Cosmic dynamos
★
observations of magnetic stars

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the quest for magnetic stars

do we really understand the magnetic Sun?

dynamo: interplay btw (differential) rotation & (cyclonic) convection
generate toroidal from poloidal fields & vice versa @ base of CZ
theory almost completely tailored on one single star - how general?
models unable to fit all observations (eg poloidal vs toroidal field)
› explore other magnetic stars

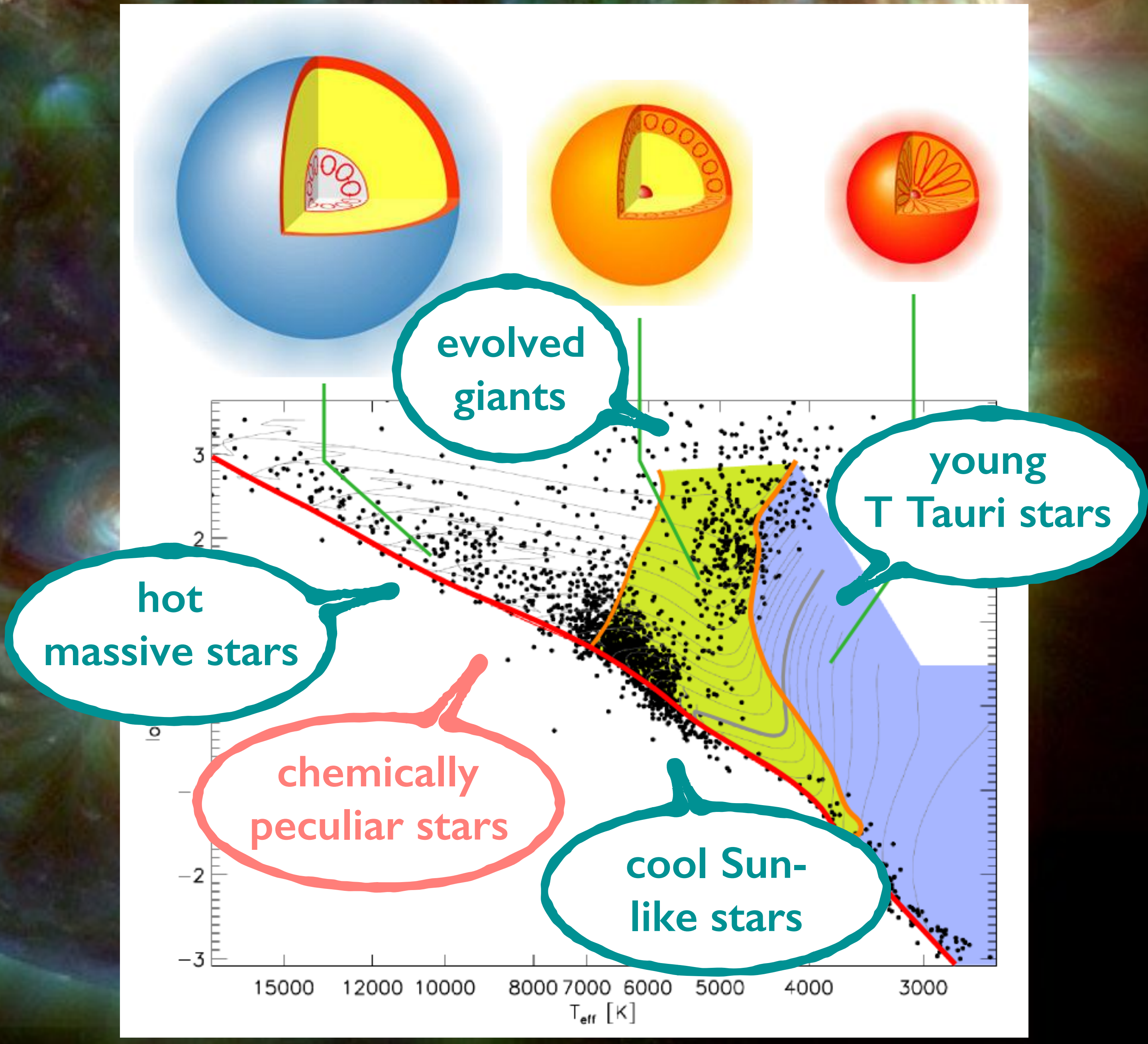
what is the origin of magnetic fields in stars?

contemporaneous fields produced through MHD processes : dynamo
remnants from earlier evolutionary phase : fossil
› explore magnetic stars throughout HR diagram

what is the impact of magnetic fields on stars?

in MS stars : magnetic energy << kinetic energy << gravitational energy
same orders of magnitude in molecular clouds
› magnetic fields in young stars & accretion discs

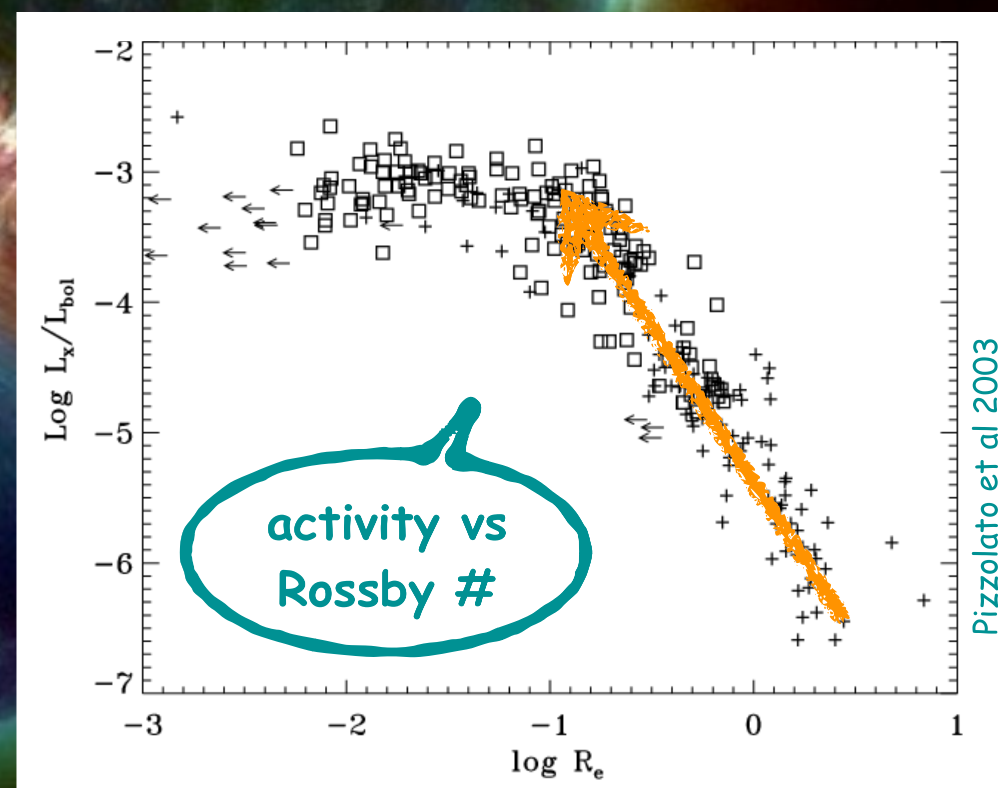
the HR diagram of magnetic stars



fields of low-mass stars

magnetic proxies: activity

eg : emission in optical & UV spectral lines > chromospheres & coronae
eg : regular photometric variability > cool spots & bright faculae
detected in all low-mass stars (ie w/ outer CZ)
correlates w/ rotation rate > attributed to dynamo fields



Pizzolato et al 2003

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magnetic fields

need to properly estimate fields themselves rather than proxies
study how they vary with stellar parameters
work out impact on stellar physics & evolution

measuring magnetic fields

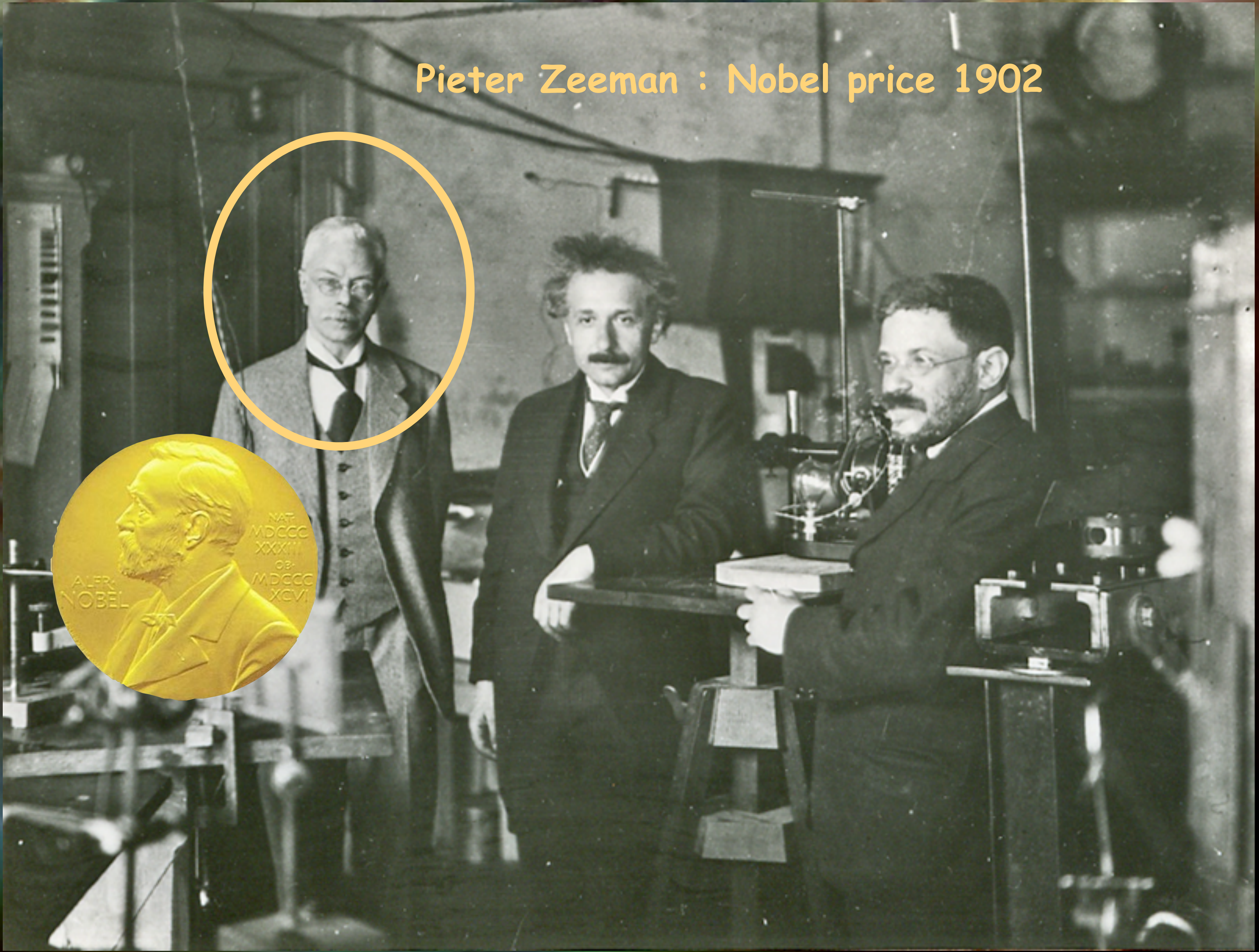
Zeeman effect on spectral lines

discovered in 1896 by Pieter Zeeman (Nobel prize 1902)

magnetic field of the Sun & the solar dynamo by GE Hale (1908)

> explore fields of stars other than the Sun

the Zeeman effect



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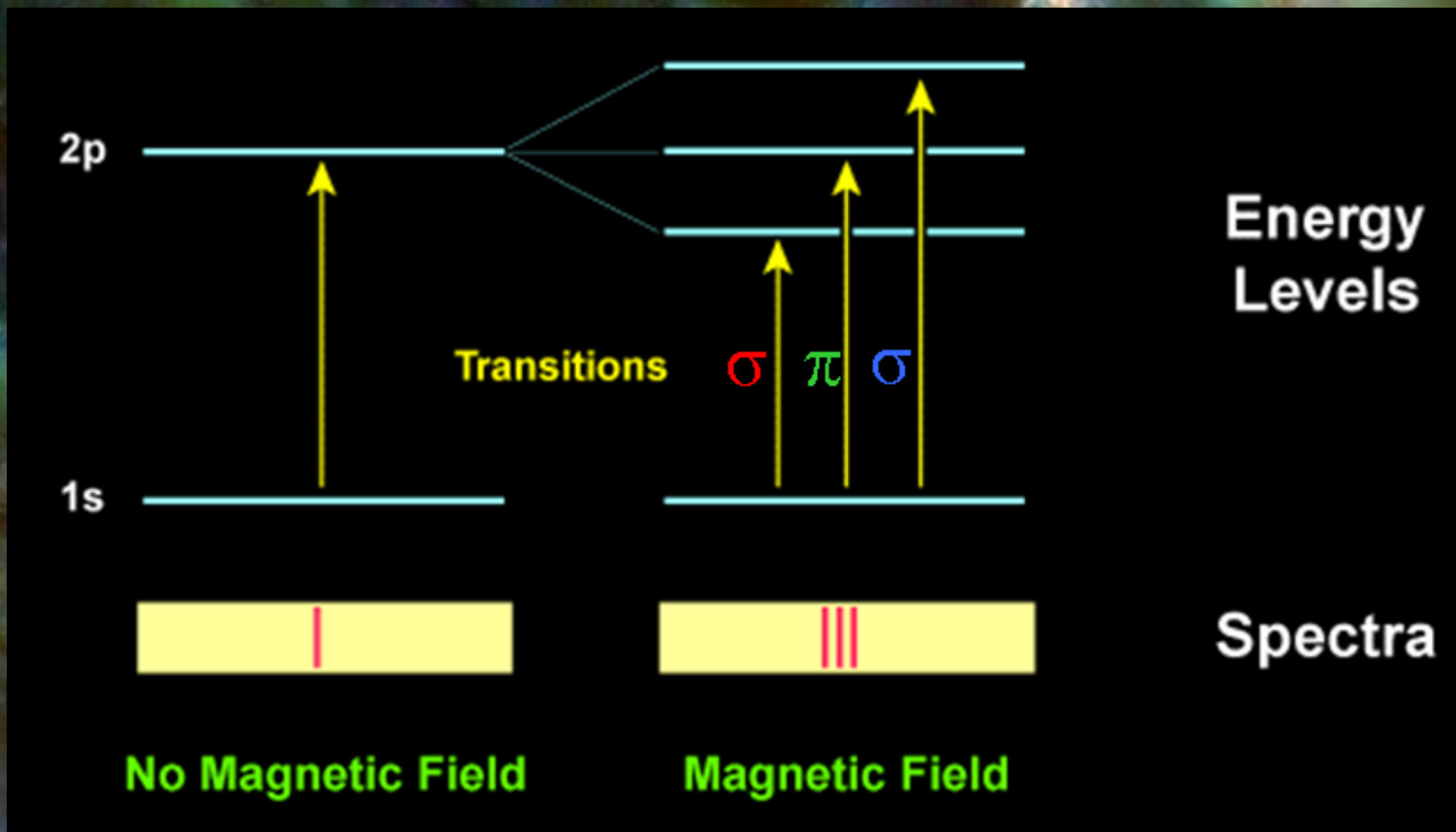
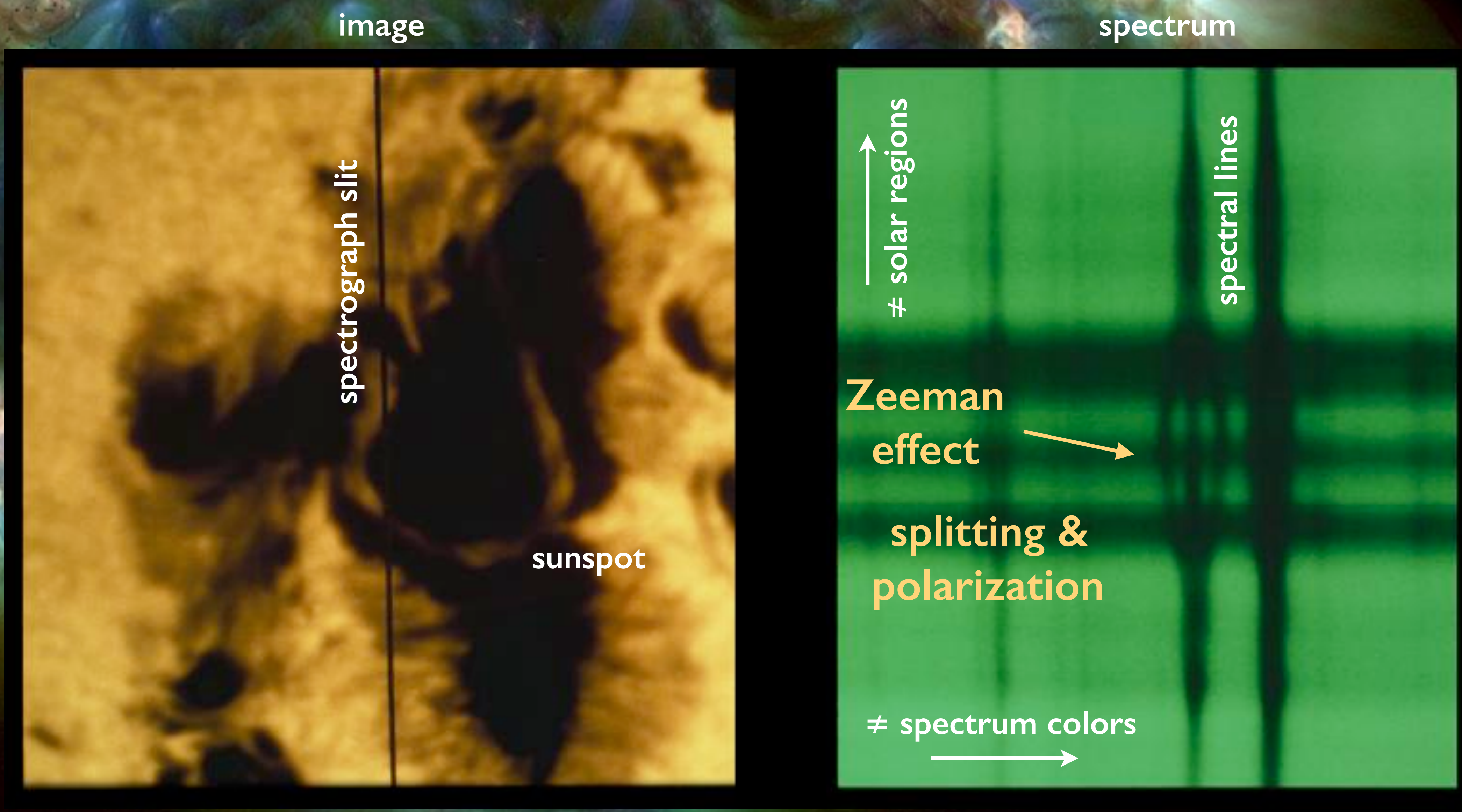


the Zeeman effect on the Sun



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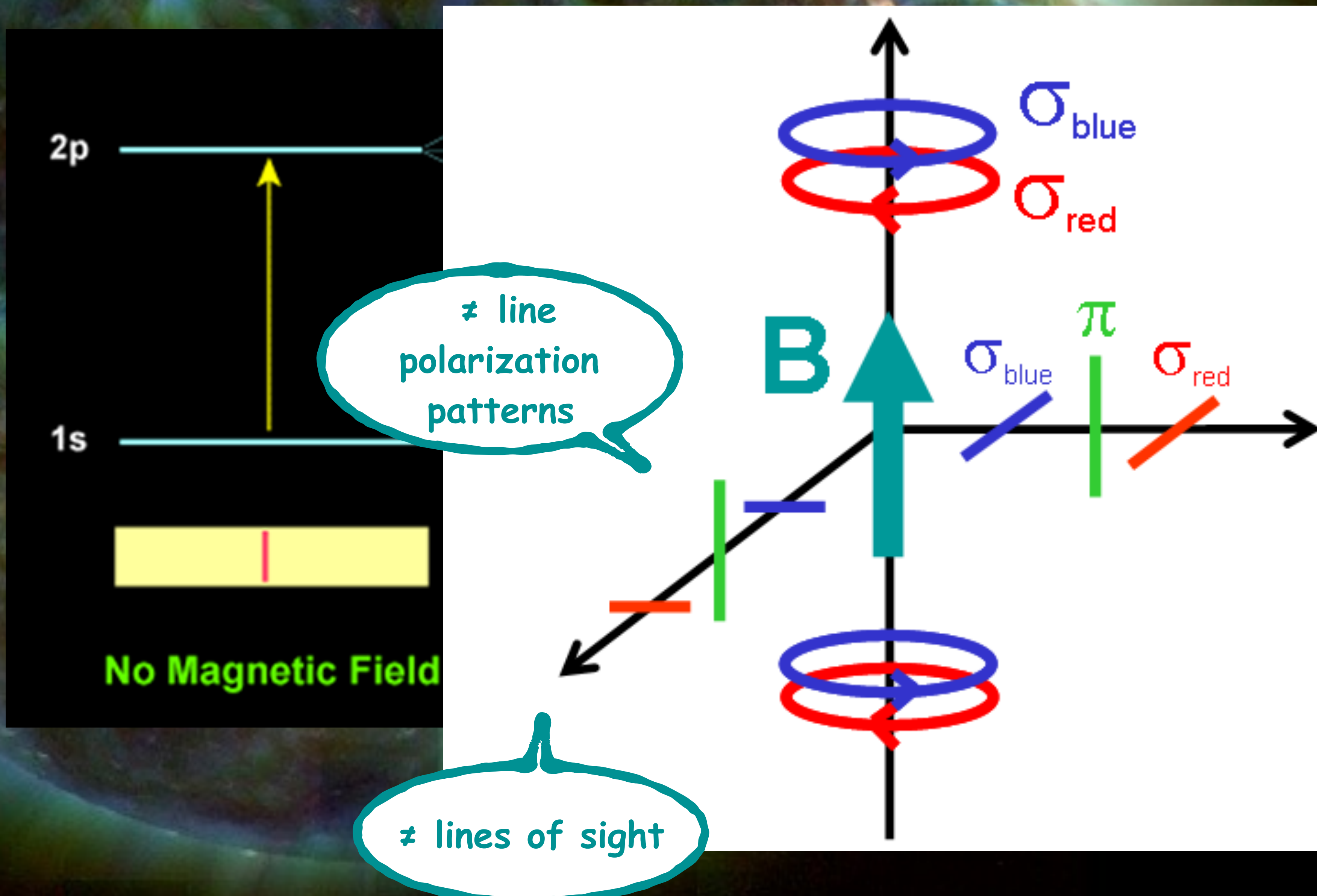

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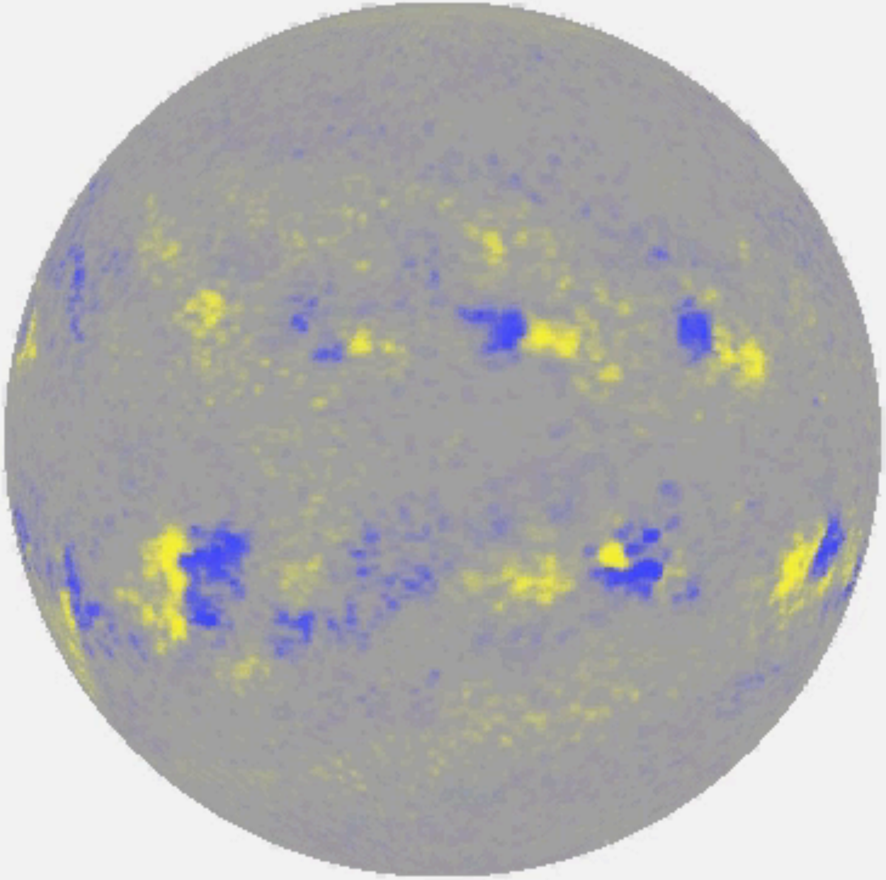
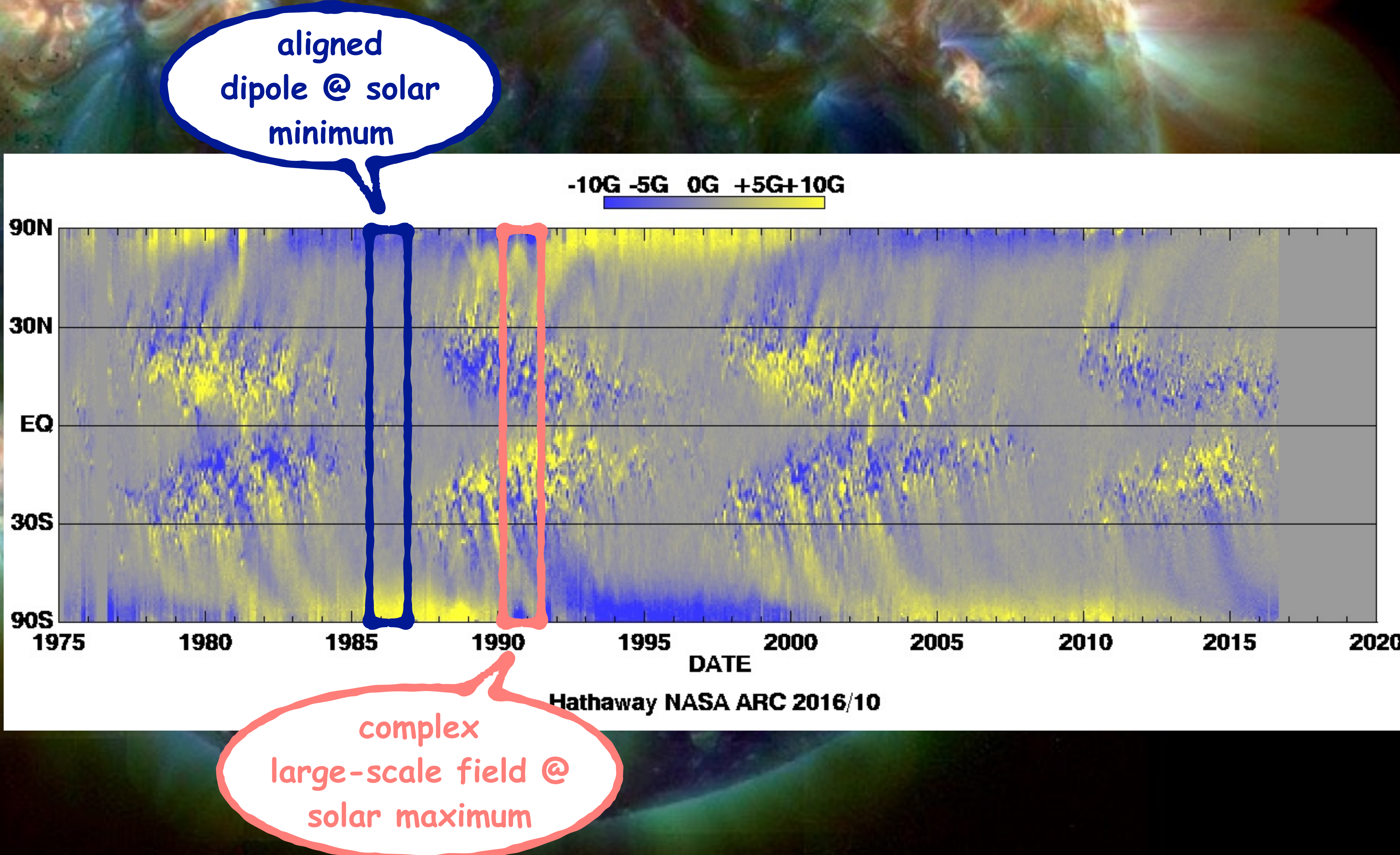


https://solarscience.msfc.nasa.gov/movies/HathawayMovie.avi

the solar dynamo



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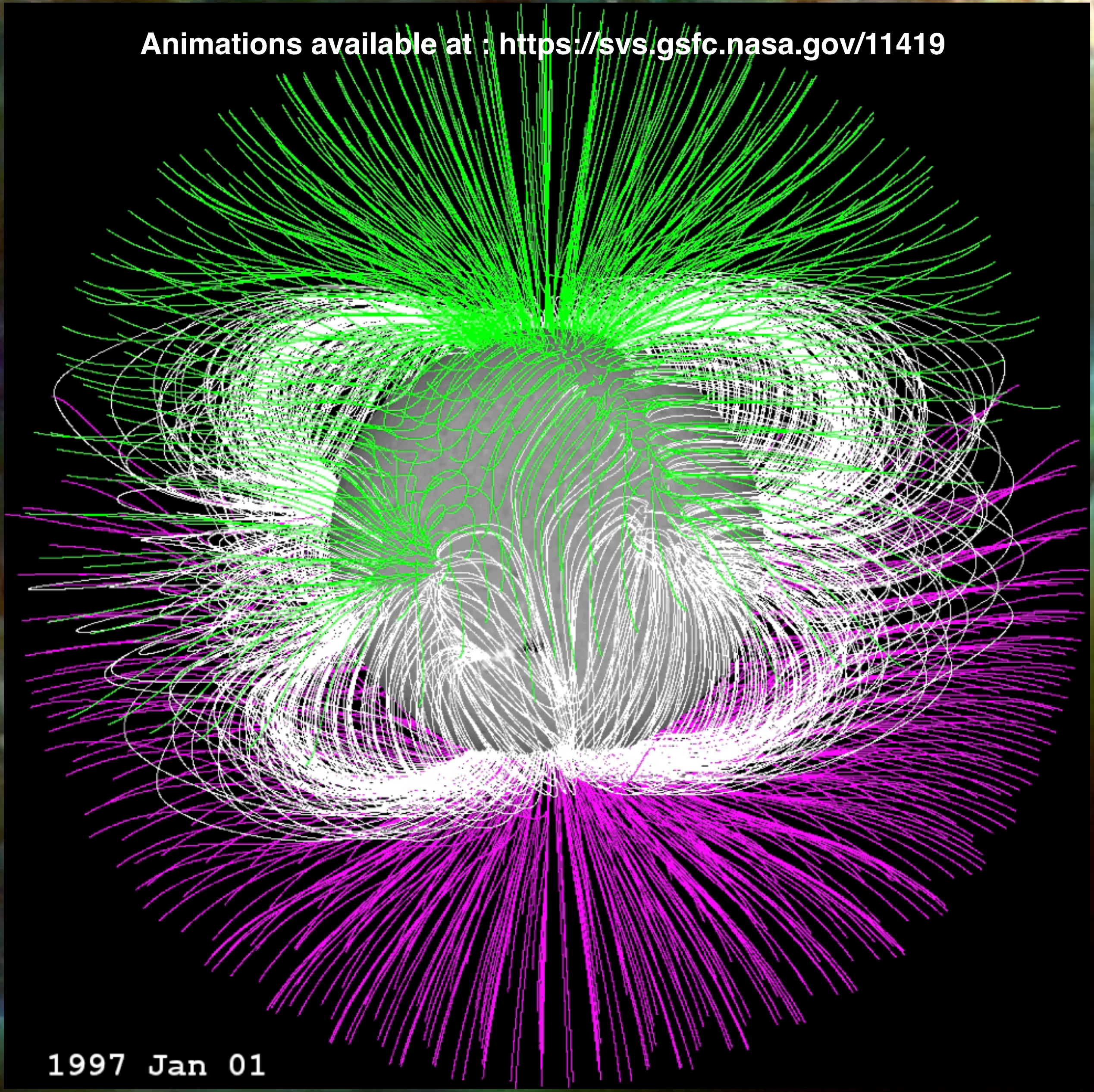

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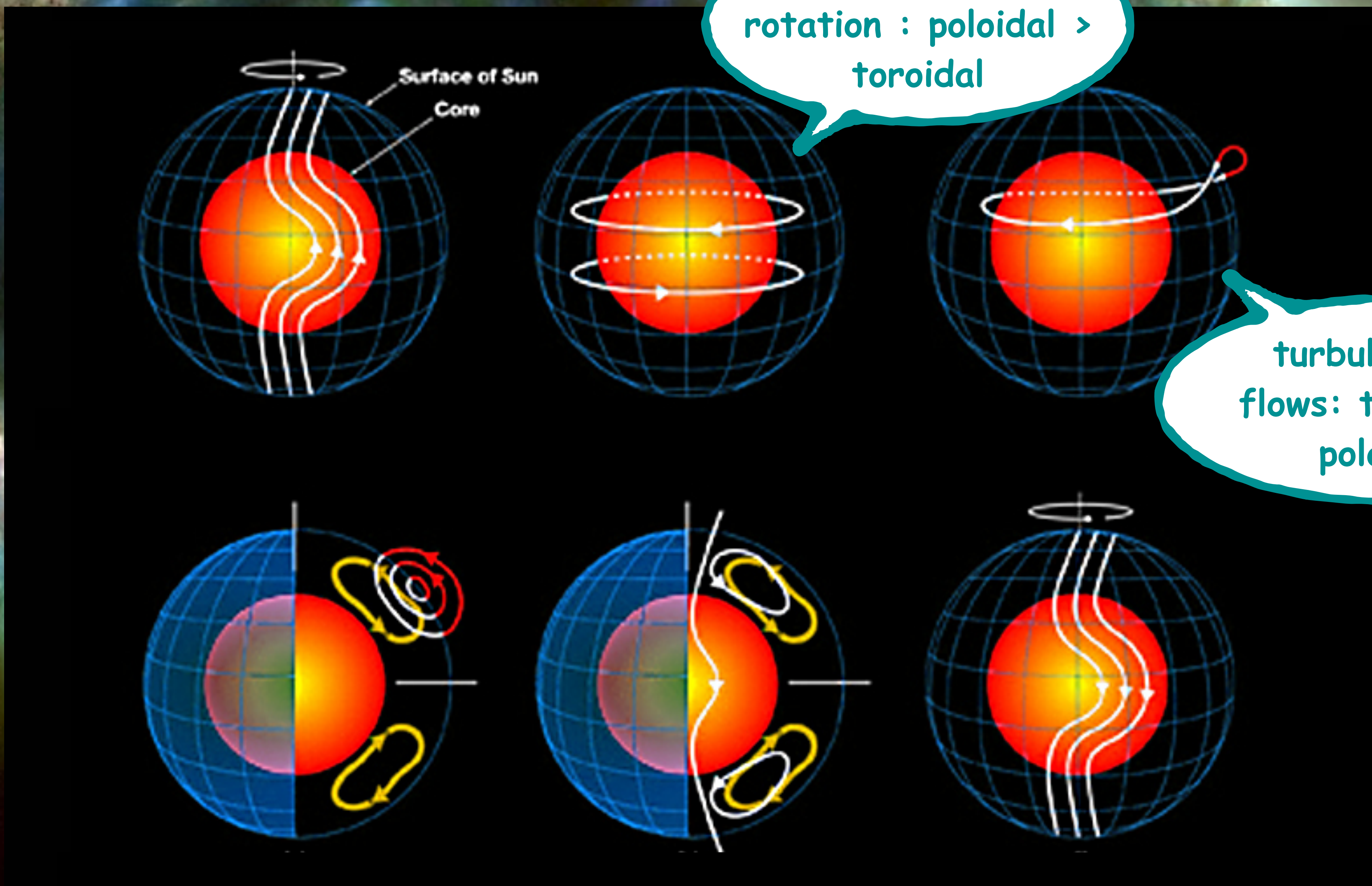

measuring magnetic fields

Zeeman effect on spectral lines

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› explore fields of stars other than the Sun

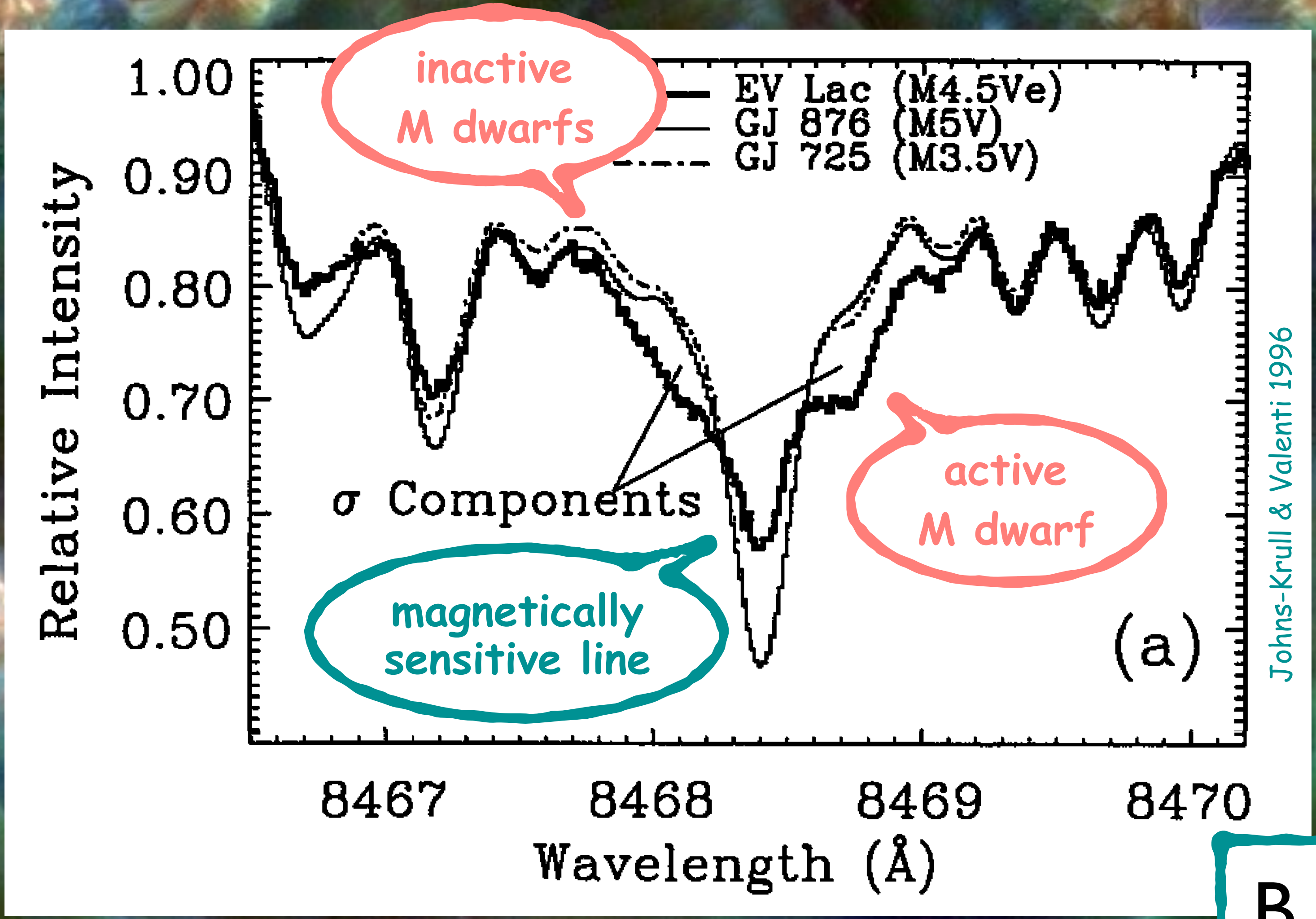
Zeeman spectroscopy: field strength & coverage

differential broadening / intensification of spectral lines

› field strength & fractional coverage - no information on topology

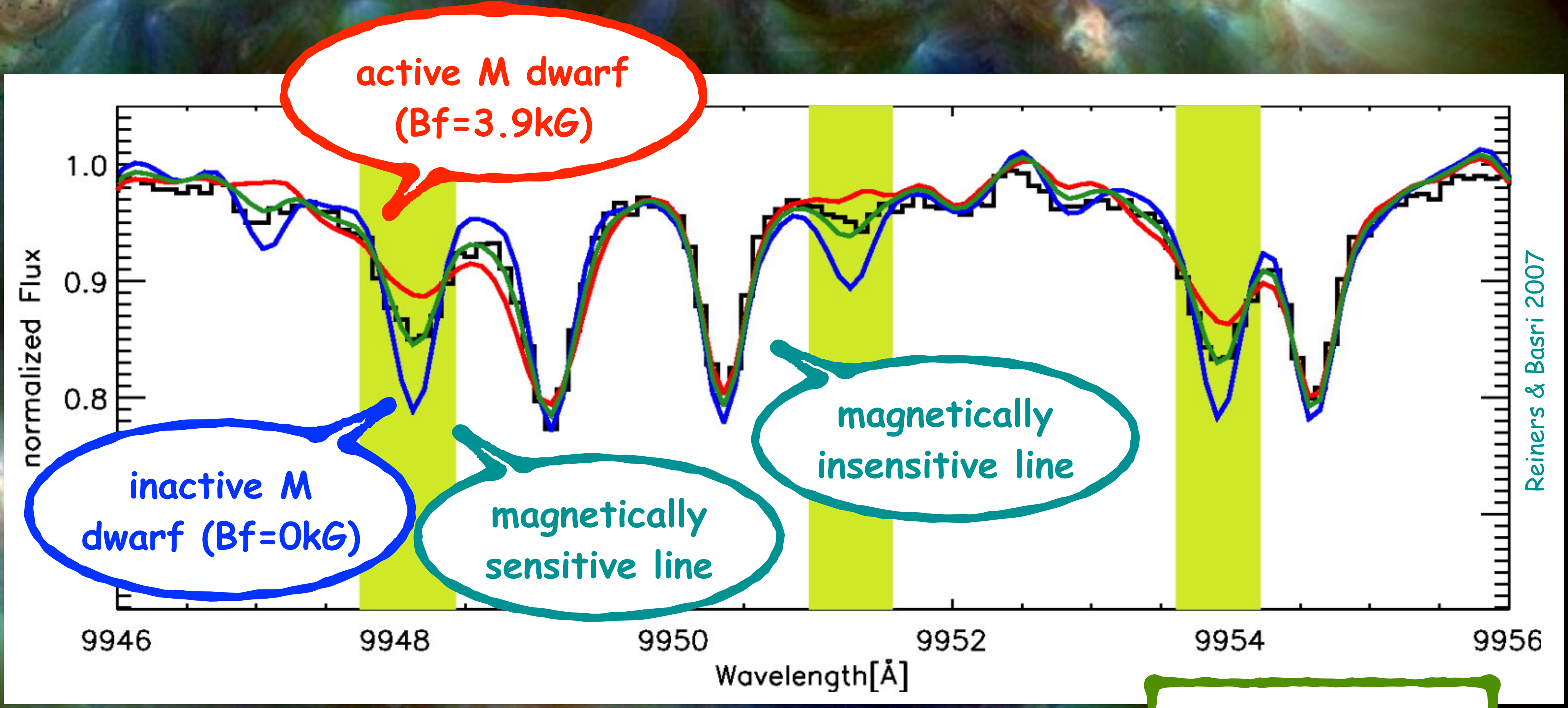
› small-scale field detected in KM dwarfs & PMS stars

Zeeman broadening / intensification



B = 3.8±0.5 kG
f = 50±13%

Zeeman broadening / intensification



Bf = 2.2 kG

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spectropolarimetry: large-scale topologies

polarisation of spectral lines
> large-scale fields detected & mapped throughout HR diagram
> w/ ESPaDOnS@3.6m-CFHT, NARVAL@2m-TBL, HARPSPol@3.6m-ESO

Zeeman spectropolarimetry

polarization in line profiles

circular polarization sensitive to line-of-sight (longitudinal) B component

linear polarization sensitive to transverse B component

cancelation from nearby opposite polarities

> insensitive to small-scale bipolar groups

Least-Squares Deconvolution (LSD)

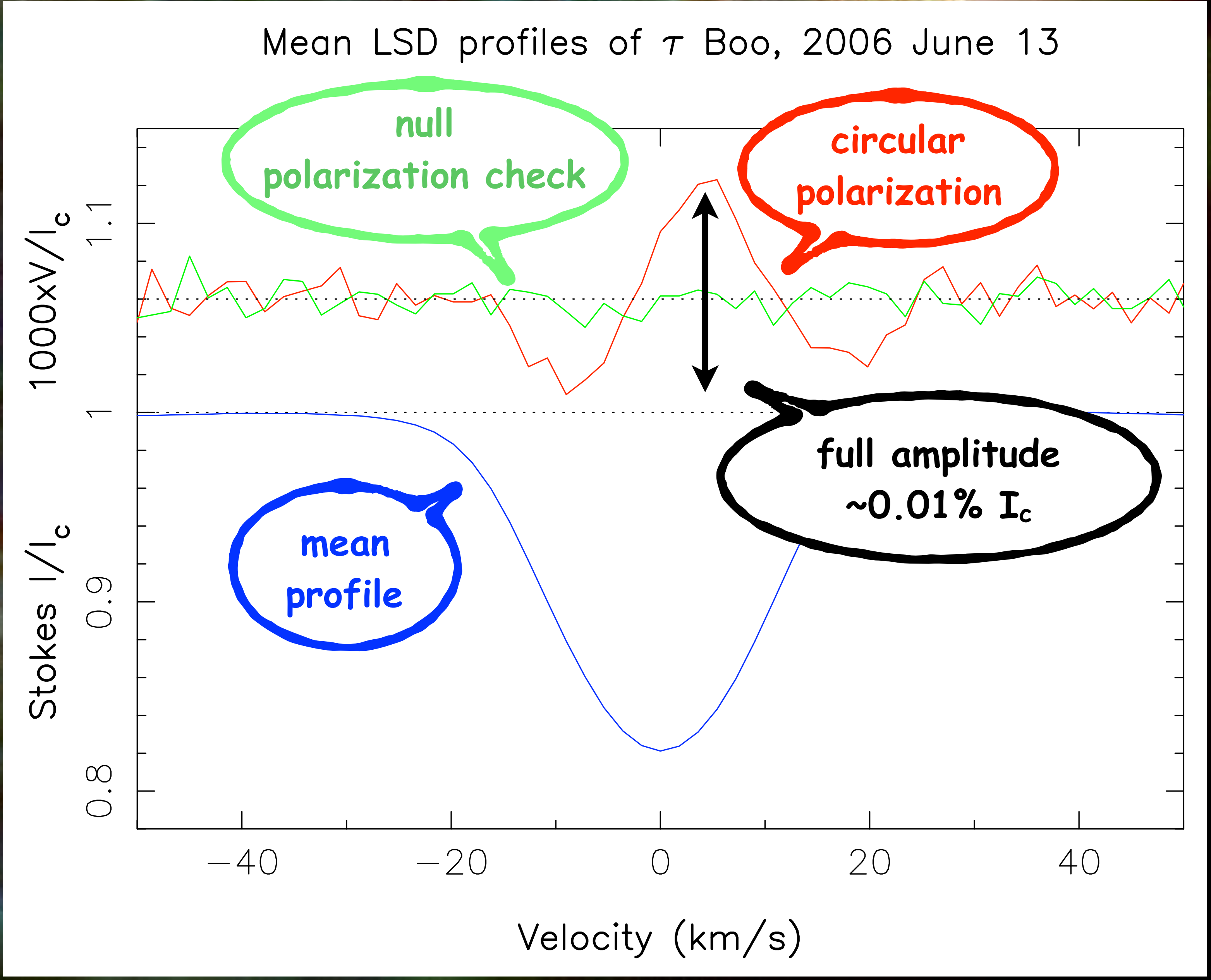
small circular polarization Zeeman signatures : 1%-0.01% of unpolarized flux

linear polarization signatures much smaller than circular ones

extract polarisation information from up to 10,000 lines

> LSD Zeeman signatures

Zeeman spectropolarimetry



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linear polarization signatures much smaller than circular ones
extract polarisation information from up to 10,000 lines
> LSD Zeeman signatures

rotational modulation & long-term variability

use temporal series collected over >1 rotation cycle
> large-scale topology (w/ tomographic imaging)
> rotation, period, surface differential rotation & activity cycles

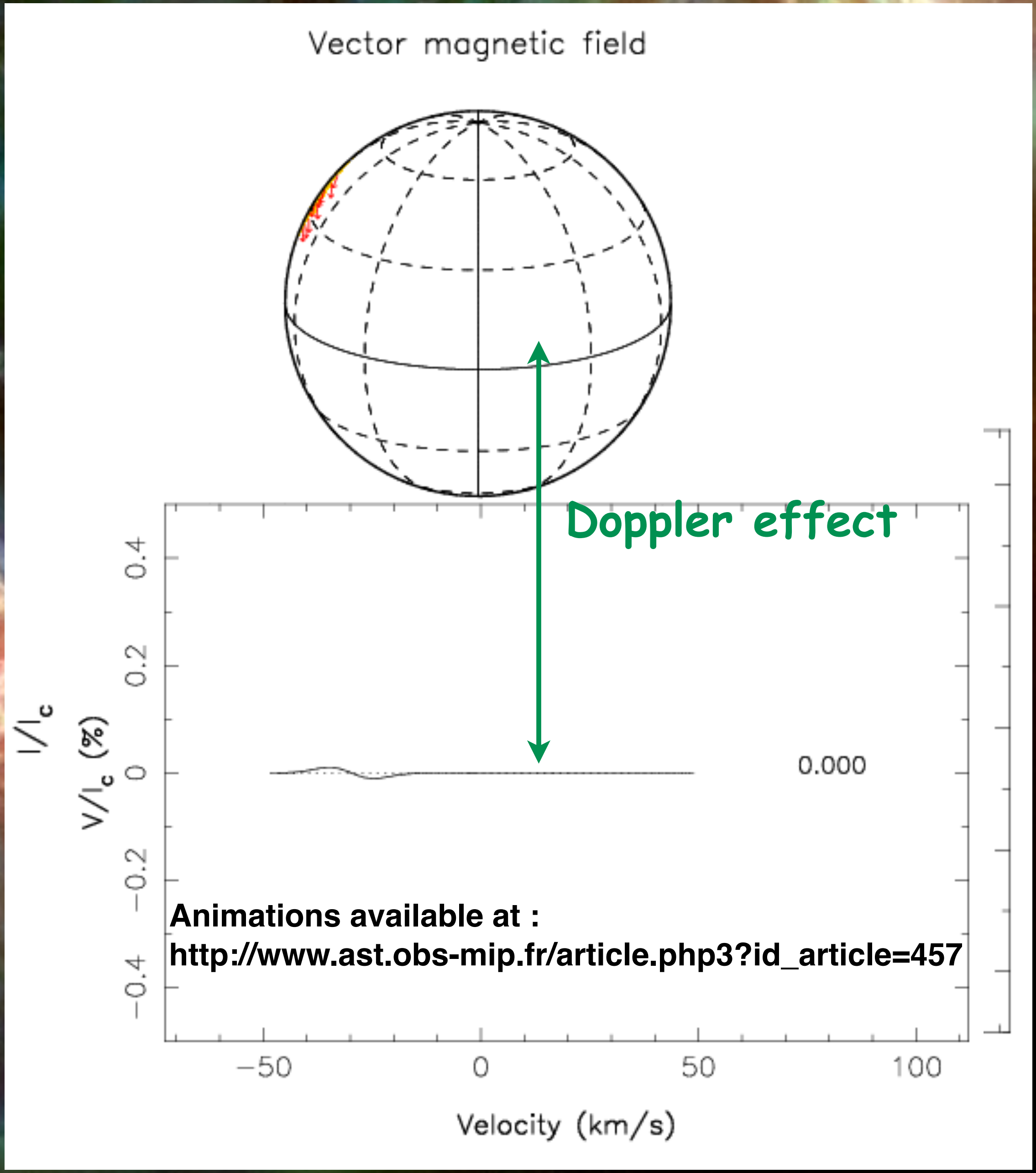
Zeeman-Doppler imaging (ZDI)

use spectropolarimetric series...

rotational modulation of Zeeman signature (Doppler effect)

> recover spot location & field orientation

Zeeman-Doppler imaging (ZDI)



Zeeman-Doppler imaging (ZDI)

use spectropolarimetric series...

rotational modulation of Zeeman signature (Doppler effect)

> recover spot location & field orientation

...to reconstruct the large-scale topology...

use spherical harmonics decomposition & tomographic imaging

line profile modelling using Unno-Rachkovsky's equations

> infer magnetic topology : poloidal & toroidal components

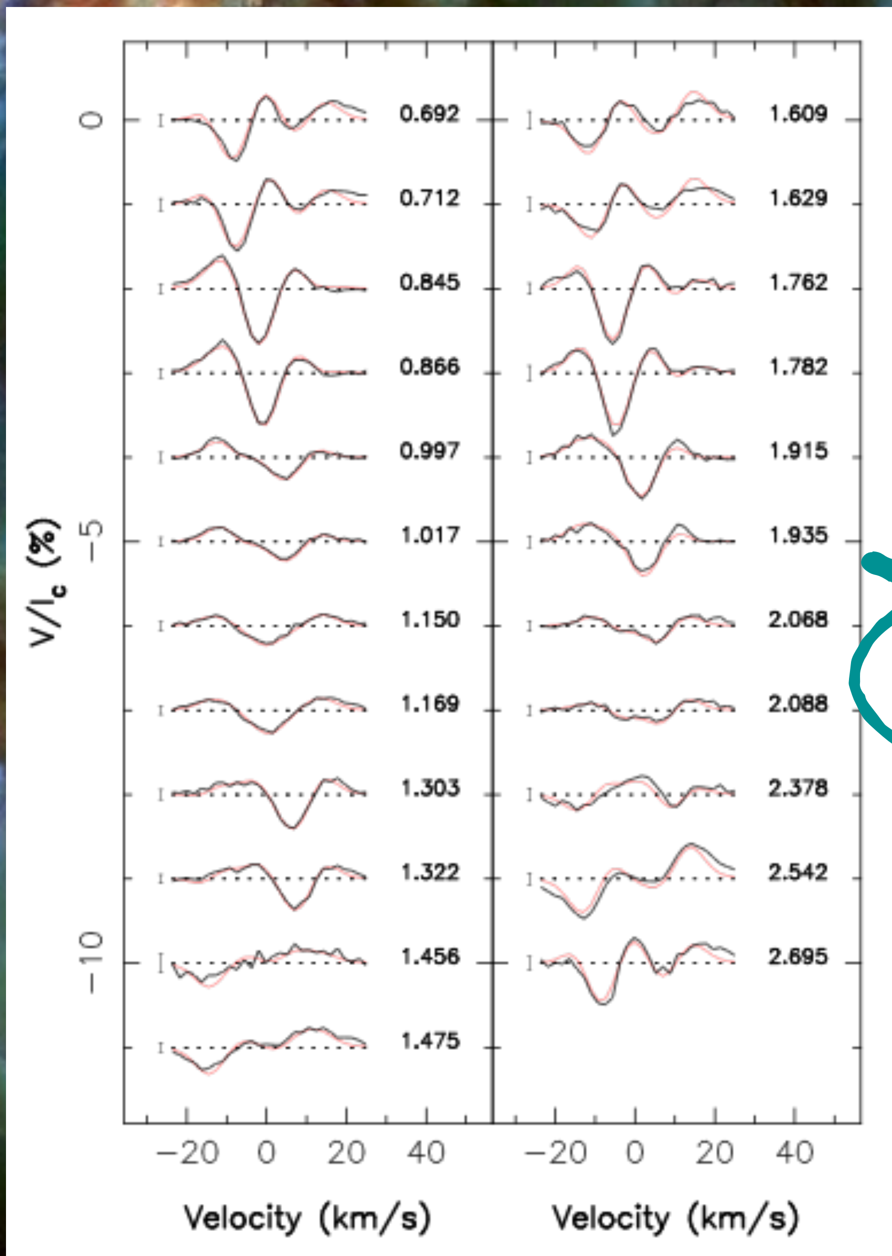
> works well for slow rotators as well

...and extrapolate it outwards

assume potential field topology (lowest energy state)

> get 3D image of stellar magnetosphere

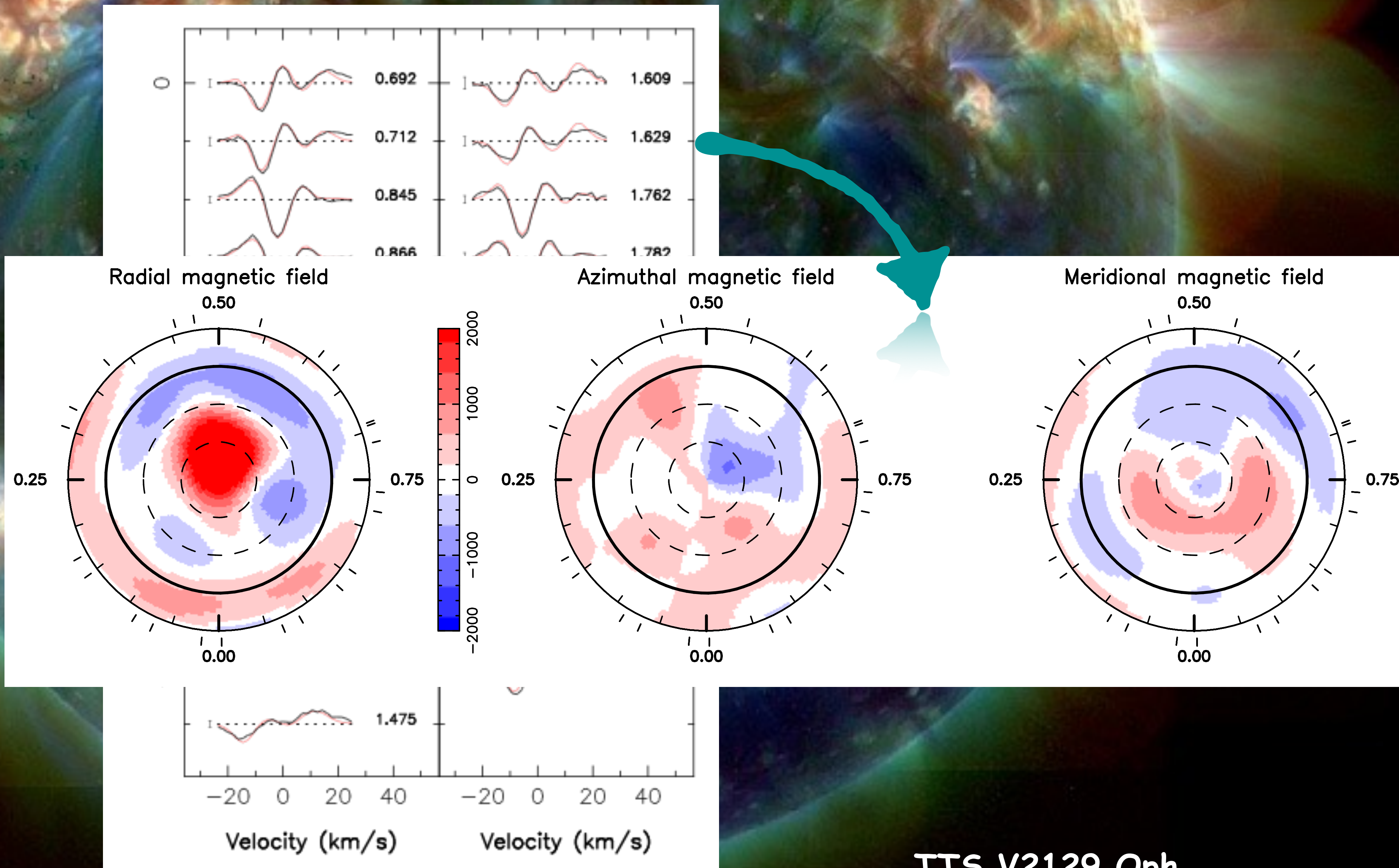
Zeeman-Doppler imaging (ZDI)



Stokes V profiles vs rotation phase

TTS V2129 Oph

Zeeman-Doppler imaging (ZDI)



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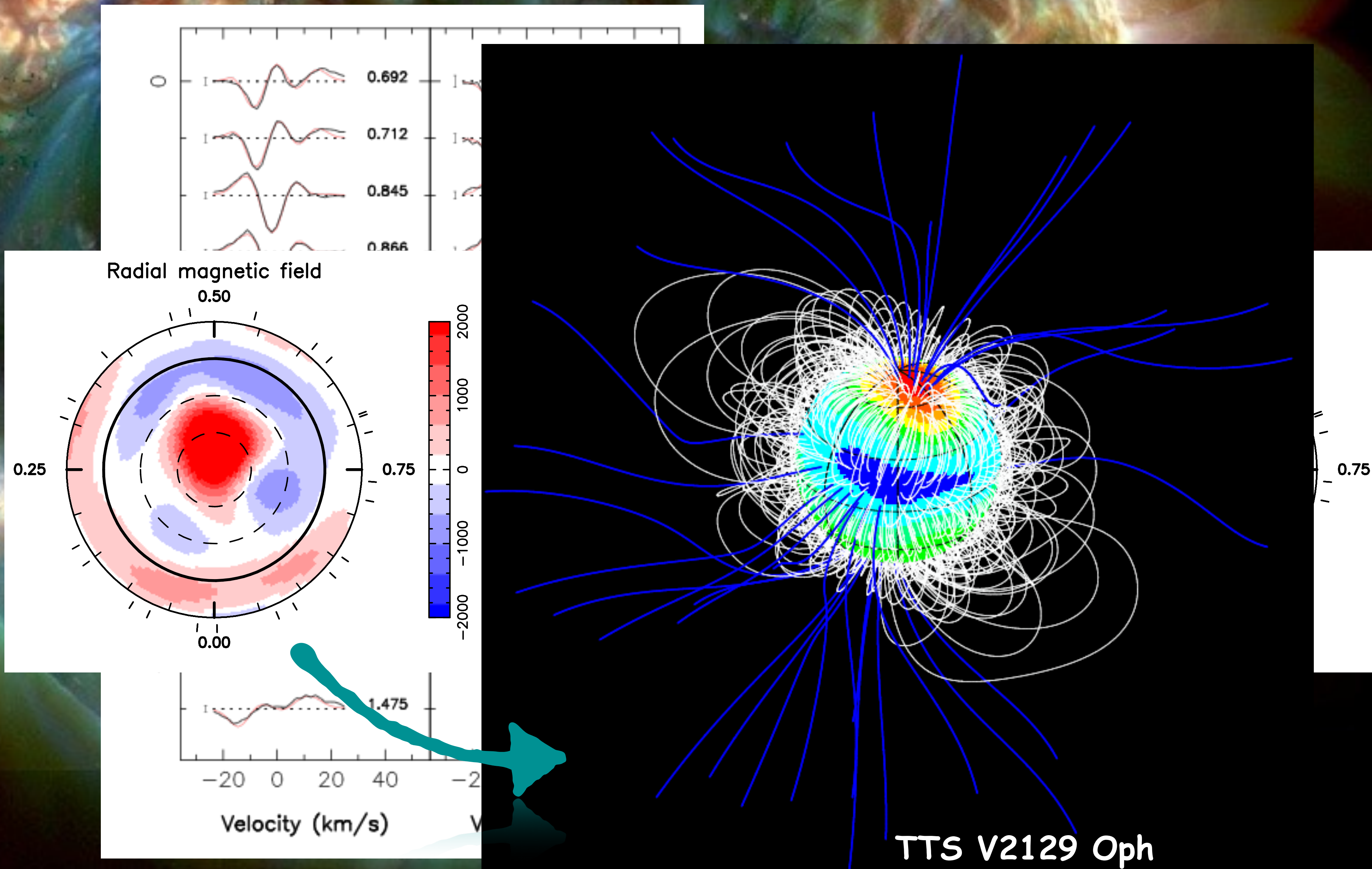
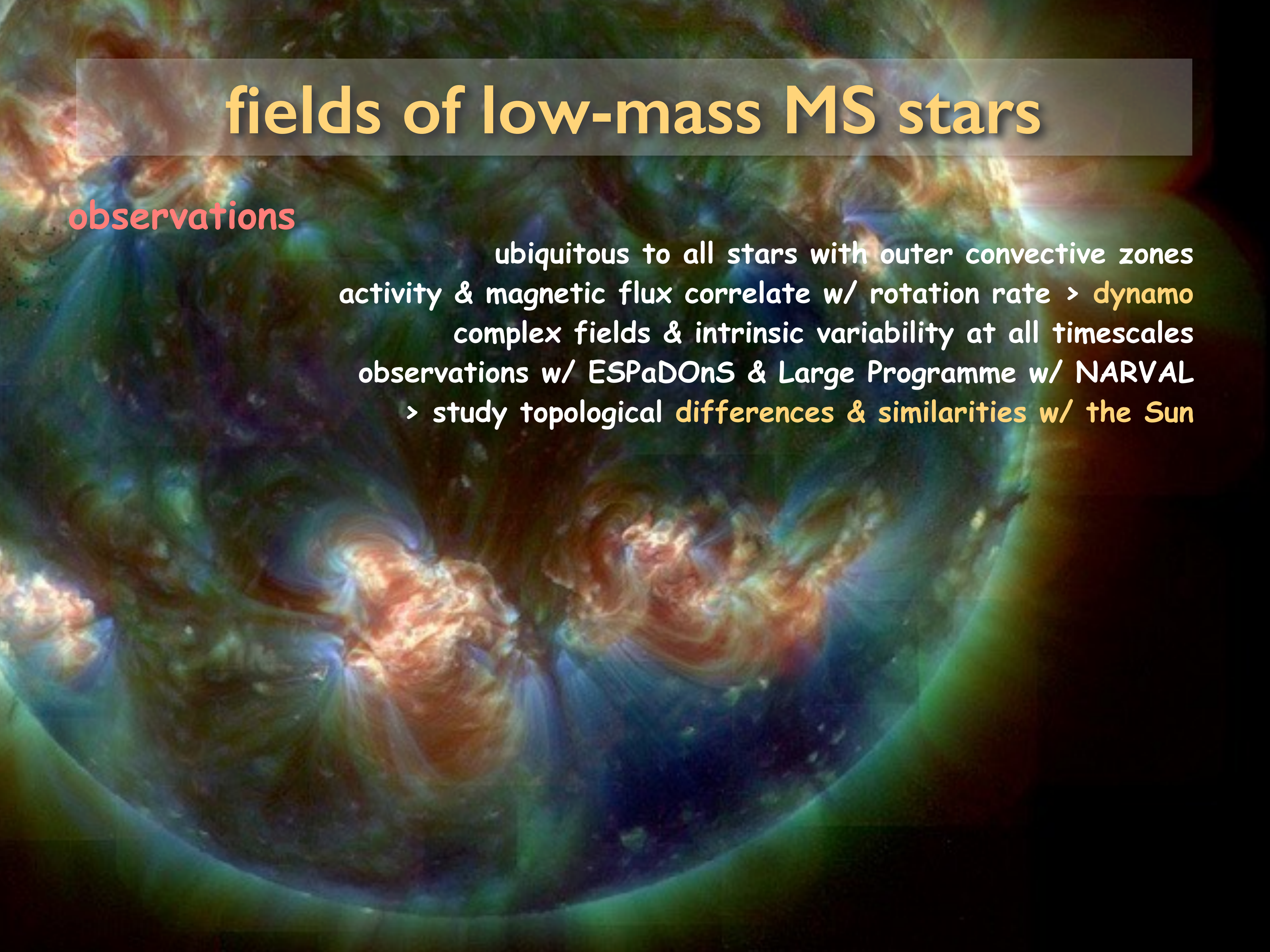




fields of low-mass MS stars

observations

ubiquitous to all stars with outer convective zones

activity & magnetic flux correlate w/ rotation rate > dynamo

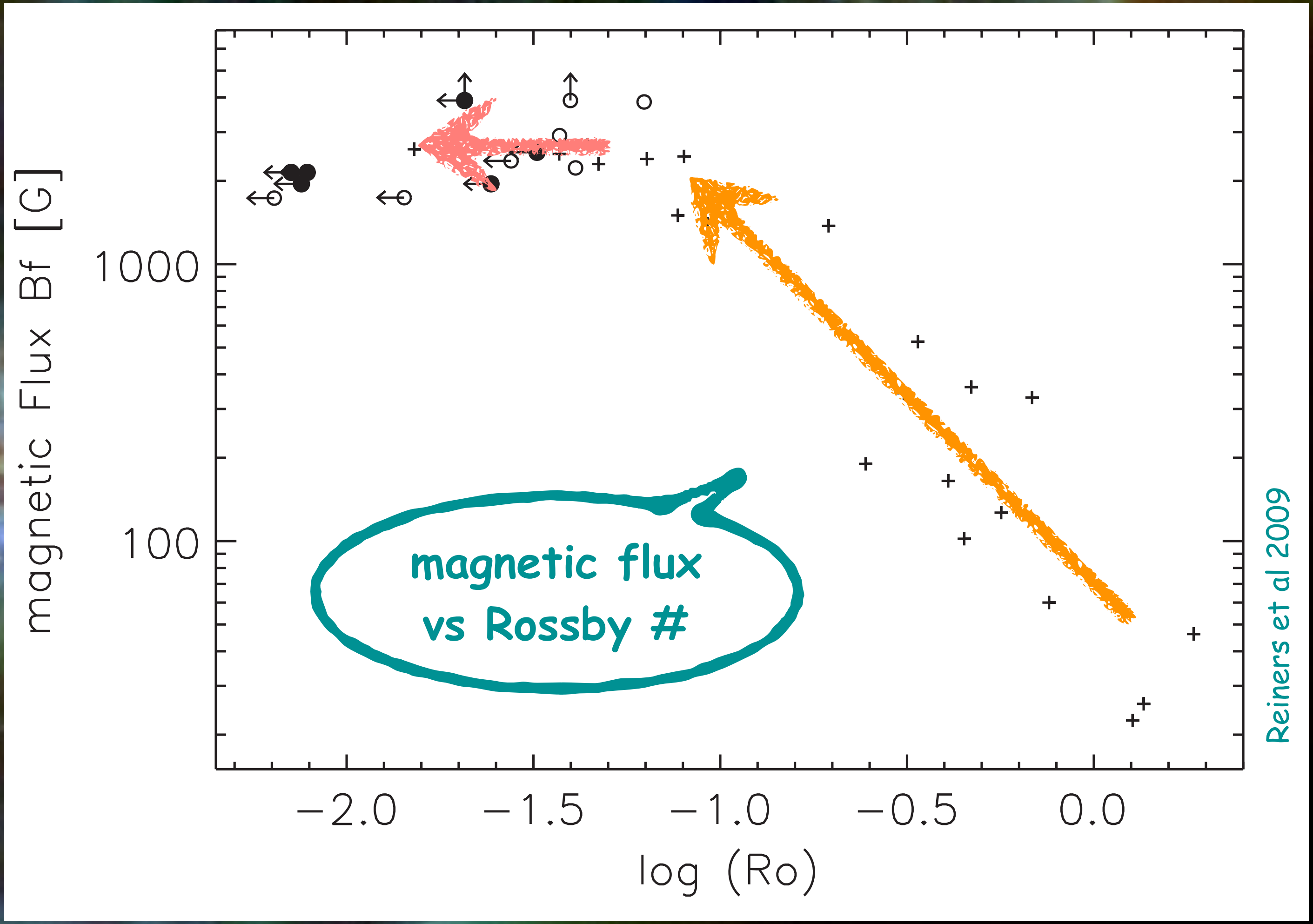
complex fields & intrinsic variability at all timescales

observations w/ ESPaDOnS & Large Programme w/ NARVAL

> study topological differences & similarities w/ the Sun

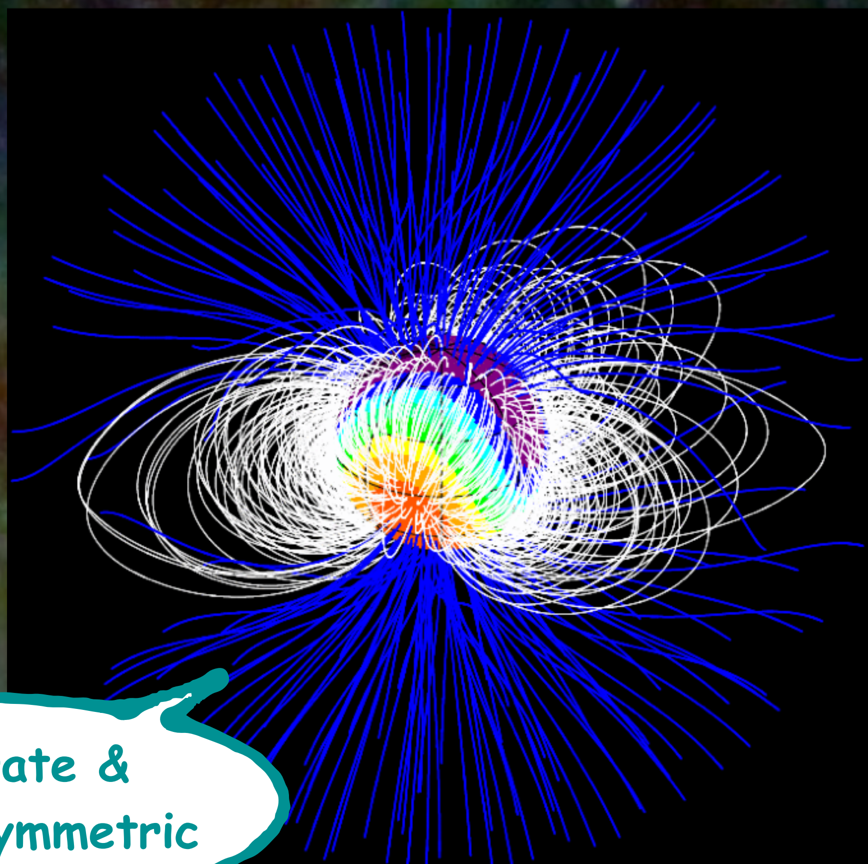
fields of low-mass MS stars

small-scale fields from Zeeman broadening

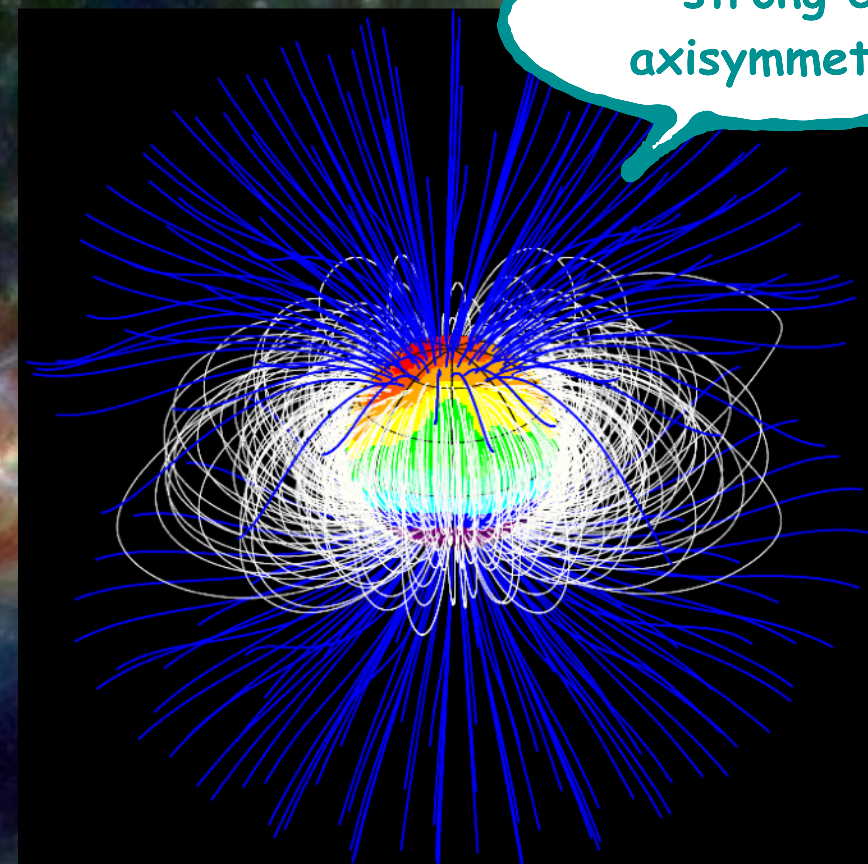


fields of low-mass MS stars

large-scale fields from Zeeman spectropolarimetry



HD 209100, K5 star : max 40 G
0.7 M⊙, Prot 34 d



V374 Peg, M4 dwarf : max 1.2 kG
0.3 M⊙, Prot 0.45 d

fields of low-mass MS stars

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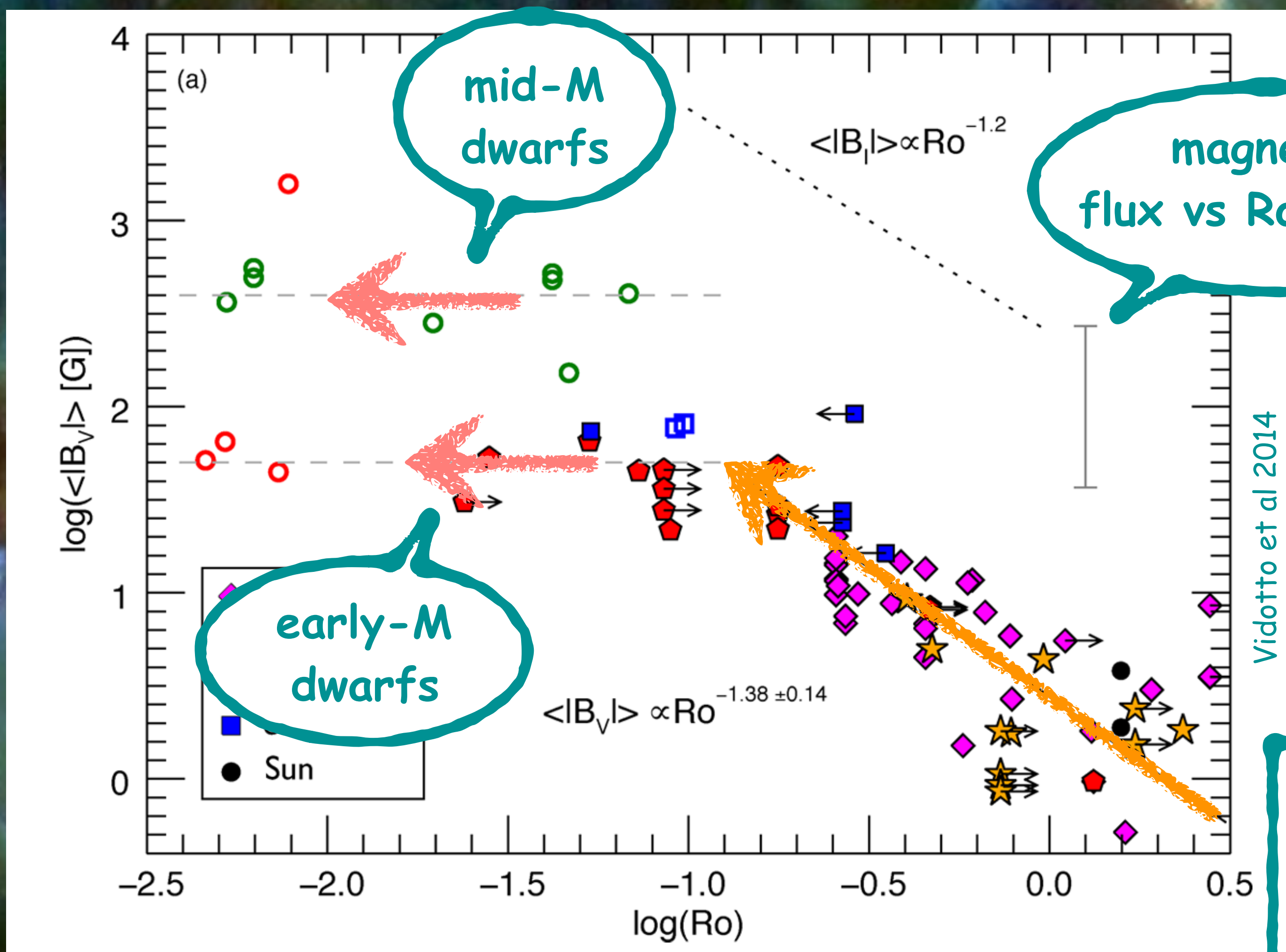

only 5-15% of magnetic flux in large-scales

fields of low-mass MS stars

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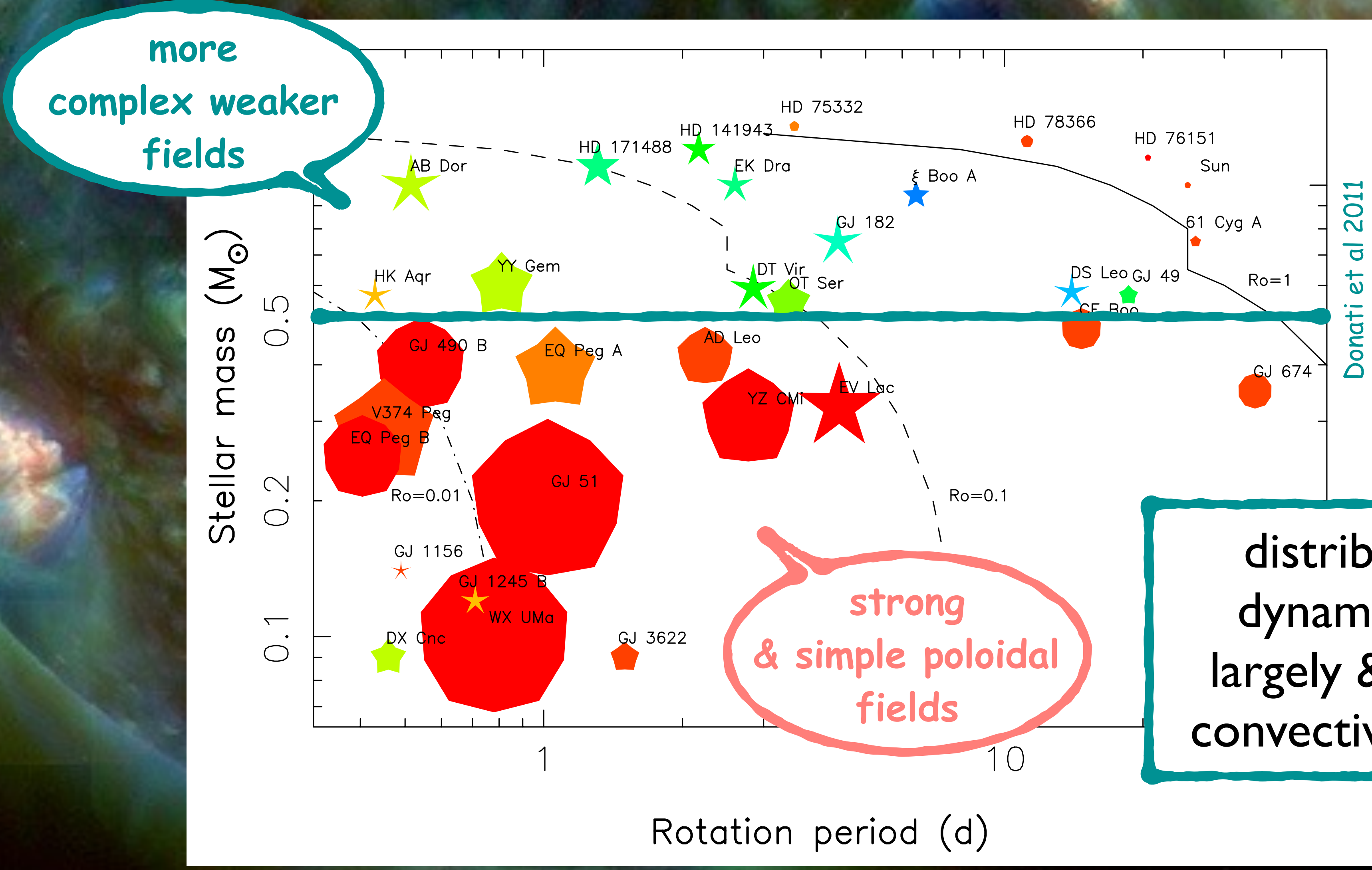
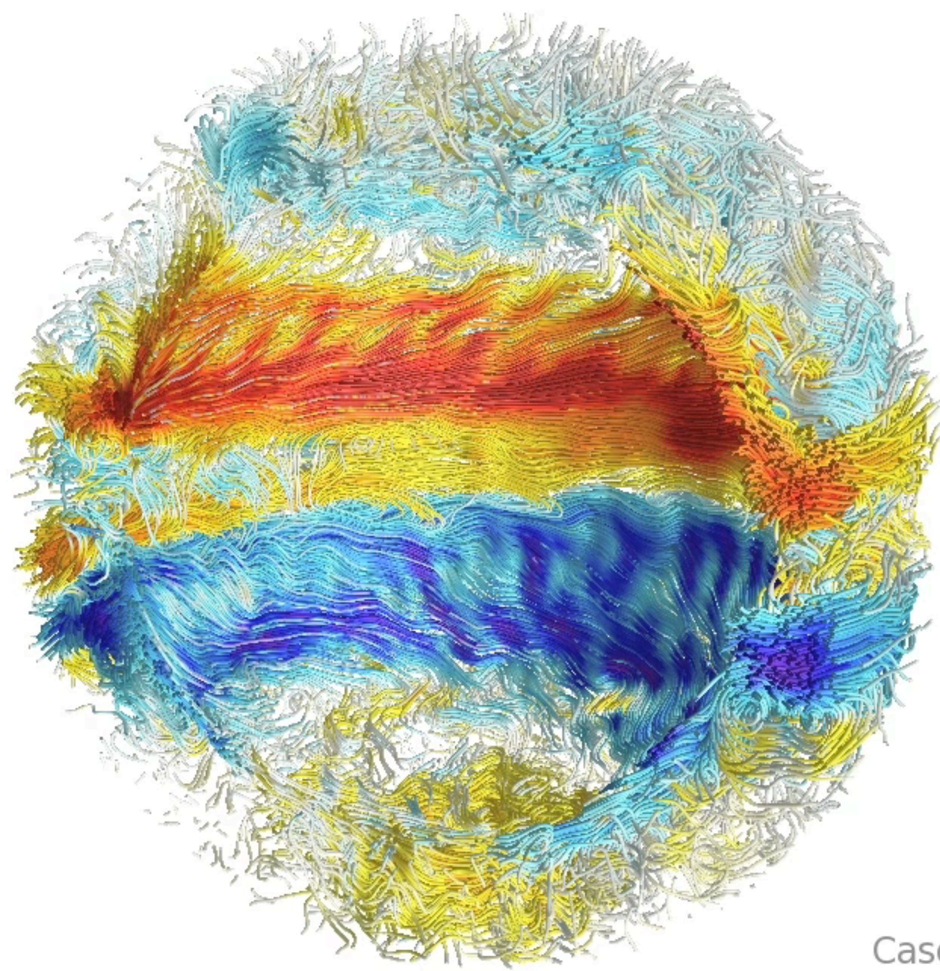


distributed dynamos in largely & fully-convective stars

fields of low-mass MS stars

distributed dynamos in numerical simulations



Case D5
(Brown et al. 2011)

qualitative agreement with observations

fields of low-mass MS stars

observations

ubiquitous to all stars with outer convective zones
activity & magnetic flux correlate w/ rotation rate > dynamo
complex fields & intrinsic variability at all timescales
observations w/ ESPaDOnS & Large Programme w/ NARVAL
> study topological differences & similarities w/ the Sun

dynamo fields

strong & simple poloidal fields in mostly convective stars: distributed dynamos
moderate & complex fields in mostly radiative stars: mixed dynamos
activity cycles of stars ≠ than the Sun

fields of low-mass MS stars

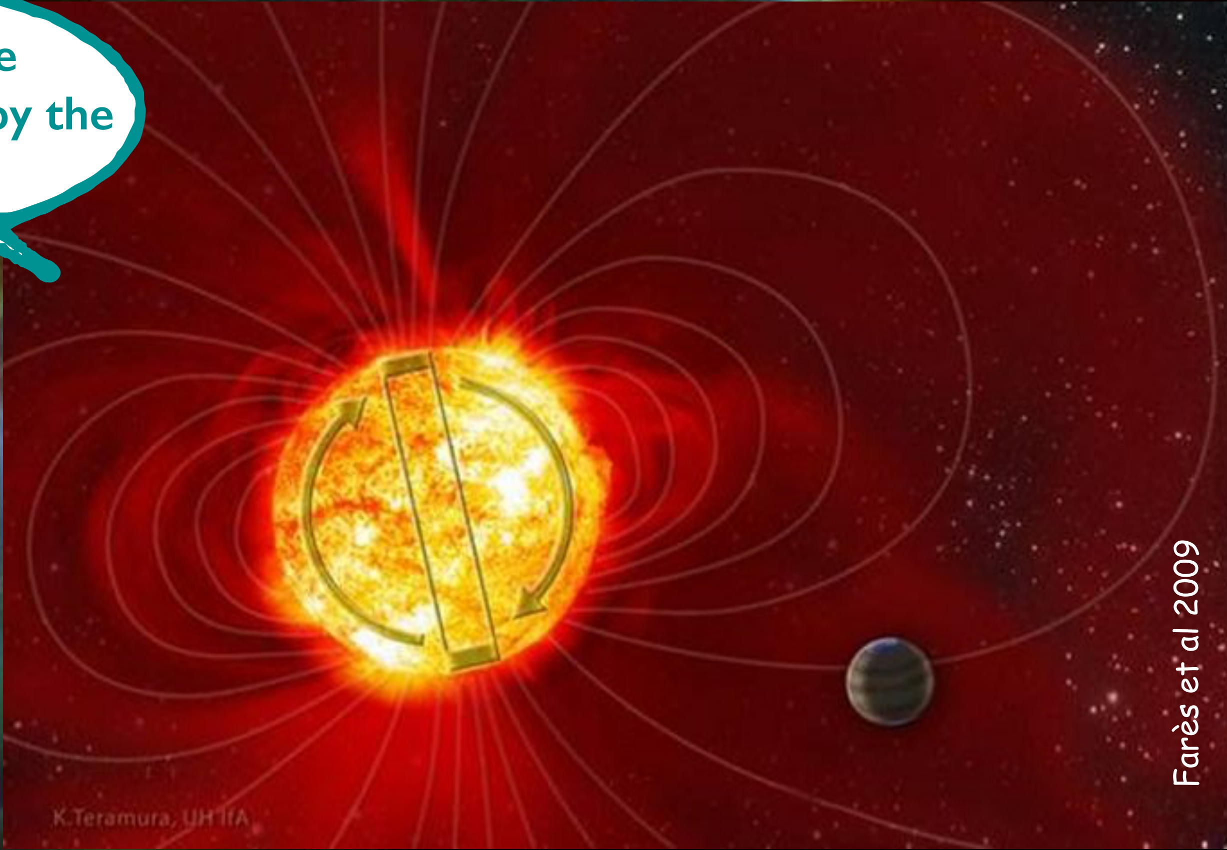
magnetic cycles of low-mass stars

magnetic cycles detected on a few low-mass stars, e.g., tau Boo, 61 Cyg

very short cycle periods for F stars, e.g., 2 yr for tau Boo ?

dynamo cycles of fully-convective M dwarfs

a 2yr magnetic cycle for tau Boo - triggered by the hot Jupiter?



Farès et al 2009

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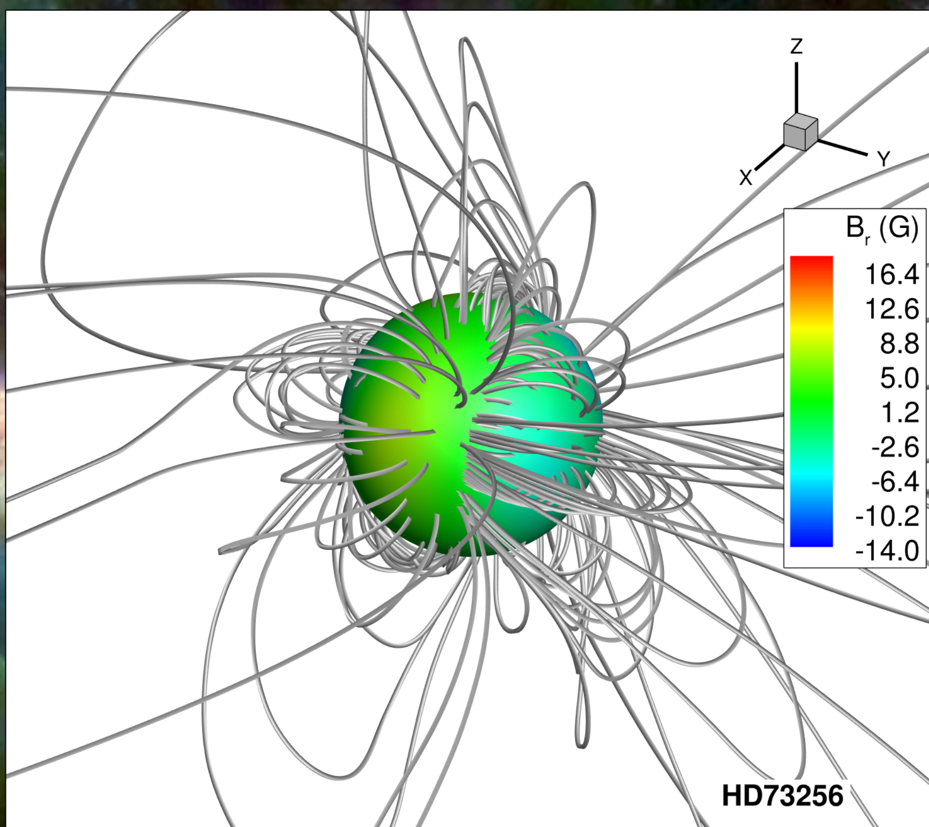
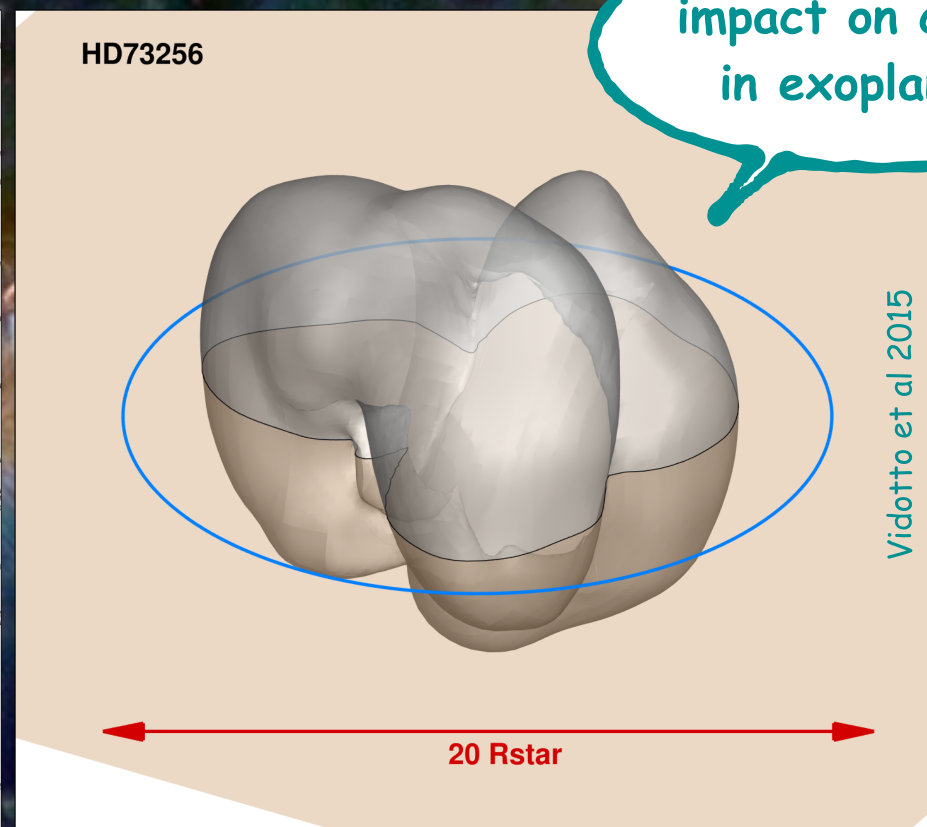
impact on evolution & planets

coronae & winds causing magnetic braking & slow rotation
fields & winds of low-mass stars can impact close-in planets

fields of low-mass MS stars

modeling winds of low-mass stars



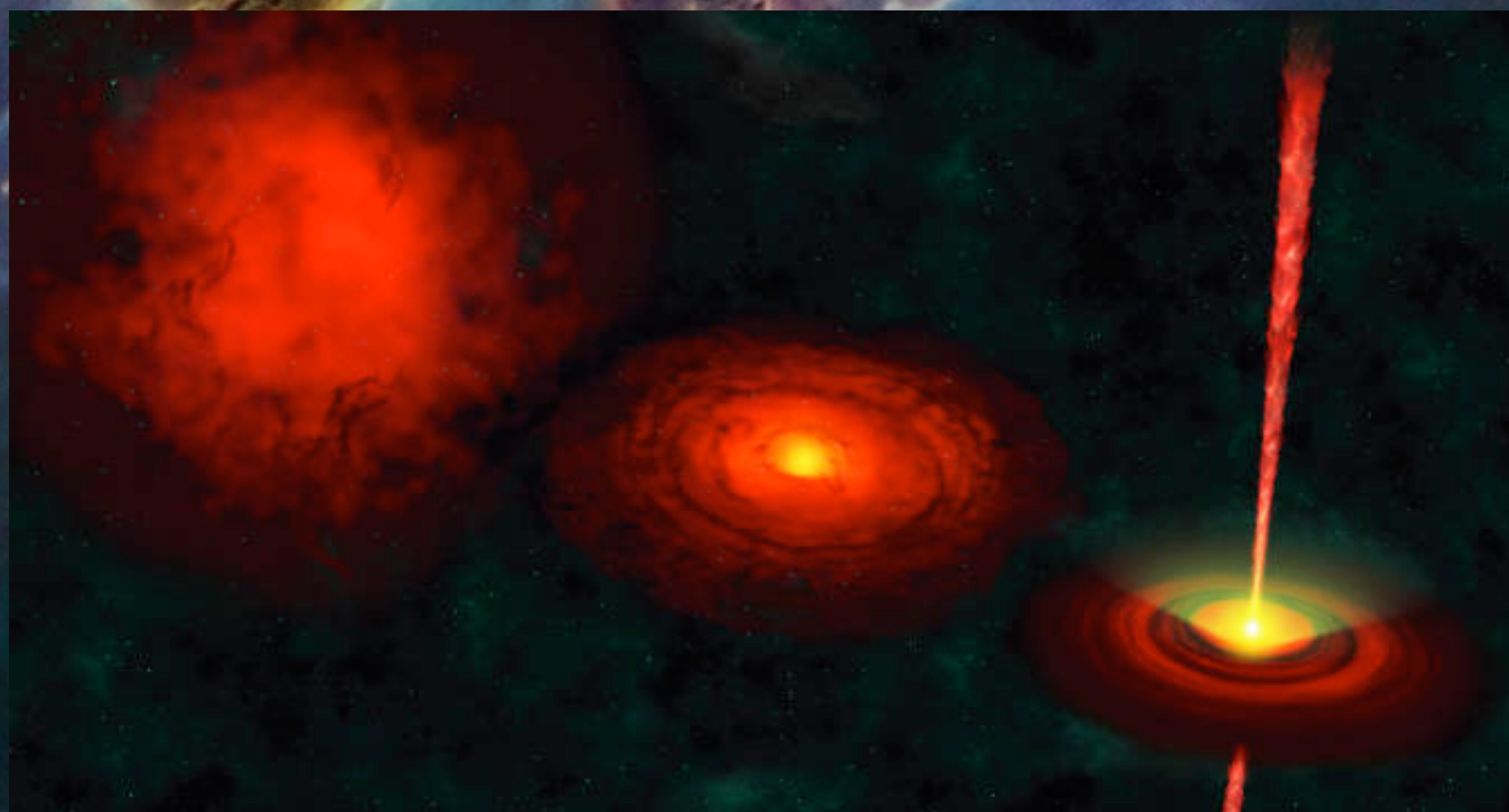


impact on close-in exoplanets

fields of young low-mass stars

formation of low-mass stars

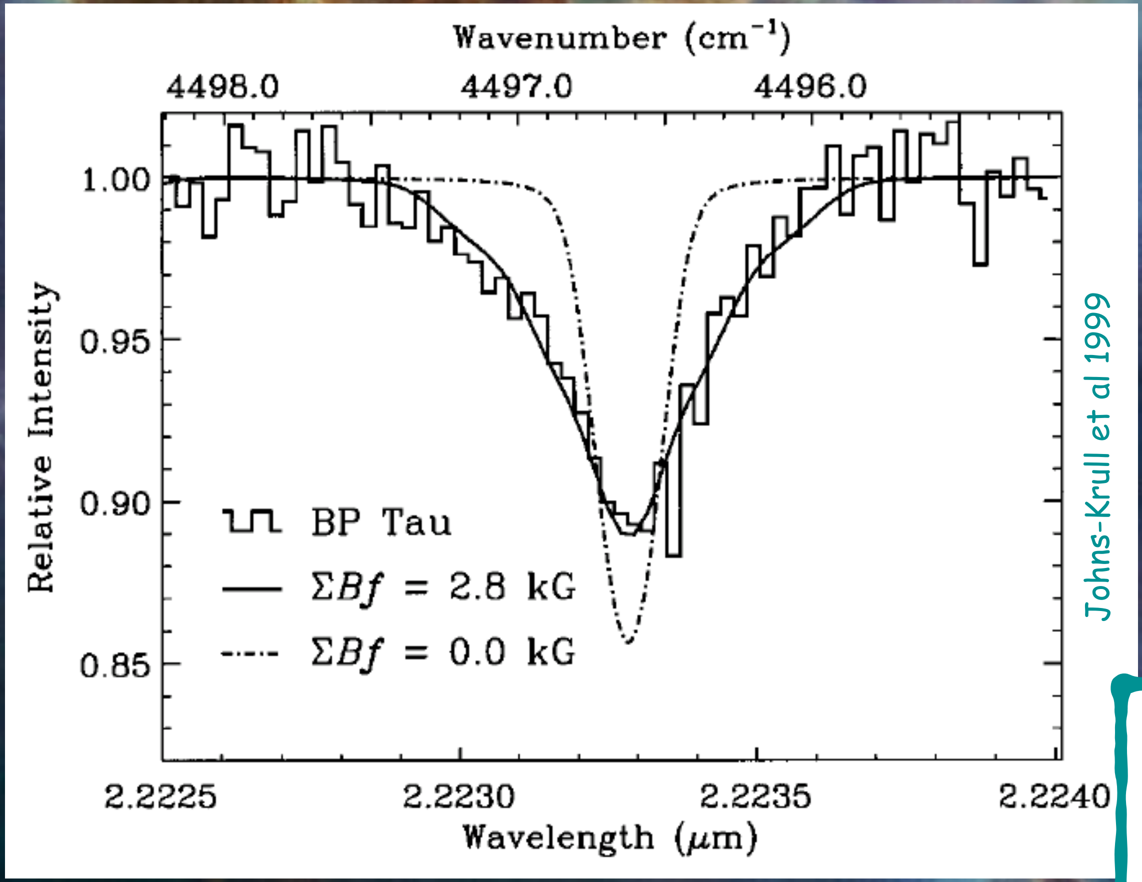
stars form from the collapse of giant molecular clouds
magnetic fields play key role in the process
control accretion, trigger jets / outflows
remove angular momentum from protostar



fields of young low-mass stars

observations

strong fields reported but no info on large-scale topologies



Johns-Krull et al 1999

kG fields from Zeeman broadening of IR spectral lines

fields of young low-mass stars

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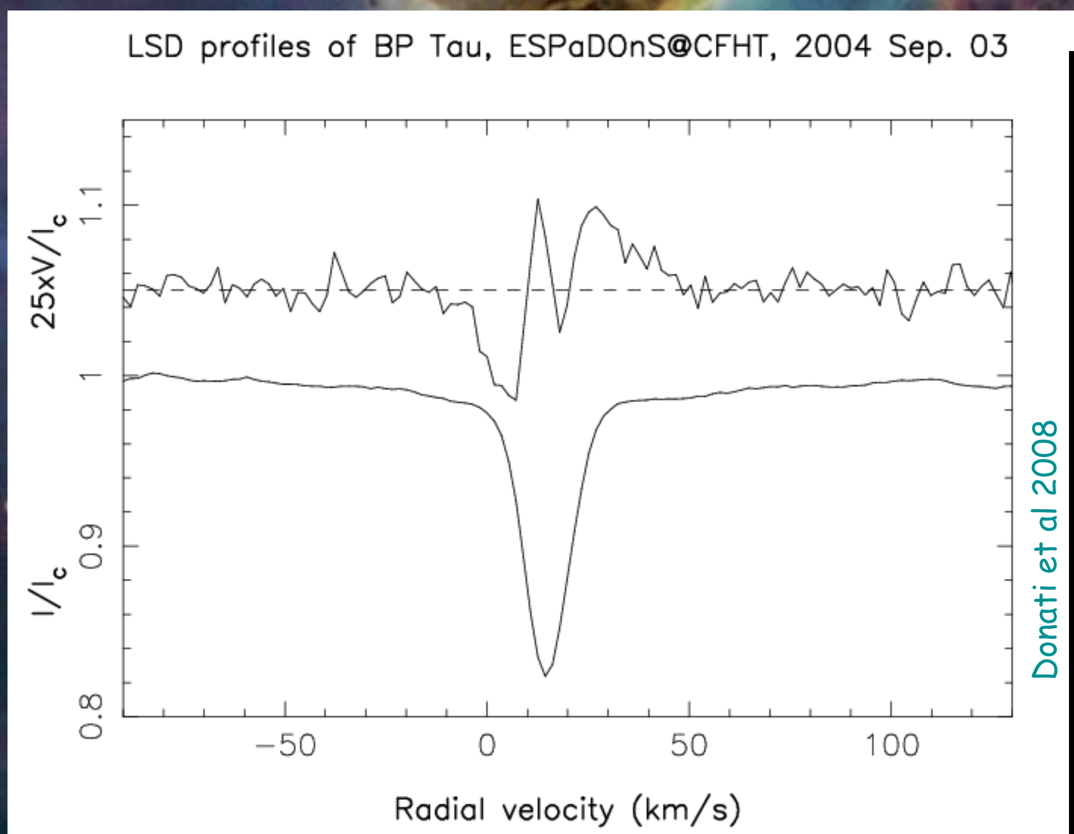
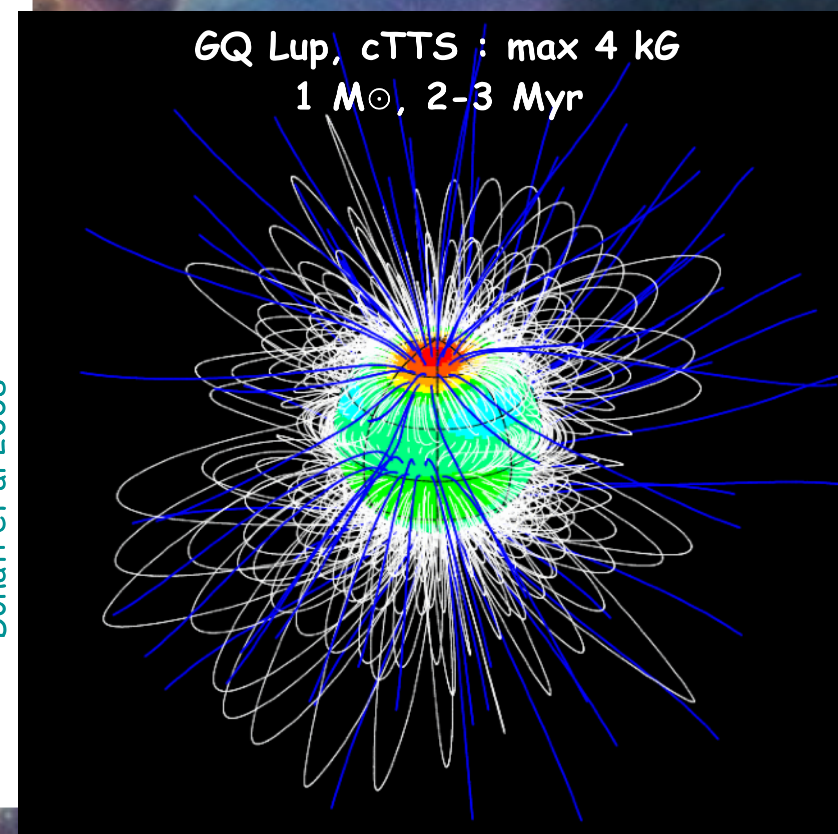
coupling with surrounding accretion discs - outflows (winds & jets)

disc fields & the formation / migration of planets

coordinated programmes to study large-scale fields of T Tauri stars



Donati et al 2008



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large-scale fields

large-scale fields often complex > dominant octupole component

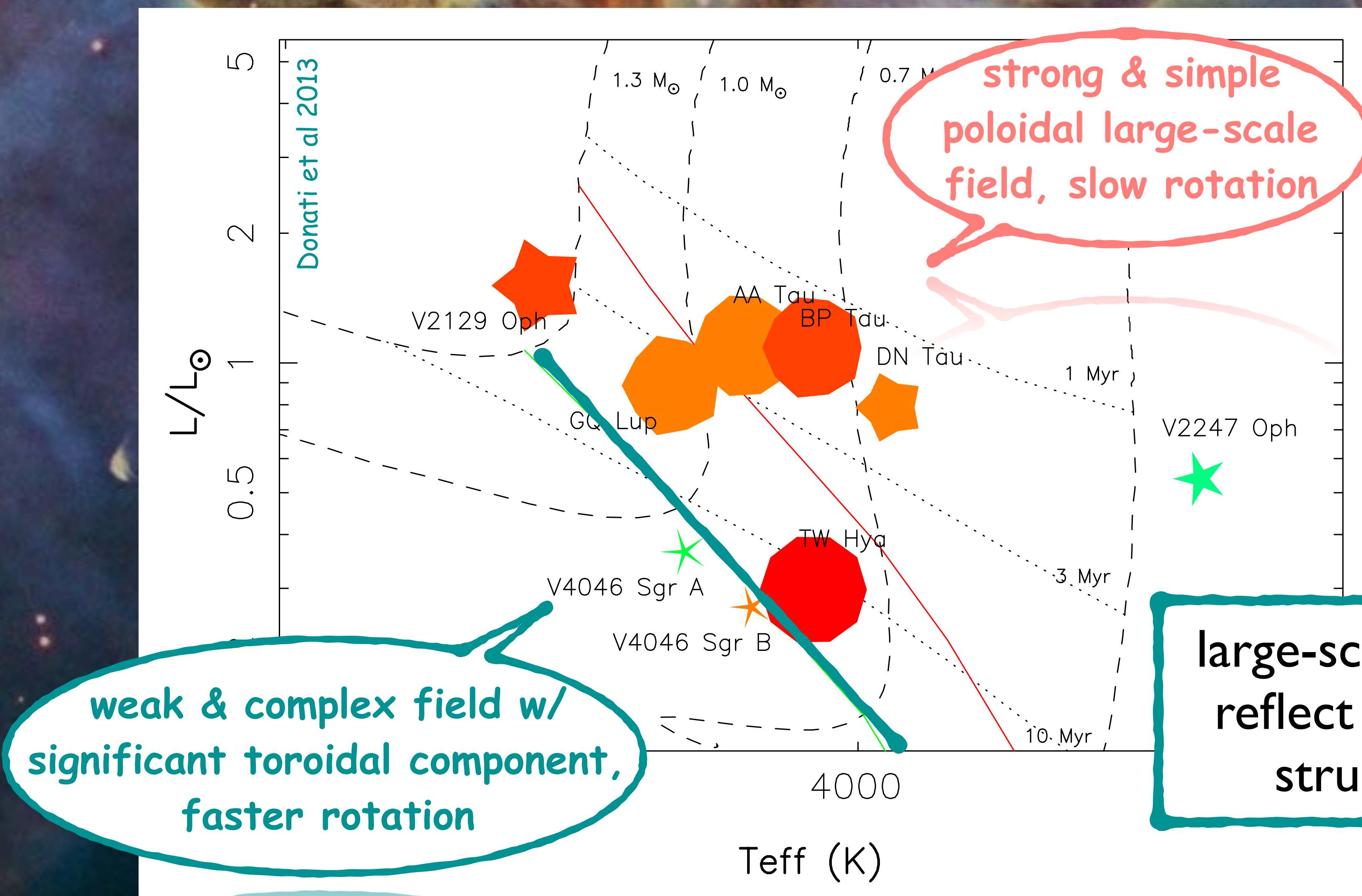
variability on timescales of yrs > dynamo fields (rather than fossil)

strong & simple when fully convective, weaker & more complex otherwise

reflect internal structure > vary on evolutionary timescales

fields of young low-mass stars

large-scale fields from Zeeman spectropolarimetry



large-scale fields reflect internal structure

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reflect internal structure > vary on evolutionary timescales

magnetospheric accretion & planet formation

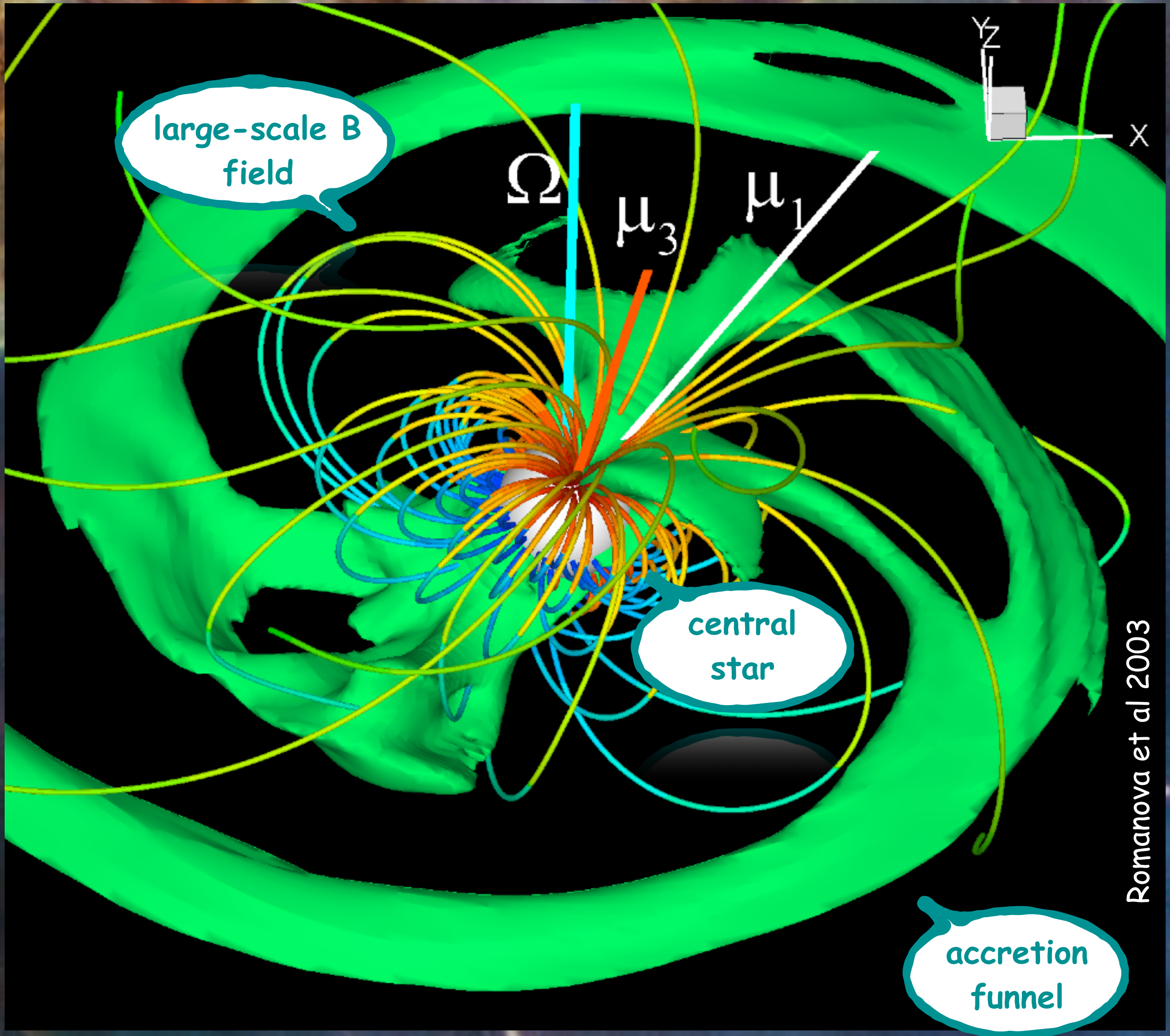
coupling w/ accretion disc > explain slow rotation of cTTSs ?

impact of magnetic fields on rotation & accretion history of PMS stars

impact of fields on discs & planet formation / migration

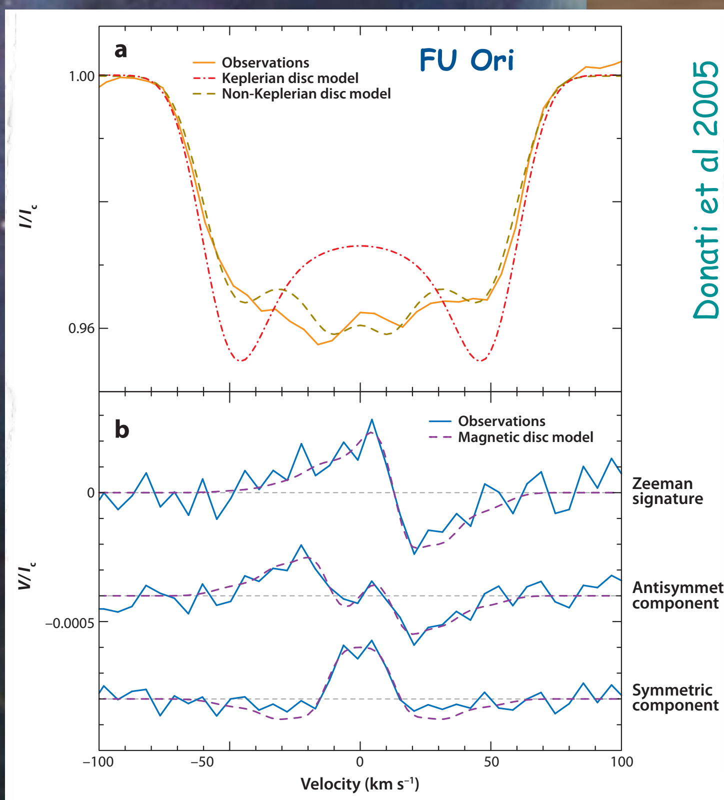
fields of young low-mass stars

3D MHD modeling of magnetospheric accretion

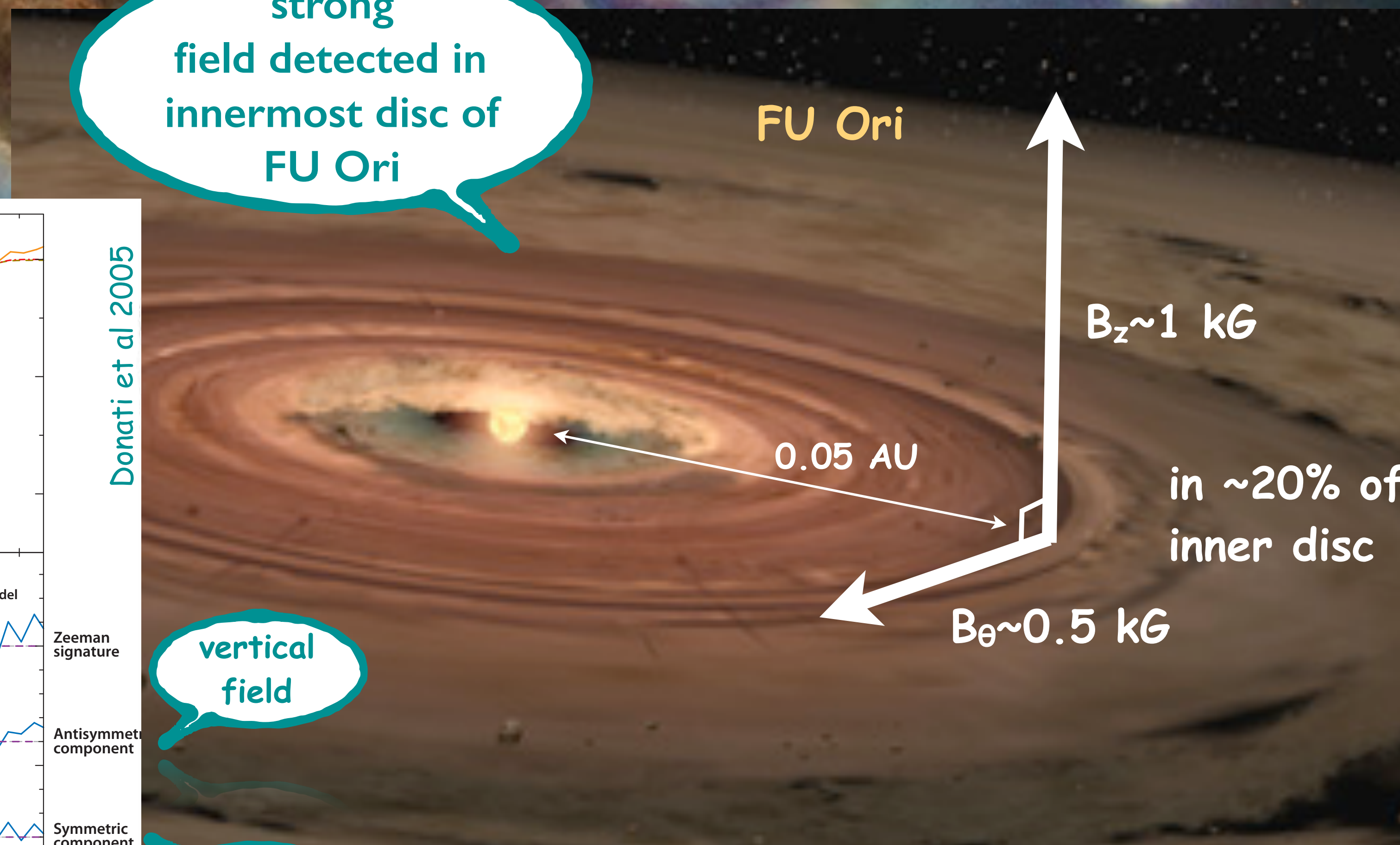


fields of young low-mass stars

magnetic fields of inner accretion discs



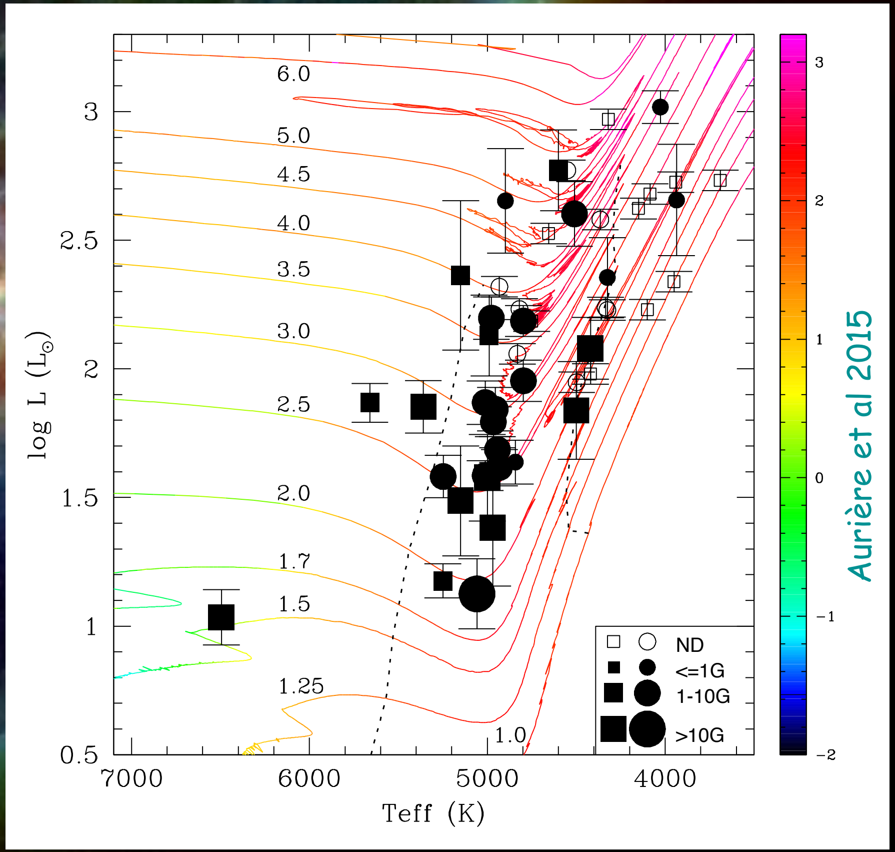
Donati et al 2005



fields of evolved giants

exploring the field of evolved giants

little known to date even on brightest stars, e.g. Arcturus
weak large-scale fields detected on a large fraction of the sample
often variable on short timescale > local dynamo

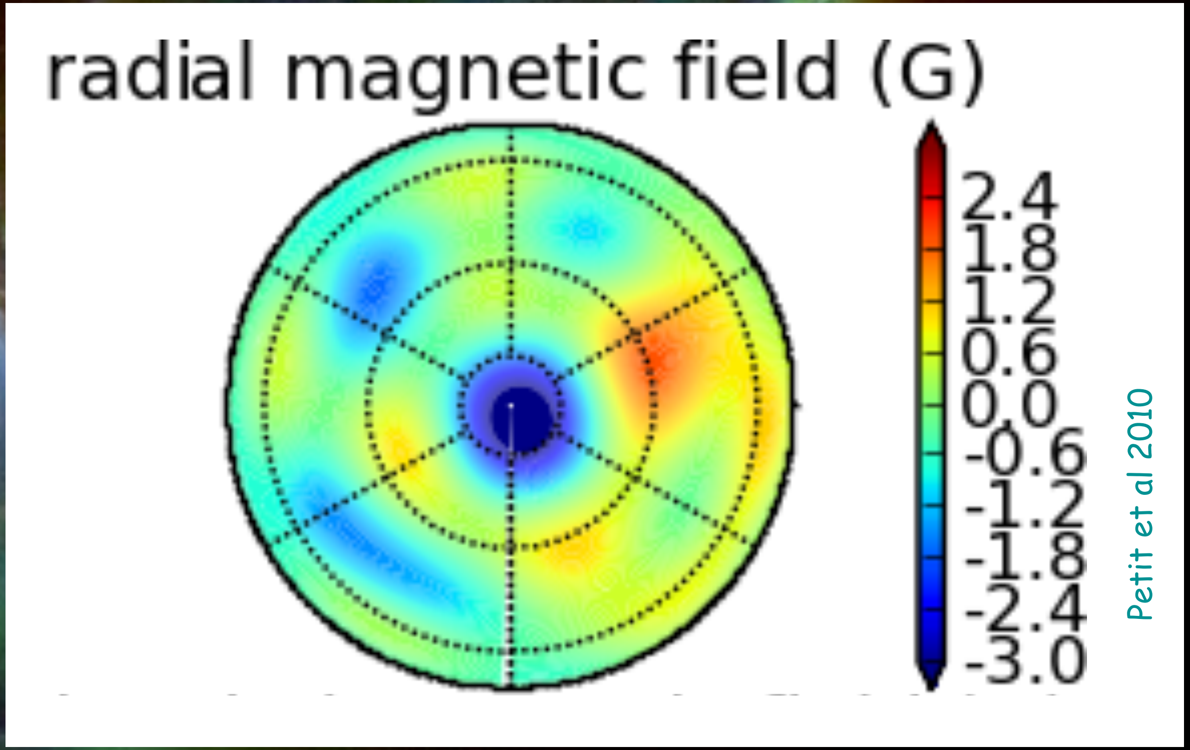


Aurière et al 2015

exotic fields of hot stars

exploring non-fossil fields of hot stars

5-10% of hot stars usually host simple large-scale fossil fields
are 'non-magnetic' hot stars truly non-magnetic?
weak fields detected on bright hot stars, e.g. Vega
exotic dynamos triggered by instabilities in radiative envelopes ?

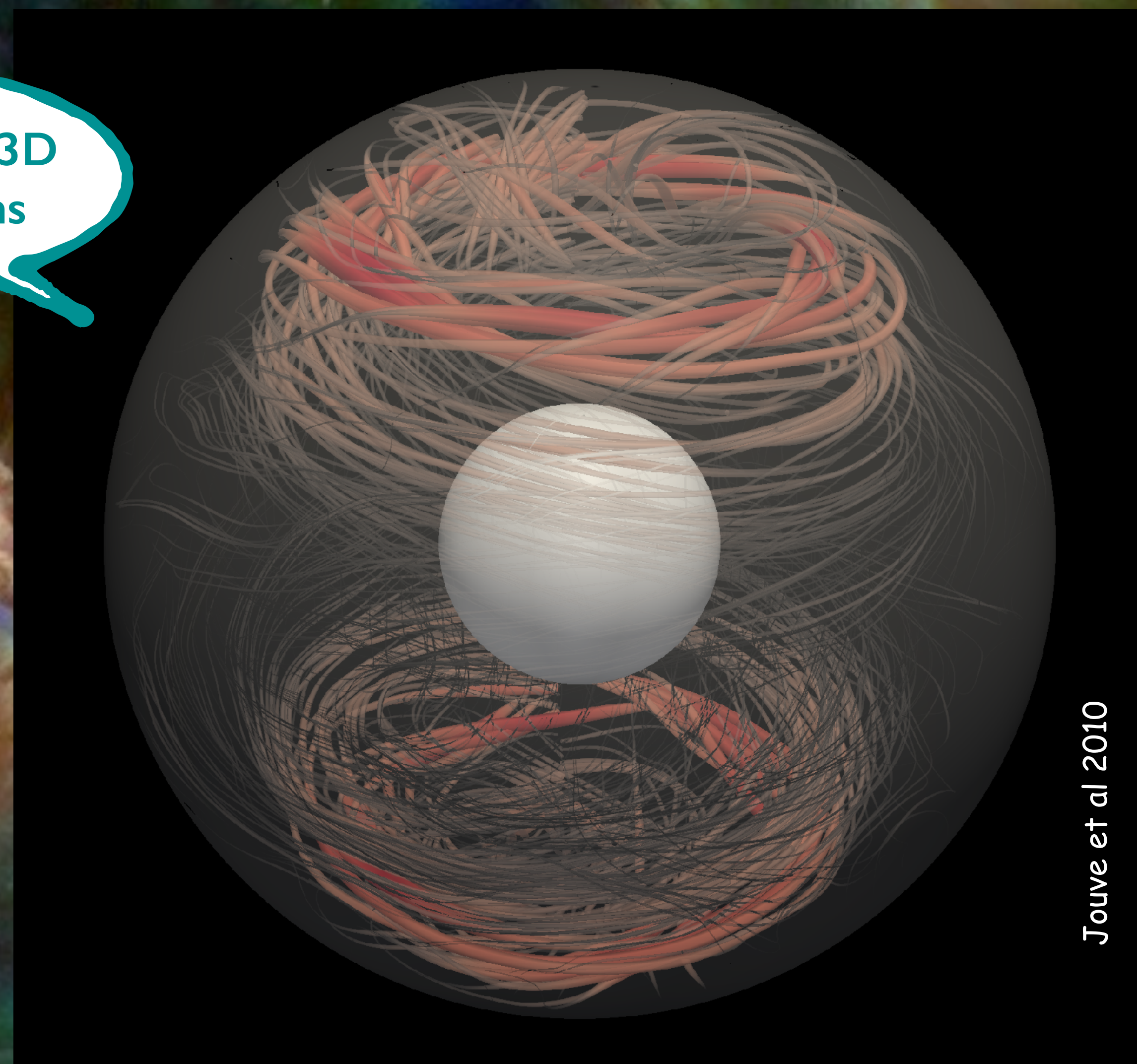


Petit et al 2010

exotic fields of hot stars

magnetic instabilities in radiative envelopes

ongoing work w/ 3D MHD simulations



future prospects

coordinated observations & simulations

worldwide programmes on dynamo fields various classes of stars
coordinated multi-wavelength campaigns (Xray, UV, nIR, radio)
> explore magnetic HR diagram & the many faces of dynamos
test theoretical predictions from numerical simulations
guide theory towards more realistic dynamo models

new instruments

SPIRou @ CFHT : nIR cryogenic spectropolarimeter (1-2.4 μm)
magnetic topologies of low-mass dwarfs & young Suns
> boost sensitivity to large- & small-scale fields
> planetary systems of nearby M dwarfs