First detection of outer 3D sub-miligauss field with atomic alignment

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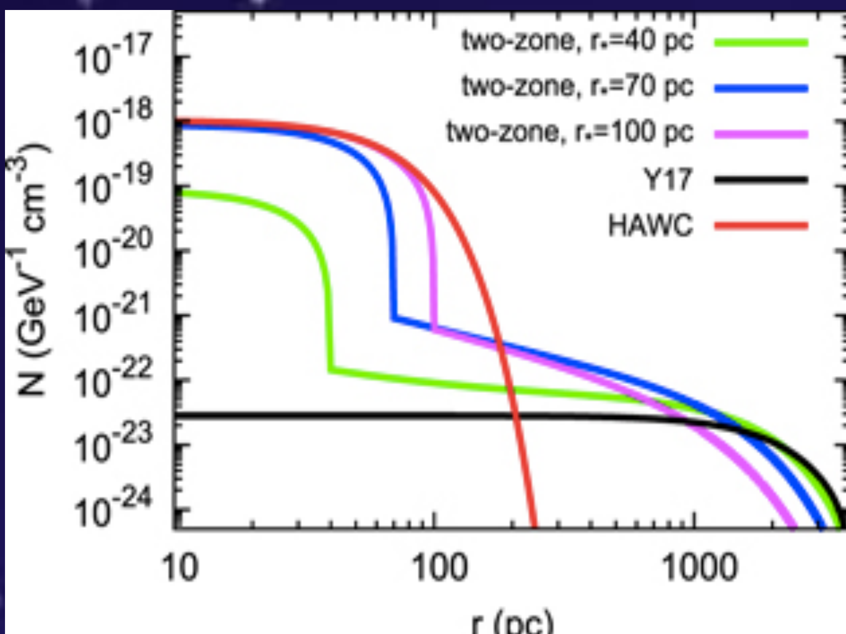
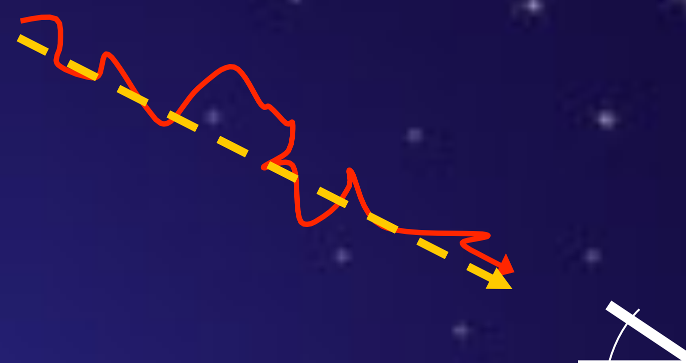
Understanding of astroplasma is limited by knowledge of B field!

Puzzle of Geminga's TeV halo

Two zone diffusion vs. Anisotropic diffusion





Abeysekera+2017; Fang+ 2018

Liu, HY, Zhang 2019

There is no universal magnetic diagnostics in diffuse medium

Most common ways of tracing magnetic fields:

- Zeeman splitting ($B_{\|}$):

- Faraday rotation ($B_{\|}$):

- Synchrotron radiation ($B_{\perp}$):
- Light polarization by dust ($B_{\perp}$):
  - Star light polarization
  - Grain IR emission

Outline

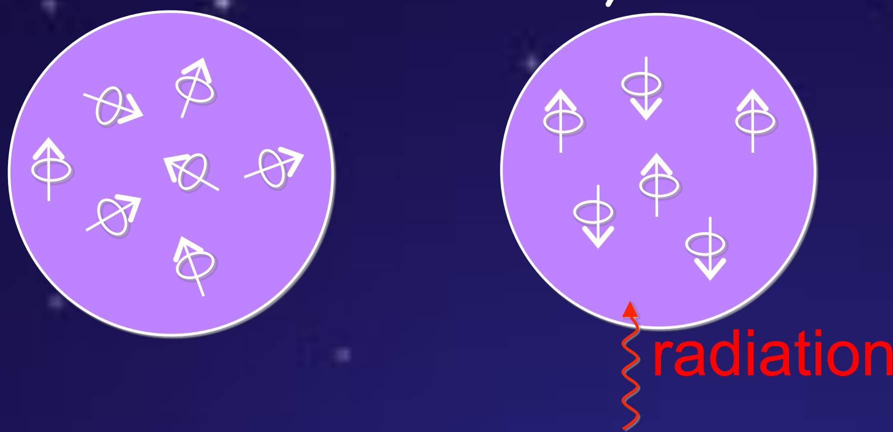
- Brief Review of GSA theory
- Discovery of absorption line polarimetry from GSA
- Other observational perspectives

Atoms on the ground state can be aligned by anisotropic radiation

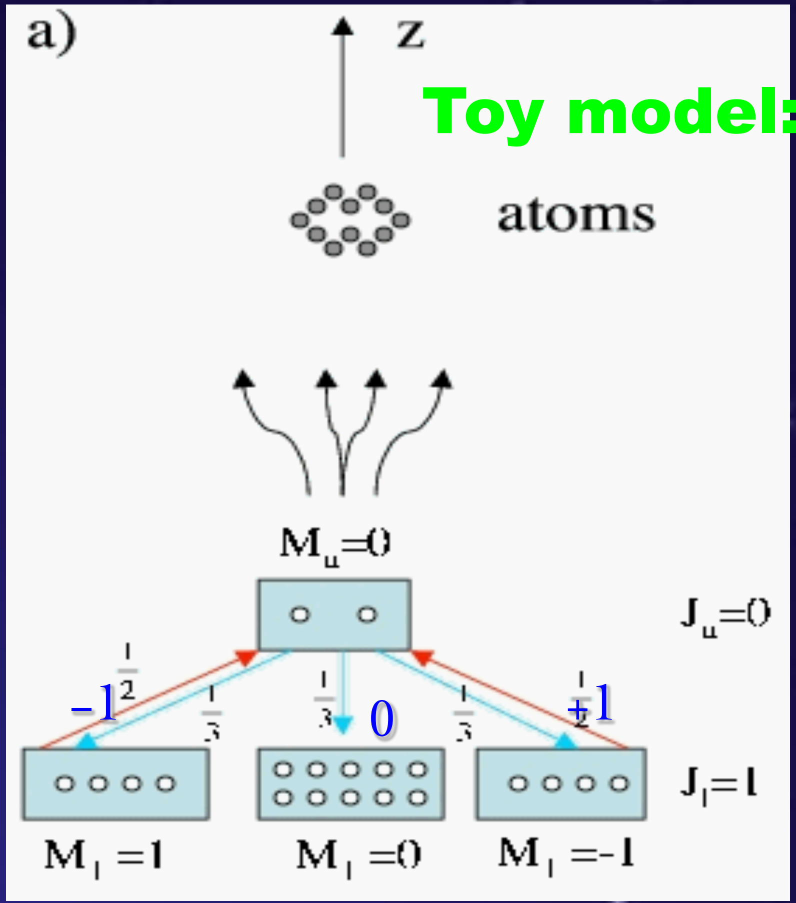
Classical Analogy

Thermal system

Radiatively pumped system



Ground state alignment (GSA) is differential occupation of the sublevels of the ground (or metastable) state.



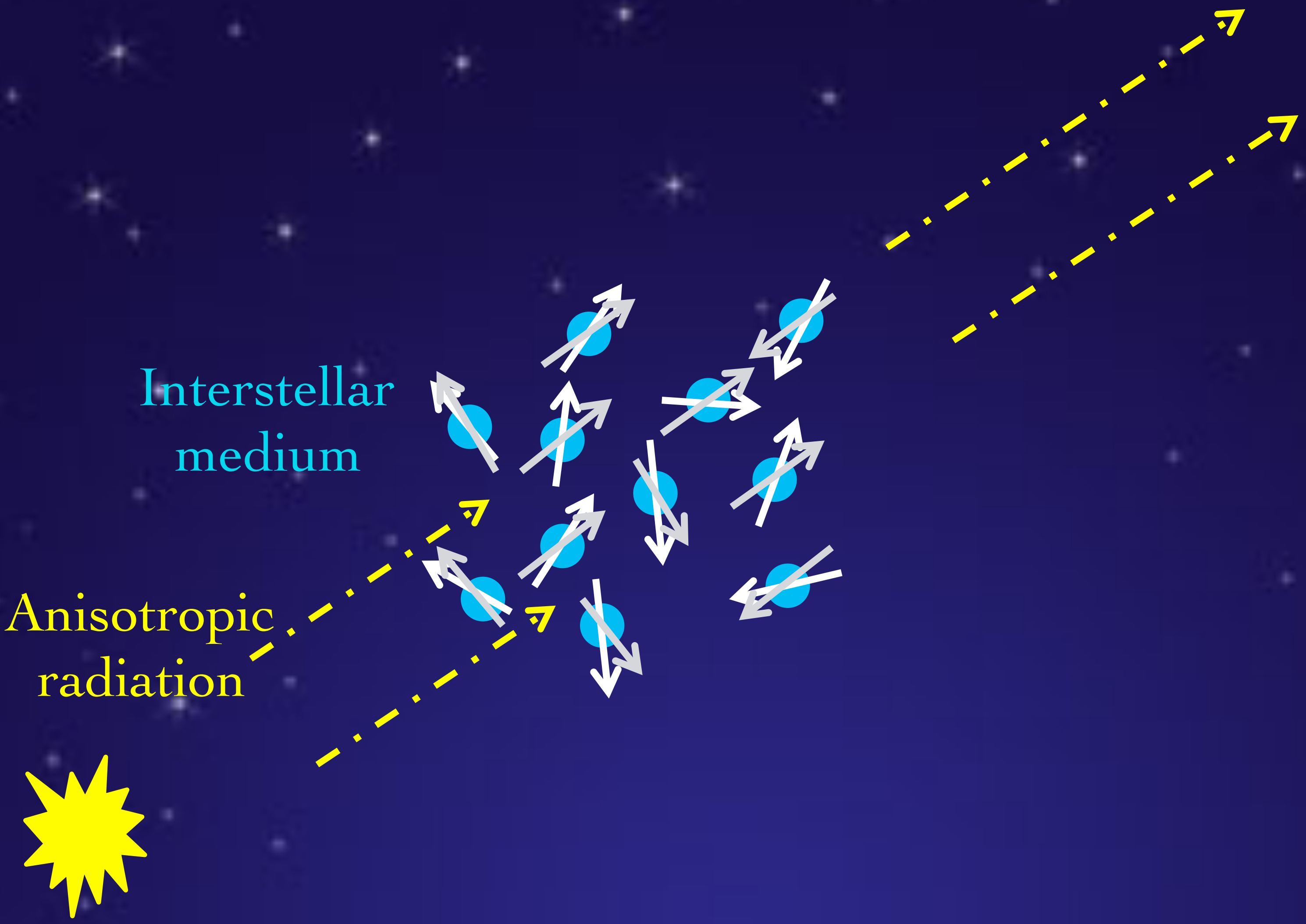
Induced ±1 transition followed by isotropic emission.

Alignment by unpolarized light requires >2 sublevels

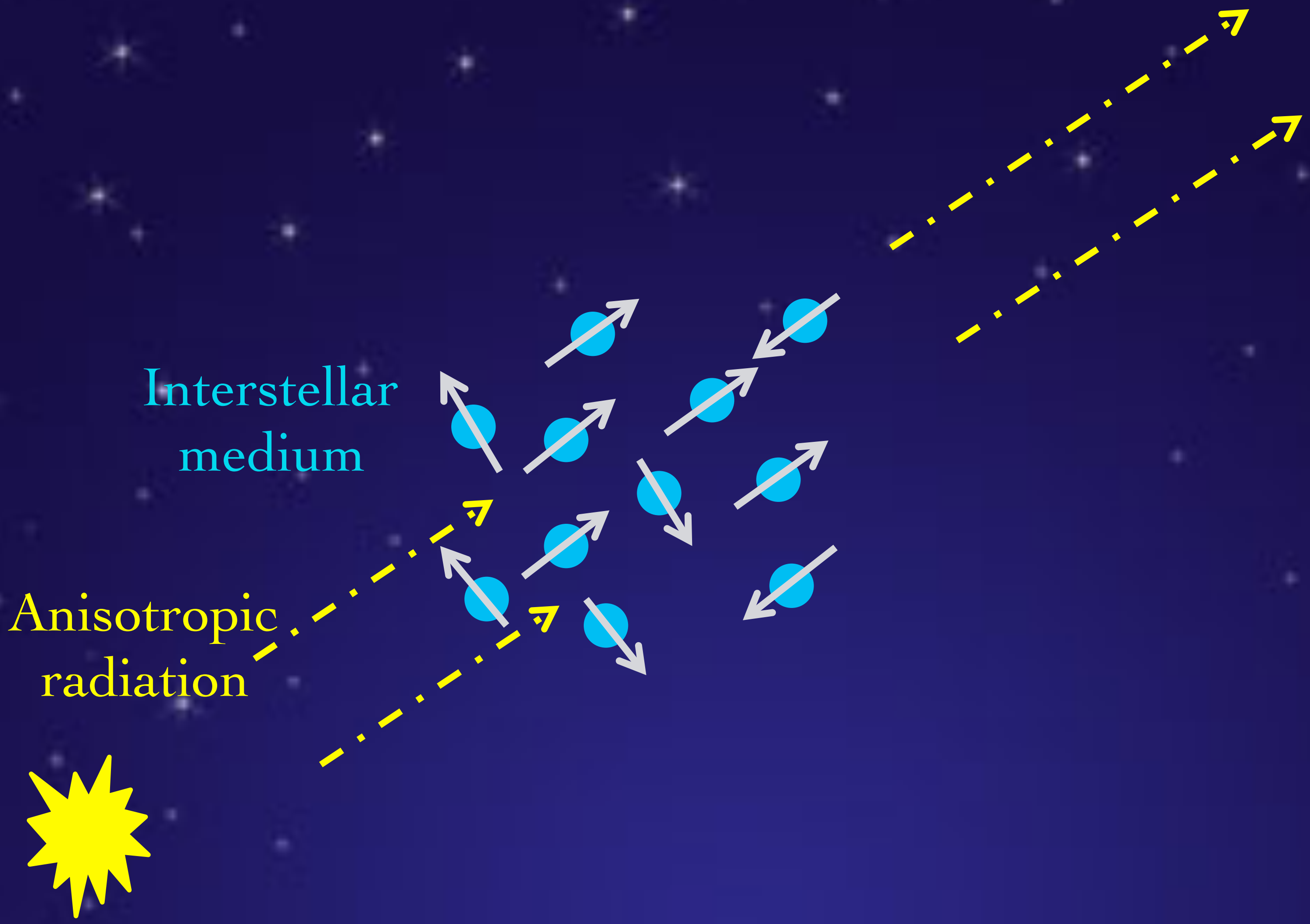
- anisotropic radiation (unpolarized light is sufficient)

- there are at least 3 sublevels on the ground state.

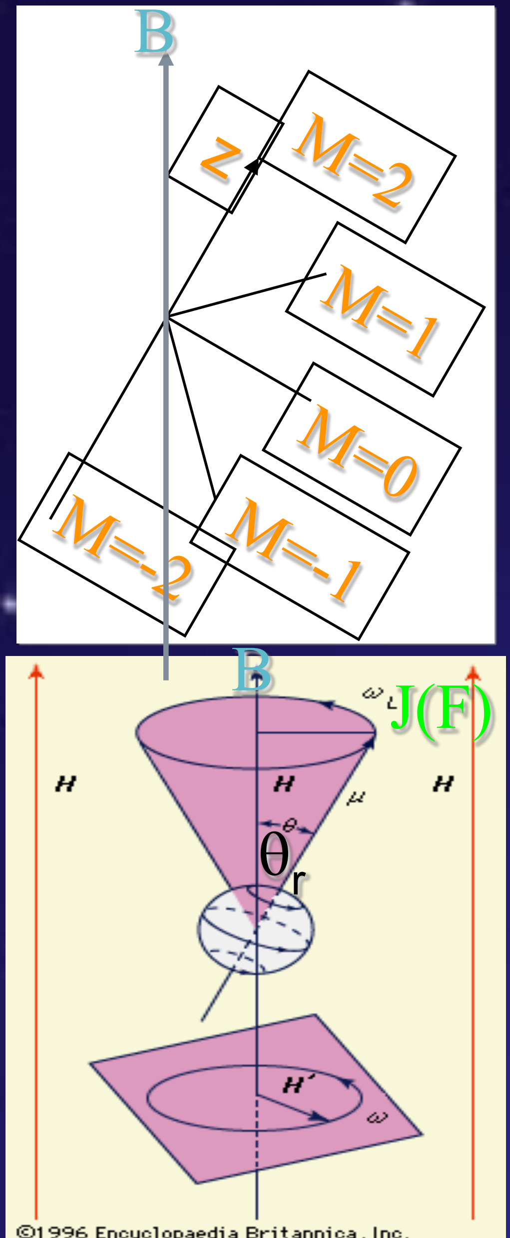
Physics for Atomic Alignment

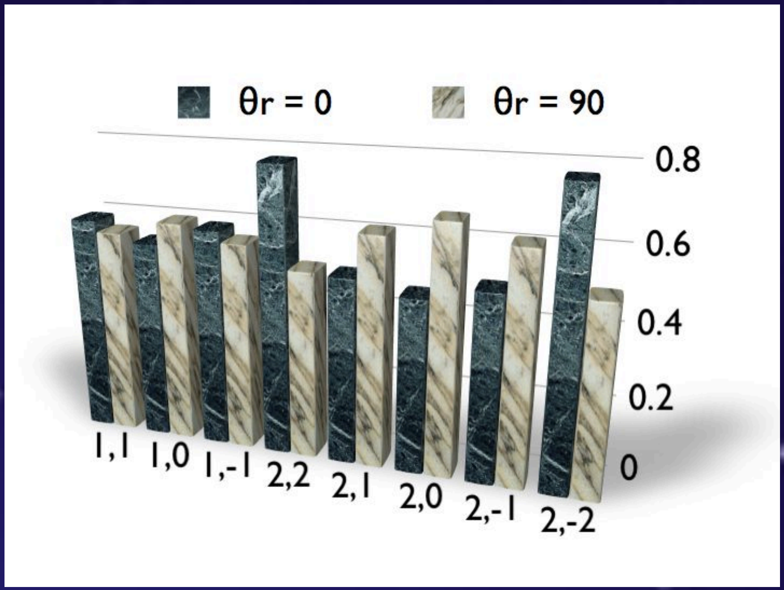


Physics for Atomic Alignment



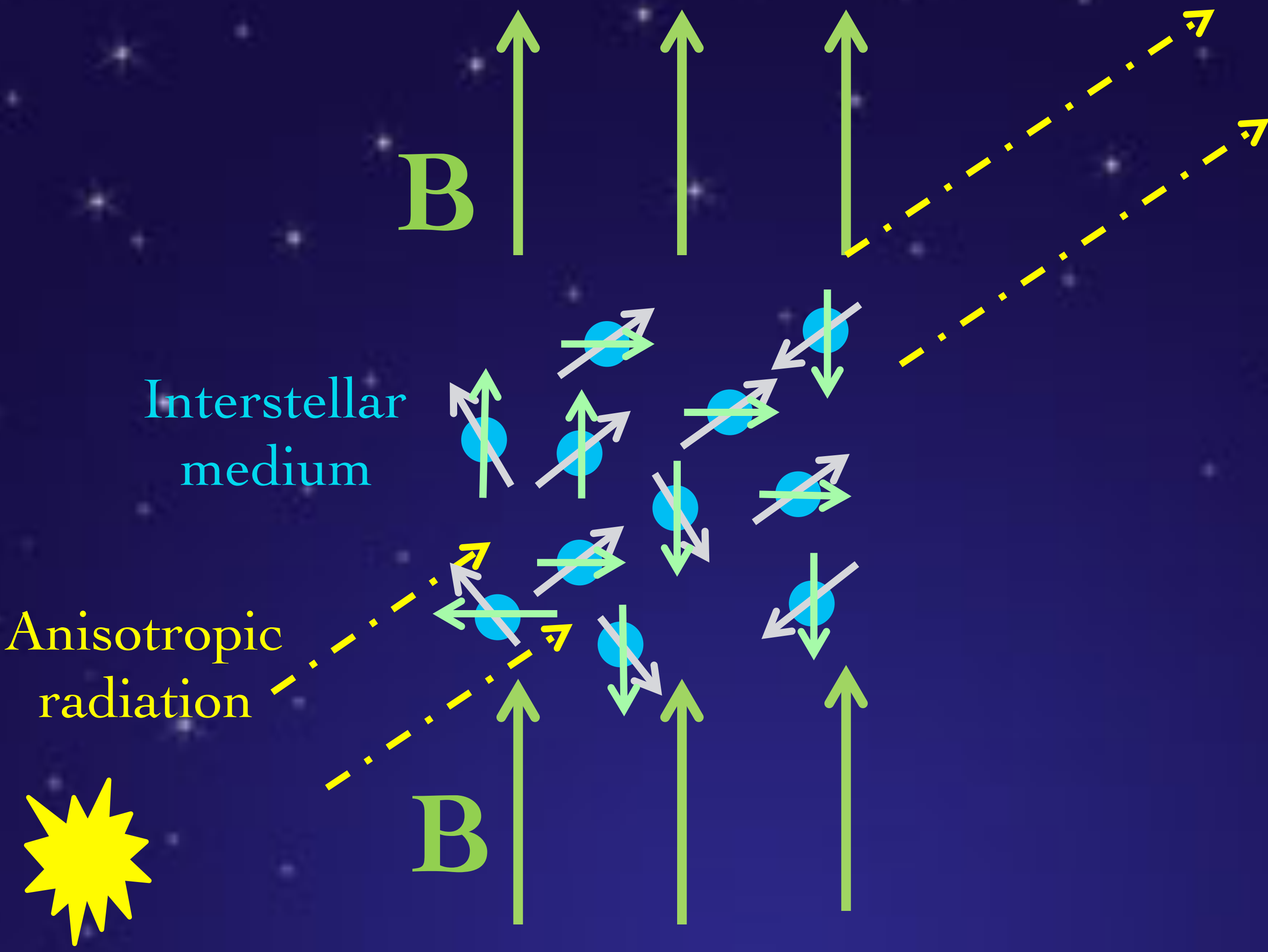
Magnetic field induces precession and realigns atoms



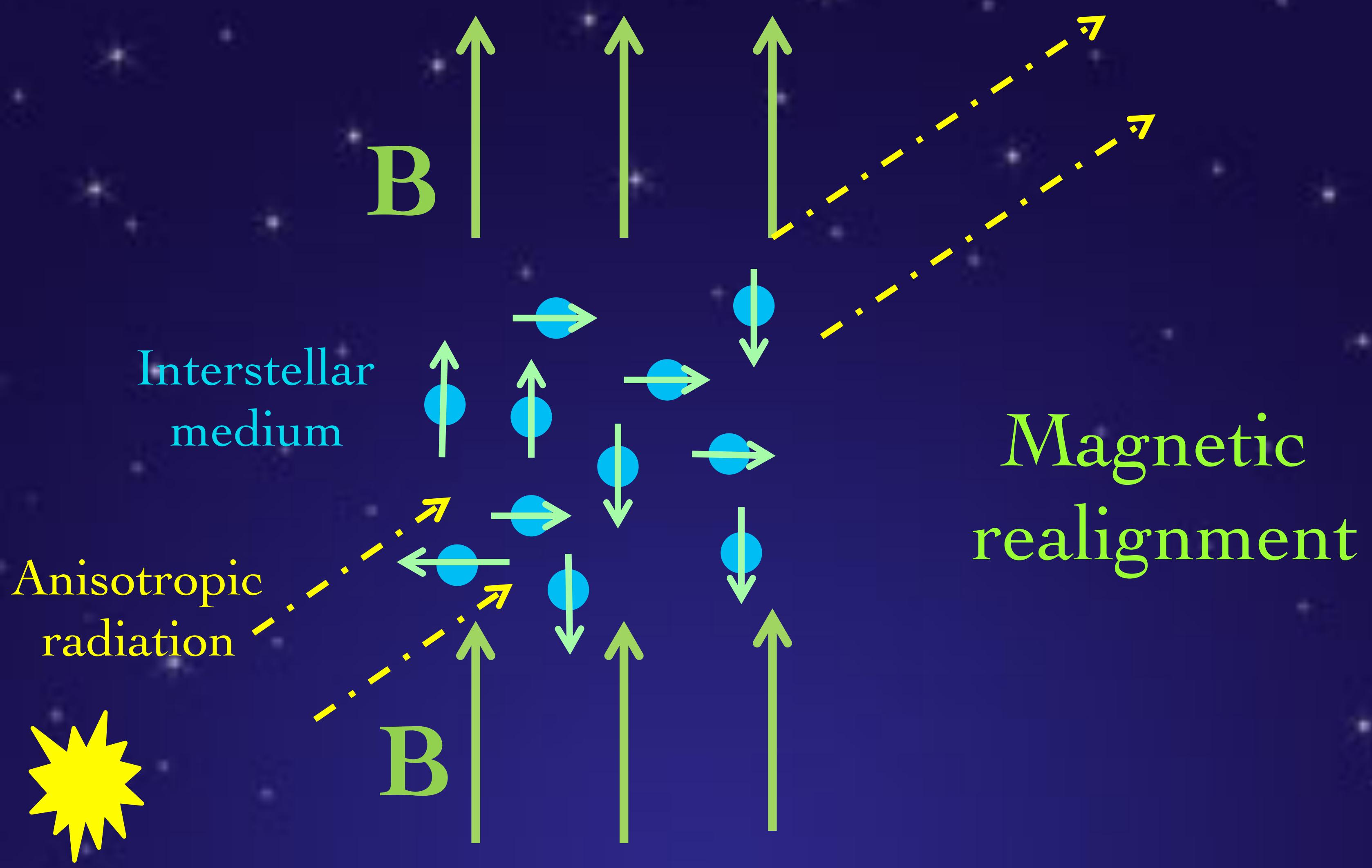


- Long lived ground state means sensitivity to weak B.
- Alignment is either || or ⊥ to B due to fast magnetic precession.

Physics for Atomic Alignment

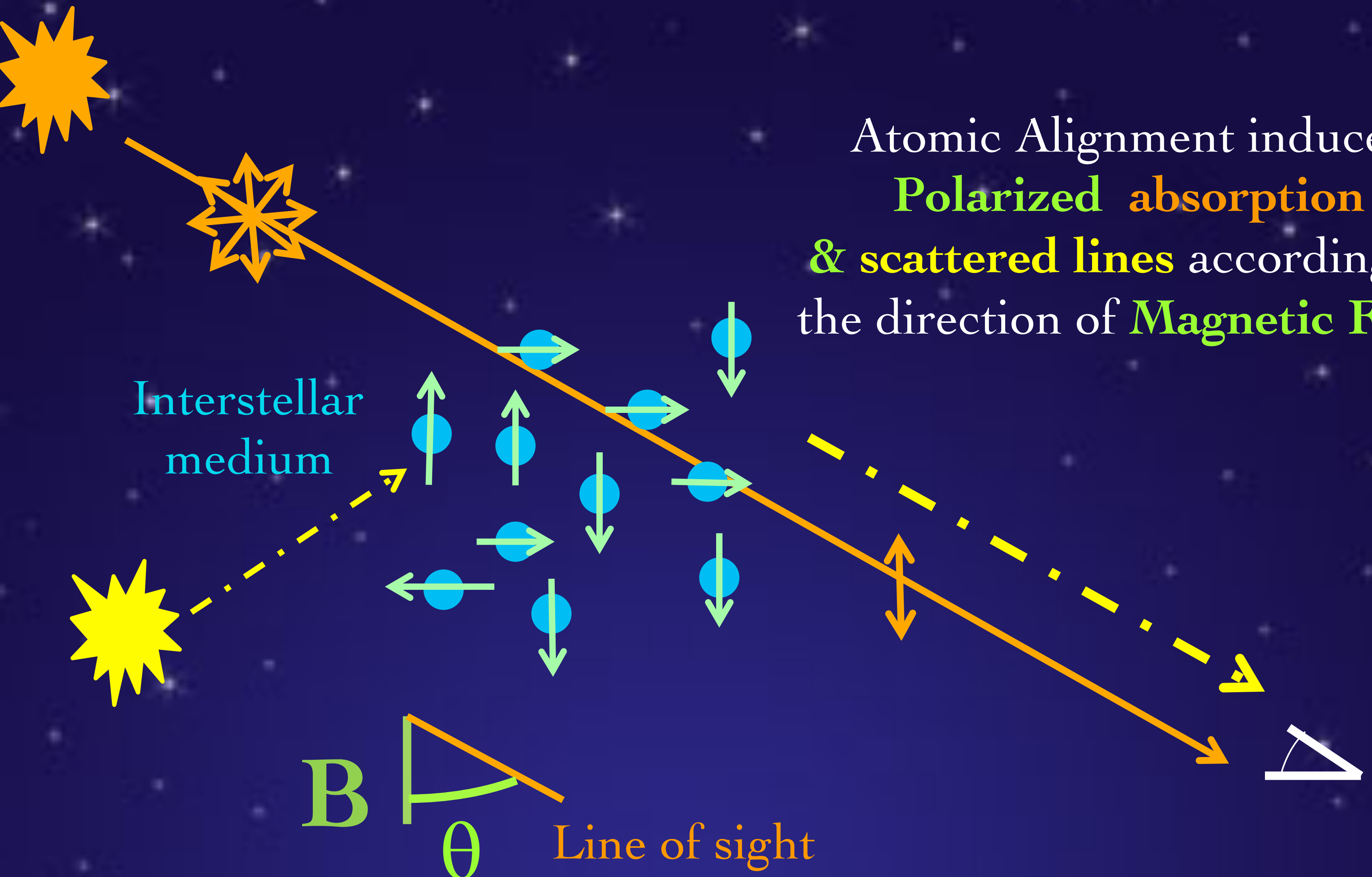


Physics for Atomic Alignment

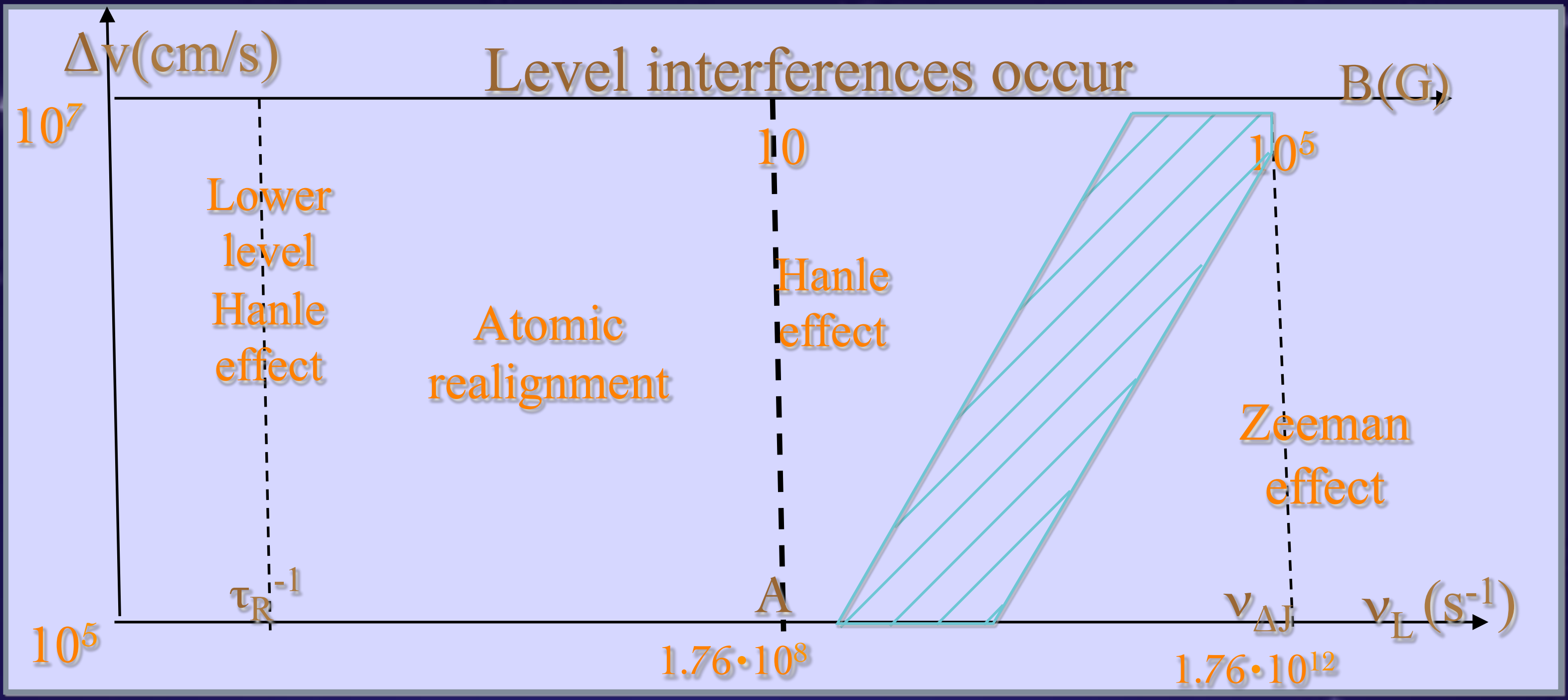


Observational Geometry

Atomic Alignment induces
Polarized absorption
& scattered lines according to
the direction of **Magnetic Field**



Atomic realignment is sensitive to weak magnetic fields

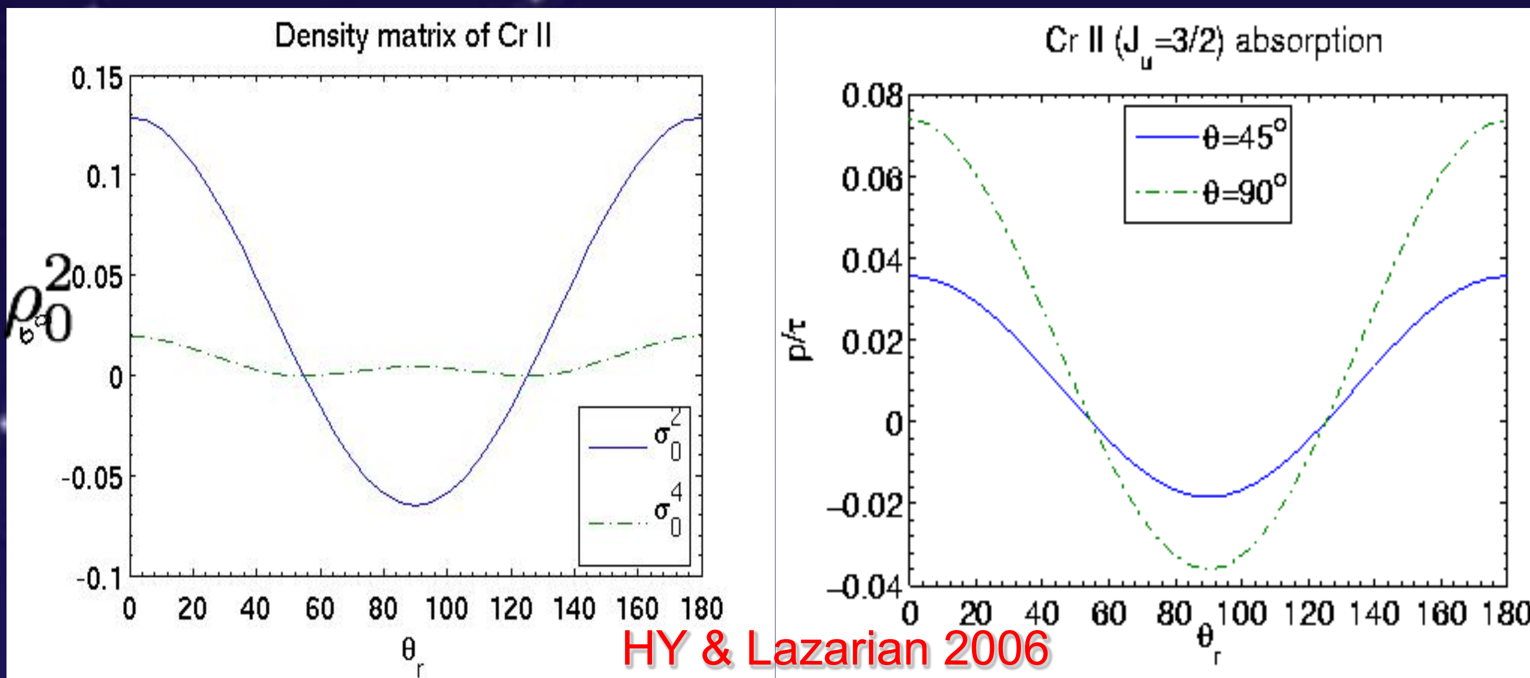


ν_L–Larmor frequency

A-Einstein coefficient, $\nu_{\Delta J}$– $E_{\Delta J}/h$

For a wide range of field (<nG, 1G) in diffuse medium, atomic alignment happens (HY & Lazarian 2006).

Polarization of absorption is either || or ⊥ to the magnetic field



HY & Lazarian 2006

$\rho^2_0 = (\rho_1 + \rho_{-1} - 2\rho_0)/\sqrt{6}$ (for J /F=1)

Polarization changes direction at Van Vleck angle between pumping radiation and magnetic field $\theta_r = 54.7^o$, $180^o - 54.7^o$.

Our results: many observed absorption lines have appreciable polarization

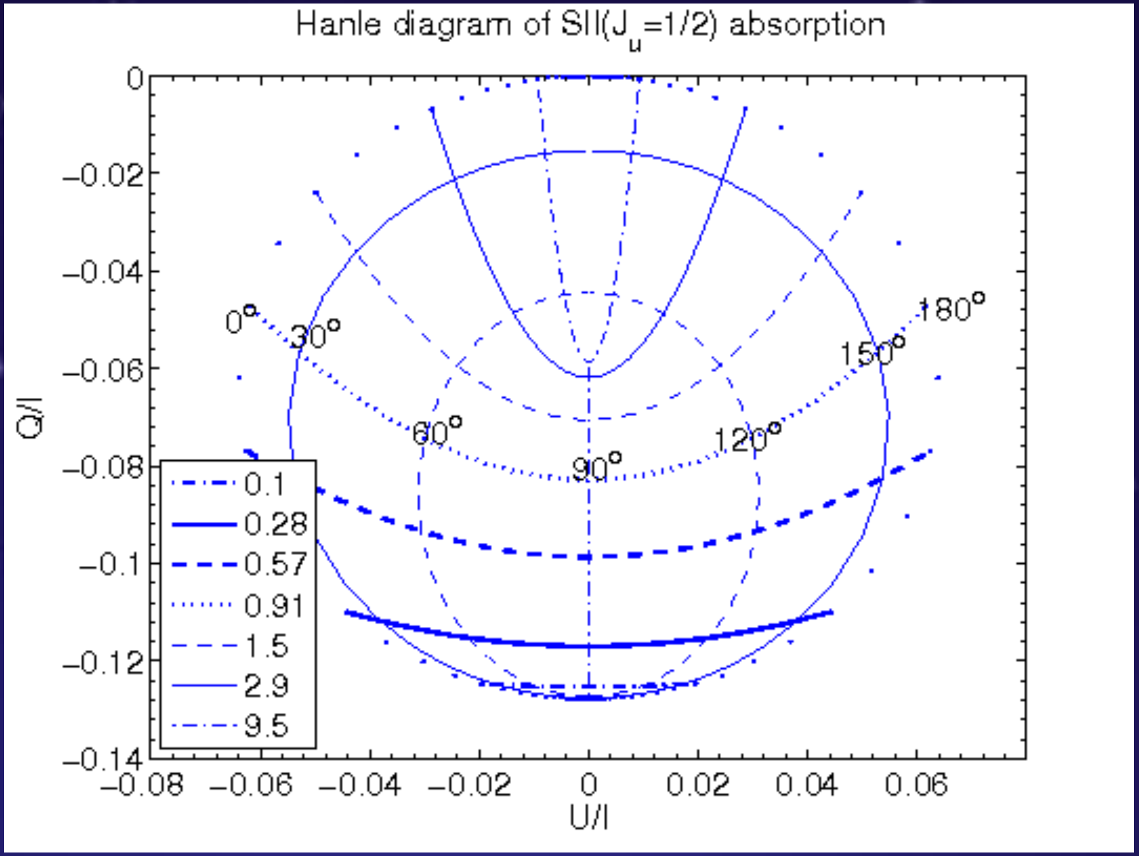
Calculated Examples:

Ion	C I	C II	Si I	Si II	O I	S I
Wavl (A)	1329-1561	1336	1695-2529	1265	1302	1807
P_{max}	18%	15%	20%	7%	29%	22%
Ion	S II	Ti II	Cr I	Cr II	NI	S III
Wavl (A)	1250	3385	4254-4290	2741-2767	1200	1012-1202
P_{max}	12%	7%	5%	21%	5.5%	24.5%

Many more lines:

Fe I, Fe II, Fe III, Fe III, Mn II, Ti III, C II, N II, …

B Strength is directly obtained when $\nu_L \sim T_R^{-1}$

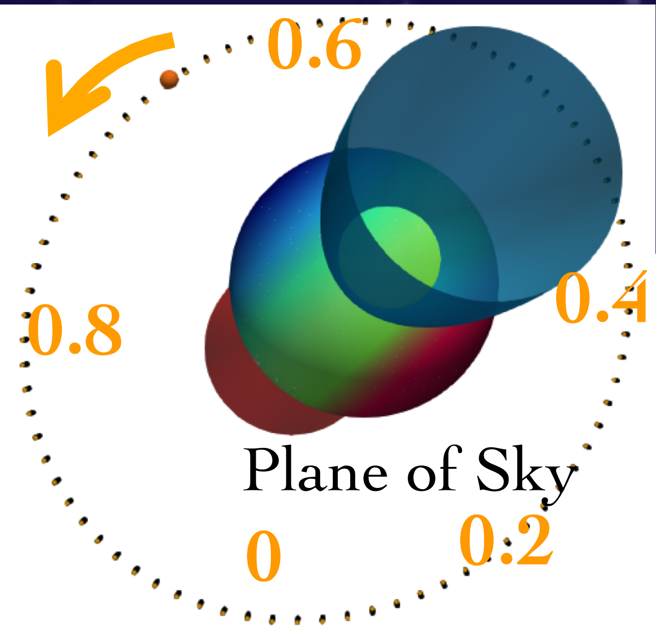


HY & Lazarian (2008)

Outline

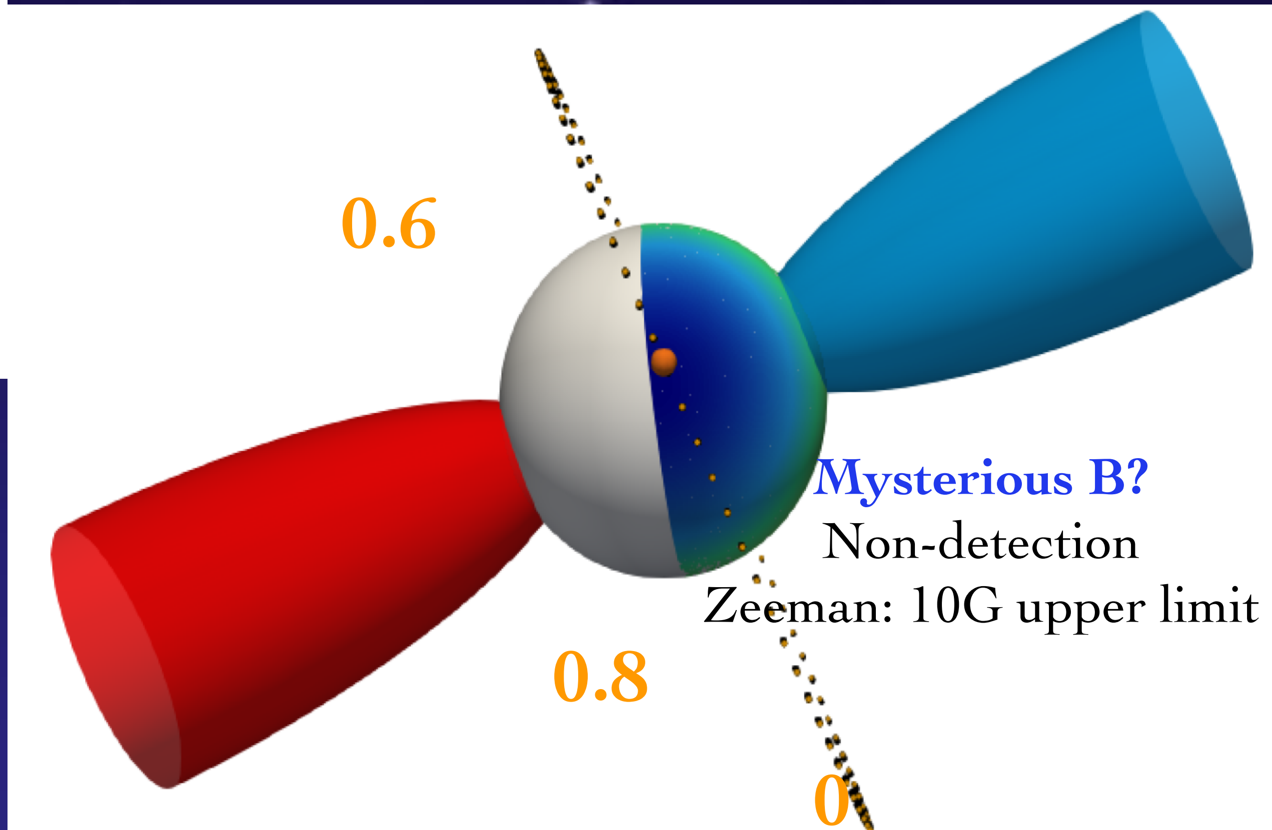
- Review of GSA theory
- Discovery of absorption polarimetry from GSA
- Other observational perspectives

OBSERVATION OF GSA



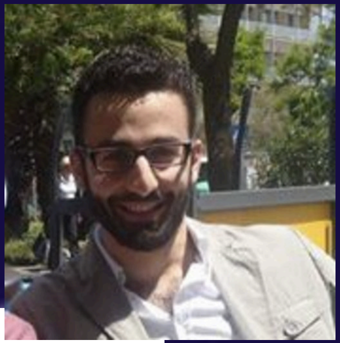
89Her

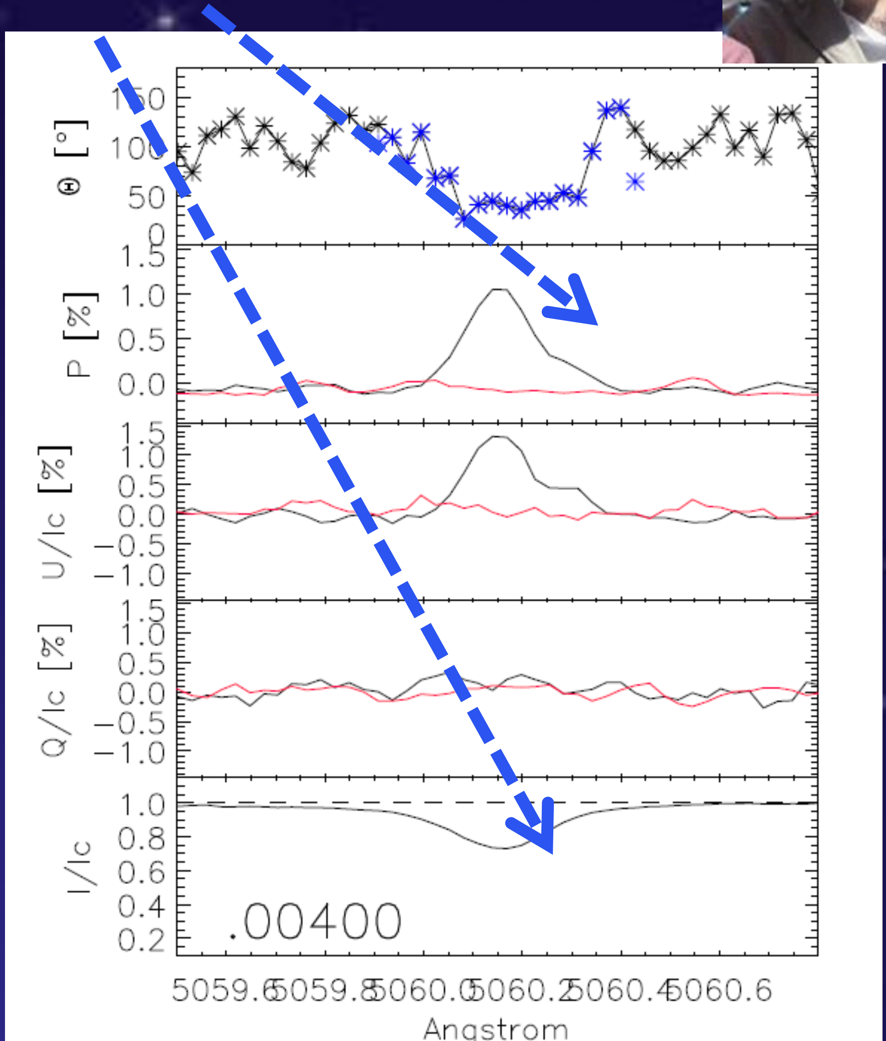
	Sp. Type	$T_{eff}[K]$	lgg	Fe/H	$R[R_\odot]$	$\tau_h[R_\odot]$
Primary	F2Ibp	6500	$0.5 \sim 1.0$	-0.5	41	$3.8 \sim 12.6$
Secondary	M0V	4045	4.7		0.6	



Zhang+2019 (arXiv:1903.08675)

Polarized Absorption from GSA discovered!





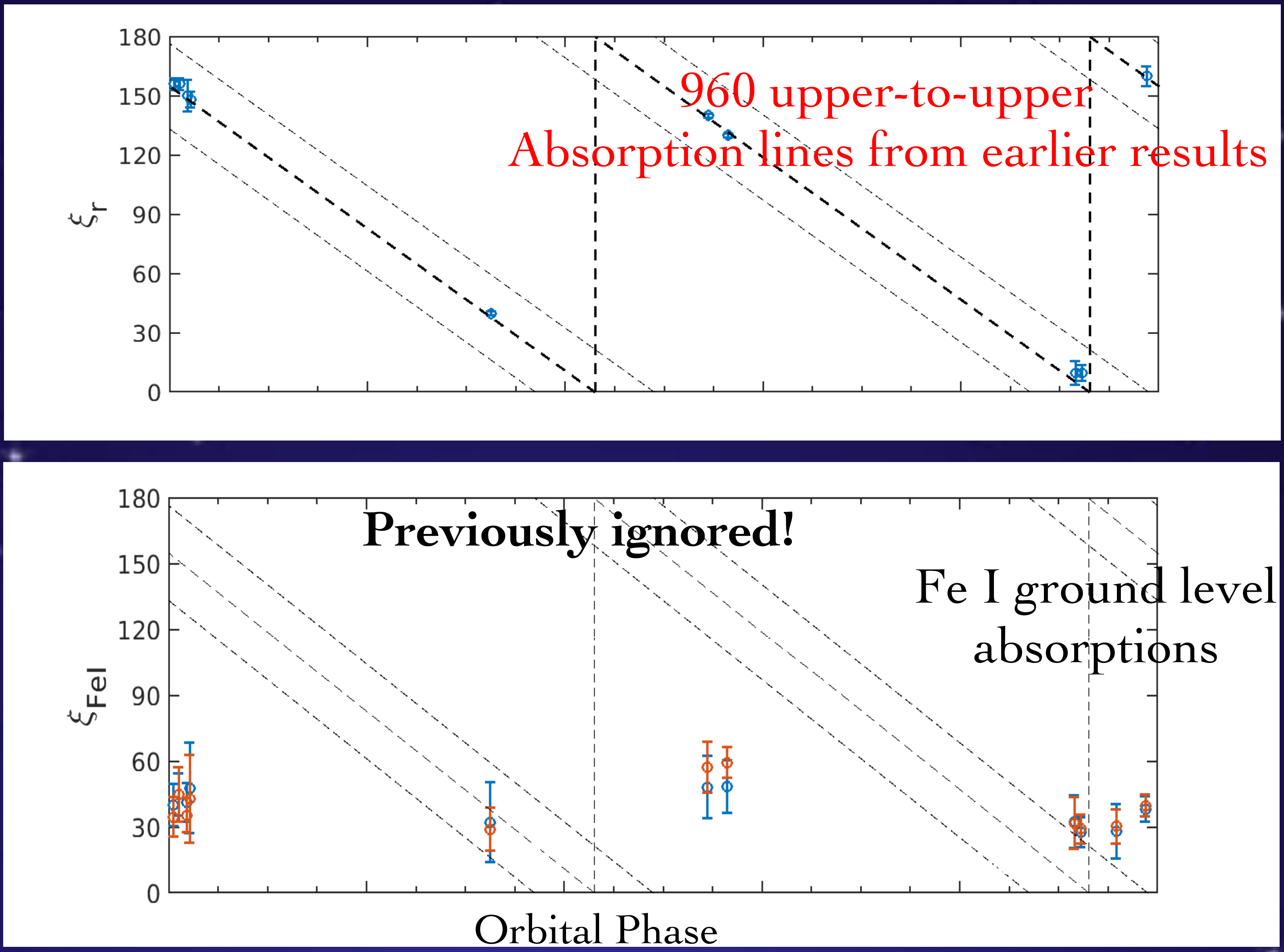
Counter-intuitive high P in very weak line!

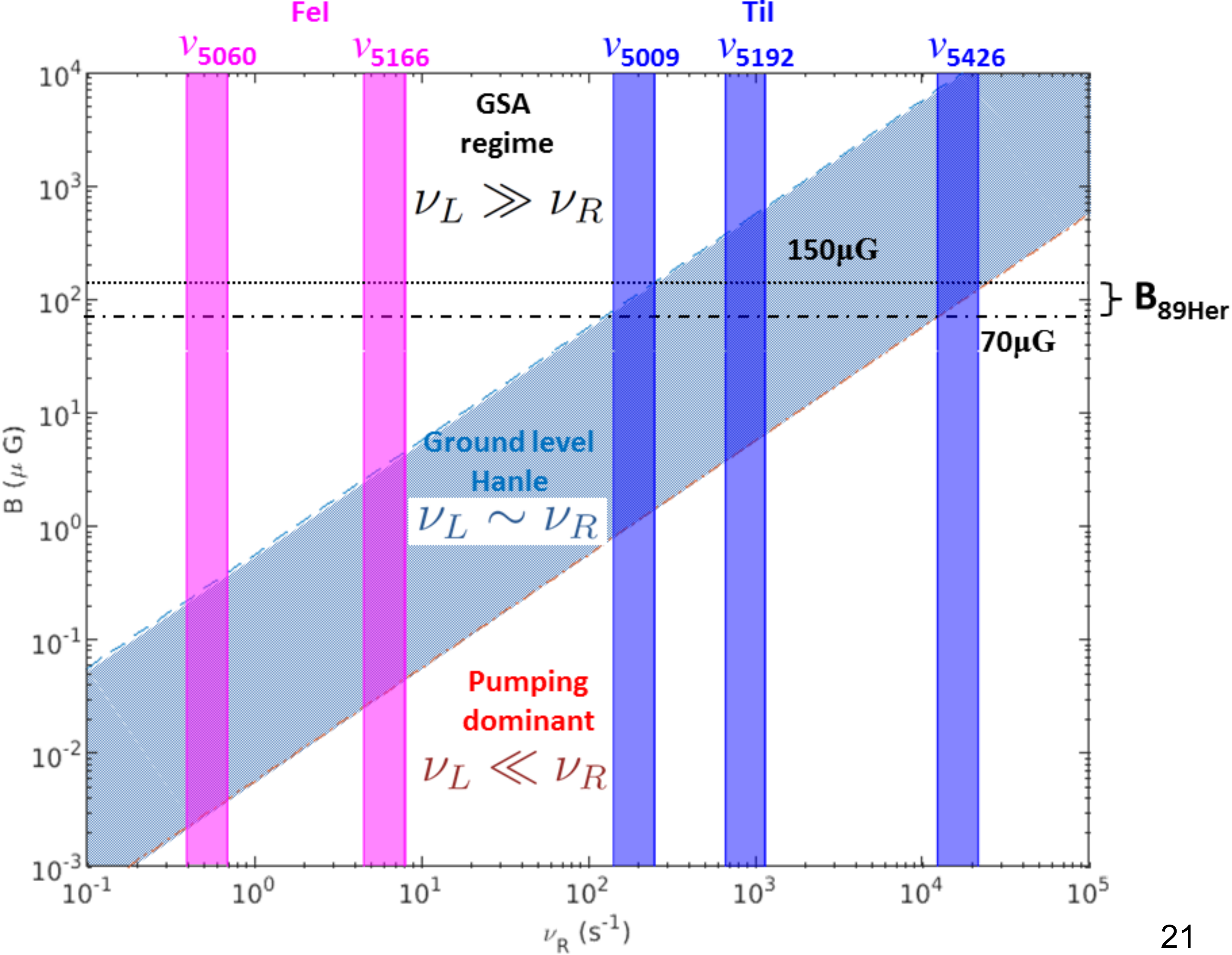
From CFHT archive data more than a decade old!!

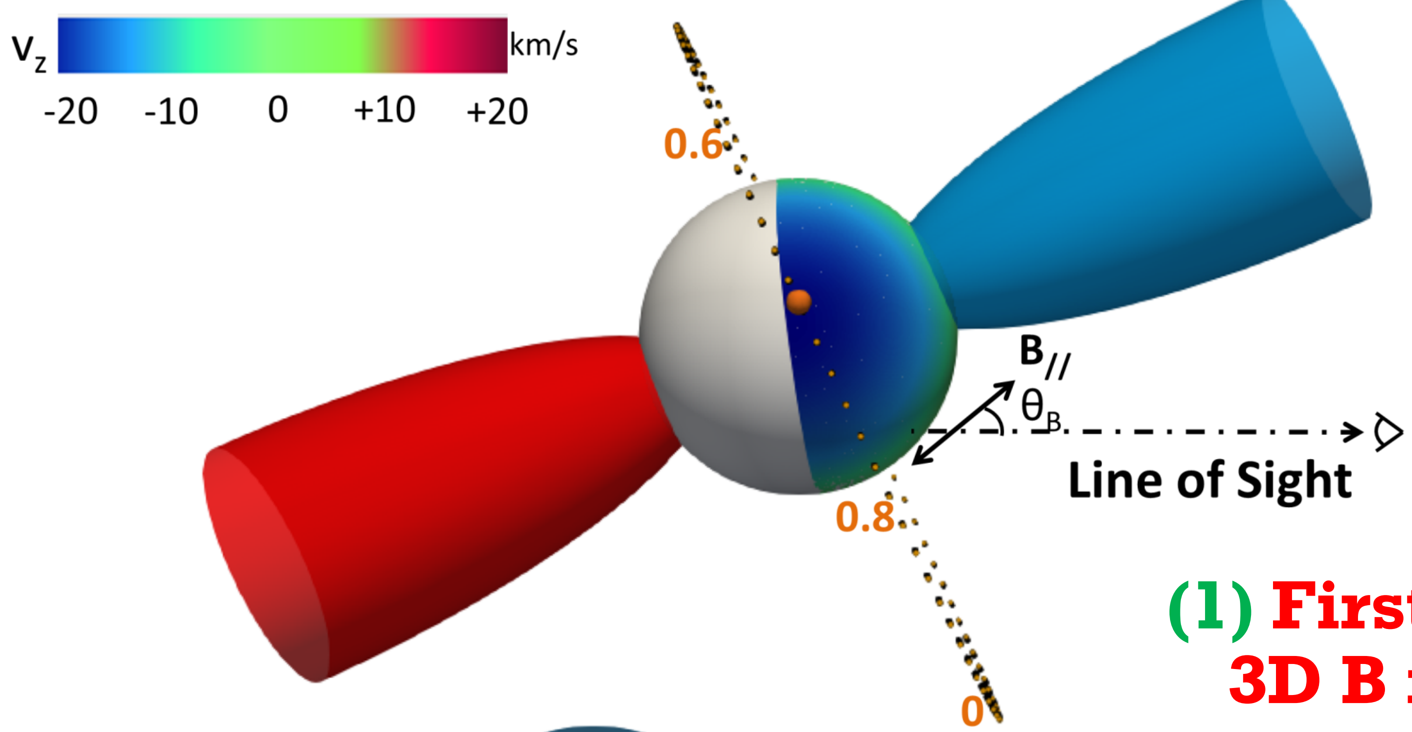
(Zhang, Gangi, Leone, Taylor, HY 2019)

Fe I 5060Å small τ!

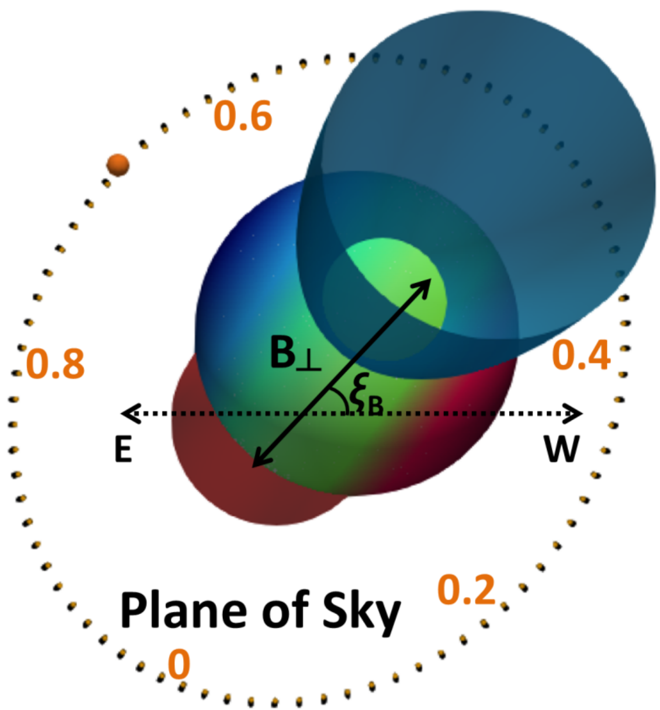
Phase independent polarization is identified!




FeI
ν_{5060}
ν_{5166}
TiI
ν_{5009}
ν_{5192}
ν_{5426}
GSA regime
$\nu_L \gg \nu_R$
150μG
B89Her
70μG
Ground level Hanle
$\nu_L \sim \nu_R$
Pumping dominant
$\nu_L \ll \nu_R$
B (μ G)
ν_R (s^{-1})
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}



(1) First direct 3D B field!



(2) Strength: 70~150μG

5 decades higher precision than non-detection of Zeeman (10G)

	0.0	0.3	0.6	0.9
θ_B	32°	25°	26°	28°
ξ_B	42°	31°	53°	33°

What we achieved with GSA

- $B_\perp$ is directly obtained from direction of polarization
- $B_{||}$ is constrained from degree of polarization
- B field strength is constrained to ~100μG level!

Outline

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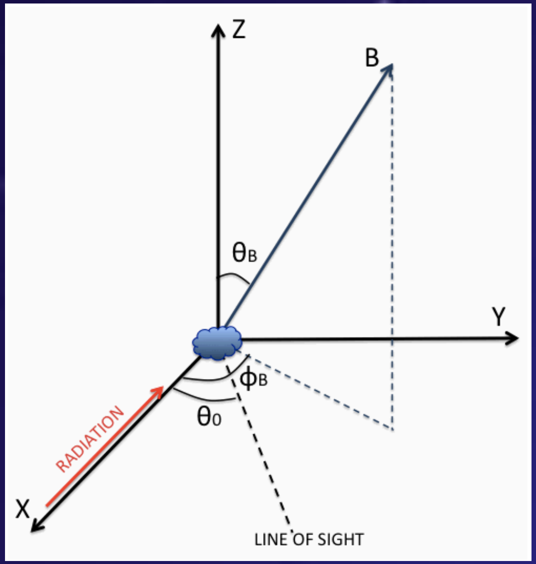
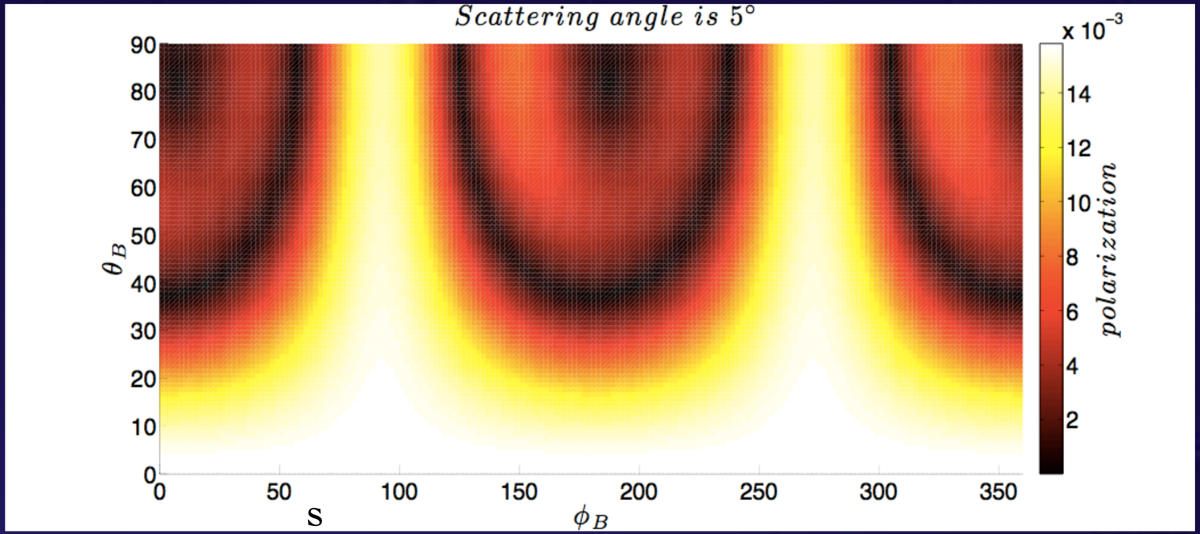
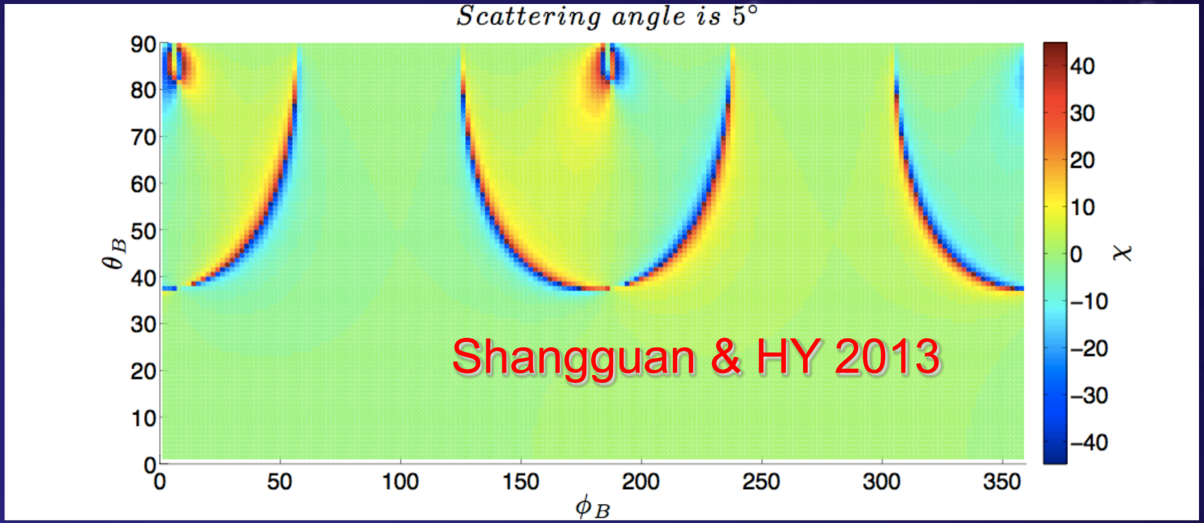
Scattering polarization has the imprint of local magnetic field due to GSA







Our results: polarization of emission lines from aligned atoms

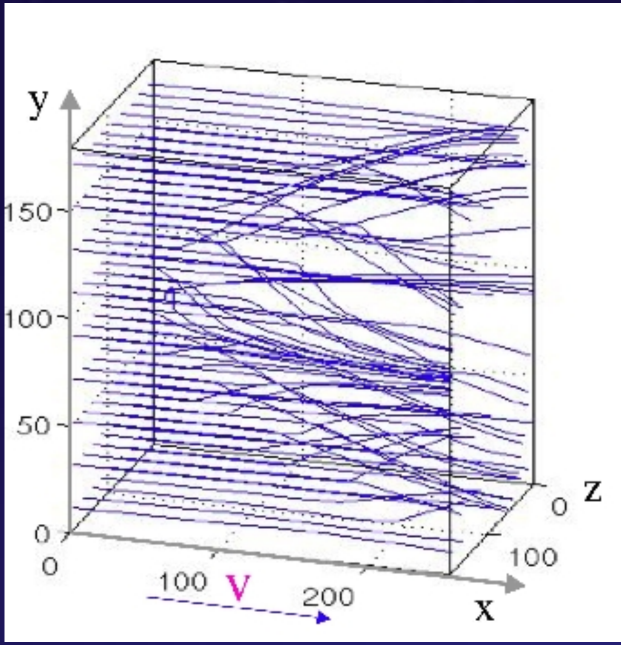
Calculated Examples:

ion	HI (Bal)	Na I	K I	N V	O I	P V	S II	Al II	Ti II
Wavl	3646-6365	5892	7667	1243	5555-7254	1118	1254-1259	8843	3073
P_{max}	25%	21%	20%	22%	2.3%	27%	31%	20%	7.3%

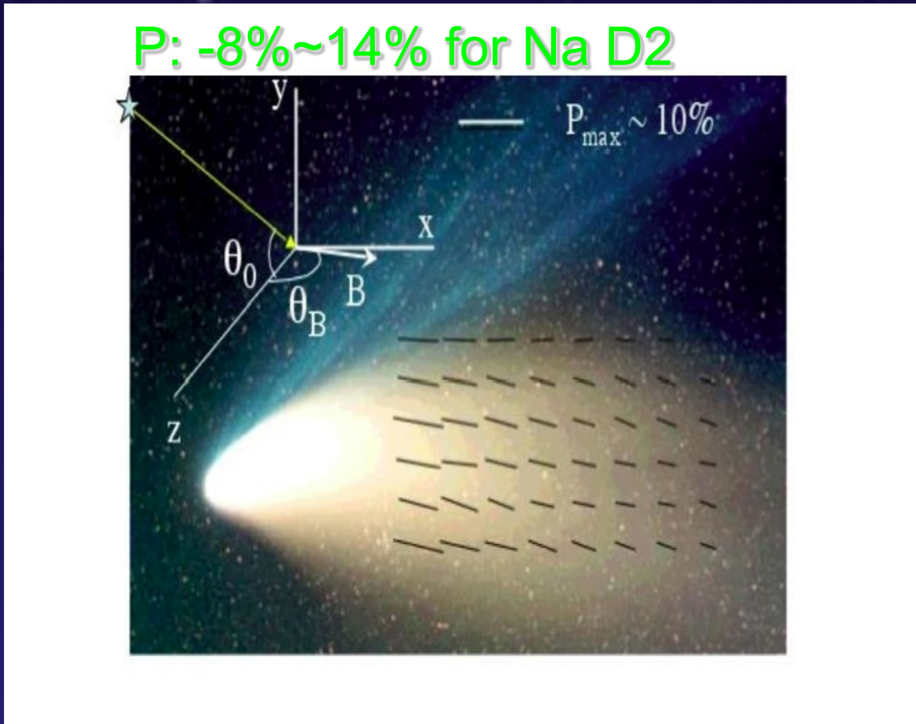
Many more lines:

N I, N II, N III, P III, Al I, Al III, Fe I, Fe II, Fe III, Fe III, Mn II, Ti III, C II, N II, Cr I …

Alignment allows studies of magnetic field in comet wake



MHD simulations of comet's wake.

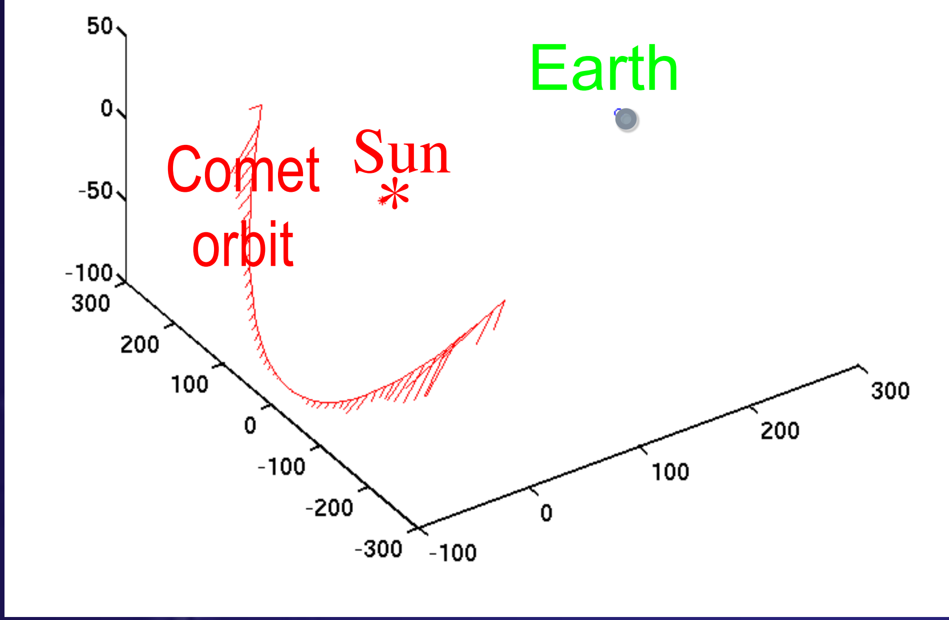


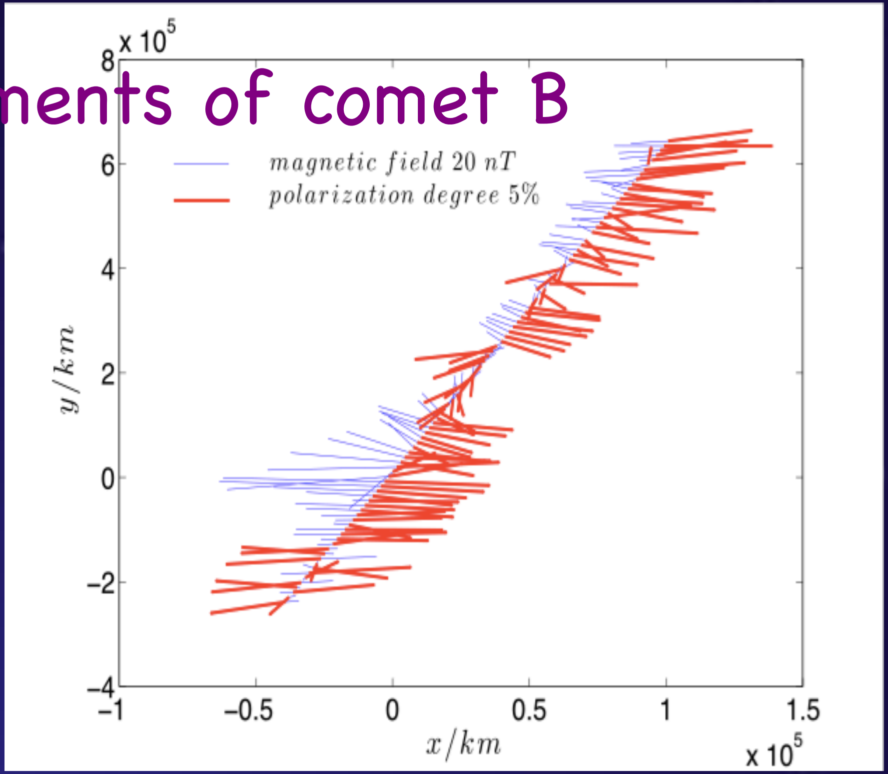
Resonance scattering of solar light by sodium tail from comet.

Spatial and temporal variation of magnetic field can be detected (HY & Lazarian 2007).

Ex. II: Alignment allows tracing heliosphere B with comet

synthetic measurements of comet B

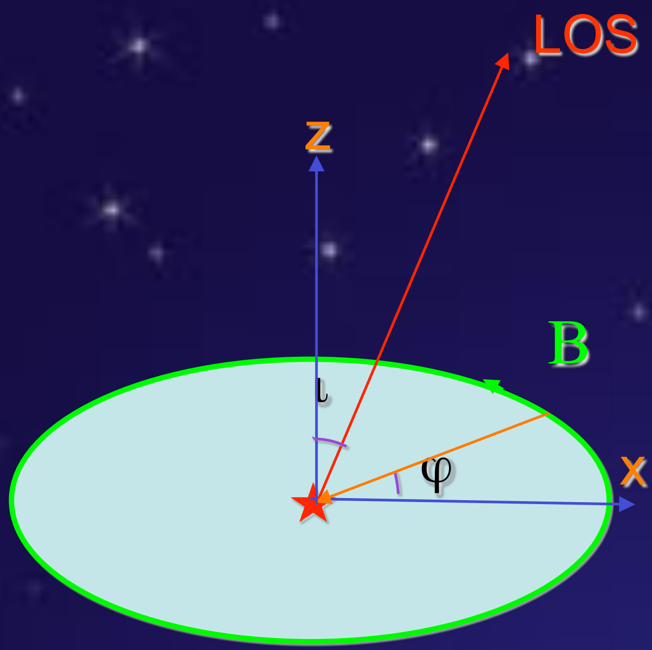


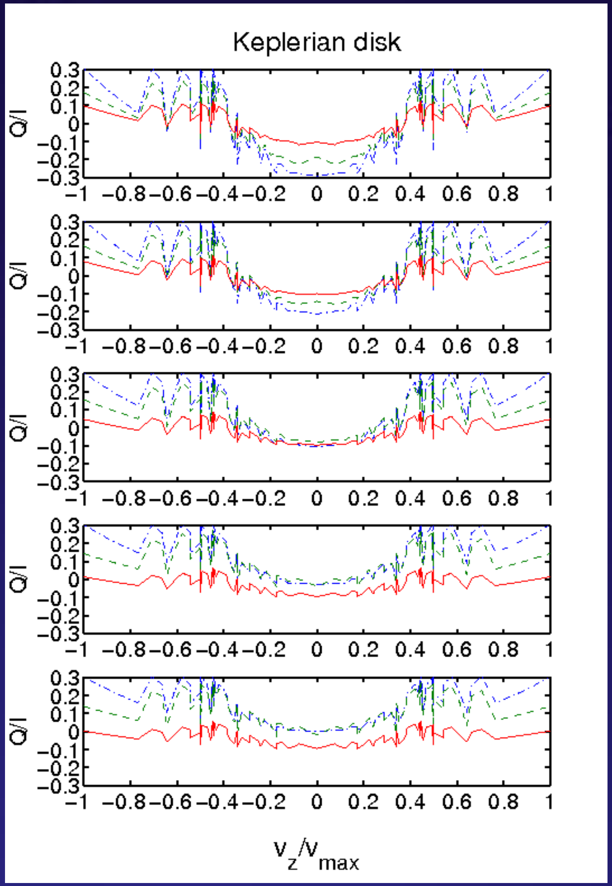


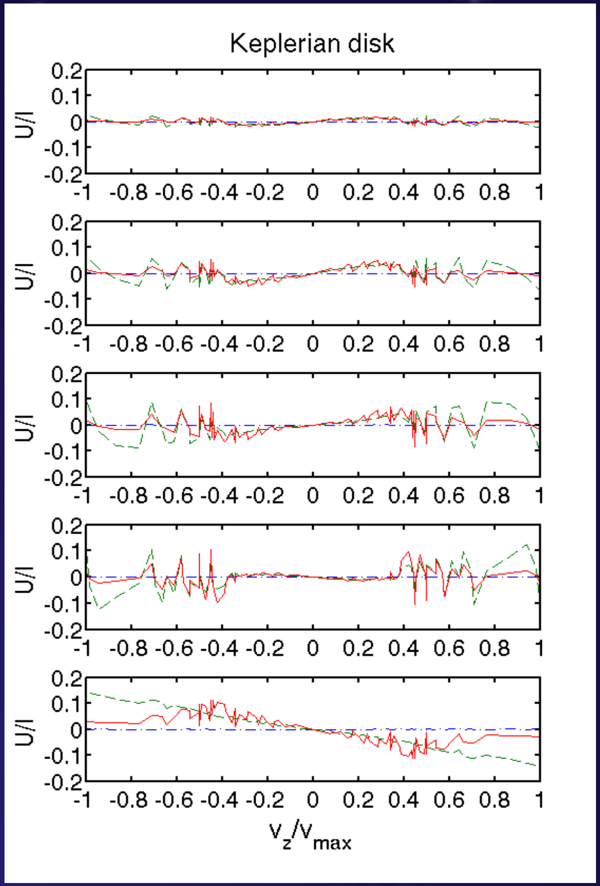
Shangguan & Yan (2013)

Cost effective way of study of B in heliosphere compared to sending thousands of satelites!

Ex. V: Polarization from Disk



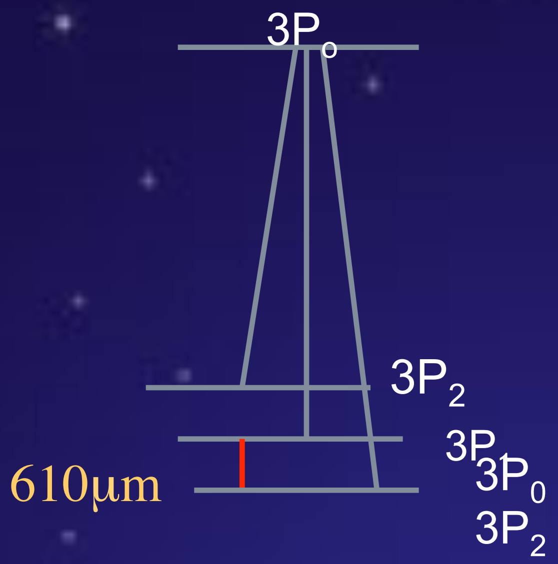




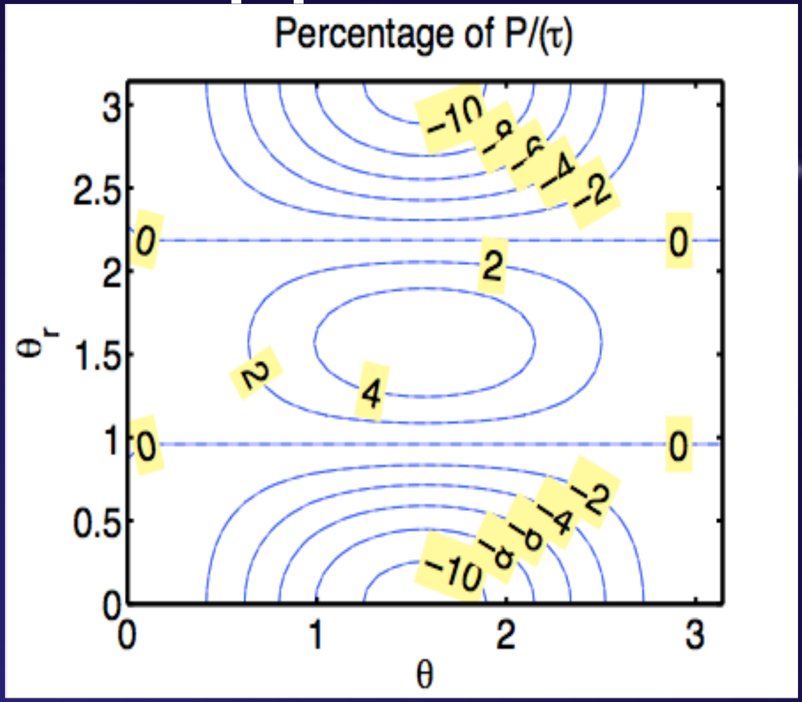
HY & Lazarian 2008

Fine structure (submm, IR) transitions within the aligned ground state

Schematics of UVpumping of CI 610μm emission (similar to Wouthuysen-Field effect)



[CI] Emission



☑ qualitative measurement is adequate for determining 2D field in the pictorial plane (HY & Lazarian 2008).

Further GSA opportunities:
Submillimeter band

Higher percent P
Expected in **Submm**!

Table 1. Maximum Polarization FOR SUBMILLIMETER EMISSION LINES

Strong pumping

Species	Transition	Wavelength	$max(P_{em})$
[C I]	$3P_1 \rightarrow 3P_0$	$610\mu m$	21%
[C I]	$3P_2 \rightarrow 3P_1$	$370\mu m$	18%
[C II]	$2P^{\circ}_{3/2} \rightarrow 2P^{\circ}_{1/2}$	$157.7\mu m$	28.5%
[O I]	$3P_1 \rightarrow 3P_2$	$63.2\mu m$	4.2%
[Si II]	$2P^{\circ}_{3/2} \rightarrow 2P^{\circ}_{1/2}$	$34.8\mu m$	12.6%
[S I]	$3P_1 \rightarrow 3P_2$	$25.2\mu m$	3.2%
[Fe II]	$a6D_{7/2} \rightarrow a6D_{9/2}$	$26.0\mu m$	4.9%

Table 2. Maximum Polarization FOR SUBMILLIMETER ABSORPTION LINES

Species	Transition	Wavelength	$max(P_{ab})$
[C I]	$3P_1 \rightarrow 3P_2$	$370\mu m$	2%
[O I]	$3P_2 \rightarrow 3P_1$	$63.2\mu m$	30.8%
[O I]	$3P_1 \rightarrow 3P_0$	$145.5\mu m$	49.1%
[S I]	$3P_2 \rightarrow 3P_1$	$25.2\mu m$	27.7%
[S I]	$3P_1 \rightarrow 3P_0$	$56.3\mu m$	45.2%
[Fe II]	$a6D_{9/2} \rightarrow a6D_{7/2}$	$26.0\mu m$	9.9%

Table 5
The polarization of forbidden lines.

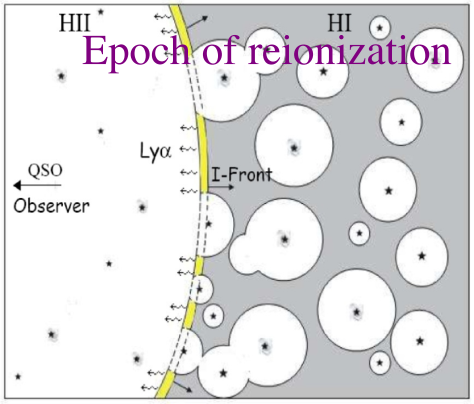
Lines	Lower level	Upper level	Wavelength (μm)	P_{max} (%)
[CI]	$3P_0$	$3P_1$	610	20
[OI]	$3P_2$	$3P_1$	63.2	24
[CII]	$3P_{1/2}$	$3P_{3/2}$	157.7	2.7
[SiII]	$3P_{1/2}$	$3P_{3/2}$	34.8	4
[SIV]	$3P_{1/2}$	$3P_{3/2}$	610	10.5

Weak pumping

HY & Lazarian 2012

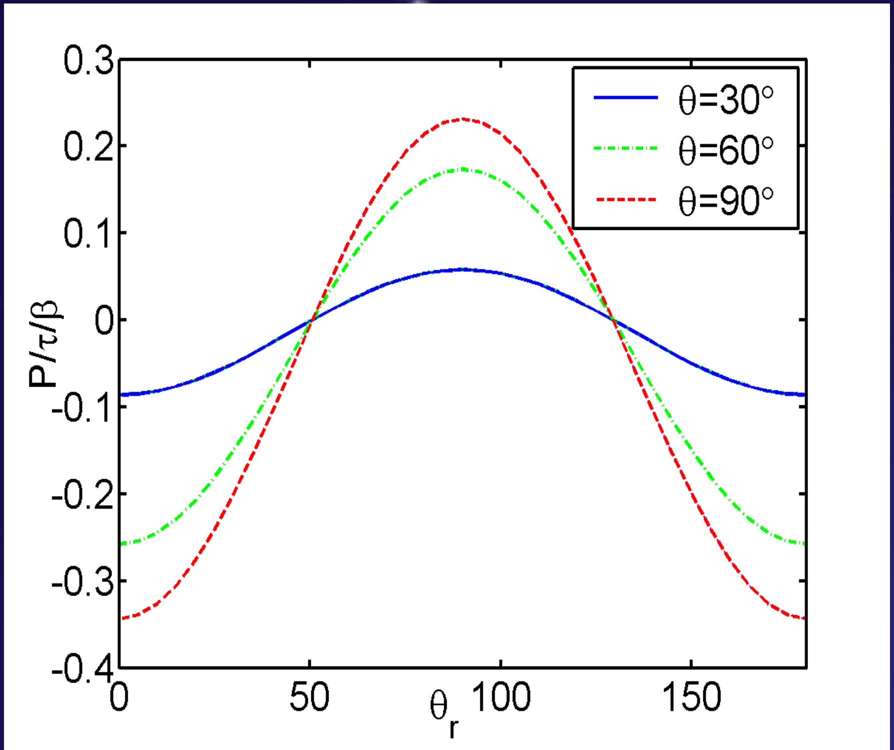
Zhang & HY 2018

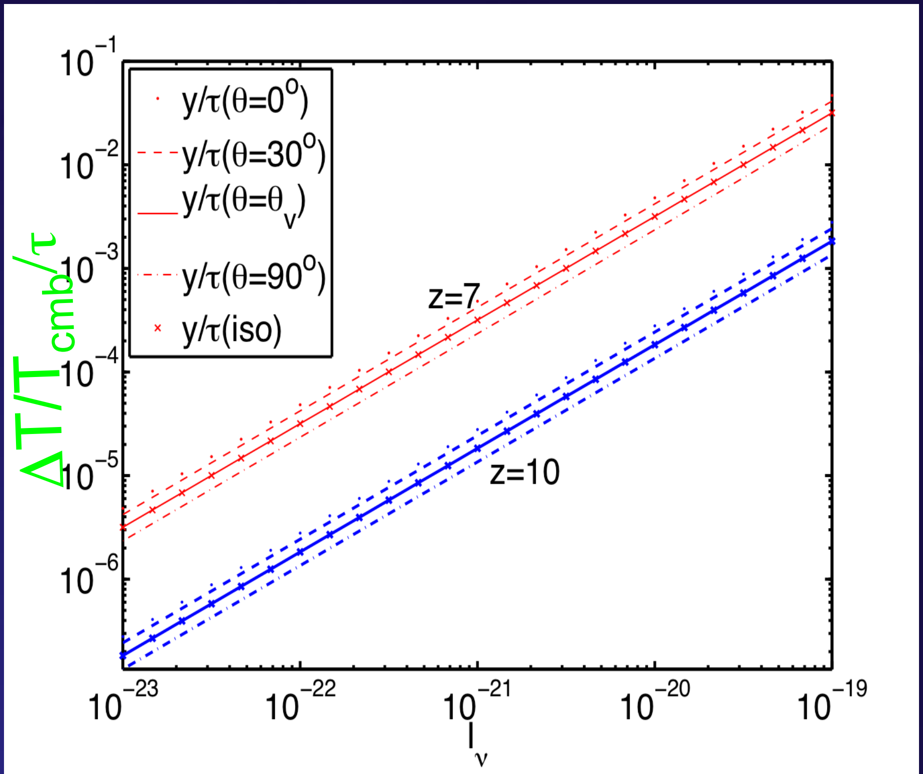
Ex. VI: alignment in the epoch of Reionization



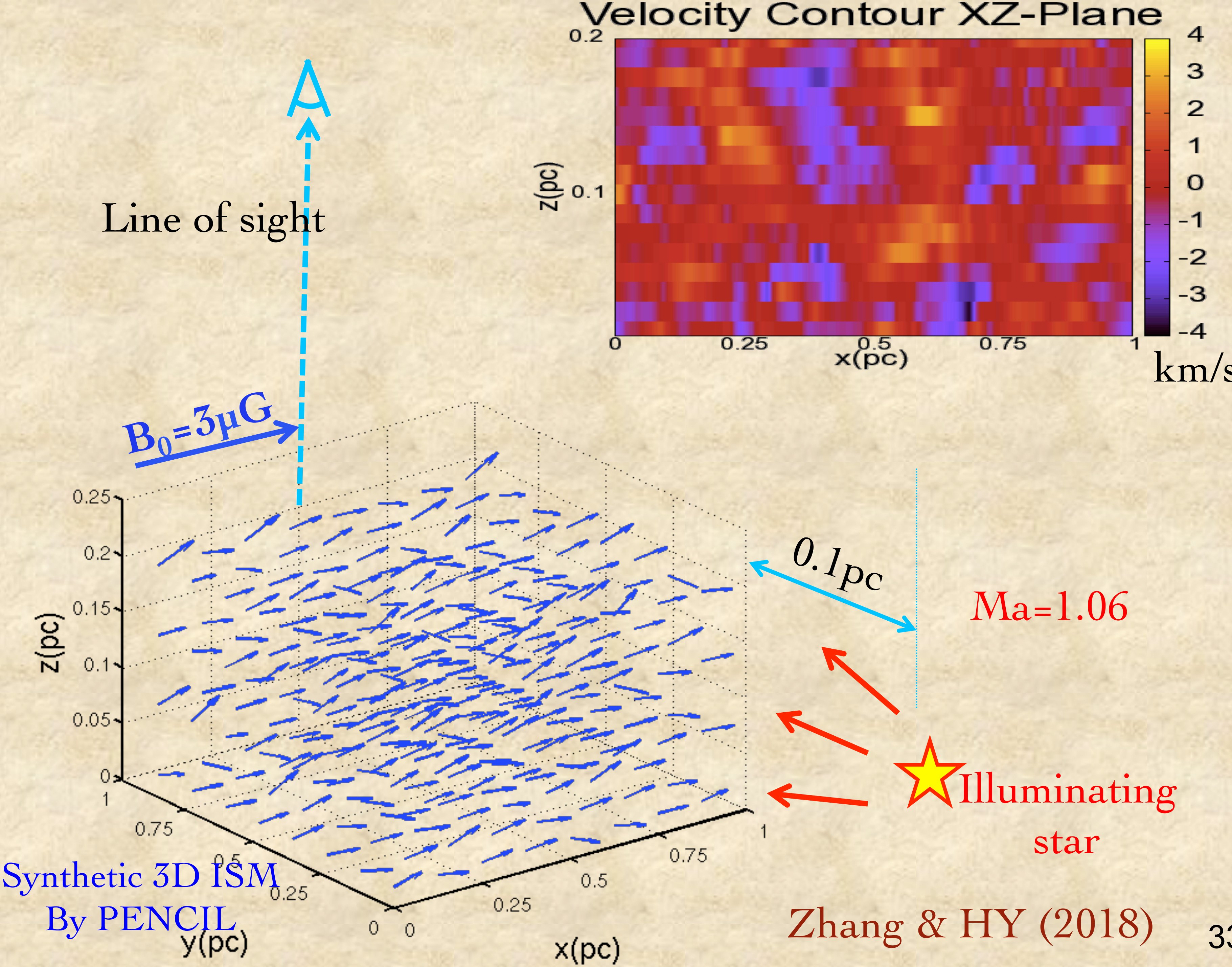
From Cantalupo et al. (2008)

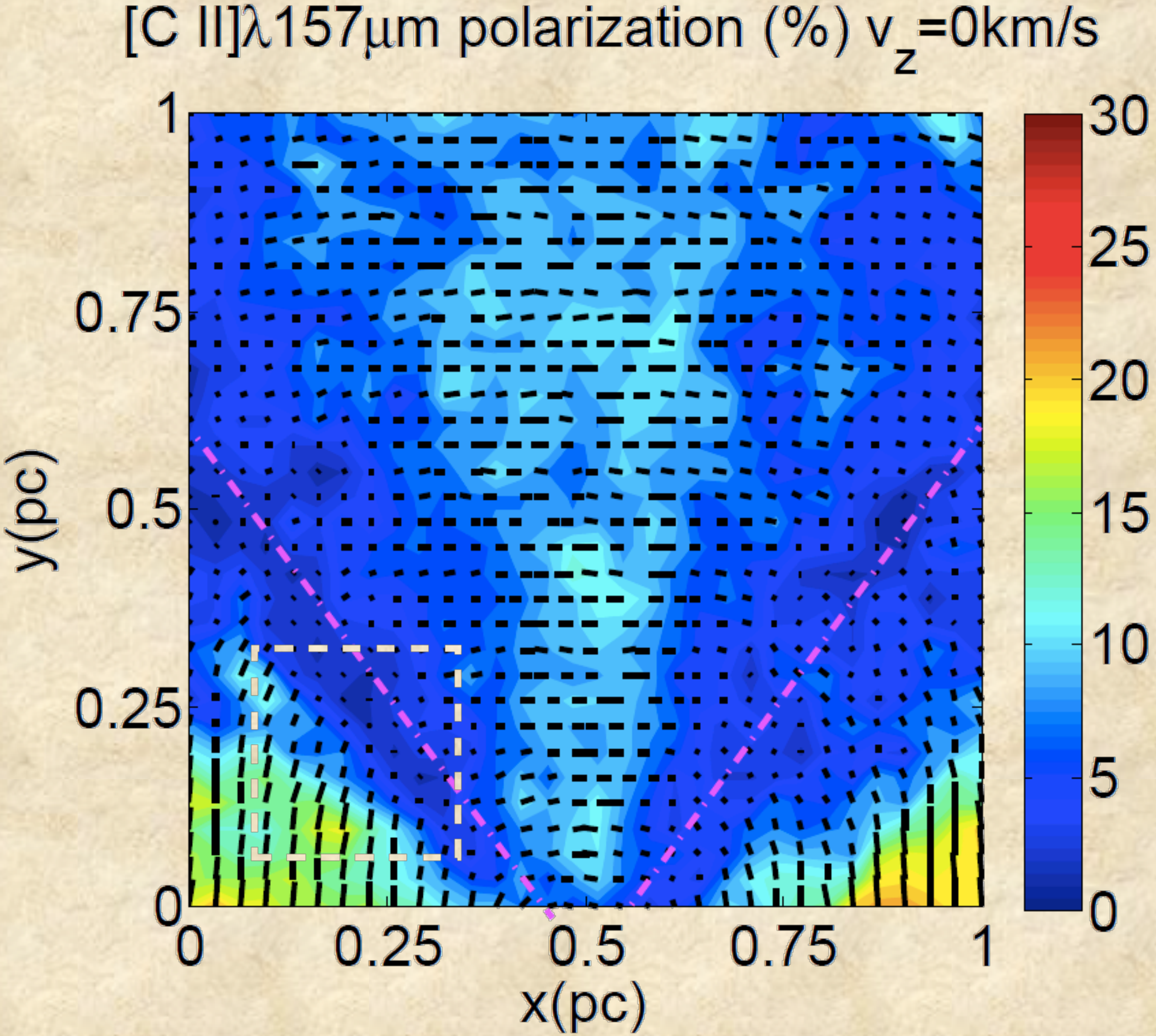
Polarization of OI 63.2 μm



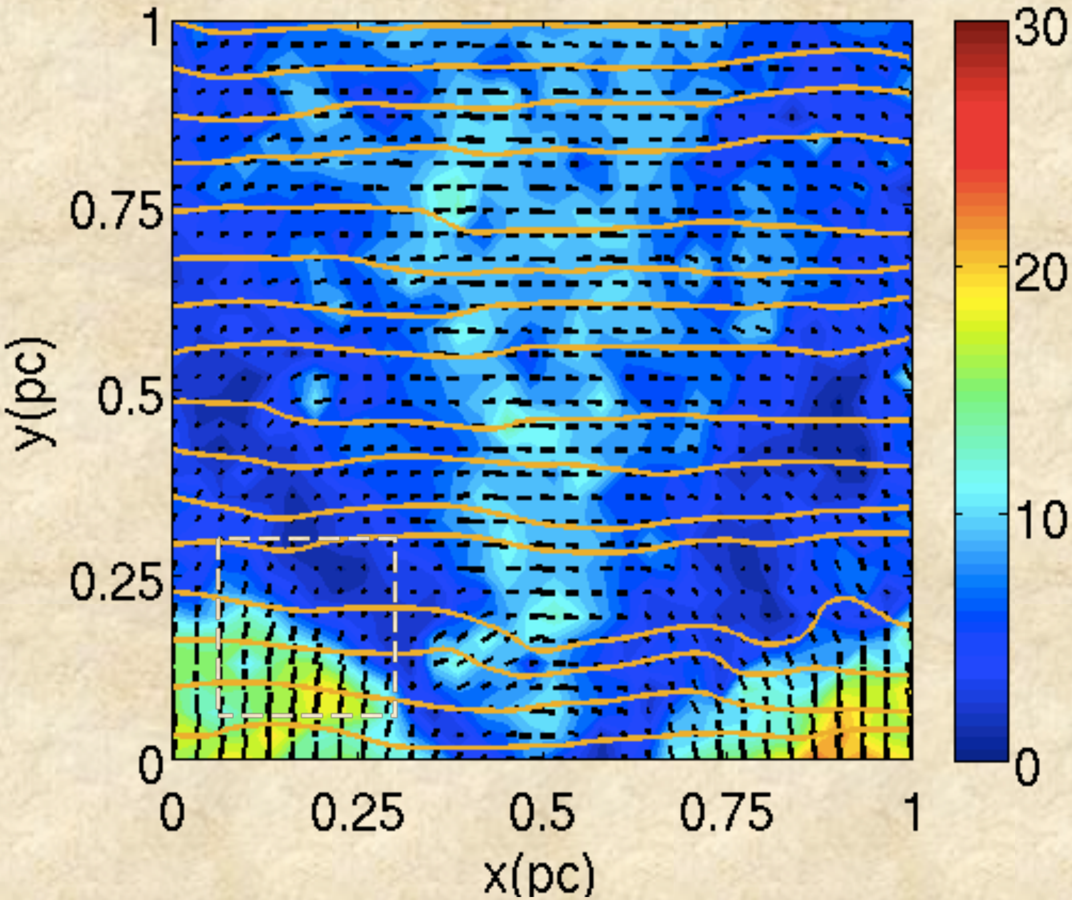


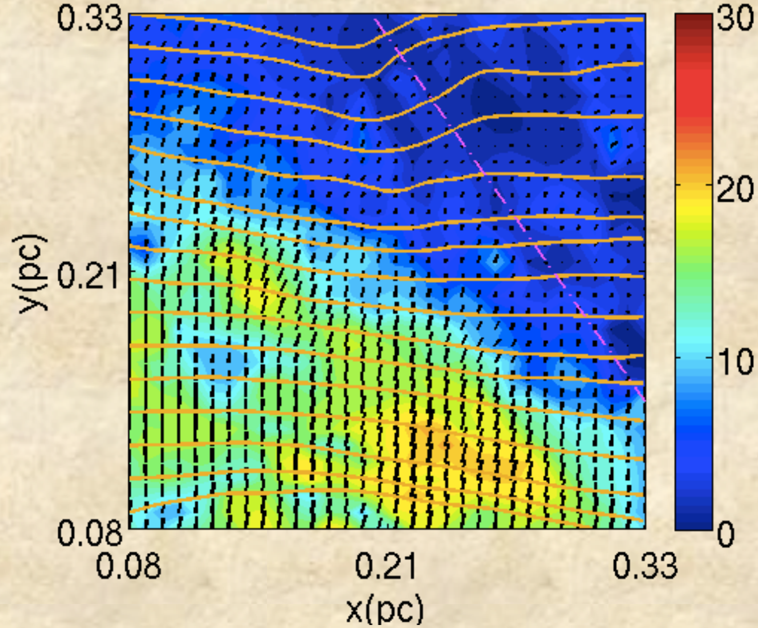
β= UV excitation rate/ CMB excitation rate
(Yan & Lazarian 2008)

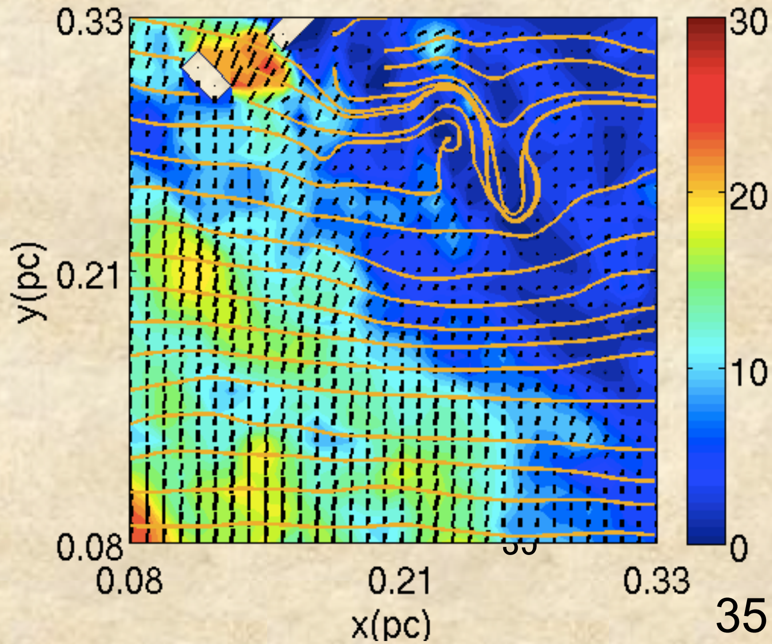

Velocity Contour XZ-Plane
z(pc)
x(pc)
0.2
0.1
0
0.25
0.5
0.75
1
4
3
2
1
0
-1
-2
-3
-4
km/s
Line of sight
B0=3μG
0.1pc
Ma=1.06
Illuminating star
z(pc)
0.25
0.2
0.15
0.1
0.05
0
y(pc)
x(pc)
Synthetic 3D ISM
By PENCIL
Zhang & HY (2018)



Zhang & HY (2018)







Zhang & HY (2018)

B_0

Wide avenues for B field detections