Lecture 9:
„Dust physics and surface chemistry"

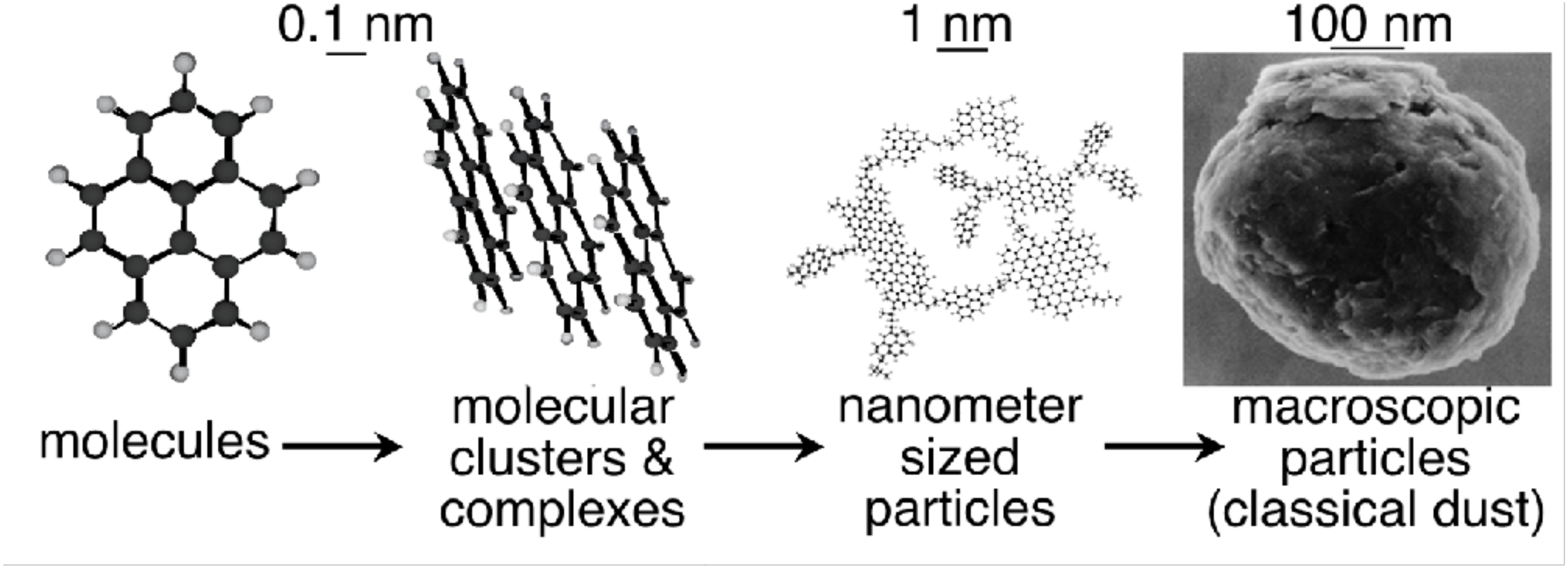
"Sure it's beautiful, but I can't help thinking about all that interstellar dust out there."

Outline

1. **Physics of cosmic dust:**
    - Basic properties
    - Interaction with light
    - Formation and destruction
2. **Chemical processes on dust surfaces:**
    - Accretion
    - Surface reactions
    - Desorption

I. Cosmic Dust

What is dust?



- Microscopic "dust" particles: size ~ 0.5 – 3 nm (5 – 30 Å)

– Polycyclic Aromatic Hydrocarbons (PAHs) made of benzene rings

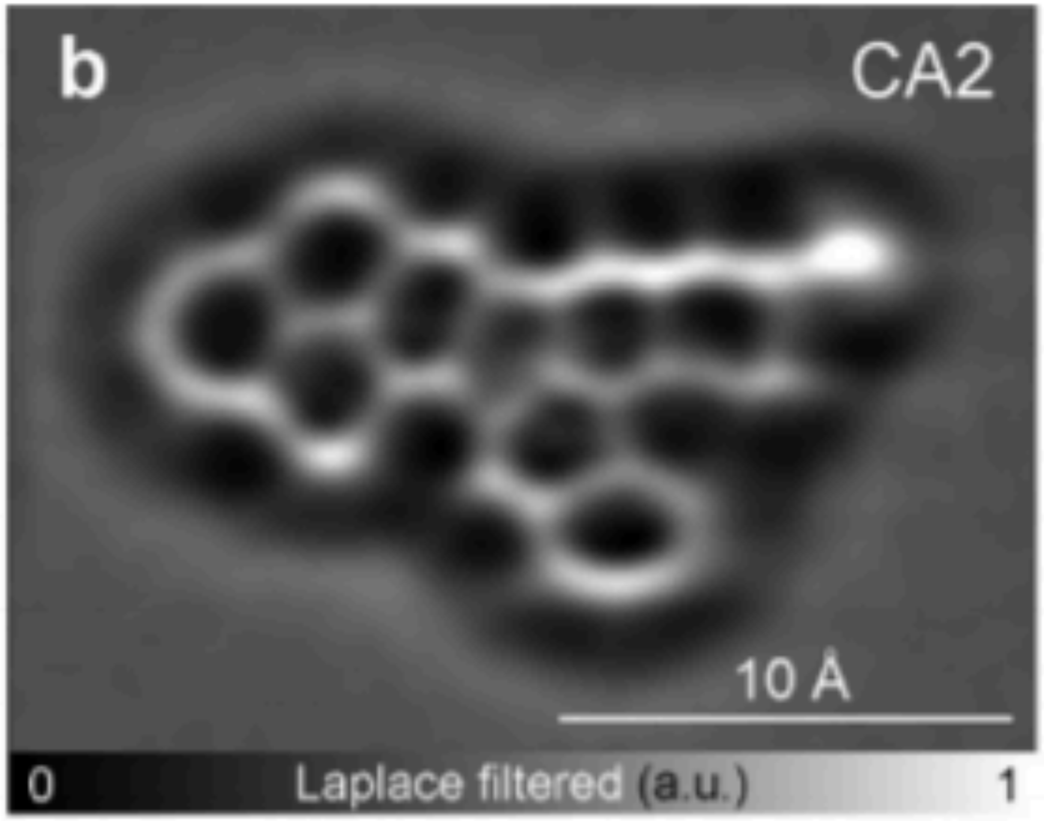
- Macroscopic dust particles: size ~ 3 nm – 1 mm

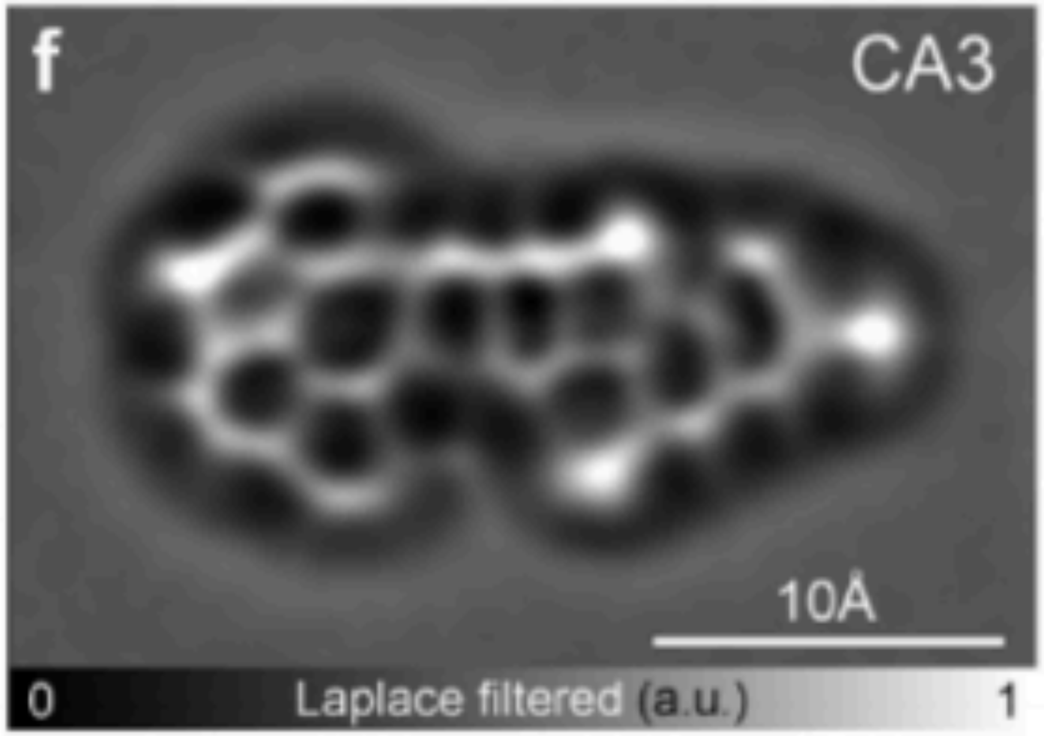
– e^- mean free path << size

– Mainly silicates, amorphous carbon, ices

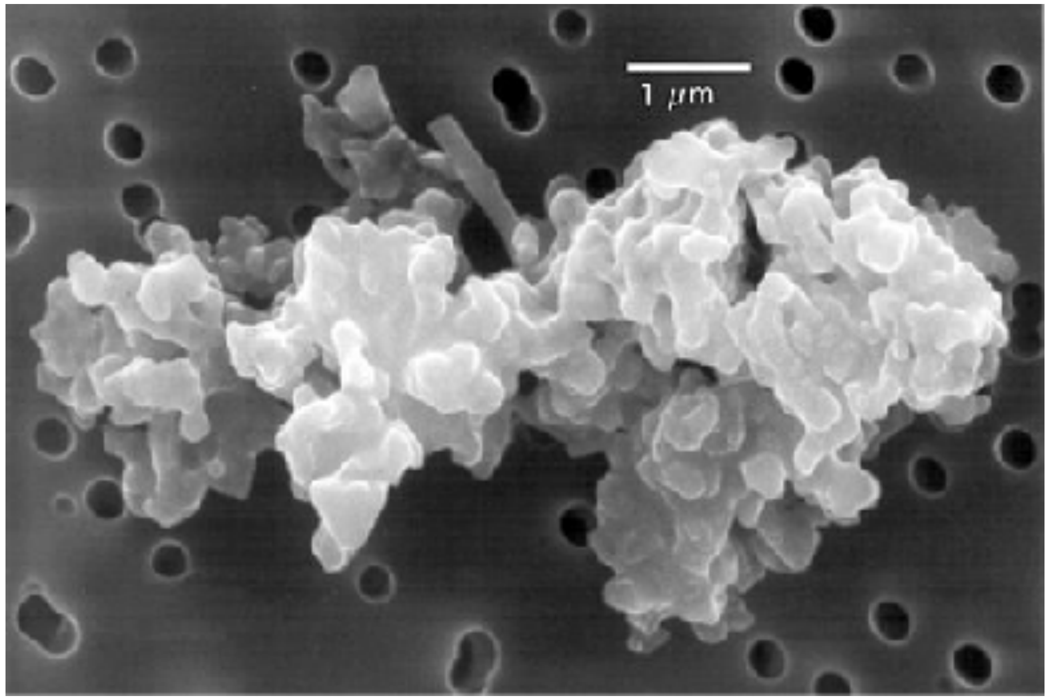
PAHs & dust grains images

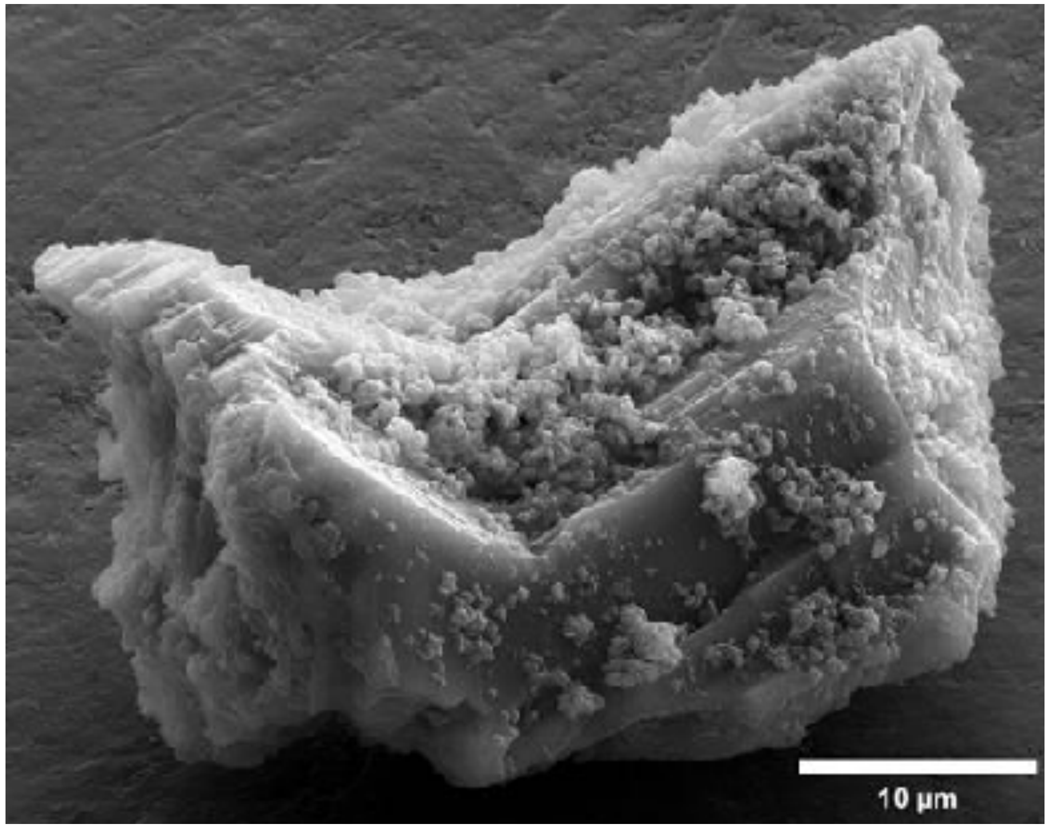
PAHs





Interplanetary Dust Particles (IDPs)





Schuler et al. (2015), Brownlee (2016)

How to see cosmic dust with naked eyes

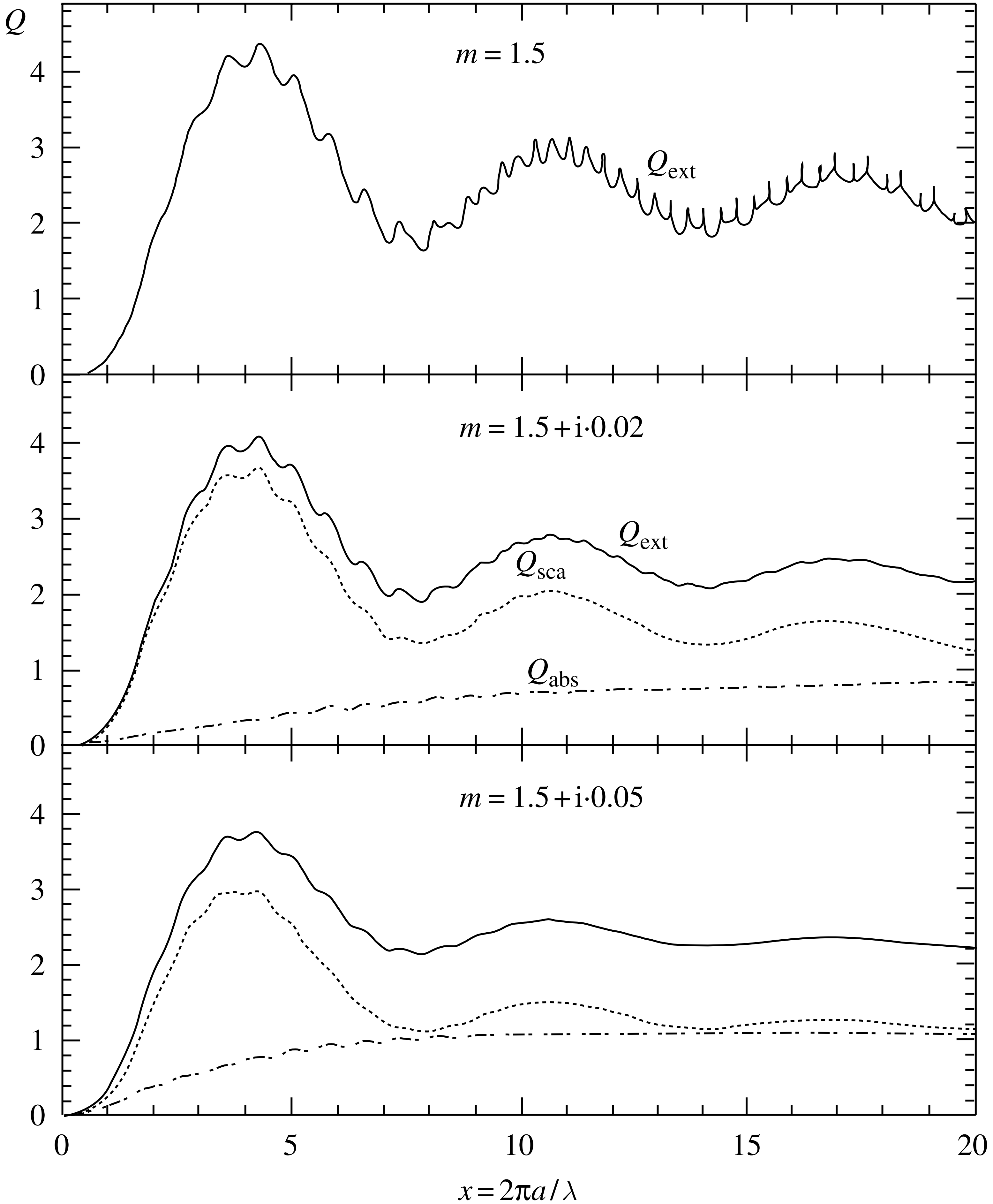
ESO/Y. Beletsky

- Sporadic meteors and meteor showers

Interaction with light: basics

- Extinction = Absorption + Scattering: $Q_{\mathrm{ext}} = Q_{\mathrm{abs}} + Q_{\mathrm{sca}}$
- Cross-section for grain of radius "a": $C_{\mathrm{ext}} = \pi a^2 Q_{\mathrm{ext}}$
- Size parameter for a wavelength "λ": $x = \frac{2\pi a}{\lambda}$
- Complex refractive index: $m = n - ik$
- Single-scattering albedo: $\omega = Q_{\mathrm{sca}}/Q_{\mathrm{ext}}$
- Mie theory for a homogeneous sphere (G. Mie, 1908)

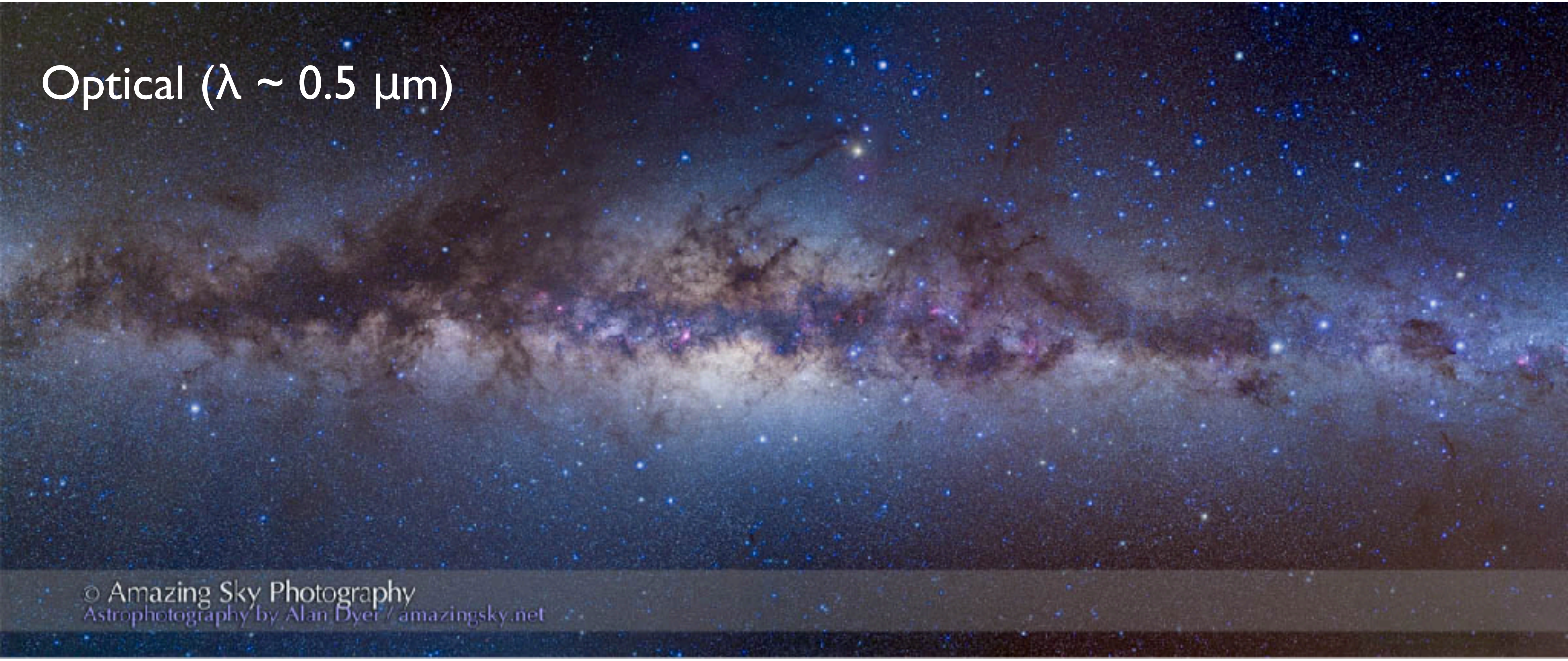
Q-factors for a spherical particle



- Rayleigh limit: $|mx| \rightarrow 0$
  - Scattering: $Q_{\rm sca} \propto \lambda^{-4}$
  - Absorption: $Q_{\rm abs} \propto \lambda^{-1}$
- Geometric optics: $x \rightarrow \infty$
  - Extinction: $Q_{\rm ext} = 2$
- Intermediate case:
  - Q-factors as infinite series of Bessel & Hankel functions

Mie (1908), Tielens (2007)

Dust in the Milky Way: extinction


Optical (λ ~ 0.5 μm)

© Amazing Sky Photography
Astrophotography by Alan Dyer / amazingsky.net

- Noticed by W. Herschel & F. von Struve (~1850)
- Sub-micron-sized dust particles (silicates and carbonaceous)
- First dust extinction measurements by Trumpler (1930)

First dust extinction measurements

Trumpler (1930):

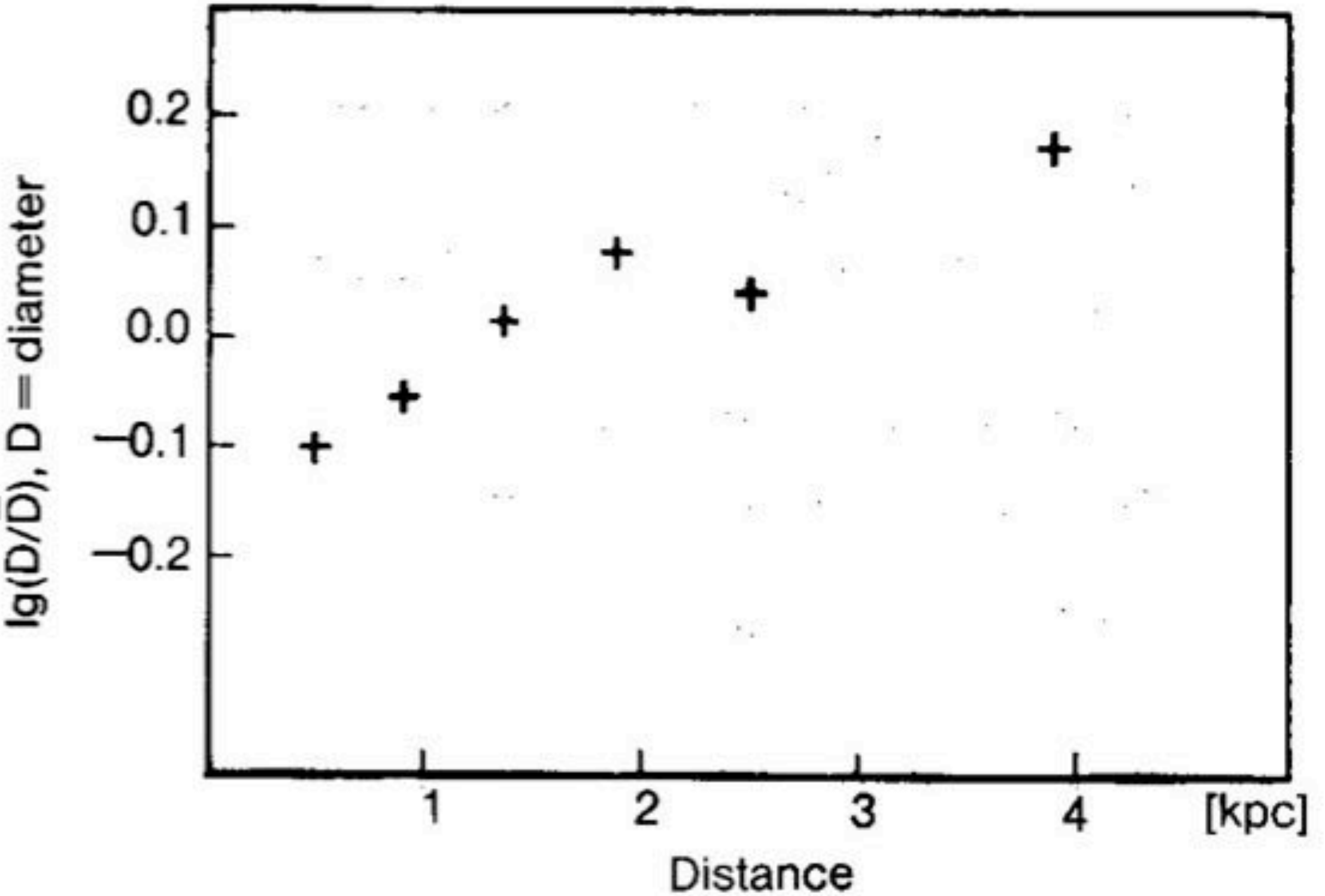
– Open stellar clusters (>100 stars in a tight group)

– Absolute magnitude "M" = apparent magnitude "m" at 10 pc

– $M = m - 5(\log_{10}(r) - 1) \Rightarrow$ distance *r* [pc] if M and m are known

– Linear diameter *D* and the measured angular diameter *d*: $D = d \times r$

– Strange result: *D* increases with increasing distance *r*

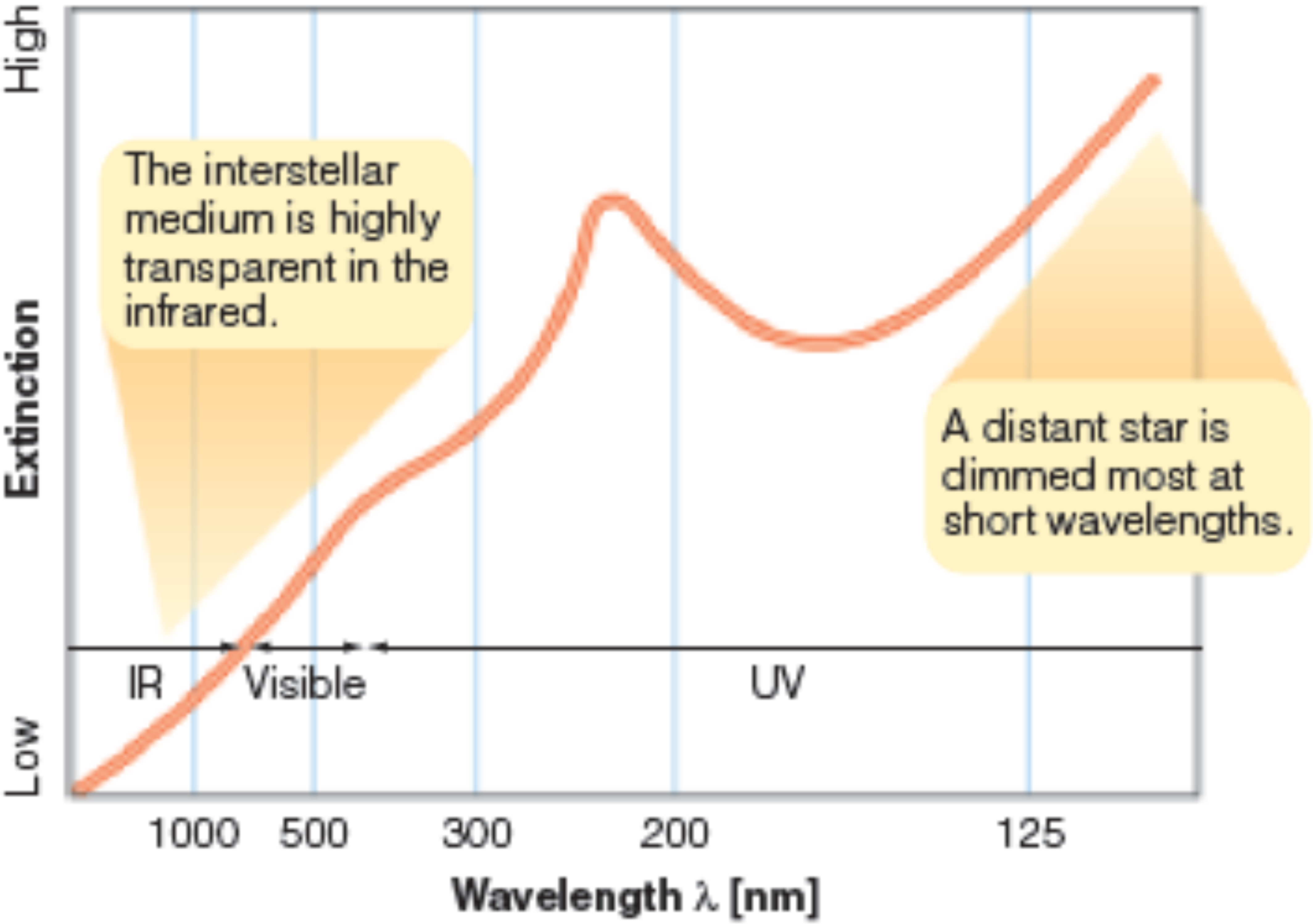


Trumpler: 0.70 mag/kpc

Modern value: 1.8 mag/kpc

Interstellar reddening

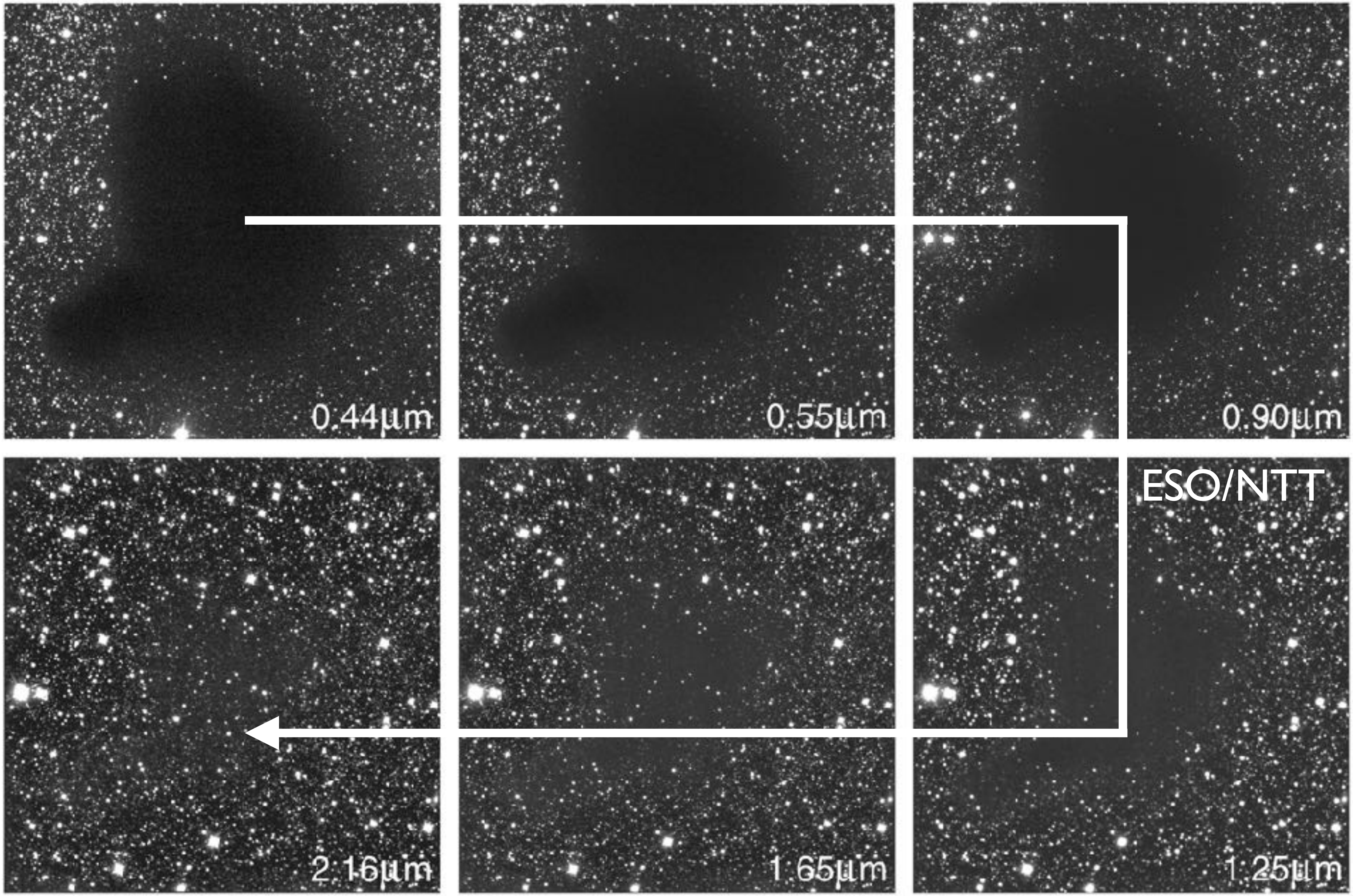
$$I_\lambda = I^0_\lambda \exp(-A_\lambda)$$



The interstellar medium is highly transparent in the infrared.

A distant star is dimmed most at short wavelengths.

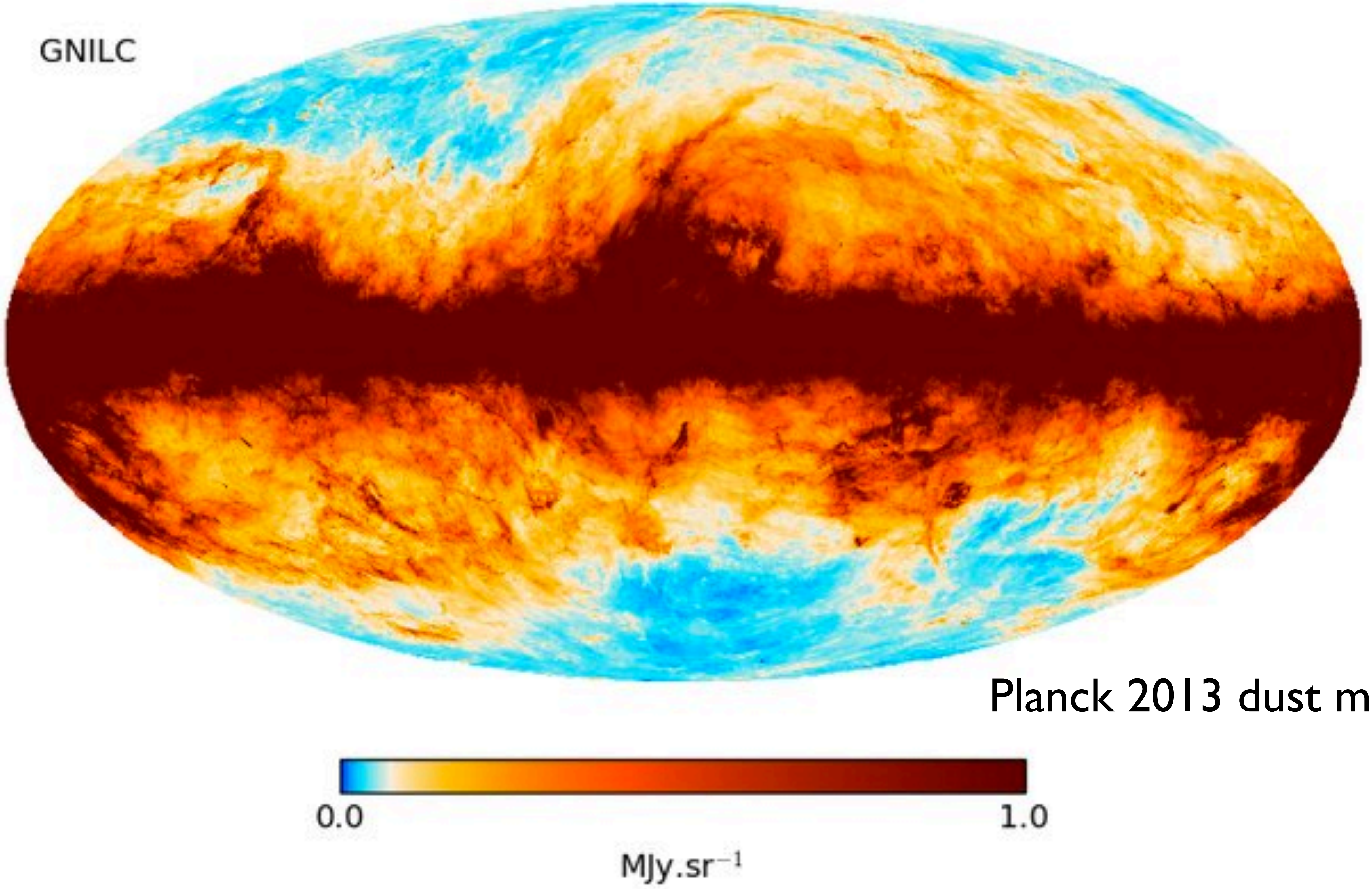
Dust at different wavelengths: B68



- Absorption is effective for $x = \dfrac{2\pi a}{\lambda} \gtrsim 1 \Rightarrow$ grain size $\lesssim$ 0.1 – 0.5µm

Dust in the Milky Way: emission

Sub-millimeter (λ = 0.85mm / 353 GHz)



Planck 2013 dust map

- Thermal emission from dust: M_d, N_d

Infrared spectroscopy of dust

- Ground-based telescopes (many): limited by atmosphere => observations at ~1–3 μm
- Space-borne facilities (a few):

  ISO: 2 – 200 μm

  SOFIA: 60 – 200 μm

  Spitzer: 5 – 40 μm

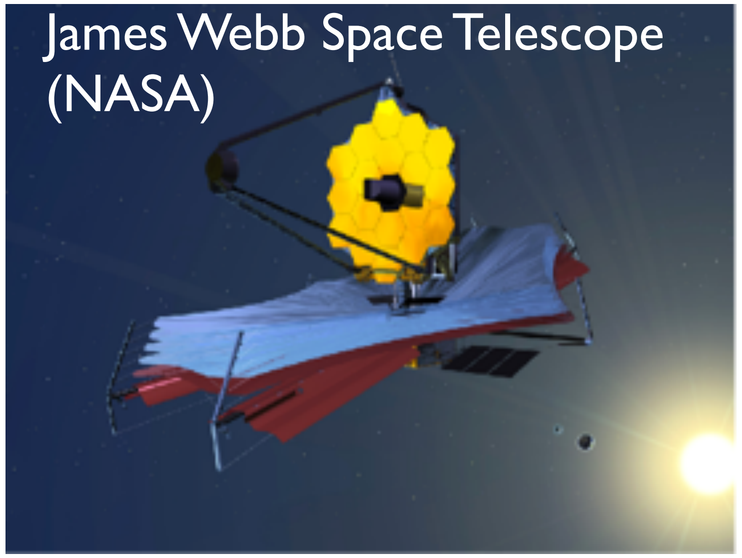
  Herschel: 40 – 260 μm

  James Webb Space Telescope: 0.6 –28 μm

- Laboratory spectra for identification


SOFIA


Herschel (ESO)


James Webb Space Telescope (NASA)

IR spectroscopy: solid-state bands

- Water ice (O-H stretching): 3µm

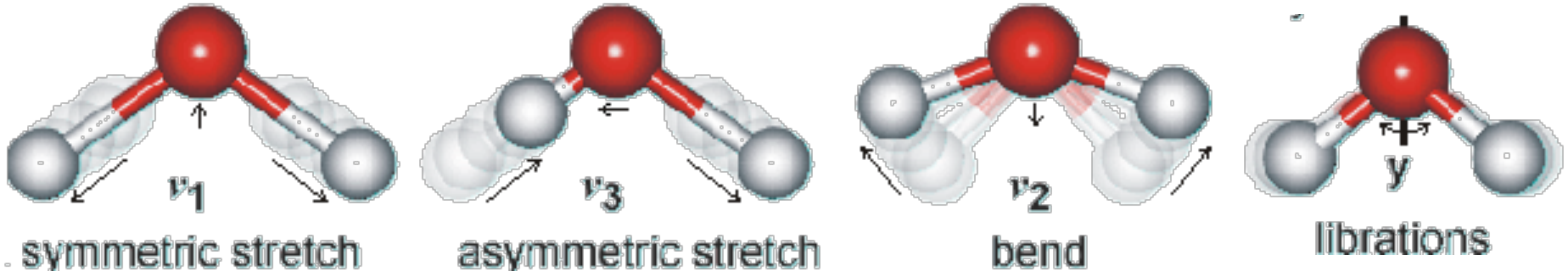
- PAHs (C-H & C-C stretching and bending): 3.3, 6.2, 7.7, 8.6, 11.3µm, …

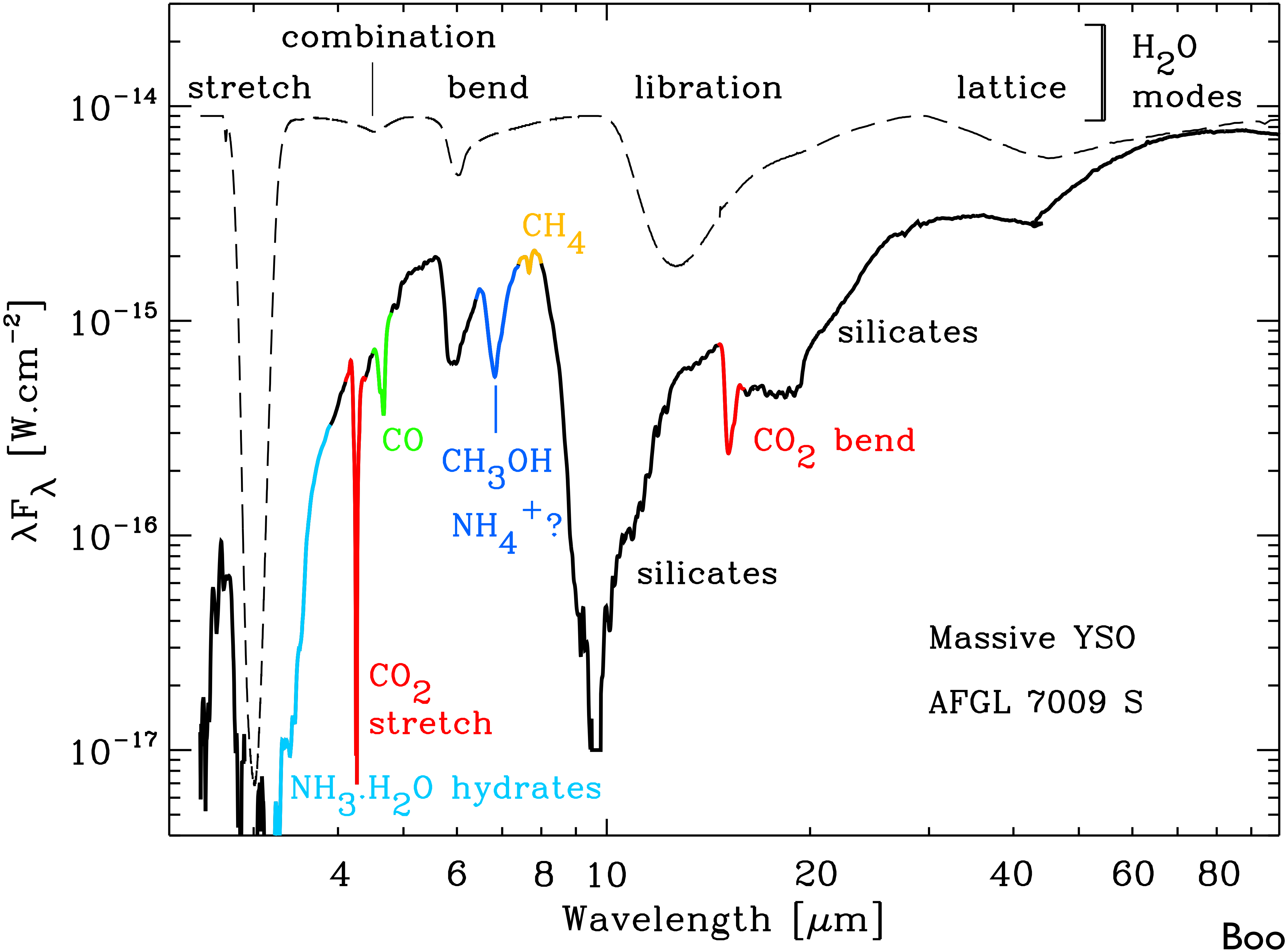
- Hydrogenated amorphous carbon: 3.4, 6.8, 7.2µm, …

- Amorphous silicates (Si-O stretching, O-Si-O bending): 9.8, 18µm

- Crystalline silicates (lattice): 10.2, 11.4, 16.5, 19.8, 23.8, 27.9, 33.7, 69µm

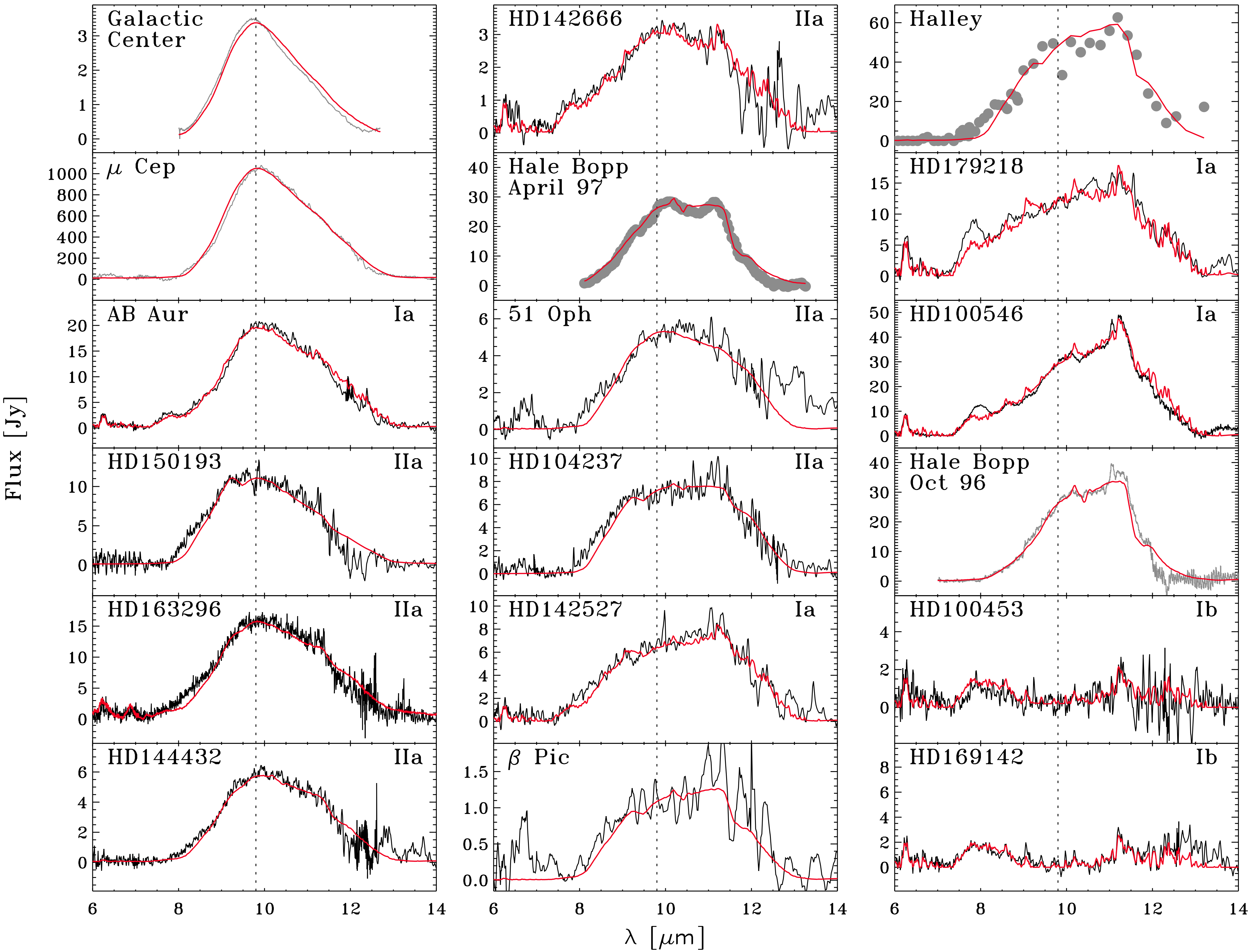
Solid-state IR absorption bands: cold dust





Boogert et al. (2015)

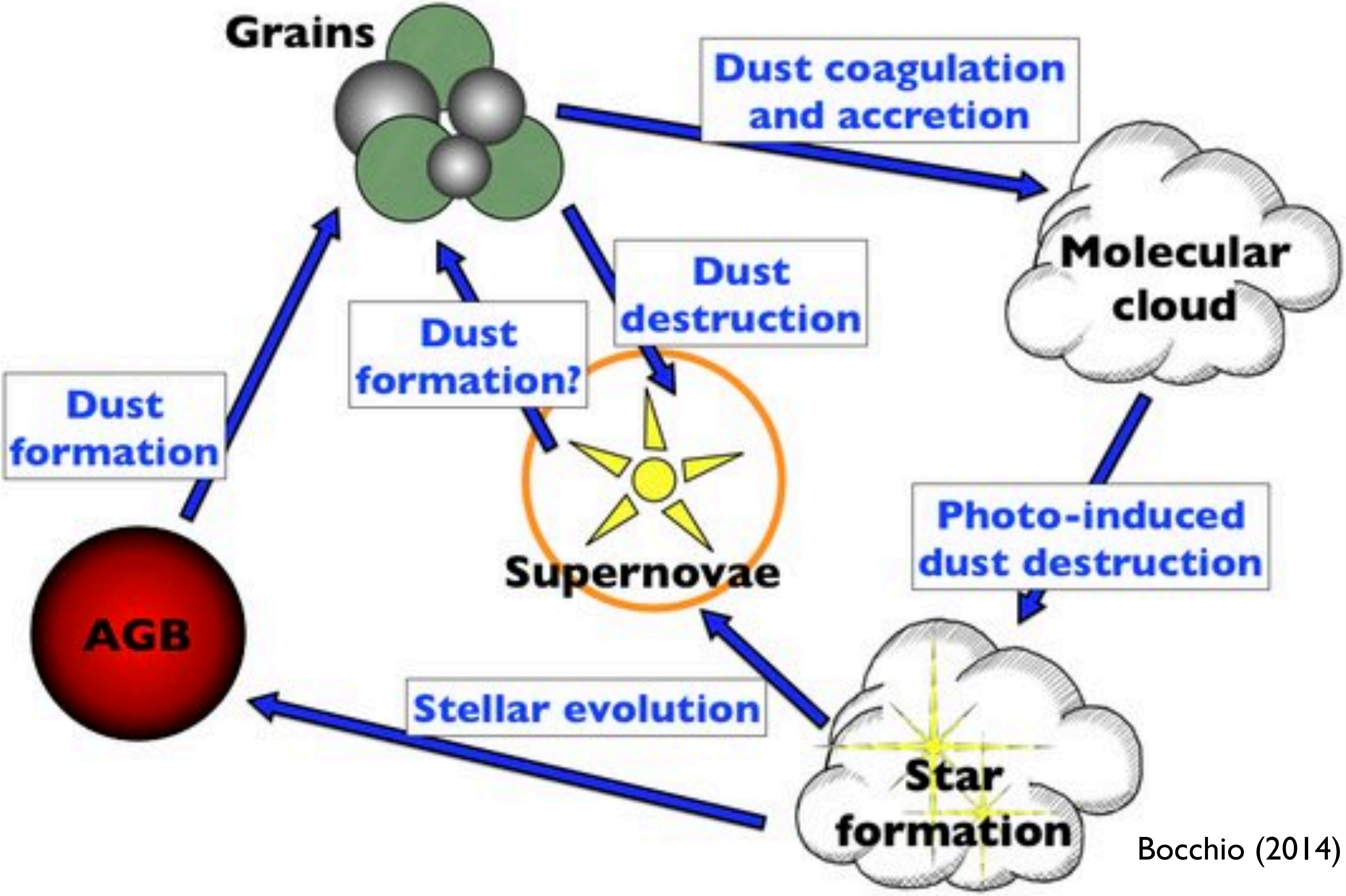
Silicate emission at 10μm: warm dust



- Composition, plus some info on temperature, size

Bouwman et al. 2001

Life cycle of dust in the Milky Way



Bocchio (2014)

- Dust around young stars is old, and dust around old stars is young!

Dust production in AGB stars

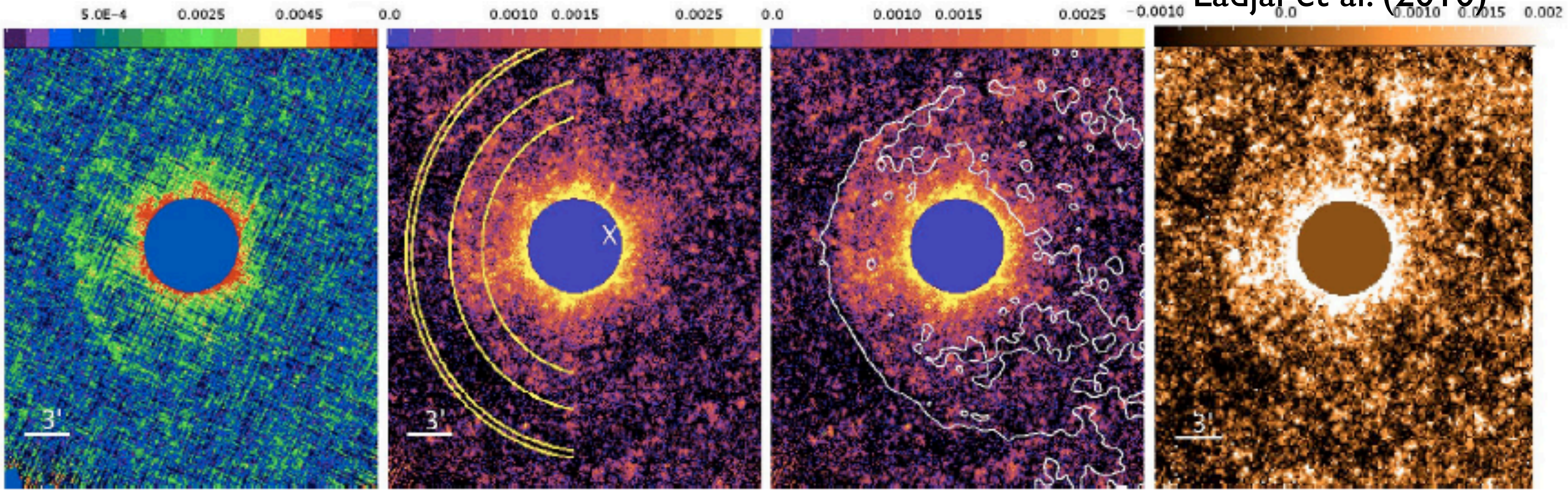
Source	Dust mass loss rate, M_{Sun}/yr	Dust composition
Carbon-rich, 2 – 4 M_{Sun}	~10^{-9} – 10^{-7}	Amorphous carbon, PAHs, SiC
Oxygen-rich, 4 – 8 M_{Sun}	~10^{-9} – 10^{-6}	Amorphous & crystalline silicates, oxides

Ejecta of AGB stars

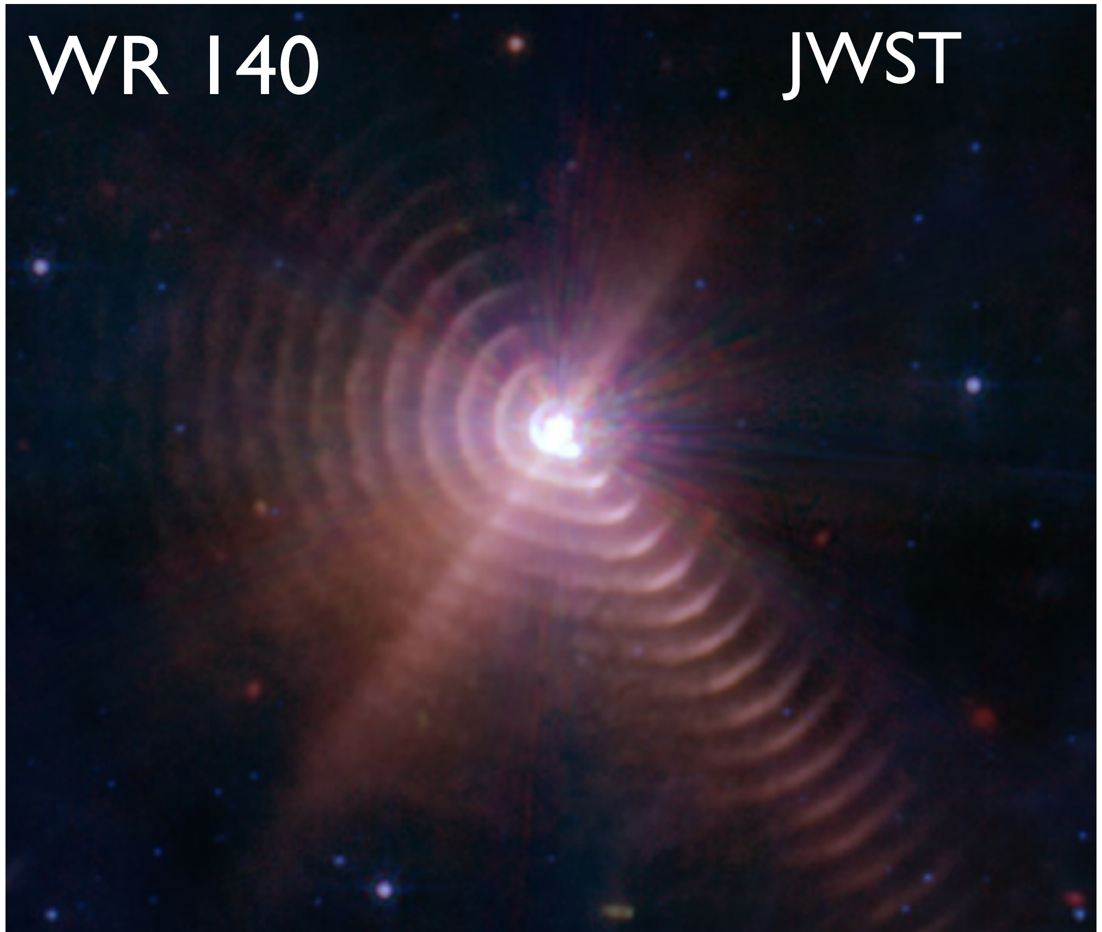
The Eskimo Nebula,
Hubble Space
Telescope, WFPC2

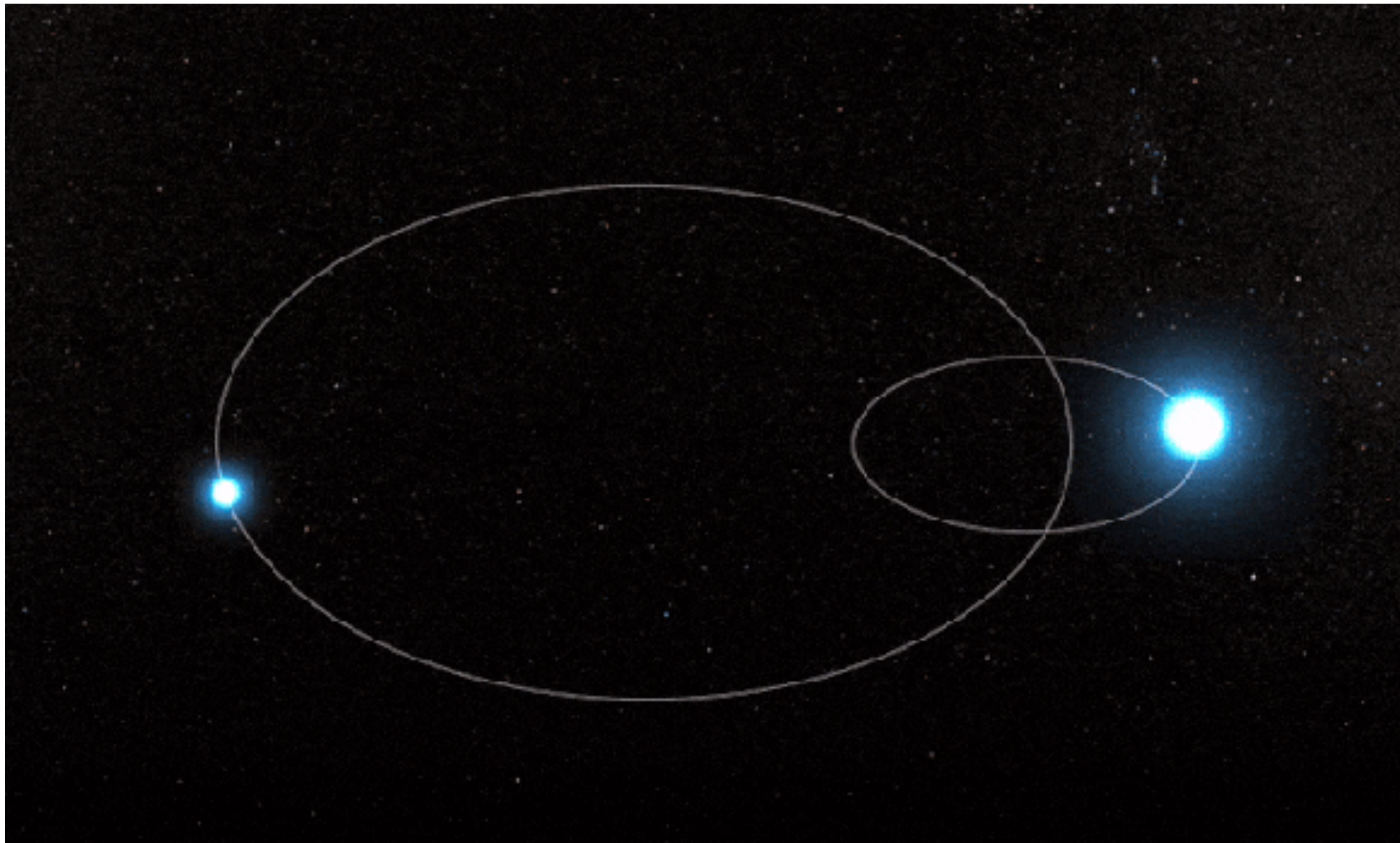
Observed dust around AGBs

Herschel images of IRC + 10216

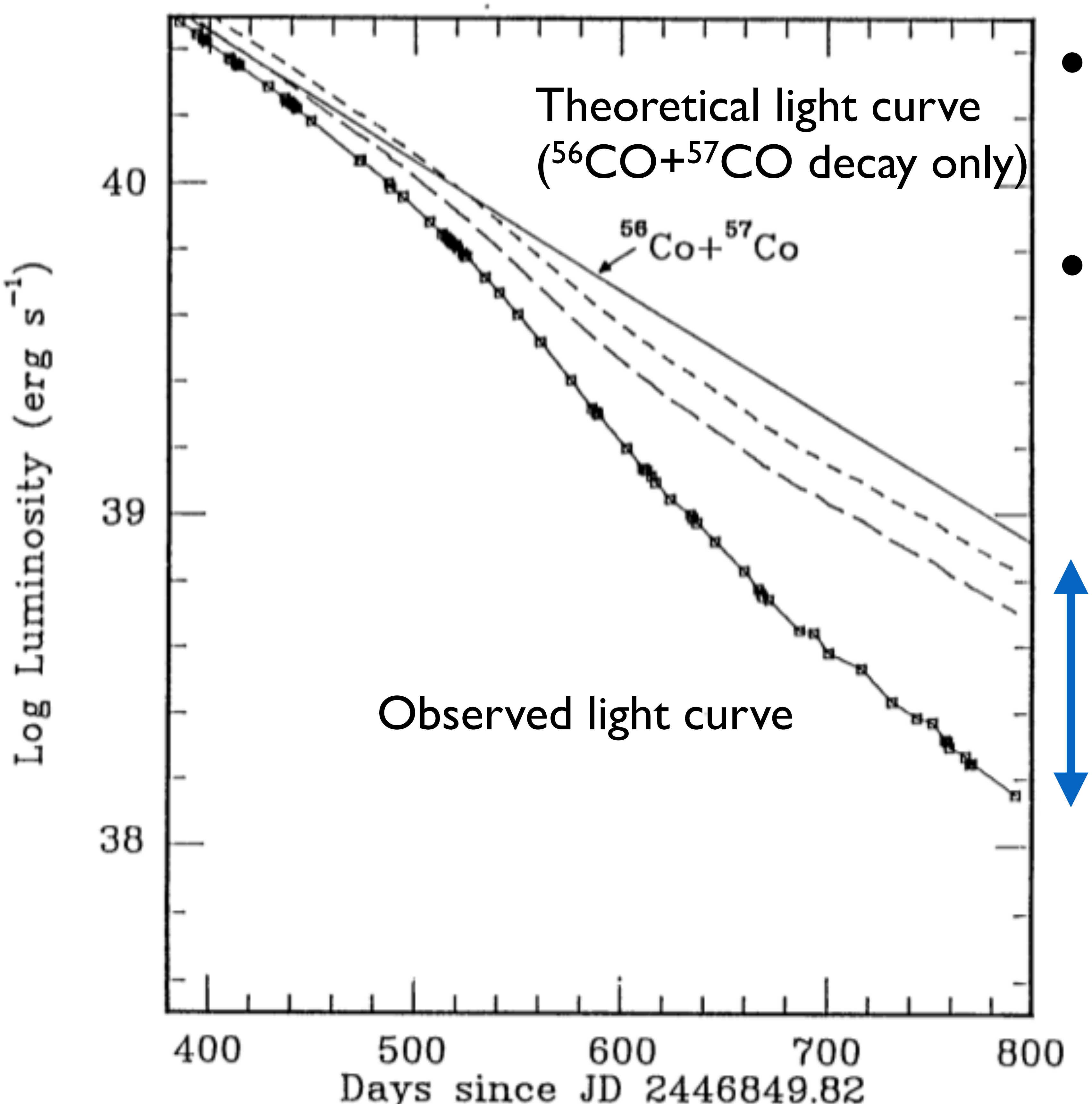

PACS 160 SPIRE 250 SPIRE 350

Ladjal et al. (2010)





Dust formation in supernovae: Supernova 1987A



Theoretical light curve
(^{56}CO+^{57}CO decay only)

Observed light curve

- Large Magellanic Cloud, 24.02.1987
- Too rapid light curve decay => dust formation after explosion

Dust extinction

Whitelock et al. (1989)

Dust production in supernovae

Source	Dust mass per explosion, M_{Sun}	Dust composition
Supernovae	$<10^{-4} – 0.1$	Amorphous carbon and silicates, iron
Supernovae remnants, <400 yr old	$\sim10^{-3} – 0.1$	Amorphous carbon and silicates

Cosmic dust formation

- Stellar ejecta:
  - Winds: giant and AGB stars (~40%)
  - Explosions: novae and supernovae (~60%)
- Composition determines mineralogy:
  - O-rich ejecta: silicates, oxides
  - C-rich ejecta: graphite and soot
  - SN: Fe, Ni, Co,…
- Grains gain ~ 50% in mass in the ISM
- Ice forms on grains at <20–100K

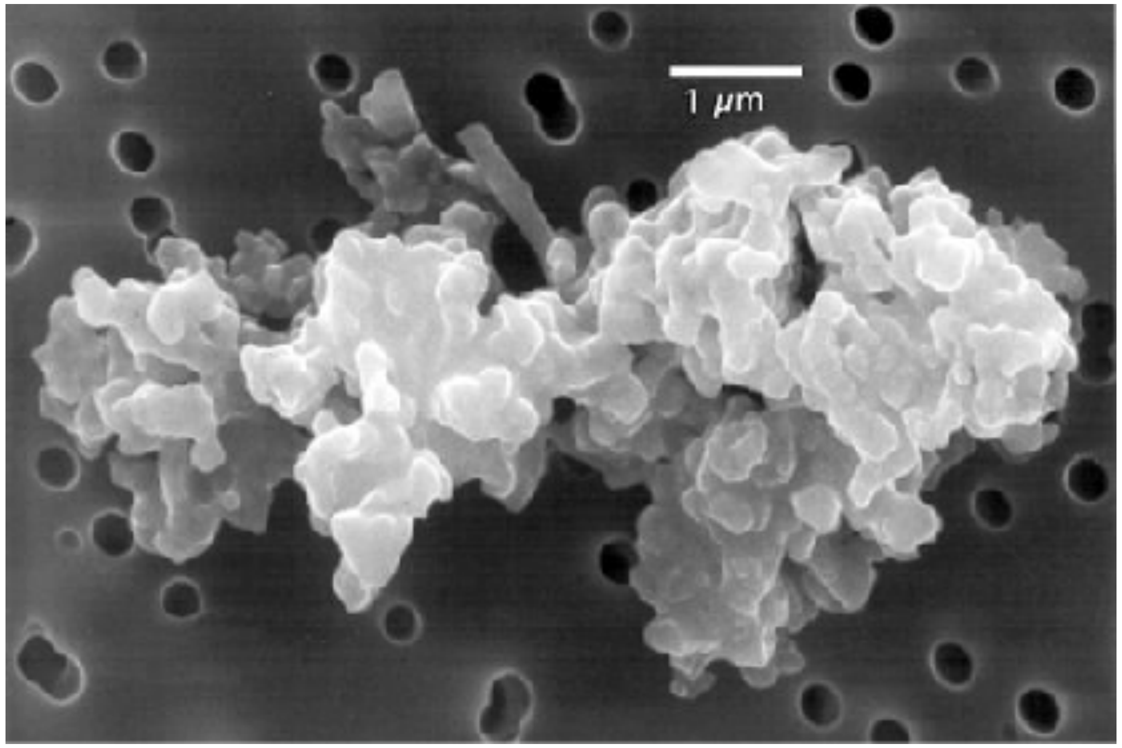
Cosmic dust destruction

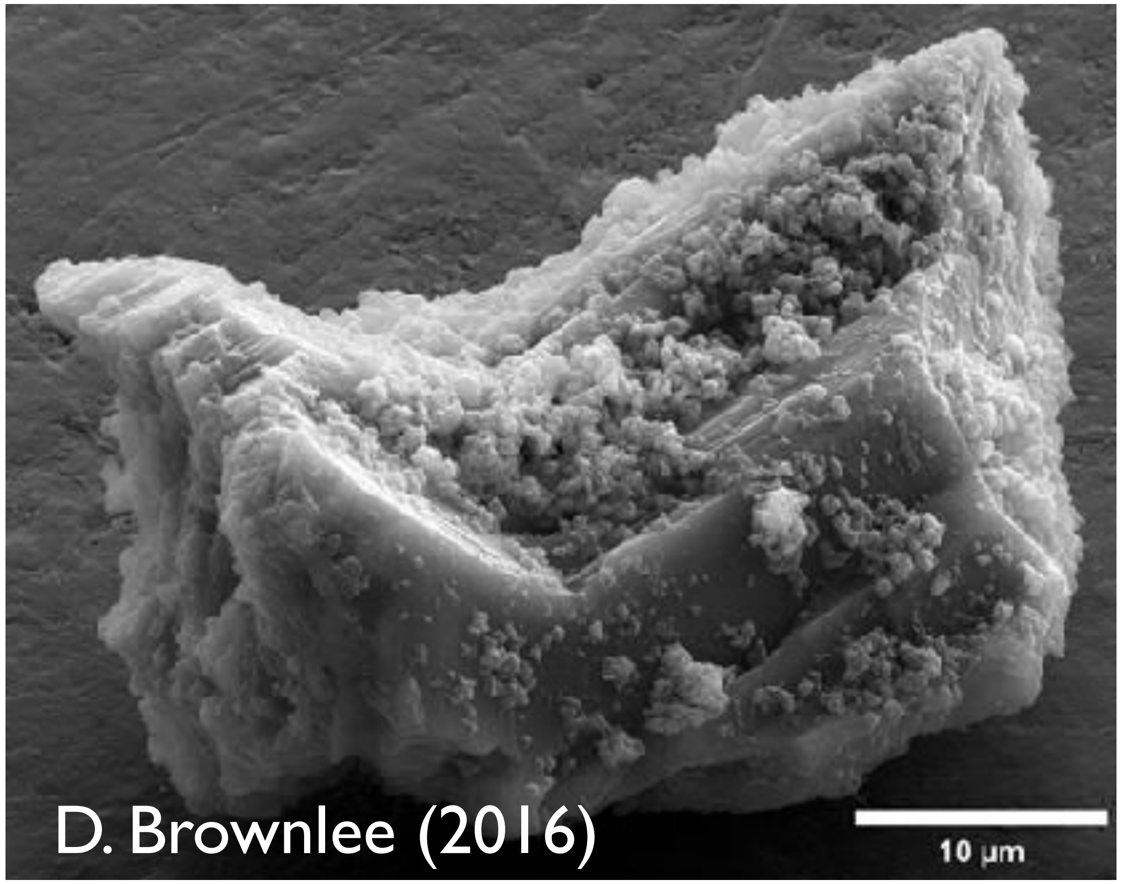
- Erosion by FUV photons with E > 5-6 eV
- Grain-grain collisions (>10 m/s)
- Shocks in turbulent ISM:
  - $V \sim 50$ km s^{-1}: grain-grain collisions (1% efficiency)
  - $V > 200$ km s^{-1}: gas-grain collisions (50% efficiency)

Survival timescale ~ 5 10^8 yrs < Injection timescale ~ 3 10^9 yrs!

Cosmic dust: overview

- Dust/gas by mass: ~ 1%
- Sink of heavy elements (> Na)
- Typical radius is 0.1µm
- Opaqueness of matter (opacities)
- Heating & cooling
- Catalytic surfaces for reactions





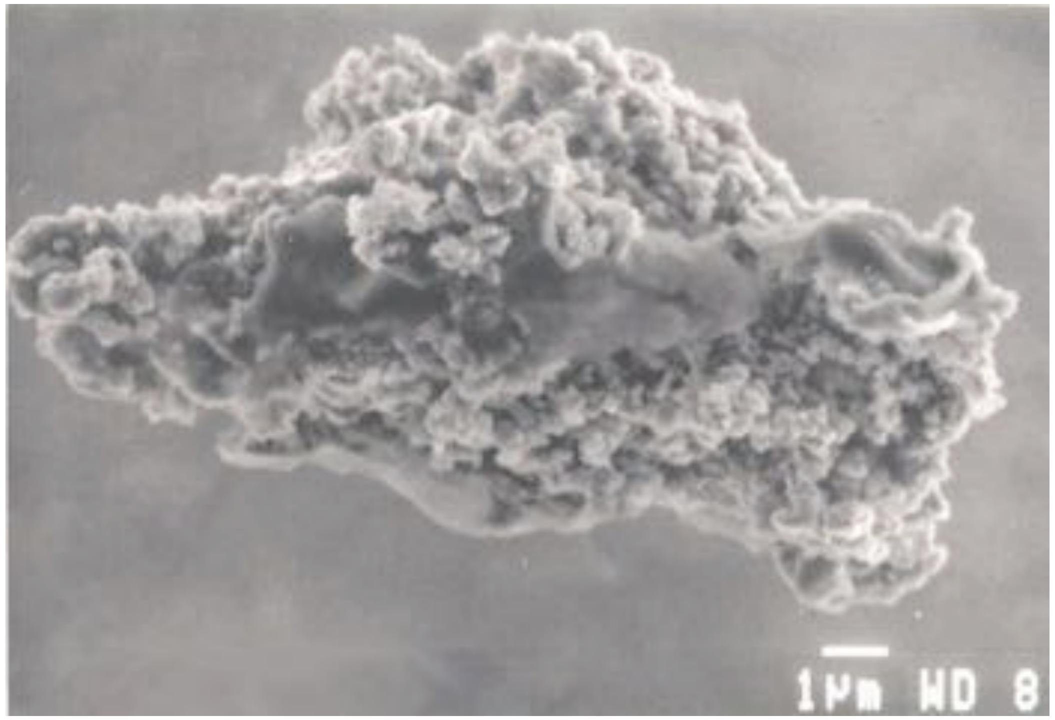
D. Brownlee (2016)

II. Chemical Processes on Dust Surfaces

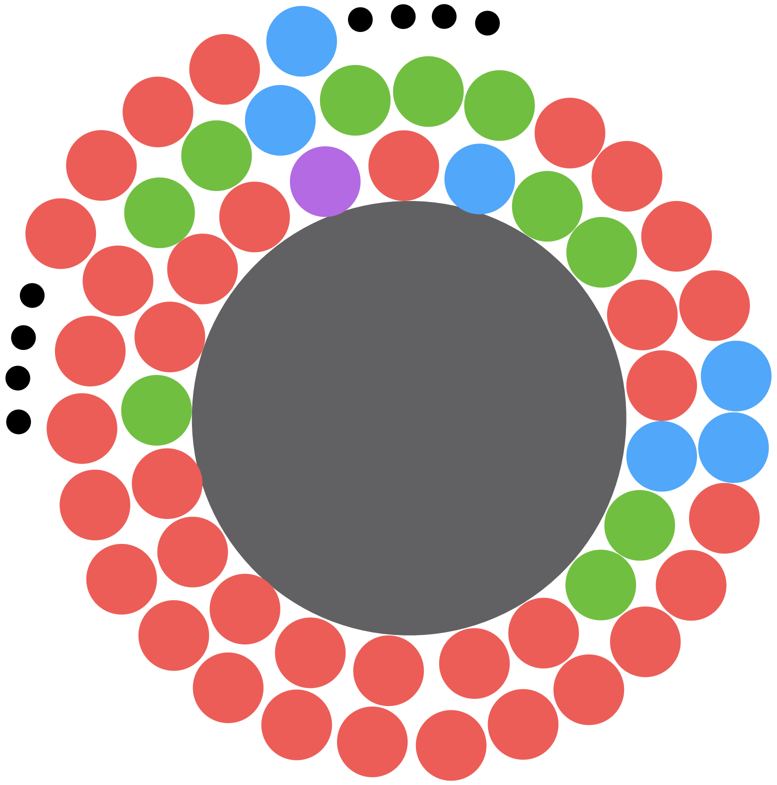
Dust grains as catalysts for chemistry

- Carbonaceous/silicates
- Size distribution (usually a single size in chemical models)
- Fluffy, porous structure (usually assumed spherical and compact)
- Molecules stick to dust surface:
  - $\sim 10^6$ binding sites on 1000Å grain
  - a binding site has a size ~1Å
  - ~100–300 monolayers of ice

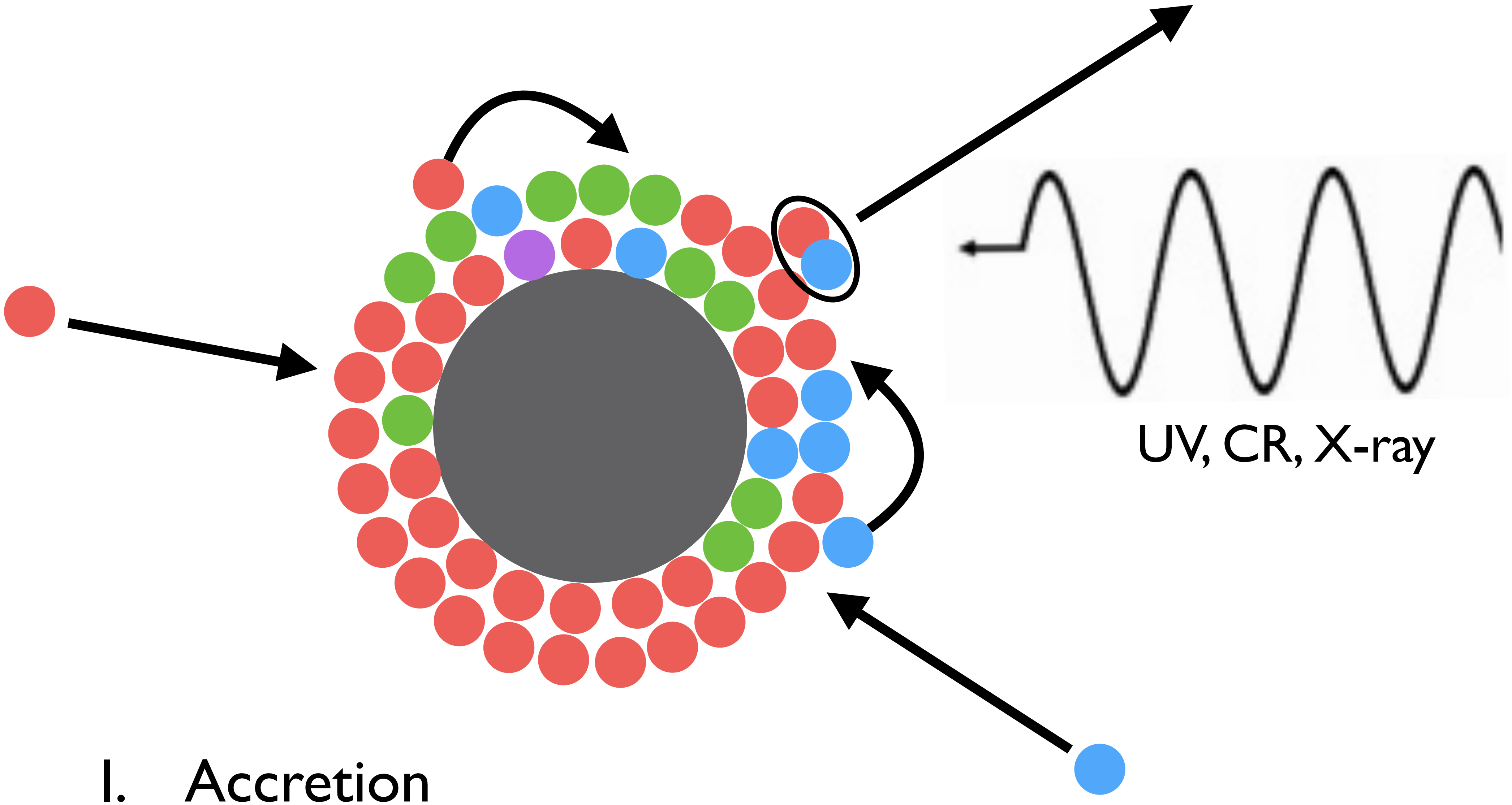
dust particle from space



dust particle in the models



Chemistry in space: surface processes



I. Accretion

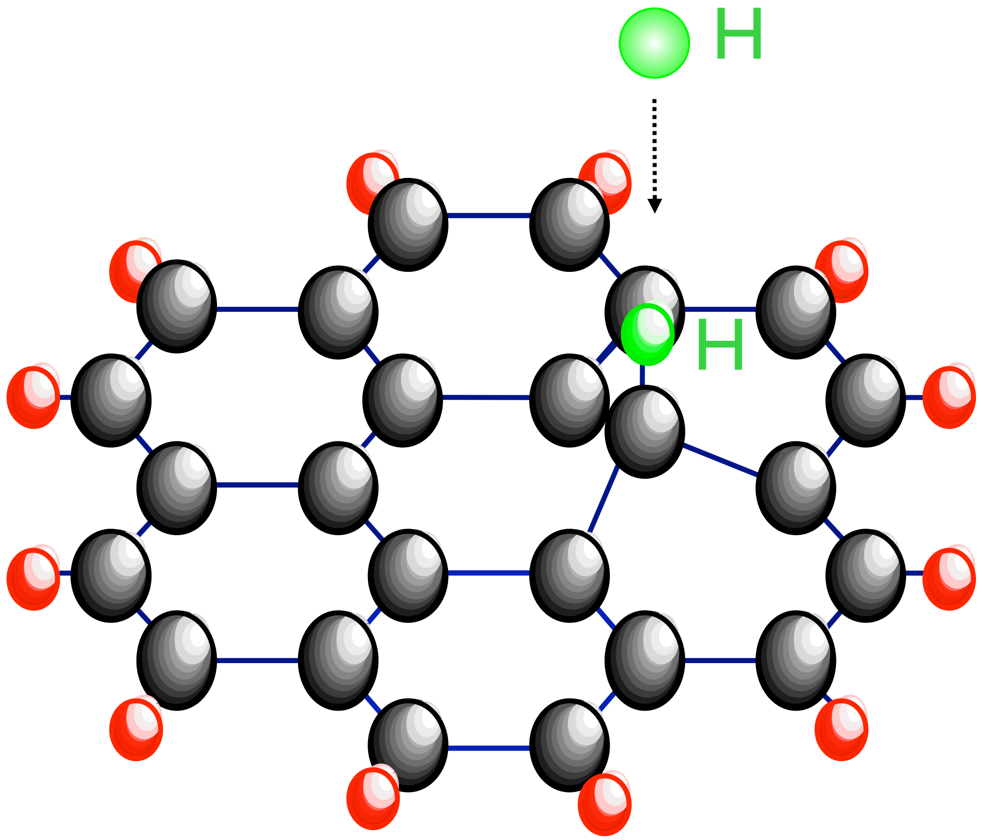
II. Diffusion via hopping or tunneling

III. Surface recombination: H_2, H_2O, organics,…

IV. Desorption or destruction (UV, X-ray, CR,…)

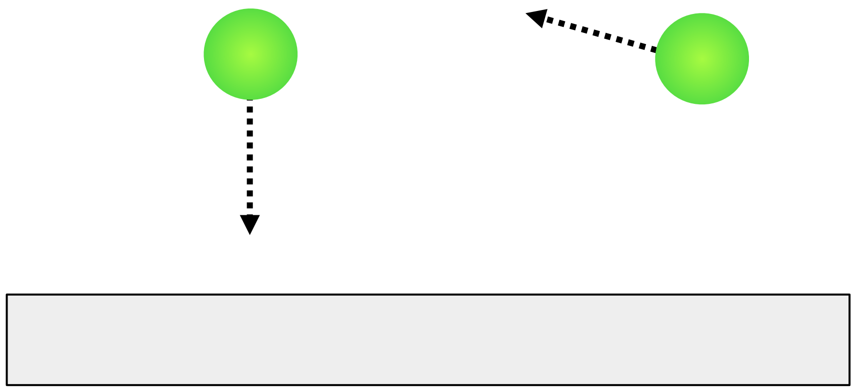
Two sorts of binding sites for accretion

Chemisorption



- Chemical bonds
- Binding energies: ~ 0.5–5 eV or >20,000 K

Physisorption



- Weak electrostatic van der Waals force
- Binding energies: ~10–100 meV or ~100–5,000 K

Accretion and freeze-out rates

- Accretion rate: $k_{\mathrm{ac}} = n_{\mathrm{d}}\sigma_{\mathrm{d}} v S(T, T_{\mathrm{d}}) \simeq 10^{-17}\left(\frac{T}{10\,\mathrm{K}}\right)^{1/2} n\,\mathrm{s}^{-1}$

  n_{d} is dust density, σ_{d} is dust cross section, v is thermal velocity, S is sticking coefficient (~1)

- Freeze-out timescale: $t_{\mathrm{freeze}} \sim 1/k_{\mathrm{ac}} \approx 3\times 10^{9}/n_{\mathrm{H}}$ years

- Arrival timescale: $\tau_{\mathrm{ar}} = (n_i\sigma_{\mathrm{d}} v)^{-1} \simeq 3\left[\frac{10^4\,\mathrm{cm}^{-3}}{n}\right]\left[\frac{1000\,\mathrm{\mathring{A}}}{a}\right]^2$ days,

▶ Radius a = 1000Å, dust/gas = 0.01, T = 10 K, $n_{\mathrm{H}} = 10^4\ \mathrm{cm}^{-3}$:

$n_{\mathrm{d}} \sim 10^{-12}\,n$, $\sigma_{\mathrm{d}} \sim 3\times10^{-10}\ \mathrm{cm}^2$, $v(\mathrm{H}) \sim 300$ m/s

- Accretion rate: $10^{-13}\ \mathrm{s}^{-1}$
- Freeze-out timescale: 3×10^{5} years
- Arrival timescale: 3 days

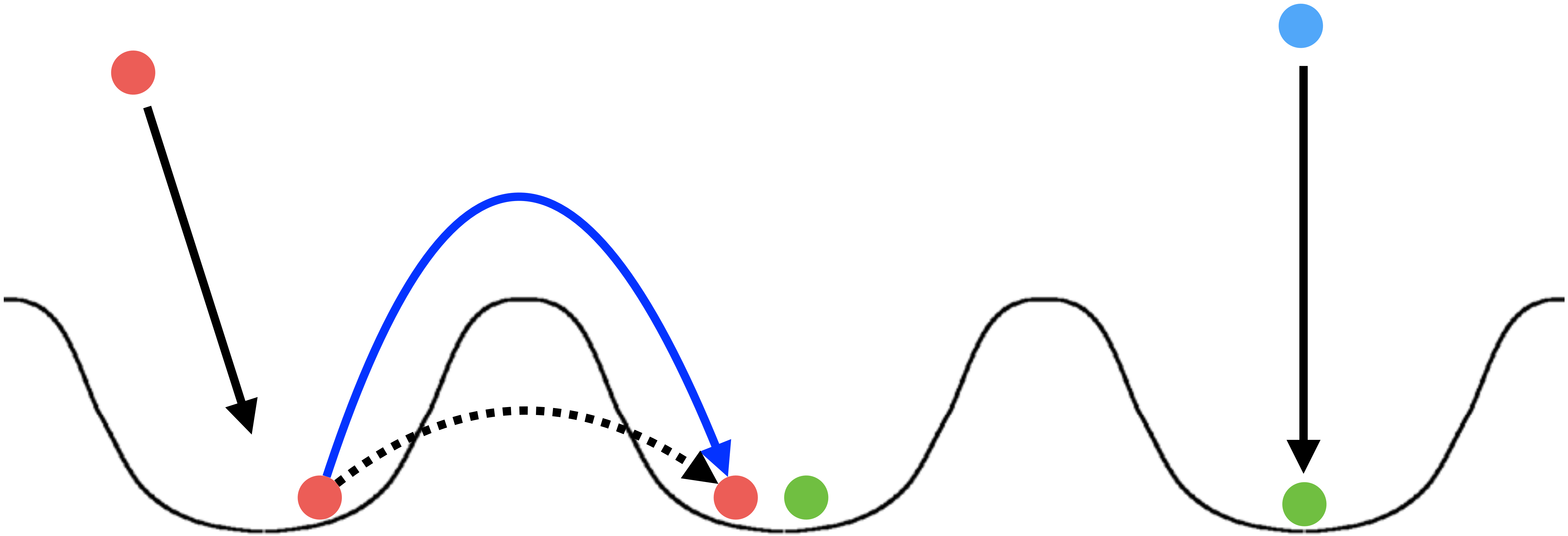
Major ices in the ISM

'Typical' abundances (H_2O ice = 100%)

CO	few-50%
CO_2	15-35%
CH_4	2-4%
CH_3OH	<8, 30%
HCOOH	3-8%
[NH_3]	<10, 40% (?)
H_2CO	<2, 7%
[HCOO-]	0.3%
OCS	<0.05, 0.2%
[SO_2]	<=3%
[NH_4^+]	3-12%
[OCN^-]	<0.2, 7%

Oberg et al. (2012)

Mechanisms of surface recombination



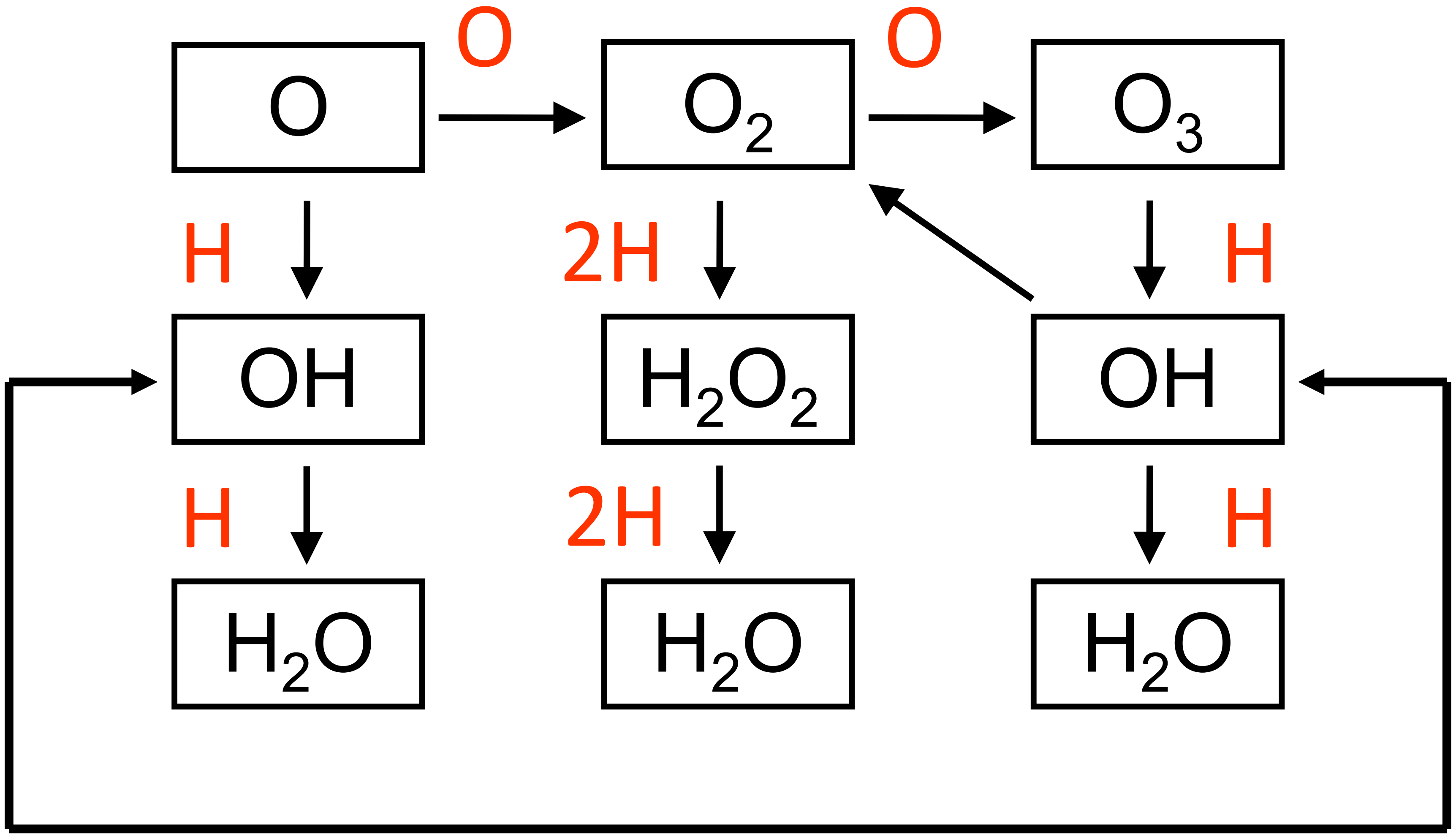
- Langmuir-Hinshelwood: recombination after hopping/tunneling

- Eley-Rideal: direct "stick-and-hit" recombination

- Hot-atom: combination of both

- Excess of energy is absorbed by dust lattice

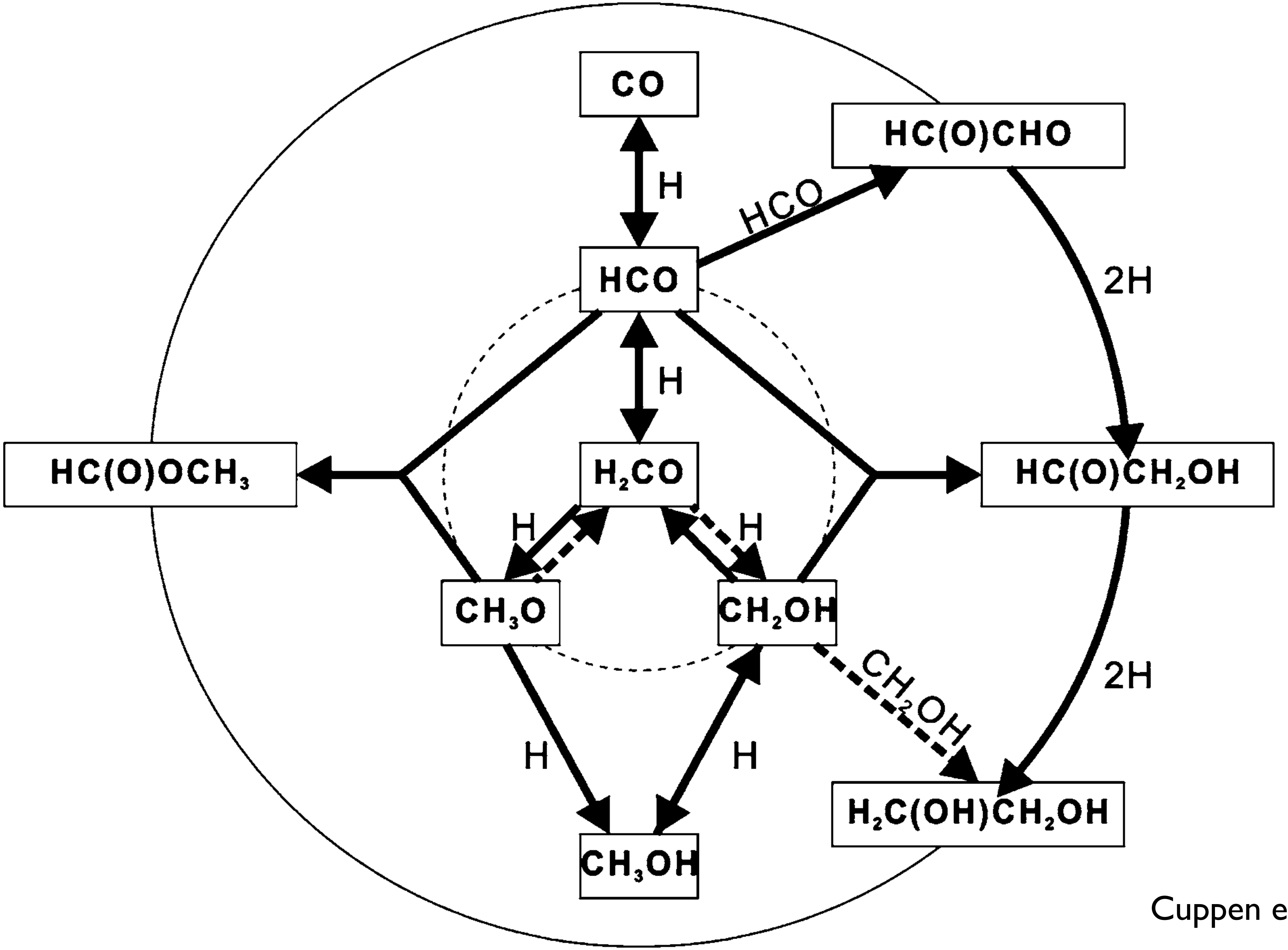
Surface synthesis of water



Tielens & Hagen 1982

- All reaction steps were studied in laboratory

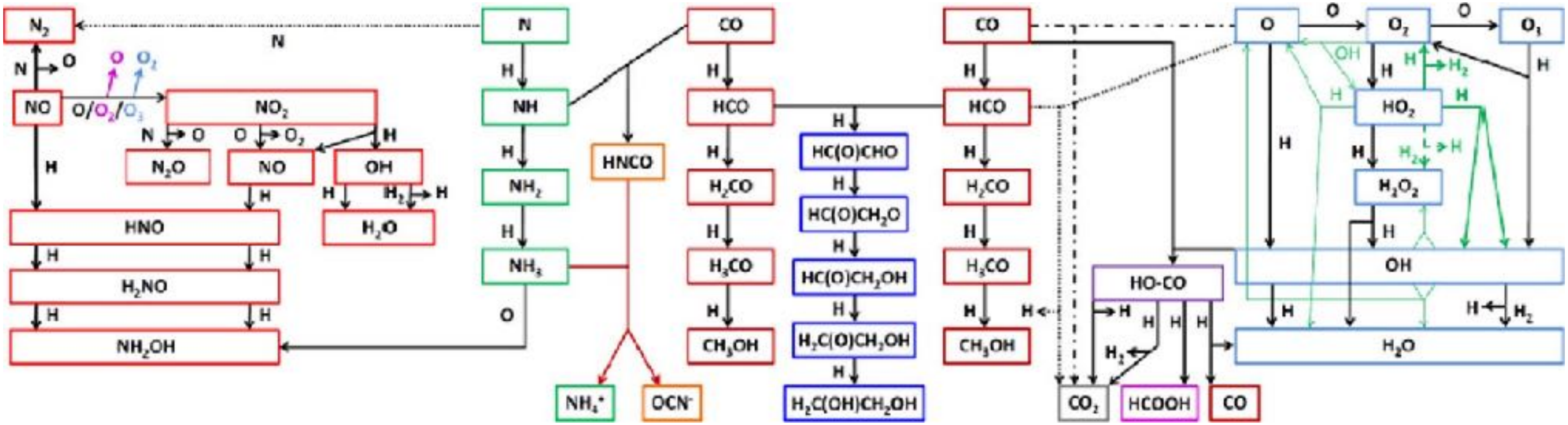
Surface hydrogenation of CO



Cuppen et al. (2016)

- CO is converted to complex organic molecules

Surface chemistry: an overview



- Most of reactions were studied in laboratory
- Diffusivity of H: fast already at 10 K
- Diffusivity of O, C, N is slow at 10 K => hydrogenation prevails
- Polyatomic "CHON" molecules: synthesis requires energy (UV, CRP, e^-)

Cuppen et al. (2016)

Surface chemistry rates & timescales

- Cold molecular cloud:

a = 1000Å, dust/gas = 0.01, T = 10 K, n_H = 10^4 cm^{-3}, $E_\mathrm{diff} = 0.3E_\mathrm{des}$

- Arrival time: $t_\mathrm{ar} \sim 3$ days

- Hopping timescale ($\sim 1/k_\mathrm{h}$):

H_2 (E_des= 440K): $t_\mathrm{h} \sim 5 \times 10^{-7}$ s

C (E_des= 800K): $t_\mathrm{h} \sim 0.03$ s

O (E_des= 1660K): $t_\mathrm{h} \sim 4 \times 10^9$ s or 135 years

H_2O (E_des= 5600K): $t_\mathrm{h} \sim$ infinity

Desorption of ices: summary

- Thermal desorption at specific T ("snowline"):

    ~16 – 19 K for N_2

    ~20 K for CO, CH_4

    ~35 – 40 K for CO_2

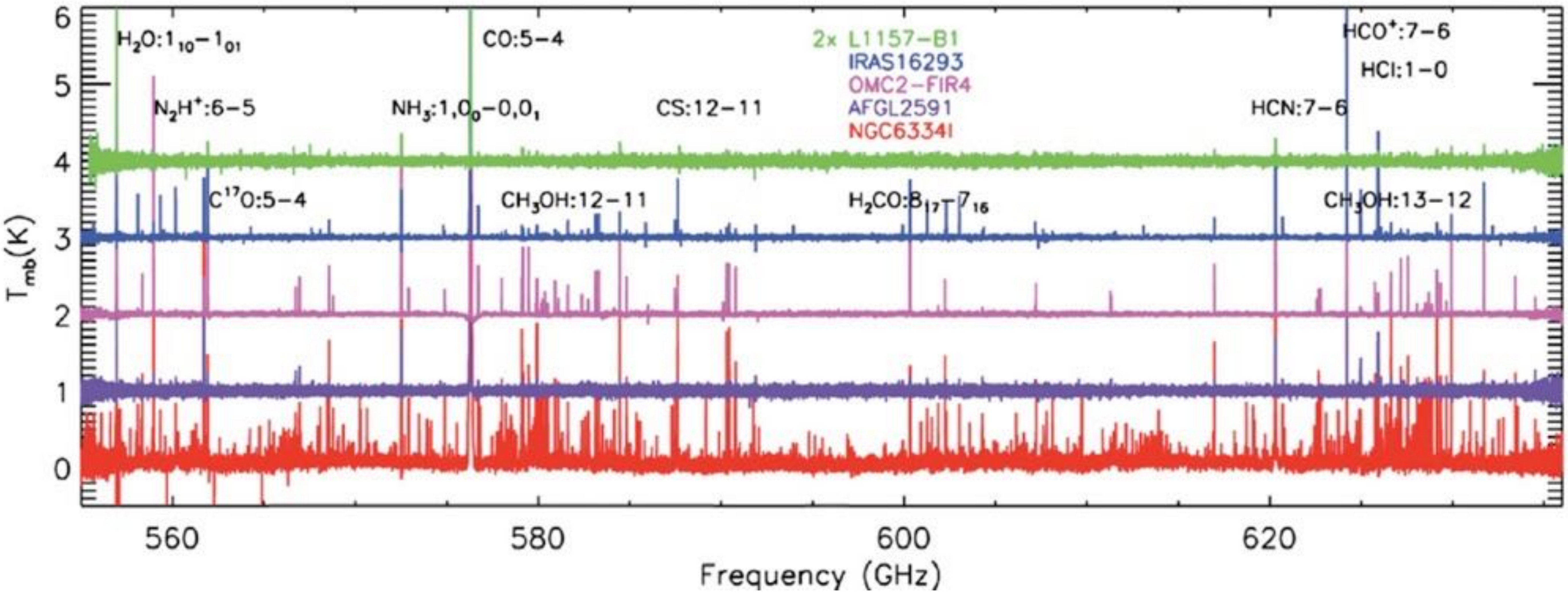
    ~55 – 60 K for NH_3

    ~100 – 150 K for H_2O, CH_3OH, ...

- Photodesorption: regions which FUV photons can reach
- CRP desorption: occurs in dense regions (low probability)
- Chemical desorption: can occur after surface reaction

(variable probability)

From ices to gas: dense cores ⇒ hot cores



Ceccarelli et al. (2010), A&A 521, L22

- Ices are synthesized and sublimated when T increases
- More complex molecules become detectable
- High-resolution laboratory spectra

Suggested literature

- B. Draine, "Astrophysics of Dust in Cold Clouds" (2003): https://arxiv.org/abs/astro-ph/0304488
- A. G.G.M. Tielens, "Molecular Universe" (2021), CUP
- H. Cuppen et al. , "Grain Surface Models and Data for Astrochemistry" (2017), Space Sci. Rev. 212/1-2
- A. Potapov & M. McCoustra, "Physics and Chemistry on the Surface of Cosmic Dust Grains: A Laboratory View" (2021): https://arxiv.org/pdf/2105.01387.pdf

Merry Christmas and Happy New Year!