The effects of M dwarf magnetic fields and winds on potentially habitable planets

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University of Geneva

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J. Morin (Montpellier), P. Lang (St Andrews), A.J.B. Russell (Glasgow)

Habitability of planets around M dwarfs may be affected by....

- Coronal Mass Ejections (Khodachenko+07, Lammer+07)
- cosmic rays (Griessmeier+05,09)
- X-EUV radiation (Lammer+07)
- Planetary magnetic protection
- Stellar winds & magnetic fields

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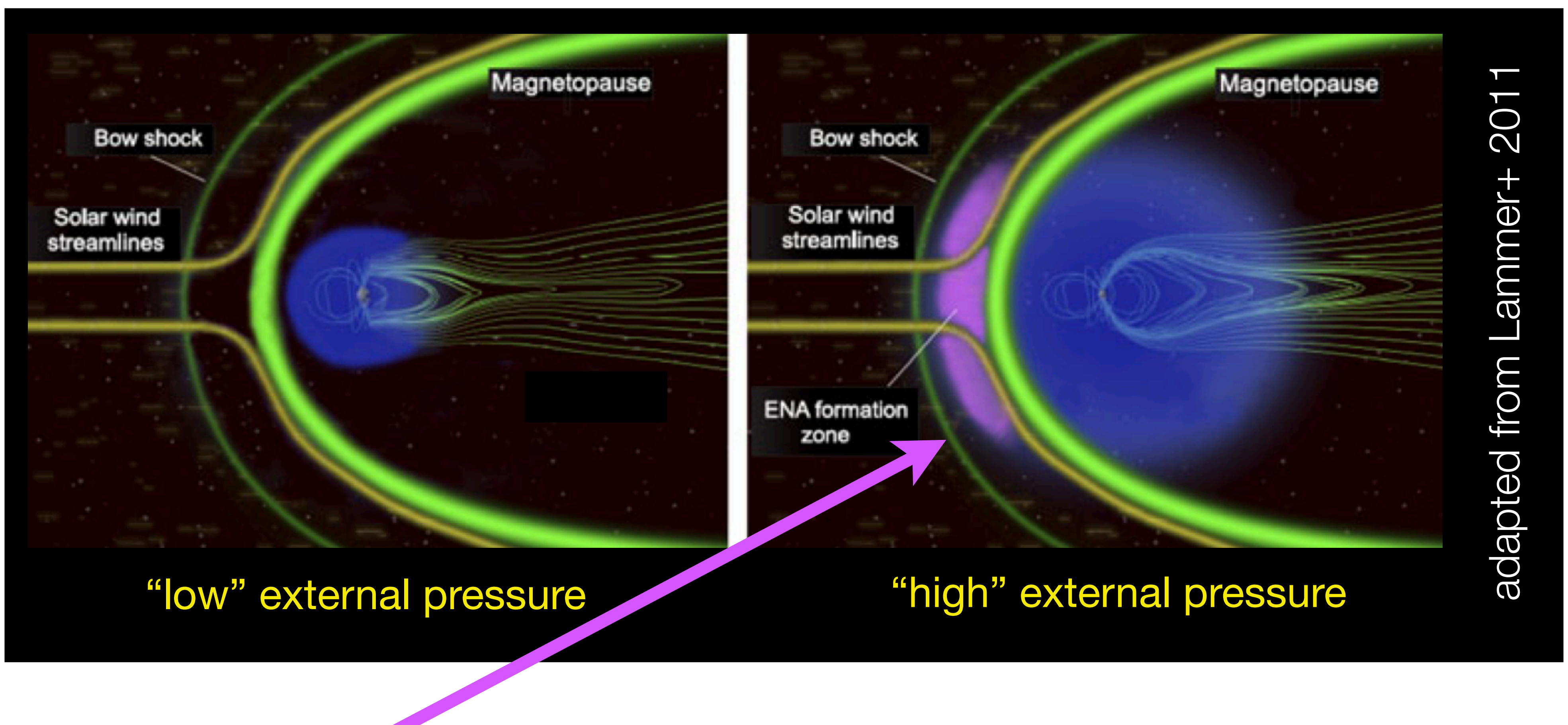
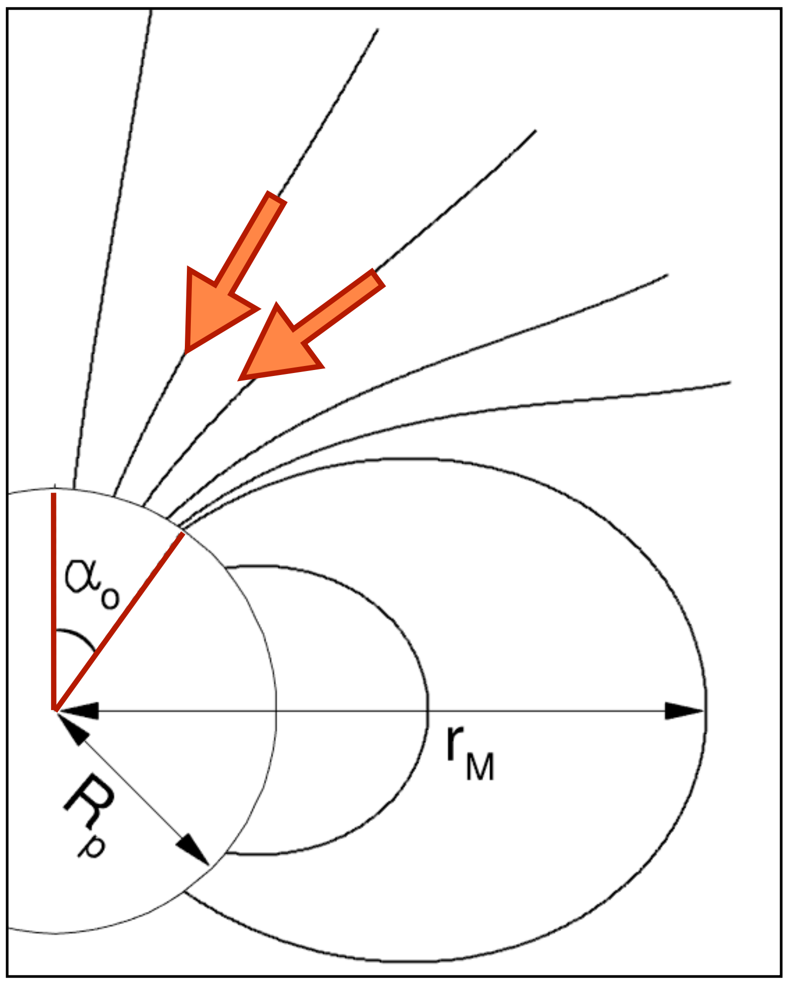


Habitability effect: exposure of planet’s atmosphere to erosion by cosmic particles

Planetary 'magnetic shield'

Large magnetosphere



Small auroral oval α_0

$$\alpha_0 = \arcsin\left[\left(\frac{r_p}{r_M}\right)^{1/2}\right]$$

(Siscoe & Chen 75, Tarduno+10, Vidotto+11a, Zuluaga+12)

Precipitating electrons

- auroral emission: radio, IR, visible, UV, X-ray
- electron heating, enhancing atmospheric evaporation → blown away by the solar wind

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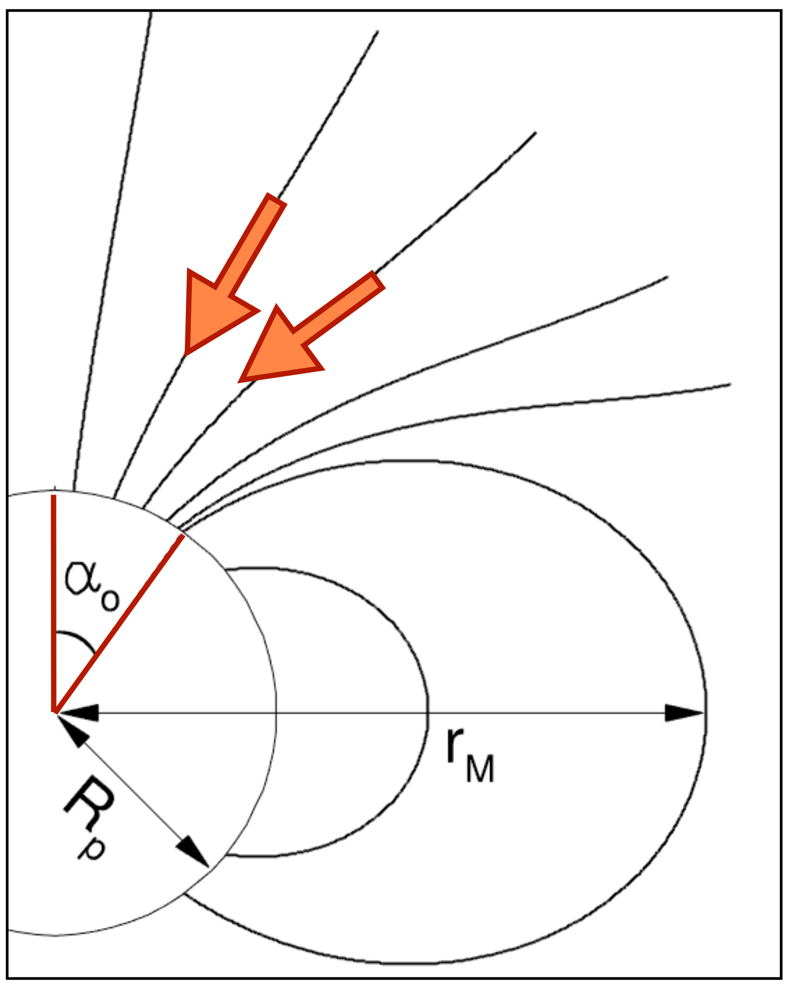

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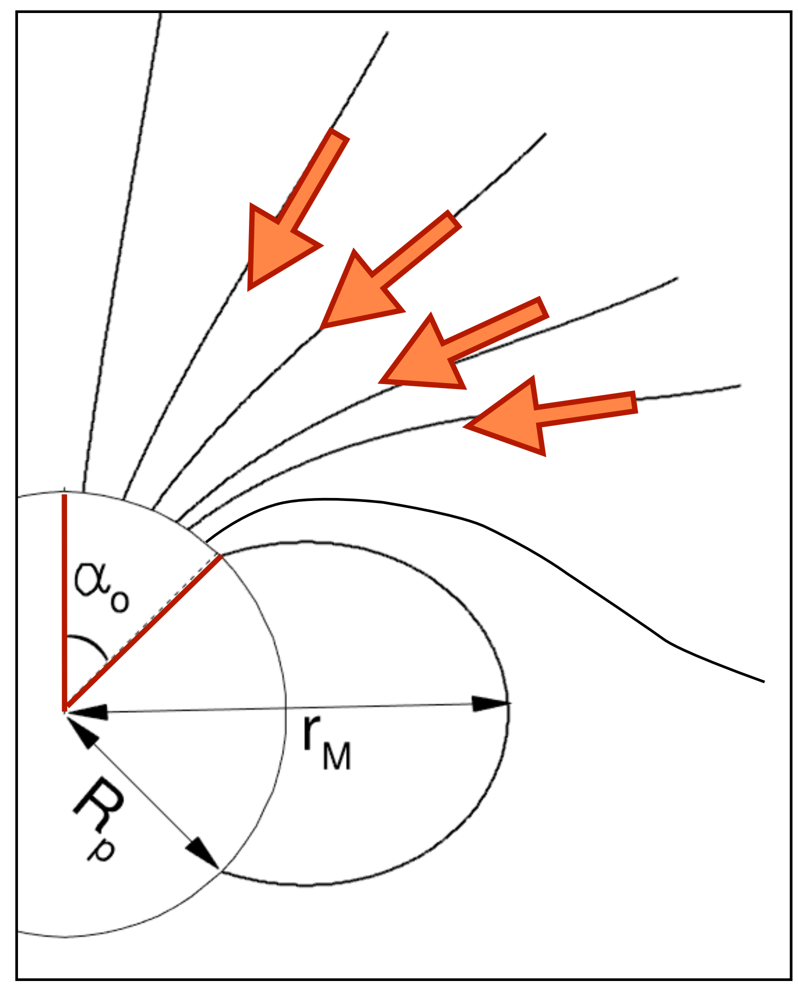

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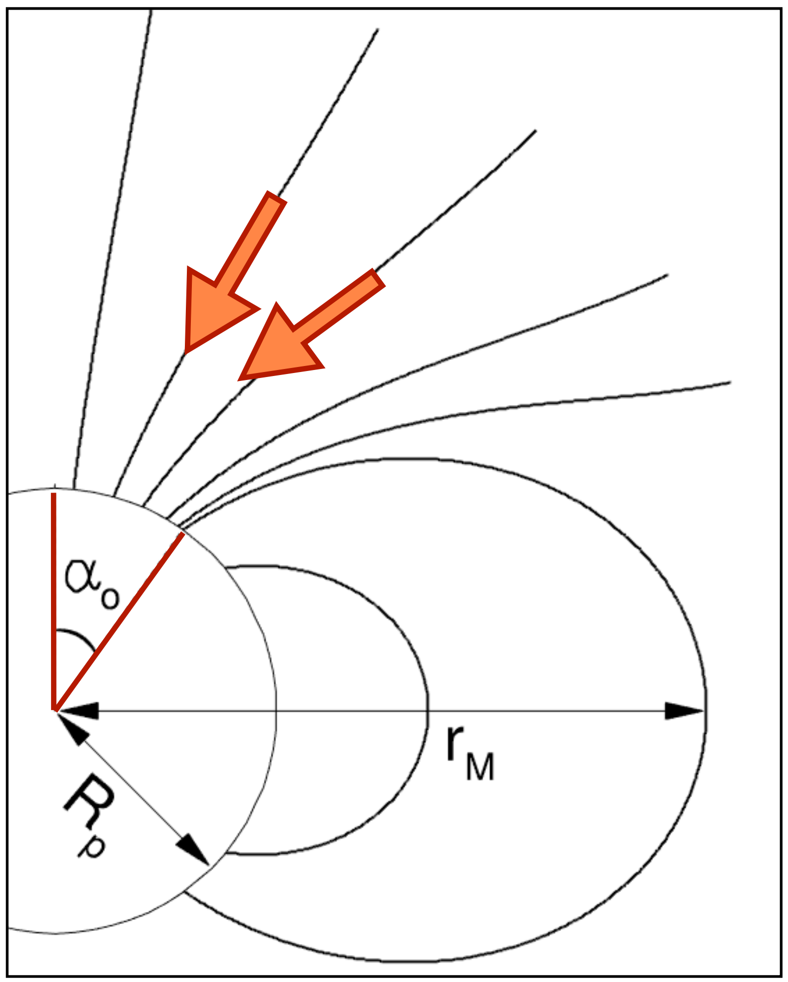

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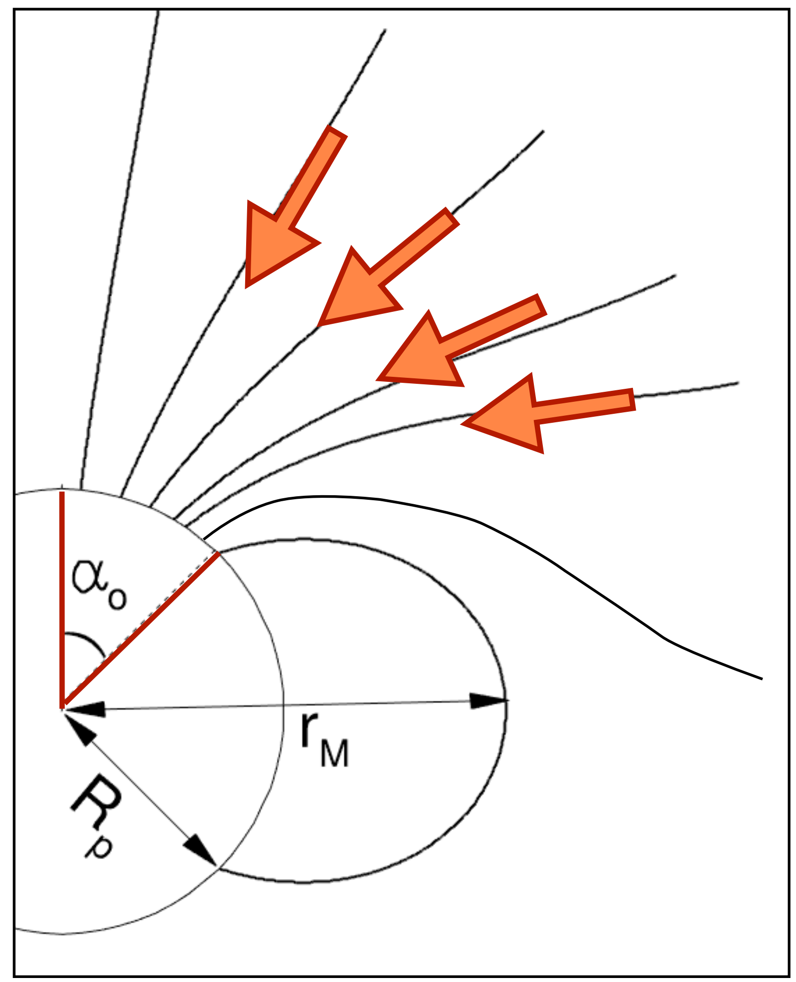

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Potential impact on habitability

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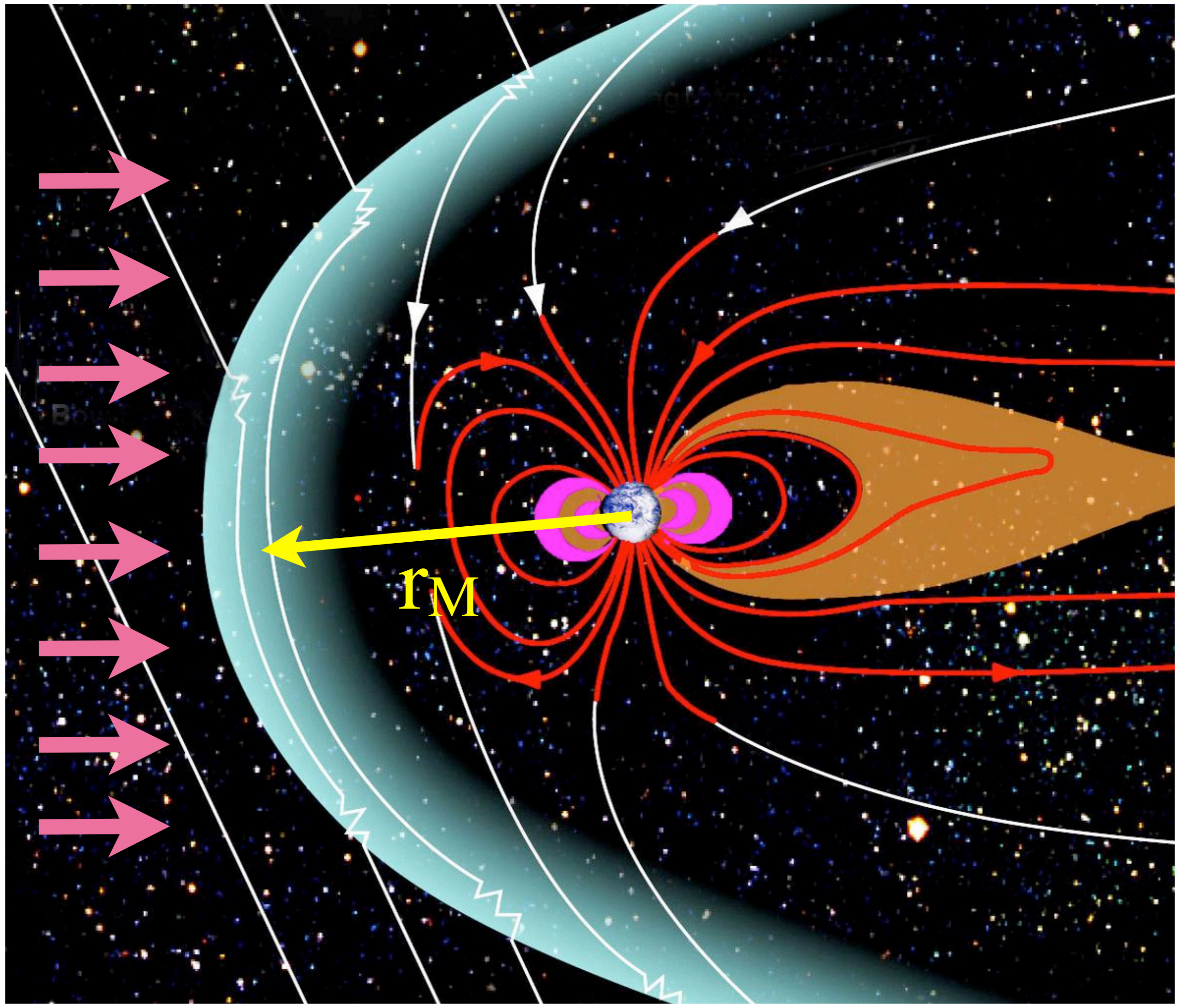
Interaction: Sun-Earth

- Pressure balance between the stellar coronal medium and the planet

$$\rho u_{\rm rel}^2 + \frac{[B_\star(R_{\rm orb})]^2}{8\pi} + p = \frac{[B_p(r_M)]^2}{8\pi} + p_p$$



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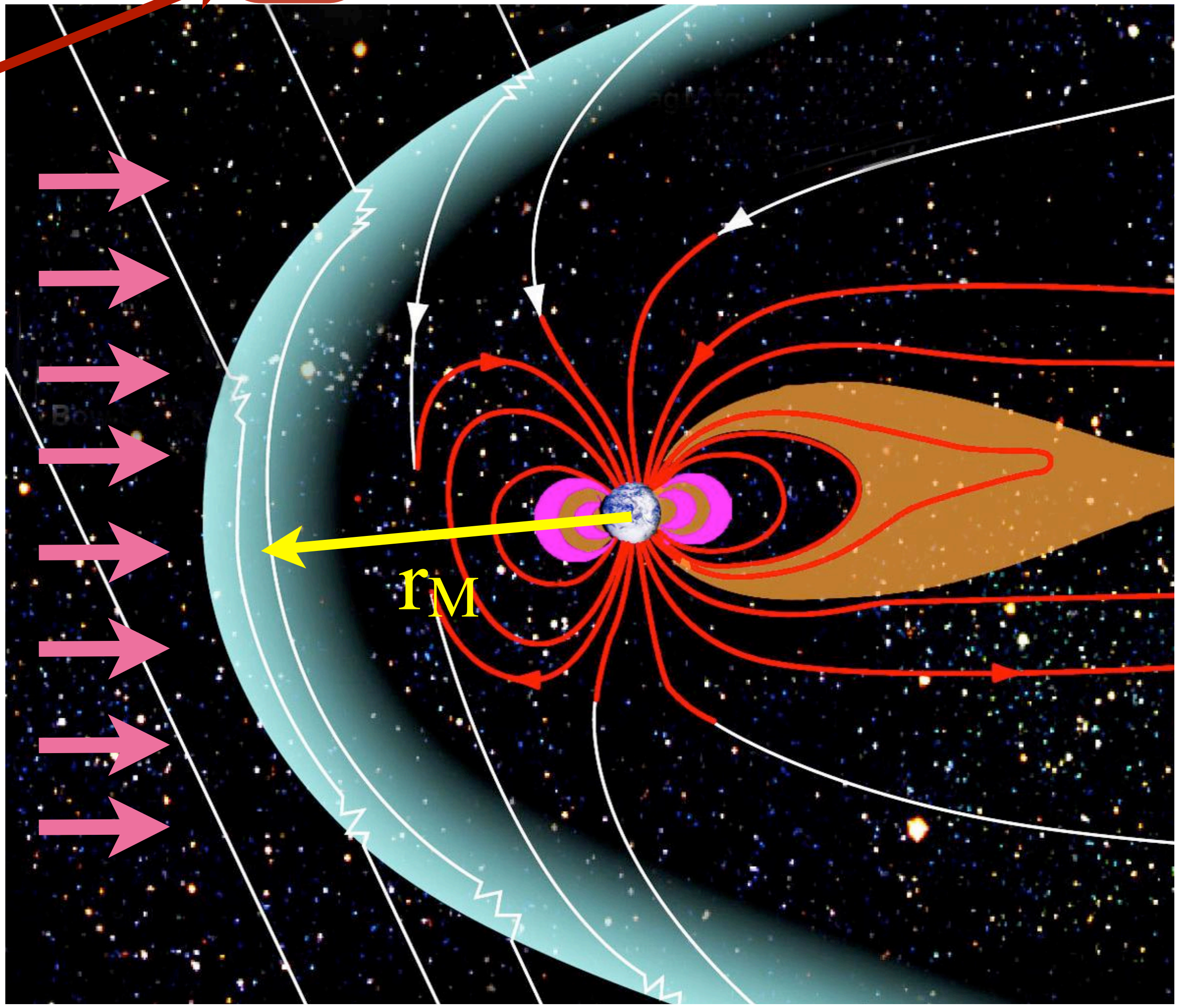

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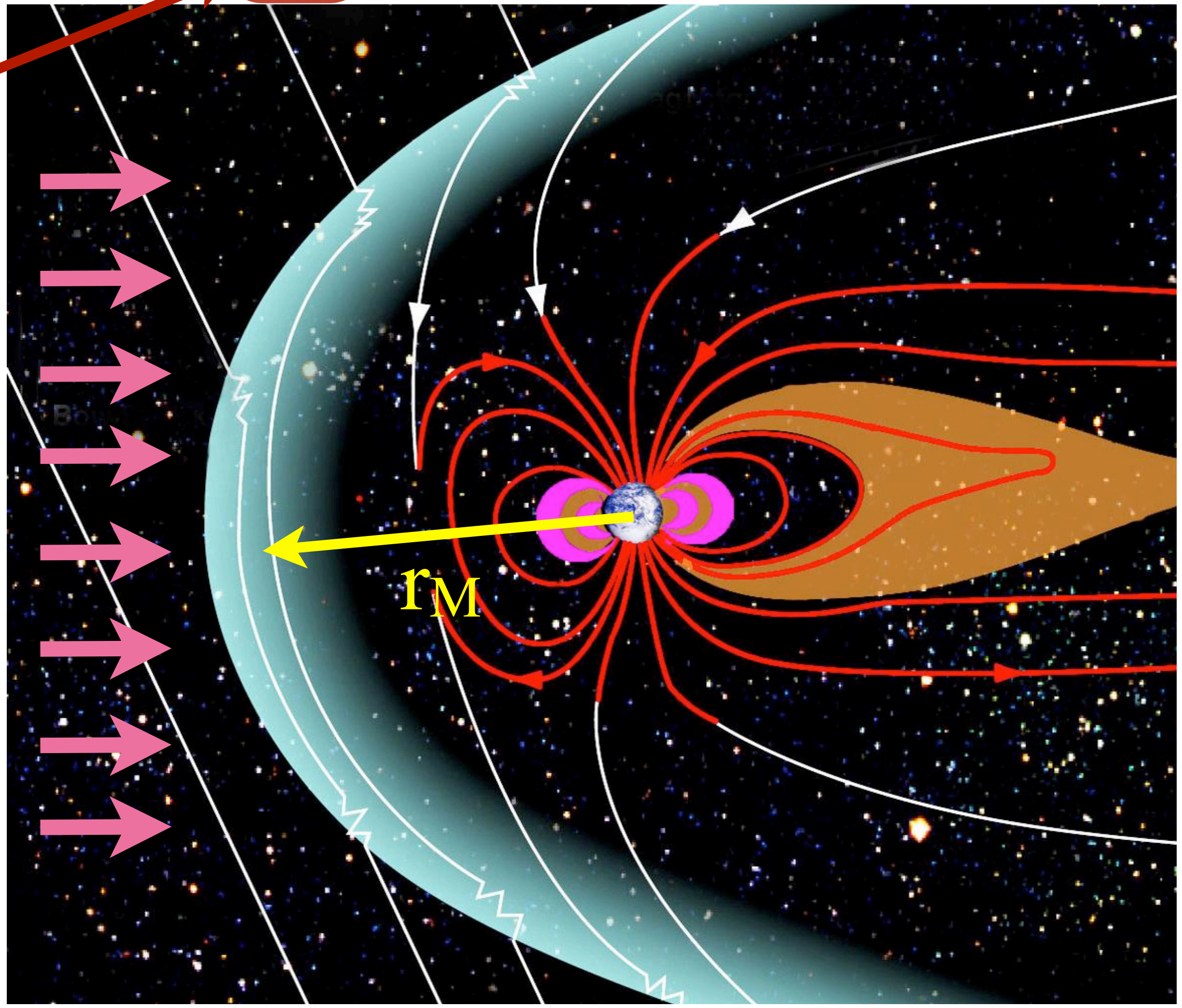

- considering Earth B is dipolar:

$$\frac{r_M}{R_\oplus} = \left(\frac{(B_{\rm pole}/2)^2}{8\pi\rho u_{\rm SW}^2} \right)^{1/6} \simeq 11$$

(Chapman & Ferraro 1930)

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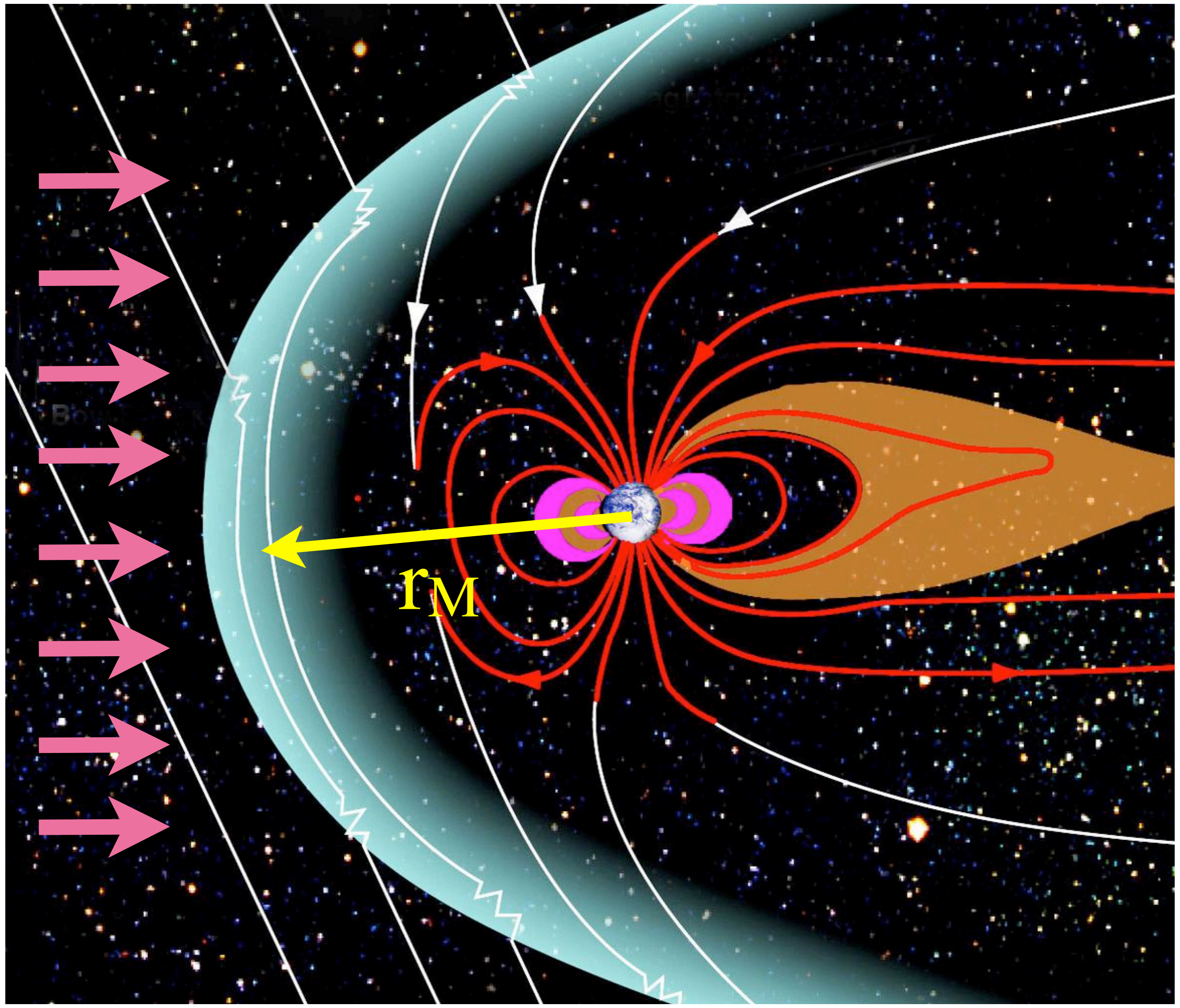

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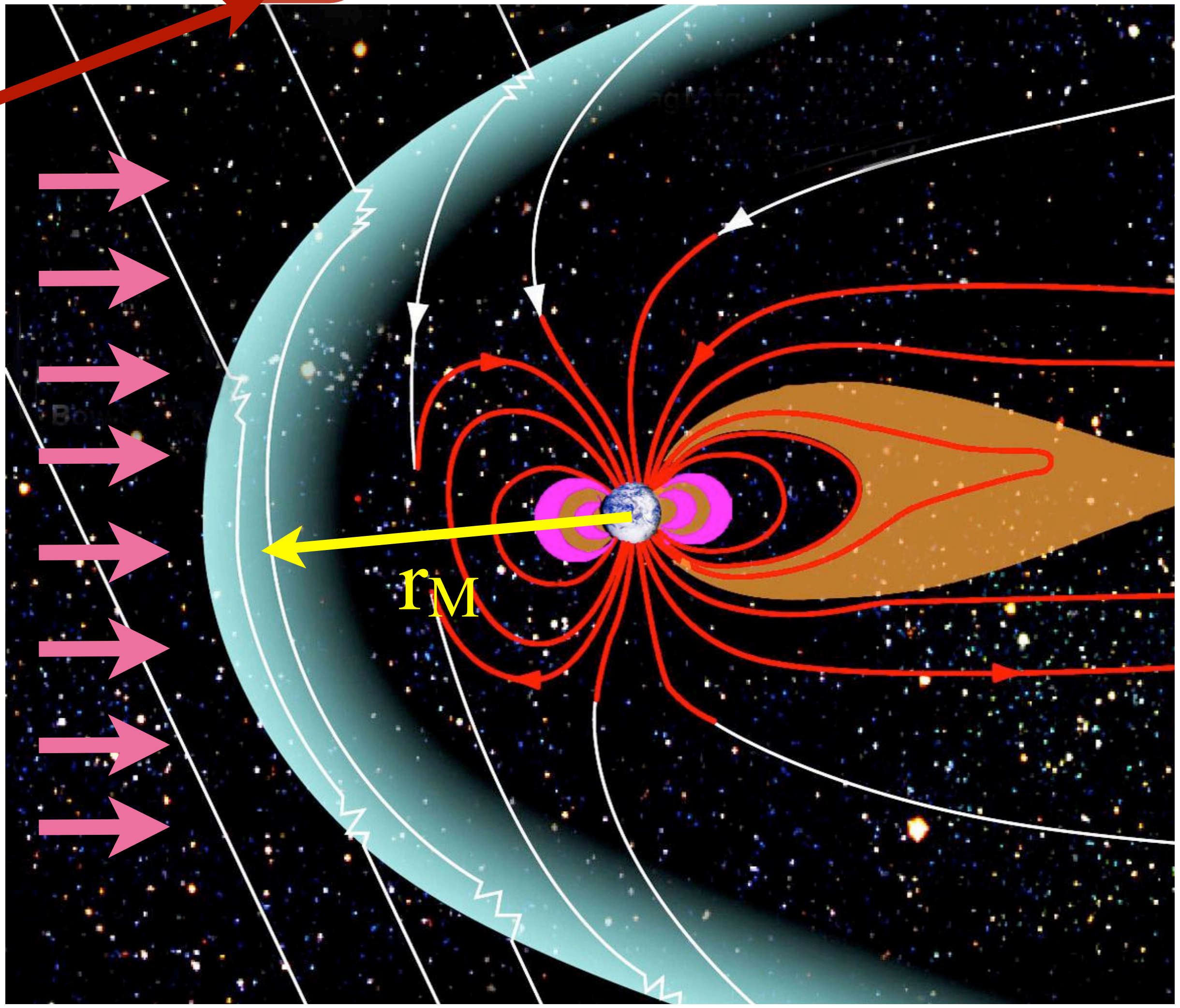

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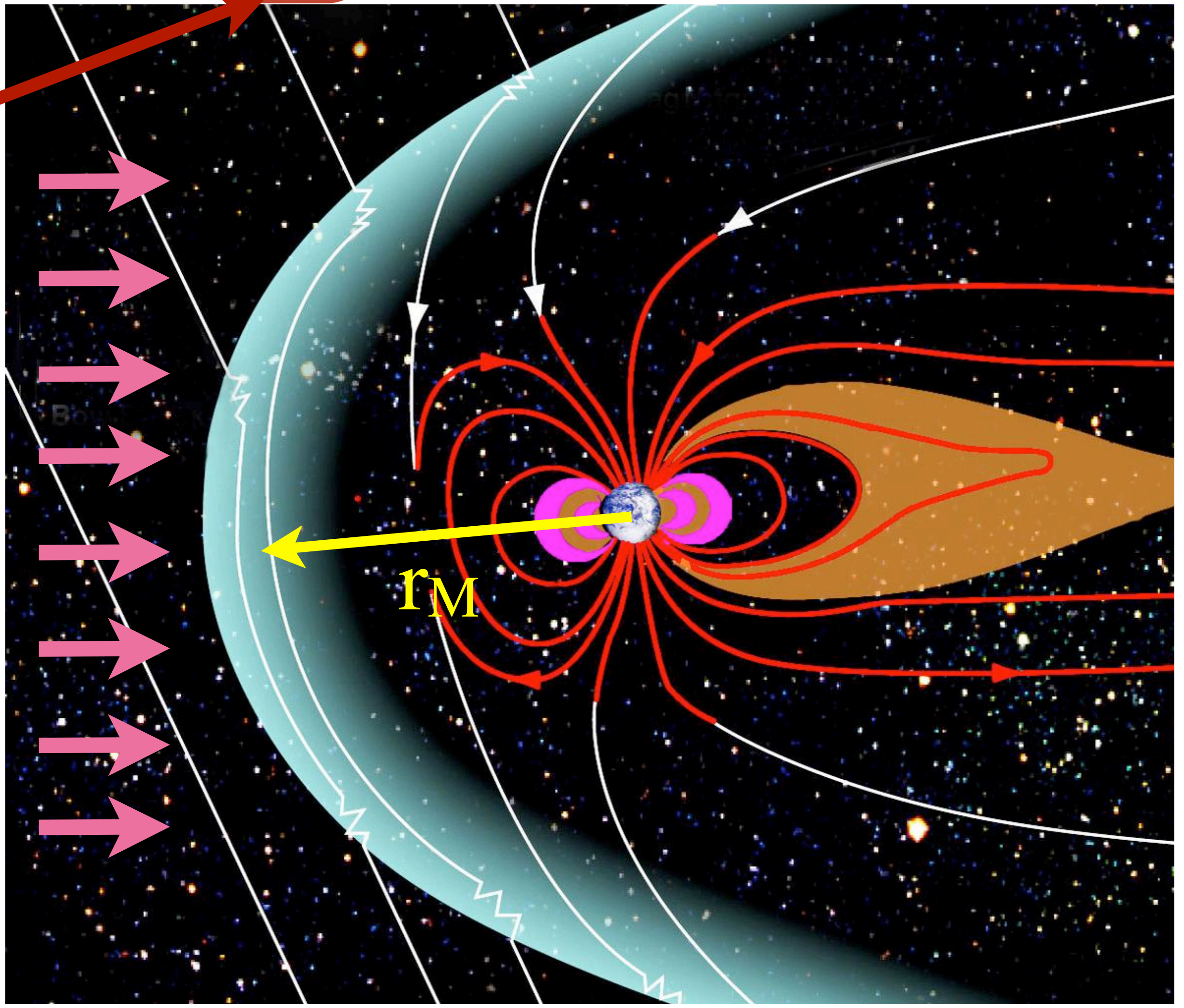

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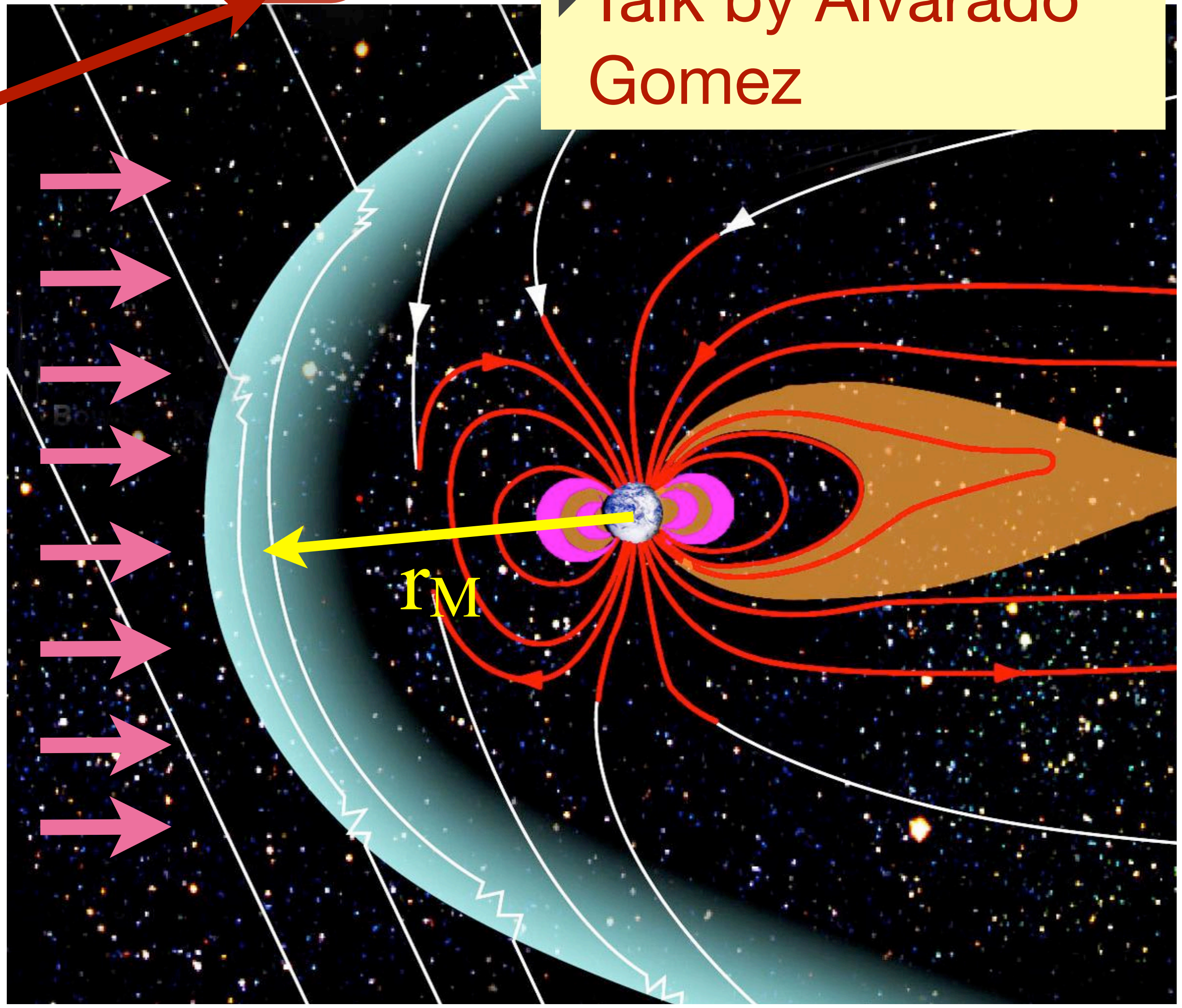

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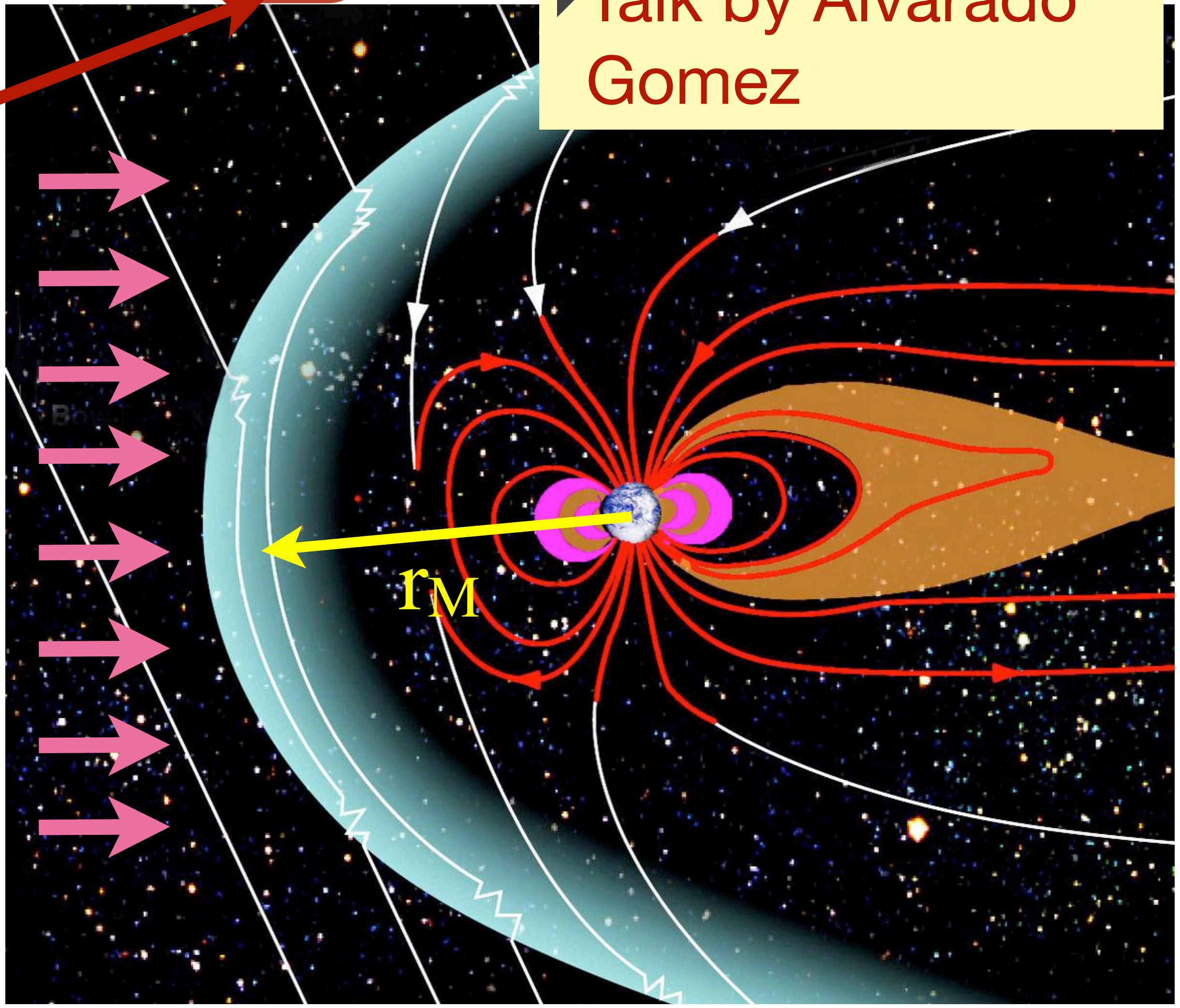

Lower limit of the external pressure:

(neutral points: Dungey 61, Lanza 09)

$$\frac{[B_\star(R_{orb})]^2}{8\pi} < \frac{[B_{pl}(r_M)]^2}{8\pi}$$

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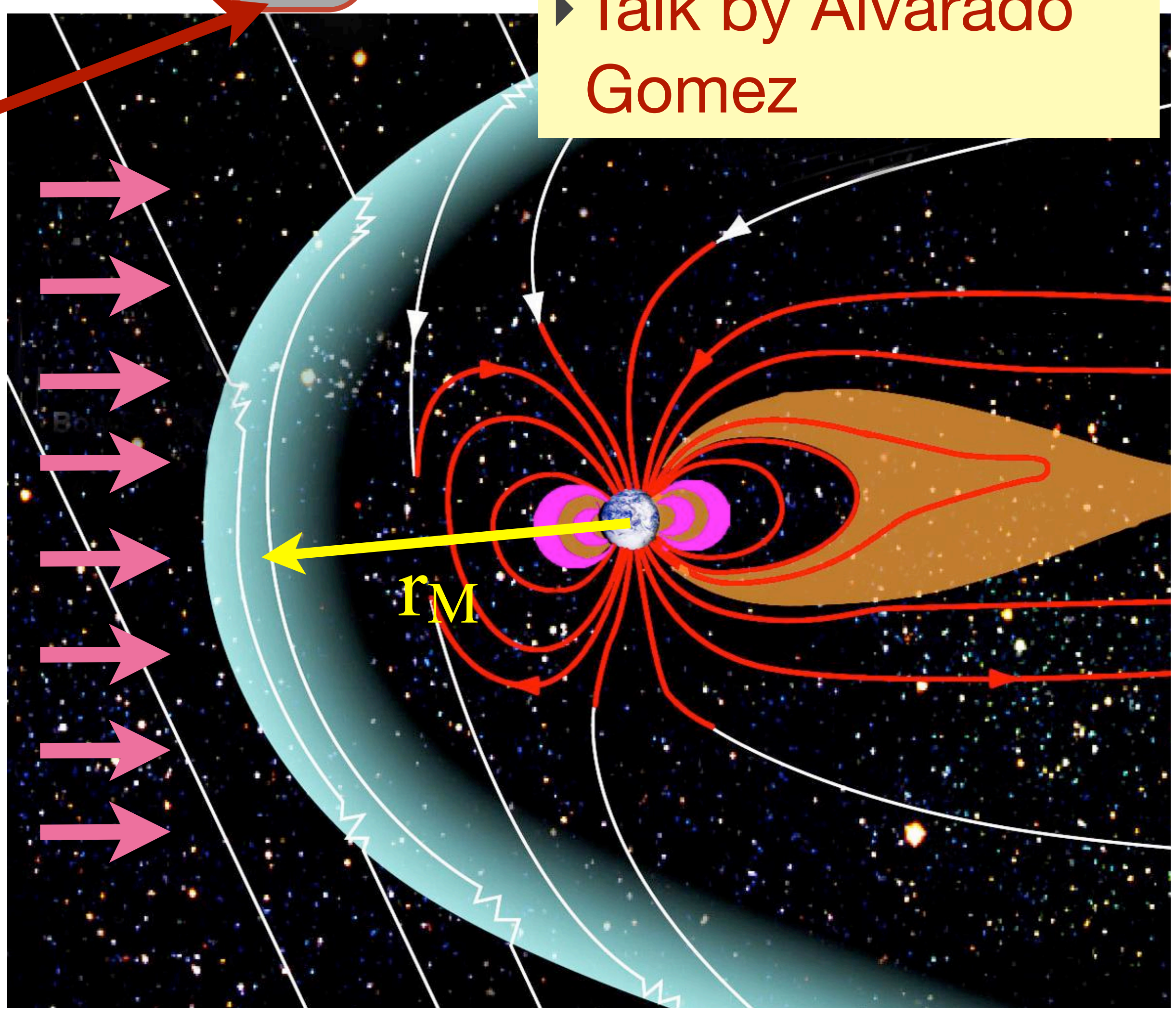

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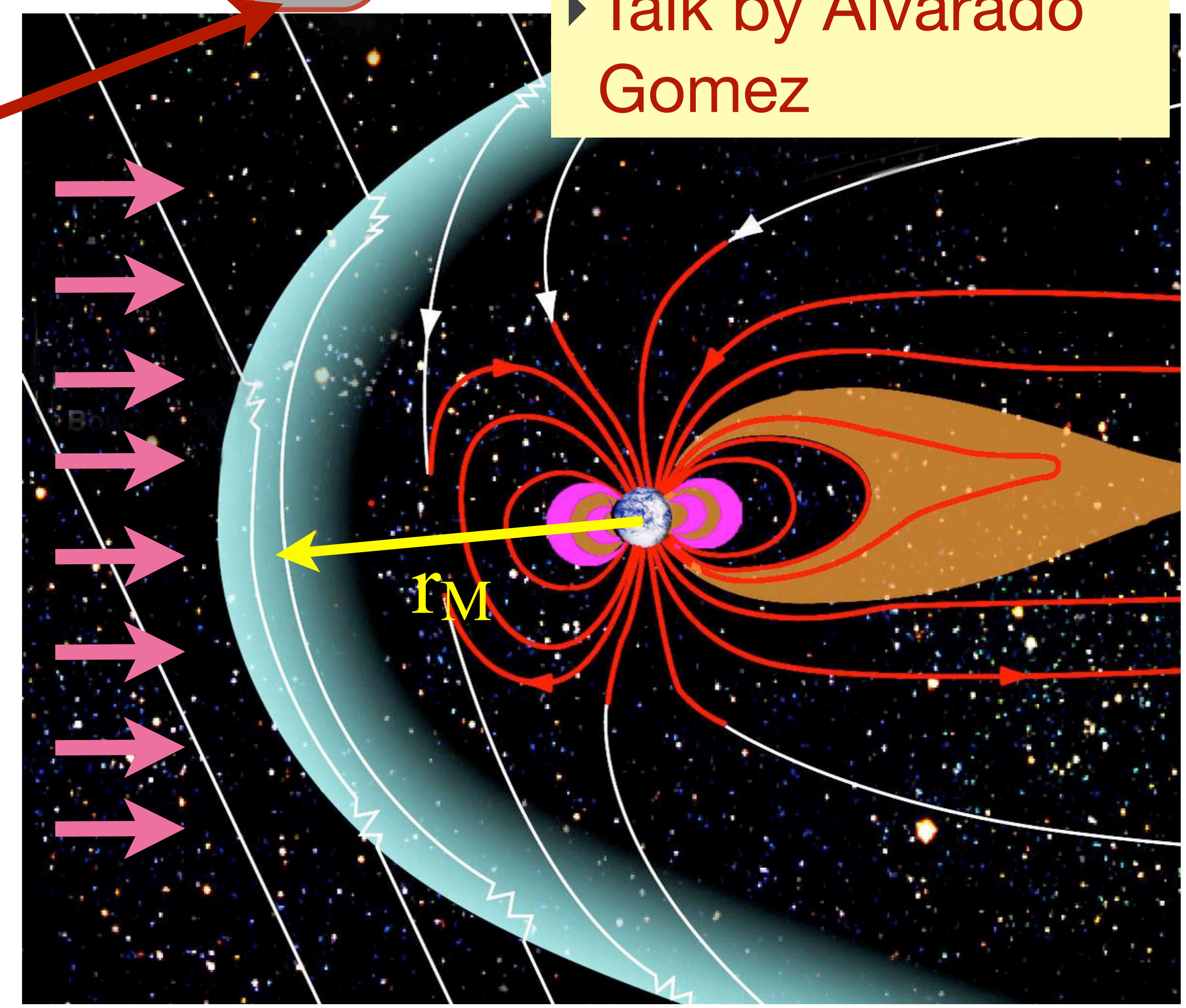

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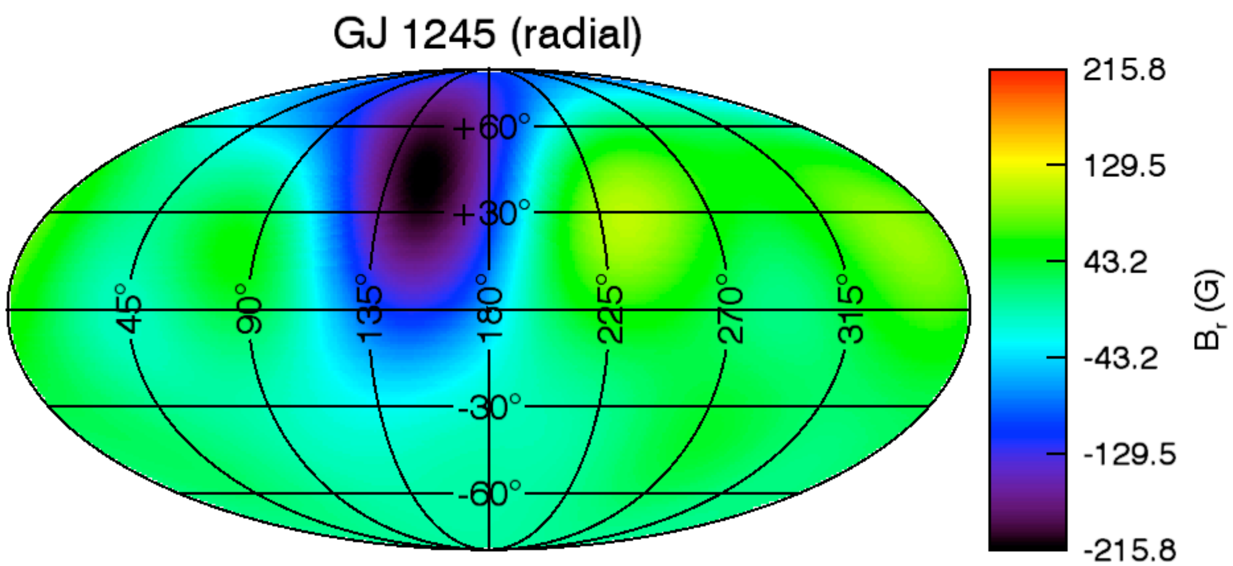
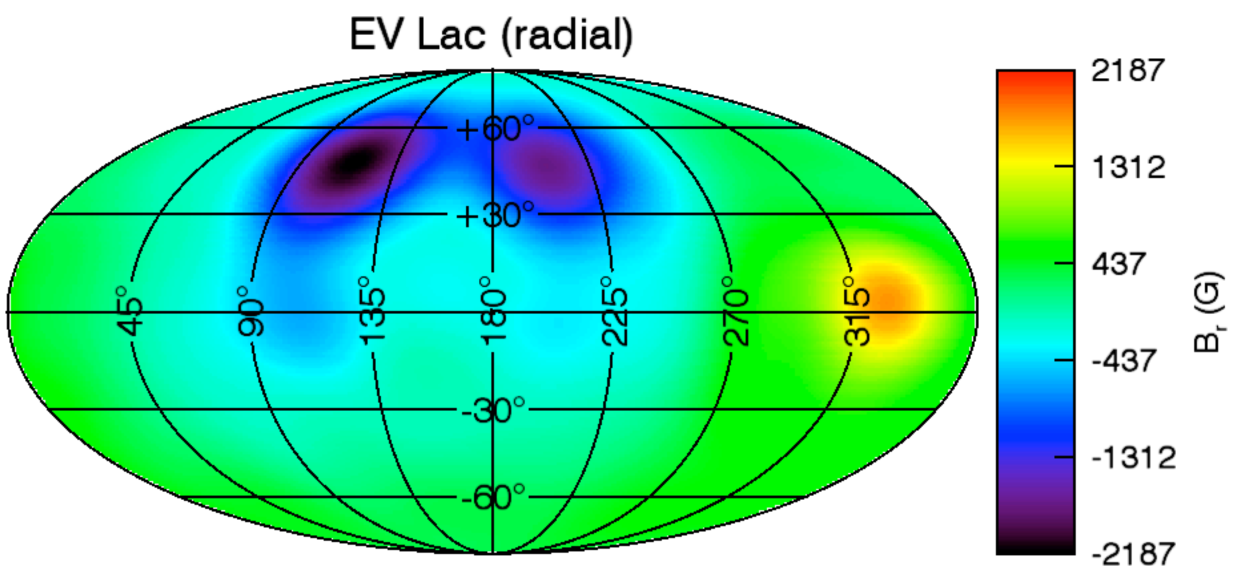
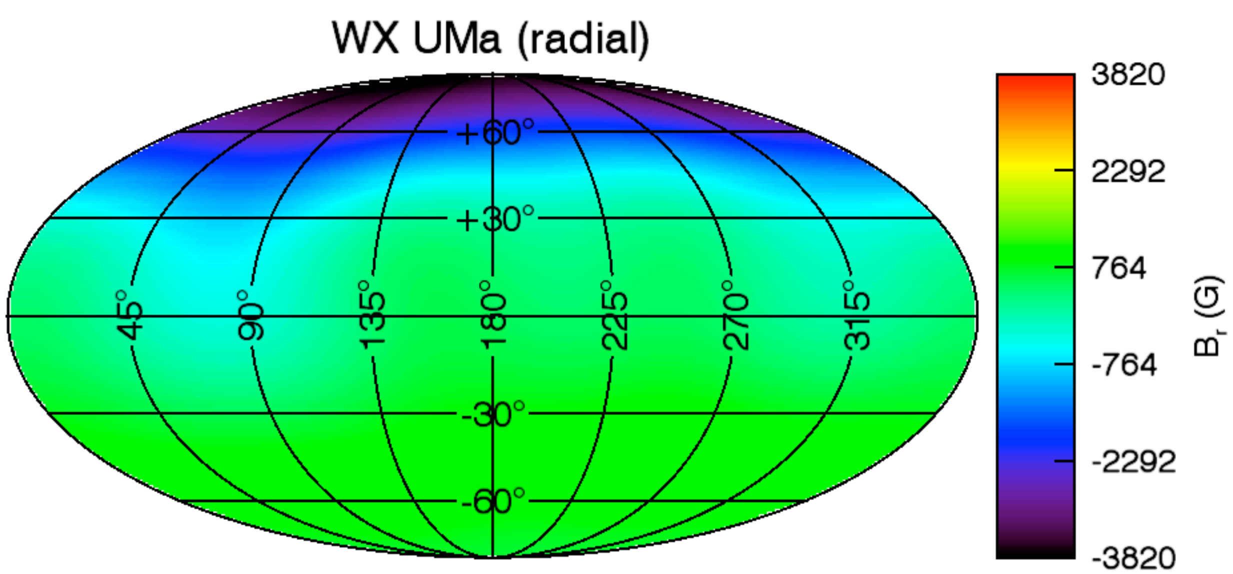
How do we image stellar magnetic fields?

Zeeman Doppler imaging: magnetic fields of cool stars

Donati+08, Morin+08,10







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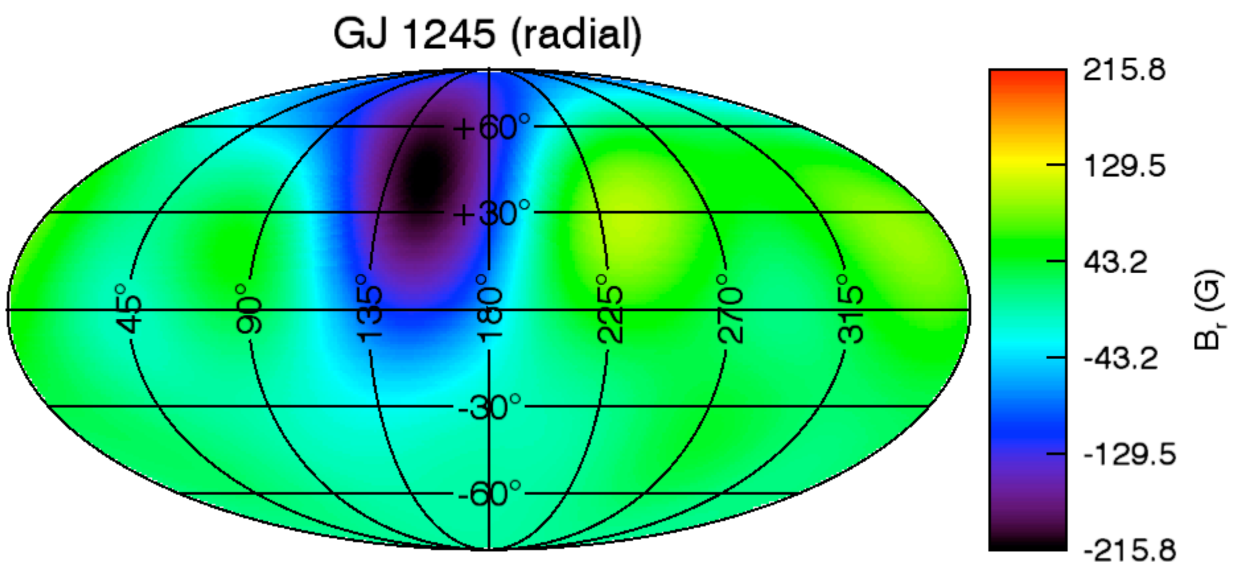
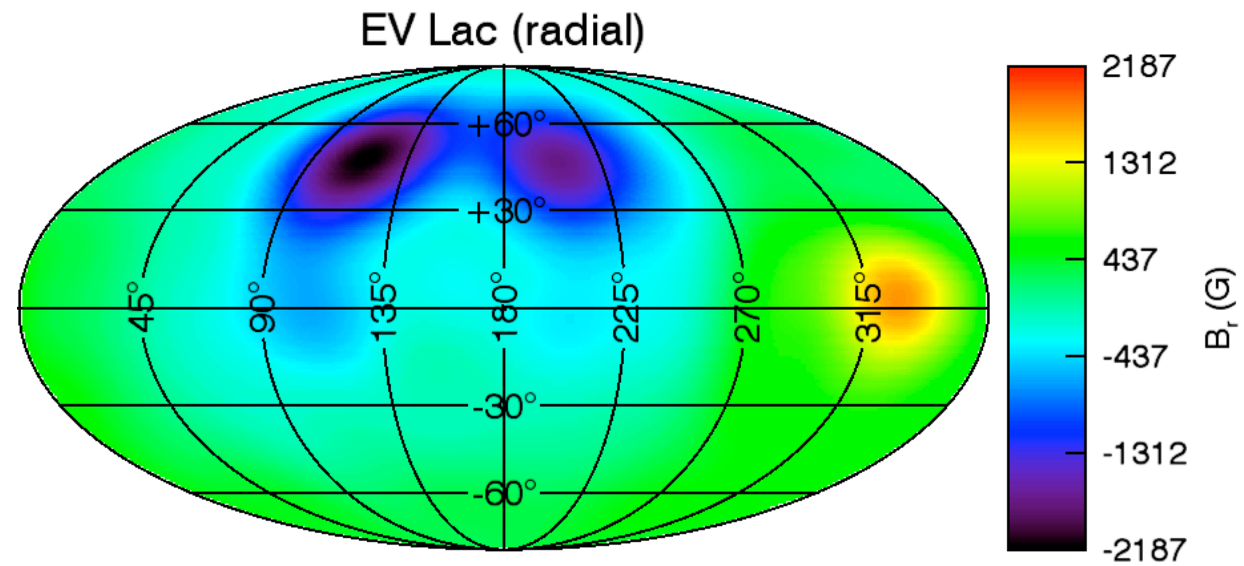
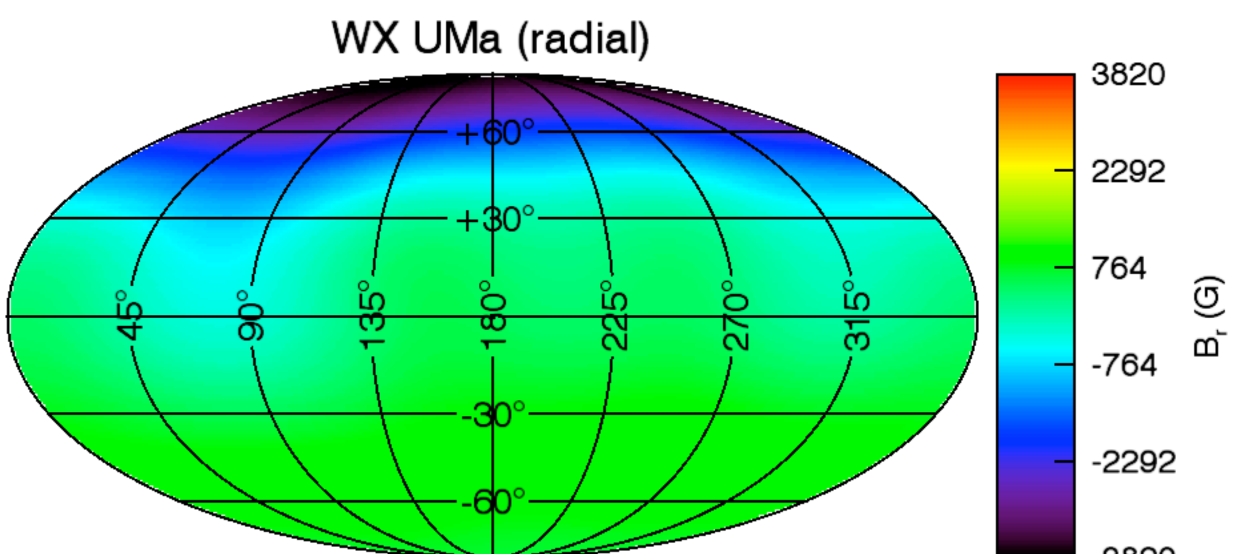
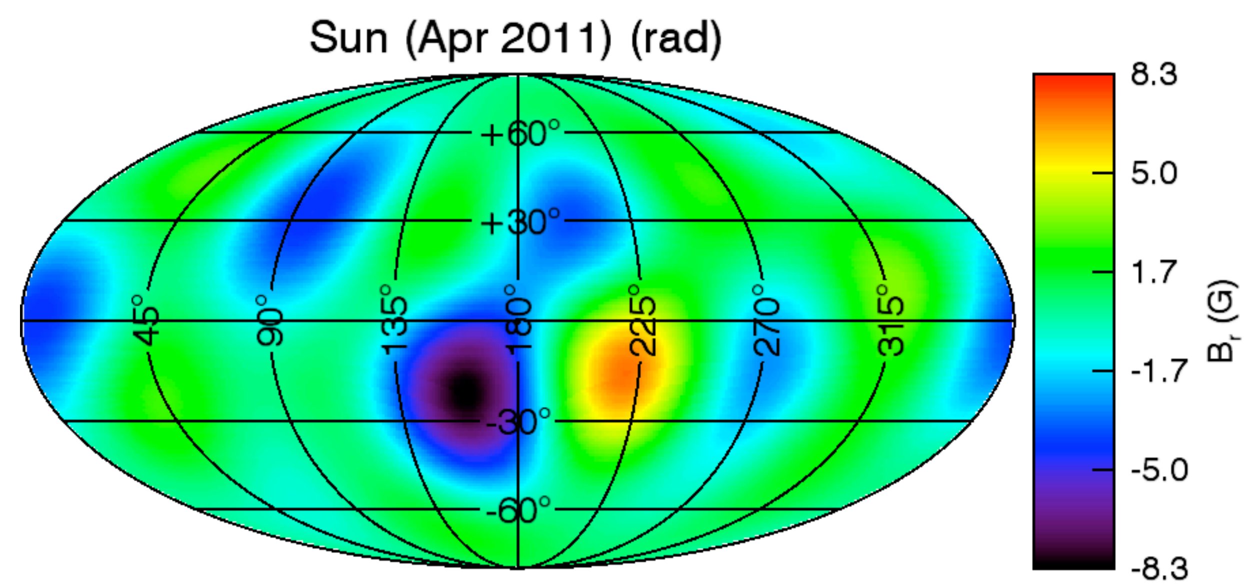


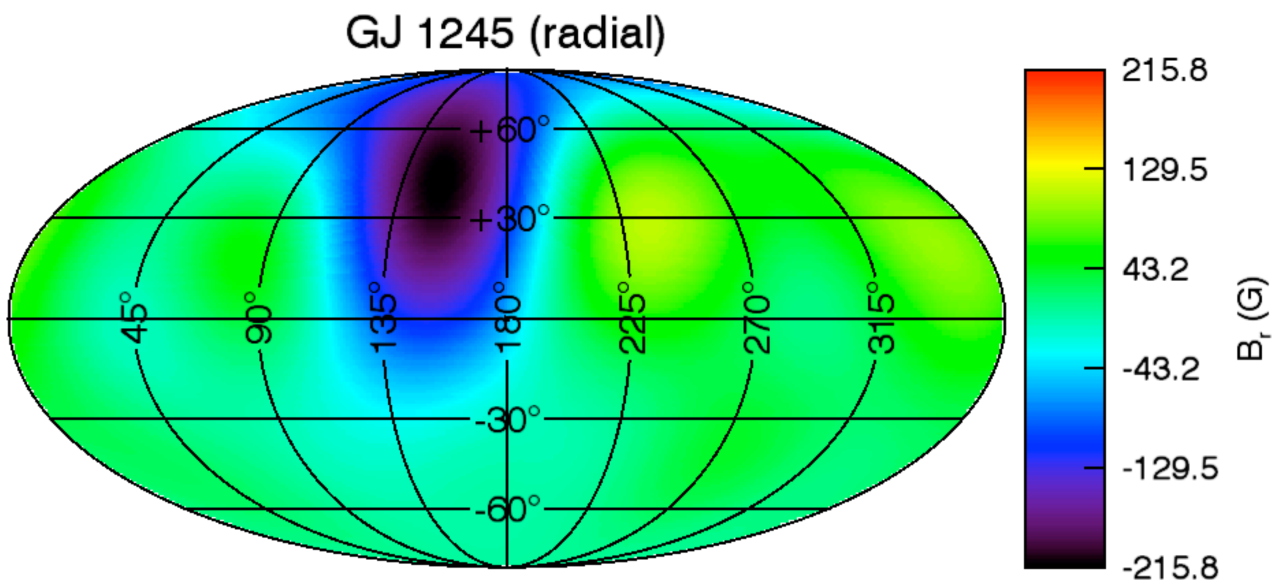


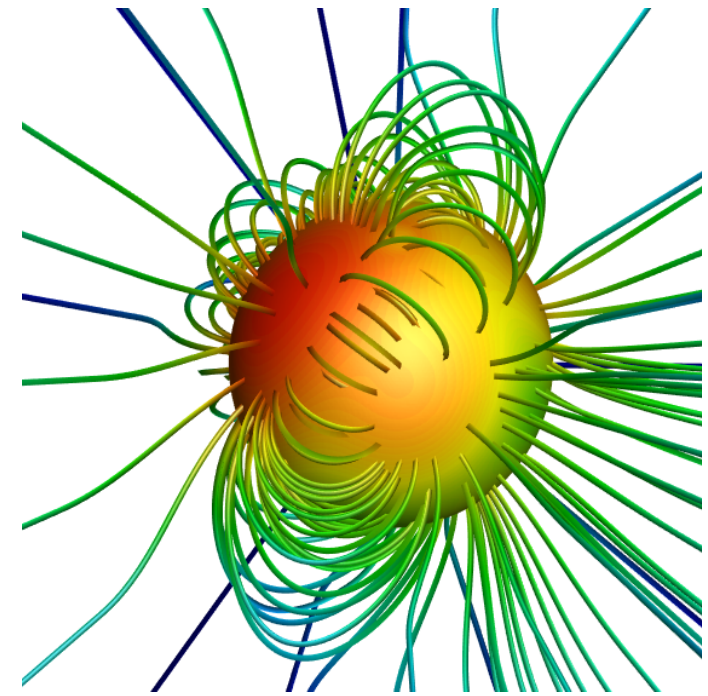




Vidotto+2016b

The magnetic field at the planet's orbit

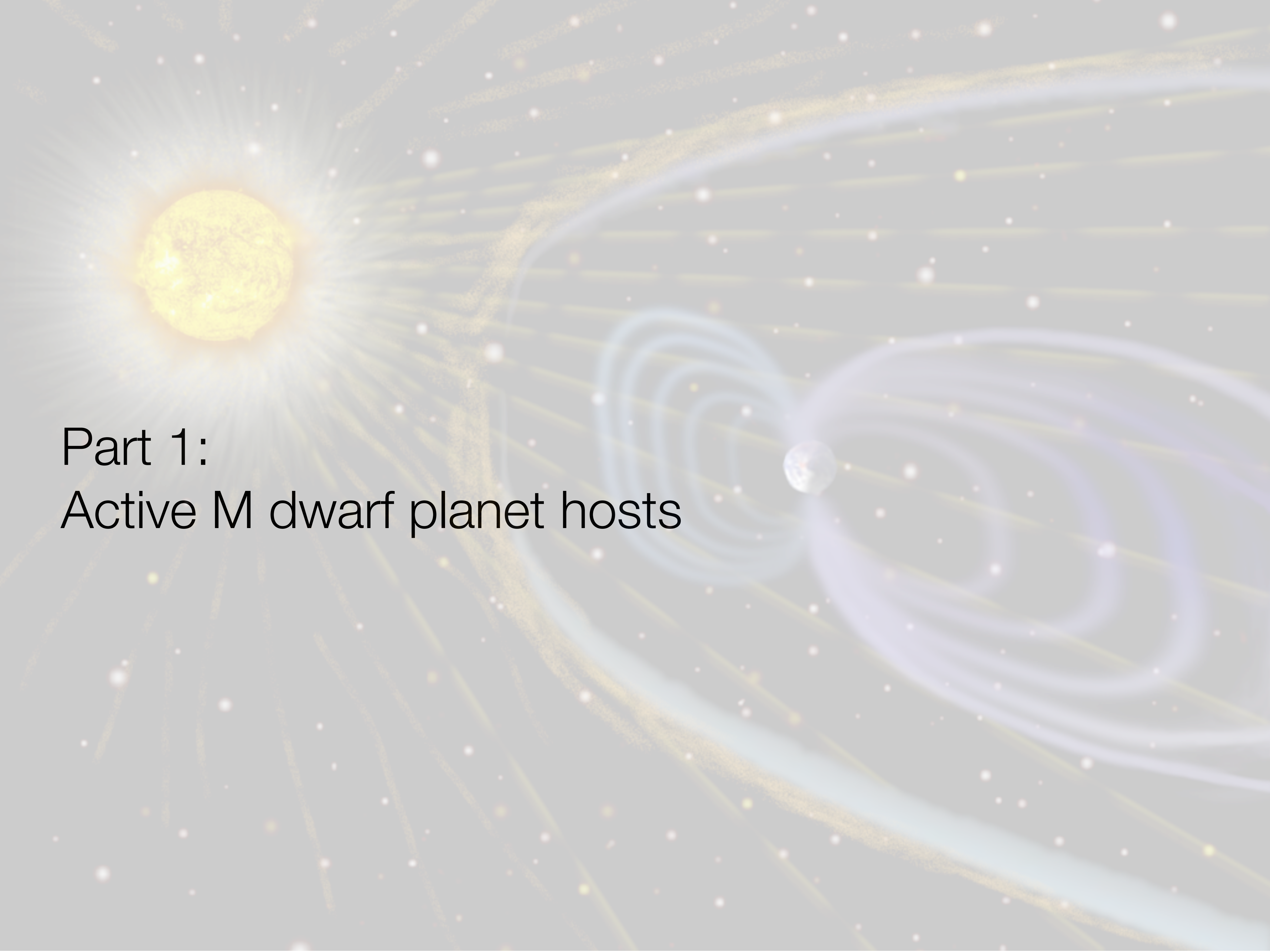




$$\frac{r_M}{R_p} \lesssim \left(\frac{B_{\rm pole}/2}{B_\star(R_{\rm orb})} \right)^{1/3}$$

"Potential field source surface extrapolation"
(Altschuler & Newkirk 69, Jardine+99)

$$\nabla \times \mathbf{B} = 0 \rightarrow \mathbf{B} = -\nabla \Psi$$
$$\nabla \cdot \mathbf{B} = 0 \rightarrow \nabla^2 \Psi = 0$$



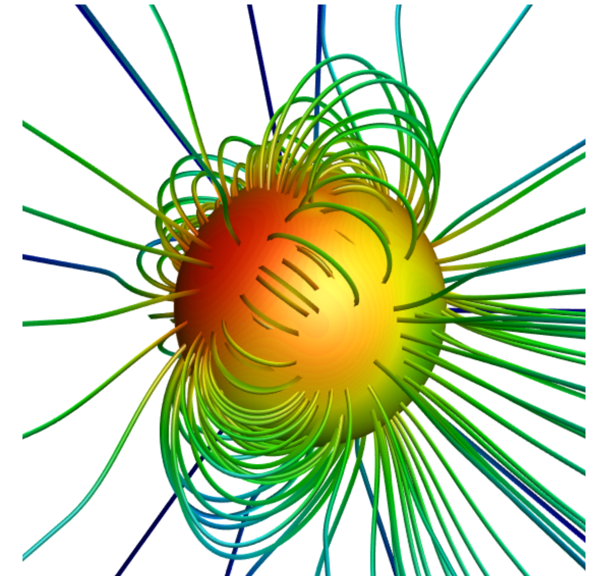
Part 1:
Active M dwarf planet hosts

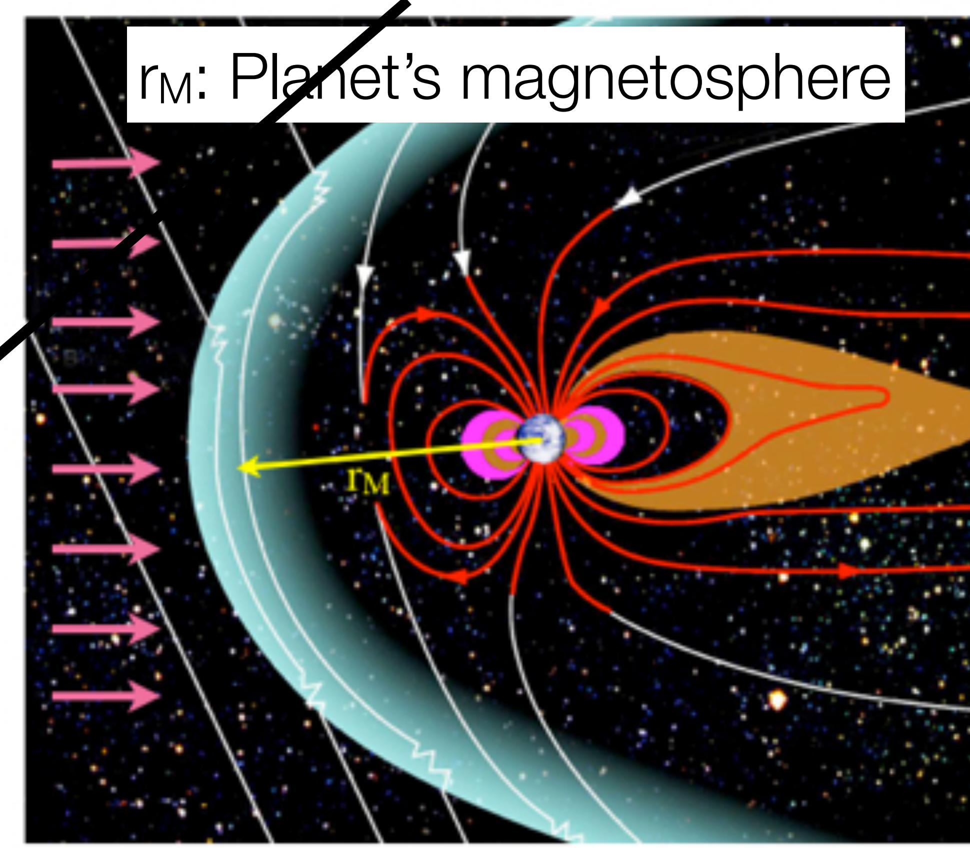
The sample of dM stars

Data from:
Donati+08, Morin+08,10

Star ID	Year obs.	Sp. type	M_* ($M_\odot$)	R_* ($R_\odot$)	P_{rot} (d)	$\langle B_\star^{ZDI} \rangle$ (G)
GJ 182	2007	M0.5	0.75	0.82	4.35	172
DT Vir	2008	M0.5	0.59	0.53	2.85	149
DS Leo	2008	M0	0.58	0.52	14.00	87
GJ 49	2007	M1.5	0.57	0.51	18.60	27
OT Ser	2008	M1.5	0.55	0.49	3.40	123
CE Boo	2008	M2.5	0.48	0.43	14.70	103
AD Leo	2008	M3	0.42	0.38	2.24	180
EQ Peg A	2006	M3.5	0.39	0.35	1.06	480
EV Lac	2007	M3.5	0.32	0.30	4.37	490
V374 Peg	2006	M4	0.28	0.28	0.45	640
EQ Peg B	2006	M4.5	0.25	0.25	0.40	450
GJ 1156	2009	M5	0.14	0.16	0.49	100
GJ 1245 B	2008	M5.5	0.12	0.14	0.71	60
WX UMa	2009	M6	0.10	0.12	0.78	1060
DX Cnc	2009	M6	0.10	0.11	0.46	80

What would be the size of the magnetosphere of an “Earth” orbiting around an M dwarf?





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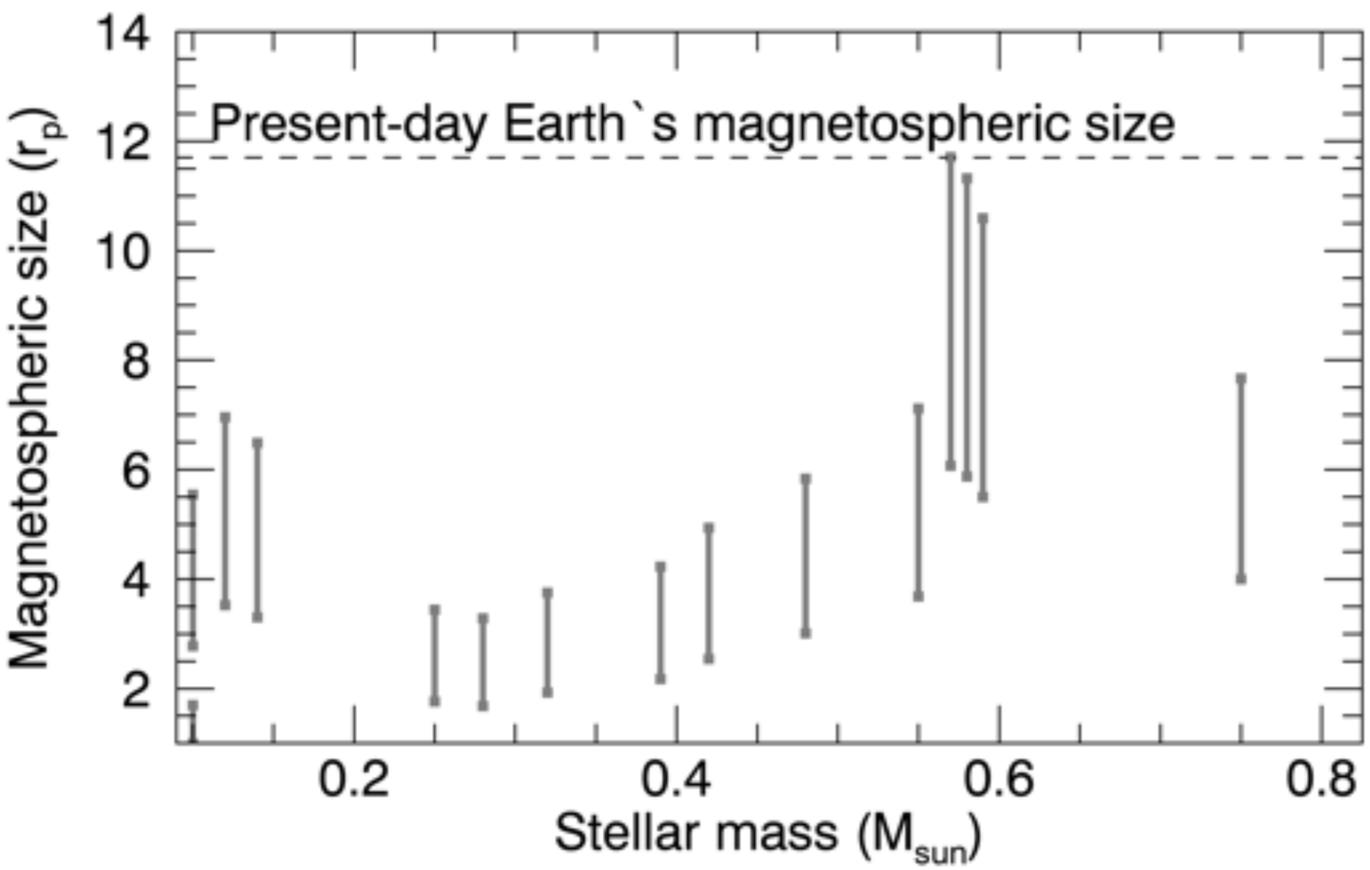

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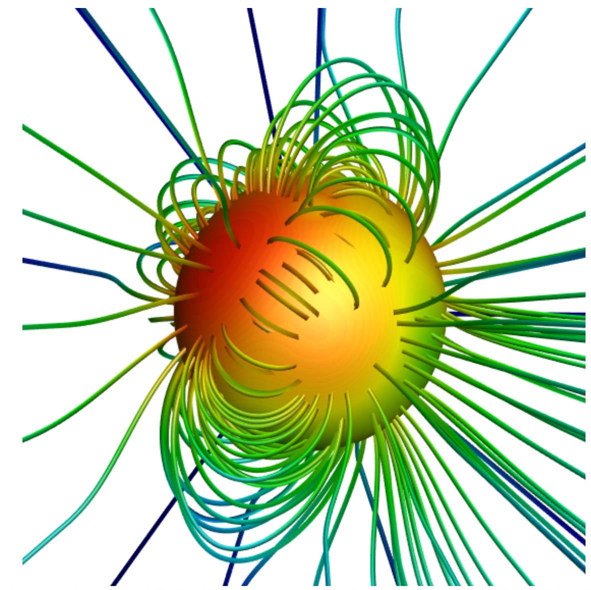

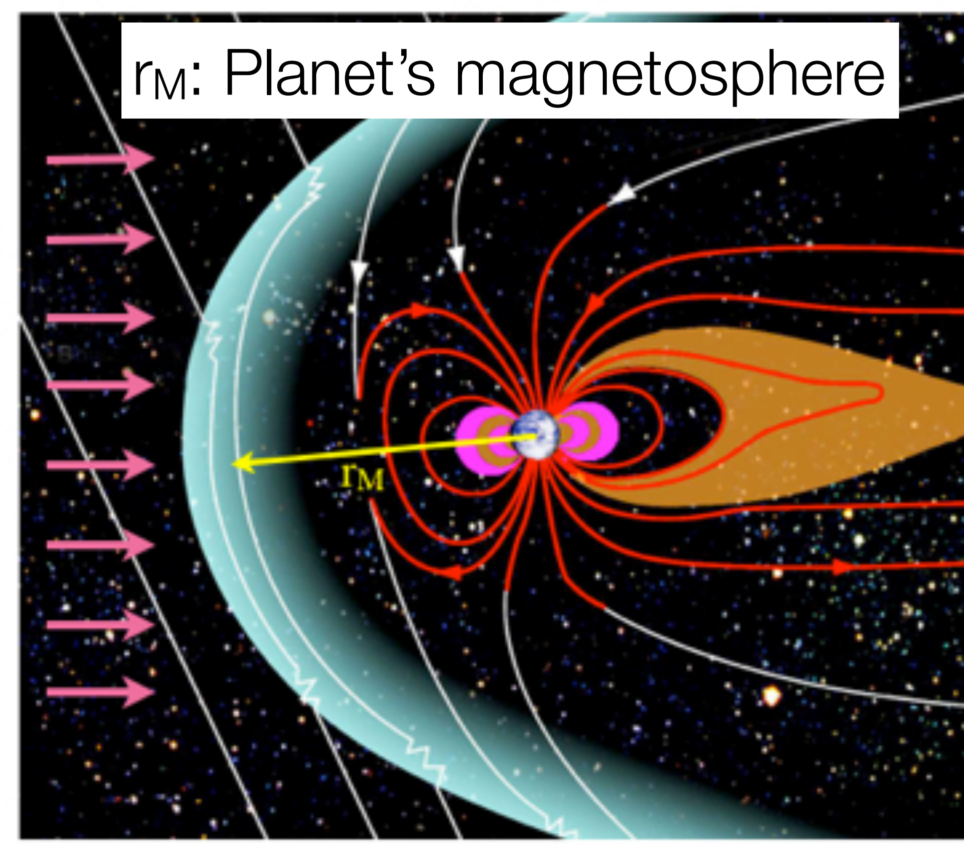

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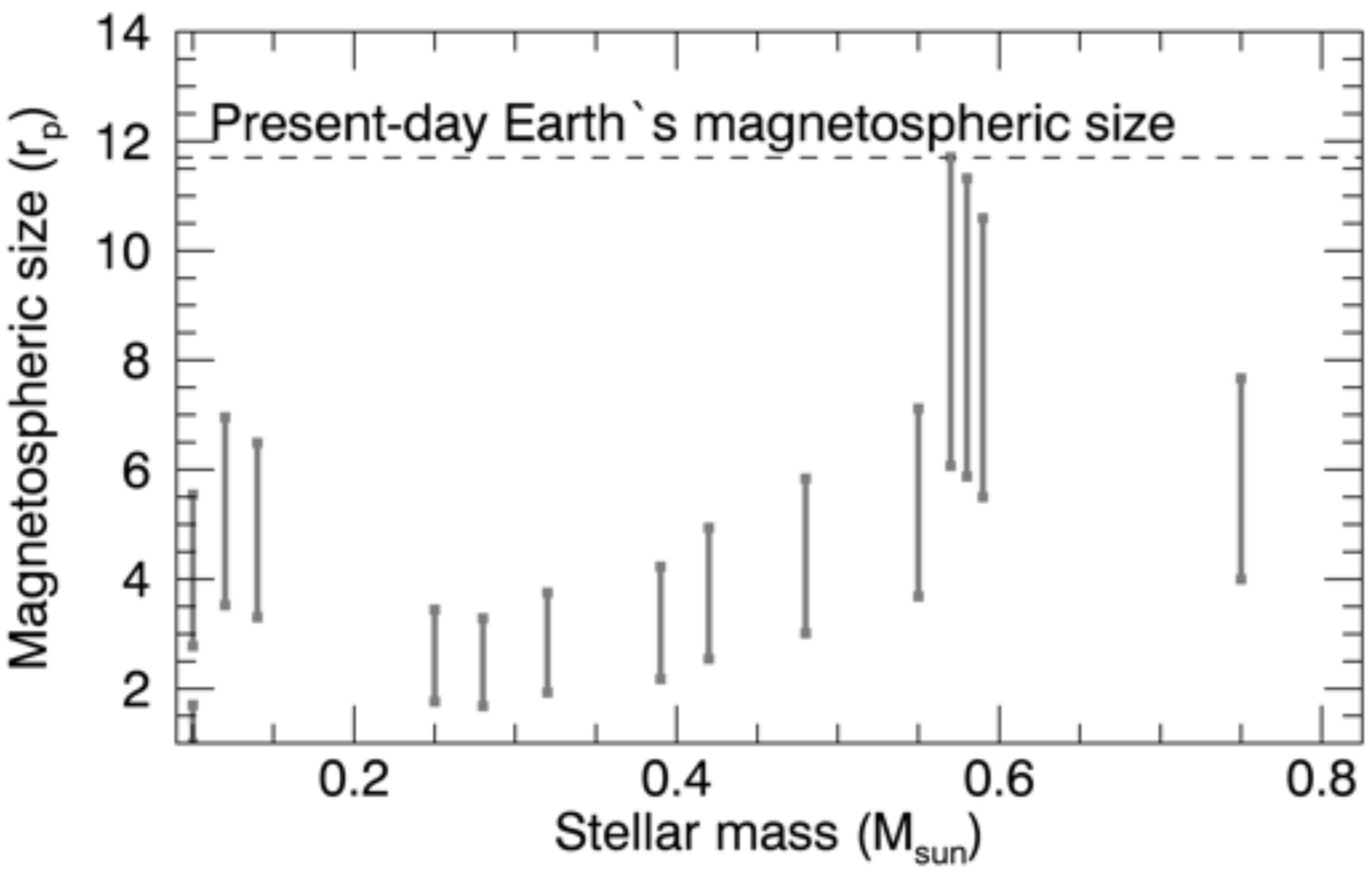

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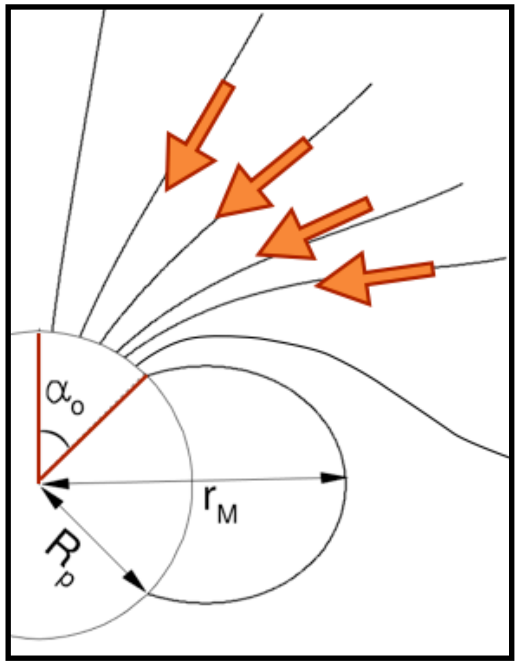

- Unprotected area of the planet:
  - 11-100% if at inner HZ
  - 5-44% if at outer HZ

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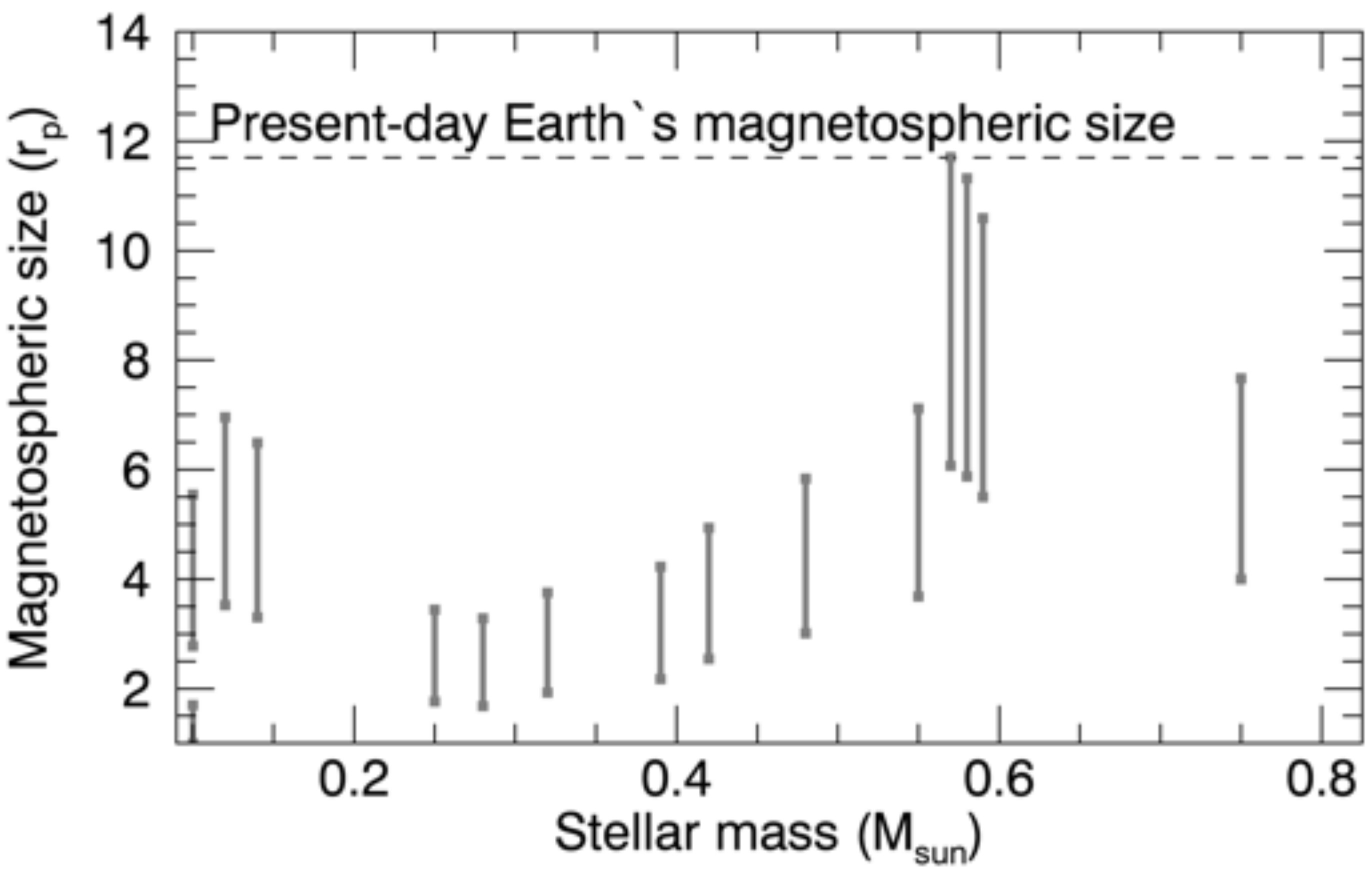

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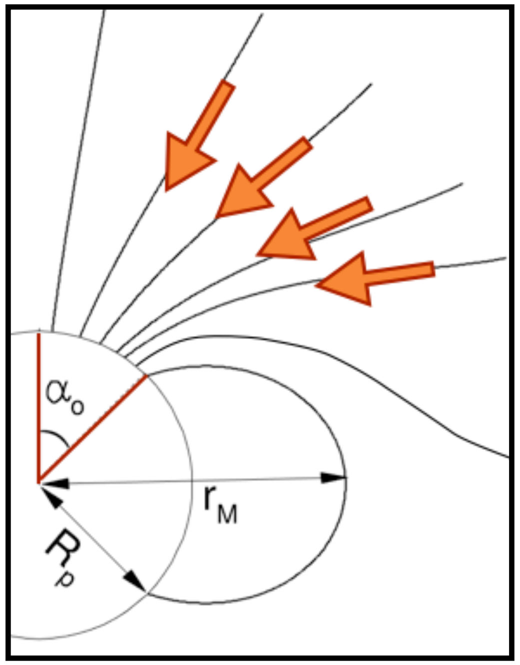

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- Active dM stars:
  - habitability → imperative that planets can regenerate their atmospheres

Part 2:
Weakly-active M dwarf planet hosts

Stellar rotation evolution

fast rotators:
efficient dynamo,
large B

star evolves,
lose angular
momentum
through winds

slow rotators:
inefficient dynamo,
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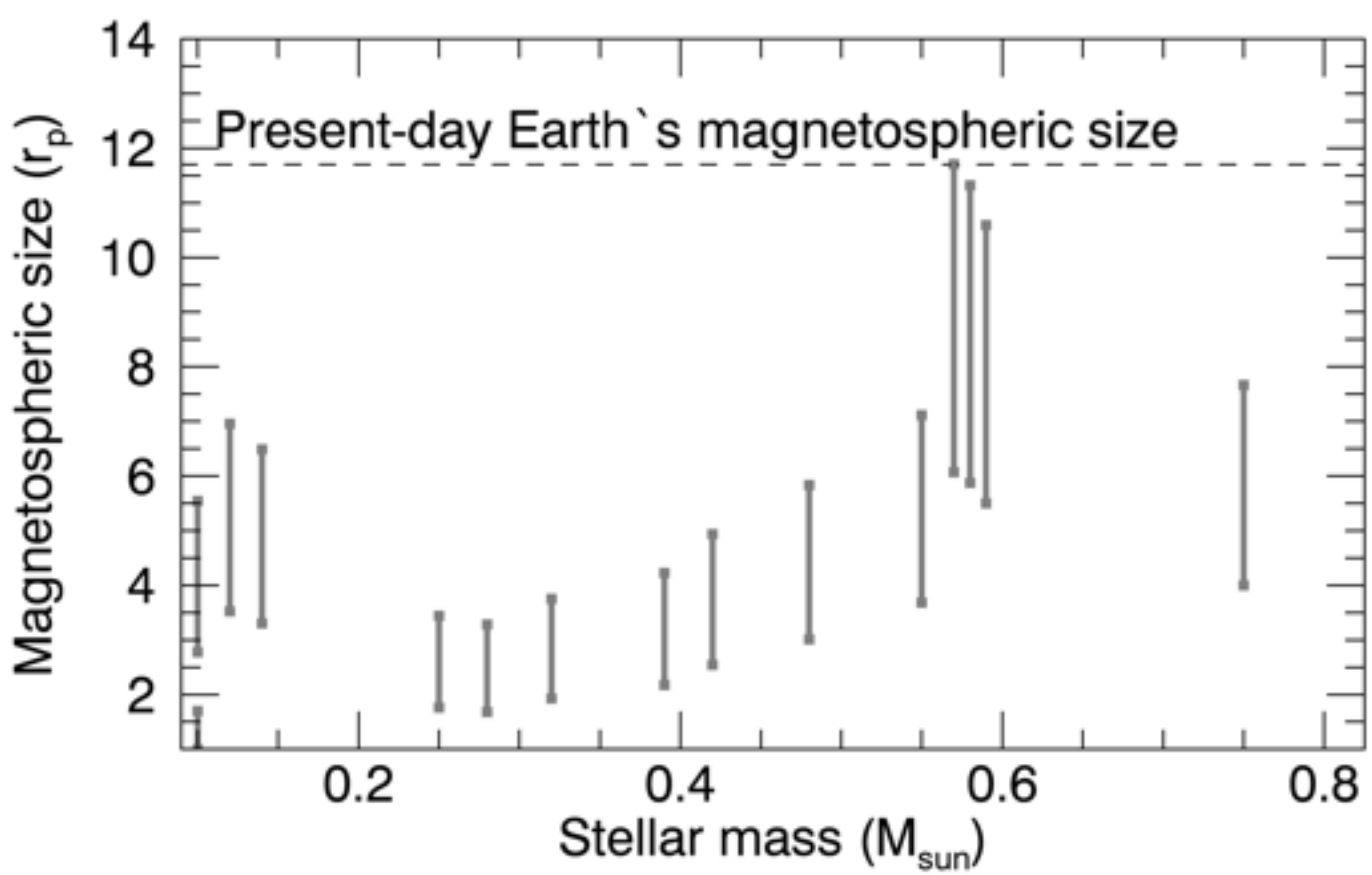

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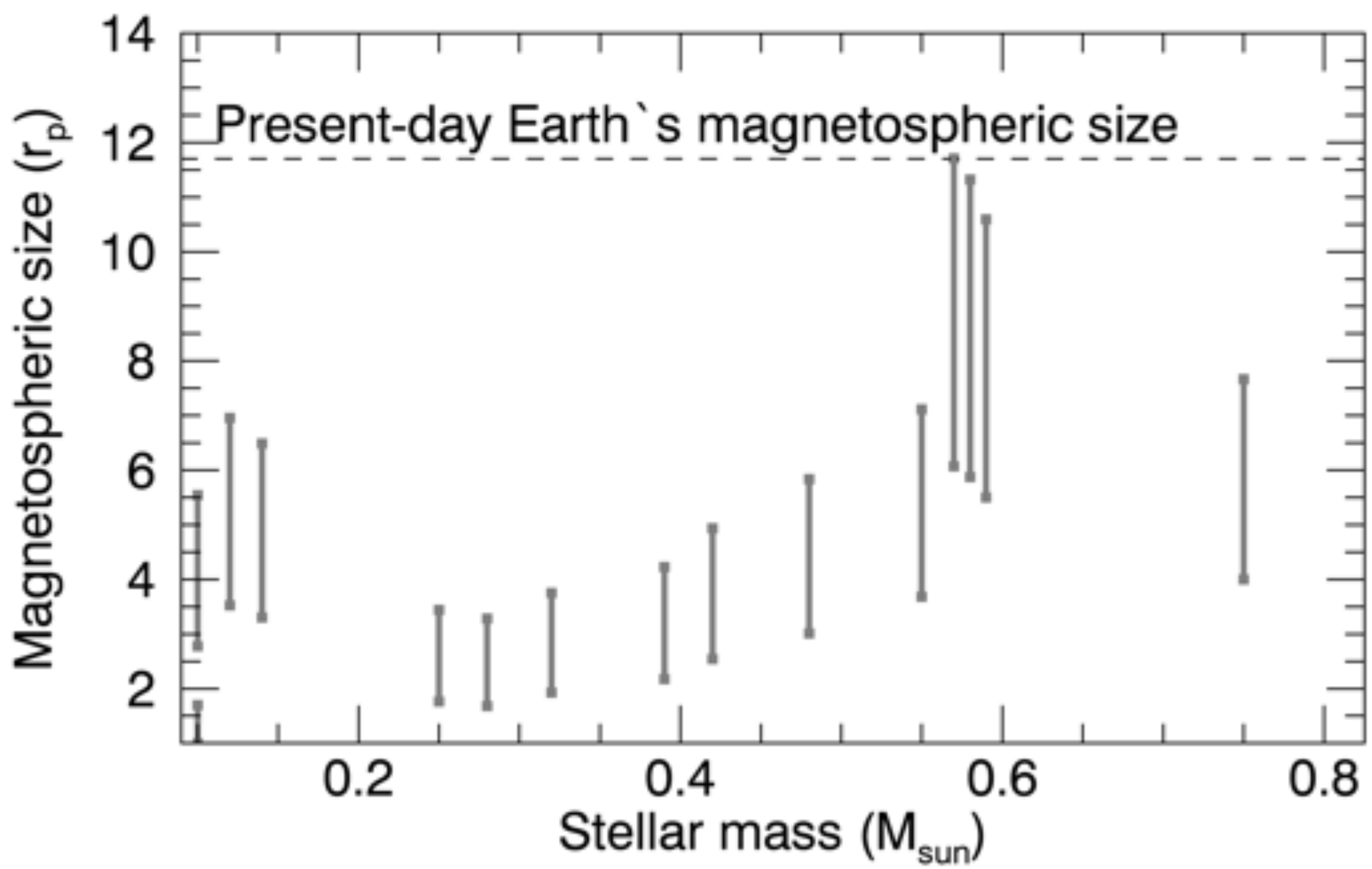

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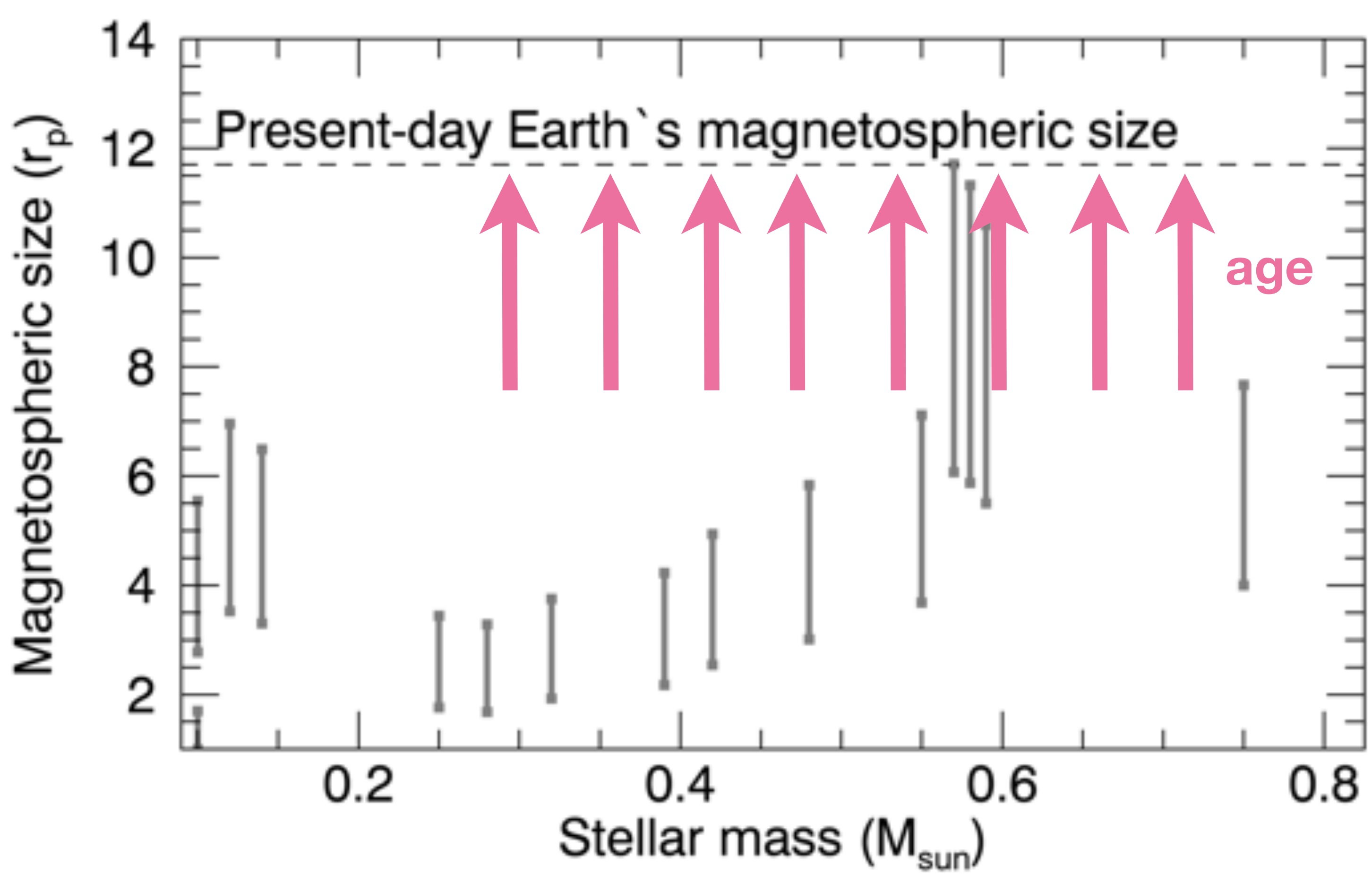

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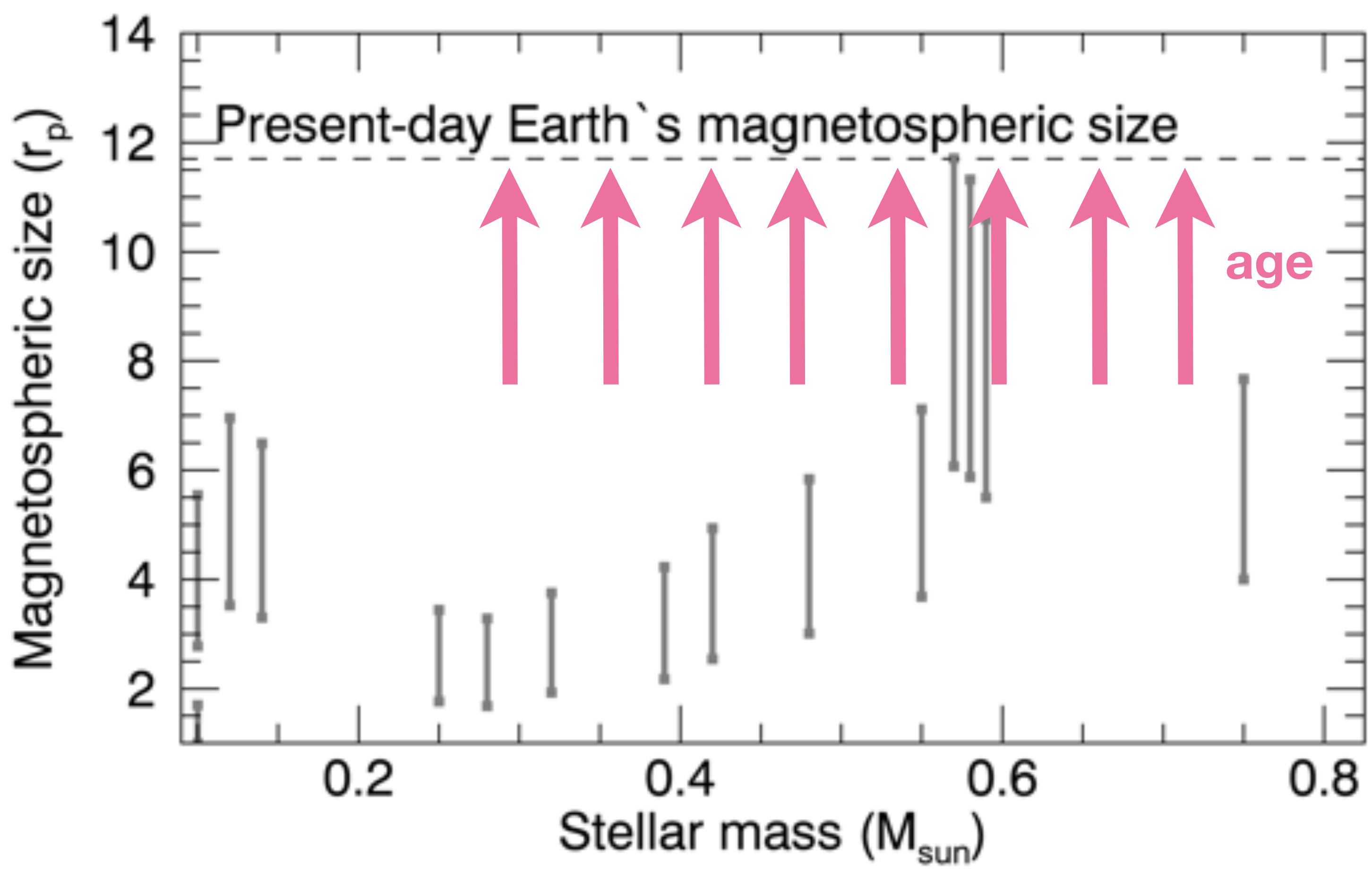
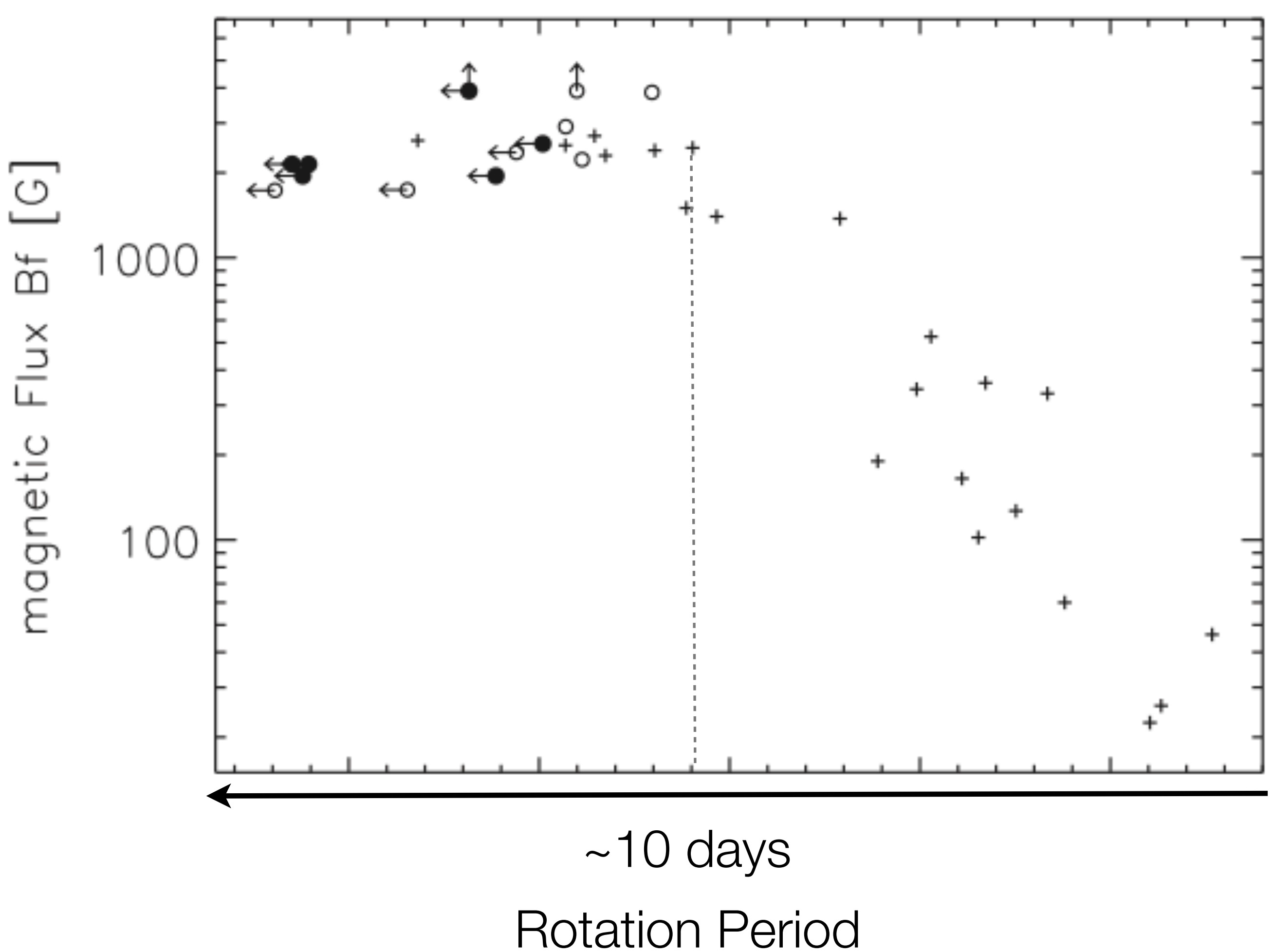


How long does it take?

Instead of ‘how old?’ we ask ‘how slow?’

- Empirical magnetism-rotation relations:

Reiners+09, Reiners & Mohanty 12



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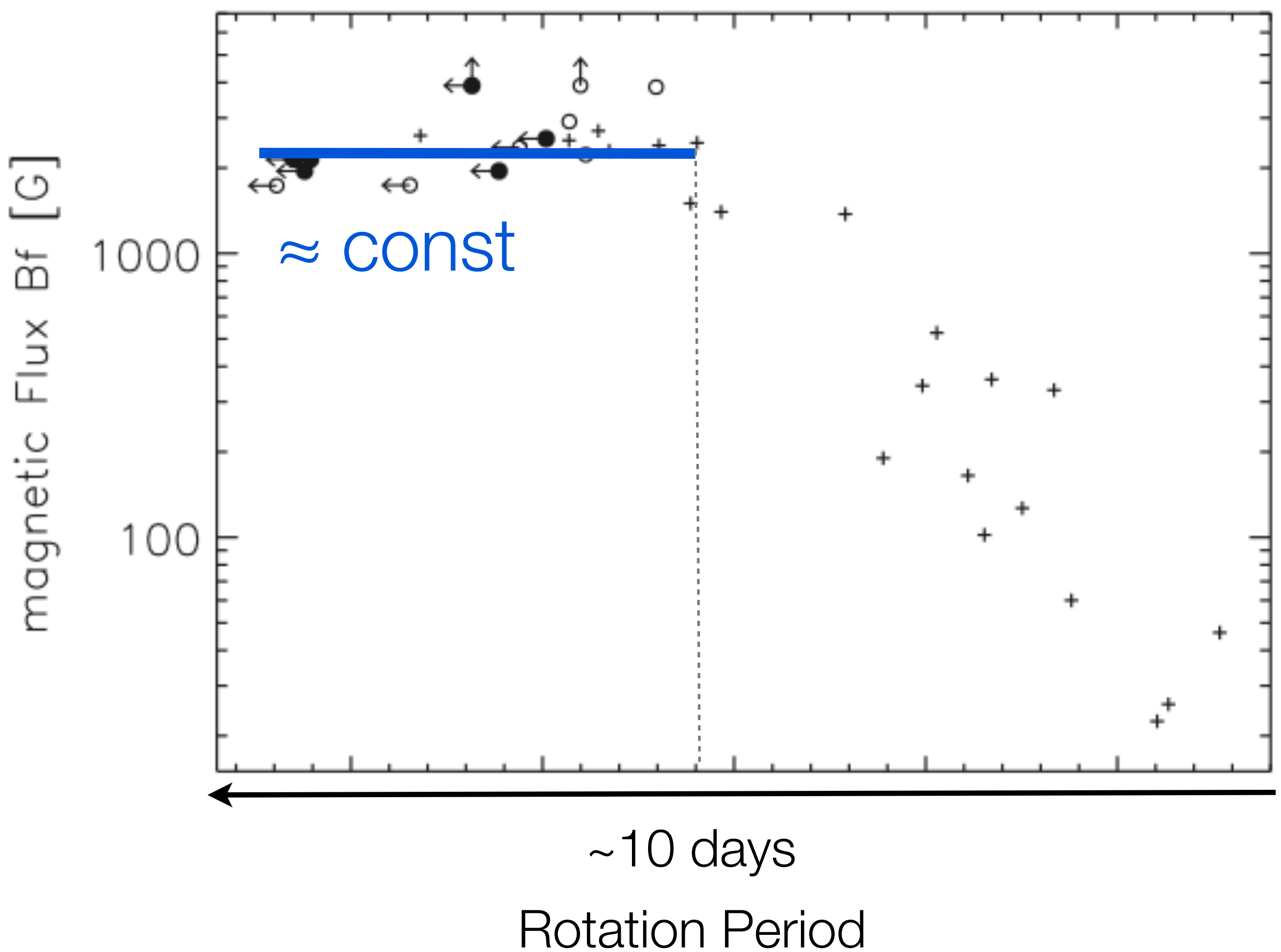

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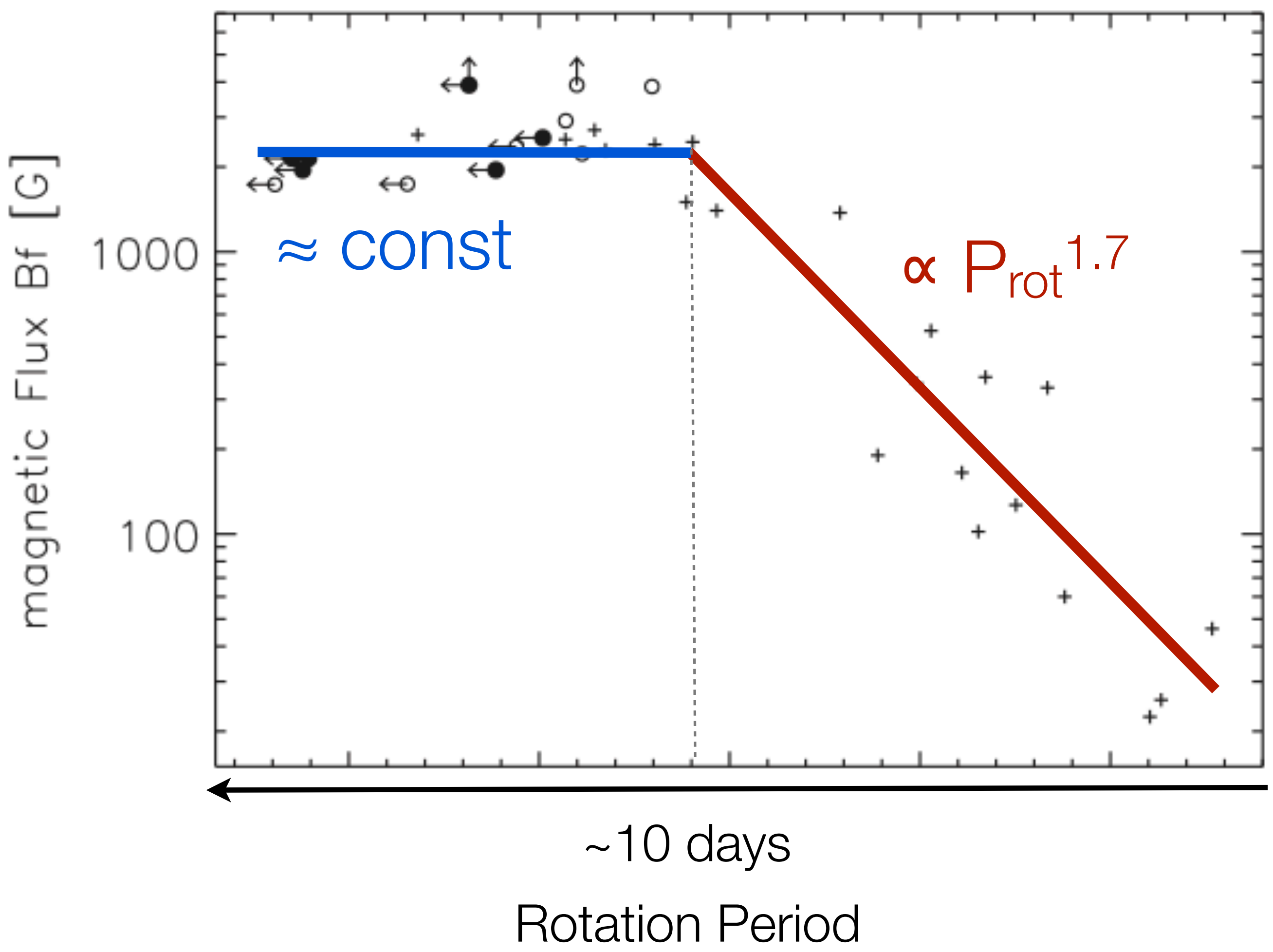
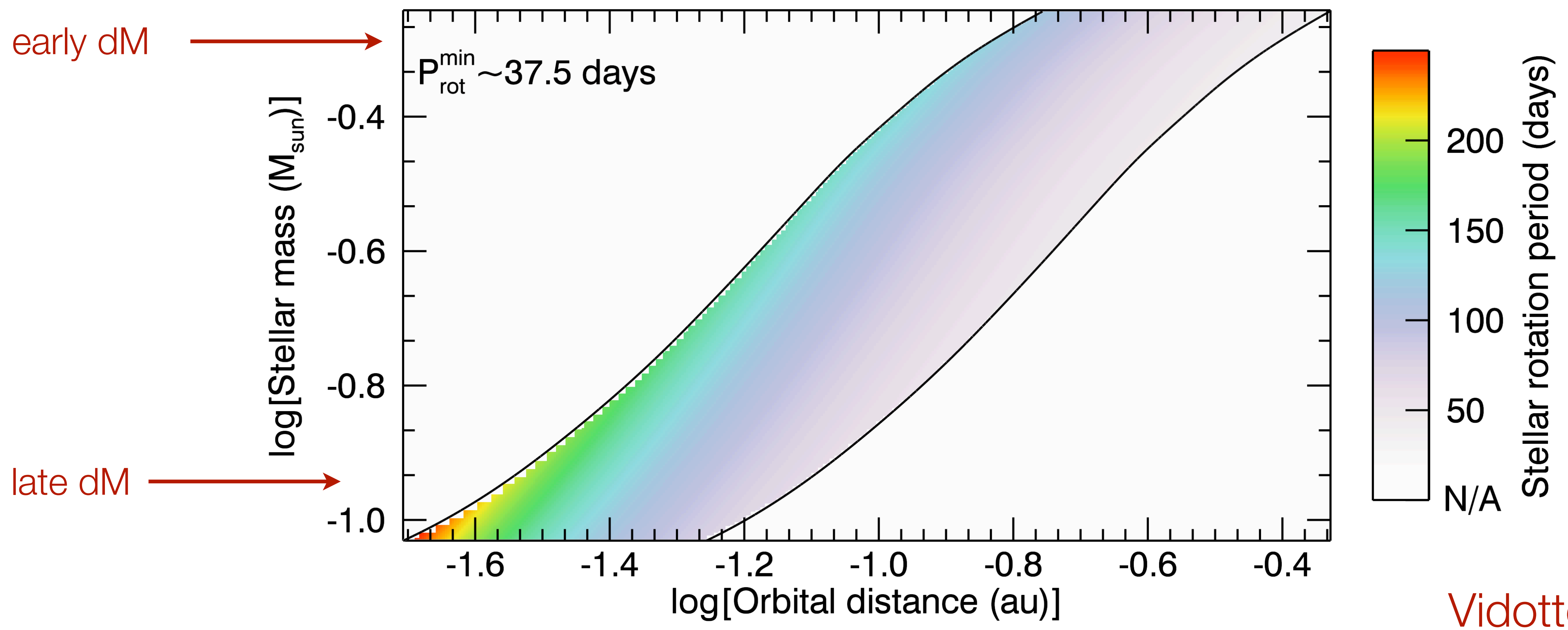


How slow should dM stars rotate so that a planet at the HZ would have an Earth-sized magnetosphere?



Vidotto+13

- early- and mid-dM stars: Prot > 35 - 154 days
- late-dM stars: Prot > 49 - 200 days

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    - difficult for <u>old</u> Earth-like planet to generate significant fields

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- Fraction of inactive (slowly rotating stars) decreases at later spectral types
- For late dMs: rotational braking timescales (~6-10 Gyr) ≫ timescale for dipole-dominated planetary fields (Zuluaga & Cuartas 12)
  - difficult for old Earth-like planet to generate significant fields
- conditions are more easily achieved for planets orbiting slowly rotating early- and mid-dM stars

Conclusions: Earth-like planets around dM stars

1. Active dMs:
   Planets with similar terrestrial magnetisation present smaller magnetospheric sizes than the Earth's one, with larger open area → potential impact on habitability?
   - imperative that planets can regenerate their atmospheres

2. Inactive dMs:
   Most suitable targets to host planets with $r_M \approx r_{M,\oplus}$, are slowly rotating early- and mid-dM stars.

IAU Symposium 328

"Living around active stars"

Maresias, Brazil
17-21 October

Maresias Beach Hotel:
http://www.maresiasbeachhotel.com.br

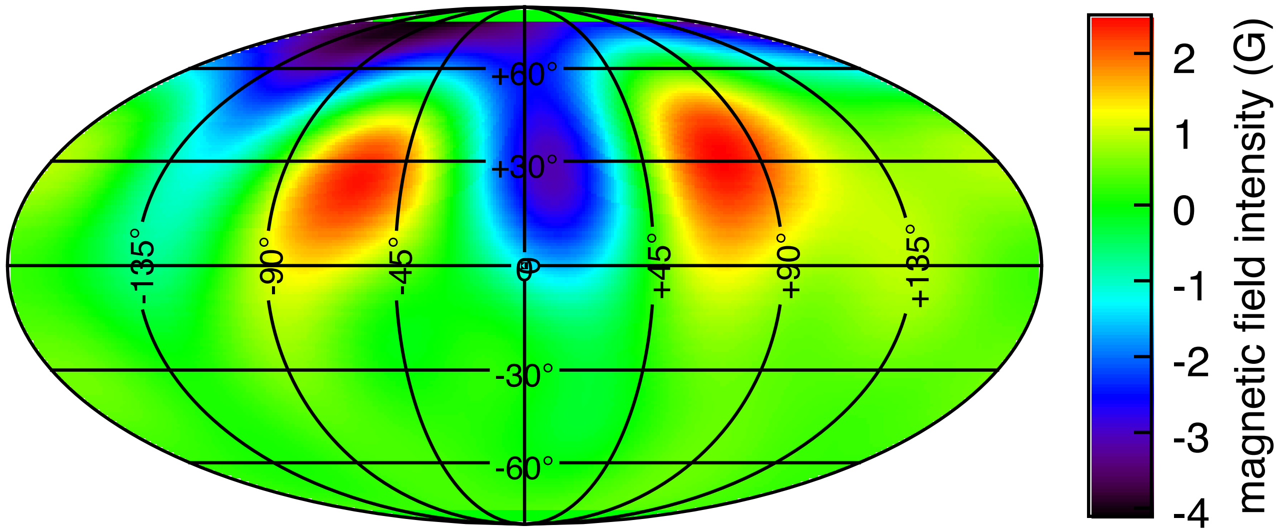
- Divisions E (Sun and Heliosphere)
- Division F (Planetary systems & Bioastronomy)
- Division G (Stars & Stellar Physics)

Extra slides

1. How do we characterise the interplanetary medium?

Characterising the background stellar wind

Magnetic field from observations



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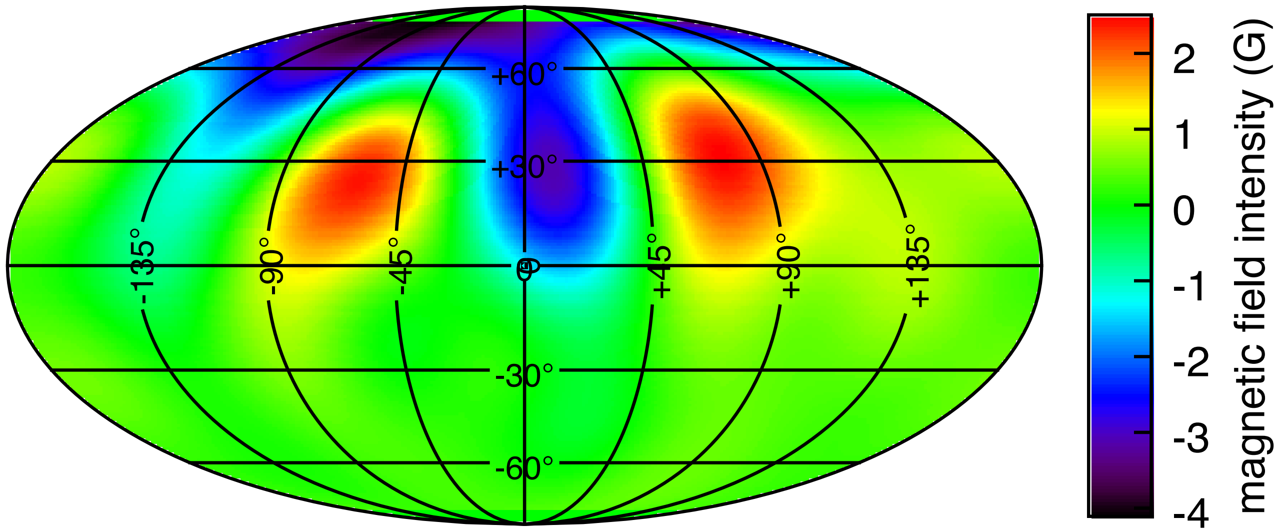
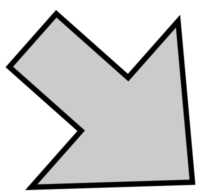
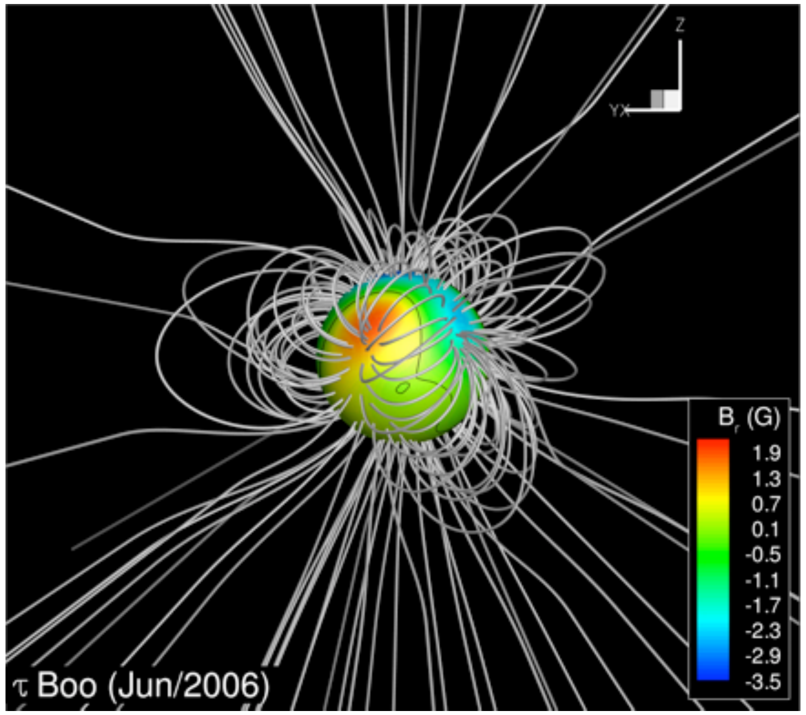


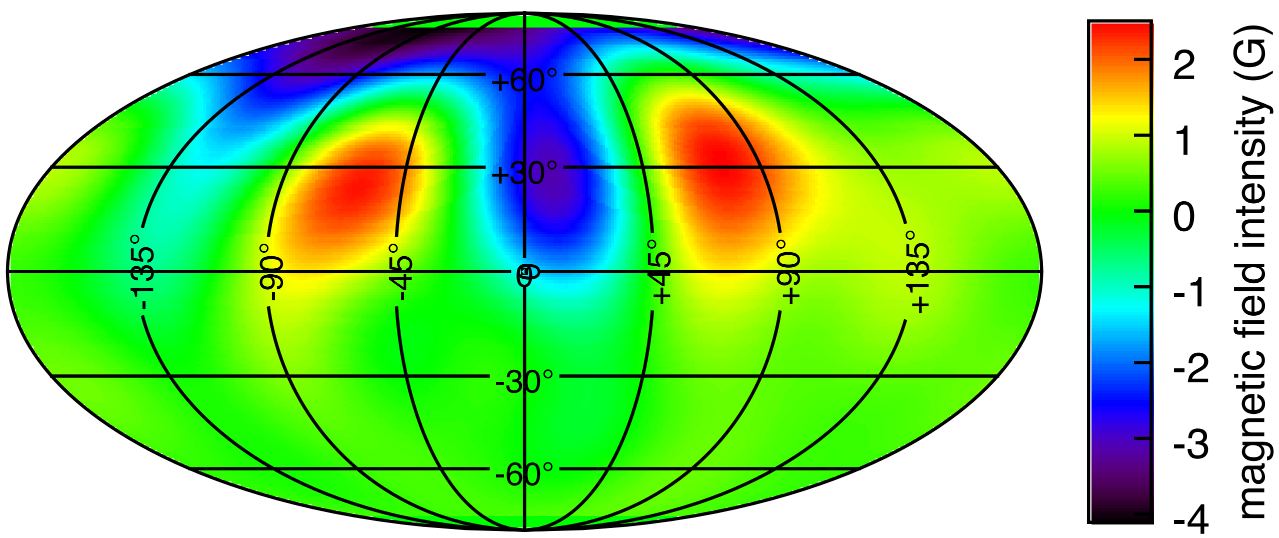




Initial state:
potential field incorporated in MHD simulations

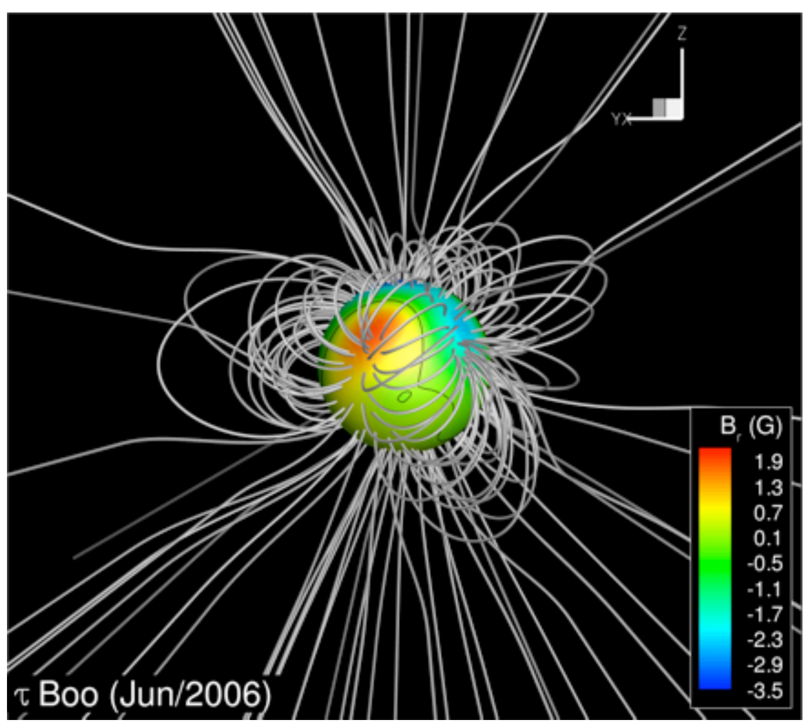
Characterising the background stellar wind

Magnetic field from observations

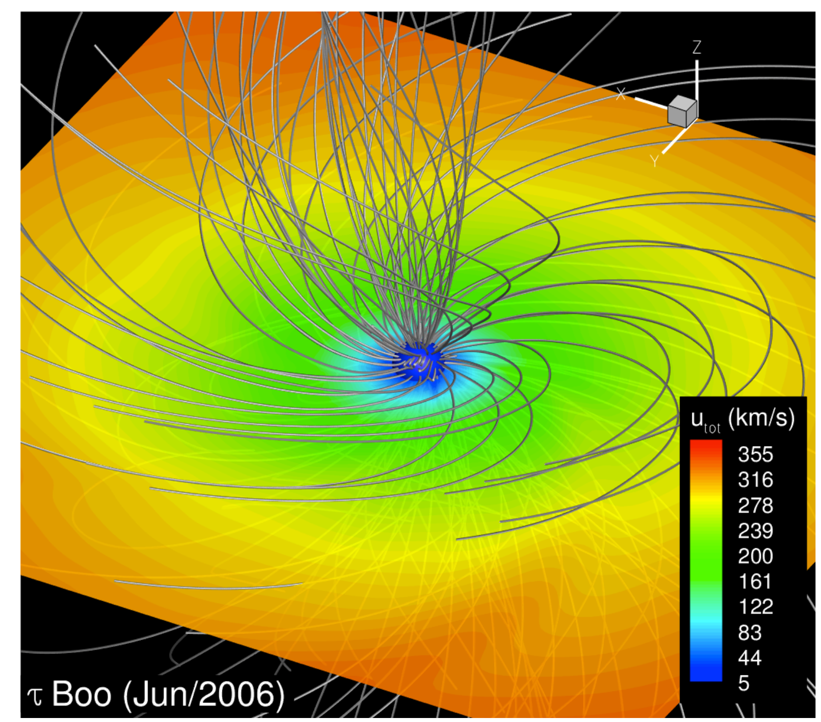


→ more on the technique & other objects: Vidotto+09a, 10ab,11a,12,14a,15; etc

Initial state: potential field incorporated in MHD simulations

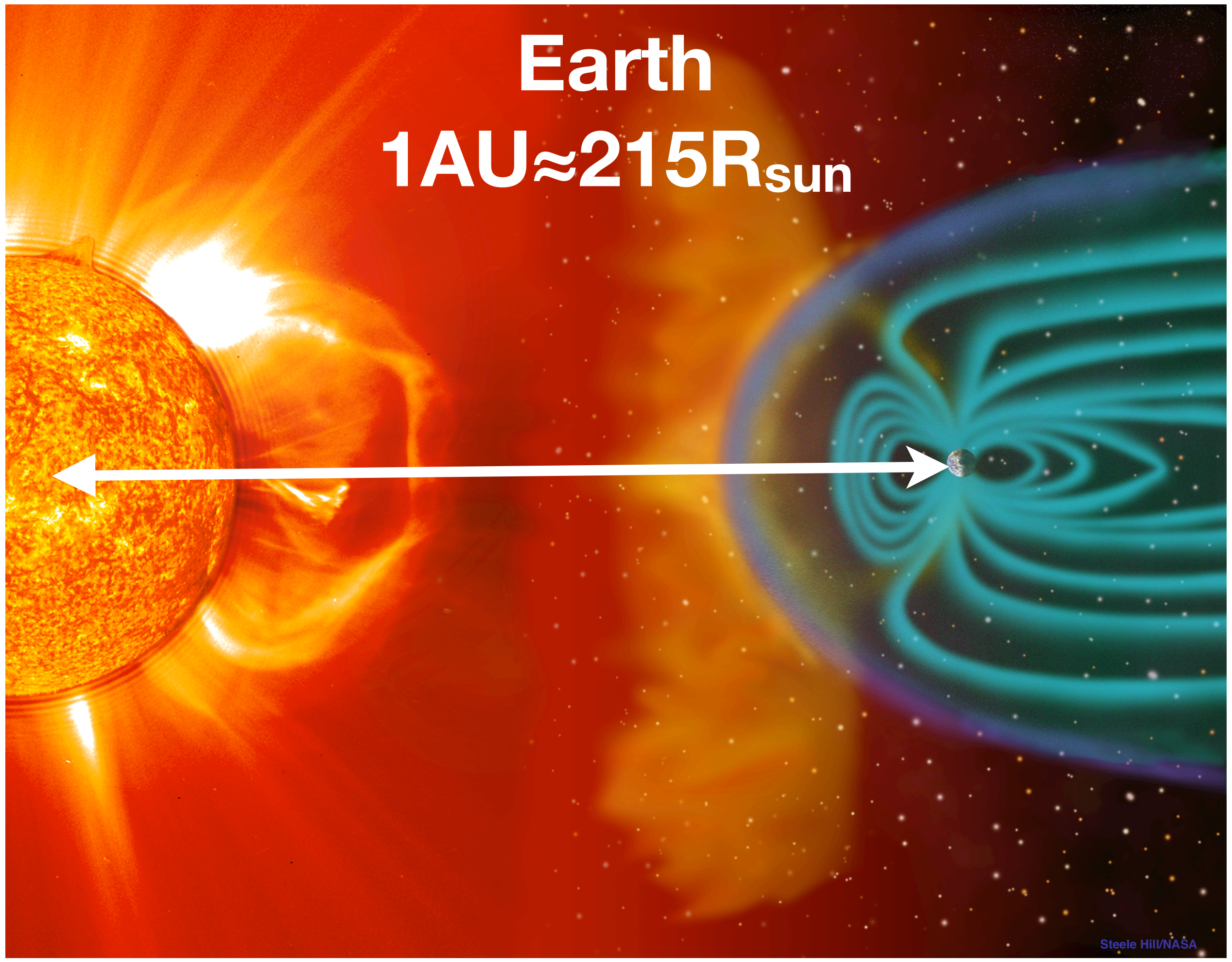


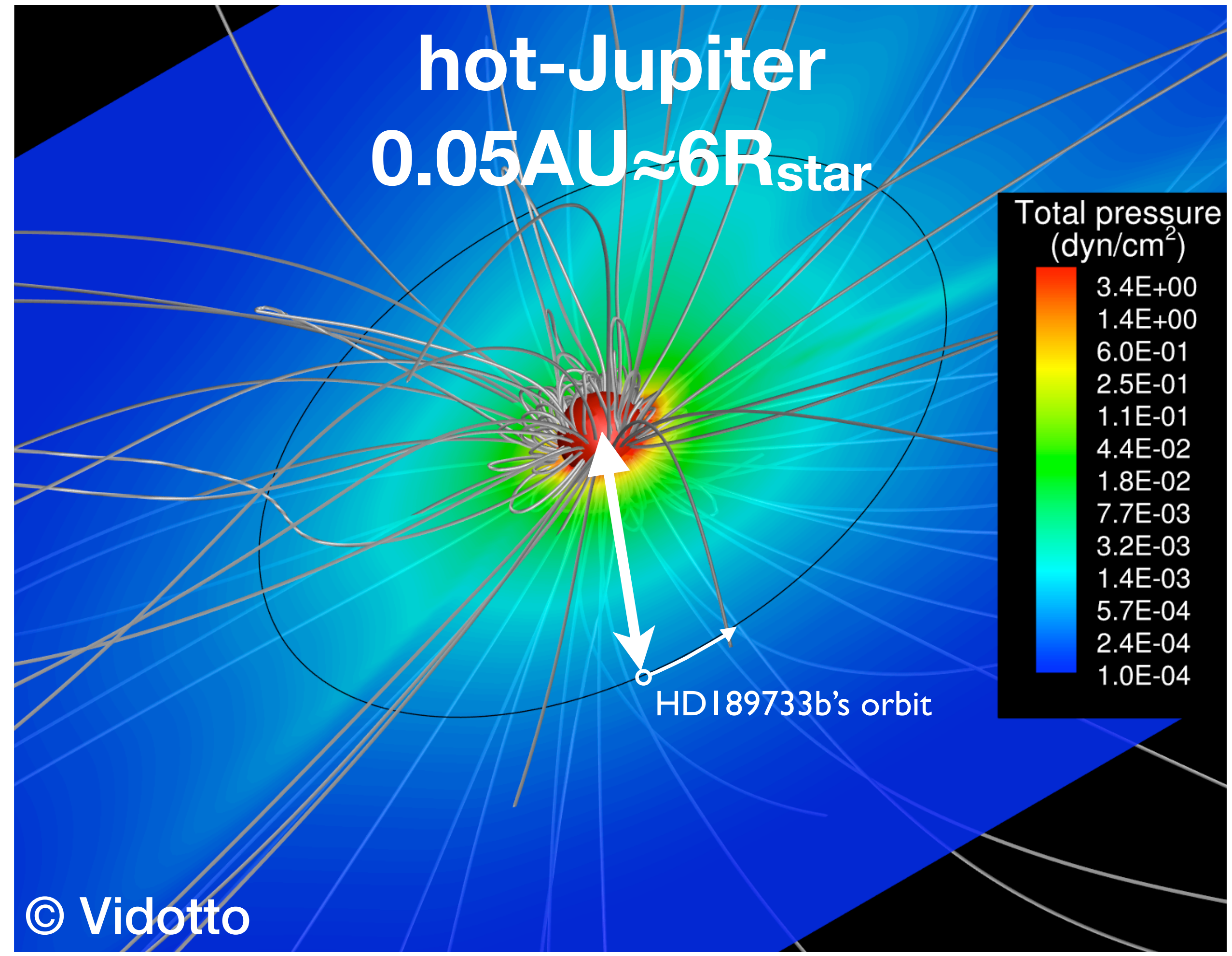
Final state: self-consistent MHD wind solution



(BATS-R-US)

Interplanetary medium: filled with stellar wind particles and magnetic fields



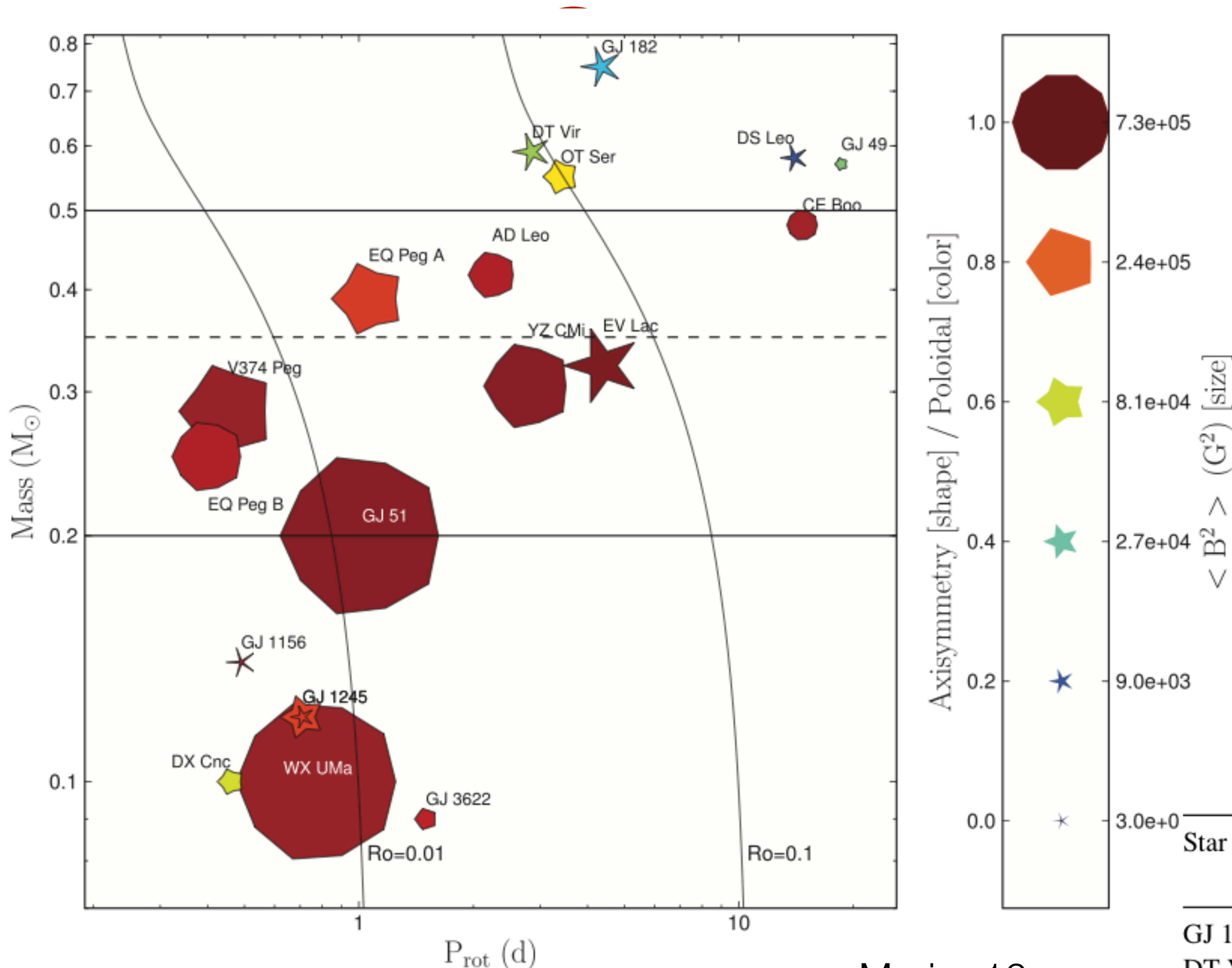


Compared to the Earth: close-in location of hot-Jupiters implies they interact with

- higher density external environment
- higher ambient magnetic fields
- lower wind velocities (acceleration zone)
- higher orbital velocities

Even harsher environment once CMEs/flares impact on exoplanets

Including observed maps in the simulations: early-dM



Morin+10

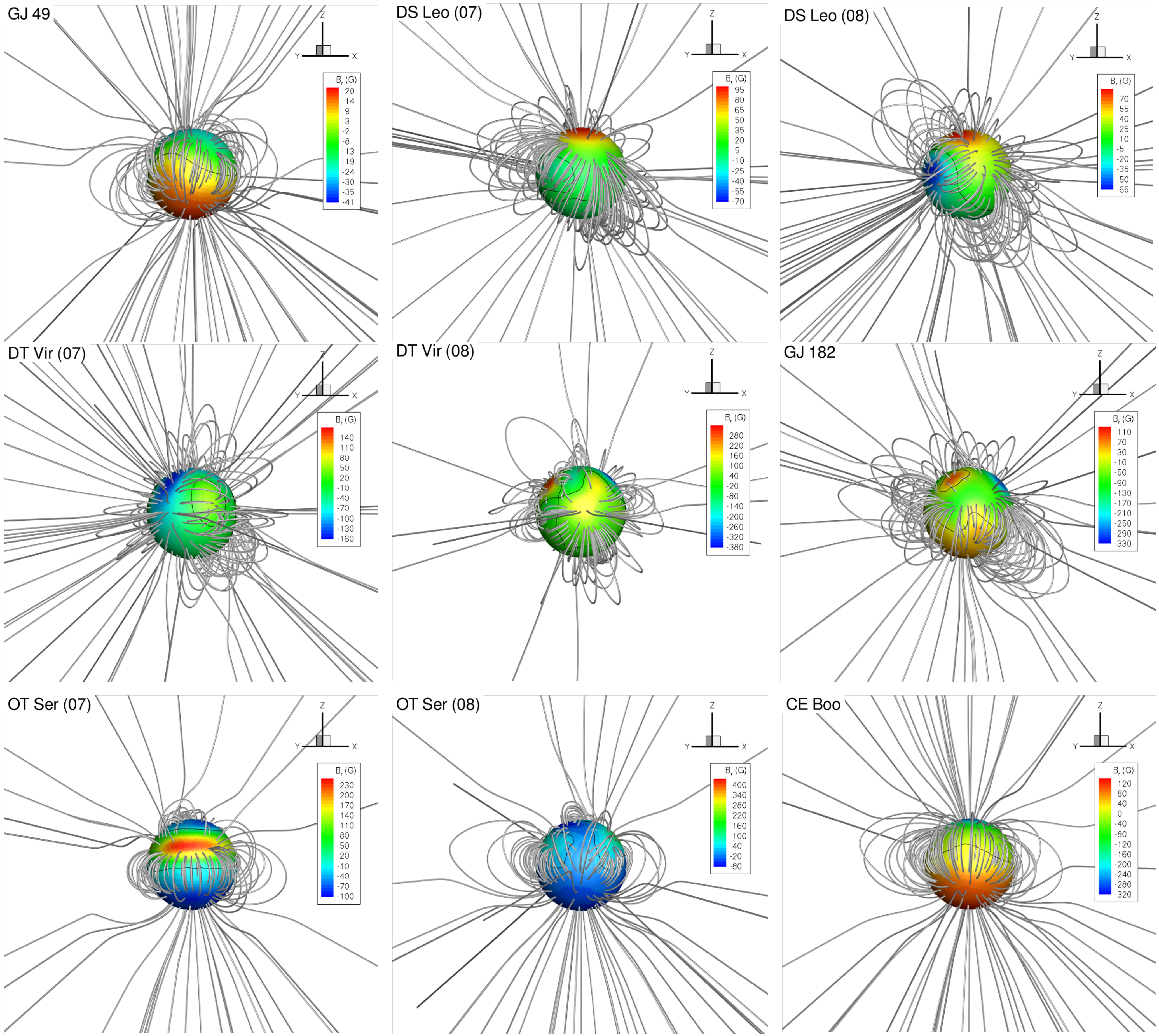
- Clusters: Same rotation period, mass, radius, but different magnetic field topology & intensity:
  - Wind?
  - AM loss?

Star	ST	$M_\star$ ($M_\odot$)	P_{rot} (d)	$R_\star$ ($R_\odot$)
GJ 182	M0.5	0.75	4.35	0.82
DT Vir/GJ 494A	M0.5	0.59	2.85	0.53
DS Leo/GJ 410	M0	0.58	14.0	0.52
GJ 49	M1.5	0.57	18.6	0.51
OT Ser/GJ 9520	M1.5	0.55	3.40	0.49
CE Boo/GJ 569A	M2.5	0.48	14.7	0.43

Including observed maps in the simulations: early-dM

- Base density: $n_0=10^{11}$ cm-3
- Base temperature: $T_0=2\times10^6$ K

- 6 objects → 9 maps
  - Wind solution for all of them
  - Calculate dJ/dt and dM/dt


GJ 49
Z
Y
X
B_r (G)
20
14
9
3
-2
-8
-13
-19
-24
-30
-35
-41
DS Leo (07)
95
80
65
50
35
20
5
-10
-25
-40
-55
-70
DS Leo (08)
70
55
40
25
10
-5
-20
-35
-50
-65
DT Vir (07)
140
110
80
50
20
-10
-40
-70
-100
-130
-160
DT Vir (08)
280
220
160
100
40
-20
-80
-140
-200
-260
-320
-380
GJ 182
110
70
30
-10
-50
-90
-130
-170
-210
-250
-290
-330
OT Ser (07)
230
200
170
140
110
80
50
20
-10
-40
-70
-100
OT Ser (08)
400
340
280
220
160
100
40
-20
-80
CE Boo
120
80
40
0
-40
-80
-120
-160
-200
-240
-280
-320

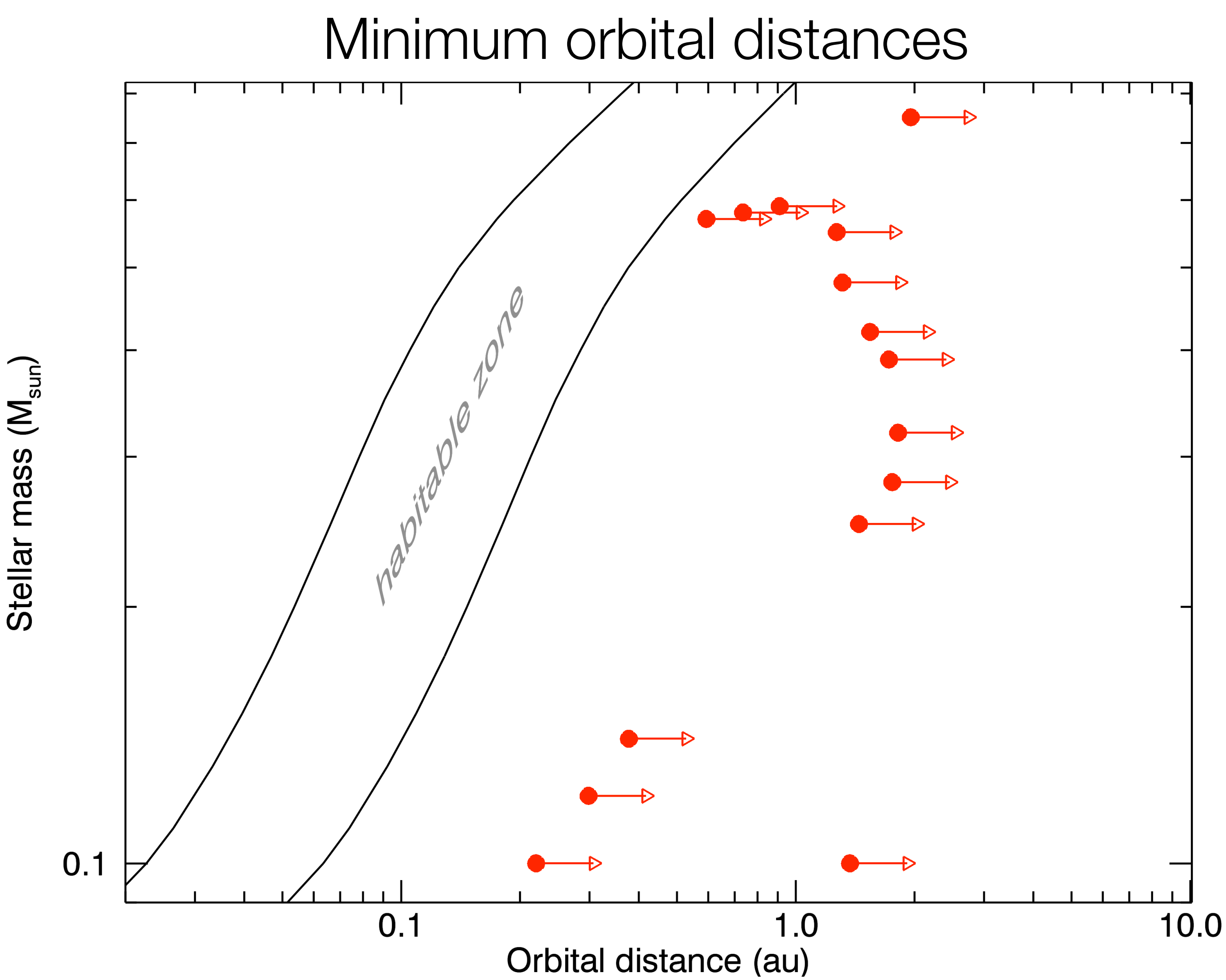
Earth-sized magnetosphere

Assumption: **Earth analog**

- dipolar B_{planet}
- @ pole: $B_{p,0} \approx 1G$

- $r_M = 11.7 R_p$ (present-day)
- $r_M = 5 R_p$ (young Earth)

Earth-sized magnetosphere



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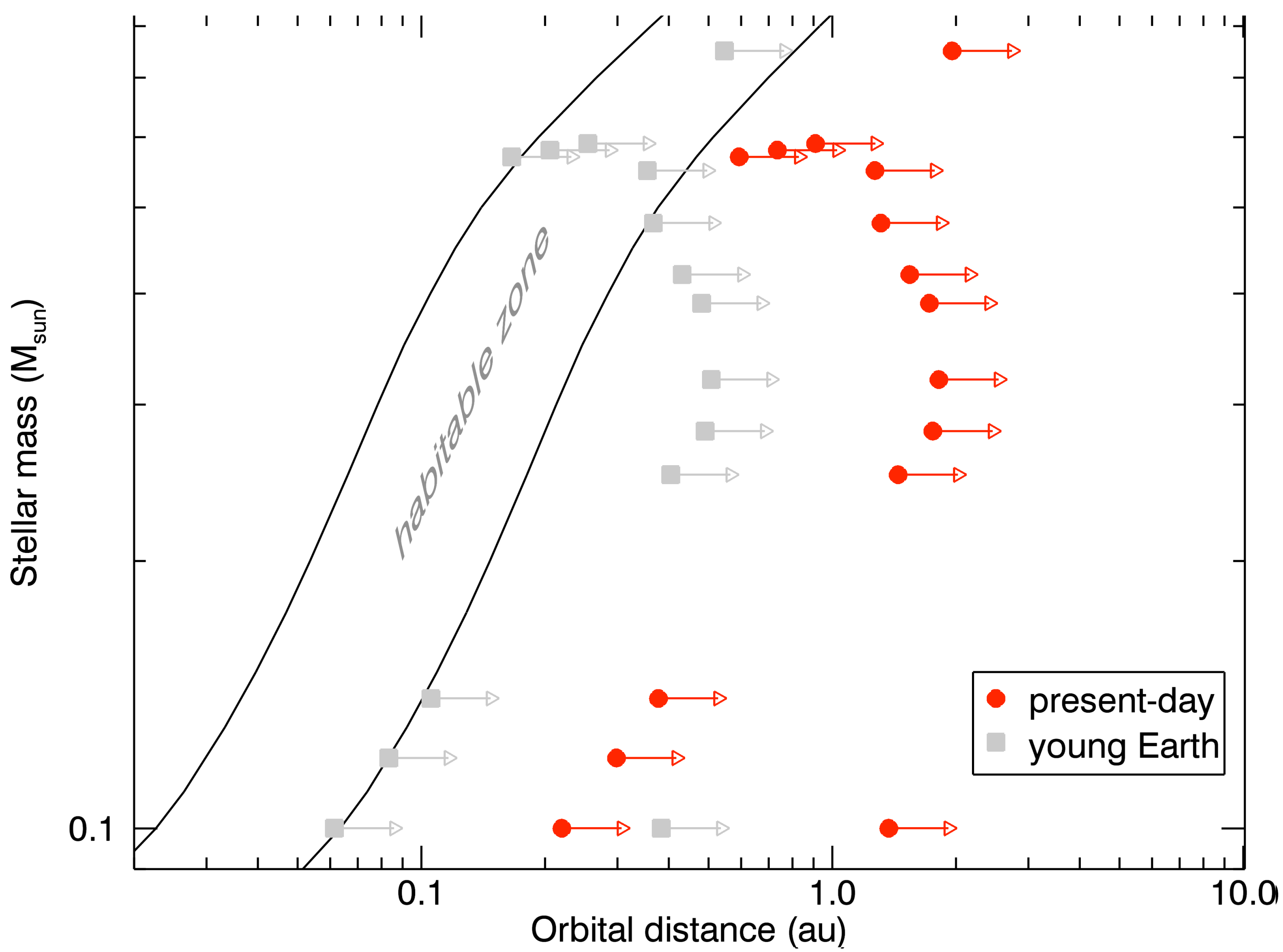
Earth-sized magnetosphere

Minimum orbital distances



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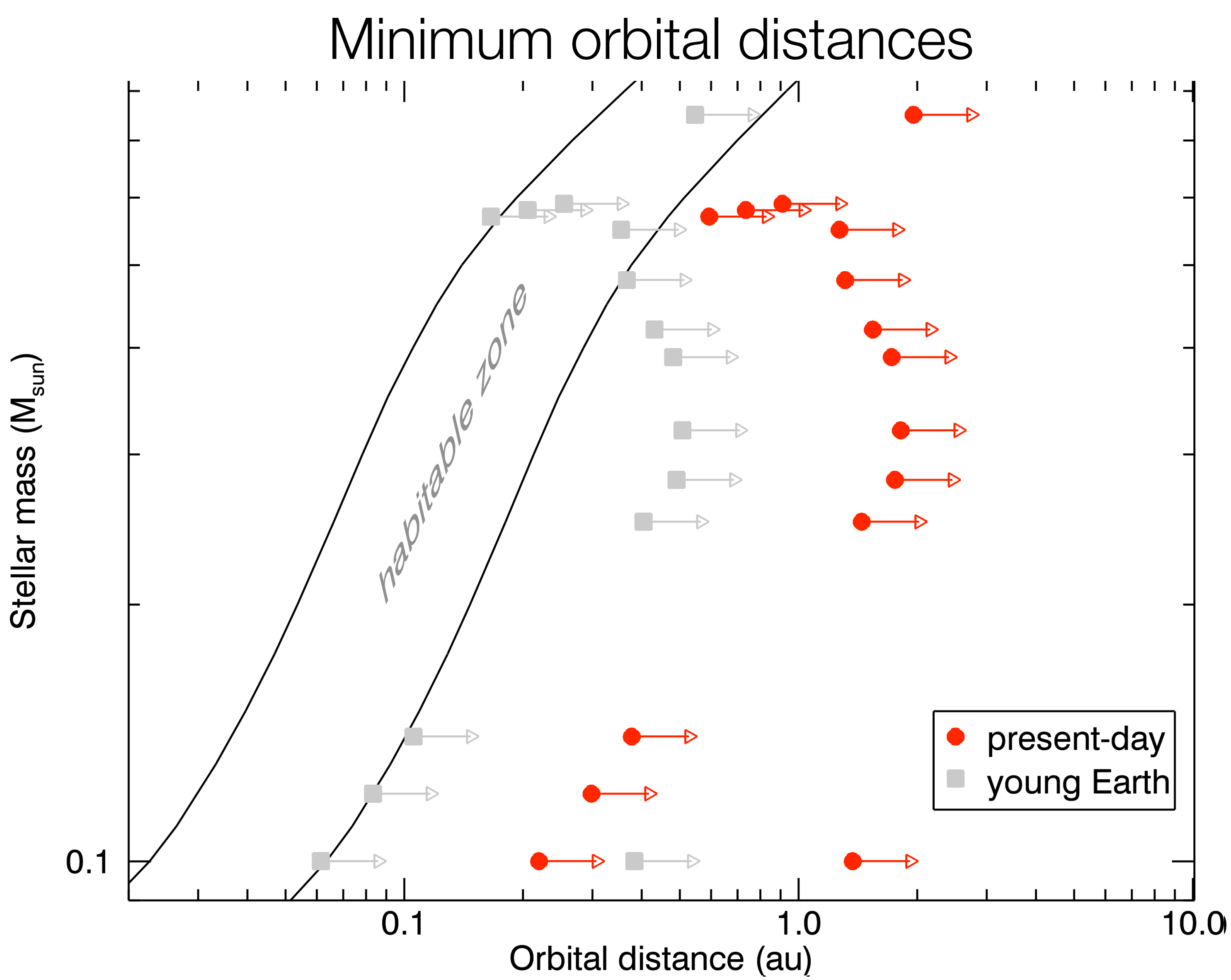
Earth-sized magnetosphere



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Potential impact on habitability?

Earth-sized magnetosphere

Earth-sized magnetosphere

Minimum planetary magnetic fields

Star ID	Year obs.	Sp. type	M_* ($M_\odot$)	$B_{p,0}^{\rm min}$ (G) [present]	$B_{p,0}^{\rm min\,\dagger}$ (G) [young]
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DS Leo	2008	M0	0.58	[2.6, 18]	[0.20, 1.4]
GJ 49	2007	M1.5	0.57	[1.8, 13]	[0.14, 0.98]
OT Ser	2008	M1.5	0.55	[9.4, 68]	[0.73, 5.3]
CE Boo	2008	M2.5	0.48	[15, 110]	[1.2, 8.5]
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EQ Peg B	2006	M4.5	0.25	[67, 500]	[5.2, 39]
GJ 1156	2009	M5	0.14	[13, 98]	[1.0, 7.6]
GJ 1245 B	2008	M5.5	0.12	[12, 94]	[0.95, 7.4]
WX UMa	2009	M6	0.10	[510, 4100]	[40, 320]
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- @ the HZ

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- $r_M = 11.7 R_p$ (present-day)
- $r_M = 5 R_p$ (young Earth)

Possible to generate/ sustain such large B_{pl}?