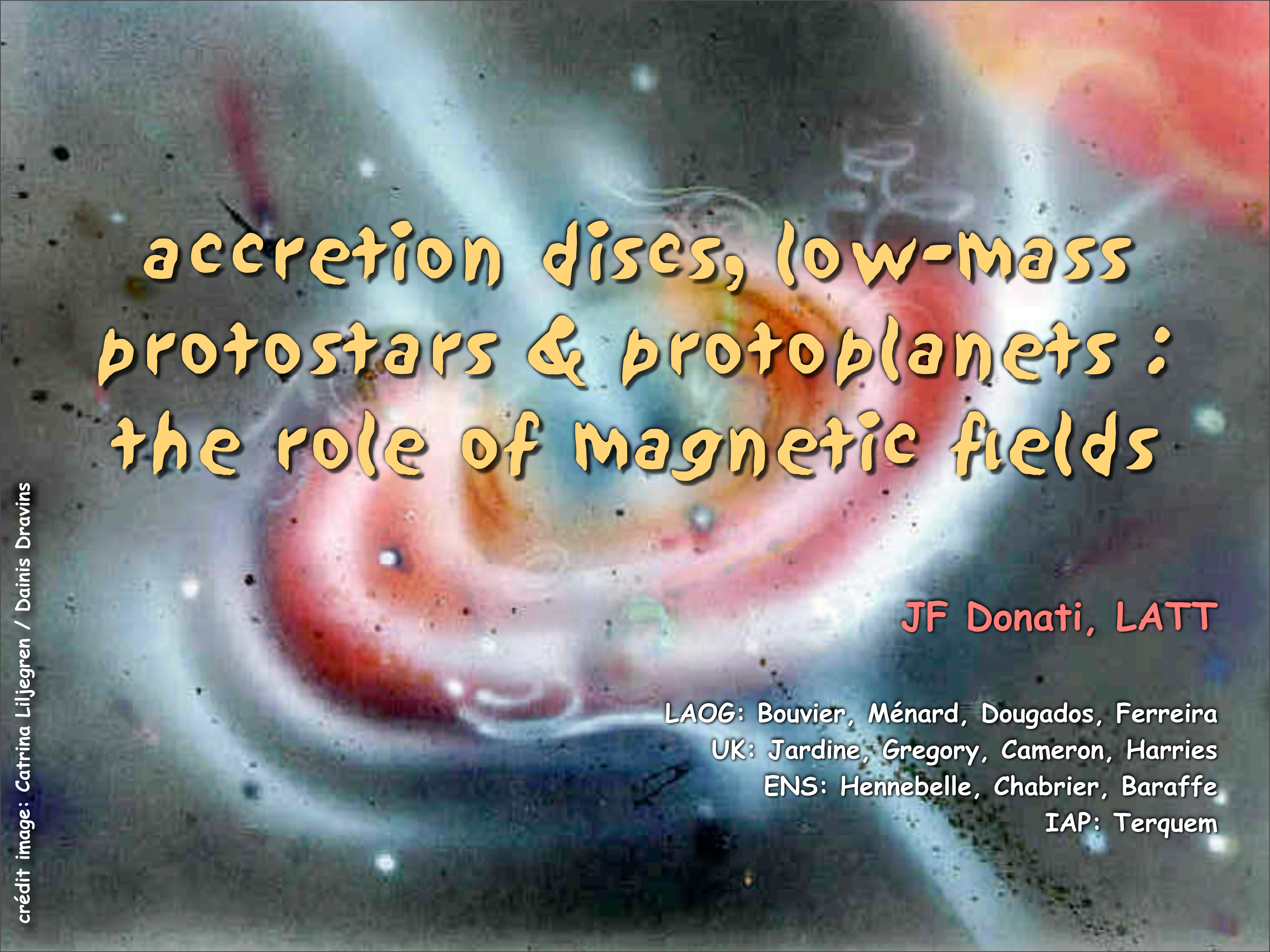

accretion discs, low-mass protostars & protoplanets : the role of magnetic fields

JF Donati, LATT

LAOG: Bouvier, Ménard, Dougados, Ferreira
UK: Jardine, Gregory, Cameron, Harries
ENS: Hennebelle, Chabrier, Baraffe
IAP: Terquem

crédit image: Catrina Liljegren / Dainis Dravins

background

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origin of the Sun & the solar system

Kant (1755) & Laplace (1799)
solar system formed from a rotating nebula
condensing into a central star & surrounding planets

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> magnetic turbulence (Shakura & Sunyaev 1973) & magnetorotational instability (eg Balbus & Hawley 1991)

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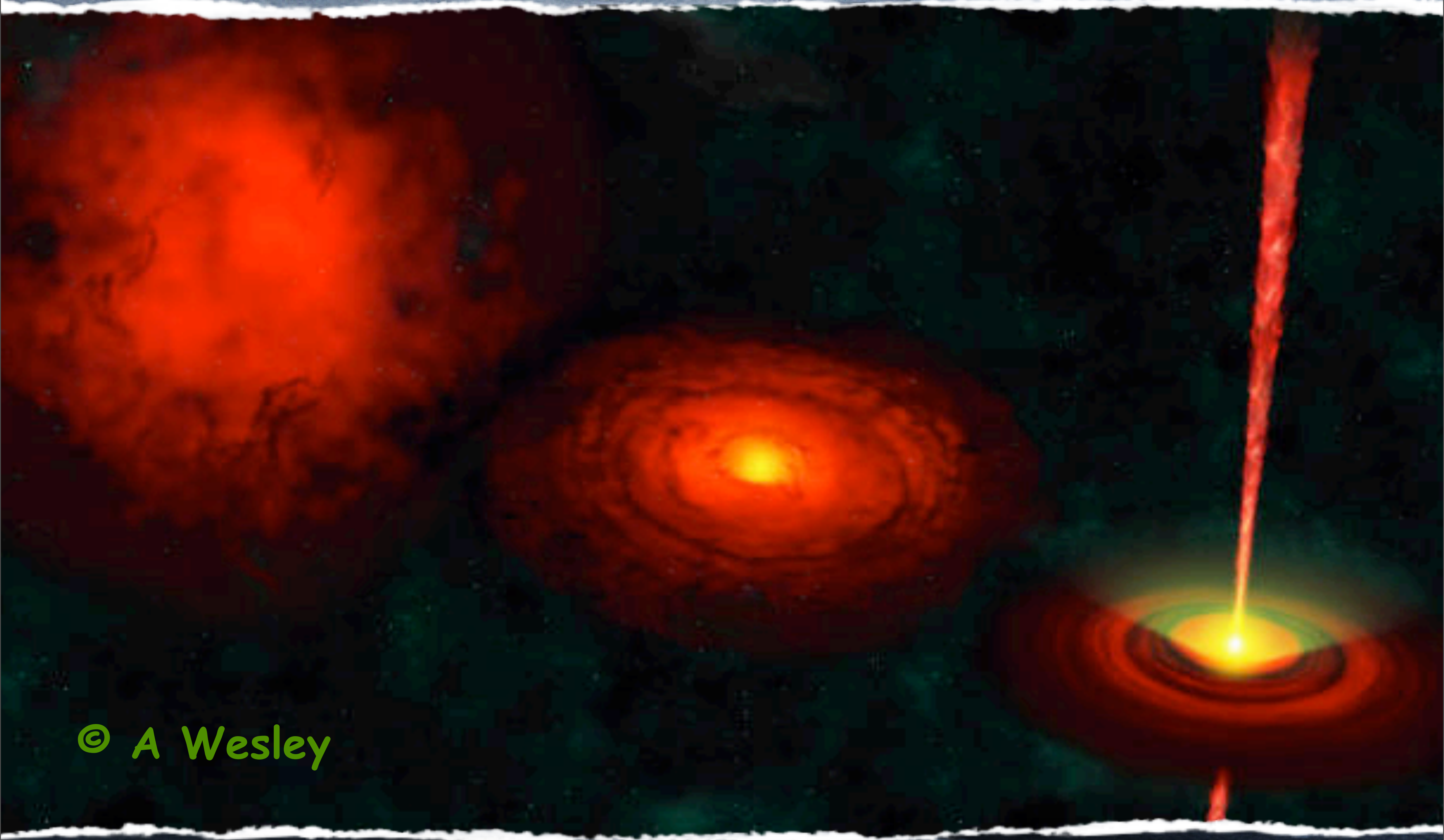

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evacuating the disc core & braking stellar rotating ?

SED fitting and HAR imaging show central hole in accretion disc
› disc core disrupted by magnetic field of protostar (eg Konigl 1991)

slow rotation of accreting protostars (cTTSs, eg Bertout 1989)
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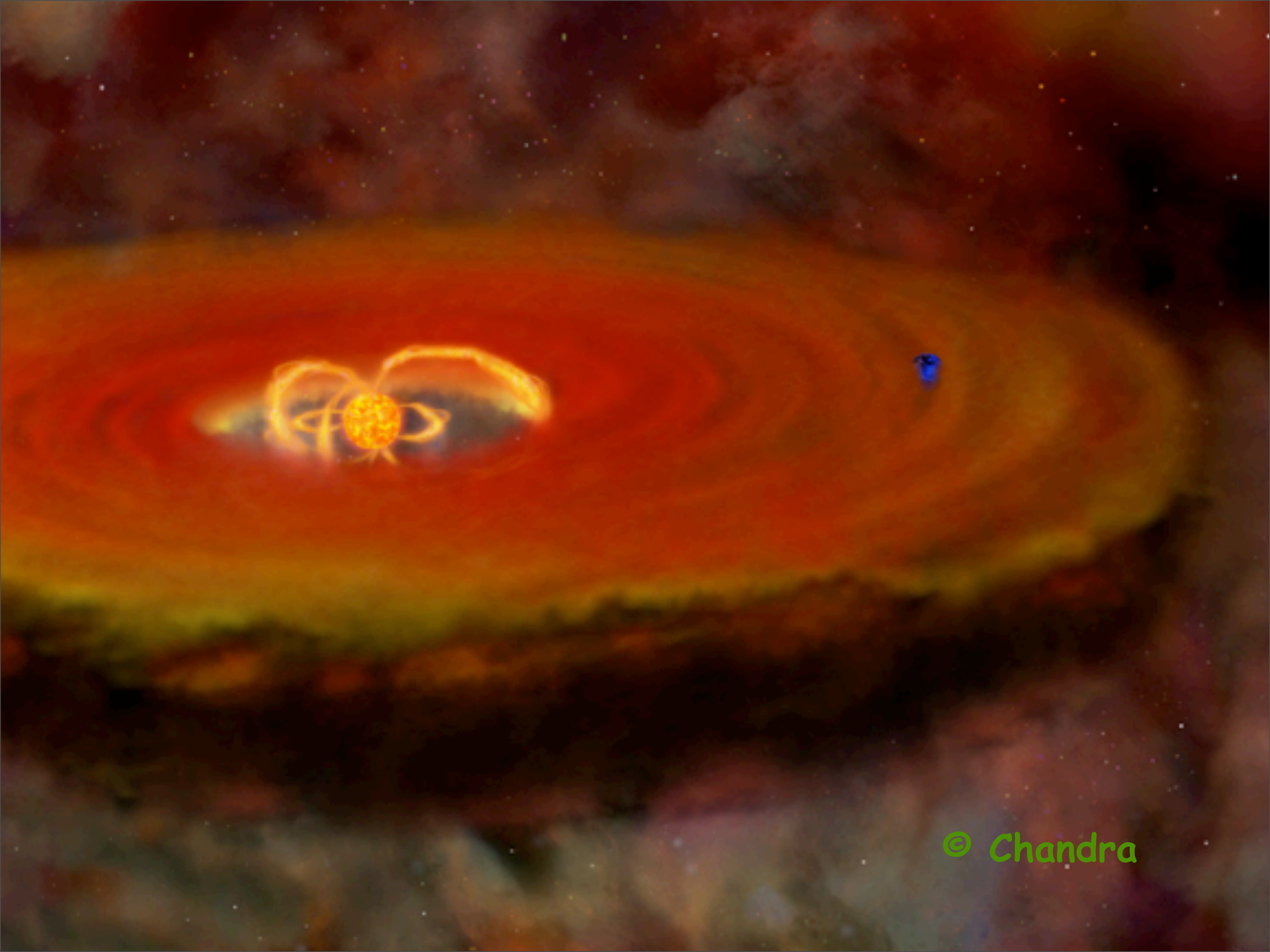
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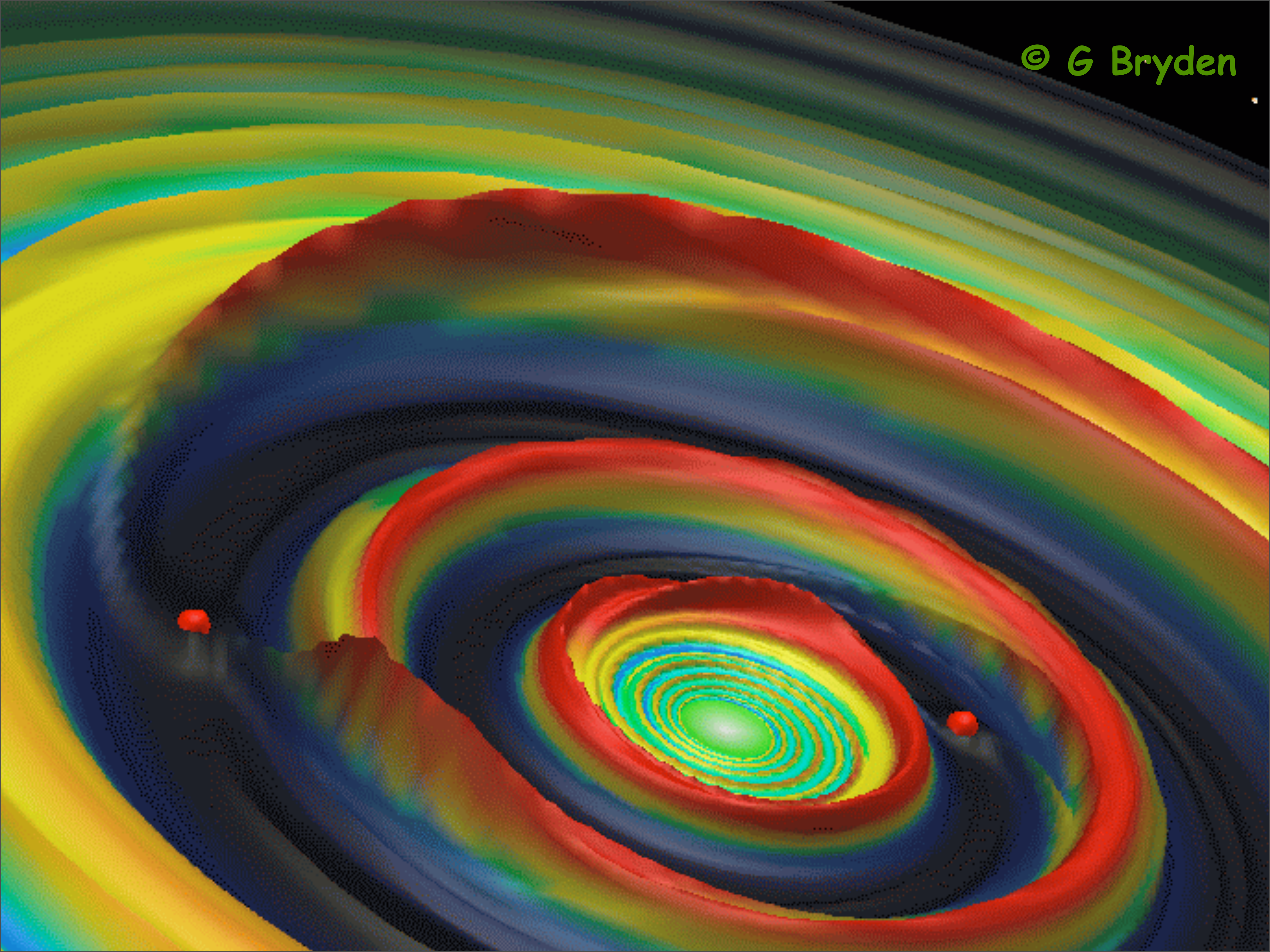
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magnetic disruption & coupling

magnetic torques build up from rotation shear (Ghosh & Lamb 1979)
> disrupt the inner disc & generate star/disc angular momentum transfer
> rotation rate of protostar forced into equilibrium state (fn of mass-accretion rate and large-scale field, eg Cameron & Campbell 1993)
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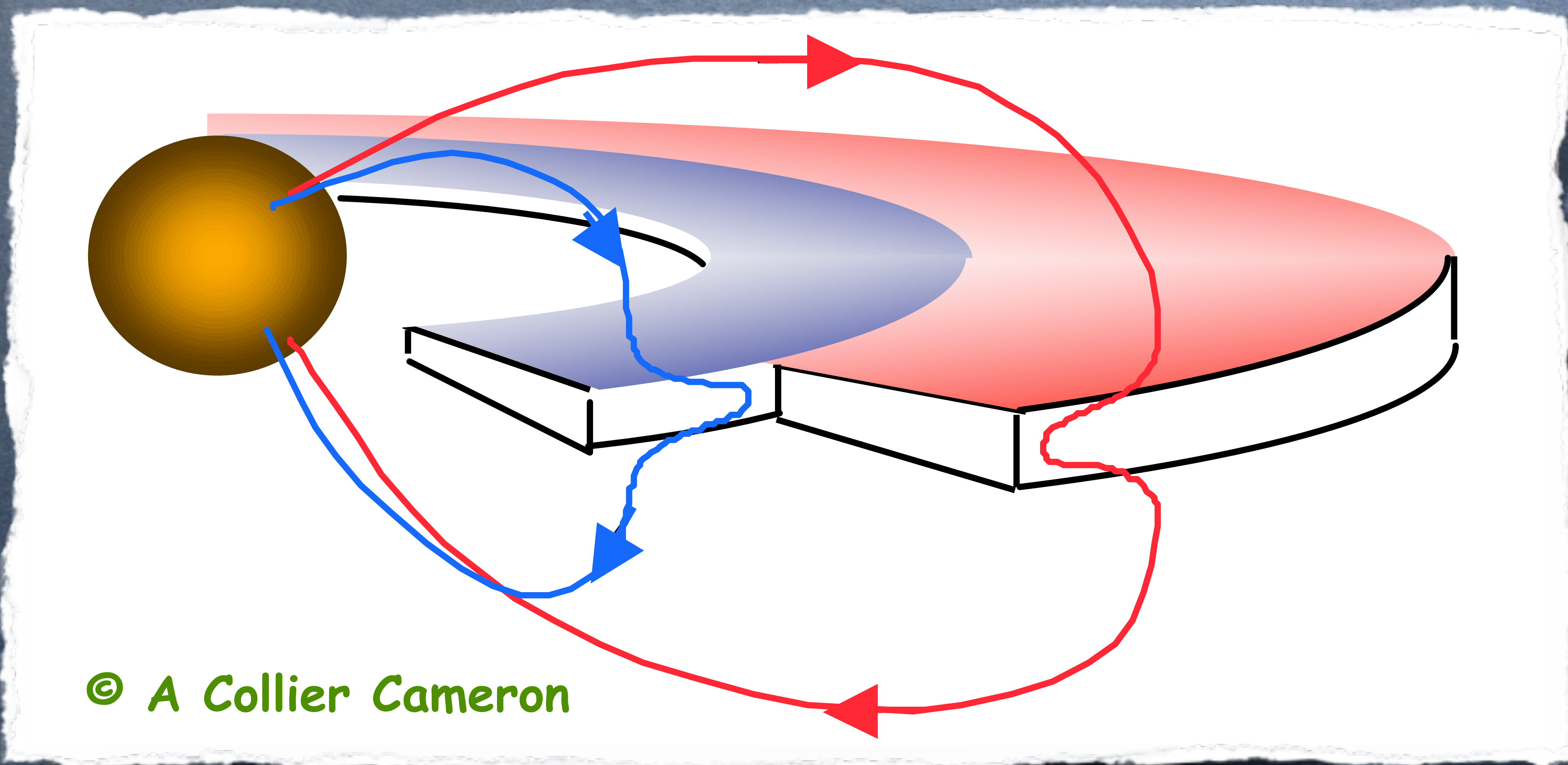

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wind/corona & field opening

wind from the star /disc opens field lines (eg Safier 1998)
> reduces coupling and spin-down torque
> cannot reproduce observed rotation of cTTSs (eg Matt & Pudritz 2004)

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3D MHD accretion models

disc material accreted through tilted magnetosphere

> complex stream-like accretion funnels linking star to inner disc

> polar hot spots at footpoints of accretion funnels for dipolar fields

(eg Romanova et al 2003, 2004; Long et al 2007)

angular momentum balance (including corona)

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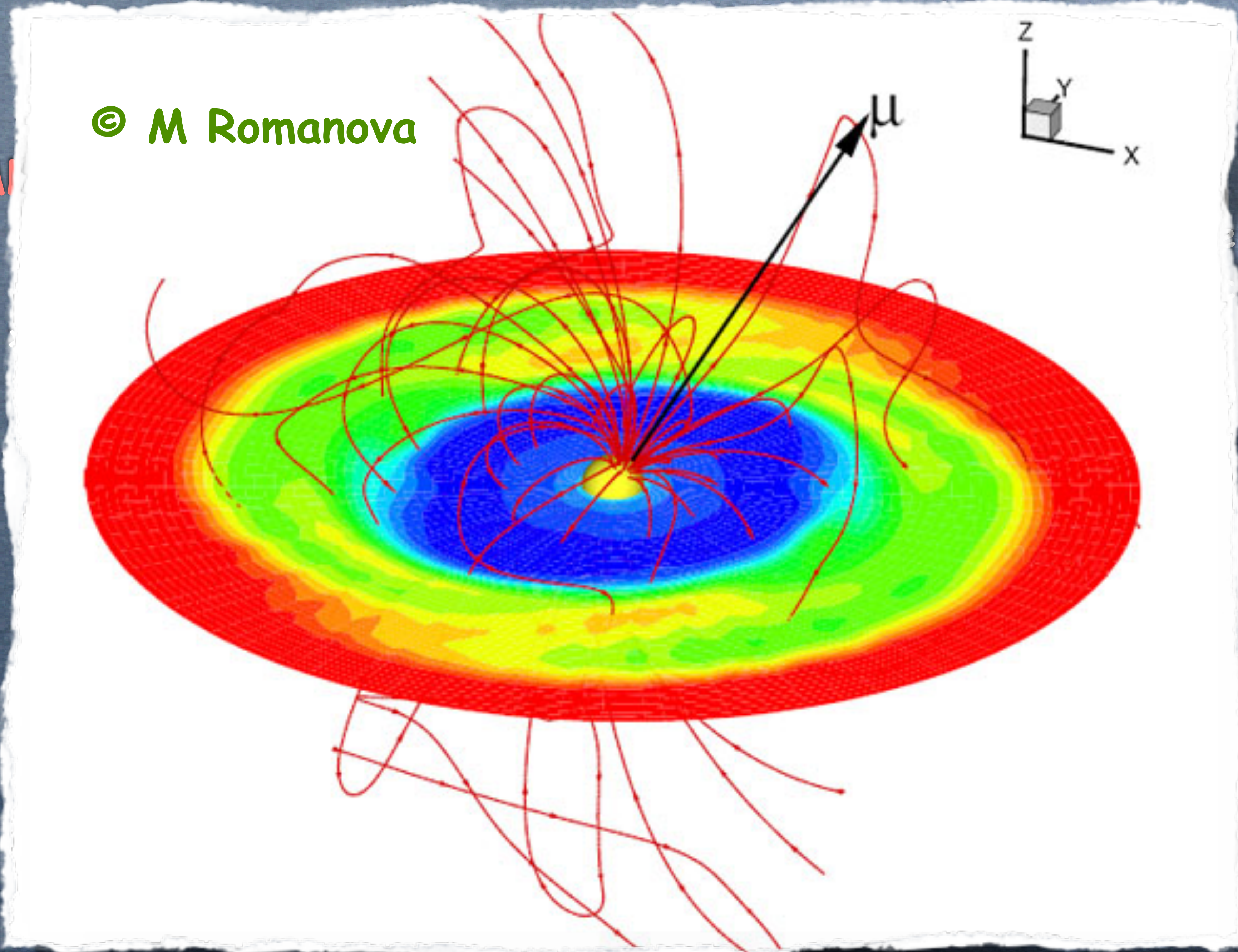

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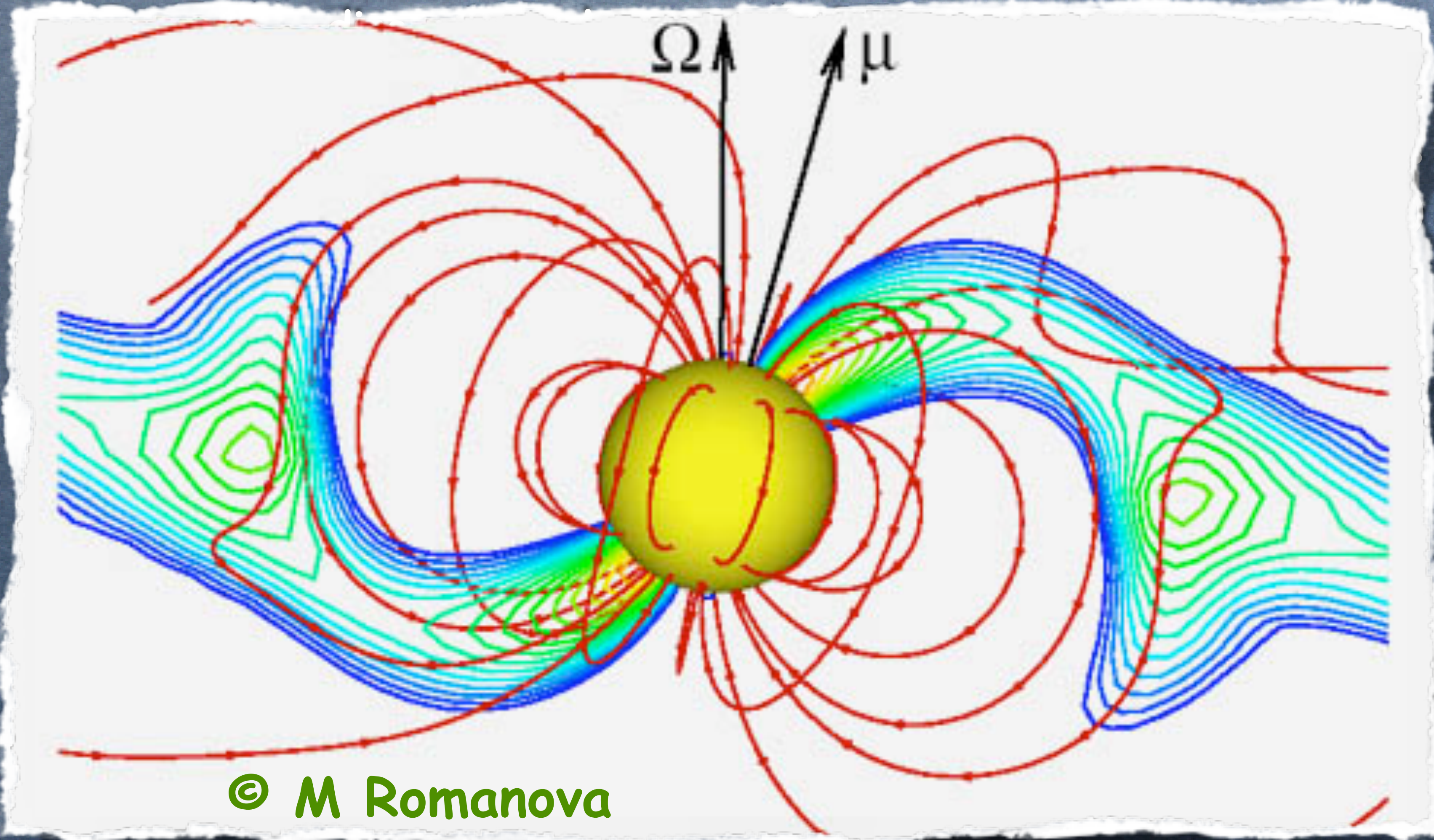

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2.5D models including disc field & wind

including disc dynamo & wind
> large fraction of disc material diverted into wind
> complex star/disc dynamo fields less efficient at slowing down cTTSs
(eg vonReckowski & Brandenburg 2004, 2006)

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Zeeman effect in stellar lines

B splits spectral lines in multiple subcomponents

splitting increases linearly with wavelength (wrt line Doppler width)

B produces circular & linear polarisation signatures in lines profiles

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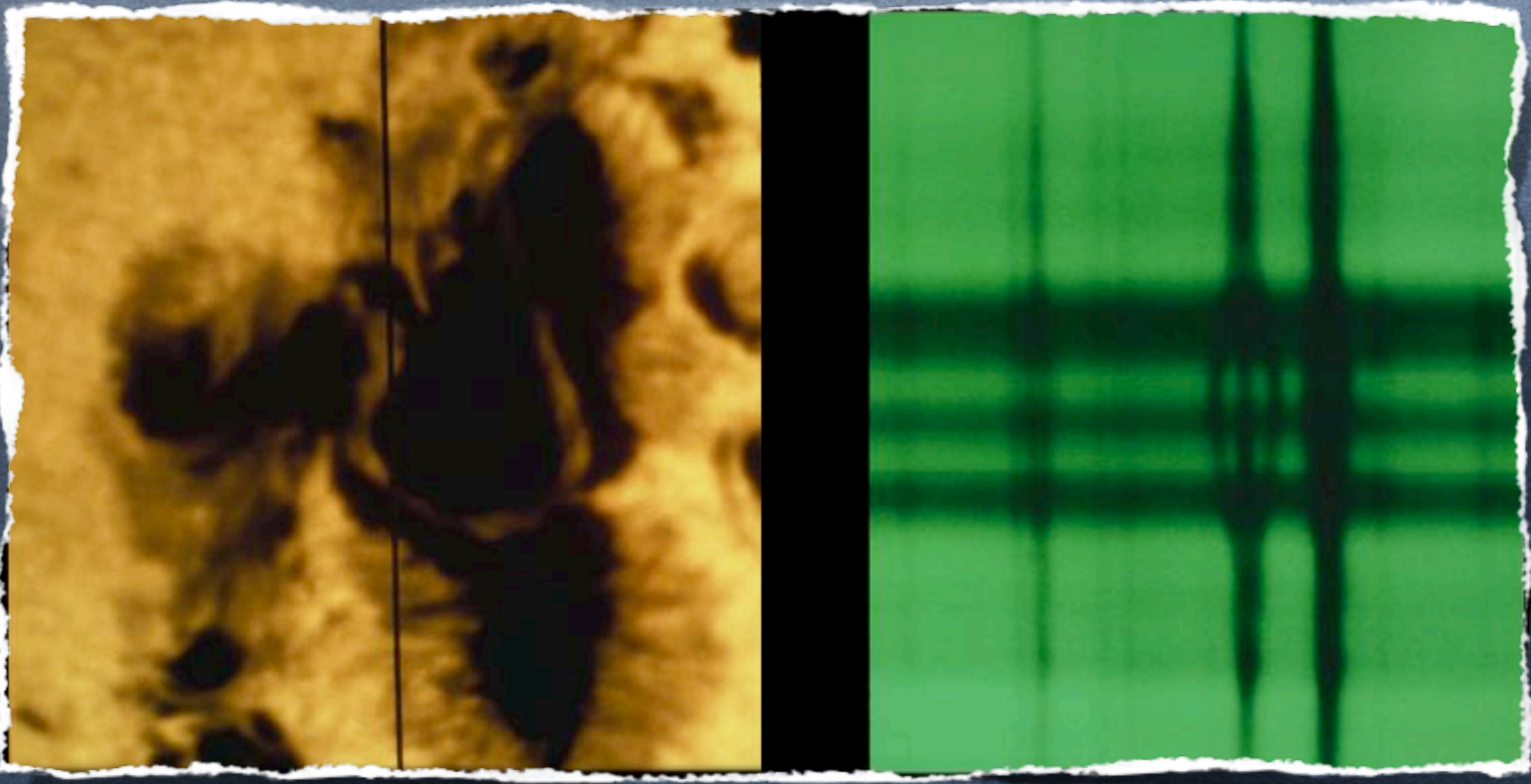

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unpolarised light

detect Zeeman broadening & desaturation
sensitive to average field strength (and filling factor)
> high resolution (nIR) spectroscopy (eg Phoenix/Gemini)

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> high resolution (nIR) spectroscopy (eg Phoenix/Gemini)

polarised light

detect circular (linear) polarisation Zeeman signatures
sensitive to longitudinal (transverse) magnetic field
> high resolution spectropolarimeters (eg ESPaDOnS/CFHT, NARVAL/TBL)

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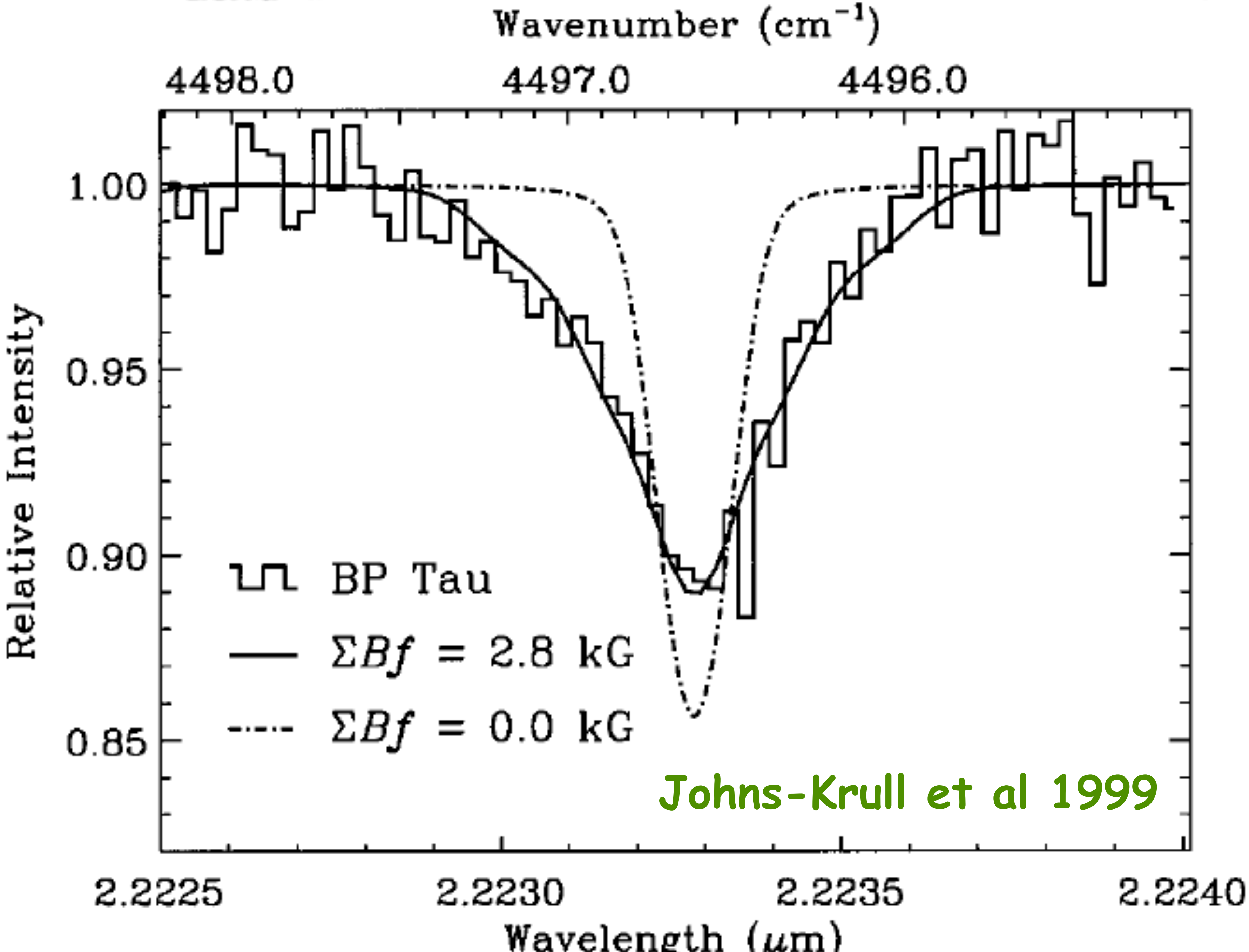
magnetic broadening

in photospheric absorption lines (eg nIR)
> average magnetic flux of several kG
eg: 2.8 kG on BP Tau (Johns-Krull et al 1999)
magnetic flux x2 stronger in the nIR than in the optical
> strong magnetic fields concentrating in dark spots

field detected in ~15 cTTS (mostly in Taurus)



Wavenumber (cm^{-1})
4498.0
4497.0
4496.0
1.00
0.95
0.90
0.85
Relative Intensity
BP Tau
ΣBf = 2.8 kG
ΣBf = 0.0 kG
Johns-Krull et al 1999
2.2225
2.2230
2.2235
2.2240
Wavelength (μm)

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field detected in ~15 cTTS (mostly in Taurus)

pros & cons

pros: no signal cancellation from opposite polarities
> estimates average field strength and rough surface coverage

cons: very little sensitivity to field orientation
only possible for slow rotators (vsini < 10 km/s)
> no constraint on field topology

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magnetic strengths of cTTSs

magnetic fluxes ranging from 1 to 3 kG (Johns-Krull 2007)

significantly larger than equipartition fields

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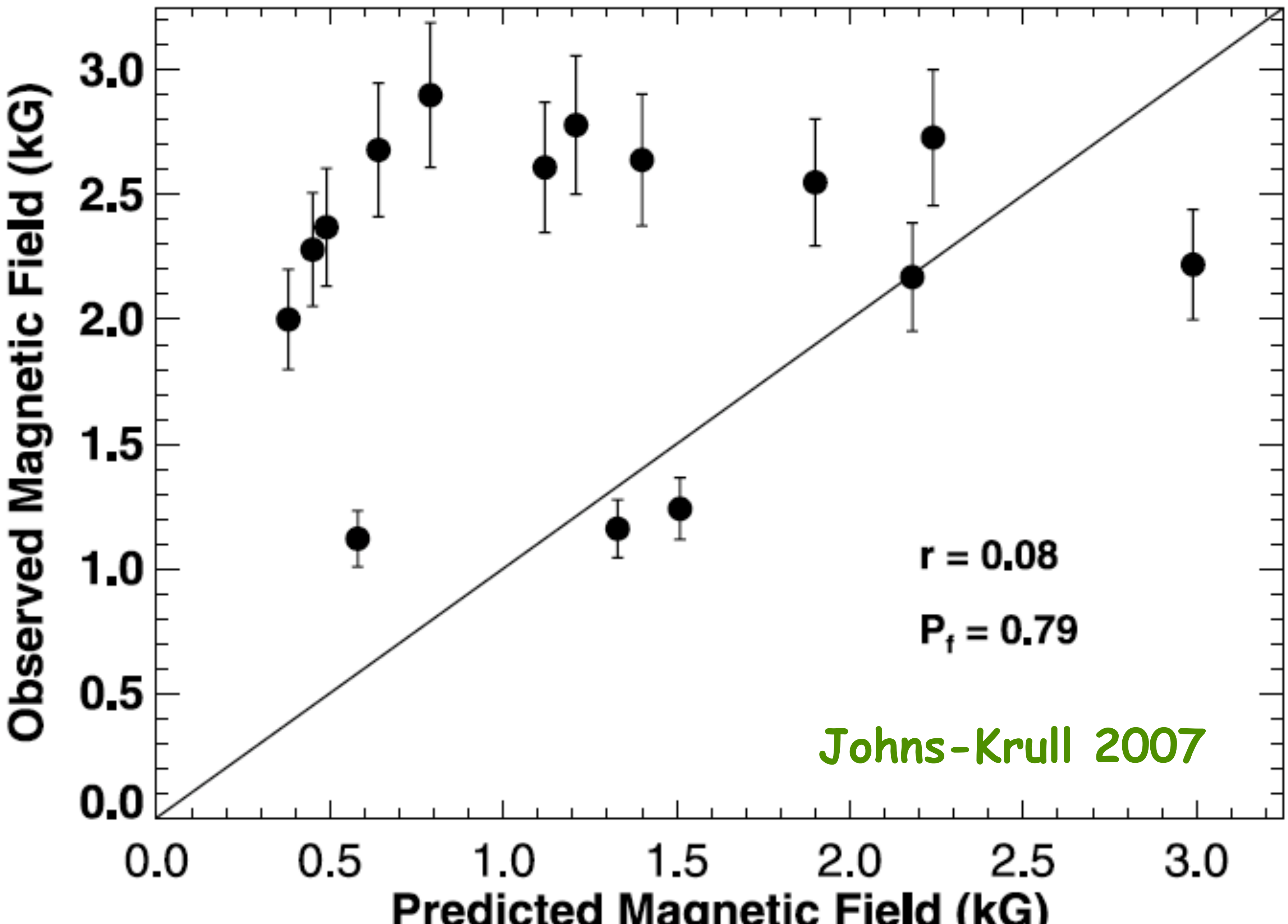
validity of disc-locking ?

no correlation between magnetic flux and disc-locking field


Observed Magnetic Field (kG)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Predicted Magnetic Field (kG)
r = 0.08
P$_f$ = 0.79
Johns-Krull 2007

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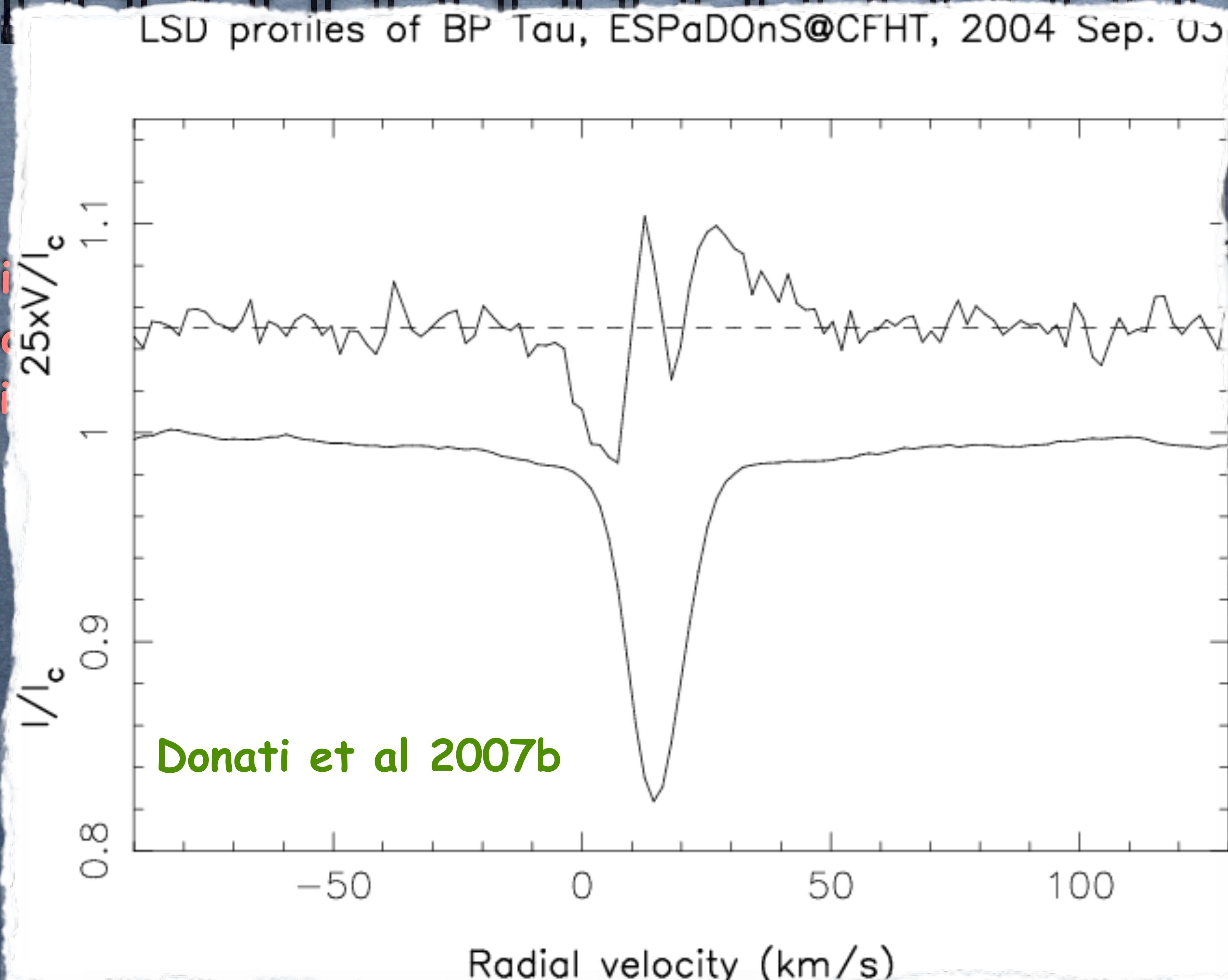
circular polarisation signatures

in emission lines tracing accretion (eg He I D3, Ca II IRT)
> tracing monopolar longitudinal fields of several kG
eg: 3 kG on BP Tau in He I D3 (Johns-Krull et al 1999)

in photospheric absorption lines (eg LSD profiles)
> tracing more complex longitudinal fields of a few 100 G
eg: ~500 G on BP Tau (Donati et al 2007)

longitudinal fields detected in ~10 cTTSs



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pros & cons

pros: sensitive to vector field properties
> map large-scale magnetic topology (using tomographic imaging)

cons: cancellation from nearby opposite polarities
> insensitive to small-scale bipolar groups

accreting protostars

accreting protostars

use spectropolarimetric series...

rotational modulation of Zeeman signature (Doppler effect)

> recover spot location and field orientation

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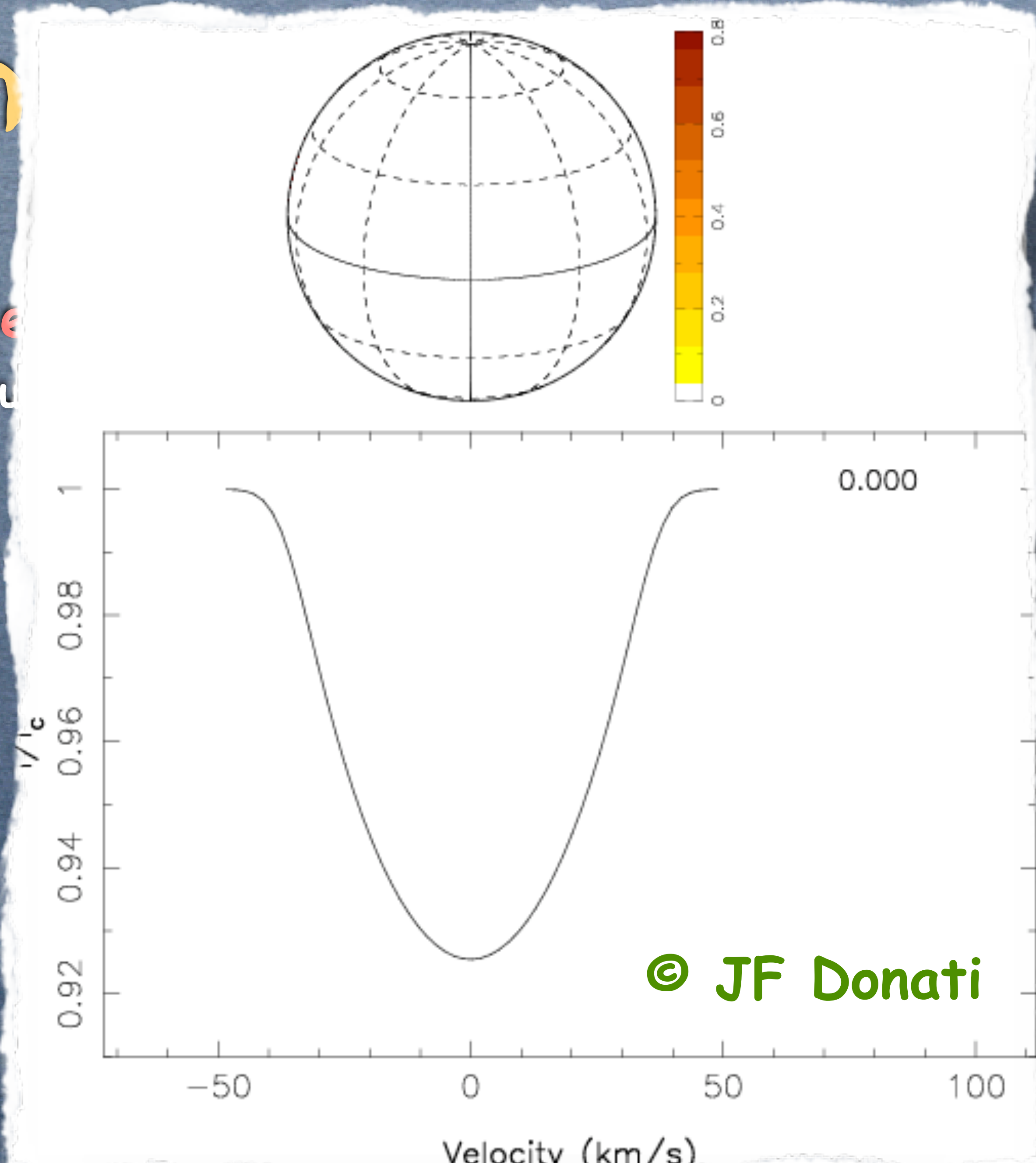
rotational modu



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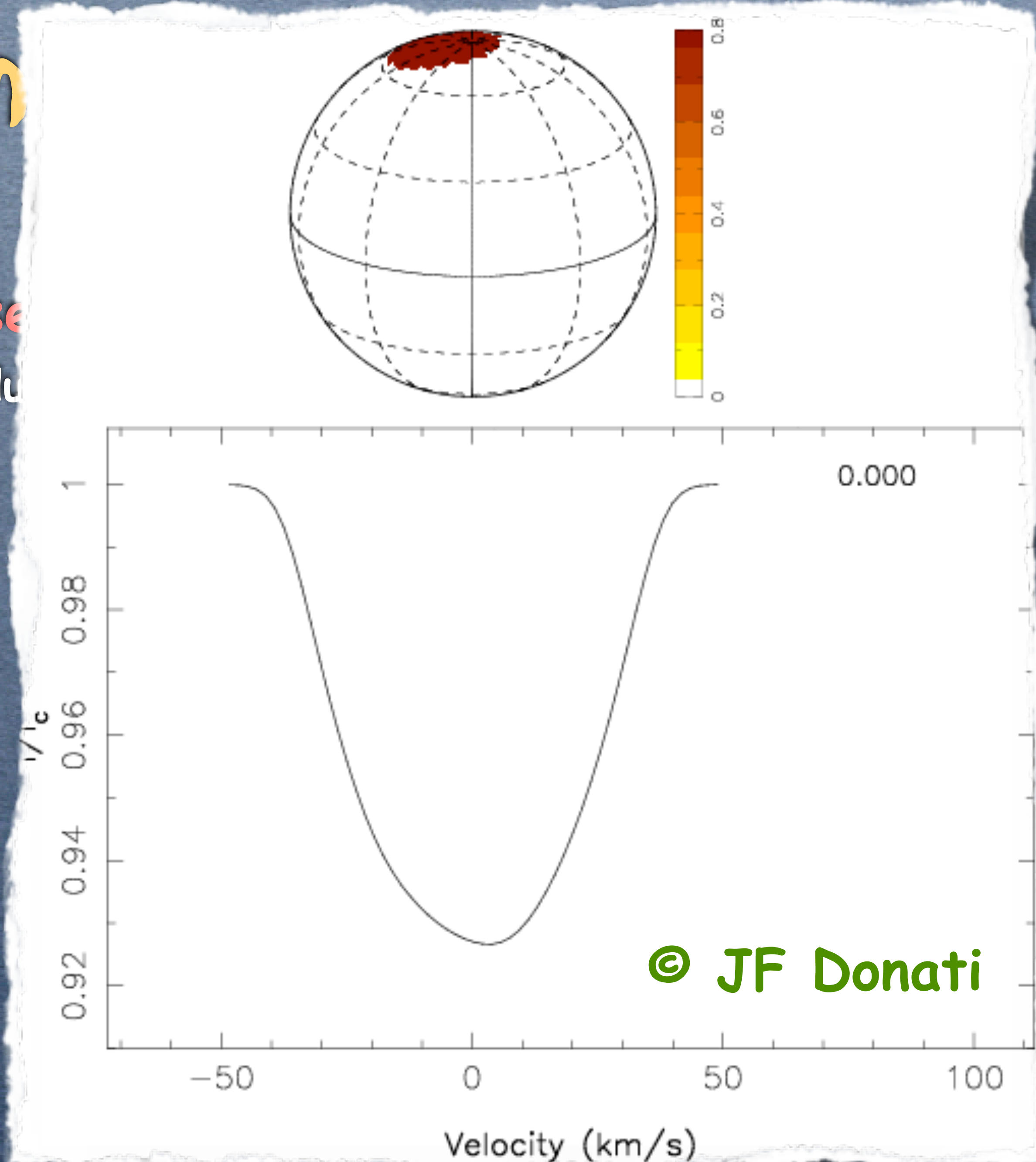

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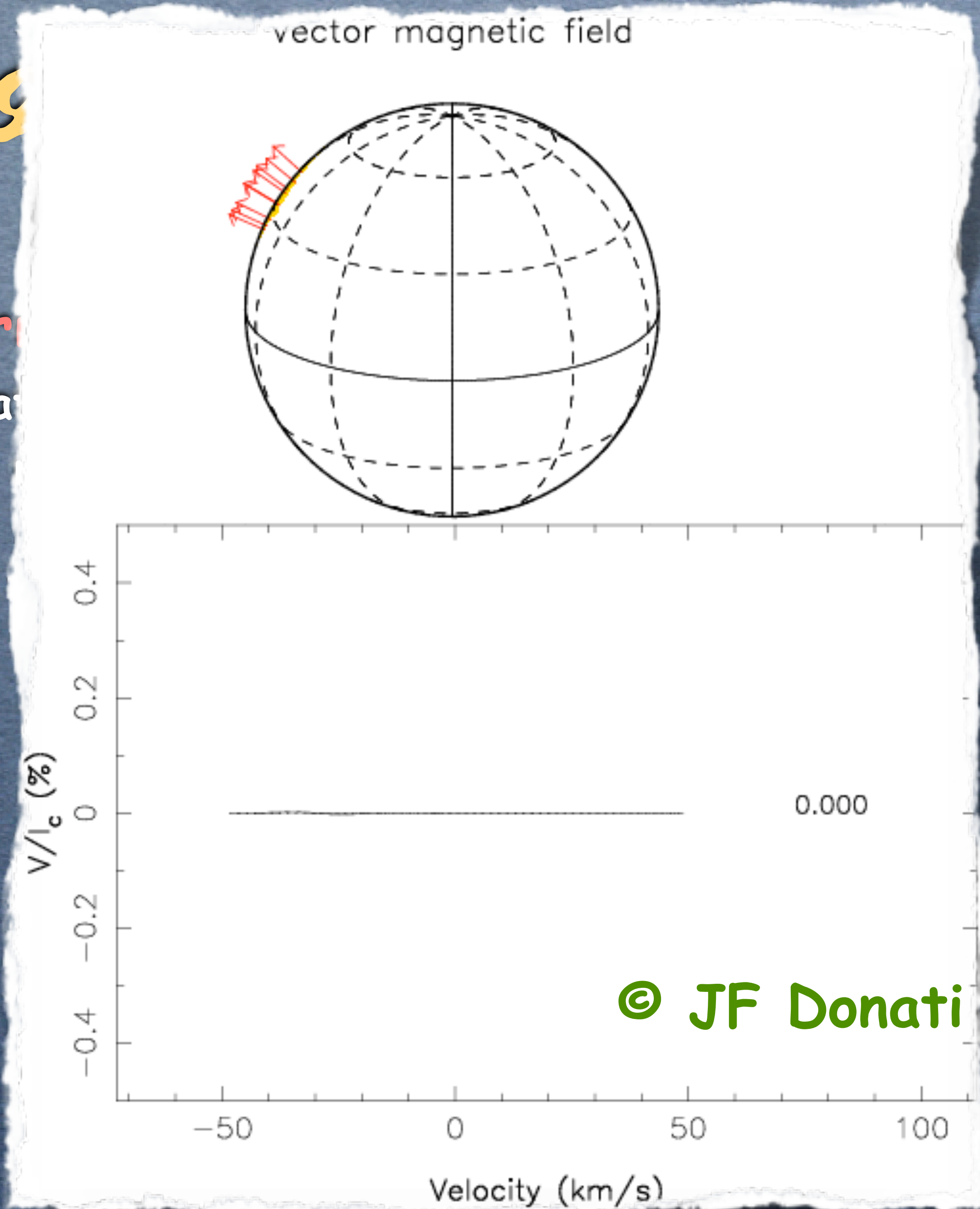

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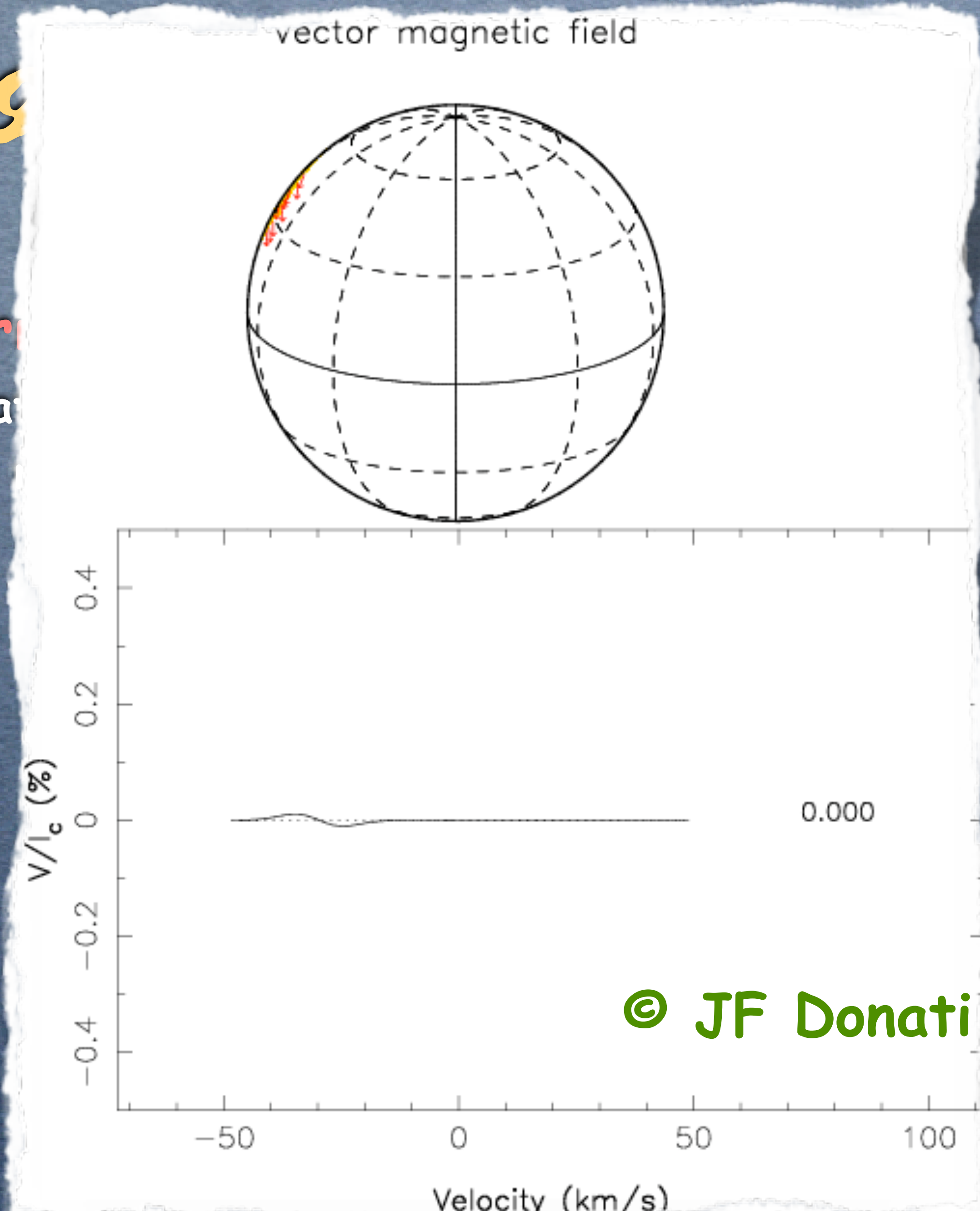

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...to reconstruct surface magnetic topology...

use spherical harmonics decomposition and tomographic imaging

> infer magnetic topology (poloidal/toroidal components)

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> recover spot location and field orientation

...to reconstruct surface magnetic topology...

use spherical harmonics decomposition and tomographic imaging

> infer magnetic topology (poloidal/toroidal components)

...and extrapolate it outwards

assume potential field topology

> get 3D image of stellar magnetosphere

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Zeeman signatures

different Zeeman signatures in LSD profiles & emission lines

(i) assume accretion spot contributing to emission lines only

(ii) assume surrounding photosphere contributes to LSD profiles only

> fit Stokes I & V LSD and Ca II IRT profiles simultaneously

> derive maps of magnetic field & accretion spots

accretin

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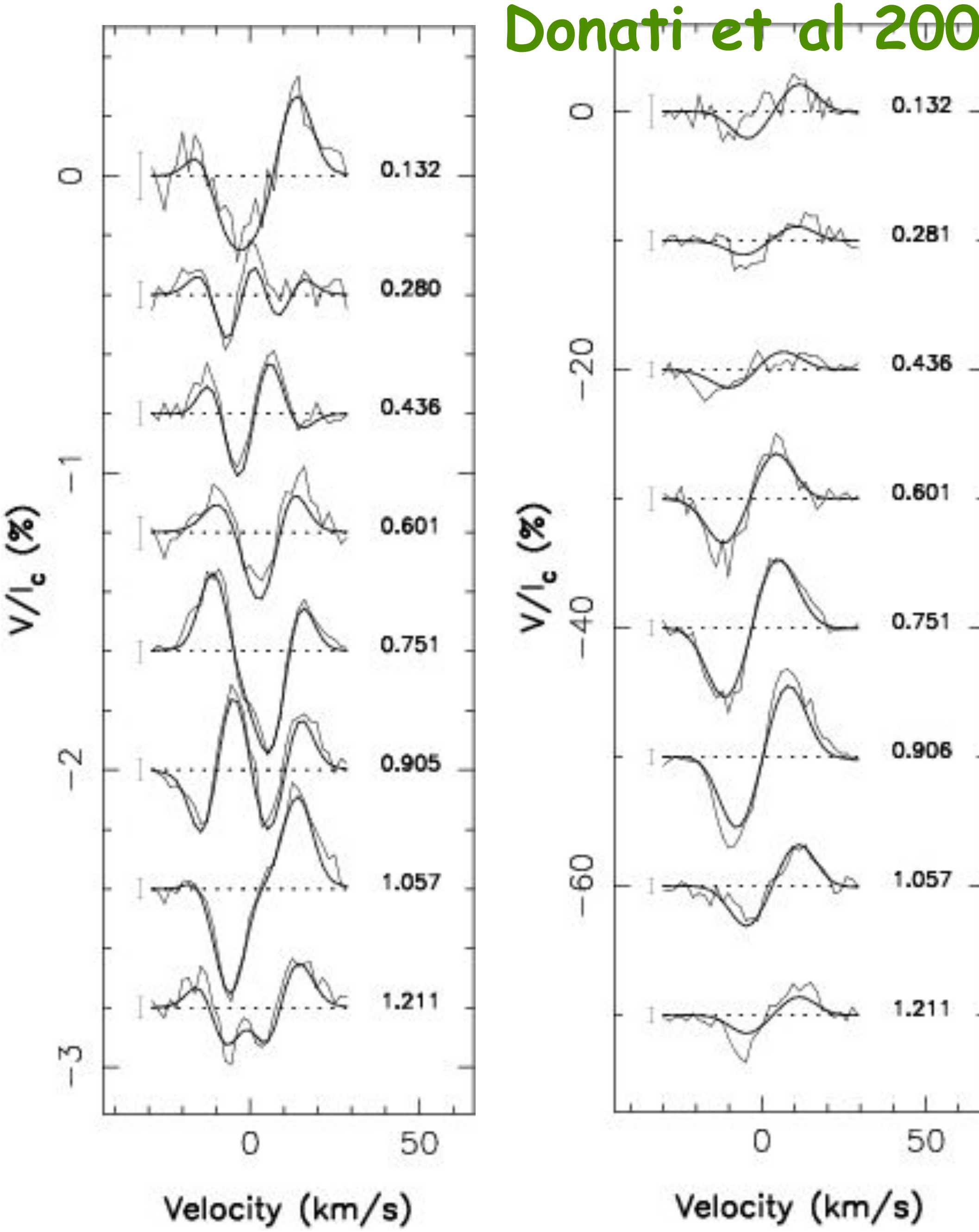
V2129 Oph, 2005 June

Donati et al 2007a



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magnetic field and accretion spots

accretion spot located close to the pole

kG radial field in the accretion spot

small toroidal field (10-20% of magnetic energy)

large scale poloidal field includes dipole+octupole components

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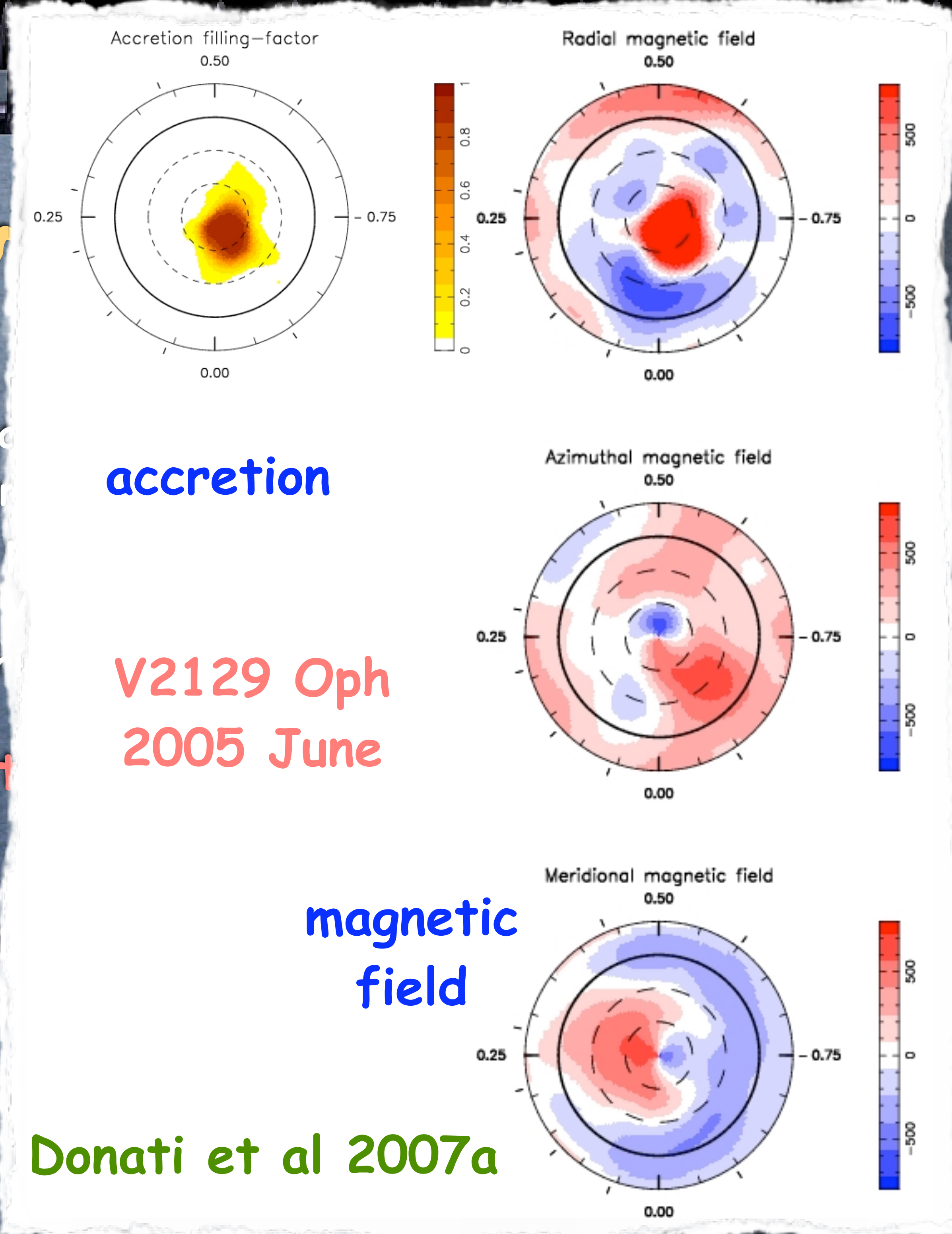

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coronal structure

work by M Jardine & S Gregory @ StAndrews

extrapolate surface field assuming no current (potential)

complex field lines close to the surface

simple large loops further away

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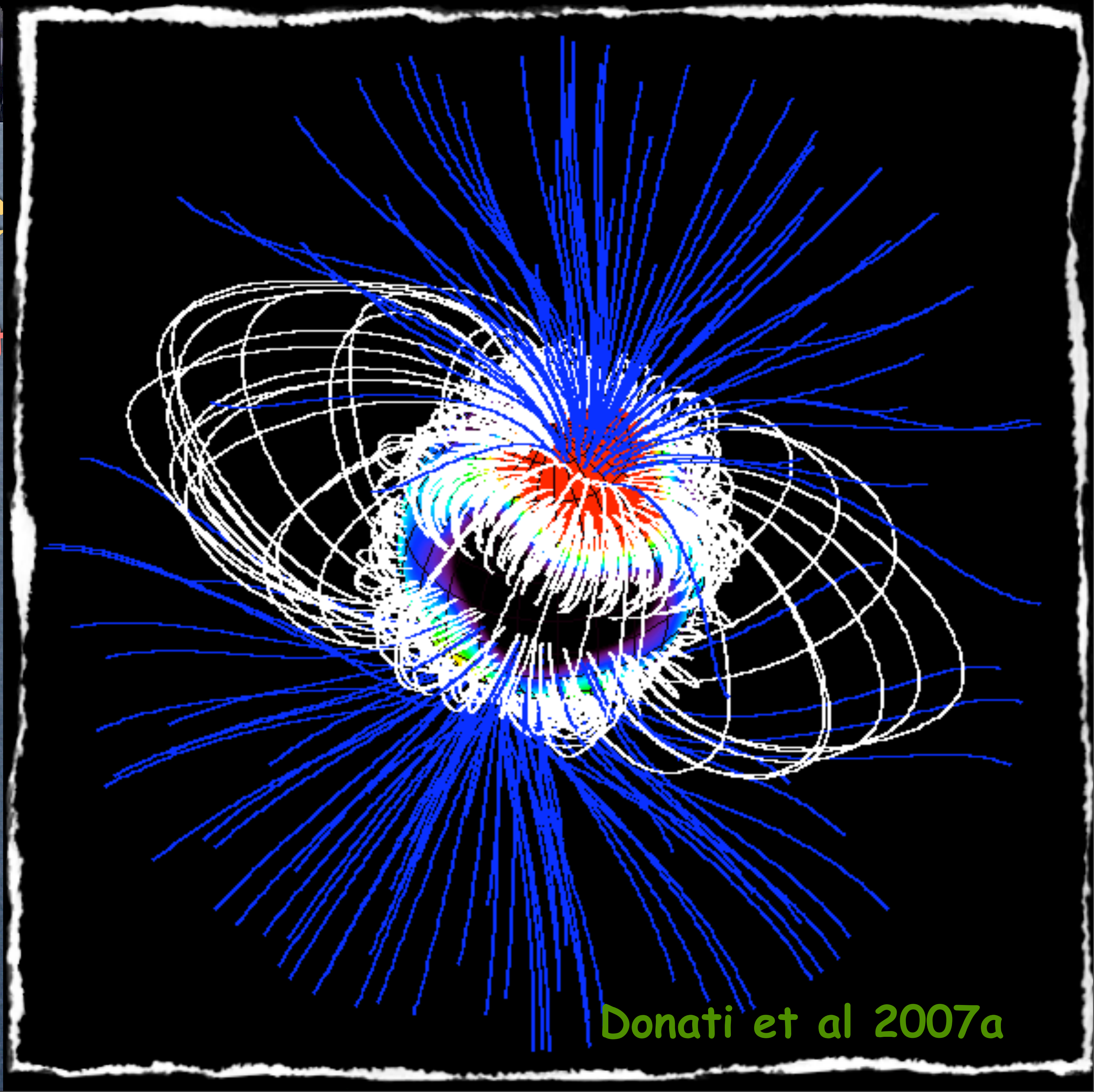

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geometry of accretion funnels

compute location of accreting field lines for various r_A

select value of r_A producing accretion spots matching observations

> V2129 Oph : $r_A \approx 7\ R_*$ ($\approx r_C$)

> BP Tau : $r_A \geq 5\ R_*$ ($r_C \approx 7.5\ R_*$)

> disc magnetically warped in BP Tau ?

disc-locking scenario ?

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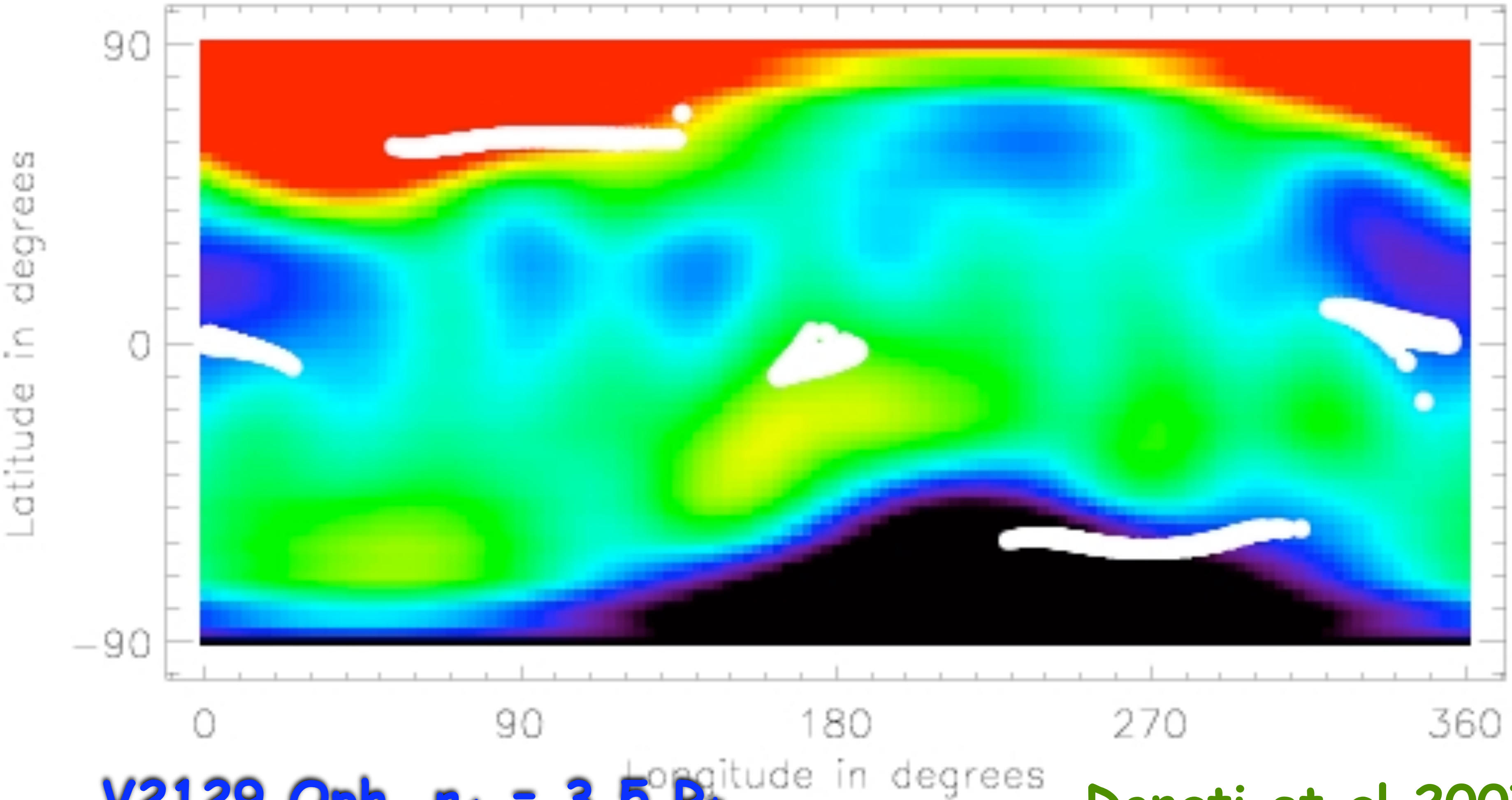

V2129 Oph, r_A = 3.5 R_*

Donati et al 2007a

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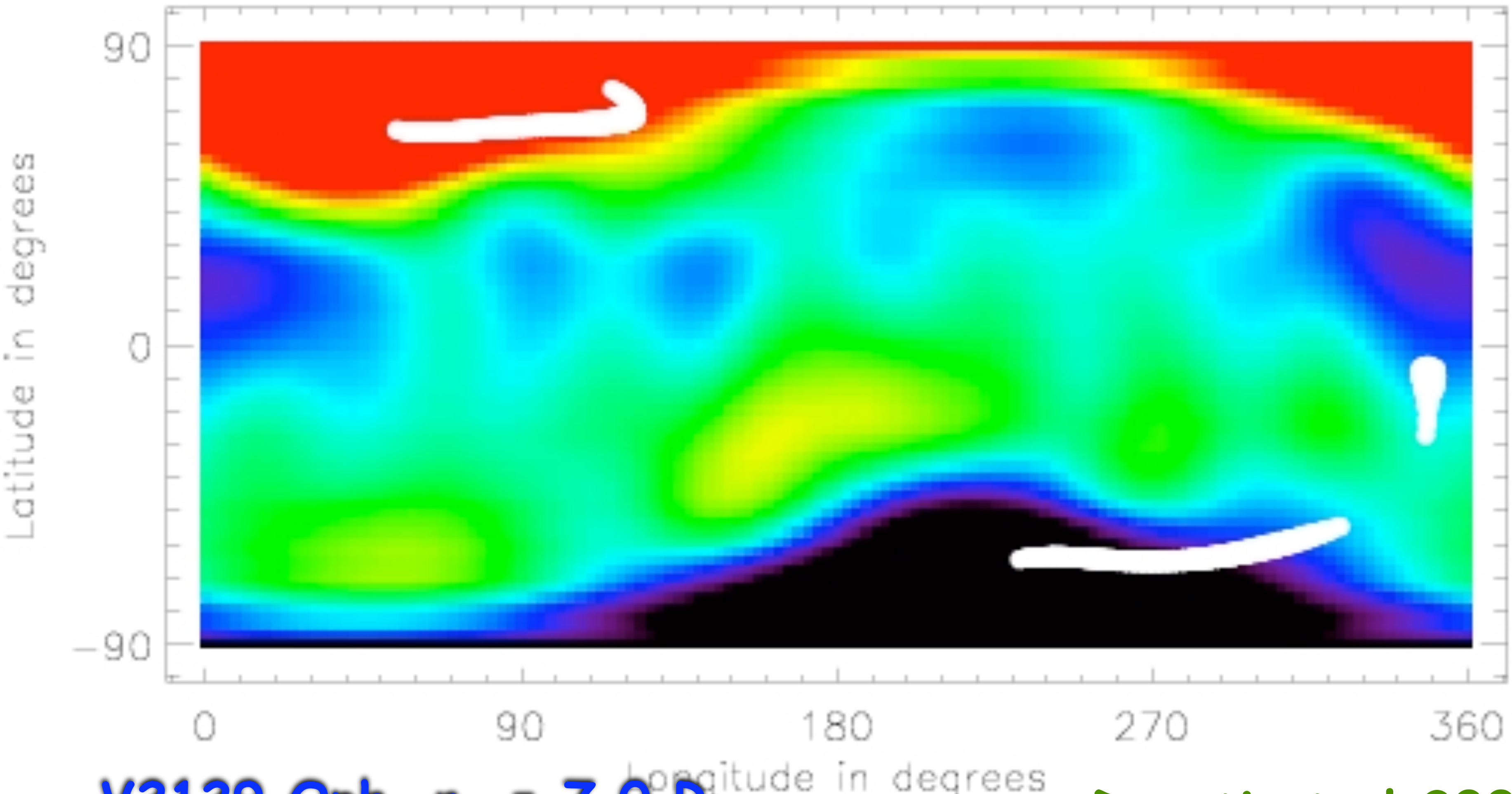

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indirect indicators : photopolarimetric rotational modulation

AA Tau: prototype cTTS viewed ~equator on

modelling photopolarimetric rotational modulation

> quasi-periodic occultations by warped disc with inner edge at 8-9 R_* (Bouvier et al 1999, 2007; Ménard et al 2003)

> non stationary magnetospheric accretion (Bouvier et al 2003, 2007)

> 5.2 kG dipole tilted by 30° to explain warp (O'Sullivan et al 2005)

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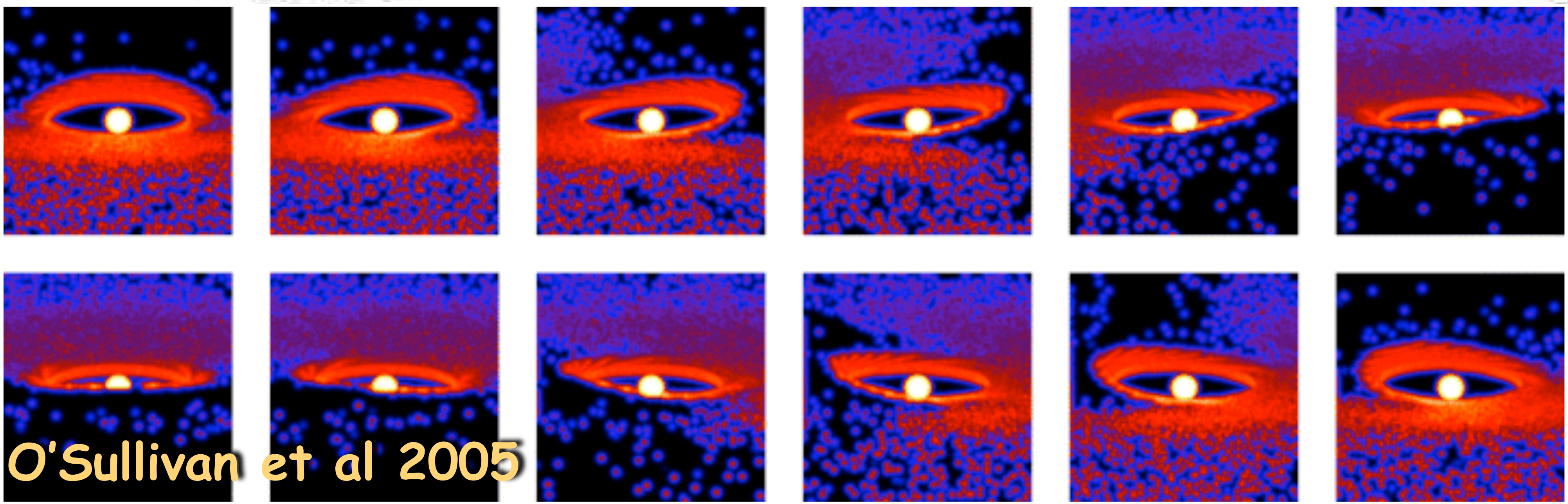

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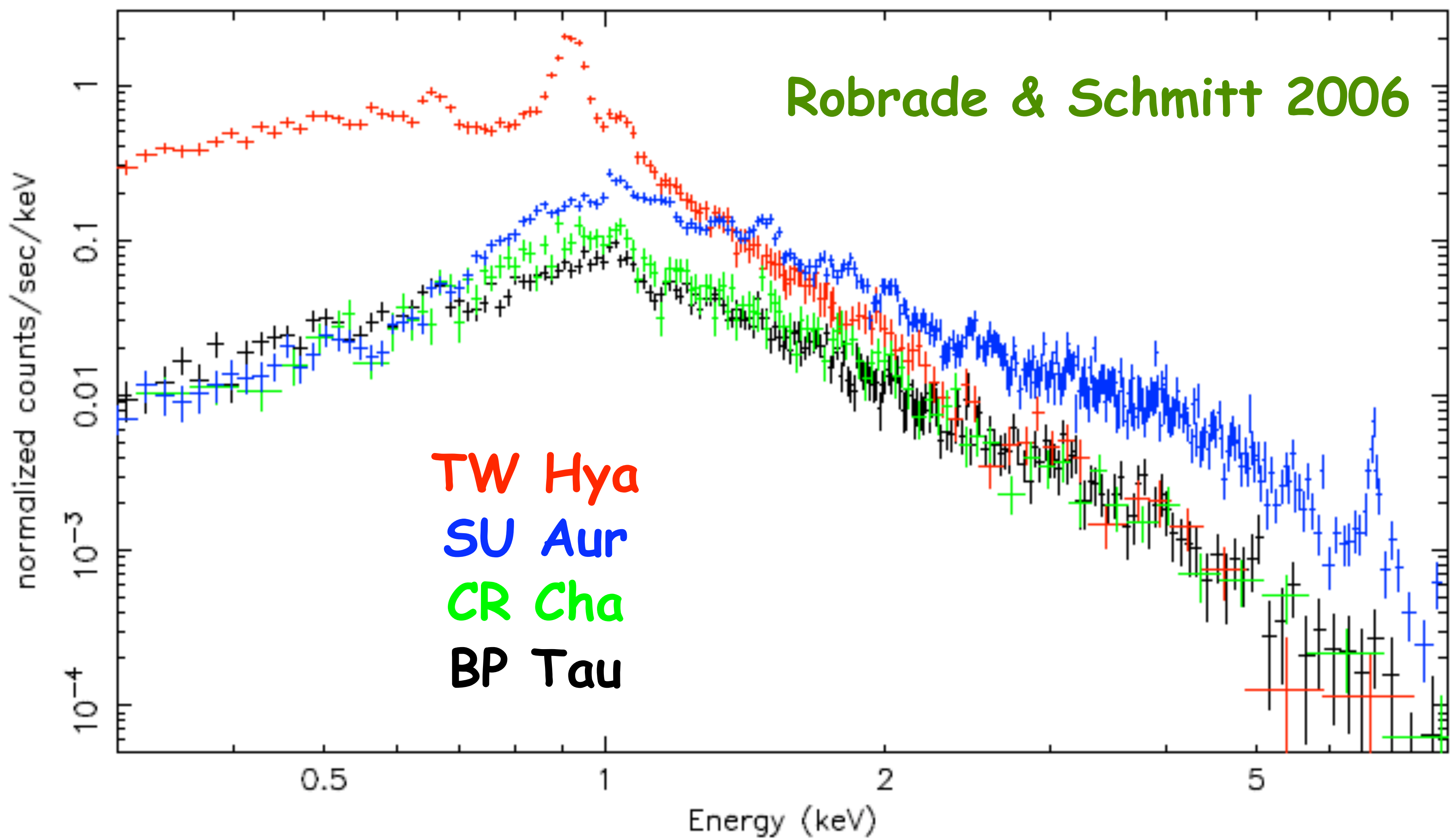
COUP: 10d observation of Orion Nebula Cluster with Chandra
XEST: Extended Survey of the Taurus Molecular Cloud with XMM

cTTSs show $L_x/L_{bol} > 10^{-5}$, ie >10x brighter than the Sun
cTTSs emit 1/2 as much X-rays wrt/ non-accreting TTSs
no activity vs. rotation dependence of Xray flux (saturation)
Xray and optical variability do not correlate
Xray correlate with M_*

most (hard 10-30 MK) Xrays come from coronal activity
little (soft 1-3 MK) Xrays from accretion shocks
most X-rays come from small field loops
evidence for large magnetic loops from Xray flare data

accreting protostars



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magnetised discs

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models of magnetised discs

cloud collapse & advection of large-scale magnetic field

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MHD simulations of magnetised collapse (eg Banerjee & Pudritz 2006)

> predict orientation & distribution of magnetic field in accretion disc

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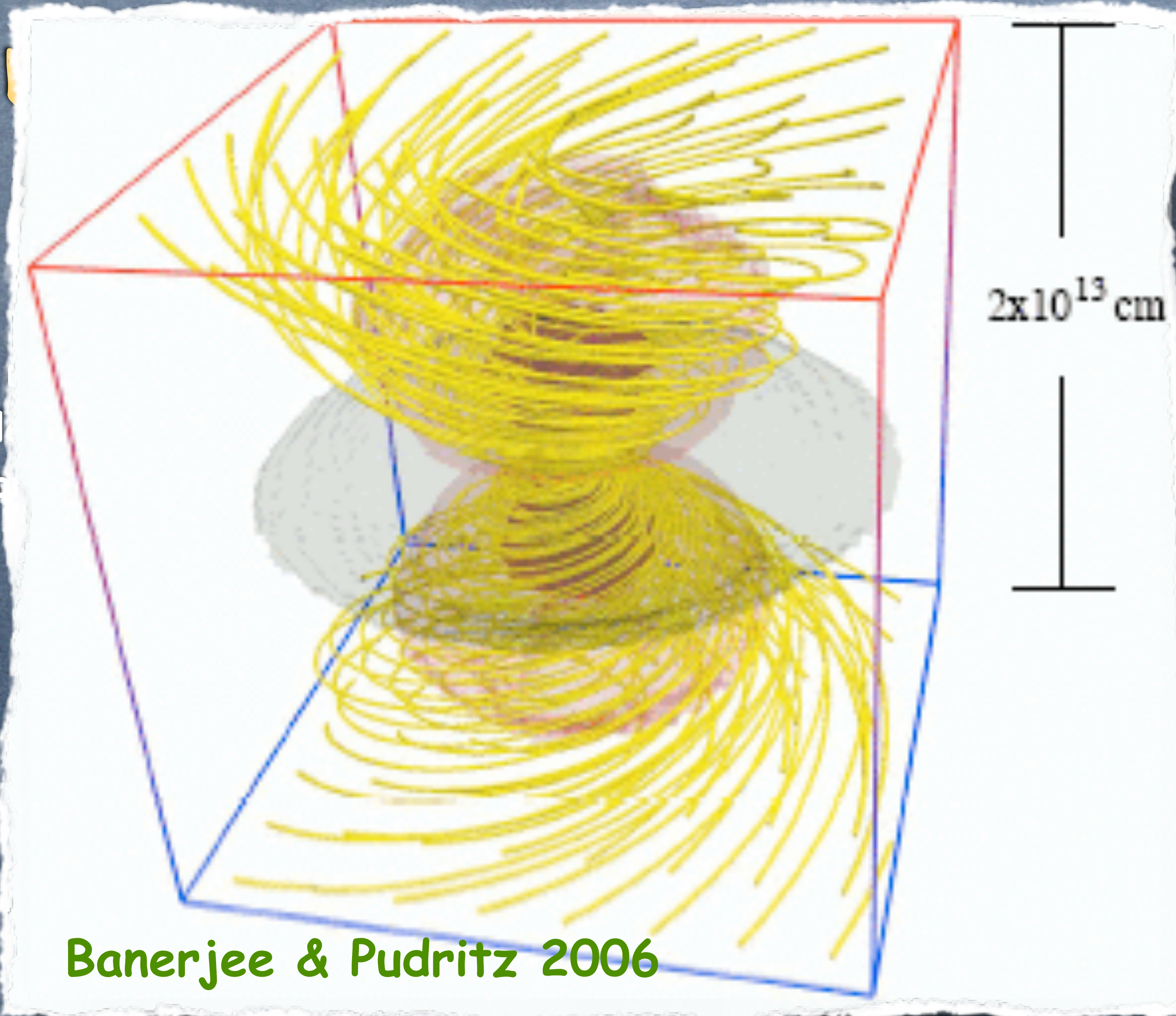

Banerjee & Pudritz 2006

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planet formation/migration in magnetic discs
giant planet migration stopped by magnetic fields ? (Terquem 2003)
disc fragmentation inhibited by magnetic fields ? (Fromang et al 2005)

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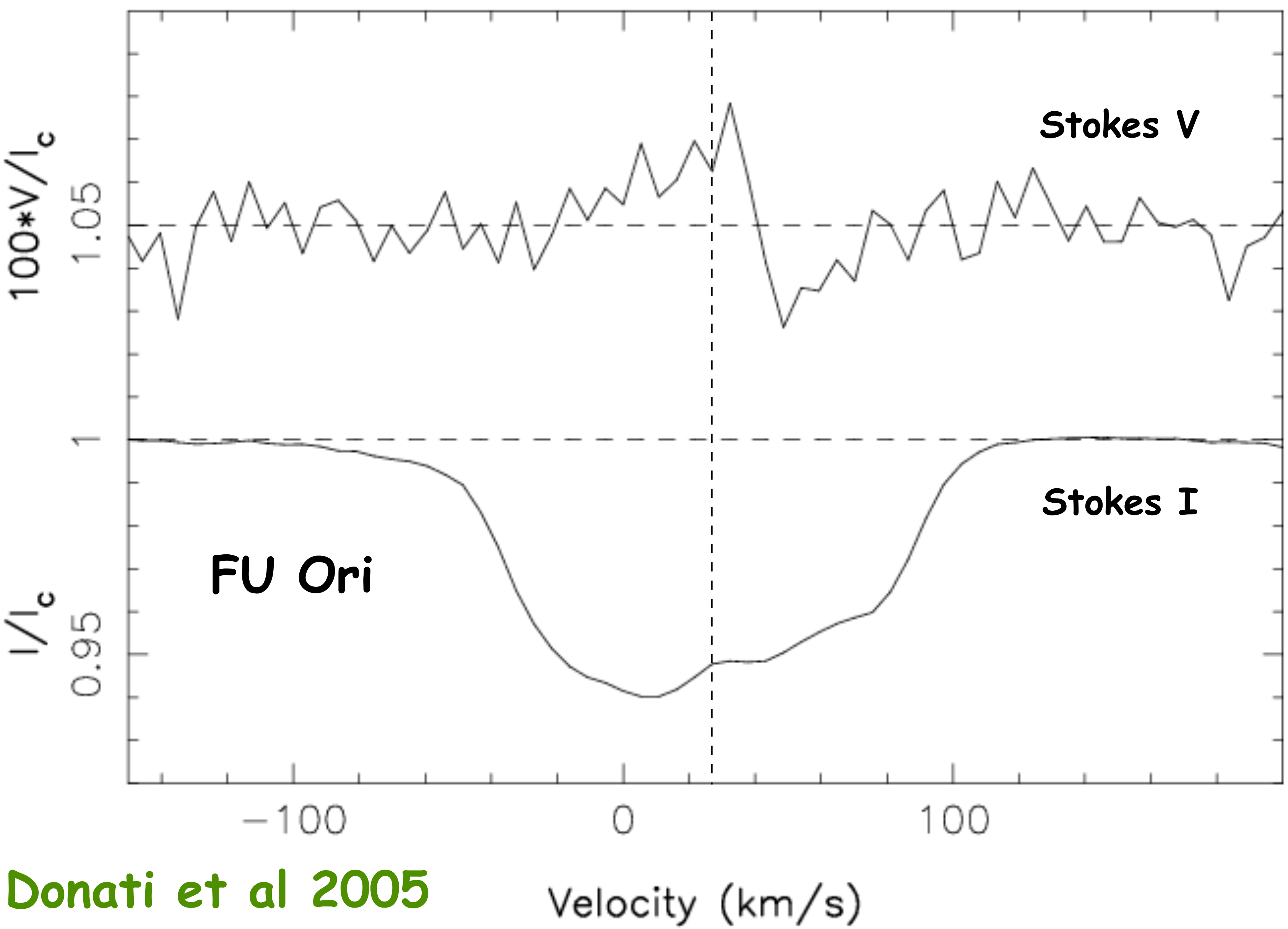
detecting magnetic fields in accretion discs

Zeeman signatures in LSD profiles of FU Ori (Donati et al 2005)

> kG equipartition field near centre (<0.1au) of accretion disc



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assuming axisymmetric magnetic field configuration in the disc
decomposing Zeeman signature in symmetric and antisymmetric components
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modelling disc mag

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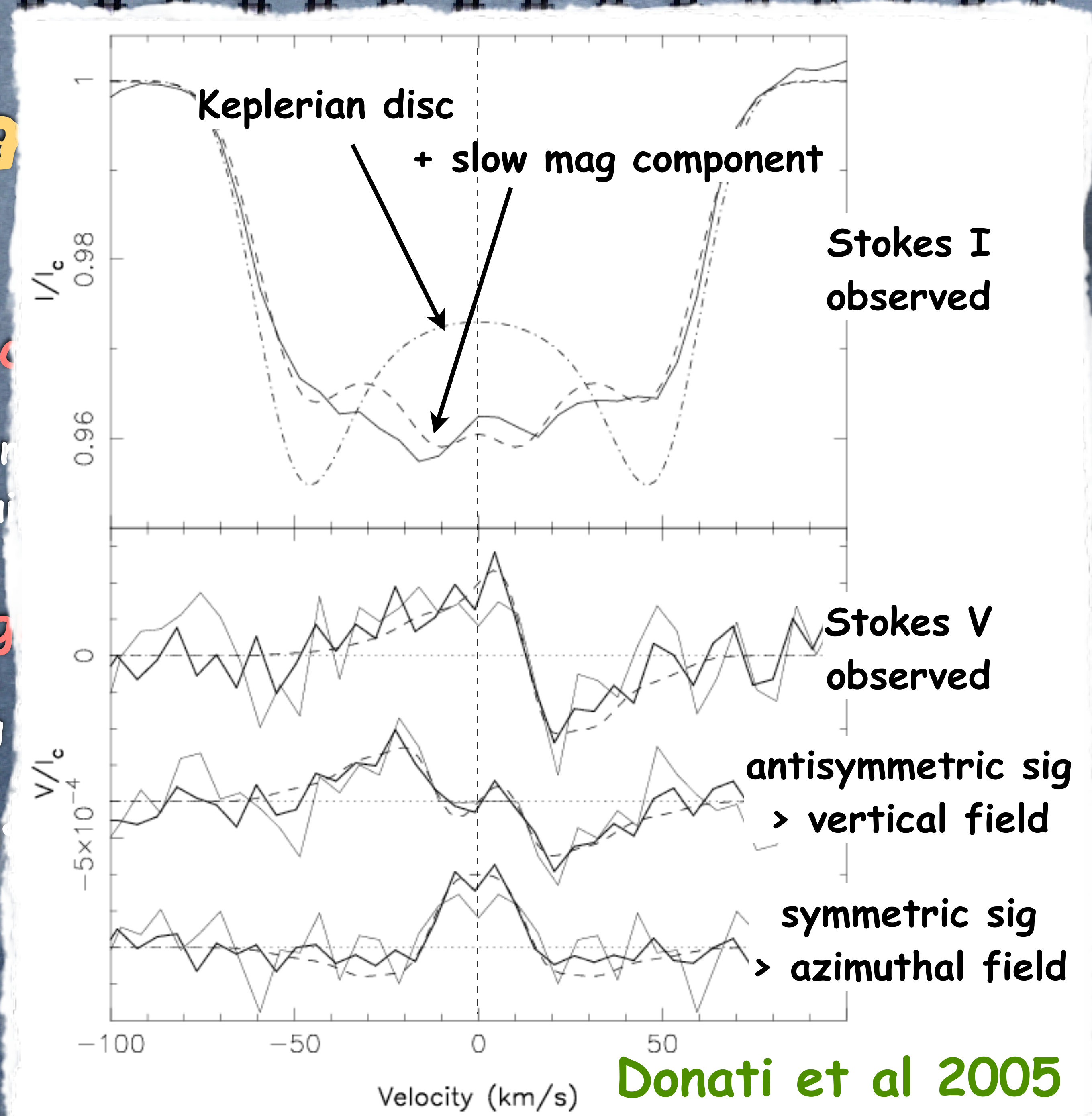

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need well sampled data over 15d to confirm modulation & find periods

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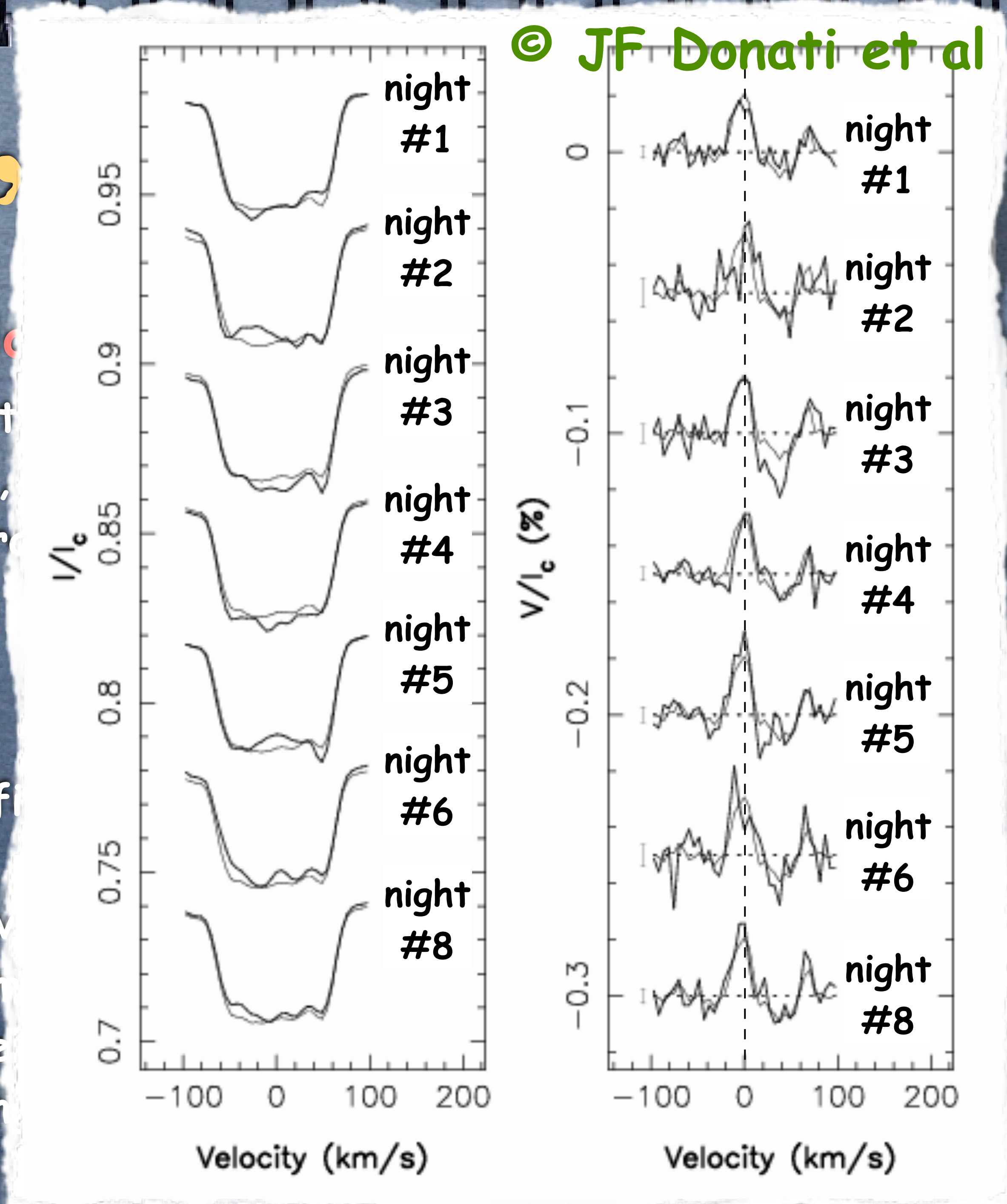

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cTTS: determine large-scale field & accretion patterns

characterise dependence wrt/ stellar parameters and temporal evolution

discs: determine magnetic field & density distribution close to disc centre

find out relation to jets & protoplanets

investigate origin of magnetic fields & evaluate impact on stellar formation

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instruments

use & abuse of existing instruments (LPs on ESPaDOnS/NARVAL)
promote/build Cass polarimeters for existing high-res spectrographs
build new instruments: eg SPIRou (nIR spectropolarimeter 0.9-2.4 mic)