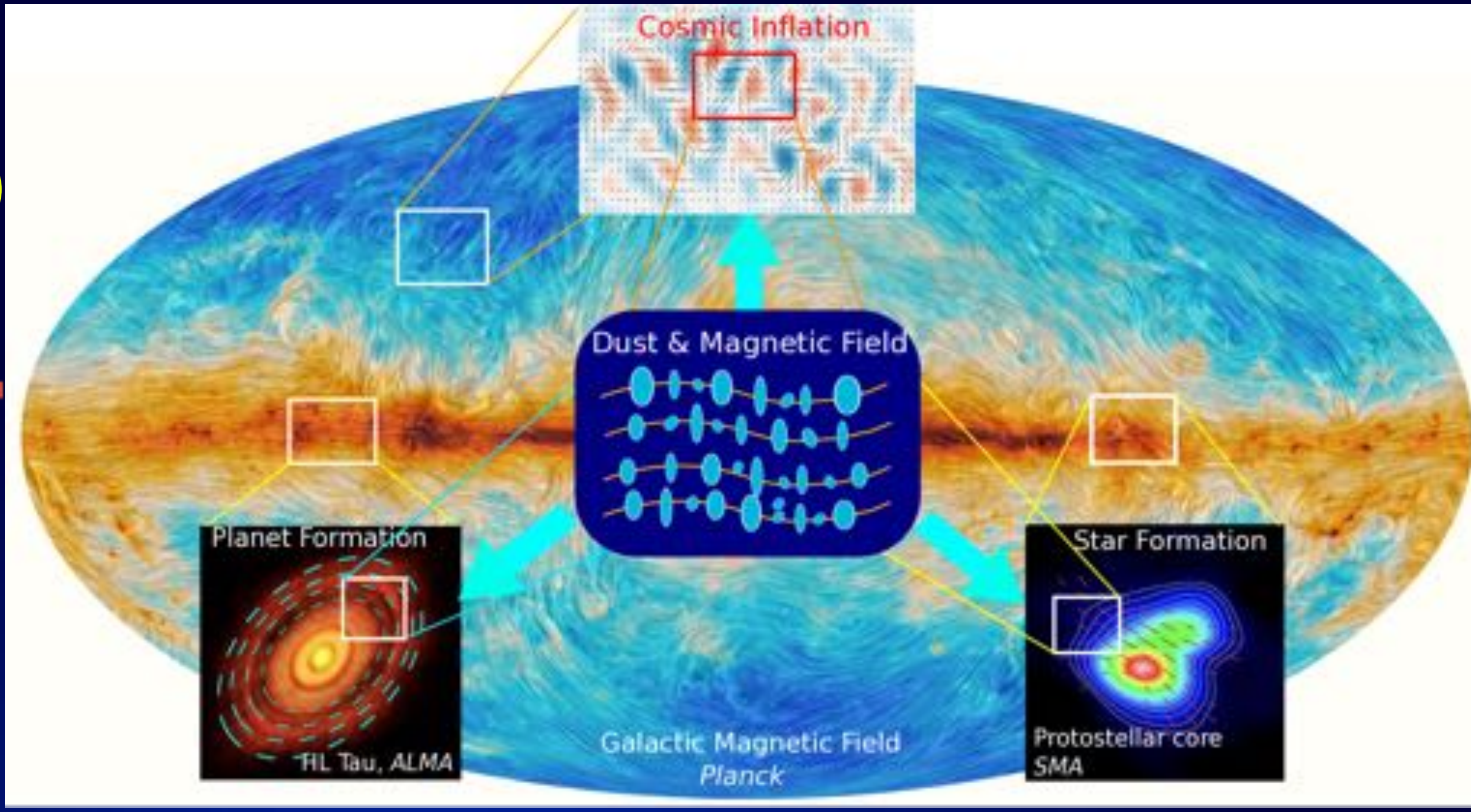
Dust Properties in our Galaxy

Polarization and Microwave Emission

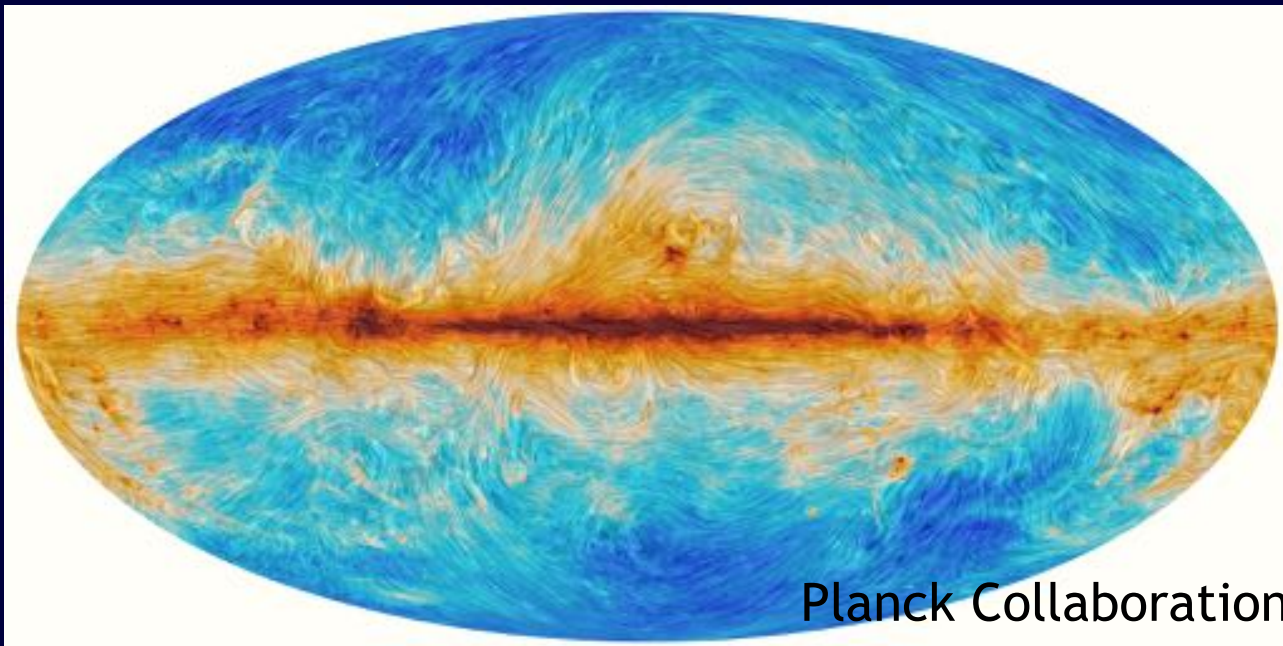
Thiem Hoang
(KASI & UST)

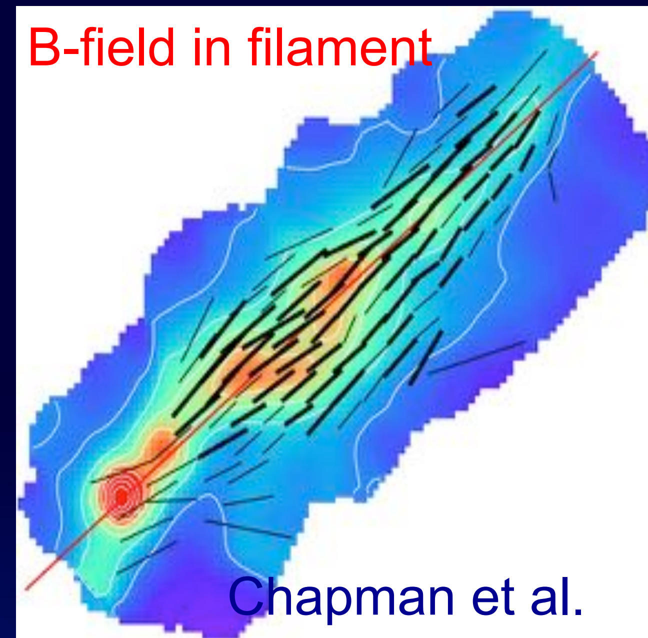


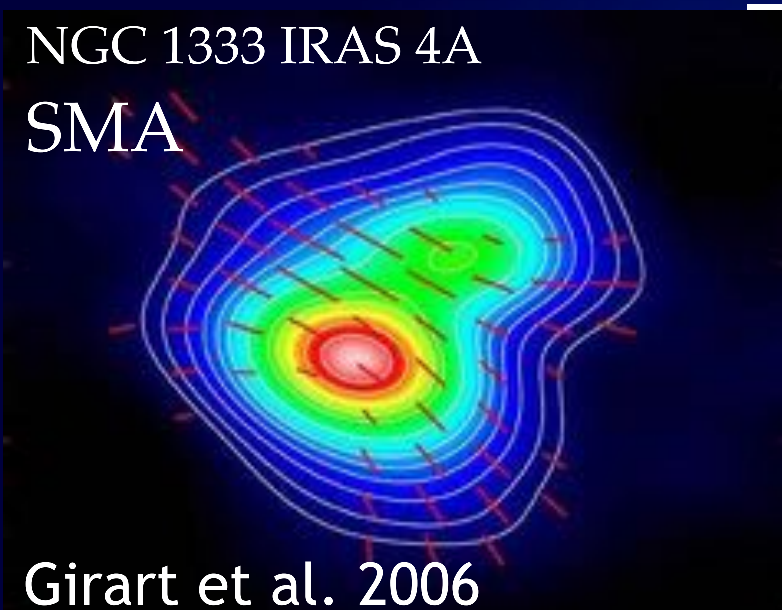
Thanks to A. Lazarian (UW-Madison), BT Draine (Princeton), B-G Andersson (NASA), D. Whittet (Rochester), J. Cho (Chungnam), PG Martin (CITA), C. Telesco (UFL), H Zhang (UFL)

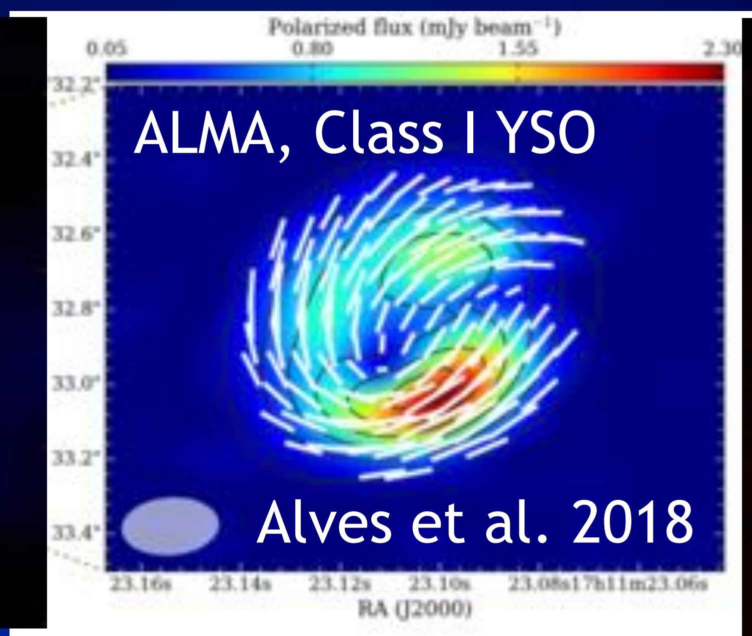
Cosmic Cycle of Dust and Gas, Quy Nhon, July 8-14, 2018

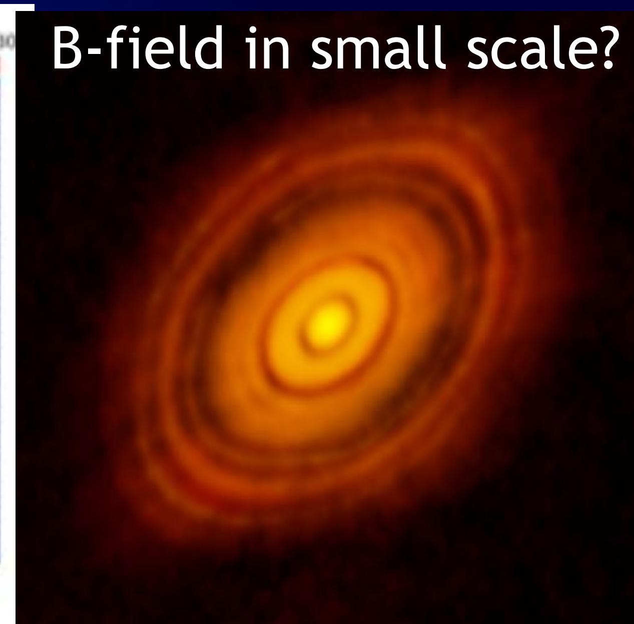
Golden Age of Dust Polarimetry:
Unveiling the Role of Magnetic Fields in Star Formation







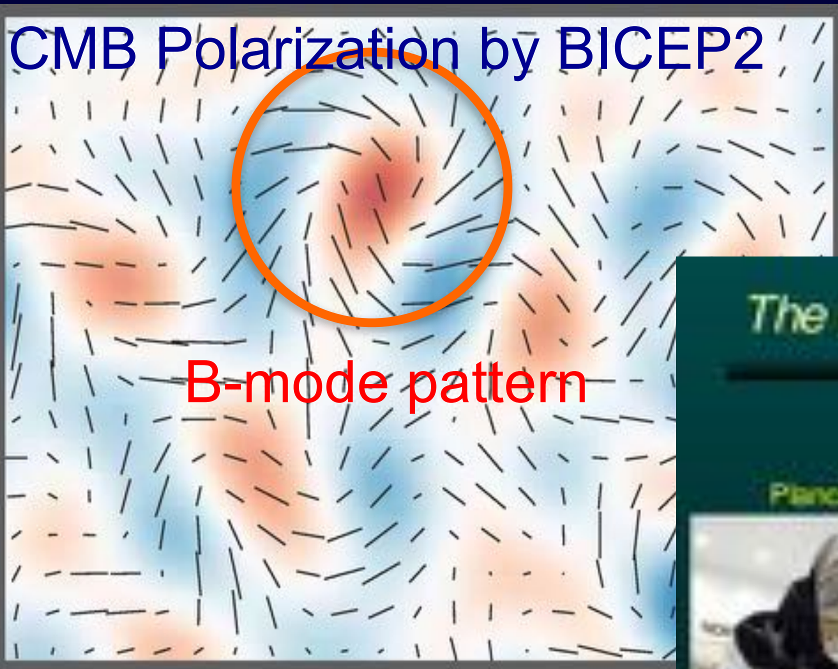


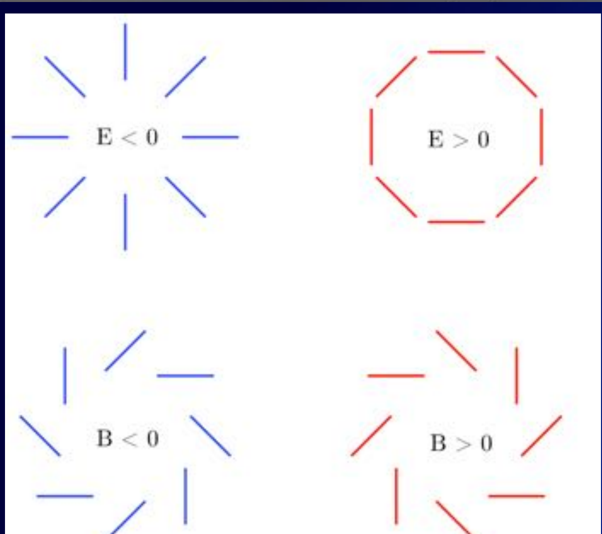


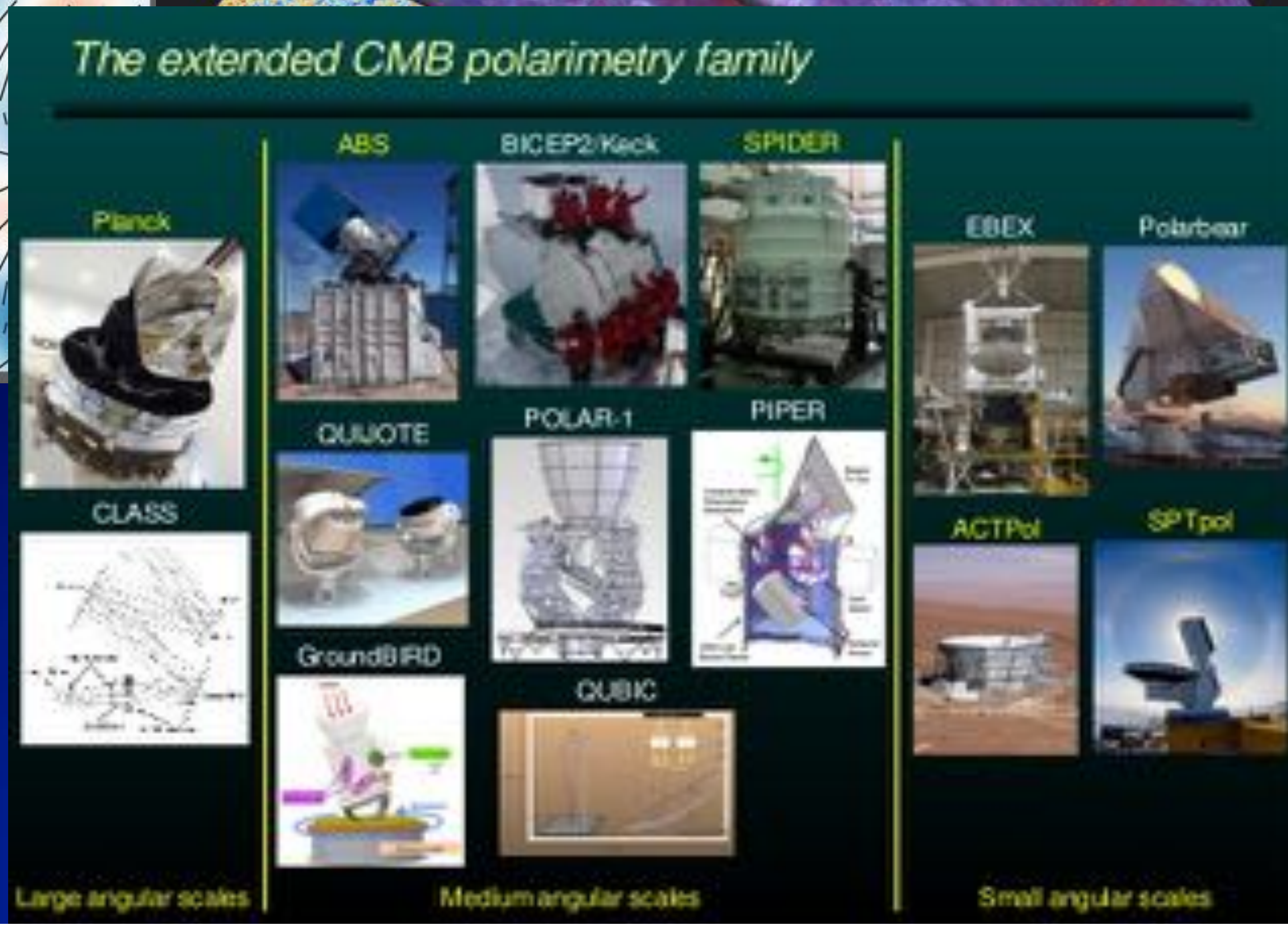
Golden Age of CMB Polarimetry:

Measuring Gravitational Waves with CMB B-Modes

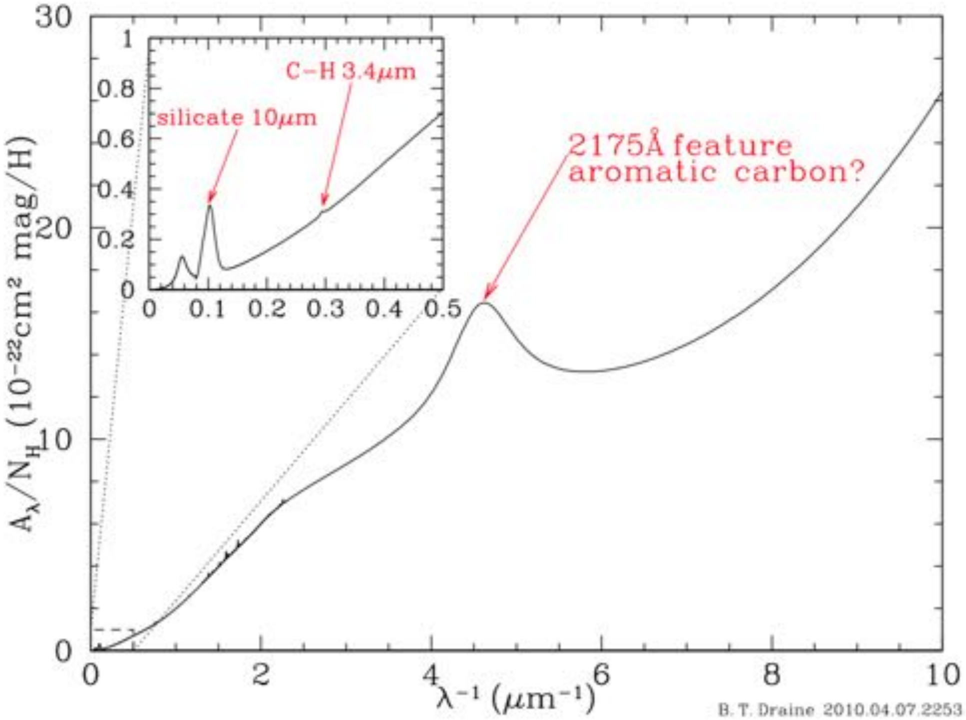
CMB: Cosmic Microwave Background

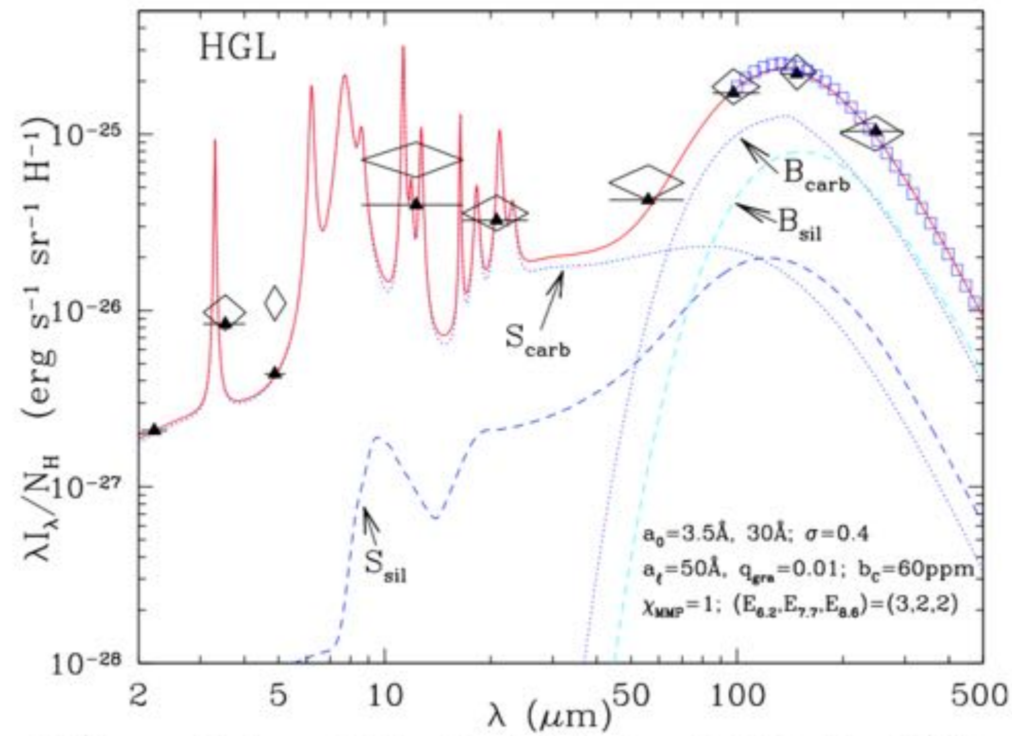






Dust Extinction and Emission

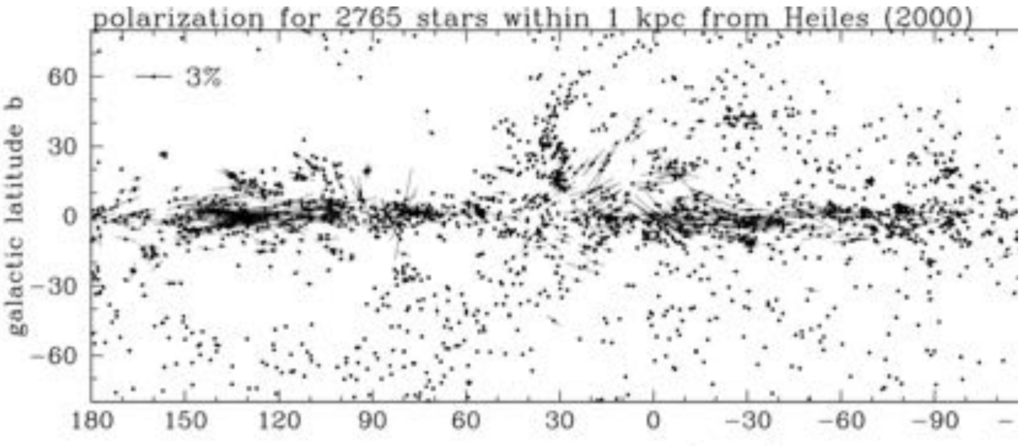




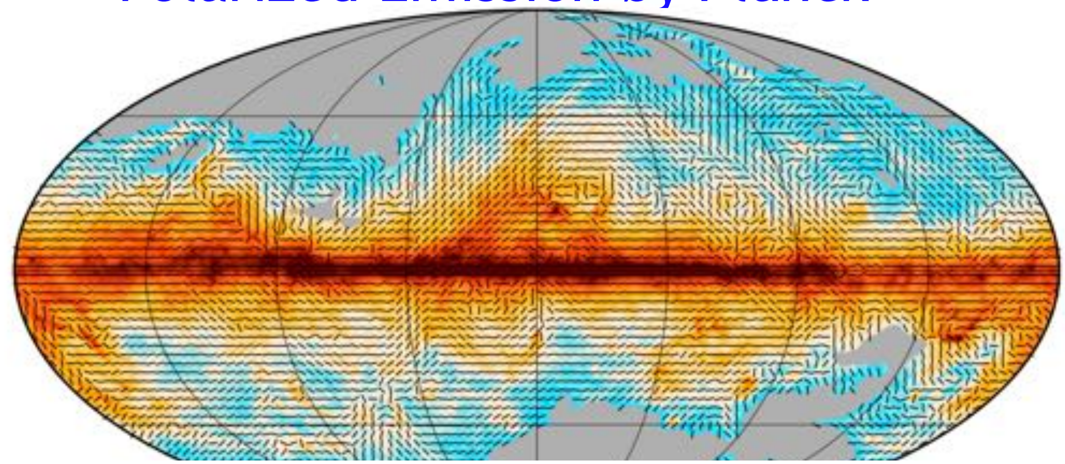
- PAHs and Nanoparticles absorb UV photons and reemit in mid-IR
- Big grains absorb starlight and reemit in IR
- Interstellar dust consists silicate and carbonaceous grains

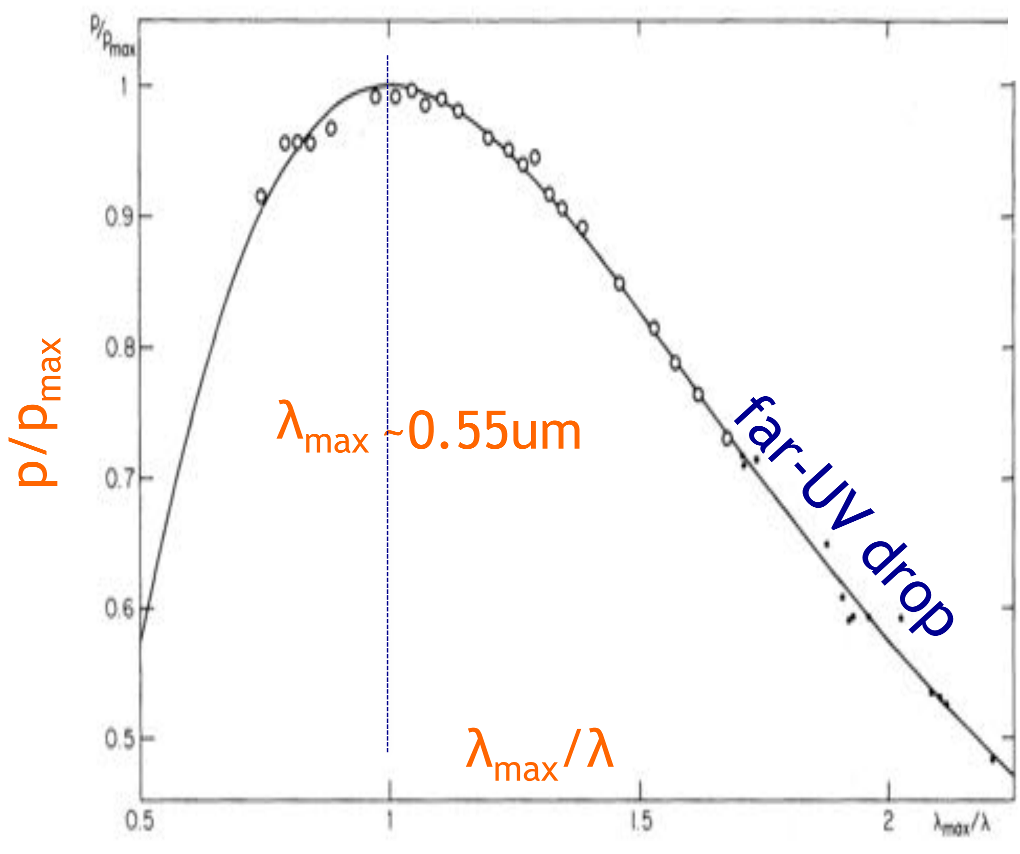
Starlight Polarization and Polarized Emission

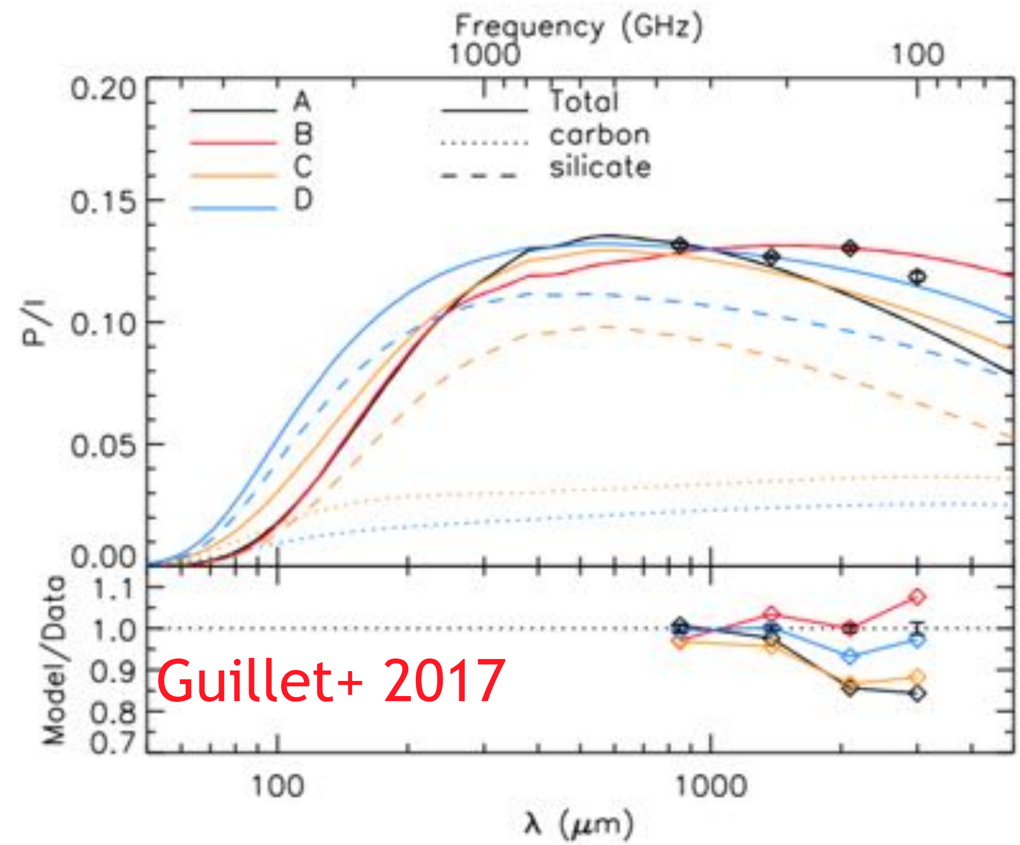
Starlight Polarization (1951: Hall, Hilner)



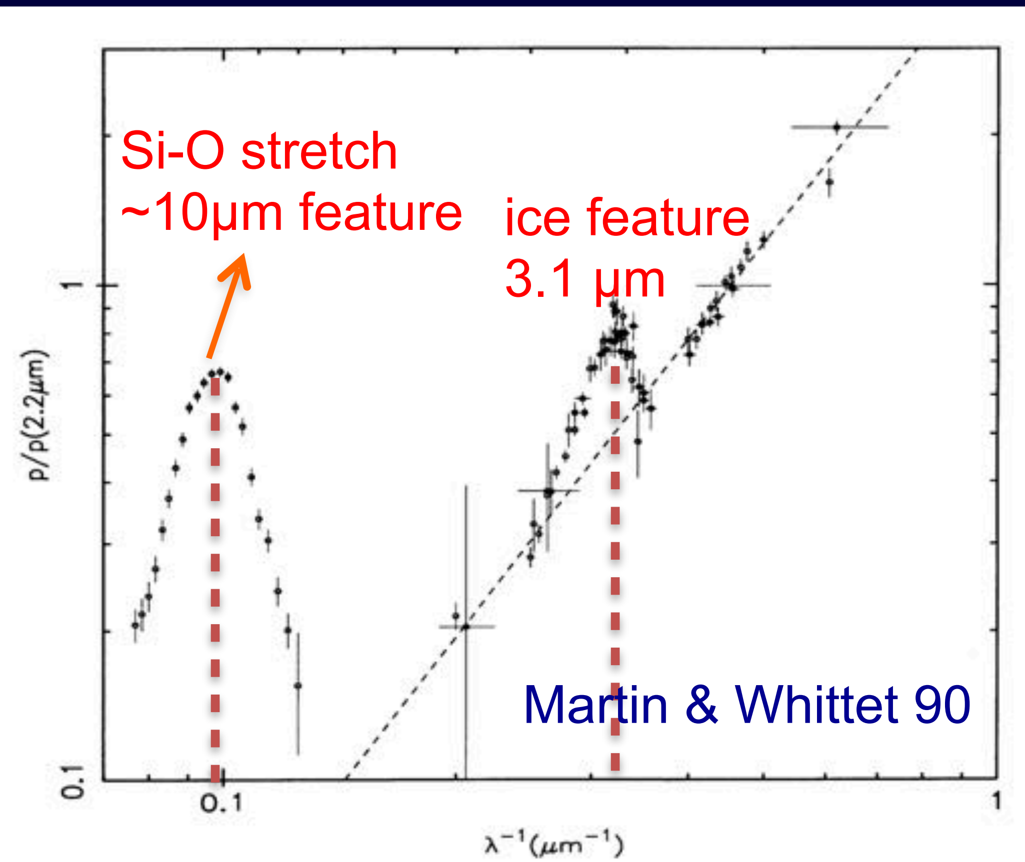
Polarized Emission by *Planck*

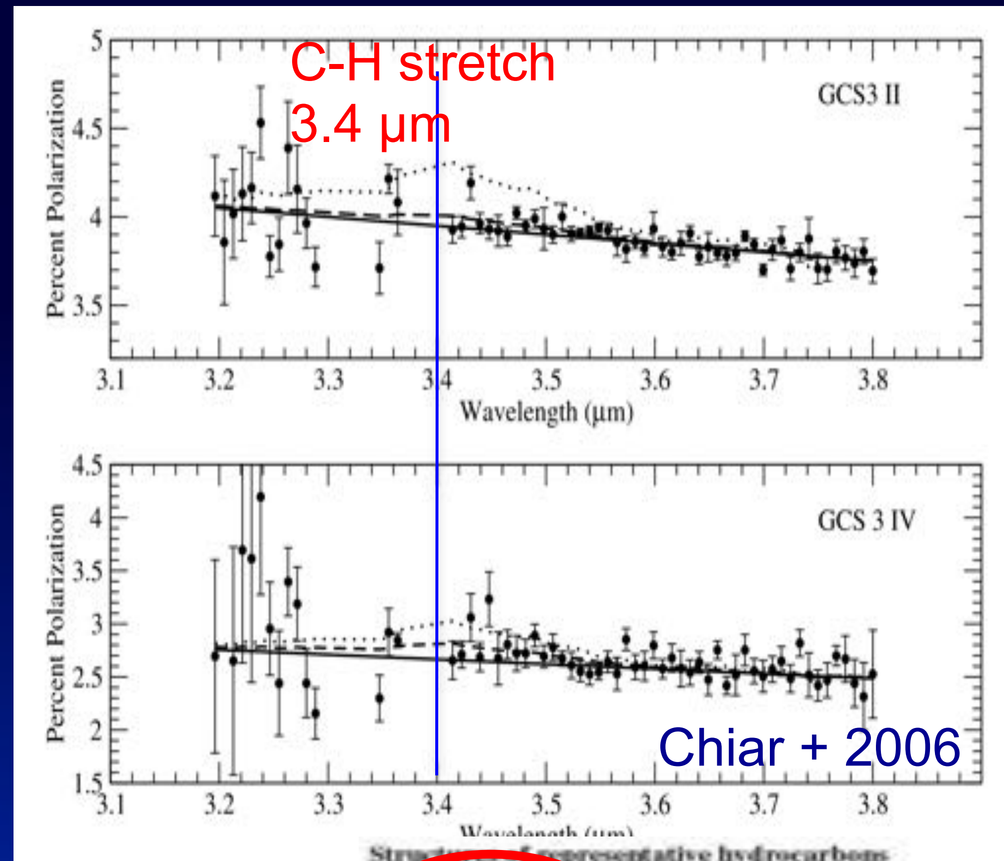






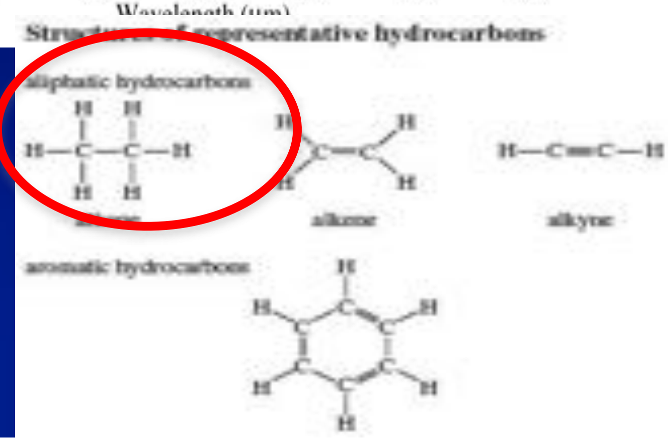
Polarization of Spectral Features: Silicate and Carbonaceous Dust



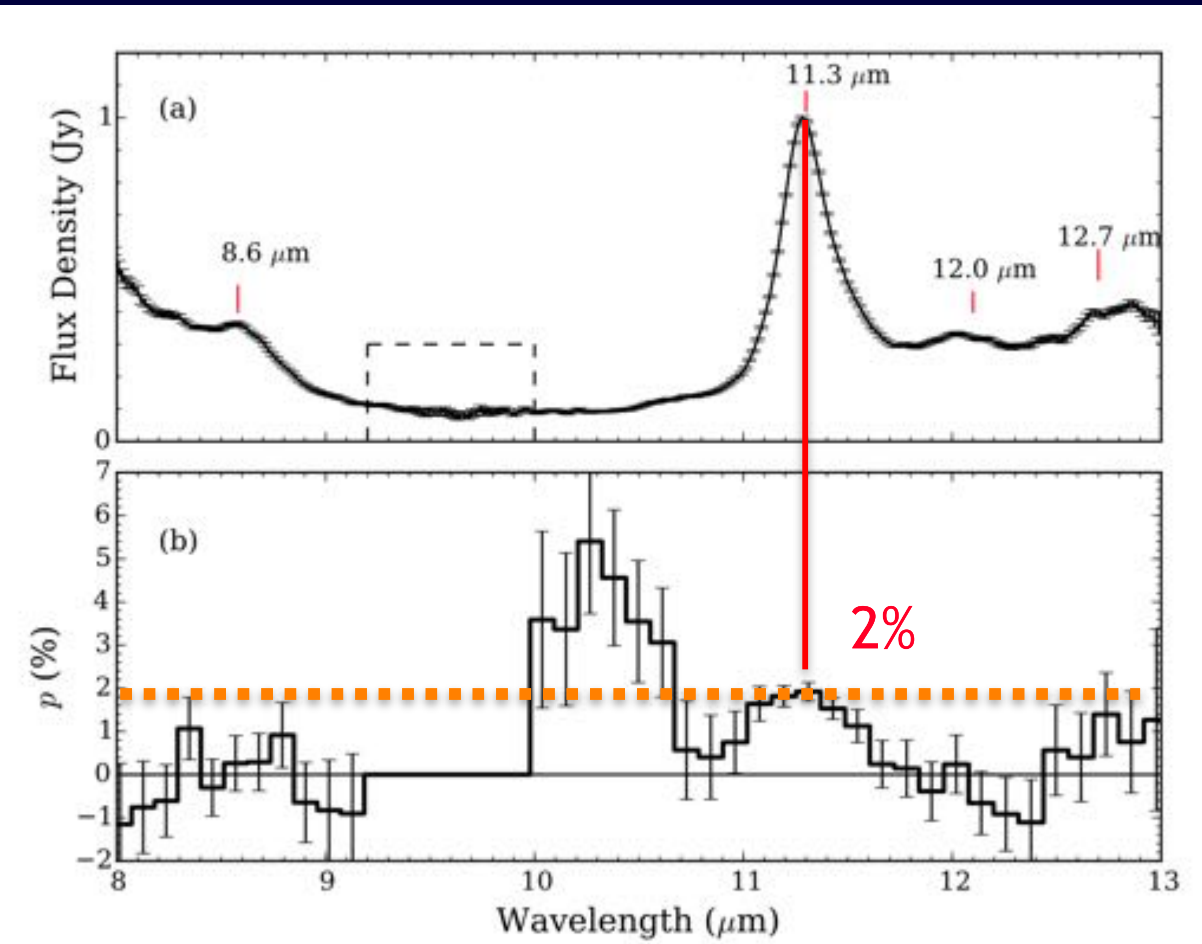


Amorphous silicate:
e.g., $MgFeSiO_4$

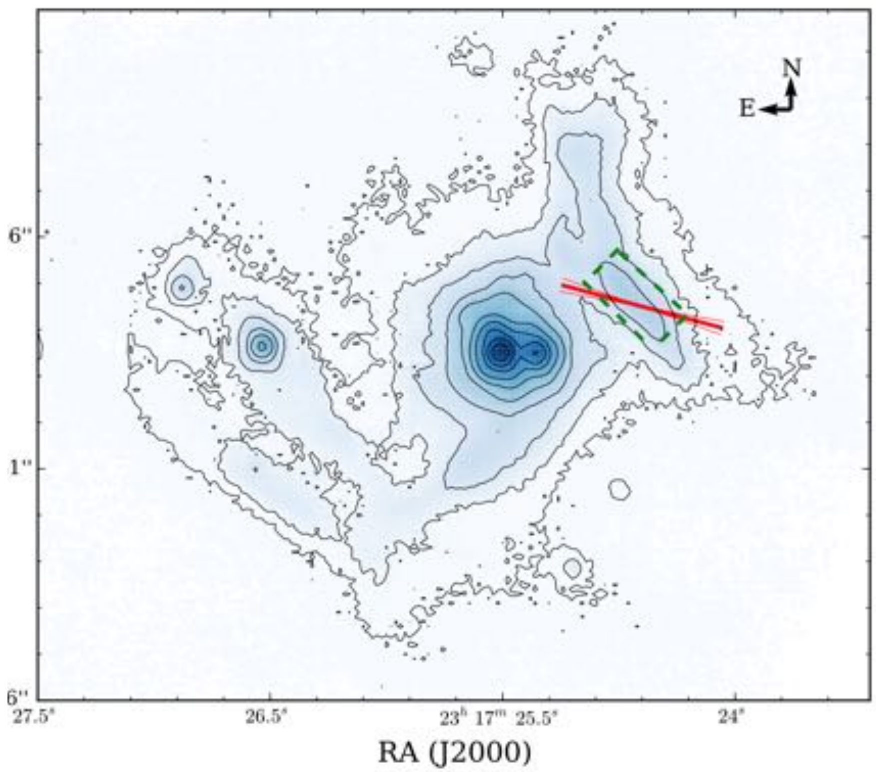
Aliphatic hydrocarbons



First Detection of Polarized PAH Feature



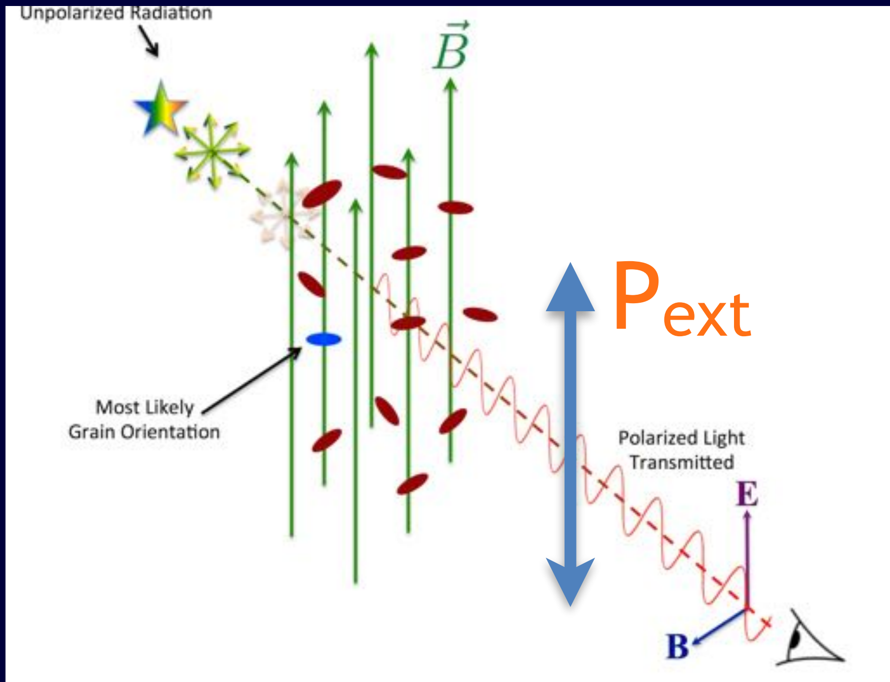
Out-of-plane (C-H) mode: 11.3um

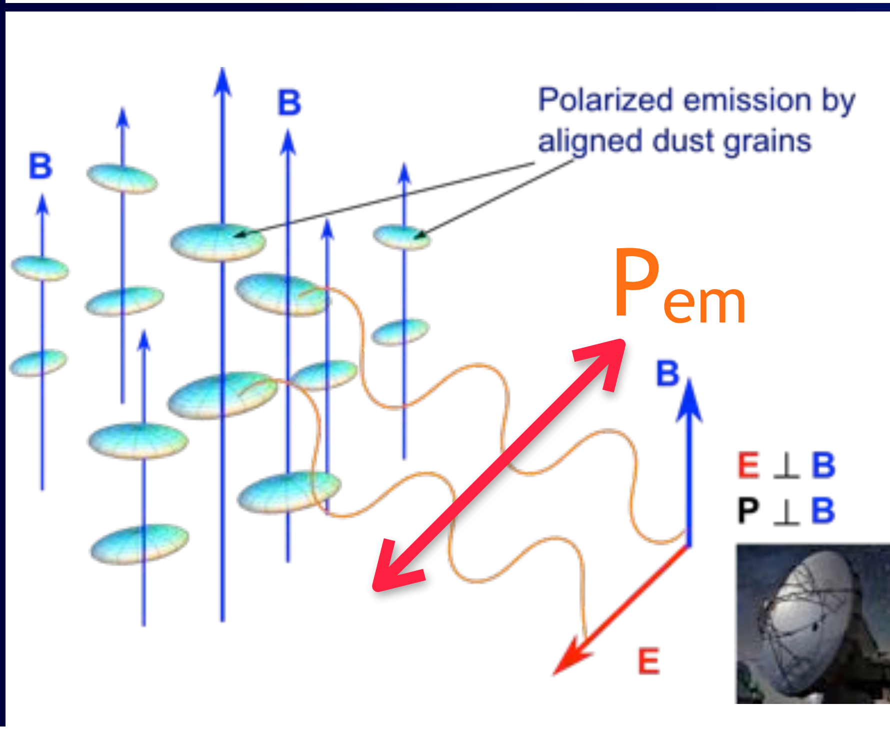


Han, Telesco, Hoang, Pantin, et al. (2017) Using CanariCam/GTC telescope

Theoretical Predictions by Hoang (2017b)

How dust produce polarization?





- Polarization depends on grain alignment degree & grain elongation

70-Year History of Grain Alignment Theory

1949: Discovery of starlight polarization (Hall 1949, Hilner 1949)

1949: **L Spitzer** & Turkey: Ferromagnetic alignment (grains as compass needle)

1951: Davis & Greenstein: Paramagnetic Relaxation. Text book!!!

1951: T. Gold: Mechanic torque alignment based stochastic collisions

1976: Dolginov & Mitrophanov: Radiative torques (RATs) caused by photon angular momentum

1979: **E. Purcell**: Pinwheel torques+ paramagnetic relaxation

1986: J Mathis: Superparamagnetic relaxation (grains with iron inclusion)

1997: Lazarian & Draine: thermal flipping and trapping

1996-2003: Draine & Weingartner: numerical study of RATs, empirical

2007- present: Lazarian & Hoang, Hoang & Lazarian

Analytical Model of RATs and Era of Quantitative Polarimetry

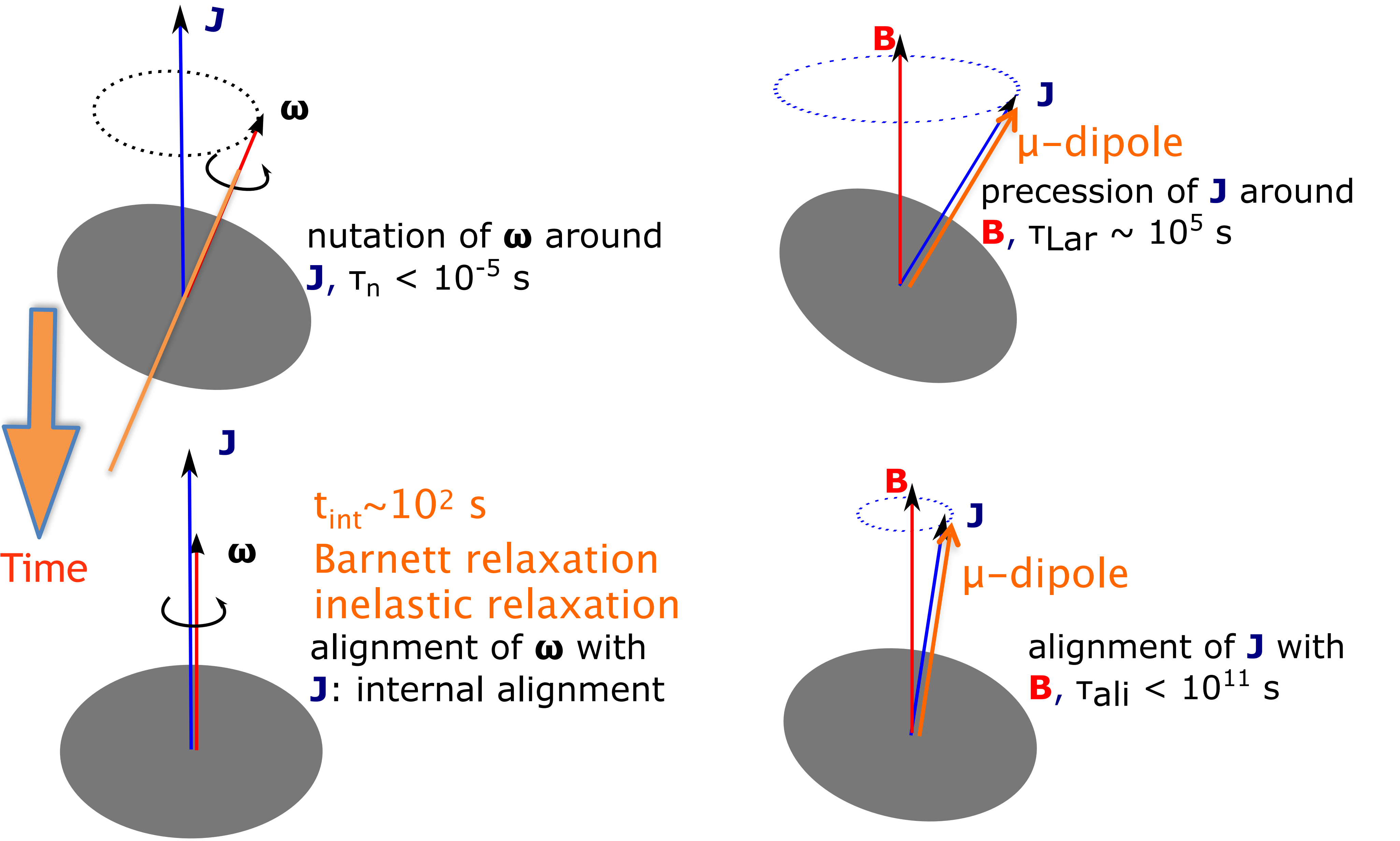
2016: Hoang & Lazarian: a unified theory of grain alignment

2018: Mechanical torque (MAT) alignment (Hoang, Lazarian, Cho 2018)

Internal and External Alignment

Stage 1: ω aligned with J

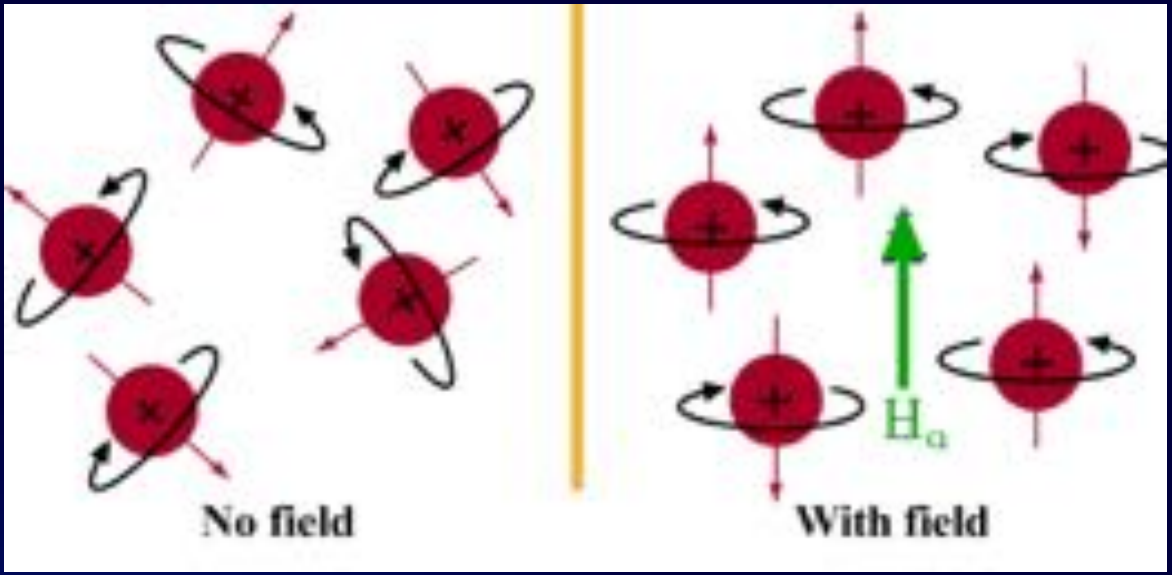
Stage 2: J gets aligned with B



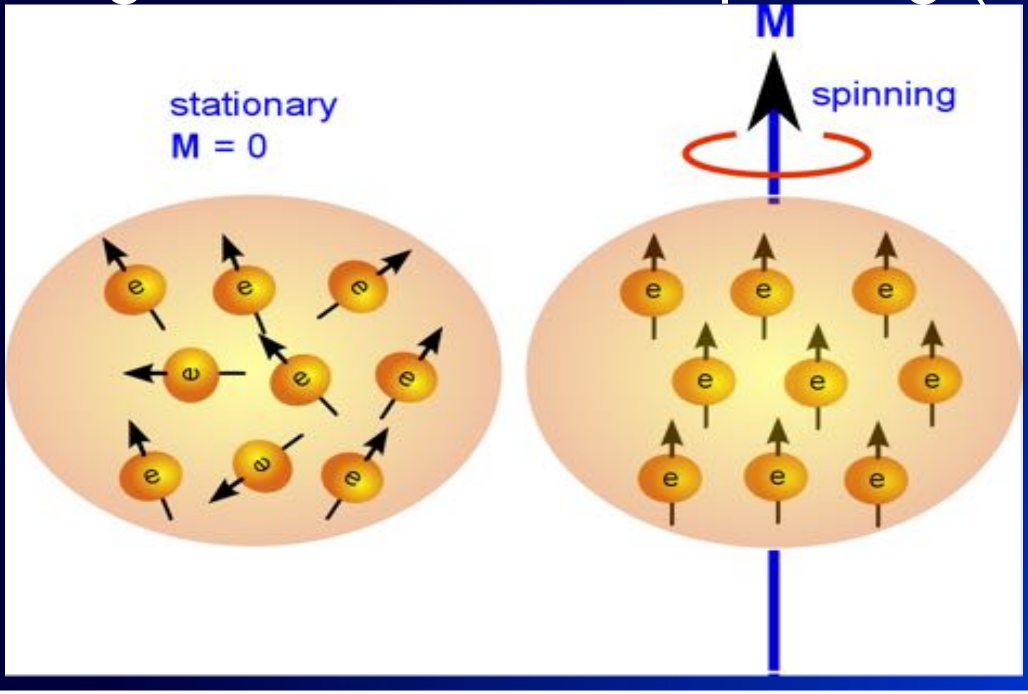
How dust grains interact with B-field?

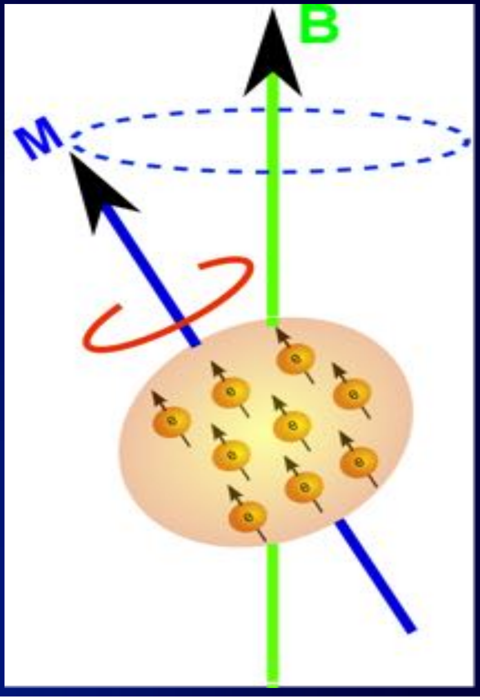
Paramagnetic grain

Magnetization by external field



Magnetization due to spinning (Barnett effect): more efficient

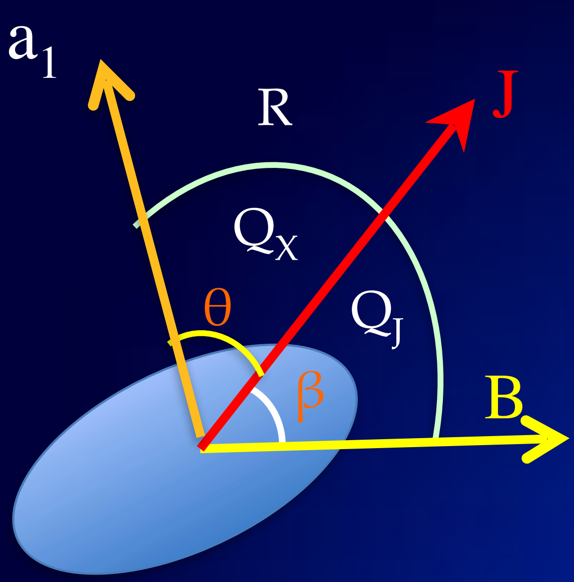


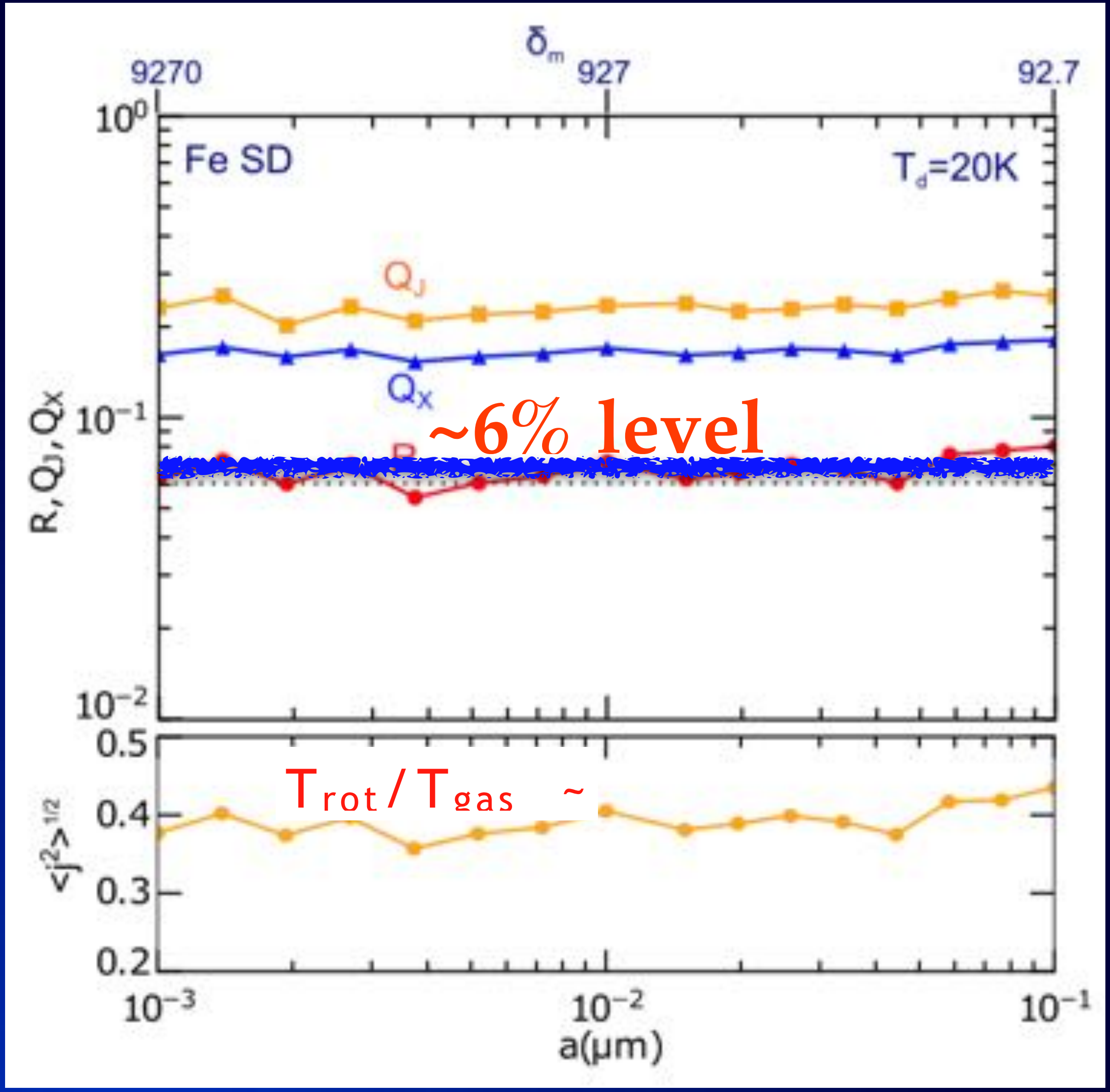


Paramagnetic Relaxation: Textbook Mechanism is not efficient

Davis & Greenstein (1951)

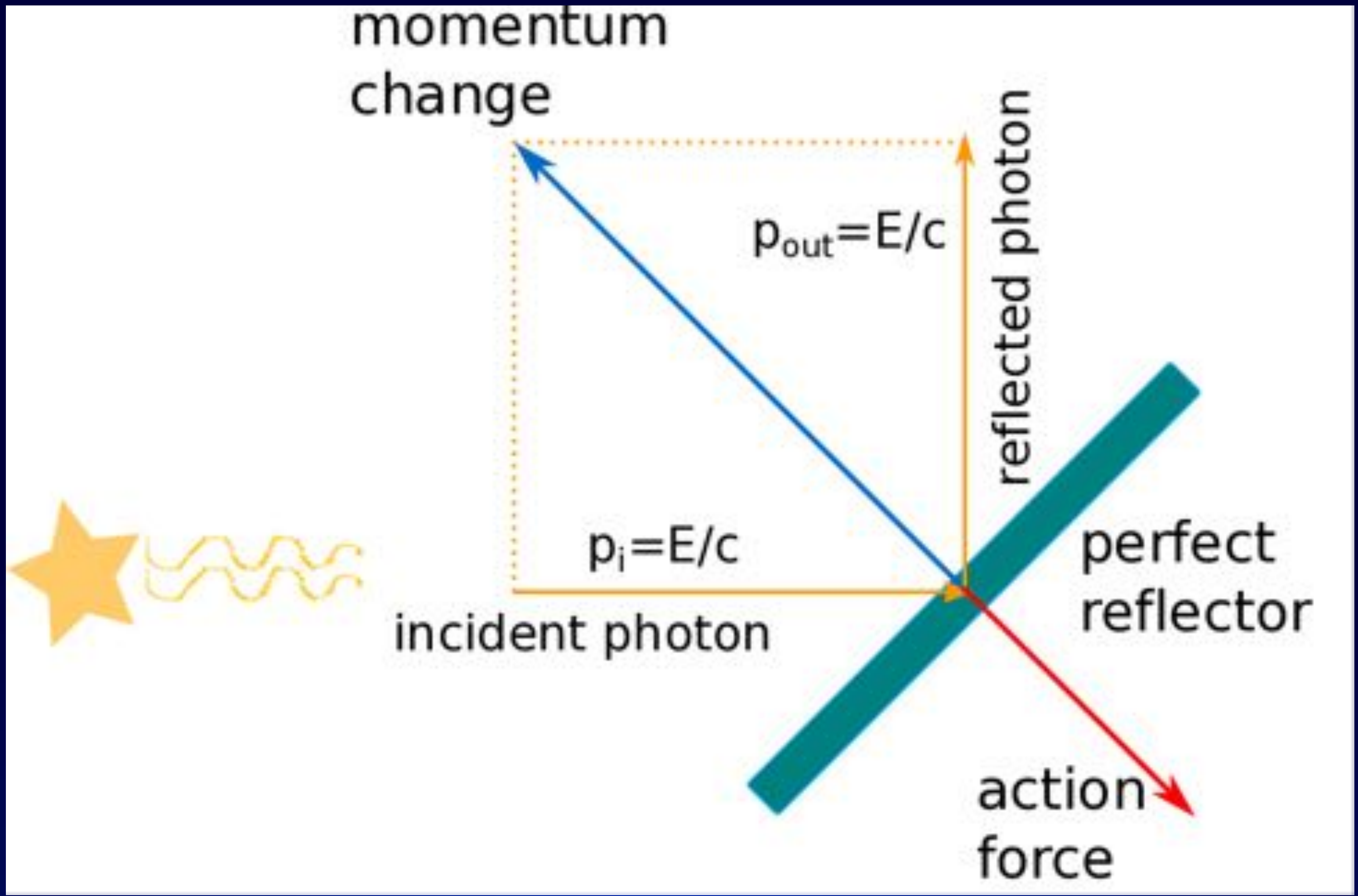
- Grains are paramagnetic
- Relaxation induces gradual alignment with B-field





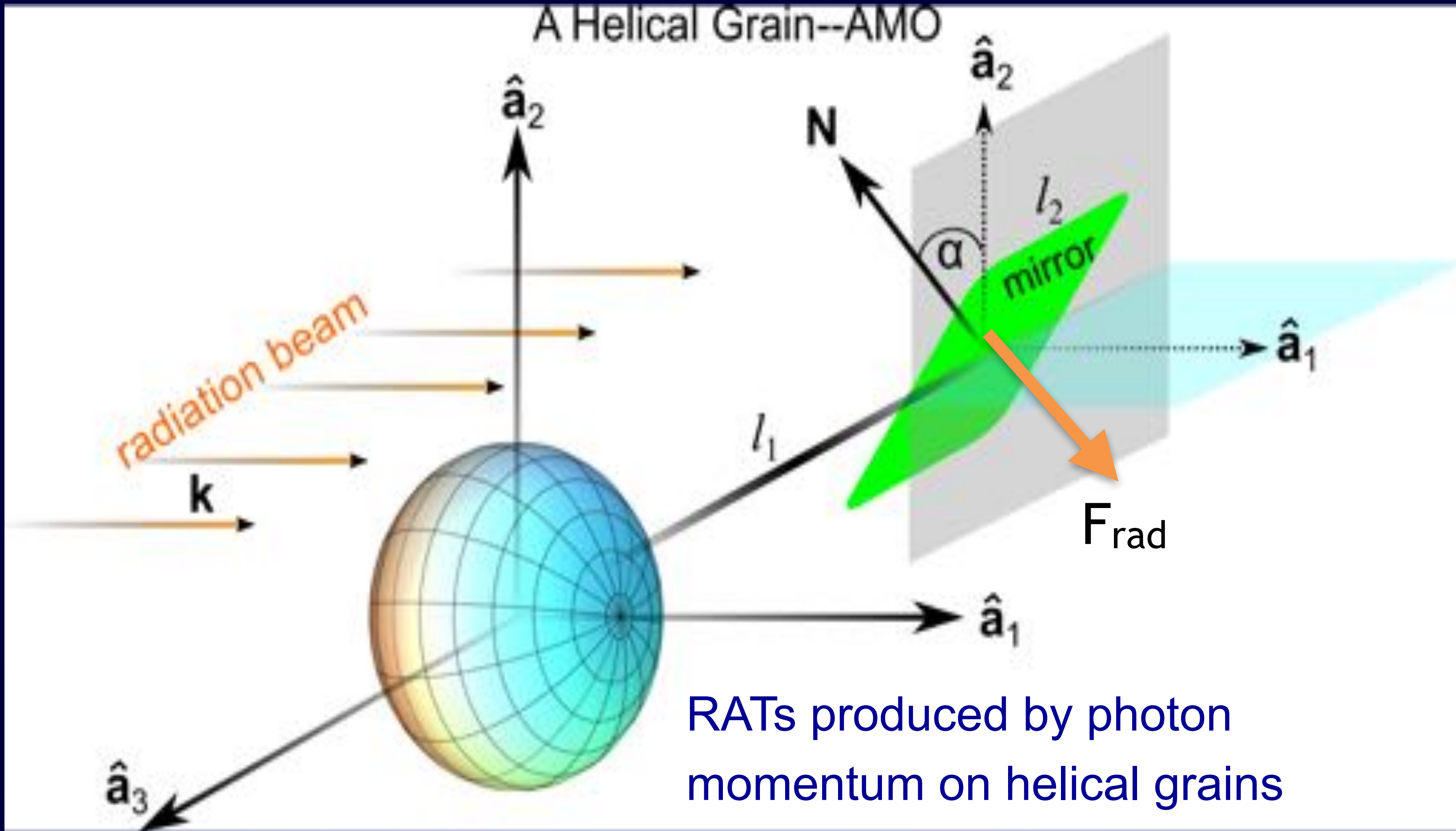
Hoang & Lazarian (2016)

Radiative Torque (RAT) Alignment Mechanism



Lazarian & Hoang (2007ab)
Hoang & Lazarian (2008, 2009ab, 2014, 2016, 2018)

Analytical Model (AMO) of RATs



k *is radiation beam direction*,

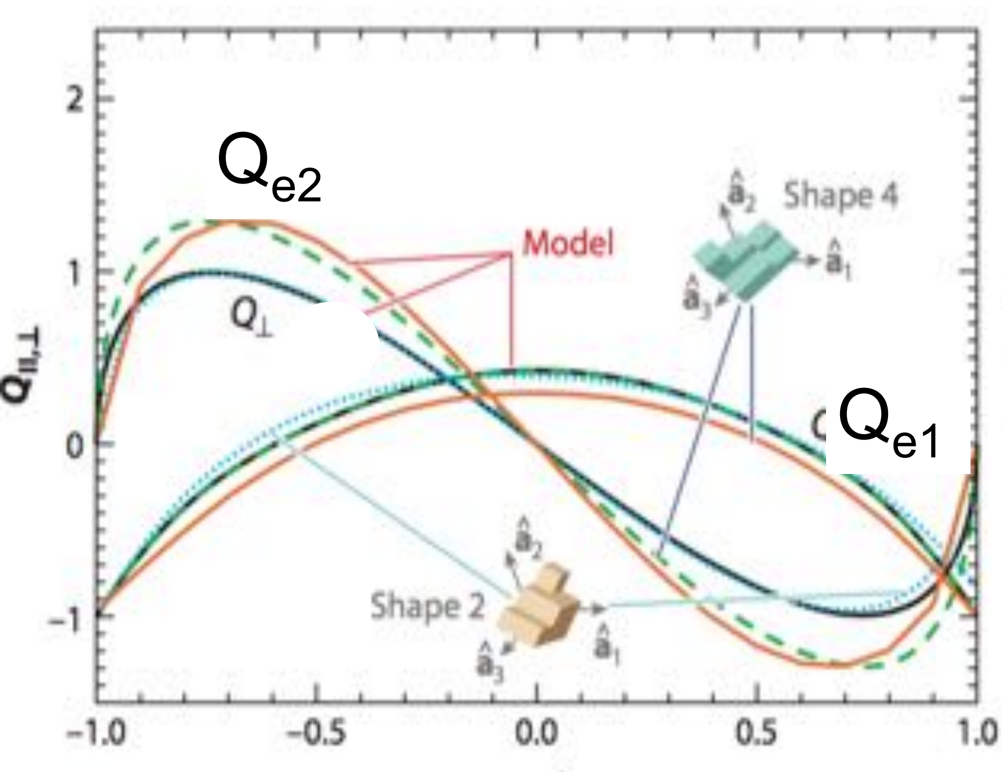
a_1 *is grain maximum inertia axis,* a_2a_3 *grain principal axes*

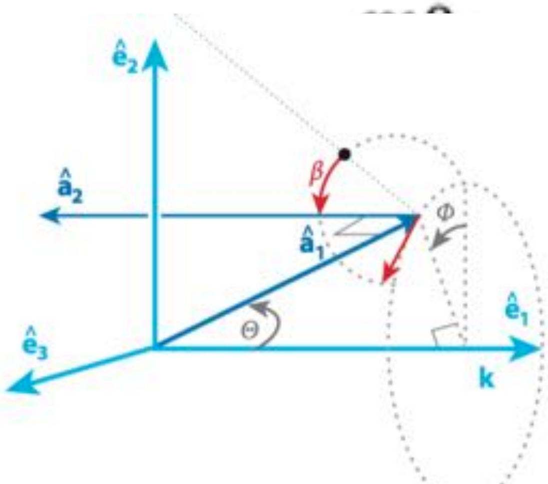
N*, normal vector of mirror, lies in* a_1a_2 mirror plane tilted by angle α with a_2a_3

Lazarian & Hoang (2007a)

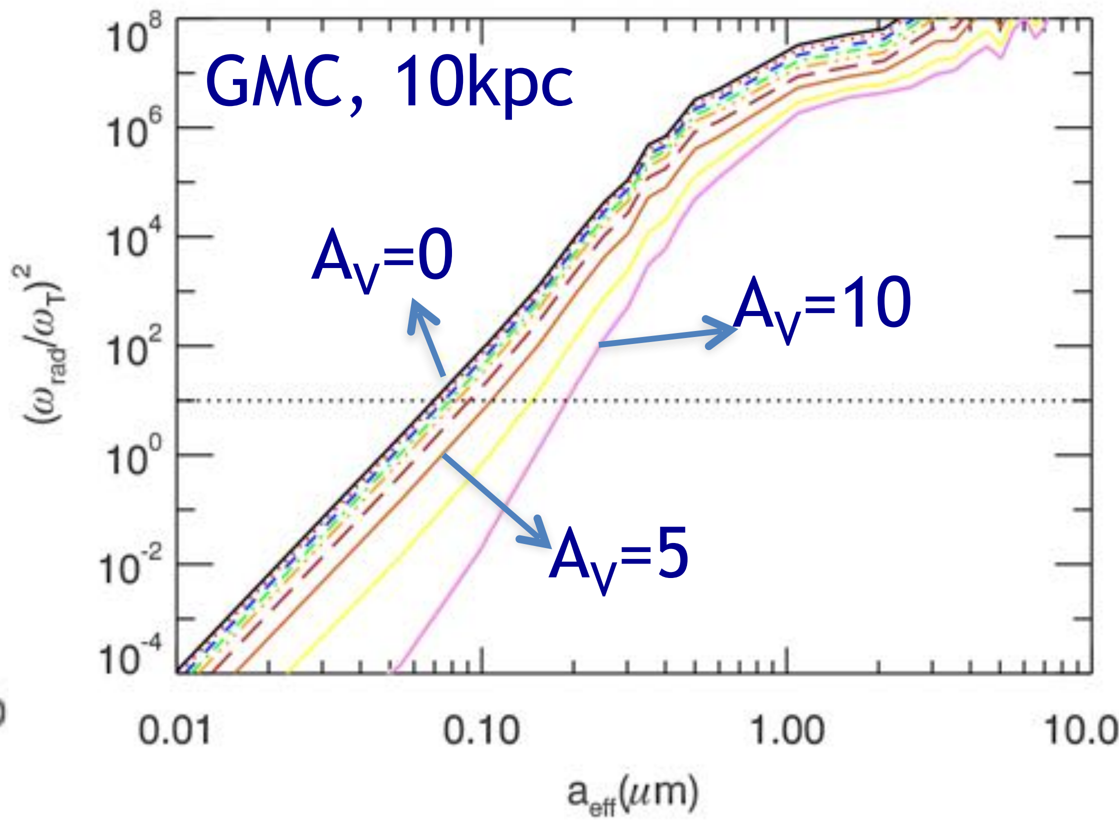
Analytical Model (AMO) of RATs

RATs from AMO vs. DDSCAT





Suprathermal rotation by RATs



Lazarian & Hoang 2007a

Hoang & Lazarian 2008

Testing of a One-Bladed 30-Meter-Diameter Mod-O

-BLADED N88-19014
NASA
ASA)
CSCL 10B Unclas
G3/44 0129984

SUMMARY

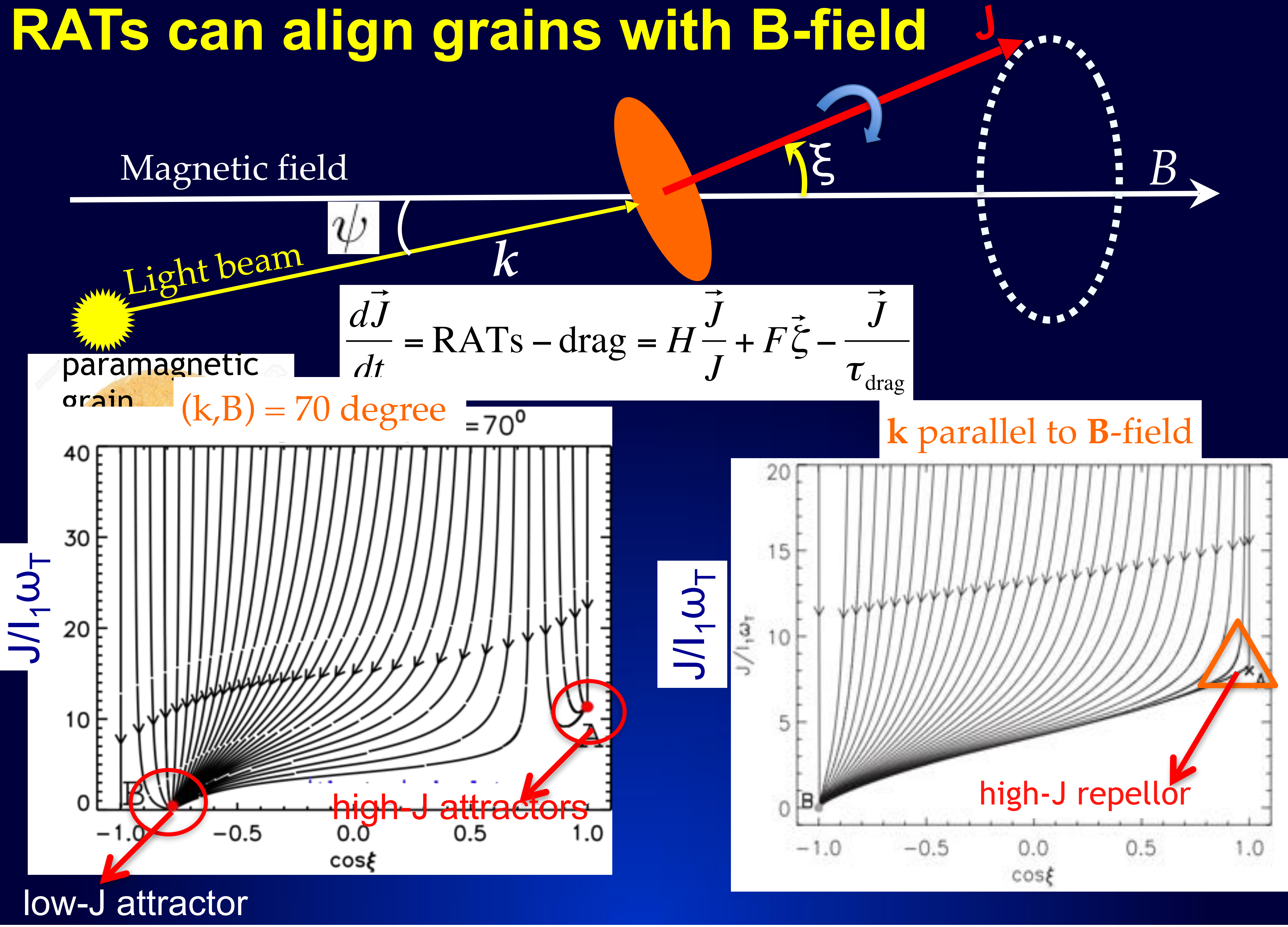
As part of the Federal Wind Energy Program of the Department of Energy, NASA Lewis Research Center conducted tests on the DOE/NASA Mod-0 horizontal-axis wind turbine with a one-bladed rotor configuration. The single blade had an overall length of 15.2 m, and used a pitchable tip that spanned 12 percent of the blade radius. The blade was balanced by a counterweight assembly that consisted of a solid steel ellipsoid supported at an outer radius of 4.6 m by a steel spar. The blade and counterweight assembly were mounted to a teetered hub in a downwind configuration.

The objectives of these tests were to obtain data on the performance, loads, and dynamic characteristics of an intermediate-size, one-bladed rotor. These data, measured at a nominal rotor speed of 49 rpm, were compared with corresponding data for a two-bladed rotor at 33 rpm, having the same blade length and airfoil characteristics. The two-bladed rotor was previously operated on the same machine. The one-bladed and two-bladed rotors used common components wherever possible and did not represent optimized rotor designs.

The results of the one-bladed rotor tests showed that this configuration can be operated successfully. There were no significant dynamic loads with this configuration, and the fatigue loads were comparable to those of a two-bladed rotor. A decrease in power output equivalent to a reduction in wind-speed by 1 m/sec occurred with the one-bladed rotor when compared with the aerodynamically similar two-bladed rotor operating at two-thirds of the rotor speed. Analytical methods for predicting the performance and dynamic characteristics of a one-bladed rotor were verified.

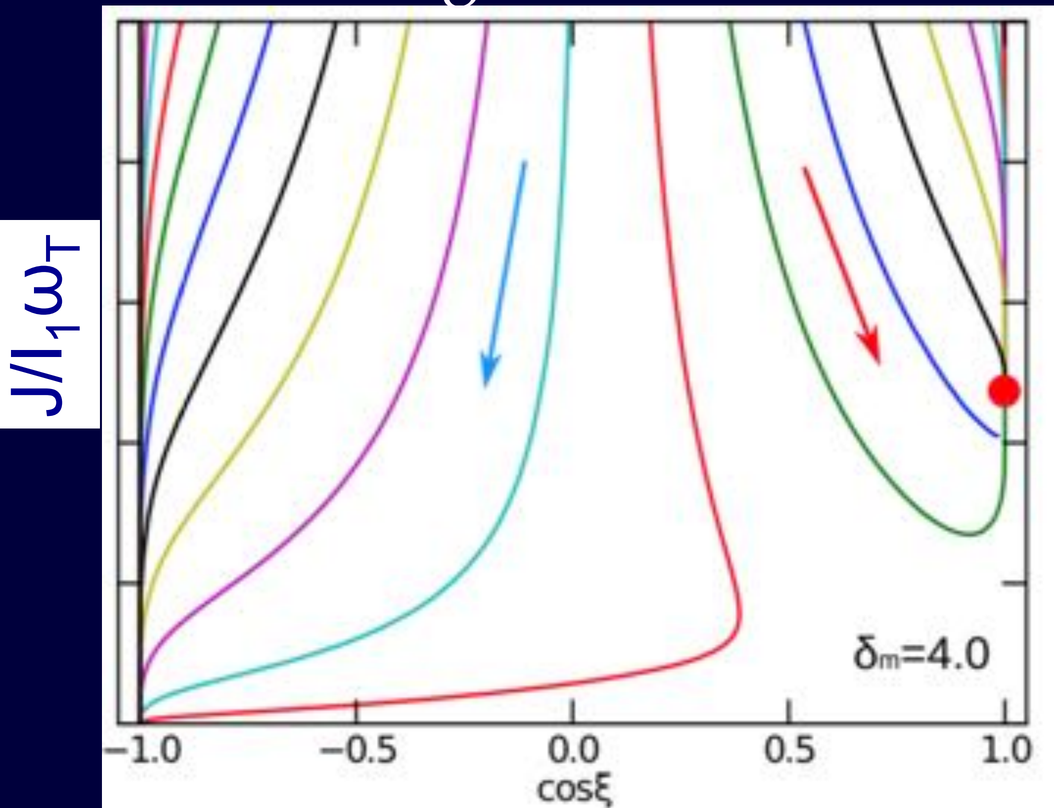
RATs can align grains with B-field

$$\frac{d\vec{J}}{dt} = \text{RATs} - \text{drag} = H\frac{\vec{J}}{J} + F\vec{\xi} - \frac{\vec{J}}{\tau_{\text{drag}}}$$

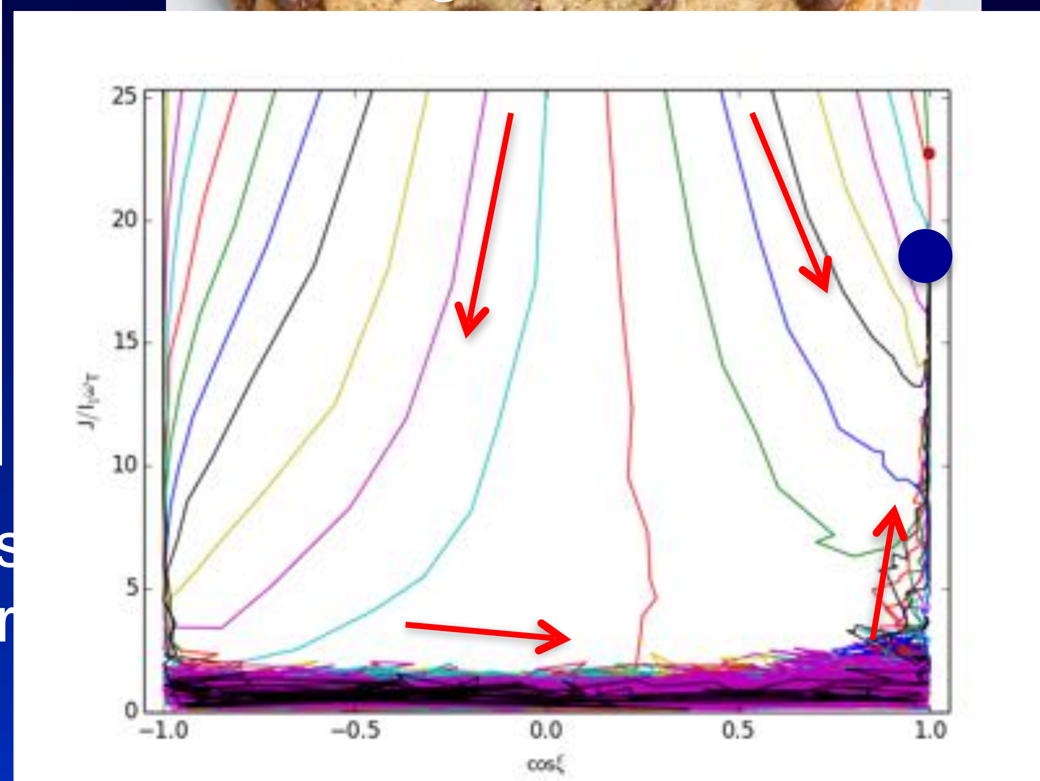


Super-RATs: grains with iron inclusions can be perfectly aligned

SRAT: no gas randomization



SRAT: with gas randomization



- New effect: gas random collisions kick grains out of the low-J attractor
- SRAT alignment can be perfect

Hoang and Lazarian (2008, 2016)

Lazarian & Hoang (2007a)
Hoang & Lazarian (2008, 2009ab, 2014, 2016)

Predictions of RAT Alignment

1. Larger grains are more efficiently aligned than small grains
2. Alignment efficiency increases/decreases with increasing/decreasing the radiation intensity
3. Alignment efficiency decreases with the angle of radiation and B field
4. Grains are aligned with the magnetic field, but can also be aligned with the radiation direction
5. Pinwheel torques (H_2 formation) can enhance grain alignment
6. RAT alignment is perfect for superparamagnetic grains

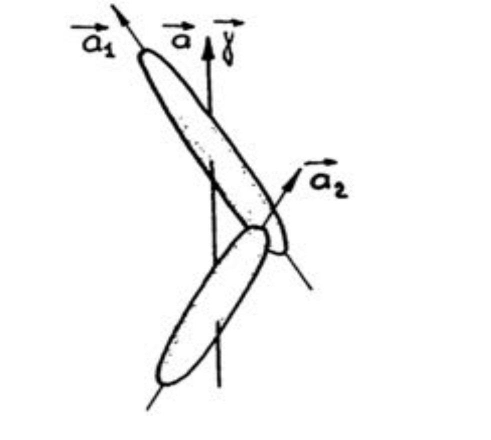
Review by Lazarian, Andersson, & Hoang 2015 for theory

See ARAA by Andersson et al. for observational tests

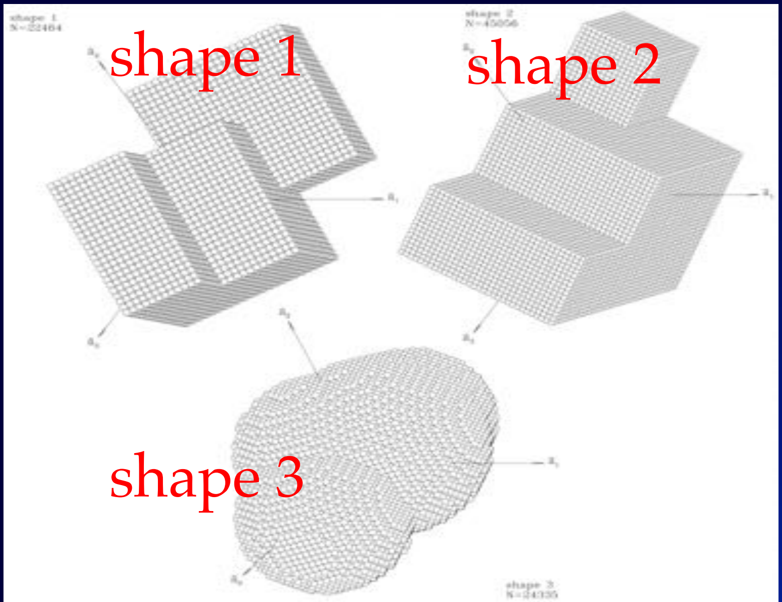
RAT theory implemented in public codes (POLARIS code (Reissl & Bauer)

Other Works on RAT Alignment

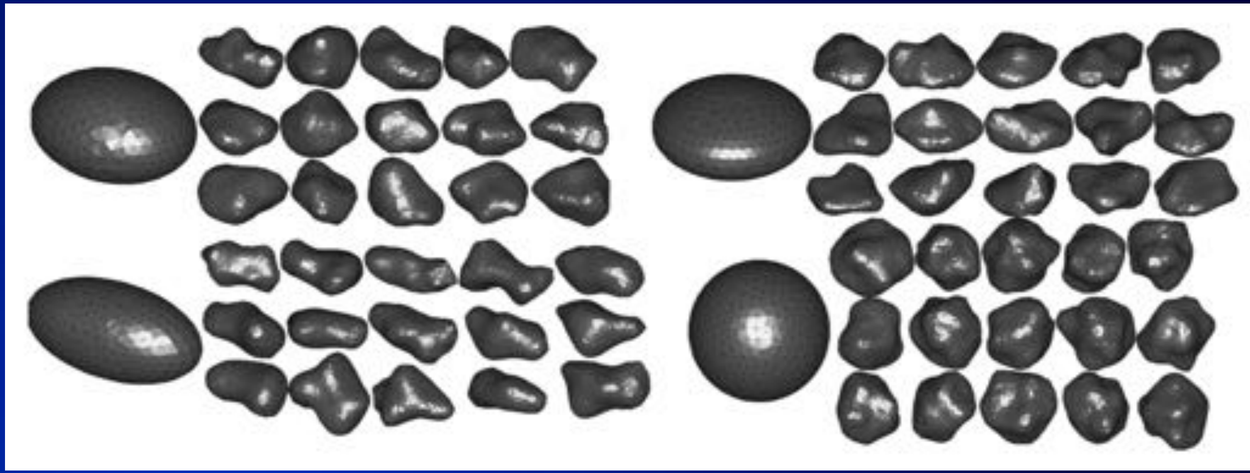
- Dolginov & Mytrophanov (1976):
  - noticed the importance of grain helicity
  - calculated RATs for two twisted spheroids



- Draine & Weingartner (1996, 1997) computed RAT for three grain shapes using Discrete Dipole approximation code (DDSCAT)

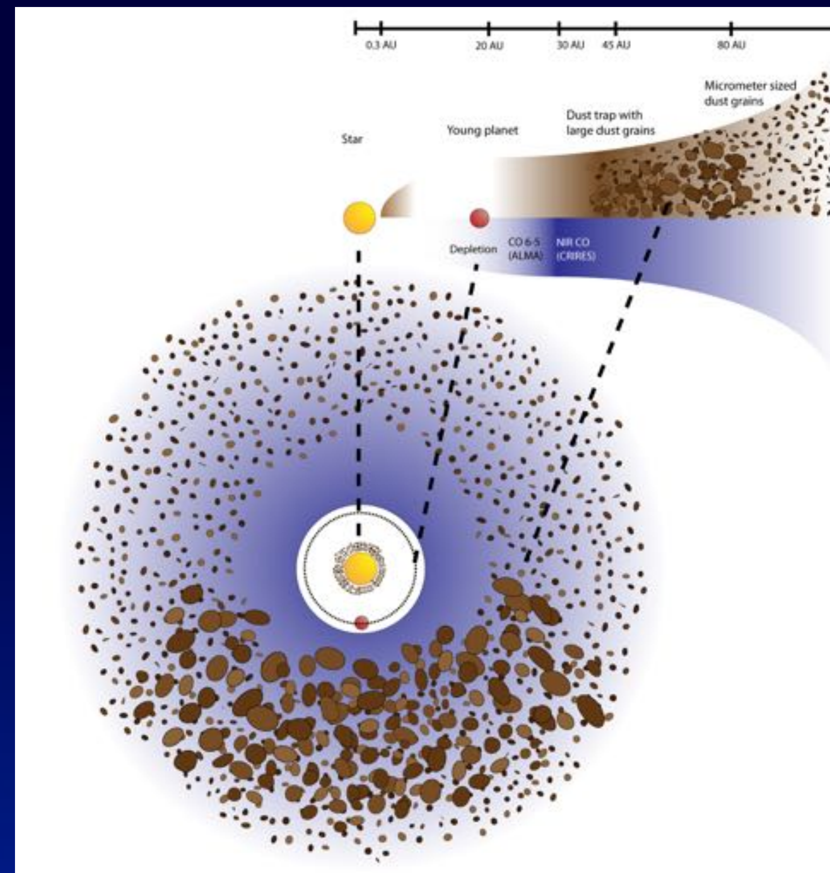


- Herranen, Markkanen & Muinonen (2018) computed RATs for many shapes. RAT alignment demonstrated numerically



Dust Polarization in Circumstellar Disk

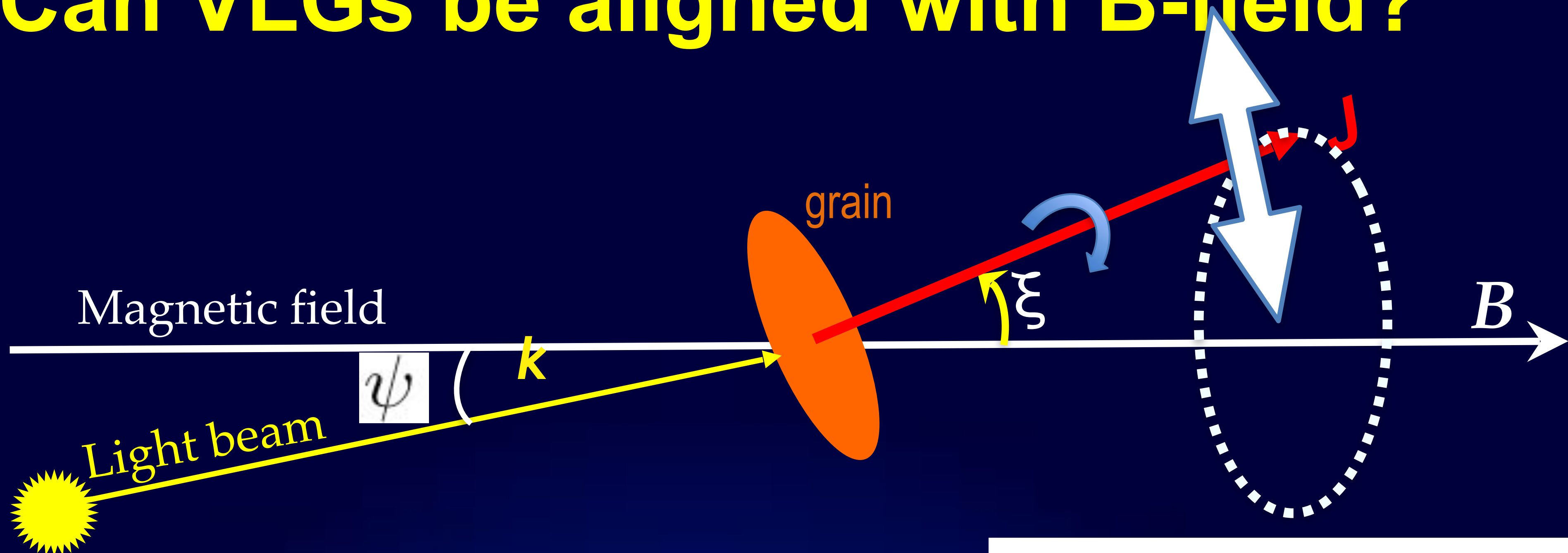
- **Very high gas density**
- **Very large grains (VLGs)**



Polarization Mechanisms

1. Grain alignment with magnetic field (LH 2007, HL08, 09ab)
2. Grain alignment with radiation field (LH07, HL08, Tazaki+17)
3. Self-scattering (Kataoka et al.)

Can VLGs be aligned with B-field?



$$\frac{\tau_{\rm Lar,sup}}{\tau_{\rm gas}} \simeq 22.2 \times 10^{-3} \frac{n_{10} T_2^{1/2} a_{-5} \Gamma_{\parallel}}{N_{\rm cl,5} \phi_{\rm sp,-2} B_3}$$

$$a_1 < 436 \frac{N_{\rm cl,5} \phi_{\rm sp,-2}}{n_{10} T_2^{1/2} B_3 \Gamma_{\parallel}}\ \mu{\rm m},$$

- Paramagnetic grains (N_{cl}=1) cannot be aligned with B-field
- Grains with iron inclusions (N_{cl}>>1) can be aligned with B-field

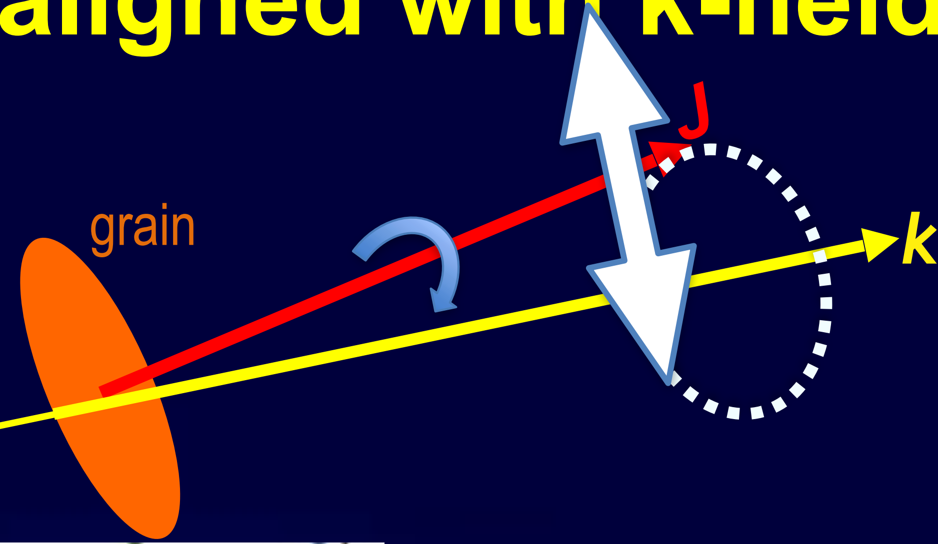
Hoang & Lazarian (2016)

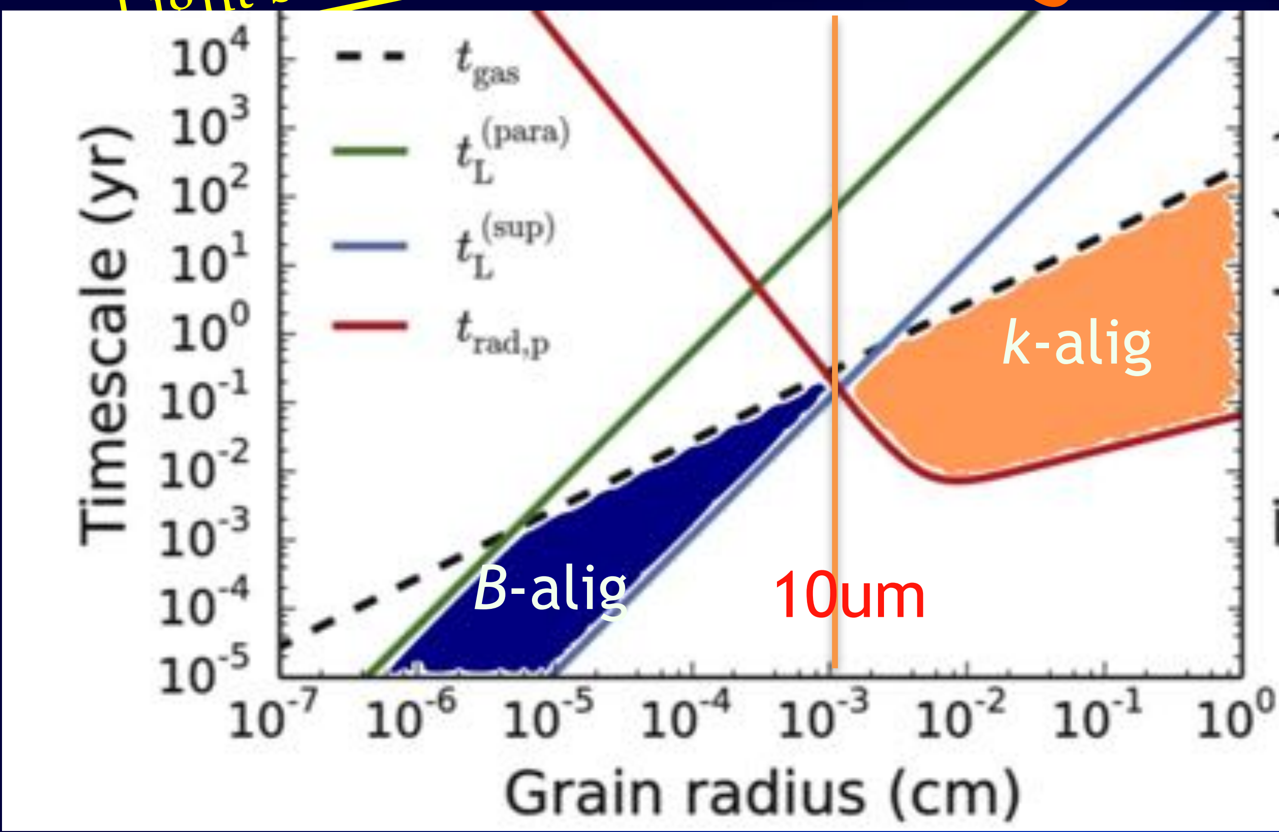
- **Mid-plane Alignment:**
  - a_1 ~ 0.005 μm for N_{cl} ~ 1
  - a_1 ~ 0.5 μm for N_{cl} ~ 100
  - a_1 ~ 50 μm for N_{cl} ~ 10^4

$N_{cl} = 10^4$ ~ 2nm Fe nanoparticle

Can VLGs be aligned with k-field?

Alignment with illumination direction: *k* - RAT align





1. VLGs can be aligned with **k**-field, but not **B**-field
2. Small grains with iron inclusions can be aligned with B-field

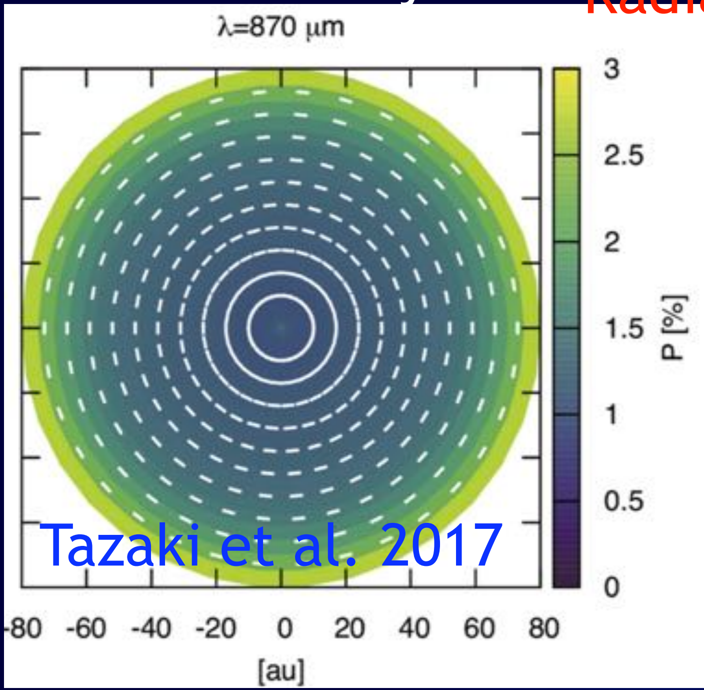
Lazarian & Hoang (2007a)
Hoang & Lazarian (2014, 2016)

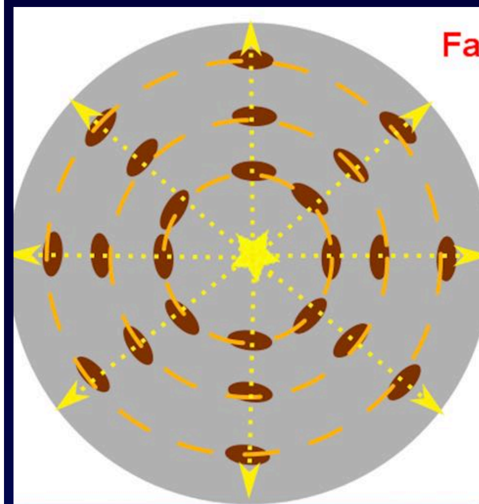
Modified from Tazaki et al. 2017

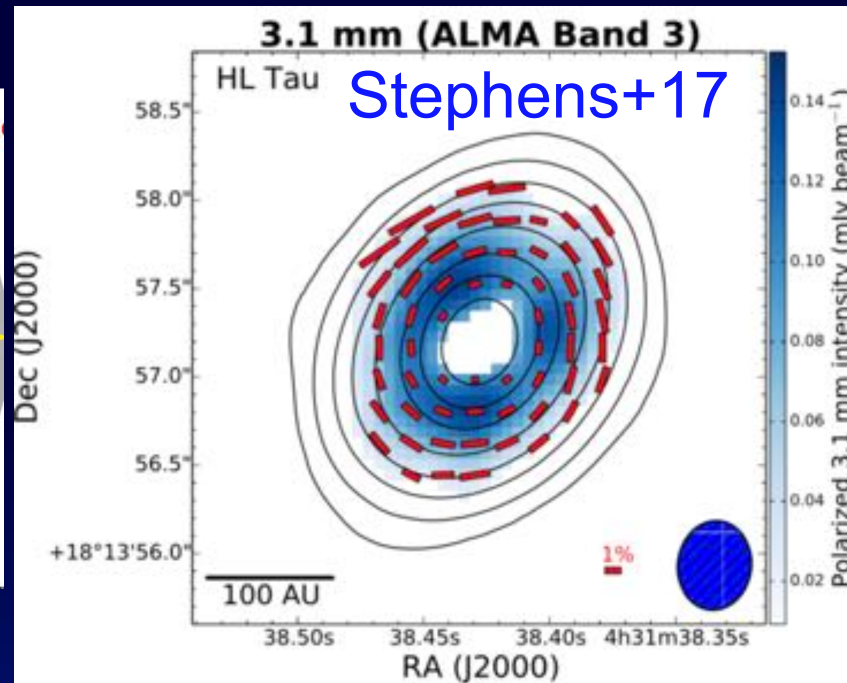
ALMA Polarization from HL Tau

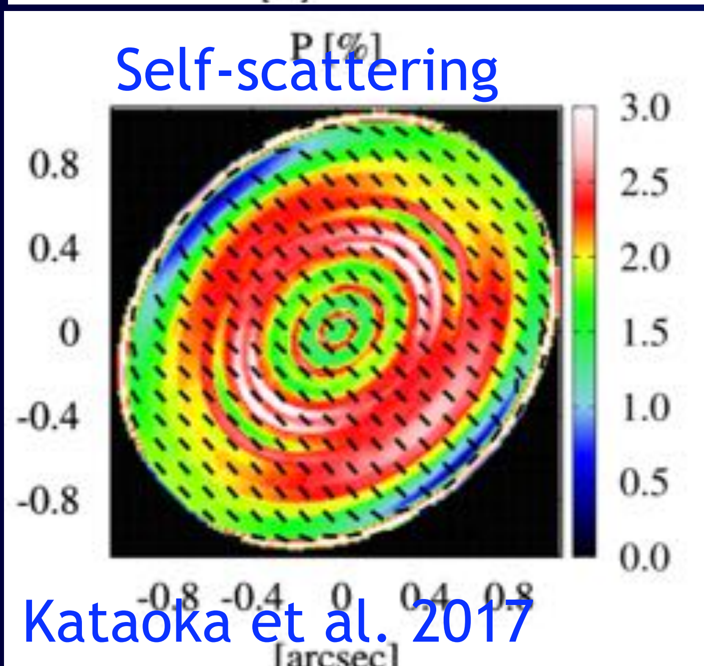
Theory

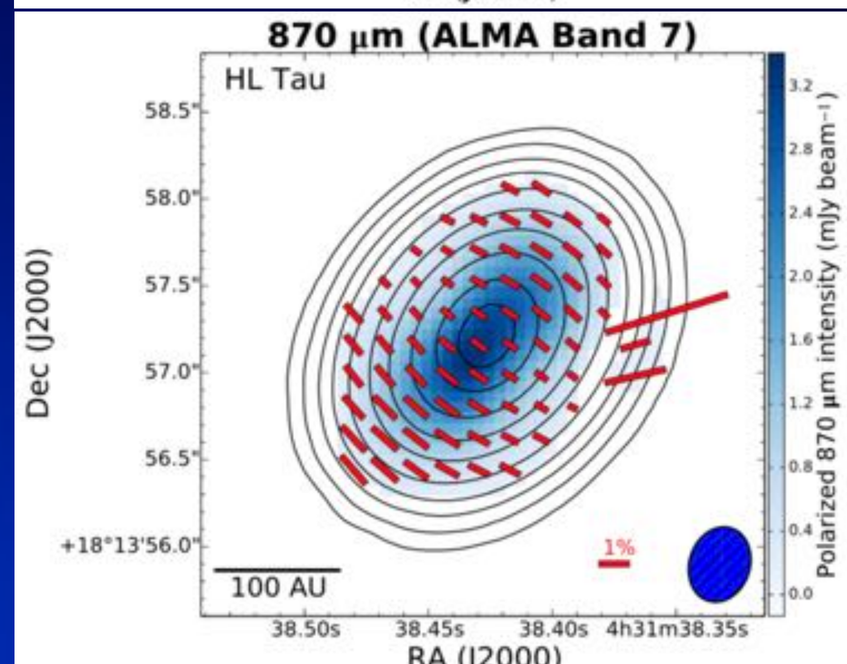
Observations







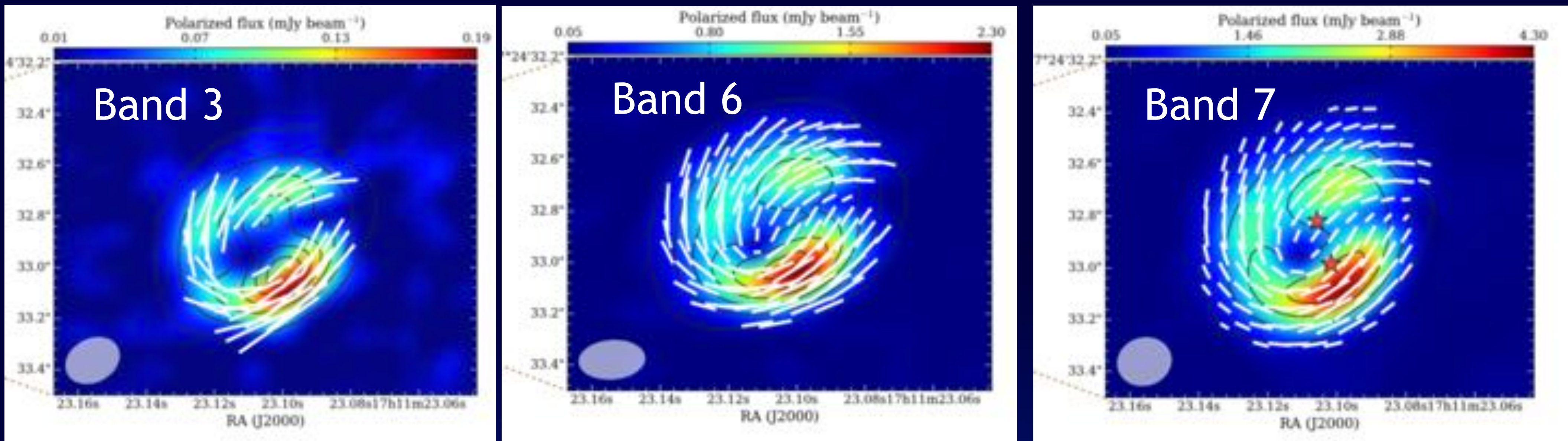




ALMA Polarization from Circumbinary Disk

Alves et al. 2018

Detection of Poloidal Fields?

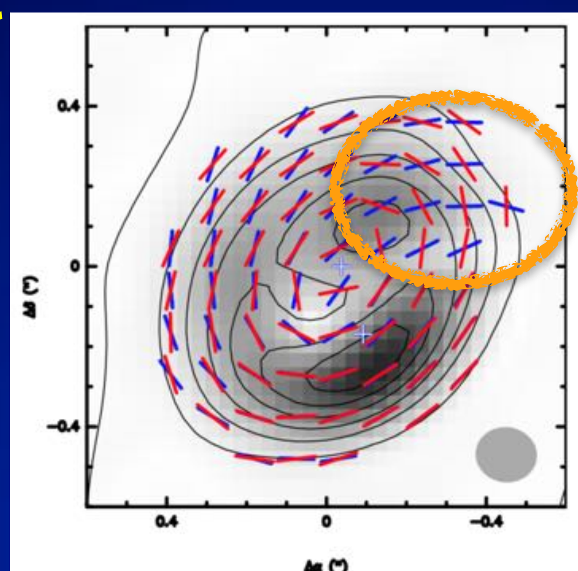


Radiative Alignment

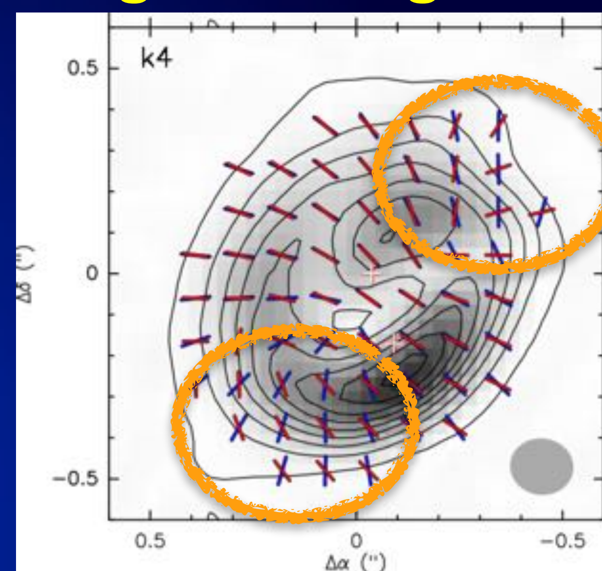
- Polarization pattern does not change with wavelength

See Sadavoy+ 2018,

Hull+2018, Girat+2018

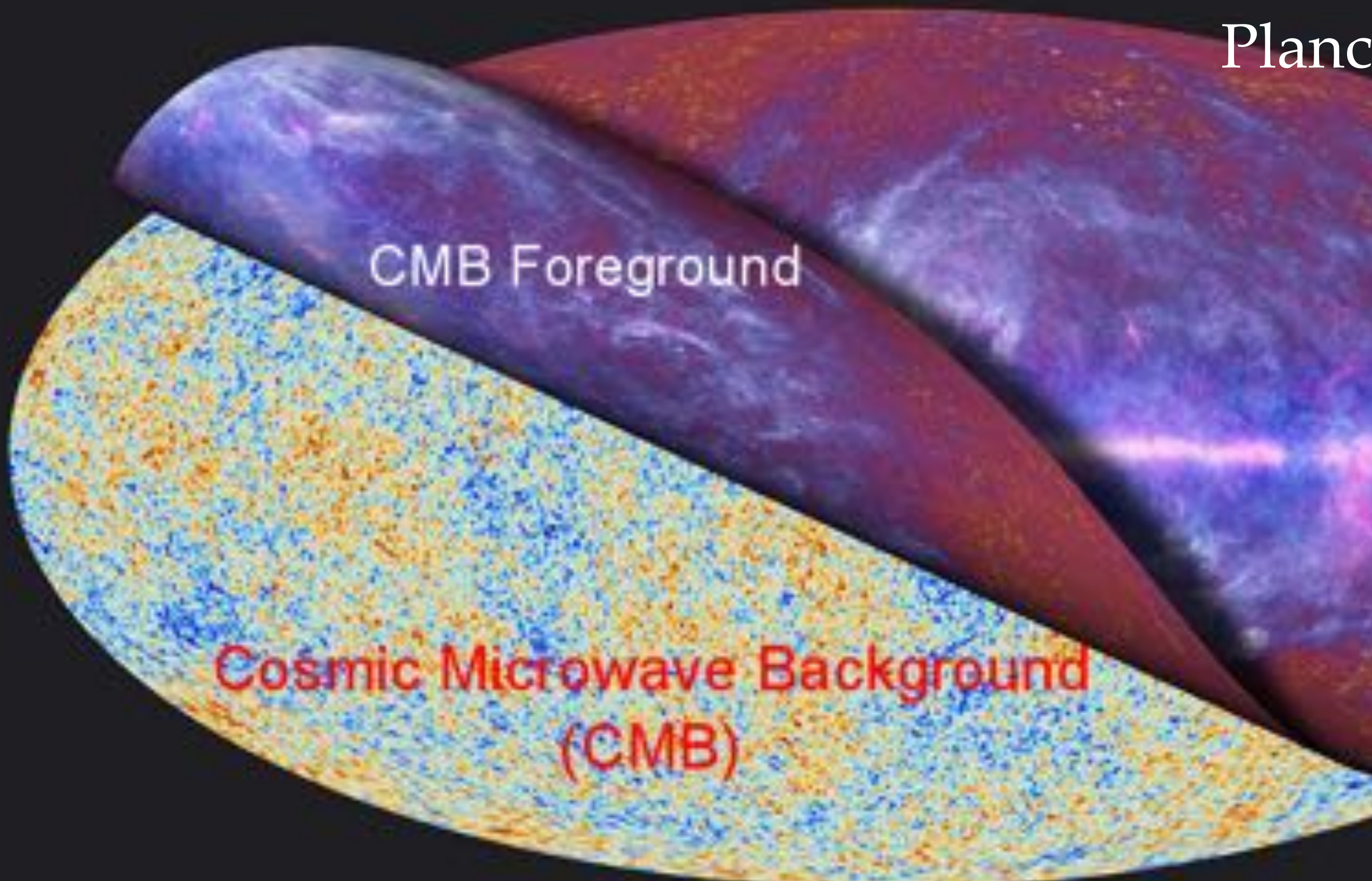


Magnetic Alignment



Anomalous Microwave Emission (AME)

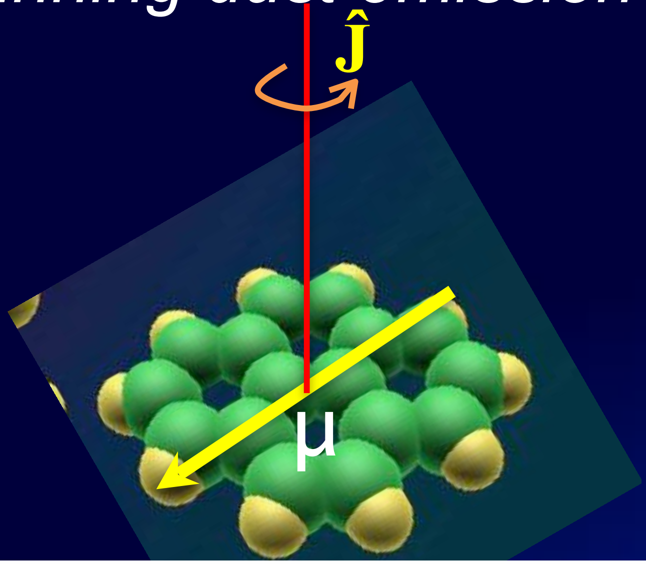
Planck Collaboration

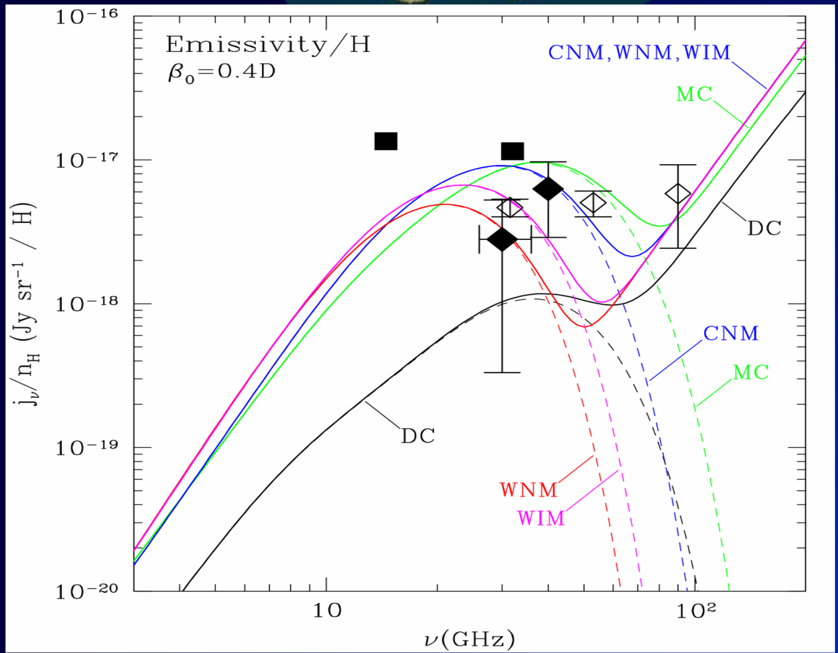


- 1996 Kogut et al. found emission excess at 31 GHz from COBE data
- 1997 Leitch et al. found emission excess at 14.5 & 31GHz (AME intro)

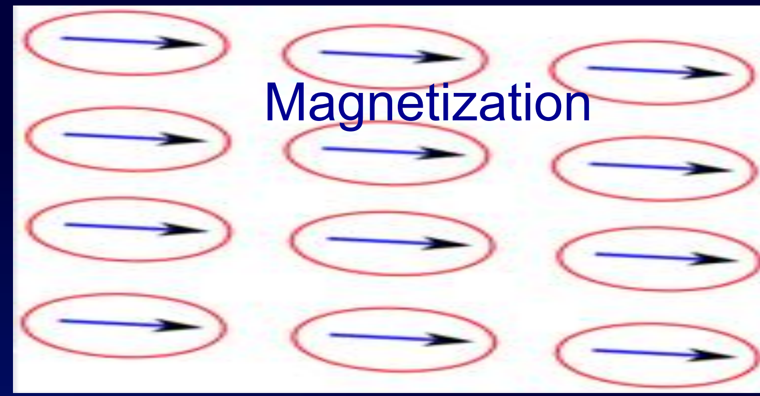
AME Origin

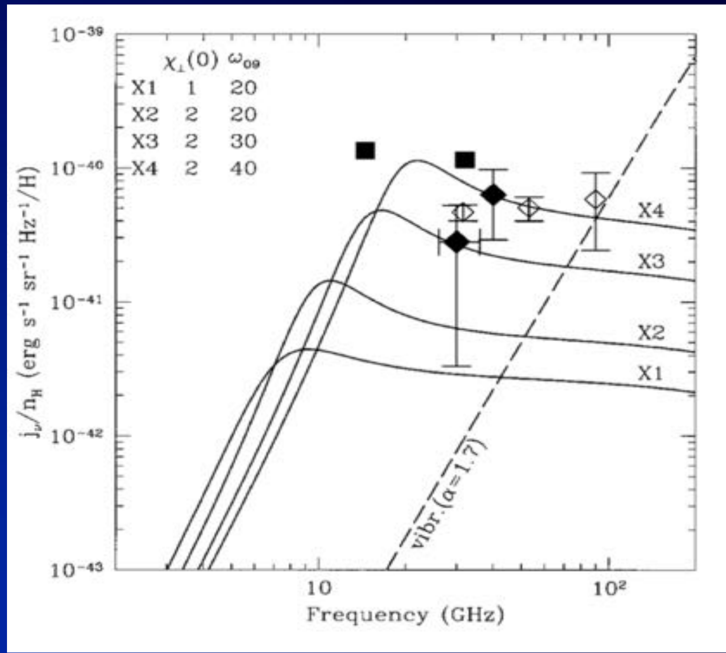
- 1998 Draine and Lazarian: *spinning dust emission*



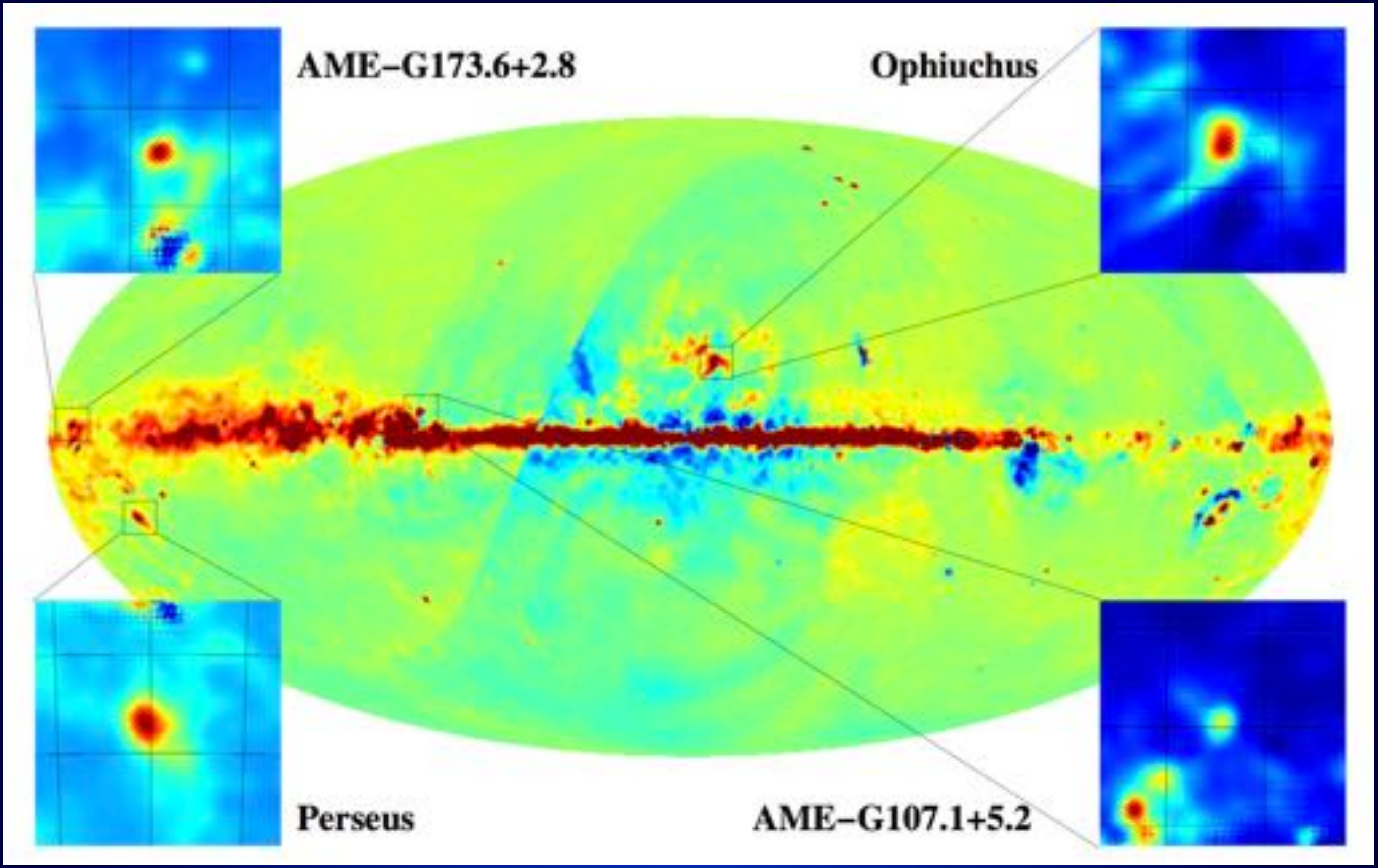


- 1999 Draine and Lazarian: *magnetic dipole emission from iron nanoparticles*



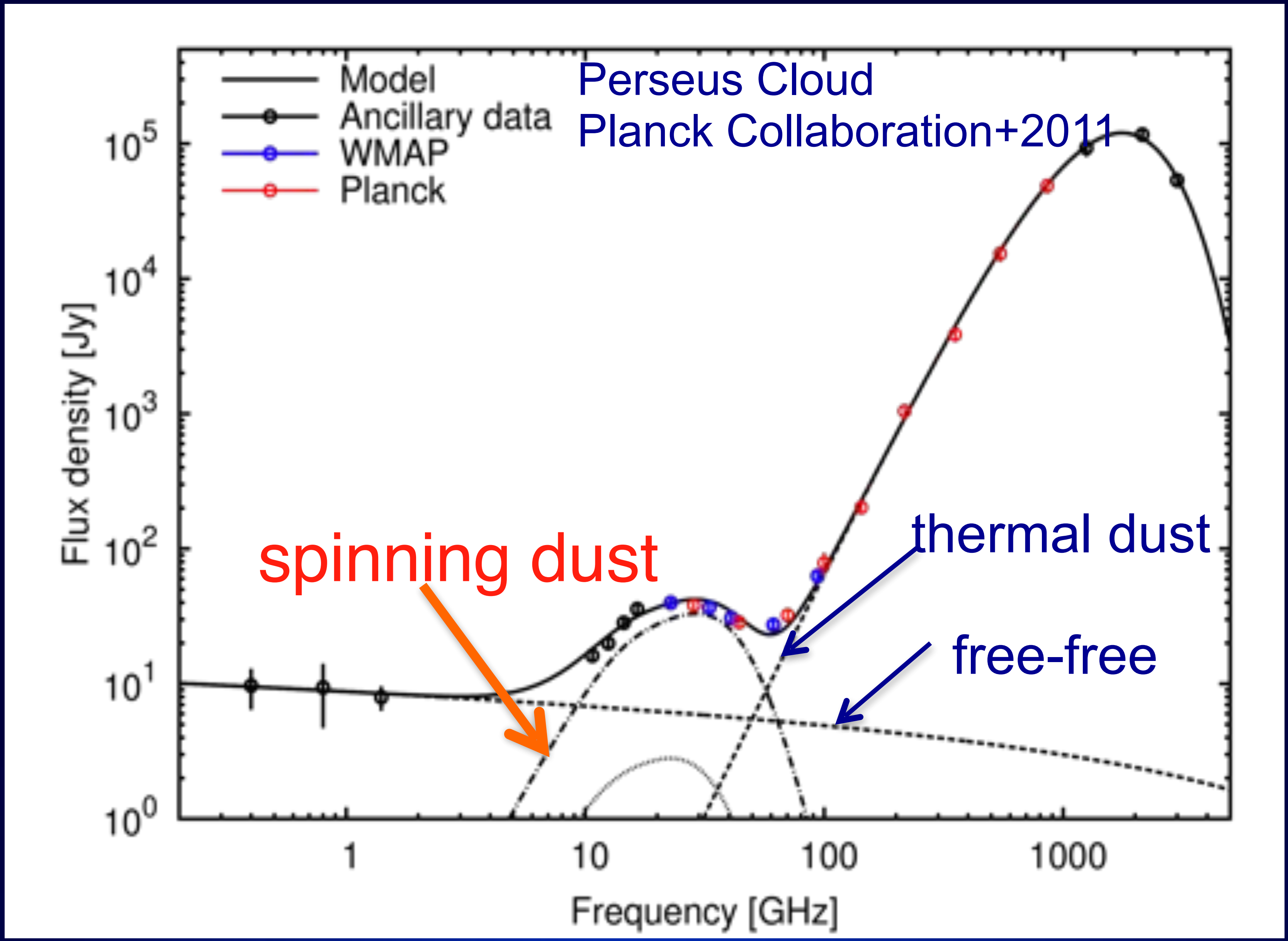


Selected AME regions discovered by Planck 2011

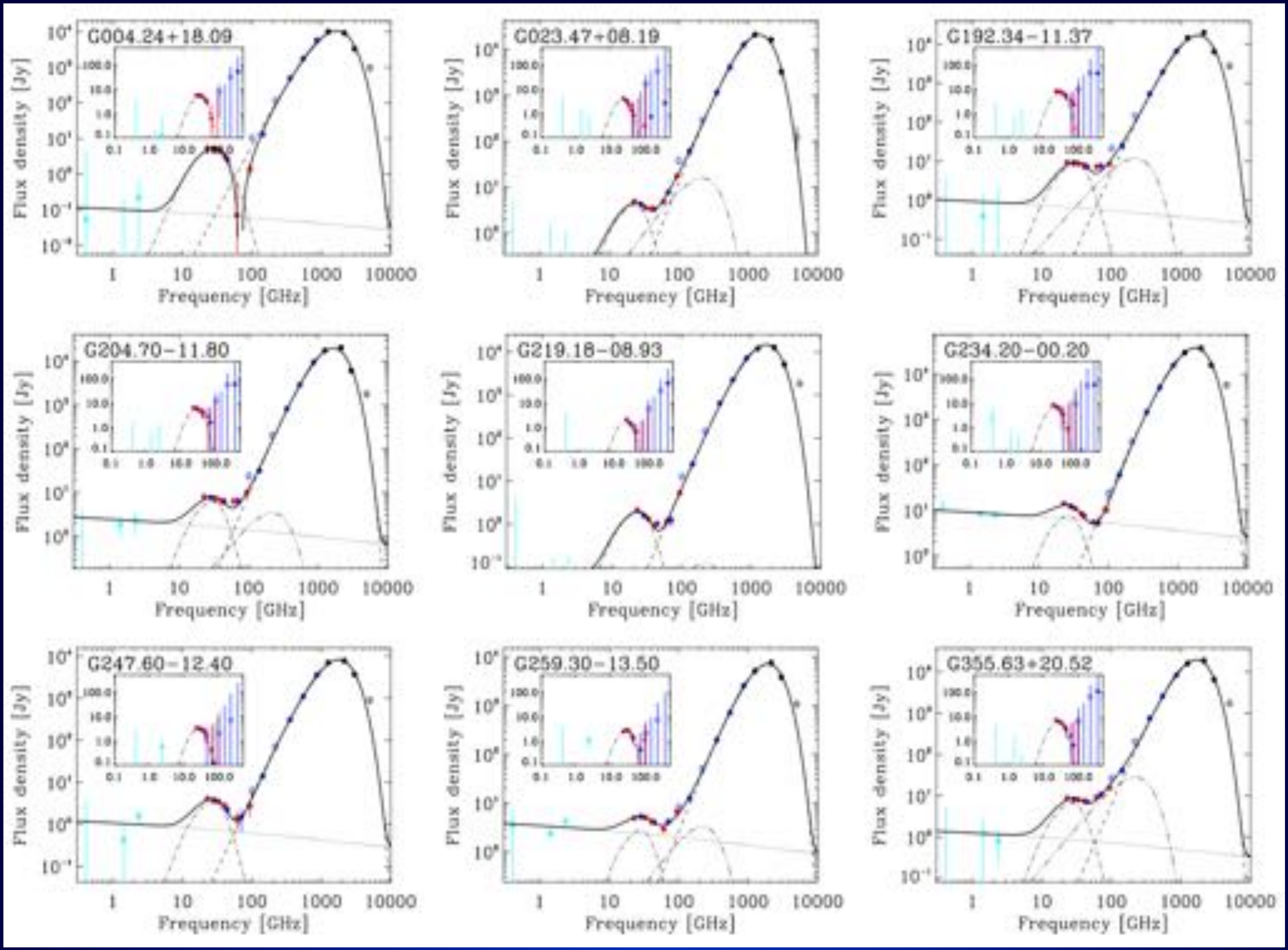


Planck Collaboration 2011, A20

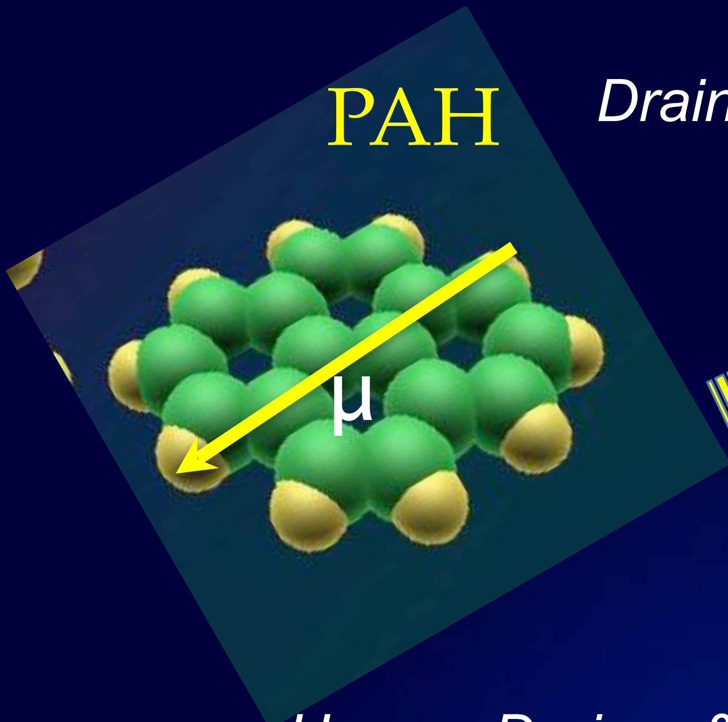
Spinning dust provides a great fit to AME from *Planck*



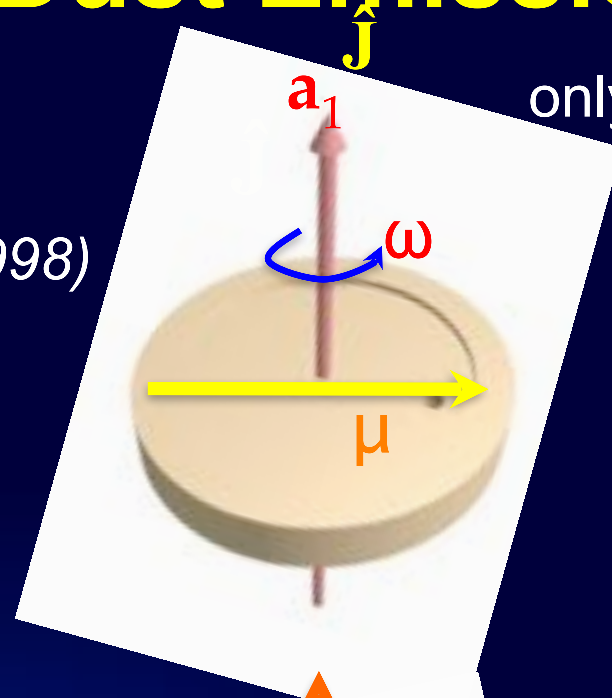
98 clouds with AME discovered by Planck 2013



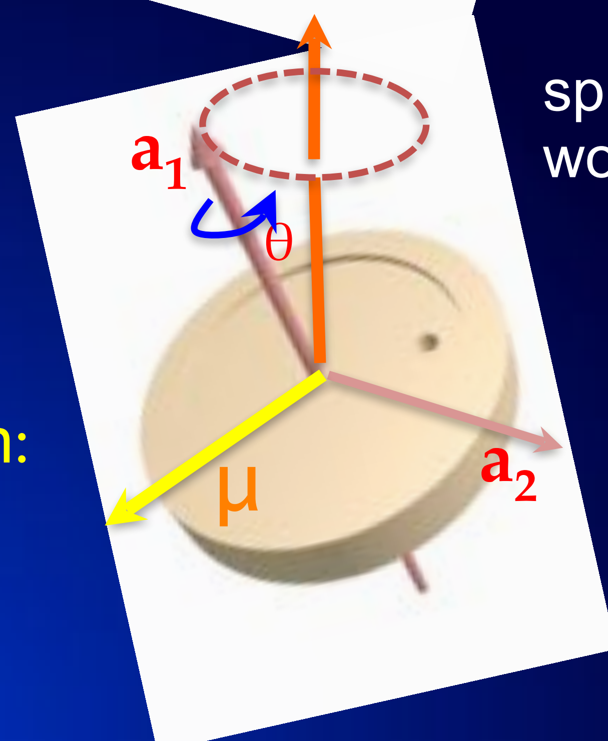
Theory of Spinning Dust Emission



Draine & Lazarian (1998)



only spinning



spinning & wobbling

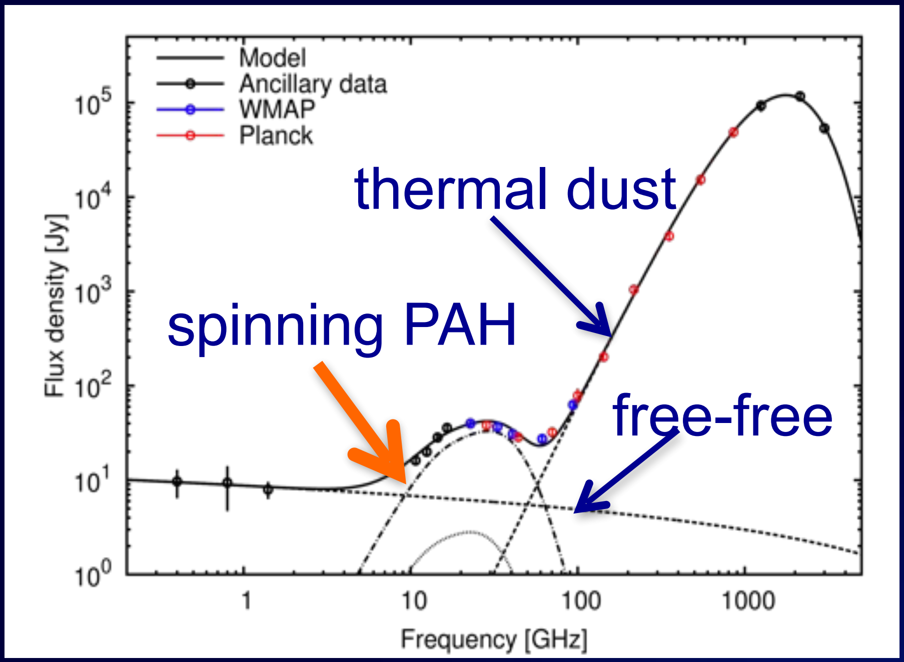
Hoang, Draine, & Lazarian (2010)

Hoang, Lazarian, & Draine (2011)

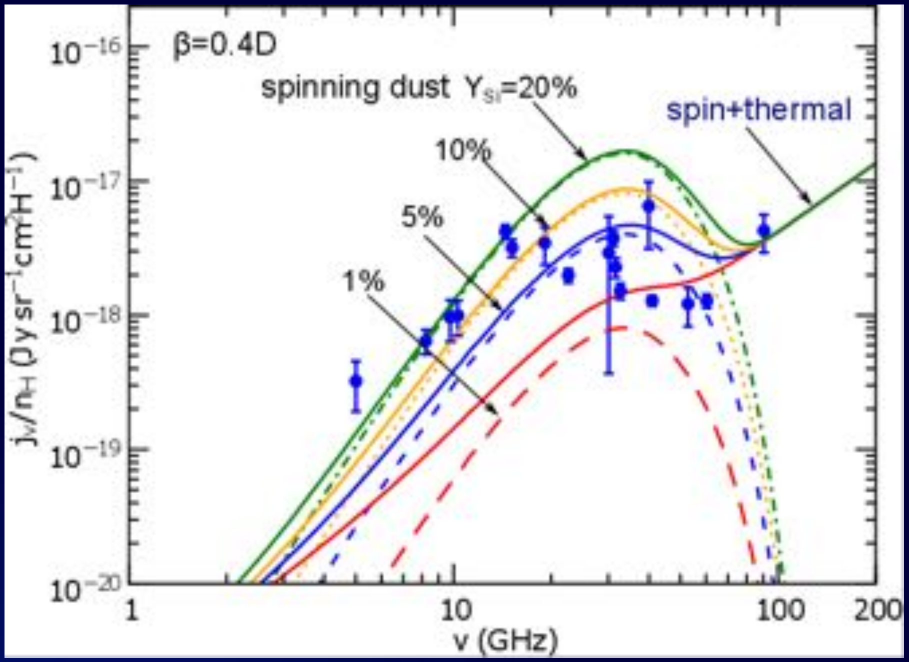
Emissivity integrated over size distribution:

$$\frac{j_\nu}{n_H} = \frac{1}{4\pi}\int_{a_{\rm min}}^{a_{\rm max}} da \frac{1}{n_{\rm H}}\frac{dn}{da} 4\pi\omega^2 f_\omega 2\pi P_{\rm ed}(\omega)$$

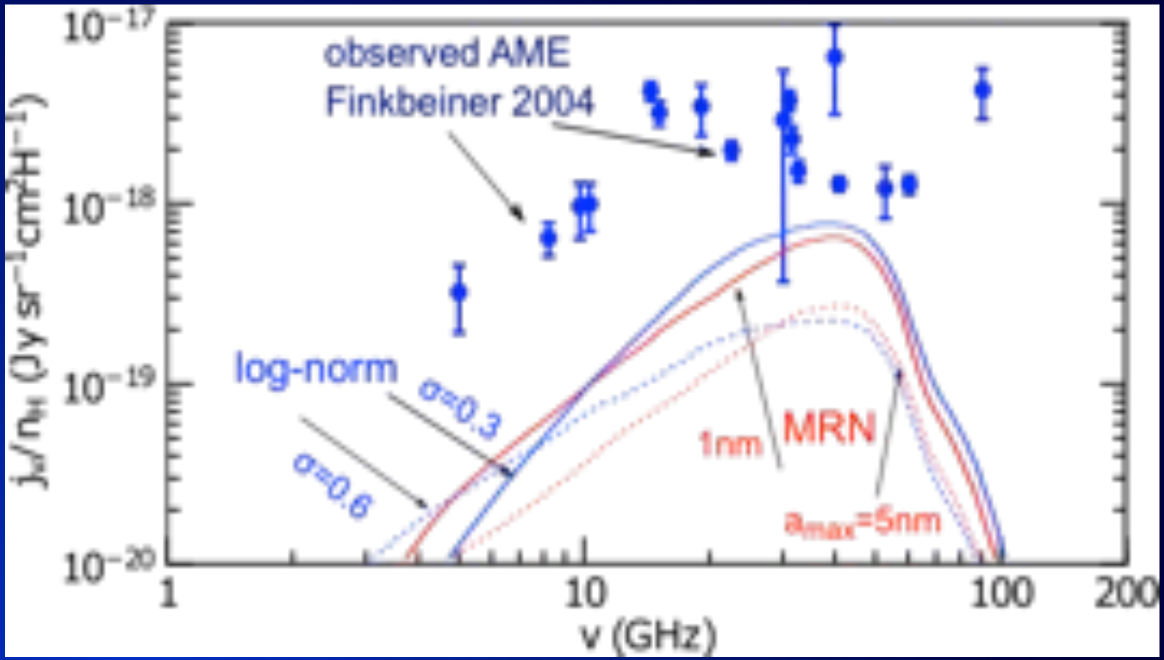
spinning PAH (Planck collaboration 2011)



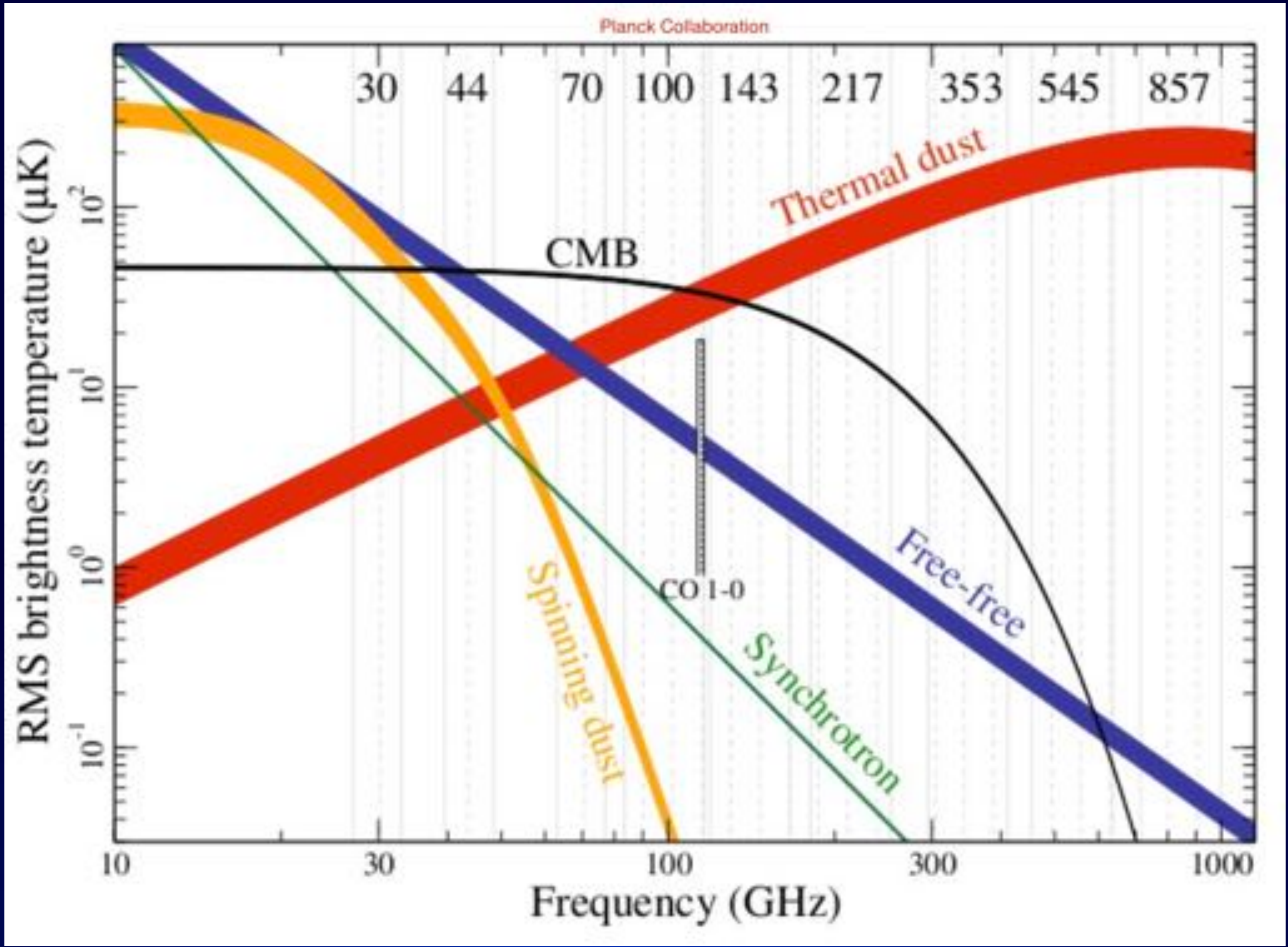
spinning nanosilicates (Hoang, Vinh, & Lan 2016)



spinning iron nanoparticle (Hoang & Lazarian 2016)



Spinning dust becomes an accepted CMB foreground component



Key Developments of Spinning Dust Theory

Development	Reference
First proposal for electric dipole radiation fr	Erickson (1957)
First full treatment of spinning dust grain th	Draine and Lazarian (1998b)
Quantum suppression of dissipation and ali	Lazarian and Draine (2000)
Factor of two correction in IR damping coe	Ali-Haïmoud et al. (2009)
Fokker-Planck treatment of high-ω tail	Ali-Haïmoud et al. (2009)
Quantum mechanical treatment of long-wav	Ysard and Verstraete (2010)
Rotation around non-principal axis	Hoang et al. (2010); Silsbee
Transient spin-up events	Hoang et al. (2010)
Effect of tri-axiality on rotational spectrum	Hoang et al. (2011)
Effects of transient heating on emission fro	Hoang et al. (2011)
Magnetic dipole radiation from ferromagne	Hoang and Lazarian (2016b)
Improved treatment of quantum suppressio	Draine and Hensley (2016)

AME from nanosilicates: Hoang + (2016), Hensley & Draine (2017)

AME polarization: Hoang + (2013), Hoang & Lazarian (2016a, 2017)

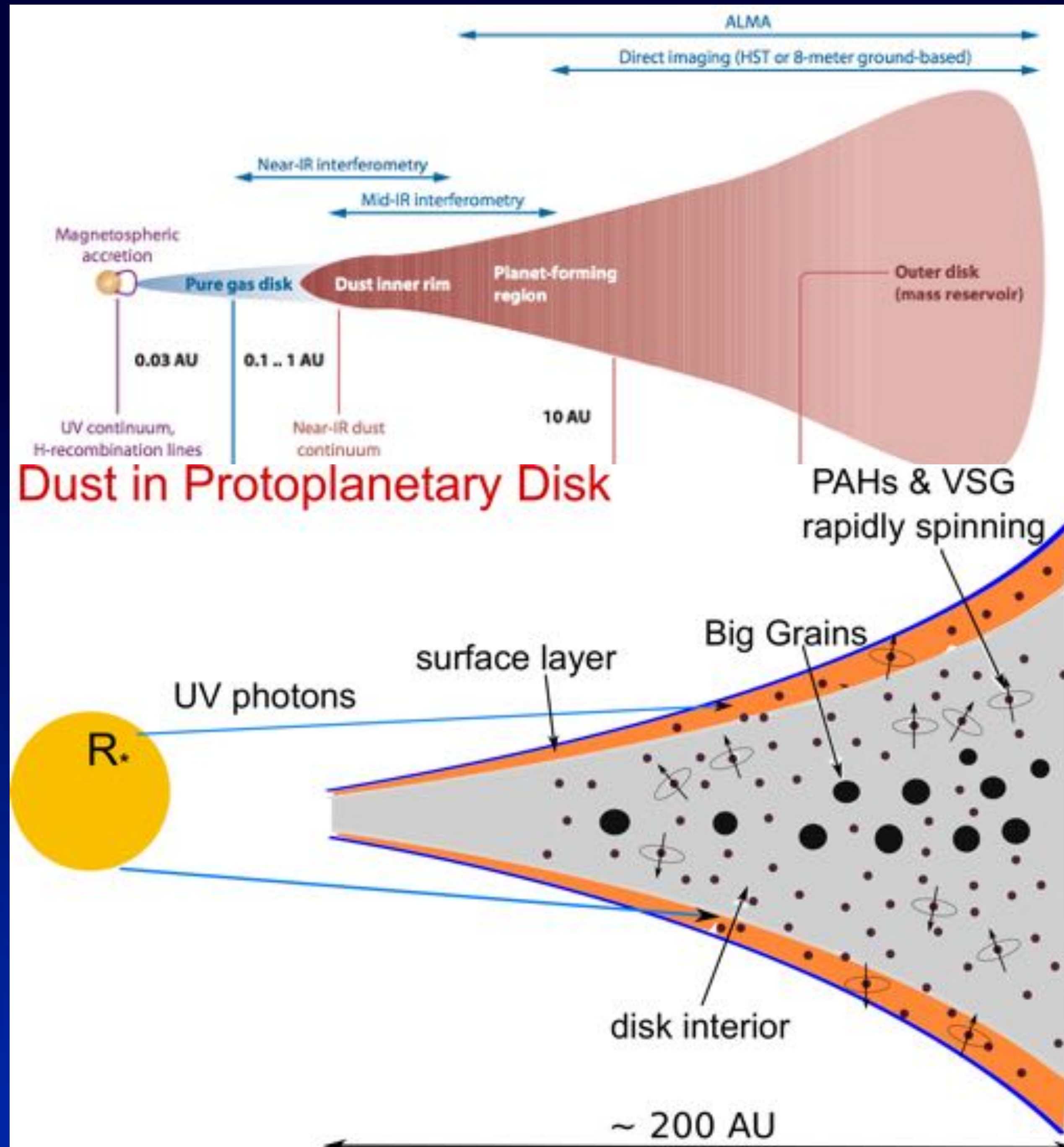
Spinning dust as a tracer of nanoparticles

Why nanoparticles?

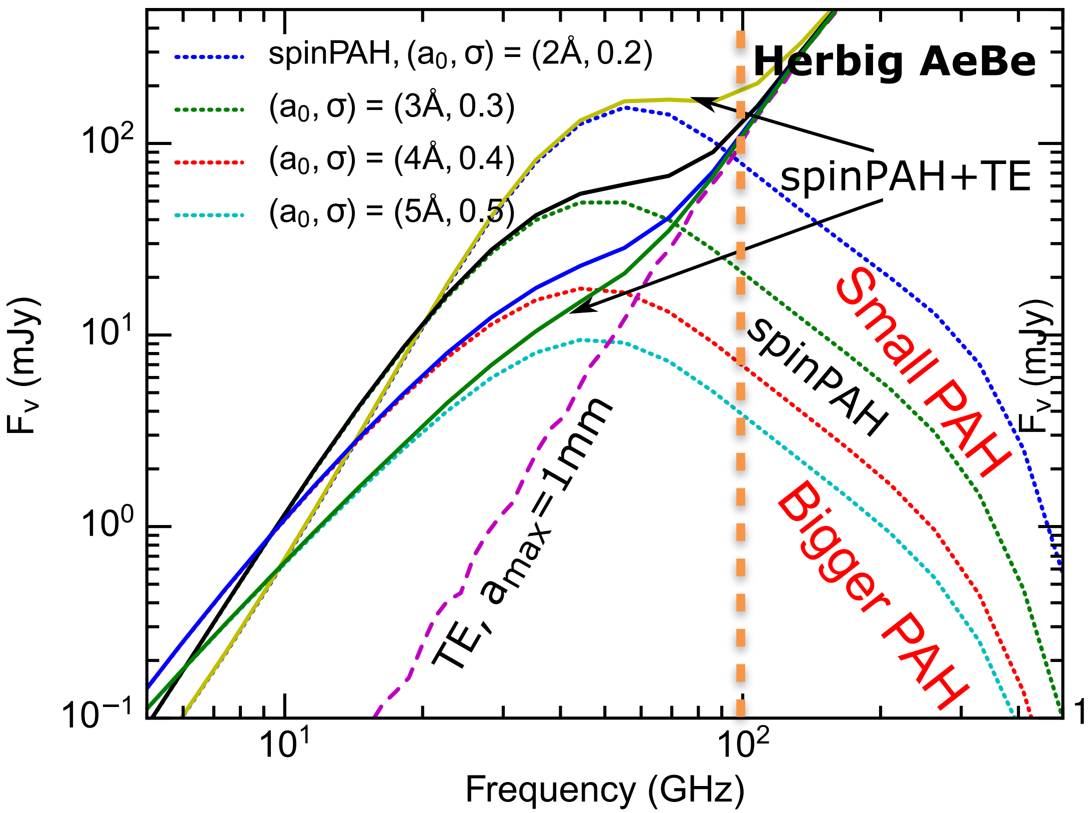
- Nanoparticles play important roles in disks (e.g., MRI activity, ambipolar diffusion

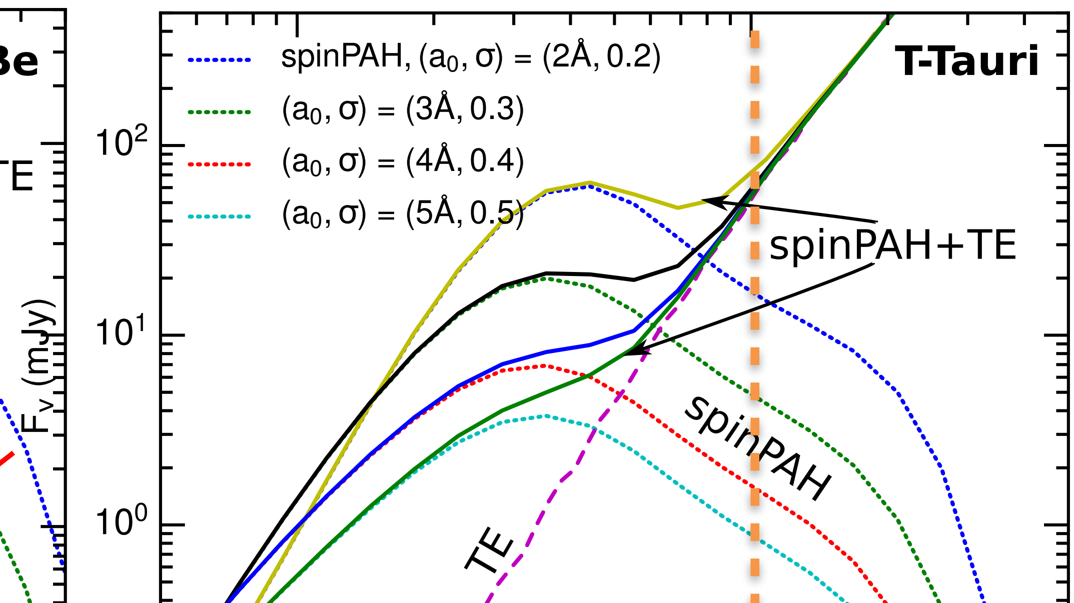
Advantages over mid-IR

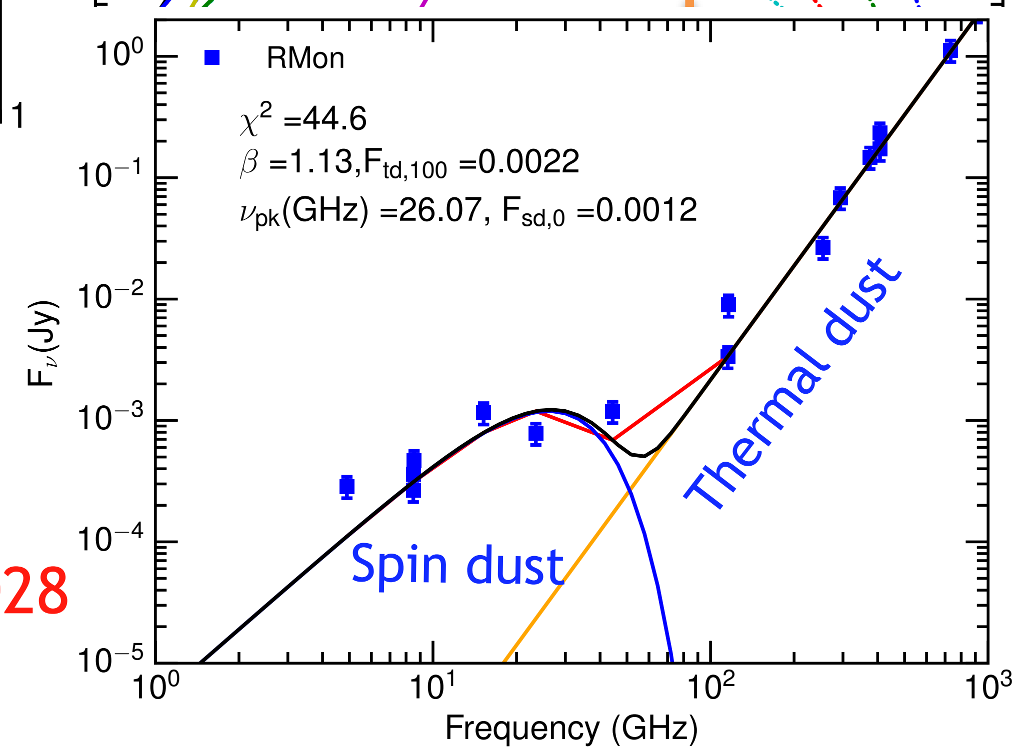
- Can trace nanoparticles in any regions (cf. Mid-IR)



Spinning Dust Emission from Disks





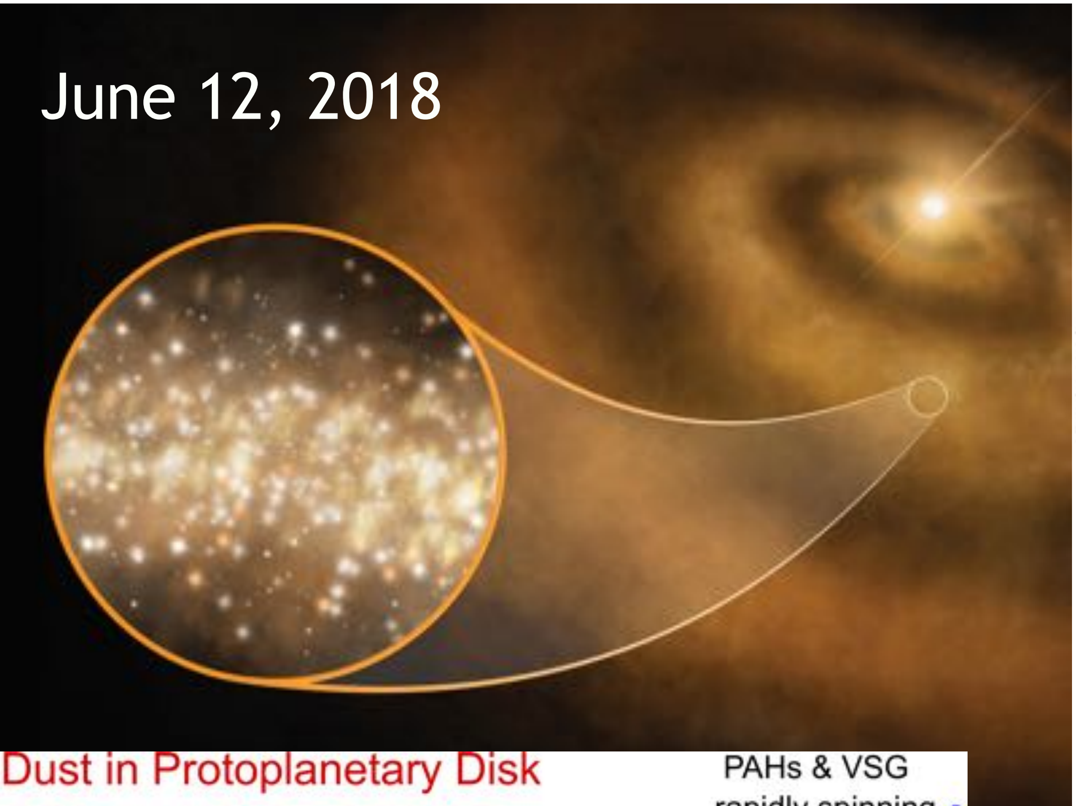


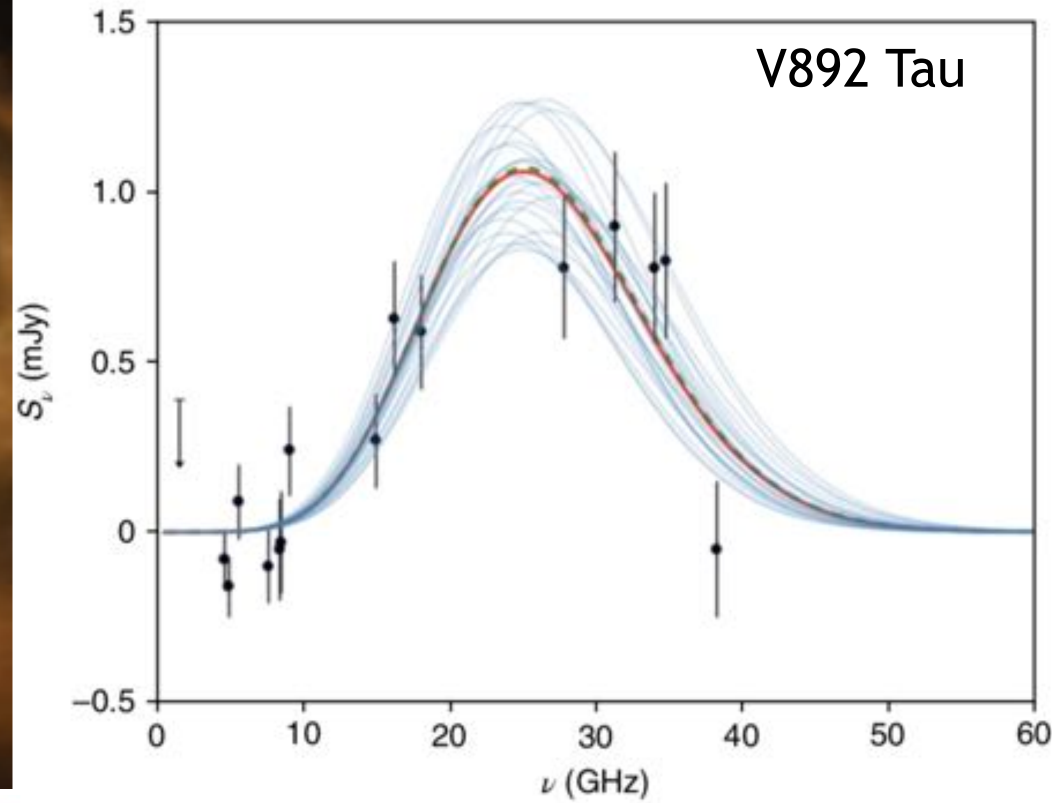
- Spinning dust dominates over thermal dust at freq < 70 GHz

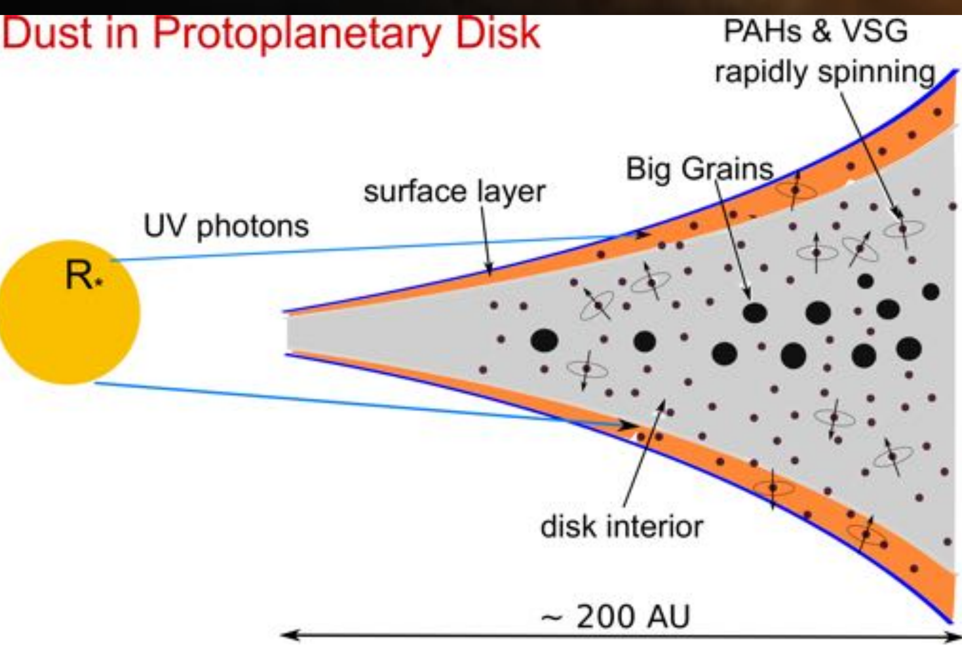
Posted on March 29, ArXiv: 1803.11028

Hoang et al. 2018, ApJ, in press

Diamond Dancing in Circumstellar Disk?

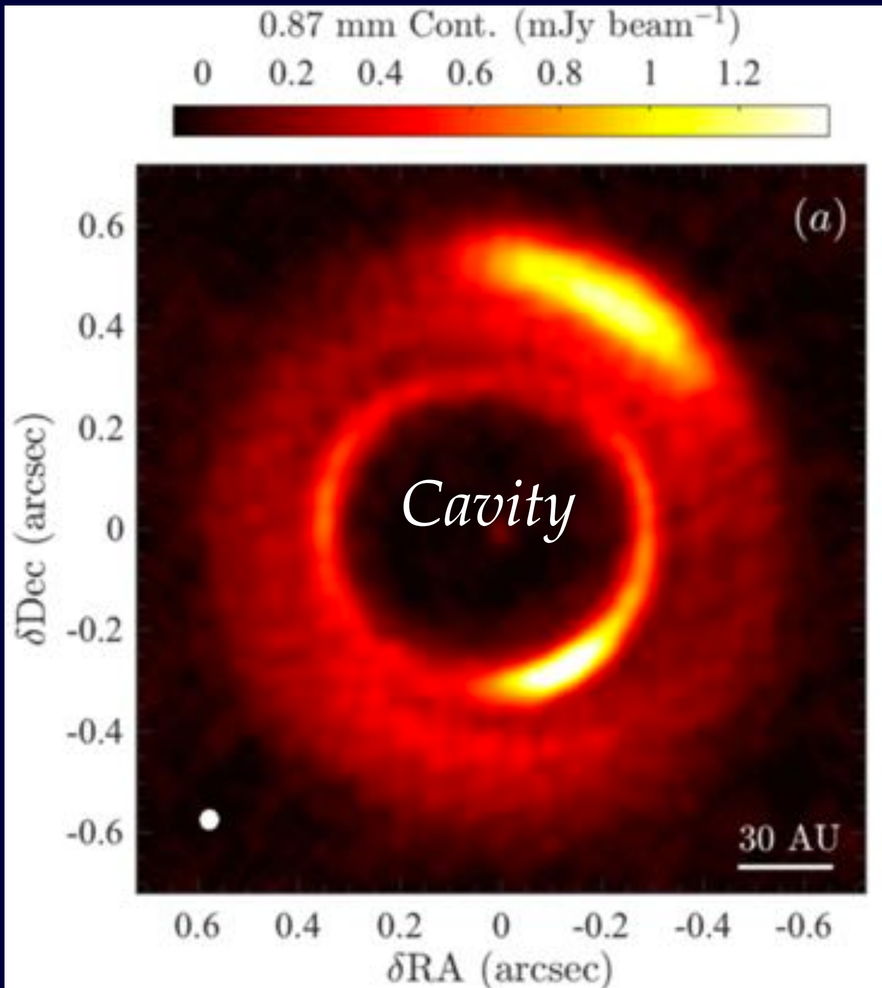




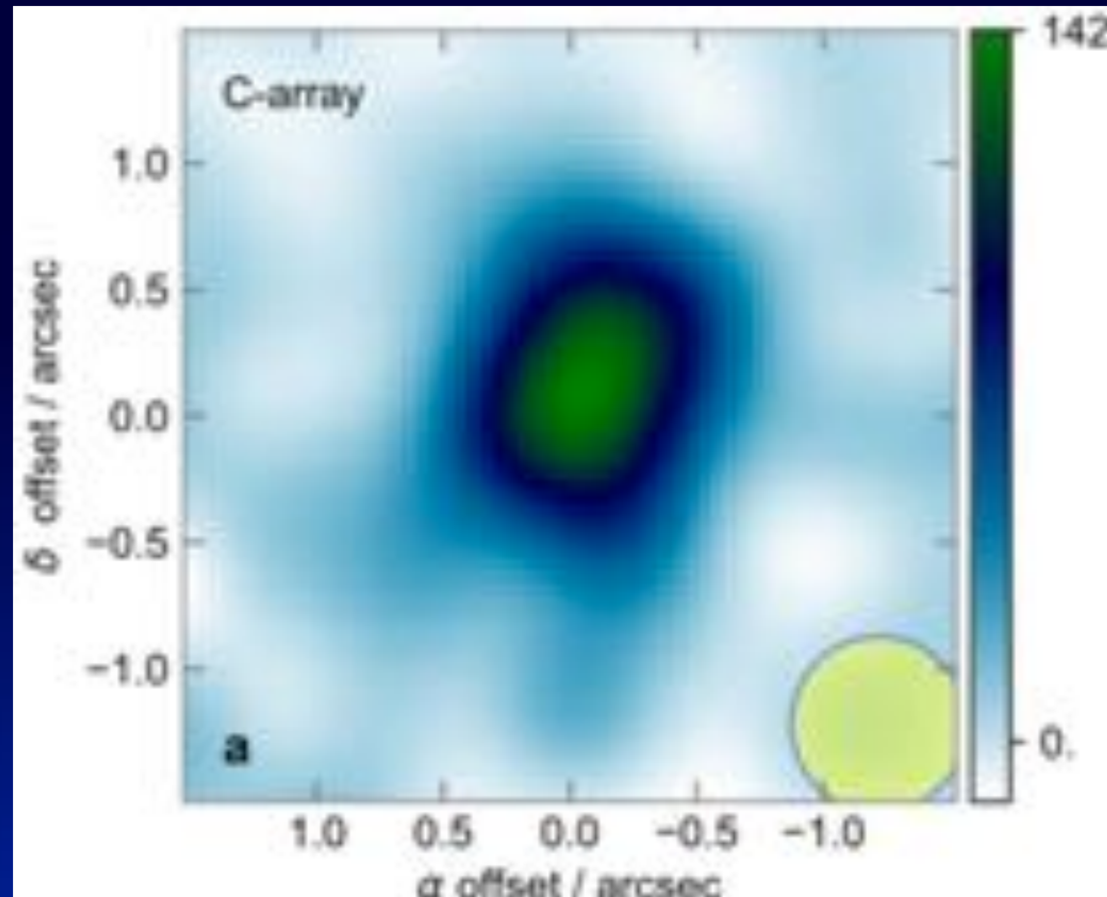


- AME might not originate from nanodiamond
- Spinning PAHs/Nanosilicates cannot be ruled out

Microwave Emission from Disk Cavity



33 GHz



Dong et al. 2018, arXiv:

Casassus et al. 2018, arXiv:

Summary

- Dust polarimetry is a powerful technique to study magnetic fields, dust properties, and important for cosmic inflation.
- Interstellar Polarization: Radiative torque (RAT) alignment is main mechanism, tested with numerous observations.
- Disk Polarization: Multiple mechanisms exist. Evidence of Radiative Alignment and Self-scattering. How to distinguish them? Circular polarization? Multiwavelength observations?
- Polarized PAH emission: first detection, consistent with theoretical predictions by PAH alignment with B-field
- Microwave emission: spinning dust from nanoparticles. Become a tracer of nanoparticles, huge potential with ngVLA, SKA, and ALMA Band 1
- Future: how to use quantitative polarimetry to probe dust properties (iron inclusions and magnetic properties)?

2018 Cosmic Dust and Magnetism Conference, Oct 30-Nov 2, Daejeon, Korea

Registration: before Aug 31st

- COSMIC DUST and MAGNETISM
- INVITED SPEAKERS
- ORGANIZERS
- REGISTRATION and ABSTRACT SUBMISSION
- PARTICIPANTS
- PROGRAM
- ACCOMMODATION
- TRAVEL
- CONTACT

Welcome to Cosmic Dust and Magnetism 2018

Scientific Rationale and

Dust and magnetic fields are ubi
of star and planet formation, wh
astrophysical phenomena, incluc
synchrotron emission. The align
fields, resulting in dust polarizat
Dust polarization has been succ
scales, from ~ kpc to ~ 1000 AU
wavelengths from disks (~ 100 A
not trace magnetic fields, but gr
time, polarized dust emission is
understanding how the universe
Therefore, accurate modeling of
astrophysics, gas density, and m
detection. The aim of this works
experts in dust astrophysics and
important aspects:

1. Dust Properties and Dust Ev
planetesimals
2. Physics of Dust Polarization
tests
3. What is the role of magnetic
4. What can we learn from mm
era: Magnetic fields or Grain G
5. Alternative ways to trace ma
6. Related important issues: tu
7. What dust astrophysics and
Galactic foreground for CMB B

First
Cosmic Dust an
Theoretical Astro

- COSMIC DUST and MAGNETISM
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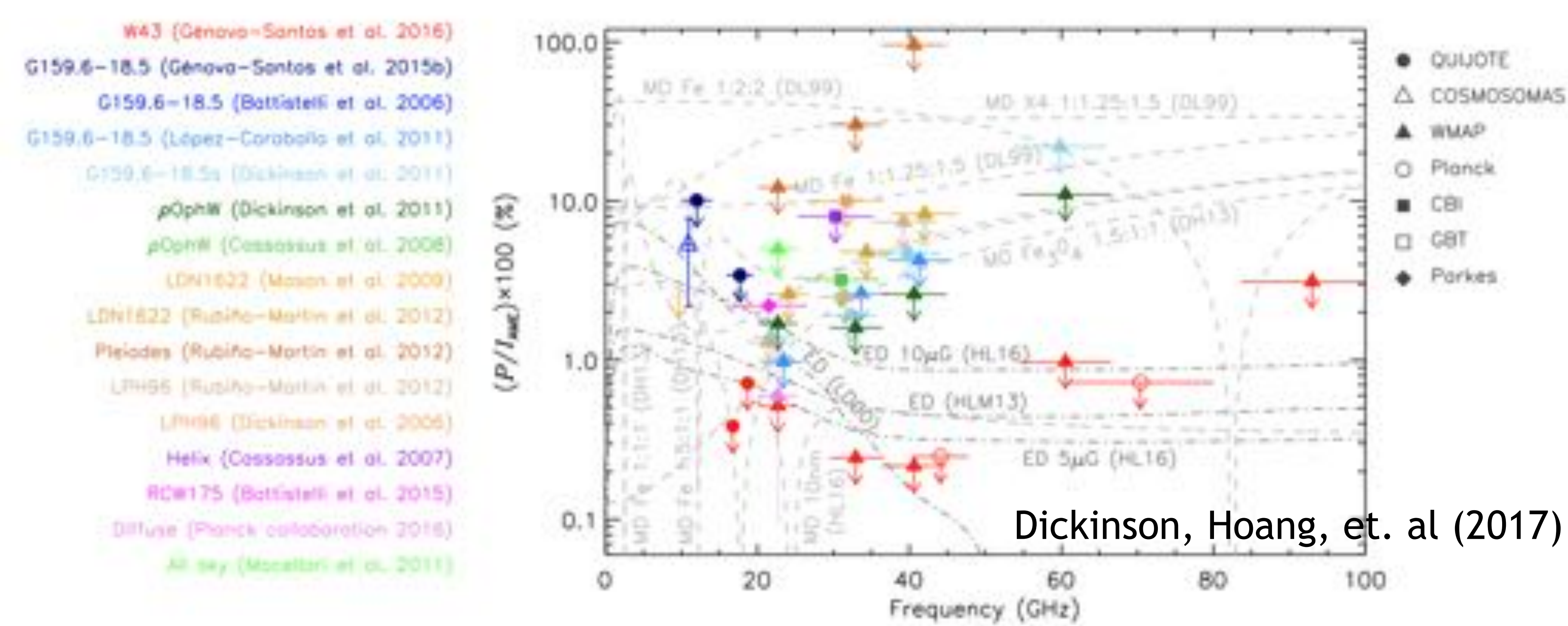
- ACCOMMODATION
- TRAVEL
- CONTACT

Confirmed Inv

- Andersson, B-G (N
- Balsara, Dinshaw (
- Boulanger, Francoi
- Burkhart, Blakesley
- Clemens, Dan (Bos
- Draine, Bruce (Prin
- Federrath, Christop
- Fissel, Laura (NRAC
- Girart, Josep M. (C
- Guillet, Vincent (IA
- Hensley, Brandon (
- Hirashita, Hiroyuki
- Hoang, Thiem (KAS
- Houde, Martin (UW
- Hull, Chat (NAOJ, C
- Kataoka, Akimasa
- Kwok, Sun (Univers

Theoretical predictions vs. Observations



Dickinson, Hoang, et. al (2017)

ratio by more than 1σ. For sensitive CMB experiments, omitting in the foreground modelling a 1% polarized spinning dust component may induce a non-negligible bias in the estimated tensor-to-scalar ratio.

Simulations by Dickinson's