The spin evolution of solar-type stars

Jérôme Bouvier

Observations

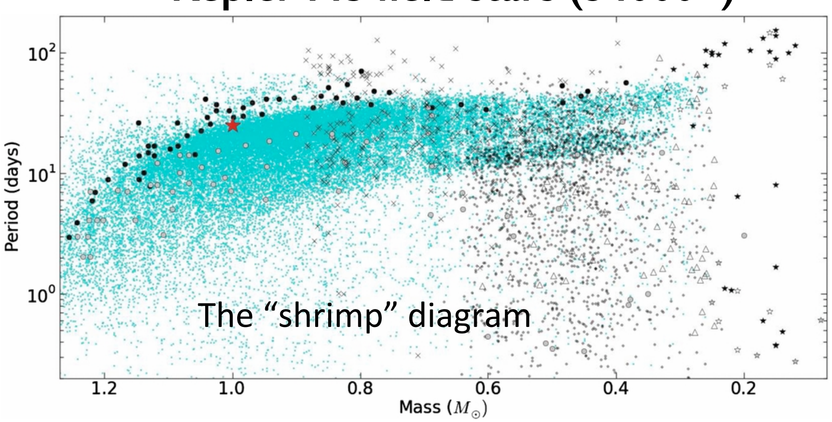
Models

STELLAR ROTATION: CURRENT STATUS

Stellar rotation: a renewed context

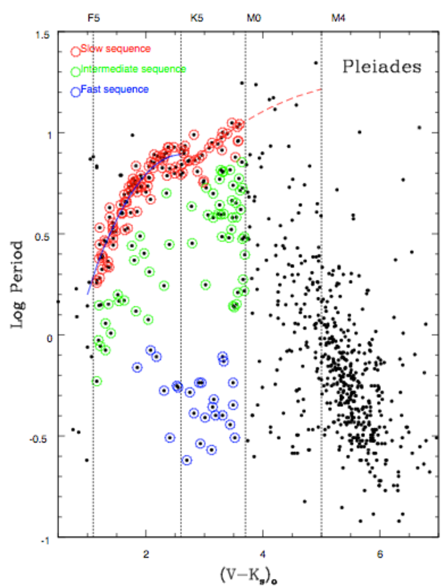
- CoRoT, Kepler/K2 => access to high quality obs. => detail pattern/features
- Rebull et al. (2016) with K2 => new measures of rotation in Pleiades @ 125 Myr
- Gaia DR2

Kepler MS field stars (34000+)



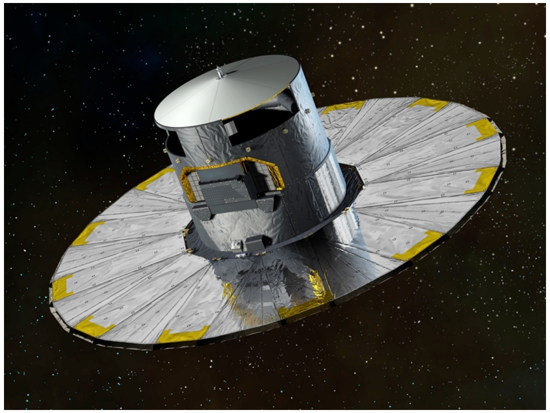
McQuillan, Mazeh, Aigrain (2014)

K2 Pleiades



Rebull, Stauffer et al. (2016)

GAIA (147000+ rot. var.)



Lanzafame et al. (2018)

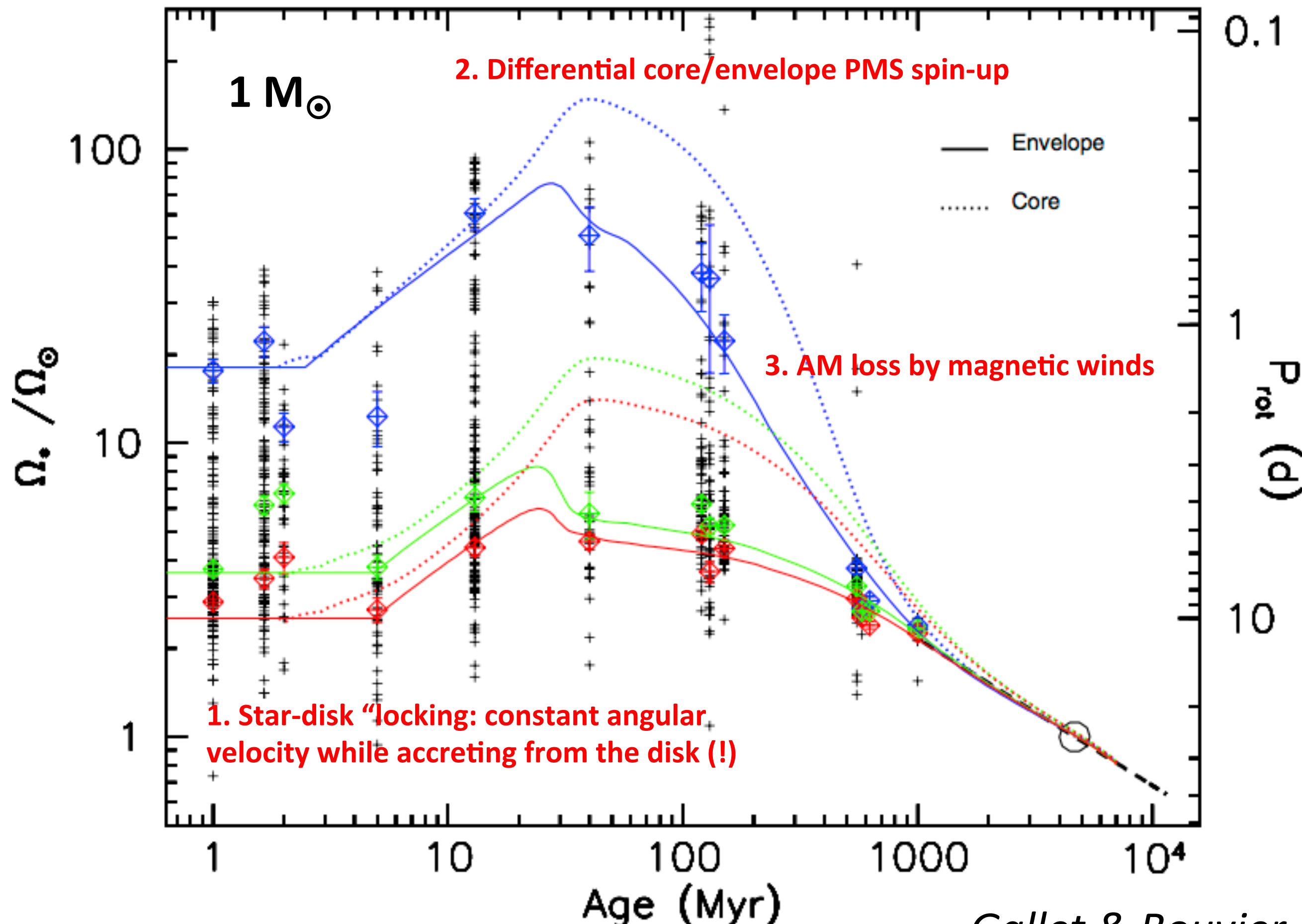
A new era for angular momentum evolution models ?

Key processes governing stellar angular momentum evolution

- **Initial conditions:** star-disk interaction during the early pre-main sequence (first few Myr)
  - Initial conditions are remembered for >1-8 Gyr in G-M stars!
- **Pre-main sequence contraction** and structural evolution (spin up)
  - Up to a factor of 10 spin up!
- **Magnetized winds** (spin down)
  - braking rate ≈ Ω^n with n=[1,3] -> rotational convergence
- **Internal angular momentum transport** within the star
  - AM storage in the stellar core -> reduced spin down rate

AM evolution models

Evolution of angular momentum governed by 3 main processes:
star-disk interaction, magnetized wind braking, and core-envelope decoupling.



Gallet & Bouvier 2013, 2015

Magnetic field

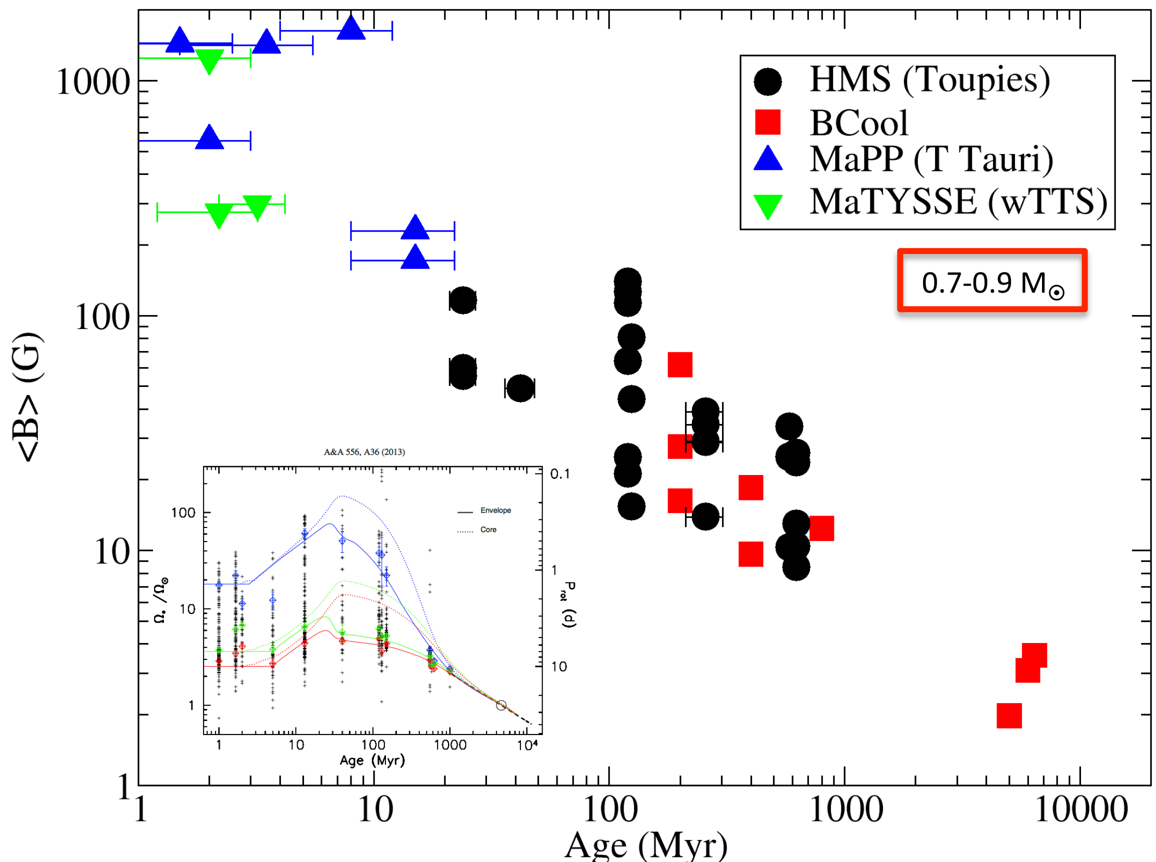
Wind braking

Angular momentum transport

MODEL INGREDIENTS: EVOLUTIONARY TRENDS

The evolution of stellar magnetic fields

A steady decrease of magnetic field strength with time



TOwards Understanding the sPIn Evolution of Stars

Zero-age main sequence dwarfs
Solar-type main sequence stars
Non-Accreting T Tauri stars

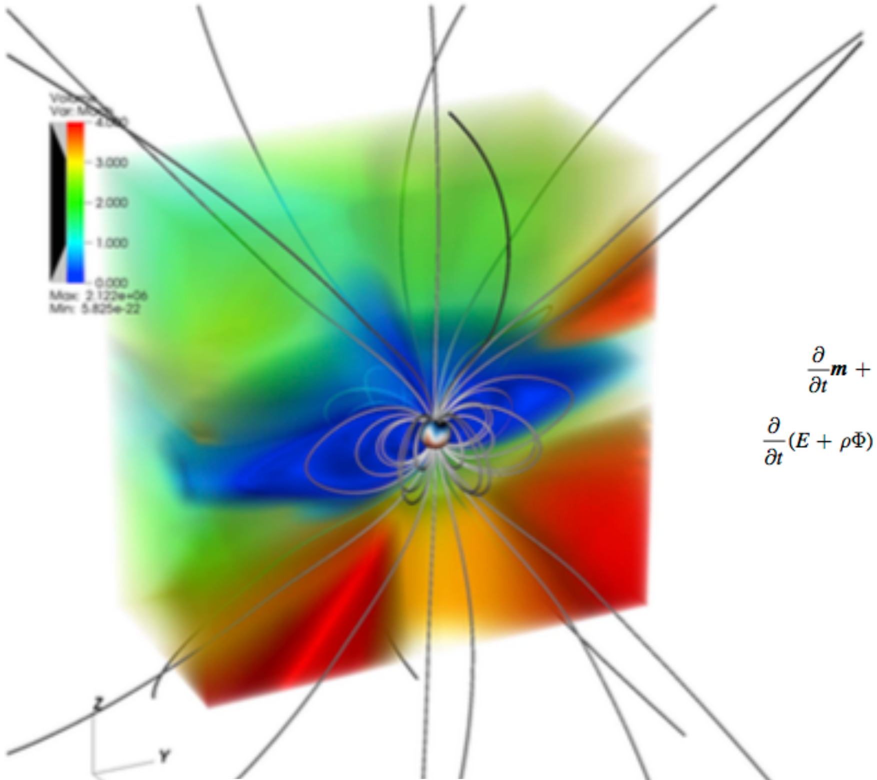
PMS B evolution due to structural properties (not linked to rotation!)

ZAMS & MS B evolution due to rotational braking: dynamo

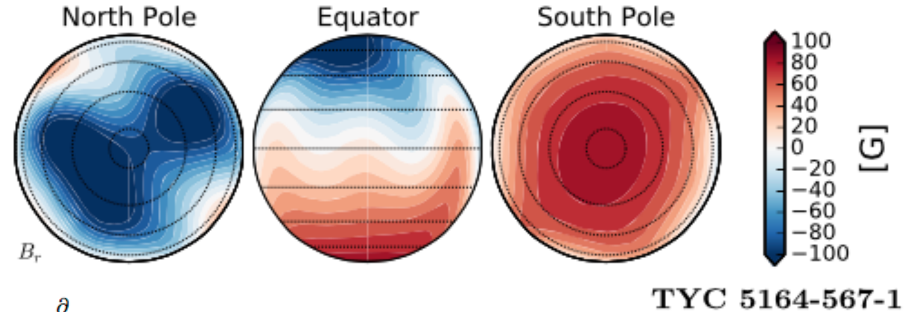
Folsom, Bouvier, Petit+17

Wind braking: 3D models

TYC 5164



Realistic magnetic topologies



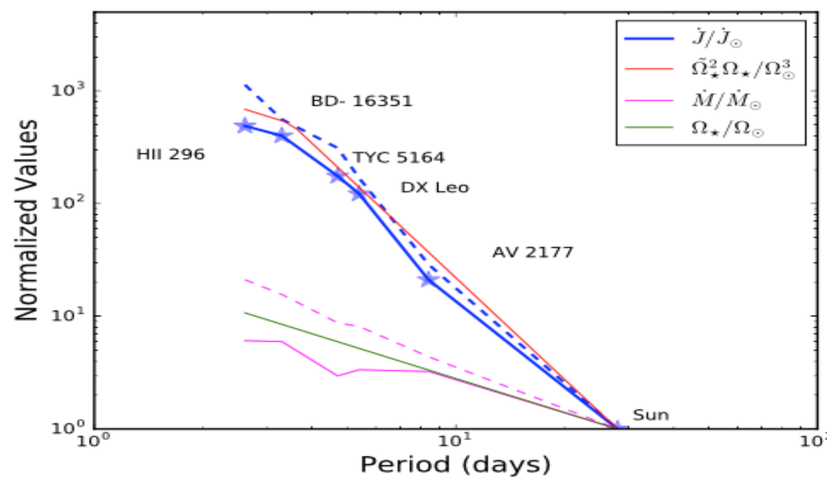
$$\frac{\partial}{\partial t}\rho + \nabla \cdot \rho \boldsymbol{v} = 0, \qquad (2)$$

$$\frac{\partial}{\partial t}\boldsymbol{m} + \nabla \cdot (\boldsymbol{m}\boldsymbol{v} - \boldsymbol{B}\boldsymbol{B} + \boldsymbol{I}p) = -\rho\nabla\Phi + \rho\boldsymbol{a}, \qquad (3)$$

$$\frac{\partial}{\partial t}(E + \rho\Phi) + \nabla \cdot ((E + p + \rho\Phi)\boldsymbol{v} - \boldsymbol{B}(\boldsymbol{v}\cdot\boldsymbol{B})) = \boldsymbol{m}\cdot\boldsymbol{a}, \qquad (4)$$

$$\frac{\partial}{\partial t}\boldsymbol{B} + \nabla \cdot (\boldsymbol{v}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{v}) = 0, \qquad (5)$$

$$T = T_\odot \left(\frac{\Omega_\star}{\Omega_\odot}\right)^{0.1}, \quad n = n_\odot \left(\frac{\Omega_\star}{\Omega_\odot}\right)^{0.6}$$



Réville, Folsom, Strugarek+16
(see also *Pognan et al. 2018*)

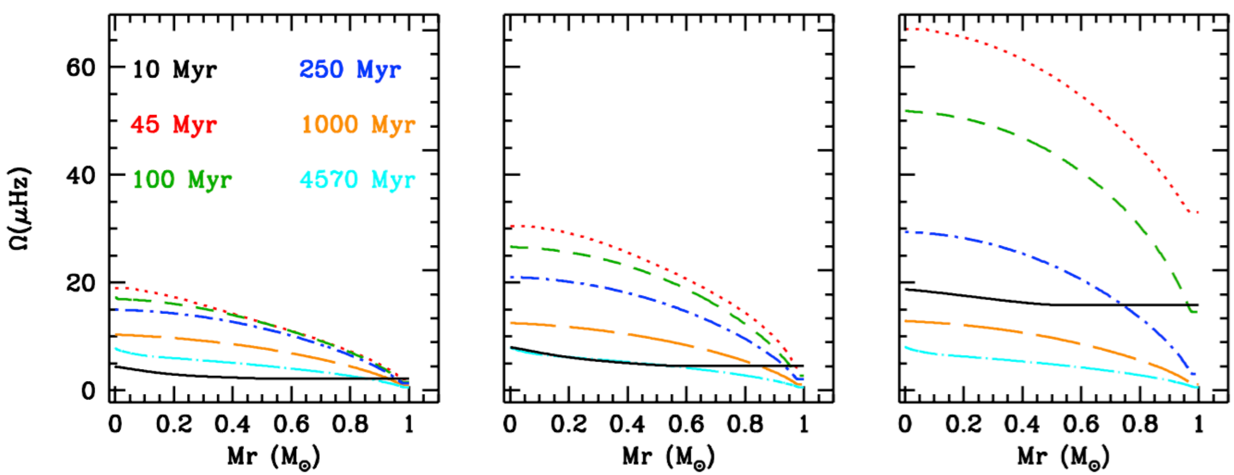
Internal angular momentum transport

STAREVOL rotating models

AM transport:

$$\rho \frac{\mathrm{d}}{\mathrm{d}t}\left(r^2\Omega\right) = \underbrace{\frac{1}{5r^2}\frac{\partial}{\partial \mathrm{r}}\left(\rho r^4 \Omega U_r\right)}_{\text{Meridional circulation}} + \underbrace{\frac{1}{r^2}\frac{\partial}{\partial \mathrm{r}}\left(r^4 \rho \nu_v \frac{\partial \Omega}{\partial \mathrm{r}}\right)}_{\text{Shear turbulence}} \left(+ \underbrace{\tau_W}_{\text{Surface stellar wind torque}} \right)$$

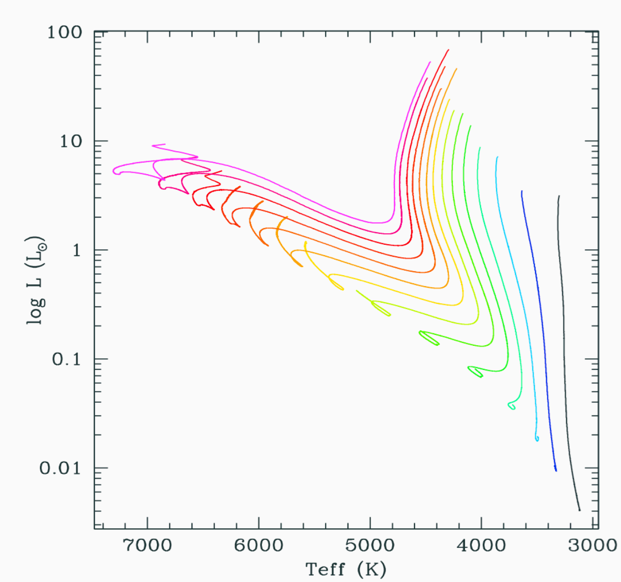
Internal rotational profiles as a function of time



SLOW

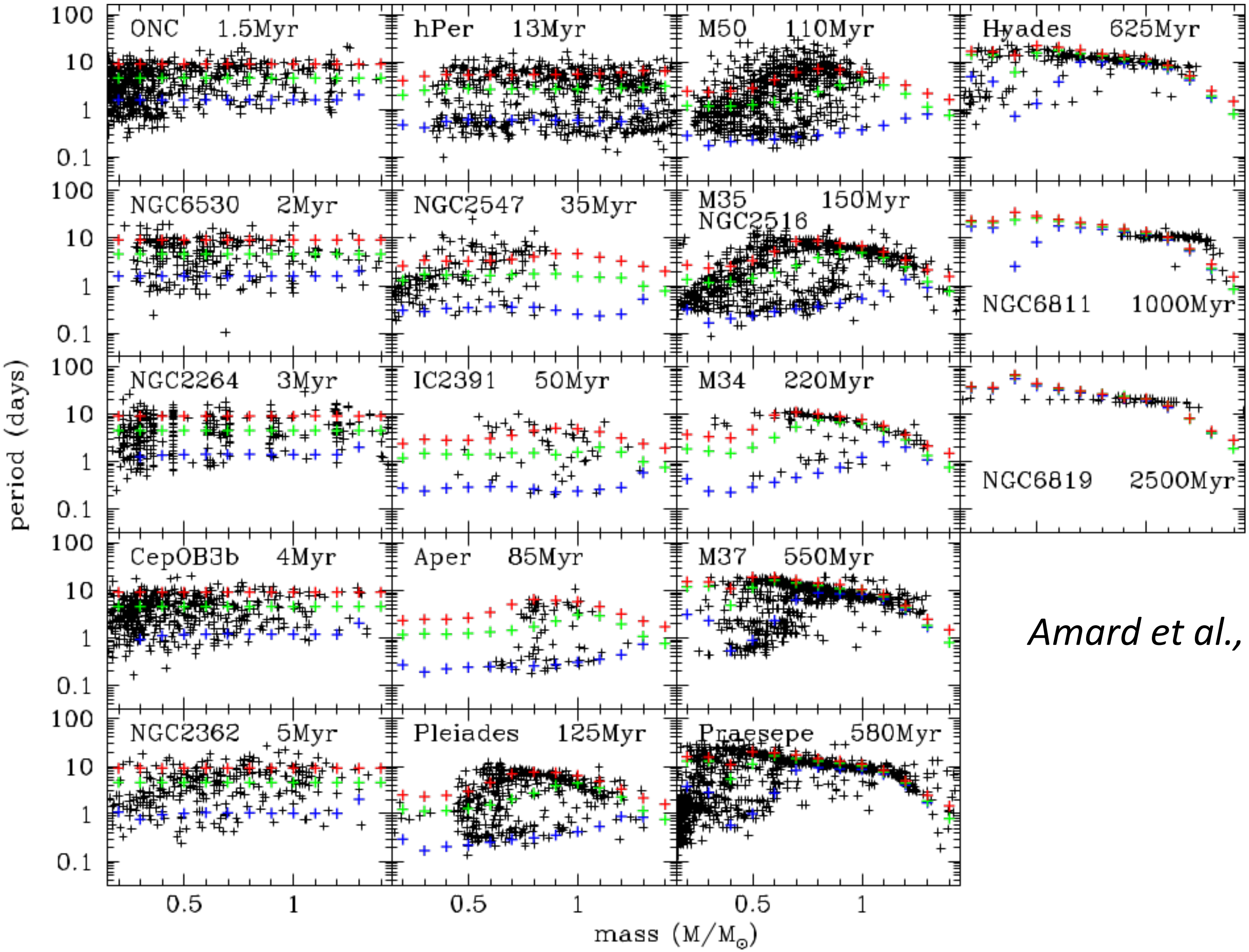
MEDIAN ROTATORS

FAST



(Amard, Palacios, Charbonnel+16)

Evolution of rotational distributions



Amard et al., in prep.

CoRoT

Kepler, K2

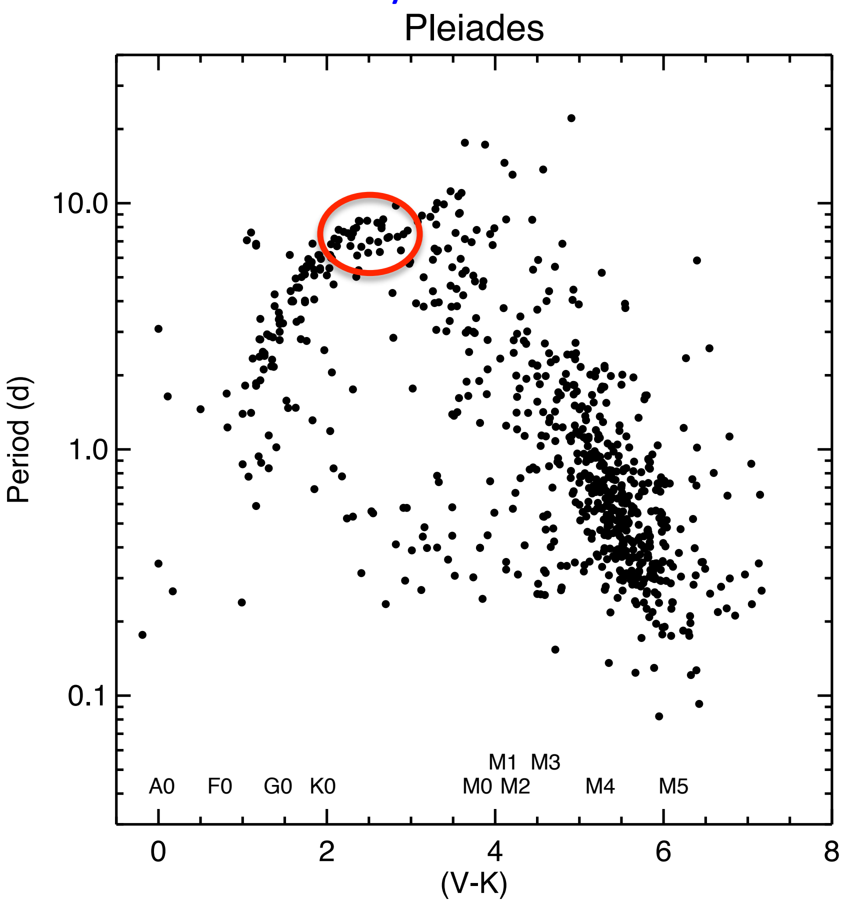
Gaia, TESS, Plato

SPACE PHOTOMETRY: THE REVOLUTION

Open clusters

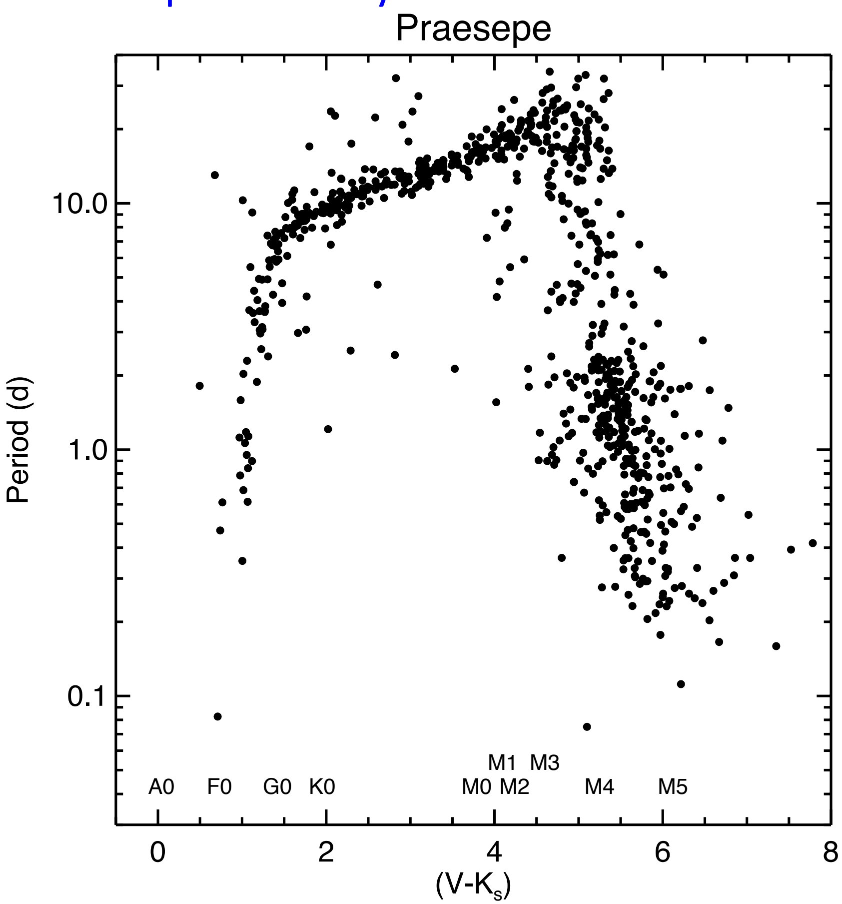
e.g., Kepler/K2 Pleiades & Praesepe

Pleiades ~125 Myr



Rebull, Stauffer, Bouvier+16

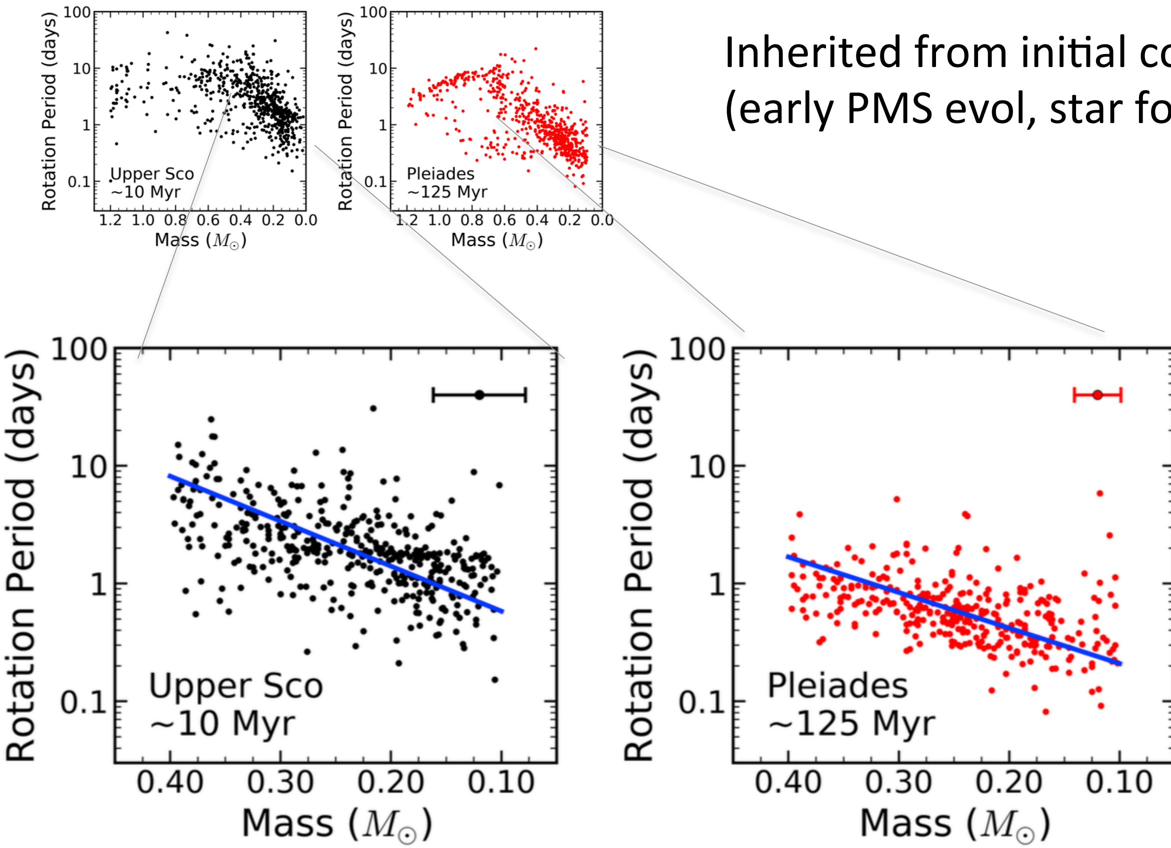
Praesepe ~700 Myr



Rebull, Stauffer, Hillenbrand+17

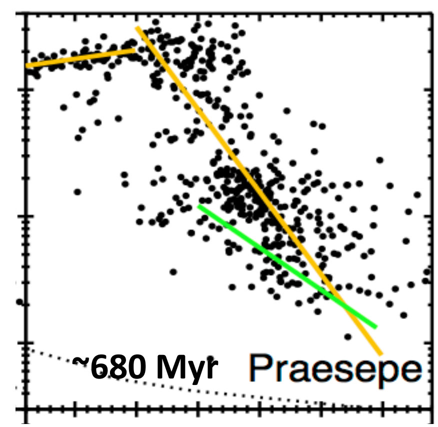
M stars…

A tight rotation-mass correlation



Inherited from initial conditions
(early PMS evol, star formation)

and propagates onwards…



Somers, Stauffer, Rebull+17

Rebull, Stauffer, Hillenbrand+17

Super-Earths

Mini-Neptunes

Hot Jupiters

STAR-PLANETS SYSTEMS

Signature of planetary mergers on stellar spins

Qureshi+18

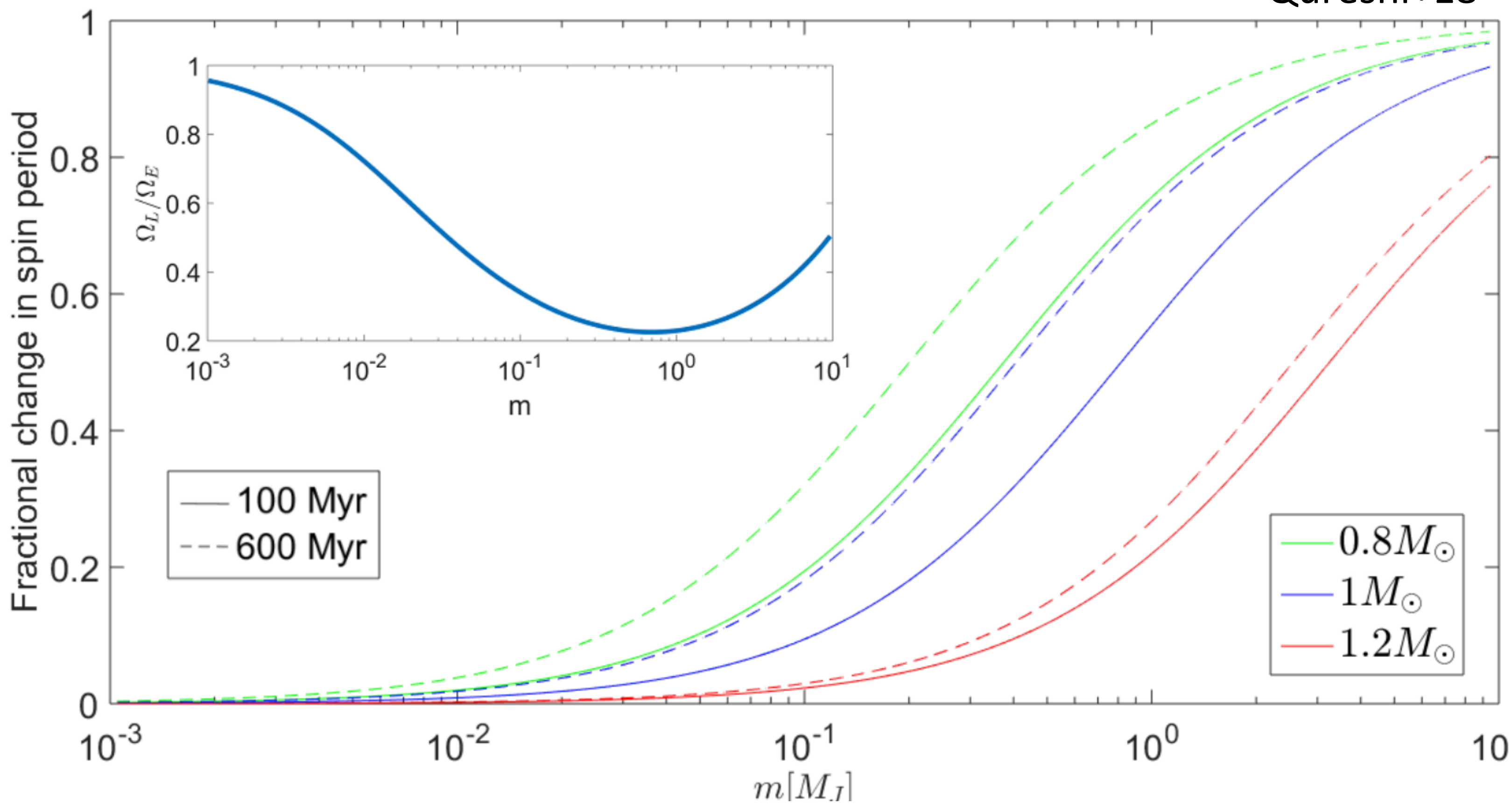
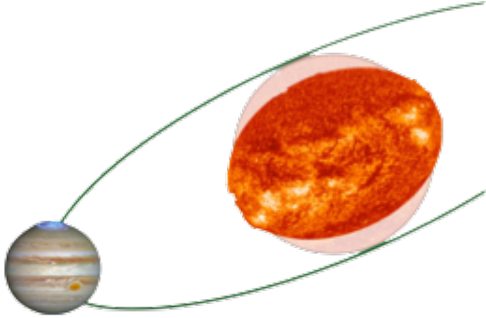


Figure 1. The spin-period absolute percentage change defined as: $|P_{\Omega,i} - P_{\Omega,f}|/P_{\Omega,i}$ as a function of the planet mass. The solid lines depict a merger that took place after 100 Myrs, while the dashed lines represent a merger after 600 Myrs of stellar evolution. The planet was assumed to plunge in from a 5 au distance (as noted above the actual initial distance does not change significantly the results). We consider three representative stellar masses 0.8, 1 and 1.2 $M_\odot$, green, blue and red respectively. In the inset, the ratio of the post-spin for angular momentum over conservation of energy is plotted versus the mass of the planet in terms of M_J.

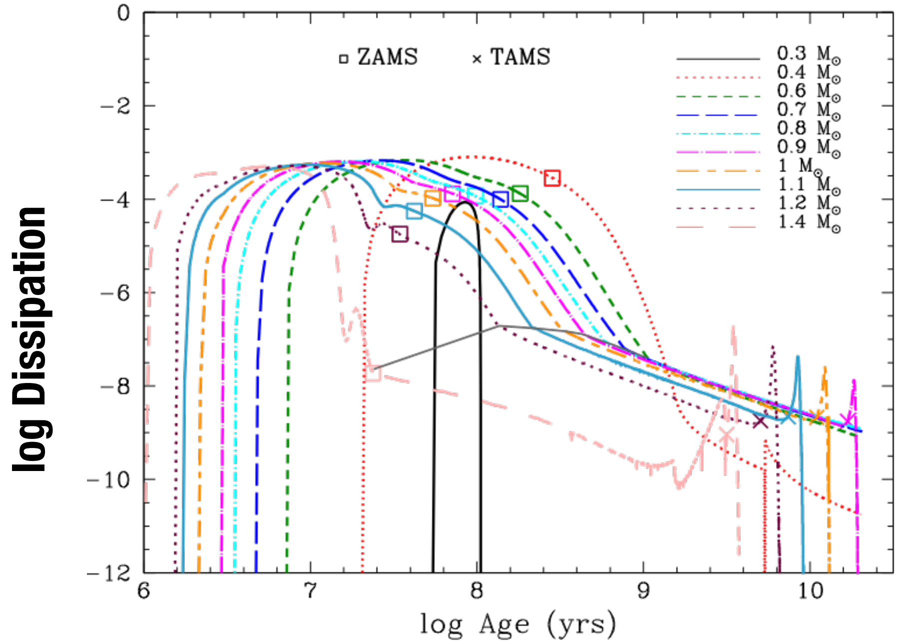
Stellar dissipation

Dynamical tides



- Dissipation of the dynamical tides
  - variation over orders of magnitude
  - amplitude on MS decreases with mass (thickness of the CE)

– Importance of coupling **structural** and **rotational** evolution



$$\frac{3}{2\overline{\overline{Q'}}} = \frac{k_2}{\overline{\overline{Q}}} = \textbf{Dissipation} = \frac{100\pi}{63}\epsilon^2\left(\frac{\alpha^5}{1-\alpha^5}\right)(1-\gamma)^2$$

$$\times(1-\alpha)^4\left(1+2\alpha+3\alpha^2+\frac{3}{2}\alpha^3\right)^2\left[1+\left(\frac{1-\gamma}{\gamma}\right)\alpha^3\right]\left[1+\frac{3}{2}\gamma+\frac{5}{2\gamma}\left(1+\frac{1}{2}\gamma-\frac{3}{2}\gamma^2\right)\alpha^3-\frac{9}{4}(1-\gamma)\alpha^5\right]^{-2}$$

with
$$\begin{cases} \alpha = \frac{R_c}{R_s},\quad \beta = \frac{M_c}{M_s} \quad \text{and} \quad \gamma = \frac{\rho_e}{\rho_c} = \frac{\alpha^3(1-\beta)}{\beta(1-\alpha^3)} < 1. & \text{structure} \\ \epsilon^2 \equiv \left(\Omega/\sqrt{\mathcal{G}M_s/R_s^3}\right)^2 = (\Omega/\Omega_c)^2 \ll 1 & \text{rotation} \end{cases}$$

Dissipation maximum during PMS

PMS = dissipation controlled by structure

MS = dissipation controlled by rotation

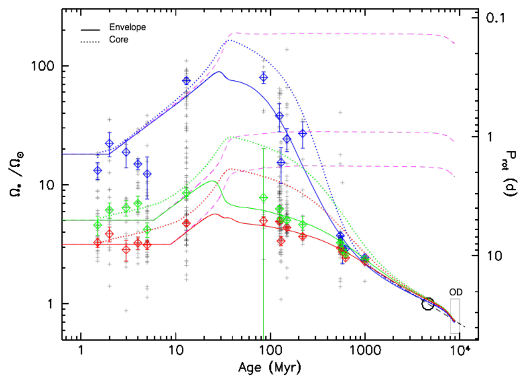
Mathis (2015) & Gallet et al. (2017b)

Star-planet interaction

Coupled rotational-orbital evolution code

Rotational evolution

Gallet & Bouvier (2013, 2015)



Orbital evolution

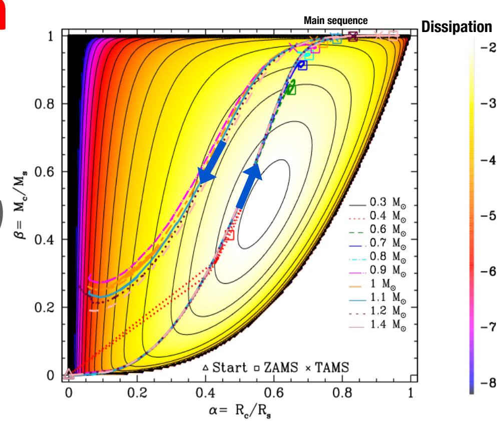
Bolmont et al. (2012,2016)

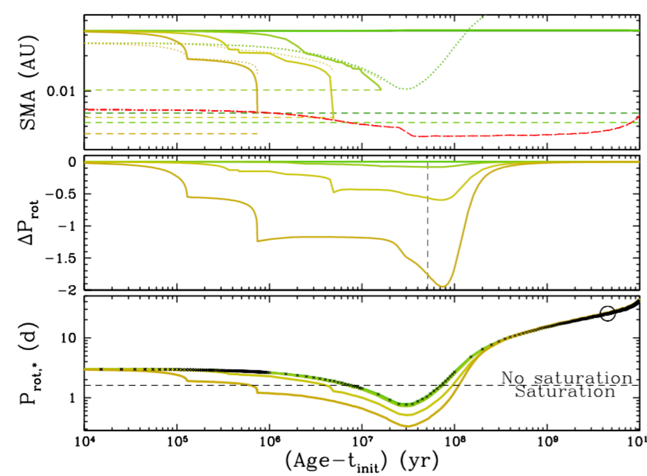
$$\frac{1}{a}\frac{da}{dt} = -\frac{1}{T_\star}\left[1-\frac{\Omega_\star}{n}\right],$$

$$T_\star \propto \frac{M_\star}{M_p(M_p+M_\star)}\frac{a^8}{R_\star^5}\frac{1}{<\mathcal{D}>_\omega}\frac{|n-\Omega_\star|}{\mathcal{G}}$$

Dissipation

Gallet et al. (2017b)

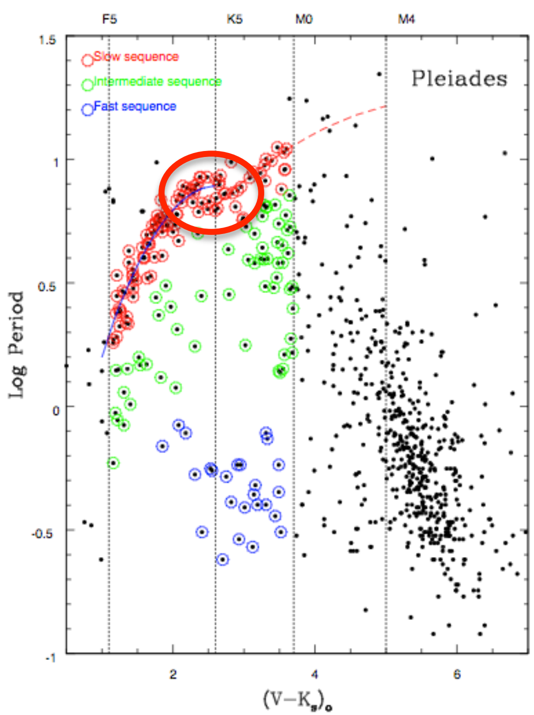




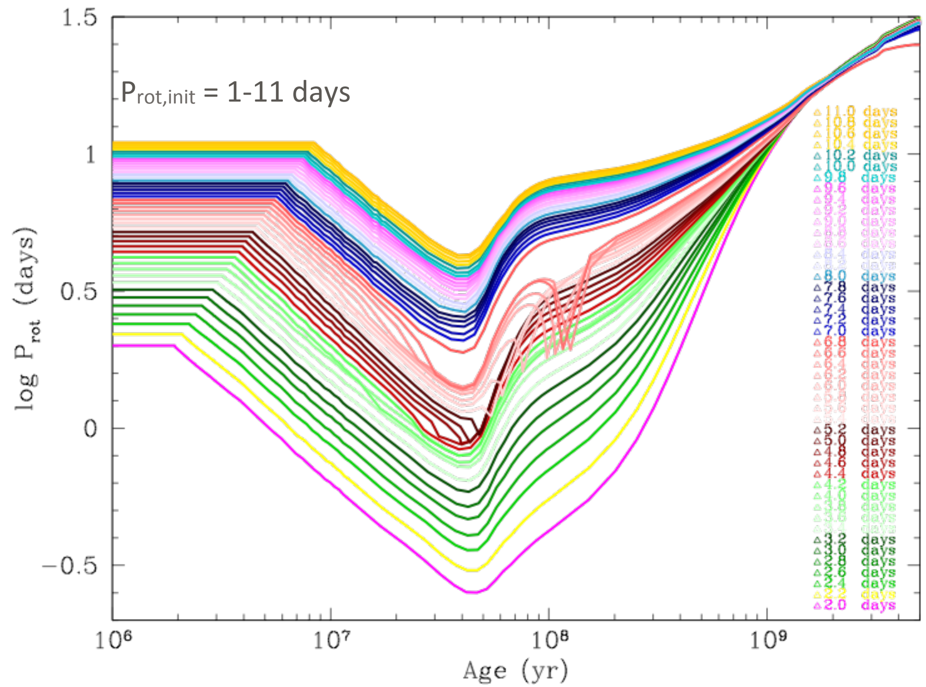
Spin evolution of star-planet systems

Impact on rotational distributions

K2



Stauffer et al. (2016)



Model grid: $0.8M_{\odot}$ + 2 M_{jup}
SMA_init = $0.5R_{co}$ ~ a few 0.01 AU.

Gallet et al., in prep.

Gyrochronology

Magnetochronology

Tidal chronology

Chemical chronology (LiI, BaII, YI)

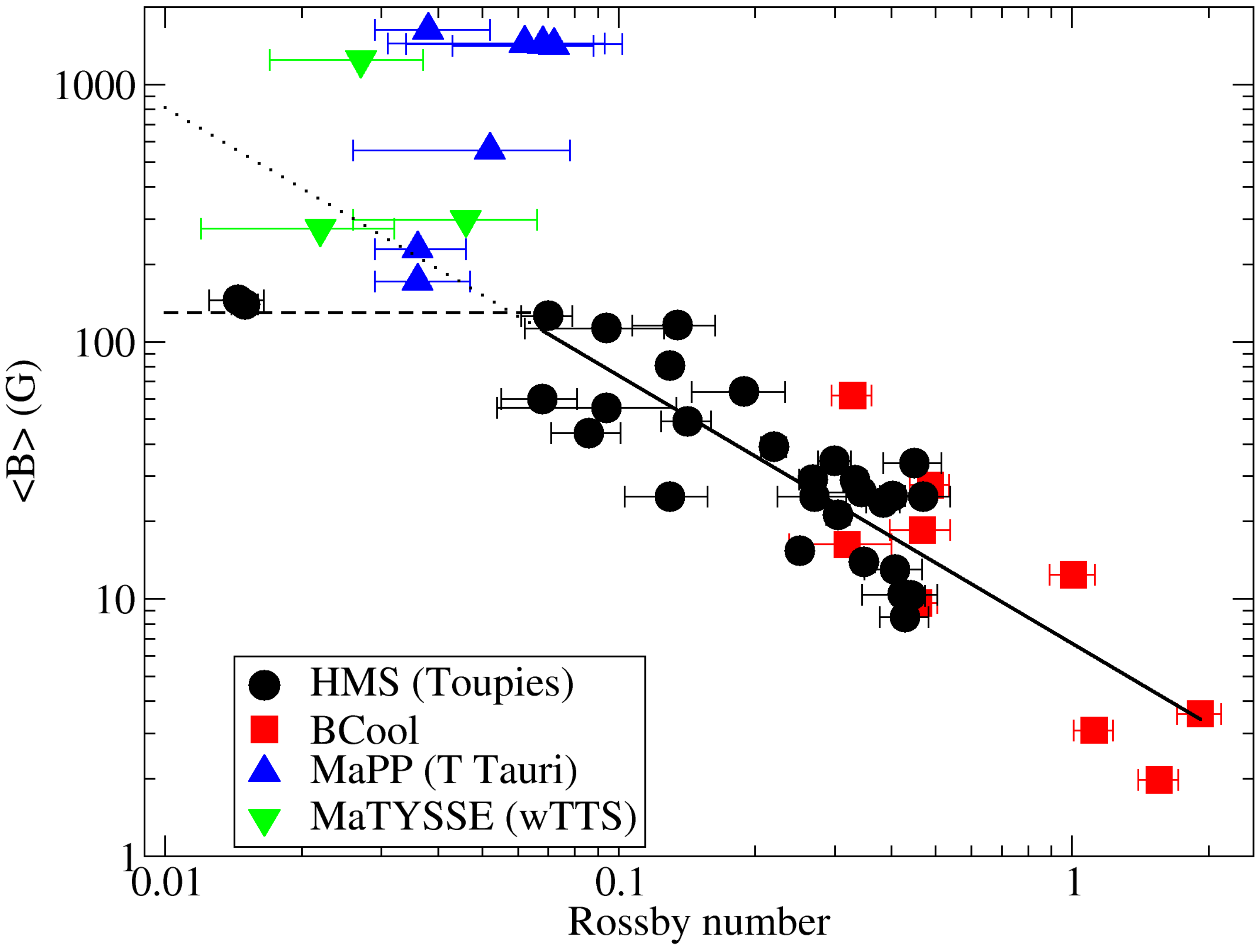
CHRONOLOGY: A COMPLEX INTERPLAY

Age, lithium, and rotation

- Rotation = f(age) non monotonic + outliers (binaries, planet hosts, mergers, etc.)
- Activity = f(rotation, stellar structure) via Rossby number/dynamo process
- Lithium = f(age, rotation, metallicity, planet)
- **The relationship between age, activity, rotation, and lithium is polymorphic**
- Chronology may hold statistically for a coeval population, but may break down for individual objects

Evolution of the mean longitudinal magnetic field

Folsom, Bouvier, Petit+17



Rossby Number = P_{rot} / τ_c (τ_c from Amard et al. in prep)

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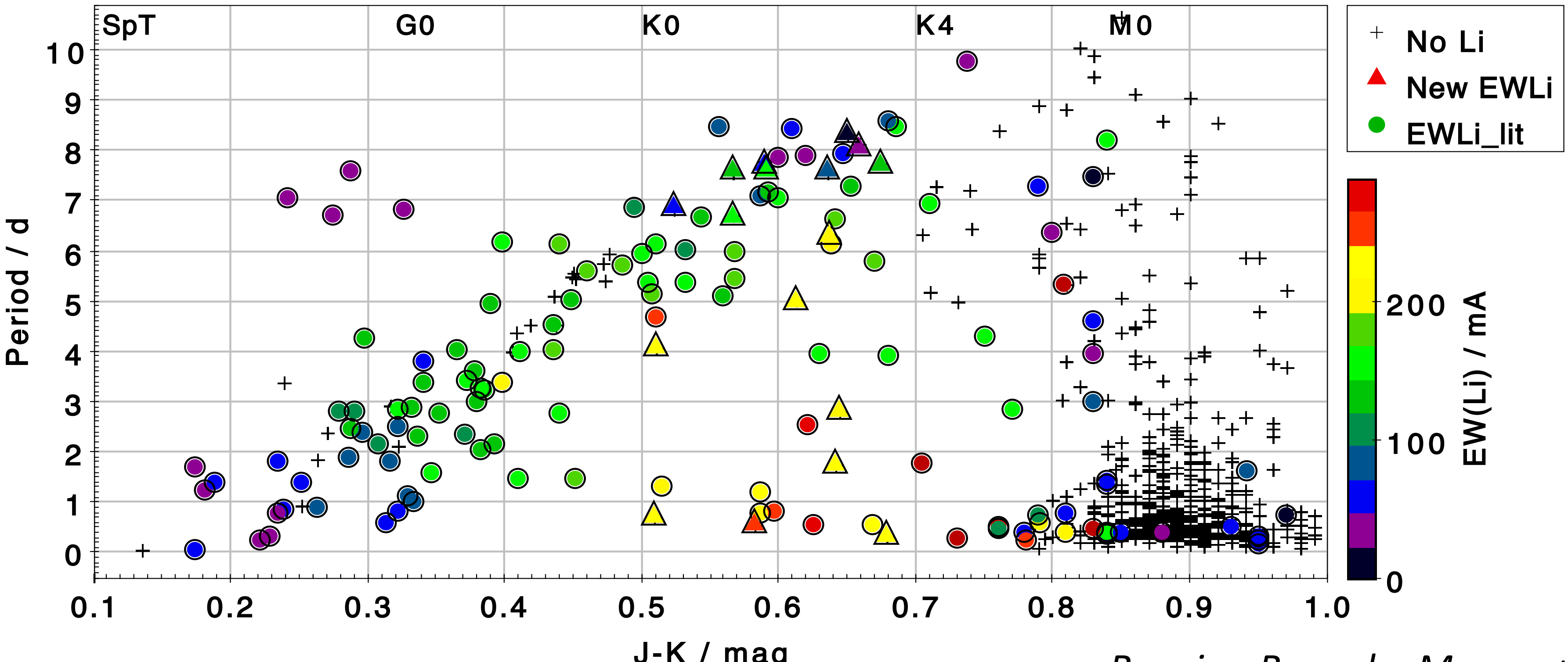
The lithium-rotation connection

Lithium abundances and rotation rates are correlated in the PMS at least up to ZAMS

Pleiades ~125 Myr



Bouvier, Barrado, Moraux+17

Also seen in NGC 2264 at 5 Myr!

Bouvier, Lanzafame, Venuti+16

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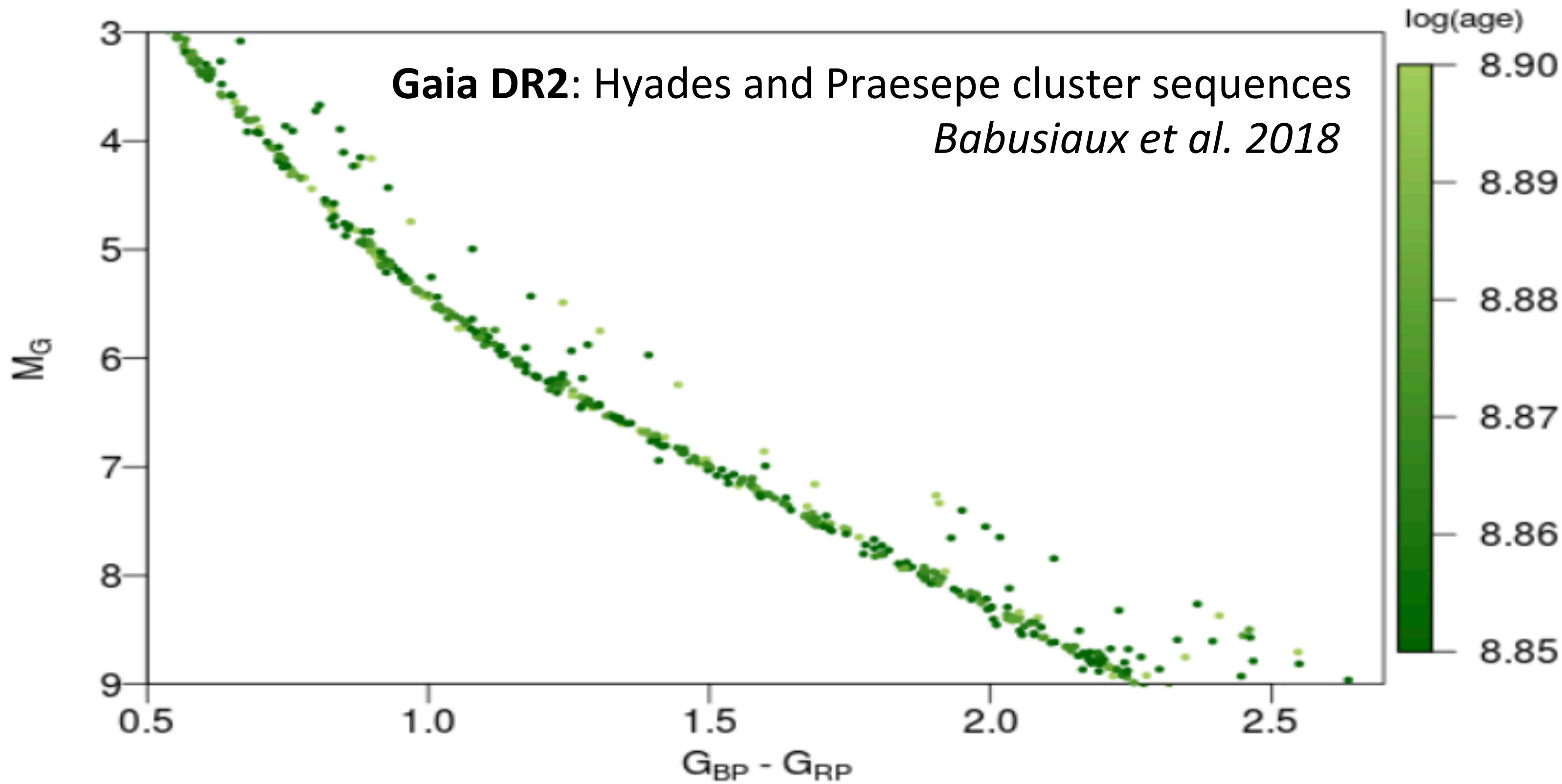
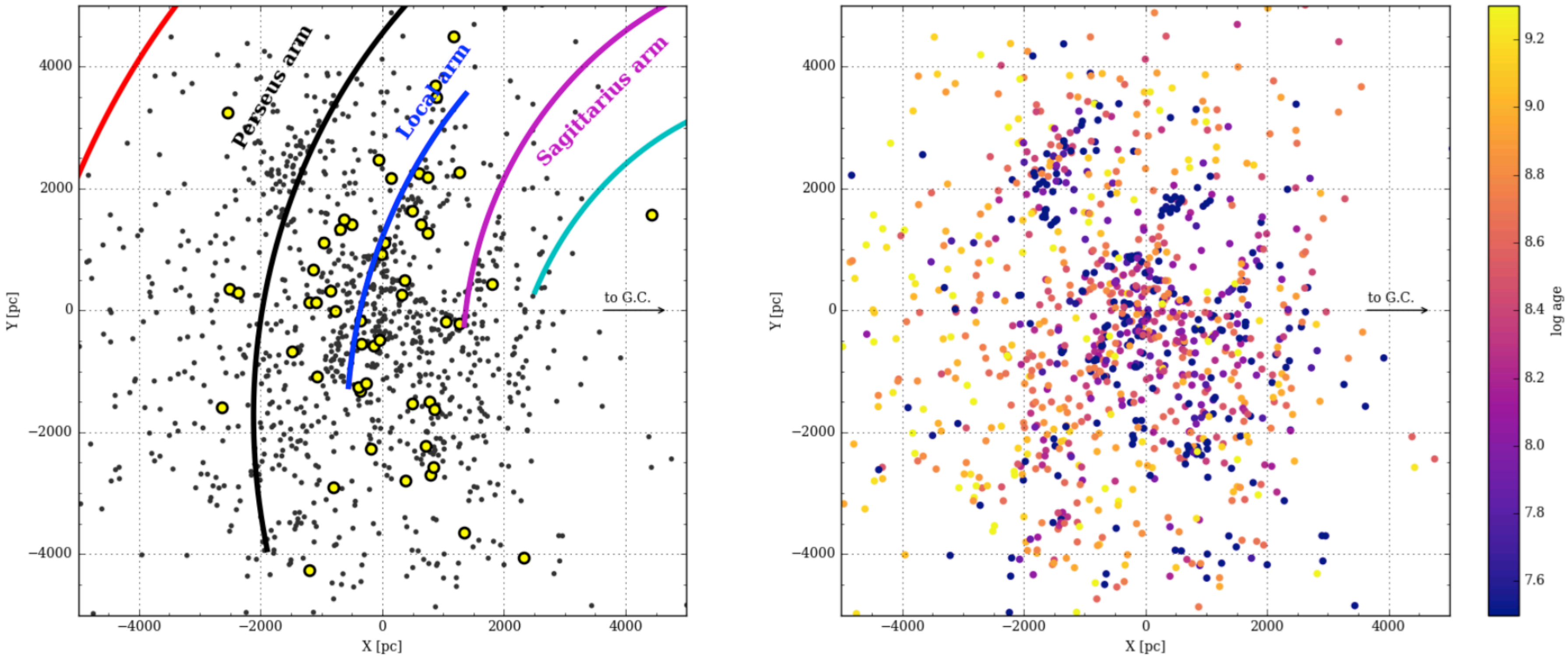


- **Open clusters provide the ultimate age scale** especially in the post-Gaia era.
- **Plato could be the decisive tool** to properly calibrate the stellar age scale using clusters!

T. Cantat-Gaudin et al.: A *Gaia* DR2 view of the Open Cluster population in the Milky Way



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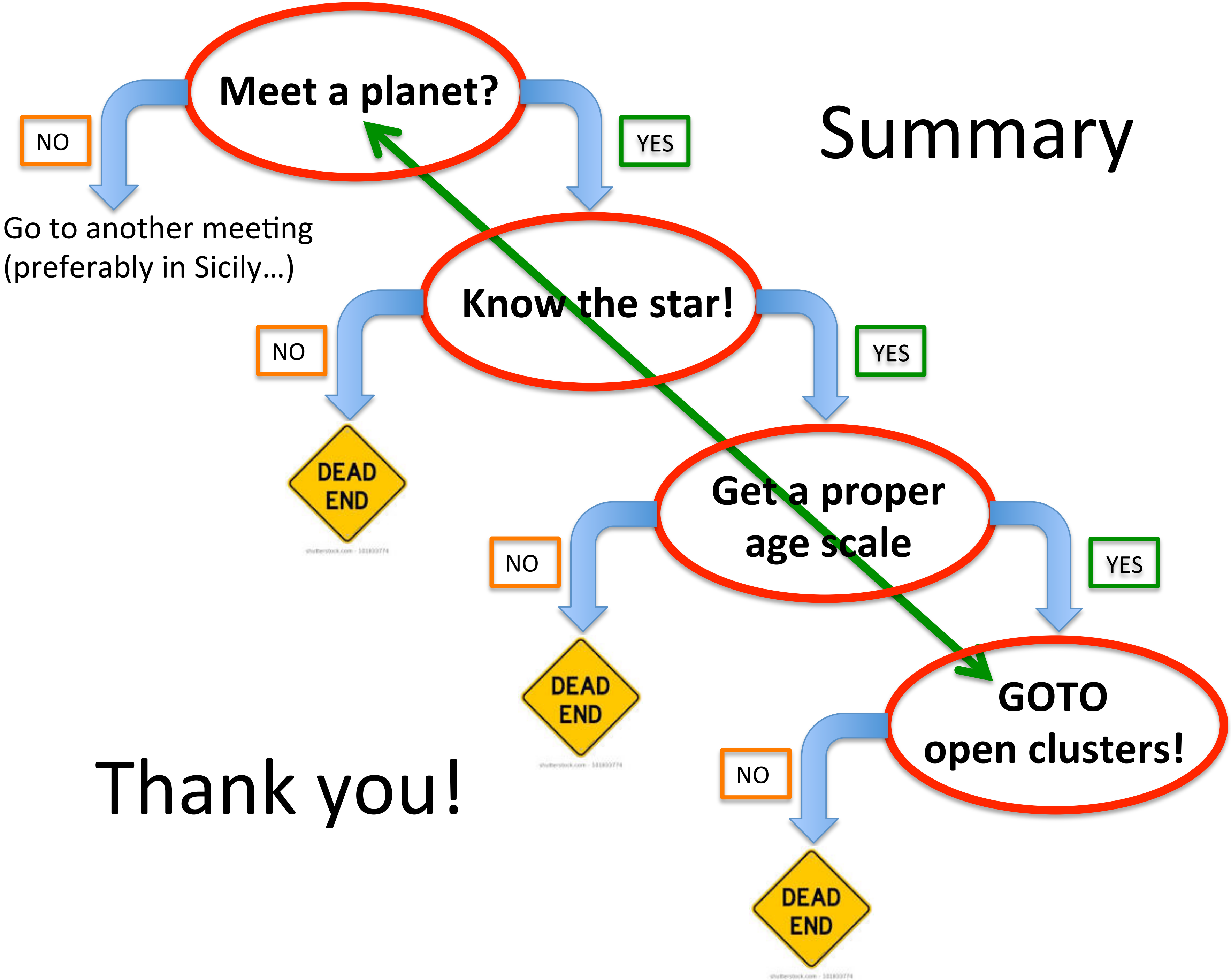
Summary



Thank you!