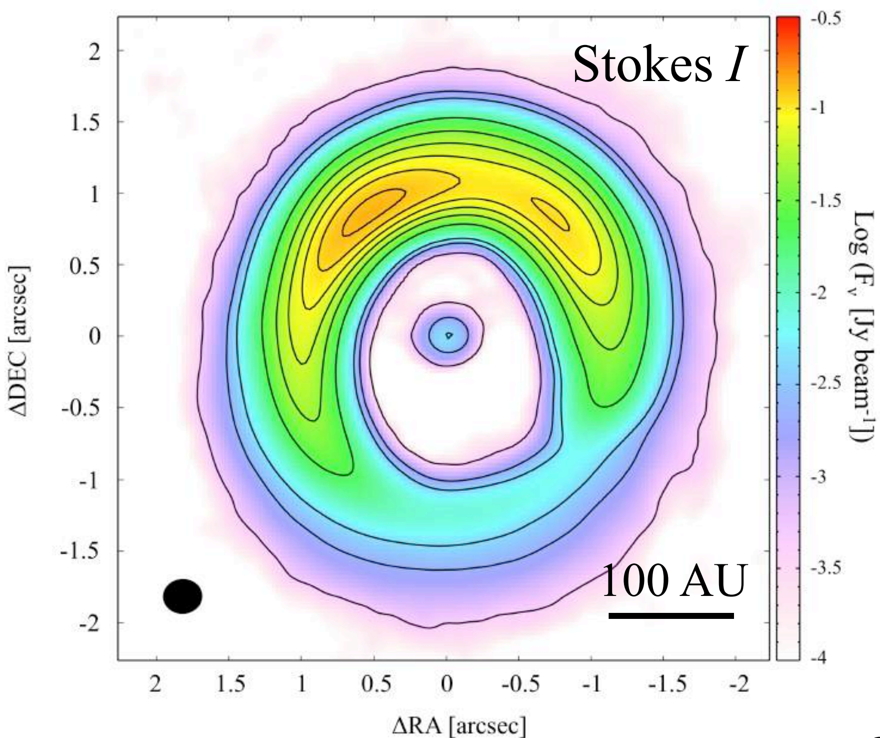
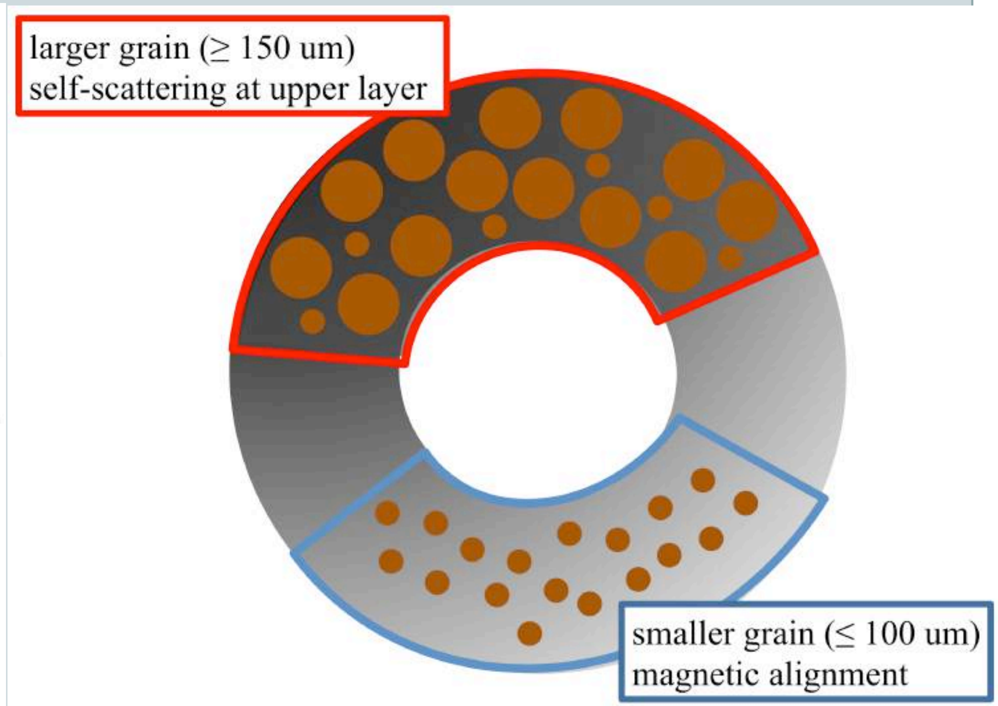
# 原始惑星系円盤のALMA偏光観測

大橋聡史（理研,基礎科学特別研究員）
片岡章雅、永井洋、塚越崇、深川美里（国立天文台）、百瀬宗武（茨城大）、花輪知之（千葉大）、武藤恭之（工学院大）、村川幸史（大阪産業大）、芝井広（大阪大）

HD 142527



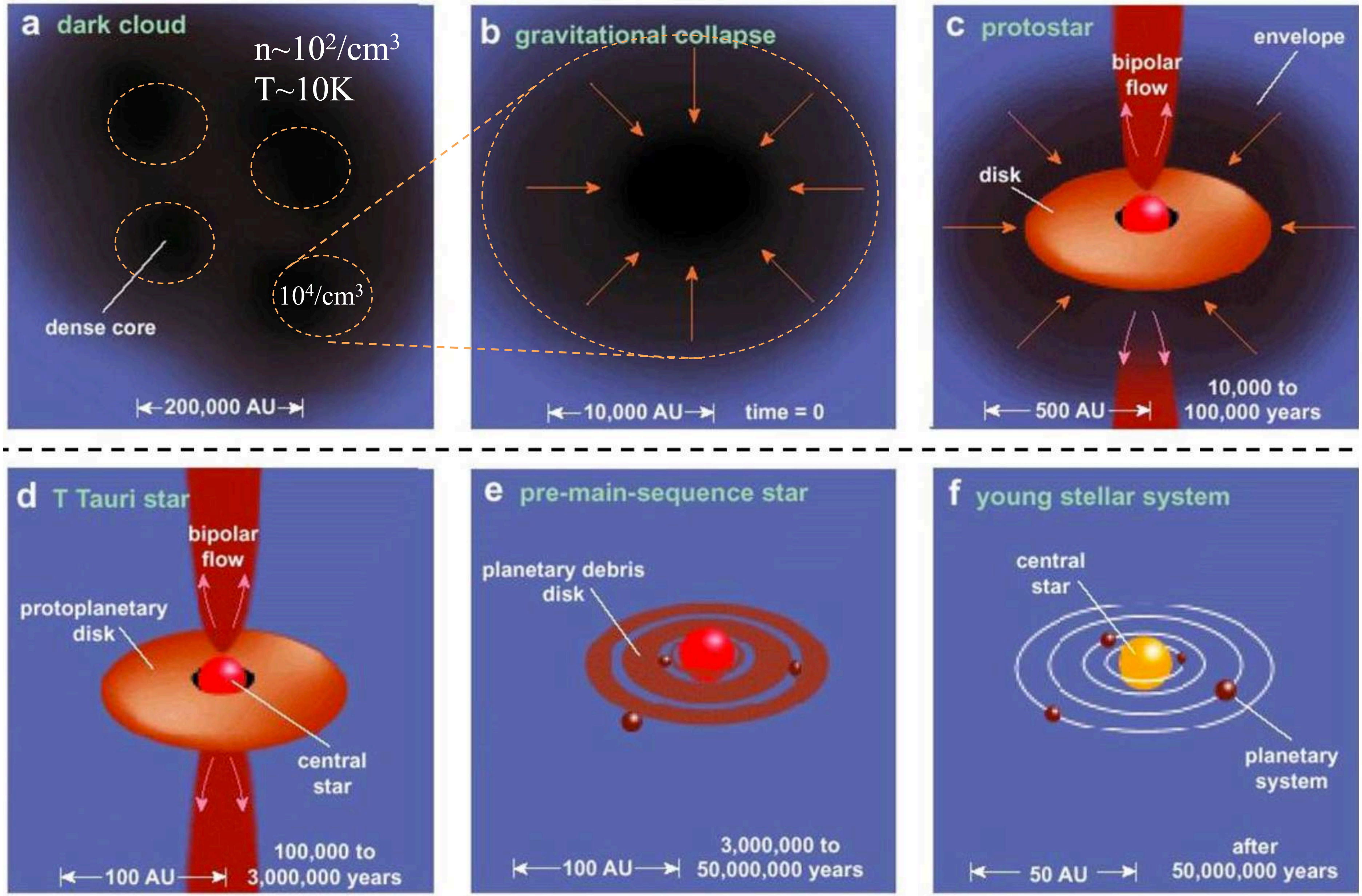




Ohashi et al. 2018 ApJ, 864, 81

# Outline

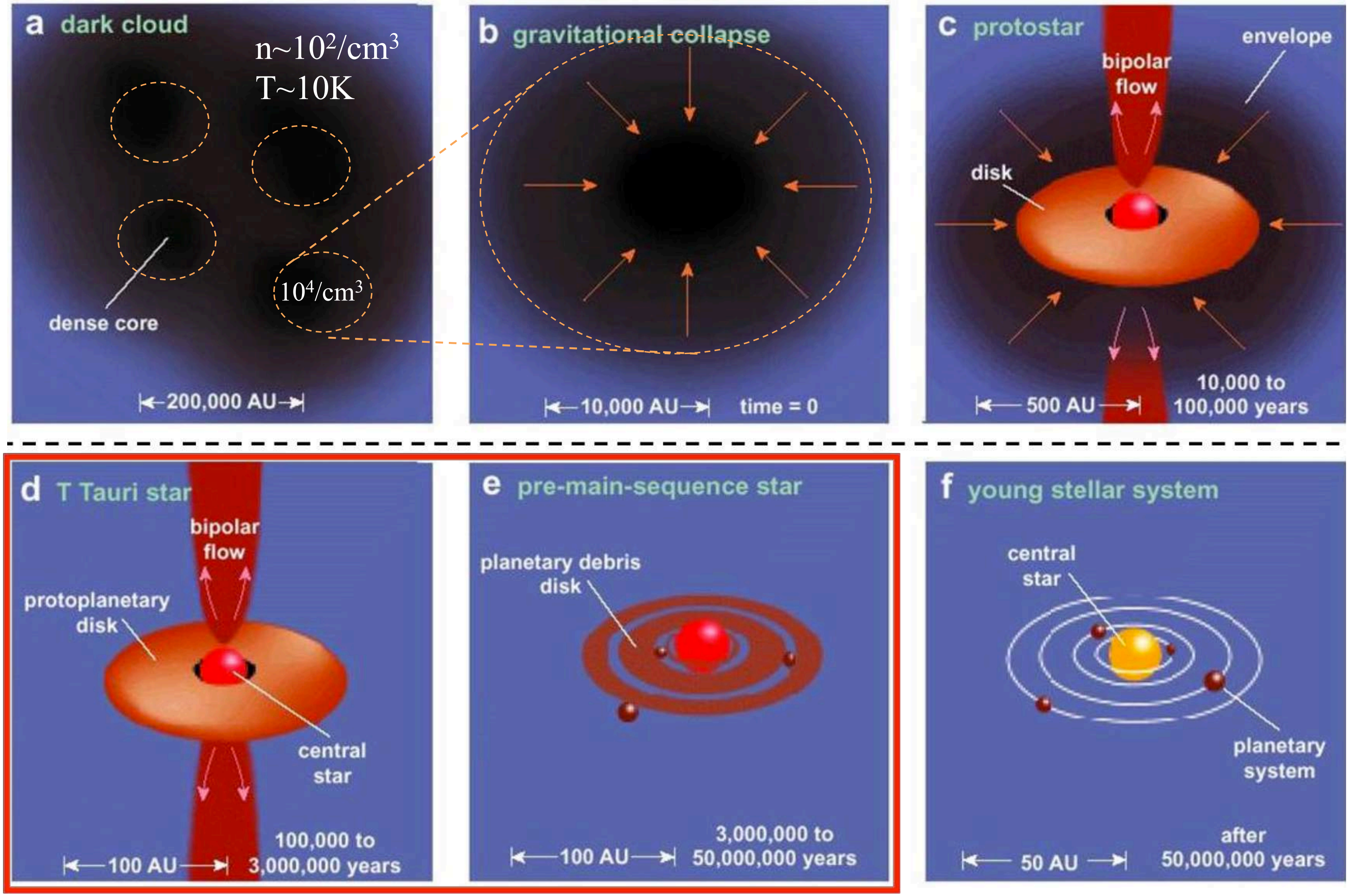
- 原始惑星系円盤の描像
  - 星形成から惑星形成に至るまで
  - 円盤での惑星形成
- ダスト偏光観測のメカニズム
  - 従来のダスト偏光観測がみているもの
- 原始惑星系円盤の偏光観測
  - 偏光観測を円盤へアプライ

# 星·惑星系形成



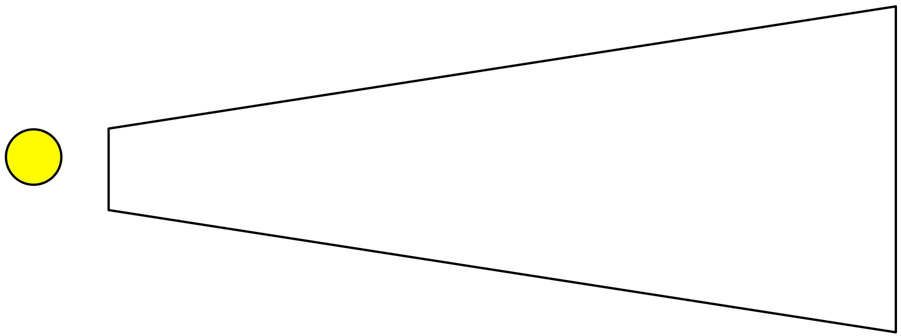
a dark cloud
$n \sim 10^2/cm^3$
$T \sim 10K$
$10^4/cm^3$
dense core
200,000 AU
b gravitational collapse
10,000 AU
time = 0
c protostar
bipolar flow
envelope
disk
500 AU
10,000 to 100,000 years
d T Tauri star
bipolar flow
protoplanetary disk
central star
100 AU
100,000 to 3,000,000 years
e pre-main-sequence star
planetary debris disk
100 AU
3,000,000 to 50,000,000 years
f young stellar system
central star
planetary system
50 AU
after 50,000,000 years

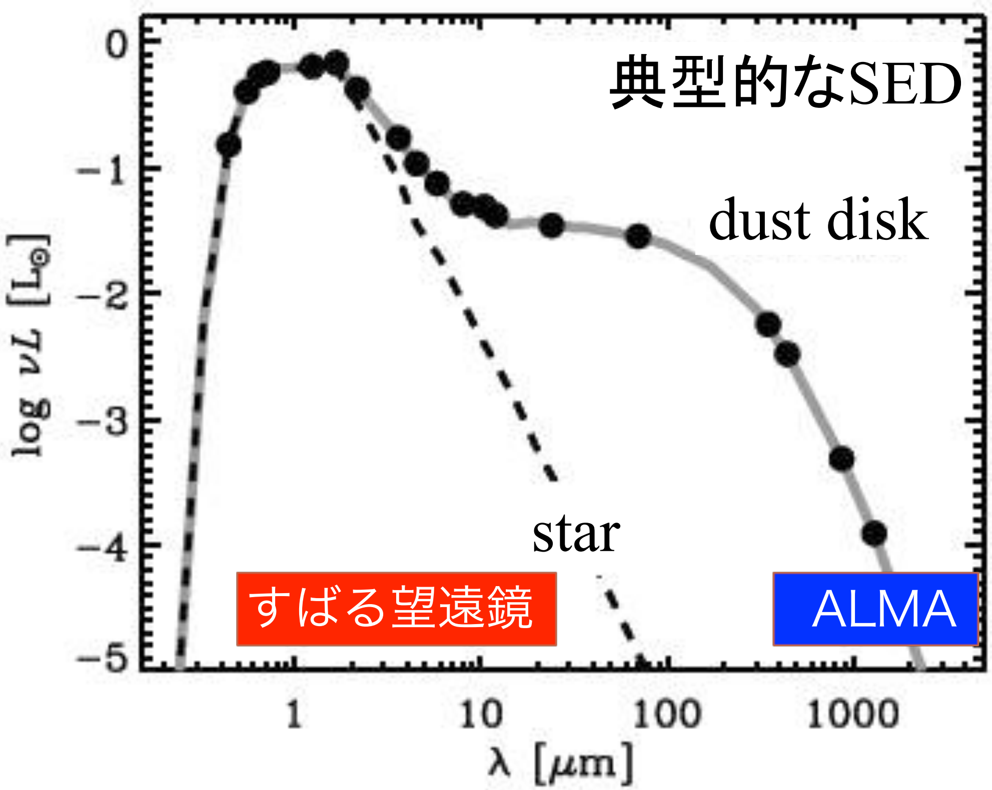
# 星·惑星系形成

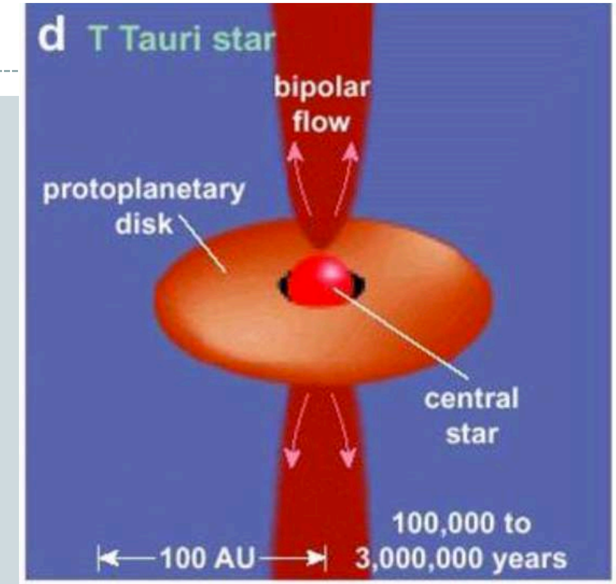


a dark cloud
n~10²/cm³
T~10K
dense core
10⁴/cm³
200,000 AU
b gravitational collapse
10,000 AU
time = 0
c protostar
envelope
bipolar flow
disk
500 AU
10,000 to 100,000 years
d T Tauri star
bipolar flow
protoplanetary disk
central star
100 AU
100,000 to 3,000,000 years
e pre-main-sequence star
planetary debris disk
100 AU
3,000,000 to 50,000,000 years
f young stellar system
central star
planetary system
50 AU
after 50,000,000 years

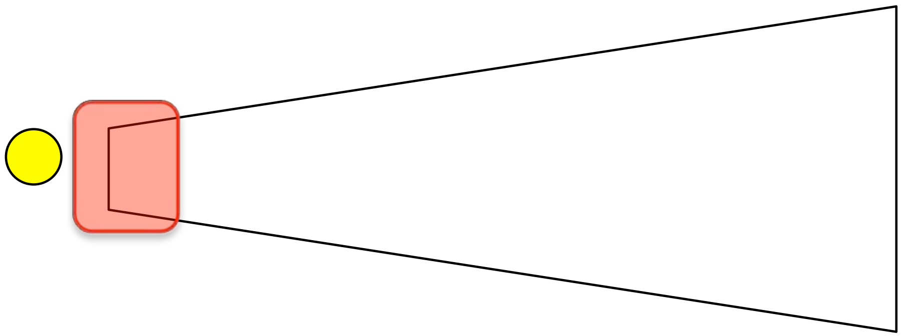
# 星･惑星系形成(観測)

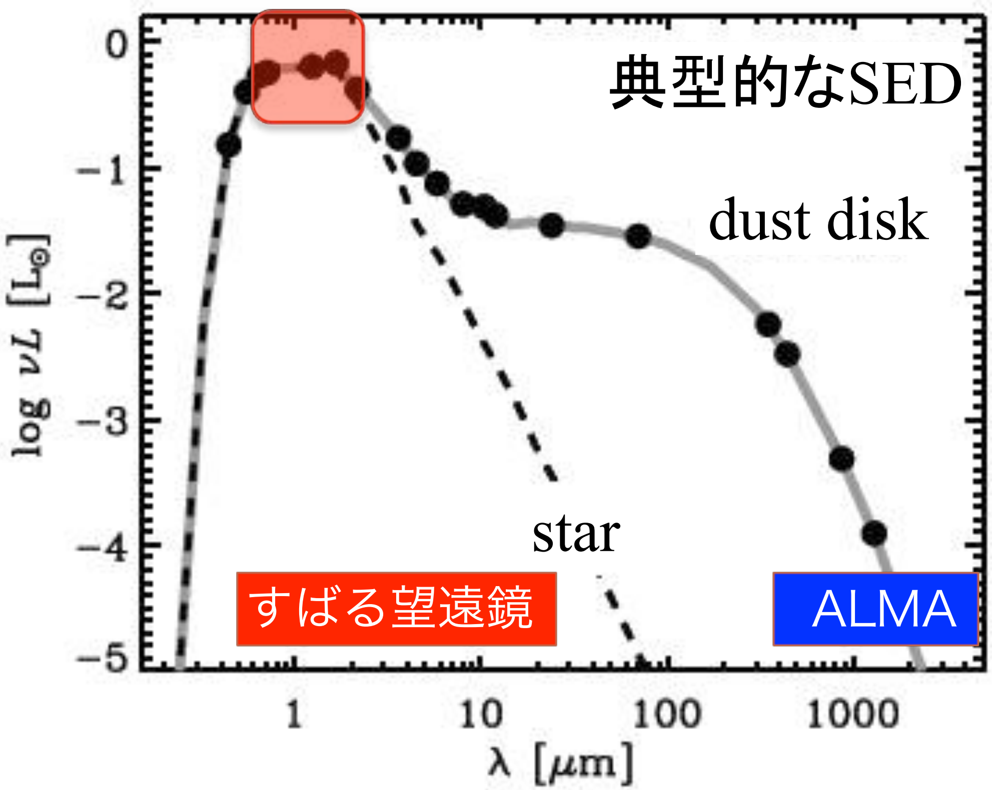



典型的なSED
dust disk
star
すばる望遠鏡
ALMA
log νL [L$_\odot$]
0
−1
−2
−3
−4
−5
1
10
100
1000
λ [μm]


d T Tauri star
bipolar flow
protoplanetary disk
central star
100,000 to 3,000,000 years
100 AU

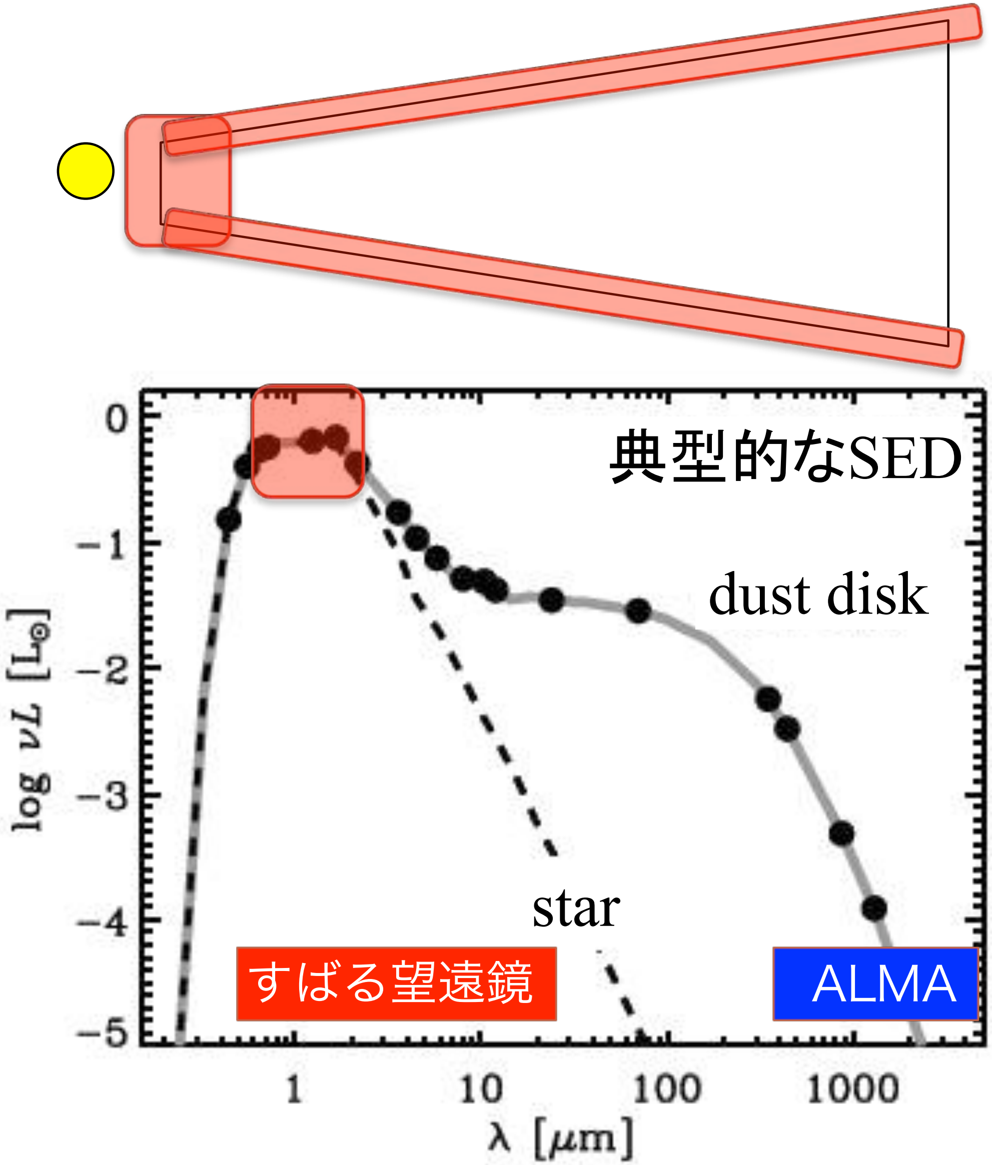
# 星･惑星系形成（観測）





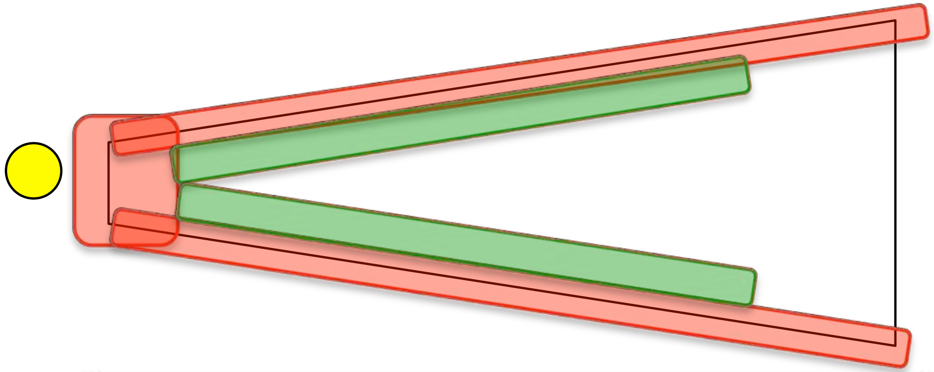

近赤外線：原始星付近の円盤
からの熱放射

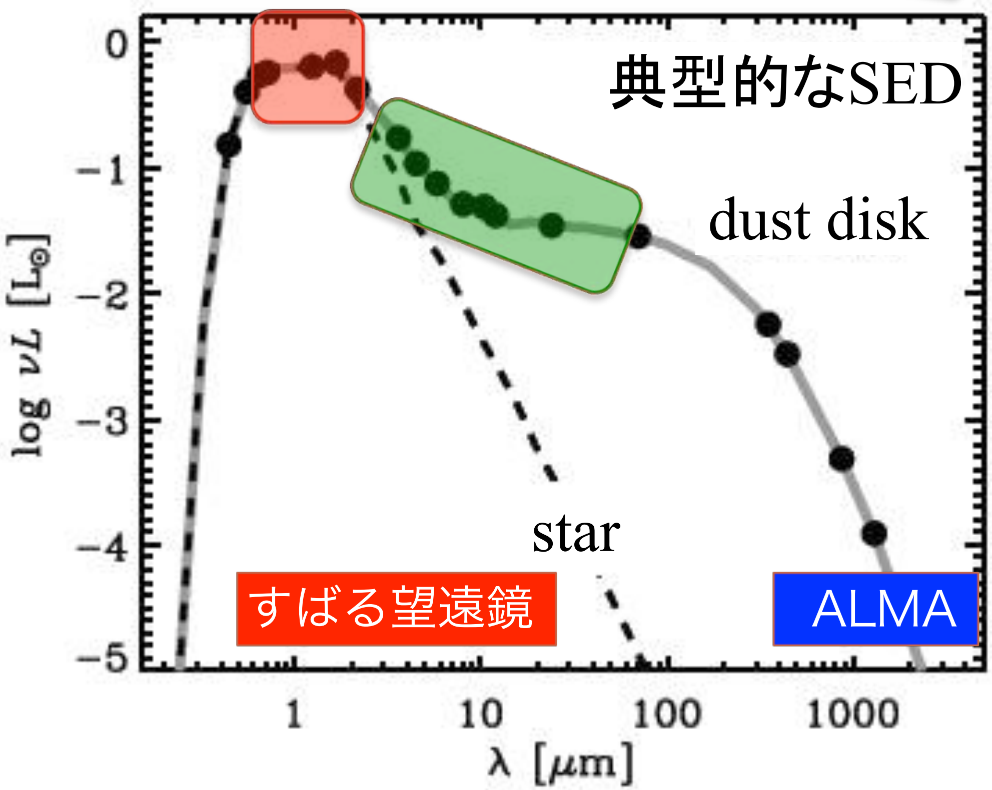
# 星・惑星系形成(観測)




近赤外線：原始星付近の円盤からの熱放射
：円盤表面の散乱光

# 星･惑星系形成(観測)

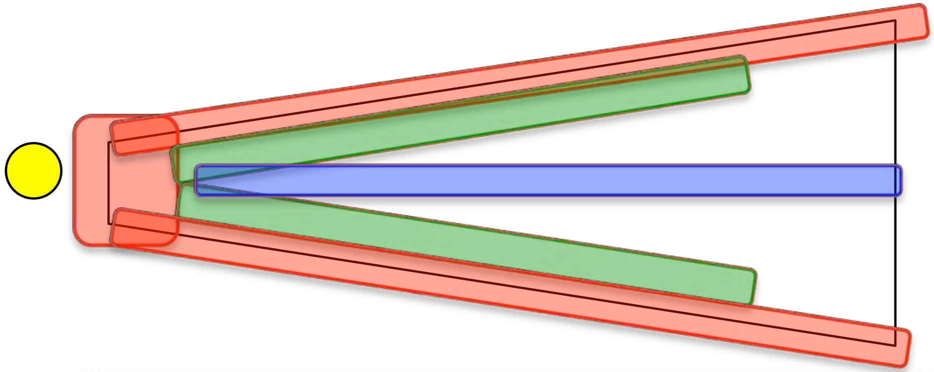


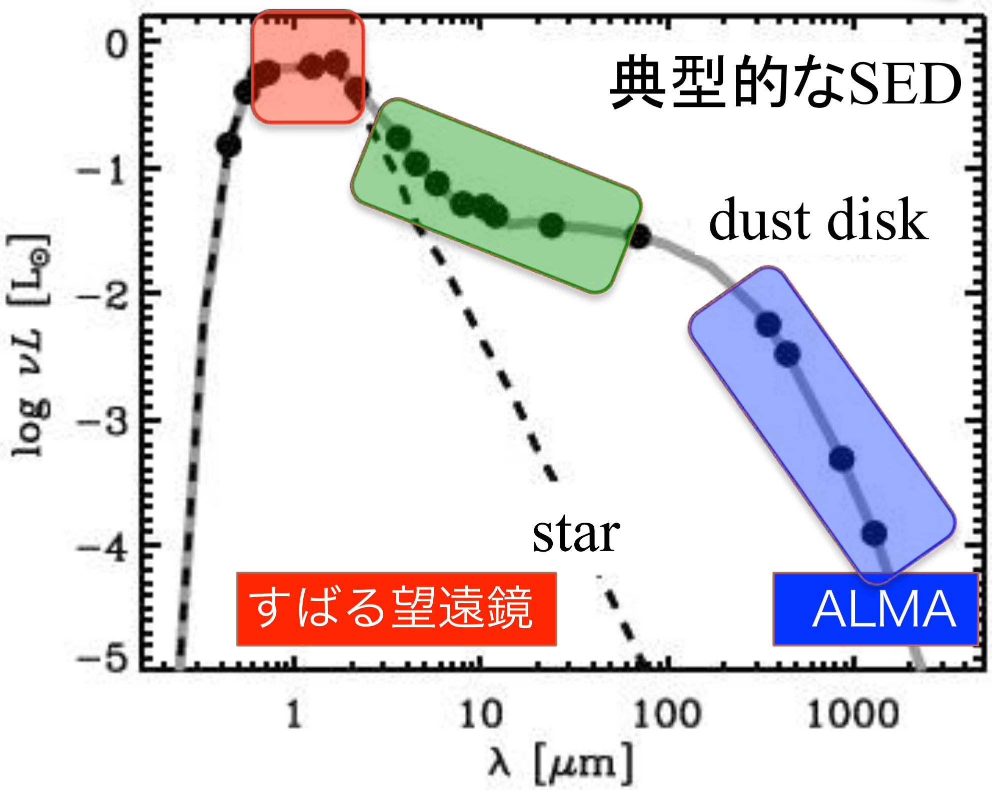



近赤外線：原始星付近の円盤からの熱放射
：円盤表面の散乱光

中間赤外線: ~ 10 AUの熱放射

# 星・惑星系形成（観測）



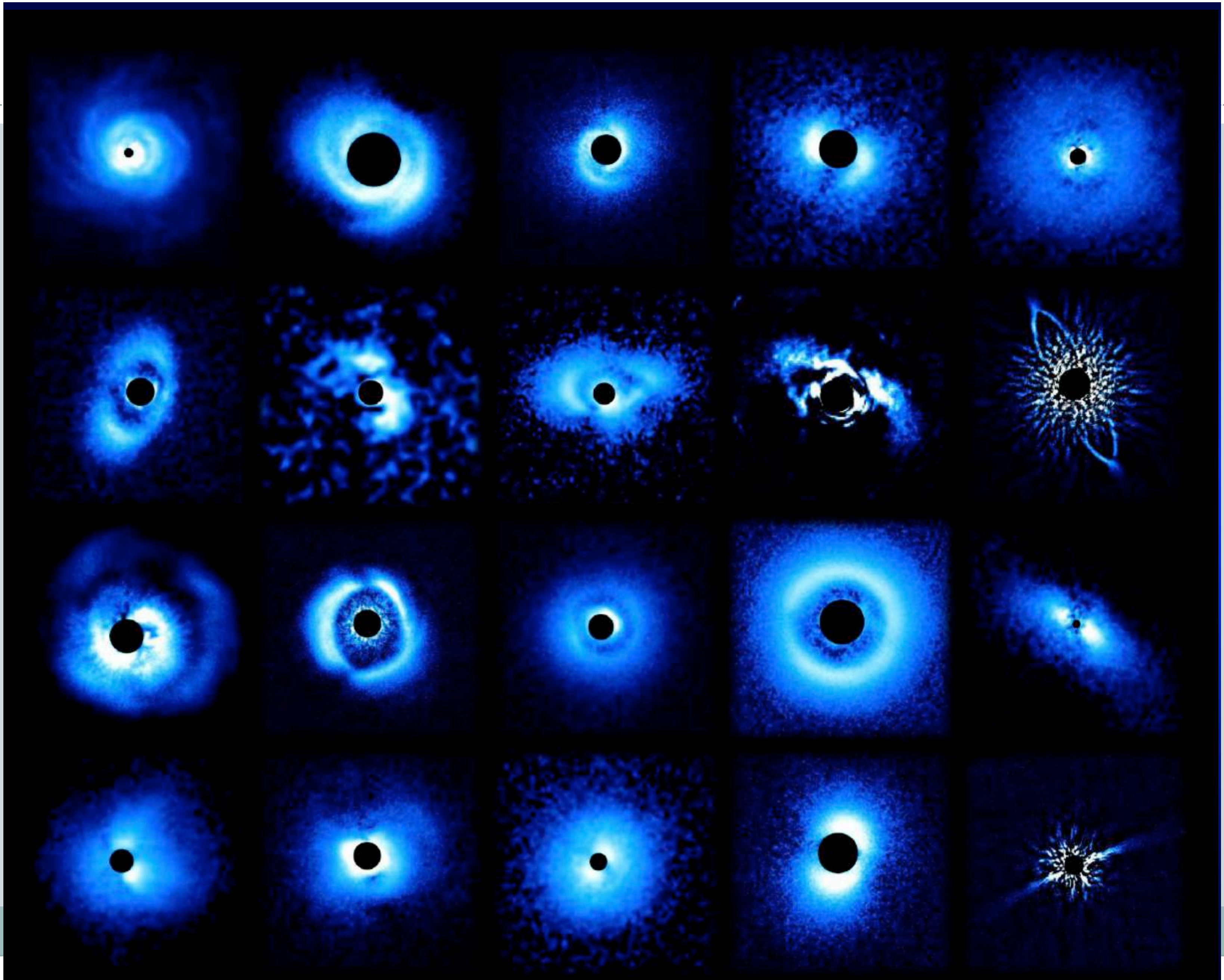



近赤外線：原始星付近の円盤からの熱放射
：円盤表面の散乱光

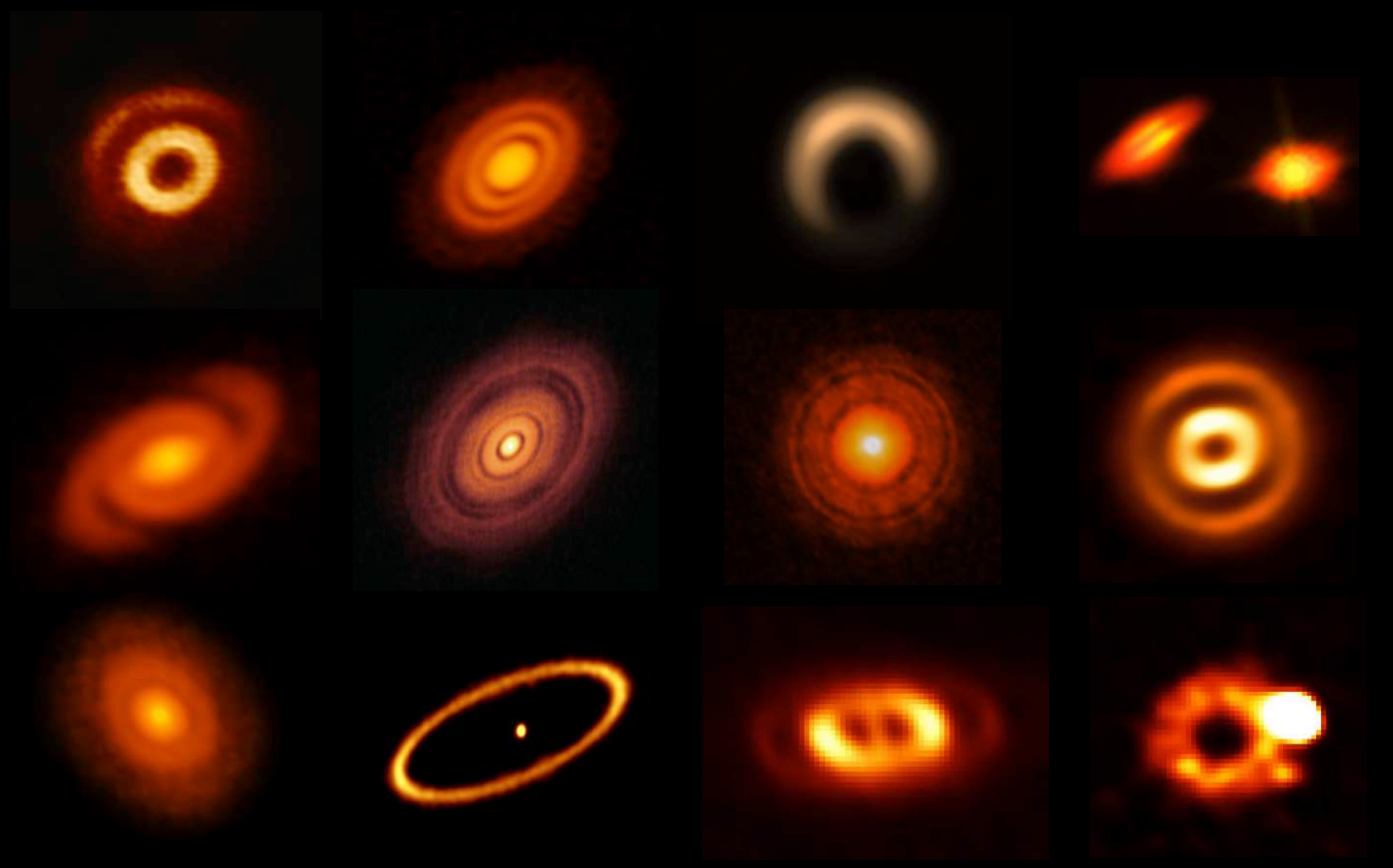
中間赤外線: ~ 10 AUの熱放射

ミリ波：円盤赤道面からの熱放射

# 原始惑星系円盤の観測(すばる)

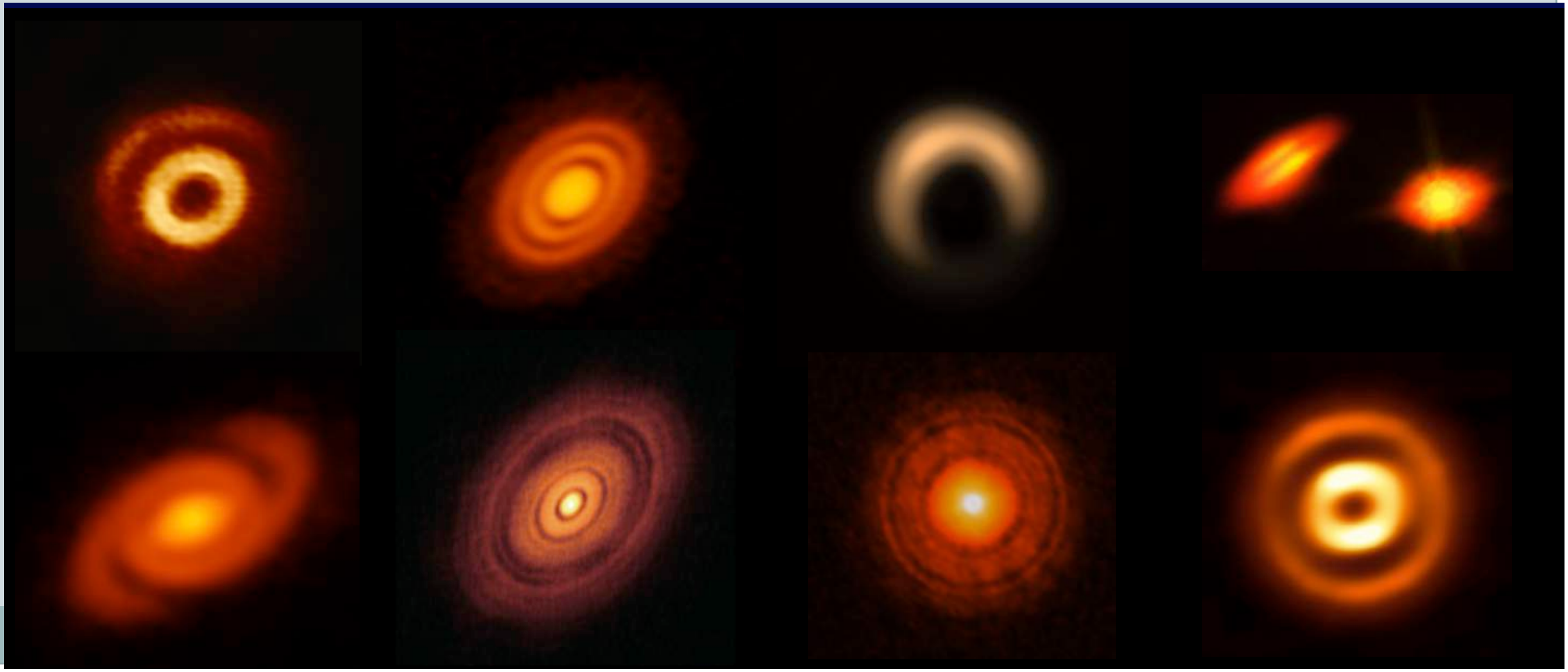


# 原始惑星系円盤の観測(ALMA)

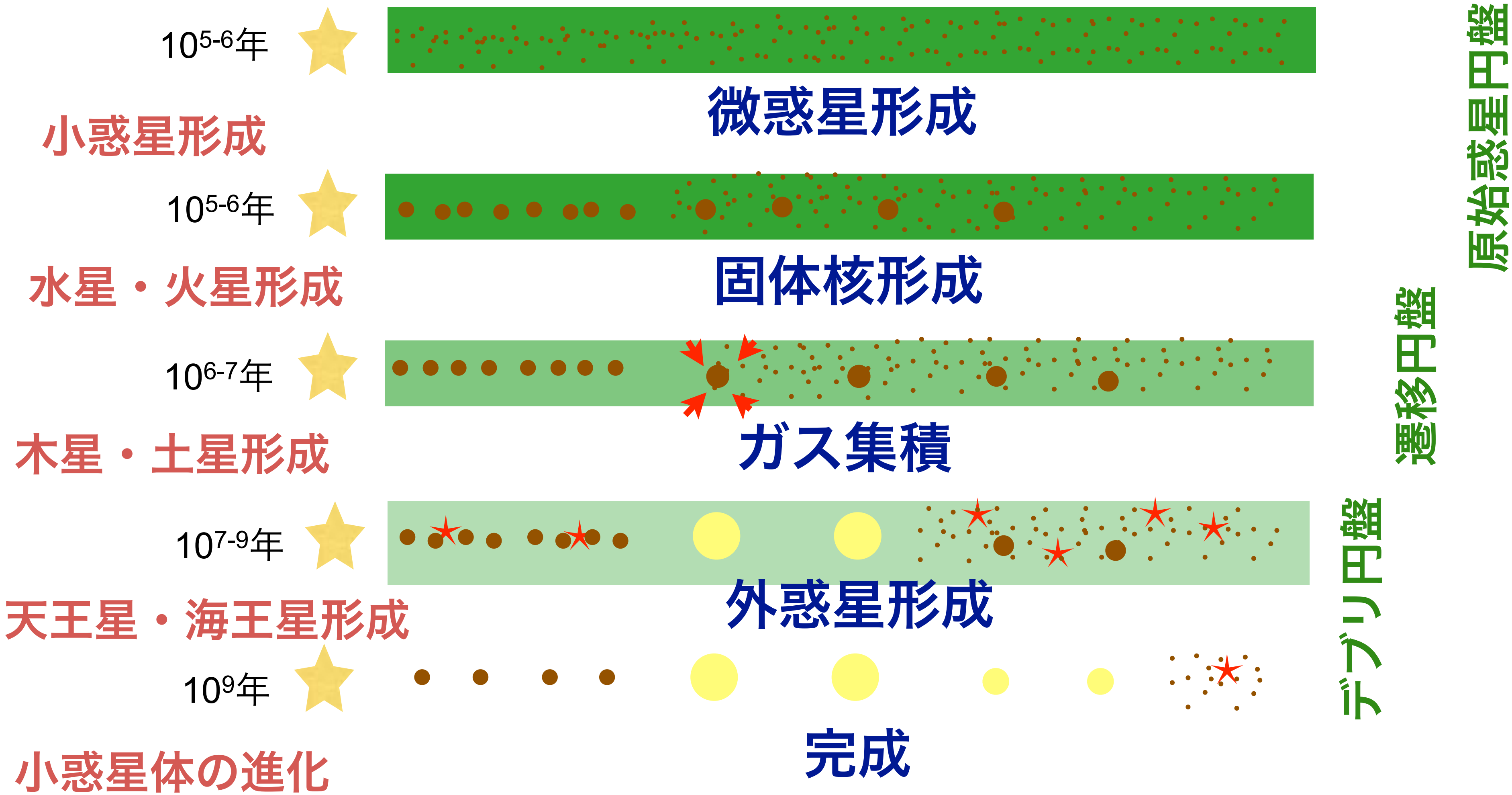


# 原始惑星系円盤の観測的特徴

- 複数のリング+ギャップ構造を持つ円盤がほとんど
- 非軸対象な構造の円盤も2-3天体
- スムーズな円盤はレアかもしれない？



# 星･惑星系形成



$10^{5\text{-}6}$年
微惑星形成
小惑星形成
$10^{5\text{-}6}$年
固体核形成
水星・火星形成
$10^{6\text{-}7}$年
ガス集積
木星・土星形成
$10^{7\text{-}9}$年
外惑星形成
天王星・海王星形成
$10^{9}$年
完成
小惑星体の進化
原始惑星円盤
遷移円盤
デブリ円盤

# 原始惑星系円盤の観測的特徴

- 複数のリング+ギャップ構造を持つ円盤がほとんど
- 非軸対象な構造の円盤も2-3天体
- スムーズな円盤はレアかもしれない？

既存の惑星形成モデルとは大きく異なる

円盤の物理状態（特にダストの組成）を観測から制限したい
→ 偏光観測が新たな手法となる

# Outline

- 原始惑星系円盤の描像
  - 星形成から惑星形成に至るまで
  - 円盤での惑星形成
- ダスト偏光観測のメカニズム
  - 従来のダスト偏光観測がみているもの
- 原始惑星系円盤の偏光観測
  - 偏光観測を円盤へアプライ

# 偏光観測とは

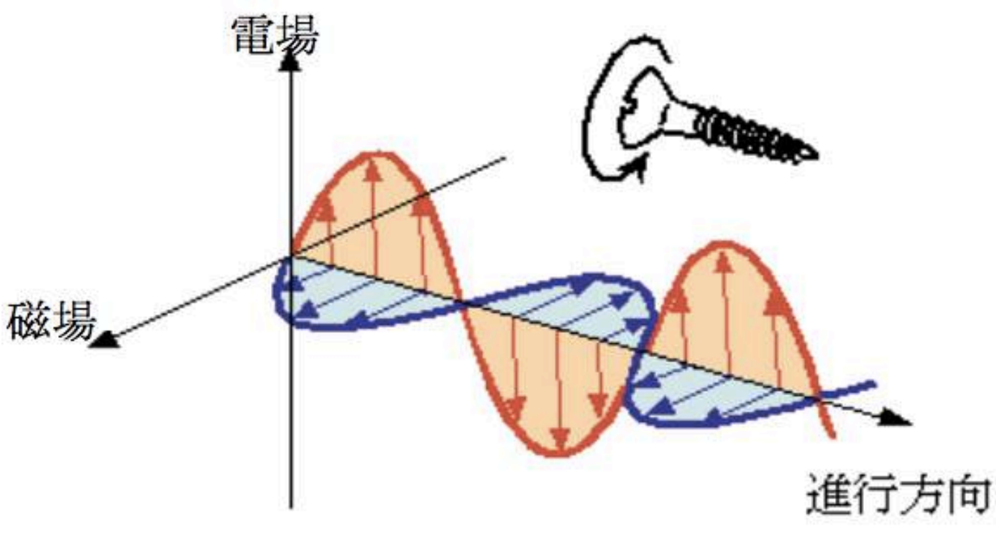



図 1.2　電磁波の伝わり方


偏光（へんこう、英: polarization）は、電場および磁場が特定の（振動方向が規則的な）方向にのみ振動する光のこと
(wikipedia)

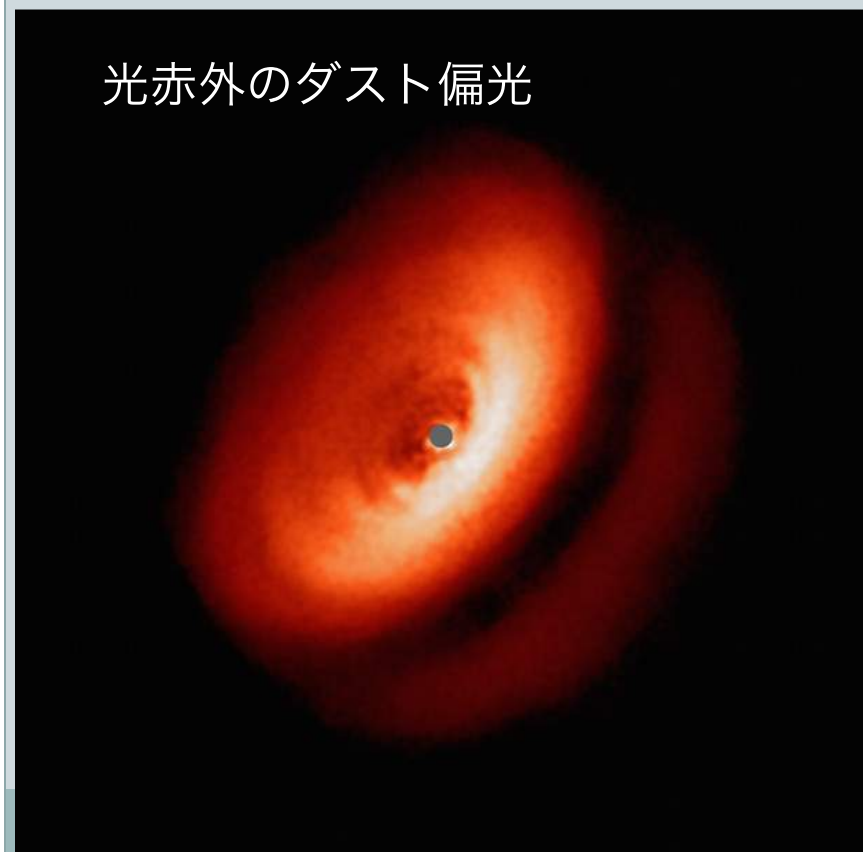
# 偏光する主な原因

散乱 か 磁場

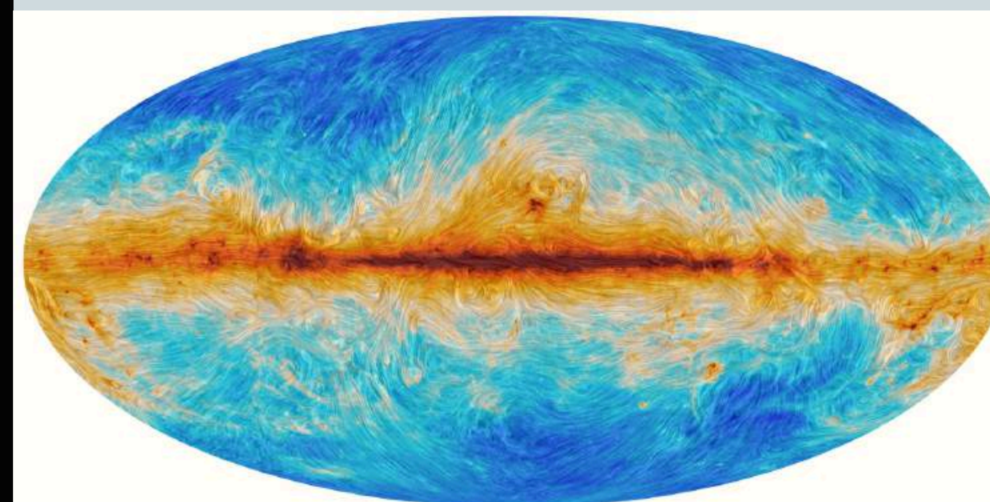
# 偏光する主な原因

## 散乱 か 磁場

トムソンやレイリー散乱（小さいダスト）

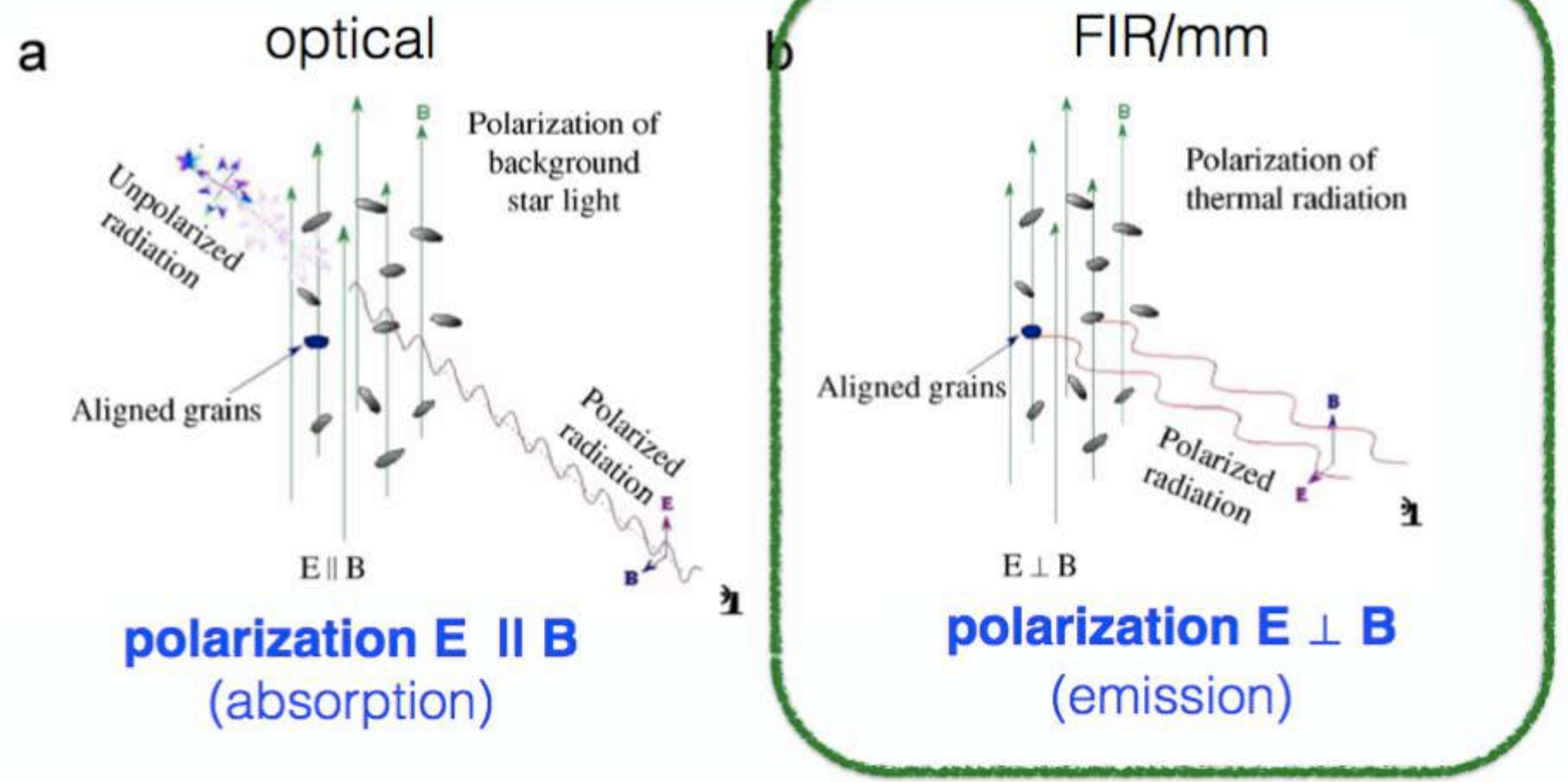



ミリ波のダスト偏光



# ダスト整列と偏光

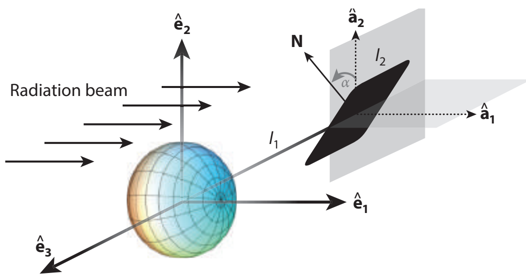
Lazarian (2007)

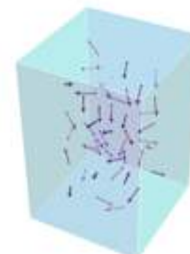


# Overview of RAT alignment

Lazarian & Hoang 2007

**Helical grain**



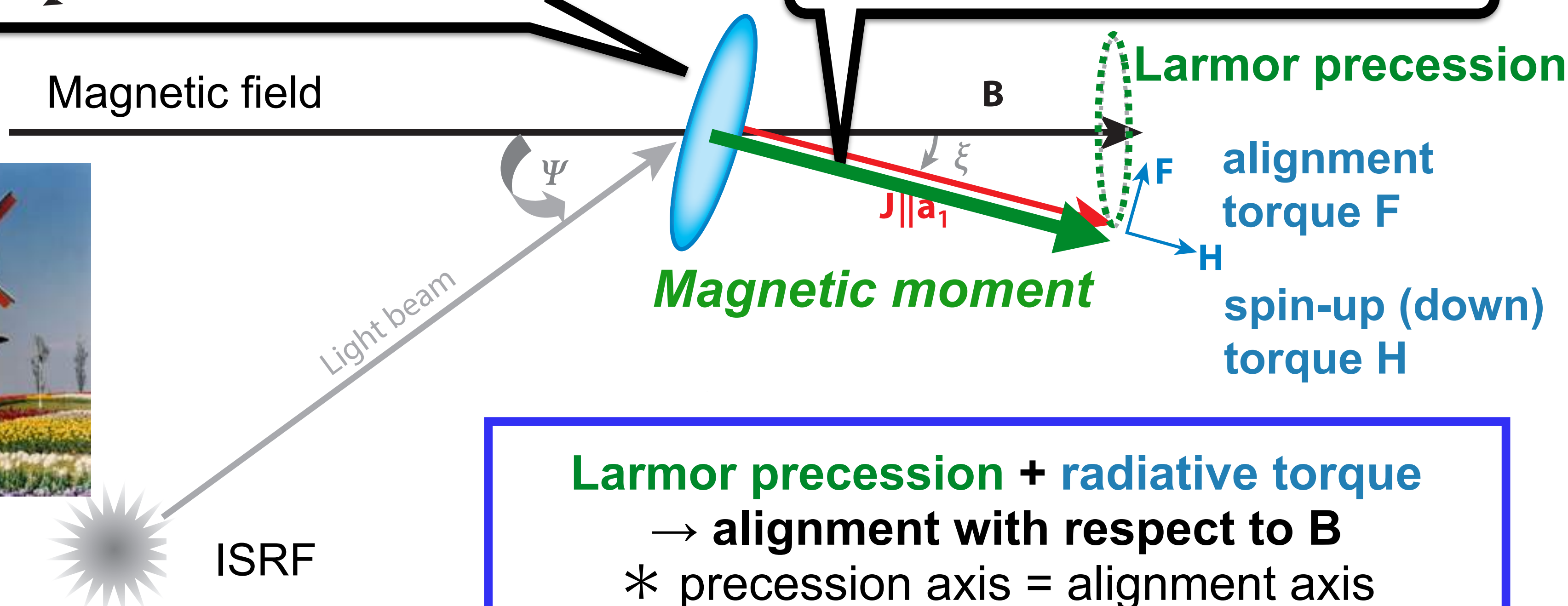



(© M Matsuo)

**"Barnett effect"**

**Magnetization due to grain spinning**

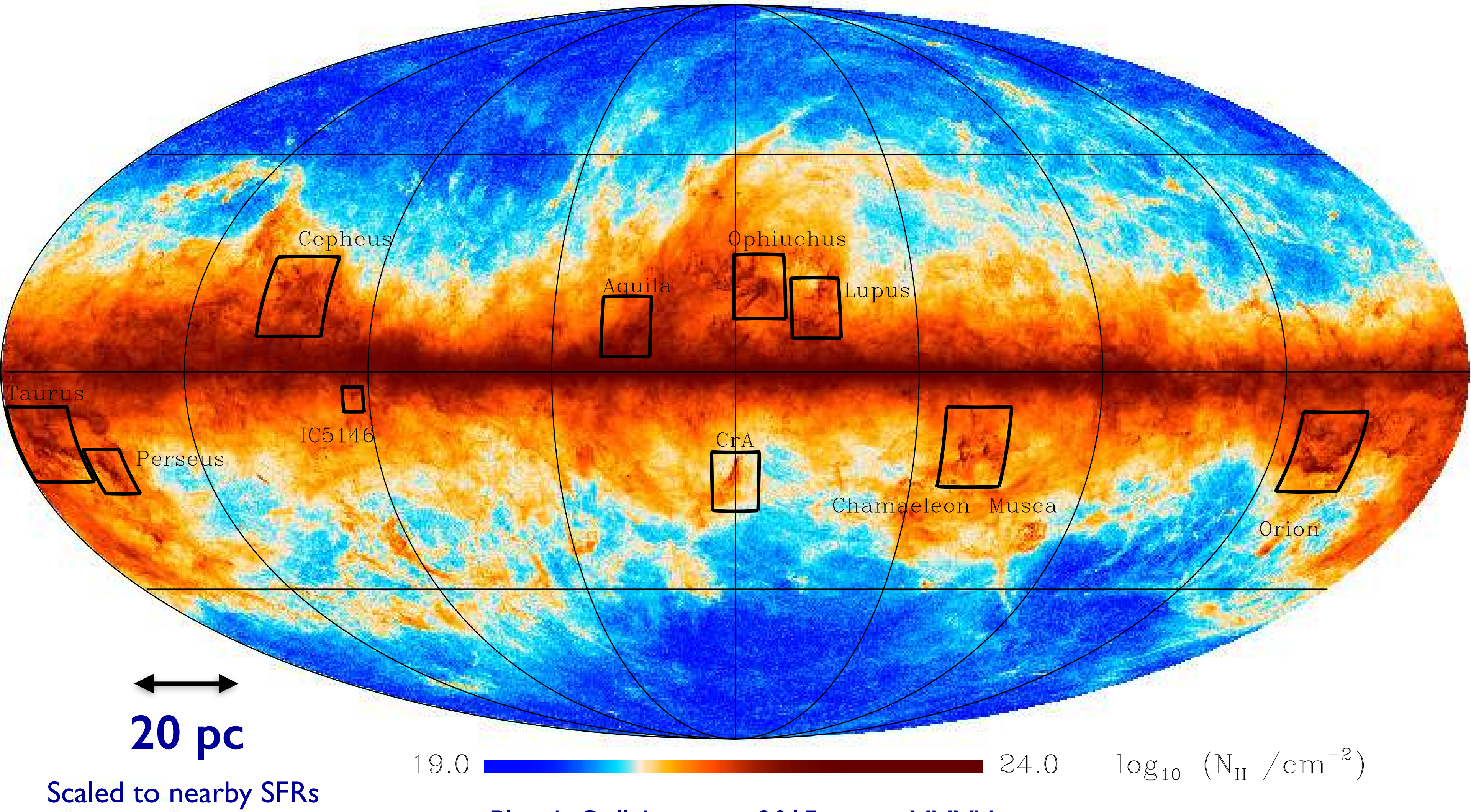
(Inverse effect of Einstein-de Haas effect)




*Andersson et al. 2015*

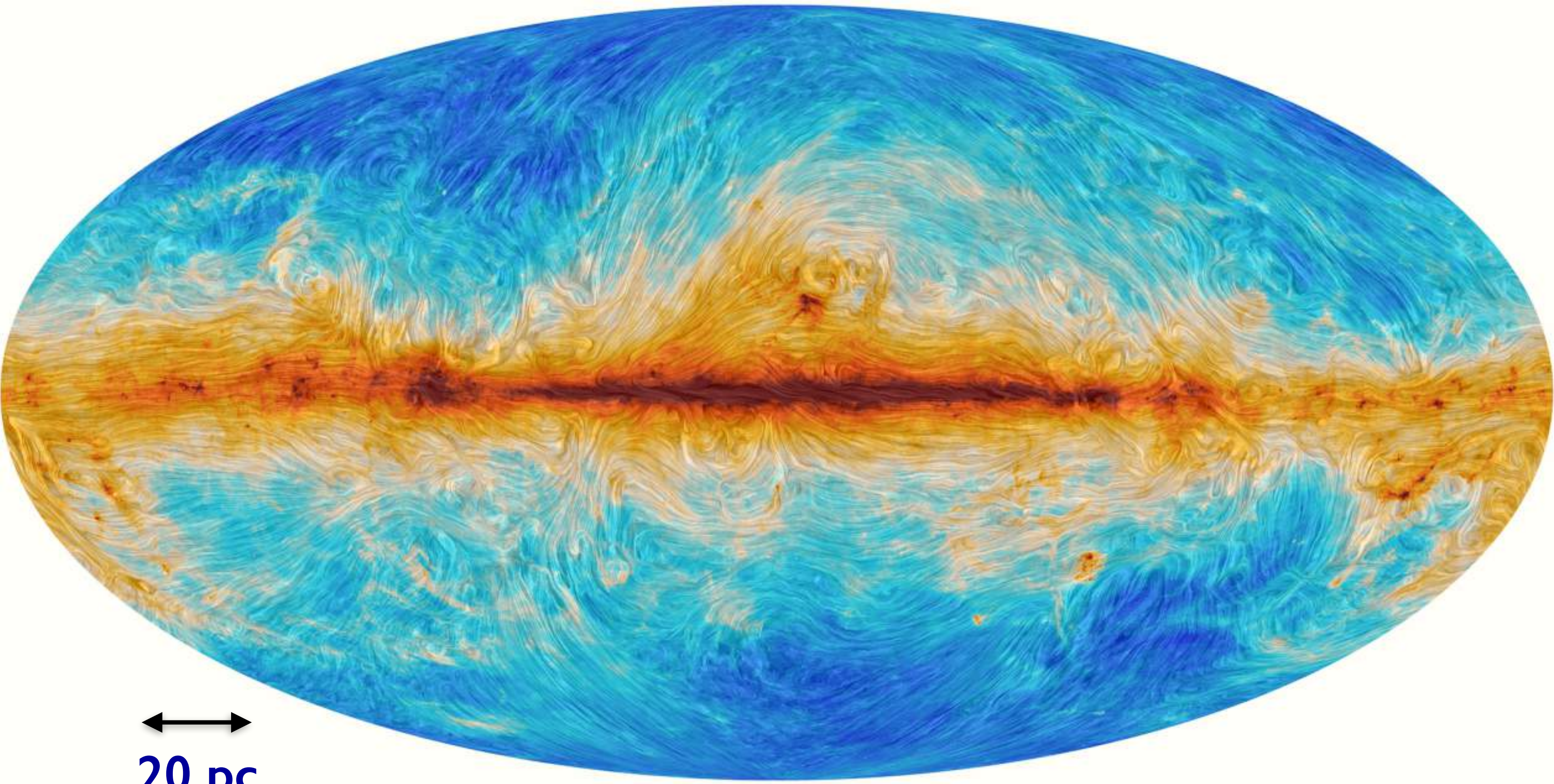
**Larmor precession** + **radiative torque**
**→ alignment with respect to B**
∗ precession axis = alignment axis

# Magnetic fields on large (Planck) scales




Planck Collaboration 2015, paper XXXV

# Magnetic fields on large (Planck) scales




Scaled to nearby SFRs

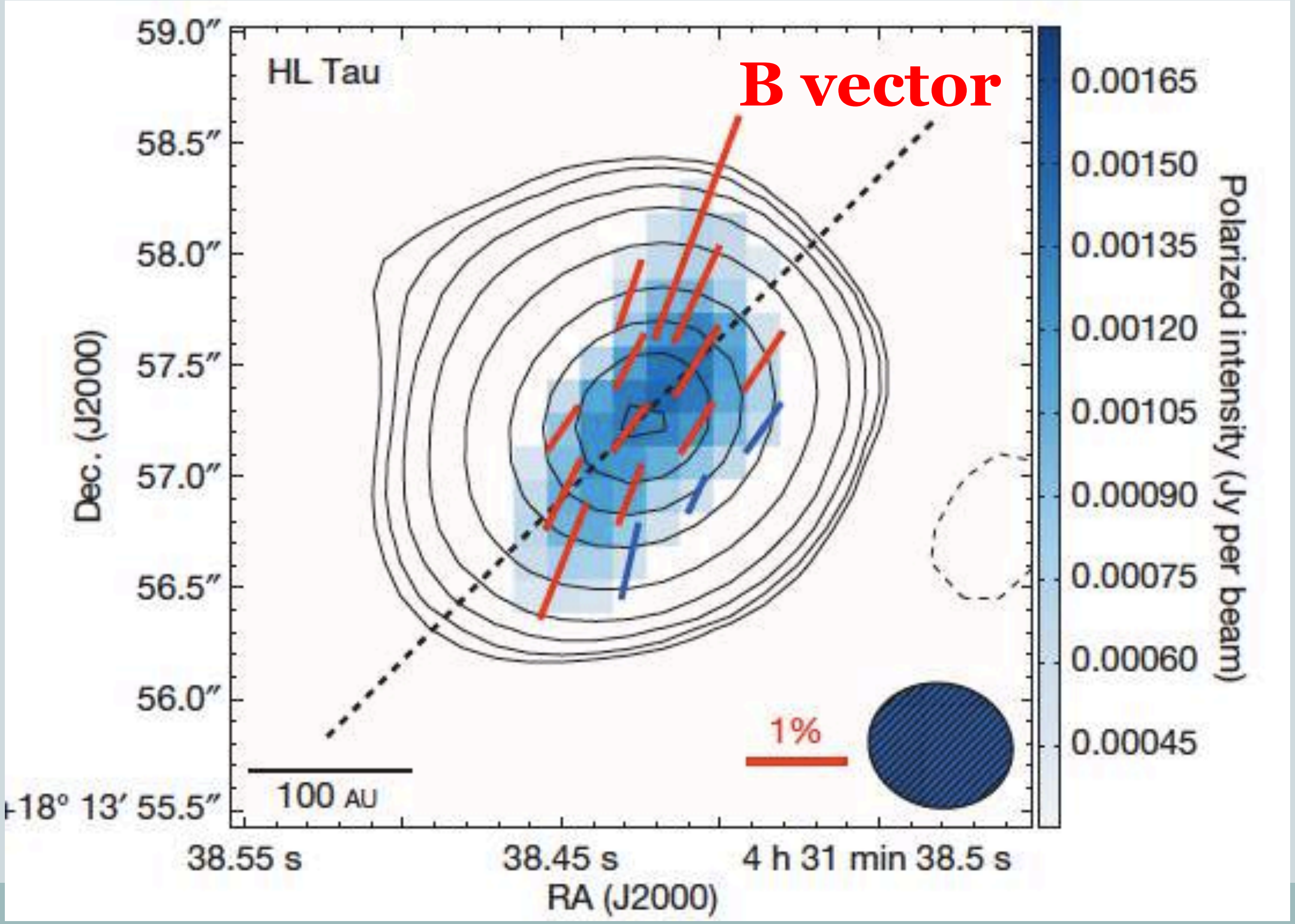
Planck Collaboration
planckandthemagneticfield.info

# Outline

- 原始惑星系円盤の描像
  - 星形成から惑星形成に至るまで
  - 円盤での惑星形成
- ダスト偏光観測のメカニズム
  - 従来のダスト偏光観測がみているもの
- 原始惑星系円盤の偏光観測
  - 偏光観測を円盤へアプライ

# 原始惑星系円盤の偏光観測

- 円盤で偏光を検出した最初の論文 Stephens 2014 Nature



# 原始惑星系円盤の偏光観測

- 円盤で偏光を検出した最初の論文 Stephens 2014 Nature

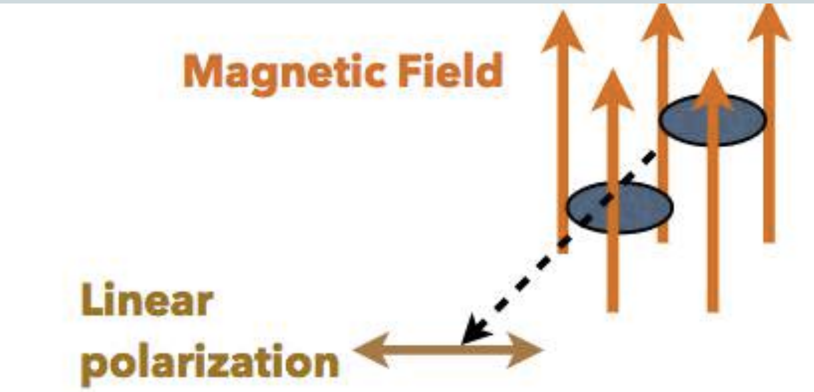
The magnetic field on a scale of 80 astronomical units is coincident with the major axis (about 210 astronomical units long12) of the disk. Fromthis we conclude that the magnetic field inside the disk at this scale cannot be dominated by a vertical component, though a purely toroidal field also does not fit the data well. The unexpected morphology suggests that the role of the magnetic field in the accretion of a T Tauri star is more complex than our current theoretical understanding.

# 原始惑星系円盤の偏光観測

- 円盤の場合、偏光は磁場だけではない可能性

# 円盤での偏光メカニズム

- 1. 磁場に沿ったダスト偏光




e.g., Lazarian and Hoang 2007

- 2. 大きなダストの散乱

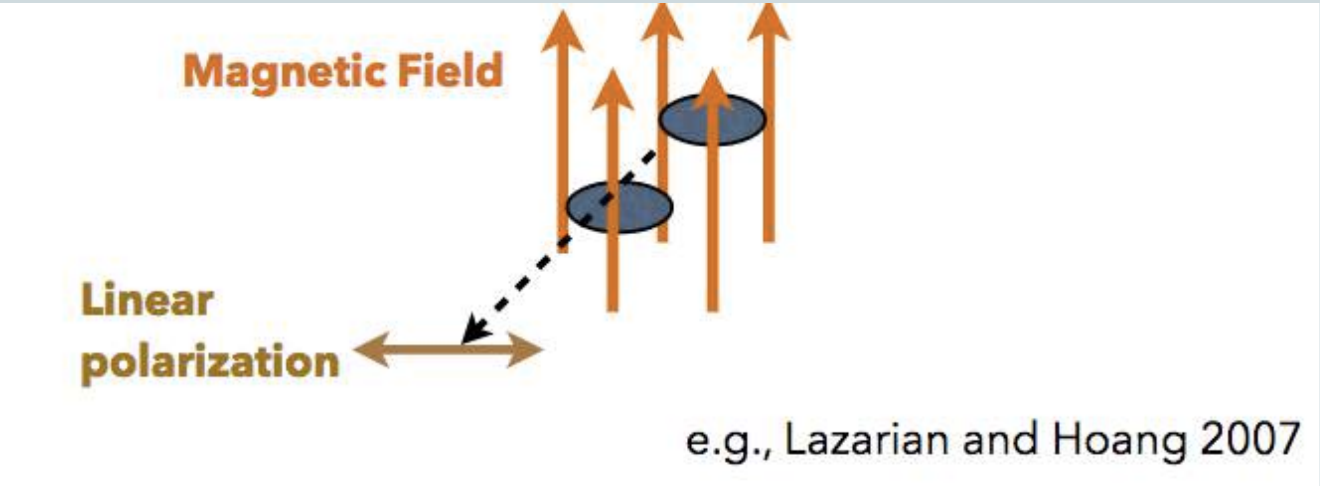
e.g., Kataoka et al. 2015

- 3. 輻射に沿ったダスト偏光

e.g., Hoang & lazarian 2007, Tazaki et al. 2017

# 円盤での偏光メカニズム

- 1. 磁場に沿ったダスト偏光



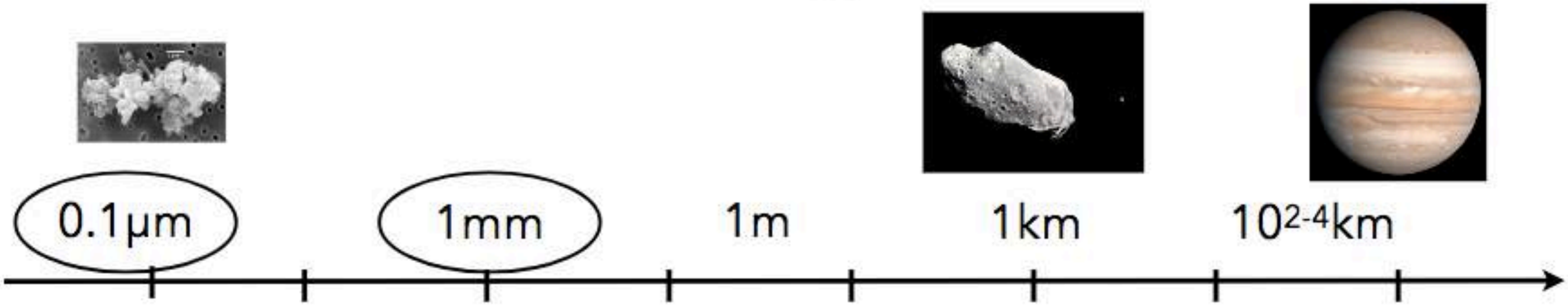

- 2. 大きなダストの散乱

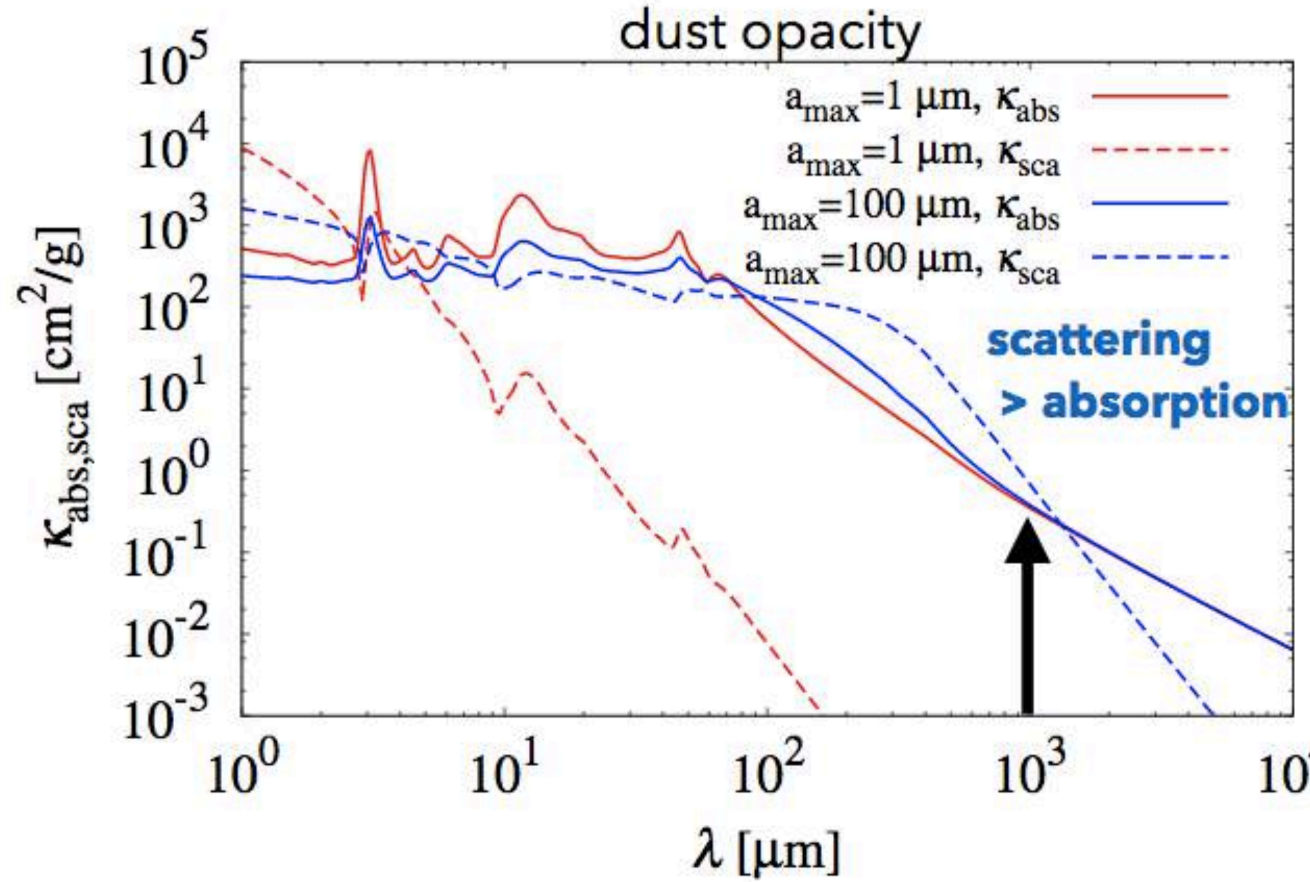
  e.g., Kataoka et al. 2015

- 3. 輻射に沿ったダスト偏光

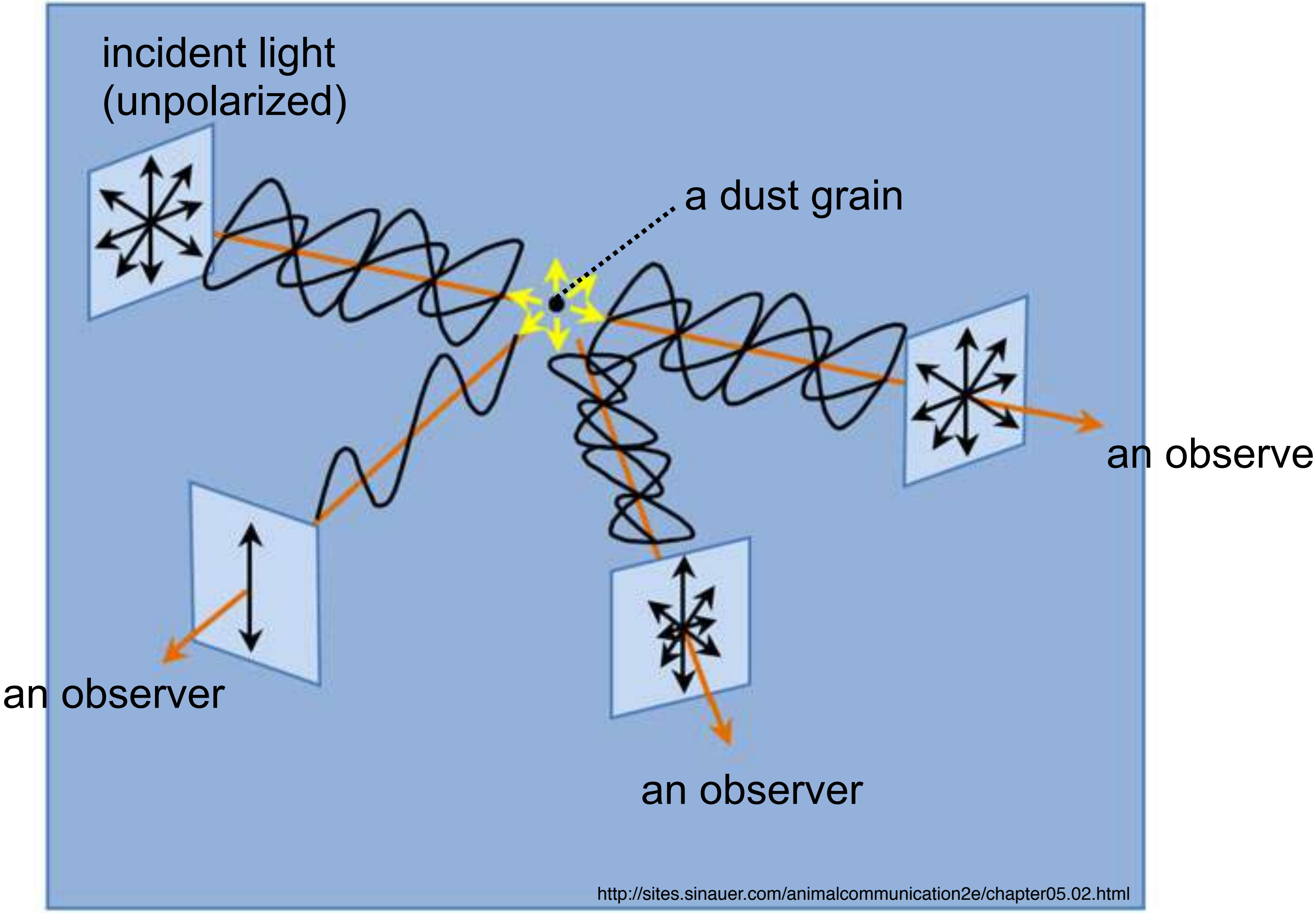
  e.g., Hoang & lazarian 2007, Tazaki et al. 2017

# Dust is big in disks

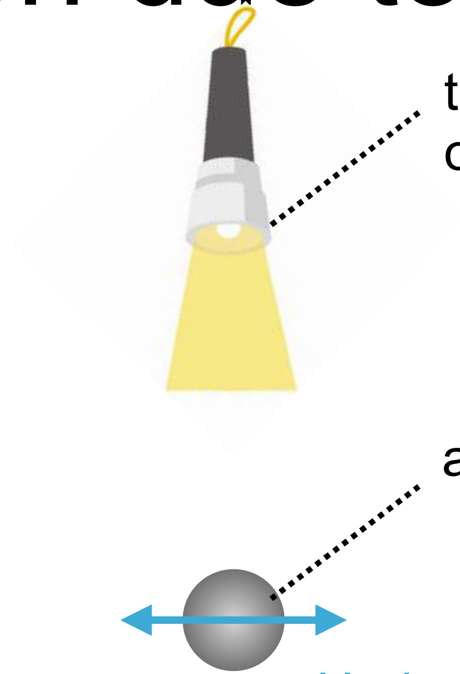


# ミリ波の散乱とは


incident light
(unpolarized)
a dust grain
an observer
an observer
an observer
http://sites.sinauer.com/animalcommunication2e/chapter05.02.html

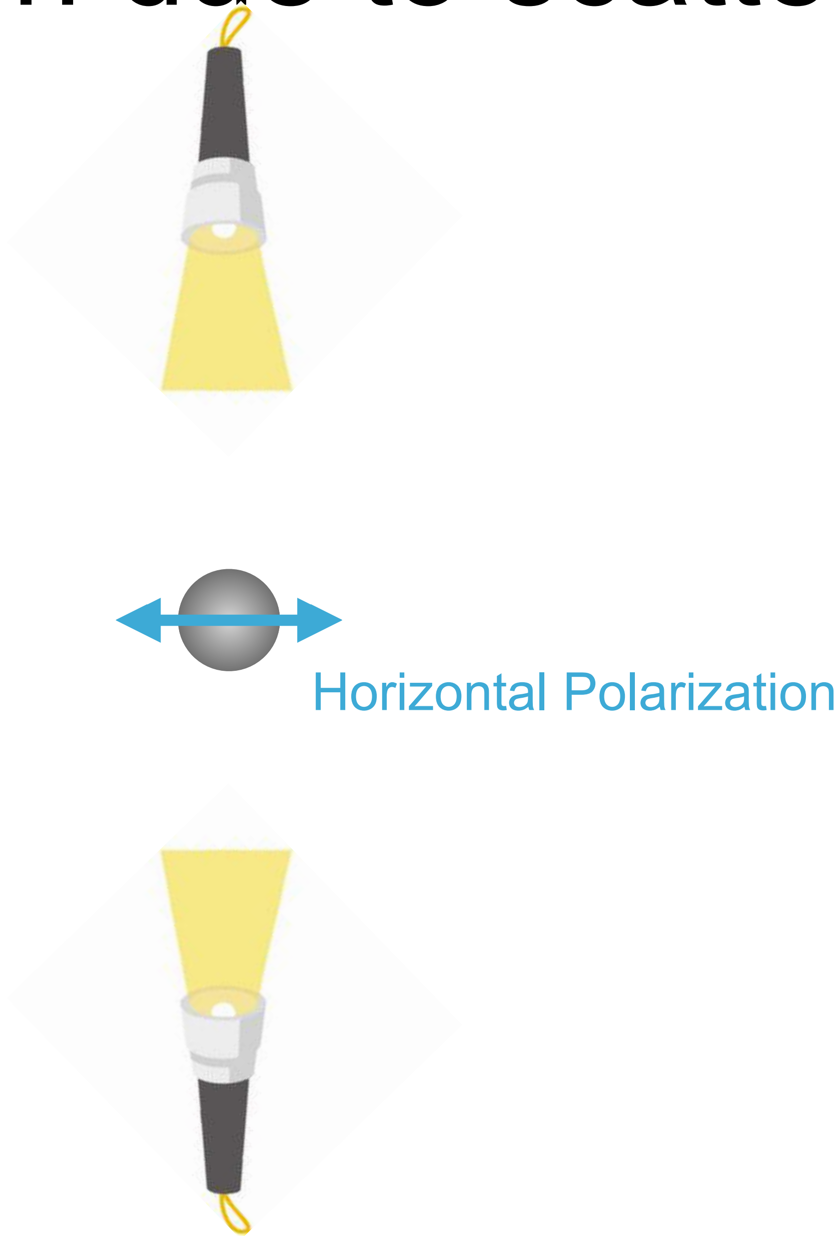
# Polarization due to scattering



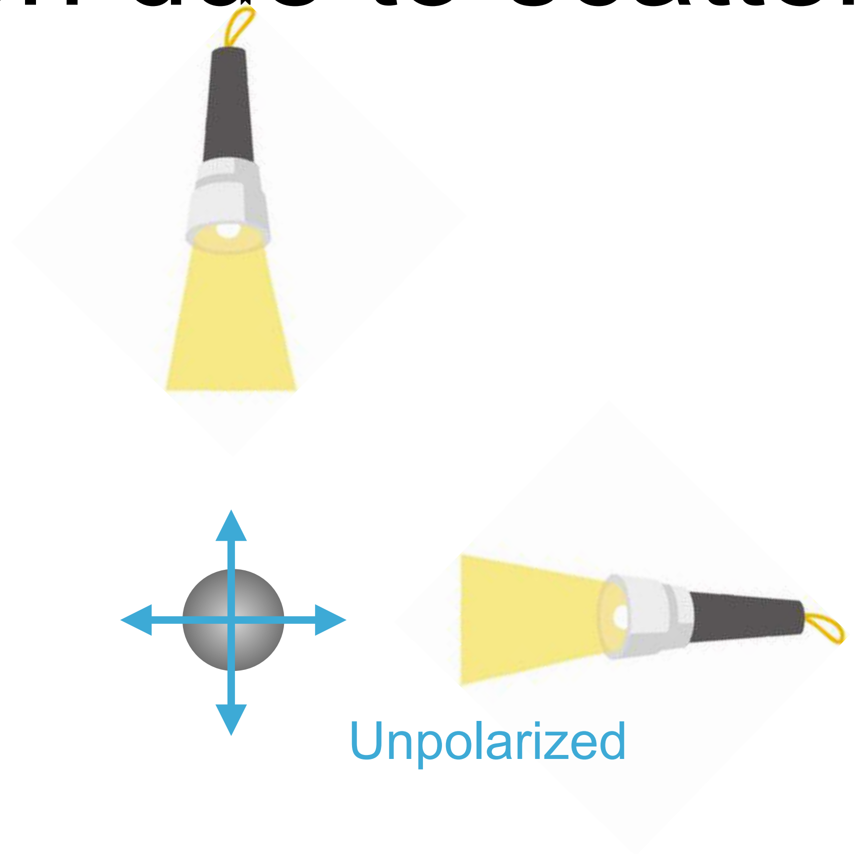

The observer is you.

(the line of sight is perpendicular to the plane of this slide)

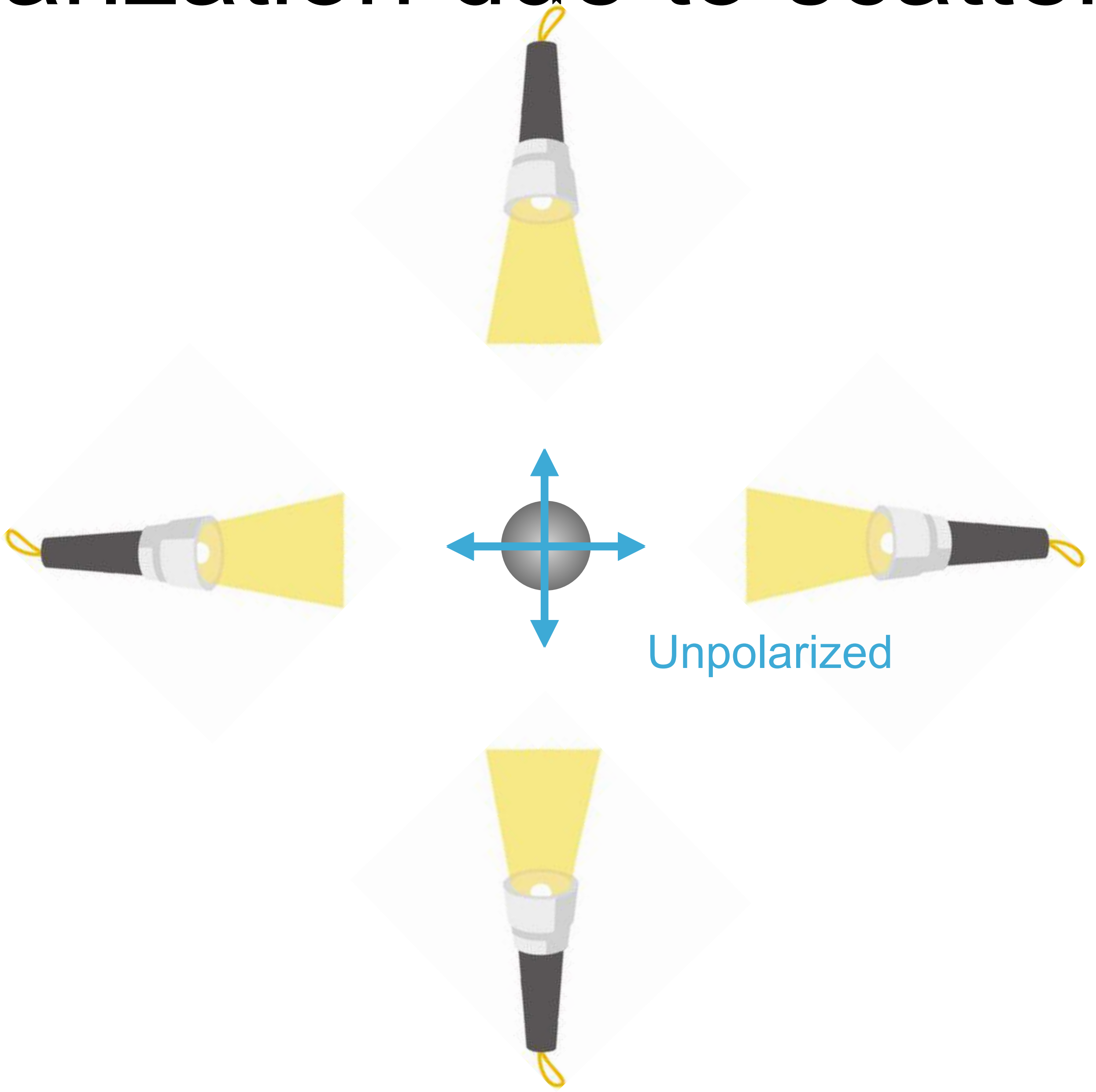
# Polarization due to scattering



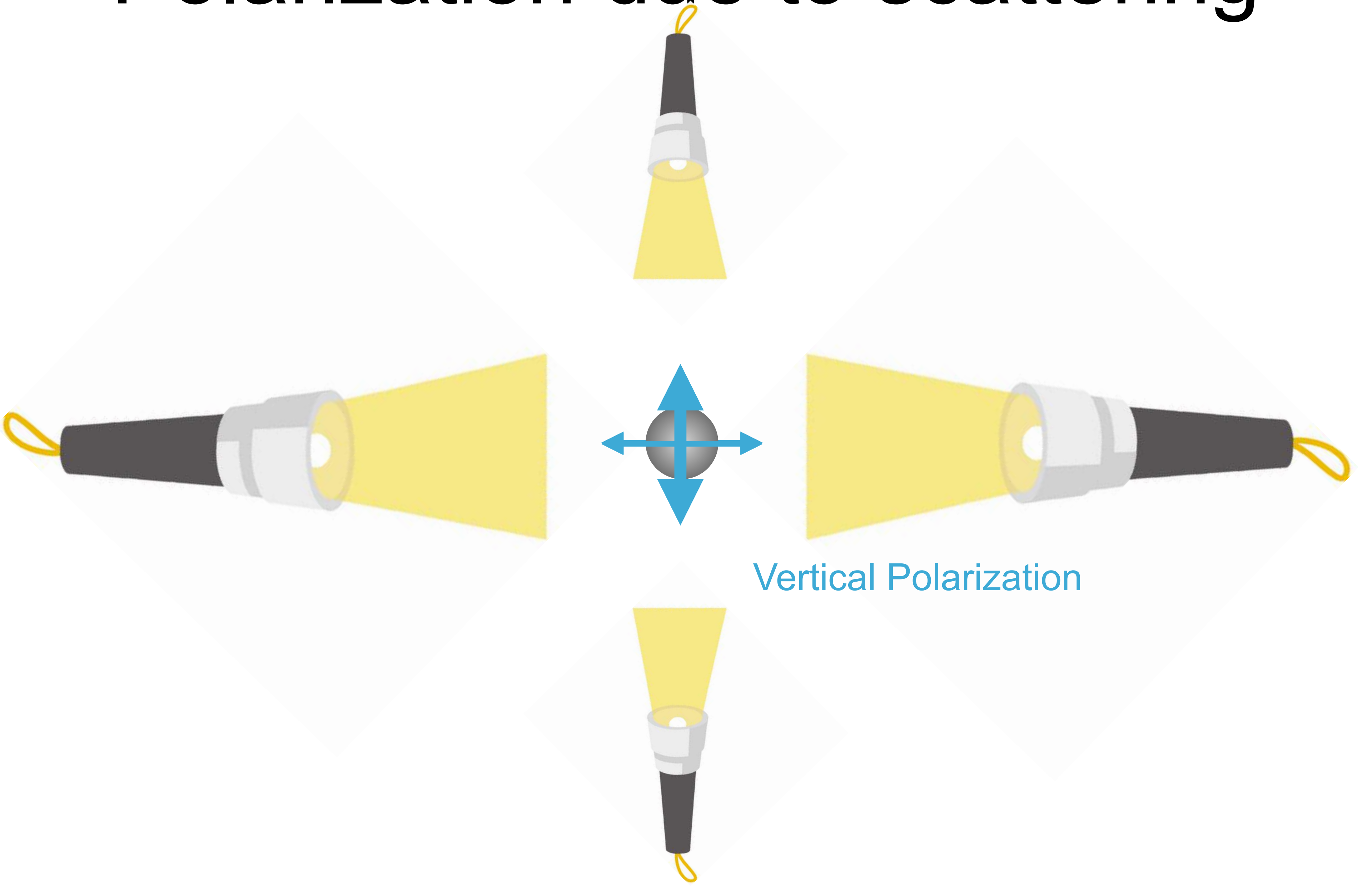
# Polarization due to scattering



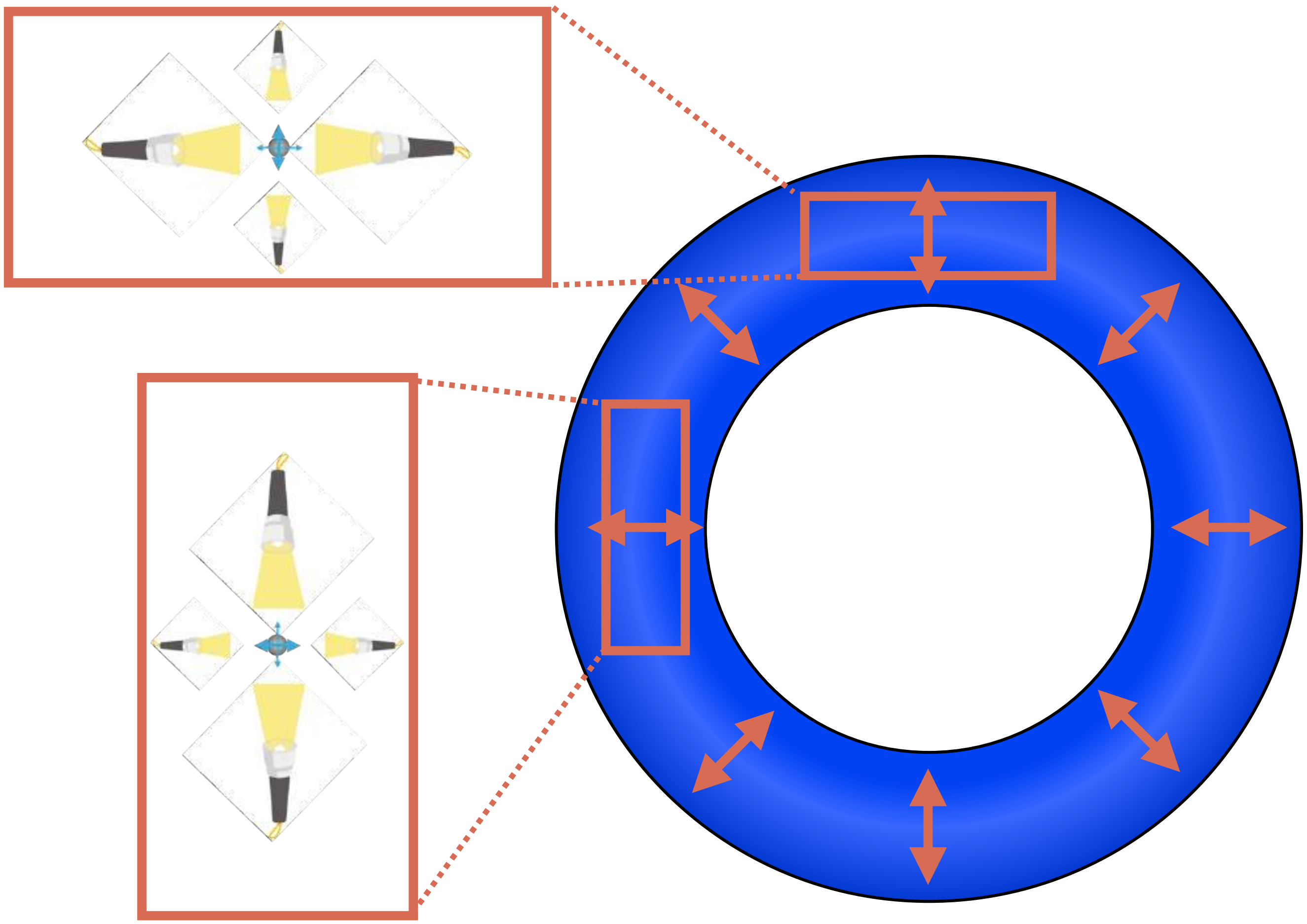
# Polarization due to scattering



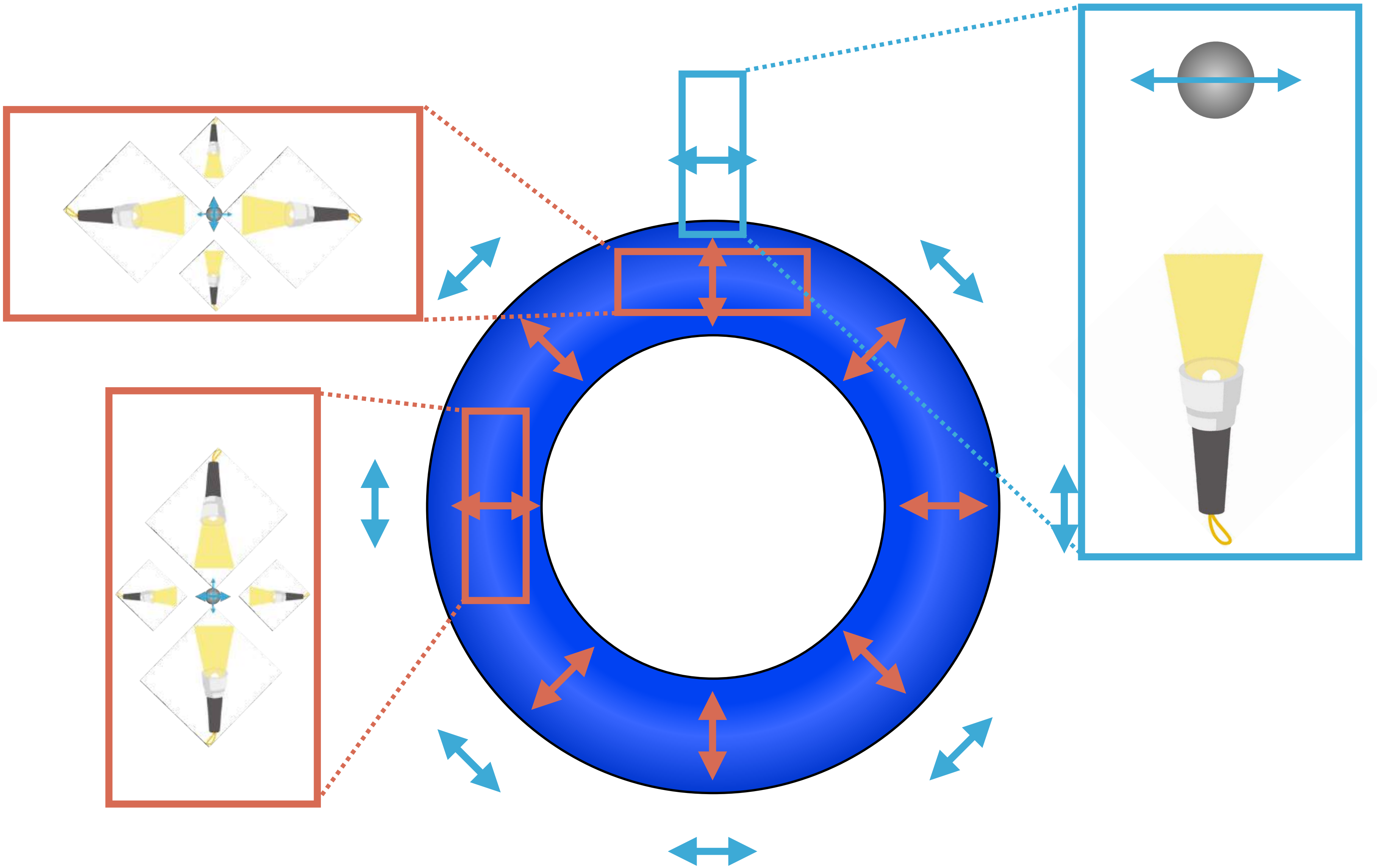
# Polarization due to scattering



# self-scattering in a protoplanetary disk



# self-scattering in a protoplanetary disk



# Conditions of dust grains for polarization

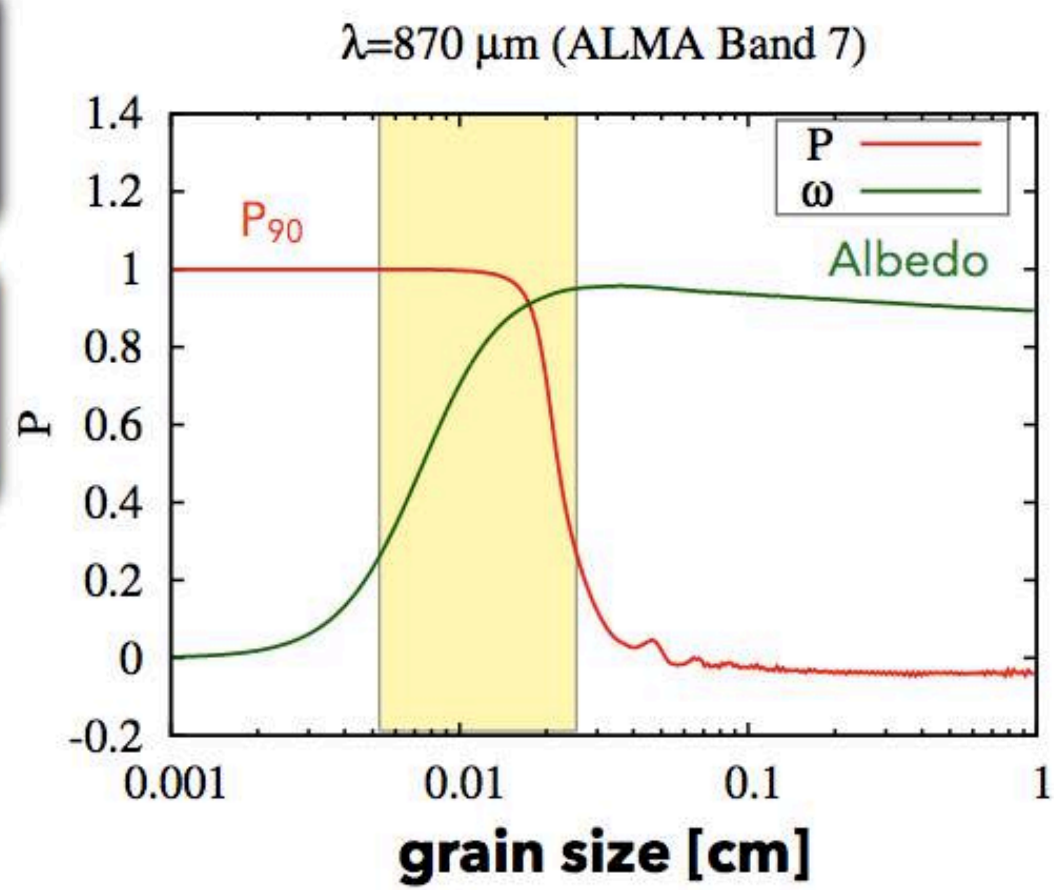
- For efficient scattering

  **(grain size) >~ λ**

- For efficient polarization

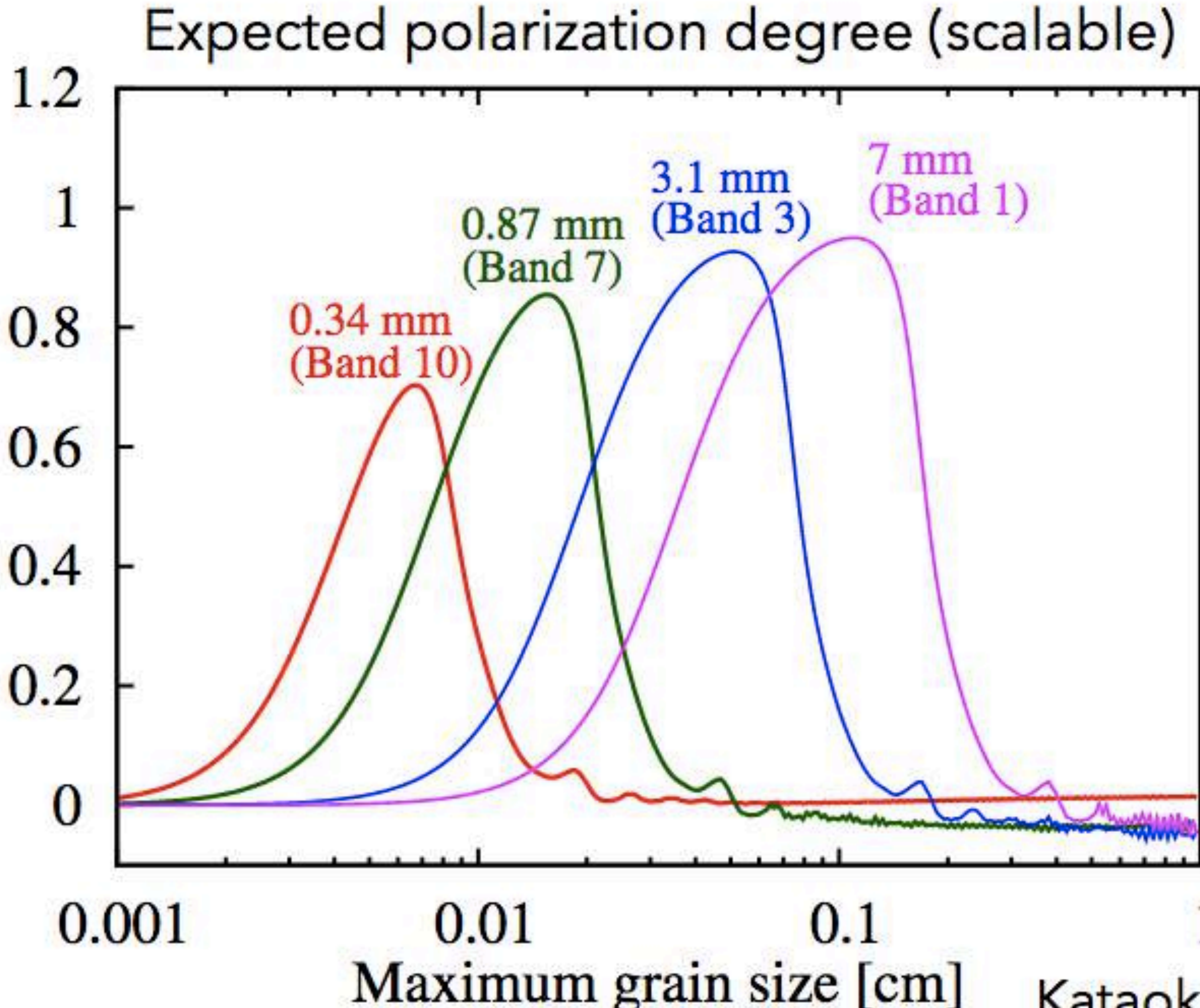
  **(grain size) <~ λ**

There is a grain size which contributes most to the polarized emission




**If (grain size) ~ λ/2π, the polarized emission due to dust scattering is the strongest**

# Grain size constraints by polarization

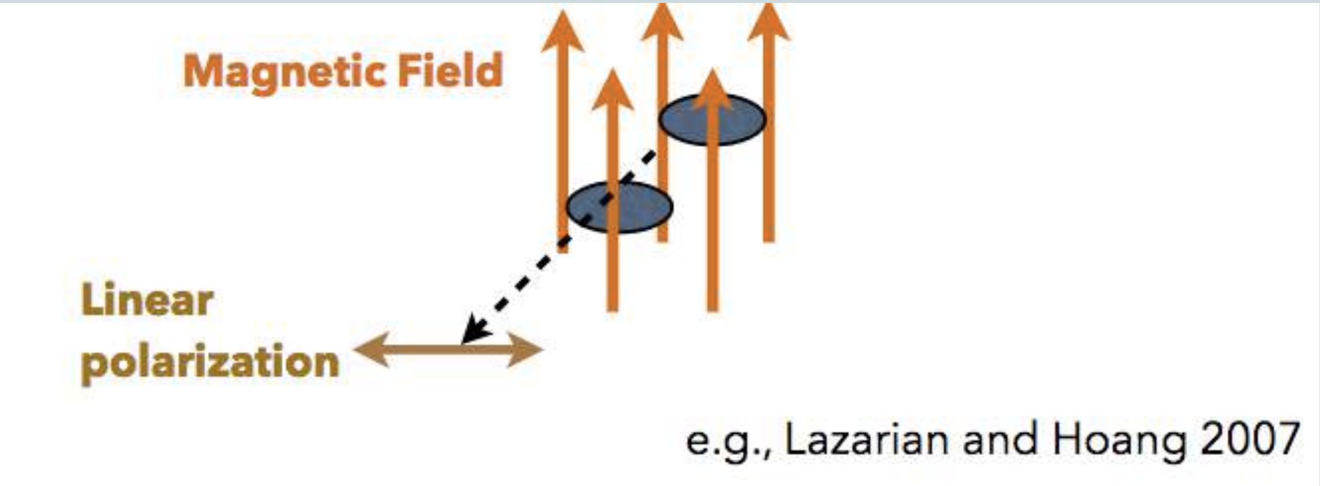



Kataoka, et al., 2015

**Multi-wave polarization → constraints on the grain size**

# 円盤での偏光メカニズム

- 1. 磁場に沿ったダスト偏光




- 2. 大きなダストの散乱

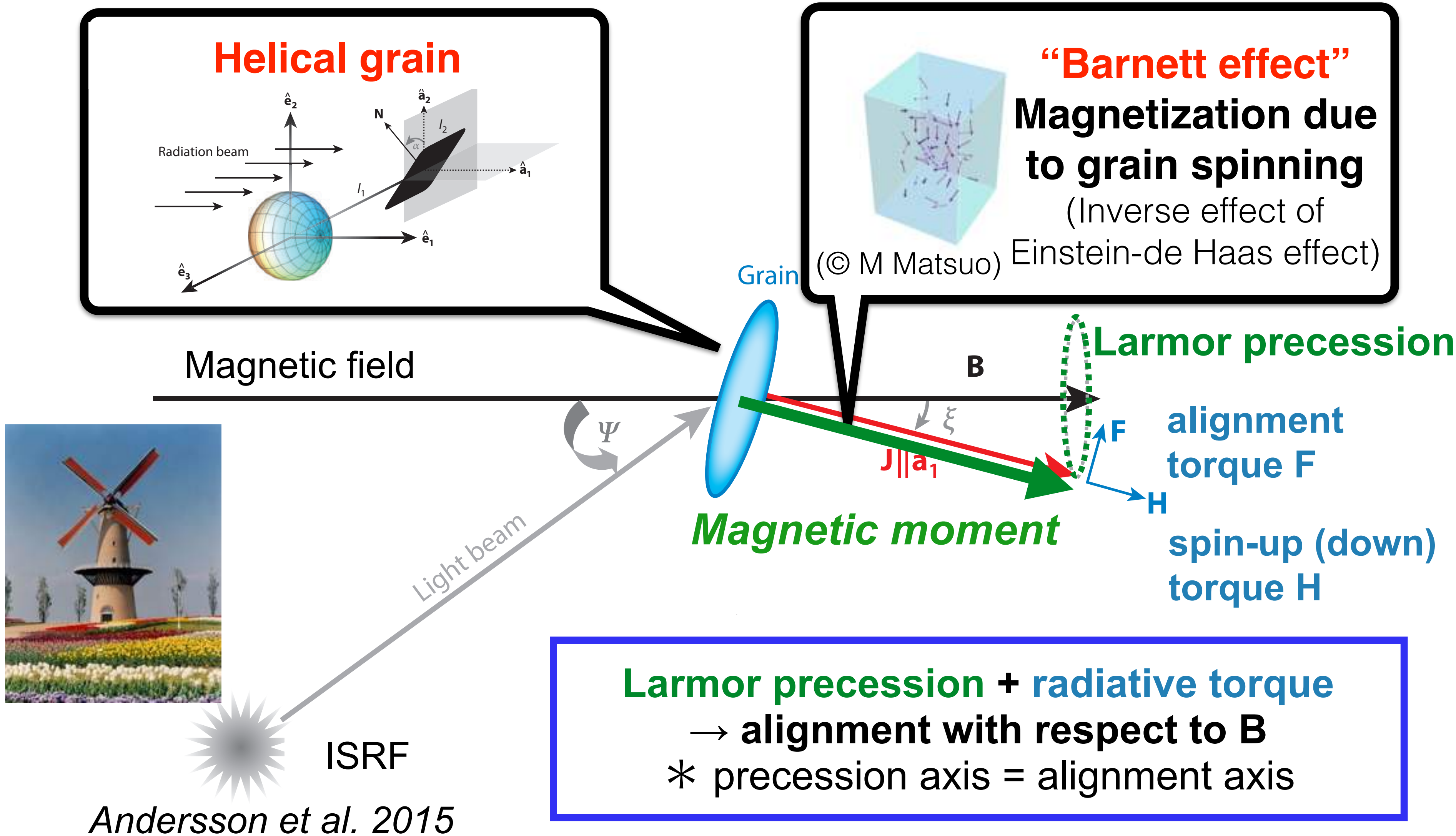
e.g., Kataoka et al. 2015

- 3. 輻射に沿ったダスト偏光

e.g., Hoang & lazarian 2007, Tazaki et al. 2017

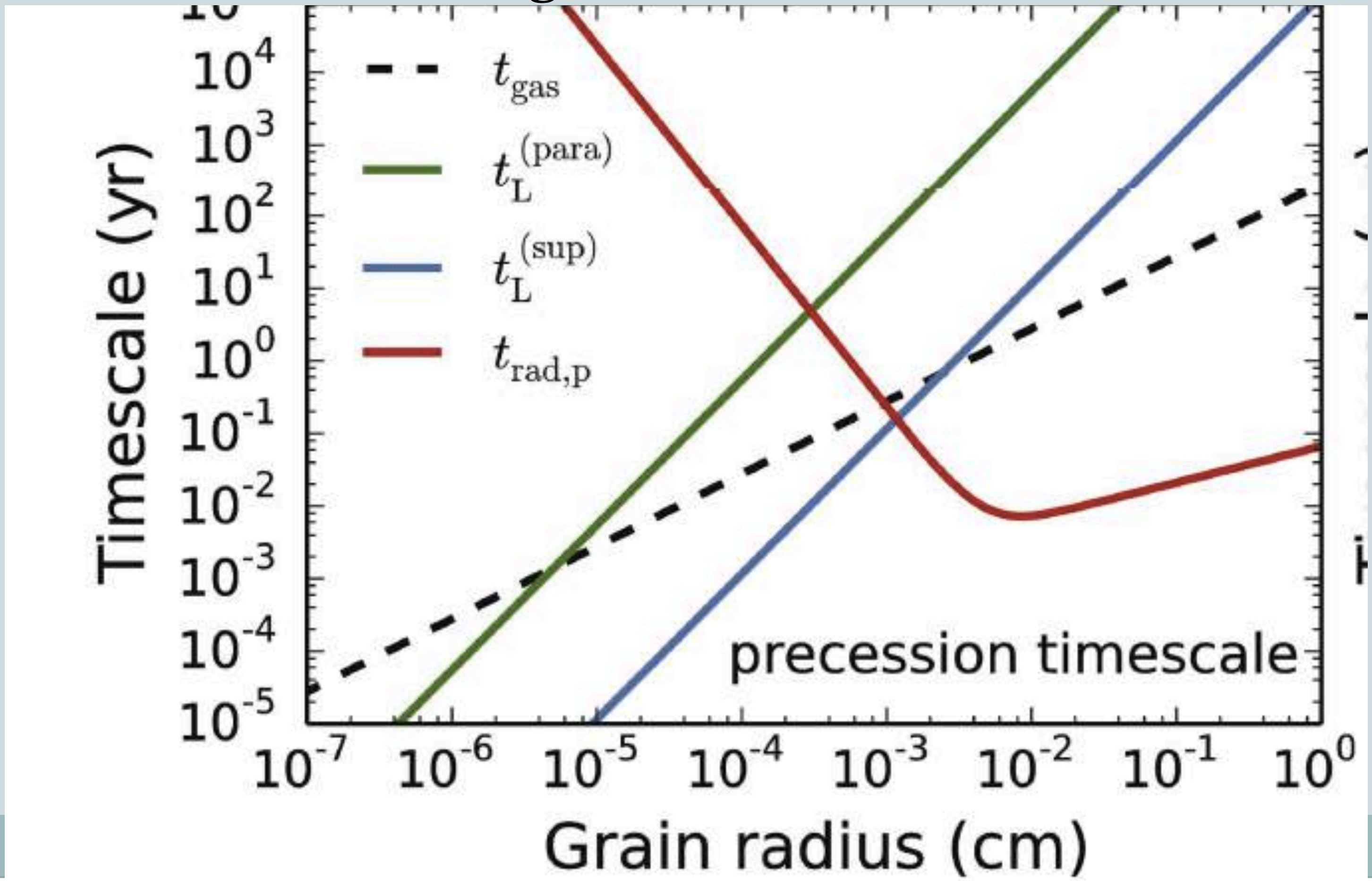
# Overview of RAT alignment

Lazarian & Hoang 2007



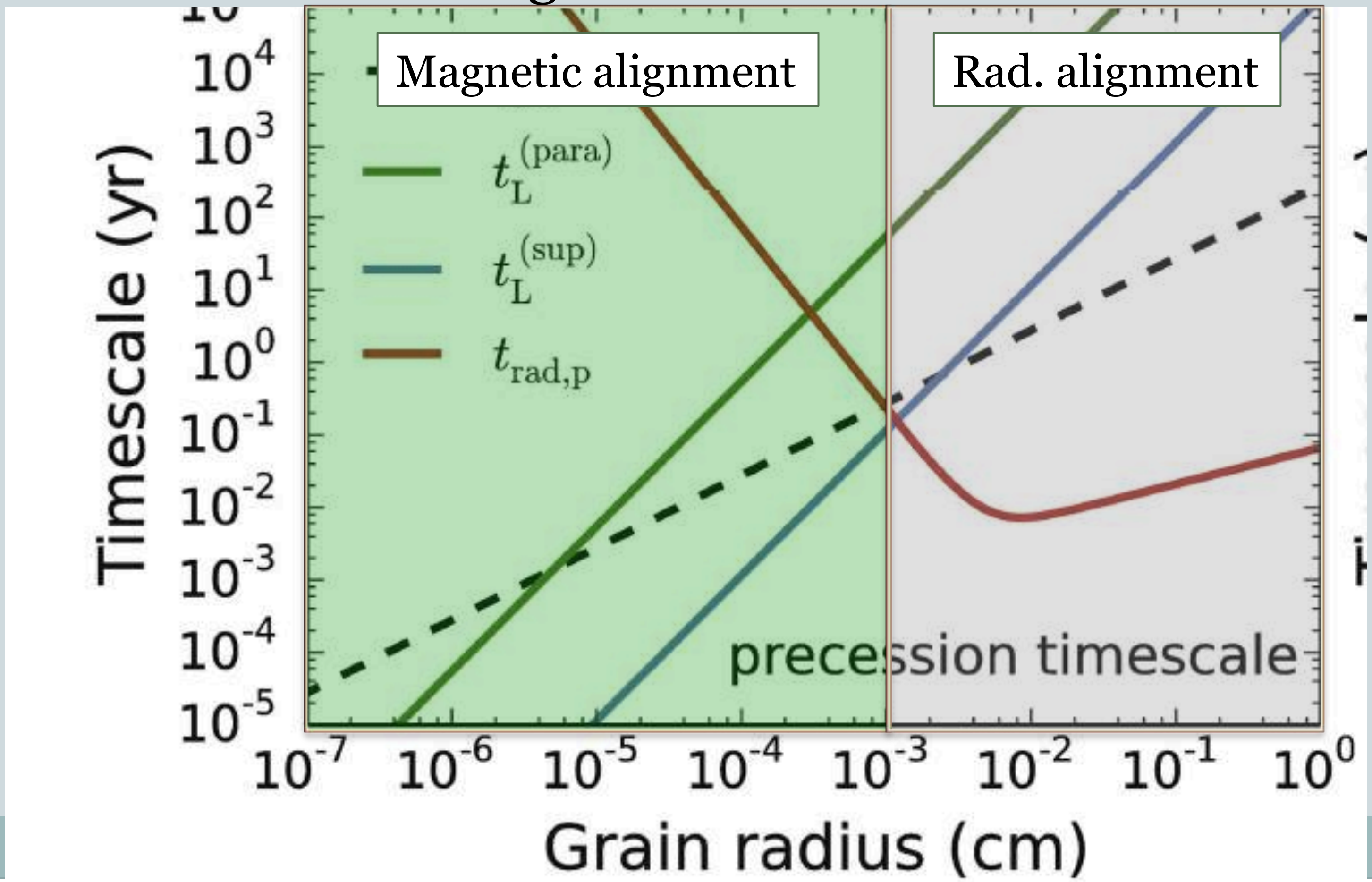
# RAT vs B field

- However, Tazaki et al. (2017) pointed out that the rad. precession is faster for grains > 10um

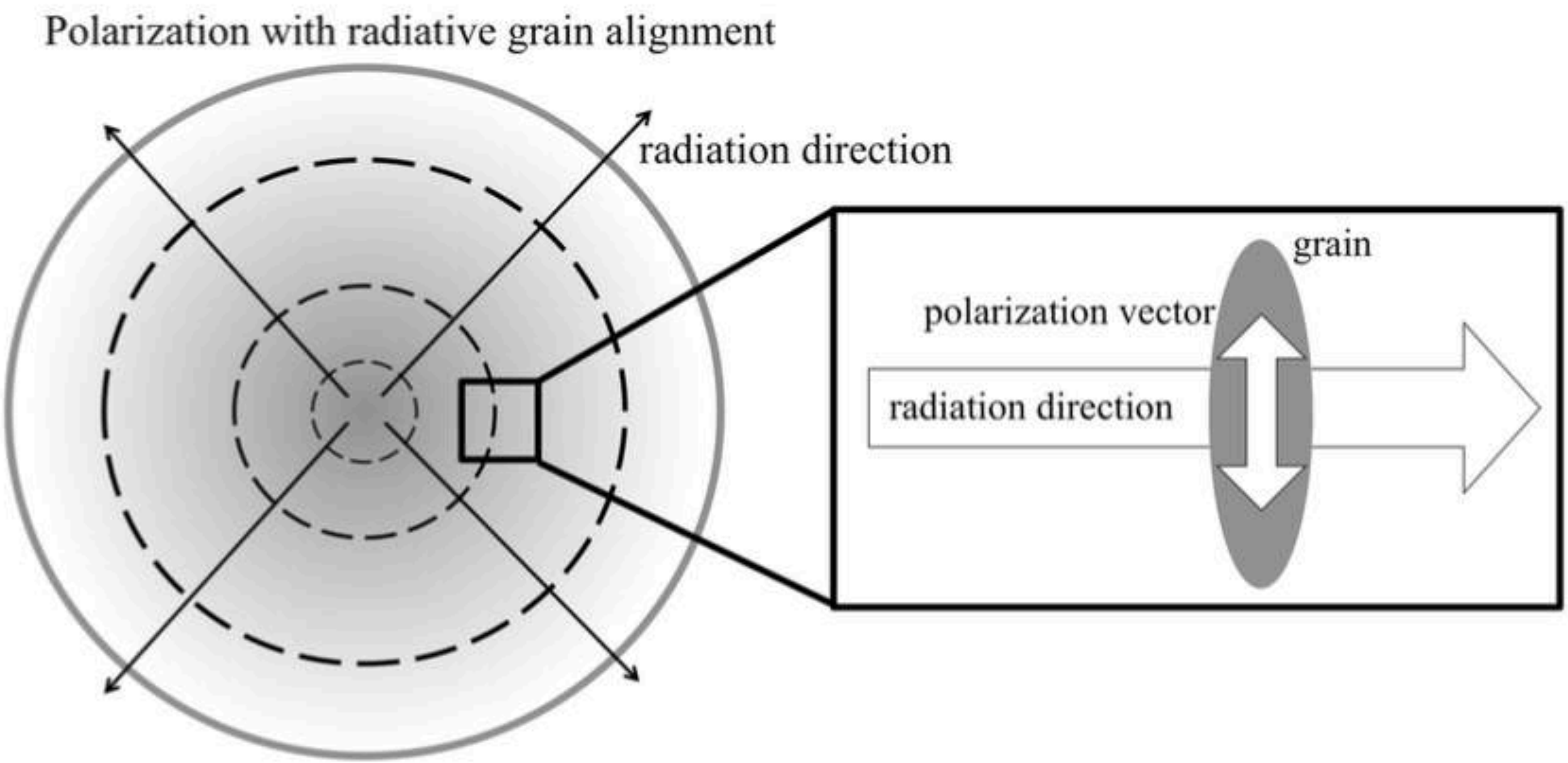


# Grain alignment with radiation gradient

- However, Tazaki et al. (2017) pointed out that the rad. precession is faster for grains > 10um

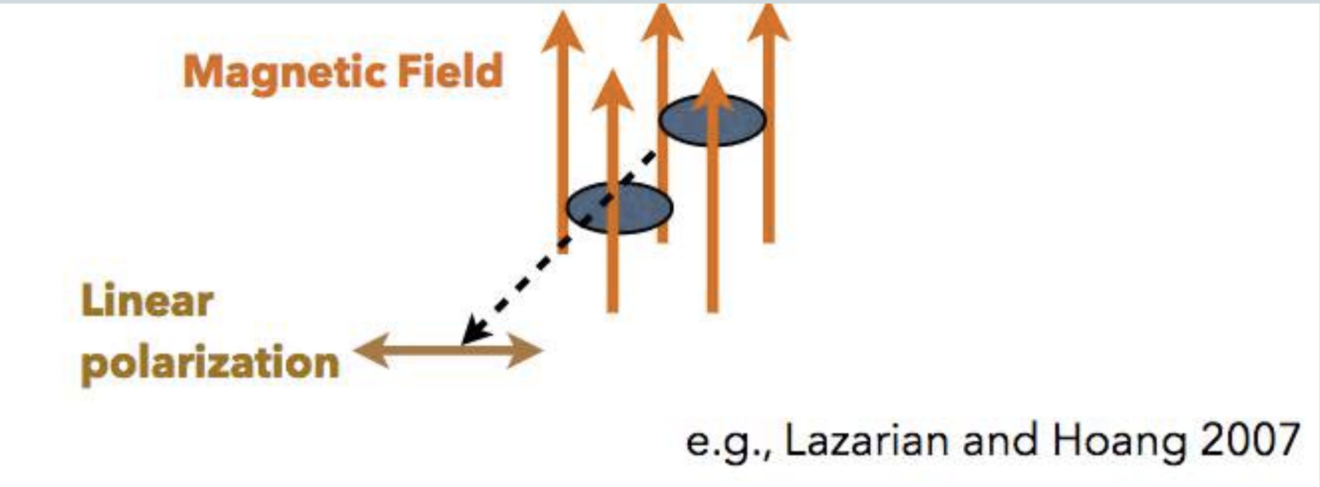


# 輻射場に沿うダスト整列



# 円盤での偏光メカニズム

- 1. 磁場に沿ったダスト偏光




- 2. 大きなダストの散乱

e.g., Kataoka et al. 2015

- 3. 輻射に沿ったダスト偏光

e.g., Hoang & lazarian 2007, Tazaki et al. 2017

# 円盤の偏光観測の意義

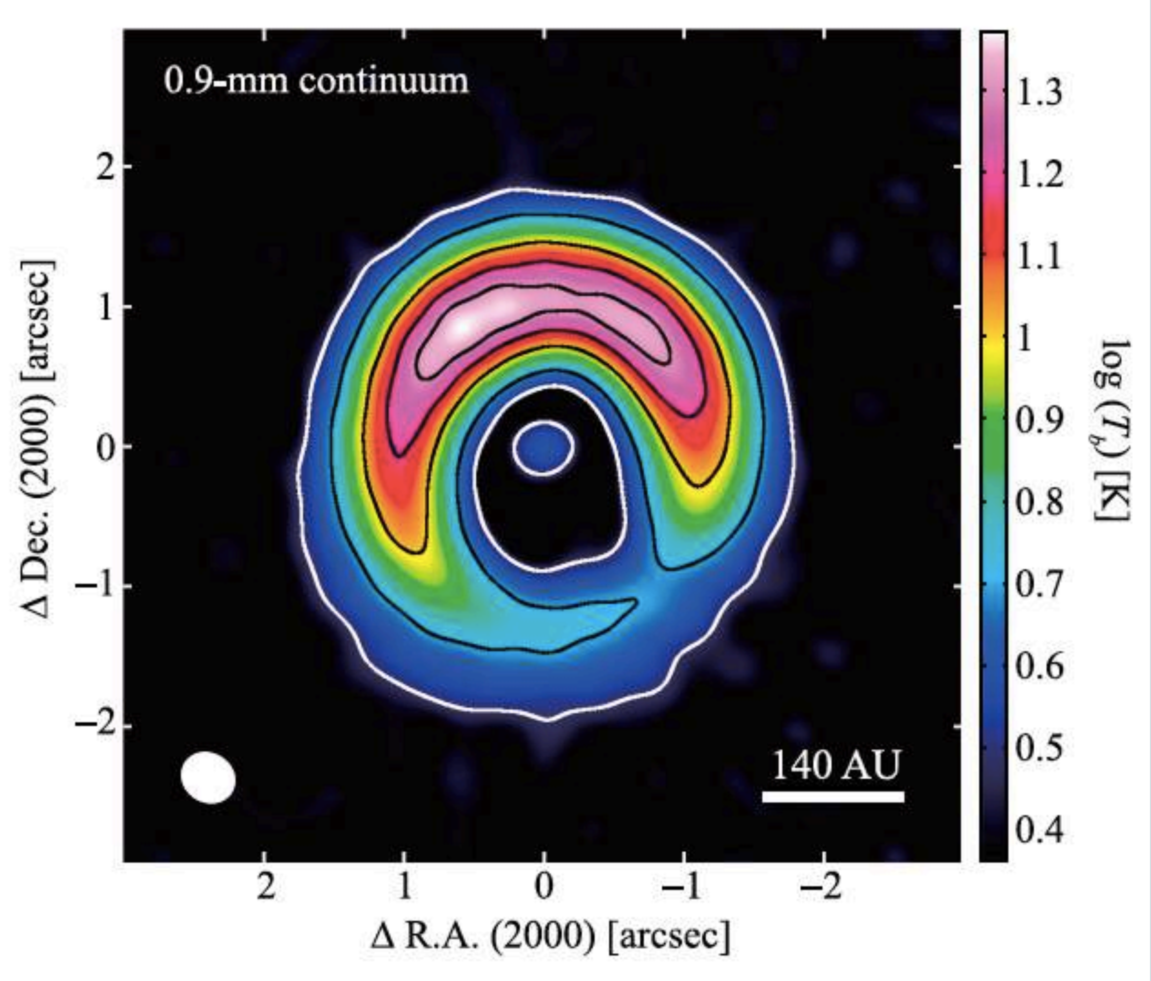
- 円盤の偏光メカニズムはよくわかっていない

散乱？ vs 整列？（磁場？ vs　輻射？）

- 偏光メカニズムはダスト組成によりそう

→ ダスト成長を調べられるかもしれない

# HD 142527




(Fukagawa et al. 2013, Casassus et al. 2013))

Gas to dust to dust mass ratio

~3 in north

~30 in south

Suggested by
Muto et al. 2015,
Boehler et al. 2017

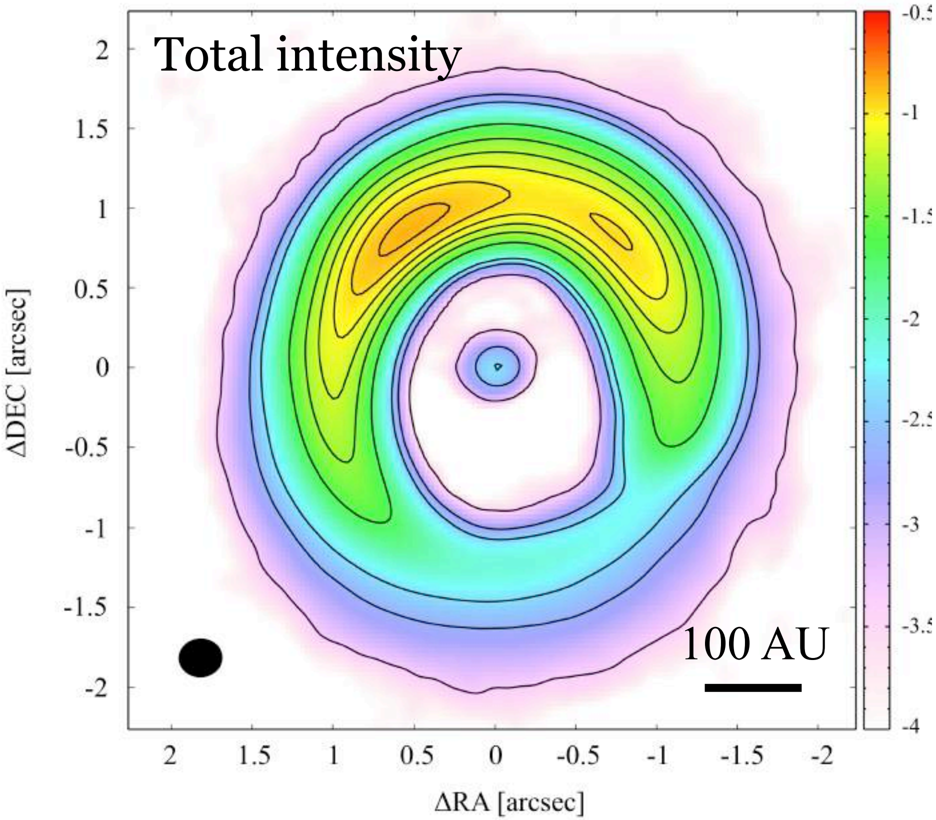
# ALMA polarization observations cycle 3&4

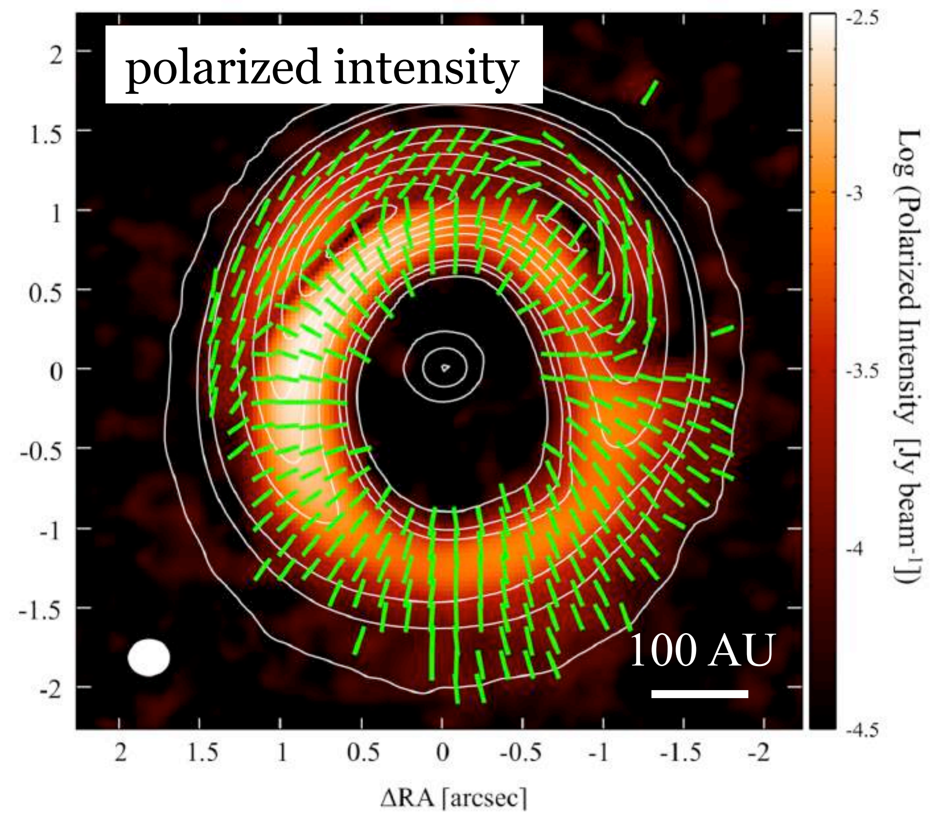
| Band 7 (870 um) | beamsize | rms (stokes I) | rms (PI) |
|---|---|---|---|
| Cycle 3&4 | $0.27'' \times 0.24''$ | 43 $\mu$Jy beam$^{-1}$ | 29 $\mu$Jy beam$^{-1}$ |

$1'' \sim 156$ AU
$0.25'' \sim 40$ AU

# Polarization of HD 142527

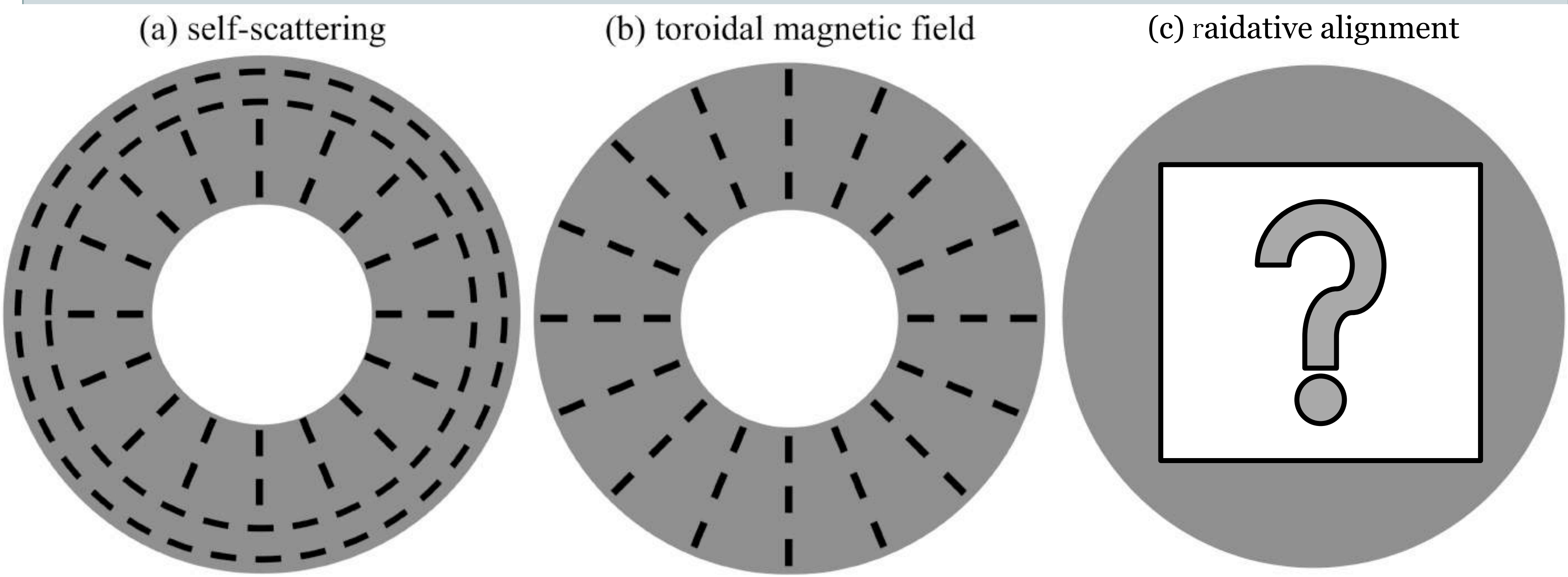
- We have improved the resolution and sensitivity



# possible polarization in HD 142527

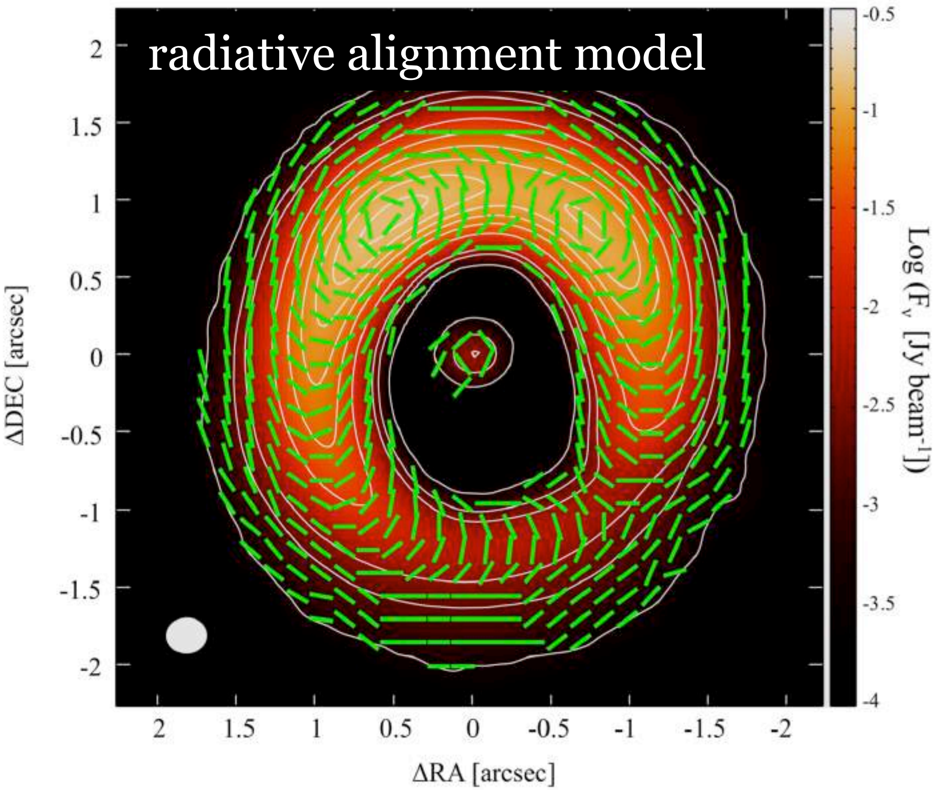
各偏光メカニズムで予想されるHD 142527の偏光ベクトルの様子

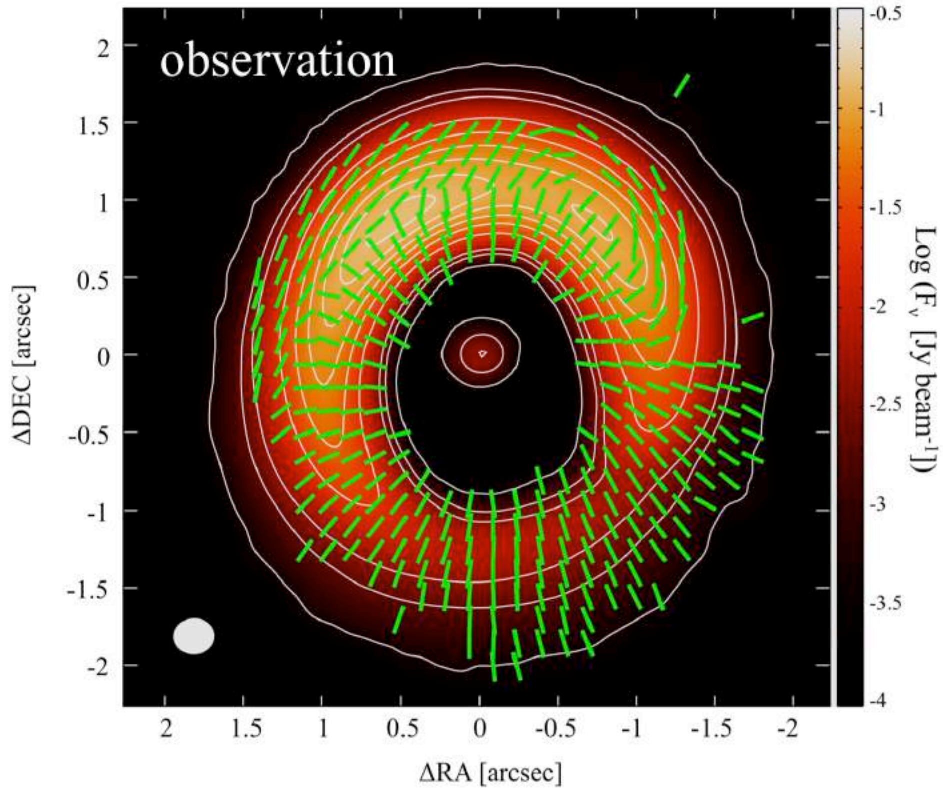



Kataoka+16　　Cho & Lazarian 07　　(Tazaki+17)

# Model of radiative grain alignment

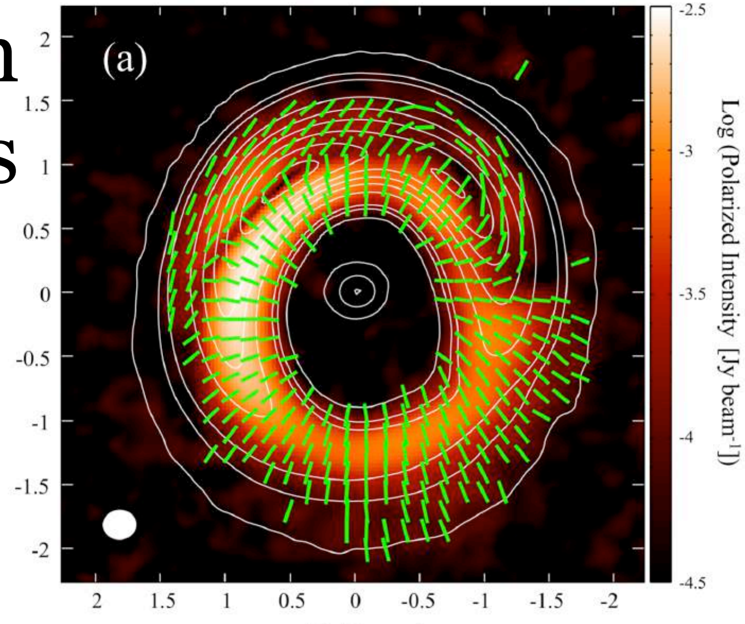
0.87 mmのイメージを輻射場として、各ピクセルにおける輻射場の方向を計算、輻射場によるダスト整列と偏光ベクトルを予想



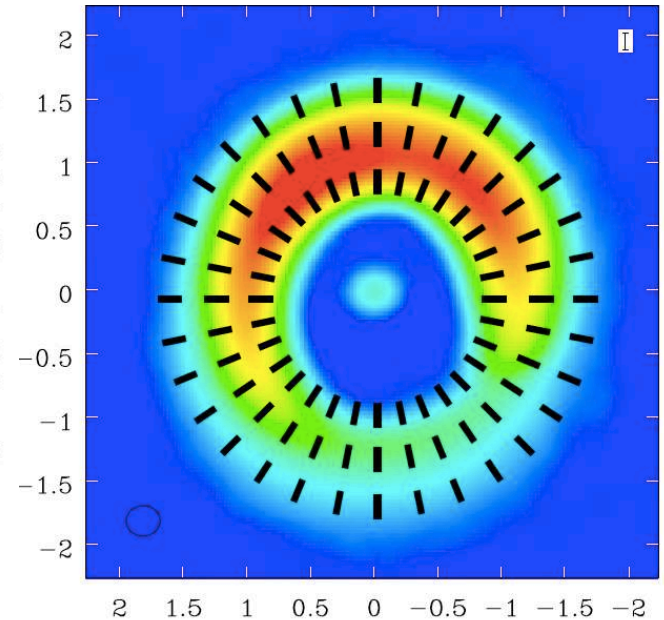



# Comparison with models

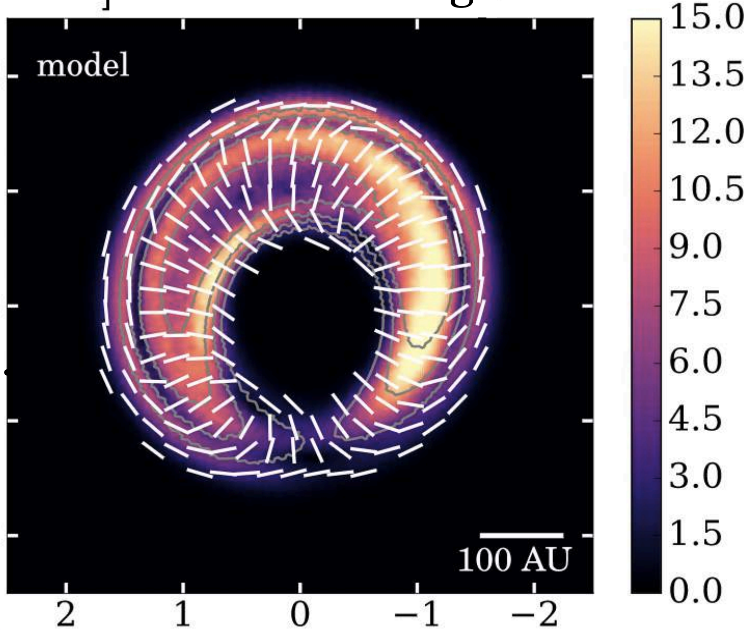
observation



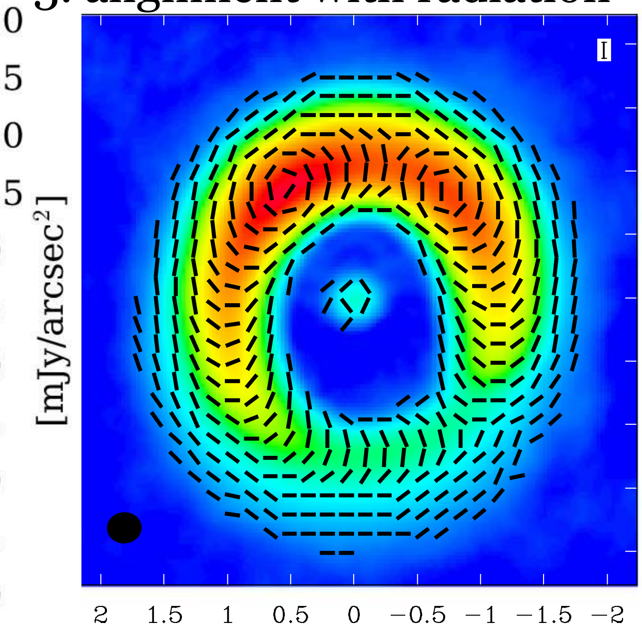

1. alignment with B field



2. self scattering




3. alignment with radiation

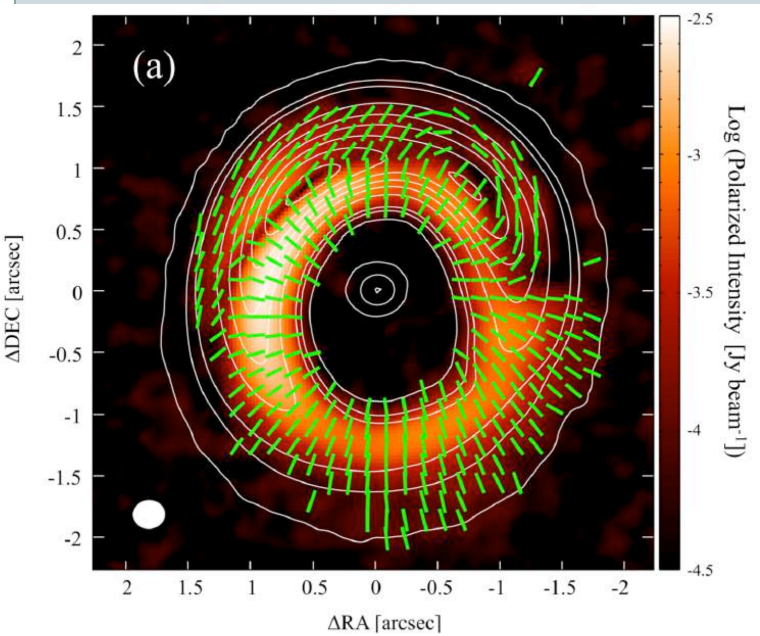


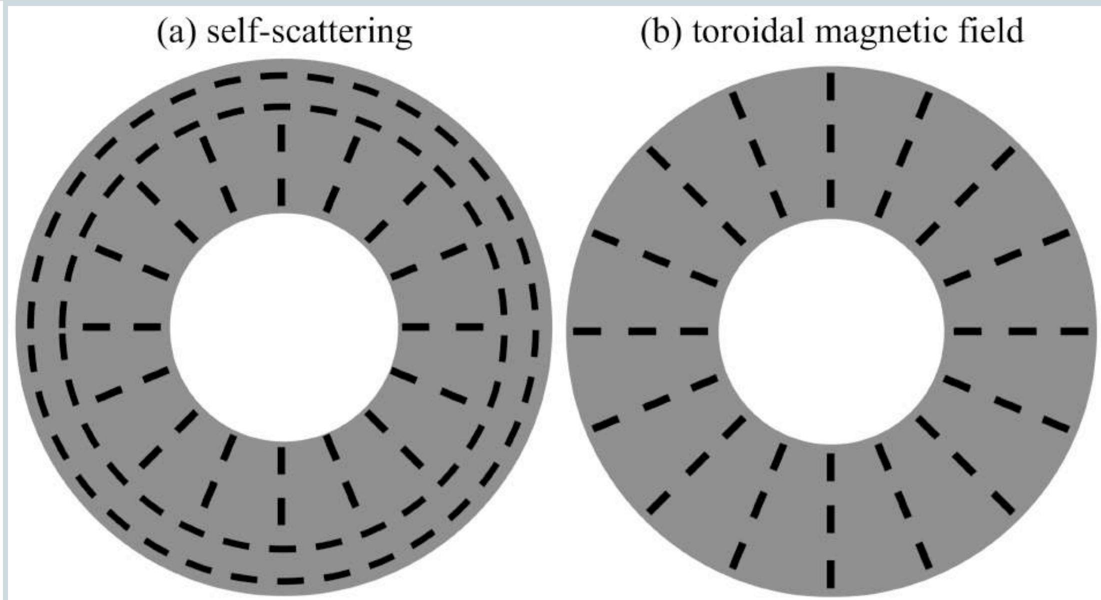
(see also Kataoka et al. 2015)

# Polarization of HD 142527

**Table 1.** Possible mechanisms of polarization

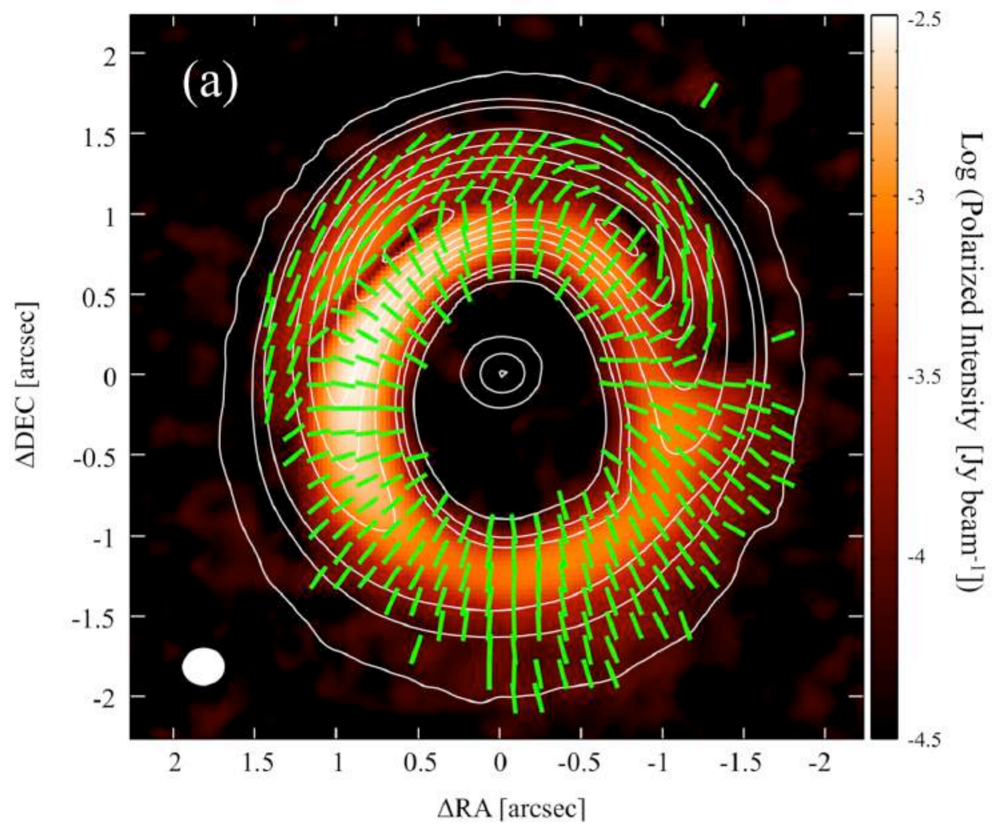
| Polarization | Northern region | Southern region |
|---|---|---|
| Self-scattering | ✓ | ✗ |
| Grain alignment with magnetic field | ✗ | ✓ |
| Grain alignment with radiation gradient | ✗ | ✗ |



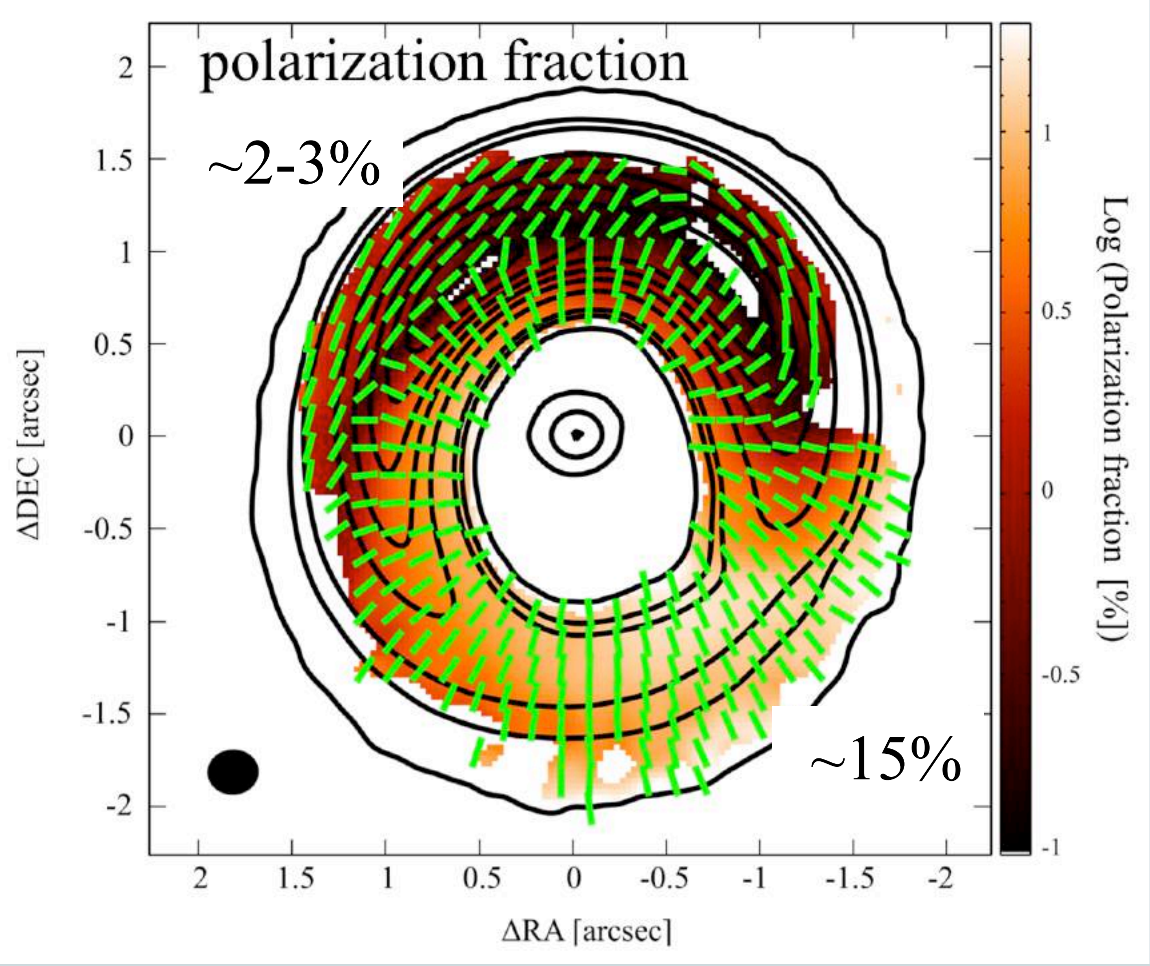
# Polarization of HD 142527

- The northern polarization is likely due to the self-scattering
- But the southern polarization cannot be explained by either the self-scattering or radiative grain alignment




magnetic field is still important!

# The polarization fraction



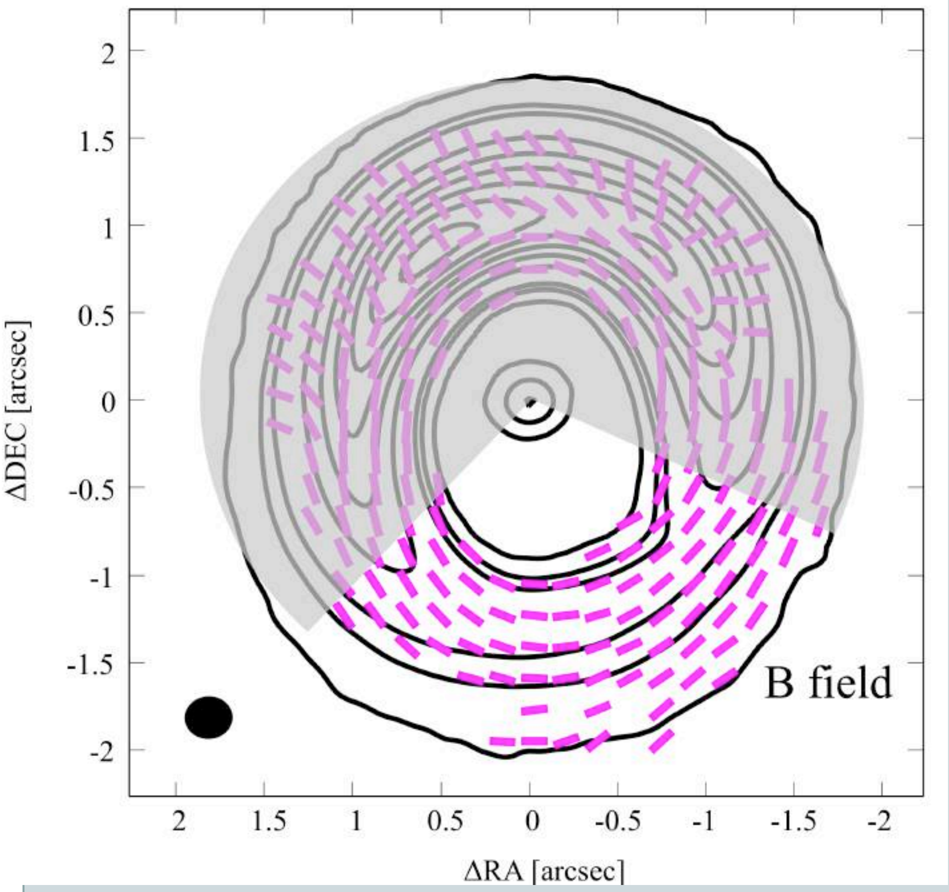

The polarization fraction is as high as 15%

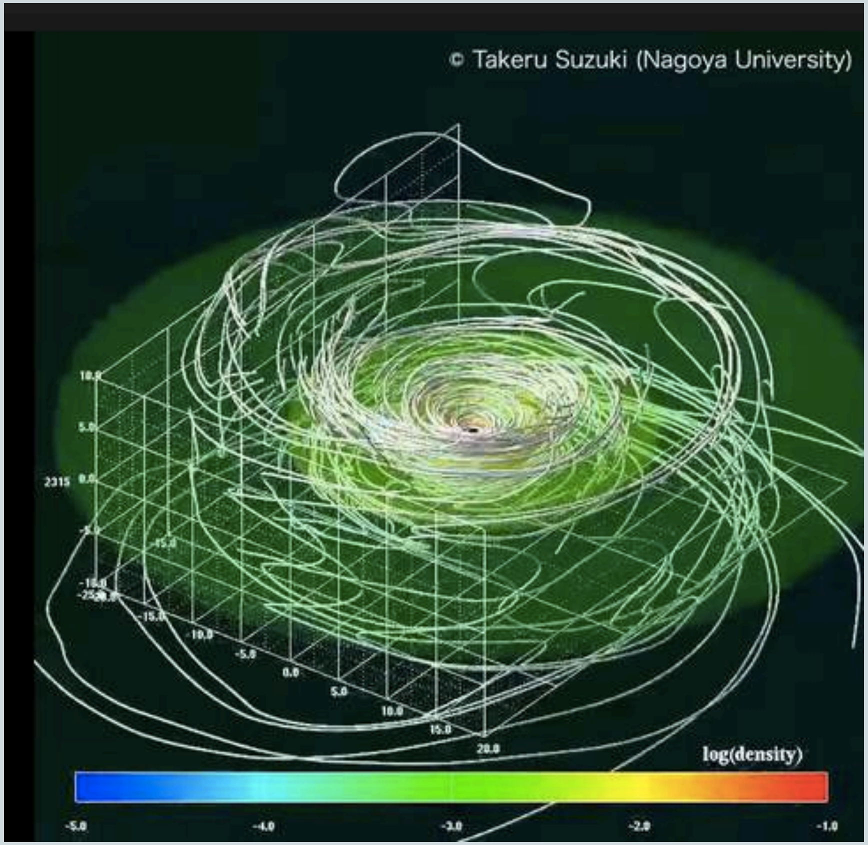
High polarization fraction is consistent with magnetic fields (e.g., Bertrang et al. 2017)

# The toroidal magnetic fields

- We finally find the magnetic fields, which is toroidal

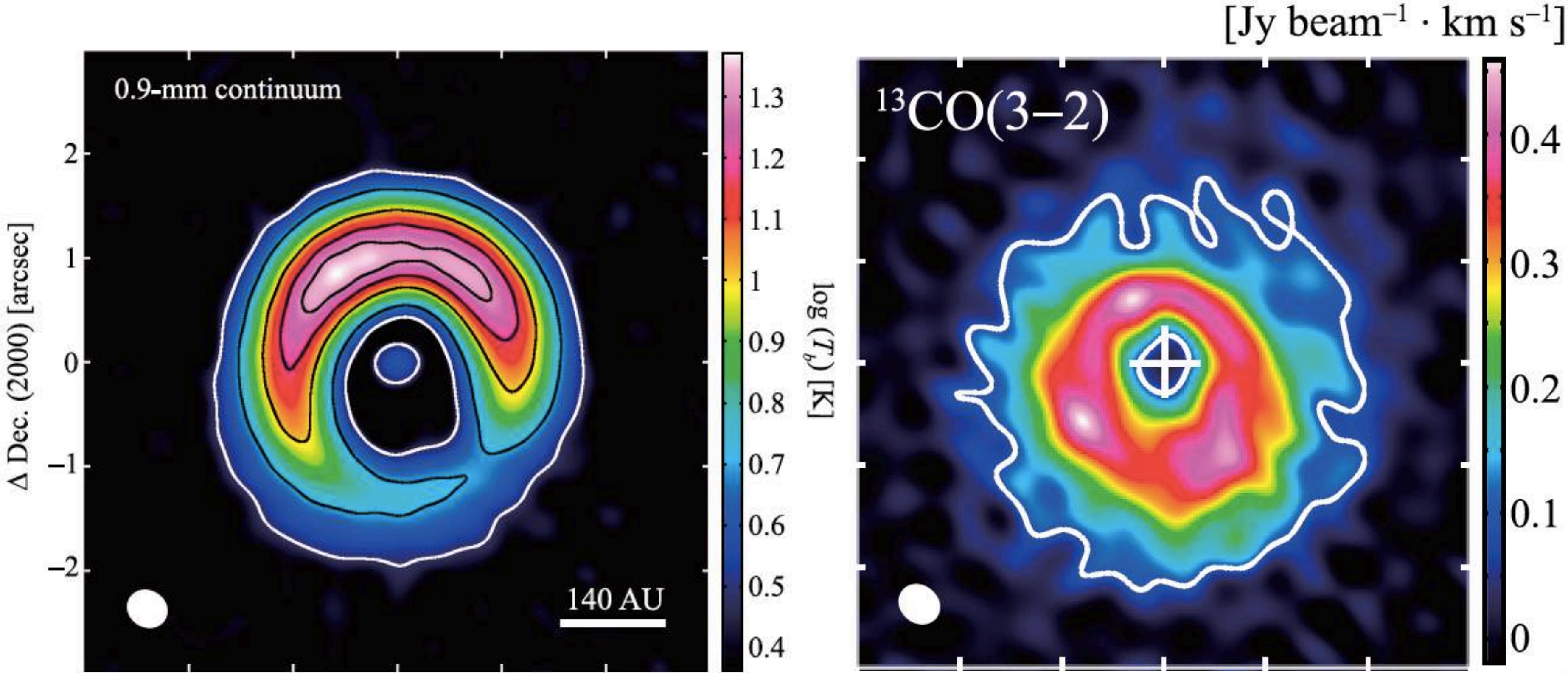
クレジット:CfCA



# Dust vs Gas

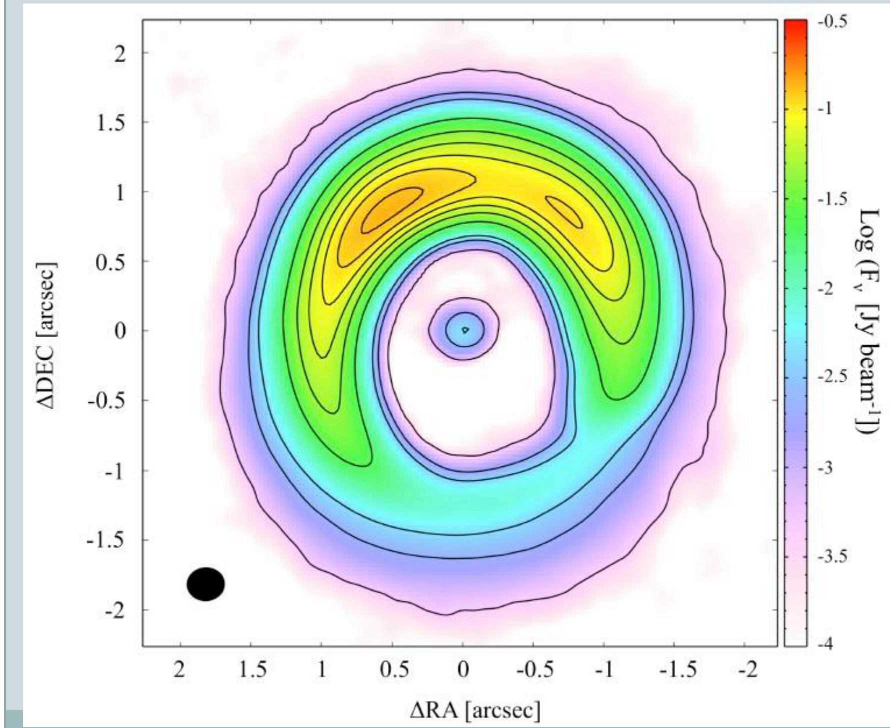
small grains are well coupled with gas, but larger grain goes to region where the pressure is high

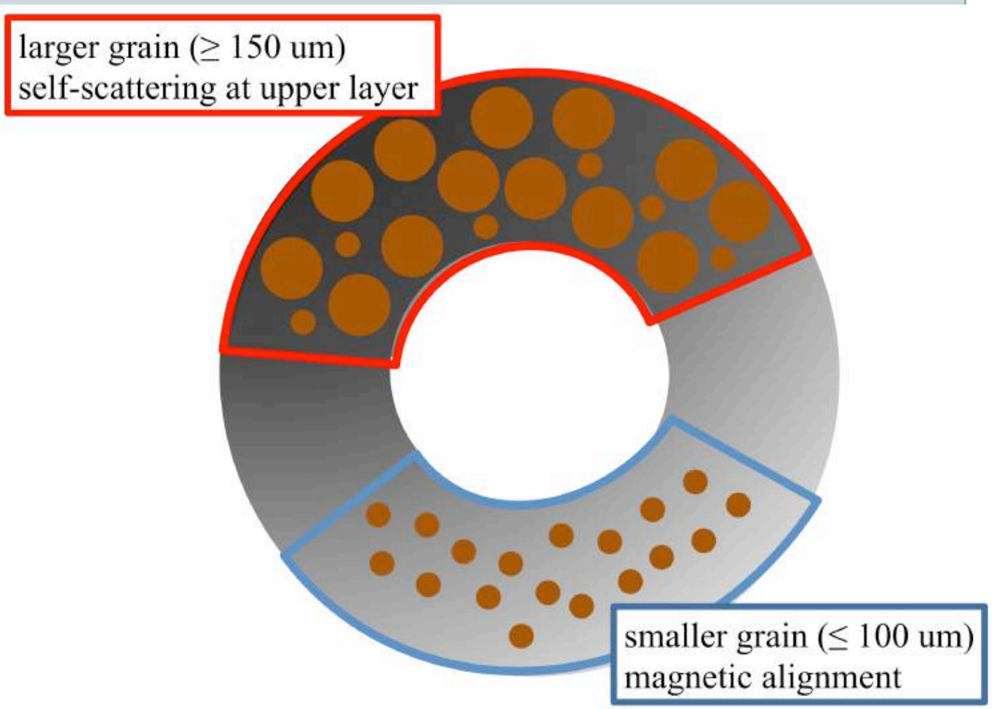



Casassus et al. 2013, Fukagawa et al. 2013, Muto et al. 2016, Boehler et al. 2017

# Possible polarization of HD 142527

- The flip is likely to be the self-scattering
- Larger dust may be settled into the midplane
- The southern region has micron grains aligned by magnetic field
- grains even with 100 um are trapped by gas pressure



# まとめ

- 原始惑星系円盤の偏光起源はよくわかっていない

  散乱 vs 整列　（磁場 vs 輻射）

- ALMAによる高感度、高分解能観測で散乱と磁場による整列の偏光が見えてきた
- ダストのサイズや観測波長によって偏光メカニズムは変化する