Origin of Interstellar Dust: Formation and Evolution

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- Composition of Dust in the Diffuse ISM
- Sources of Dust
- Evolution in the ISM
- Puzzles
- Prospects for Progress

Dust Composition: Spectroscopic Clues

Depletions from Gas → Fraction in Grains

Most Mg, Si, Ca, Al, Fe, Ni is in grains

(talk by Jenkins this morning)

- Almost all Mg and Si are in amorphous silicates
- ∼30% of Fe in amorphous silicates
- **∼70% of Fe: unknown form (metal? oxides?)**

∼40-50% of C is in grains

- ∼15-20% of C in "PAH" nanoparticles
- ∼5-10% of C in aliphatic hydrocarbon (Chiar et al. 2013)
- ∼20% of C: unknown form
  (graphitic? glassy C? amorphous C?)

Interstellar Dust: Sources and Sinks

Sources

- Injection of "stardust" from stellar sources
- **Growth of solid matter in ISM**

Sinks

- Destruction of solid material in ISM
  - **sputtering (in shock waves and shock-heated gas)**
  - **grain-grain collisions $\rightarrow$ vaporization**
  - photodesorption
  - other *(cosmic rays, Coulomb explosions, sublimation...)*
- Incorporation into protostars
- Removal in galactic outflow

Sources of Interstellar Dust
Stardust in Stellar Outflows

- **Cool star winds**
  $\sim 0.0025 M_\odot\,\mathrm{yr}^{-1}$
- **Planetary Nebulae**
  $\sim 0.006 M_\odot$ dust/PN $\times 0.3$/yr
  $\sim 0.002 M_\odot$/yr
- novae – not important
- OB star winds – not important
- **Supernovae**
  ($\sim$0.01/yr $\times 0.02 M_\odot$ dust/SN?
  $\sim 0.0002 M_\odot\,\mathrm{yr}^{-1}$

Stardust Injection Rate

Sum: $\dot{M}_d \approx 0.005 M_\odot$/yr

Core-collapse SNe (e.g., Cas A, SN87a)

(talk by Jeonghee Rho this morning)

- Cas A: silicates, etc.
  $M_{\rm dust} \lesssim 0.14 M_\odot$ (Arendt et al. 2014)
  $M_{\rm dust} \approx 0.6 M_\odot$ (Priestley et al. 2019)
- SN87a:
  $M_{\rm dust} \approx 0.8 M_\odot$ (Matsuura et al. 2015)
- Cas A, SN87a: very young (pre-Sedov)
  much ejecta still unshocked
  reverse shock $\rightarrow$ grain destruction
  how much SN dust survives to mix into ISM?
  some does: presolar grains in meteorites.
- SN presolar grains in meteorites rare
  guess: $< 10\%$ of SN-formed dust enters ISM
- SN dust production: secondary importance today
  possibly important in first $\sim 10^8$ yr of galaxy

Importance of Grain Growth in ISM

- *If* no grain growth: all atoms entering ISM as gas would remain in gas.
- Substantial fraction of Si, Ca, Ti, Fe do enter ISM in gaseous form (fast winds from OB stars, SNIa, SNII)
- But: in diffuse HI, ∼90-99% of Si, Ca, Ti, Fe... are **missing from gas ("depleted")**
- Simple conclusion: **mechanisms for conversion of gas to solid must be rapid** collisions between metal ions and solid surfaces, followed by incorporation of newly-arrived atom into solid material (e.g., silicate or carbonaceous material)

  Kinetics:
  Can "deplete" atoms/ions from gas on short times in moderately dense H I regions.

Can understand depletion observed in more diffuse regions
if rapid exchange of matter between low-density and high-density phases.
(Draine 1990; Weingartner & Draine 1999; Draine 2009)

Grain Destruction in ISM

- Sputtering and grain-grain collisions in SN-driven shock waves:
  many papers over last 40 yrs, e.g.
  Barlow & Silk (1977)
  Barlow (1978)
  Shull (1978)
  Draine & Salpeter (1979)
  Dwek & Scalo (1979)
  Seab & Shull (1983)
  Jones et al. (1994)
  ...

  Zhukovska et al. (2016) *(talk by Zhukovska this afternoon)*

- *General conclusion:*

Lifetime of solid material in Galactic ISM is short: $\sim 4\times 10^8$ yr

Balance of Formation and Destruction

Total dust mass in ISM: $\sim \mathbf{0.007} \times \mathrm{M_{ISM}} \approx \mathbf{3.5} \times \mathbf{10^7 M_\odot}$
Balance:

$$\begin{aligned}
\textbf{Stardust Injection} &+ \textbf{Formation in ISM} = \textbf{Removal} \\
\sim \mathbf{0.005} M_\odot\,\mathbf{yr^{-1}} &+ \textbf{Formation in ISM} = \frac{\sim 3.5\times 10^7 M_\odot}{\sim 4\times 10^8\,\mathrm{yr}} \\
1 &+ \frac{\textbf{Formation in ISM}}{\textbf{Stardust injection}} = \frac{\sim 0.09 M_\odot\,\mathrm{yr}^{-1}}{\sim 0.005 M_\odot\,\mathrm{yr}^{-1}} \\
&\frac{\textbf{Formation in ISM}}{\textbf{Stardust injection}} = \sim \mathbf{16}
\end{aligned}$$

Conclusion: Stardust accounts for only ∼5-10% of interstellar dust.

∼90-95% is grown from gas in the ISM

Implications for Crystallinity

- Empirically:
  Mg-rich amorphous silicates must be one of the materials that is formed (and survives) when ISM gas mix impinges on cold surfaces in presence of UV.

- Crystallinity:
  Stardust silicate: appreciable crystalline fraction (20%?)
  Silicate material grown in ISM: amorphous

$$\boxed{\rightarrow \text{Interstellar silicates: crystalline fraction } \lesssim 2\%}$$

Consistent with observations (Kemper et al. 2004)

Implications for Composition and Size Distribution

- Grain growth in presence of UV:
  Photodesorption and UV-promoted diffusion may enable formation of chemically distinct domains
  - amorphous silicate
  - carbonaceous materials
  - regions with Fe and/or Fe oxides...

  all on the same grain.

- Low-speed grain-grain collisions $\rightarrow$ coagulation

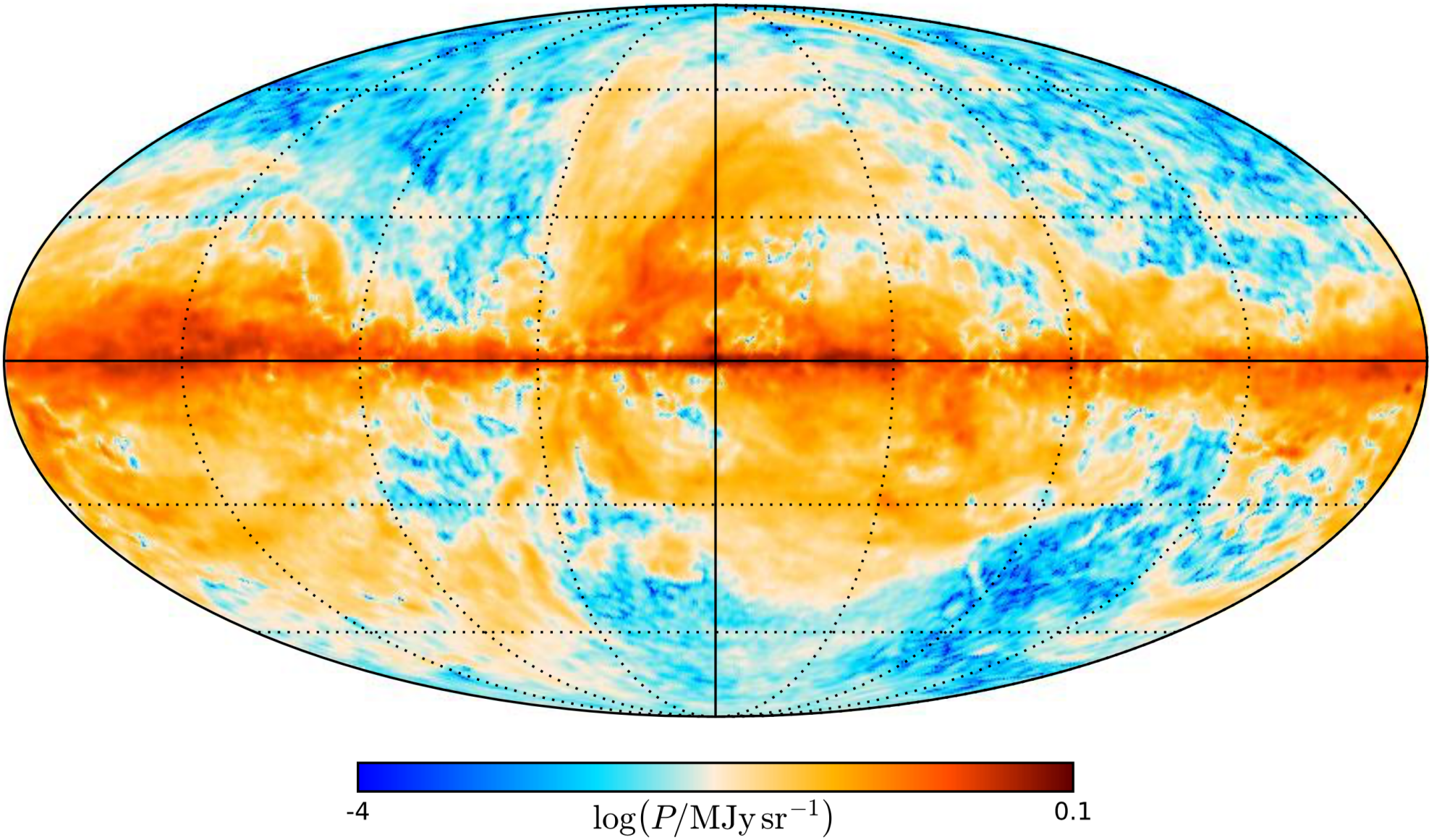
Large grains may be mixtures of many phases.

- Shattering in high-speed grain-grain collisions:
  needed to maintain observed nanoparticle population.

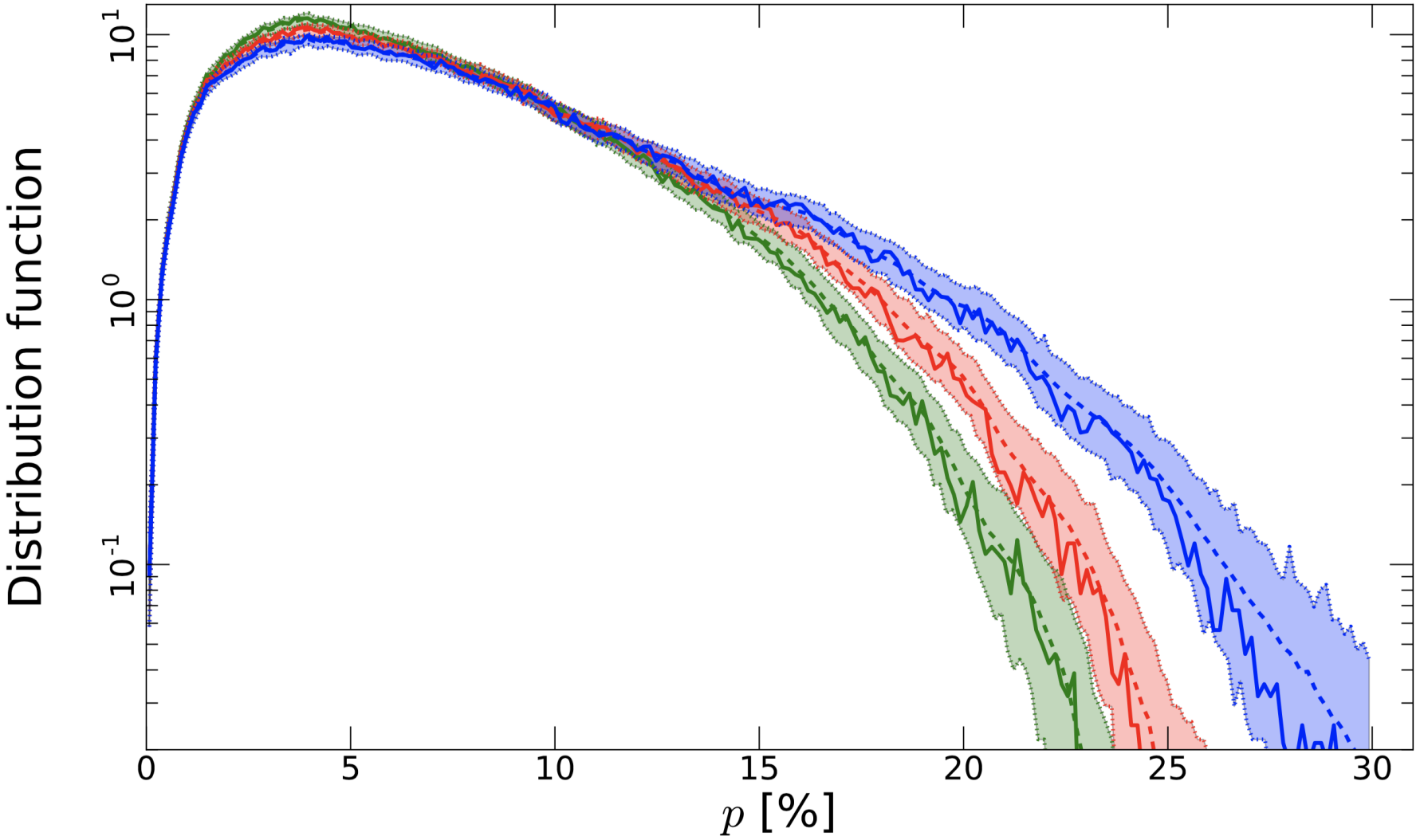
- Fragmentation of large grains in grain-grain collisions:
  may create "pure" nanoparticle populations (e.g., PAHs, nanosilicates, ...)

Polarized Submm Emission from Dust

Polarized Intensity at 850μm from Planck Collaboration et al. (2018)



Polarization Fraction at 850μm



from Planck Collaboration et al. (2018)

1% of pixels have p >19% !

0.1% have p >21% !!!

Constraints on Grain Shape, Porosity, and Alignment

- Need to reproduce starlight polarization, up to

$$\frac{p_{\rm max}}{E(B-V)} \approx \mathbf{0.13}$$

(Planck Collaboration et al. 2018; Panopoulou et al. 2019).

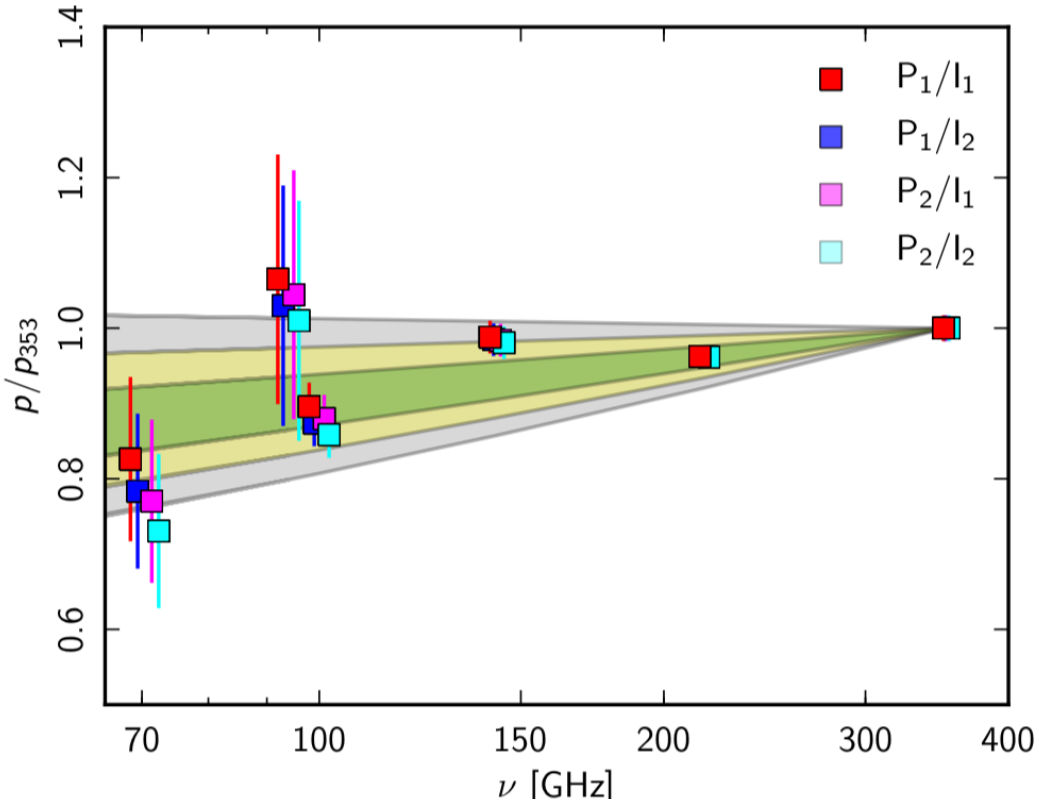
- UV polarization/extinction very small: smallest grains are *not* aligned.
  Alignment fraction appears to be almost a step function:
  $a \lesssim 0.05\mu{\rm m}$: negligibly aligned
  $a \gtrsim 0.10\mu{\rm m}$: substantially aligned

- Grains that produce starlight polarization
  must also produce polarized submm emission, up to

$$\mathbf{p \approx 21\% \text{ at } 850}\mu{\rm m}$$

Models

- Many models assumed
  partially aligned silicate grains + randomly-oriented carbonaceous grains
  e.g., Draine & Fraisse (2009), Siebenmorgen et al. (2014), Siebenmorgen et al. (2017), Guillet et al. (2018)
- Difficulty: *Planck* finds submm polarization to be high and $\sim$ independent of λ



from Planck Collaboration et al. (2015)

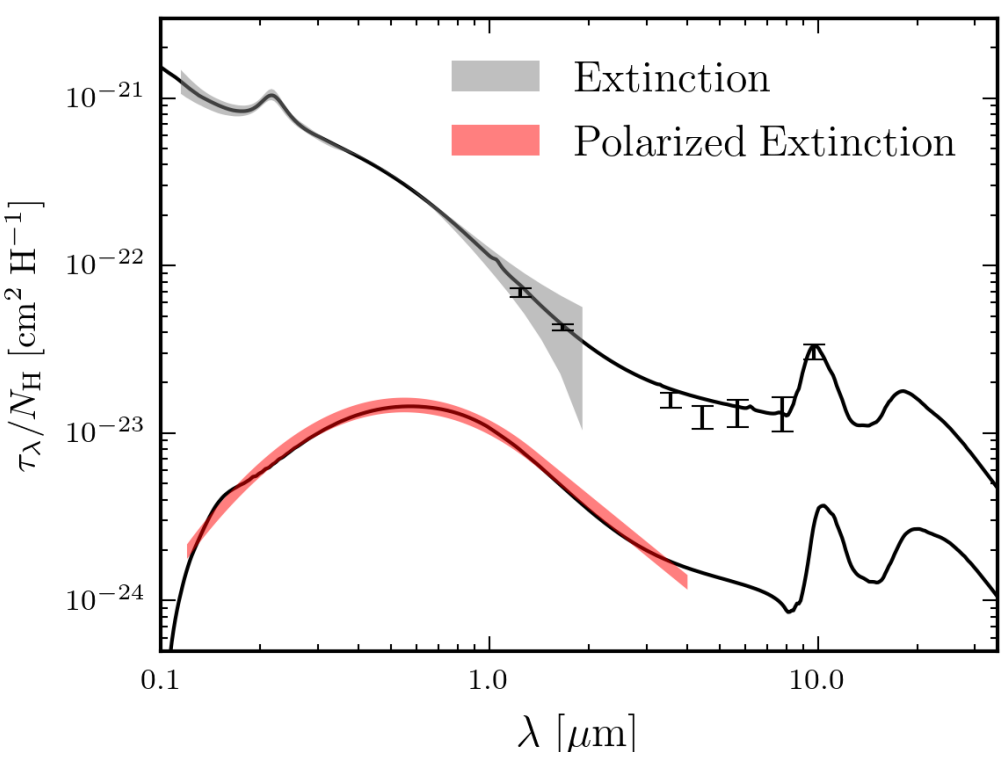
- Different materials likely to have **different submm opacities** *and* **different** T
- How likely to have 2 components adding to give polarized fraction independent of λ?

More likely: <u>one</u> component dominating both total and polarized emission.

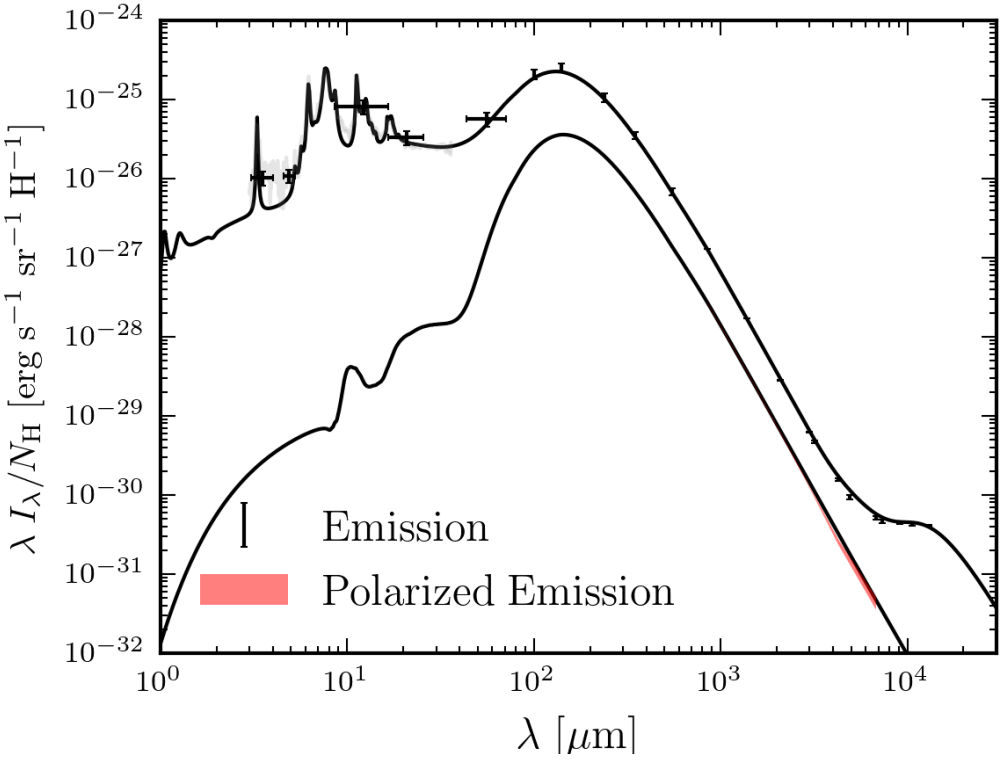
"AstroDust" Model

- Most dust mass: "astrodust" formed in ISM:
  mixture of silicate and nonsilicate material (including hydrocarbon component)
- Also: PAHs and silicate nanoparticles
- Model reproduces observational constraints *(talk by Brandon Hensley)*

Total Extinction
Polarized Extinction



Total Emission
Polarized Emission



from Hensley & Draine (2019)

Other Galaxies, Lower Metallicities, and Earlier Times

- **Star-forming galaxies** with $Z/Z_\odot \gtrsim 0.2$: dust similar to Milky Way dust, with

$$\frac{M_{\rm dust}}{M_{\rm gas}} \approx 0.007 \times \frac{Z}{Z_\odot}$$

  Refractory elements (Mg, Si, Fe, ...) are largely in solid form.

- For $Z/Z_\odot \lesssim 0.2$, dust properties seem to change:

  - **PAH fraction appears to drop at low Z:**
    (Engelbracht et al. 2005; Madden et al. 2006; Draine et al. 2007)
    e.g. SMC with $Z/Z_\odot \approx 0.2$ (Sandstrom et al. 2010, 2012; Chastenet et al. 2019)
    (talk by Chastenet Thursay morning)

  - **Flatter frequency dependence and enhanced opacity at mm wavelengths**
    (e.g. Galliano et al. 2003, 2005; Galametz et al. 2009, ...)

- **for $Z/Z_\odot \lesssim 0.1$: dust/metals ratio falls** (growth in ISM $\propto Z^2$, destruction $\propto Z$)
  (e.g. Rémy-Ruyer et al. 2014; De Vis et al. 2019)

Galaxies at High z

After star formation begins in pristine gas, time delay before injection of stardust:

- $\sim 5\,\mathrm{Myr}$ for core-collapse SNe to inject metals and dust
- $\sim 10^8\,\mathrm{yr}$ for injection of dust from AGB stars.
- grain-grain collisions in turbulent ISM $\rightarrow$ fragmentation $\rightarrow$ increase in grain surface area

Evolution: As ISM is enriched with metals from SNe, stardust can act as substrate for grain growth.

- It is *not* surprising that many very young galaxies have substantial dust content, e.g.,
  - J114816+525150 at $z = 6.42$, with $M_{\rm dust} \approx 2\times10^8 M_\odot$ (Dwek et al. 2007),
  - A2744_YD4 at $z = 8.38$ with $M_{\rm dust} \approx 6\times10^6 M_\odot$ (Laporte et al. 2017).
- By analogy with low-z galaxies, expect PAH formation in ISM when $Z/Z_\odot \gtrsim 0.2$.

Some Open Questions ...

- Where is the "missing" oxygen in translucent clouds?
  $\sim$15–25% of O toward ζOph is unaccounted for!! (Poteet et al. 2015)
- How are size distribution and composition maintained in ISM?
- "Astrodust" has $3.4\mu\mathrm{m}$ CH feature coming from partially-aligned silicate-bearing grains. Is this compatible with upper limits on polarization of $3.4\mu\mathrm{m}$ feature?
- If PAHs are ubiquitous *and* produce 2175 Å feature, why isn't the 2175 Å feature more prominent in extragalactic "attenuation curves" (e.g., Calzetti law)
  May be result of
  - *radiative transfer in clumpy ISM (Seon & Draine 2016)*
  - *hot stars providing FUV radiation may be preferentially in low extinction regions*
  - *hot stars providing FUV radiation may be preferentially in regions where PAHs have been partially destroyed by ionizing radiation*
- What is non-silicate Fe? Is ferromagnetic material present?
- How does D deplete (and undeplete) in diffuse regions? Heavy deuteration of PAHs?
- What is source of "anomalous microwave emission" (AME):
  spinning PAHs? spinning nanosilicates? both?
- Is AME polarized?
- How does grain composition vary with galaxy metallicity?

(Some) Prospects for Progress

- Improved $10\mu\mathrm{m}$ spectropolarimetry of silicate feature
- Deeper spectropolarimetry to detect polarization in $3.4\mu\mathrm{m}$ feature
- X-ray scattering halos: constrain size distribution and porosity of dust.
- X-ray spectroscopy of C, O, Mg, Si, Fe absorption edges to probe dust composition.
- JWST IR spectroscopy
  - PAHs in emission (and absorption?)
  - 10 and $18\mu\mathrm{m}$ silicate profiles (substructure, variations)
  - new spectral features? (e.g., Fe_3O_4...)
- Lab studies to identify more DIBs (hard!)
- Measure size distribution and composition of interstellar particles entering heliosphere e.g.,
  - Stardust mission (Westphal et al. 2014)
  - Cassini Dust Analyzer (Altobelli et al. 2016)
  - Future missions (e.g., FOSSIL).

THANK YOU

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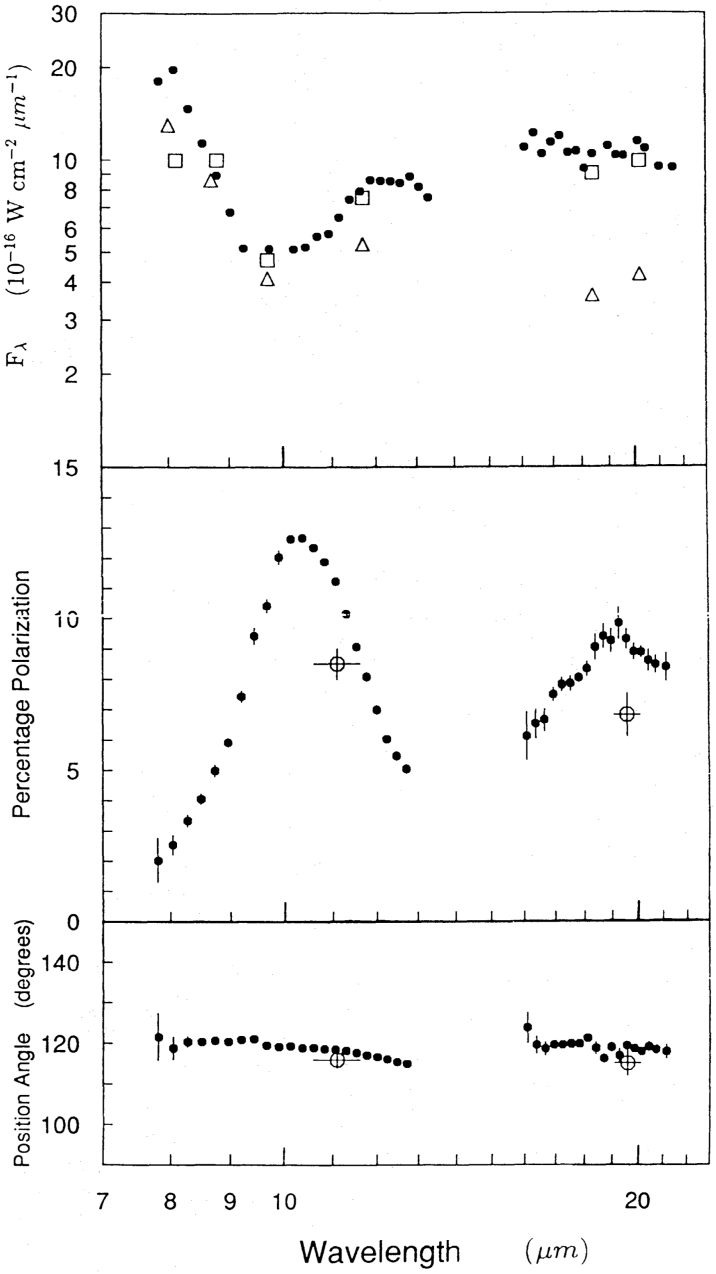
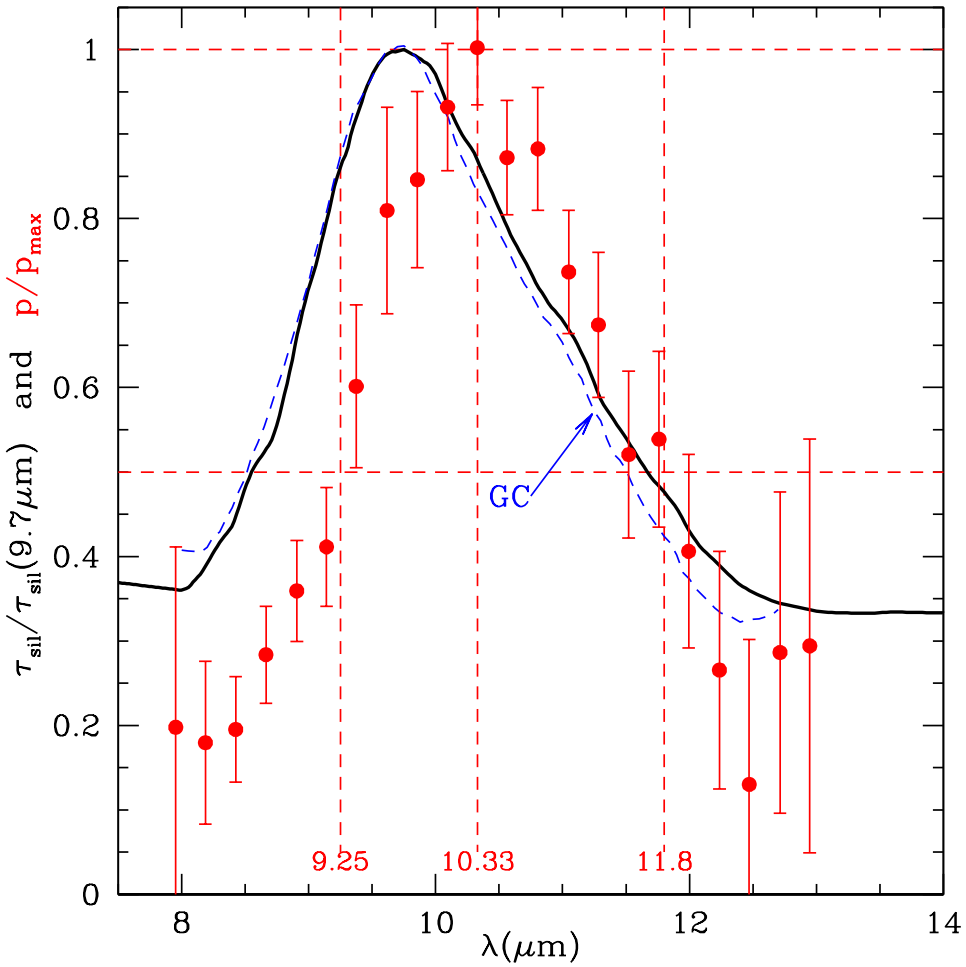
Polarization in Spectral Features

- $10\mu\mathrm{m}$ silicate Si-O stretch: **strong polarization** (in extinction)
- 2175Å feature (carbonaceous): **not** significantly polarized
  consistent with non-alignment of smallest ($a \lesssim 0.05\mu\mathrm{m}$) grains
- Diffuse Interstellar Bands (DIBs): **not** polarized
  consistent with non-alignment of nanoparticles...
- PAH features: (almost) no evidence of polarization
  consistent with non-alignment of nanoparticles...
  except perhaps 11.3μm feature in MWC 1080 (Zhang et al. 2017)...
- $3.4\mu\mathrm{m}$ C-H stretch feature: no evidence of polarization (yet)

Polarization of 10μm and 18μm Silicate Features



BN Object (Aitken et al. 1989)



extinction and **polarization** profiles in diffuse ISM

polarization data from Wright et al. (2002)

Significant offset between extinction and polarization

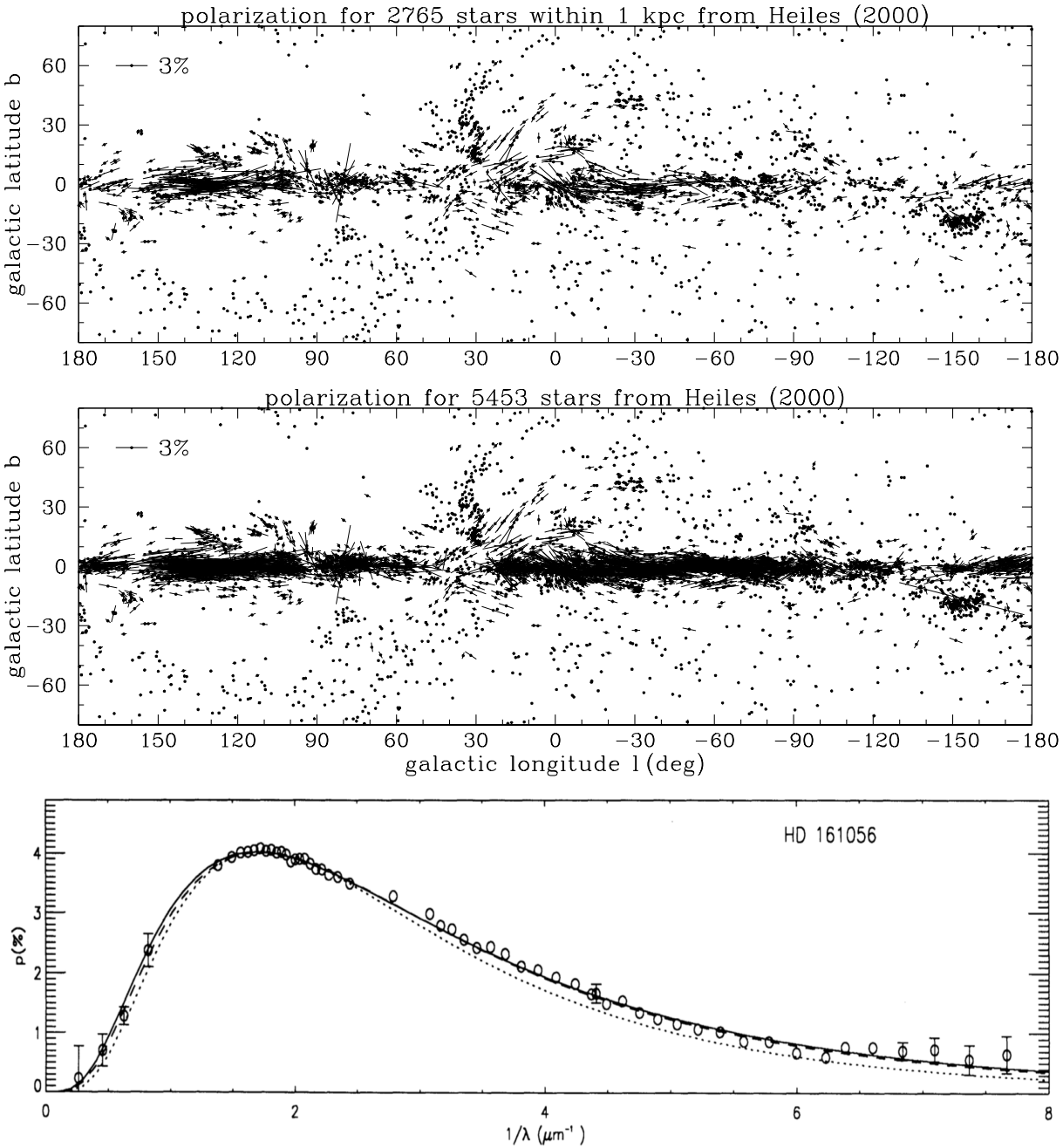
Simple Estimate of Dust Lifetime...

- Submicron grains: substantial erosion in $v_s \gtrsim v_{\rm min} = 250\,{\rm km\ s^{-1}}$ radiative shock
- Sedov SNR:
$$\begin{aligned} M_{\rm clean} &= \text{ISM mass shocked to } v_s > v_{\rm min} \\ &\approx E_0/v_s^2 = 10^{51}\,{\rm ergs}/(250\,{\rm km\ s^{-1}})^2 \approx 800 M_\odot \end{aligned}$$
- Random SN explosions $\rightarrow$ dust lifetime
$$\begin{aligned} \tau_{\rm dest} &= \frac{M_{\rm ISM}}{\dot{N}_{\rm SN} M_{\rm clean}} \\ &= 6\times 10^8\,{\rm yr} \left(\frac{M_{\rm ISM}}{5\times 10^9 M_\odot}\right) \left(\frac{0.01\,{\rm yr^{-1}}}{\dot{N}_{\rm SN}}\right) \left(\frac{800 M_\odot}{M_{\rm clean}}\right) \end{aligned}$$
- Complications:
  - multiphase ISM (shielding in dense gas)
  - correlated SNe,
  - $v_s < 250\,{\rm km\ s^{-1}}$ shocks (sputtering + grain-grain collisions)

  $\rightarrow$ factor of ~ 2 effects on $\tau_{\rm dest}$: $\tau_{\rm dest} \approx 5\times 10^8\,{\rm yr}$
- Removal by star formation:
$$\tau_{\rm SF} = \frac{5\times 10^9 M_\odot}{2.5 M_\odot\,{\rm yr^{-1}}} = 2\times 10^9\,{\rm yr}$$

Lifetime for solid matter $\tau \approx 4\times 10^8$ yr.

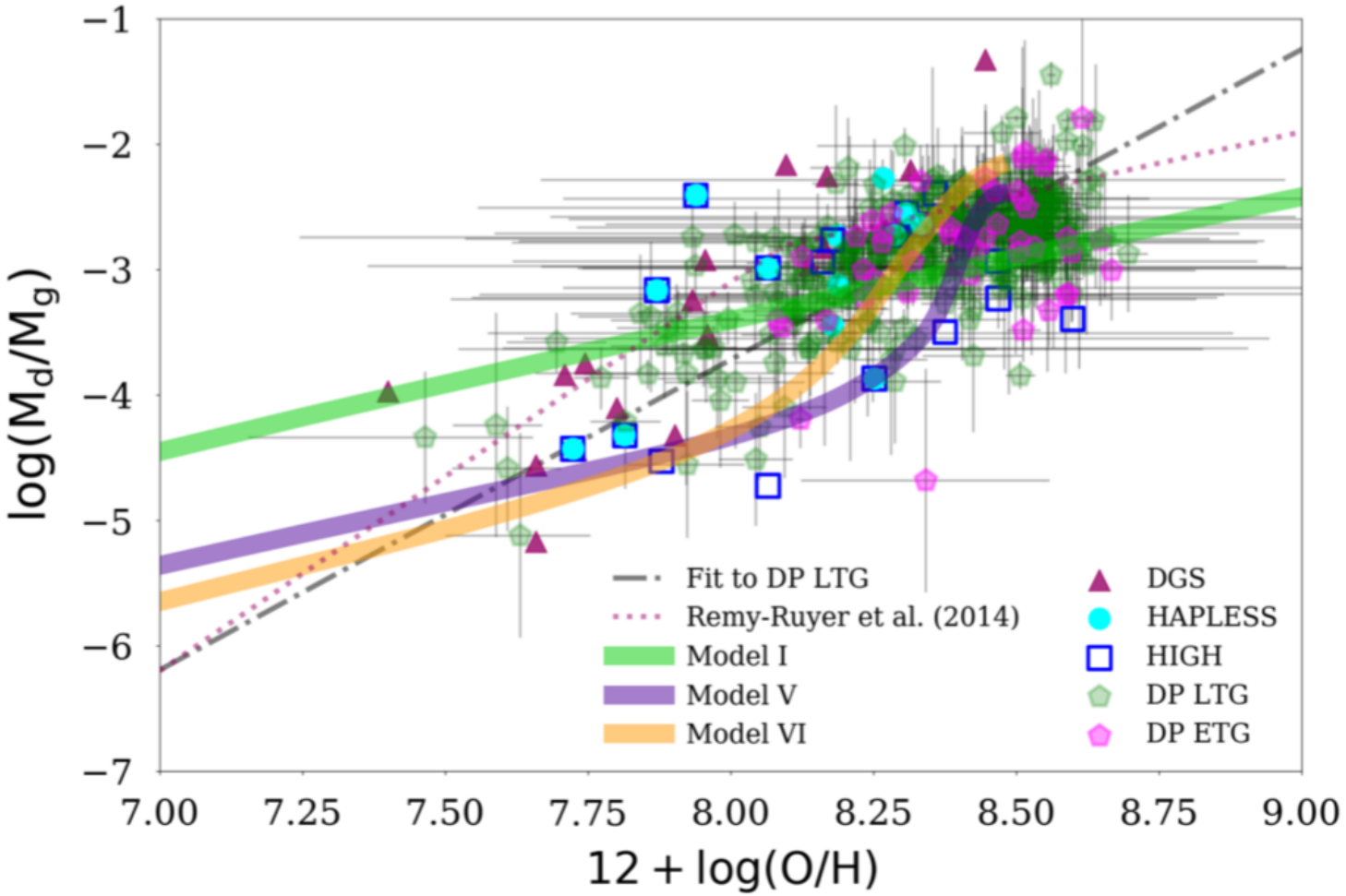
Polarization of Starlight by Polarized Extinction



HD 161056 (Clayton et al. 1995): 2175Å feature *not* polarized

Other Galaxies, Lower Metallicities, Earlier Times...

- For $Z/Z_\odot \lesssim 0.1$, fraction of metals in dust begins to fall...



from De Vis et al. (2019)

As expected if dust formation in ISM dominates for $Z \sim Z_\odot$, since dust formation in ISM $\propto Z^2$. At low Z, unable to maintain high dust abundance in ISM.