[S I] 25.2μm [S III] 33.5μm

[S IV] 10.5μm [Fe II] 26.0μm [C II] 157μm

[O I] 63μm …

[Si II] 34.8μm [C I] 610μm

Tracing magnetic fields with submillimeter spectropolarimetry

S II 125.0nm, 125.4nm, 125.9nm Si II 119.0nm

S III 101.2nm C II 133.4nm

S IV 106.3nm …

Fe II 260nm

S I 147.4nm

O I 102.6m

Heshou Zhang

DESY & Uni Potsdam

Huirong Yan

Magnetic field is important!

See Talk by everyone!

Atomic Alignment:
The B Tracer

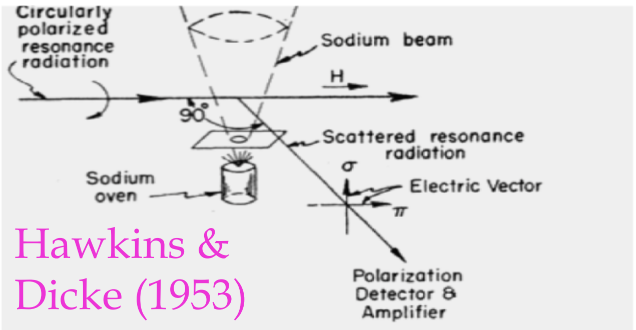


FIG. 2. Schematic view of apparatus.

Hawkins & Dicke (1953)

Kastler(1951)

Brossel et al (1952);
Hawkins & Dicke (1953),

Textbook time

The Nobel Prize in Physics 1966

Nobel Prize 1966: Kastler

Alfred Kastler
Prize share: 1/1

The Nobel Prize in Physics 1966 was awarded to Alfred Kastler *"for the discovery and development of optical methods for studying Hertzian resonances in atoms".*

Astronomy time

As Magnetic Tracer

Simulation Justification

Yan and Lazarian (2006,07,08,12,15)

Shangguan &Yan(2013)

Zhang , Yan & Dong (2015)

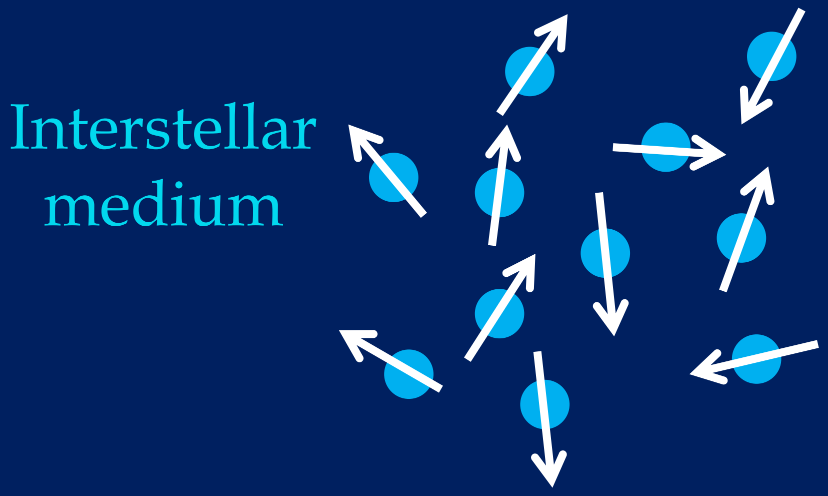
Zhang &Yan(2017)

Detection polarization of Hα
Kuhn et al (2007).

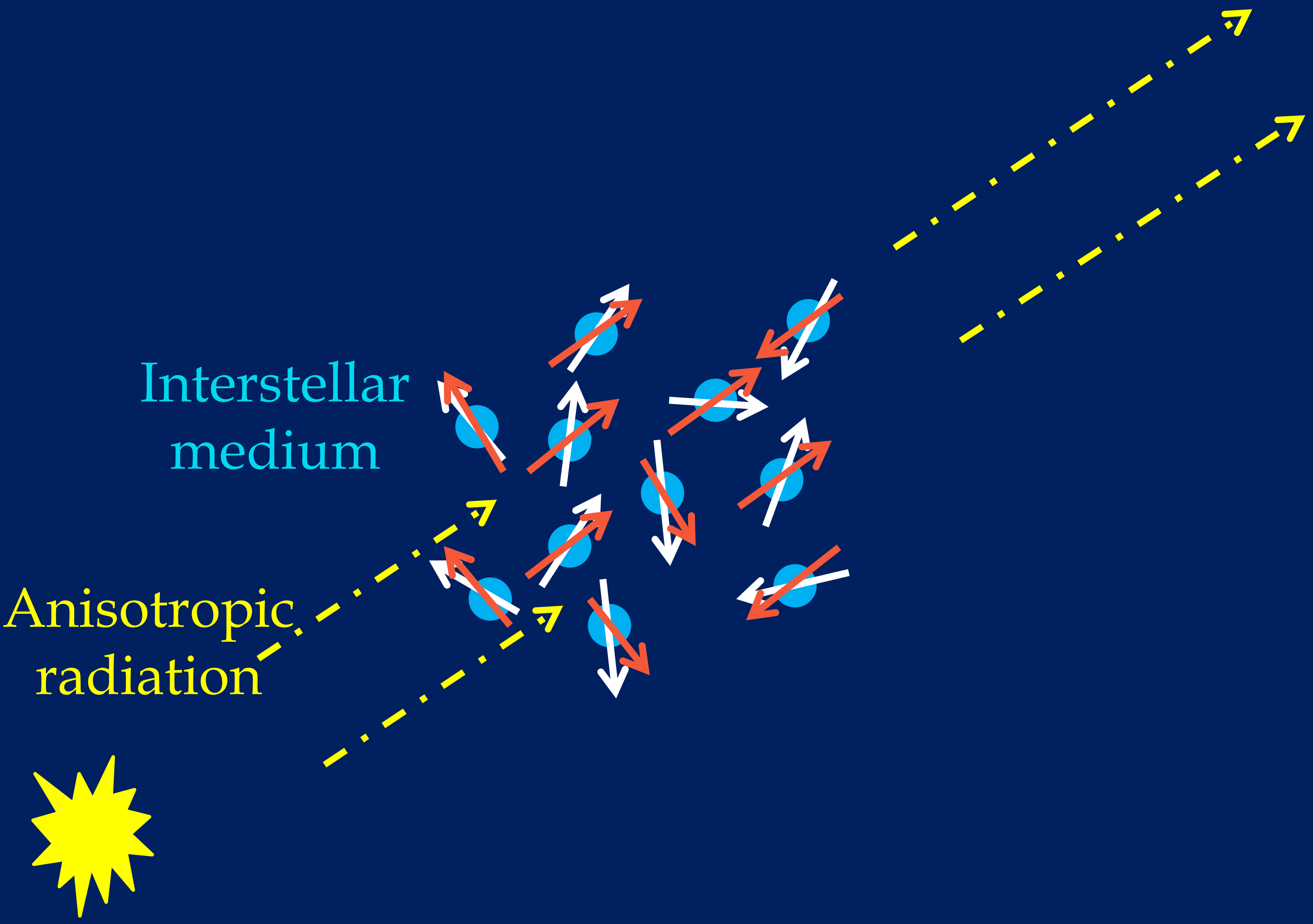
Spectroscopy application:
Zhang, Yan & Richter(2017)

It's Observation time!

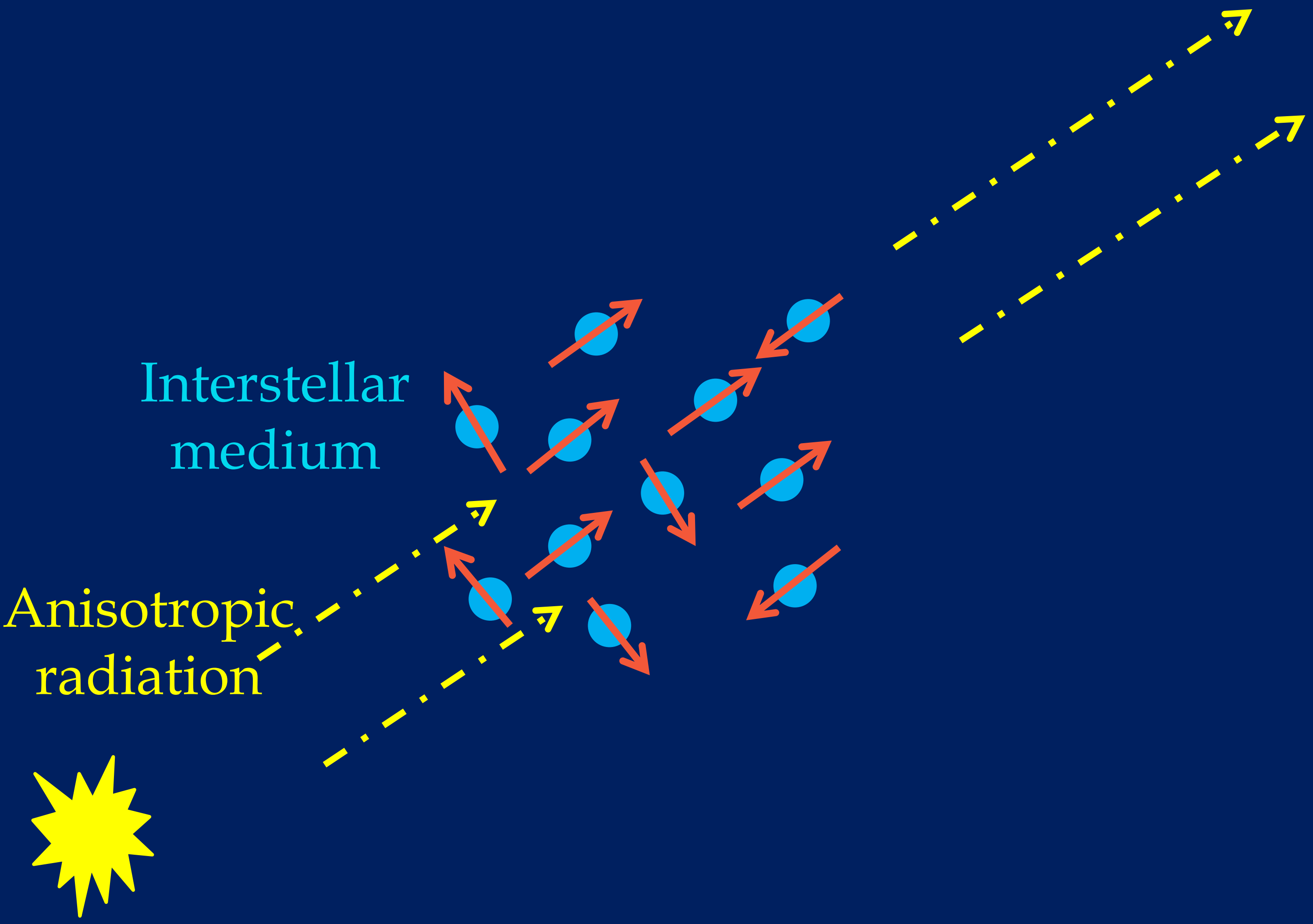
Physics for Atomic Alignment



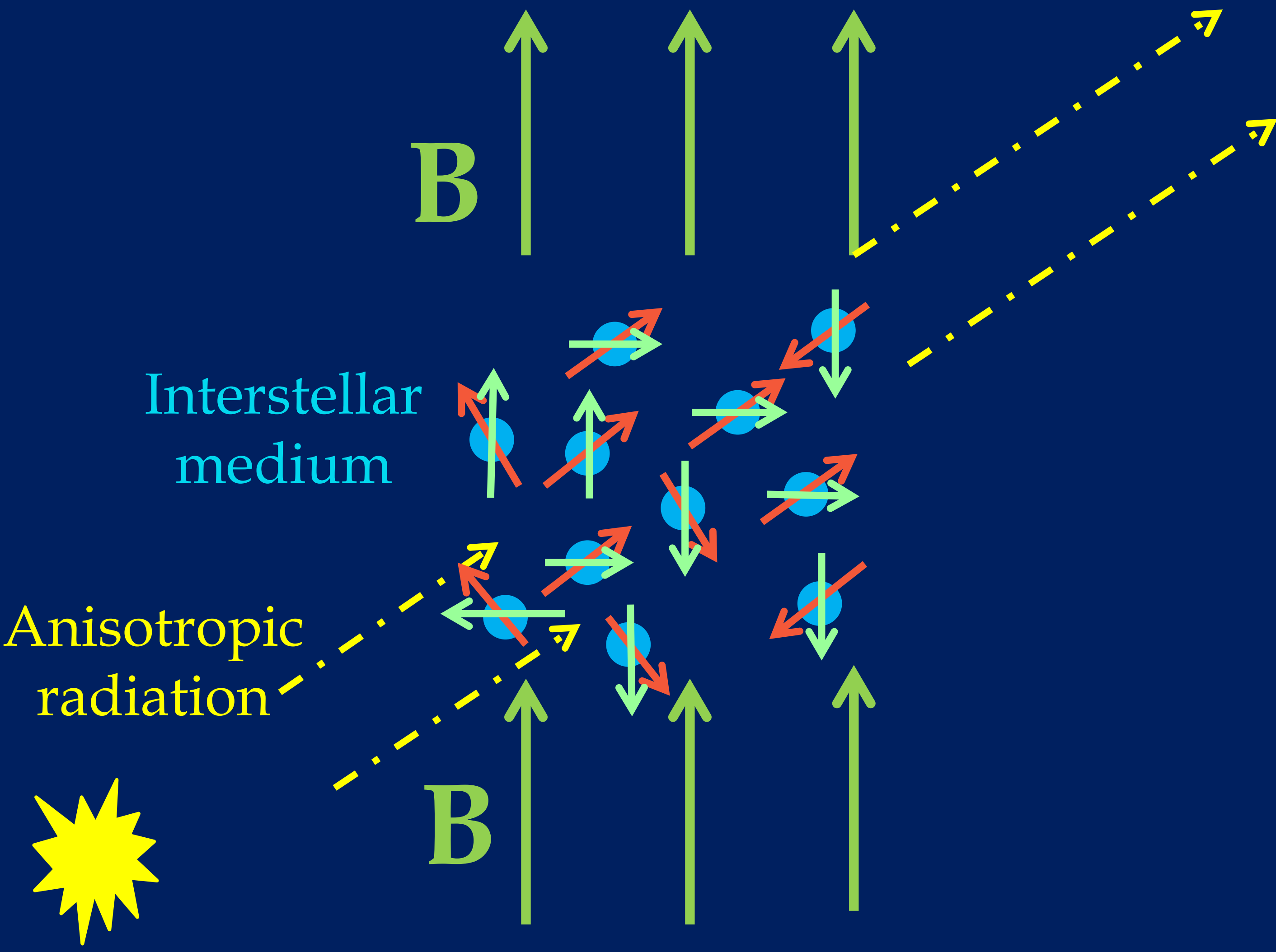
Physics for Atomic Alignment



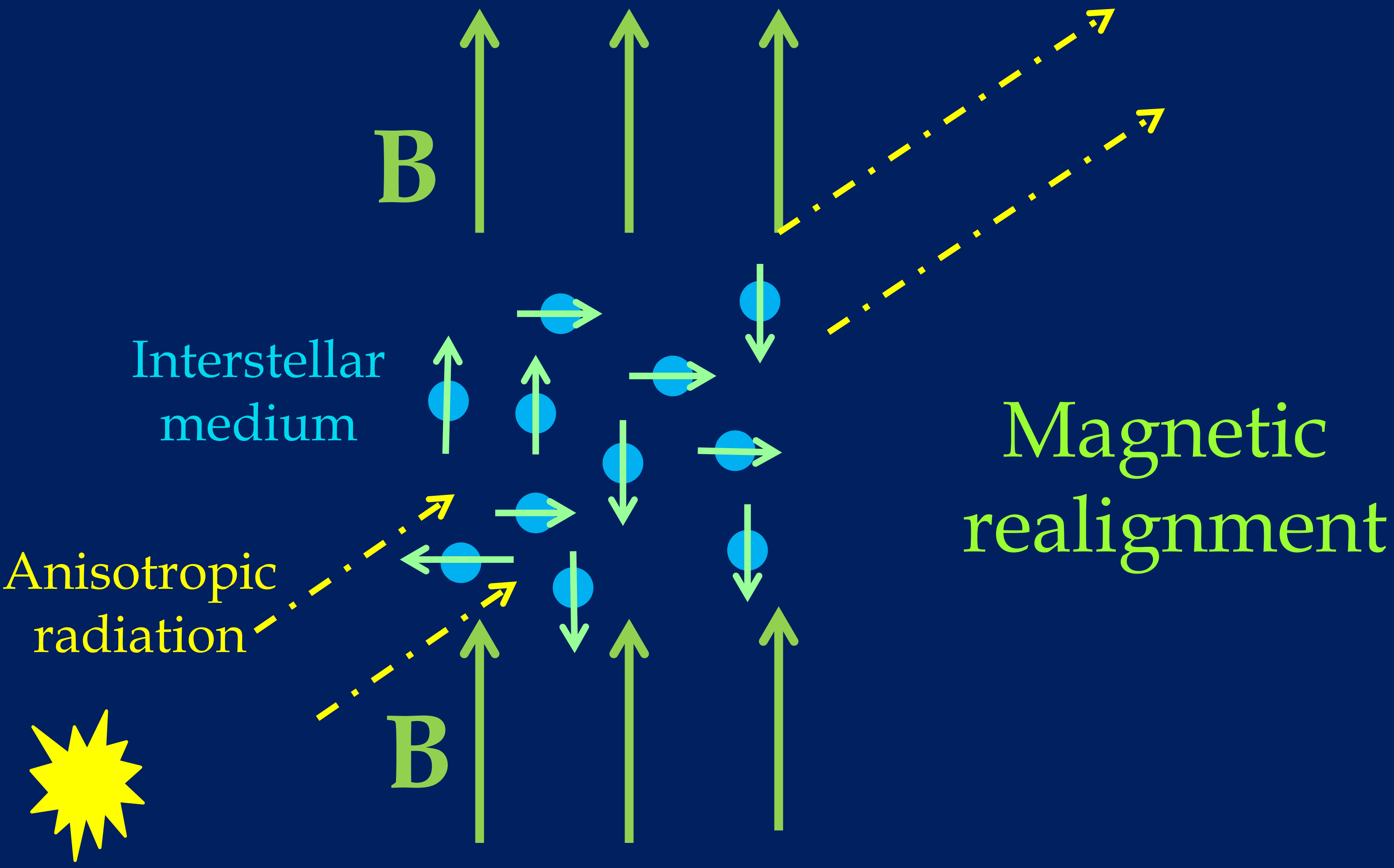
Physics for Atomic Alignment



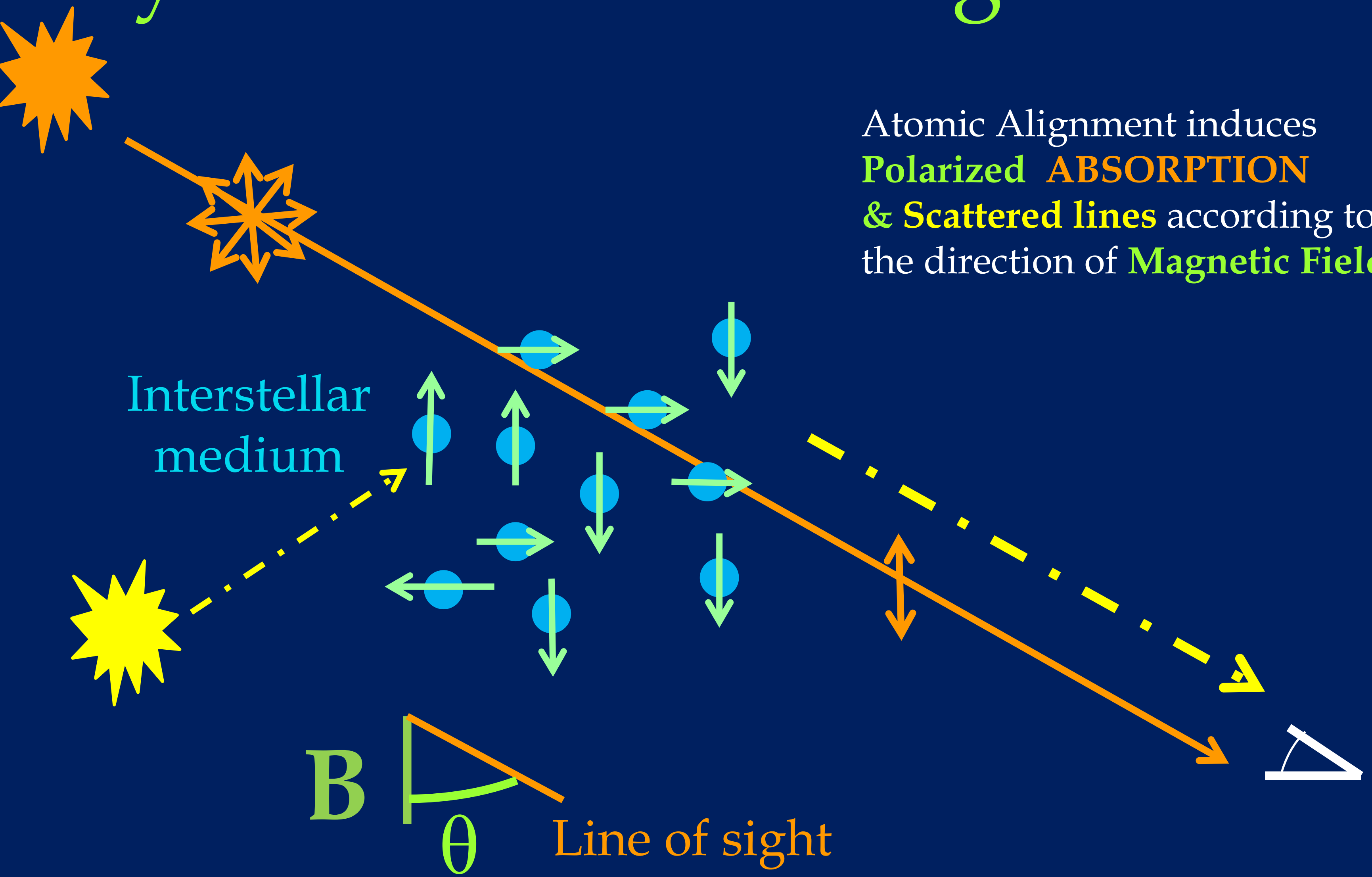
Physics for Atomic Alignment



Physics for Atomic Alignment



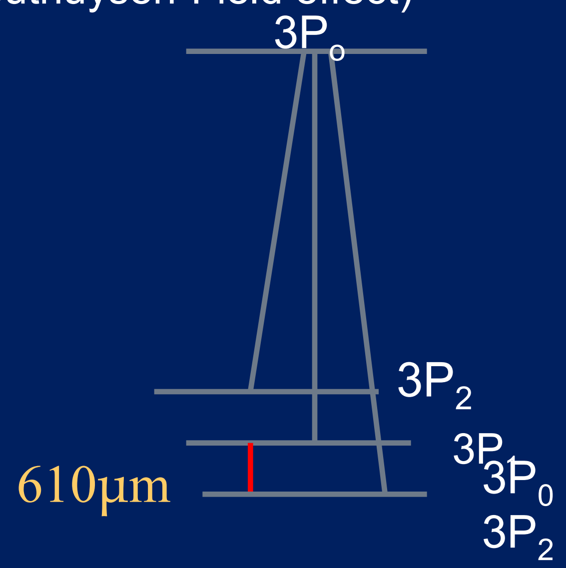
Physics for Atomic Alignment



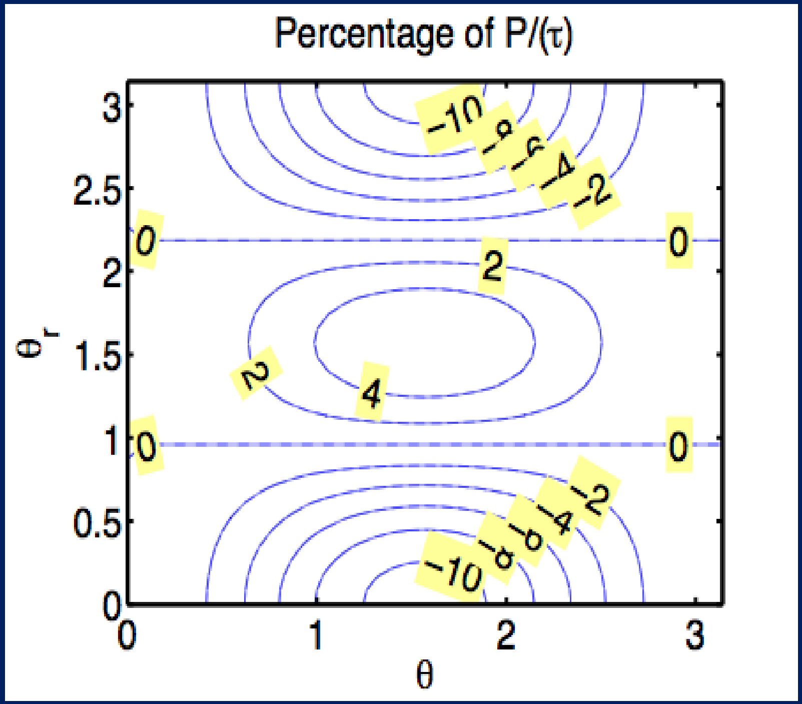
Atomic Alignment induces
Polarized ABSORPTION
& Scattered lines according to
the direction of **Magnetic Field**

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

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

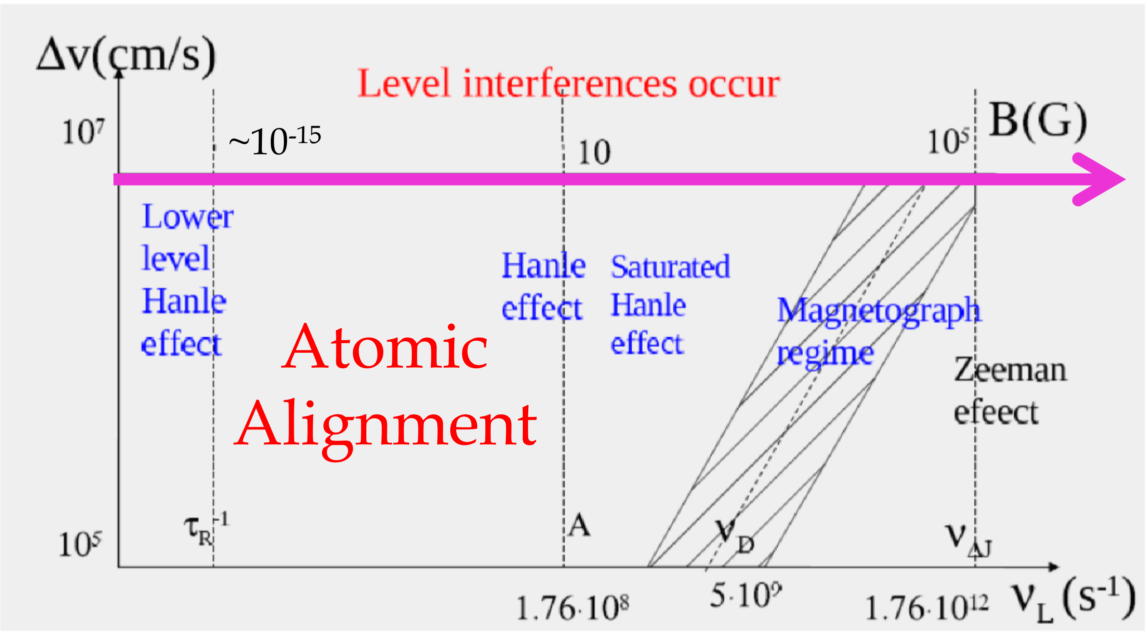


[CI] Emission



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

Atomic alignment Regime



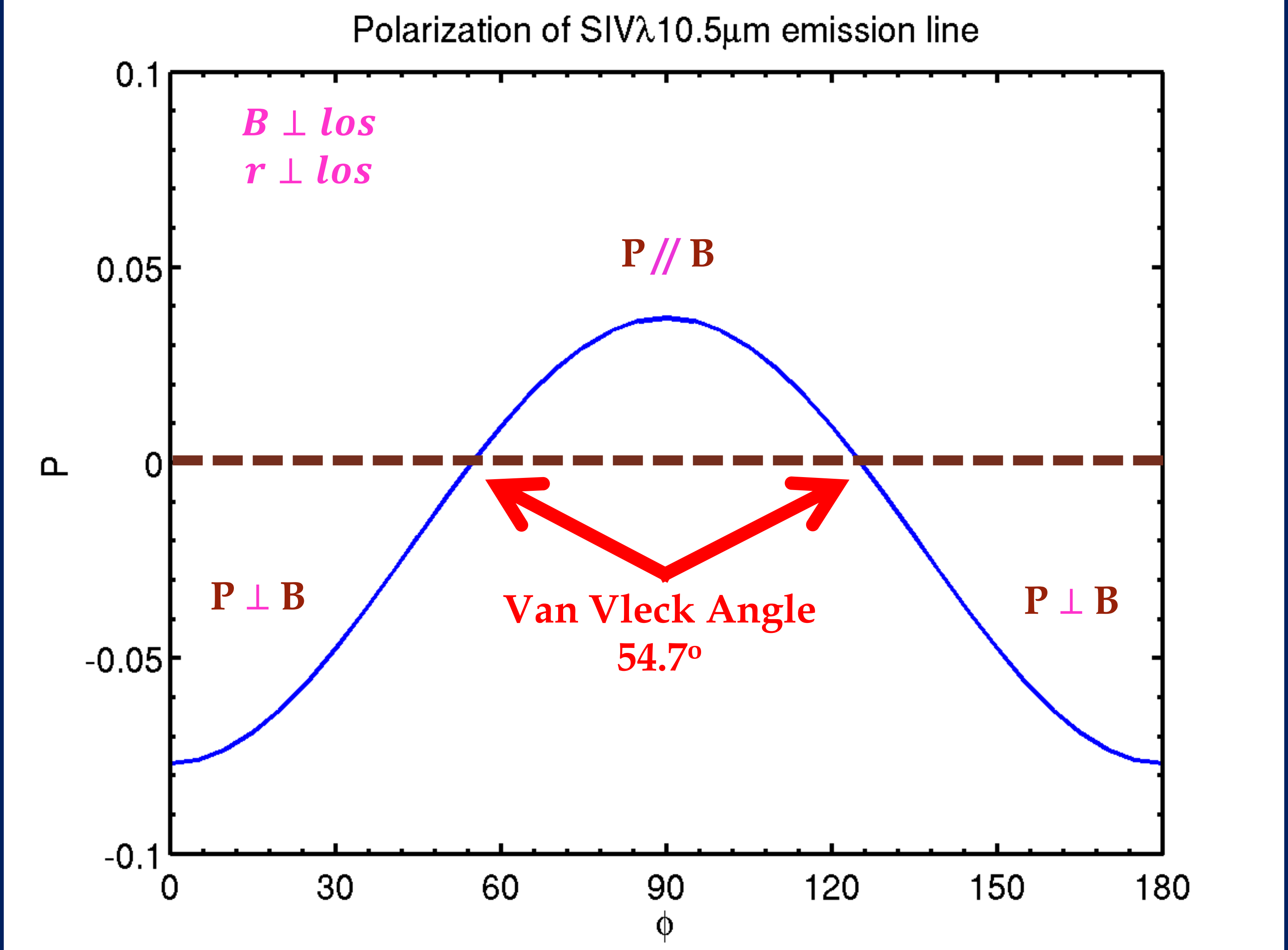
The realignment happens if $\tau_L^{-1} \gg A_m$

Time scale

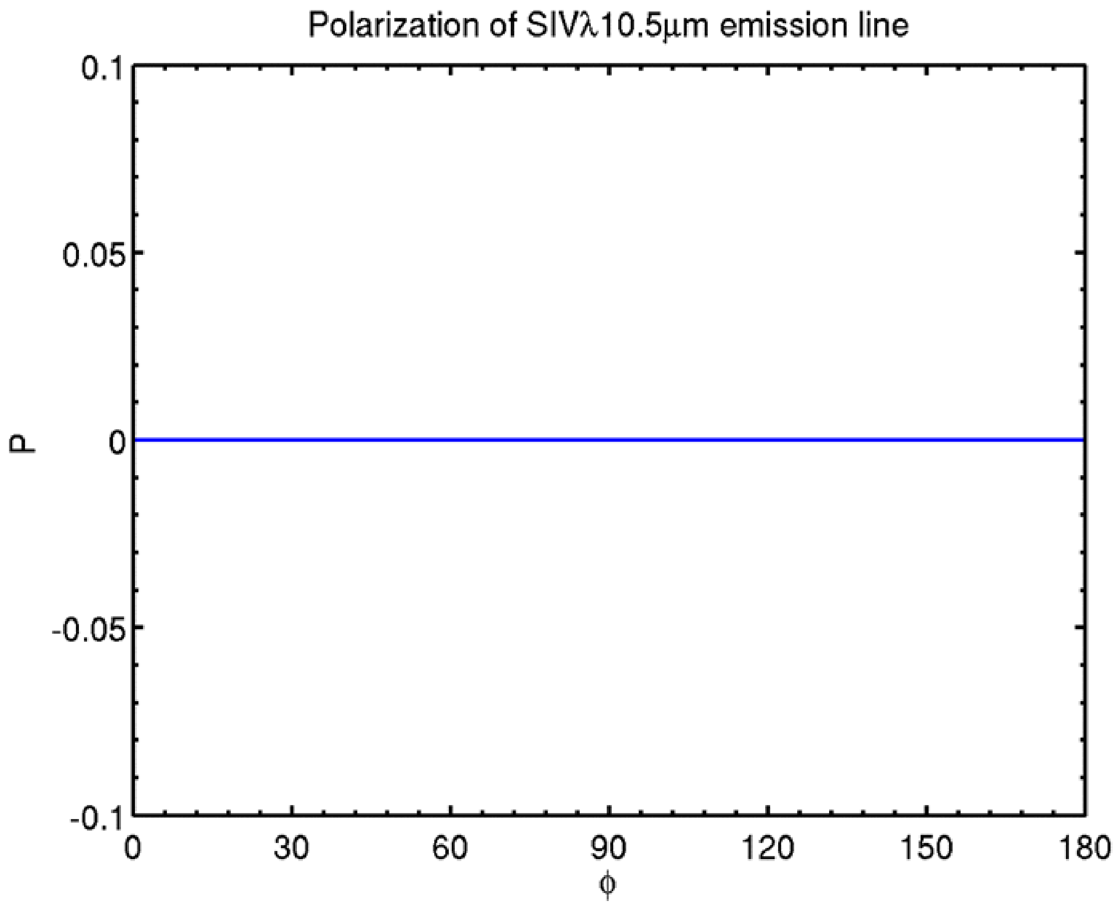
Review , Yan & Lazarian (2012)

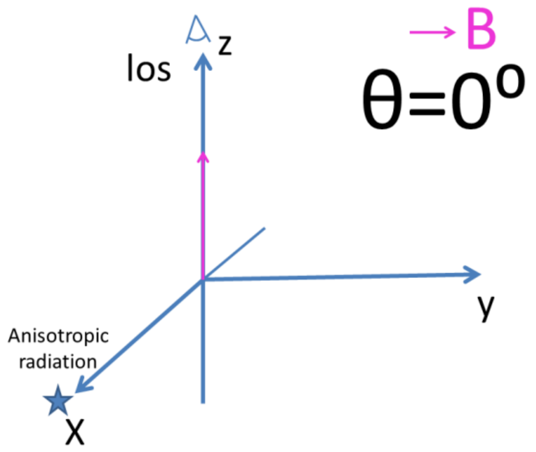
ν_L (s^{-1})	Larmor precession frequency	$\frac{eB}{m_e c}$	$88(B/5\ \mu G)$
τ_R^{-1} (s^{-1})	Radiative pumping rate	$B_{J_l J_u} I$	$7.4 \times 10^5 \left(\frac{R_*}{r}\right)^2$
τ_T^{-1} (s^{-1})	Emission rate within ground state	A_m	2.3×10^{-6}
τ_c^{-1} (s^{-1})	Collisional transition rate	$\max(f_{kj}, f_{sf})$	$6.4\left(\frac{n_e}{0.1\mathrm{cm}^{-3}}\sqrt{\frac{8000\ \mathrm{K}}{T}}\right) \times 10^{-9}$

Direction of Polarization Enough for 2D Magnetic Field with 90° degeneracy



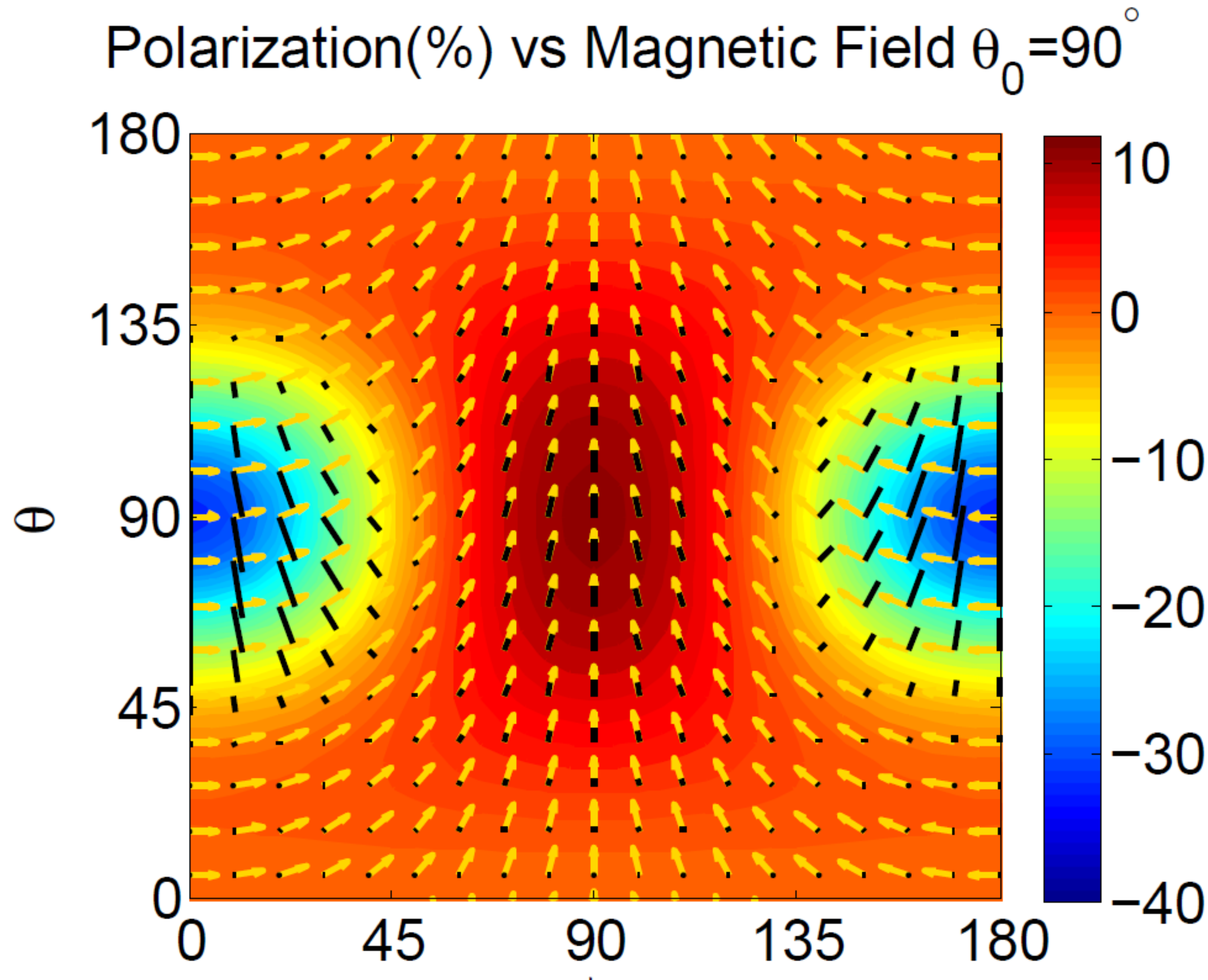
submillimeter spectropolarimetry
as a Magnetic tracer





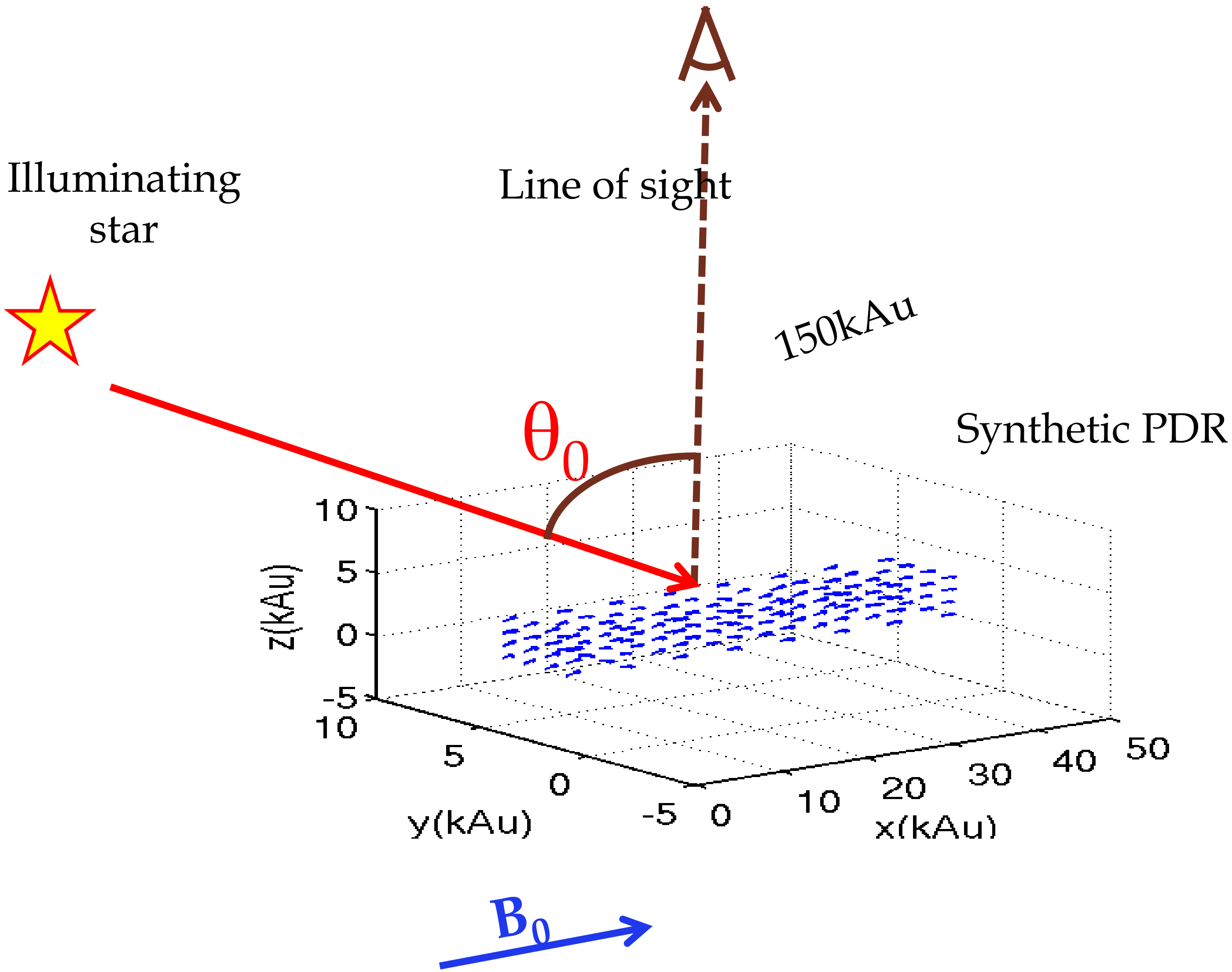
Degree of Polarization Give us 3D Magnetic Field

sub... etry



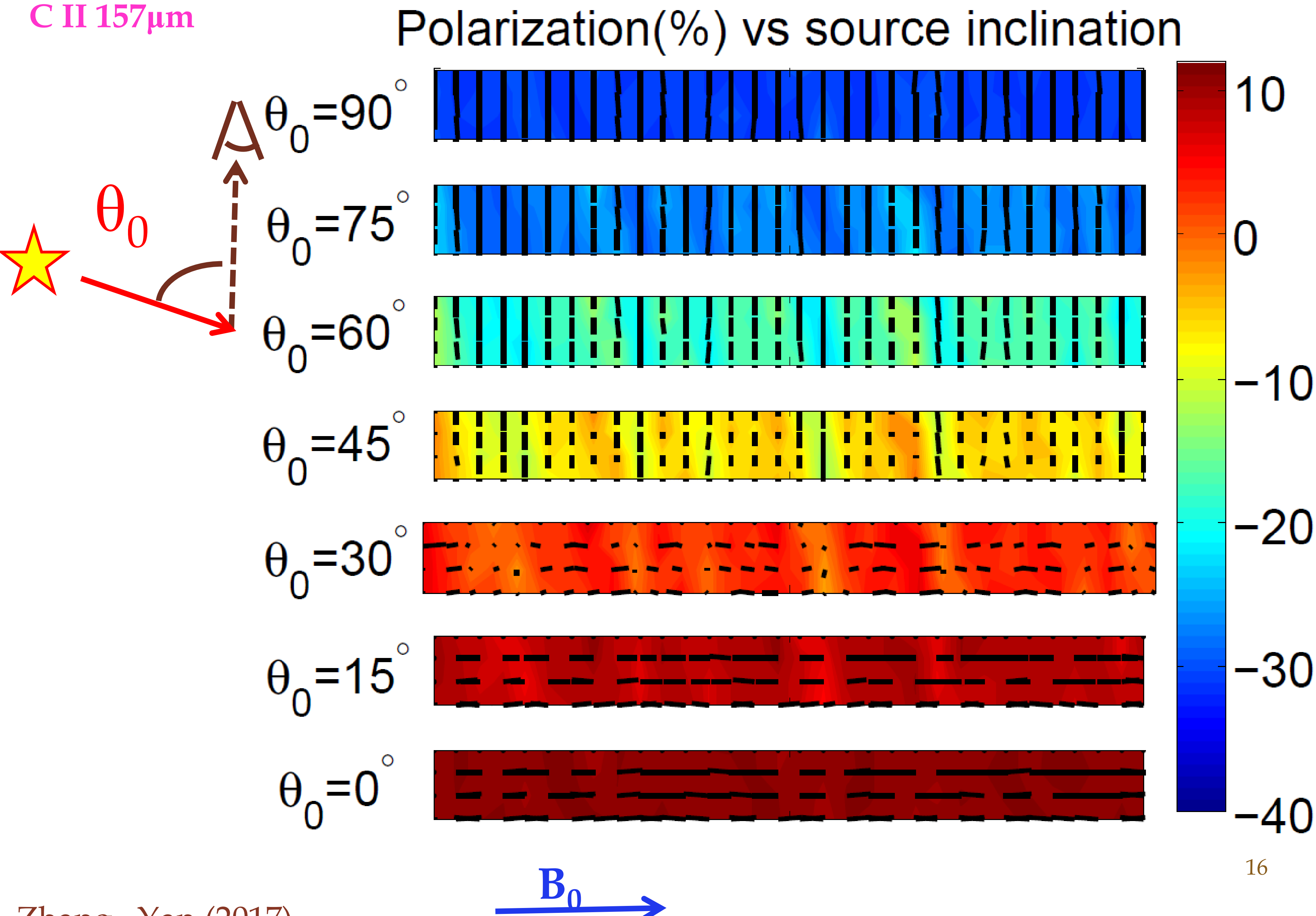
C II 157μm

Zhang , Yan (2017)

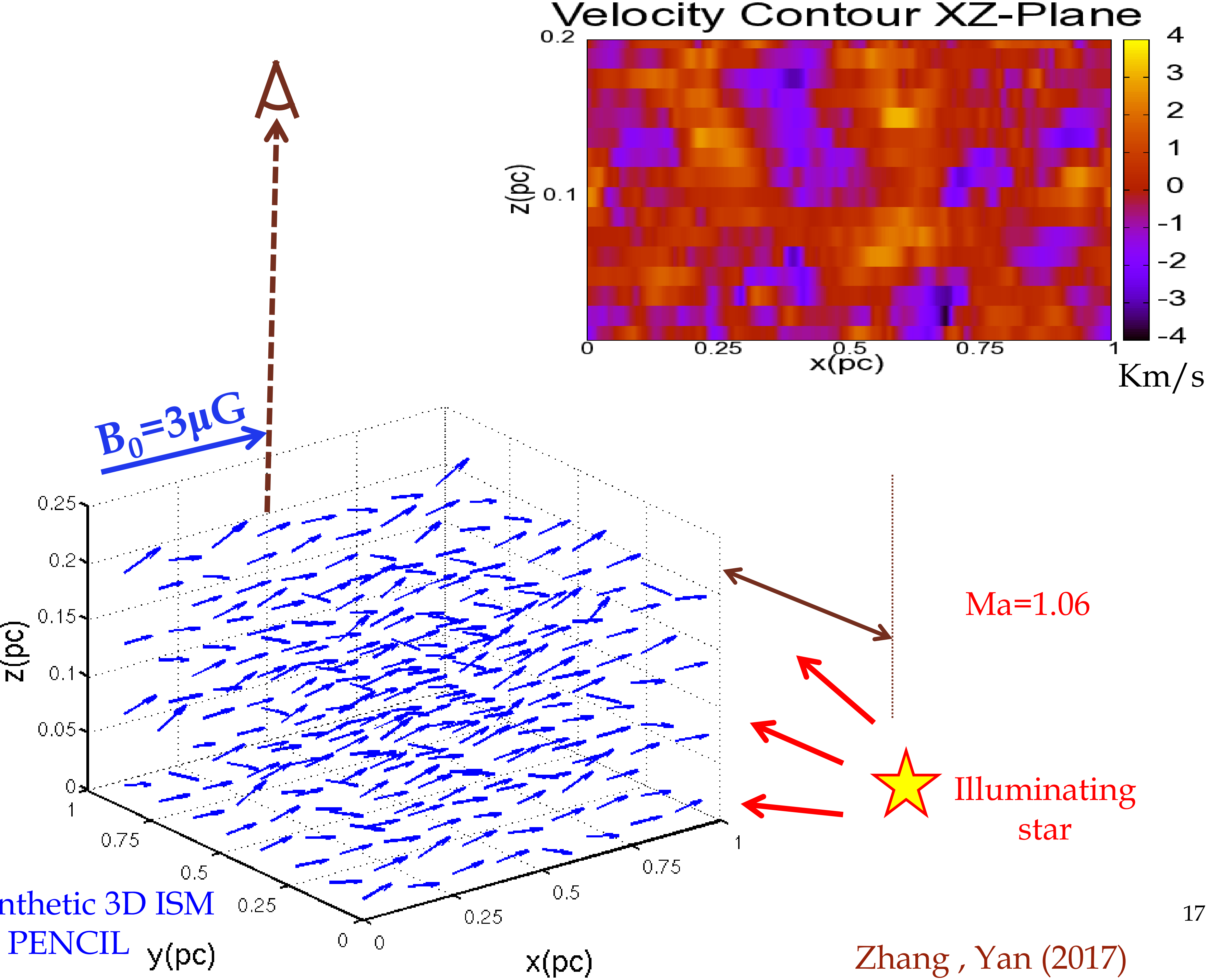


Zhang , Yan (2017)

C II 157μm

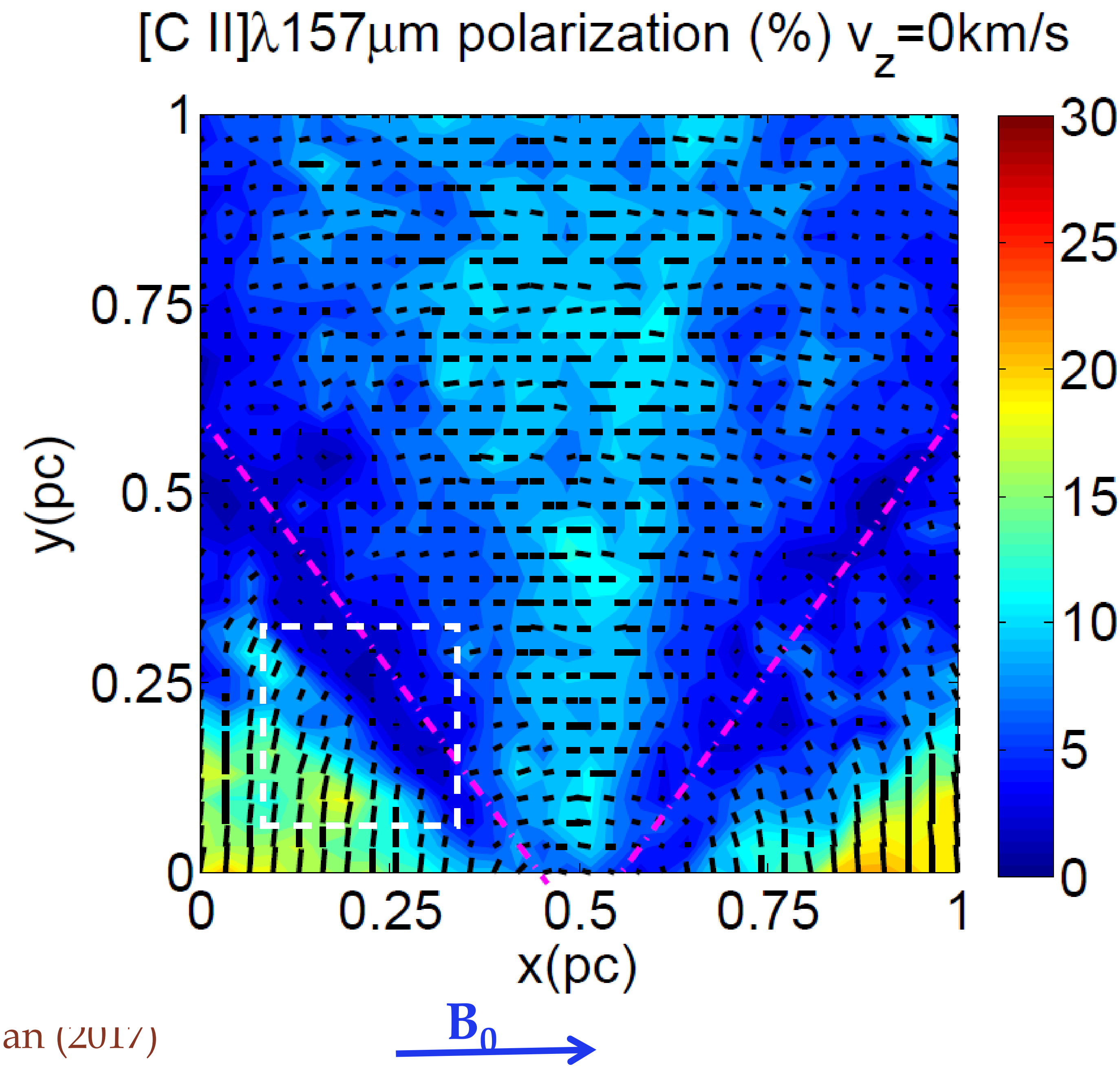


Zhang , Yan (2017)

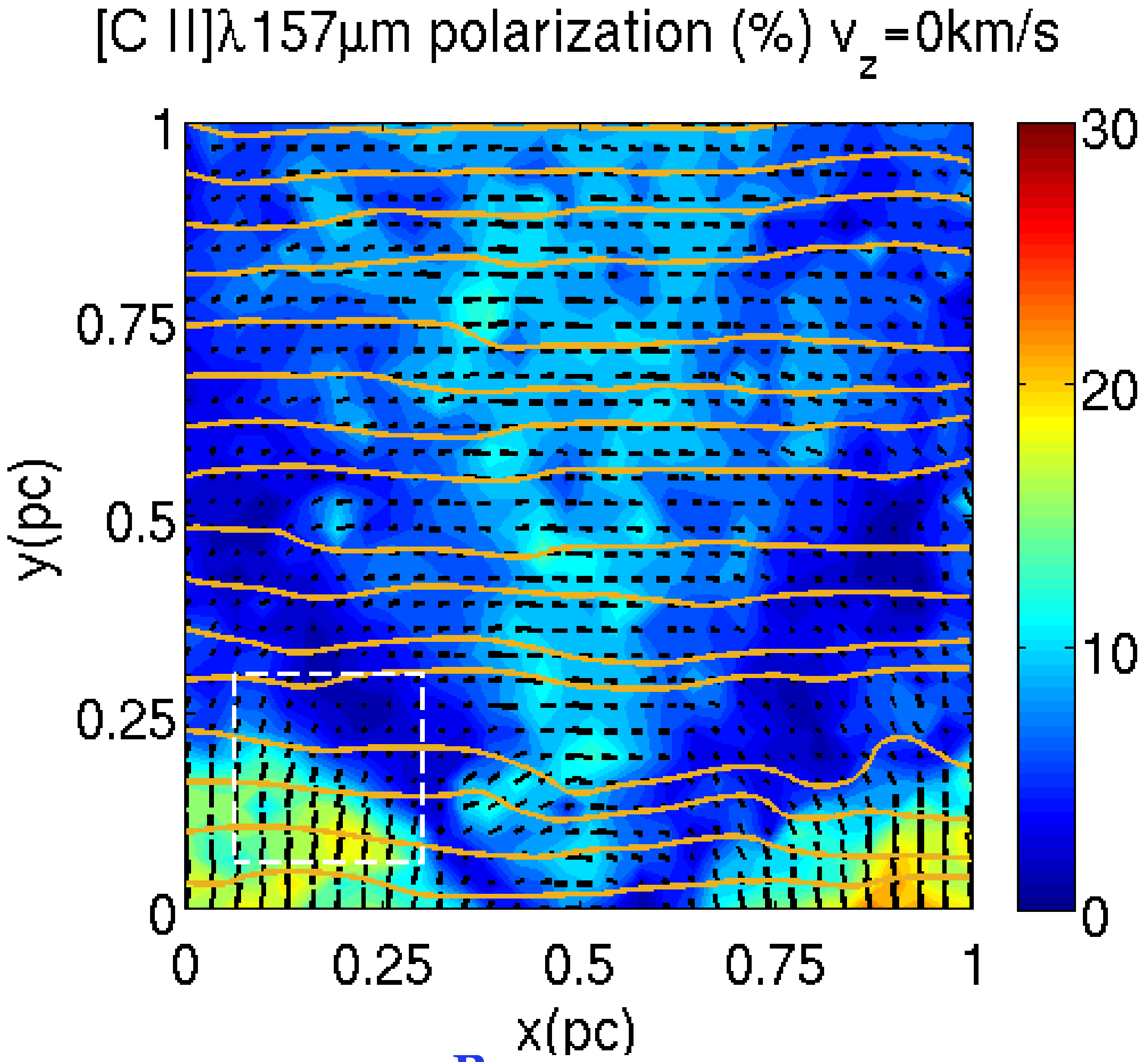


Synthetic 3D ISM
By PENCIL

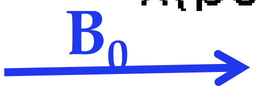
Zhang , Yan (2017)

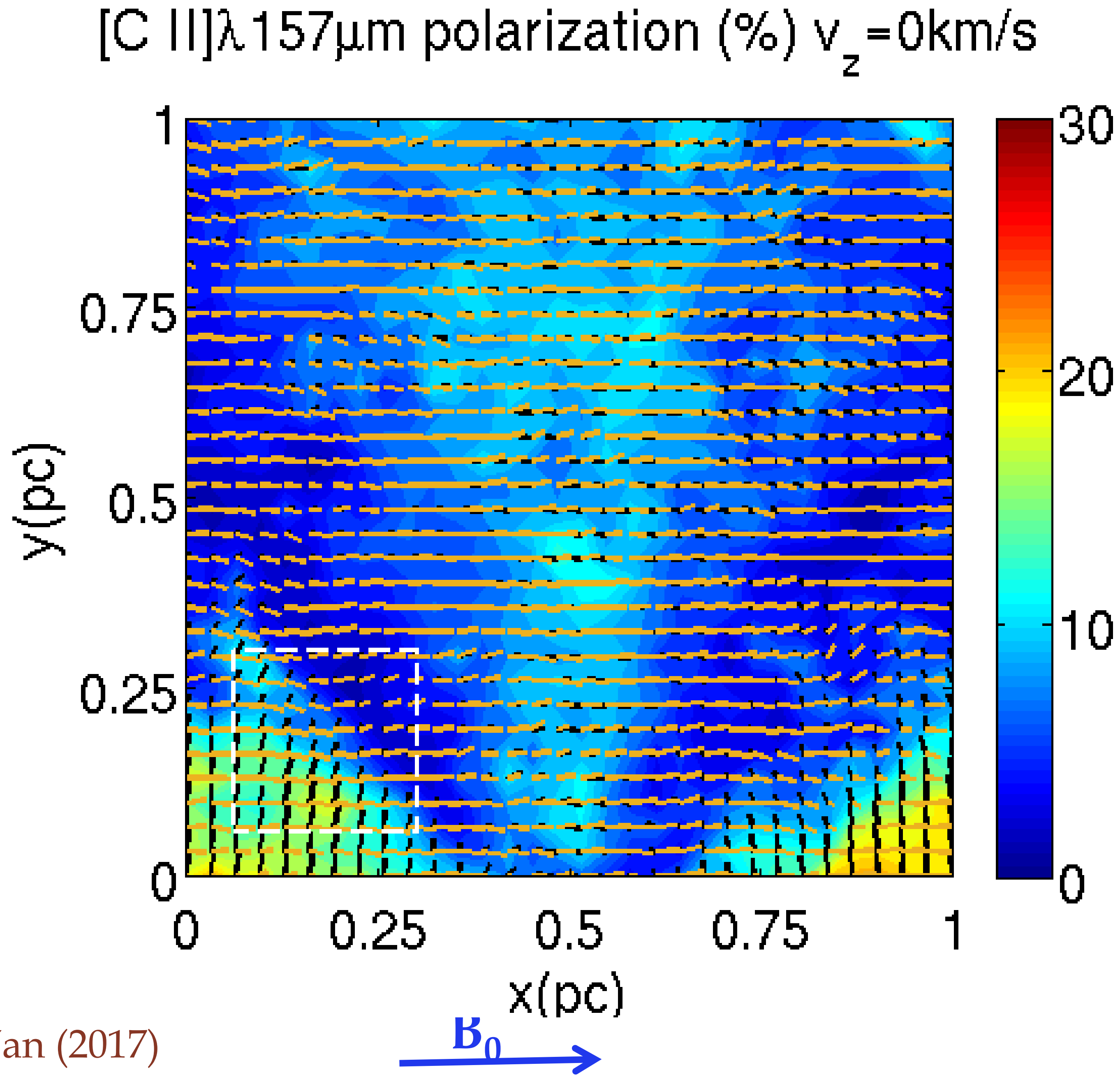


Zhang , Yan (2017)



Zhang , Yan (2017)



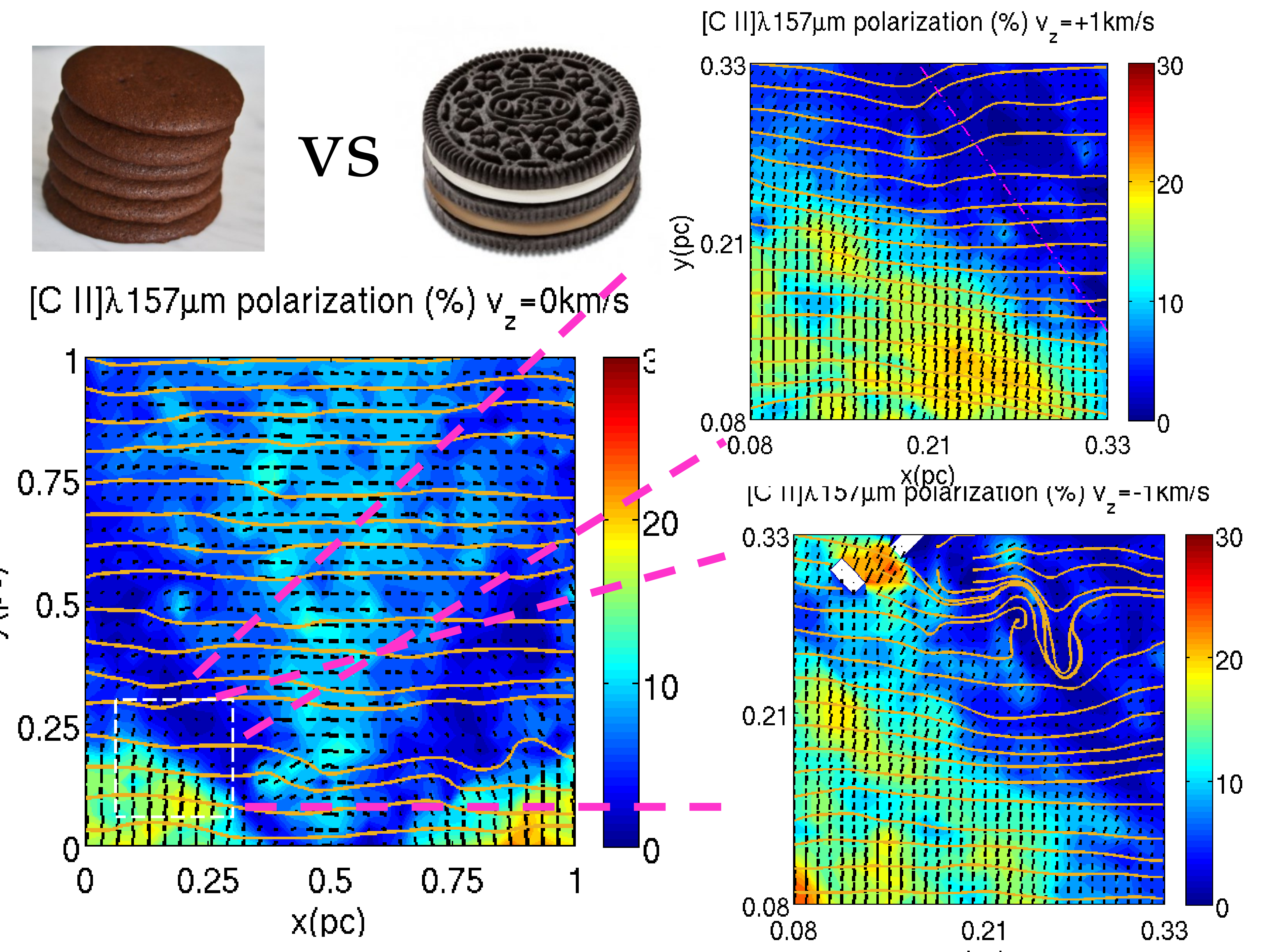


Zhang , Yan (2017)

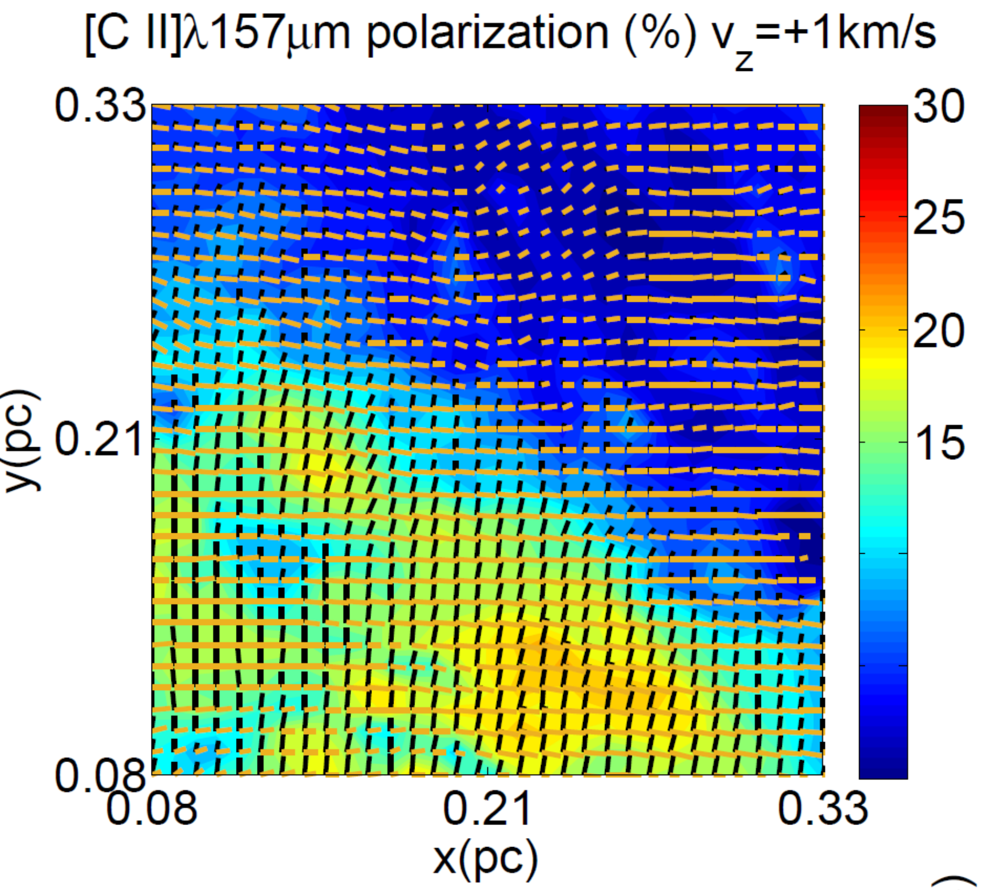
Normal waffle vs Oreo?

vs

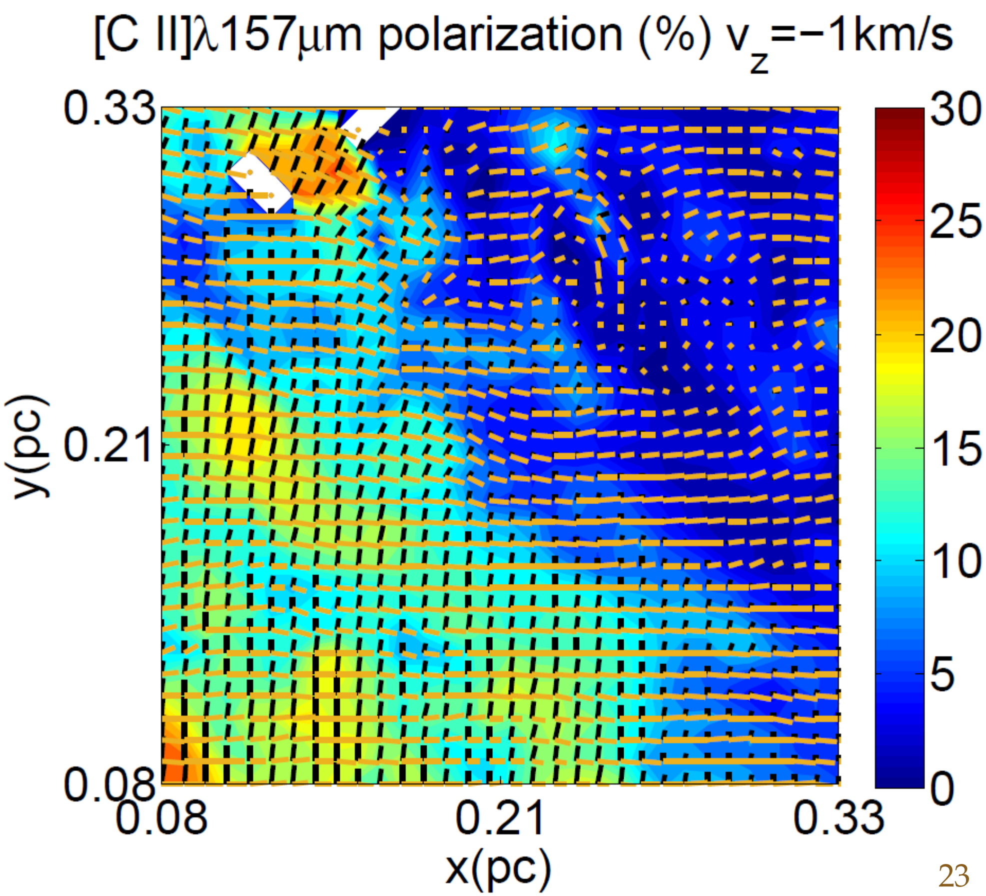
See talk by Susan & Ka ho



VS
OREO
[C II]λ157μm polarization (%) v_z=0km/s
x(pc)
[C II]λ157μm polarization (%) v_z=+1km/s
y(pc)
x(pc)
[C II]λ157μm polarization (%) v_z=-1km/s



GSA for
Small scale pattern of B



Zhang , Yan (2017)

Submillimeter emission lines in SFRs

Table 1. Maximum Polarization FOR SUBMILLIMETER EMISSION LINES

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

Zhang , Yan (2017)

Submillimeter absorption lines in Foreground medium

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%

Zhang , Yan (2017)

Advantages of Atomic Alignment as a Magnetic Field Tracer

- **Probing the degree of polarization of the line can give us 3 D information of the magnetic field.**
- sensitive to weak magnetic field
- applicable to all diffuse interstellar medium
- Different options of observation: both absorption and emission lines.
- Multi-scale magnetic pattern
- Complimentary to other magnetic tracer, e.g., dust alignment

Observation: A Bright Vision

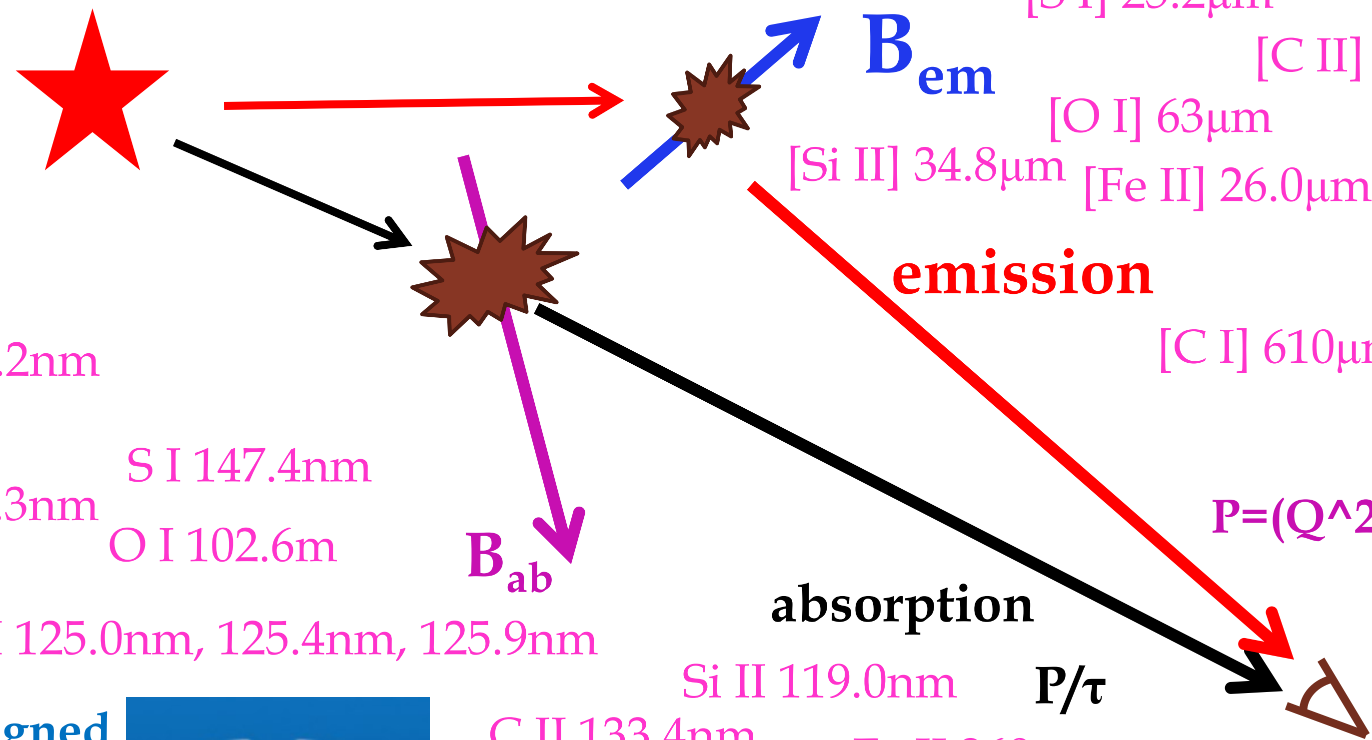
[S I] 25.2μm [S III] 33.5μm

[C II] 157μm

[O I] 63μm

[Si II] 34.8μm [Fe II] 26.0μm

[C I] 610μm



P=(Q^2+U^2)^0.5/I

S III 101.2nm

S I 147.4nm

S IV 106.3nm

O I 102.6m

S II 125.0nm, 125.4nm, 125.9nm

Si II 119.0nm

C II 133.4nm

Fe II 260nm

Ti II 336.1nm …

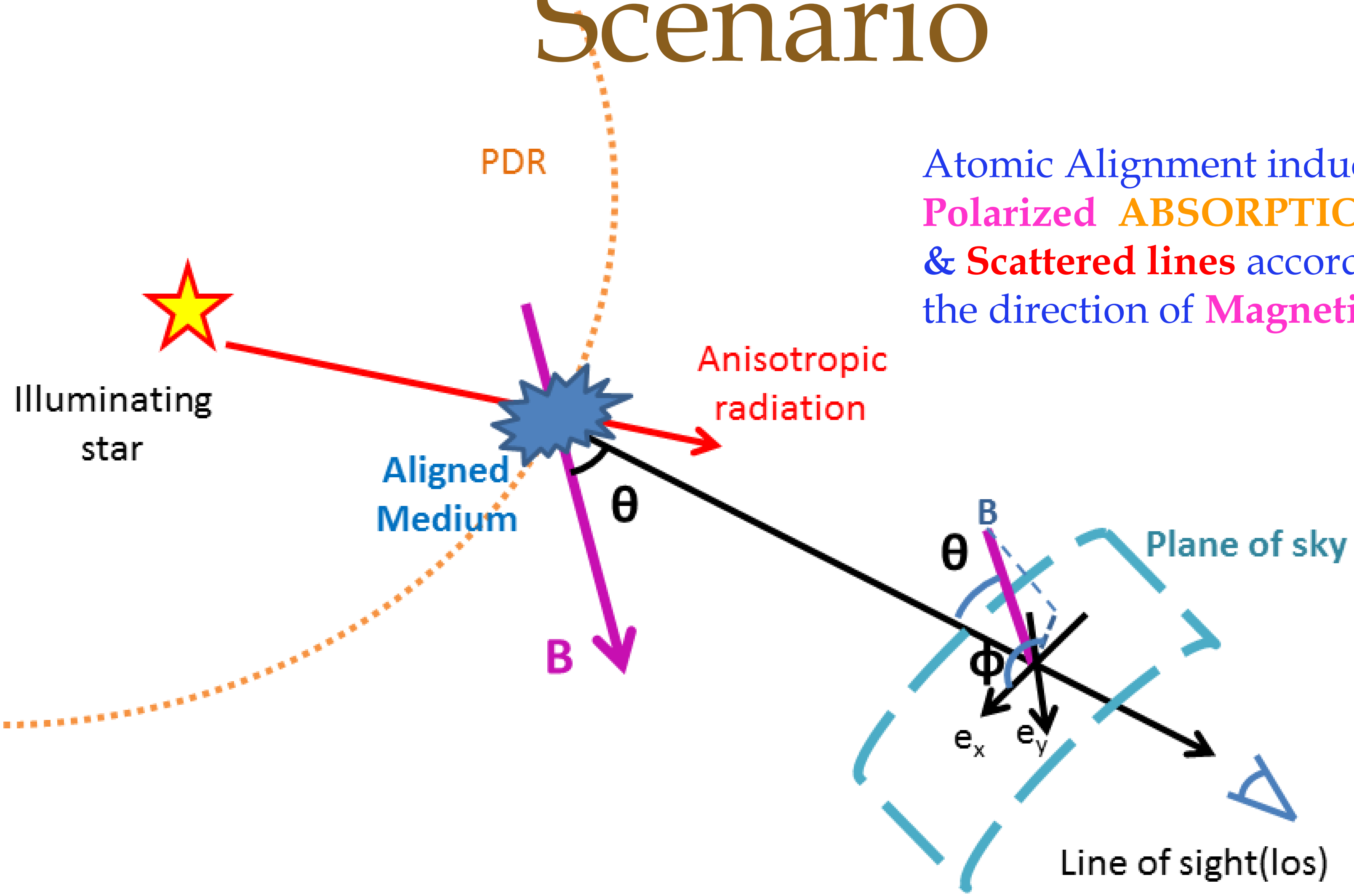
Aligned Medium

SALT

Conclusions

- **Polarization of atomic lines** is a universal and promising **magnetic tracer** in diffuse interstellar medium due to atomic alignment effect.
- A good measurability calls for cooperation with observers. **Let's unveil the magnetic fields in the distant universe!**

Scenario

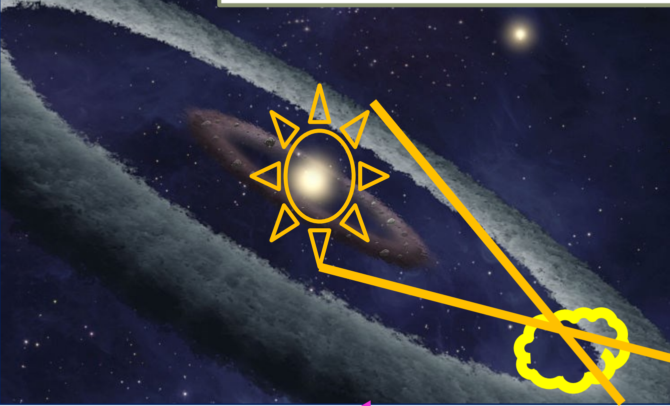


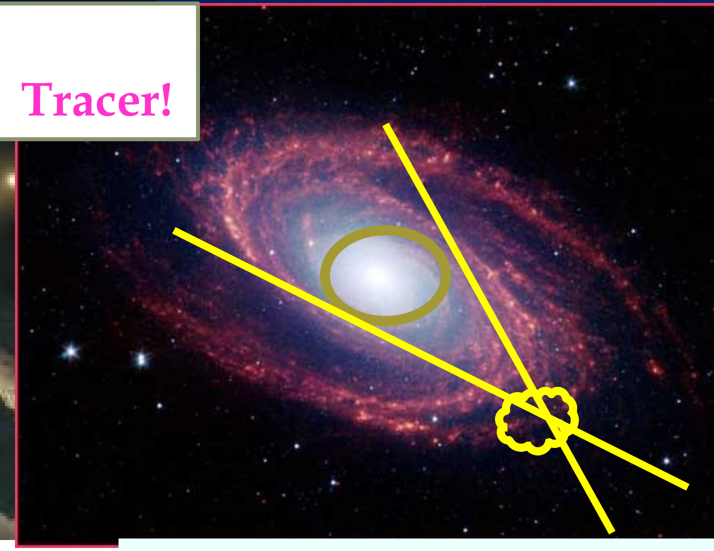
Atomic Alignment induces Polarized ABSORPTION & **Scattered lines** according to the direction of **Magnetic Field**

Atomic Alignment in comparison with Dust Alignment:

- **Provide independent test to grain alignment theory.**
- **Sensitive to smaller scale fluctuations.**
- **Combining the information from both, we can get more precise 3D information of magnetic field.**

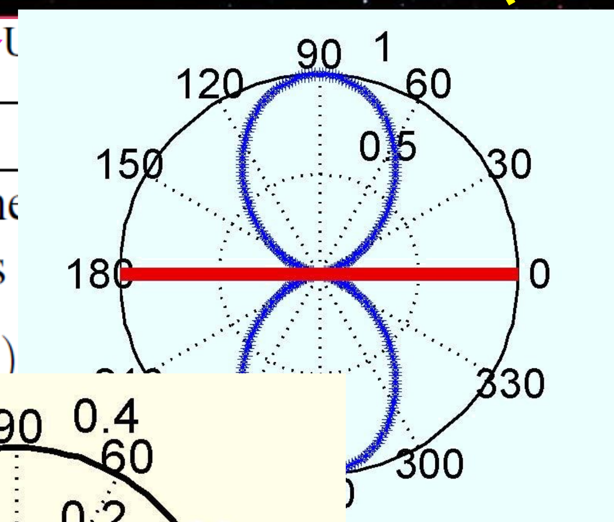
Atomic Alignment applies to general anisotropic radiation as a Magnetic Tracer!

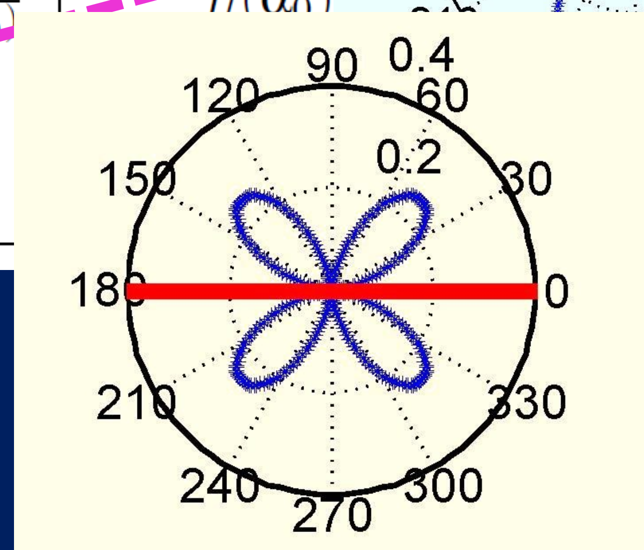




SWITCH ANGLES OF THE POLARIZATION INDU

Diffuse medium	Switch angle	
Circumstellar medium	54.7°	the
Binary systems	$\arccos \frac{1}{\sqrt{3t}}$	t is
Disc shape radiation field	$\arccos \sqrt{\frac{2}{3 f_l(\alpha_0)}}$	$f_l(\alpha_0)$
the Local ISM	35.3°	
Dipole radiation field	54.7°	
Quadrupole radiation field	54.7°	le





Zhang , Yan & Dong (2015) ApJ, 804, 142

Magnetic study in astrophysics

Most common ways of magnetic field study:

- Zeeman splitting ($B_{//}$) :strong magnetic fields in dense and cold cloud(Crutcher 2004, etc)
- Faraday rotation($B_{//}$) :large scale field(Crutcher 2008, etc)
- Synchrotron radiation($B_{\perp}$):galactic halo(R. Beck 2008, etc)
- Grain alignment($B_{\perp}$):widely used, some uncertain on shape and composition(Lazarian 2007, etc)

No universal magnetic diagnostics in diffuse medium!