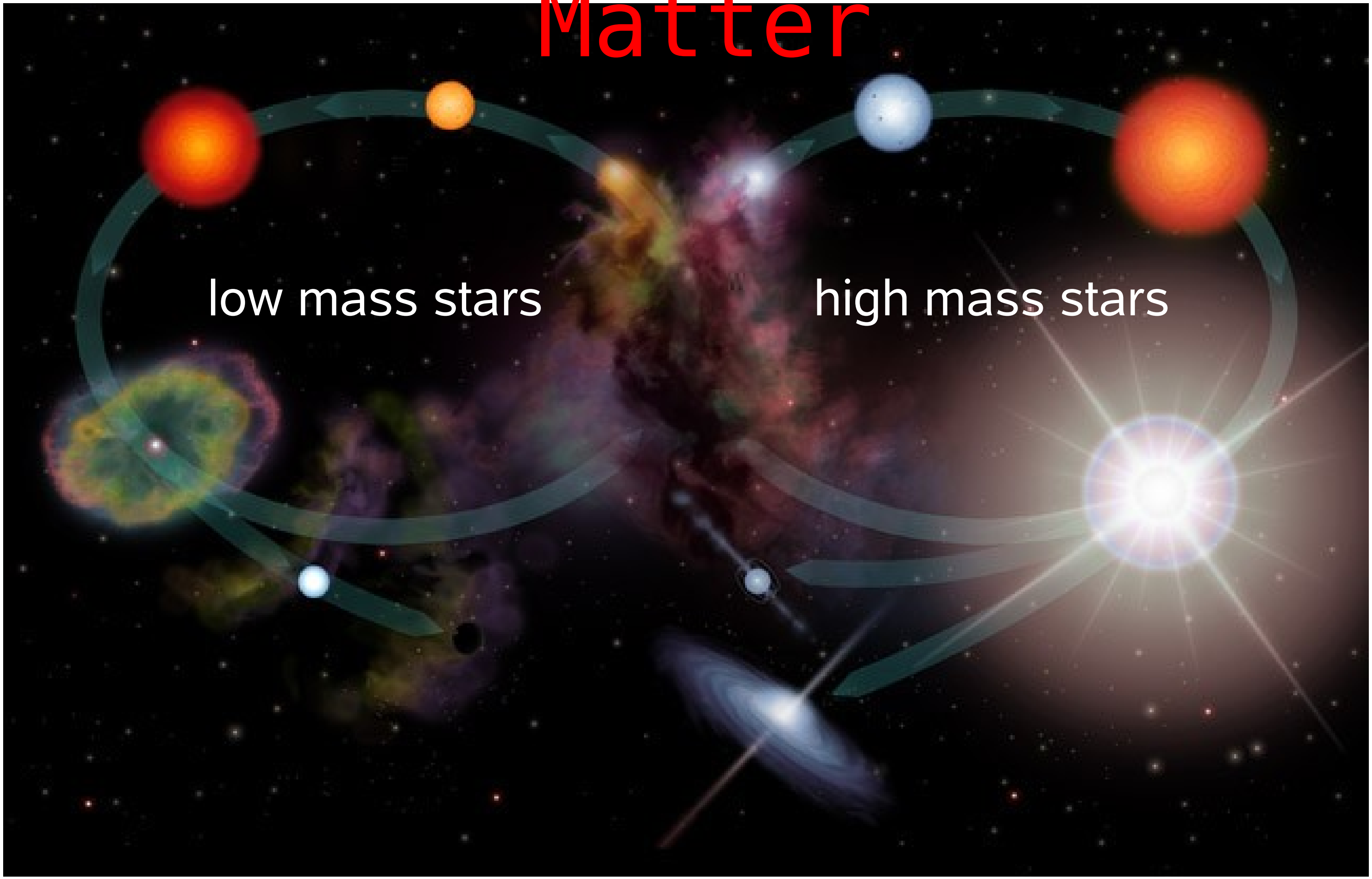
The Cosmic Journey of Dust

Xander Tielens

The Lifecycle of Baryonic Matter



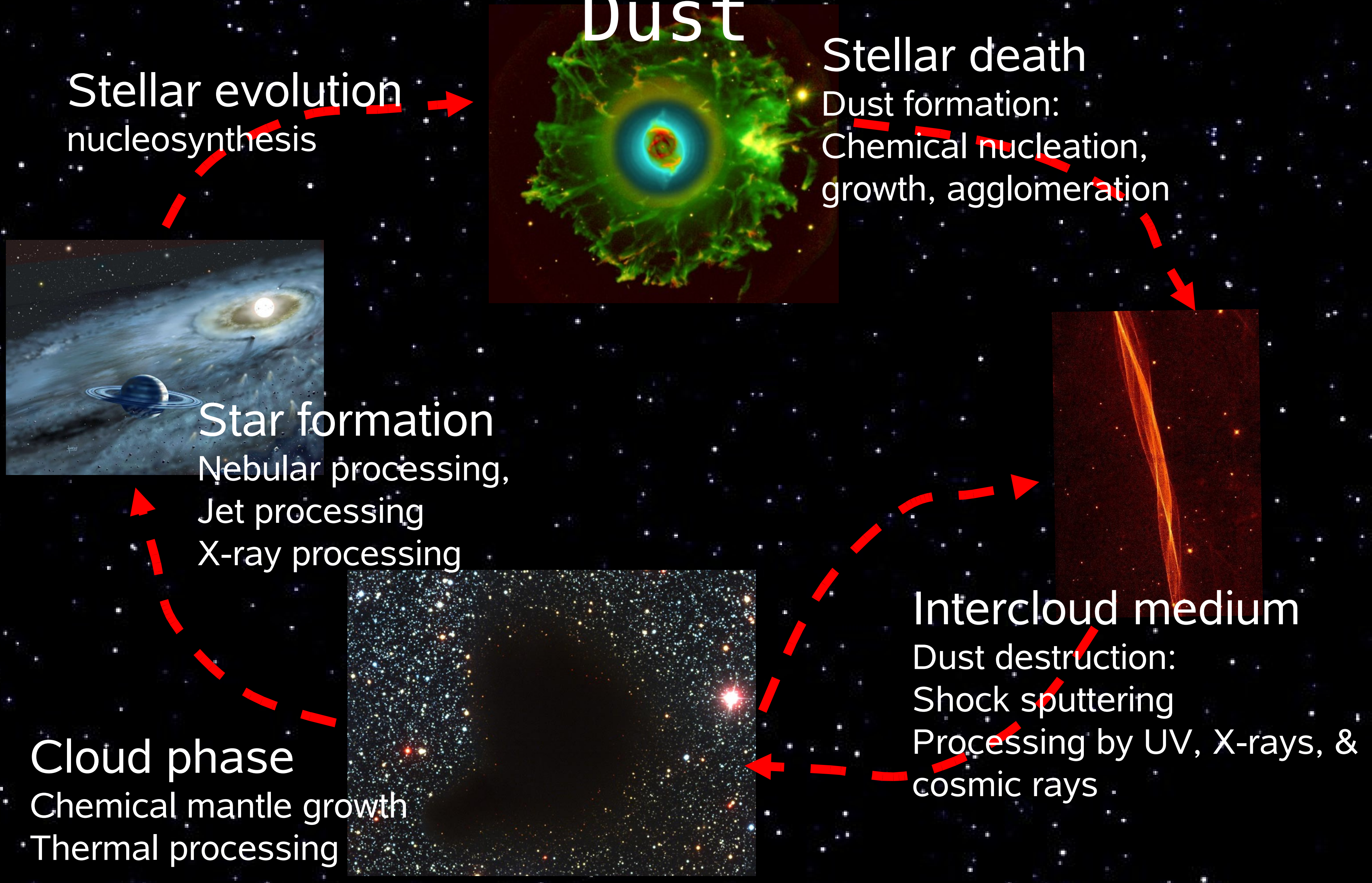
credit: http://hea-www.cfa.harvard.edu/CHAMP/EDUCATION/PUBLIC/ICONS/

Interstellar Dust

Role of dust:

- Dominant opacity source FUV-submm
- Dominates spectral appearance of galaxies
- Reservoir of elements
- Dust & molecules
  - Limits molecular photodissociation
  - Catalytic surfaces
  - Cold storage
- Photo-electric heating and the energy balance of the gas
- Cosmic Rays
- Building blocks of planetary systems

Cosmic Journey of Interstellar Dust

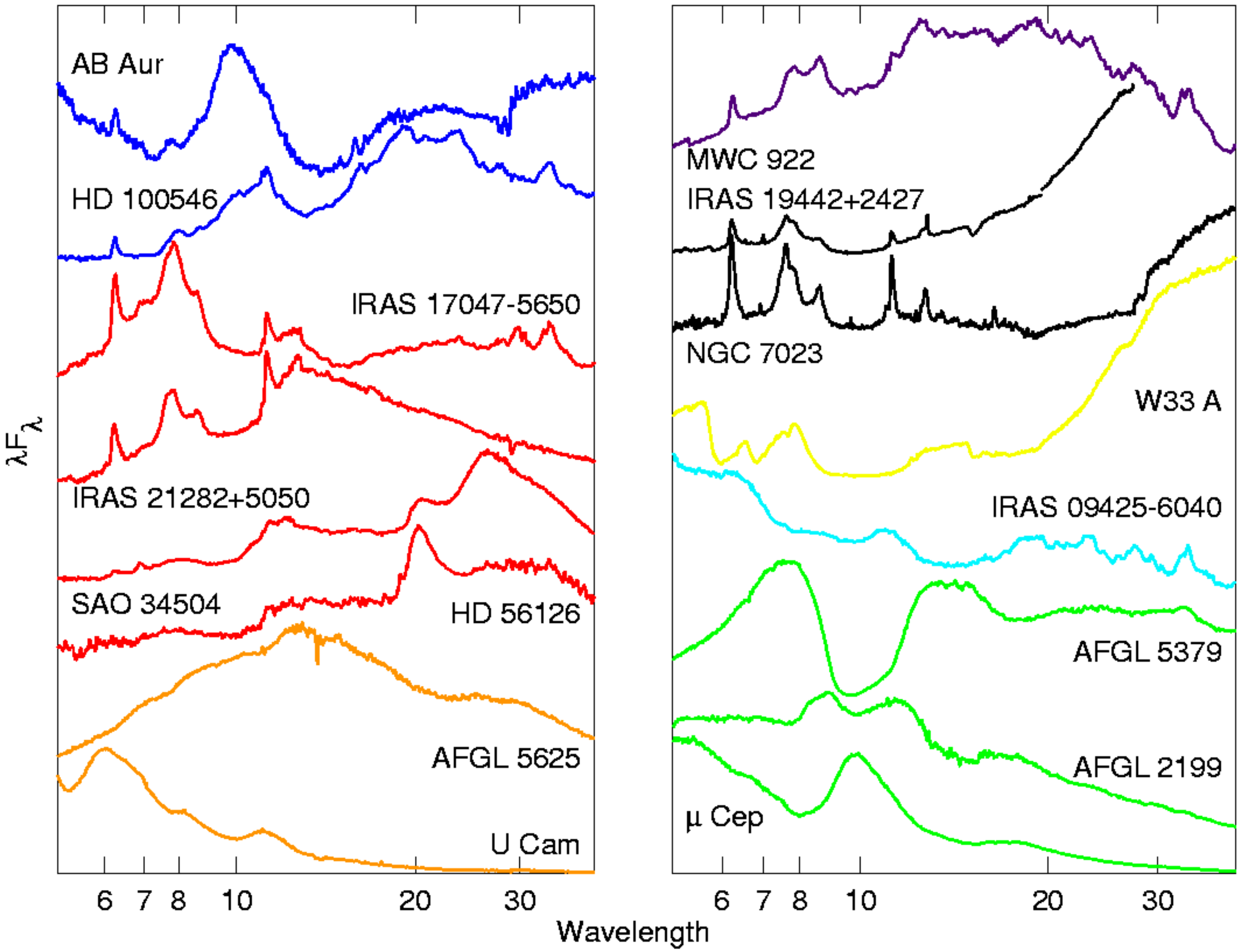


Key Questions

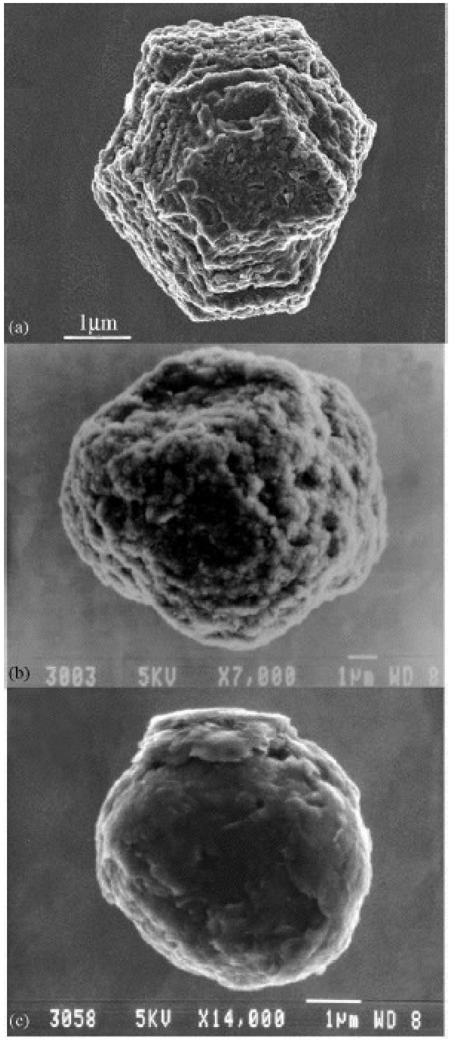
- What is the inventory of interstellar dust ?
- What are the important sources of dust and how does that depend on metallicity and star formation rate of the galaxy ?
- What processes played a role in its origin and evolution in the interstellar medium ?
- What kind of dust entered the Solar Nebula ?
- What processes played a role in its evolution in the planetary systems ?
- How did dust evolve with time in the Universe ?
- How is dust affected near black holes and in starburst environments ?
- How did the evolution of dust affect the evolution of galaxies, stars and planets ?

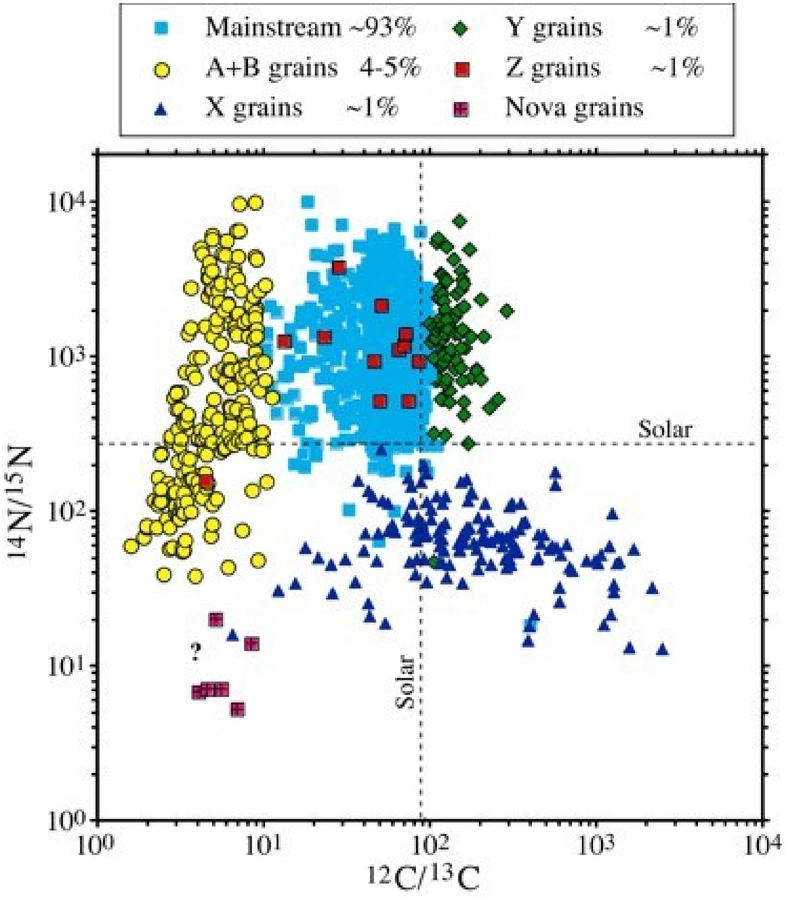
Dust Inventory & Mass Budget

The Spectral Richness of Dust



Stardust

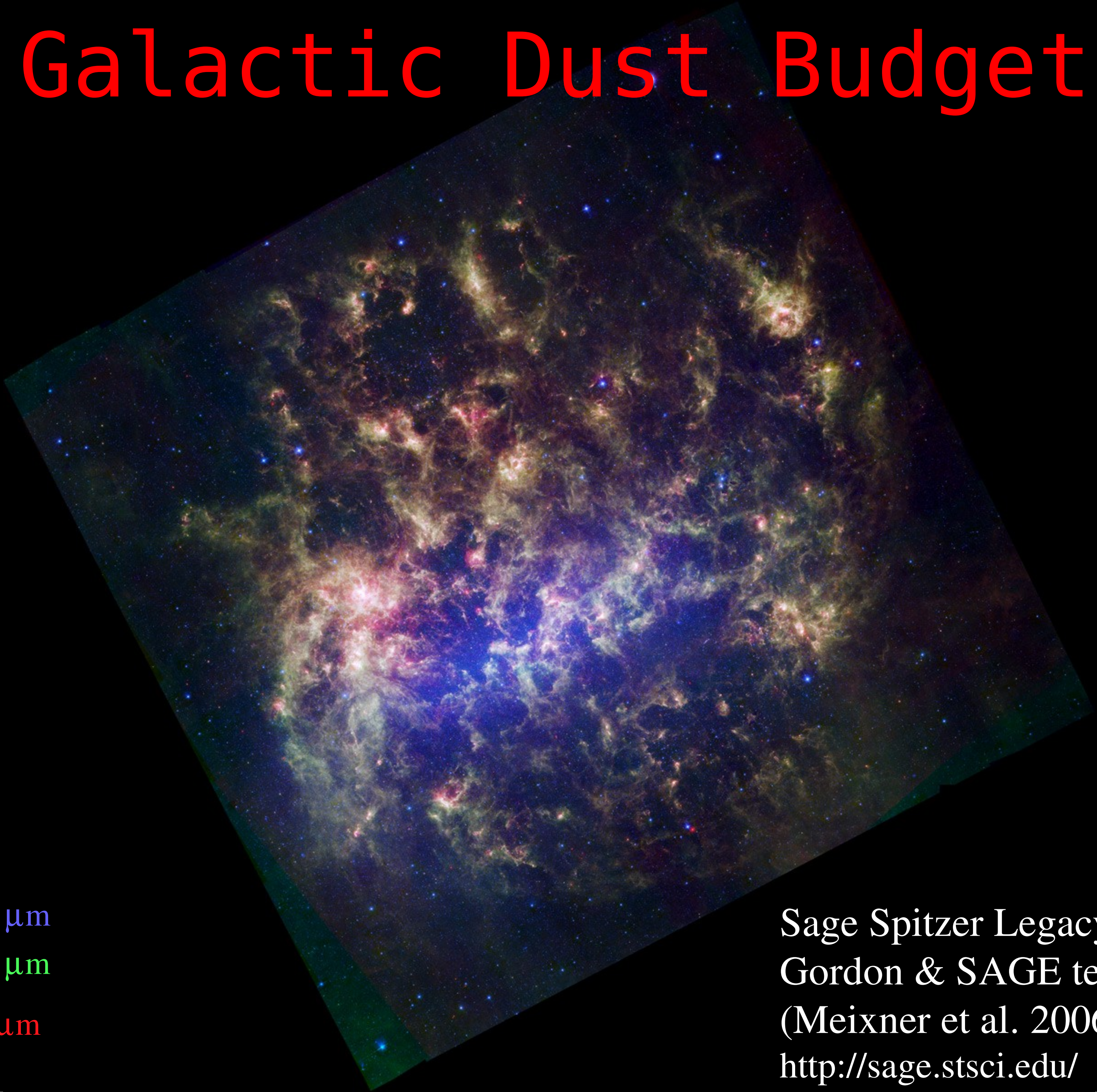

(a)
1µm
(b) 3003 5KV X7,000 1Pm WD 8
(c) 3058 5KV X14,000 1Pm WD 8


Mainstream ~93%
A+B grains 4-5%
X grains ~1%
Y grains ~1%
Z grains ~1%
Nova grains
Solar
Solar
?
$^{14}N/^{15}N$
$^{12}C/^{13}C$
10^0
10^1
10^2
10^3
10^4

Dust Inventory of the ISM

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

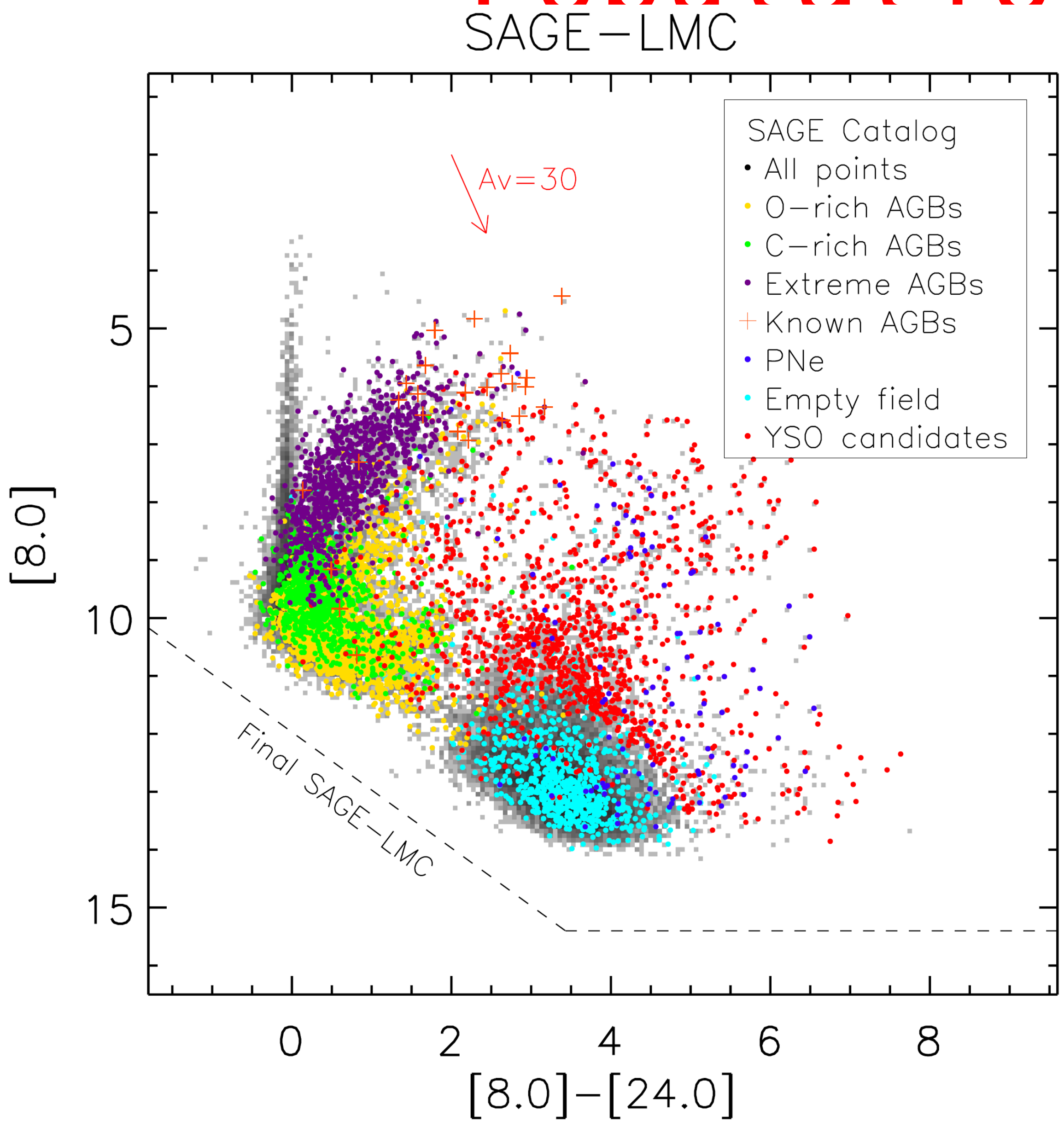
Galactic Dust Budget



IRAC 3.6 μm
IRAC 8.0 μm
MIPS 24 μm

Sage Spitzer Legacy Program
Gordon & SAGE team
(Meixner et al. 2006)
http://sage.stsci.edu/

SAGE Point Source Populations

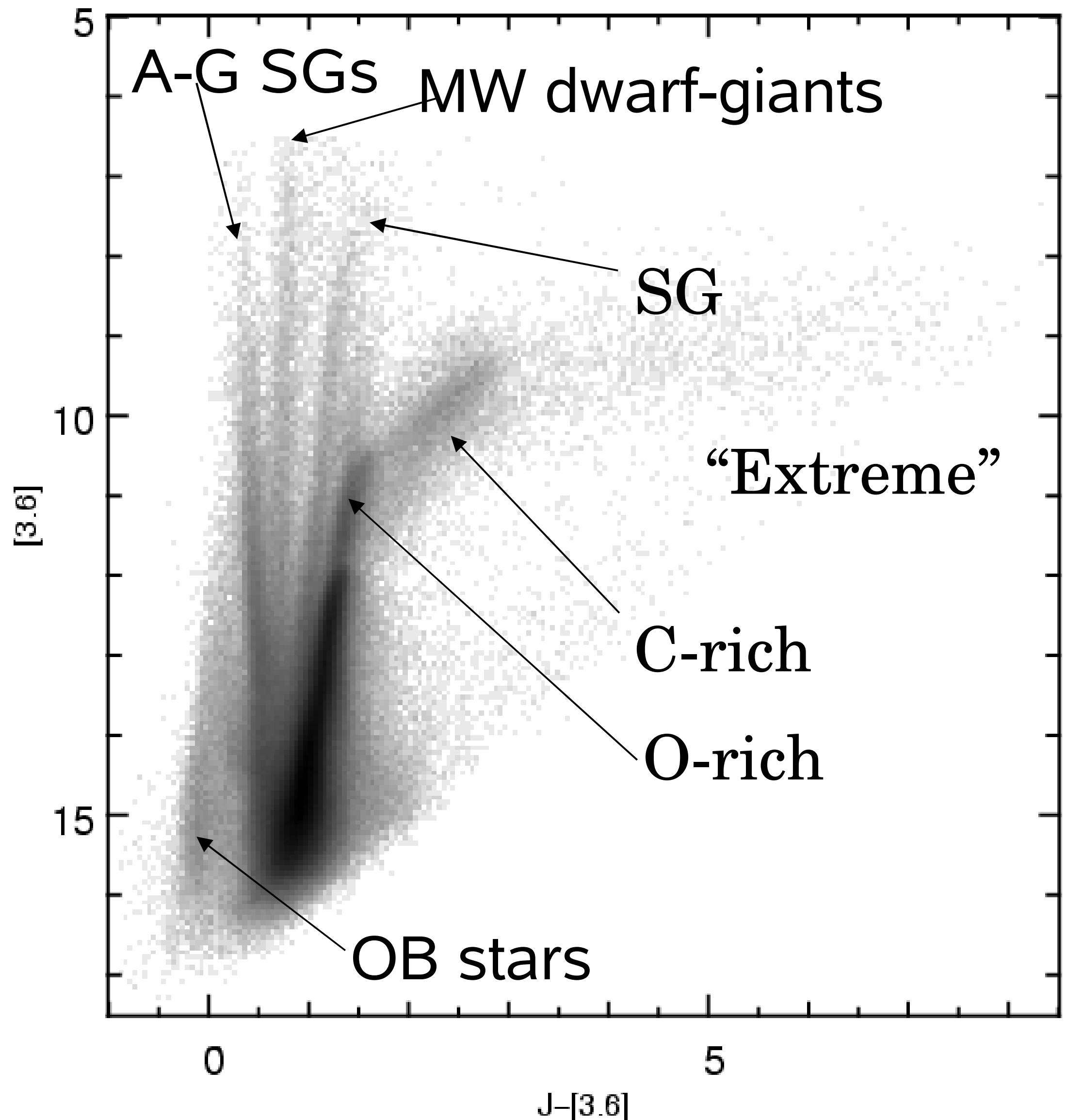


AGB stars: Blum et al. (2006, AJ, 132, 2034)
YSO candidates: Whitney et al. (2008, AJ, 136, 18)
PNe: Hora et al. (2008, AJ, 135, 726)
Empty field = background galaxies:

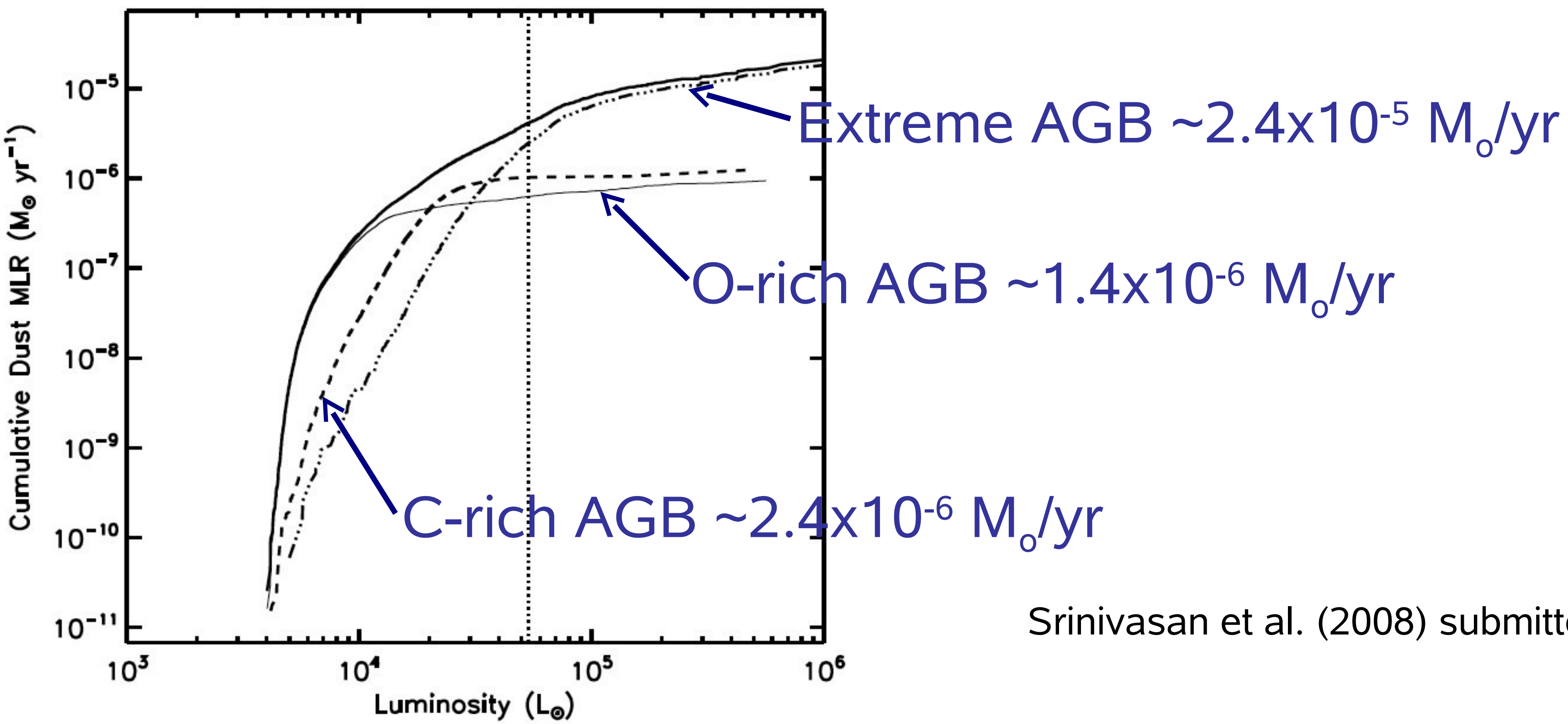
SAGE Point Source Populations II

- Asymptotic Giant Branch & Supergiants
- AGB->O-rich become C-stars during dredge up
- Lower Z, easier to get C/O > 1
- Extreme stars mostly C-rich, but need spectra to decide

Blum et al. (2006, AJ, 132, 234)



AGB Stars



Srinivasan et al. (2008) submitted

Dust mass injection into the ISM:
~23000 AGB stars & 2.7x10^{-5} M_o/yr

Galactic Dust Budget continued

Spitzer

- LMC
  - SAGE-Spec (Ciska Kemper, U Manchester) IRS & MIPS SED
- SMC
  - SAGE-SMC (Karl Gordon, STScI) photometric survey
  - SAGE-SMC-Spec (Greg Sloan, Cornell) IRS

Herschel

- LMC & SMC
  - Cold dust

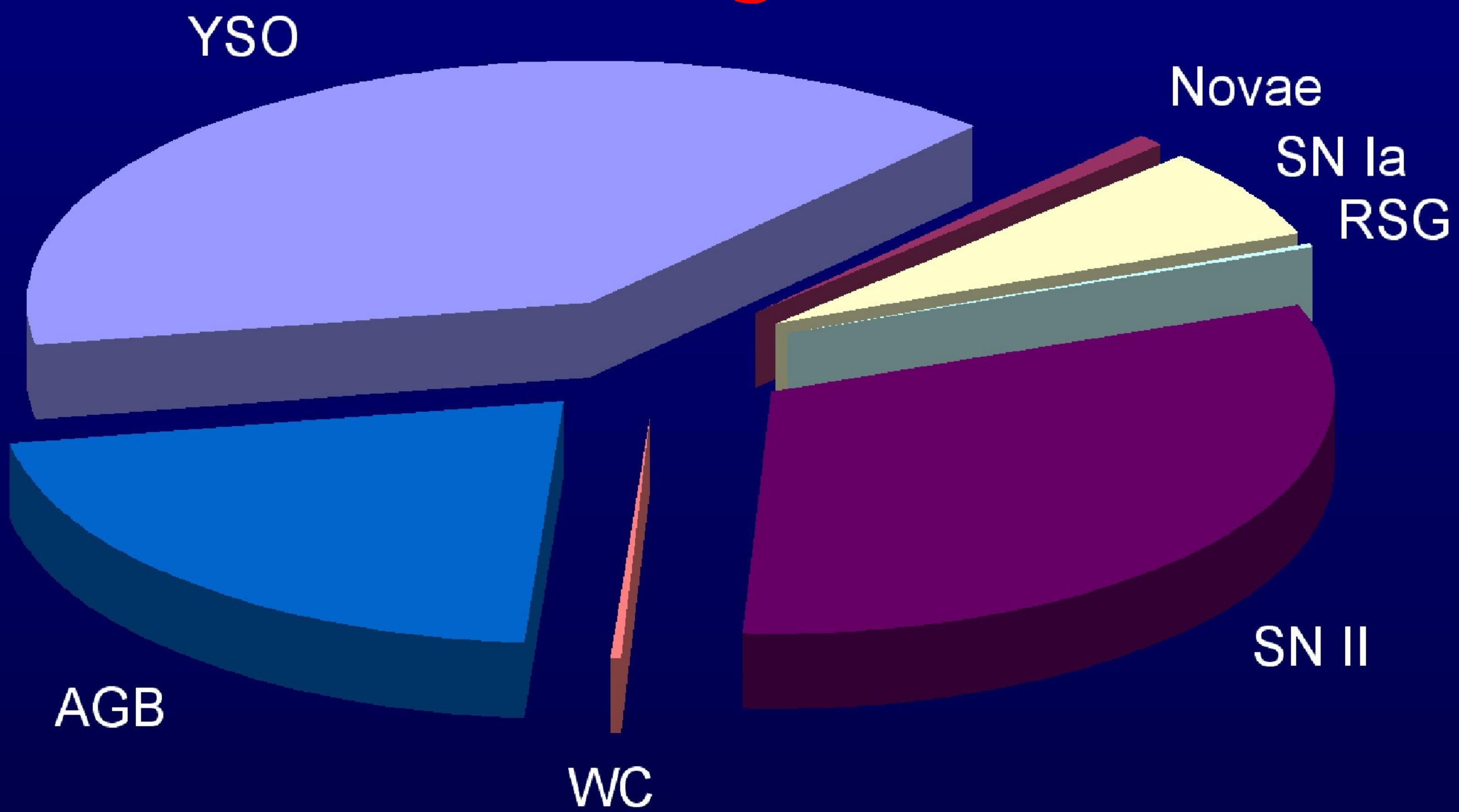
SOFIA (GAIA)

- Milky Way
  - Photometric & spectral survey

JWST

- SNe within 50 Mpc
- Photometric & spectral survey of local group galaxies

Interstellar Dust Budget



Heterogeneity of Stellar Sources

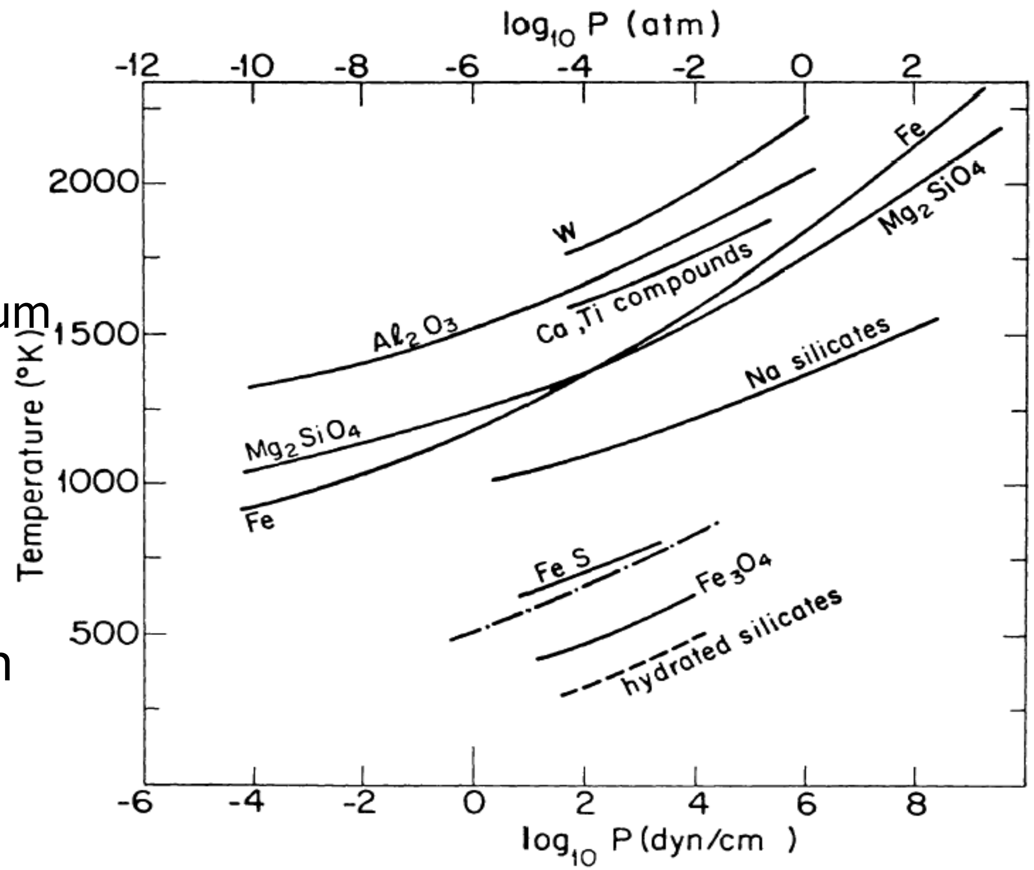
- Stars continuously inject enriched, dusty material into the interstellar medium
- Stars are continuously formed from the interstellar medium
  - Slow injection and star formation rate
- The interstellar medium is highly turbulent
  - Rapid mixing in the interstellar medium
    - Turbulence 10 km/s @ 200 pc scale

An average batch of the interstellar medium contains the ashes of ~100 Million AGB stars plus ~1 Million SNe waiting on average a billion years for star and planet formation to proceed

Dust Formation

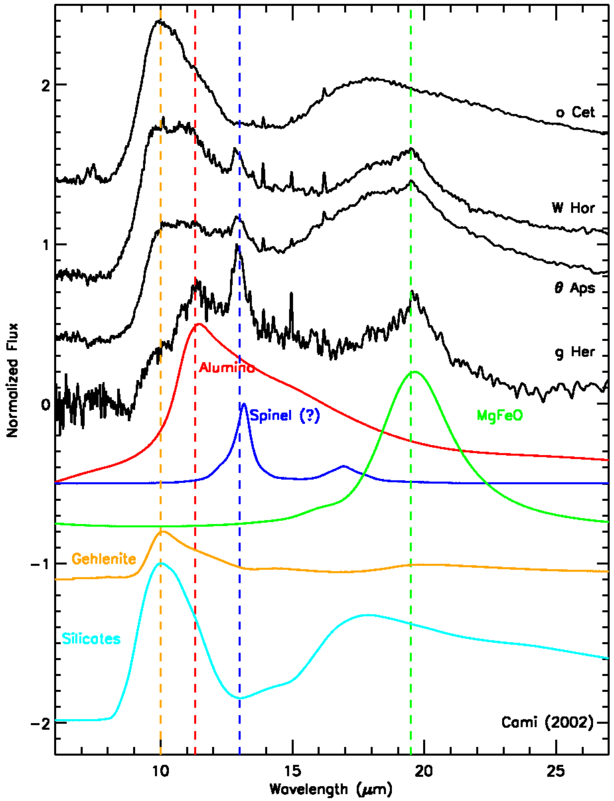
Thermodynamic Condensation Sequence

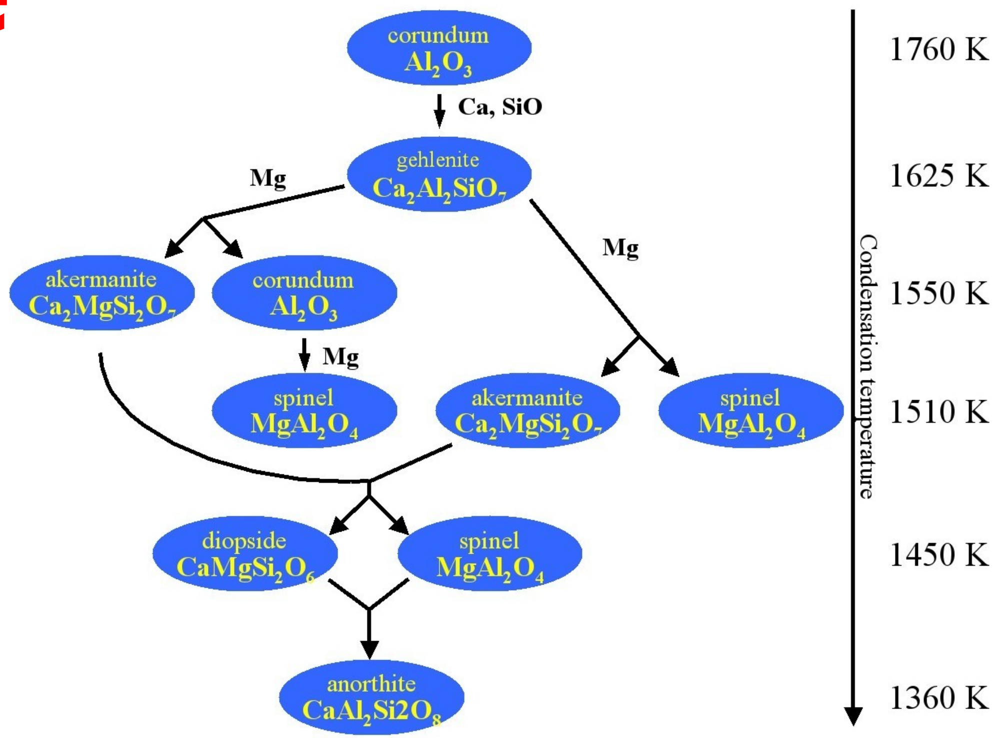
- Gas with solar system composition
- Condensation is sequential
- Two major sequences
  - Oxides: starting with aluminum oxide/spinel and ending with Ca,Al silicates
  - Silicates: starting with forsterite and forming enstatite
- Separate sequence for C-rich gas characterized by carbonaceous compounds



Salpeter, 1977, ARAA, 15, 267

Oxides Condensation Sequence





- Oxides at low mass loss rates
- Freeze out

Future: JWST & SOFIA

•Cami, 2001, PhD thesis
•Posch et al., 2002, A&A, 393, L7
•DePew et al., 2006, ApJ, 640, 97
•Sloan & Price, 1998, ApJS, 119, 1411

The Incredibly Rich mid-IR Spectrum of Crystalline Silica

Characteristics

- Crystalline silicates
  - Forsterite/enstatite
  - Magnesium-rich
  - Cold
  - Disk sources
- Amorphous silicates
  - Role of iron
- High mass loss rates
- The silicate condensation sequence

References:

Malfait et al. 1998, A&A 332, L25

Molster et al., 2000, A&A 382, 184

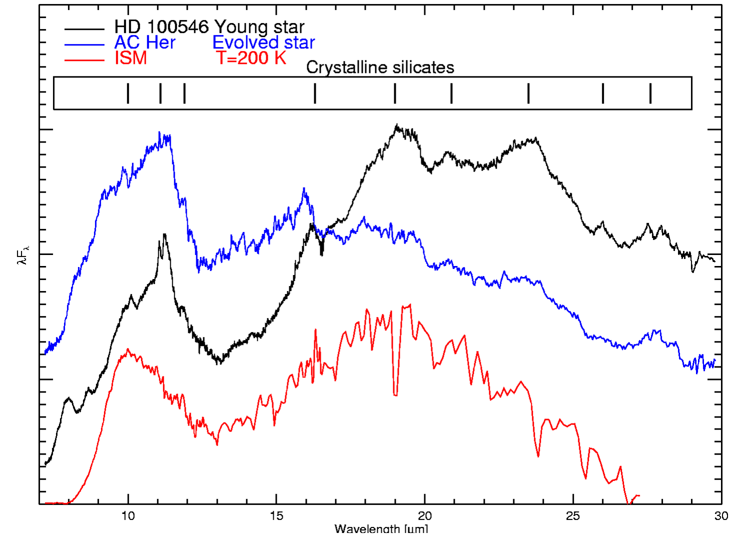
Kemper et al, 2004, ApJ 609, 826

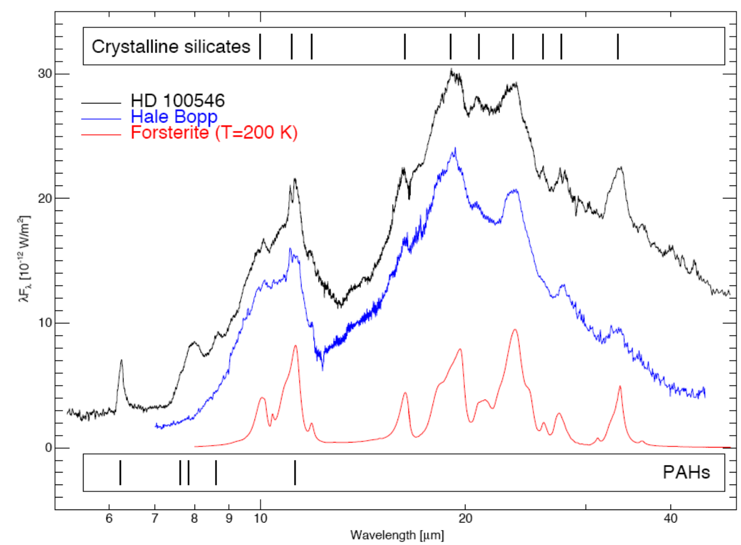
Crovisier et al, 1997, Science, 275, 1904

Watson et al., 2009, ApJS, 180, 84

Sicilia-Aguilar et al., 2007, ApJ, 659, 1637

Future: JWST & SOFIA





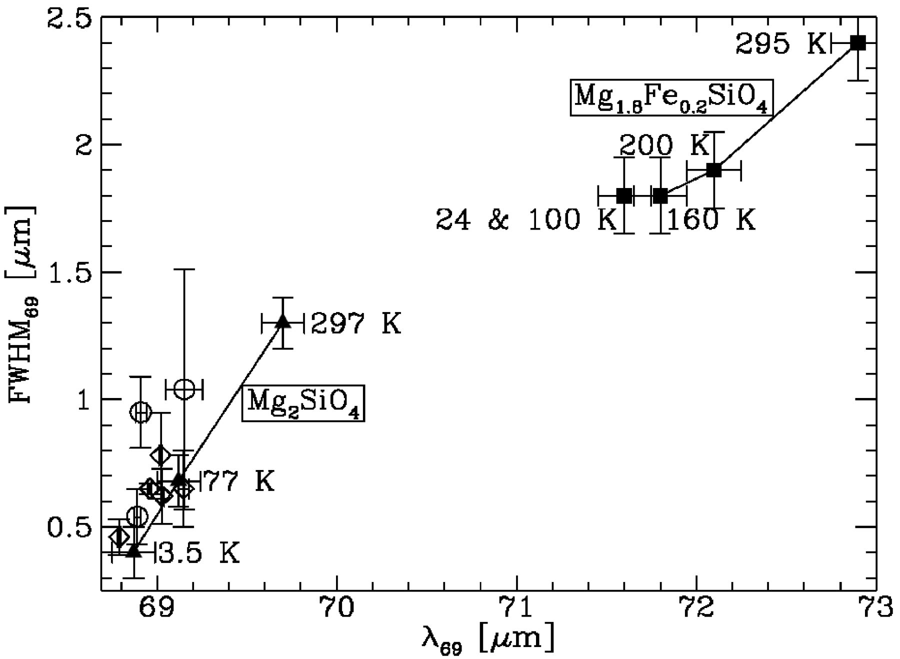
The 69 μm band

Peak position and width depend on the composition and temperature of the material

Mg-rich end members of the olivine and pyroxene families (Fe/Mg<5%): Forsterite and enstatite

T~100-200K

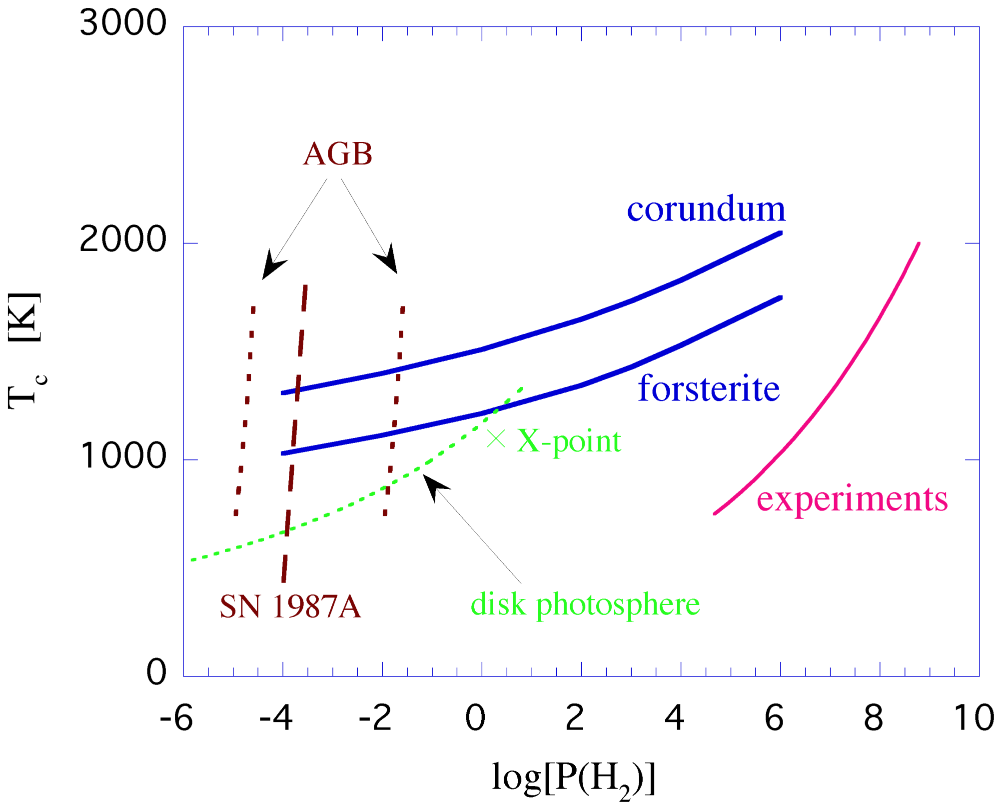
References:
Koike et al, 2000, AA, 363, 1115
Molster et al, 2002, AA, 382
Bowey, 2002, MNRAS, 331, L1



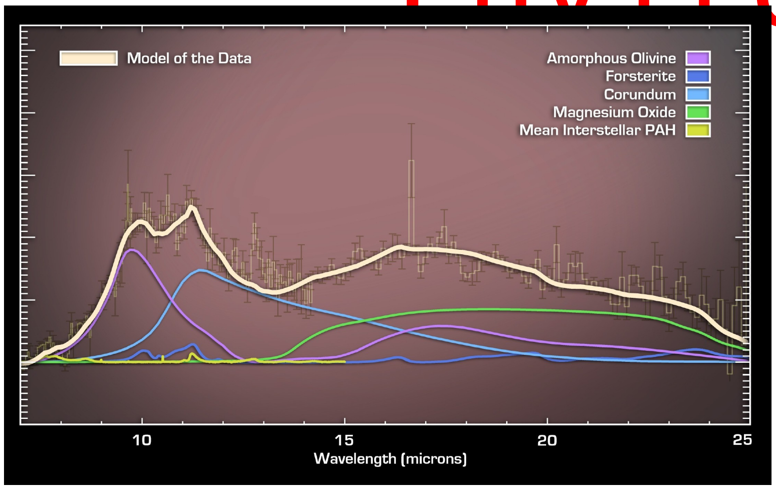
Future: SOFIA & Herschel

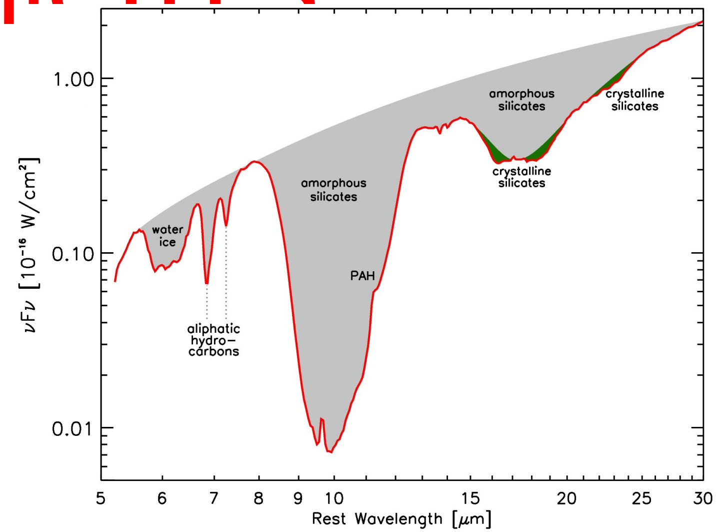
AGBs as Dust Condensation Laboratory

- Two condensation sequences:
    - Oxides
    - Silicates
- Time is of the essence
- AGBs are templates for SNe and other dust factories
- Controlled stellar samples are required



Dust in AGN/Quasars & Extreme Starburst Environments





- Quasar dust: Oxides and crystalline silicates
- Formed in torus and ejected in quasar wind ?
- Dust in extreme starburst environments: Crystalline silicates and HAC in ULIRG nuclei
- Formed by massive stars and not yet processed ?

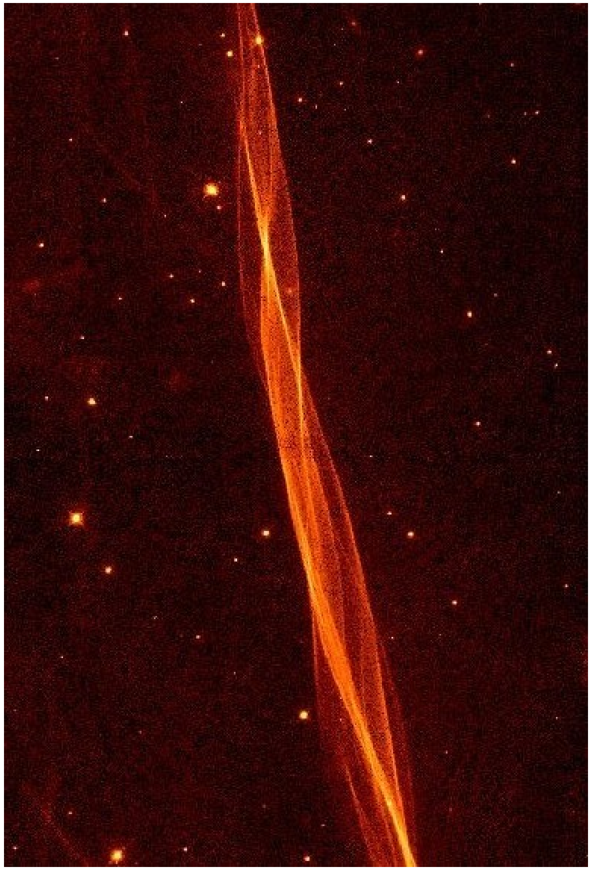
Marwick-Kemper et al., 2007,ApJ;
Armus et al, 2007, ApJ,656, 148
Spoon et al, 2006, ApJ, 638, 759

Future: JWST

Shock Processing

INTERSTELLAR SHOCKS

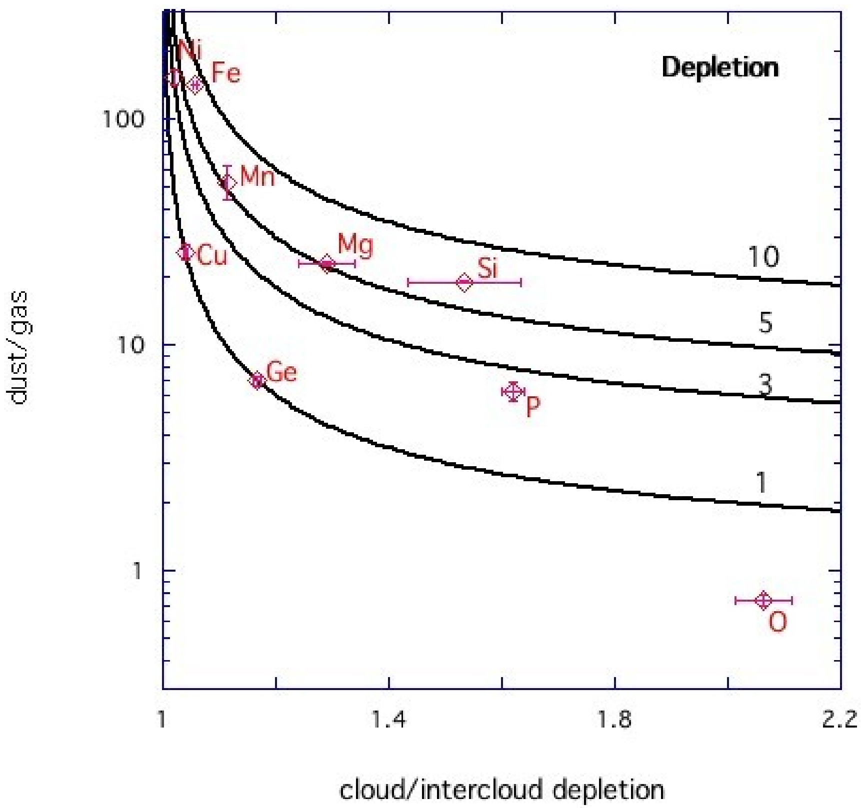
- Supernovae eject material at ~10,000 km/s
- This high velocity gas drives a strong shock wave, sweeping up interstellar material
- As the supernova remnant expands, the shock velocity will decrease until the swept up gas (and ejecta) merge with the interstellar medium
- Shocks destroy dust grains through sputtering and shattering
- 100km/s shock “chips” 30 Å layer from a 1000Å grain
- Calculated lifetime: ~500 Myr



Jones et al, 1994, ApJ, 433, 797

Shocks, Depletion & Mantles

- Depletion: elements are locked up in dust
- High velocity gas has less depletion
- Intercloud gas has less depletion than cloud gas
- Interstellar shocks in the intercloud medium sputter a thin outer layer (~30Å) which is rapidly reaccreted in diffuse clouds
- Accretion is a chemical process controlled by the interaction with the grain surface
- Carbon is not involved in these mantles
- Carbonaceous mantles from energetic processing of ices in molecular clouds or Solar nebula ??

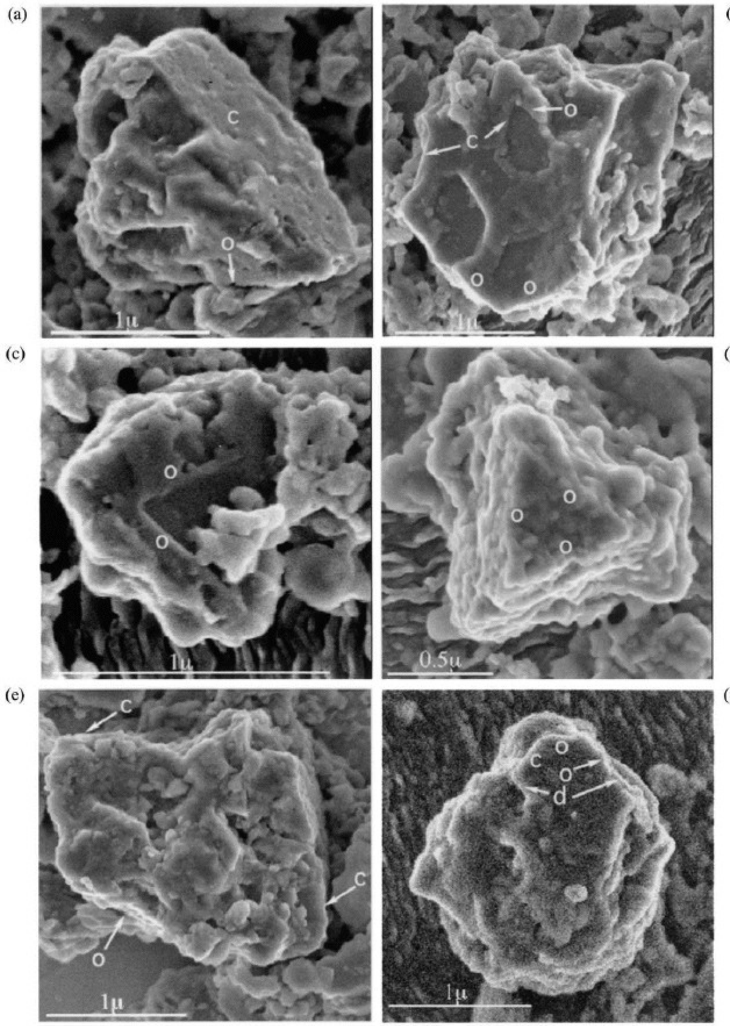


References:
Savage and Sembach, 1996, ARAA, 34, 279
Cartledge et al., 2006, ApJ, 641, 327
Tielens 1998, ApJ, 499, 267

Shocks and the Stardust Record

- Morphology pristine SiC grains (>0.4 μm)
- 89% Crystal faces
- 11% Irregular
- 60% SiC grains are coated
- Nature of coating is unknown

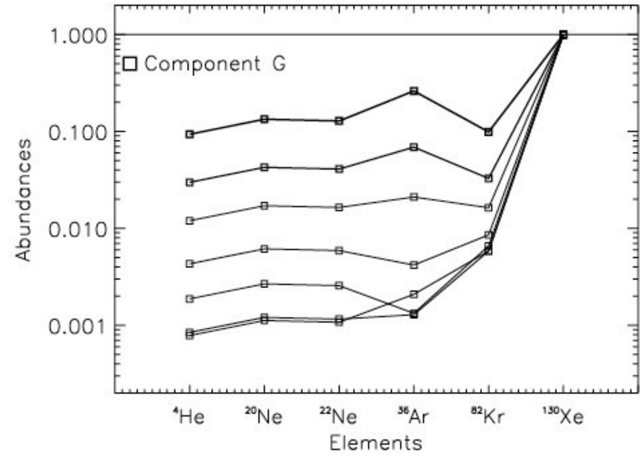
Most SiC grains did not experience a shock or were “protected” by a mantle

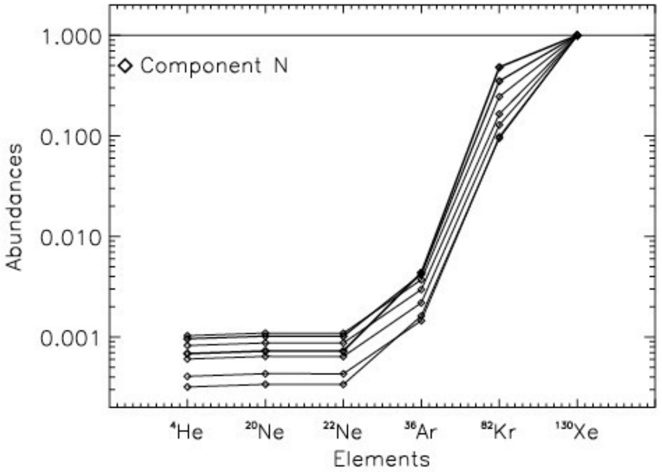


References:
Bernatowicz et al, 2003, Geochim Cosmichim Acta, 24, 4679

Noble gasses in SiC stardust

- Isotope ratios of trapped noble gasses reveal two components:
- G-component: s-process in red giants
- N-component: Solar abundances
- Light noble gasses are fractionated compared to heavy noble gasses
- This elemental fractionation depends on grain size



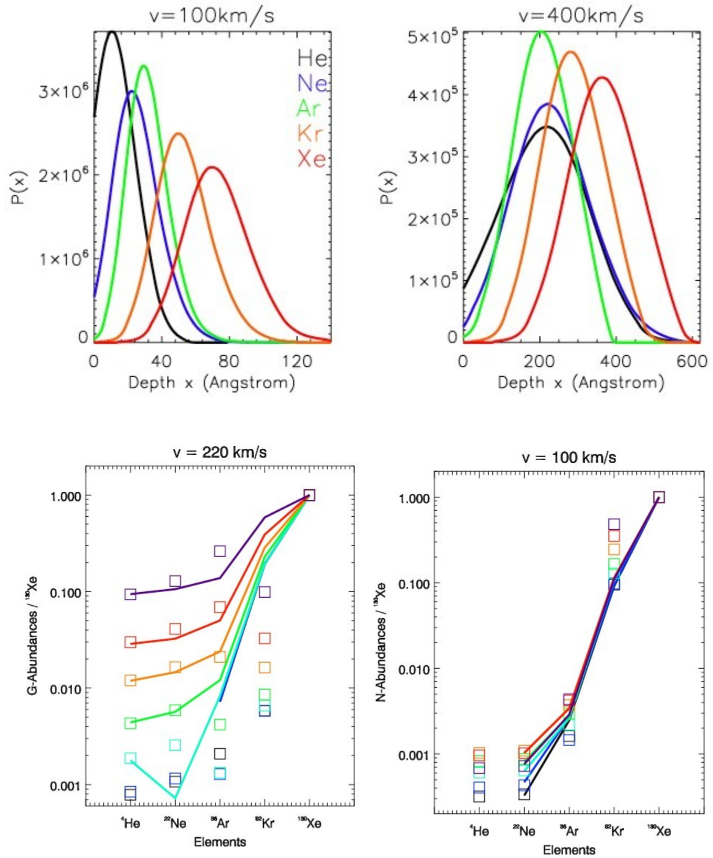


Lewis et al, 1994, GeCoA, 58, 471

Ion Implantation Studies

- Noble gases reflect ion implantation at high energy
- Depth of implantation depends on mass/energy of ion
- Ion implantation is accompanied by sputtering loss from the surface
- Combination of implantation and sputtering can lead to mass dependent fractionation

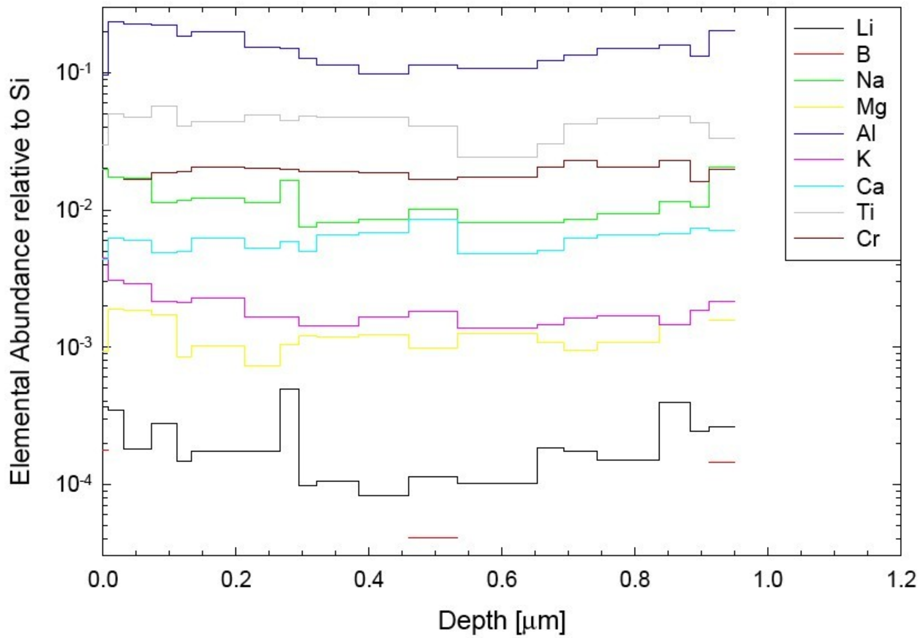
- G component implanted in PN phase when grains where radiatively accelerated to ~220 km/s at a fluence of ~3x10^{17} H atoms/cm^2 and then the N-component was implanted by interstellar shocks (100 km/s shock at a fluence of 3x10^{18} H atoms/cm^2)
- Subsequent processing (in the Solar Nebula ??) must have produced the N-component fractionation



Guillard et al, 2007, submitted

Verchovsky et al, 2004, ApJ,607, 711

Implantation in Stardust

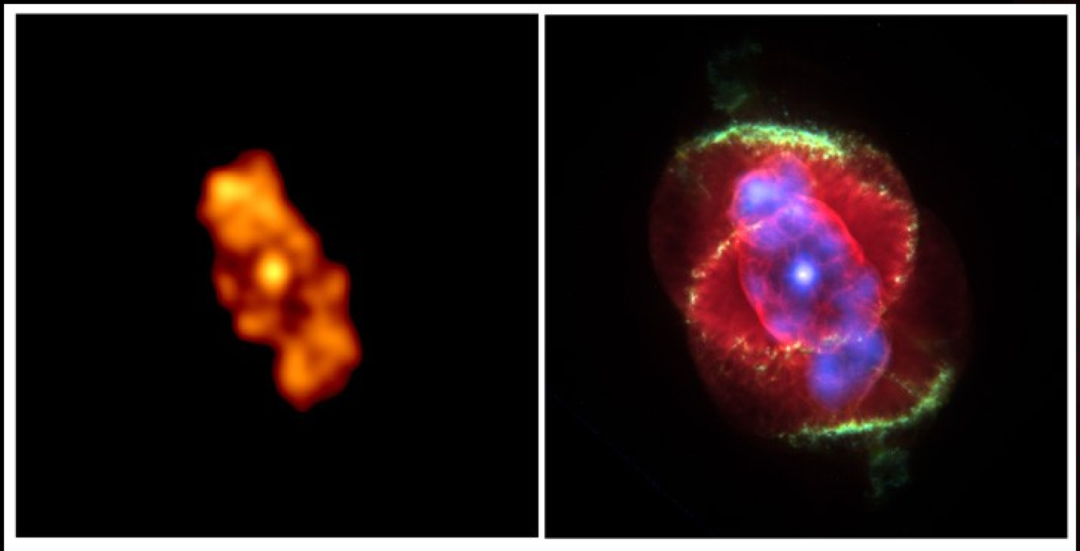


- Depth profiles of elements in individual stardust grains
- Mg, Al, K, Na factor of ~2 drop in abundance in center; Li, B factor of 4 drop
- Ion implantation @ v~500 km/s

Henkel et al, 2007, LPS, 38, 2351

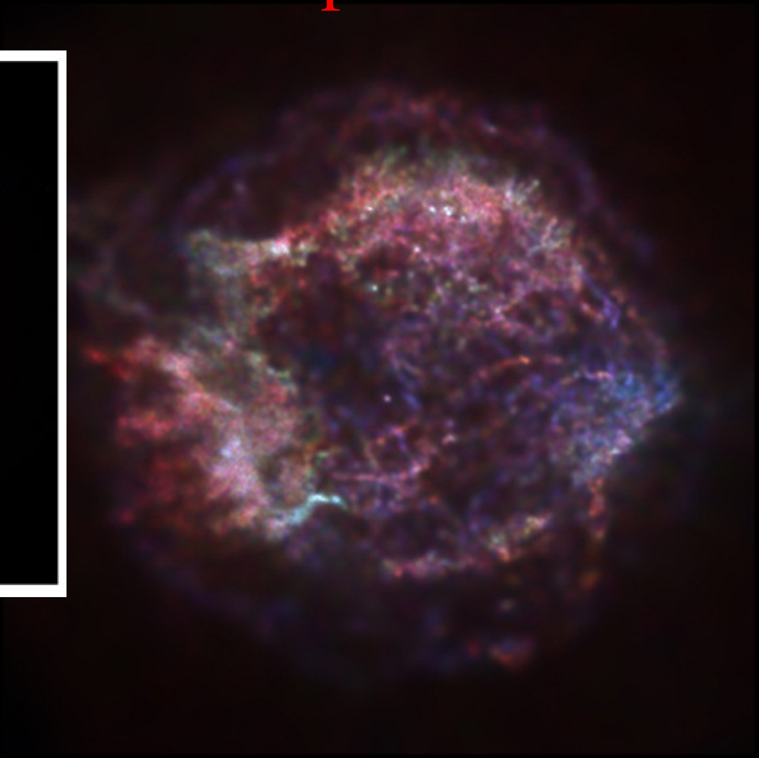
PLASMAS IN STARDUST BIRTHSITES

Planetary Nebulae



The cat's eye in X-ray and optical

Supernova



Cas A in X-rays

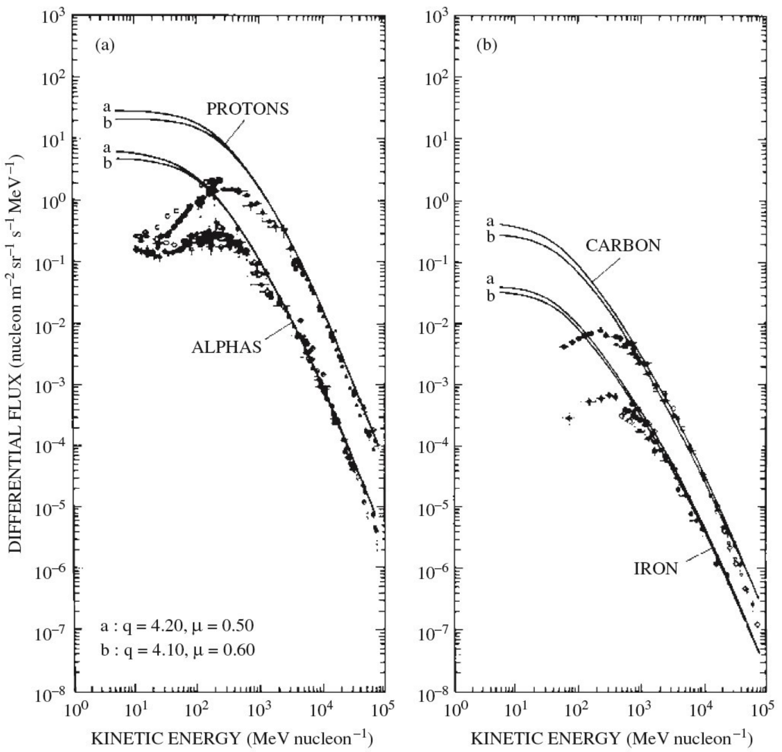
G component from stardust birth sites
N component from interstellar supernova shocks

COSMIC RAYS and DUST

Cosmic Rays

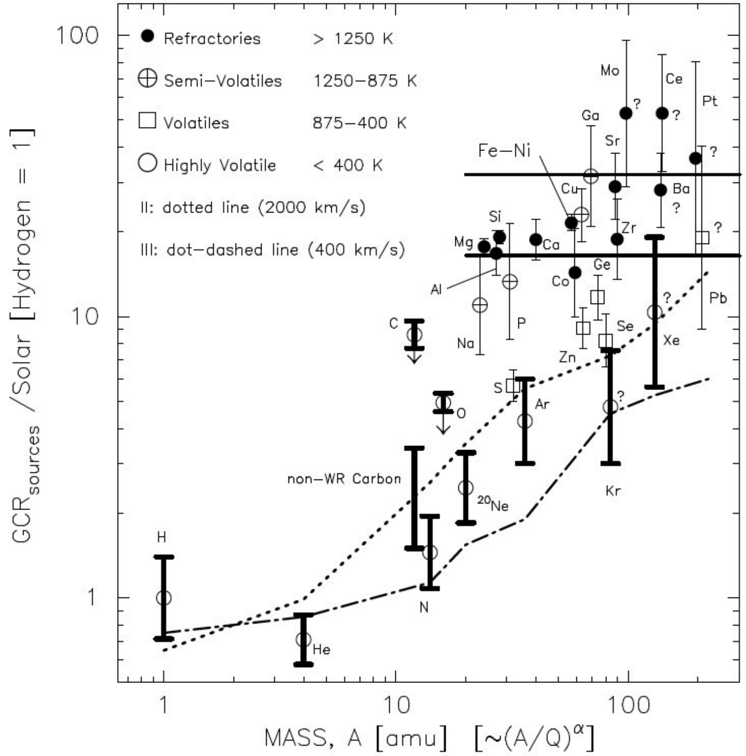
- Cosmic rays are high energy charged particles
- Cosmic rays tap into high energy events: supernova explosions
- Cosmic ray drive ionization, ion-molecule chemistry, gas heating, grain processing

∀ ζ_{CR} ~2×10^{-16} s^{-1} (molecular observations)



Dust & Galactic Cosmic Rays

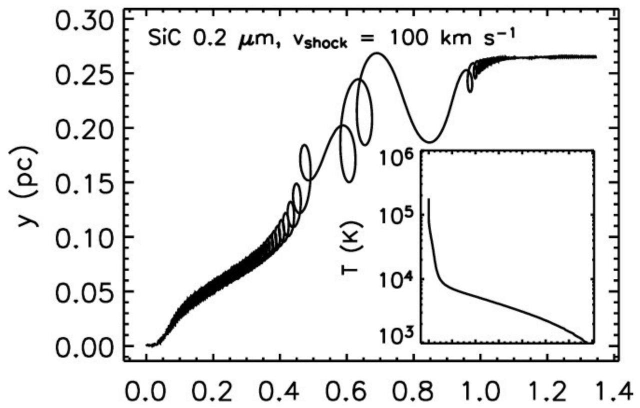
- Abundances of “dust-elements” are enhanced in galactic cosmic rays
- Fermi accelerations and sputtering of interstellar dust grains in supernova shocks
- Refractory elements are efficiently suprathermally accelerated before release into the gas phase
- Volatile elements show a mass dependent acceleration pattern

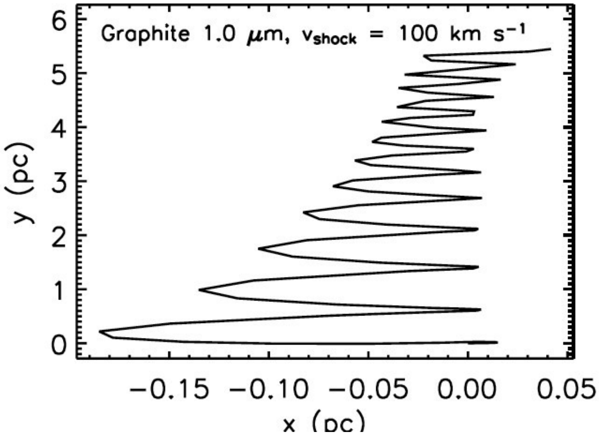


Ellison et al., 1997, ApJ, 487, 197

FERMI ACCELERATION

- Small grains are position coupled and (slightly) eroded by inertial sputtering
- Large grains bounce between two moving "mirrors" gaining rapidly in energy
- With the "right" Larmor radius, magnetic fields across a supernova shock front act as mirrors
- $R_L = mv/qB$





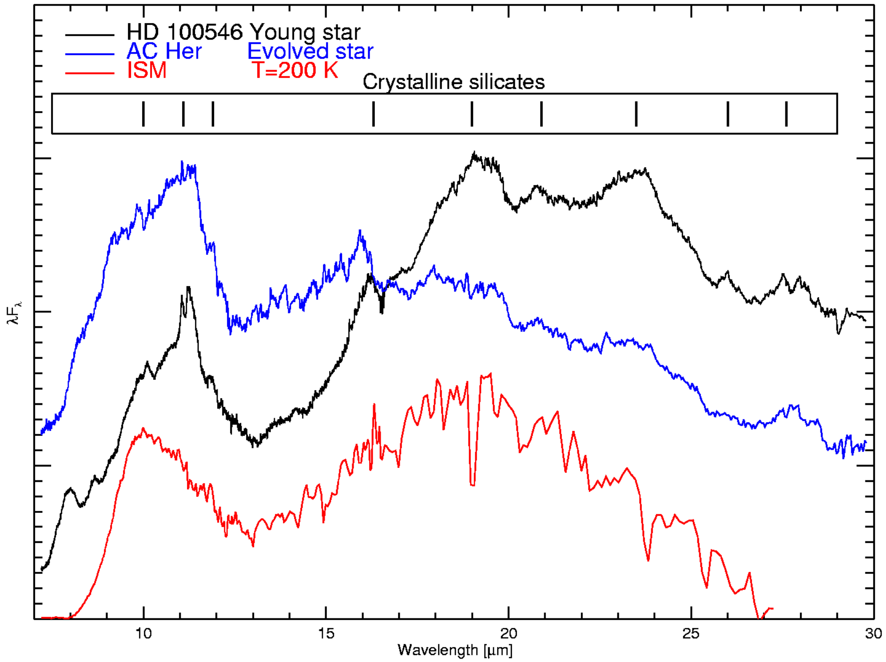
Slavin et al., 2004, ApJ, 614, 796

Processing of Crystalline Silicates

Crystalline Silicates

Crystalline silicates

- Evolutionary sequence:
  - Evolved stars
  - ISM
  - Young stars
- Observed:
  - Injected by stars >2%
  - Observed in ISM <0.5%
  - Herbig AeBe stars >5%

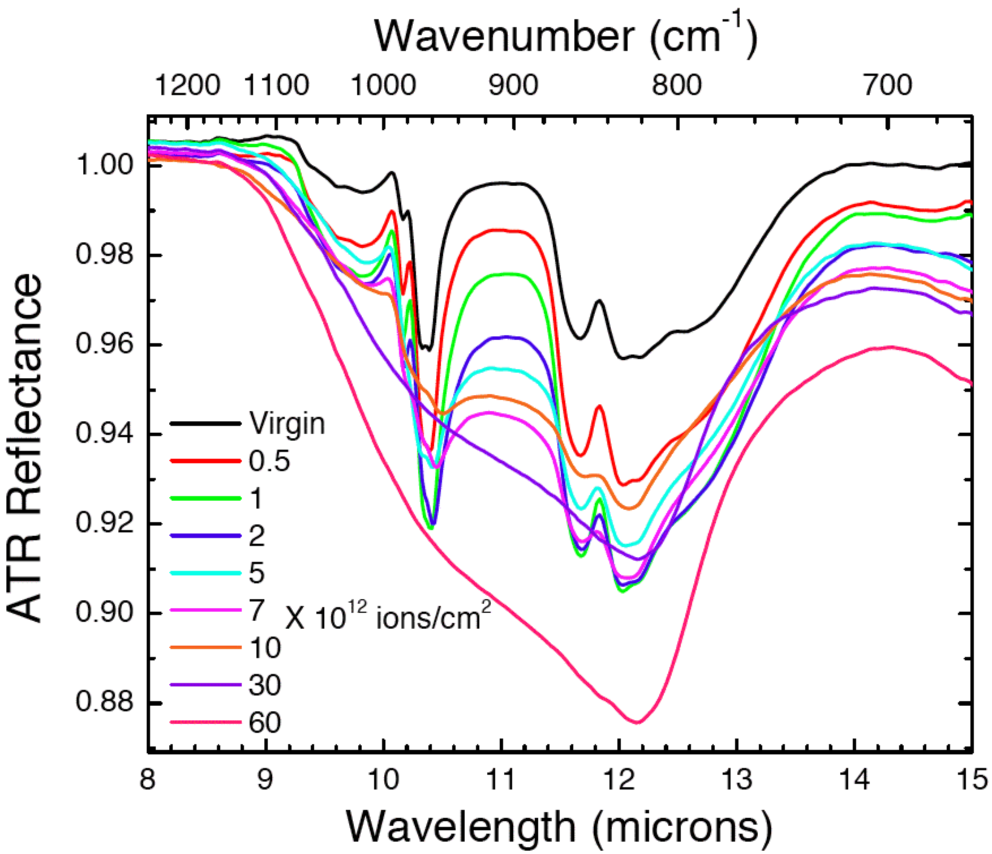


Kemper et al., 2004, ApJ, 609, 826

Cosmic Ray Processing

Amorphous-crystalline transition due to high energy ion-bombardment by cosmic rays in the ISM: Lifetime 70 Myr

Very young supernova remnants: Lifetime 1Byr



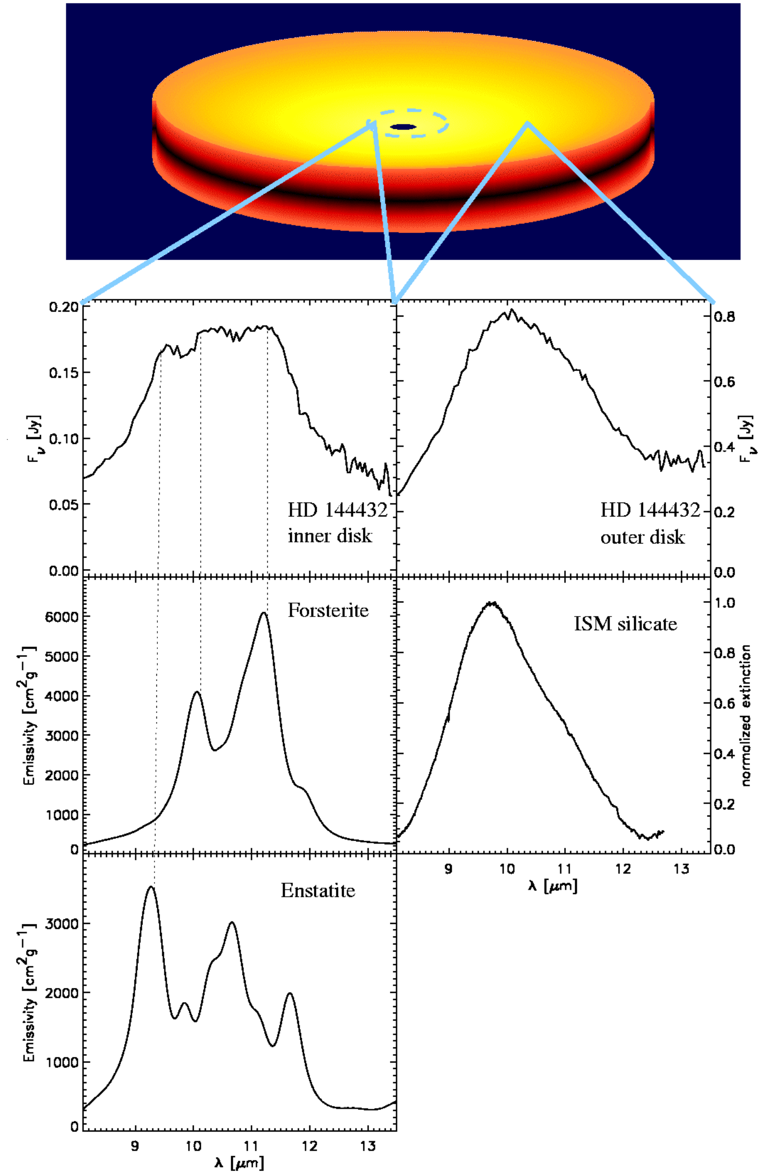
Reference:
Bringa et al, 2006, ApJ, 662, 442.

Mid-IR Interferometry

Protoplanetary disk:

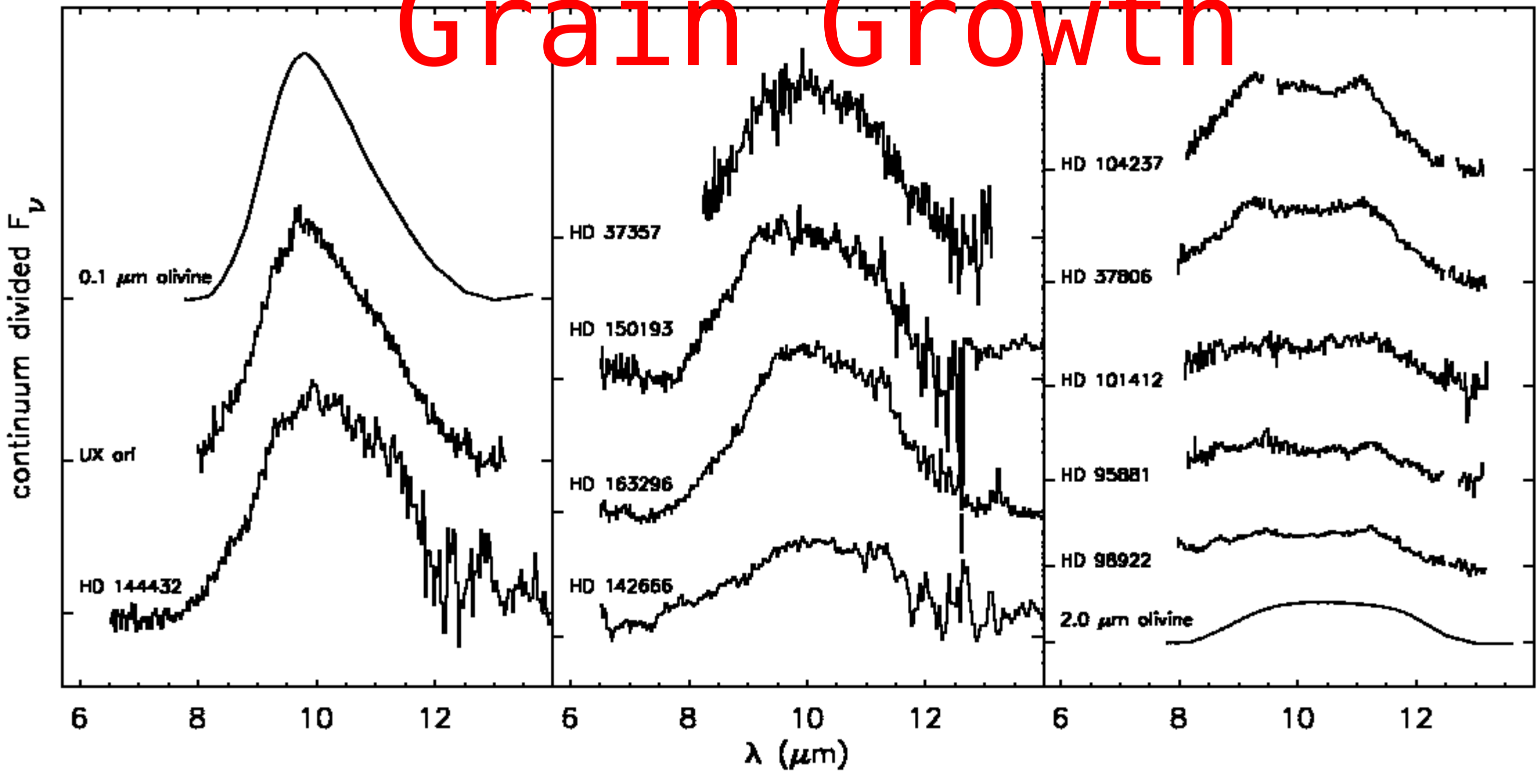
High crystalline fraction in the inner 2 AU

- Vaporization followed by (slow) condensation
- Crystallization @ ~1000K
- Melting & slow cooling (chondrule process ?)



Reference:
van Boekel et al., 2004, Nature, 432, 479

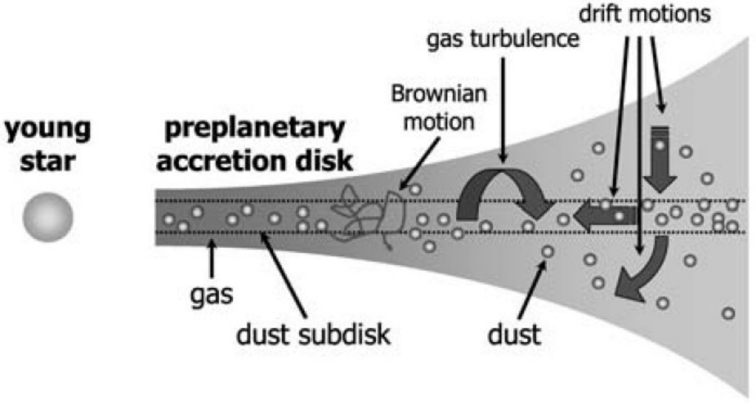
Crystallinity and Grain Growth



Reference
Van Boekel et al., 2005, AA, 437, 189
Kessler-Silacci et al., 2006, ApJ, 639, 275

Processing in Protoplanetary Disks

- Crystalline silicates produced by thermal processing in the hot inner nebula and transported outwards through turbulence or local transient processing by shocks/lightning
- Cold crystalline silicates question:
  - Comets as “pristine” interstellar material reservoirs ?
  - How is the organic inventory affected ?
  - How is the volatile inventory affected ?



Summary

- Infrared missions and meteoritic stardust analysis has provided us with an unprecedented view of the dusty Universe
- Most of the heavy elements are injected as “stardust” into the interstellar medium
- Stardust is isotopically anomalous but presolar dust can be isotopically normal
- Space is a harsh mistress: Dust is heavily processed by energetic ions and gas-grain interactions in the ISM
- Dust plays an important role in the evolution of the universe
- Undoubtedly, dust has strongly evolved over the lifetime of the universe
- The implications of this remain to be sorted out but the future looks bright with SOFIA & JWST on the horizon
- Laboratory studies will have to play a major role in this