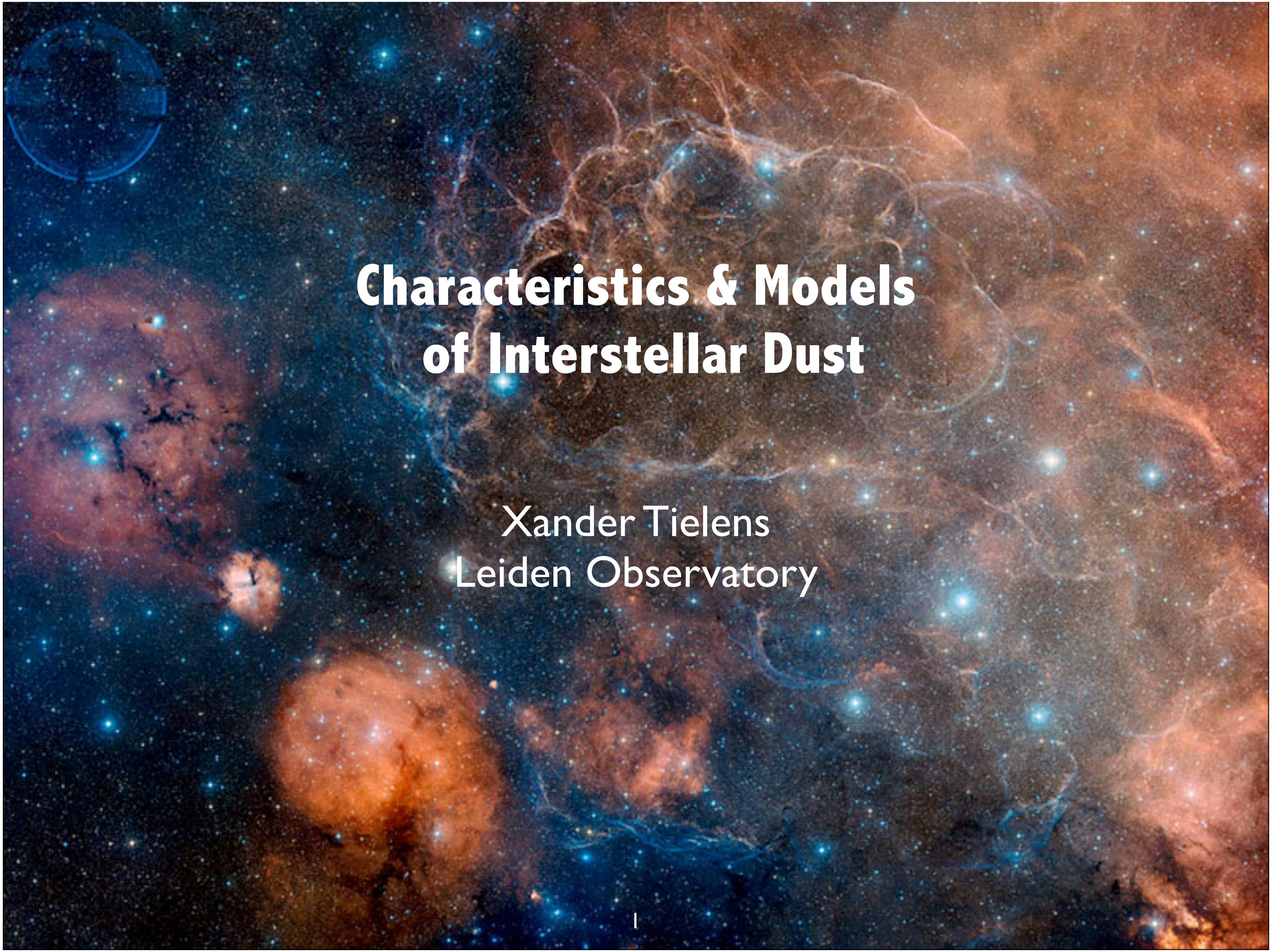
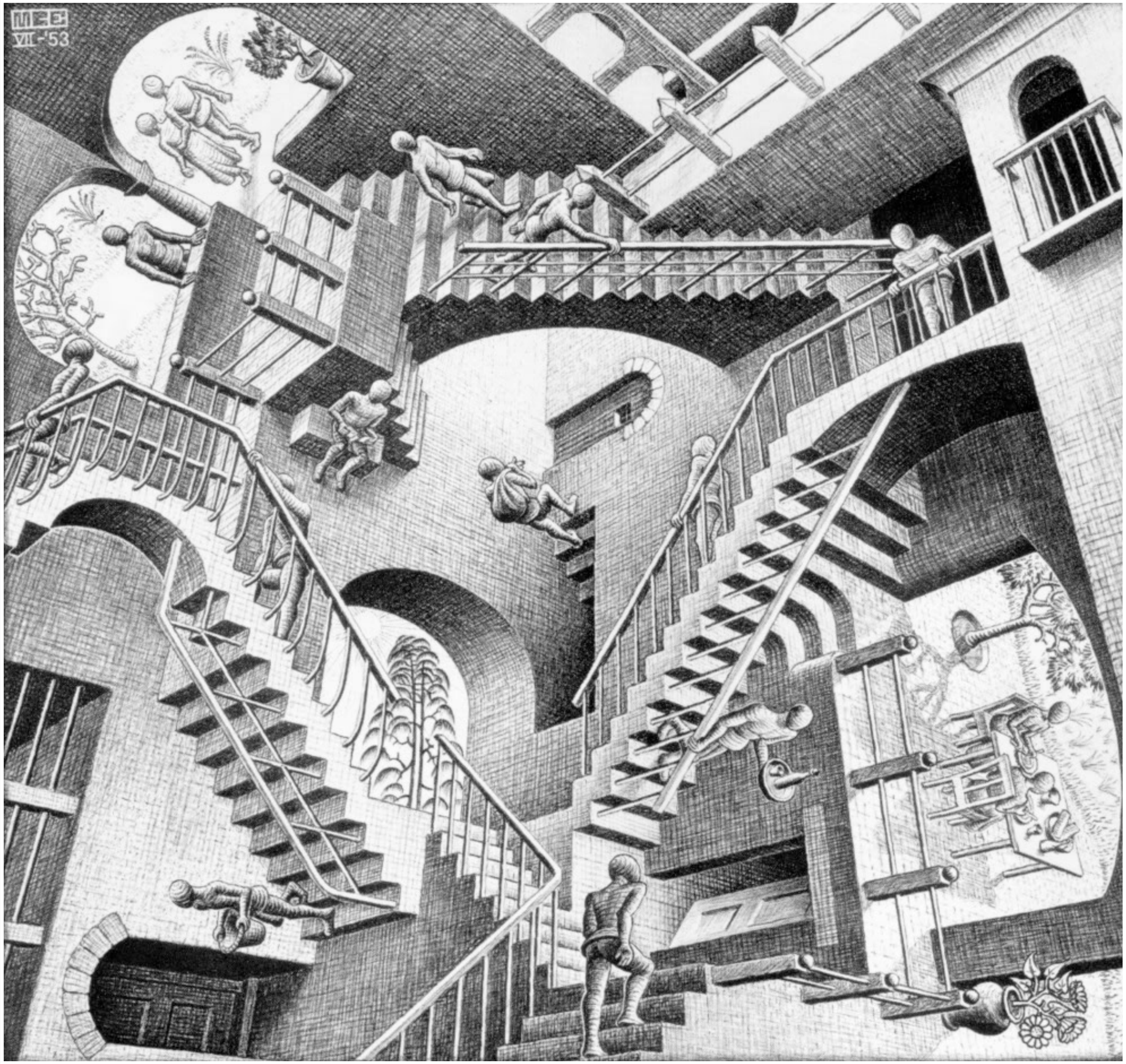


# Characteristics & Models of Interstellar Dust

Xander Tielens
Leiden Observatory



Observers, theoreticians & experimentalists working together on understanding the dusty Universe

# Key Questions

- Where: Origin of Interstellar dust
- What: Inventory of interstellar dust
- How: key processes in its formation and evolution
- When: interstellar dust over the ages
- Why: do we care

# Dust Models

# Interstellar Dust: what do we agree on ?

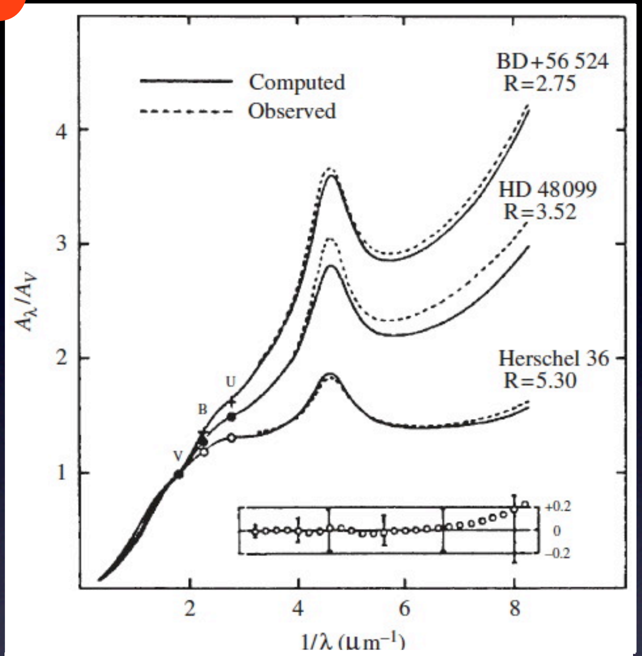
**Grain size distribution**:

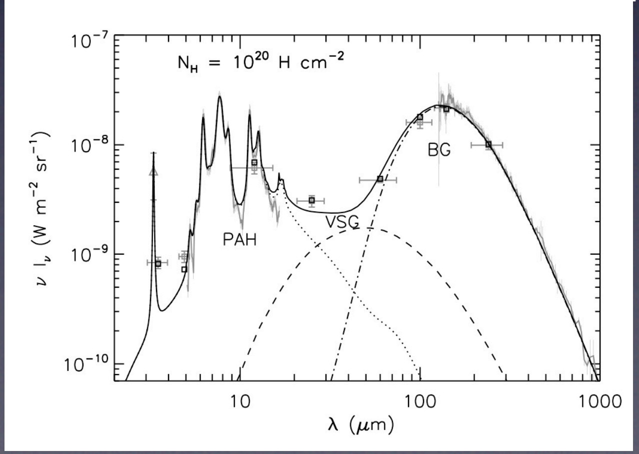
Extinction & elemental abundances

- powerlaw distribution
- exponential cut off at large end
- 50-3000 Angstrom, index -3.5
- mass in largest grains
- number density in small grains

IR emission

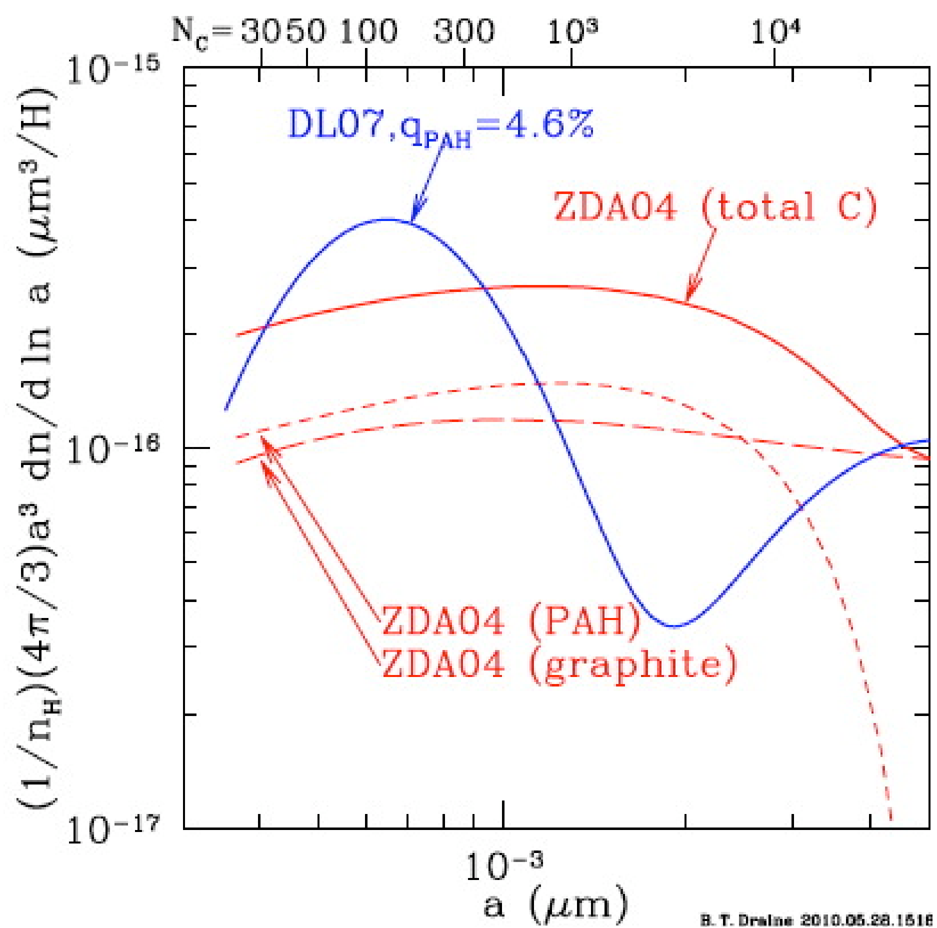
- 5-50 Angstrom





# Let's agree to disagree

and let's do that at every conference



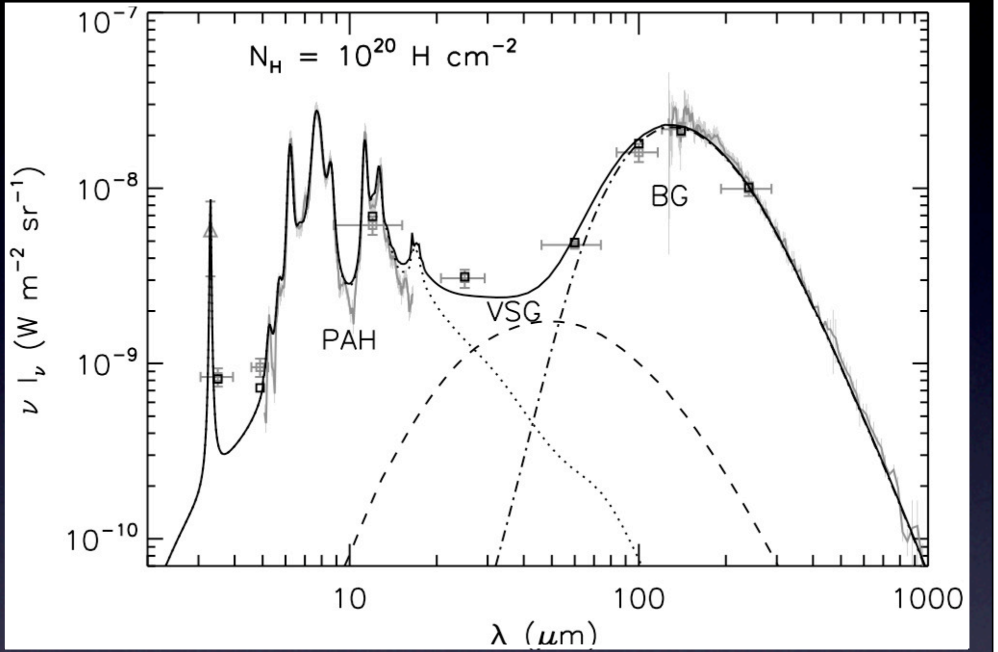
Models: Very precise but highly inaccurate

Draine & Li, 2007, ApJ, 657, 810
Desert et al, 1990, A&A, 237, 215
Zubko et al, 2004, ApJS, 152, 211

# Dust Models & SEDs

Peak wavelength of dust continuum sets $G_o$

- PAH spectrum
  - "independent" of $G_o$
  - Relative strength sets PAH/dust ratio ($q_{pah}$)
- VSG spectrum
  - Depends somewhat on $G_o$
  - Relative strength sets VSG/dust ratio
- Many assumptions differ between the models but each model provides a convenient framework to compare different sources "quantitively"



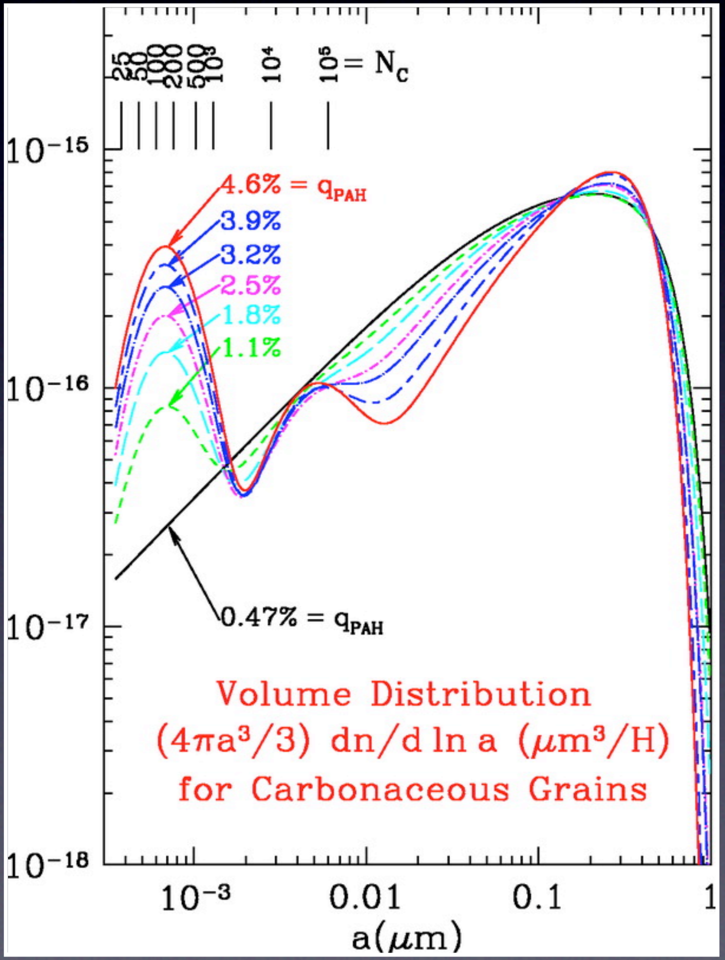
Desert model

# Models & Observed Trends

Observed variations – eg., in IRE strength – can be translated into trends in size distribution variations

Details are highly model sensitive

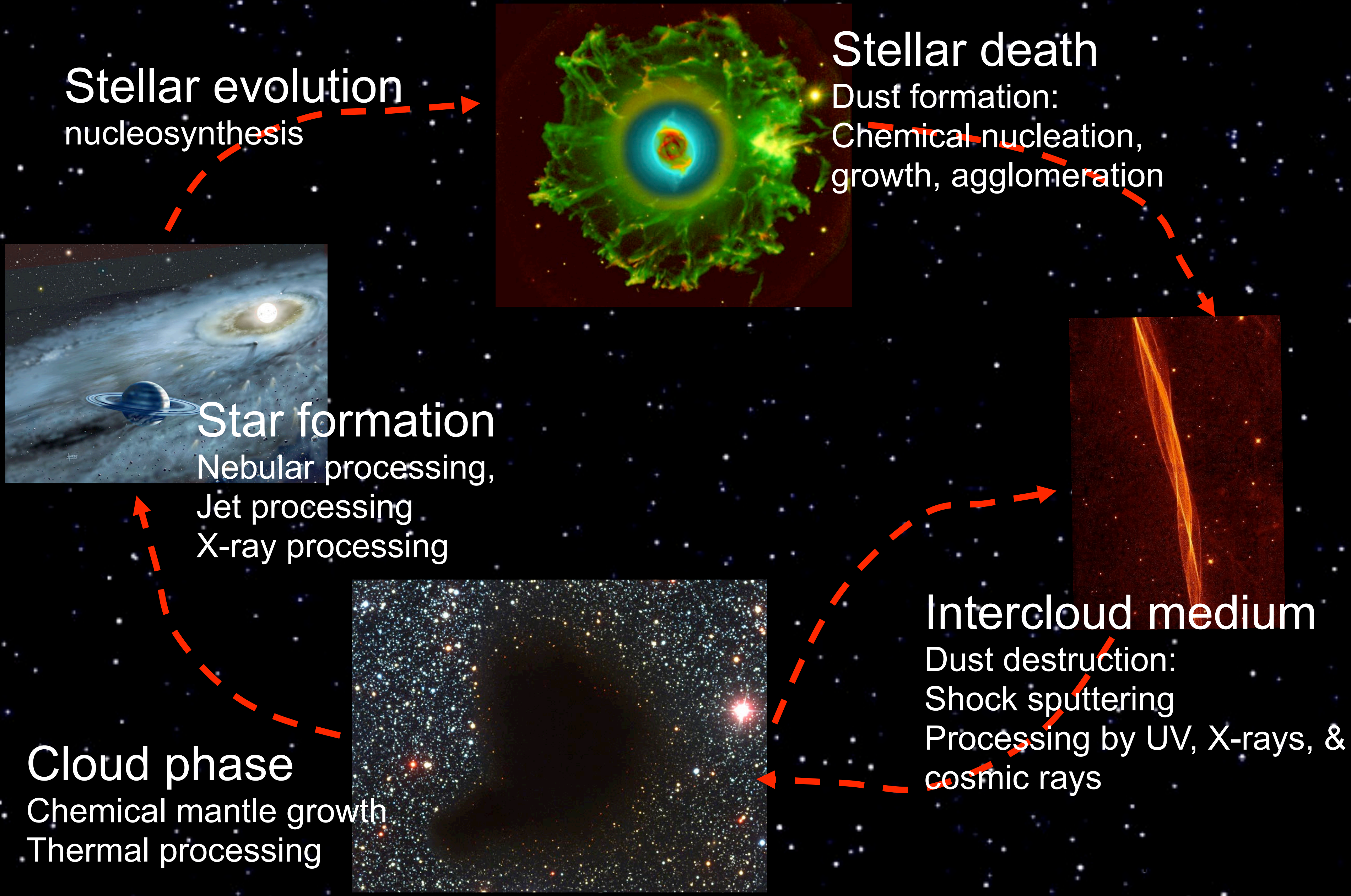
Draine & Li model



# Use them for what they are worth

# Models for Dust Evolution

# Cosmic Journey of Interstellar Dust



## Stellar evolution
nucleosynthesis

## Stellar death
Dust formation:
Chemical nucleation,
growth, agglomeration

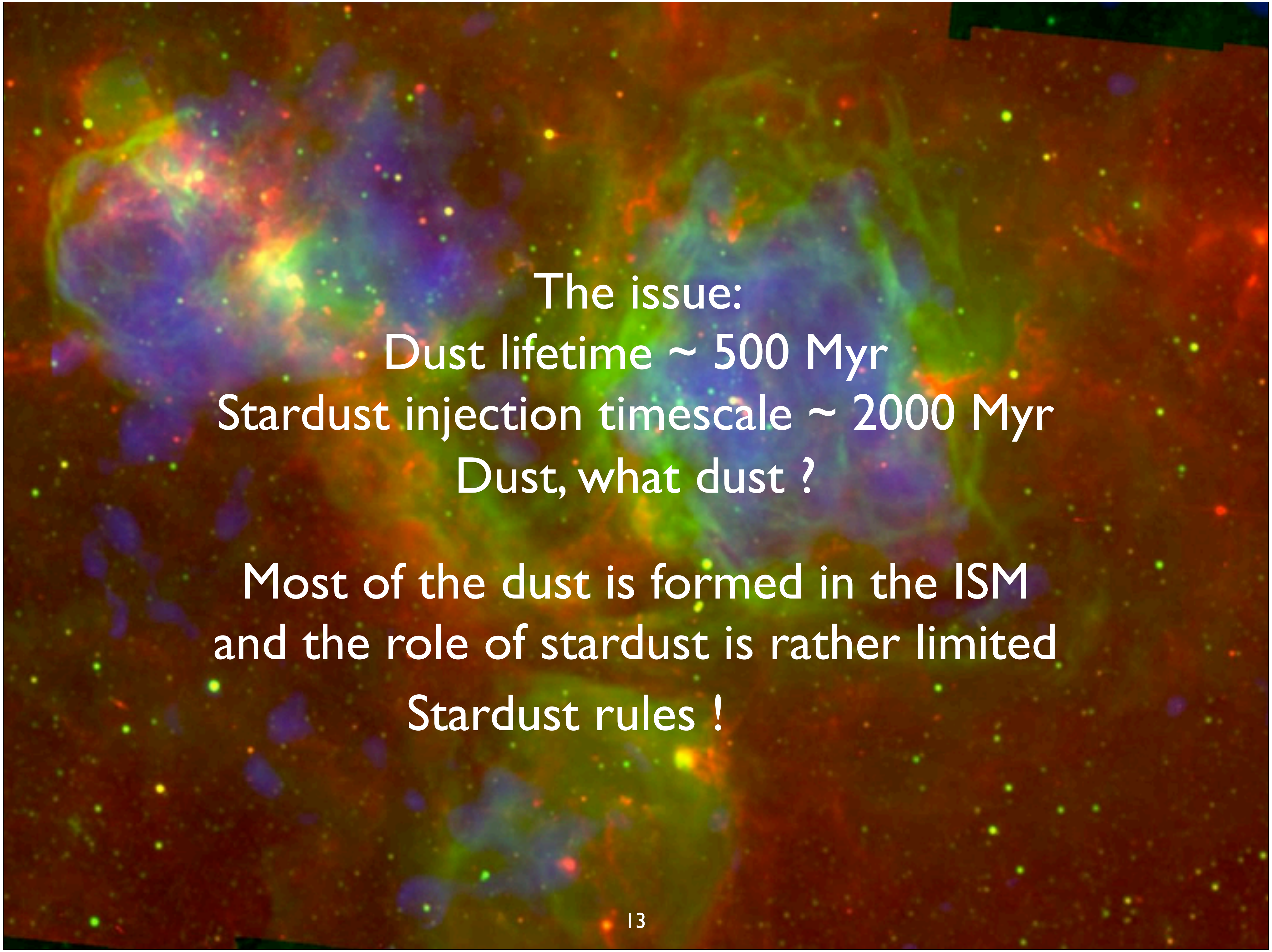
## Intercloud medium
Dust destruction:
Shock sputtering
Processing by UV, X-rays, &
cosmic rays

## Cloud phase
Chemical mantle growth
Thermal processing

## Star formation
Nebular processing,
Jet processing
X-ray processing

Many complex processes which are partly studied, poorly understood, and incompletely incorporated into astronomical models

Focus here on dust destruction



The issue:
Dust lifetime ~ 500 Myr
Stardust injection timescale ~ 2000 Myr
Dust, what dust ?

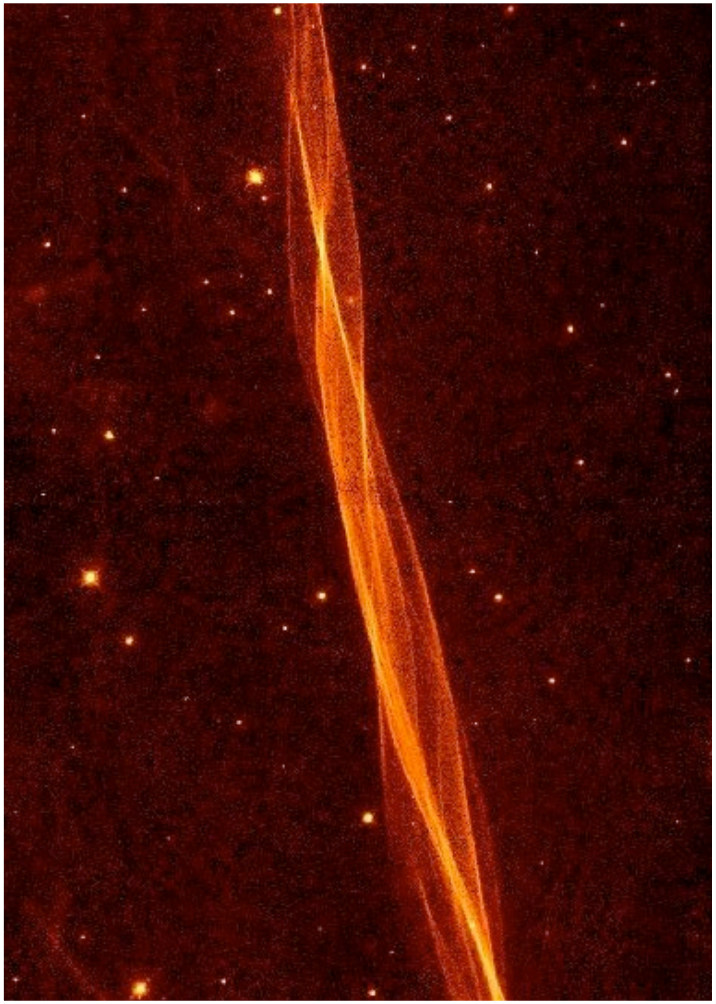
Most of the dust is formed in the ISM
and the role of stardust is rather limited

Stardust rules !

# Dust destruction: What do we agree on ?

- Supernovae shocks destroy dust grains through sputtering and shattering
- not very efficient process: ~10% destruction for 100 km/s shock
- Cumulative effect

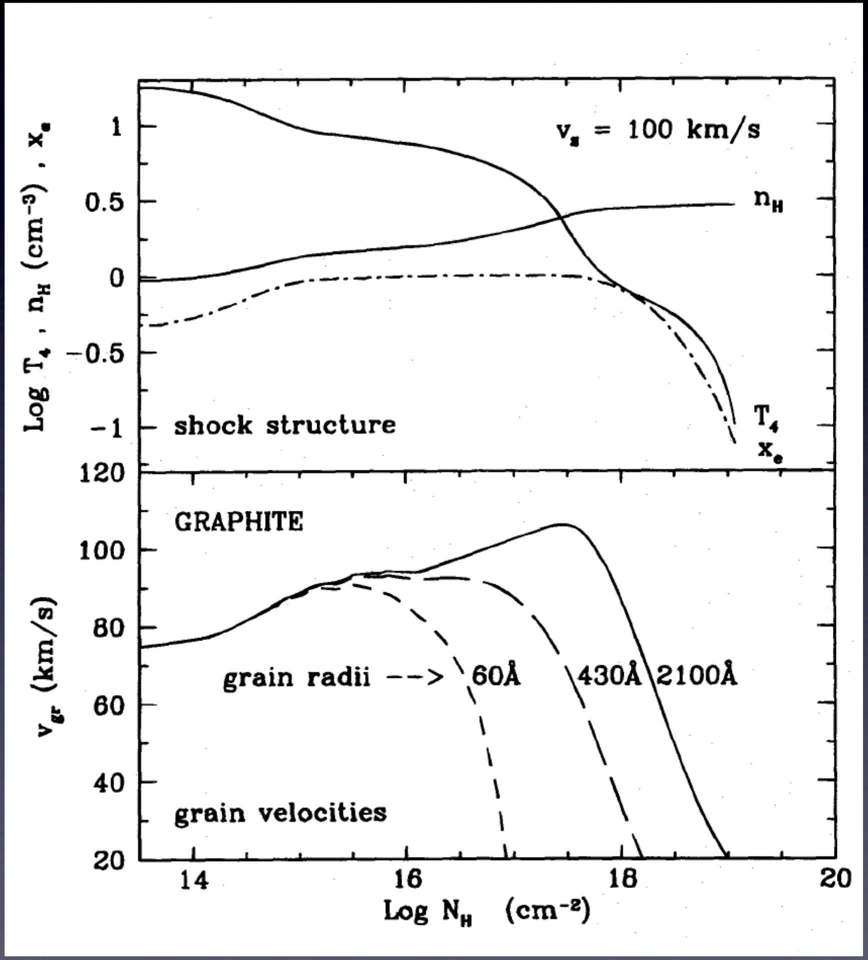
Barlow & Silk, 1977, ApJ, 211, L83
Dwek & Scalo, 1979, ApJ, 233, L81; 1980, ApJ, 239, 193
Draine & Salpeter, 1979, ApJ, 231, 77 & 438
Jones et al, 1994, ApJ, 433, 797; 1996, ApJ, 469, 740



# Shock Processing

Dust: inertial motion + betatron acceleration

Sputtering & shattering

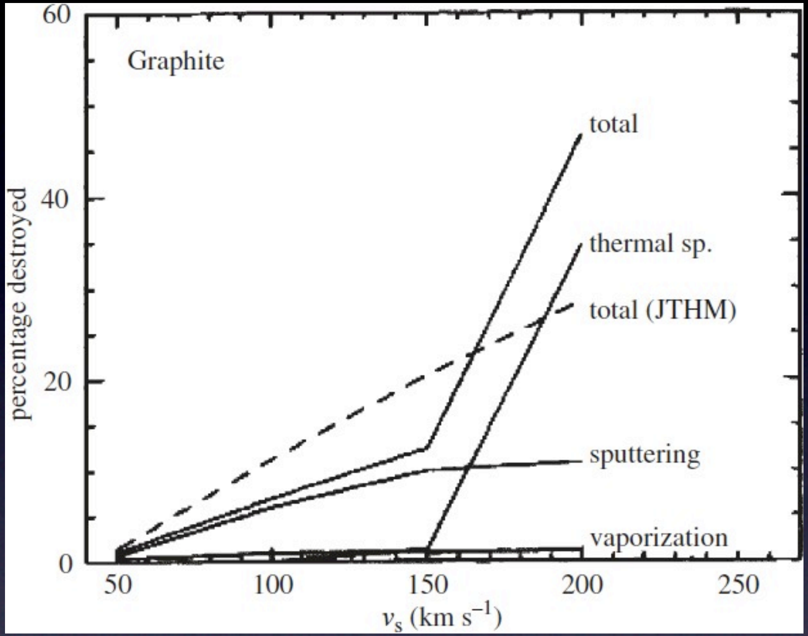


Jones et al, 1994, ApJ, 433, 797; 1996, ApJ, 469, 740

# Dust Lifetime

Need:

- Supernova rates
- Dust destruction efficiencies
- SNR evolution



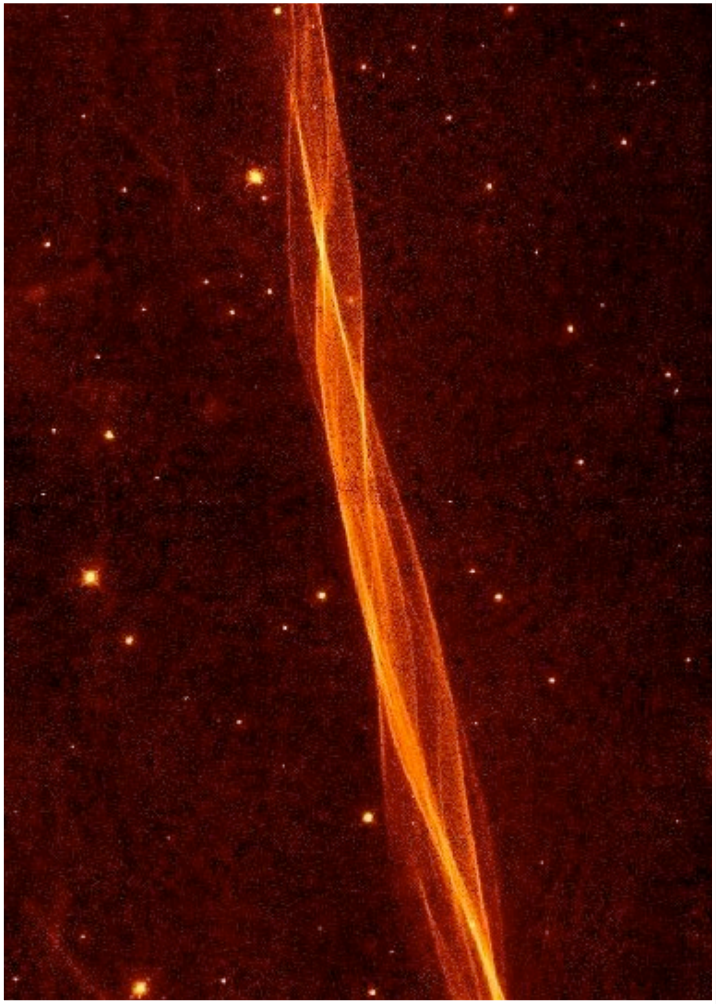
$$k_{\rm des} M_{\rm ISM} = \frac{1}{\tau_{\rm SN}} \int \epsilon(v_{\rm s}) {\rm d}M_{\rm s}(v_{\rm s})$$

$$\frac{1}{\tau_{\rm SN}} = \left(0.4 \times \frac{1}{2} + (0.5 \times 0.1 + 0.5 \times 0.6) \times \frac{1}{2}\right) \times 2 \times 10^{-2}$$
$$\simeq 8 \times 10^{-3}\,{\rm year}^{-1}.$$

**Bottom line: "cumulative lifetime" is 600 and 400 Million years for graphite and silicate grains, respectively**

# INTERSTELLAR SHOCKS

- Shocks in the WNM destroy dust grains through sputtering
- 100 km/s shock "chips" 30 Å layer from a 1000Å grain



- Reaccretion in diffuse clouds
- Calculated 'lifetime': ~500 Myr

Jones et al, 1994, ApJ, 433, 797

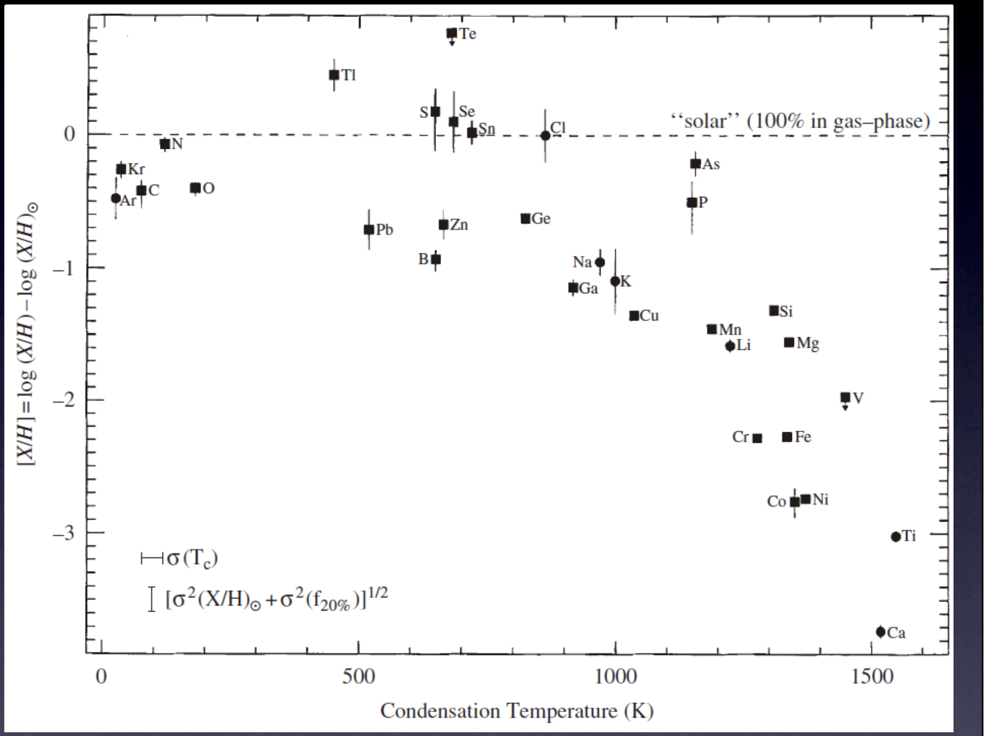
# Theoretical View

- Stardust is rapidly destroyed
- Most dust is formed by accretion/chemistry in the ISM

# Depletion Patterns

Physical and Chemical Processes

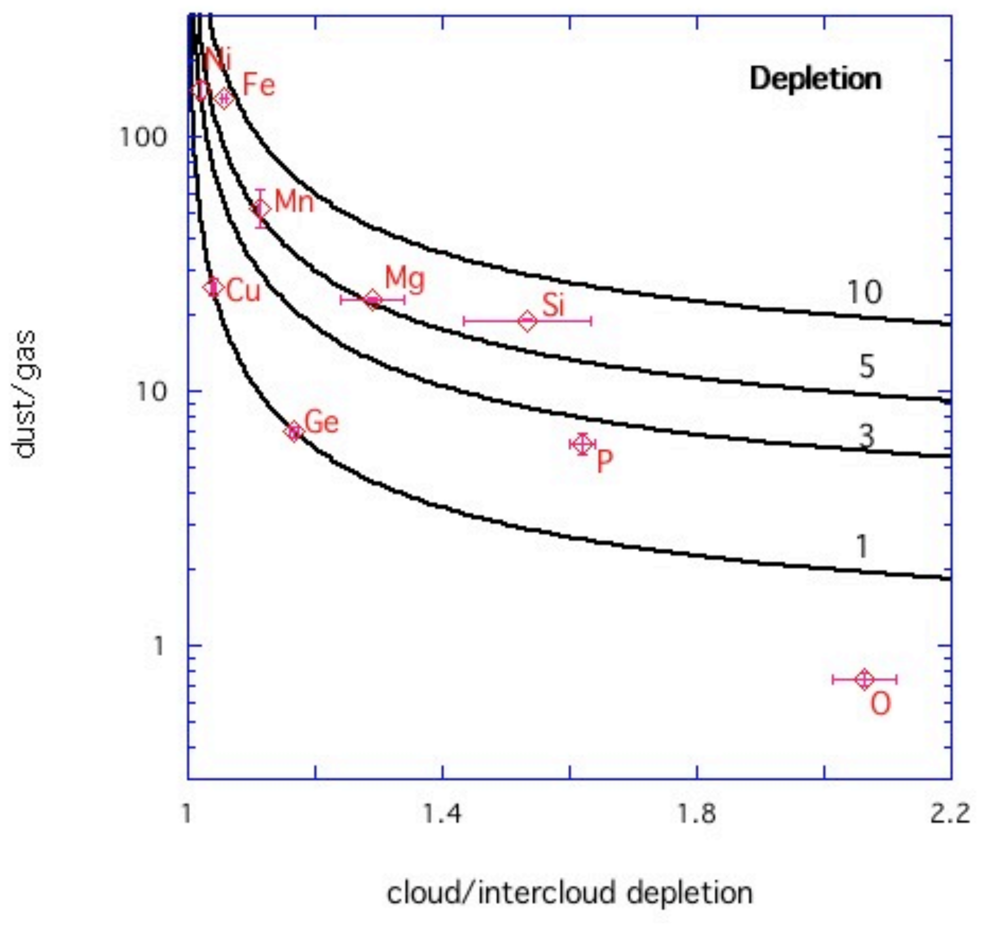
- Condensation in stellar ejecta
- Sputtering in interstellar shocks
- Grain cores & mantles
- Sticking
- Surface chemistry



Field 1974, ApJ, 187, 453
Snow 1975, ApJ, 202, L87
Barlow 1978, MNRAS, 183, 397

# Shocks, Depletion & Mantles

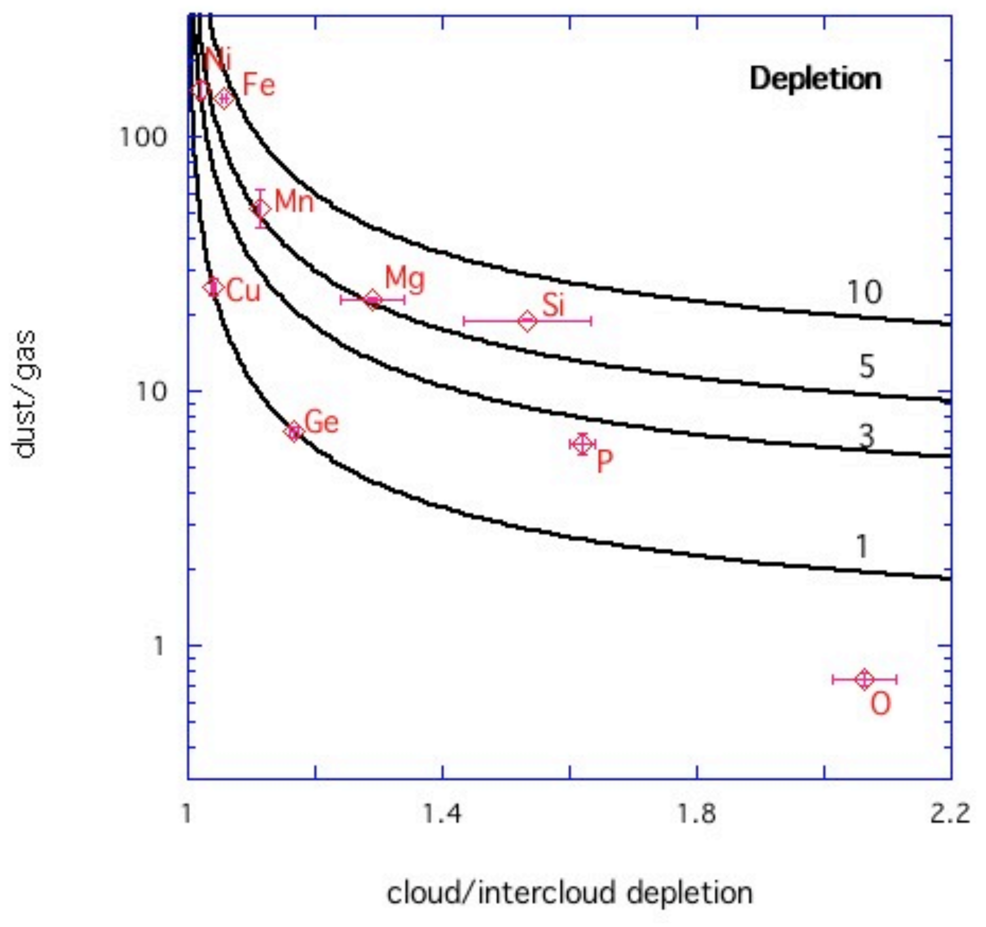
- Large variations in depletion between intercloud and cloud phases
- Shock destruction in intercloud phase
- Accretion in cloud phase
- Rapid cycling between the phases: ~100 Myr



References:
Savage and Sembach, 1996, ARAA, 34, 279
Cartledge et al., 2006, ApJ, 641, 327
Tielens 1998, ApJ, 499, 267; 2009 Astrophysics in the next decade

# Shocks, Depletion & Mantles

- Elemental depletion patterns reflect sputtering in supernova shocks and re-accretion in diffuse clouds
- Thin layer/mantle (“veneer”) is sputtered off and accreted on again but most of the core survives
- Oxygen involved in veneer but carbon is not



References:
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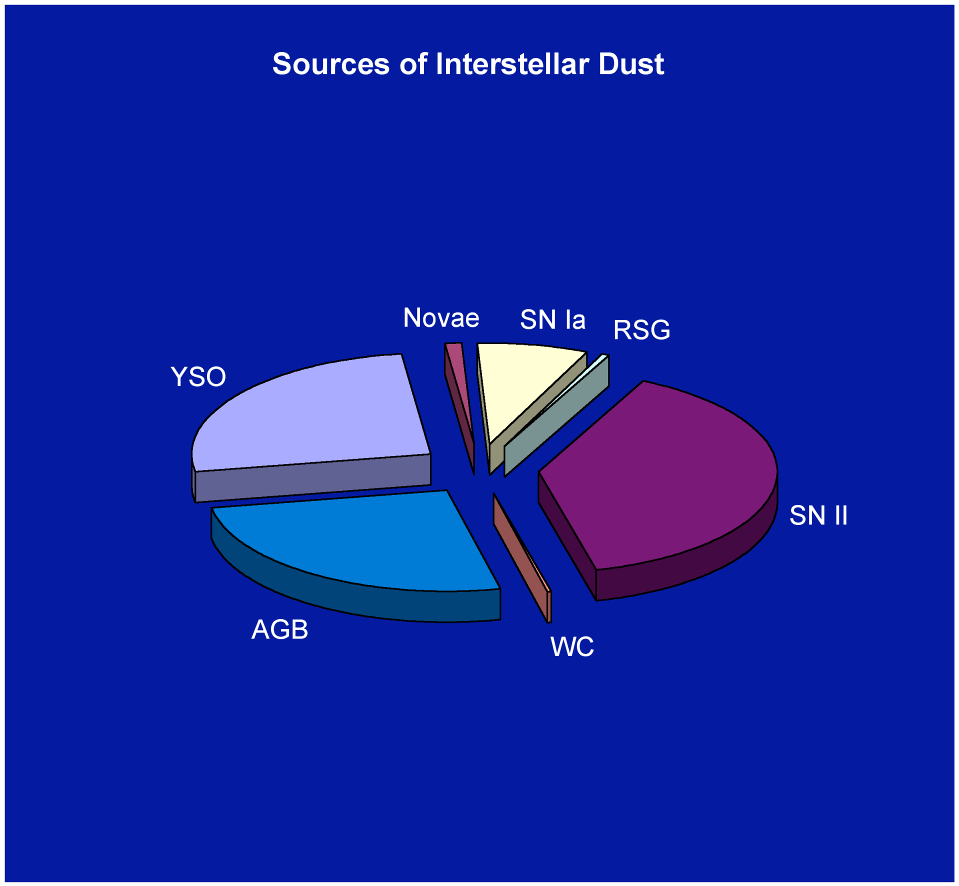
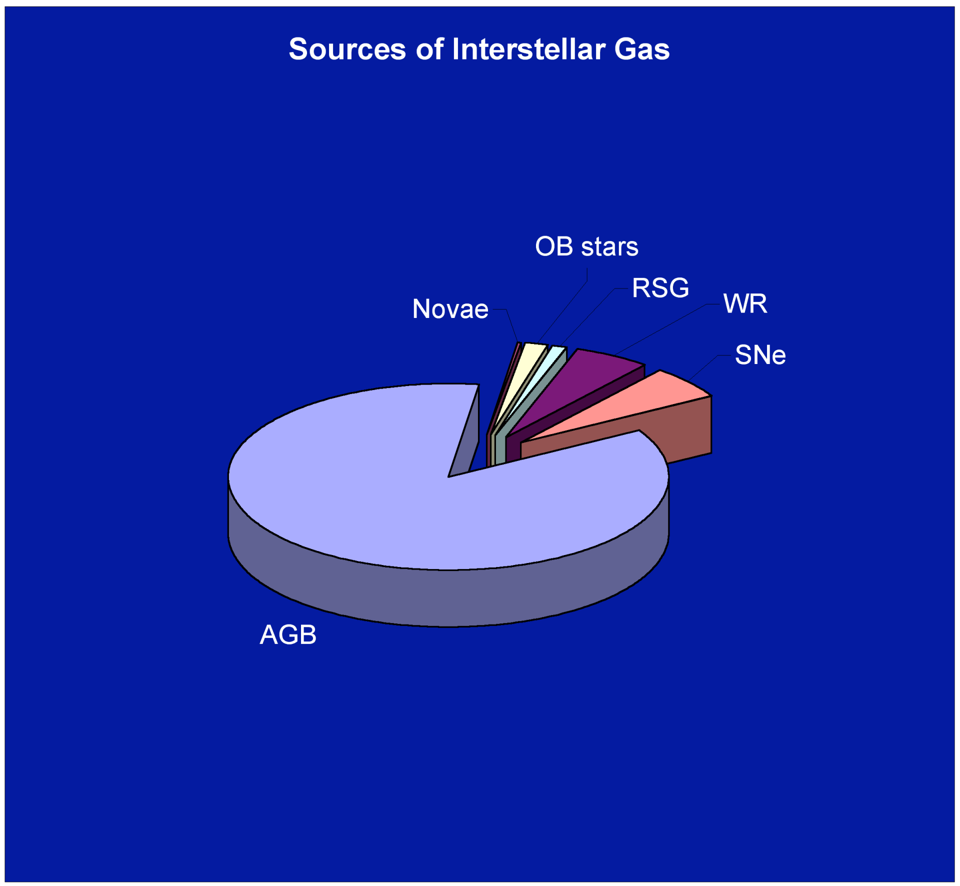
Cartledge et al., 2006, ApJ, 641, 327
Tielens 1998, ApJ, 499, 267; 2009 Astrophysics in the next decade

# Depletion Patterns


Sources of Interstellar Dust


Sources of Interstellar Gas

>10% of the elements are injected by non-dust-stellar sources

but depletion of Ca, Fe, Ti is ~90–99.9%

interstellar dust as vacuum cleaner

Jura 1987, Interstellar Processes
Barlow 2009, Astrophysics in the next decade

# Oxide Mantle Formation

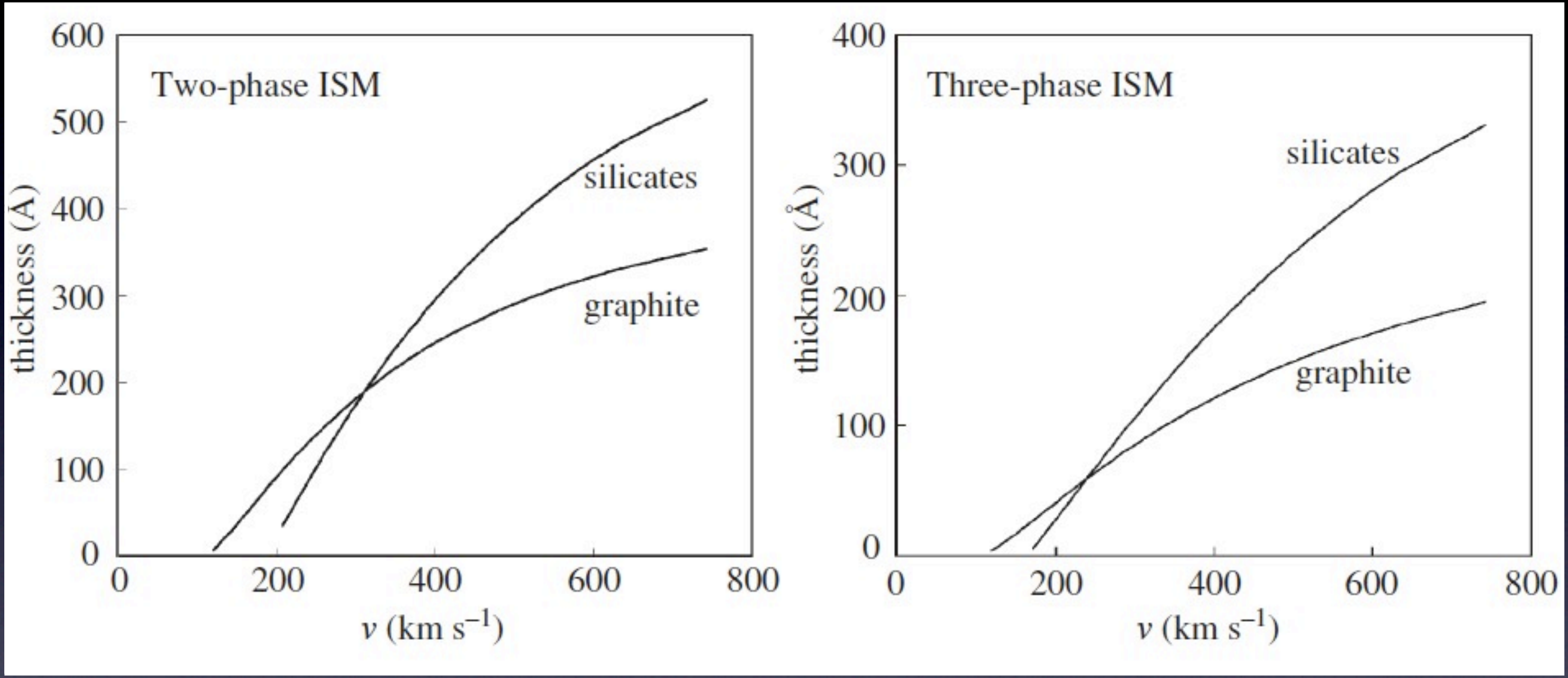
- Chemistry of surface interaction in diffuse ISM largely unexplored
  - Formation of volatile hydrides vs coordination complexes vs salts
  - Photodesorption
  - Electron recombination
  - Bottom line: some elements rapidly deplete out (Fe, Ti, Ca, ...) others are not involved (Na, K, Zn, S, N, C, ...)

# Carbon Depletion

- Some observational contradictions:
  - No variation in the diffuse cloud/intercloud depletion (eg., typically shocked to 100 km/s)
  - Very low depletion in ζ Ori high velocity (100 km/s) gas
- How can we reconcile these observations ?
- preshock gas in ζ Ori is HIM with $n \sim 10^{-3}$ $cm^{-3}$
- My interpretation: C-depletion is historical: reshocked or rejuvenated SNR

Welty et al, 2002, ApJ, 579, 304
Sofia et al, 1997, ApJ, 482, L105

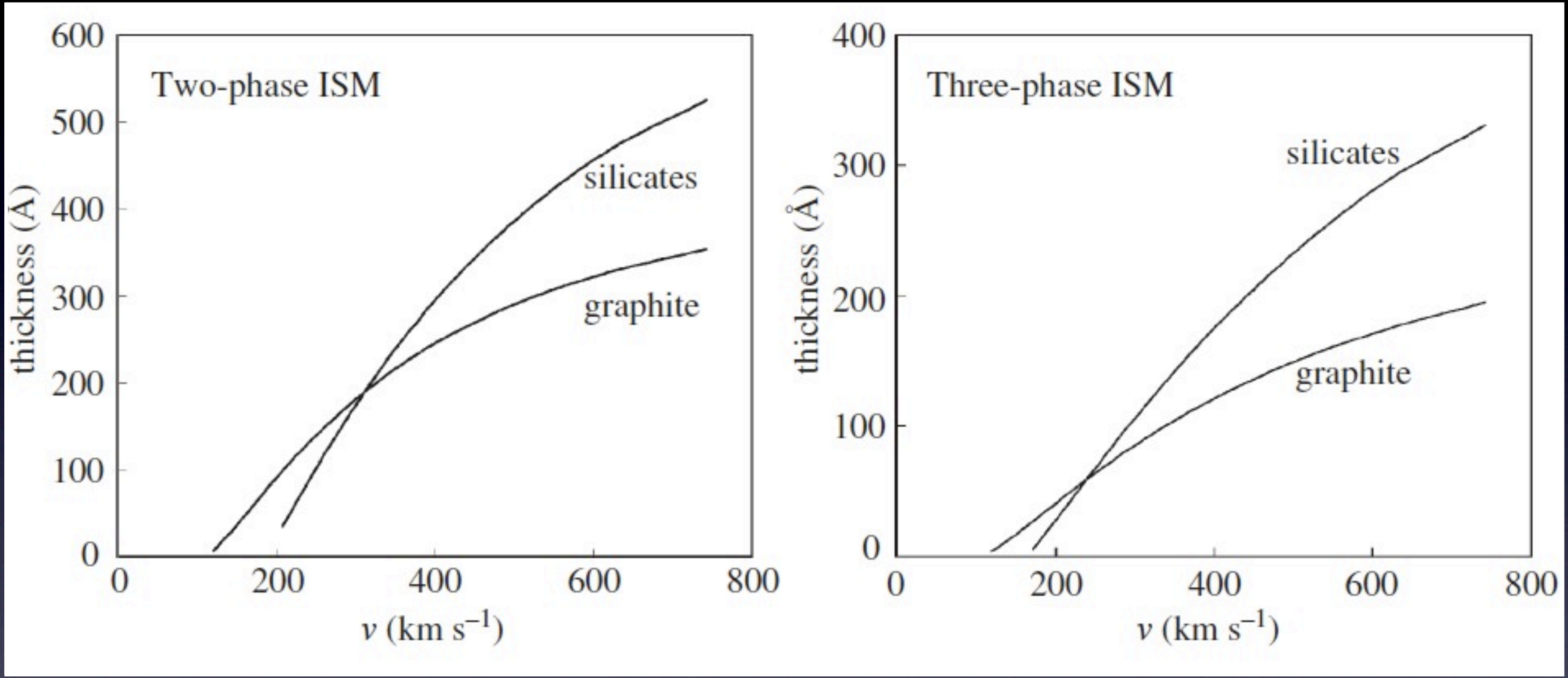
# Destruction in SNR



2-phase medium: 200 Å grains are destroyed in 750 million years
3-phase medium: 200 Å silicate/graphite grains are destroyed in 1/4.5 billion years

Jones et al, 1994, ApJ, 433, 797
Tielens, 2005, Physics and Chemistry of the ISM

# Destruction in SNR



- Destruction sensitive to model for SNR evolution
- ζ Ori high velocity cloud: rejuvenation & reprocessing of SNR material and carbon grains < 200A & silicate grains > 1000A

Jones et al, 1994, ApJ, 433, 797
Tielens, 2005, Physics and Chemistry of the ISM

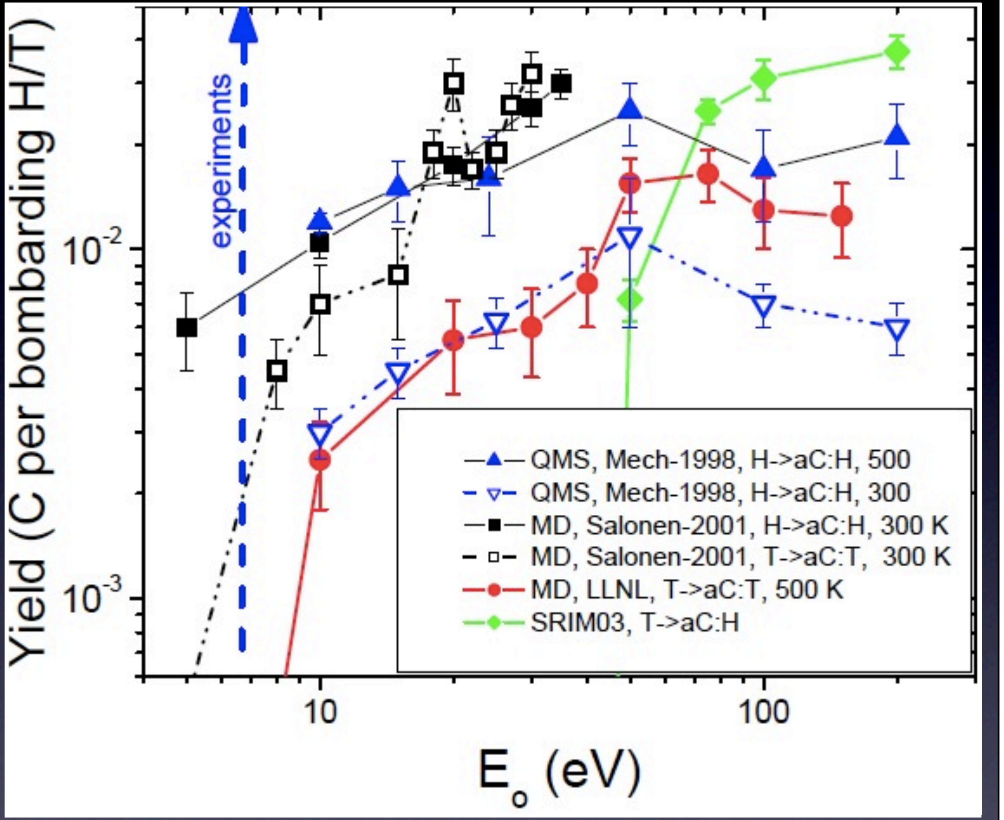
# Carbon Sputtering

- Amorphous carbon versus graphite sputtering
- New SRIM calculations predict much higher sputtering yields for amorphous carbon
- Note: (interstellar) carbon sputtering was 'always' amorphous carbon sputtering
  - There is no graphite sputtering !
  - H beam transforms graphite into amorphous carbon
- Difference in calculations reflects
  - difference in angle of incidence dependence
  - mass of sputtered atom

Serra-Diaz & Jones, 2008, AA, 492, 127
Tielens et al, 1994, ApJ, 431, 321

# Low E Carbon Sputtering

- Experiments: Chemical sputtering at low E
- T-dependent
- SRIM calculations fail
- MD calculations are becoming feasible



# Carbon: Bottom Line

- Don’t trust observations blindly
- Don’t trust experiments blindly
- Don’t trust SRIM
- Can we trust MD ?
- ...

# Dust and Depletion

- Silicates:
  - Large grains (>1000A)
  - Sputtered in WNM/WIM
  - Reaccrete oxide surface layer (chemistry ??) in CNM
  - Never fully destroyed (in SNR)
- Carbon:
  - Small grains (<200 A)
  - Not affected in WIM/WNM
  - Fully destroyed in SNR

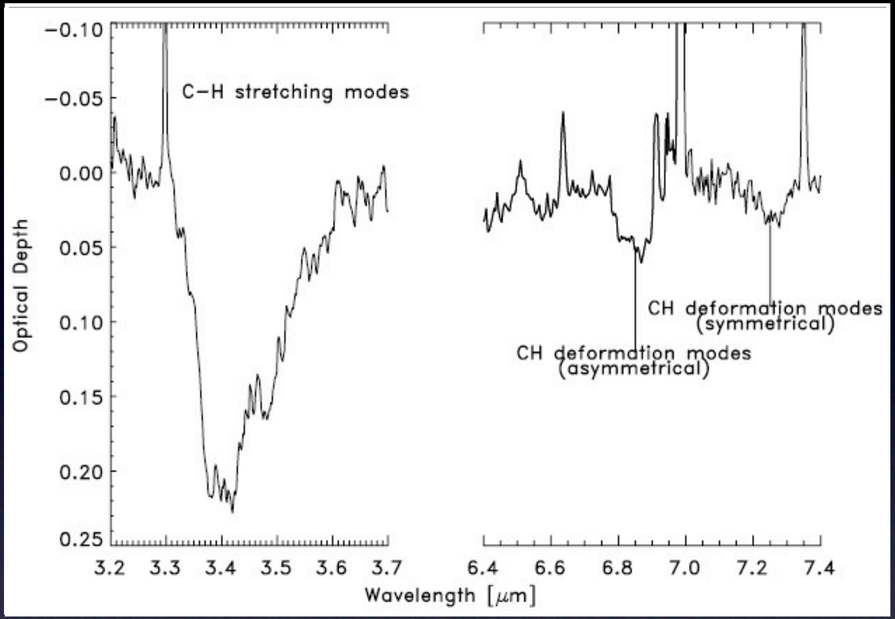
# Interstellar Hydrocarbon Solids

Hydrogenated amorphous carbon

- ~10% elemental C
- observed in
  - diffuse ISM
  - not in molecular clouds
  - GL 618

- Origin
  - Carbon soot
  - Shock processed carbon soot
  - H/UV processed carbon soot

- Surface layer ?



Mennella et al, 2002, ApJ, 569, 531
Schnaiter et al, 1999, ApJ, 519, 687
Chiar et al, 1998, ApJ, 507, 281
Tielens et al 1994, 431, 321

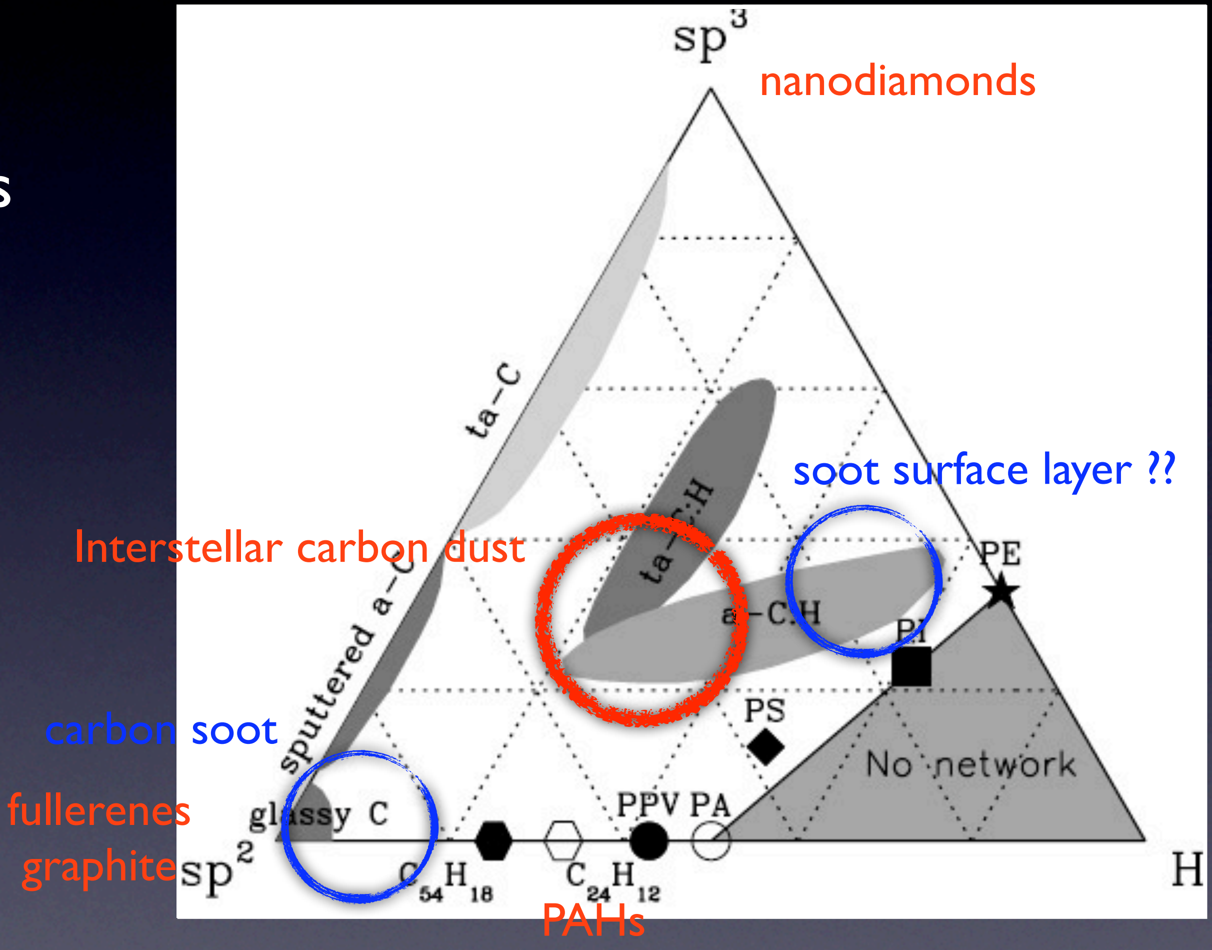
# Carbonaceous Dust

Composition:

- IR absorption features imply Hydrogenated Amorphous Carbon

Processing:

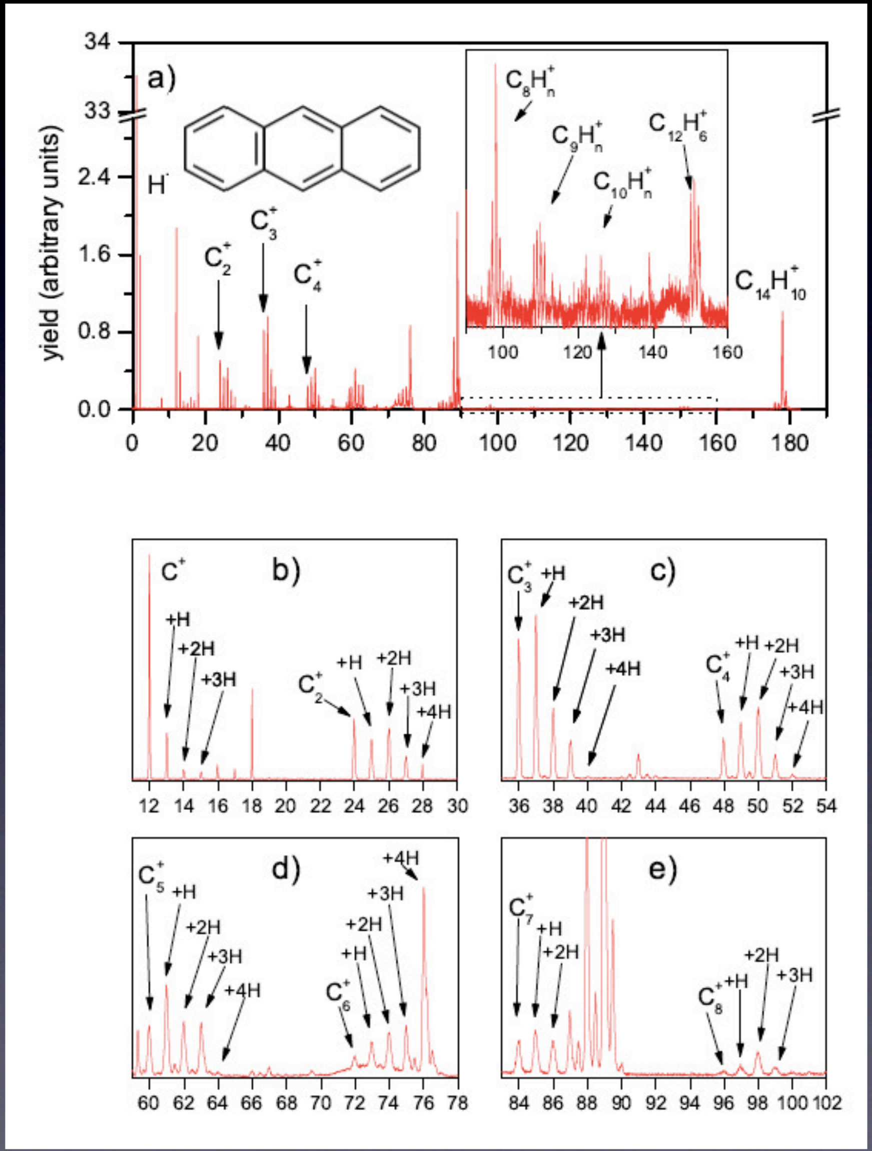
- Photobleaching & thermal H-reactions
- Ions in shocks



# Energetic Ion Interaction with PAHs

- Shock waves: (50eV/nucleon)
- Hot plasma's in supernova remnants & galactic winds (0.5k eV)
- Cosmic Rays (10MeV/nucleon)

- Ion interaction with PAHs
  - Charge exchange
  - Electronic stopping
  - Fragmentation



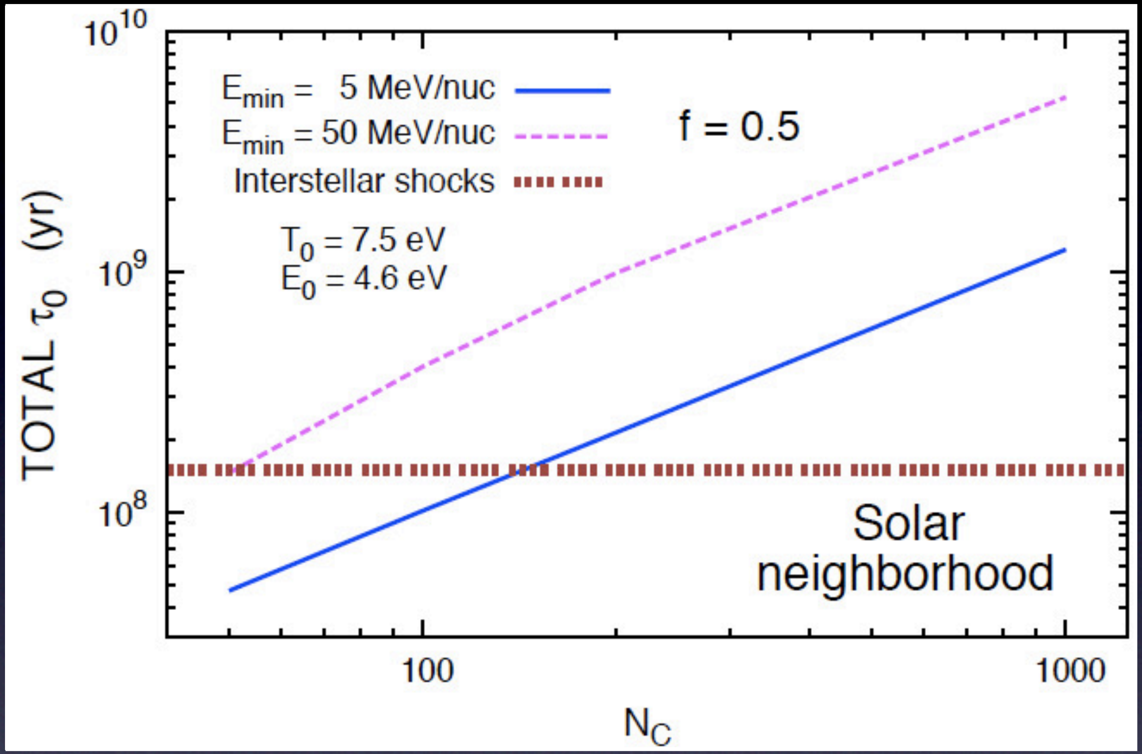
Postma et al 2010, ApJ, 708, 435

# PAH Destruction

## Lifecycle of Interstellar PAHs

Timescales estimated by extrapolating solid state concepts into the molecular domain

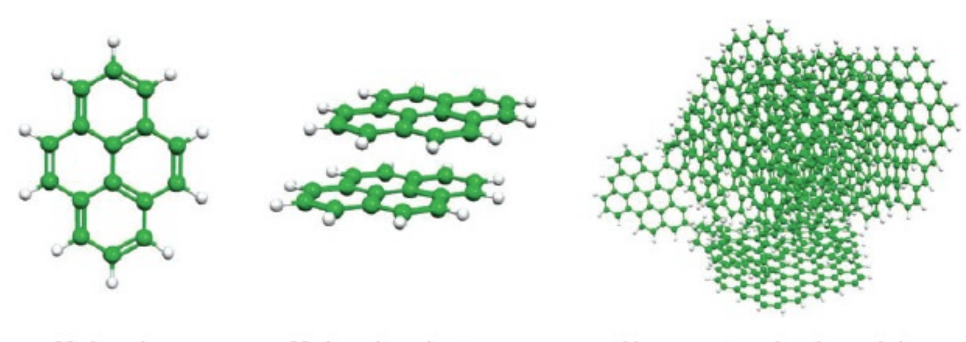
- Formation C-rich AGB stars
  - Timescale ~ 2 Byr
- Shocks/Cosmic Rays
  - Timescale ~ 100 Myr
- UV photolysis
  - Timescale ~ 100 Myr
- Reaction rates are poorly known for large PAHs

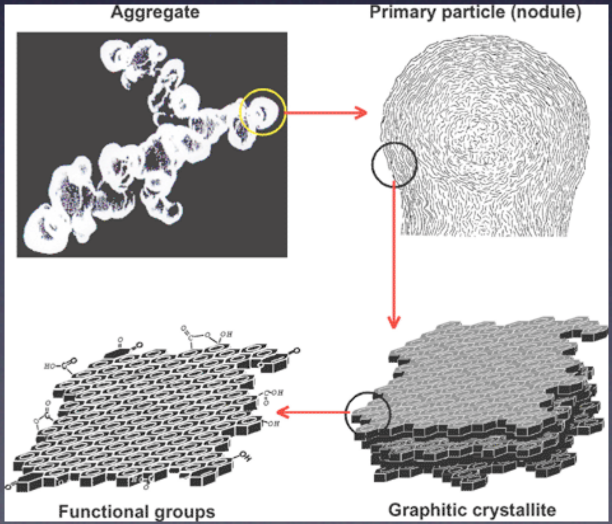


Micelotta et al, 2010, A&A, 510, A36+; 510, A37+; 526, A52+

# Shattering of Carbon Grains

- Grain-grain collisions will produce shattered fragments
- Graphite/soot
  - P~50 kbar, v~1km/s
  - Smallest sizes may be graphene/PAH-sheets
- Hydrogenated Amorphous Carbon may lead to aliphatic/aromatic cage-like structures





Jones et al, 1996, ApJ, 469, 740

# Organic Grain Mantles

- Model: accreted ice mantles are UV/ion processed to organic goop in dense clouds
- General experimental support
- Observational: no support
- Would have to completely graphitize and this has never been observed in the lab
- My interpretation: Ices and molecular cloud material do not play a role in dust formation in ISM

# Summary

- Emission models are as good as you trust them

- Dust in the Milky Way is highly processed
- Large silicate grains:
  - Shock processing: 100 km/s shock every 100 Myr
  - Sputtering/accertion of oxide-veneer in intercloud/cloud medium
- Small carbon grains:
  - ‘Unaffected’ by 100 km/s shocks
- PAHs:
  - Lost in 100 Myr
  - Replenished by shattering
- **Dust lifetime issues are resolved by accretion/shattering**

Oh, what a tangled web I weave
when I deceive ?!

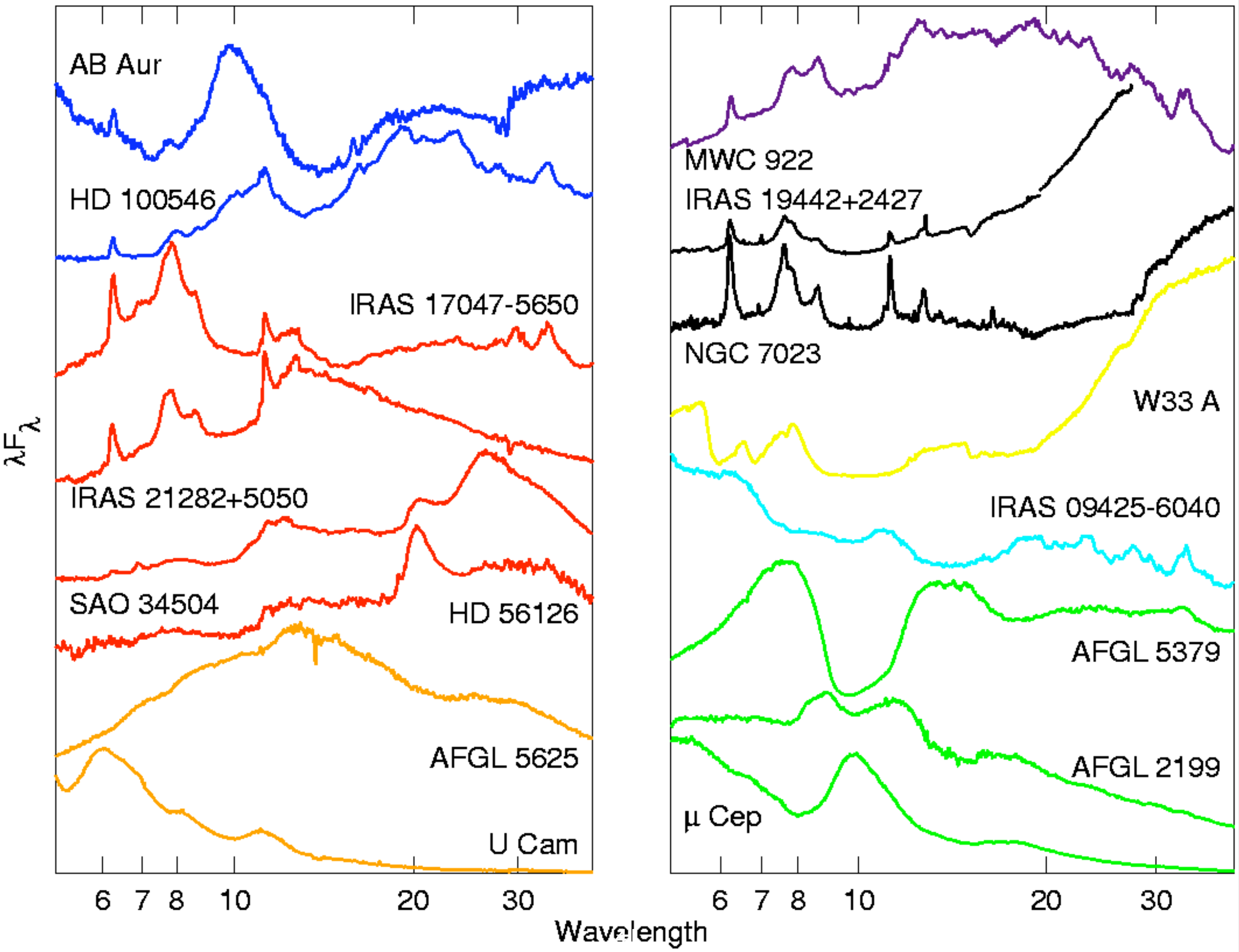
# Key Questions

- Chemistry of mantle formation ?
- Properties of mantles ?
- Are there separate oxide and carbonaceous grains & chemistry ?
- Formed by accretion versus processing ?
- What about the silicate feature ?
- What about the 2175 A bump, the aliphatic features & HAC ?
- What are true dust probes at high z ?

# Take Home Message for this Audience

- Dust properties will reflect ISM processing
- Dust properties will vary from one phase to another
- High redshift dust may be quite similar or very different from what we observe locally
- The properties of dust are only limited by our imagination

# Dust as a Tracer of Stardust Sources



# Dust Inventory of the ISM

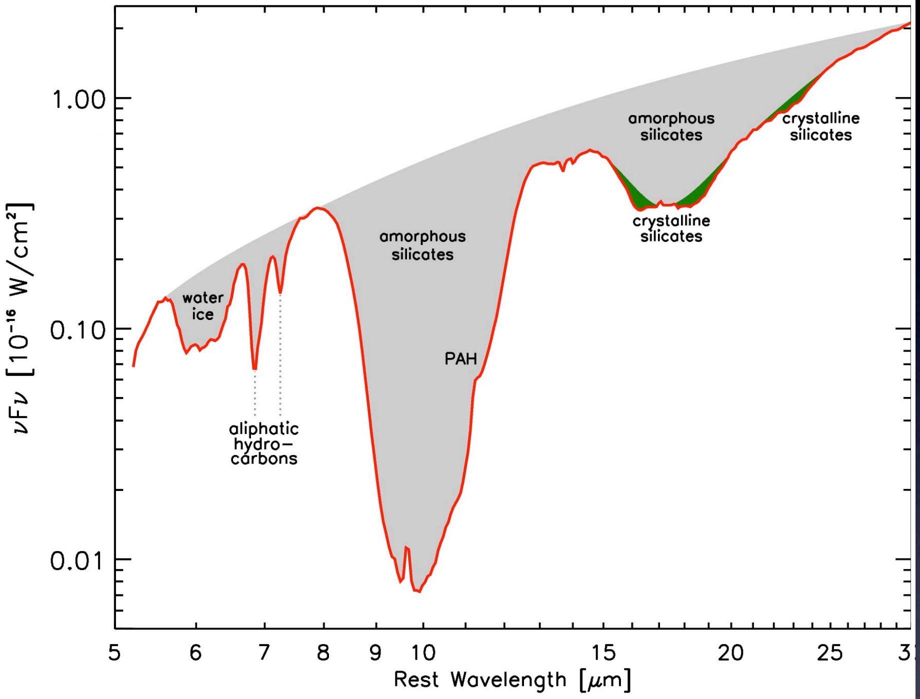
- Silicates:
  - Amorphous FeMg-silicates
  - Forsterite
  - Enstatite
  - Montmorillonite ?
- Oxides:
  - Corundum
  - Spinel
  - Wuestite
  - Hibonite
  - Rutile
- Sulfides:
  - Magnesium sulfide
  - Iron sulfide ?
- Ices
  - Simple molecules such as $H_2O$, $CH_3OH$, $CO$, $CO_2$
- Carbides:
  - Silicon carbide
  - Titanium carbide
  - And others
- “Pure” Carbonaceous compounds:
  - Graphite
  - Diamonds
  - Hydrogenated Amorphous Carbon
  - Polycyclic Aromatic Hydrocarbons
  - Fullerenes
- Others:
  - Silicon nitride
  - Metalic iron ??
  - Carbonates ?
  - Silicon (??), silicon dioxide

# Dust Composition in ULIRGs

## Starburst environments:

Crystalline silicates and HAC in ULIRGs

- "excess" dust from Red Supergiants, Luminous Blue Variables, Supernovae and Protostars
- Differences in supernova processing
- Differences in cosmic ray processing

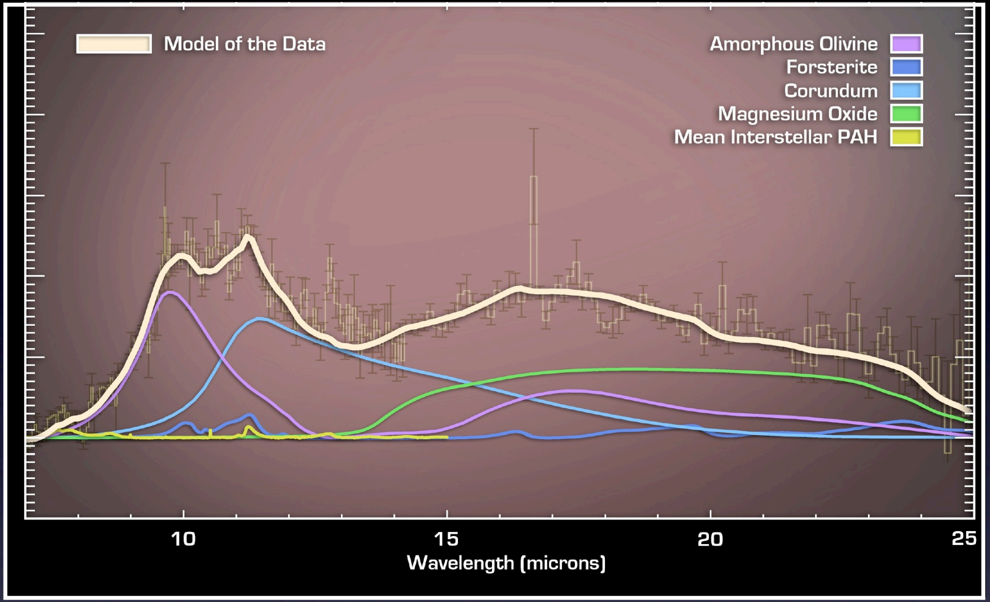


Armus et al, 2007, ApJ,656, 148
Spoon et al, 2006, ApJ, 638, 759

# Dust in AGN/Quasars Winds

Oxides and crystalline silicates

Formed in torus and ejected in quasar wind ?



Marwick-Kemper et al., 2007, ApJ,668, L107

# Tracing Dust Sources through Spectroscopy

- JWST will probe SN/LBV dust formation within 50Mpc
- JWST can probe in glorious detail characteristics of dust in AGN environments