(A highly biased view of) Polarization science with ALMA

Wouter Vlemmings (Nordic ARC/Chalmers/Onsala)

EUROPEAN ARC
ALMA Regional Centre || Nordic

ONSALA RYMDOBSERVATORIUM
CHALMERS TEKNISKA HÖGSKOLA

CHALMERS

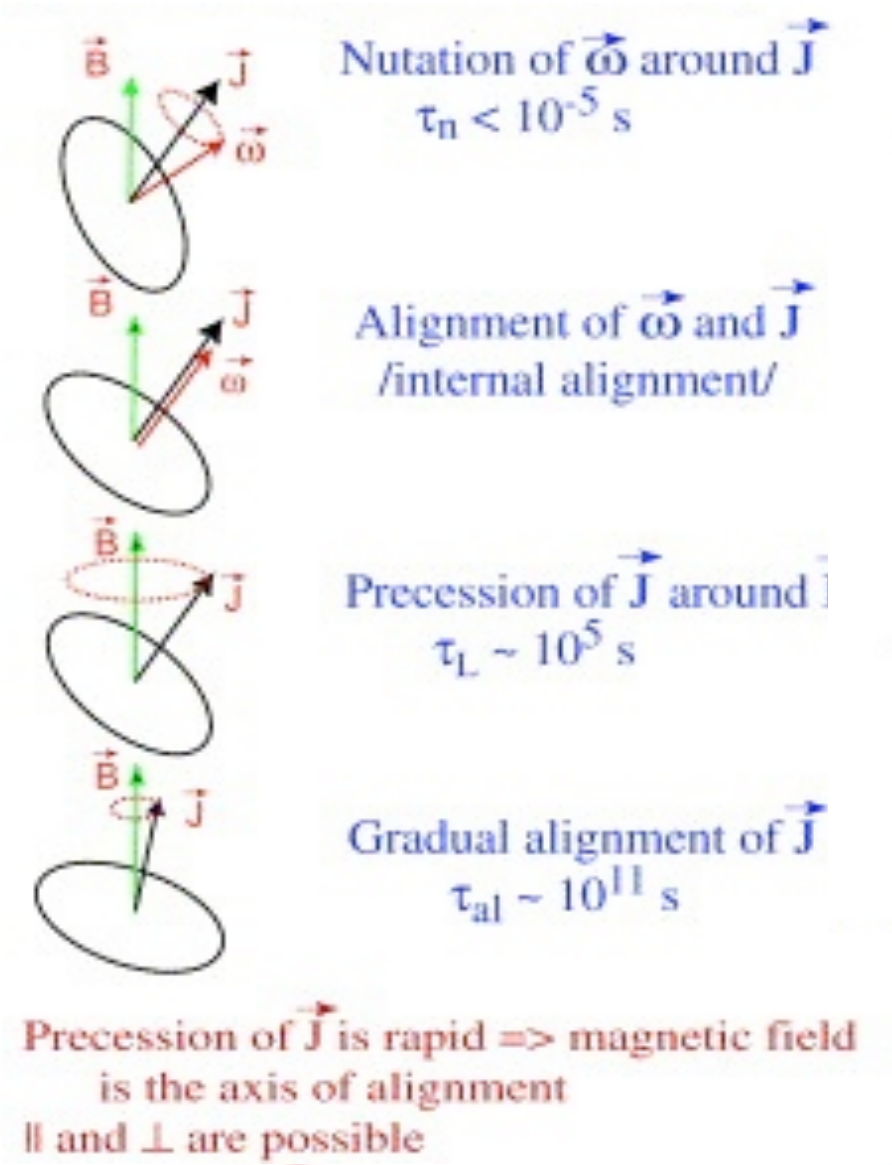
Magnetic Fields during the birth and death of stars

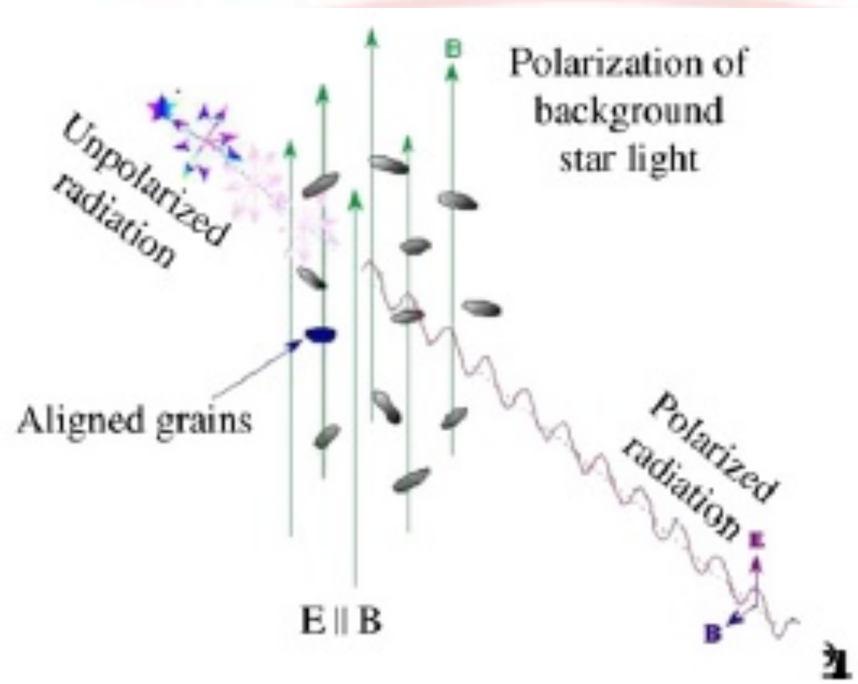
Outline

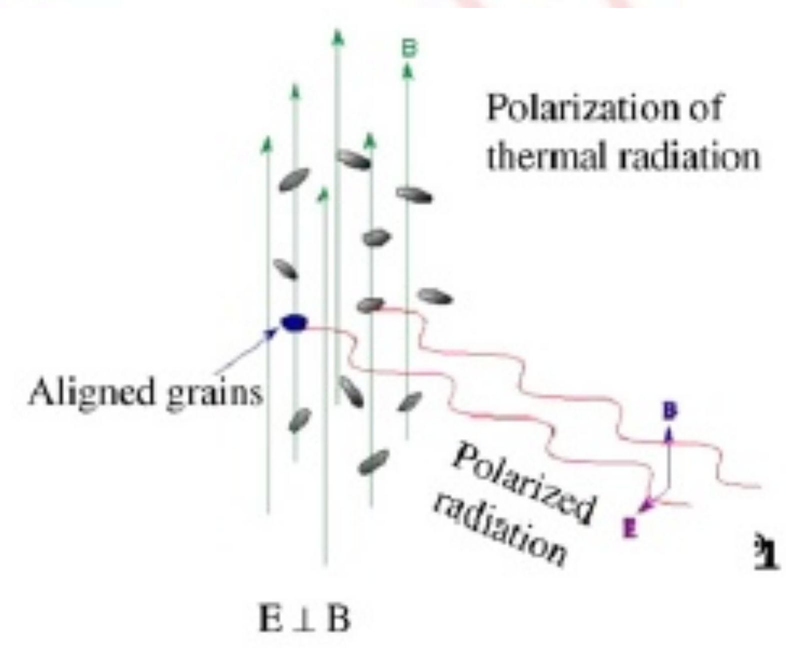
- (some) Sources of polarization
  - Continuum
    - Dust grain alignment
    - Synchrotron emission
  - Molecular lines
    - Zeeman splitting
    - Goldreich-Kylafis effect
    - Anisotropic radiation effects
- Science Targets
  - Galactic
    - Star Formation
    - Evolved Stars
    - Compact objects / Galactic Centre
  - Extra-galactic
    - Galaxies
    - GRBs
    - AGN / jets / BHs
- Conclusions

Continuum polarization: Dust grain alignment

- Torques align grain minor axis with B-field
  - P_l from net emission parallel to major axis





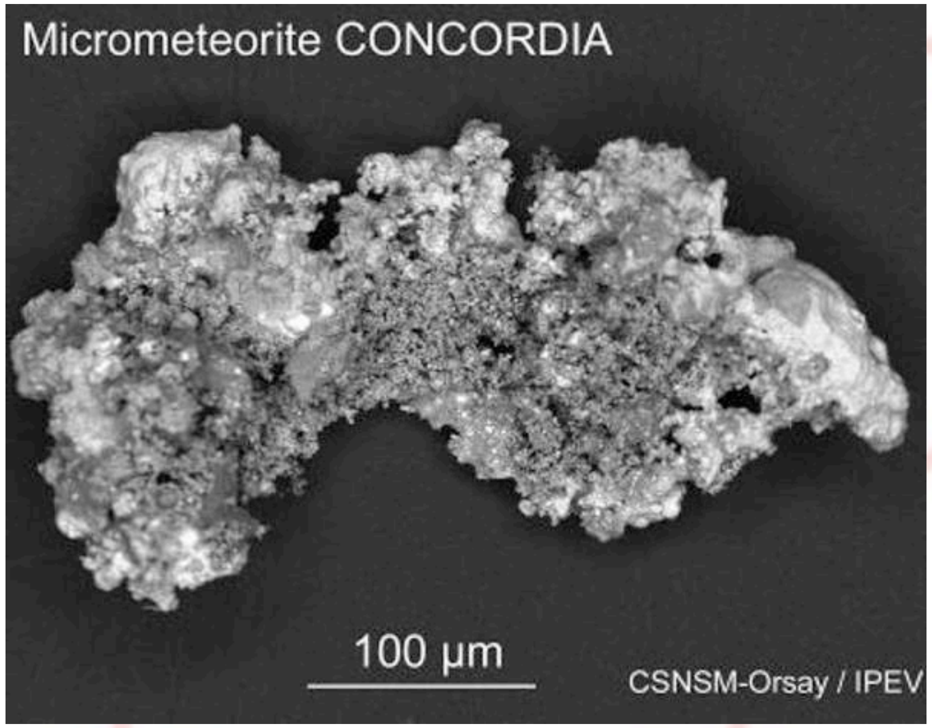


details & figures from Lazarian (2007), JQSRT 106, 225
Slide from J. Greaves

Continuum polarization: Dust grain alignment

- Torques align grain minor axis with B-field
  - P_l from net emission parallel to major axis
- Idealized approximation of dust grains
  - realistic grains will have different grain alignment efficiencies

→ P_l obs. potential probe of grain properties



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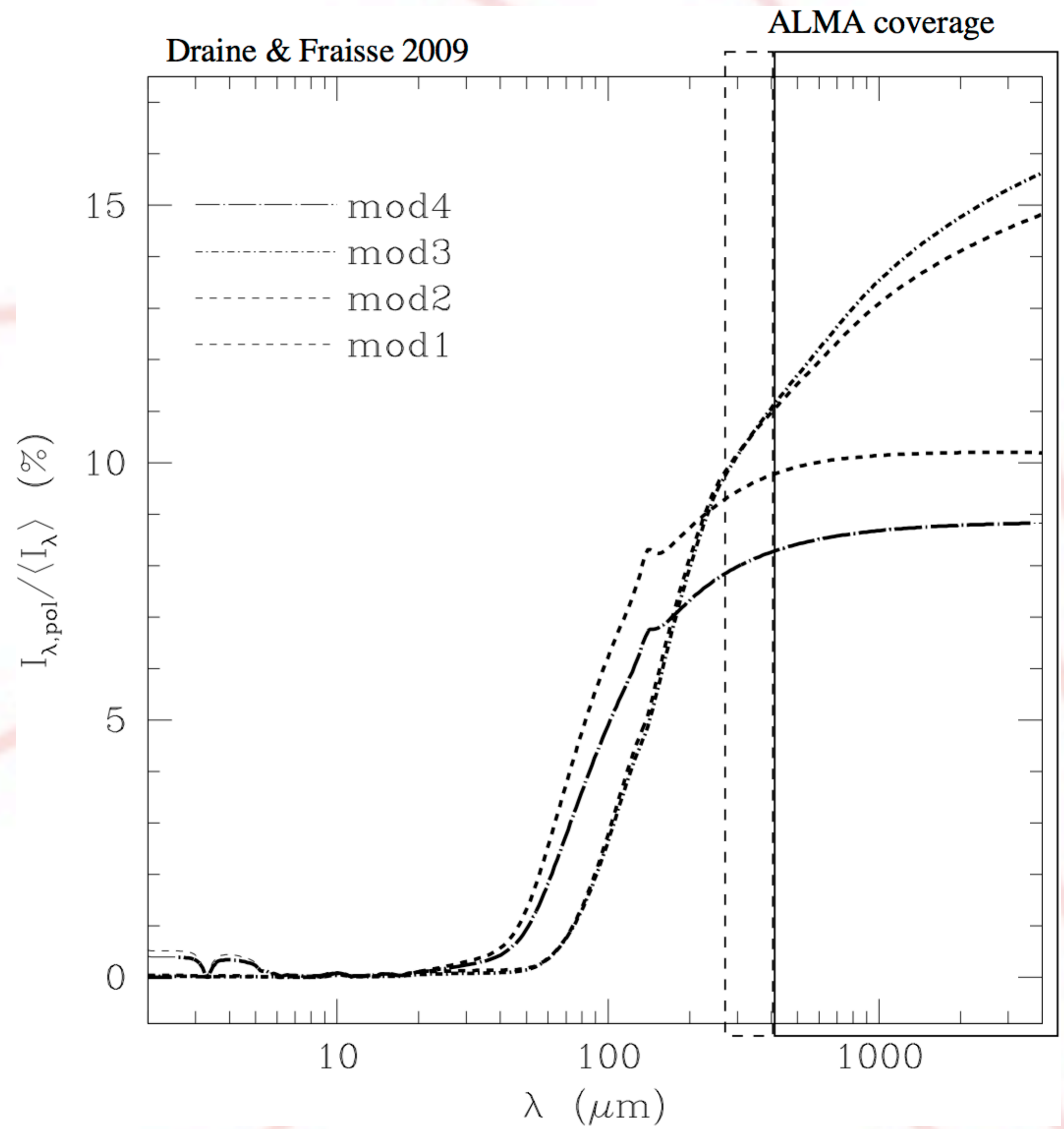
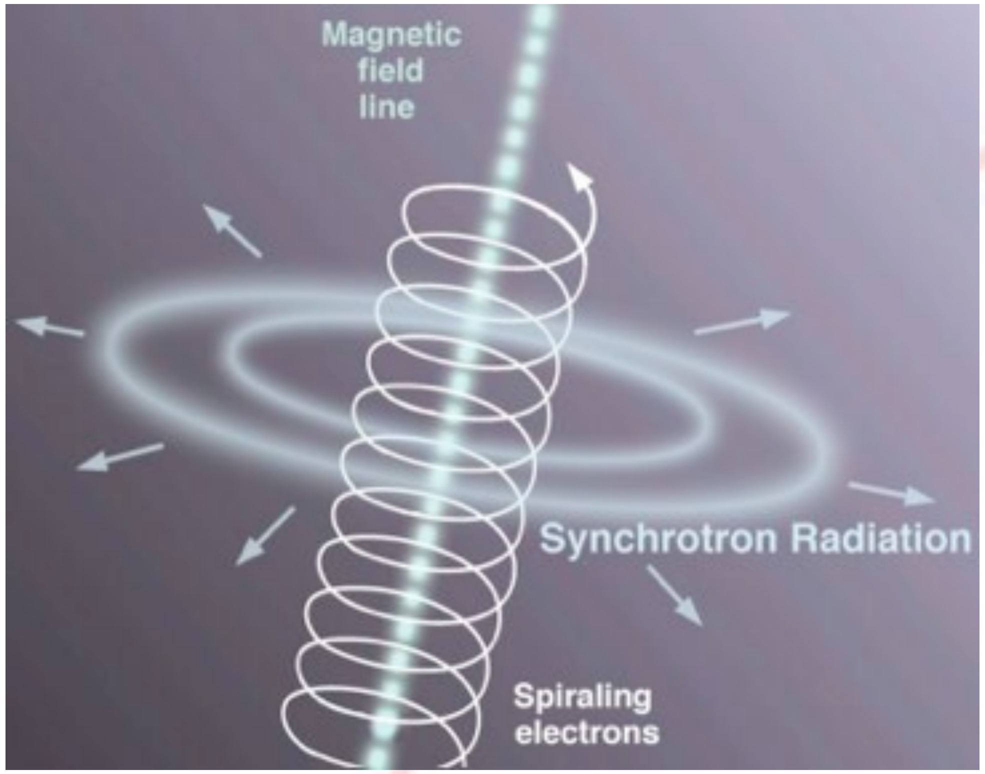
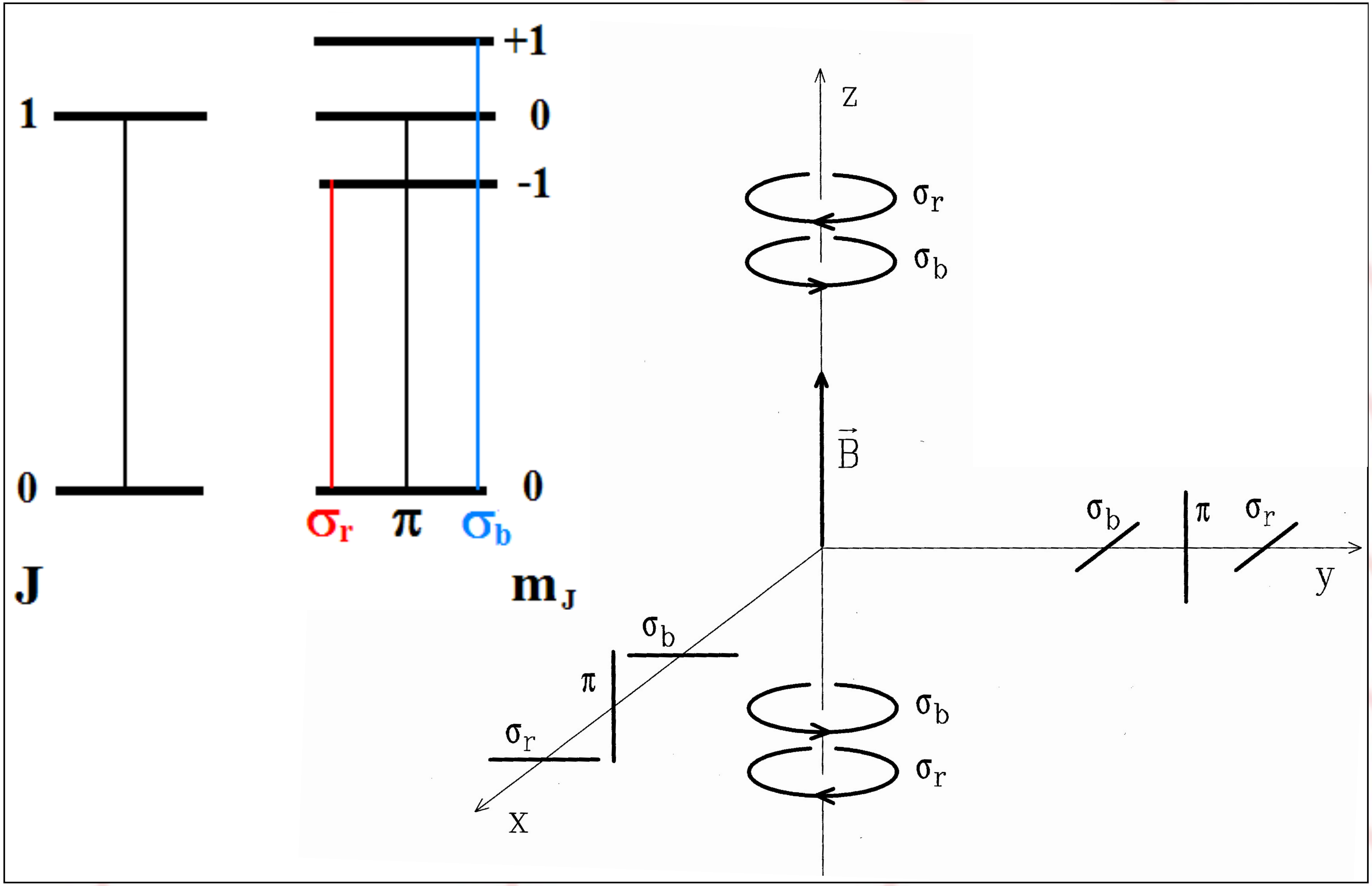


Continuum polarization: Synchrotron radiation

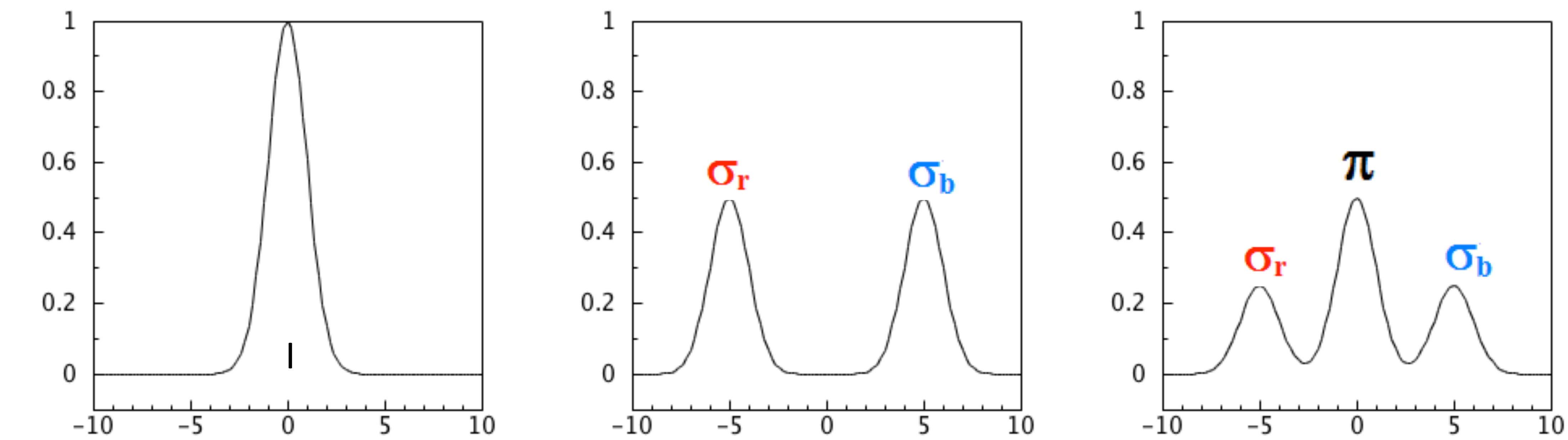


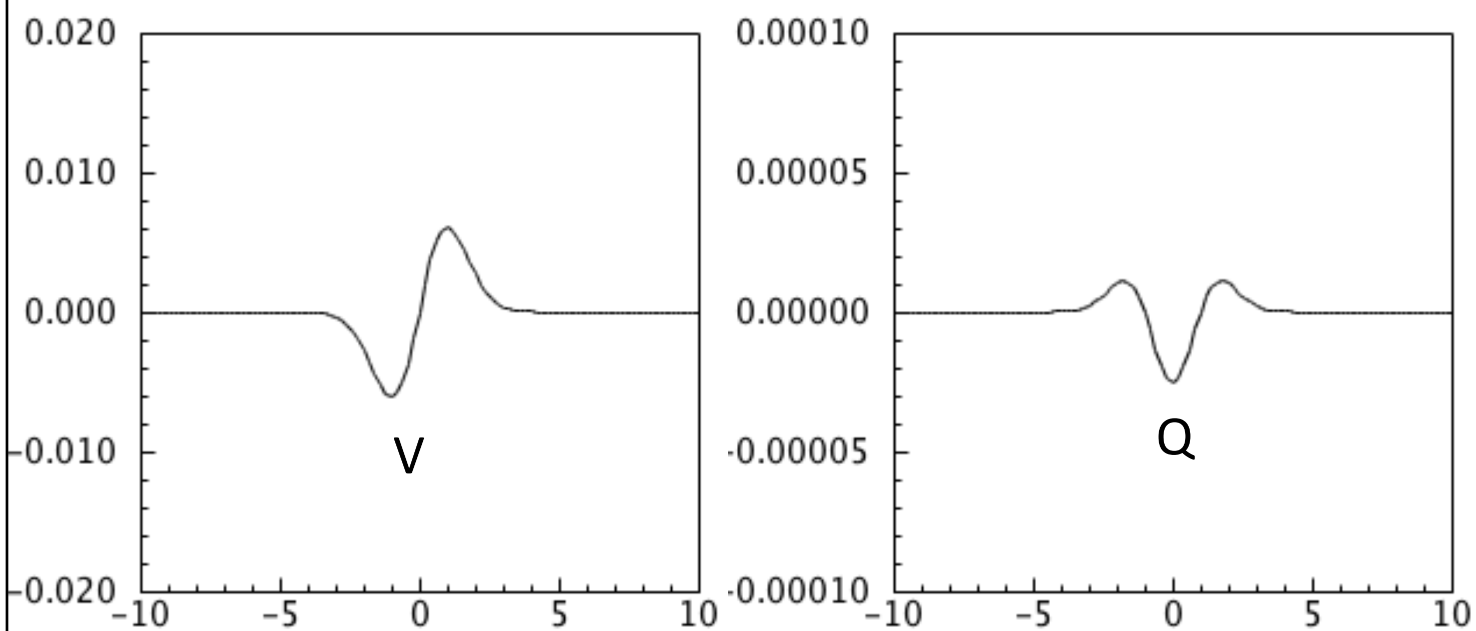
- Magnetic field acceleration of charged particles by the Lorentz force
  - radio synchrotron emission with typical spectrum of $F_\nu \propto \nu^{-0.75}$ (p=2α+1=2.5)
  - Strong polarization $\frac{P}{I} = \frac{p+1}{p+7/3}$

Line polarization: Zeeman Effect



Line polarization: Zeeman Effect





$$Q, U \propto (d^2 I / d\nu^2)(\Delta\nu_Z \sin\theta)^2$$

$$\Rightarrow \textit{plane of sky } B \ \ (\textit{not really})$$

$$Q, U \propto (\Delta\nu_Z / \textit{linewidth})^2$$

$$V = L - R \propto (dI / d\nu)(\Delta\nu_Z \cos\theta)$$

$$\Rightarrow \textit{line of sight } B$$

$$\Delta\nu_Z \propto Z\ B$$

Possible Zeeman lines

Species	Transition	ν (GHz)	Z (Hz/μG)	n_H(cm^{-3})
H I	F = 1→ 0	1.4	2.8	10^1 - 10^2
OH	Λ-doublet	1.7	~3	10^3 - 10^4
CN	N,J = 1,3/2 → 0,½	113.5	2.2	10^5 - 10^6
CN	N,J = 2,3/2 → 1,3/2	226.3	~2	~10^6
CH	J=3/2 ,F = 1→0	0.7	~3	~10^5(?)
CCH	N,J = 1,½ → 0,½	87.4	~2	
SO	N,J = 2,3 →1,2	99.3	1.0	
SO	N,J = 3,4 → 2,3	138.2	0.8	
SO	N,J = 4,3 → 3,2	159.0	1.0	
SO	N,J = 5,6 → 4,5	220.0	0.5	
SO	N,J = 2,1 → 1,2	236.5	1.7	
CO, CS, HCN, …	various	various	(few) x 10^{-4}	

+ maser lines!

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Species	Transition	ν (GHz)	Z (Hz/μG)		$n_H (cm^{-3})$
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CN	N,J = 2,³⁄₂ ➔ 1,³⁄₂	226.3	~2	Band 6	$\sim 10^6$
CH	J=³⁄₂ ,F = 1➔0	0.7	~3		$\sim 10^5$(?)
CCH	N,J = 1,½ ➔ 0,½	87.4	~2	Band 3	
SO	N,J = 2,3 ➔1,2	99.3	1.0	Band 3	
SO	N,J = 3,4 ➔ 2,3	138.2	0.8	Band 4	
SO	N,J = 4,3 ➔ 3,2	159.0	1.0	Band 4	
SO	N,J = 5,6 ➔ 4,5	220.0	0.5	Band 6	
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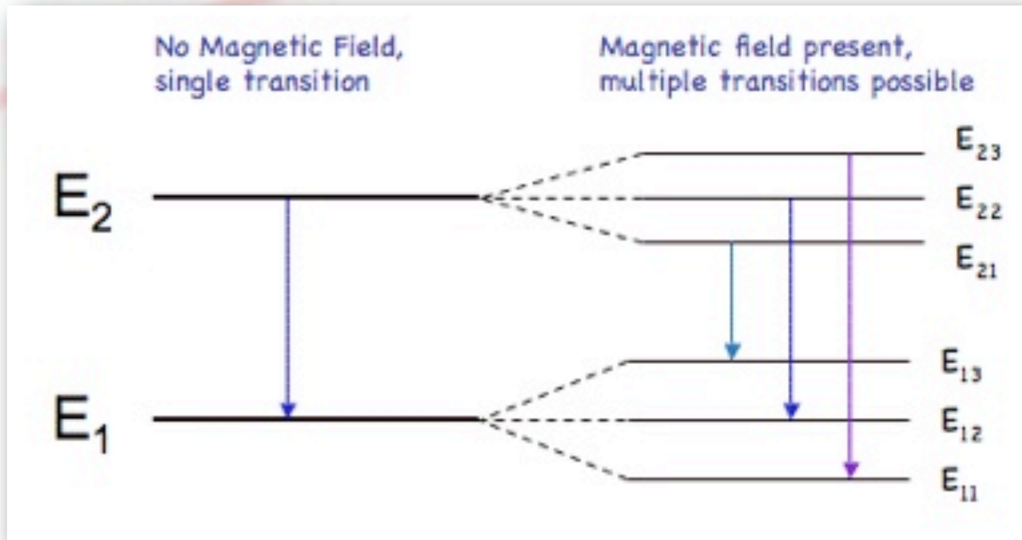
Example:
CN@113.5 for 1 mG has a splitting of 5.8 m/s or about 10^{-3} of its intrinsic linewidth leading to a circular polarization of ~0.1%

+ maser lines!

Goldreich-Kylafis effect I

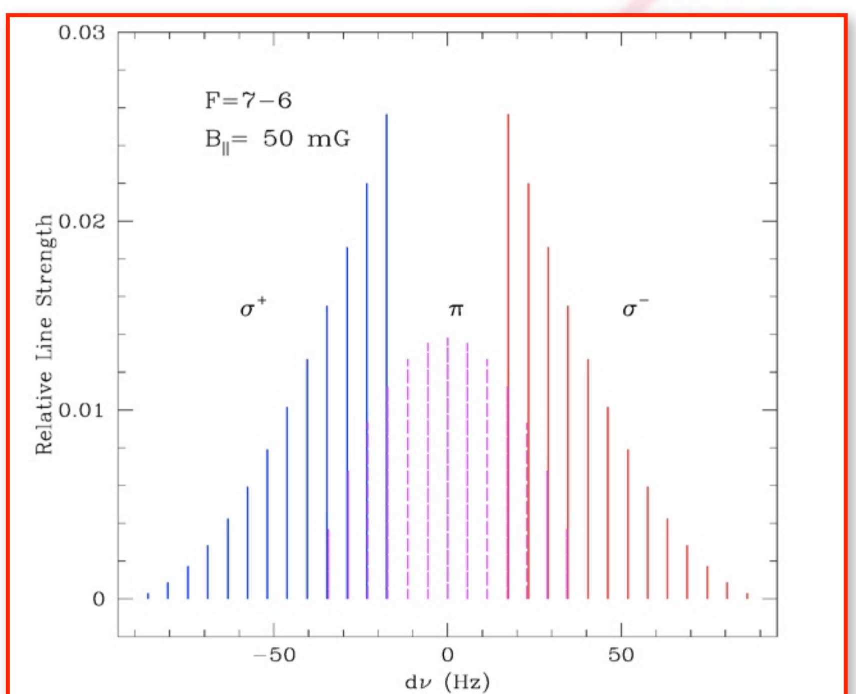


$$\frac{dI^{\perp}_{JJ'}}{ds} = -\kappa^{\perp}_{JJ'}\left(I^{\perp}_{JJ'} - S^{\perp}_{JJ'}\right)$$

$$\frac{dI^{\parallel}_{JJ'}}{ds} = -\kappa^{\parallel}_{JJ'}\left(I^{\parallel}_{JJ'} - S^{\parallel}_{JJ'}\right)$$

$\Delta m_F = \pm 1;\quad \sigma^{\pm}$ – *circularly polarized* $\perp B$

$\Delta m_F = 0;\quad \pi$ – *linearly polarized along* B



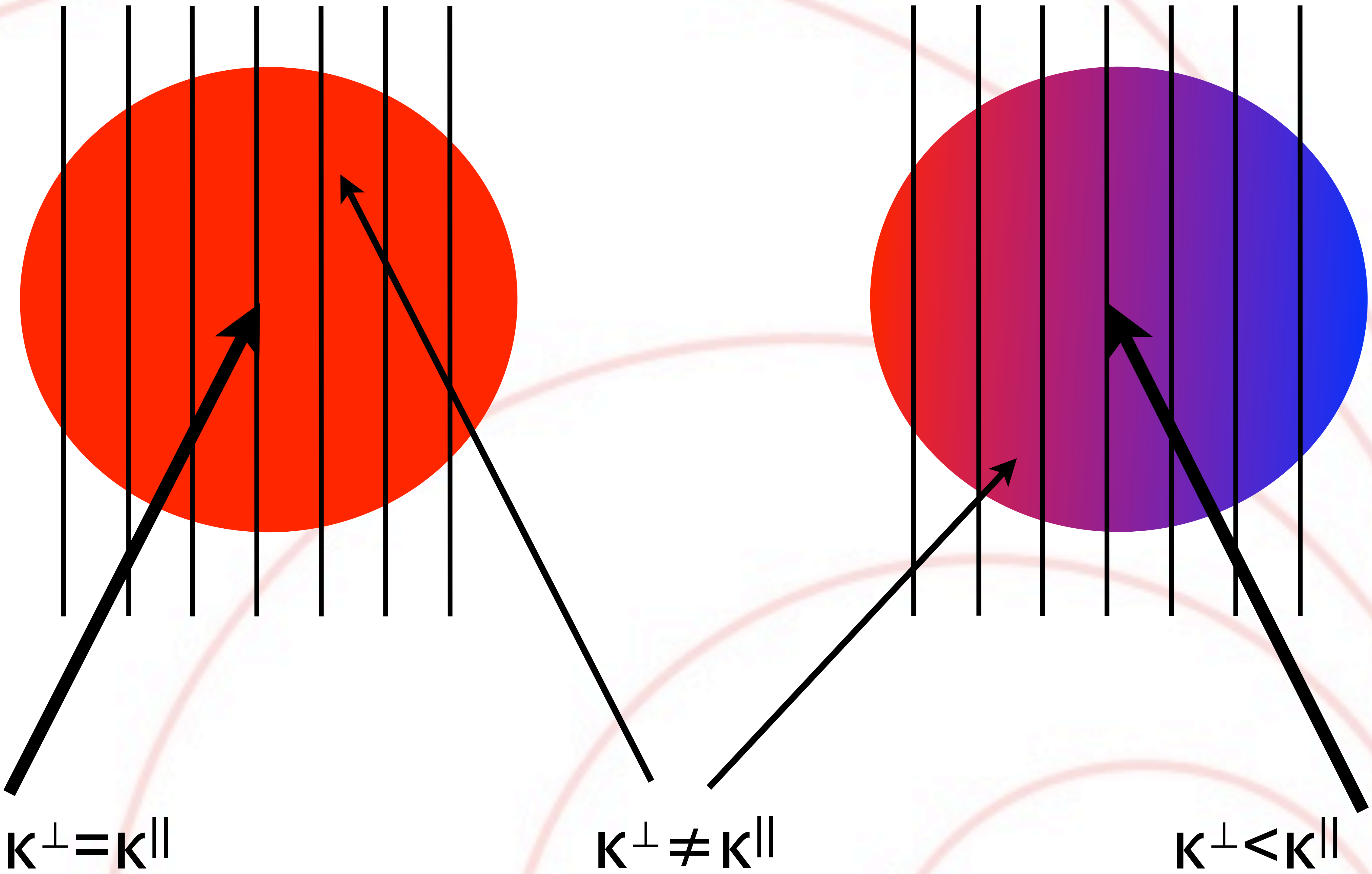
$$\kappa^{\perp}_{JJ'} = \frac{1}{2}\phi(\nu - \nu_{JJ'}) \sum_{\Delta M=1} \kappa_{JMJ'M'}$$ Opacity

$$S^{\perp}_{JJ'} = \frac{\sum_{\Delta M=1} \kappa_{JMJ'M'} S_{JMJ'M'}}{\sum_{\Delta M=1} \kappa_{JMJ'M'}}$$ Source term

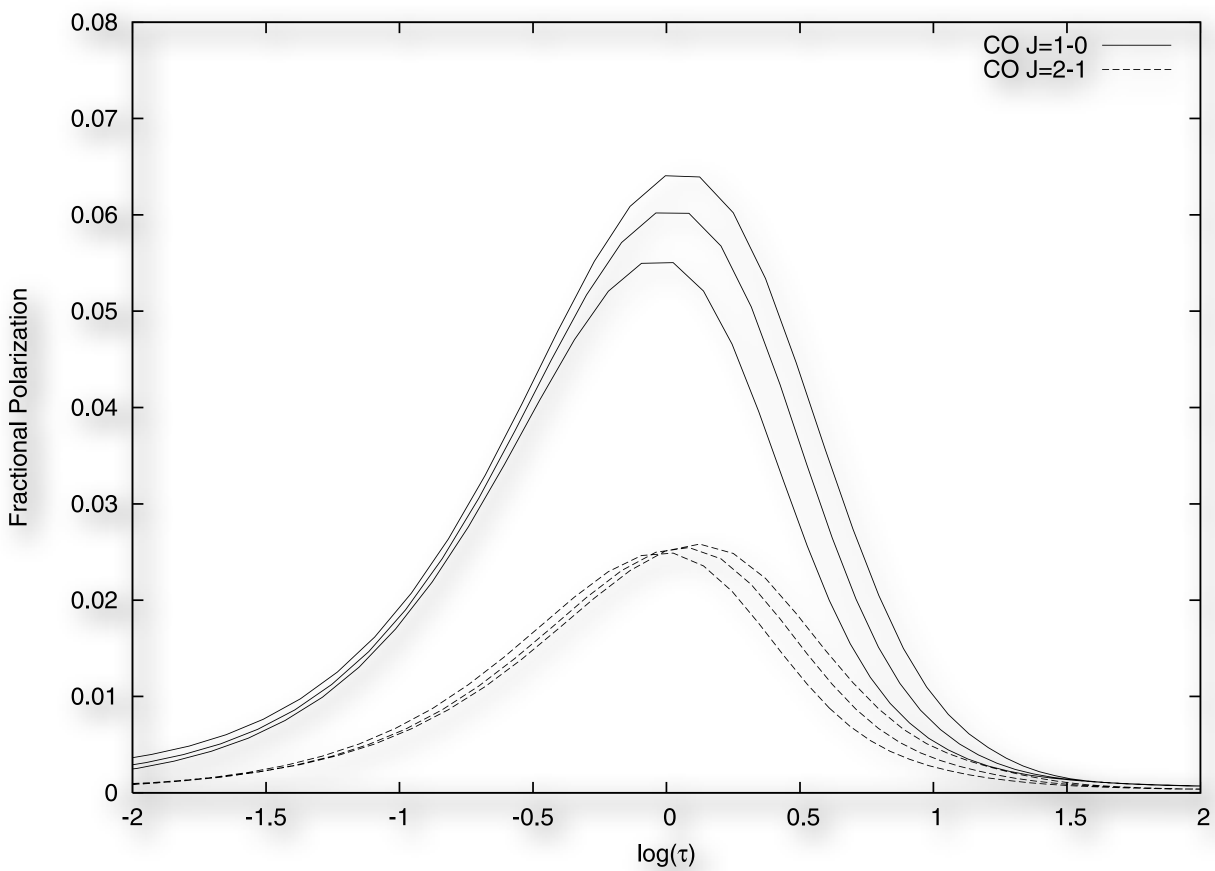
$$\kappa^{\parallel}_{JJ'} = \phi(\nu - \nu_{JJ'})\left(\sin^2\theta \sum_{\Delta M=0} \kappa_{JMJ'M'} + \frac{1}{2}\cos^2\theta \sum_{\Delta M=1} \kappa_{JMJ'M'}\right)$$

$$S^{\parallel}_{JJ'} = \left(\sin^2\theta \sum_{\Delta M=0} \kappa_{JMJ'M'} S_{JMJ'M'} + \frac{1}{2}\cos^2\theta \sum_{\Delta M=1} \kappa_{JMJ'M'} S_{JMJ'M'}\right) \times \left(\sin^2\theta \sum_{\Delta M=0} \kappa_{JMJ'M'} + \frac{1}{2}\cos^2\theta \sum_{\Delta M=1} \kappa_{JMJ'M'}\right)^{-1}$$

Goldreich-Kylafis effect II

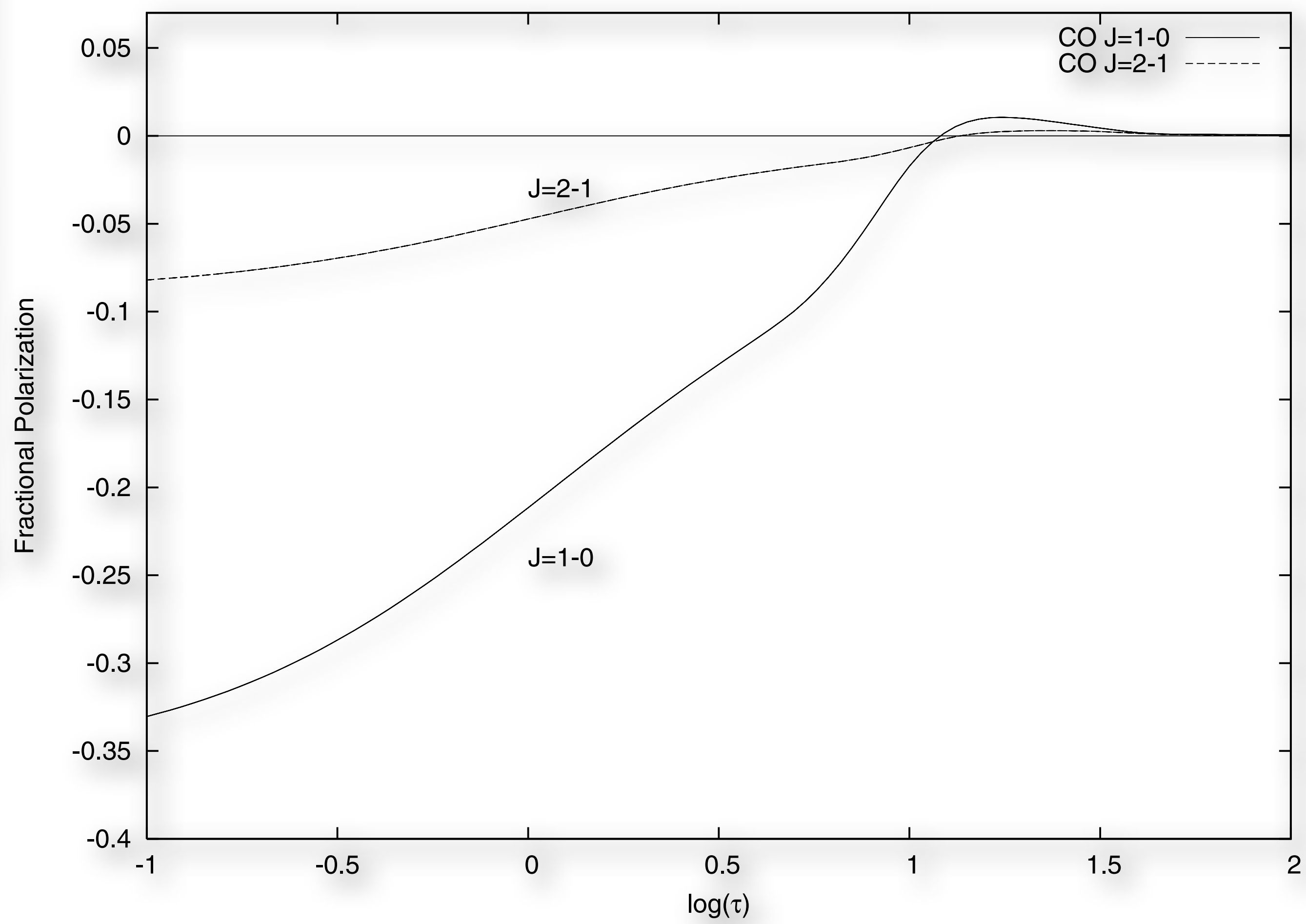


Goldreich-Kylafis effect III



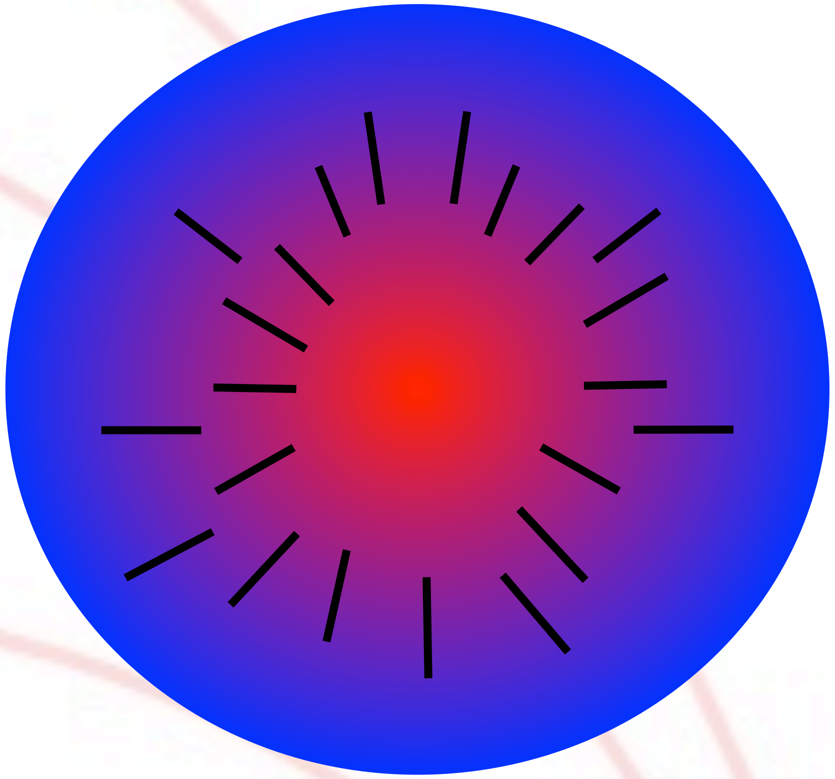
Velocity anisotropy perpendicular to B

Radiation anisotropy

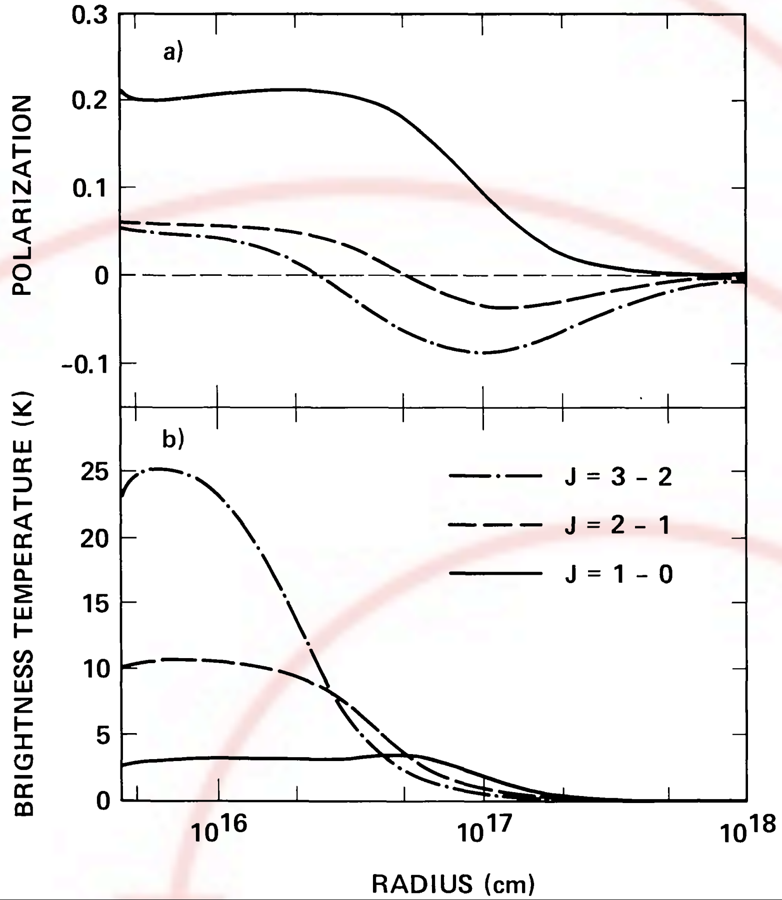


Cortes et al. 2005

GK related Caveats....

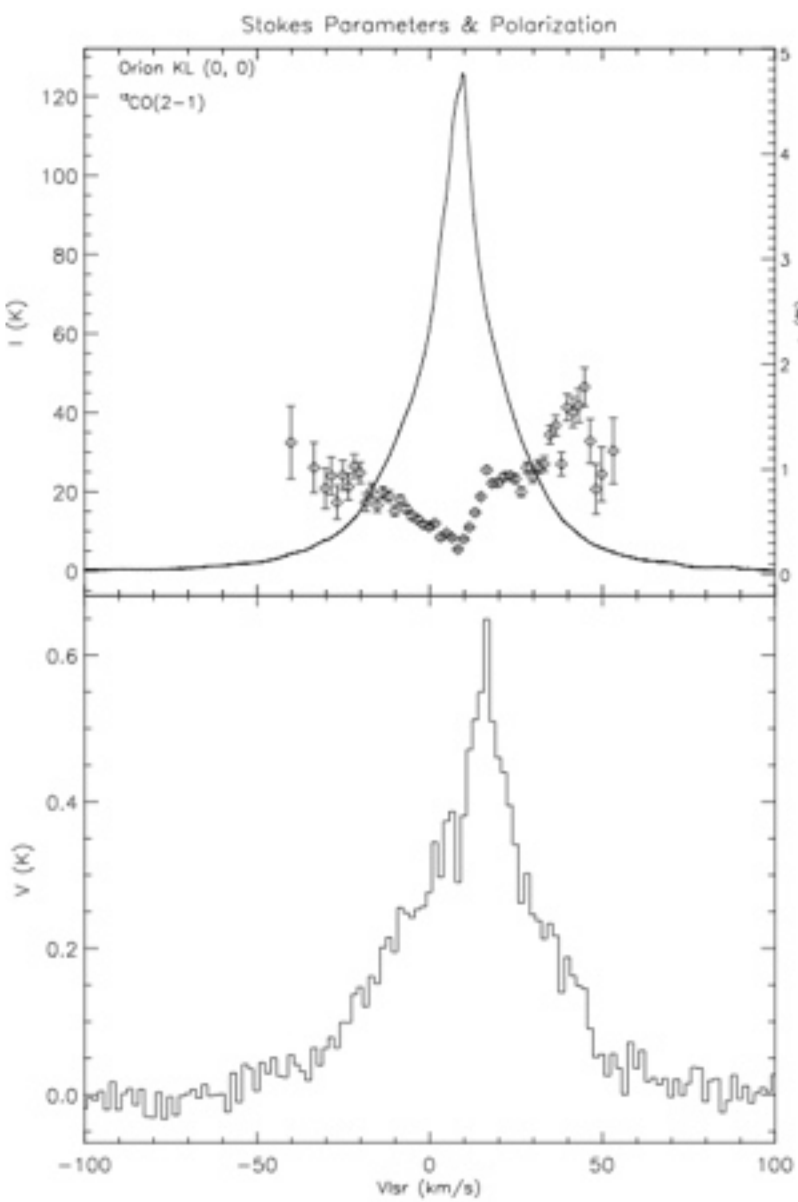


- Molecular alignment by radiative (infrared) pumping (Morris et al. 1985)
    - Linear polarization becomes radial or tangential to IR radiation source (i.e. central star)
- Multi-level excitation



non-Zeeman circular

- Linear to circular polarization conversion through anisotropic resonant scattering



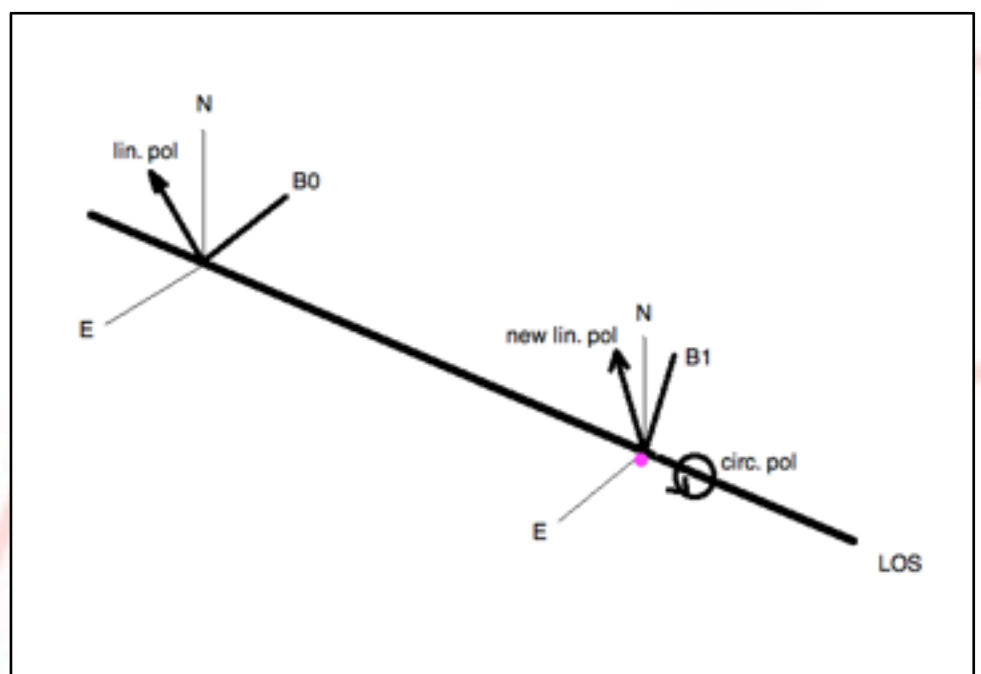
$$|\psi_0\rangle = \alpha_0 |n_\parallel\rangle + \beta_0 |n_\perp\rangle$$ Incident background radiation

$$|\psi'\rangle = \alpha_0 e^{i\varphi} |n_\parallel\rangle + \beta_0 |n_\perp\rangle$$ scattered radiation

$$q = \alpha_0^2 - \beta_0^2$$
$$u = 2\alpha_0\beta_0 \cos(\phi)$$
$$v = -2\alpha_0\beta_0 \sin(\phi)$$

Stokes parameters in the frame of foreground magnetic field

Increase of ϕ ⇒ decrease of u
increase of v



(Houde et al. 2013, slides from T. Hezareh)

Anisotropic scattering - phase shift

$$\phi(\omega) \cong -\omega_z^2 \sin^2(\iota)\ l^4 \frac{n_{CO} 3\pi c^2 A_{ba}}{4\hbar\omega_0^3\omega^2} \sqrt{u(\omega)u'(\omega)I(\omega)}$$

ω_z : the Zeeman splitting
ι : inclination angle of the magnetic field
ω : the frequency of scattered photon
ω_0 : frequency of transition
n_{CO} : density of CO molecules in lower state
l : the size of interaction region
A_{ba} : the spontaneous emission coefficient (~ 10^{-6} s^{-1})
$u(u')$: the incident (scattered) linear polarization energy density
$I(\omega)$: resonant scattering integral over incident linear polarization profile

Remember, CO Zeeman splitting would be <0.01%

Masers

Many masers, several will be highly polarized

^{28}SiO				
v	$J_u - J_d$	Freq (GHz)	A (s^{-1})	ALMA band
0	1 - 0	43.42386	3.036×10^{-6}	1
	2 - 1	86.84699	2.915×10^{-5}	2
1	1 - 0	43.12208	3.011×10^{-6}	1
	2 - 1	86.24344	2.891×10^{-5}	2
	3 - 2	129.36326	1.045×10^{-4}	4
	4 - 3	172.48102	2.569×10^{-4}	5
	5 - 4	215.59592	5.131×10^{-4}	6
	6 - 5	258.70725	9.003×10^{-4}	6
	7 - 6	301.81430	1.445×10^{-3}	7
2	1 - 0	42.82059	2.986×10^{-6}	1
	2 - 1	85.64046	2.866×10^{-5}	3
	3 - 2	128.45881	1.036×10^{-4}	4
	4 - 3	171.27507	2.547×10^{-4}	5
	5 - 4	214.08848	5.088×10^{-4}	6
	6 - 5	256.89831	8.927×10^{-4}	6
	7 - 6	299.70386	1.433×10^{-3}	7
3	1 - 0	42.51938	2.951×10^{-6}	1
	3 - 2	127.55521	1.027×10^{-4}	4
	4 - 3	170.07057	2.525×10^{-4}	5
	5 - 4	212.58248	5.044×10^{-4}	6
4	5 - 4	211.07784	4.986×10^{-4}	6

^{29}SiO				
v	$J_u - J_d$	Freq (GHz)	A (s^{-1})	ALMA band
0	1 - 0	42.87992	2.114×10^{-8}	1
	2 - 1	85.75906	2.460×10^{-7}	2
	3 - 2	128.63685	9.696×10^{-7}	4
	4 - 3	171.51255	2.532×10^{-6}	5
	5 - 4	214.38548	5.334×10^{-6}	6
	6 - 5	257.25493	9.869×10^{-6}	6
1	3 - 2	127.74849	3.350×10^{-4}	4
	4 - 3	170.32807	8.745×10^{-4}	5
	6 - 5	255.47849	3.407×10^{-3}	6
2	6 - 5	253.70317	1.11139	6

^{30}SiO				
v	$J_u - J_d$	Freq (GHz)	A (s^{-1})	ALMA band
0	1 - 0	42.373426	2.016×10^{-8}	1
	2 - 1	84.746170	2.346×10^{-7}	2
	5 - 4	211.853473	5.081×10^{-6}	6
1	4 - 3	168.323352	8.054×10^{-4}	5
2	4 - 3	167.160563	2.542×10^{-1}	5

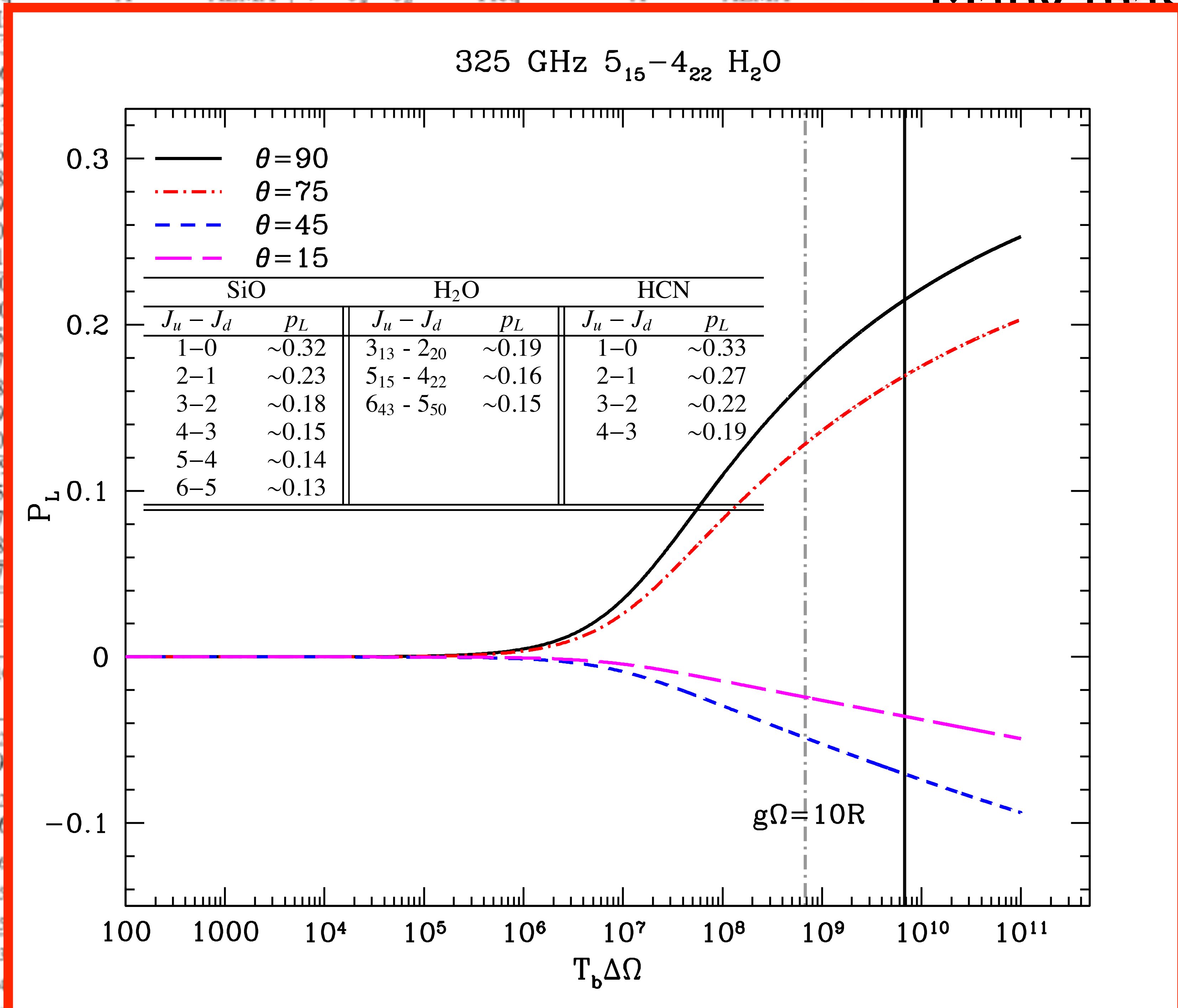
H_2O				
	Transition	Freq (GHz)	A (s^{-1})	ALMA band
	3_{13} - 2_{20}	183.31012	3.629×10^{-6}	5
	10_{29} - 9_{36}	321.22564	6.348×10^{-6}	7
	5_{15} - 4_{22}	325.15292	1.166×10^{-5}	7
	17_{413} - 16_{710}	354.8089	1.096×10^{-5}	7
	7_{53} - 6_{60}	437.34667	2.212×10^{-5}	8
	6_{43} - 5_{50}	439.15081	2.857×10^{-5}	8
	6_{42} - 5_{51}	470.88895	3.534×10^{-5}	8
$v_2 = 1$	4_{40} - 5_{33}	96.26116	4.719×10^{-7}	3
	5_{50} - 6_{43}	232.68670	4.770×10^{-6}	6
	6_{61} - 7_{52}	293.6645	-[a]	6
	1_{10} - 1_{01}	658.00655	5.568×10^{-3}	9

HCN				
	Transition	Freq (GHz)	A (s^{-1})	ALMA band
	1 - 0	88.631602	1.771×10^{-7}	2/3
$v_2 = 2^0$	1 - 0	89.0877	1.483×10^{-4}	2/3
$v_2 = 1^{1c}$	2 - 1	177.2387	4.578×10^{-5}	5
	3 - 2	267.1993	2.262×10^{-4}	6
	4 - 3	354.4605	6.122×10^{-4}	7
$v_2 = 4$	9 - 8	804.7509	-[a]	10
$v_1 = 1^1 \rightarrow v_2 = 4^0$	10 - 9	890.761	-[a]	10

Pérez Sánchez et al. 2013

Masers

Many masers, several ...ly polarized



Pérez Sánchez et al. 2013

Recap

- Various linear and circular polarization mechanisms
  - most probe line-of-sight or plane-of-the-sky magnetic field
  - most have (sub)-percent polarization fractions
    - except synchrotron and masers
  - Several fairly unique to the (sub-)mm regime
    - Goldreich-Kylafis of e.g. CO
    - Zeeman of e.g. CN/SO and various masers
    - aligned dust (submm dust peak)
    - Resonant scattering?

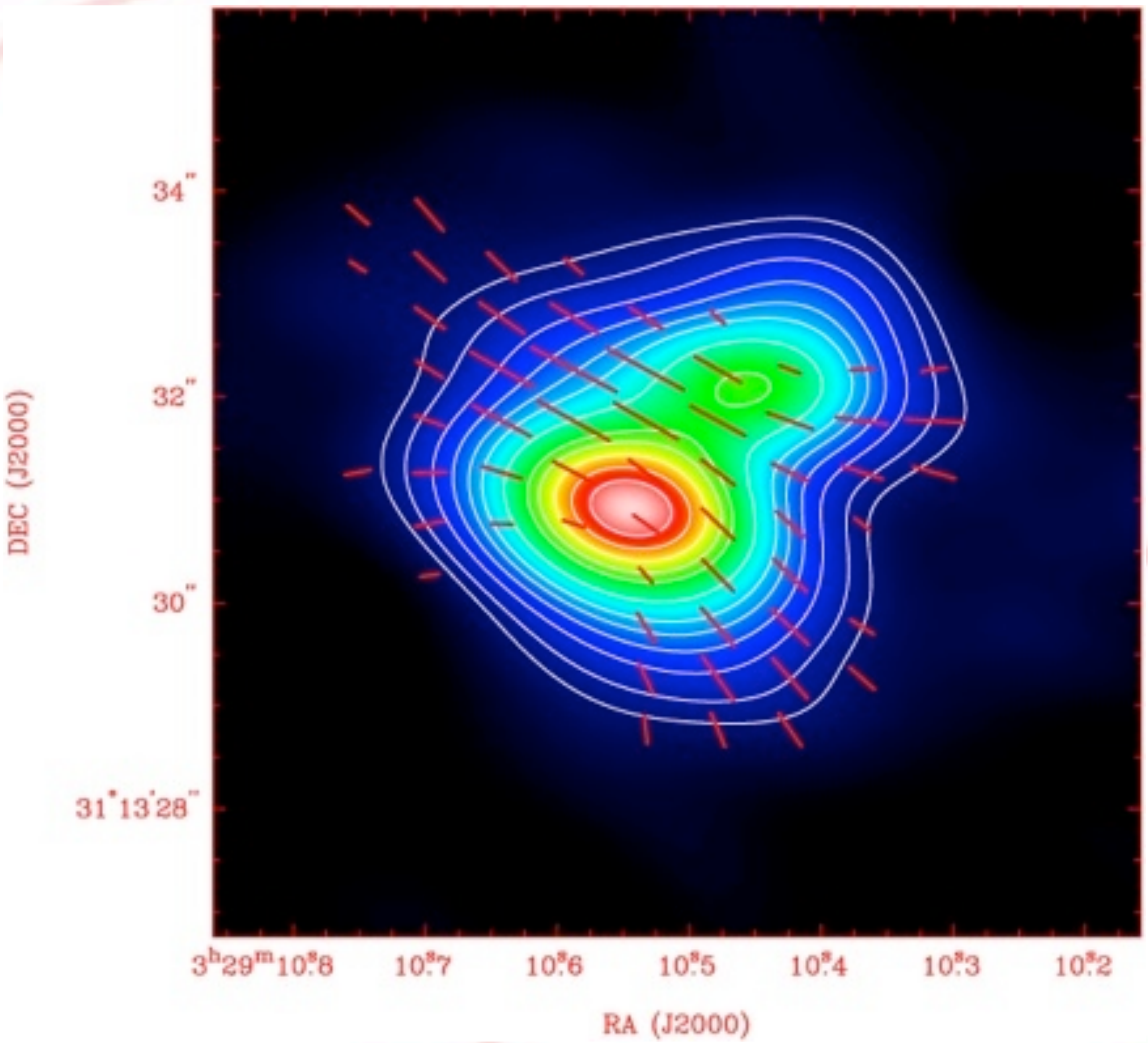
Some Science Examples:

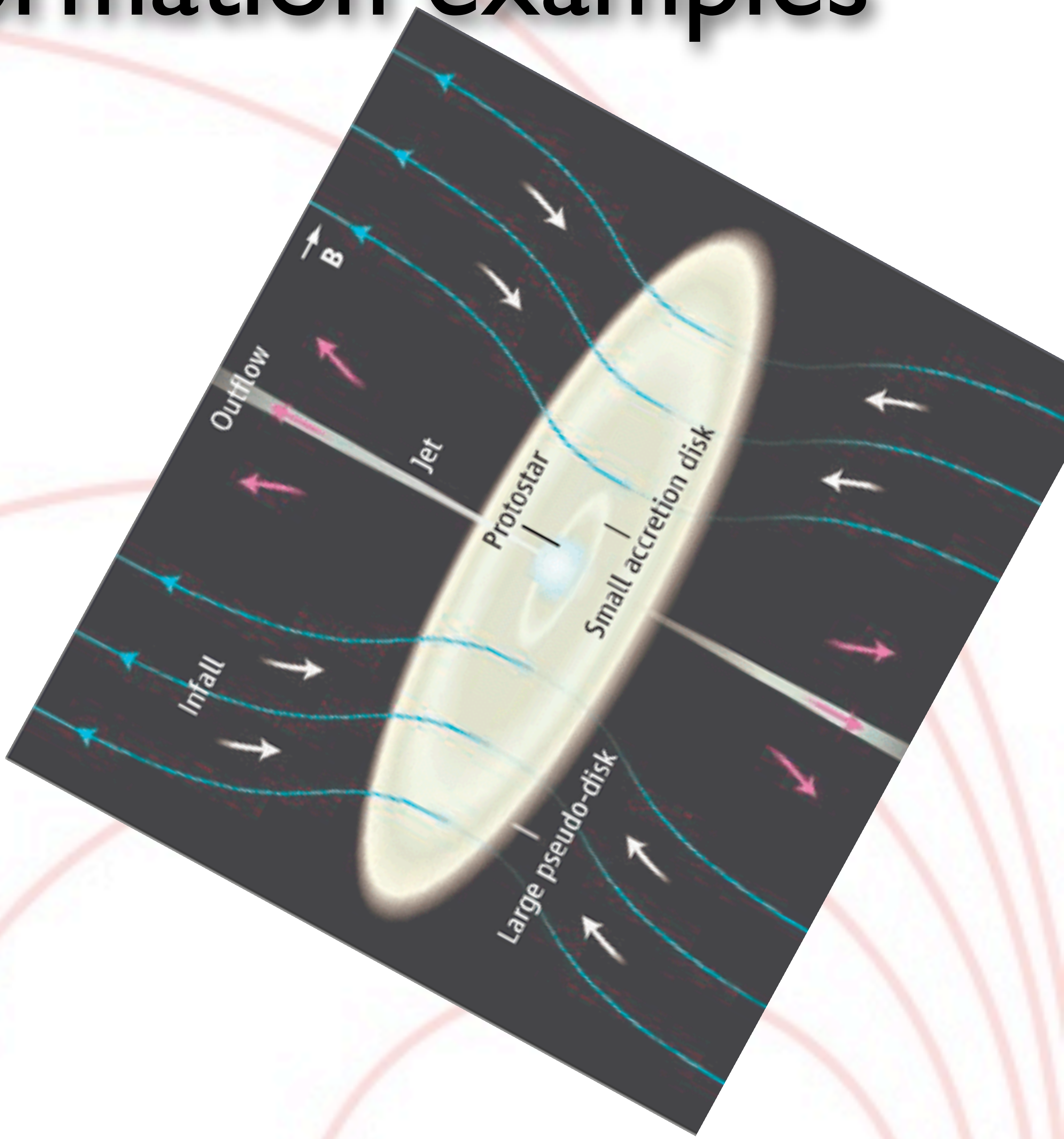
Galactic Science

Star Formation

- What is the role/influence of magnetic fields during low-mass and massive star formation
  - magnetic disk braking (catastrophe?)
    - aligned/misaligned fields?
  - outflow launching (requires magnetic field)
    - disk winds/X-winds?
  - suppression of fragmentation?
  - setting threshold for SF to occur?
  - connection between seed field and protostellar field?

Star Formation examples



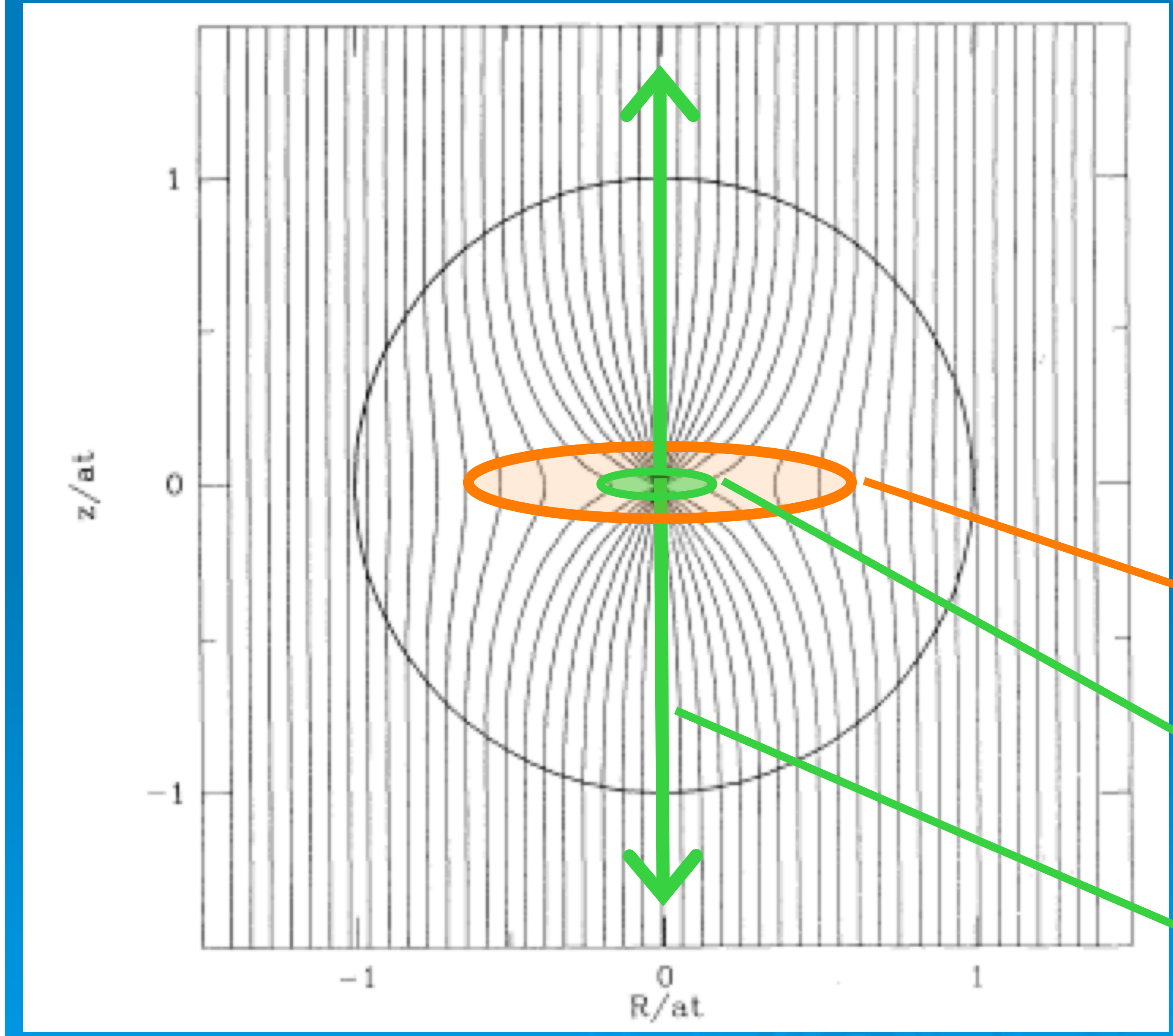


Girart et al. (2006)
Ambipolar diffusion?

Star Formation examples

Testing Magnetized Collapse Models

usually applied to formation of a single low-mass star



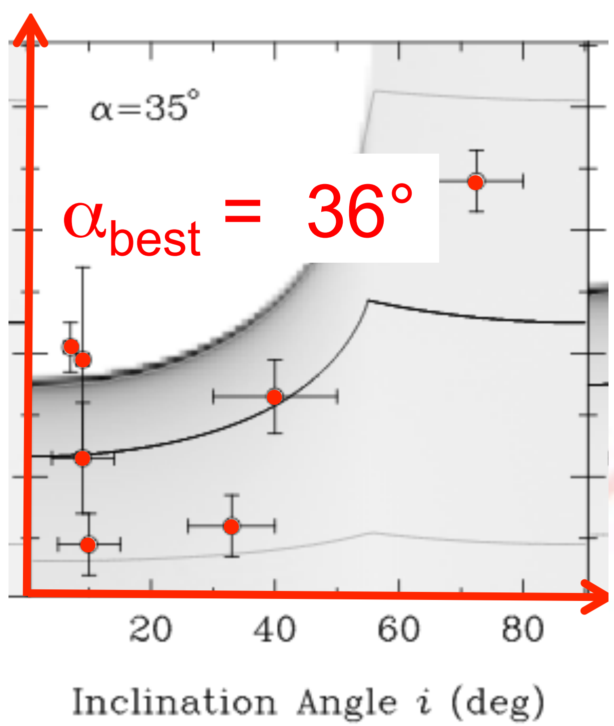
B-field from model of Galli & Shu '93
(see also Fiedler Mouschovias '93, Allen, Li, & Shu '03, Machida, Inutsuka, & Matsumoto '07, Joos, Hennebelle, & Ciardi '12)

- B-field uniform outside infall radius
- pseudo-disk: a dynamic structure (few x 1000 AU)
- Keplerian disk: rotationally supported (few x 100 AU)
- jets/outflows originate inside Keplerian disk

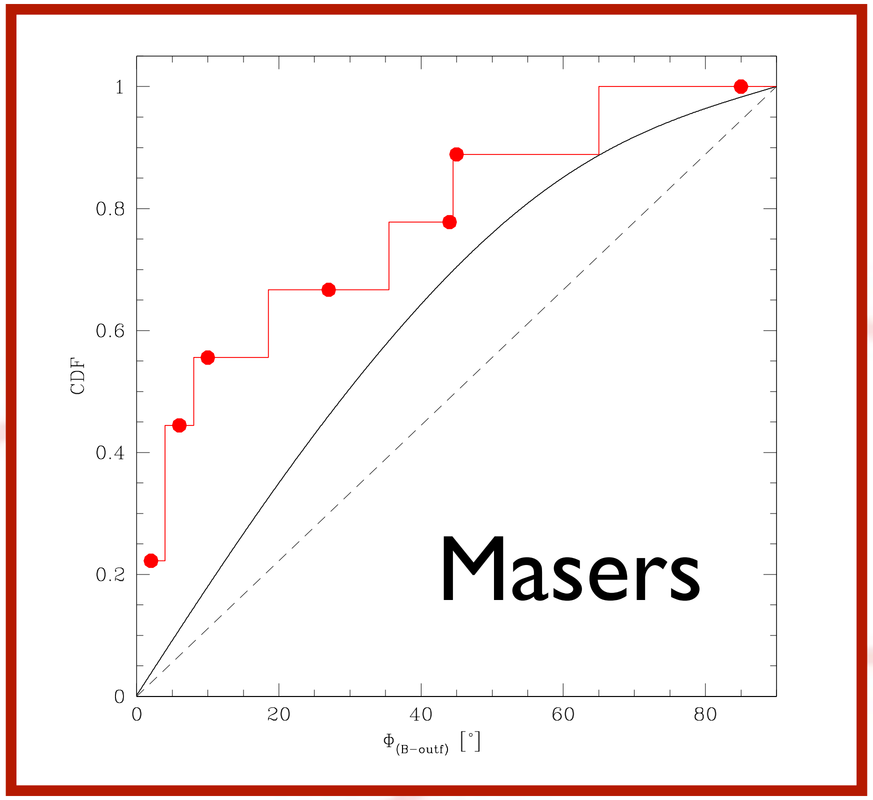
Slide courtesy Giles Novak

Star Formation examples

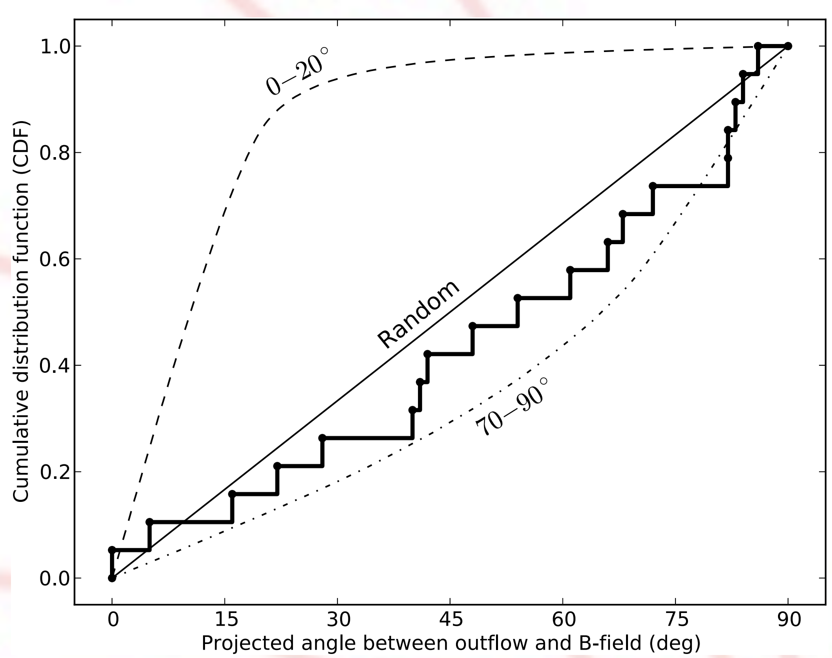
- Looking for relation between outflow/disk orientation and envelope magnetic field



Novak et al. 2013



Surcis et al. 2013



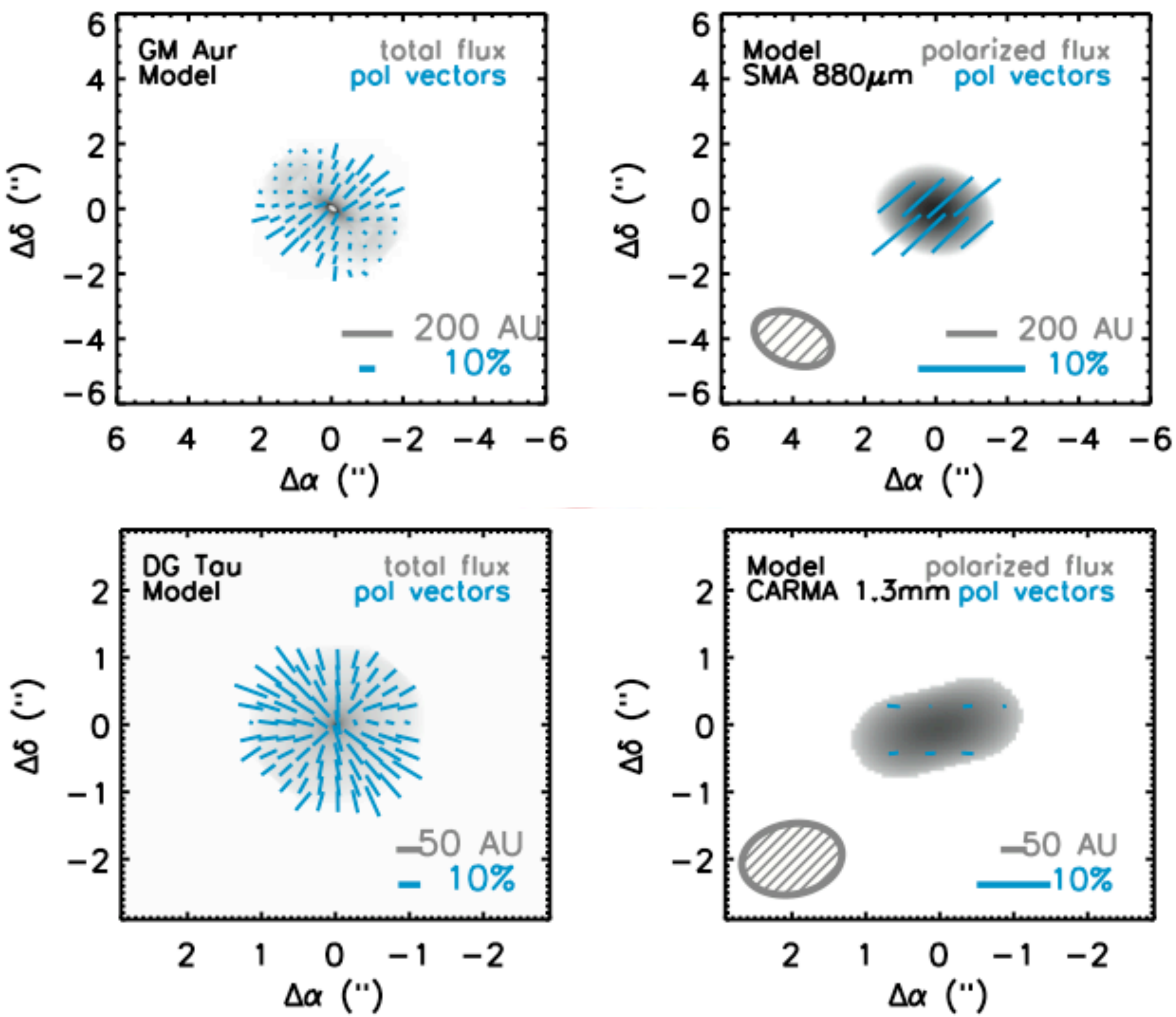
Hull et al. 2013

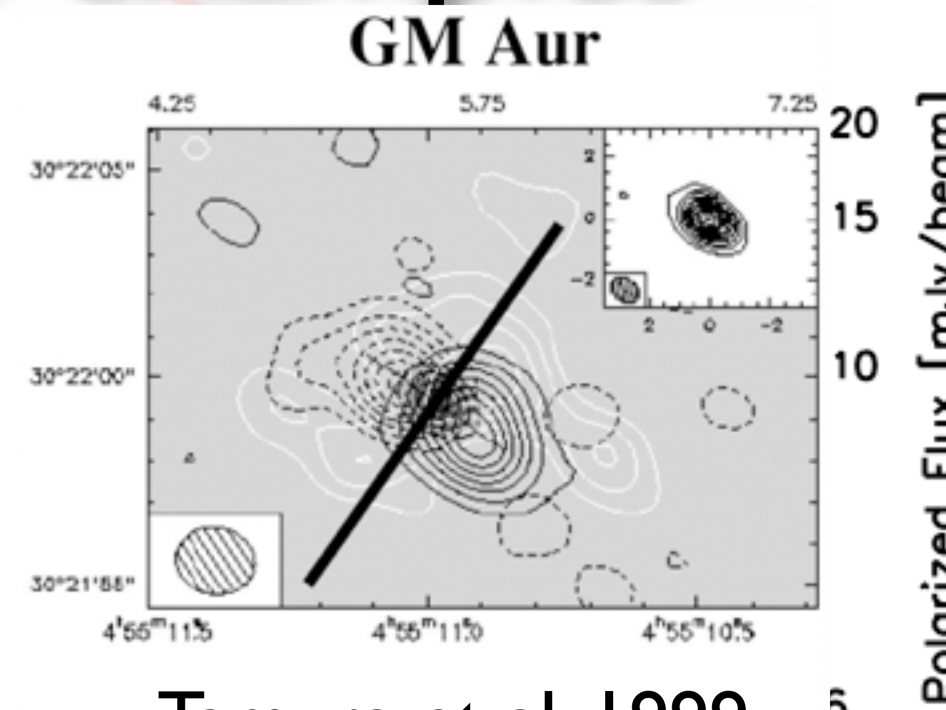
both ~35 degree or less misalignment

marginally significant non-random

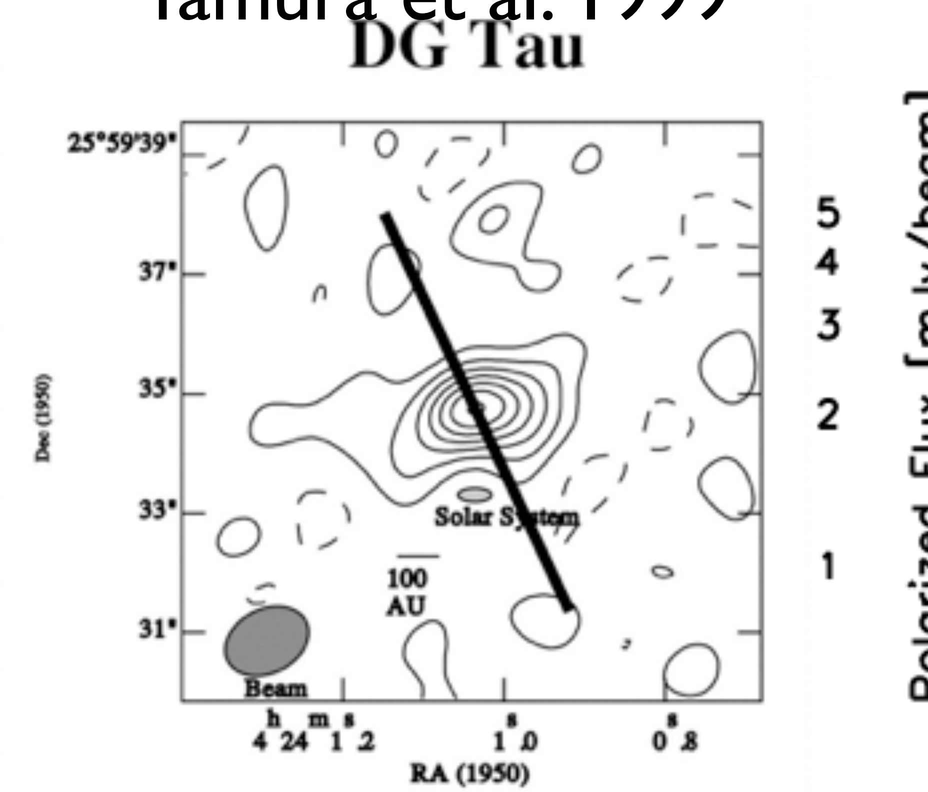
- Different answers
  - multiple sources / observing scales / statistics?

Star Formation examples



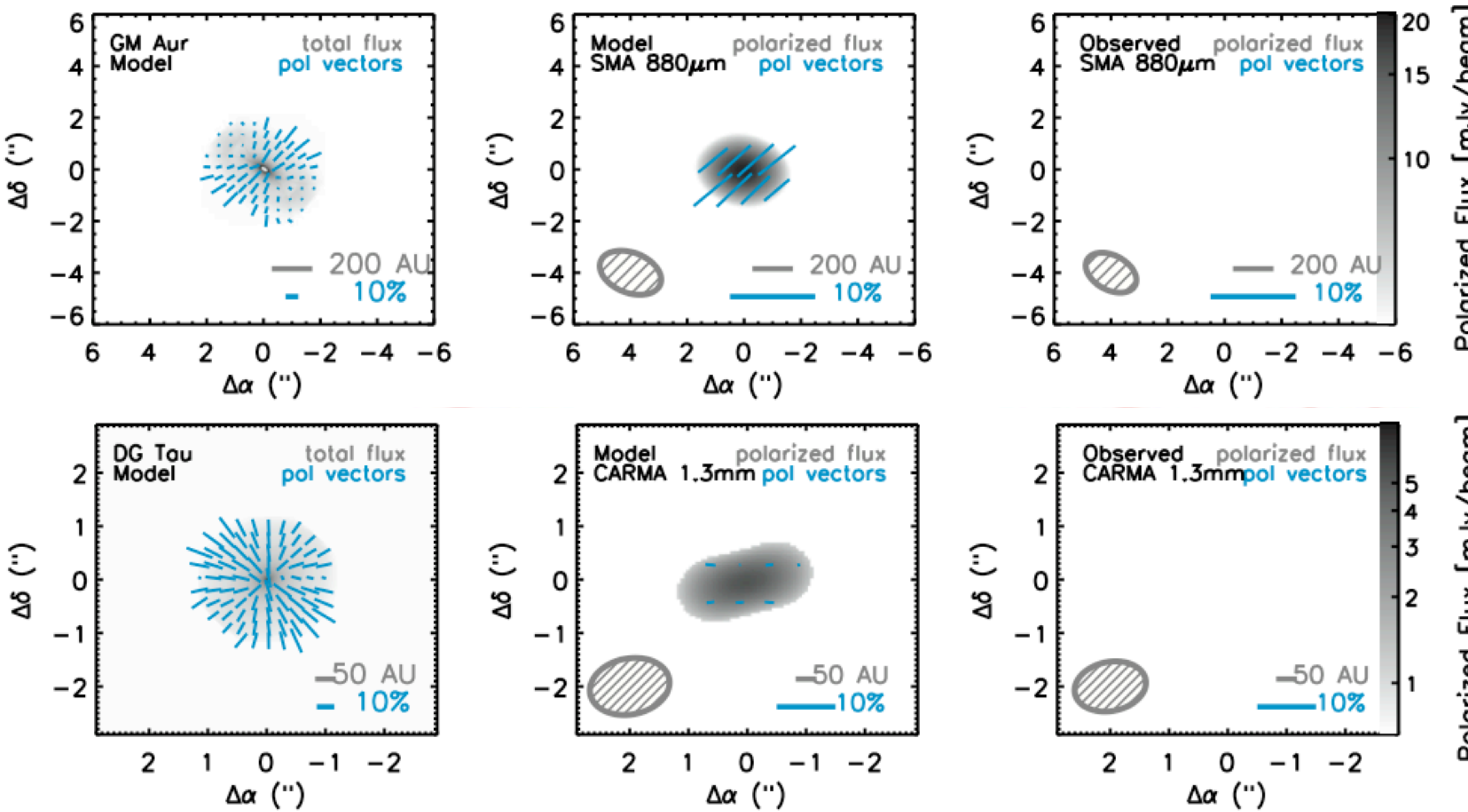


Tamura et al. 1999



T Tauri accretion disks: Hughes et al. 2009, 2013

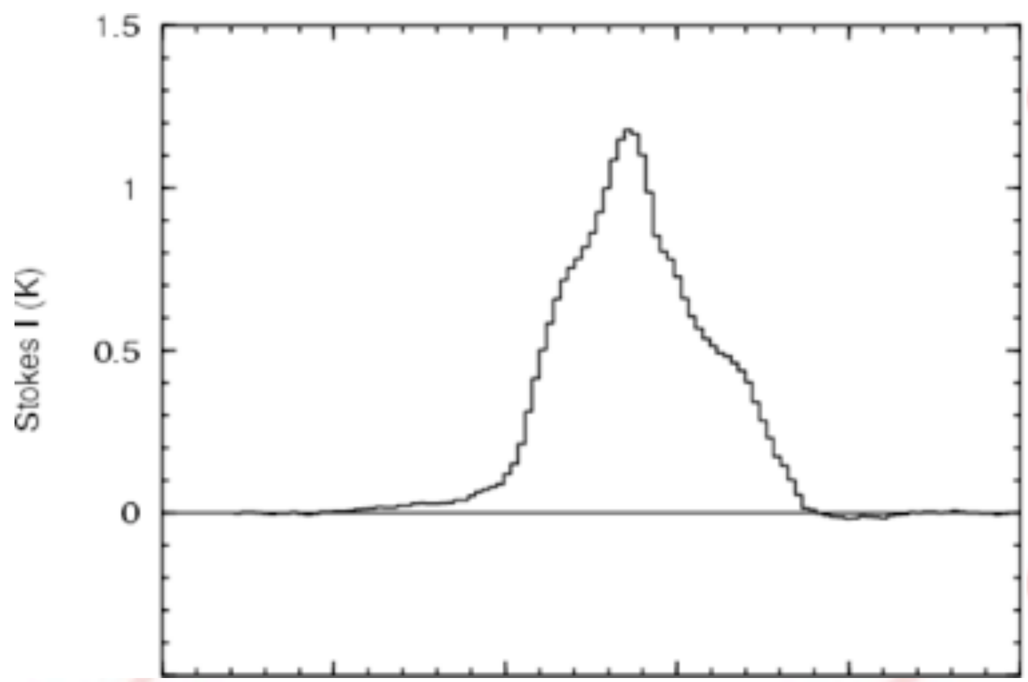
Star Formation examples

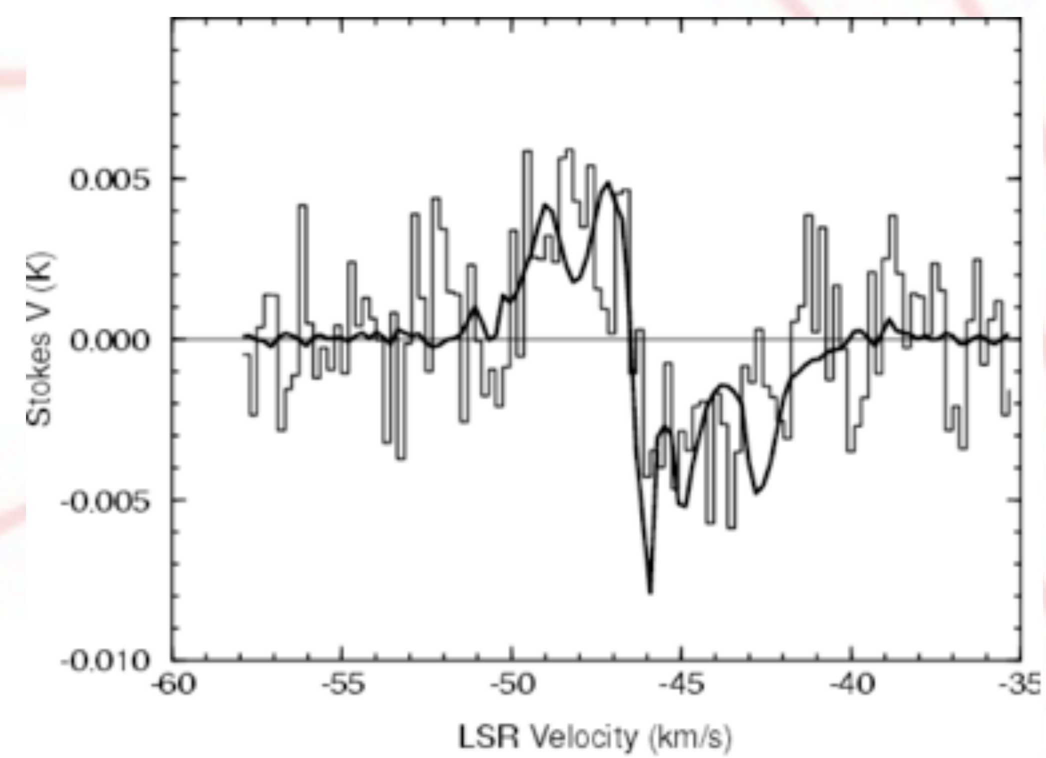


T Tauri accretion disks: Hughes et al. 2009, 2013

Star Formation examples

- Goldreich-Kylafis effect of CO
- Zeeman splitting of masers or e.g. CN/SO

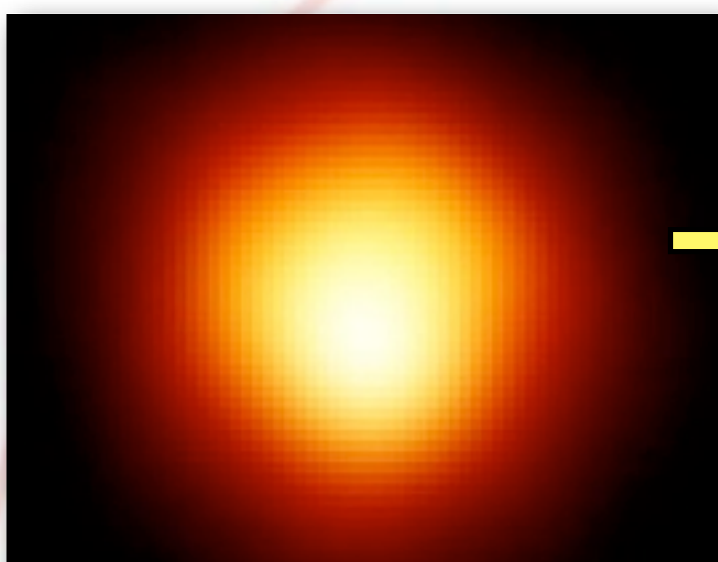




CN, Falgarone et al. 2008

Evolved Stars

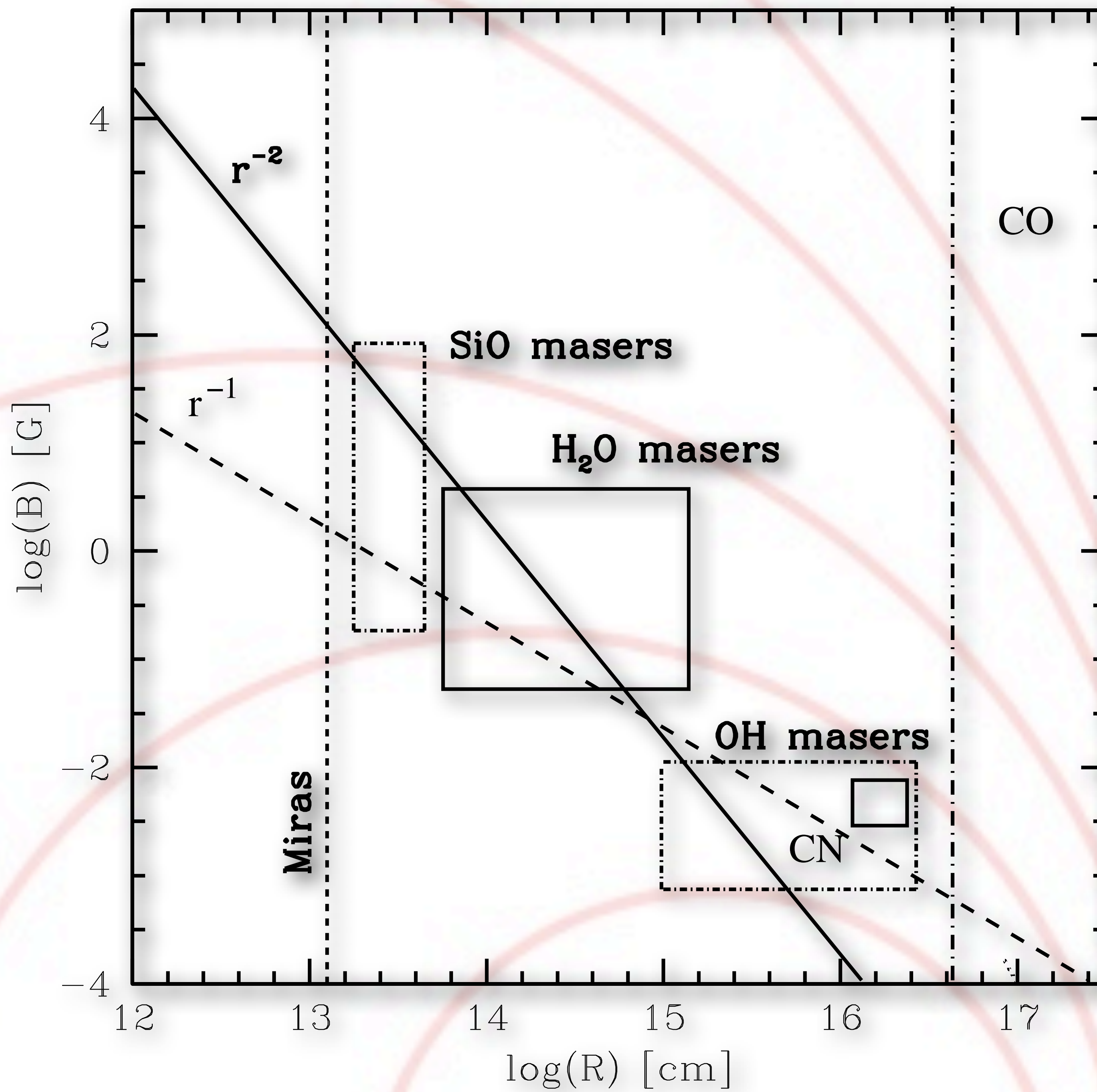
- Magnetic shaping of Planetary Nebulae?
  - origin of the magnetic field (binaries?)
- Magnetic component to AGB mass-loss?



Evolved Stars: AGB

Zeeman studies

- Oxygen rich:
  - SiO at 2 R*
    - B~3.5 (up to 10s) G
  - H_2O at ~5-80 AU
    - B~0.1-2 G
  - OH at ~100-10.000 AU
    - B~1-10 mG
- Carbon rich:
  - CN at ~2500 AU
    - B~7-10 mG

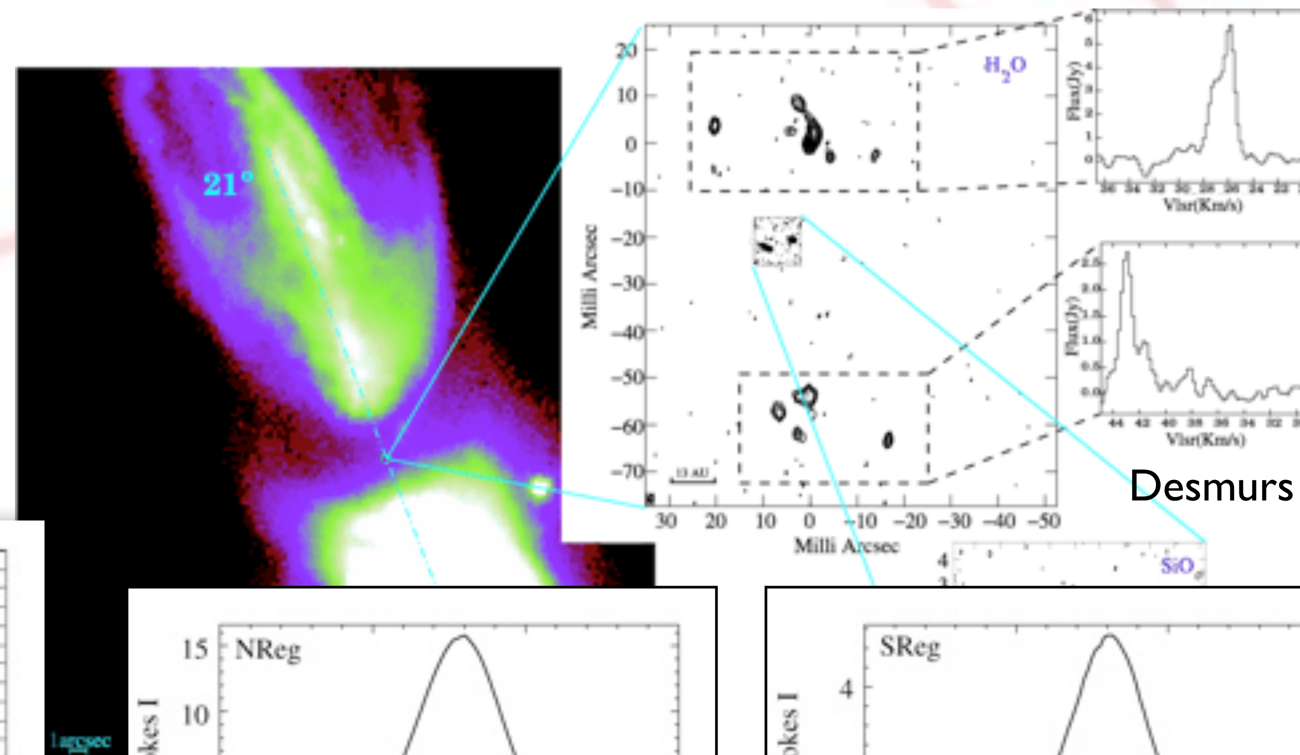


Vlemmings et al. 2002, 2005
Kemball et al. 1997, 2009
Herpin et al. 2006, 2009
Etoka et al. 2004
Reid et al. 1976
Amiri et al. 2012

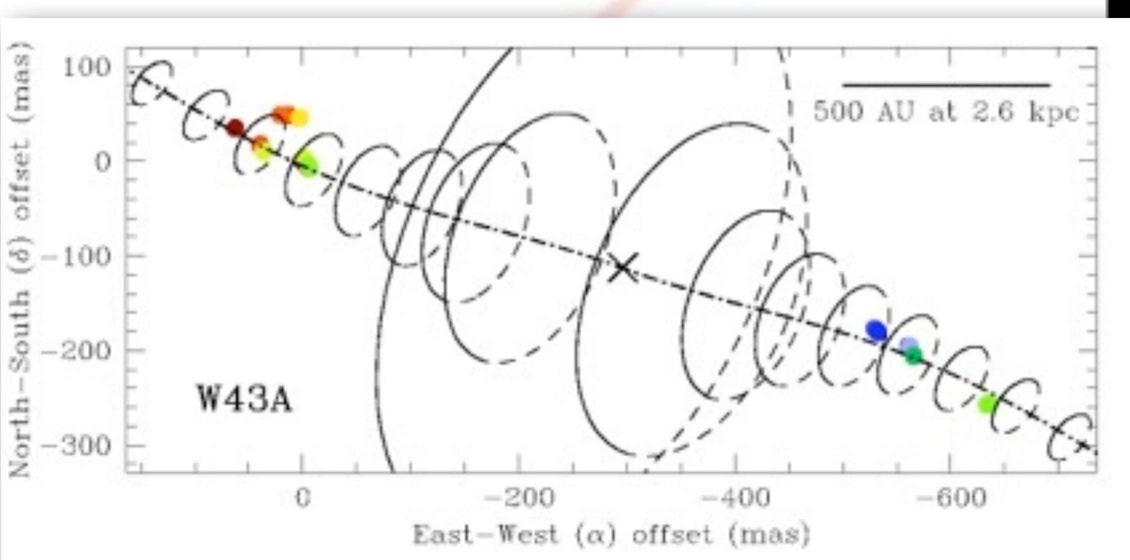
Evolved Stars: post-AGB

- W43A, post-AGB water-fountain
- Toroidal, collimating magnetic field: Bφ = 80 mG
- Enhanced in the H_2O masers
  - Around the jet B = 100 μG from OH masers
  - GBT confirmed strength in H_2O jet and shows expected reversal.
  - Extrapolated (Bφ ∝ r^{-1}) surface magnetic field of B~2 G.

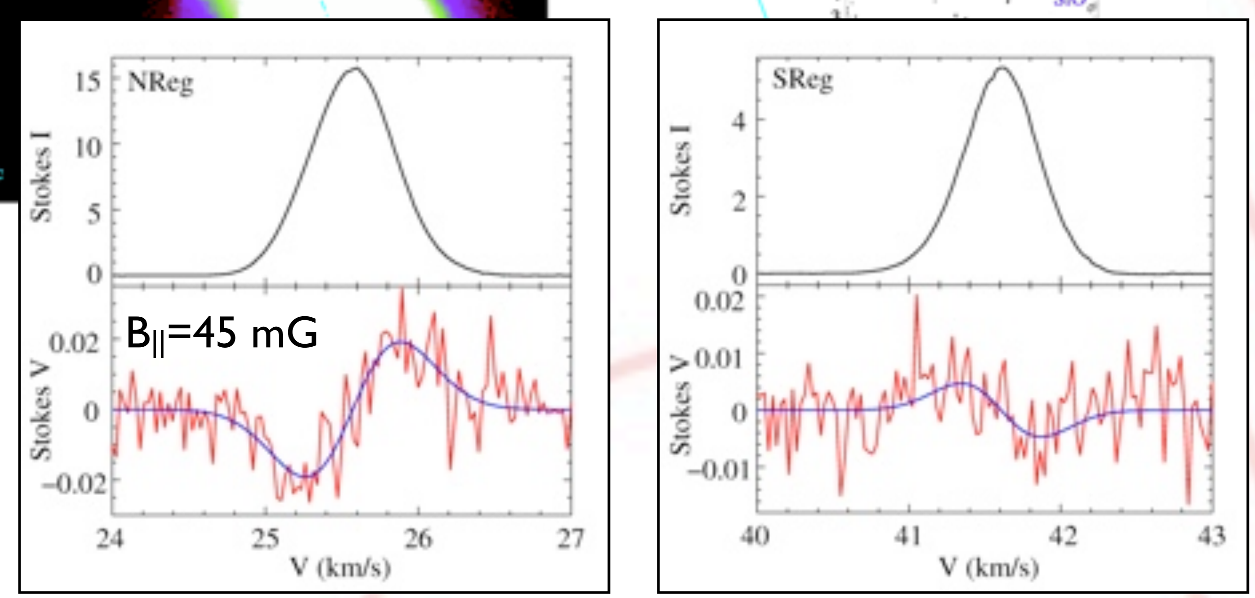
- Rotten Egg Nebula
- H_2O masers magnetic field measurement
  - Extrapolated (Bφ ∝ r^{-1}) surface magnetic field of B~3 G



Desmurs et al. (2007)

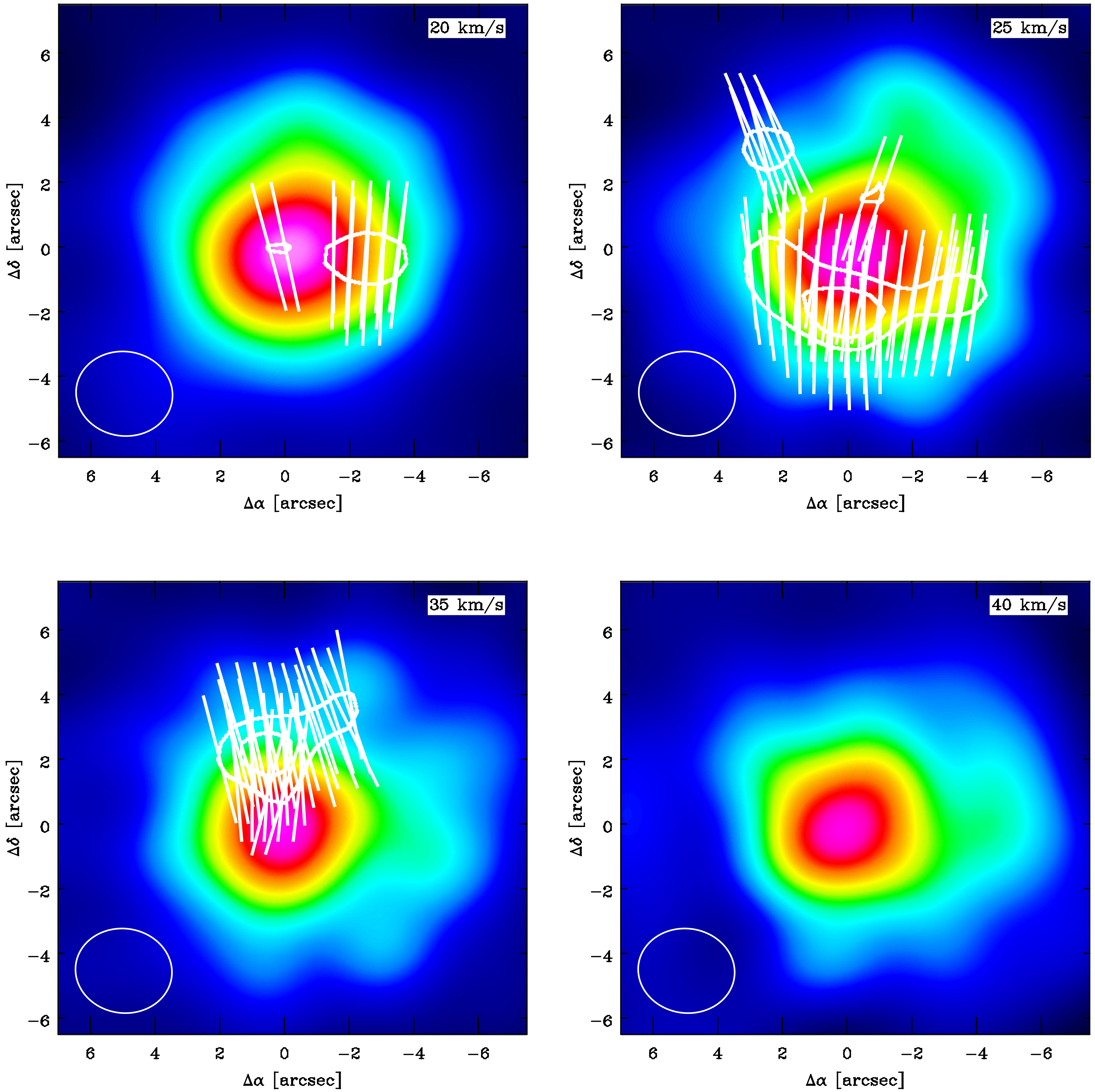


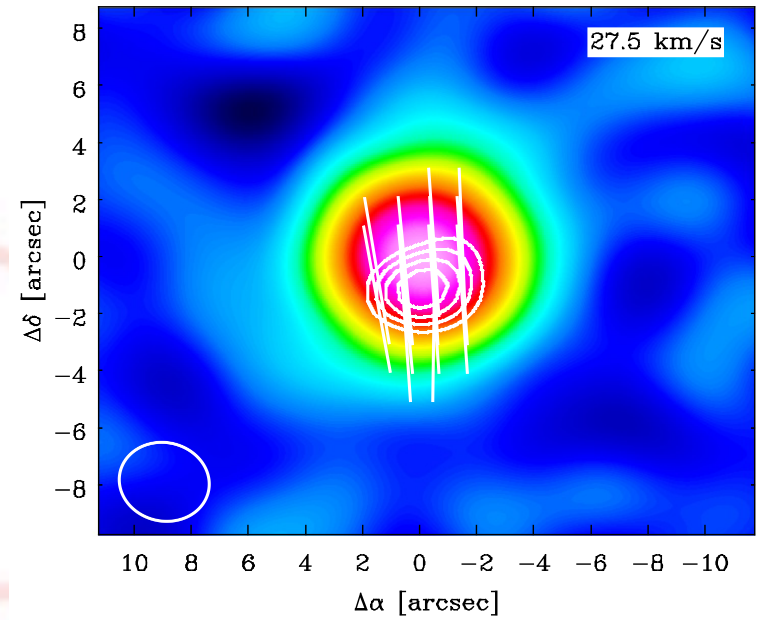
Vlemmings et al. (2006); Amiri et al. (2010)



Leal Ferreira et al. (2012)

Evolved Stars examples





SiO(5-4) - up to 8%

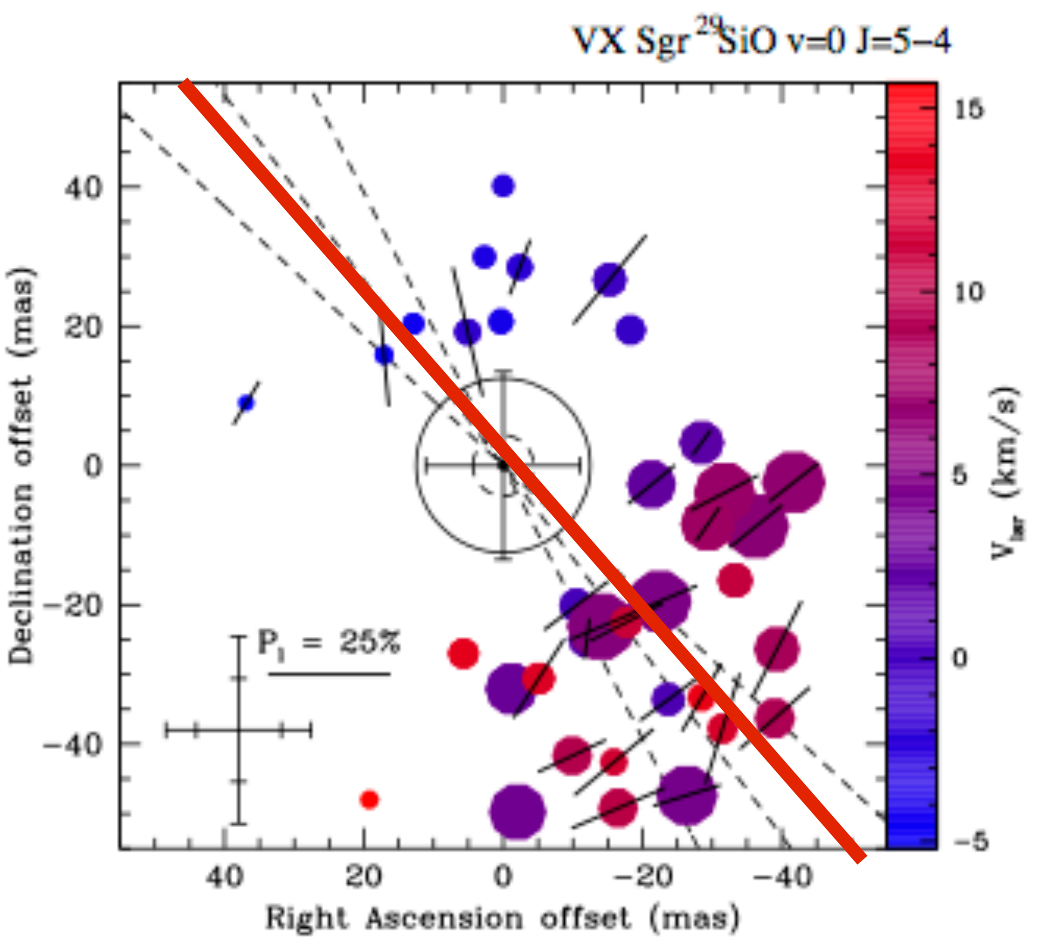
CO(2-1) - up to 13%

- non-radial
- indicative of large scale B-field

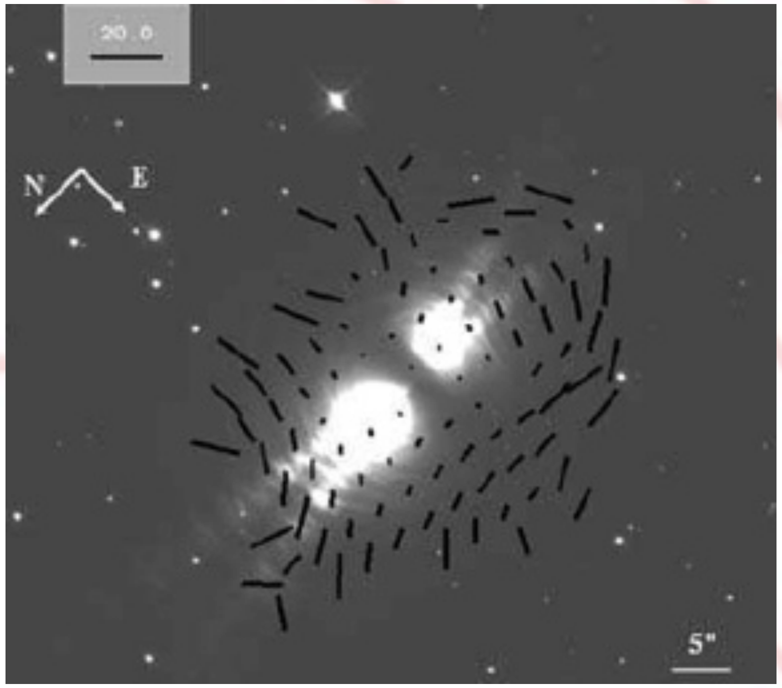
Vlemmings et al. 2012, A&A in press

Evolved Stars examples

Maser linear polarization of various lines (SiO, water, HCN)



215 GHz SiO (Vlemmings et al. 2011)

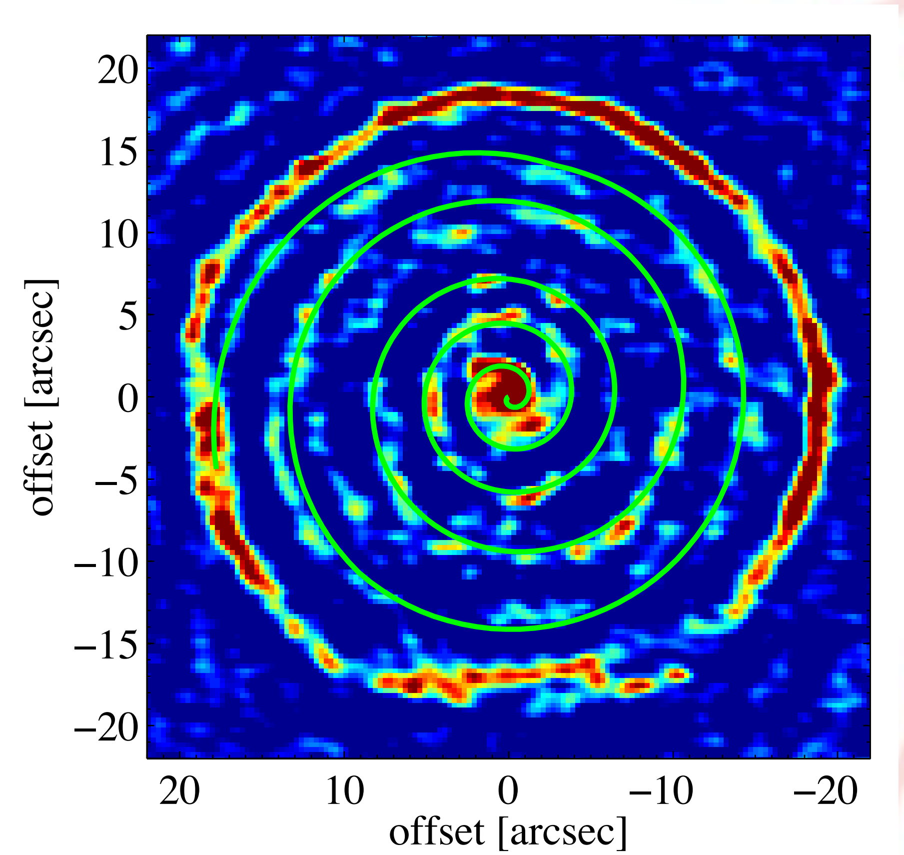


Sabin et al. 2002;
B-vectors for CRL 2688 (Egg Nebula)

Dust polarization of PNe

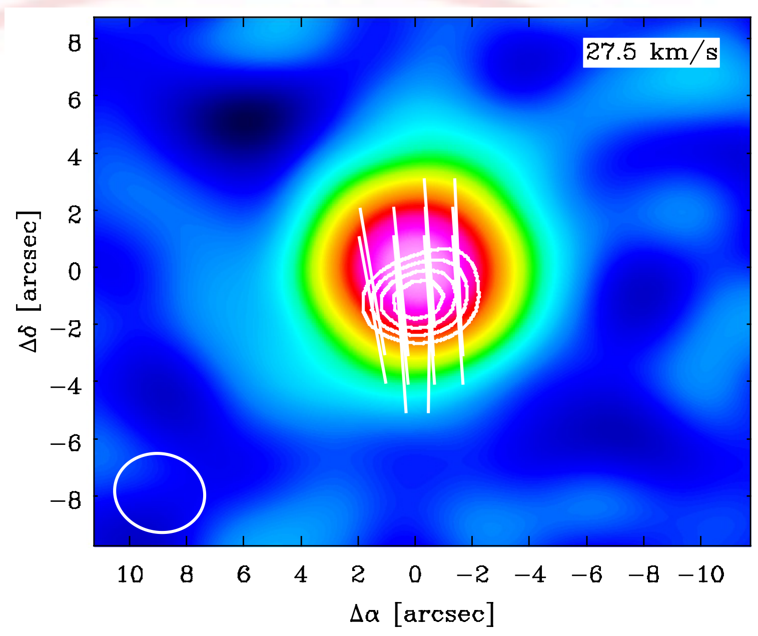
Evolved Stars examples

- Dust grain composition (of the large dust grain component) of P-PNe
- Compare CO morphology with magnetic field (GK-effect)

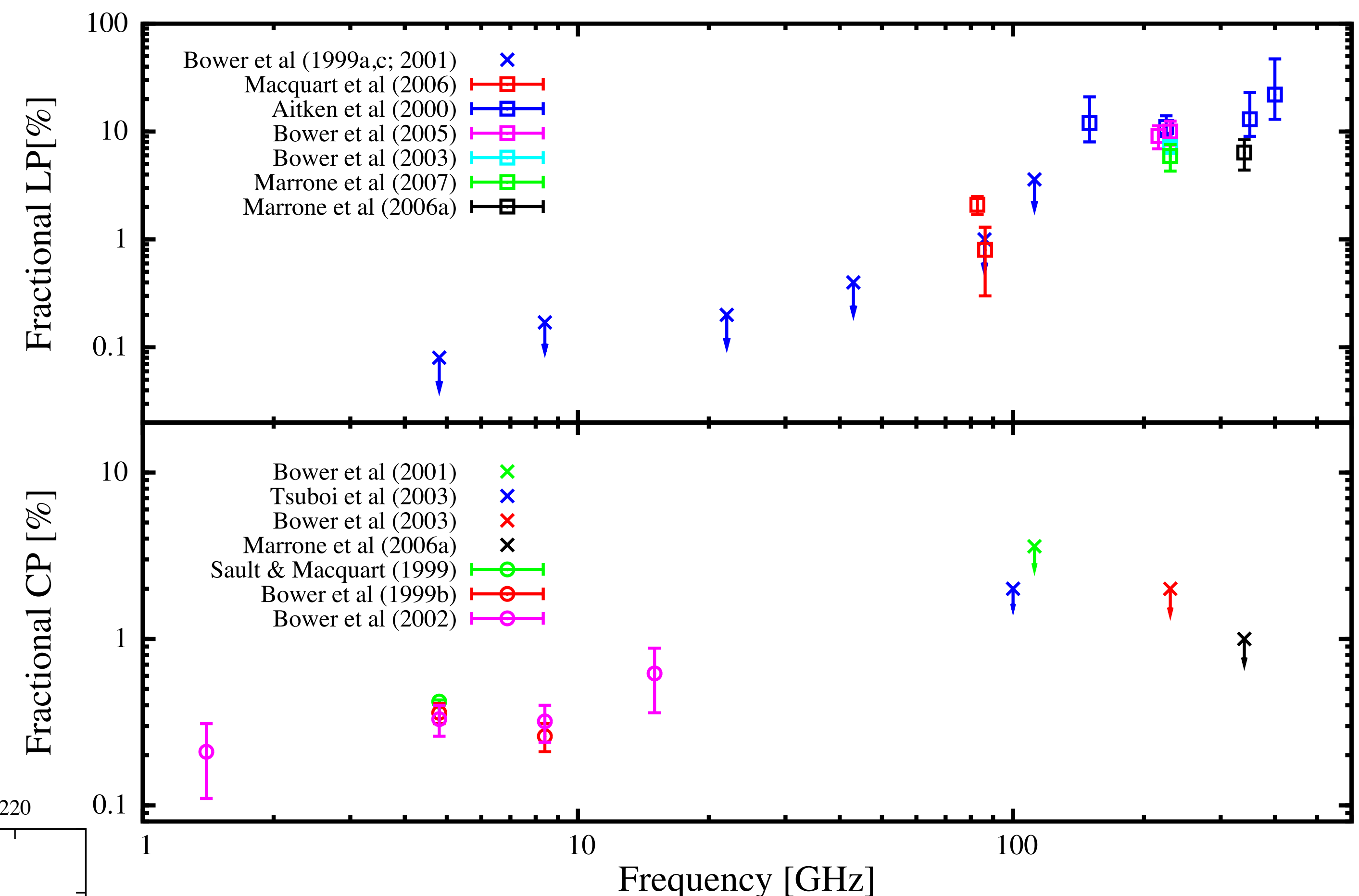


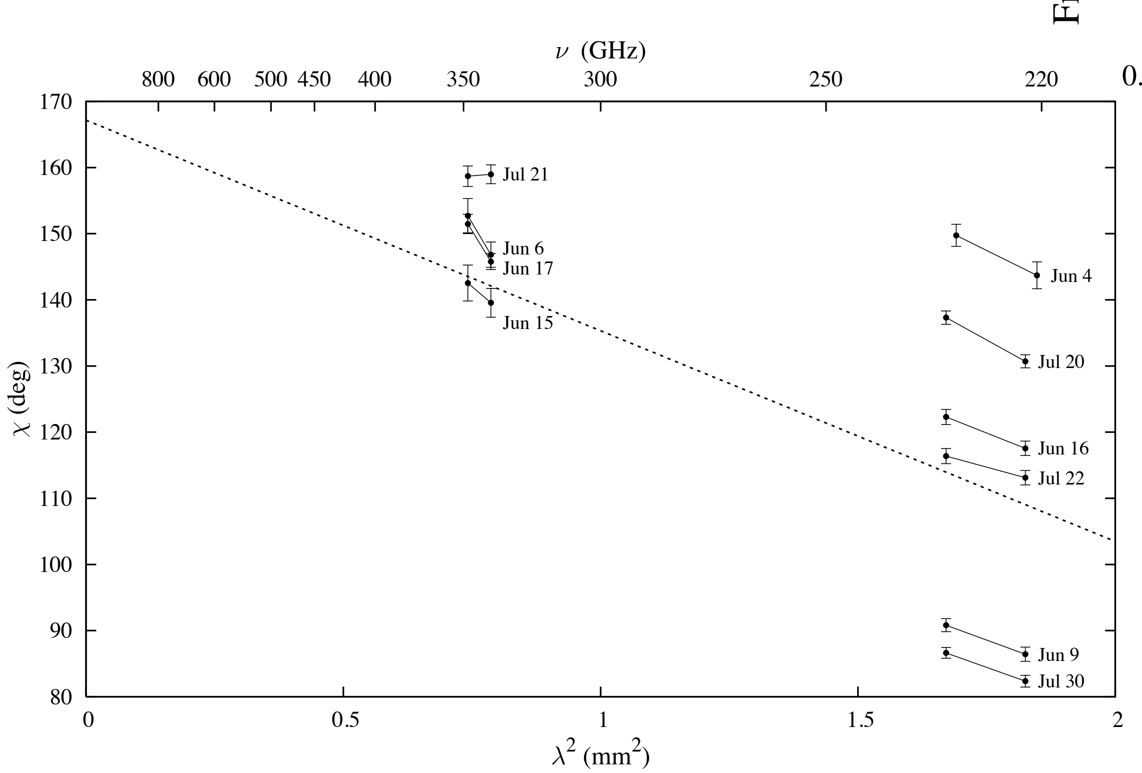
R Scl (Maercker et al. 2012)

SMA full track results can be done with ALMA in a matter of minutes



Galactic Centre



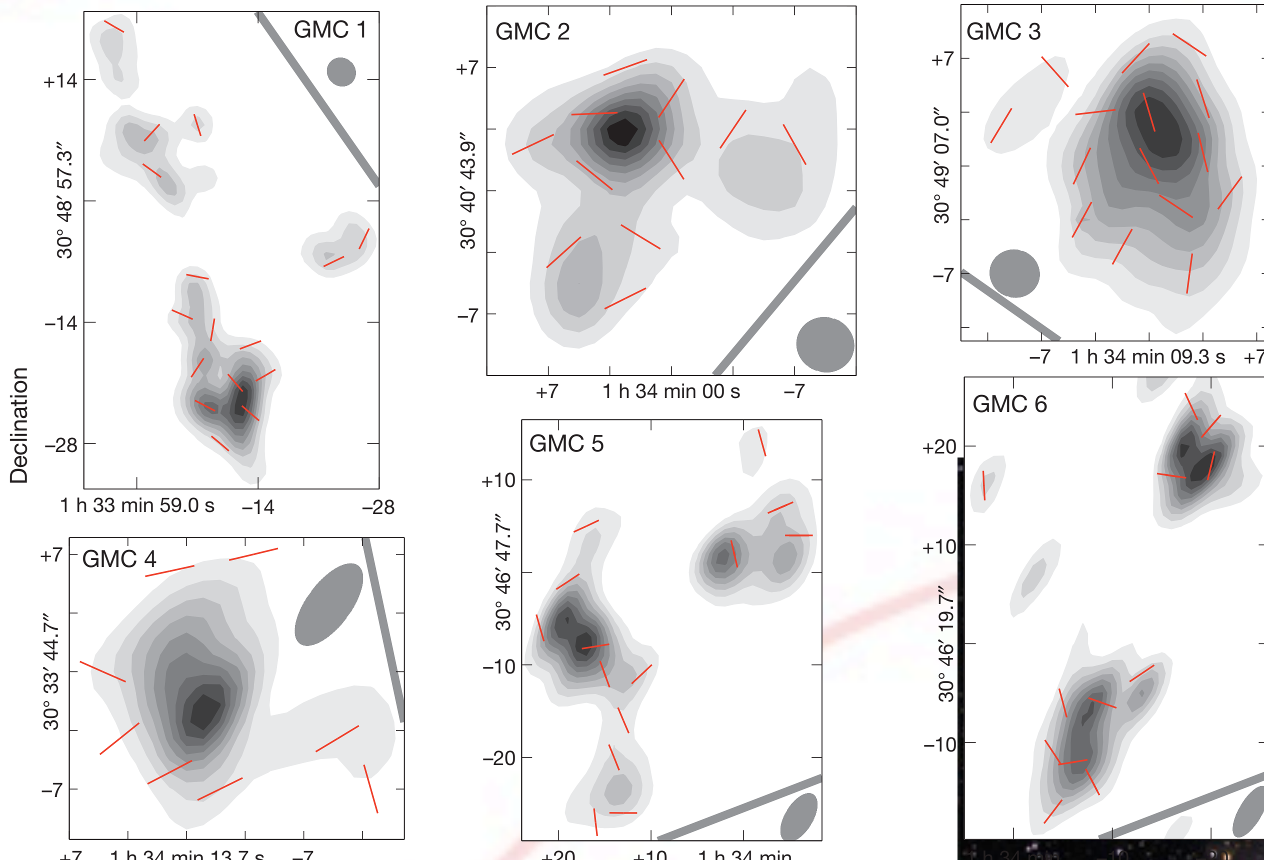


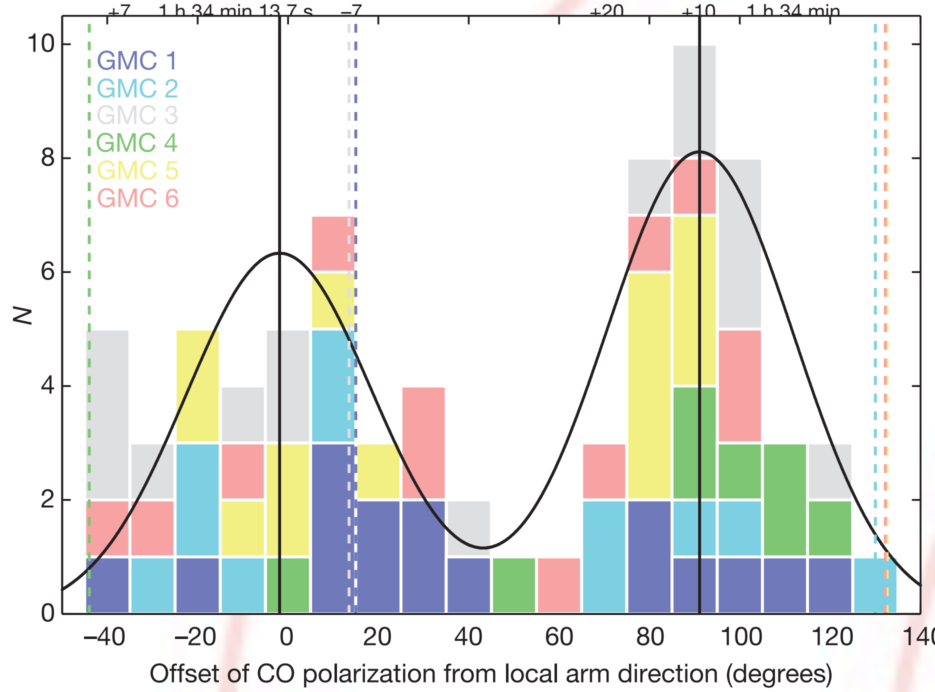
Faraday rotation:
Marrone et al. 2009

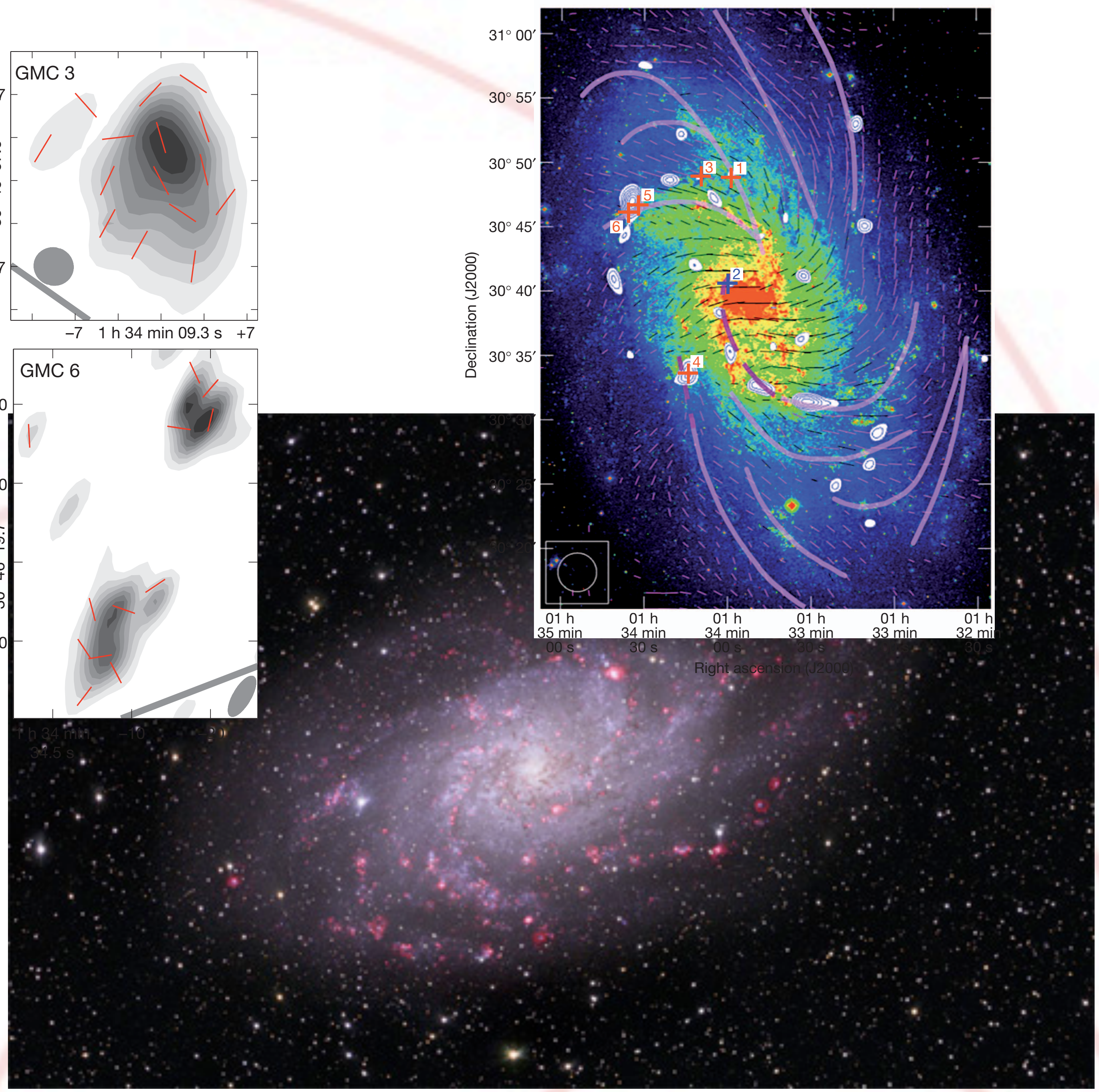
(Very few) Science Examples:

Extra-Galactic Science

Galaxies - Molecular Clouds

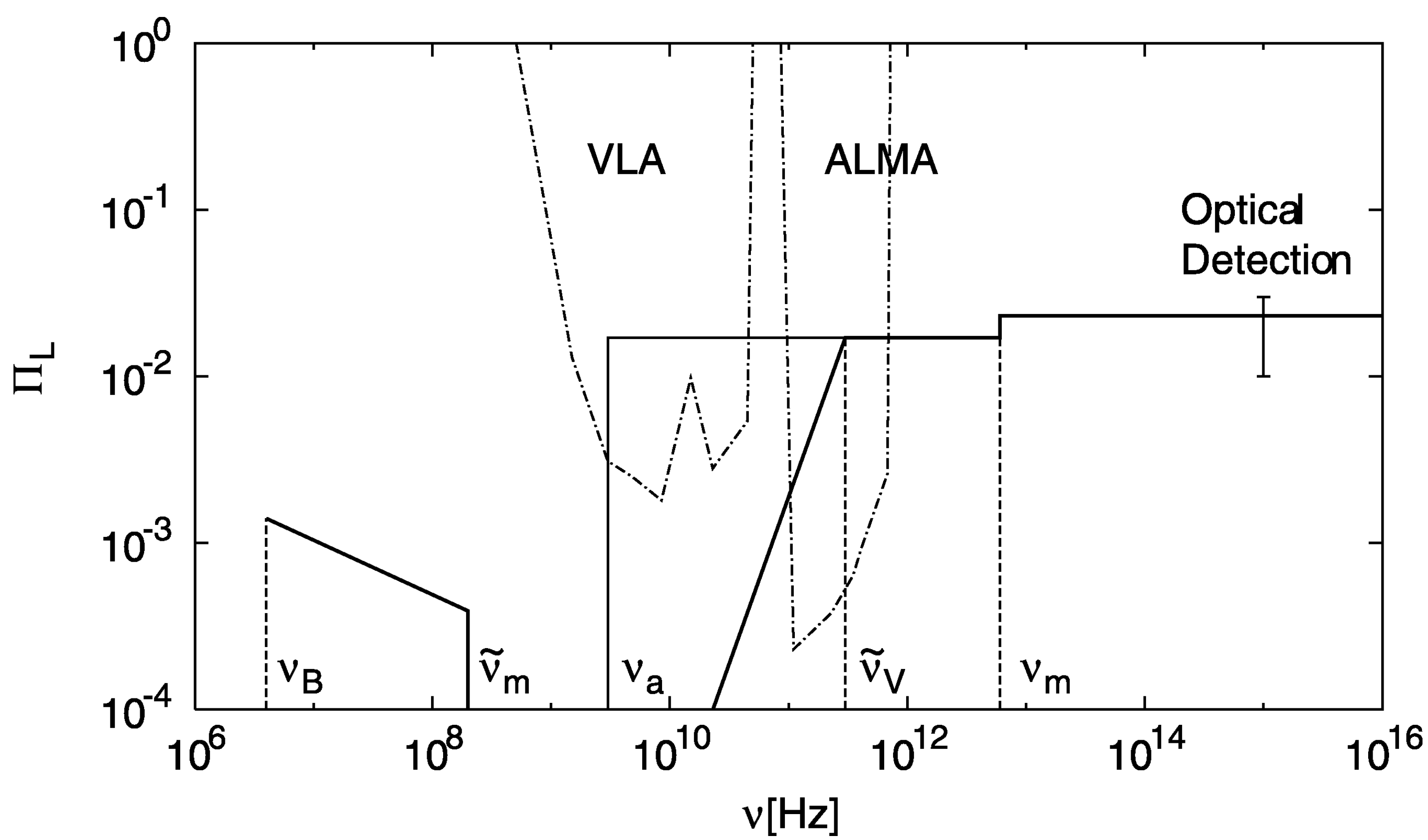






M33 (Li & Henning, 2011)

GRBs



Faraday rotation effect with ALMA

(Toma et al. 2009)

If ν_a is determined by the observation of a bright burst and the linear polarization is not detected at $\nu \gtrsim \nu_a$ with VLA and detected at $\nu \gg \nu_a$ with ALMA, it becomes clear that a number of the thermal electrons exist and the magnetic field is ordered on large scales. If we determine $\tilde{\nu}_V$, the electron-proton coupling parameter f can be constrained by equation (7).

AGN (jets)

- See Massardi/Laing talks

Some modeling options

ARTIST

Adaptive Radiative Transfer Innovations for Submillimeter Telescopes

on behalf of the ARTIST team:

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Centre for Star and Planet Formation and Niels Bohr Institutet, Copenhagen
Sterrewacht Leiden, Leiden
Institut de Ciències de l'Espai, Barcelona
Onsala Space Observatory, Onsala
Argelander Institute for Astronomy, Bonn
MPIA, Heidelberg

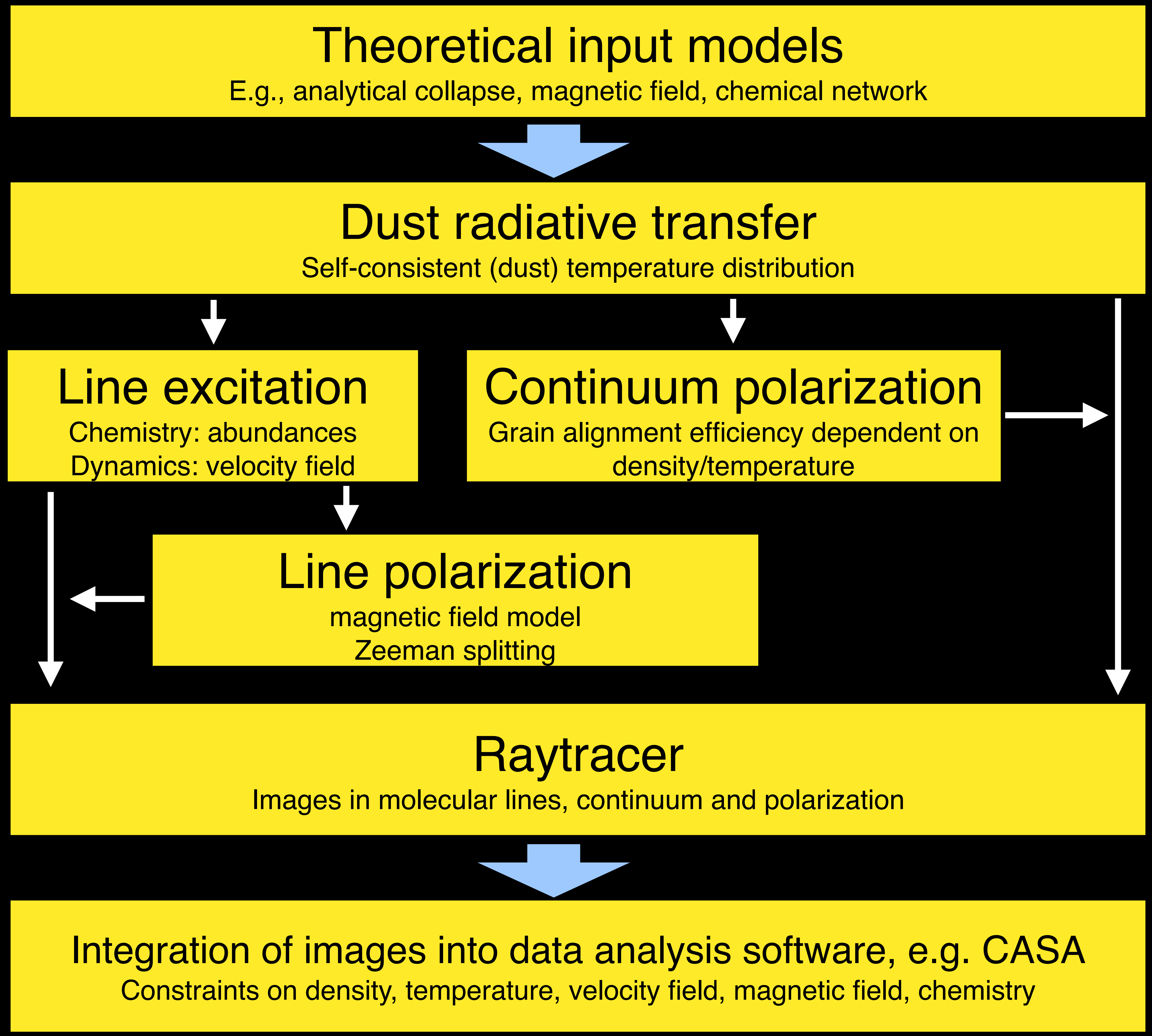
The ARTIST components

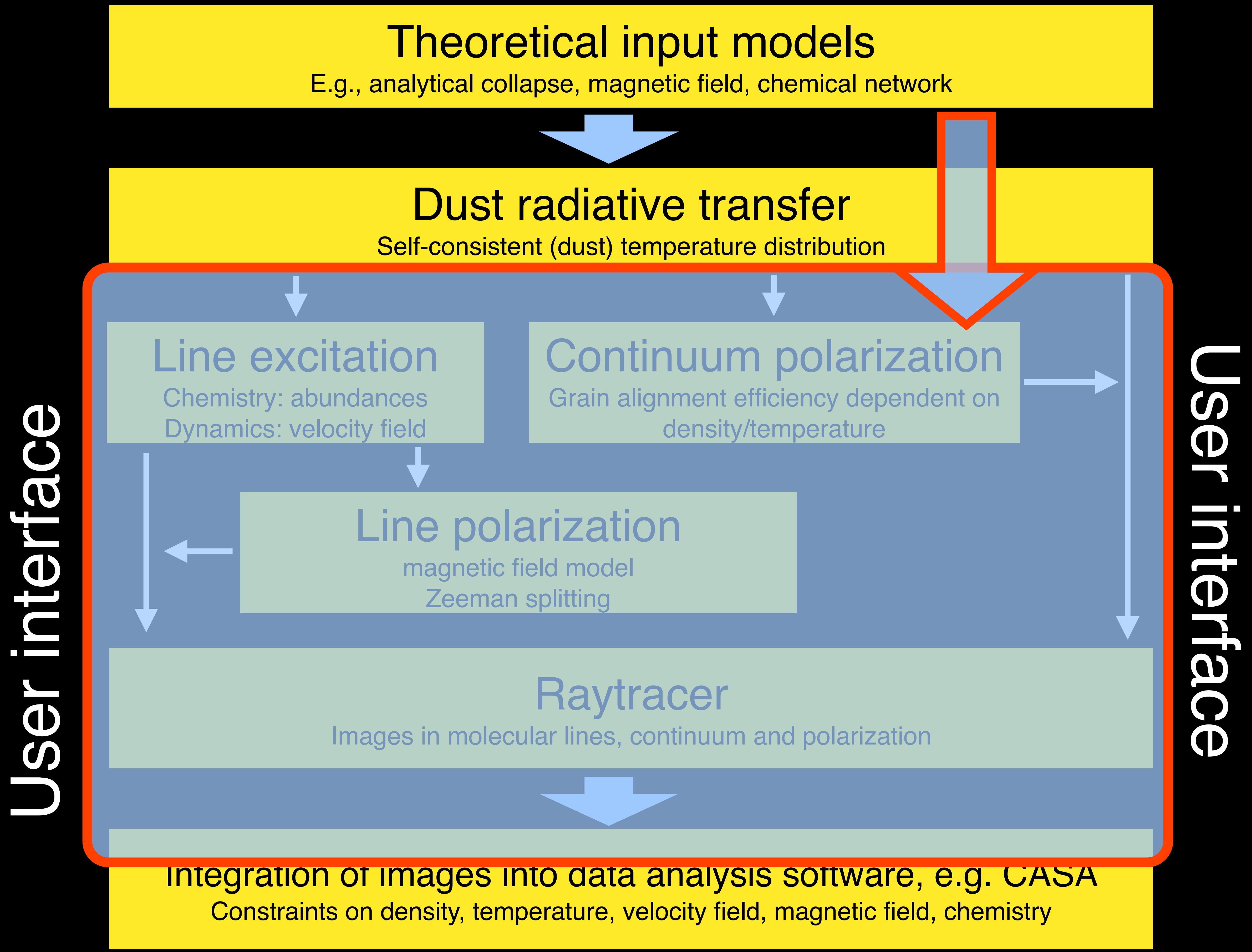
1) An innovative radiative transfer code using adaptive gridding that allows simulations of sources with arbitrary (3D) structures, ensuring rapid convergence - even for molecules with a complex level structure, e.g., H_2O

2) Tools for modeling the polarization of line and dust emission, information that will come with standard ALMA observations

3) A Python-based comprehensive interface with Graphcal User Interface connecting these packages and providing links to extrernal codes

4) A library of pre-coded common models (e.g., Shu collapse model) for the user to browse.


Theoretical input models
E.g., analytical collapse, magnetic field, chemical network
Dust radiative transfer
Self-consistent (dust) temperature distribution
Line excitation
Chemistry: abundances
Dynamics: velocity field
Continuum polarization
Grain alignment efficiency dependent on density/temperature
Line polarization
magnetic field model
Zeeman splitting
Raytracer
Images in molecular lines, continuum and polarization
Integration of images into data analysis software, e.g. CASA
Constraints on density, temperature, velocity field, magnetic field, chemistry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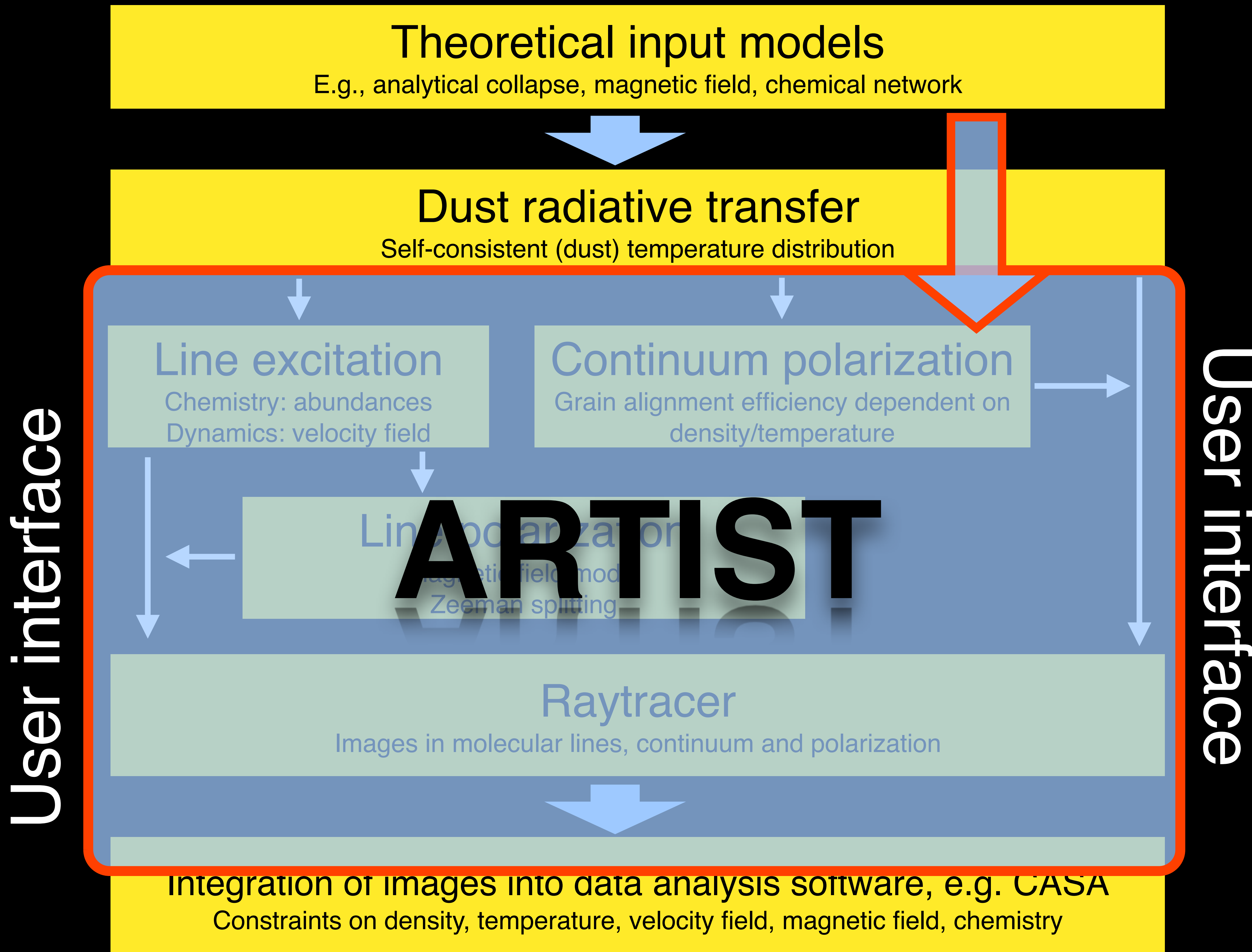
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ARTIST
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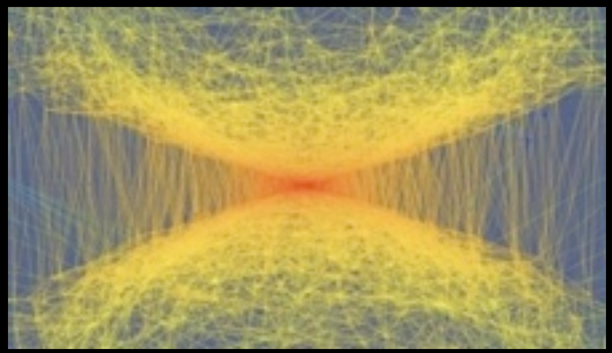
Constraints on density, temperature, velocity field, magnetic field, chemistry
User interface
User interface

Components: Line excitation / Raytracing

LIME

Brinch & Hogerheijde, 2010



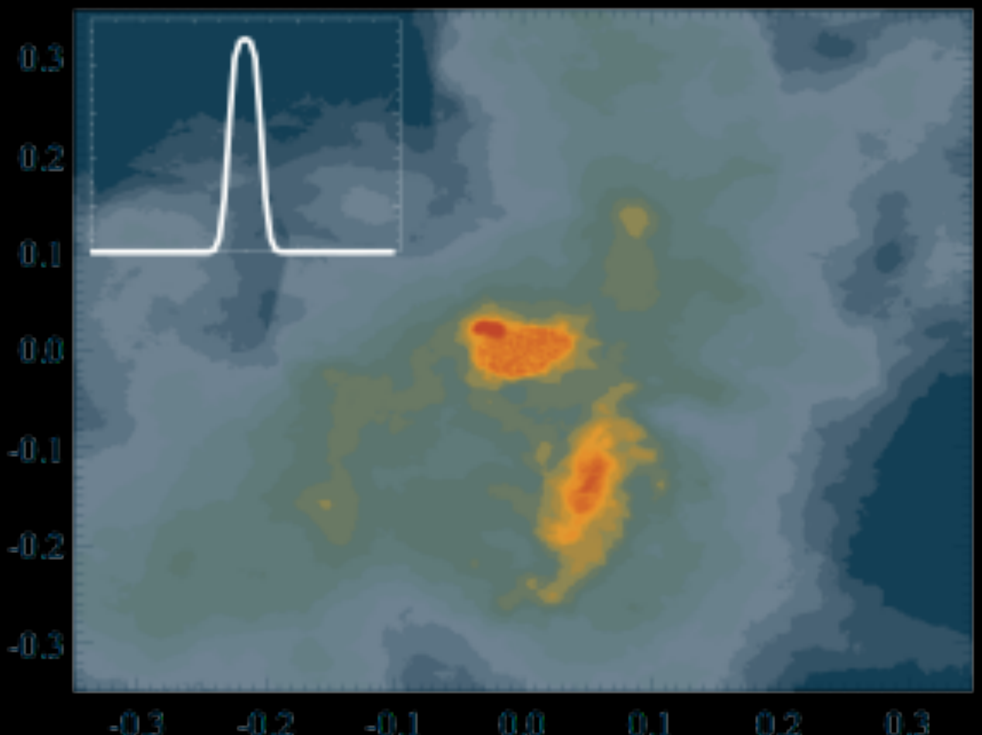
LIME is a new and innovative non-LTE spectral line radiation transfer code for 3D models in arbitrary geometries.

Instead of a 2D regular mesh (e.g. nested AMR) Lime transports photons along the edges of a 3D unstructured Delaunay-grid (Ritzerveld & Icke 2006)

Grid points are placed semi-randomly but grid point distribution is well controlled
=> grid is very flexible

Visualization with VTK

Image data are written in FITS format that can be used in directly in CASA (simdata).



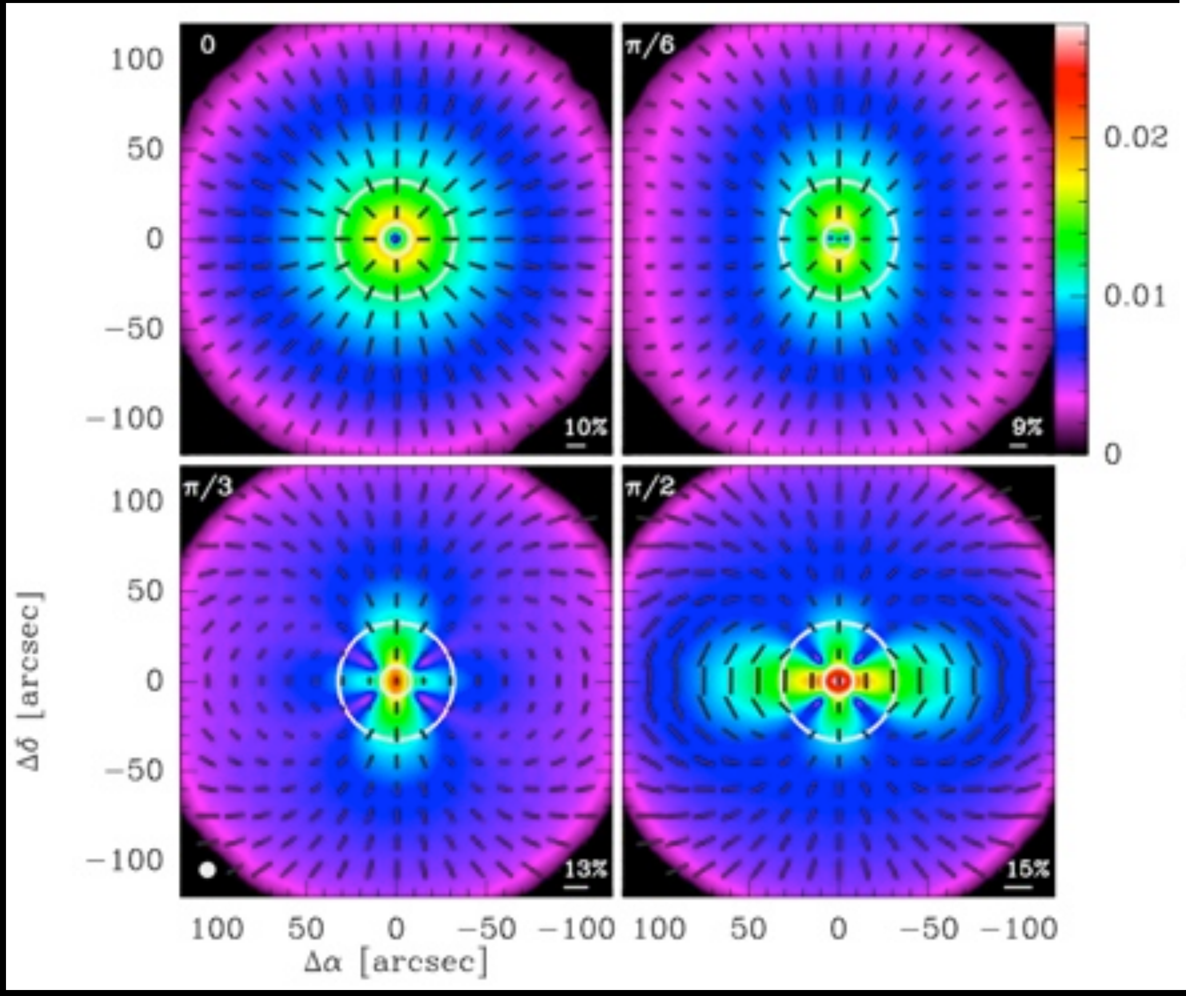
Components: Continuum polarization

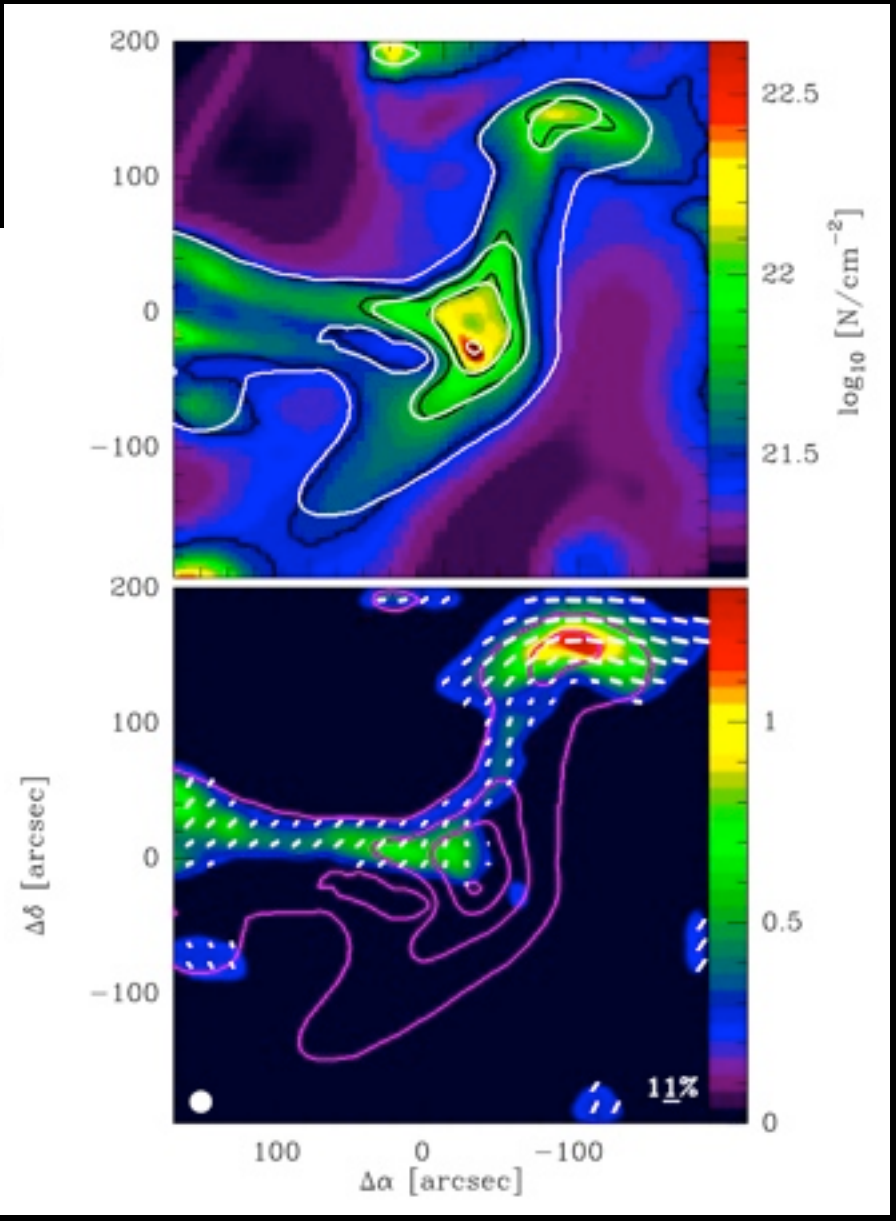
Dustpol (Padovani et al. 2012, in press.)

Calculates Stokes parameters on the basis of Lee & Draine 1985, Padoan 2011

Grain alignment efficiency (function of density/temperature)
3D magnetic field structure

=> Synthetic stokes vectors





Components: Line polarization

Line polarization (Kuiper et al. in prep) is in the testing/benchmarking phase

Full stokes radiative transfer using a modified version of LIME

Goldreich-Kylafis effect (Unequal population of magnetic-substates in an anisotropic velocity/radiation field)

Conclusions

- ALMA will provide breakthrough polarization science
  - while likely throwing up some new puzzles
- Several applications will require:
  - Extended polarization mapping with ACA and TP
  - Stable polarization across primary beam
  - Stable polarization characteristics with time
  - at least ~0.1% accuracy after calibration (preferably better)