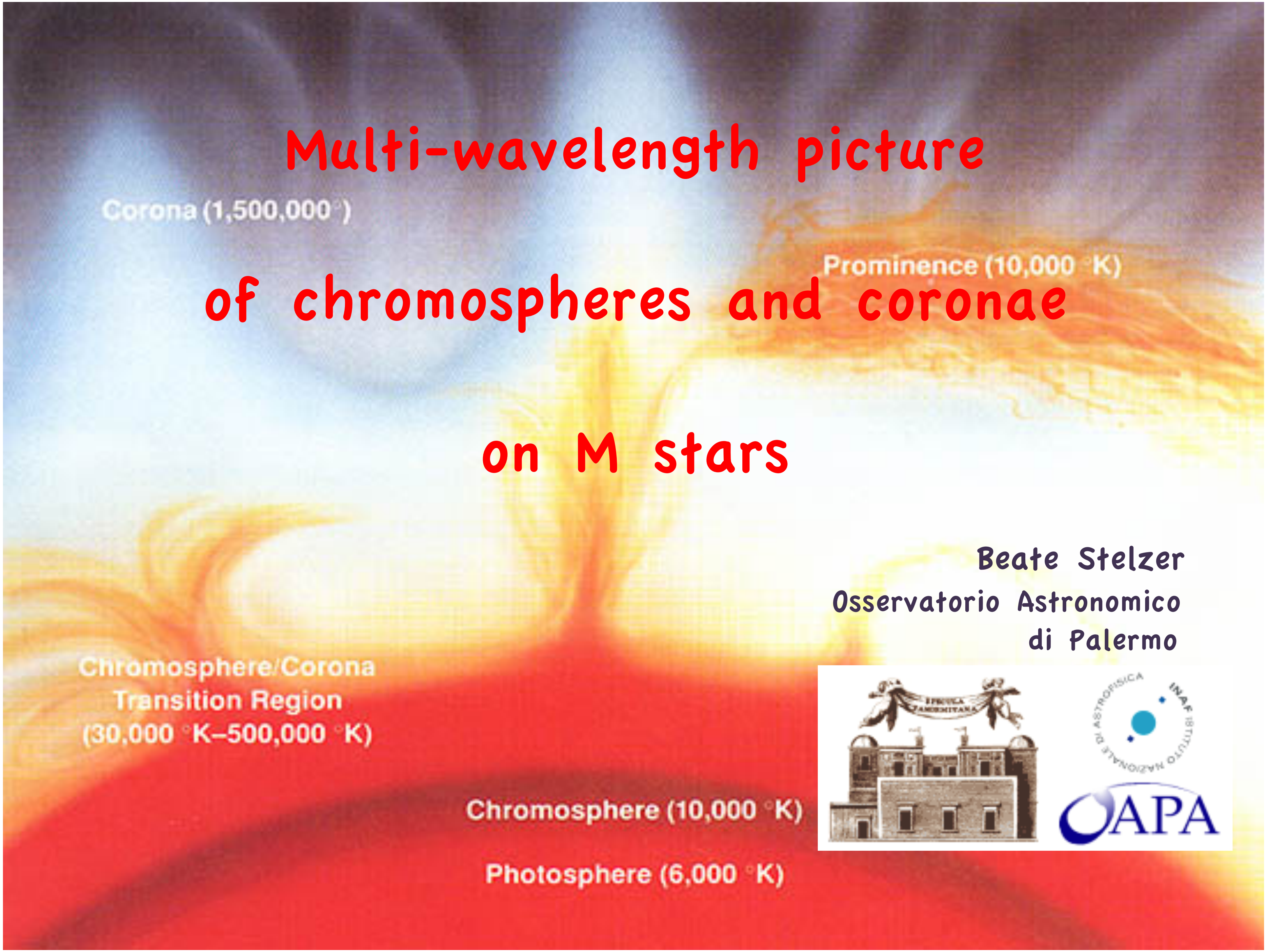
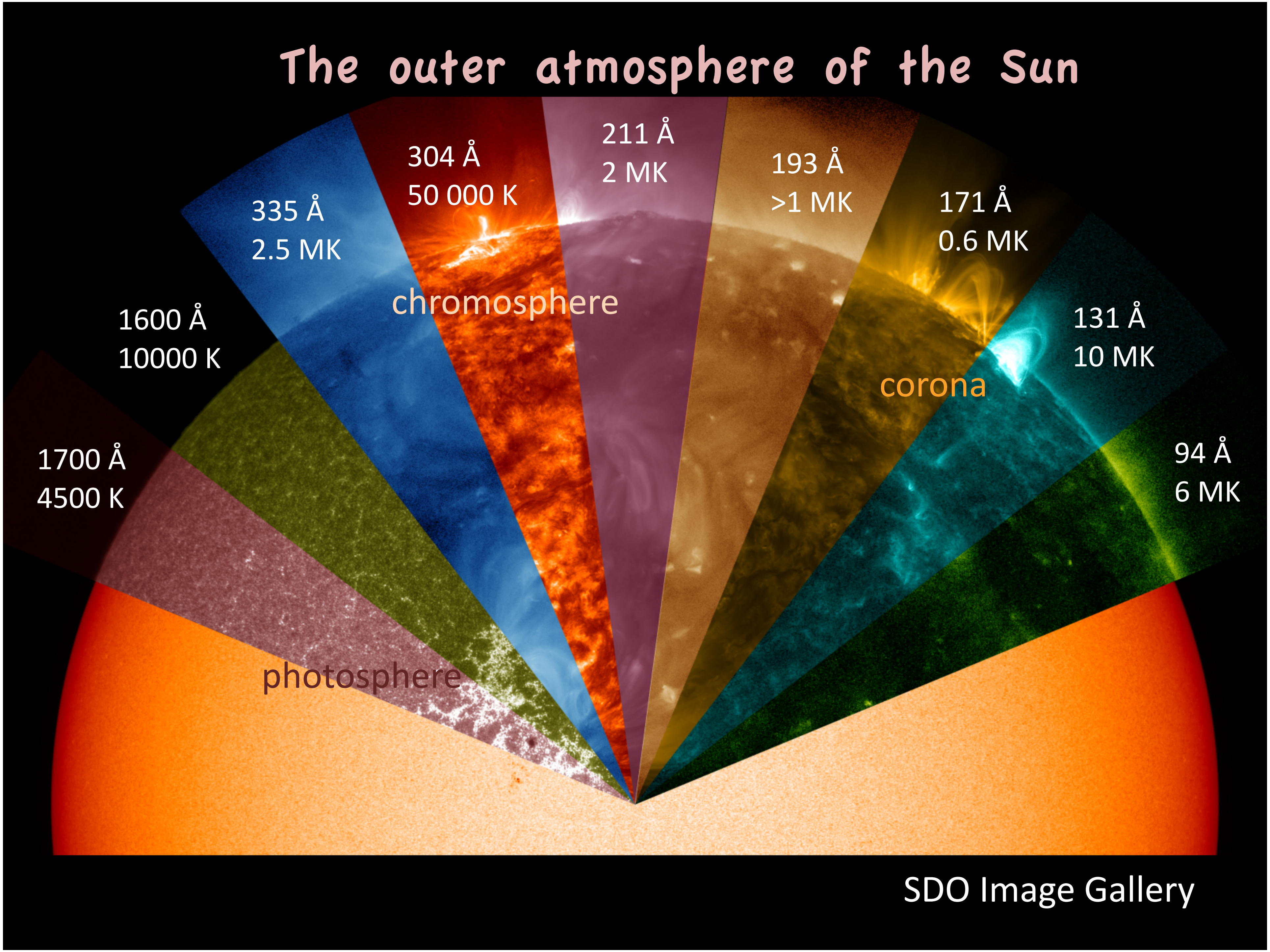
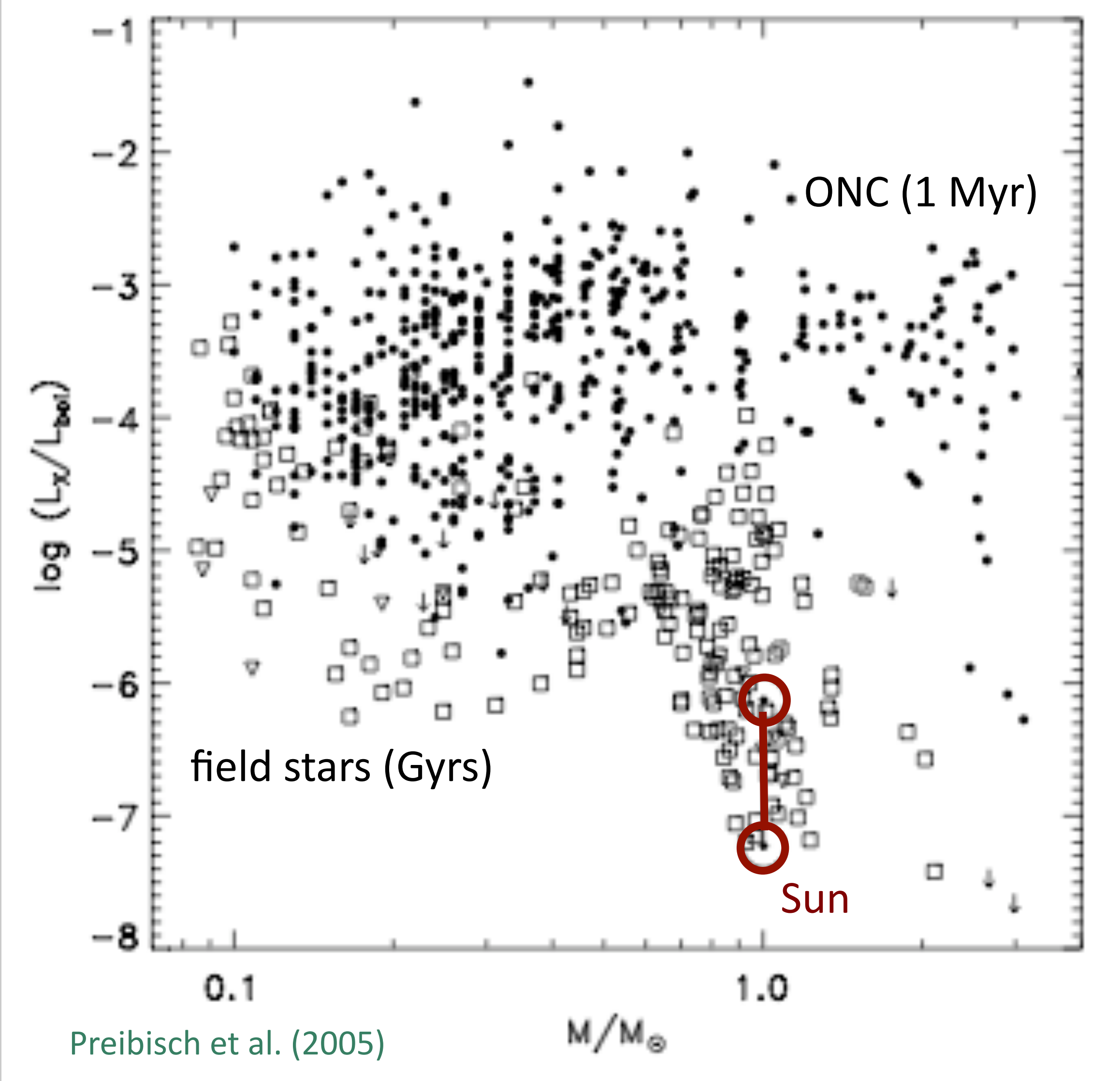
Multi-wavelength picture of chromospheres and coronae on M stars

Beate Stelzer
Osservatorio Astronomico
di Palermo



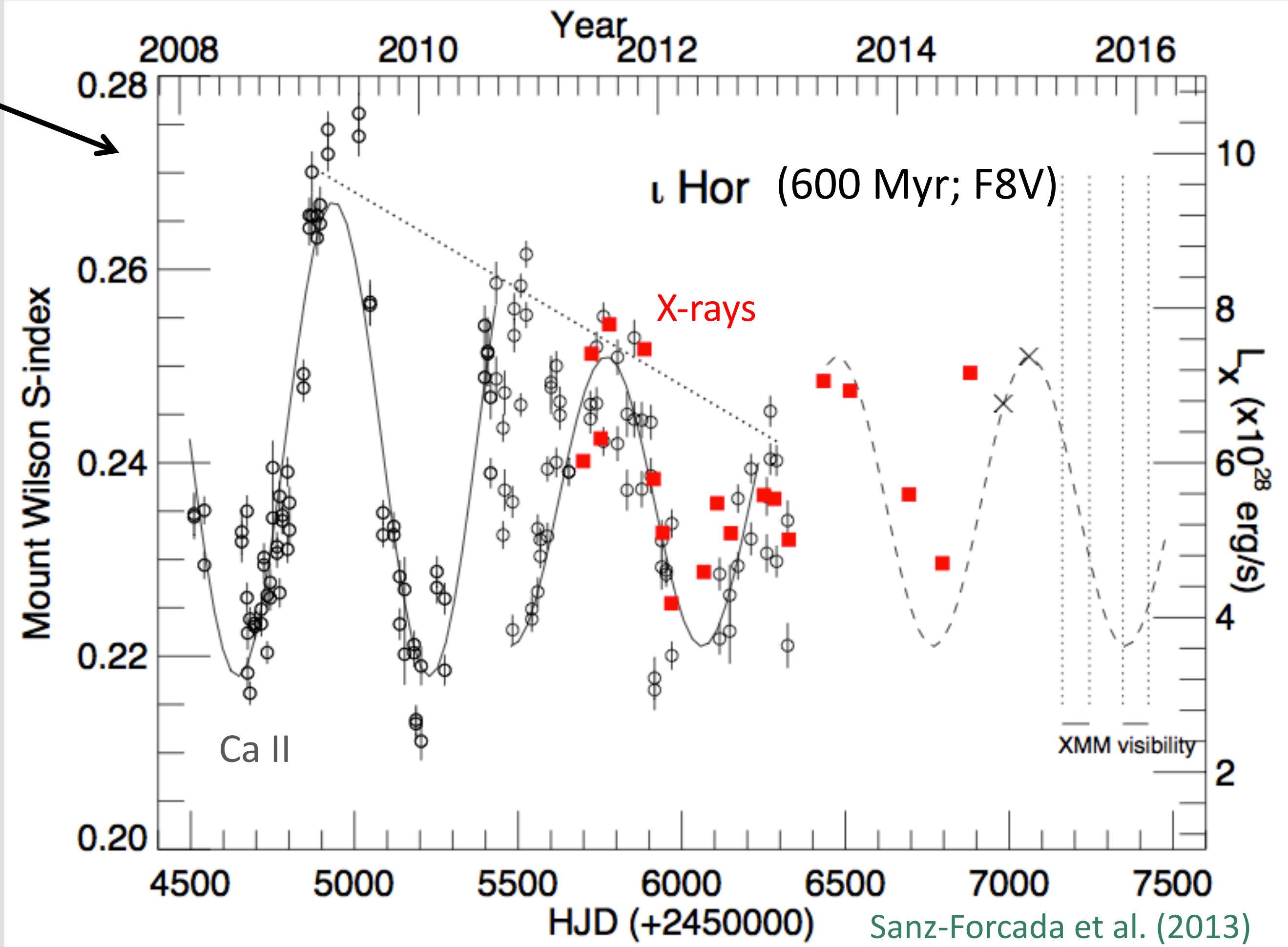

The outer atmosphere of the Sun
1700 Å
4500 K
1600 Å
10000 K
335 Å
2.5 MK
304 Å
50 000 K
211 Å
2 MK
193 Å
>1 MK
171 Å
0.6 MK
131 Å
10 MK
94 Å
6 MK
chromosphere
corona
photosphere
SDO Image Gallery

The Sun is a faint X-ray star !



Dynamo cycles in X-rays: Known for only 5 stars

Shortest known cycle: 1.6 yrs



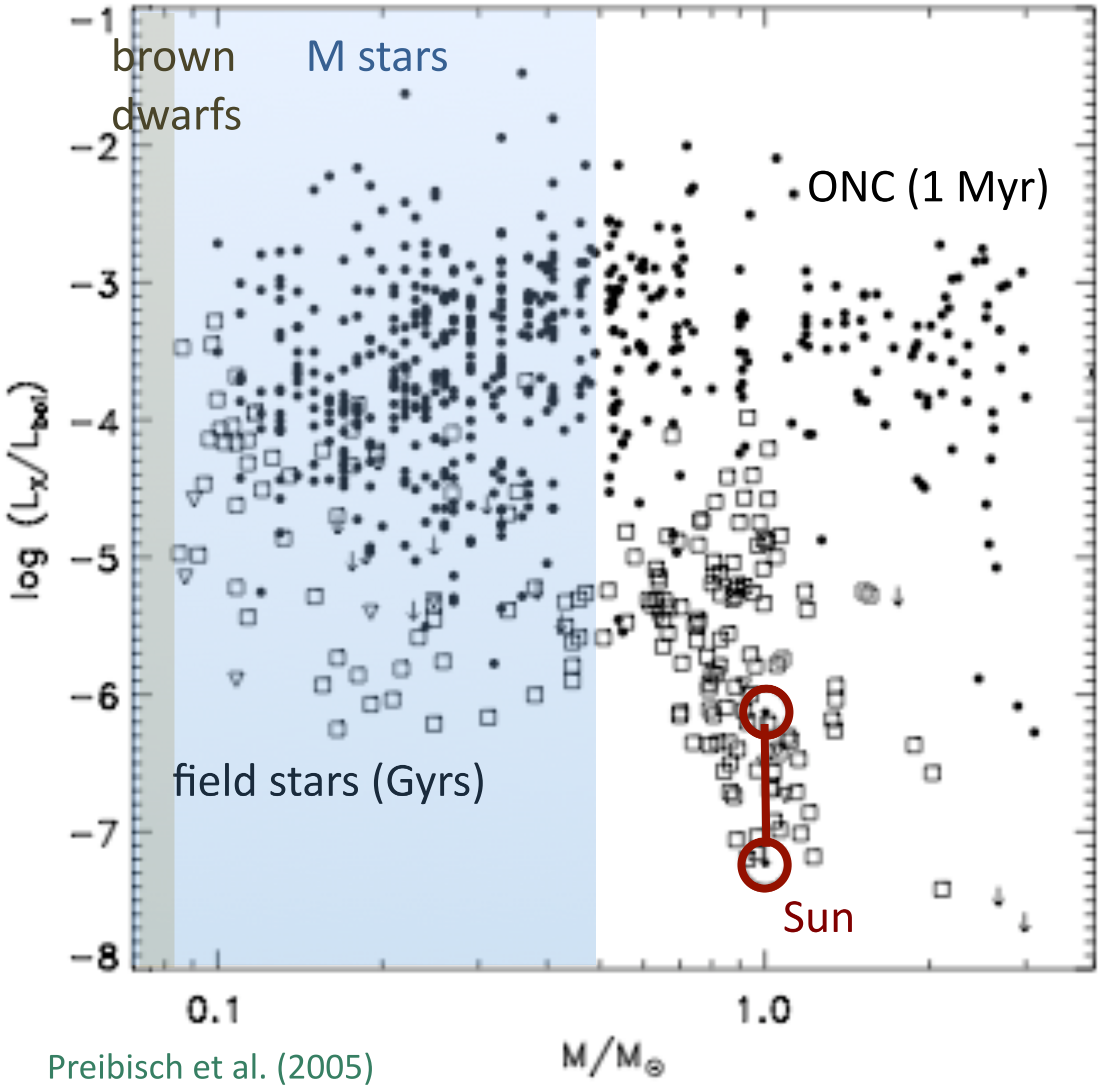
Sanz-Forcada et al. (2013)

Dynamo cycles on M stars:

X-rays: 0 (zero)

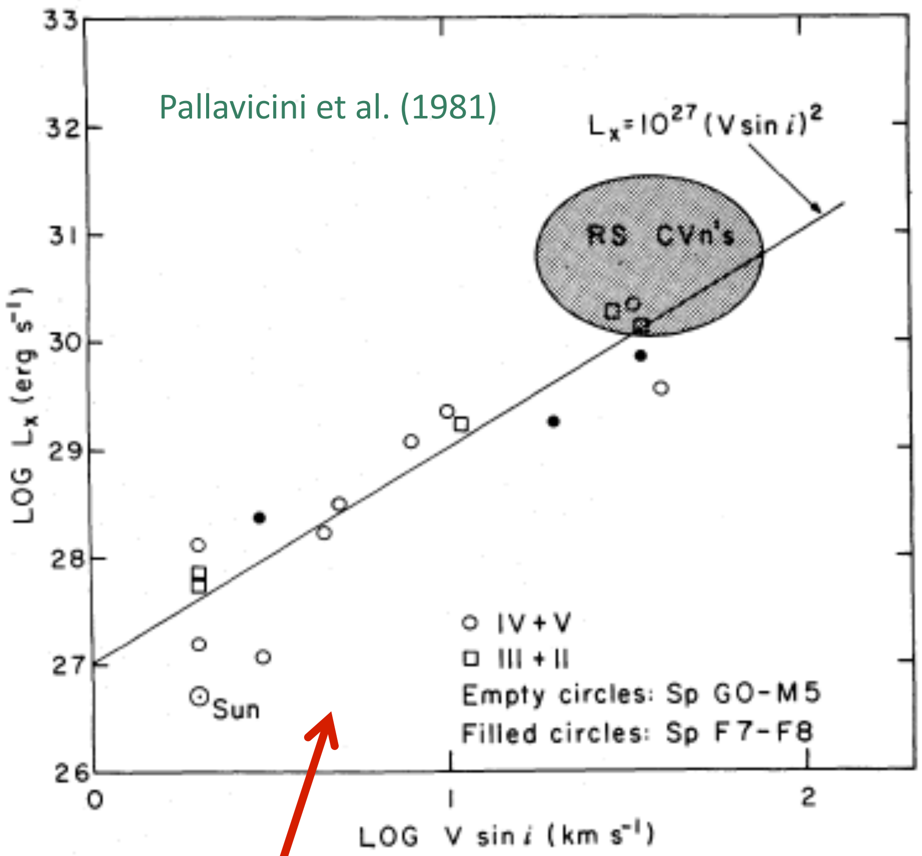
CaH&K, Hα: see planet search programs, e.g. Gomes da Silva 2011, 2012; Robertson et al. 2013

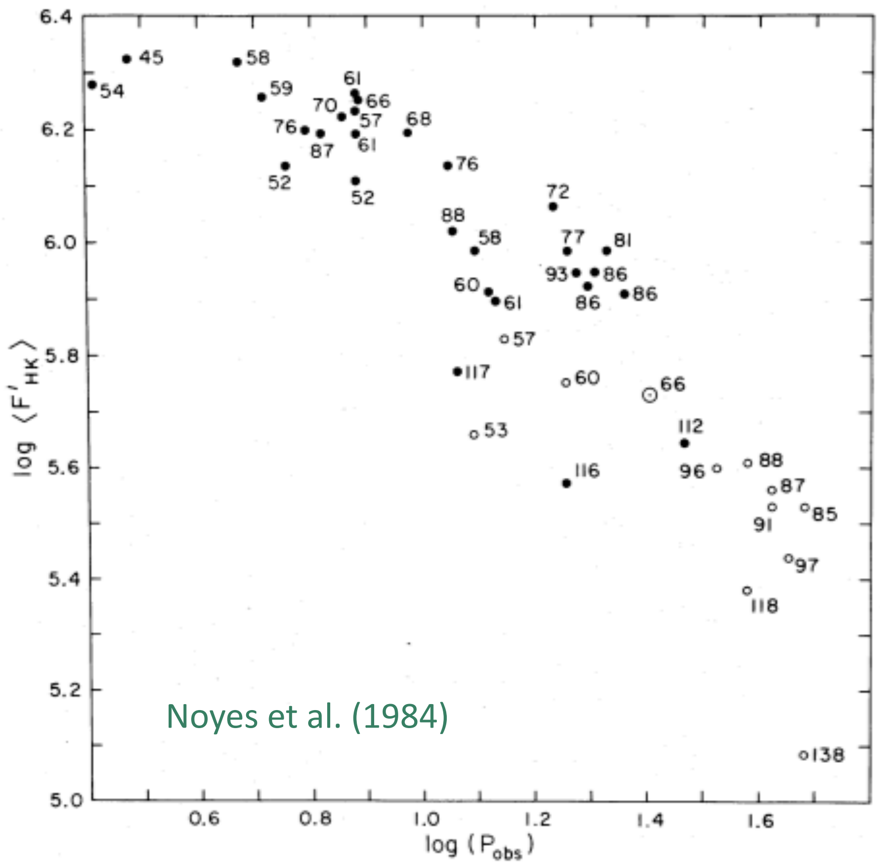
Why is there such a large spread of activity?



Preibisch et al. (2005)

X-ray + Ca HK emission depends on rotation rate
→ Activity produced by dynamo





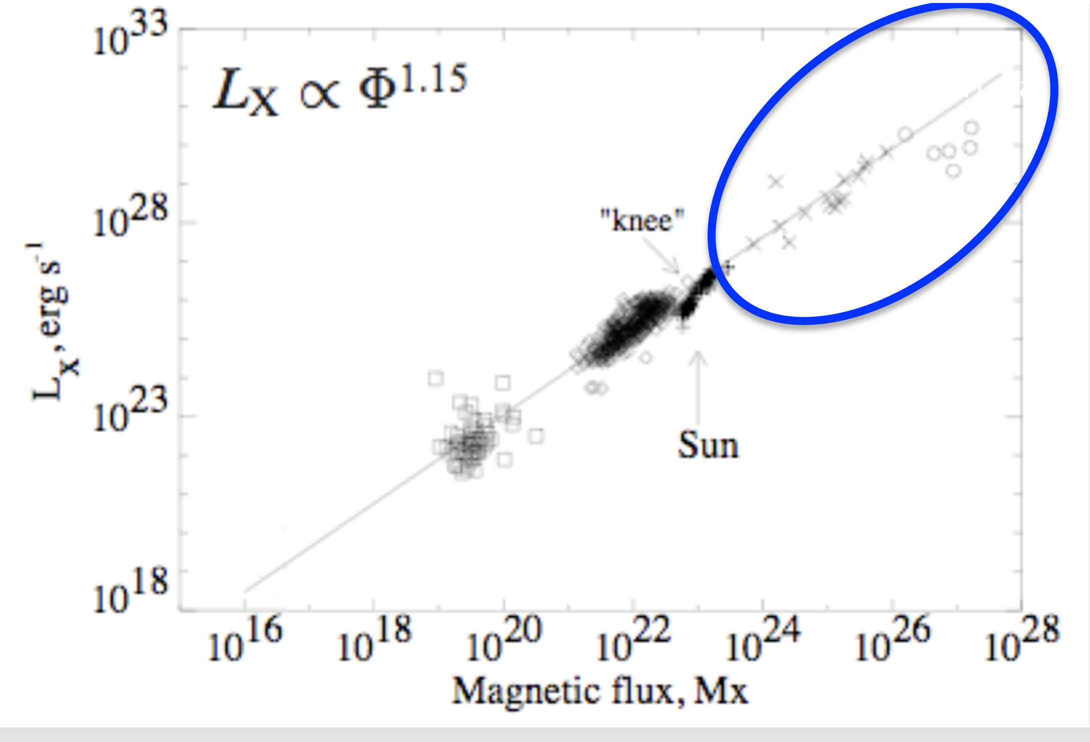
2 M stars only !

X-ray luminosity is related to magnetic flux → again the dynamo….

The aim of this paper is to show that all closed magnetic field structures appear to obey a universal observational relationship between magnetic flux and the energy radiated in X-rays, and that this relationship is linear or nearly linear over 12 orders of magnitude (see Fig. 1). While there are

Pevtsov et al. (2003)

Spatially unresolved



Comparison of Sun and stars not trivial due to different observing techniques:

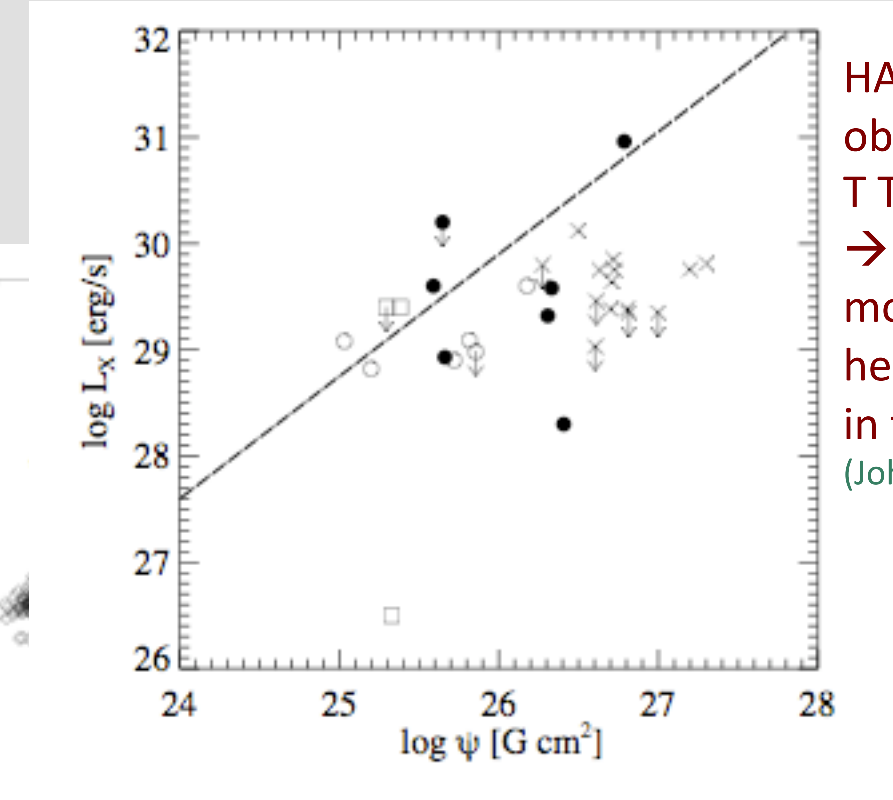
Φ_{mag} ….. from magnetogram for Sun

…… = Bf * πR_*^2 for stars

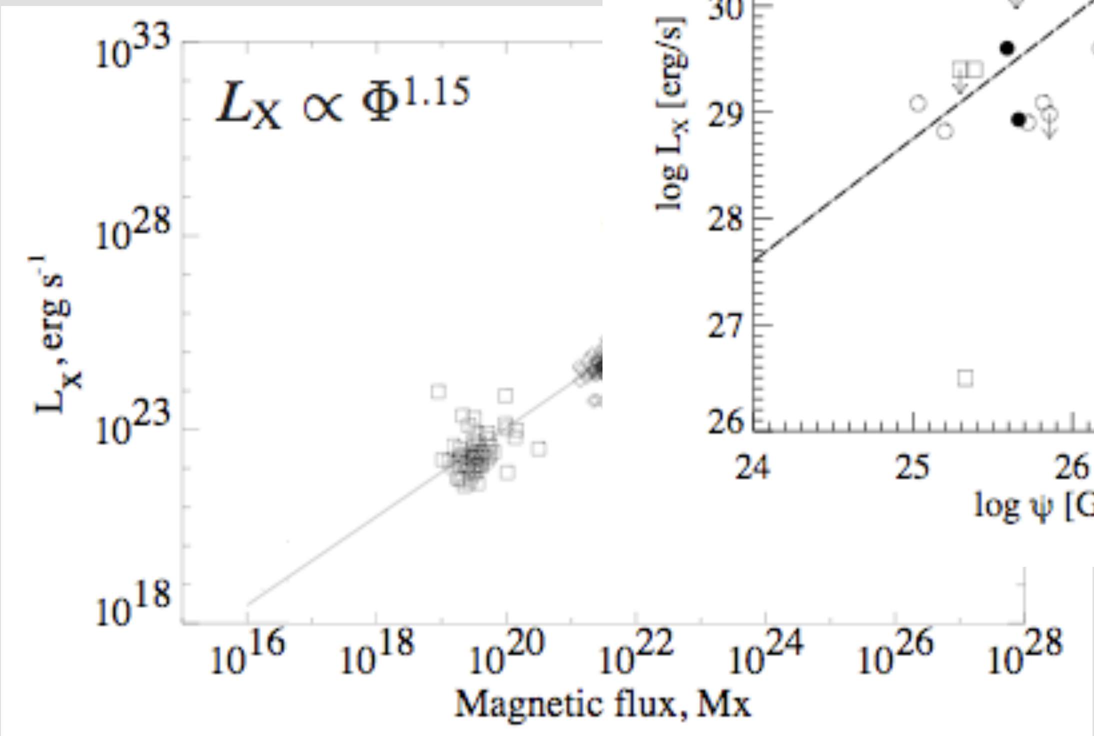
CONCLUSION:
1 dominating heating mechanism on Sun + stars, in different parts on surface

X-ray luminosity vs magnetic flux:
Special case of the pre-main sequence?

Hubrig et al. (2009)

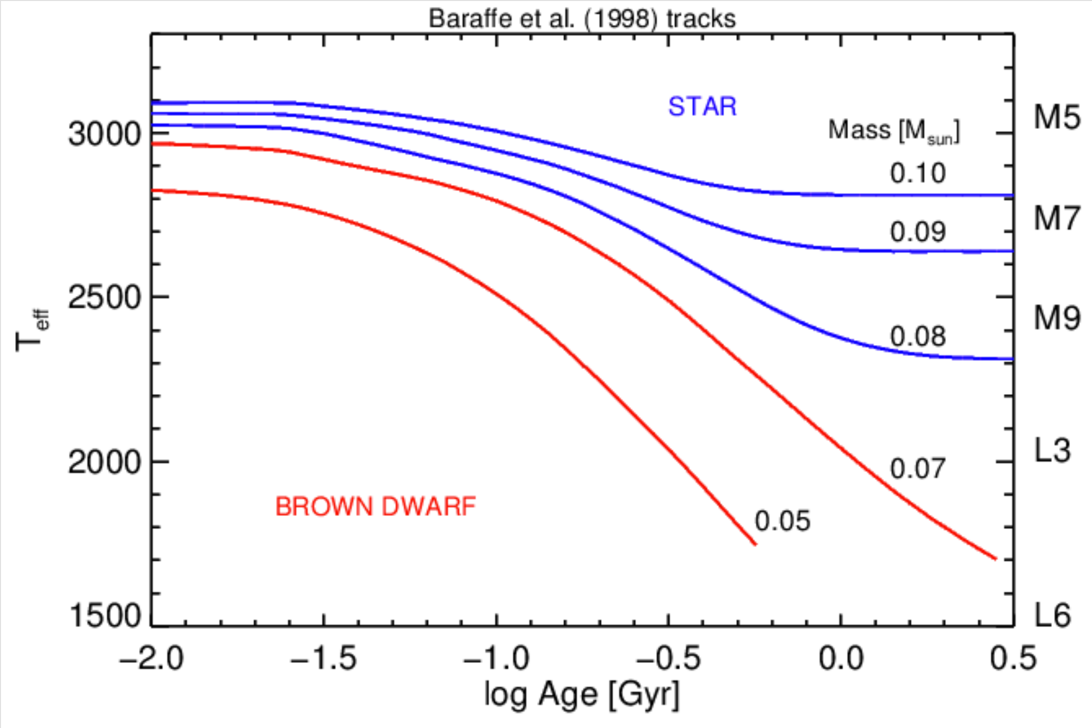


HAeBe stars
obey Pevtsov-relation,
T Tauri stars don't.
→
more inefficient
heating
in fully-conv stars?
(Johns-Krull et al. 2007)

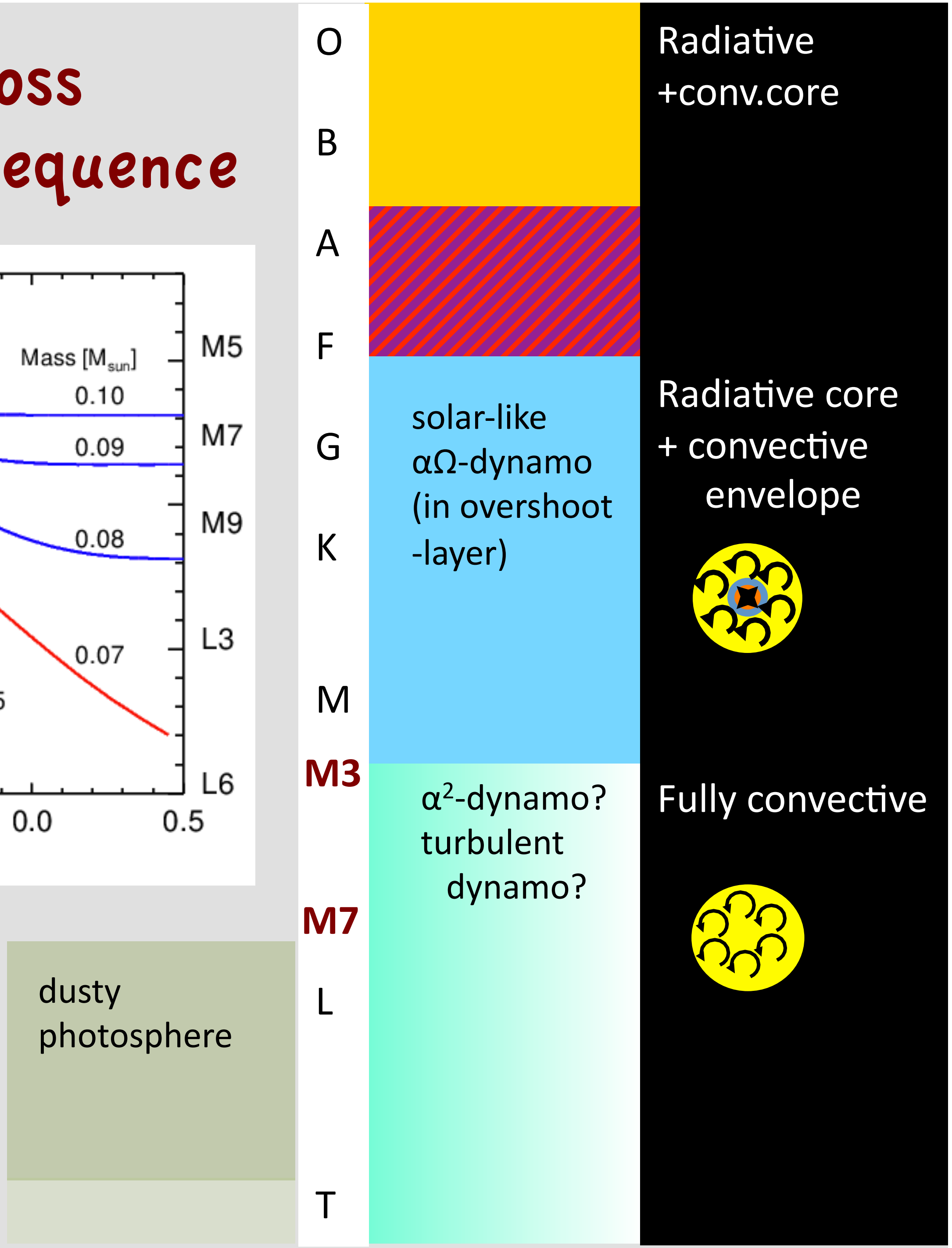


Pevtsov et al. (2003)

Magnetic activity across the stellar spectral sequence



Ultracool dwarf (UCD)
= object with SpT equal or later M7;
either star or brown dwarf



Why study activity on M stars ?

1. Understand outer atmospheres of cool stars

Link atmospheric properties of stars and planets (ultracool dwarfs)

2. Clue to angular momentum evolution

Rotation / activity / age connection

3. Quantify impact of stellar activity on circumstellar environment relevant for

STAR FORMATION

Photo-evaporation of pre-main sequence disks

EXOPLANETS

Planet atmosphere loss and chemistry

FUNDAMENTAL STELLAR PARAMETERS + EVOLUTION

"Radius inflation" and decreased T_{eff} → initial mass function

Why study activity on M stars ?

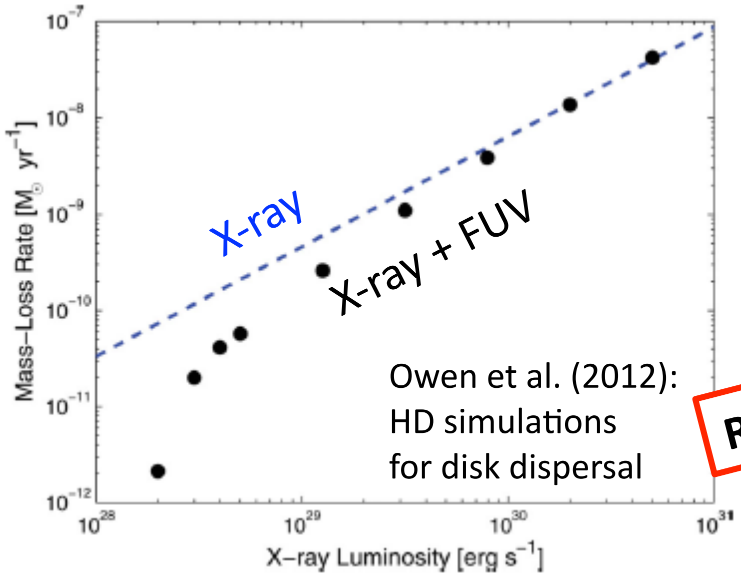
1. Understand outer atmospheres of cool stars

Link atmospheric properties of stars and planets (ultracool dwarfs)

2. Clue to angular momentum evolution

Rotation / activity / age connection

3. Quantify impact of stellar activity on circumstellar environment relevant for



STAR FORMATION

Photo-evaporation of pre-main sequence disks

Relative strength of X-rays and FUV ?

Why study activity on M stars ?

1. Understand outer atmospheres of cool stars

Link atmospheric properties of stars and planets (ultracool dwarfs)

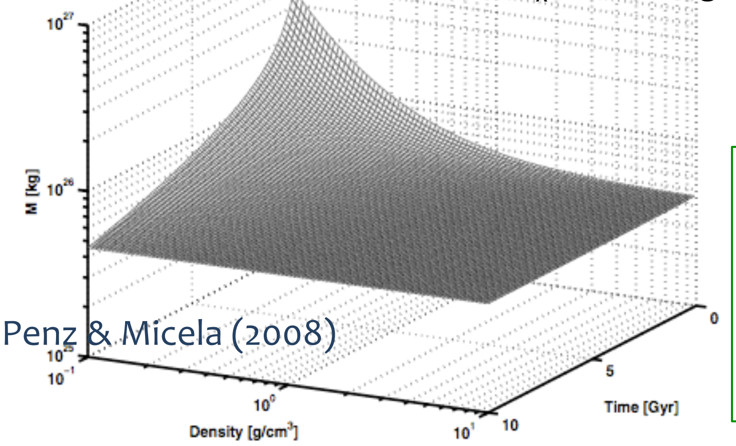
2. Quantify impact of stellar activity on circumstellar environment relevant for

EXOPLANETS

Planet atmosphere loss and chemistry

Parameters for GJ876d: 7.5 M_{earth} ,

Host star: M4, 6-10 Gyr, $L_x \sim 10^{26.5}$ erg/s



Penz & Micela (2008)

Mass loss rate

= received energy per time / potential energy

$$\frac{dM}{dt} = \frac{4\pi R_{pl}^3 F_X}{m M_{pl} G K}.$$

X-ray/UV irradiation = f(time) ?

Why study activity on M stars ?

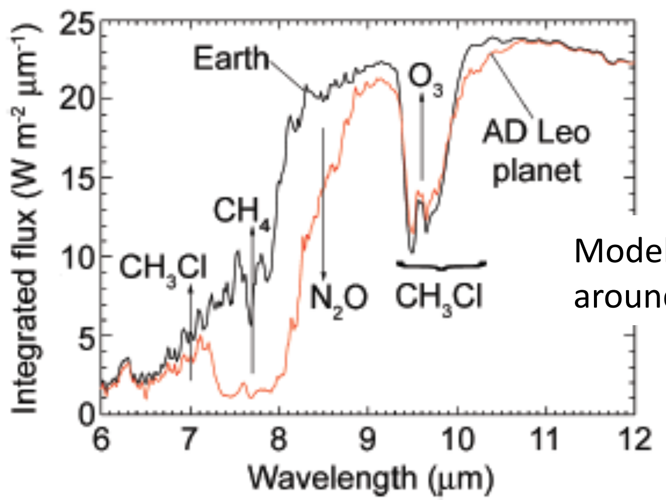
1. Understand outer atmospheres of cool stars

Link atmospheric properties of stars and planets (ultracool dwarfs)

2. Quantify impact of stellar activity on circumstellar environment relevant for

EXOPLANETS

Planet atmosphere loss and chemistry



Model spectrum of Earth and planet around M star (Segura et al. 2005)

X-ray/UV emission of TYPICAL M-star ?

Why study activity on M stars ?

1. Understand outer atmospheres of cool stars

Link atmospheric properties of stars and planets (ultracool dwarfs)

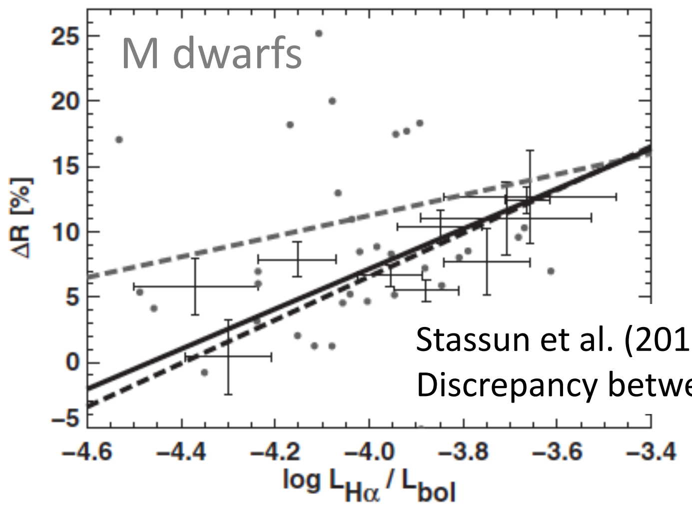
2. Clue to angular momentum evolution

Rotation / activity / age connection

3. Quantify impact of stellar activity on circumstellar environment relevant for

FUNDAMENTAL STELLAR PARAMETERS + EVOLUTION

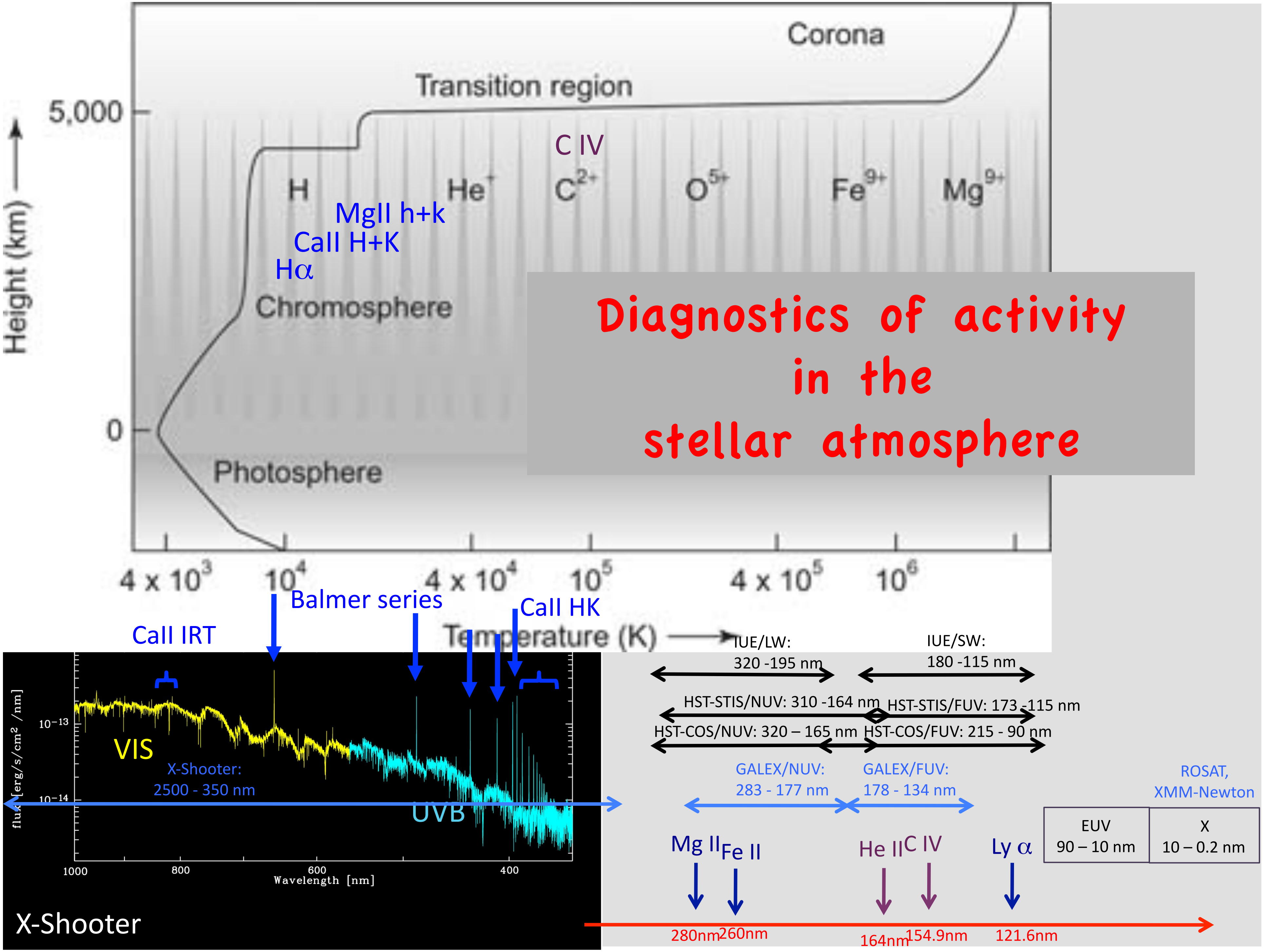
"Radius inflation" and decreased T_{eff}
→ wrong initial mass function



Stassun et al. (2012):
Discrepancy between observed and expec

Impossible to know stellar parameters without knowing activity ?

Diagnostics of activity in the stellar atmosphere



Questions to be addressed:

1. Strength of typical M star chromospheric + coronal emission (X-rays, UV, optical) ?

2. Activity on ultracool dwarfs: the link to planets ?

3. Time-evolution of M star activity from pre-main sequence to field star age ?

4. M dwarf Rotation/activity/age connection

X-Shooter GTO on low-mass star formation: accretion, outflows, activity

JETS AND DISKS AT INAF

Sample for chromospheric studies:

- 24 Class III objects in well characterized star forming regions: Lupus, sigma Ori, TWHya (1 – 10 Myrs)
- Individual interesting targets: DENIS 1048-3956

Diskless pre-main seq. stars

Nearby ultracool dwarf

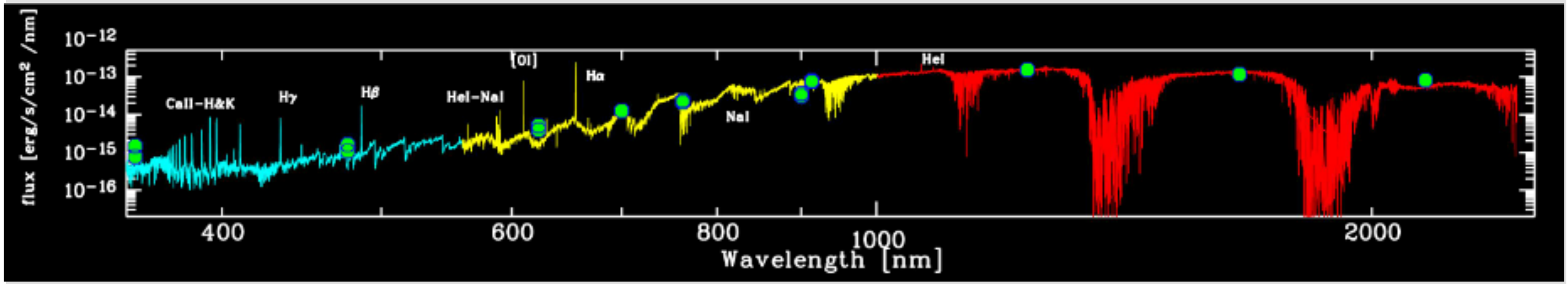
Instrument Setup:

1.0”/0.9”/0.9” (R ~ 5100/8800/5600)

0.5”/0.4”/0.4” (R ~ 9100/17400/11300)

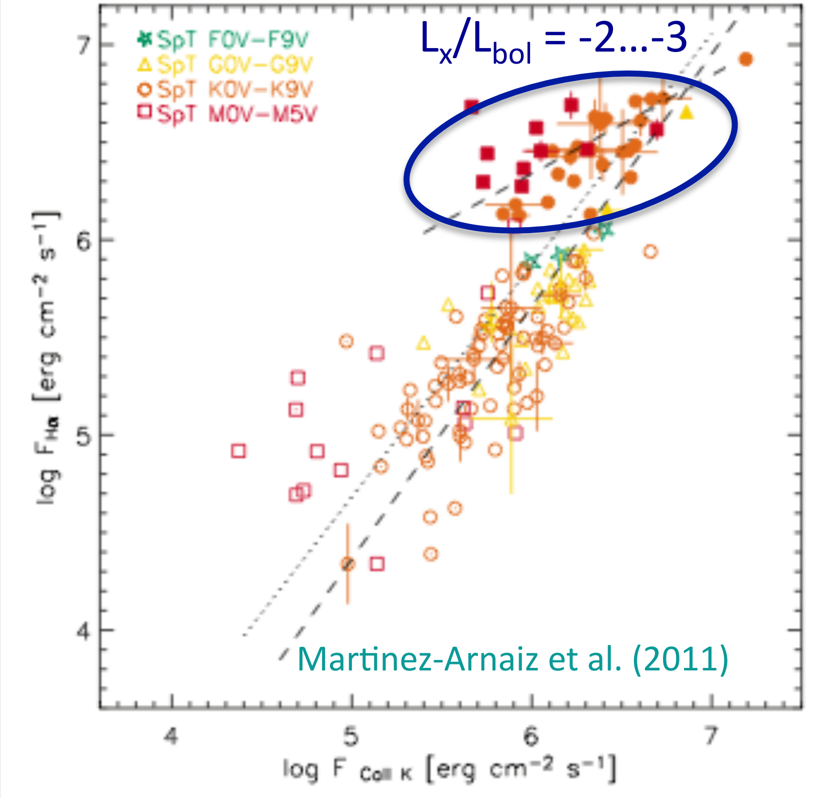
Project Status:

Observations completed: 8 nights total in P84 - P89; so far > 15 refereed papers, several others in prep.



Flux-flux relations for chromospheric activity

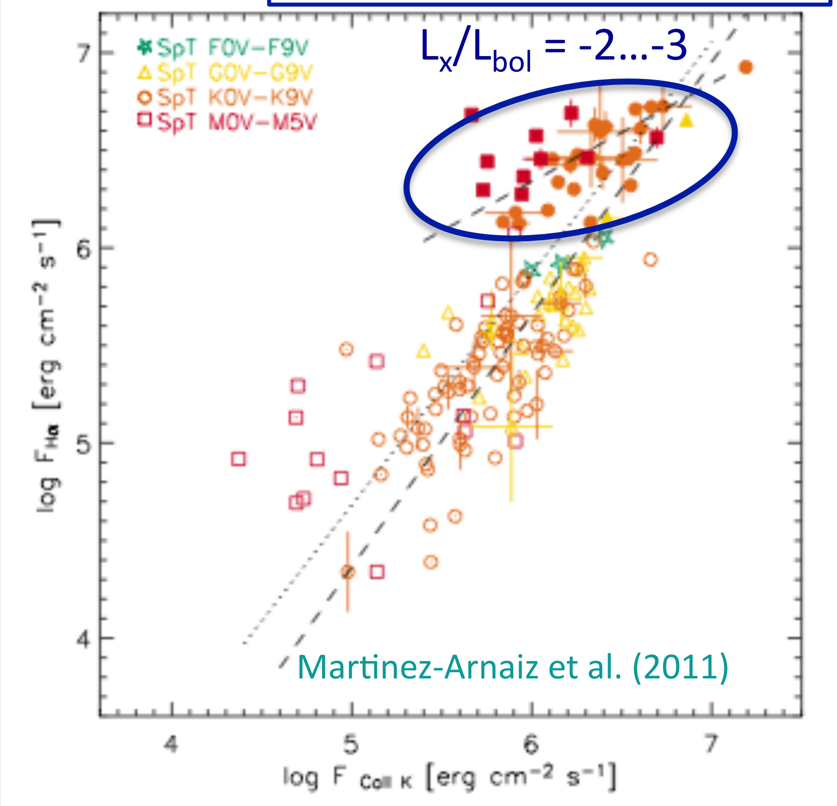
Sample:
300 single F...M dwarfs in the field



* Power-law relations
  between pairs of line fluxes
* `active' and `inactive' branch
  for M dwarfs

Flux-flux relations for chromospheric activity

Sample:
300 single F…M dwarfs in the field

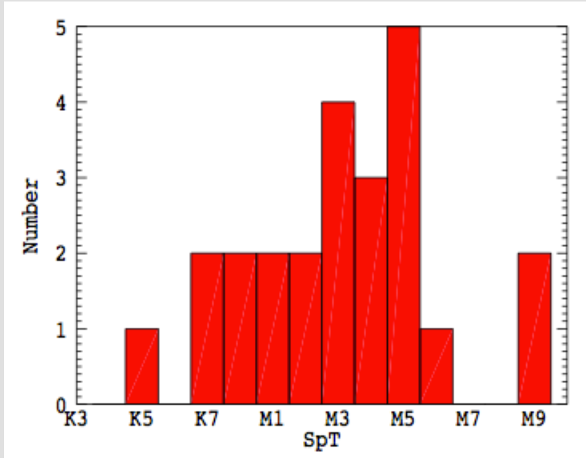


* Power-law relations
between pairs of line fluxes
* `active' and `inactive' branch
for M dwarfs

Aims with X-Shooter data:

1) flux-flux relations for ***young stars***
(Class III sample)

Stelzer et al. 2013, A&A 558A

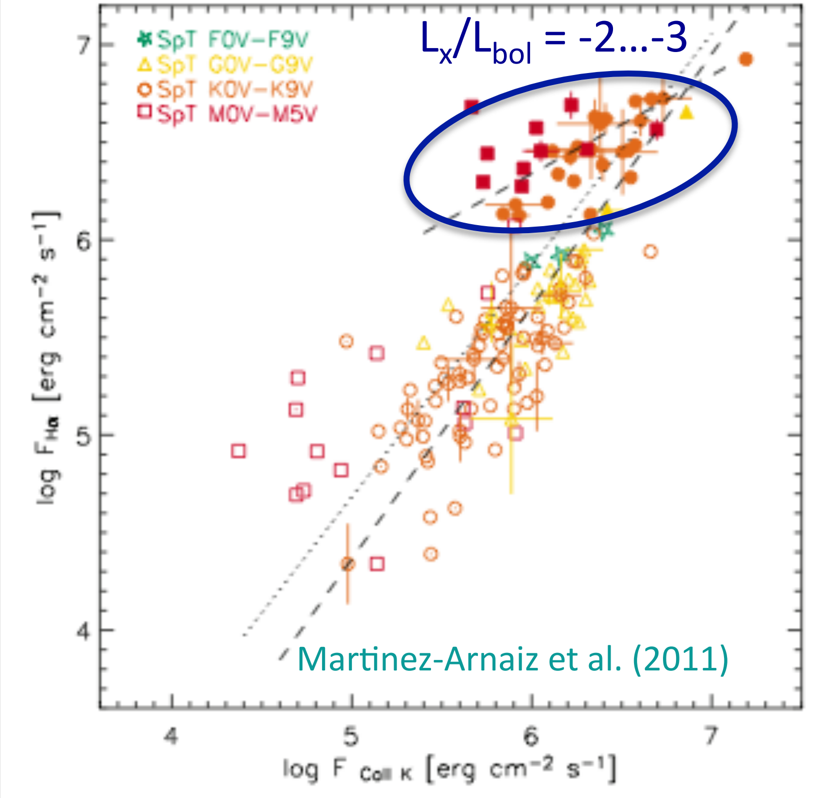


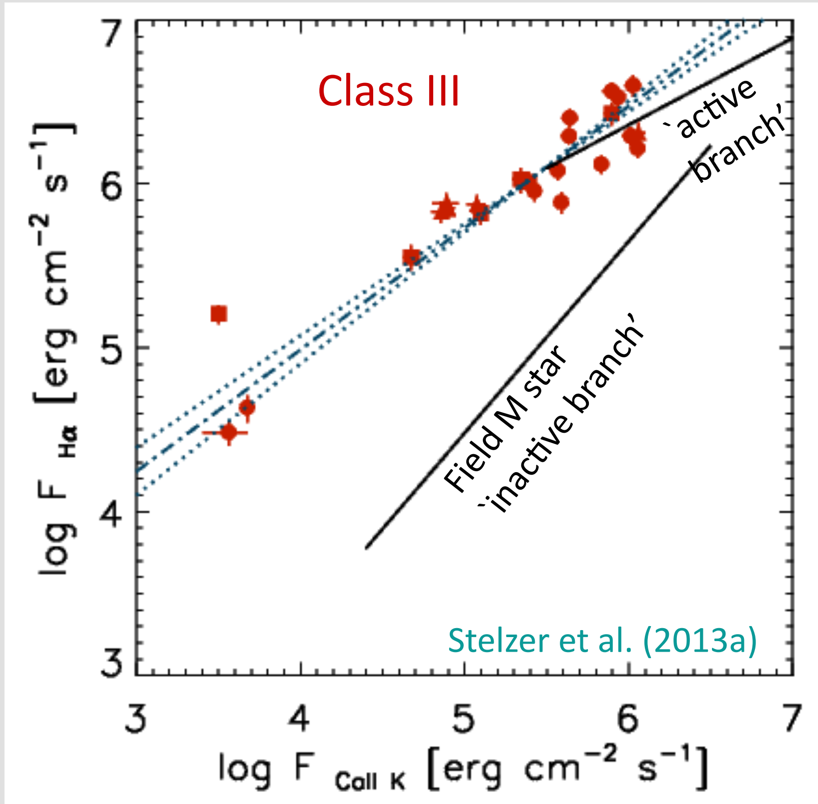
2) flux-flux relations for ***ultracool dwarfs***
(DENIS 1048-3956)

Stelzer et al. 2013, A&A 537

Flux-flux relations for chromospheric activity

Sample:
300 single F…M dwarfs in the field



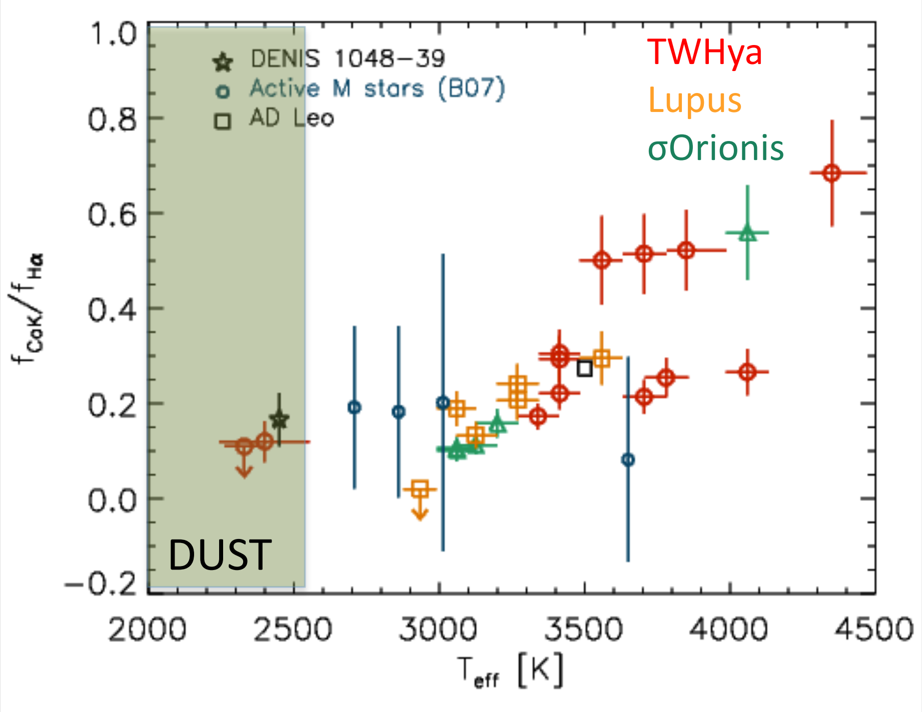


* Power-law relations
between pairs of line fluxes
* `active' and `inactive' branch
for M dwarfs

X-Shooter Class III sources:
Pre-MS stars are
on `active' branch of M dwarfs
Identify moving group members thru chromospheres

Physical conditions of chromospheric plasma

CaK/Hα ratio



Decreasing CaK/Hα with cooler T_{eff};
Hα dominant in late-M

(1) Meunier & Delfosse (2009):
Hα and CaK differently sensitive to filaments and plages on Sun

↓

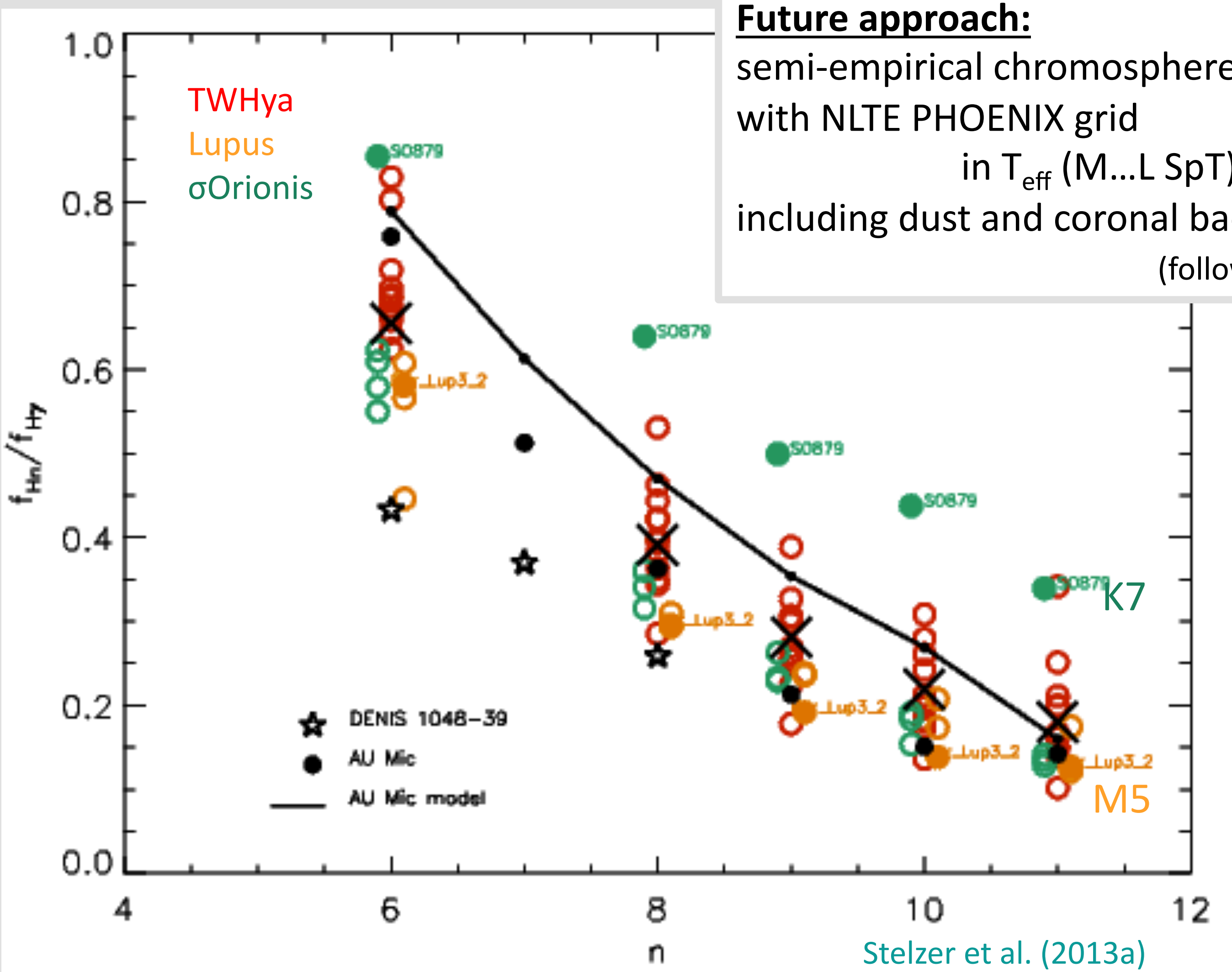
For stars:
Chromospheric structure changes with age and T_{eff}

(2) Scatter in flux ratio and flux-flux relations:

↓

chromospheric structure depends on other parameters: rotation?

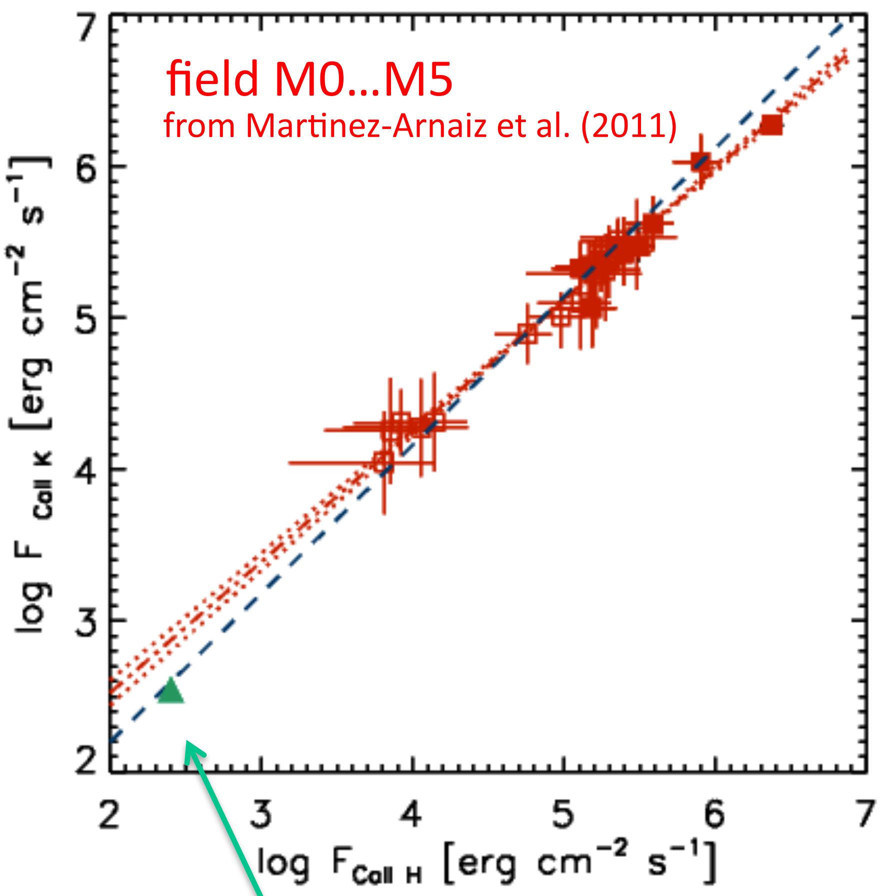
Physical conditions of emitting plasma
High-n Balmer decrements

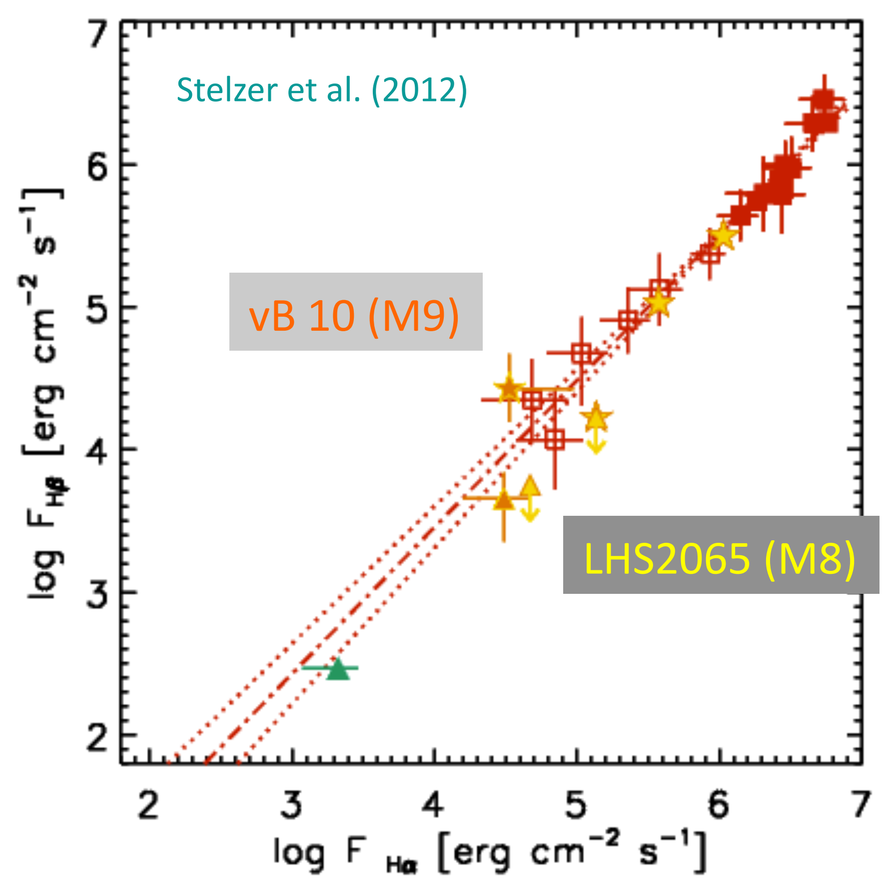


Stelzer et al. (2013a)

Future approach:
semi-empirical chromosphere model
with NLTE PHOENIX grid
in T_{eff} (M…L SpT) and log g (pre-MS…MS)
including dust and coronal backwarming
(following Fuhrmeister et al. 2005)

First extension of chromospheric flux-flux relations to ultracool dwarfs

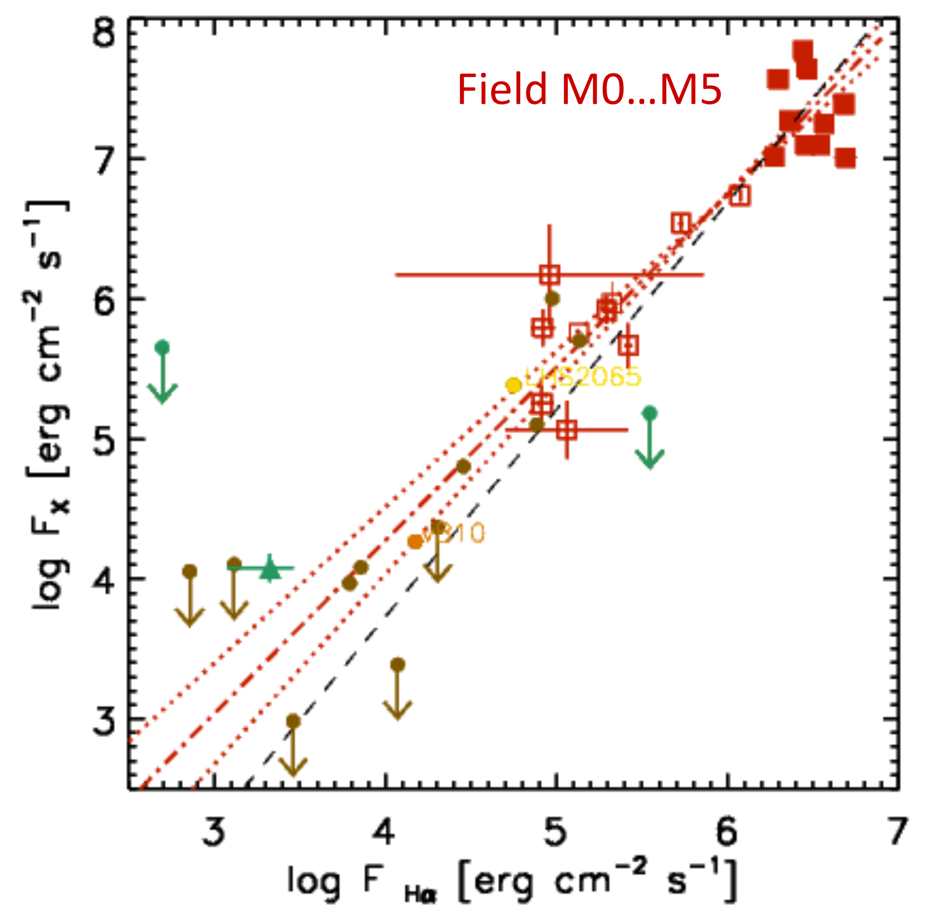


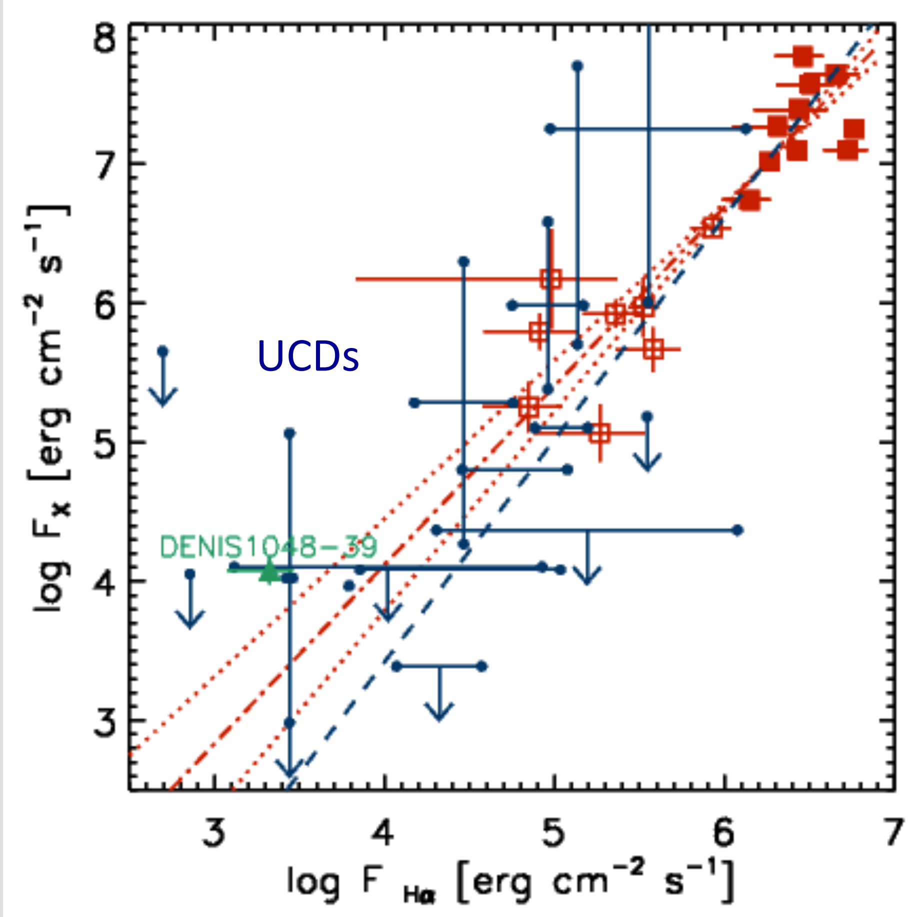


DENIS 1048-3956 (M9)

Only 1 flux-calibrated broad-band spectrum for UCD !

Coronal vs. chromospheric radiative loss (X-ray vs. Hα flux)





* UCDs represented by `quiescent' emission follow the early-M dwarf relation

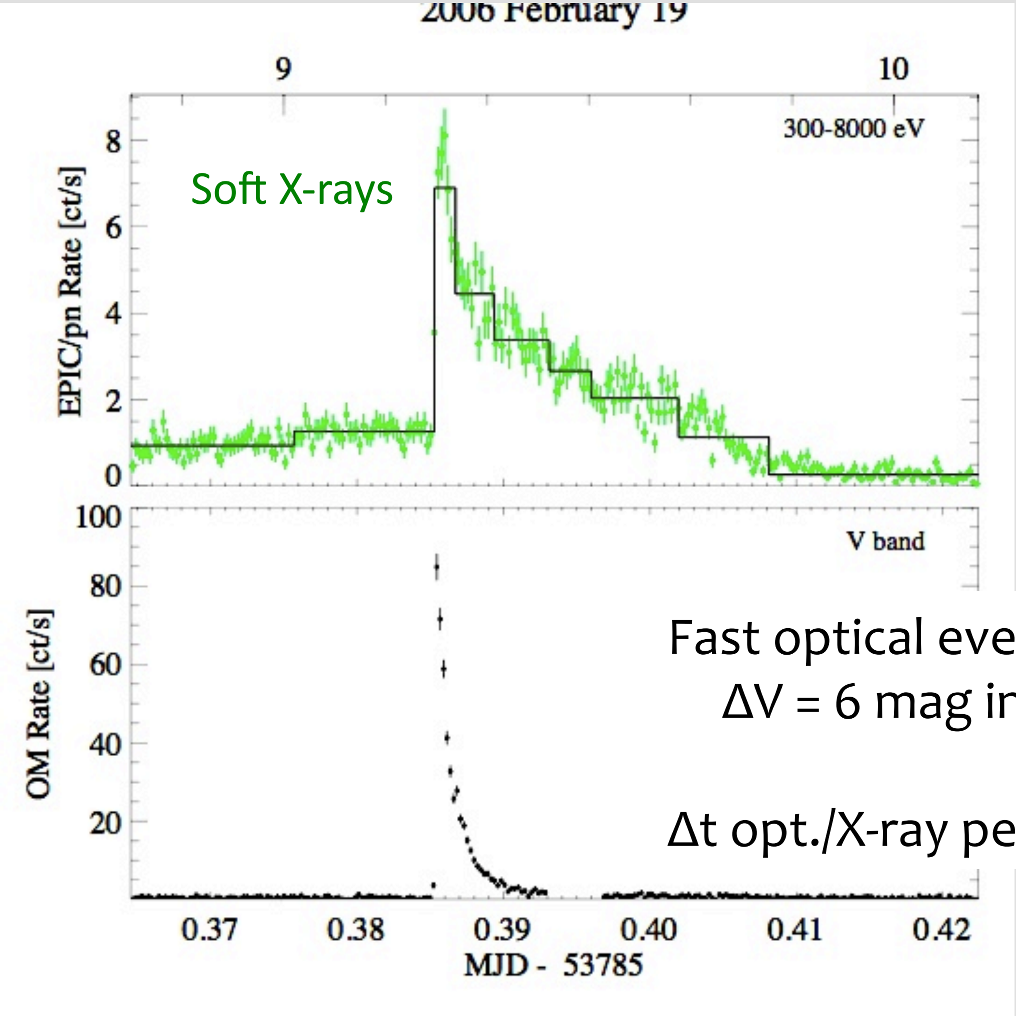
* Huge amplitudes of variability in UCDs (due to bias?)

Impressive X-ray flares on UCDs

The case of LP412-31 (M8)

SpT M9
D = 14.6 pc
W_{ha} = 24… 330 AA
B > 3.9 kG

LP412-31: simultaneous opt/X-ray flare with XMM-Newton



Fast optical event:
ΔV = 6 mag in 40 sec

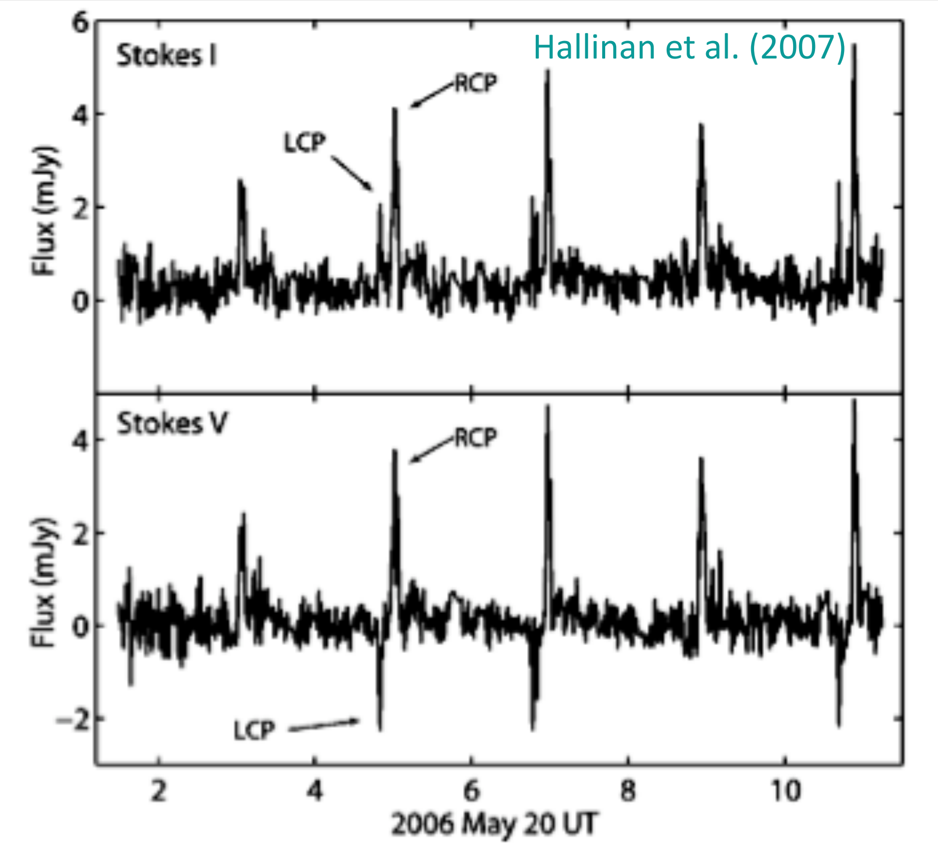
Δt opt./X-ray peak < 20 sec

Standard flare scenario predicts optical flare preceeding X-ray flare
because chromosphere is heated directly by accelerated electrons, and corona lights up in X-rays after evaporation of chromosphere.

Stelzer et al. (2006)

Radio-bursting UCDs
The case of TVLM513-46546

SpT M8.5
D = 10.6 pc
Vsini ~ 60 km/s
Log ($L_{h\alpha}$ /L_{bol}) = -4.6…-5.1
Log (L_x /L_{bol}) = -5.1



Observations:

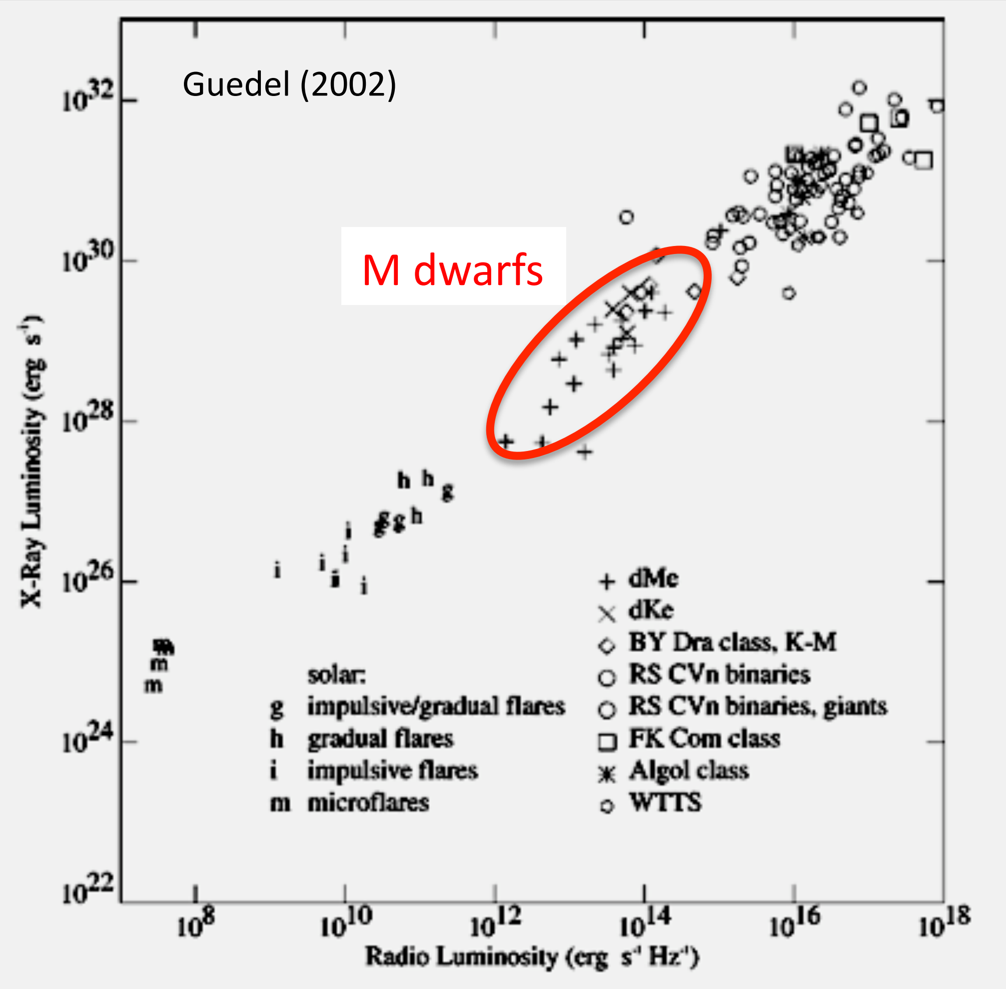
- periodic 100% LH + RH polar. bursts
- unpolarized persistent emission
- 2 bursts per rotation

→ need for beamed mechanism that produces polarized emission

Electron cyclotron maser
= instability caused by resonance between gyrating electrons and el.magn wave

The Guedel-Benz relation: Correlation of L_R and L_X for all (?) stars

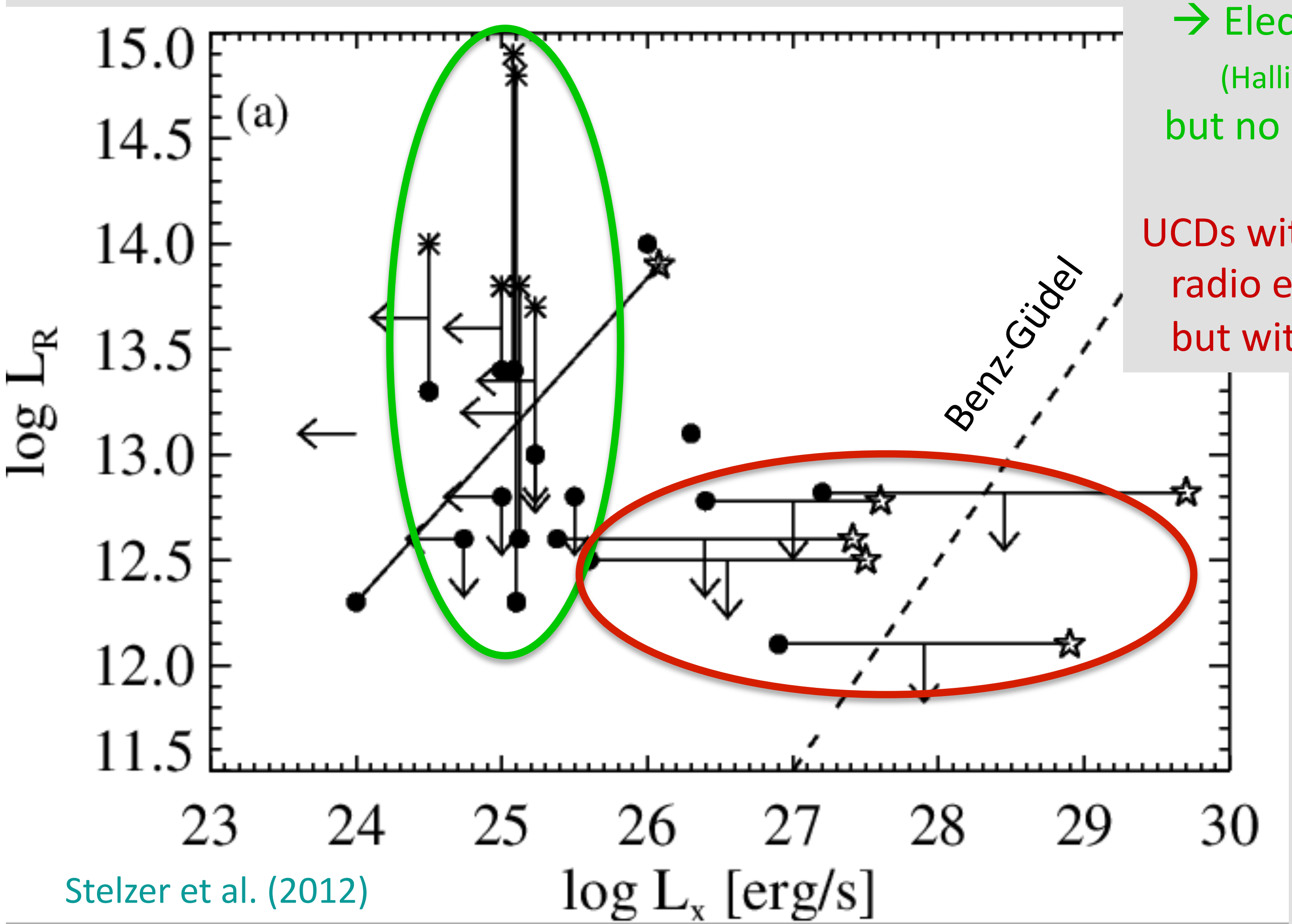
$$\log L_X \approx \log L_R + 15.5$$



X-ray and radio luminosities correlated over 6 dex
for various types of stars
(independent on age,spectral type, binarity, rotation, chromospheric activity)

Ultracool dwarfs violate the GB-relation

(first noted by Berger et al. 2002)



Stelzer et al. (2012)

UCDs with bright radio emission show radio bursts
→ Electron Cyclotron Maser
(Hallinan et al. 2006; 2008)
but no or very weak X-rays

UCDs without detectable radio emission but with X-ray flares

Origin for the radio/X-ray dichotomy of ultracool dwarfs ?

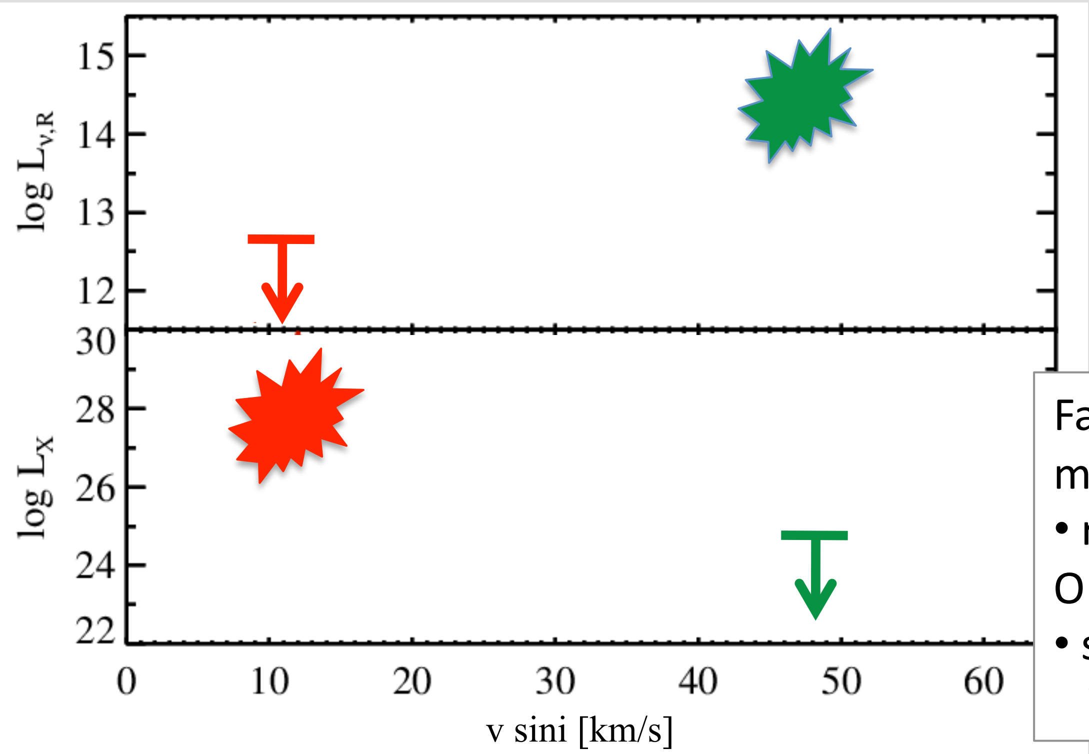
(Williams et a. 2013)

strong field ?

weak field ?

Slow rotation:
X-ray flaring, no radio

Fast rotation:
Radio bursts, no X-rays



Scenario from Stelzer et al. (2012b)

UCDs with bright radio emission show radio bursts
→ Electron Cyclotron Maser (Hallinan et al. 2006; 2008)
but no or very weak X-rays

UCDs without detectable radio emission but with X-ray flares

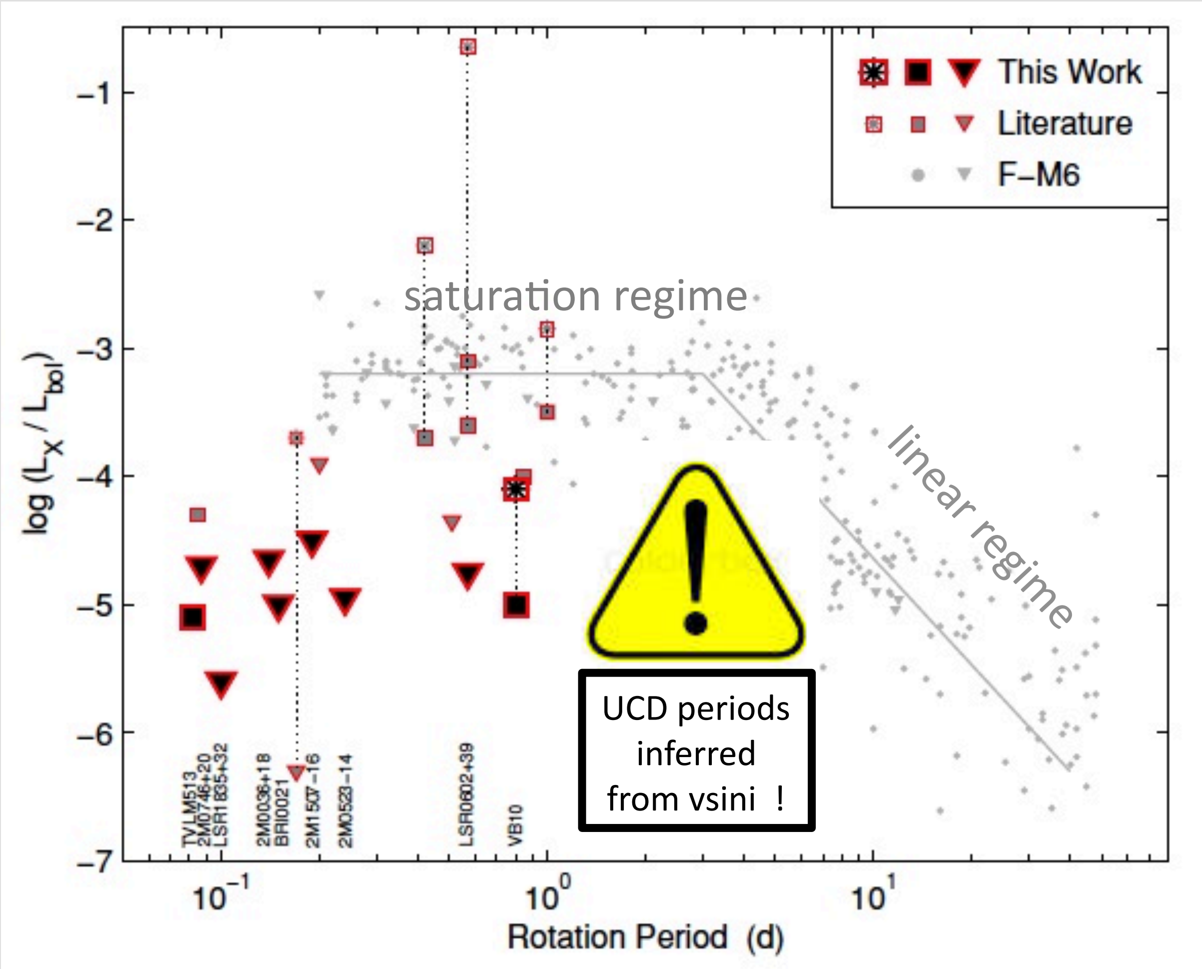
Fast rotators violate Güdel-Benz relation more than slow rotators (Berger et al. 2008)

- radio ruled by rotation, but X-rays not ?

OR

- selection effect: radio bursts not yet identified on slow rotators ?

Super-rotation in ultracool dwarfs ?



Origin for "super-saturation" in UCDs:

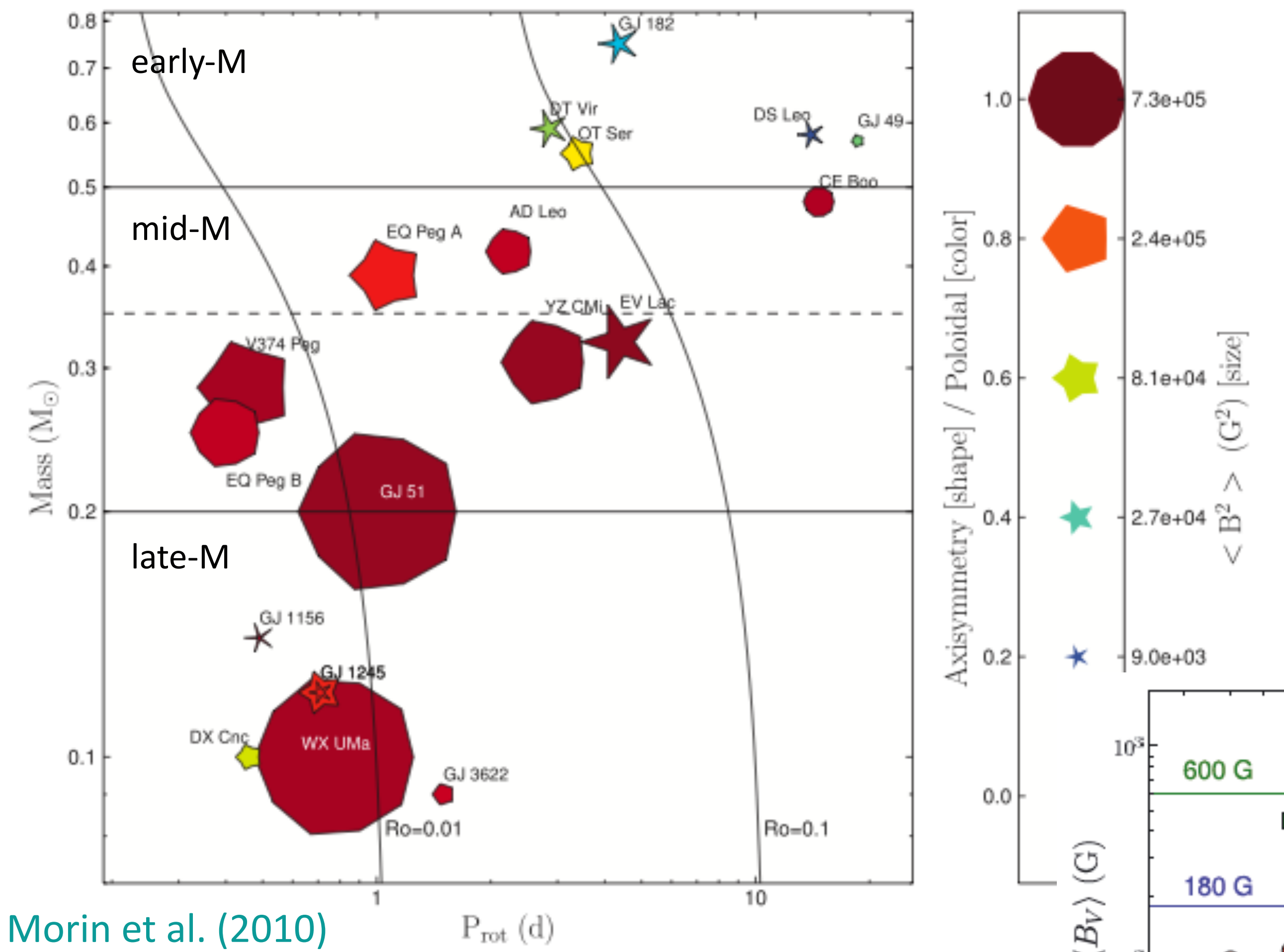
* as in higher-mass stars
(field dragged to pole;
centrifugal stripping; etc.)

* new effects:
(1) T_{eff} (high electr.resistivity)
(2) dynamo (magn.field)

Berger et al. (2010)

see also e.g. Reiners & Basri (2010); Cook et al. (2014)

Magnetic field structure in ultracool dwarfs

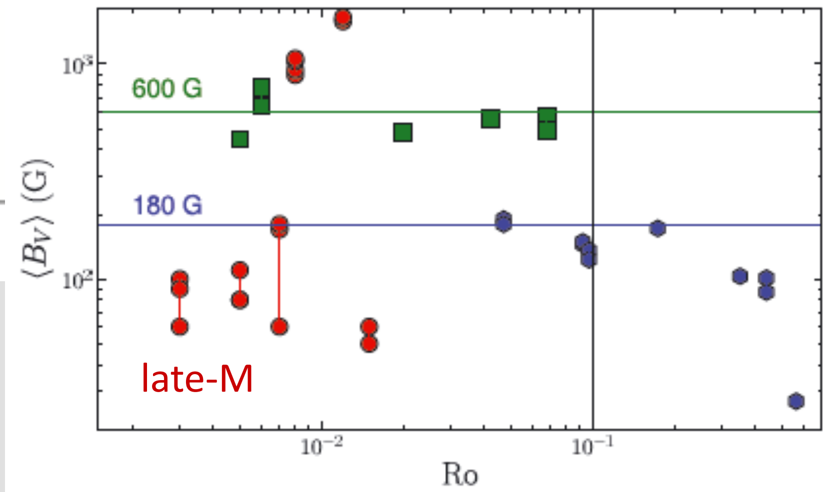


Morin et al. (2010)

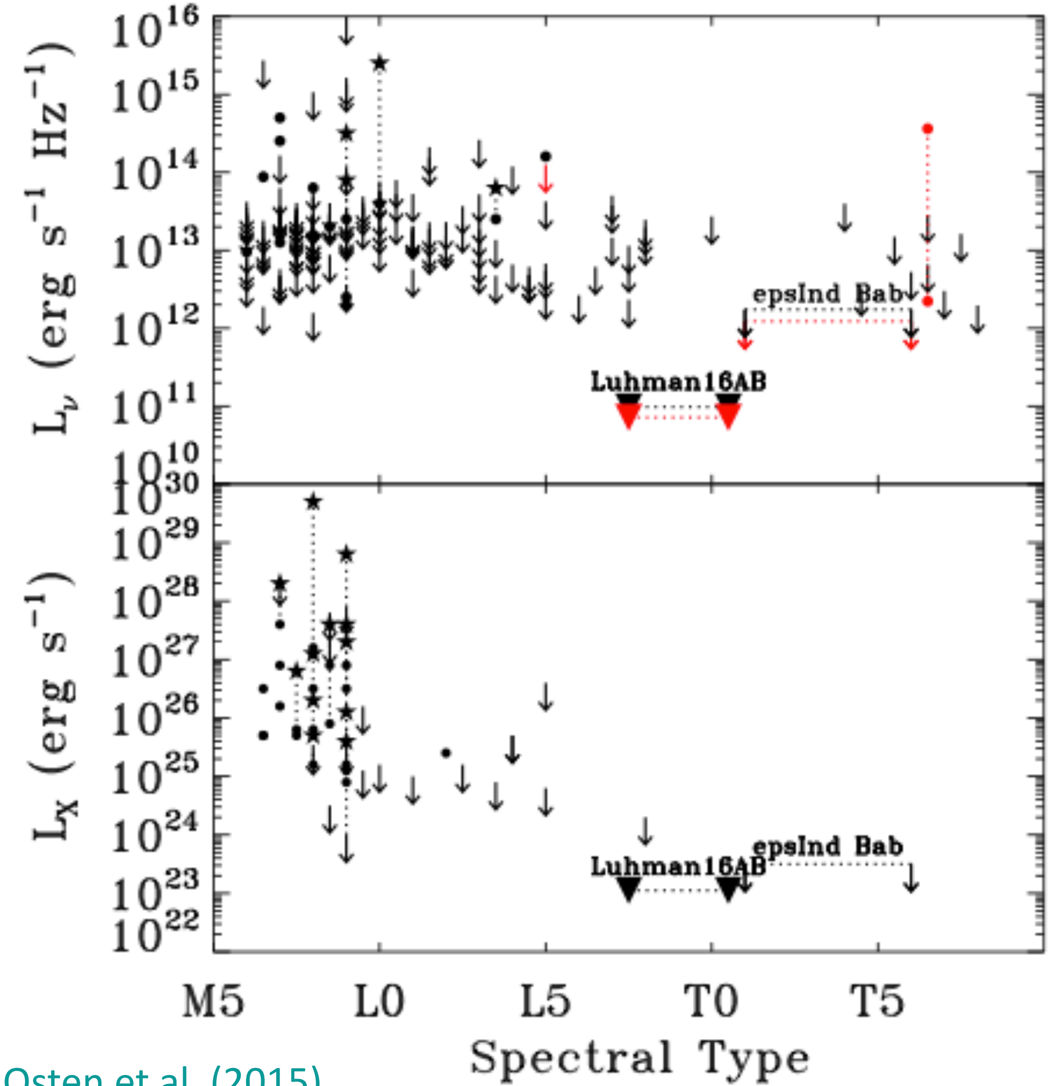
* UCDs (late-M):
Two types of fields

→

(A) two types of stars
or
(B) for given star switches between different states



Current limits for activity studies on UCDs

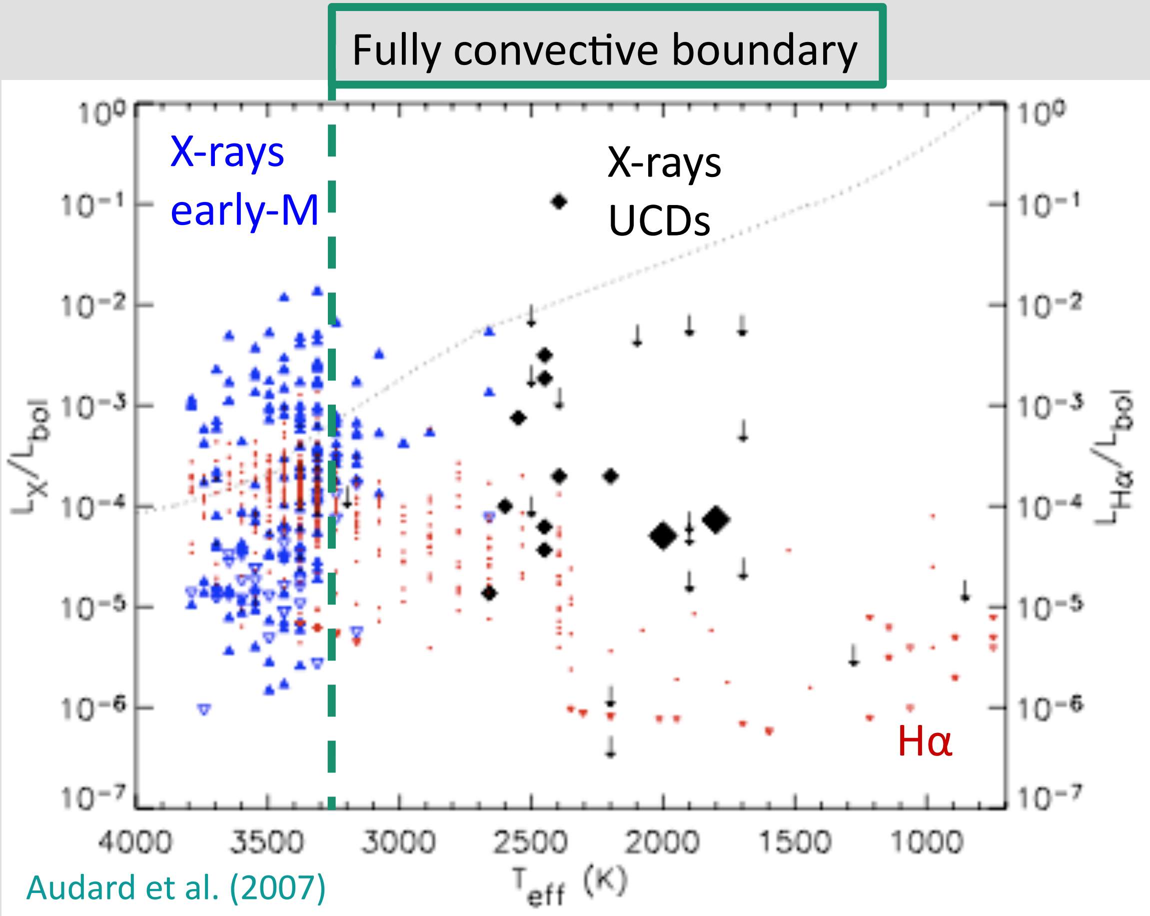


Osten et al. (2015)

Radio and X-ray upper limits for the nearest L/T dwarf,

Luhman16AB (2.0pc)

Coronae + chromospheres at the low-mass end of the main-sequence



* X-ray saturation level only during flares for ultra-cool dwarfs
→ too high resistivity in neutral atmospheres ?

* $L_{h\alpha}/L_{bol}$ decreases at >M7

* saturation level maintained across fully-convective boundary
→ no change in dynamo ?

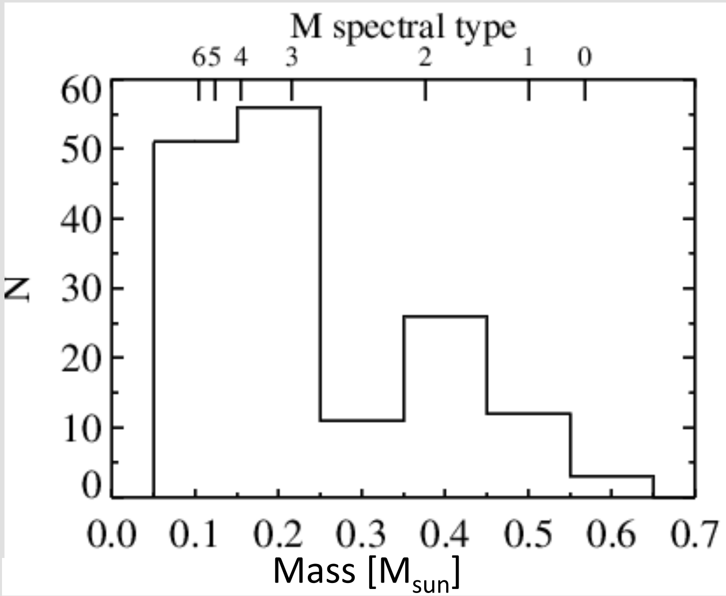
The `10pc sample' of nearby M dwarfs

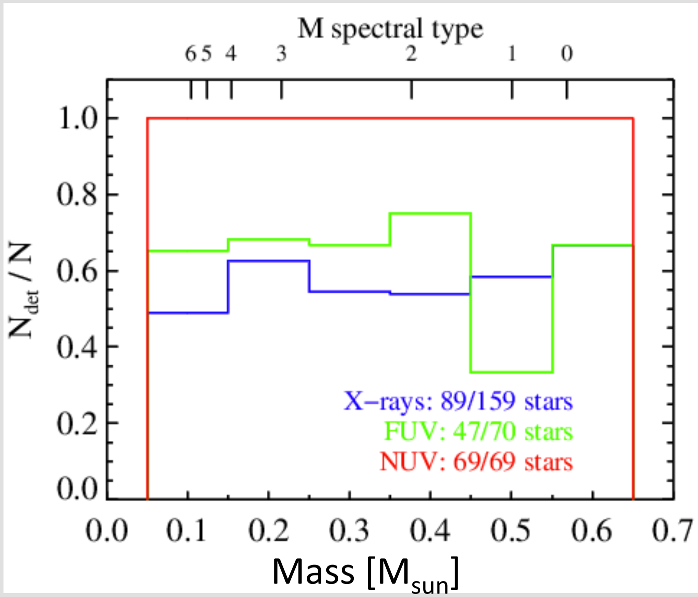
(Stelzer et al. 2013b)

Sample selection:
Lepine & Gaidos 2011 all objects within 10 pc (163 stars)

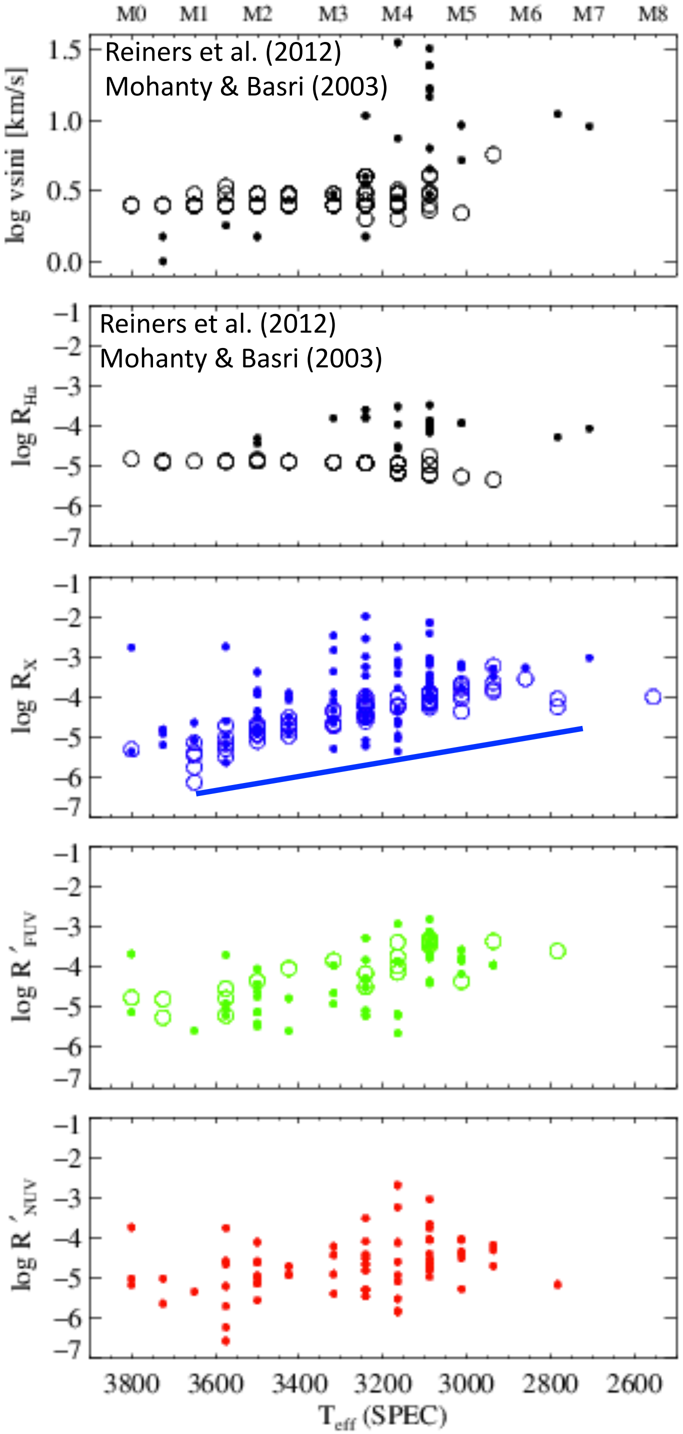
All-Sky Survey of
bright M dwarf stars (J < 10 mag; V – J > 2.7 mag)
with large proper motion (m > 40 mas/yr)

* Search GALEX GR6, ROSAT ASS, 2RXP, 2XMMi-DR3
* Determine stellar parameters (SpT, T_{eff}, bol.flux, mass)





* Completeness ~ 95% Mass function agrees with SDSS study except for lowest mass bin (SpT M5)



Activity indices and stellar properties

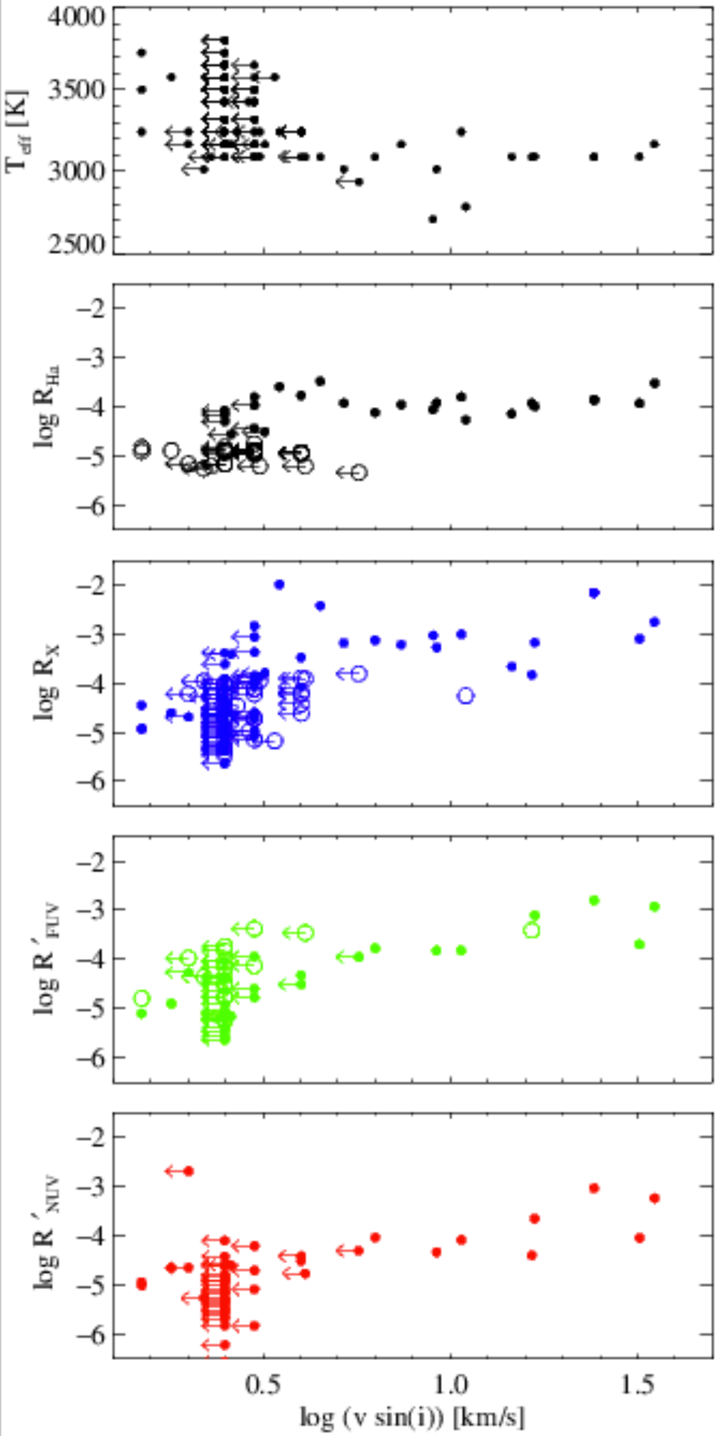
Stelzer et al. (2013b)

R_x lower envelope due to sensitivity limit of RASS

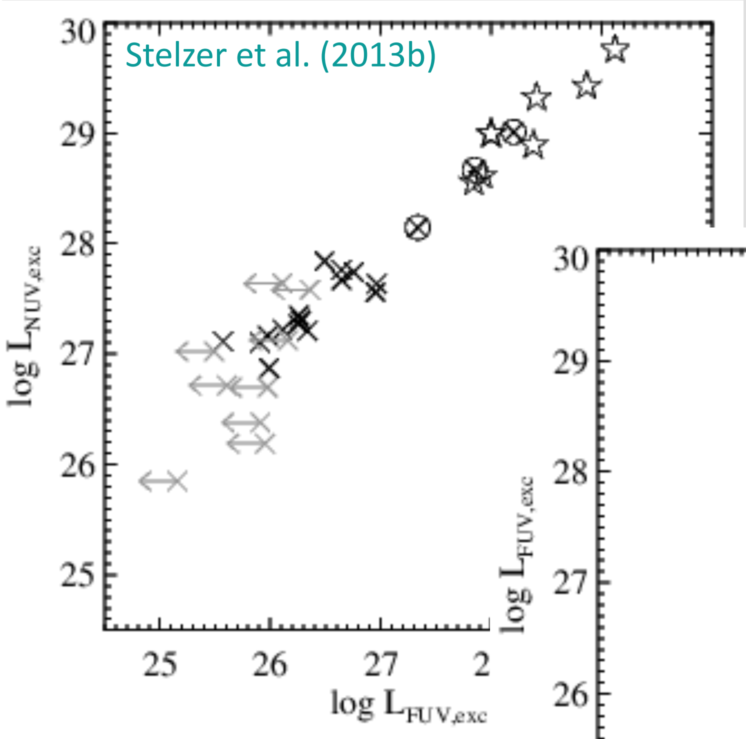
Spread of R_i for given T_{eff} due to vsini distr.
(largest spread at fully conv.boundary)

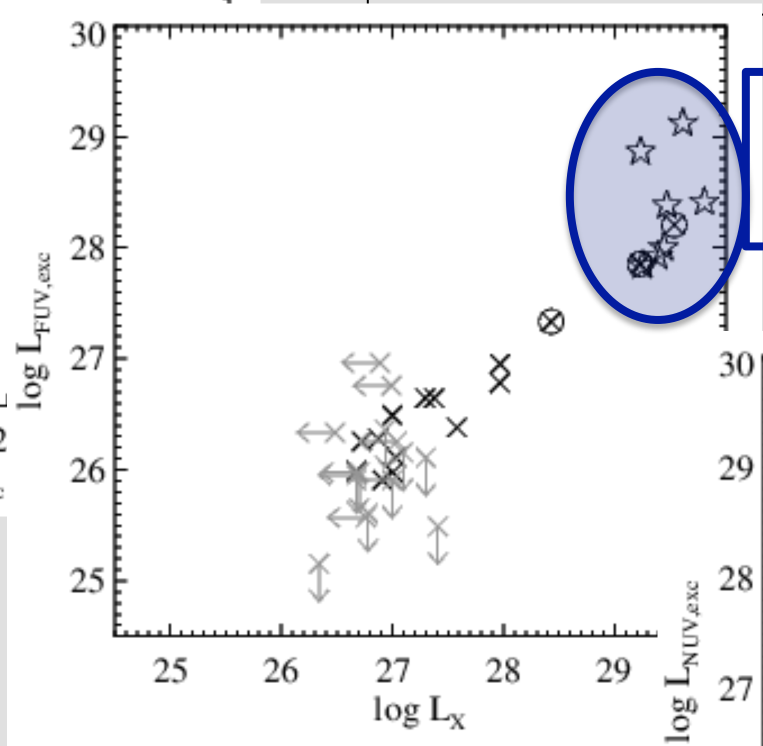
Faster rotators = higher act.levels with `saturation'

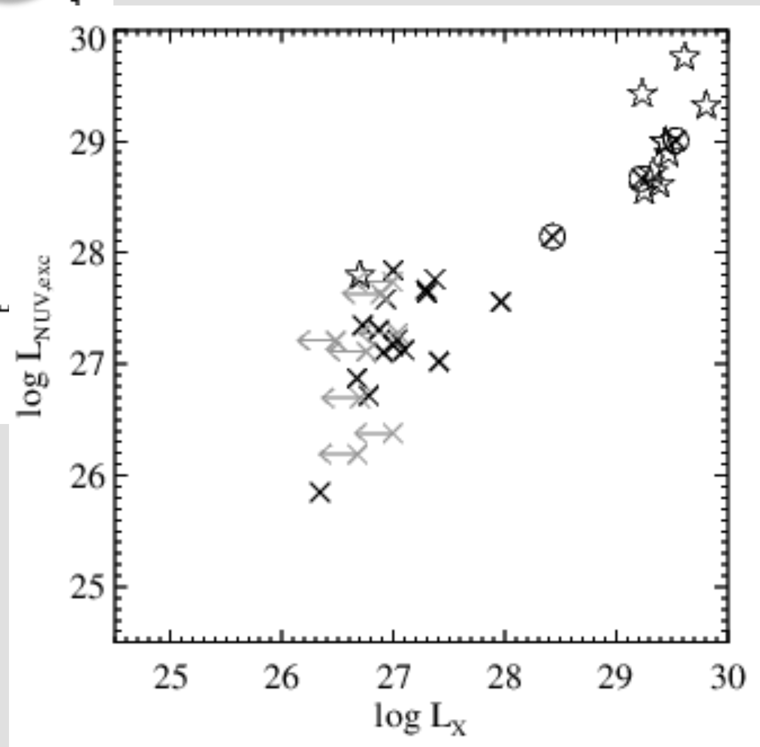
Only SpT later M3 are saturated
→ rot.evolution



Young M stars within 10pc







Early-M stars (M0…M3):

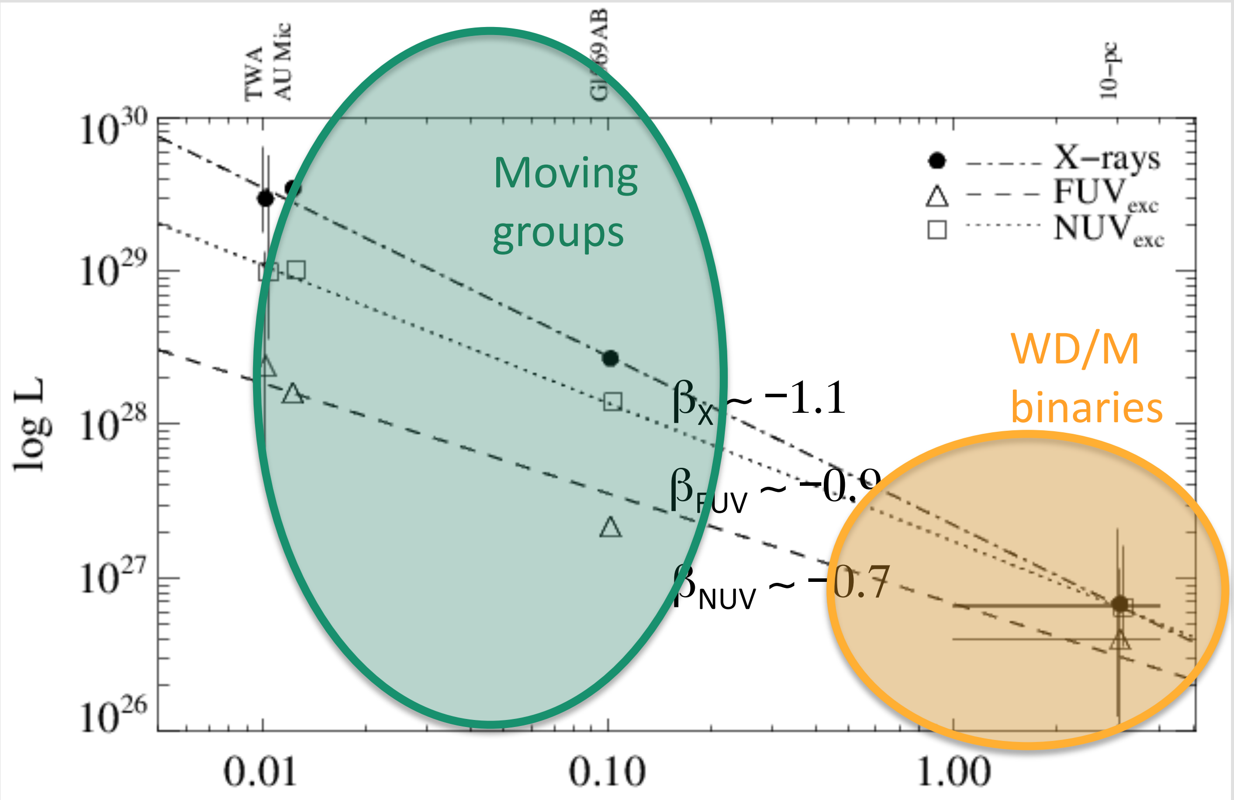
10Myr →	young field →	old field
(TWA)	(10pc-sample)	(10pc sample)
★	⊗	×

$L_X/L_{FUV} > 0.01$
→ disk photoevaporation
dominated by X-rays (Owen et al. 2012)

* All stars follow same relation
* Clear decay of activity with age

* Similar differences for R_i
(but smaller due to age dependence of L_{bol})

Age evolution of activity in M stars



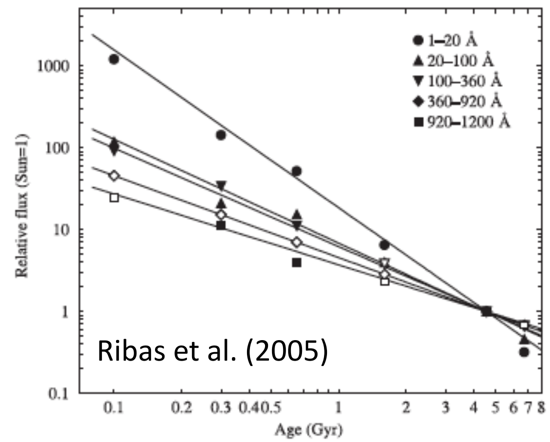
Stelzer et al. (2013)

See also Shkolnik & Barman (2014)

* high-energy emission drops by 3 dex from 10Myr to Gyrs

* age decay faster at shorter λ

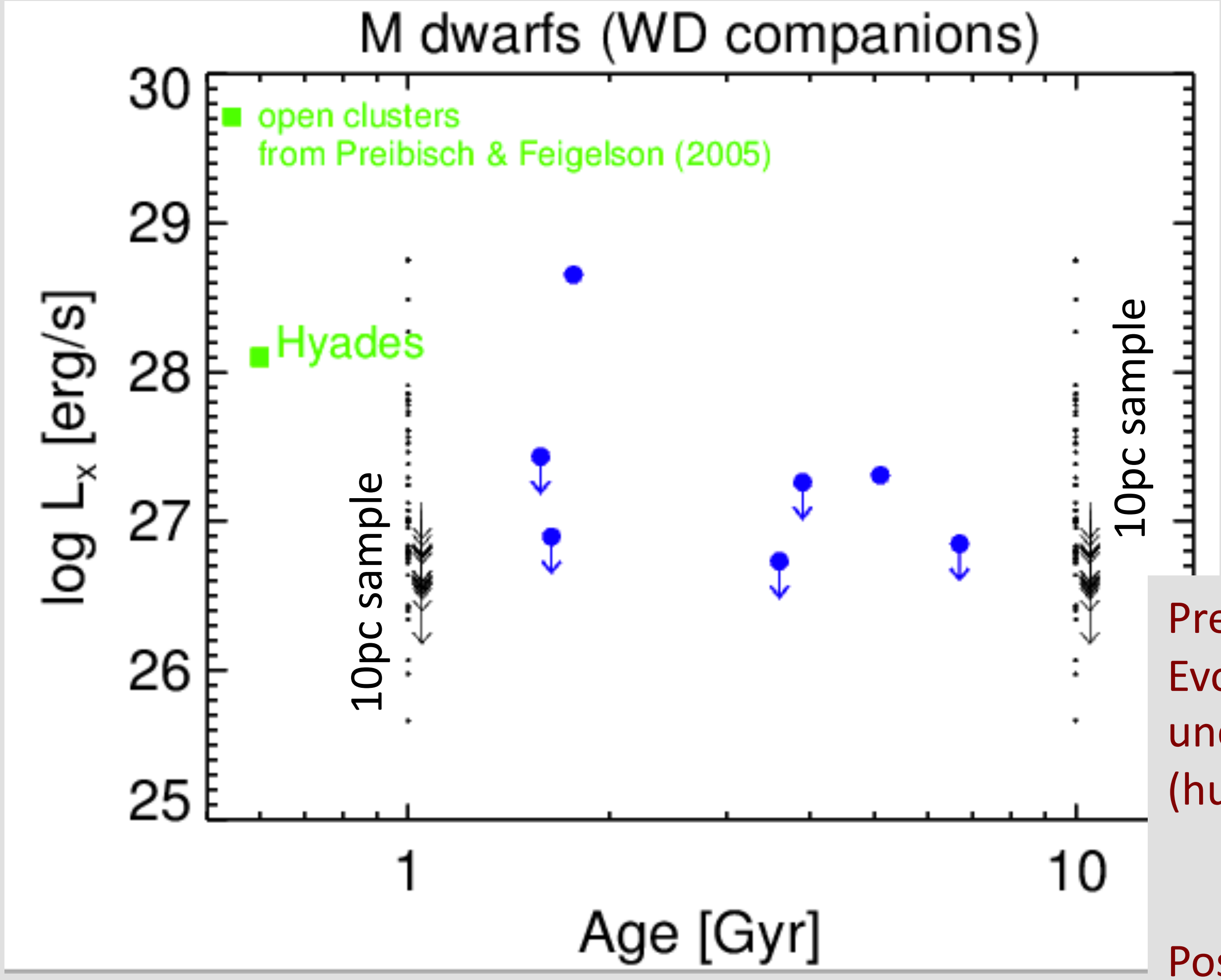
similar to G stars
"The Sun in Time"



Ribas et al. (2005)

“Calibrating the time-evolution of the high-energy emission of GKM stars”

Ongoing XMM-Newton / Chandra program (PI Ribas)

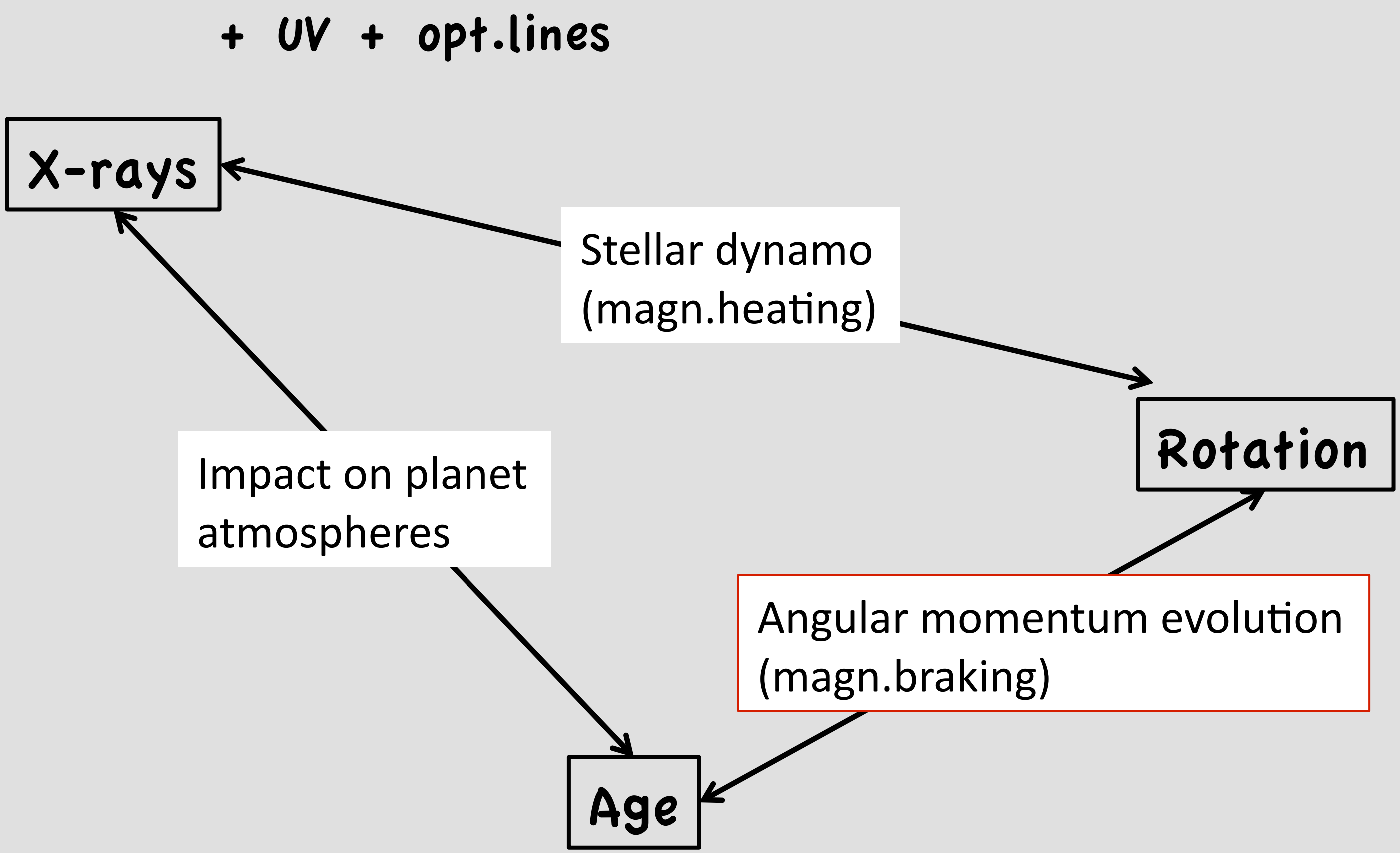


Extension of
`The Sun in time’ to M stars with WD companions

Prelim. Result:
Evolution of X-rays in M dwarfs unclear !
(huge dispersion for given age)

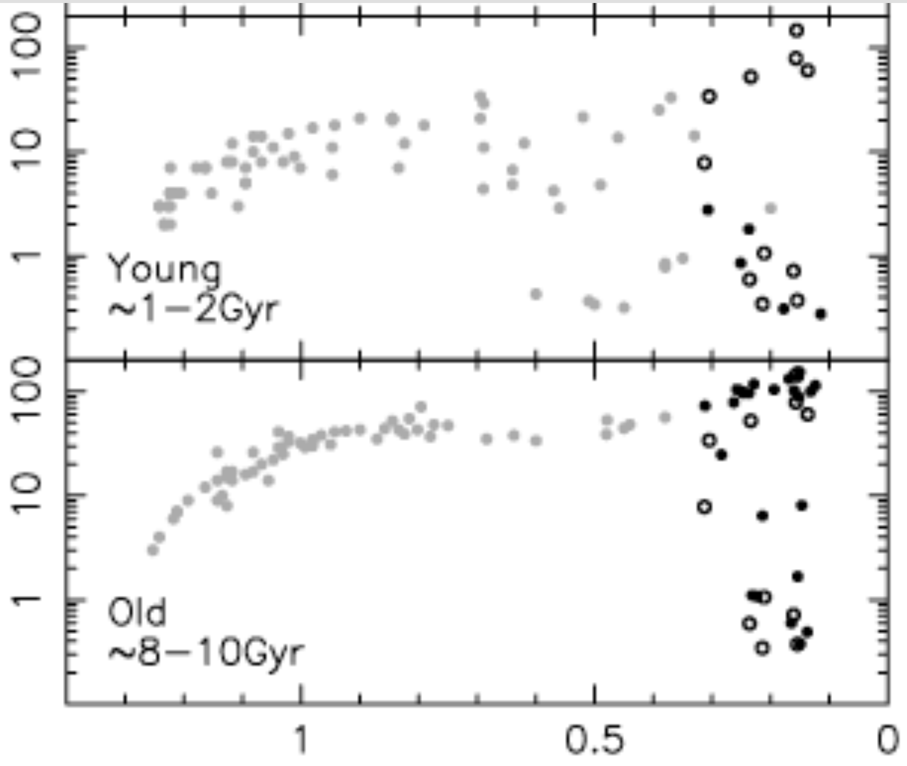
Possible explanation:
Rotation ?

Activity/age/rotation relation
Why is this useful?



Rotational evolution in M stars

o = young or old disk ?

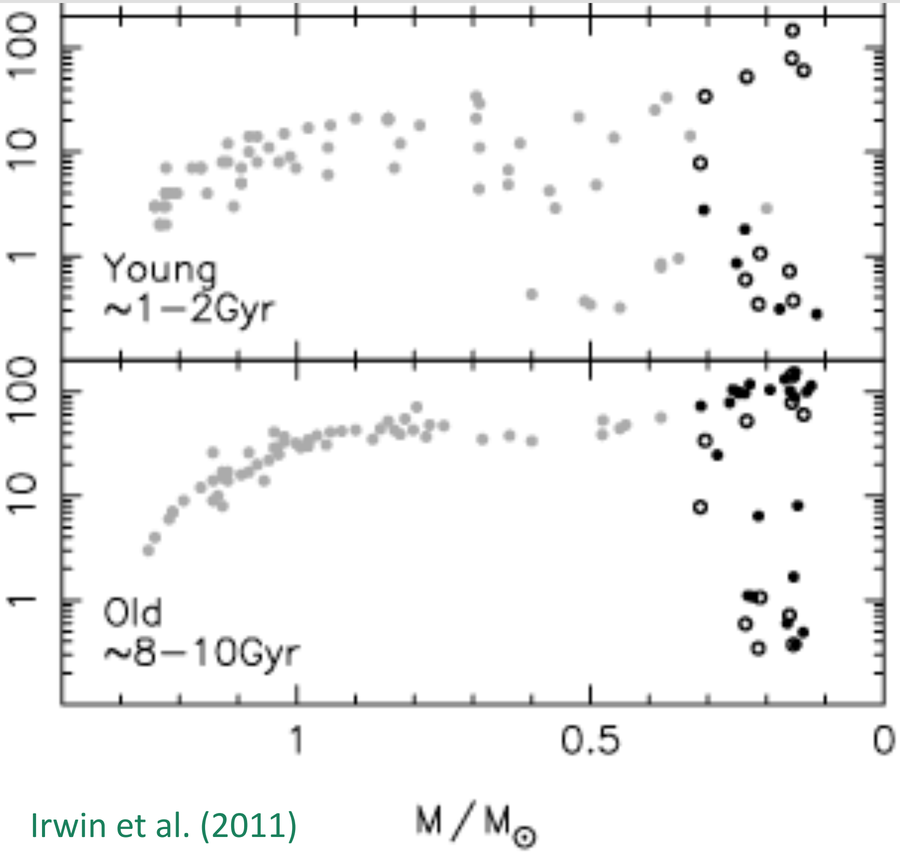


Irwin et al. (2011)

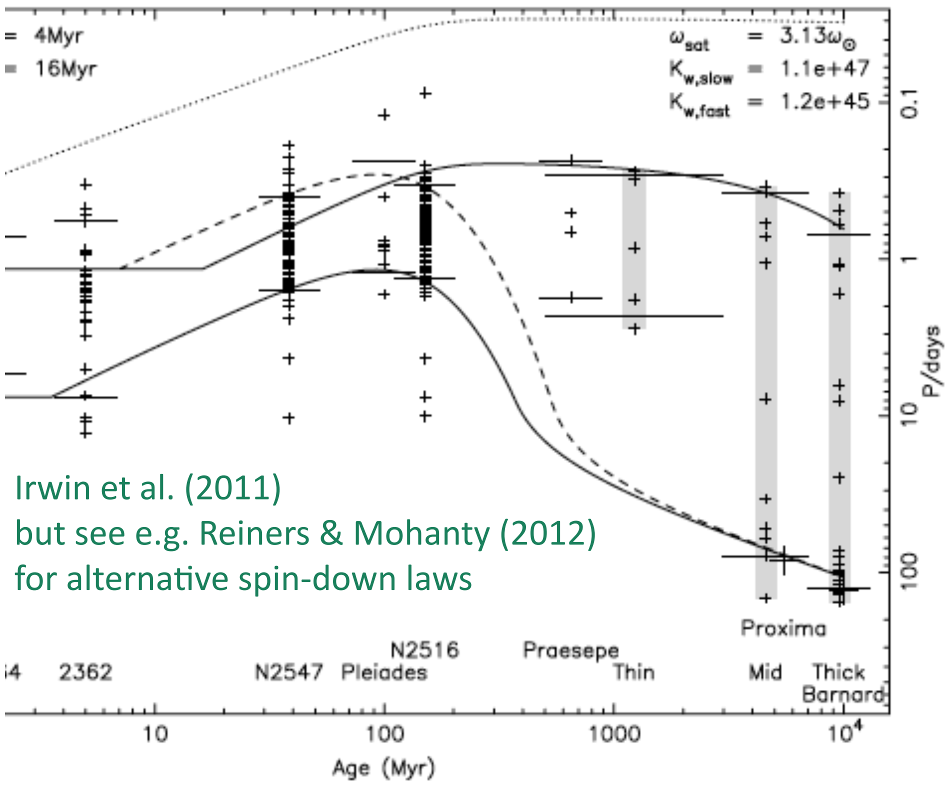
Spin-down takes Gyrs for M dwarfs
-> large range of P_{rot}
for field star sample

Rotational evolution in M stars

○ = young or old disk ?



Irwin et al. (2011)

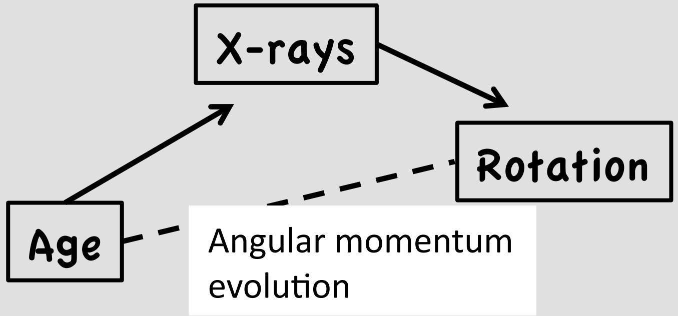


Irwin et al. (2011)
but see e.g. Reiners & Mohanty (2012)
for alternative spin-down laws

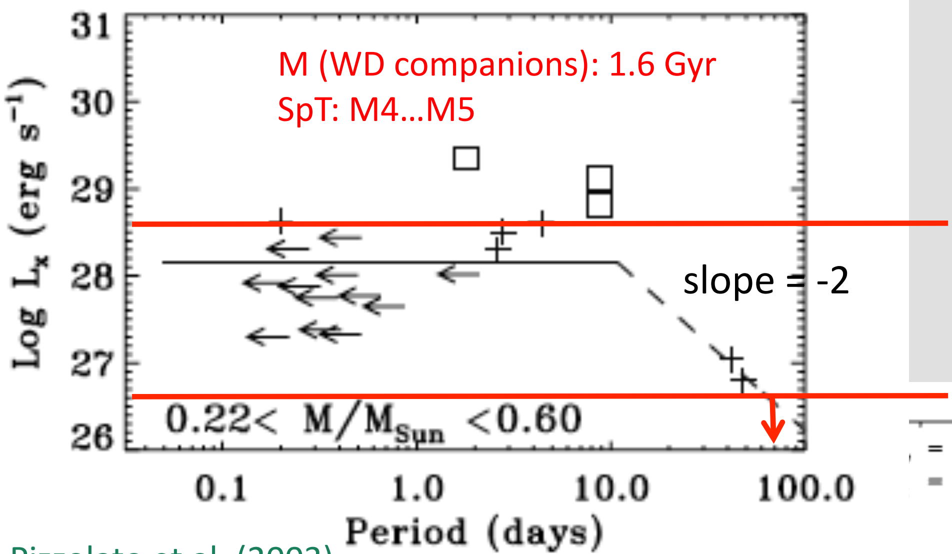
Spin-down takes Gyrs for M dwarfs
-> large range of P_{rot}
for field star sample

Need detailed age information
for constraining ang.momentum evolution
models

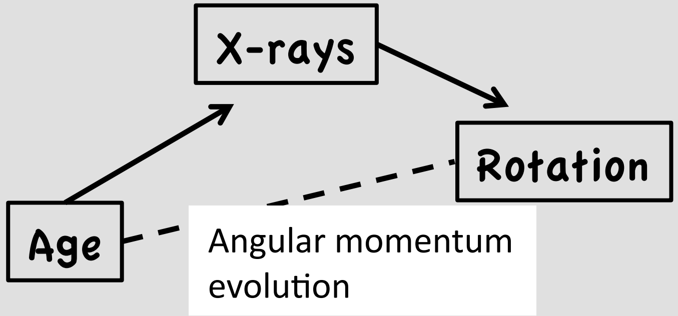
Use activity of stars with known age to infer rotation



Use activity of stars with known age to infer rotation

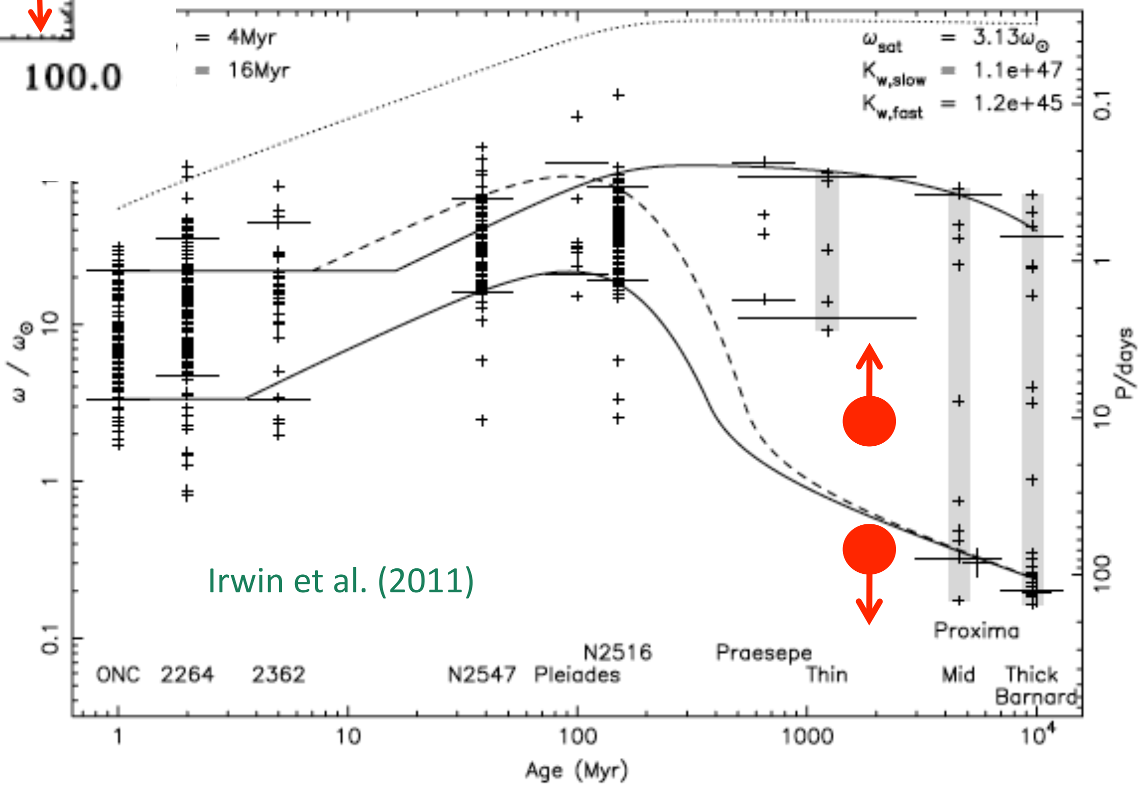


Pizzolato et al. (2003)

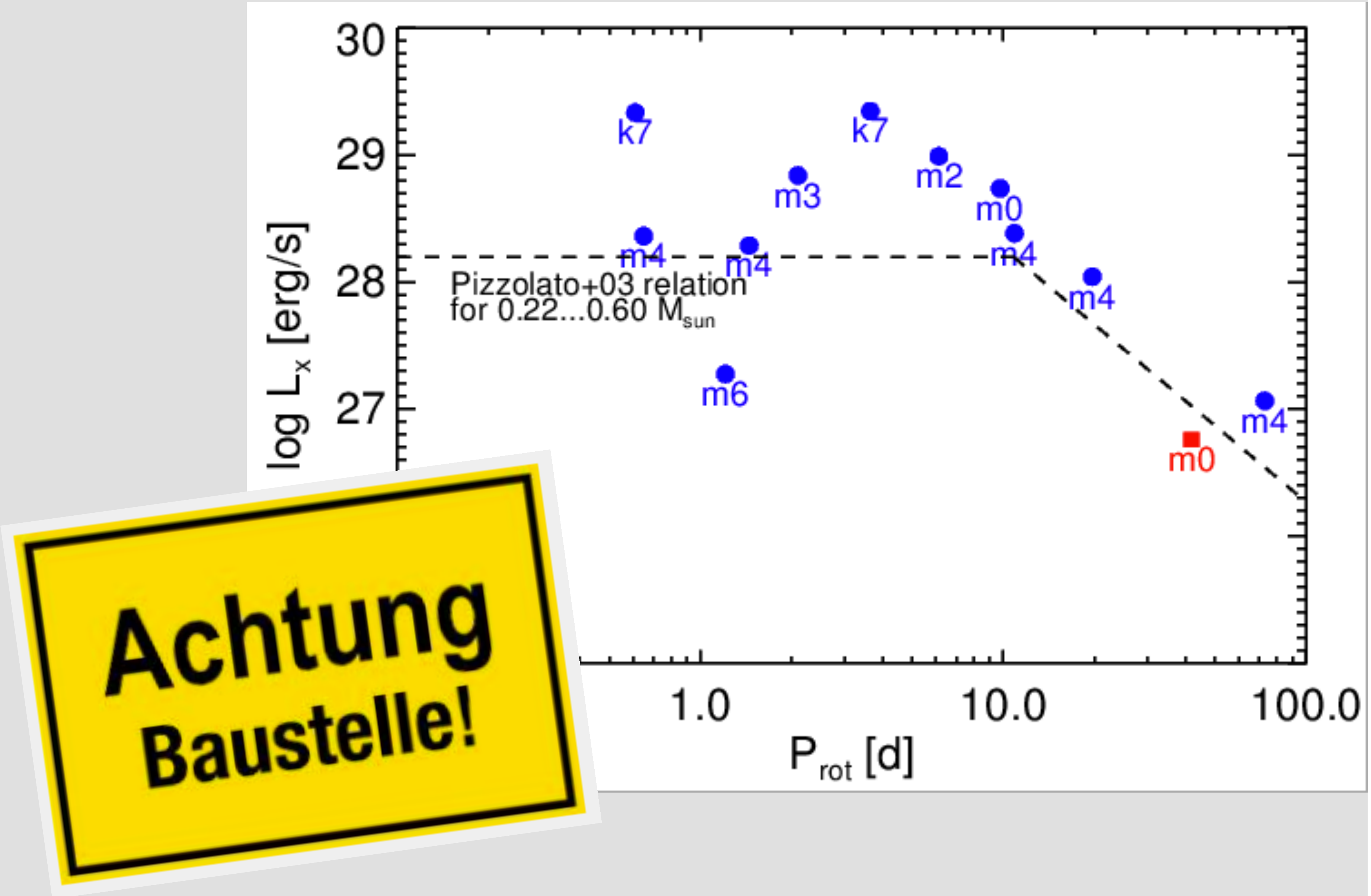


But: Wright et al. (2011) finds slope= -2.7

Rotation / activity relation
poorly known
for lowest mass stars



Rotation/activity relation for M stars with K2 periods for X-ray emitters



Summary / Conclusions

Chromospheric emission line studies (X-Shooter; pre-MS stars + UCDs):

* Saturation level and flux-flux relations
for **active** field dwarfs same as for pre-MS stars (Class III)
→ similar chromospheres at fast rotation; then dramatic drop in activity level ?
* emission line ratios = f (T_{eff}, age, rotation?) → need NLTE modelling of chromospheres
* flux-flux relations for UCDs + relation to field M dwarfs: upcoming….

X-ray / radio connection for UCDs:

* X-ray flares + no radio vs. Radio bursts + no X-rays
→ real bimodality (due to rotation or magn.fields) or observational biases ?

Transition region and coronal emission probed with UV and X-rays (M0…M6 stars in 10pc):

* Huge range of activity levels for given SpT and age
→ a probe of rotational evolution….?
* Activity decays stronger for shorter λ → magn.heating efficiency for different atmosph.layers
(need to know all of rotation – activity=f(λ) – age)

Activity / age / rotation relation of M stars:

* "The Sun in Time for M dwarfs" (WD / M binaries) → activity / age
* K2 rotation study of nearby M dwarfs → rotation / activity