2000),
   Mullan & MacDonald (2001), Feiden & Chaboyer (2012)

2. **starspots**

   Chabrier et al. (2007), Jackson et al. (2009),
   Somers & Pinsonneault (2015)

1 magnetic inhibition of convection

or, modification of adiabatic temperature gradient

Gough & Taylor (1966):

$$\nabla < \nabla_{\rm ad} + \frac{B_r^2}{4\pi\gamma P_{\rm gas}} \approx \nabla_{\rm ad} + \beta^{-1}$$

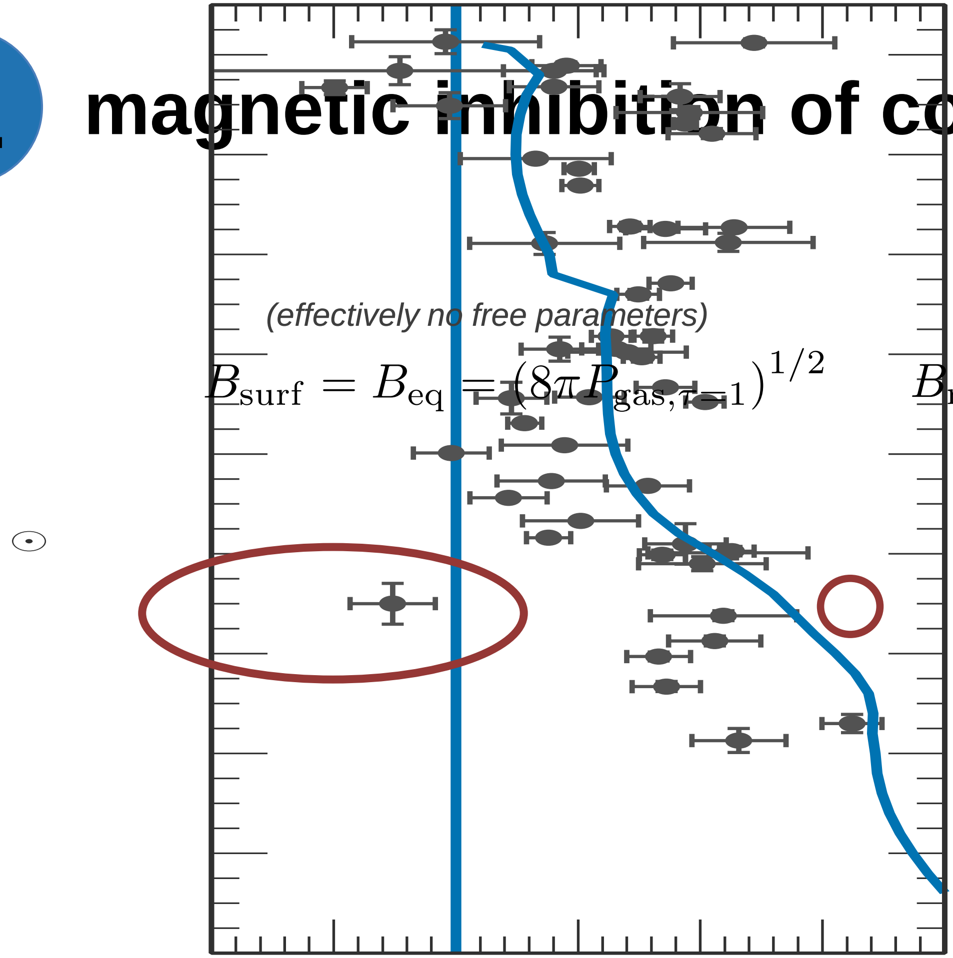
Used by D'Antona et al. (2000), Mullan & MacDonald (2001)

Lydon & Sofia (1995):

$$\nabla < \nabla_{\rm ad}\left[1 - f\frac{\nu}{\alpha}\frac{d}{d\ln P}\ln\left(\frac{B^2}{8\pi\rho}\right)\right] + (f-1)\frac{\nu}{\delta}\frac{d}{d\ln P}\ln\left(\frac{B^2}{8\pi\rho}\right)$$

Used by Feiden & Chaboyer (2012)

1 magnetic inhibition of convection



(effectively no free parameters)

$$B_{\rm surf} = B_{\rm eq} = (8\pi P_{{\rm gas},\tau=1})^{1/2} \qquad B_{\rm max} \sim 50\ {\rm kG}$$

Feiden et al. (in prep)

highly inflated, fully convective stars are difficult to reproduce

2

starspots

or, flux suppression

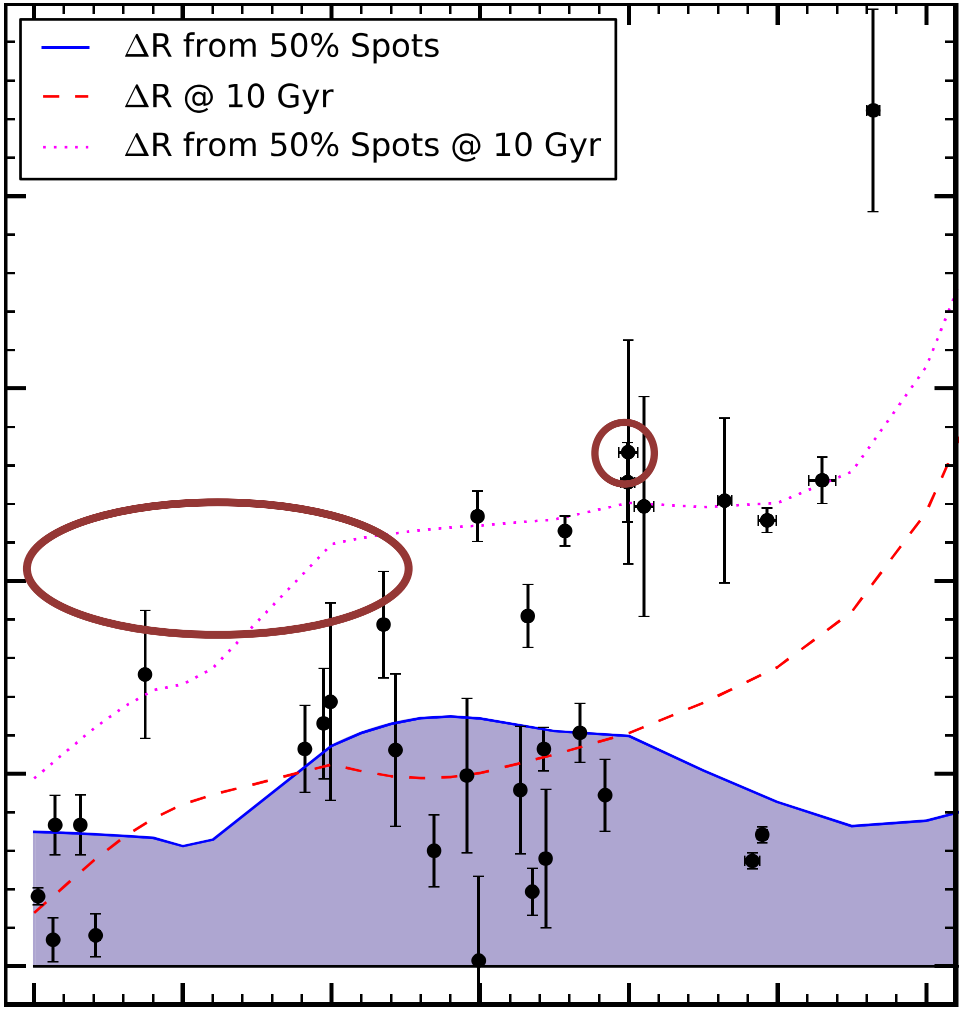
$$T_{\rm avg}^4 = (1 - f_{\rm spot})T_{\rm phot}^4 + f_{\rm spot}T_{\rm spot}^4$$

$$L_{\rm bol} = 4\pi\sigma R^2 T_{\rm avg}^4$$

Used by:
Chabrier et al. (2007), Jackson et al. (2009), Mullan & MacDonald (2010), Somers & Pinsonneault (2015)

2 starspots

Somers & Pinsonneault (2015)

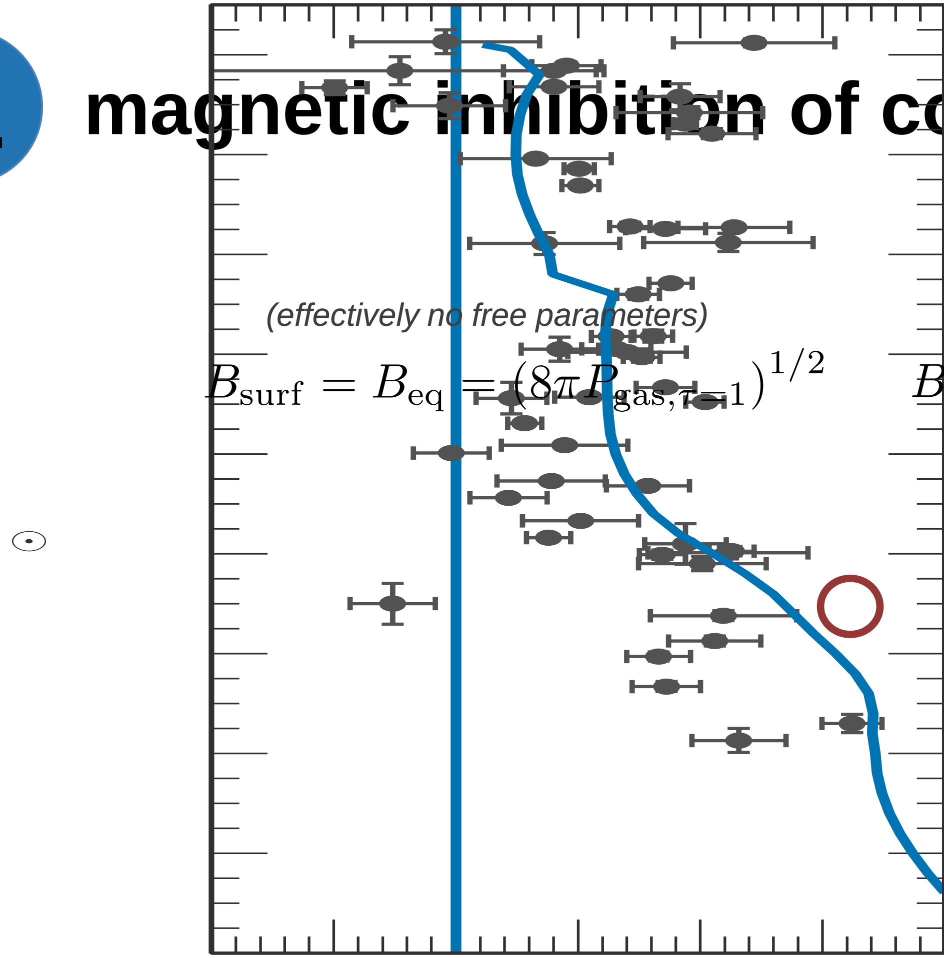


validation

1 magnetic inhibition of convection

(effectively no free parameters)

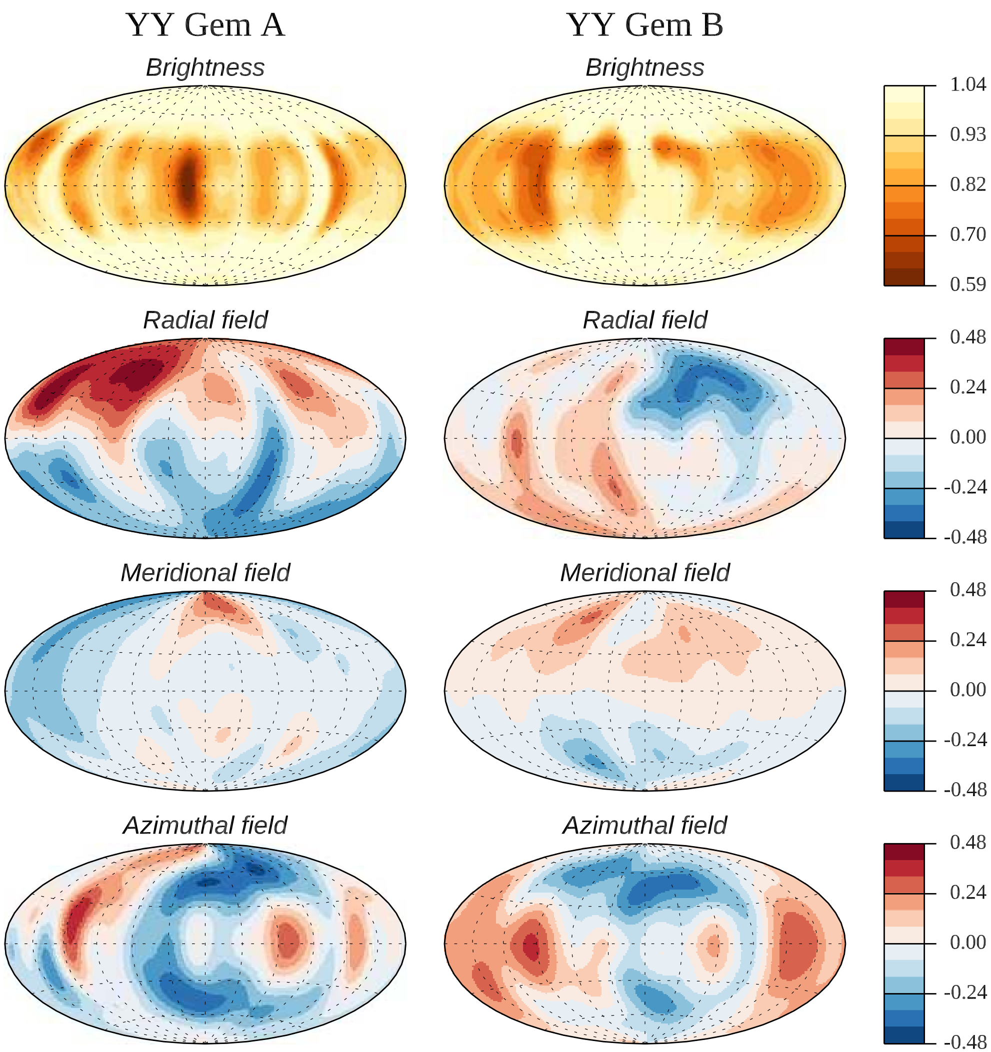
$$B_{\rm surf} = B_{\rm eq} = (8\pi P_{{\rm gas},\tau=1})^{1/2} \qquad B_{\rm max} \sim 50~{\rm kG}$$



Feiden et al. (in prep)

1 magnetic inhibition of convection

observational confirmation?



Parameter	YY Gem A	YY Gem B
From ZDI analysis:		
□B_V □(kG)	0.260	0.205
□$\|B_r\|$□(kG)	0.168	0.098
□B_h □(kG)	0.179	0.162
E_{pol} [a] (%)	70.7	71.5
$E_{m<\ell/2}$ [b] (%)	58.1	44.8
$E_{\ell=1}$ [c] (%)	52.4	45.5
From Zeeman intensification analysis:		
□B_I □(kG)	3.44	3.15
B (kG)	4.60	3.65
f	0.75	0.86

Magnetic Model Predictions

<Bf> = 3.6 kG Dartmouth

B_r = 0.5 kG Delaware

2

starspots

observational confirmation?

e.g., half of the talks at this workshop...

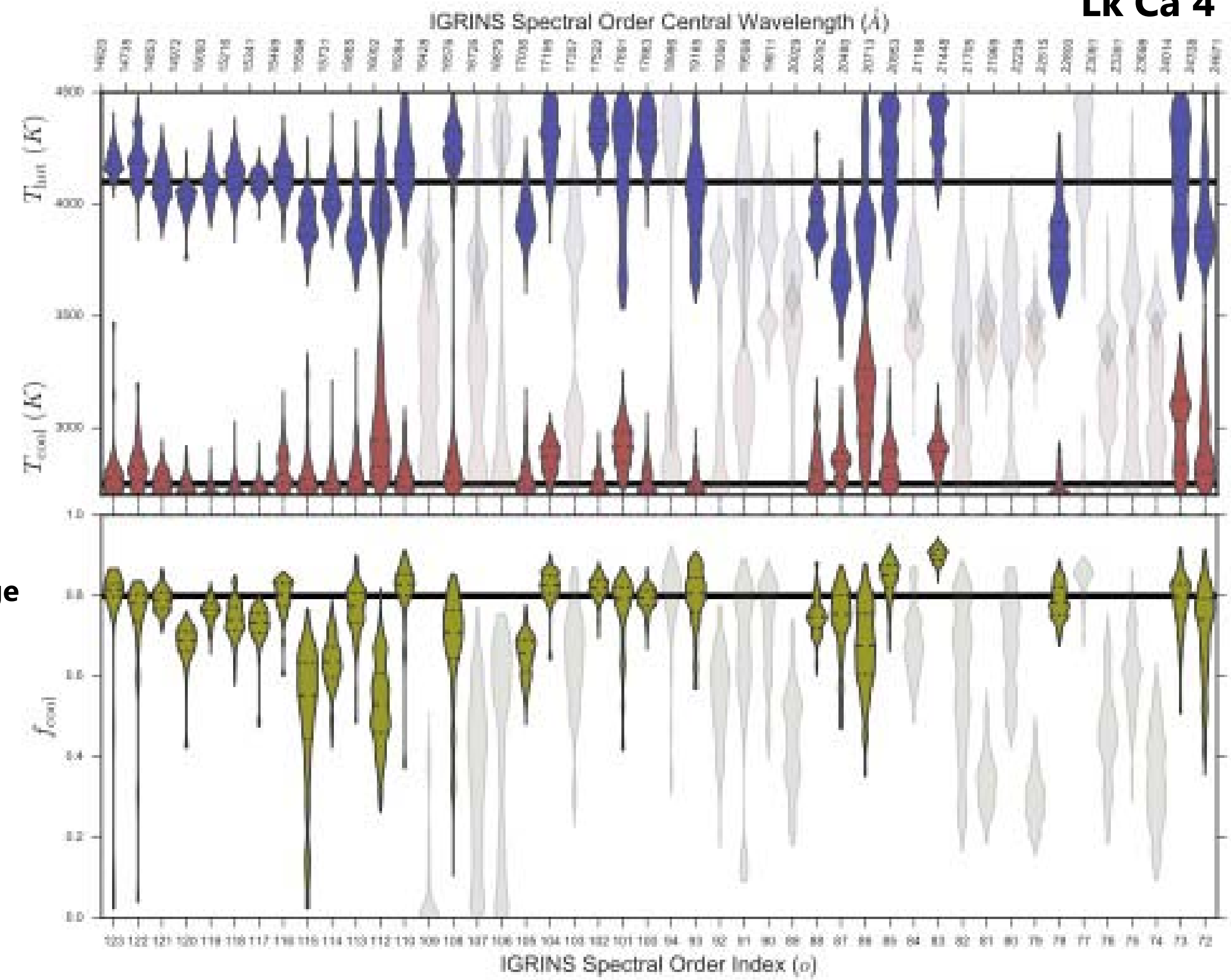
2 starspots

observational confirmation?

Lk Ca 4

~ 30% cooler

~ 80% coverage



Gully-Santiago et al. (2017)

2

starspots

observational confirmation?

Somers & Pinsonneault (2015)

Preservation of Lithium

inhibition of convection

starspots

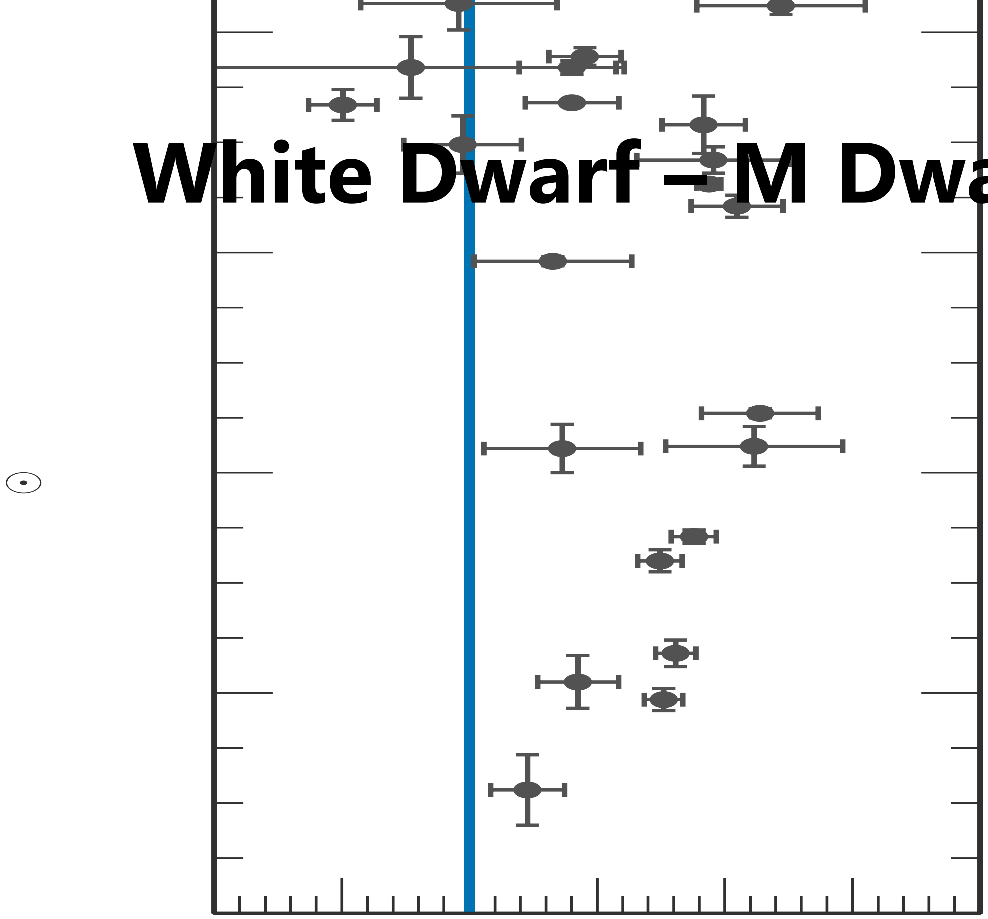
magnetic
model

standard
model

D'Antona et al. (2000), MacDonald & Mullan (2010), Malo et al. (2014), Somers & Pinsonneault (2015), Messina et al. (2016)

open problems

White Dwarf – M Dwarf EBs

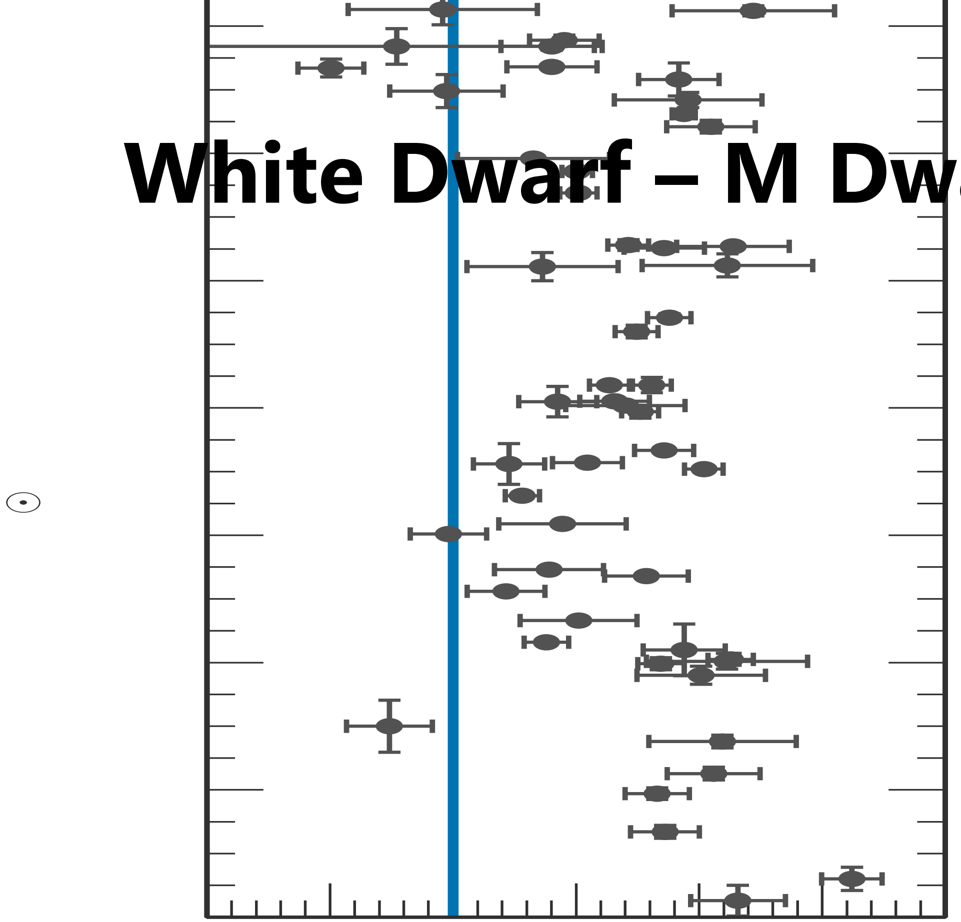


Parsons et al. (2018)

$$1.5 \text{ hrs} < P_{orb} < 18 \text{ hrs}$$

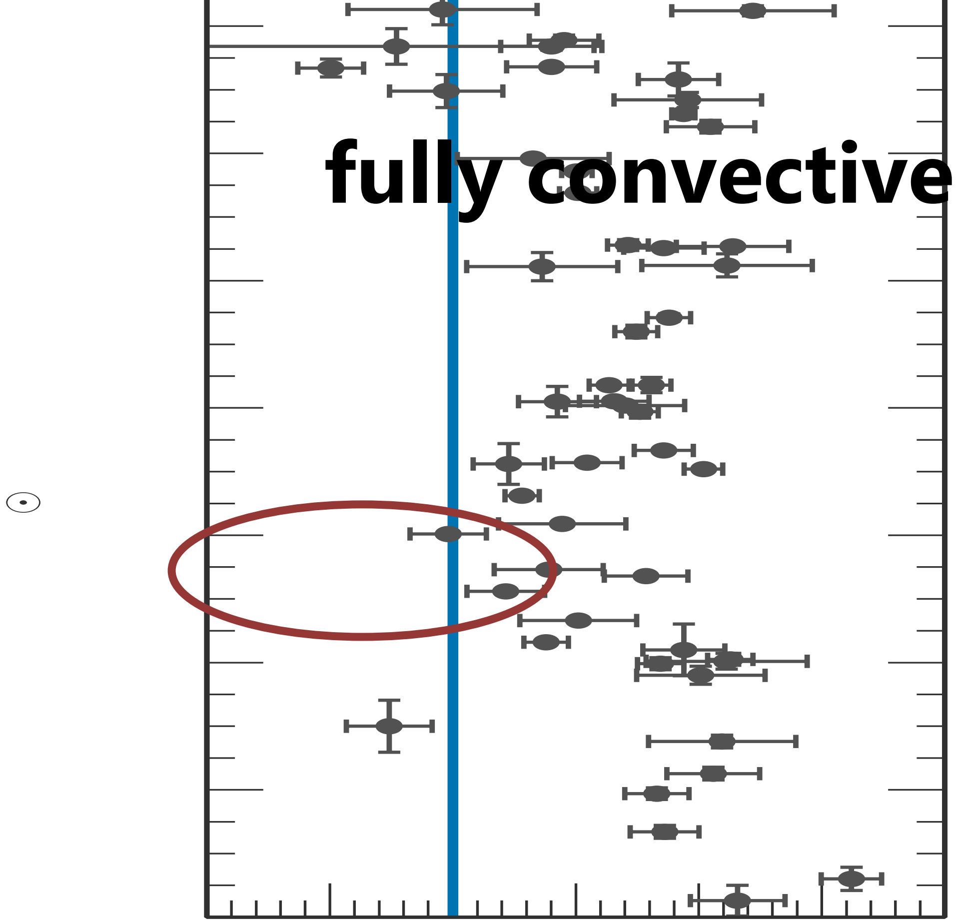
Stars with the same orbital period exhibit different inflation

White Dwarf – M Dwarf EBs



Parsons et al. (2018)

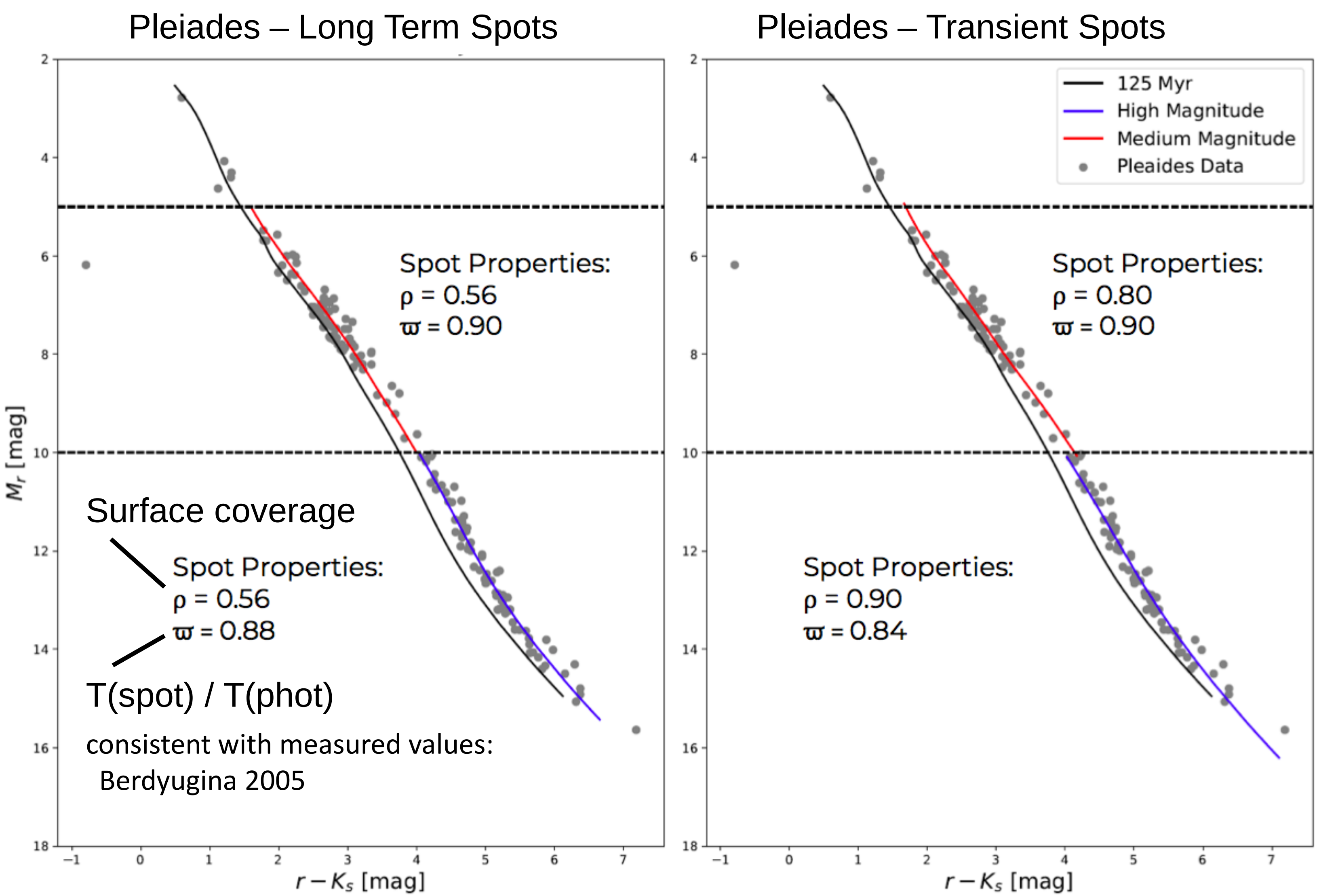
Drastically different systems, but same inflation pattern



Parsons et al. (2018)

highly inflated, fully convective stars are difficult to reproduce

how do starspots work?



Hamilton et al. (in prep), Ash et al. (in prep)

how do starspots work?

magnetic model

transient spots

standard model

transient spots work just as well

Hamilton et al. (in prep), Ash et al. (in prep)

Magnetic fields and spots can reproduce many properties of main sequence M dwarf stars. (also young ones)

Model predicted magnetic fields are consistent with observations.

Highly inflated (10%), fully convective stars are problematic.

→ New or improved physics? (e.g., EOS, atmosphere BCs)

Rotation does not correlate with inflation. Just because you have an active, rapidly rotating M dwarf doesn't mean it will be inflated, and vice versa. (Phil Muirhead's talk)

→ Related to dynamo properties?

Starspots exist, but do they impact stellar structure or do they only alter observed fluxes? Need to model global inhibition and spots?

Far from a highly accurate, predictive model. Do we have all of the pieces?