FIR/submm Astrophysics – An Overview

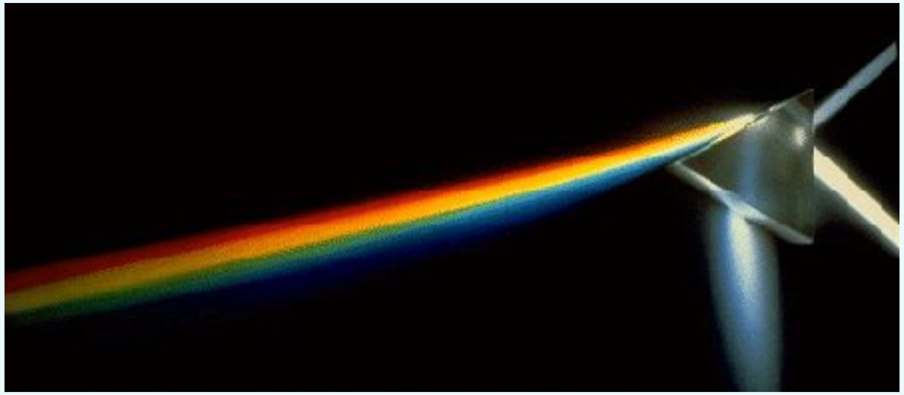
2 May 2018

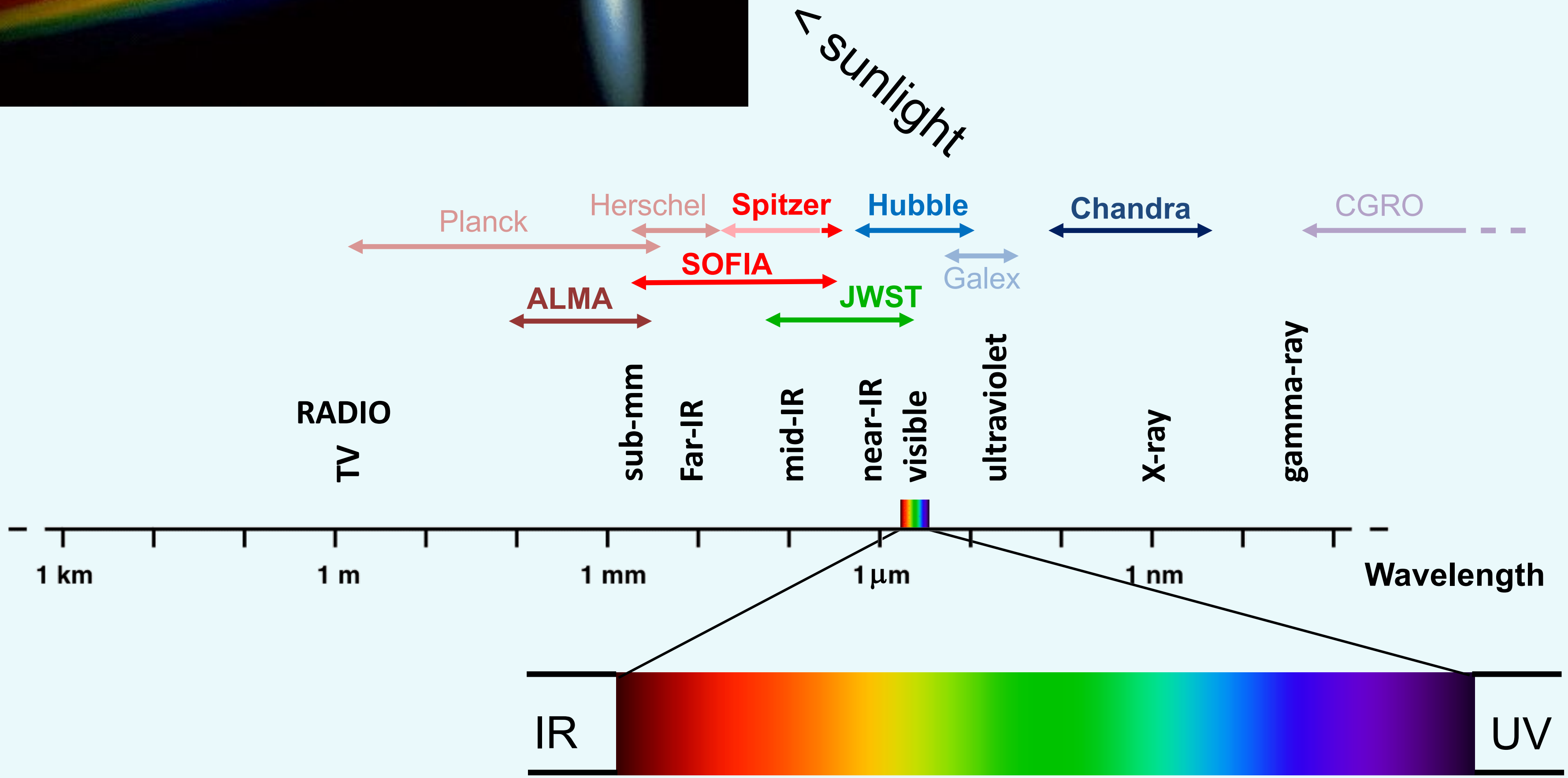
Harold W Yorke

SOFIA SMO Director

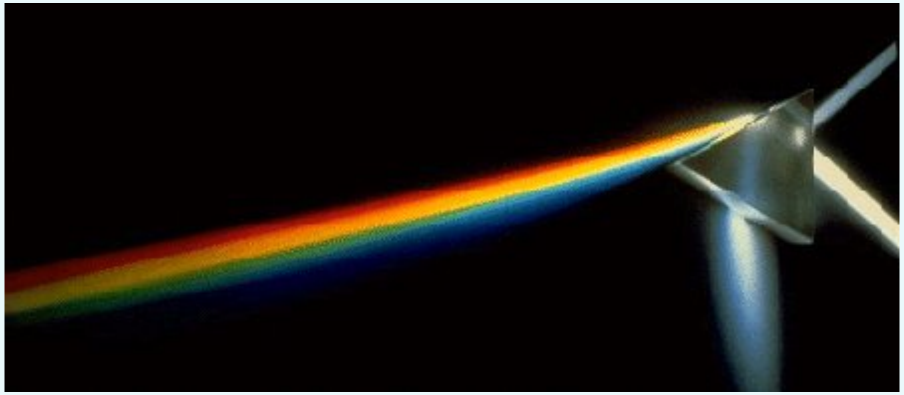
SOFIA Workshop

The Electromagnetic Spectrum

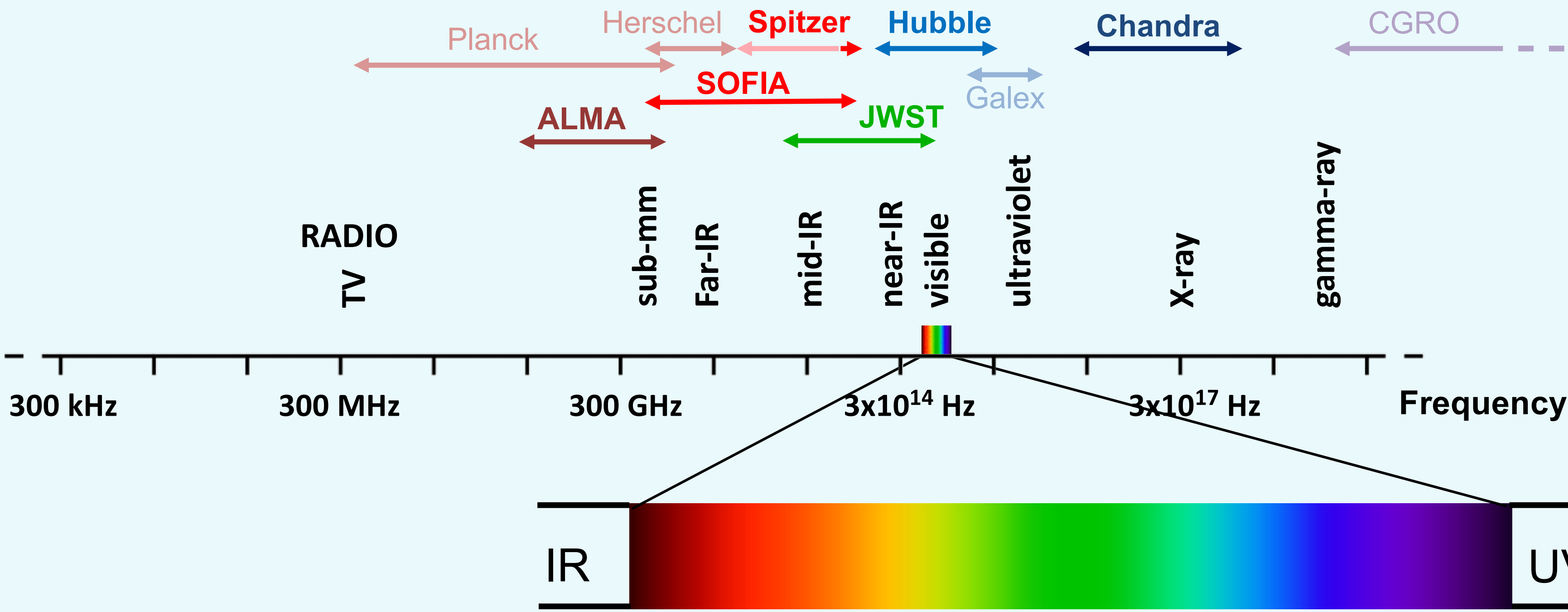




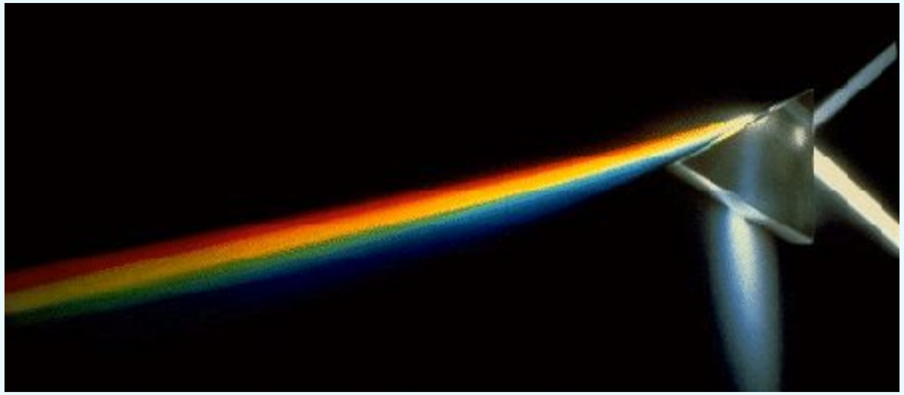
The Electromagnetic Spectrum

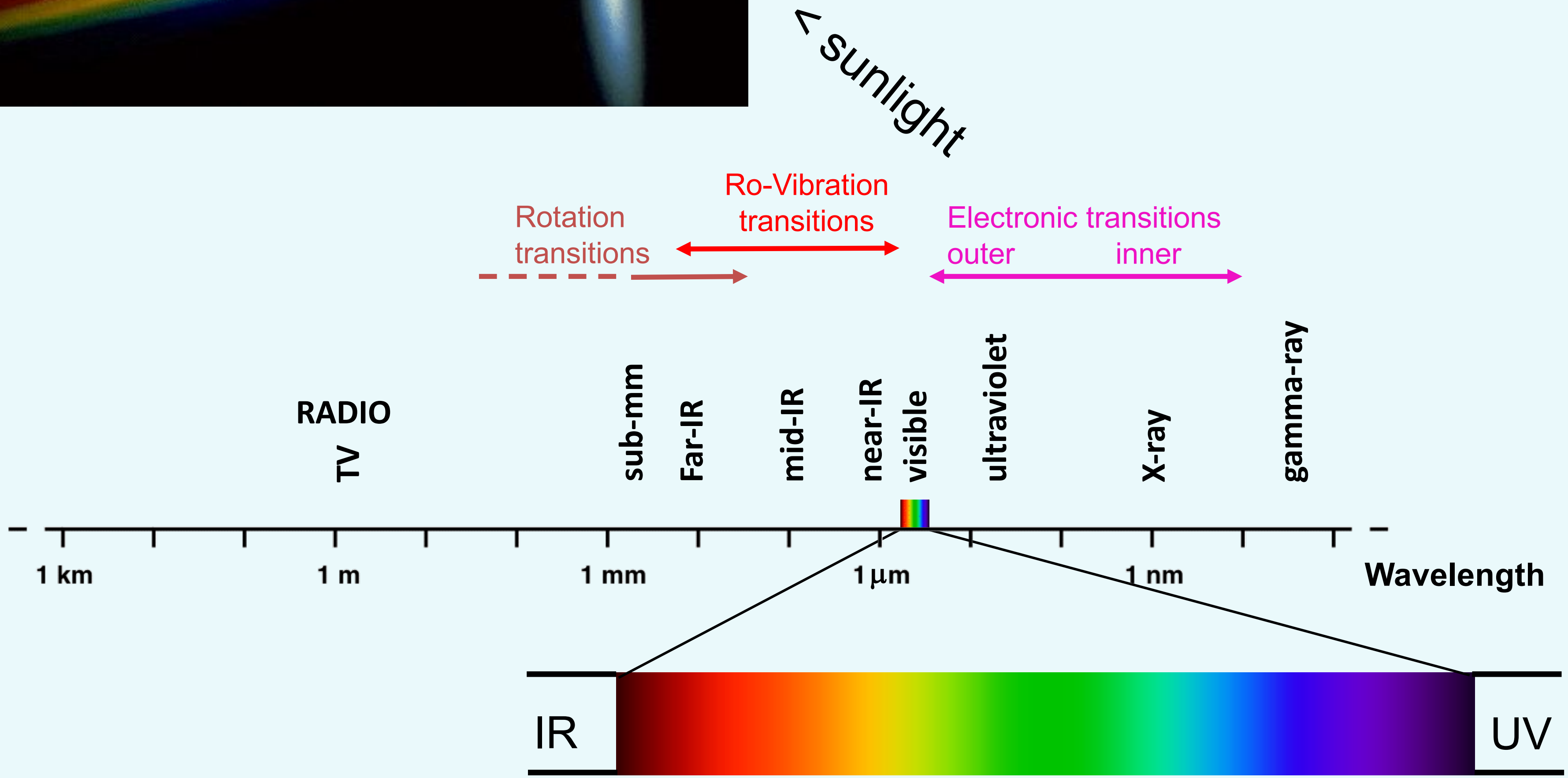


< sunlight



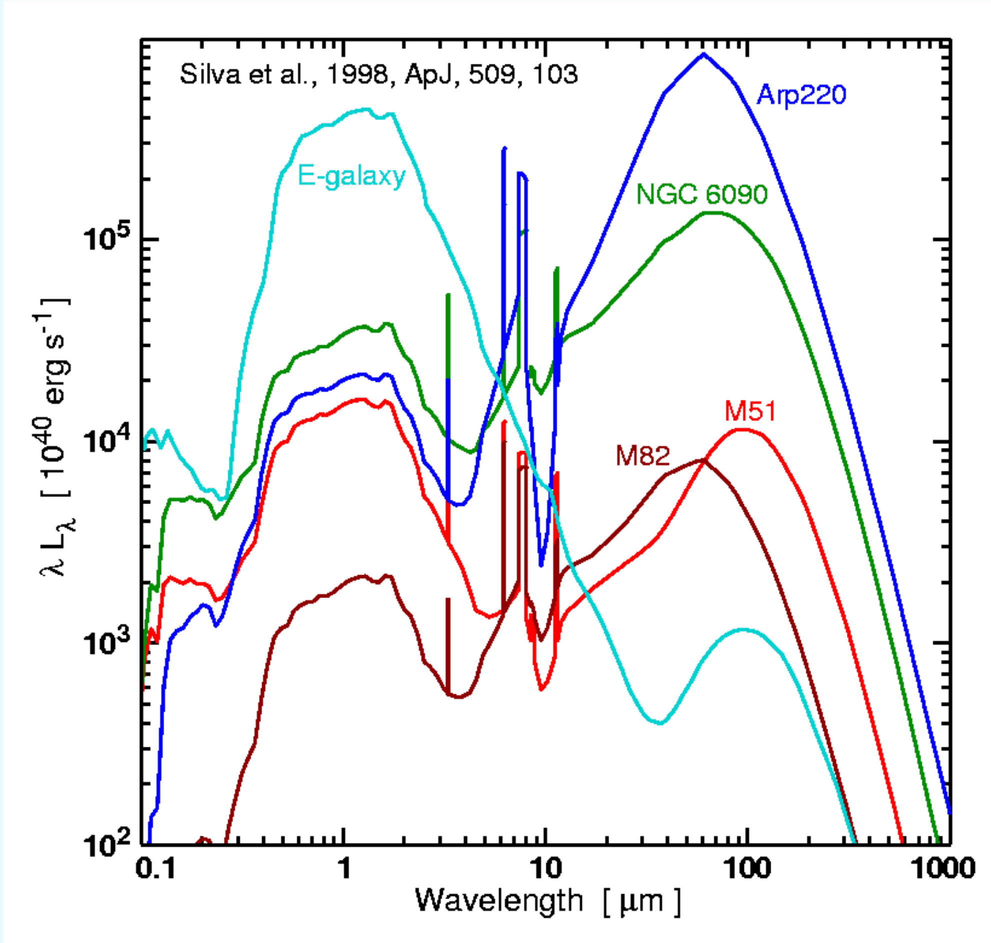
Atoms & Molecules





FIR-emission from star-forming galaxies

- Dusty galaxies emit mostly in the Far-IR. These wavelengths probe their star formation properties and evolution
- 1/2 of energy emitted since the Big Bang is in the Far-IR/submm
- Far-IR flux measures star formation activity and/or AGN activity



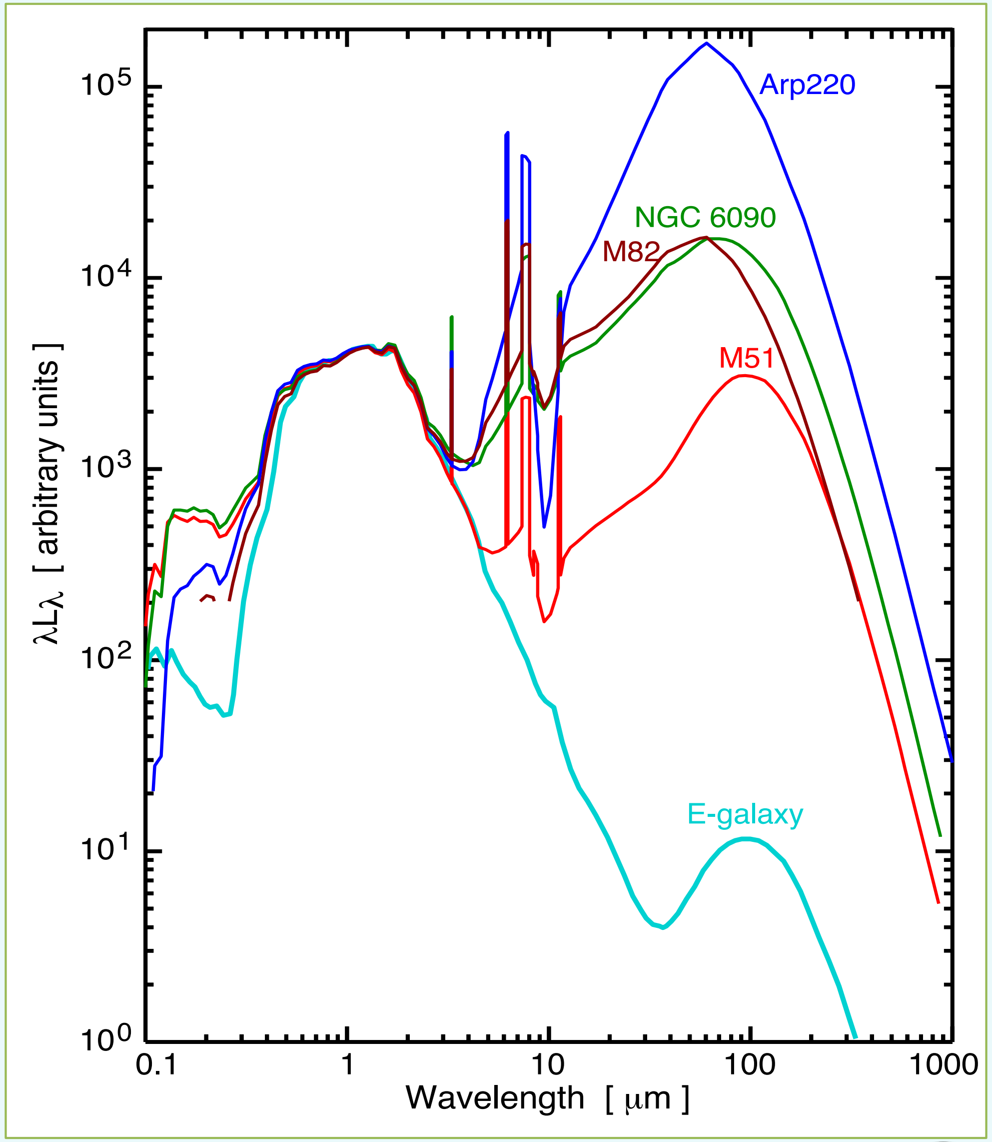
- [CII] 158μm is primary coolant of ISM gas, comprising ~1% of the Milky Way's total energy output. Other coolants and other fine structure lines provide important diagnostic information

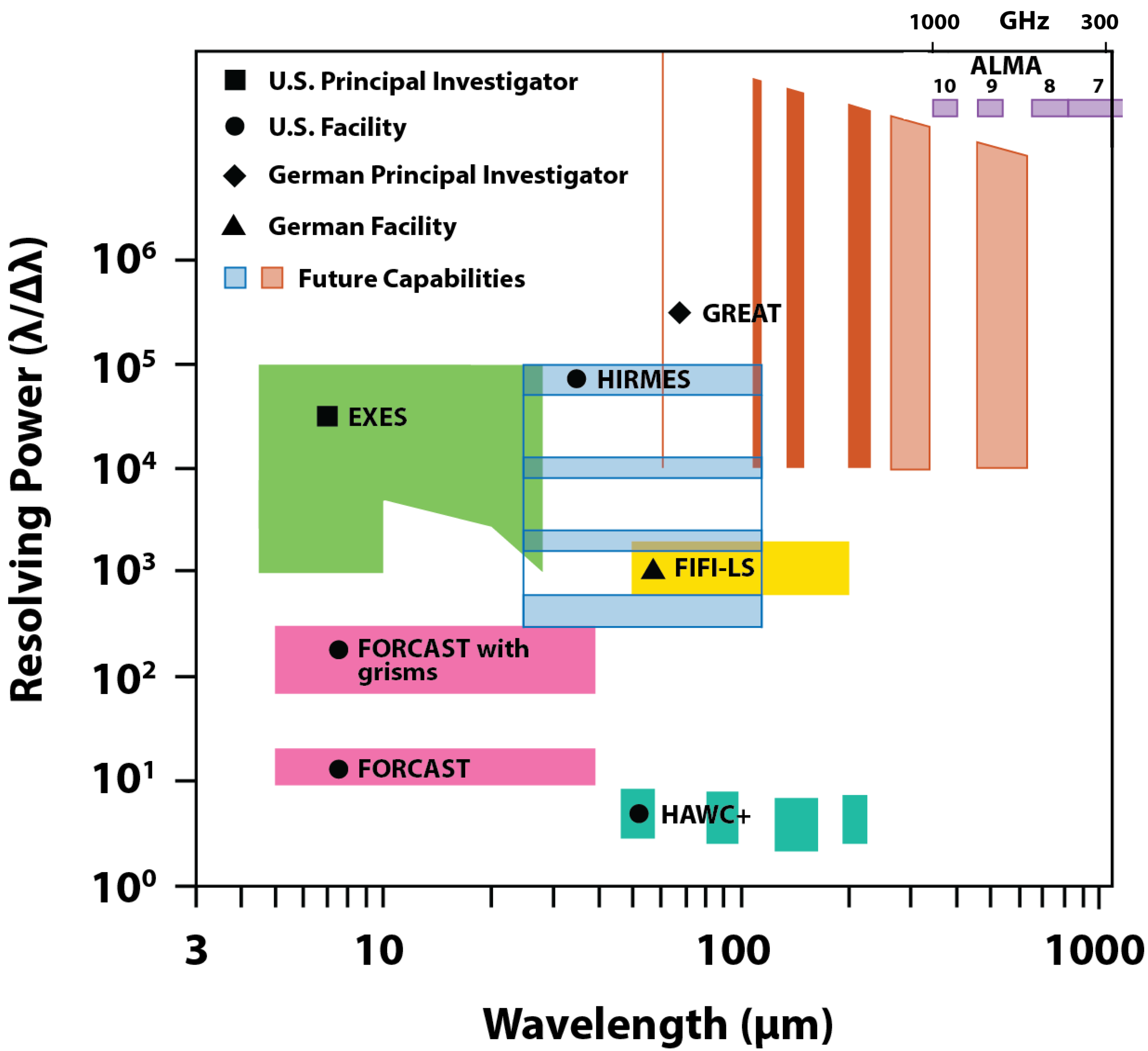
What Role does Dust play in the Structure and Evolution of the Universe?

After the Big Bang, dust appears simultaneously with the first galaxies. Since then, it has played a crucial role in heating/cooling, molecule formation, and dynamics of galactic gas.

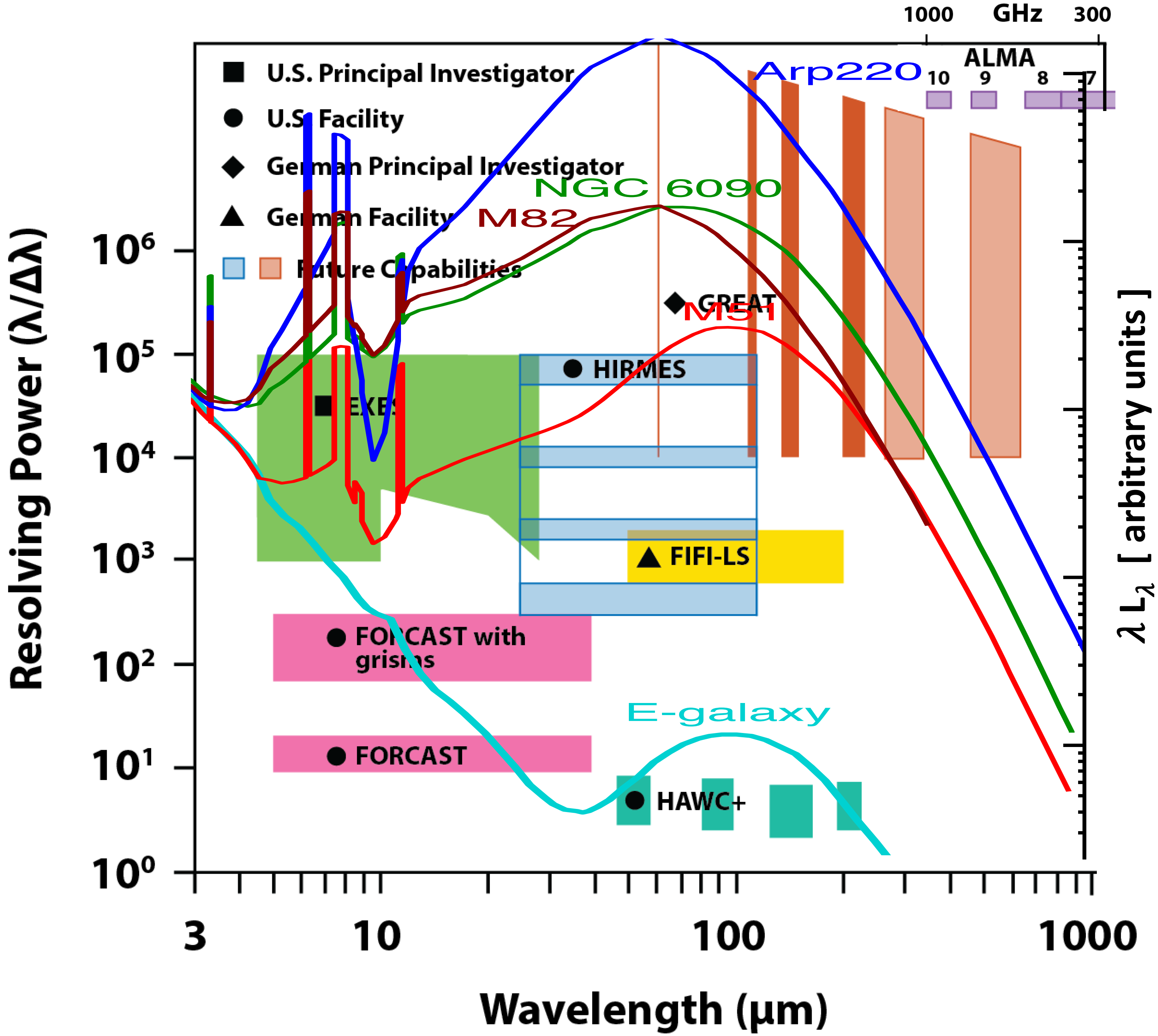
SOFIA is the premier observatory to study dust in the wavelength regime of its maximum emission.

- How and where is dust formed in explosive events (novae/SNe)?
- How does dust survive in the initial/reverse shocks?
- How is dust formed in outflows of evolved stars?
- How does dust evolve in star-forming dense molecular cores? In proto-planetary disks?





1000 GHz 300
ALMA
10 9 8 7
U.S. Principal Investigator
U.S. Facility
German Principal Investigator
German Facility
Future Capabilities
GREAT
HIRMES
EXES
FIFI-LS
FORCAST with grisms
FORCAST
HAWC+
Resolving Power (λ/Δλ)
10⁶
10⁵
10⁴
10³
10²
10¹
10⁰
3
10
100
1000
Wavelength (μm)


U.S. Principal Investigator
U.S. Facility
German Principal Investigator
German Facility
Future Capabilities
1000 GHz 300
ALMA
10 9 8 7
Arp220
NGC 6090
M82
GREAT
M51
HIRMES
EXES
FIFI-LS
FORCAST with grisms
FORCAST
E-galaxy
HAWC+
Resolving Power (λ/Δλ)
λ L$_\lambda$ [arbitrary units]
10^6
10^5
10^4
10^3
10^2
10^1
10^0
3
10
100
1000
Wavelength (μm)

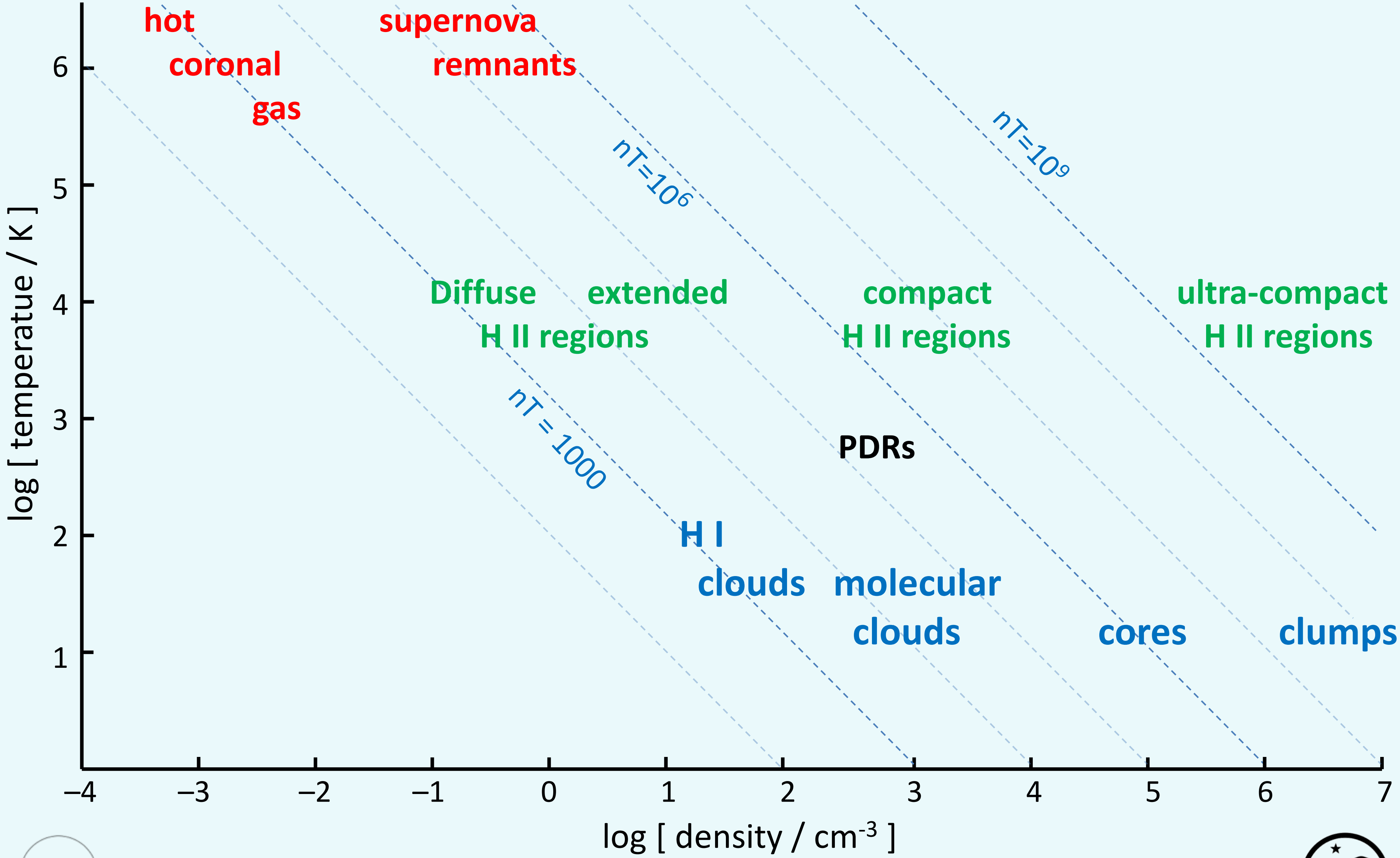
What do we mean by "Interstellar Medium"?

"Everything" in a galaxy except stars, planets, other large bodies and Dark Matter. For the MWG…

- **Gas:** $n \sim 10^{-4} – 10^{7}$ cm^{-3}, $T \sim 5 – 10^{7}$ K
  <nkT> ~ several 10^{-13} erg cm^{-3}
- **Dust:** $\rho_d \approx 0.01\ \rho_{gas}$, $T \sim 5 – 2000$ K

- **Cosmic Rays:** $\zeta \sim 10^{-16}$ s^{-1} (several 10^{-13} erg cm^{-3})
- **Magnetic Fields:** B ~ 3 μG (4 x 10^{-13} erg cm^{-3})
- **Interstellar Radiation Field:** ~ 10^{-12} erg cm^{-3}

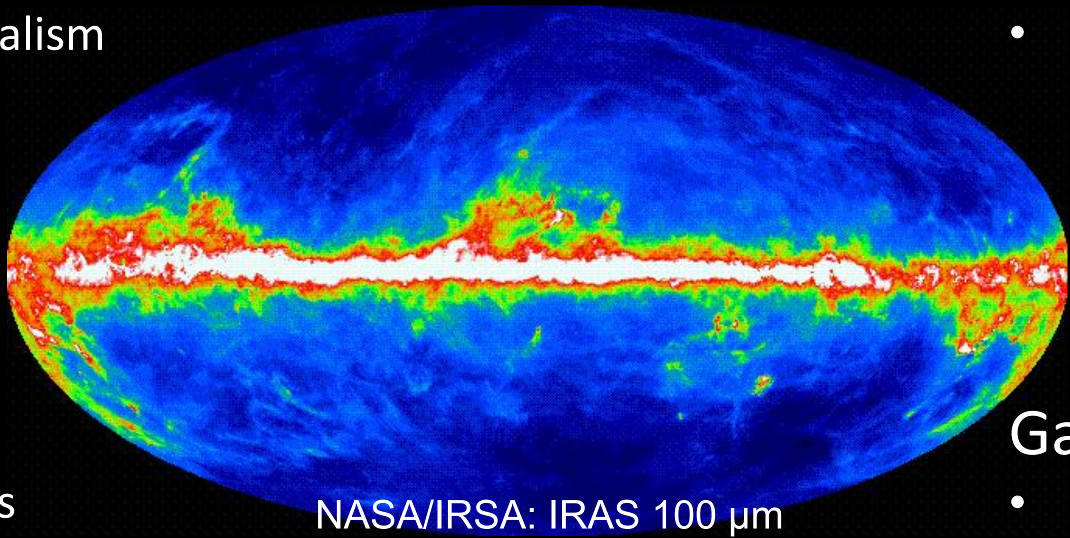
Phases of the Interstellar Medium



The Big Picture: ISM Sources and Sinks

Dust Sources:
- "Superwinds" of AGBs
- SN shocks
- Novae
- Infall from IGM
- Galactic cannibalism

Gas Sources:
- Stellar winds
- SN explosions
- Novae
- Infall from IGM
- Galactic cannibalism

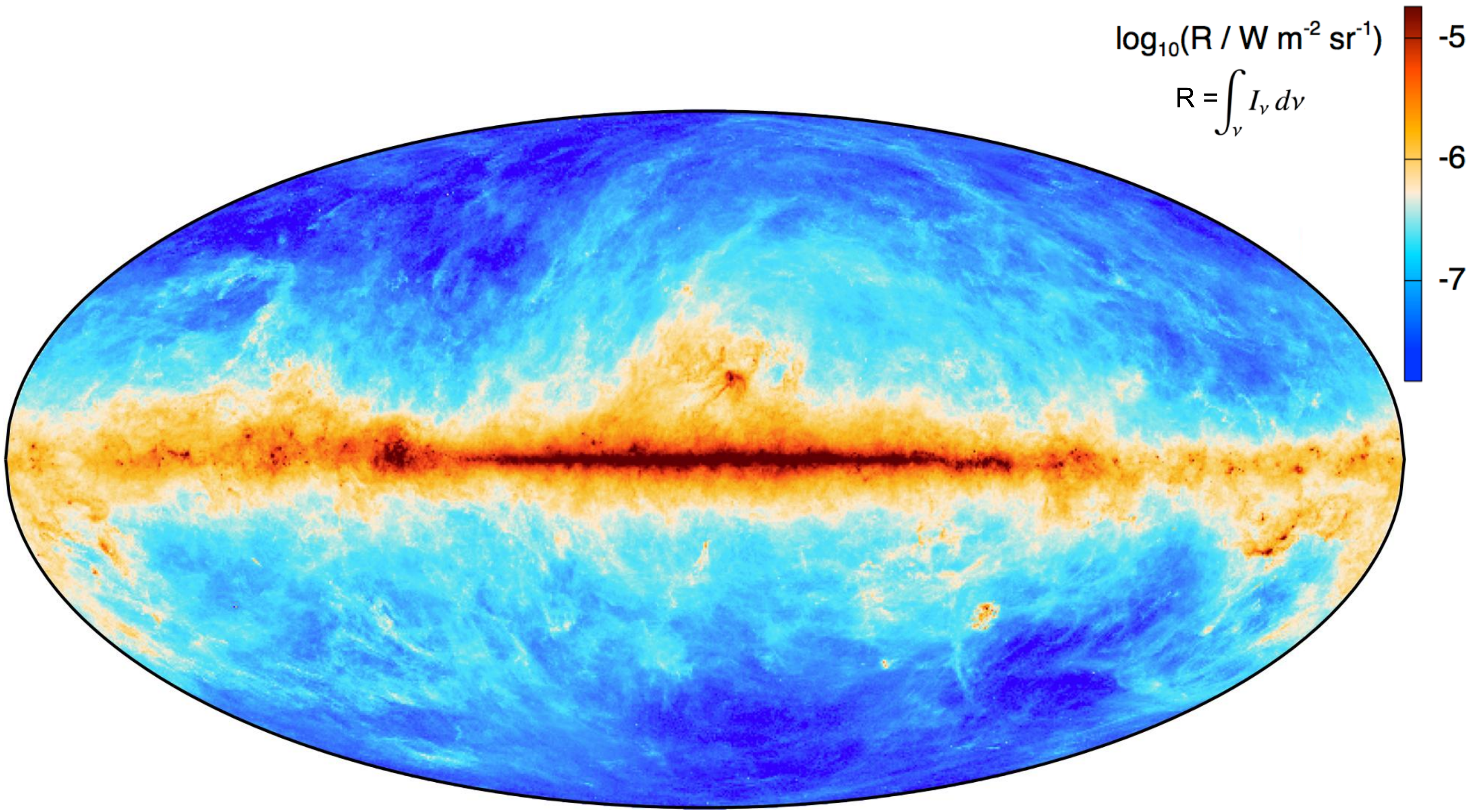


NASA/IRSA: IRAS 100 μm

Dust Sinks:
- Dust follows gas
- Destruction in shocks
- Destruction by radiation or CR
- Radiative levitation

Gas Sinks:
- Low mass objects
- Stellar remnants
- Accretion onto stars & central SMBH
- Galactic wind / jet

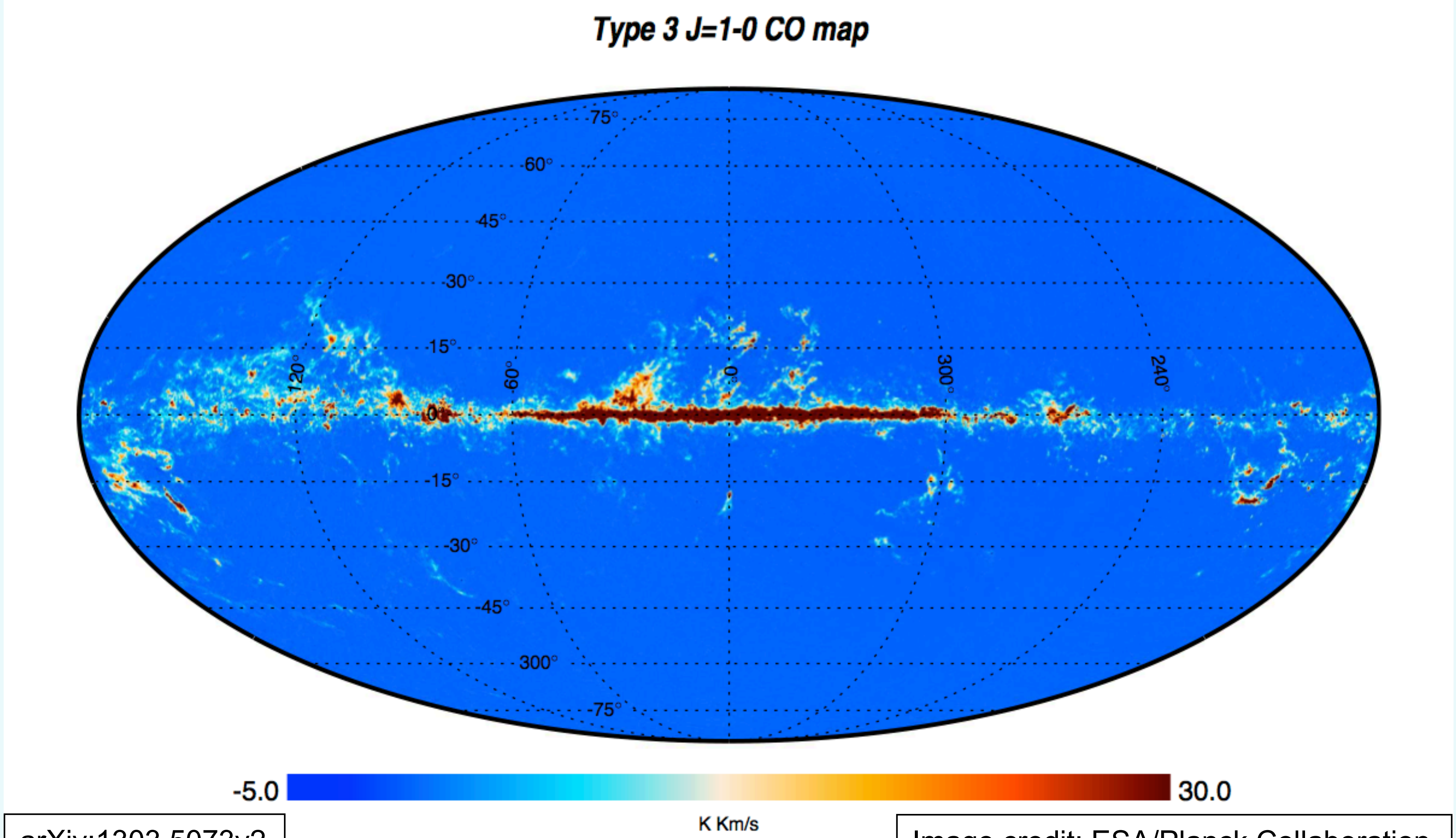
The Big Picture: Distribution of Dust Emission



arXiv:1312.1300v2

Image credit: ESA/Planck Collaboration

The Big Picture: Distribution of CO emission



arXiv:1303.5073v2

Image credit: ESA/Planck Collaboration

Continuum Radiation Transfer

Basic Equation: $d/ds(I_\nu) = -\sigma_\nu (I_\nu - S_\nu)$

Radiation Intensity: I_ν

Source function: S_ν

detailed physics

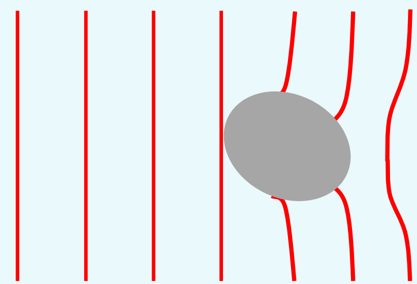
Extinction coefficient: σ_ν Often use (gram-)opacity: $\kappa_\nu = \sigma_\nu/\rho$

$$\sigma_\nu = \sigma_\nu^{sca} + \sigma_\nu^{abs}$$

- Dust often treated "classically" (this does not work for PAHs)

$$\sigma_\nu S_\nu = \sum_i \sigma_{\nu,i}^{abs} B_\nu (T_i)$$ *(sum over lots of "grey bodies")*

- Grain parameters that affect $\sigma_{\nu,i}$ (e.g. Mie theory of scattering):
  - grain composition: complex dielectric constants
    - => index of refraction: m = n + ik
  - grain size a_i (can be normalized to λ/a)
  - grain shape and orientation (polarization properties)



wavefront

Abundance of elements & ionization potentials

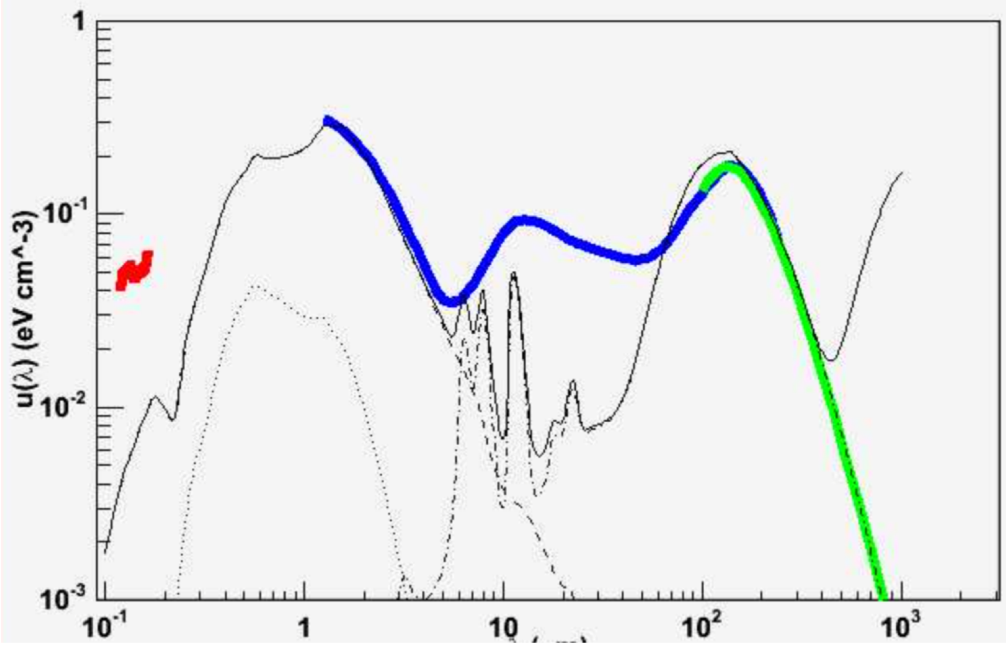
Element	Atomic Wt	Log Abundance		Ionization Potentials		
		number	mass	I	II	III
1 H	1.008	12.00	12.00	13.598		
2 He	4.003	10.99	11.59	24.587	54.416	
6 C	12.011	8.56	9.64	11.260	24.383	47.887
7 N	14.007	8.05	9.19	14.534	29.601	47.448
8 O	15.999	8.72	9.92	13.618	35.117	54.934
10 Ne	20.180	8.09	9.34	21.564	40.962	63.45
11 Na	22.990	6.31	7.67	5.139	47.286	71.64
12 Mg	24.305	7.59	8.97	7.646	15.035	80.143
13 Al	26.982	6.48	7.91	5.986	18.826	28.228
14 Si	28.086	7.56	9.00	8.151	16.345	33.492
16 S	32.065	7.25	8.75	10.360	23.33	34.83
18 Ar	39.948	6.8	8.4	15.759	27.629	40.74
20 Ca	40.078	6.30	7.93	6.113	11.871	50.91
26 Fe	55.847	7.60	9.35	7.870	16.16	30.651
28 Ni	58.693	6.3	8.04	7.635	18.168	35.17
∑ (rest)	<55.08>	6.26	8.00			

What do we learn from this table?

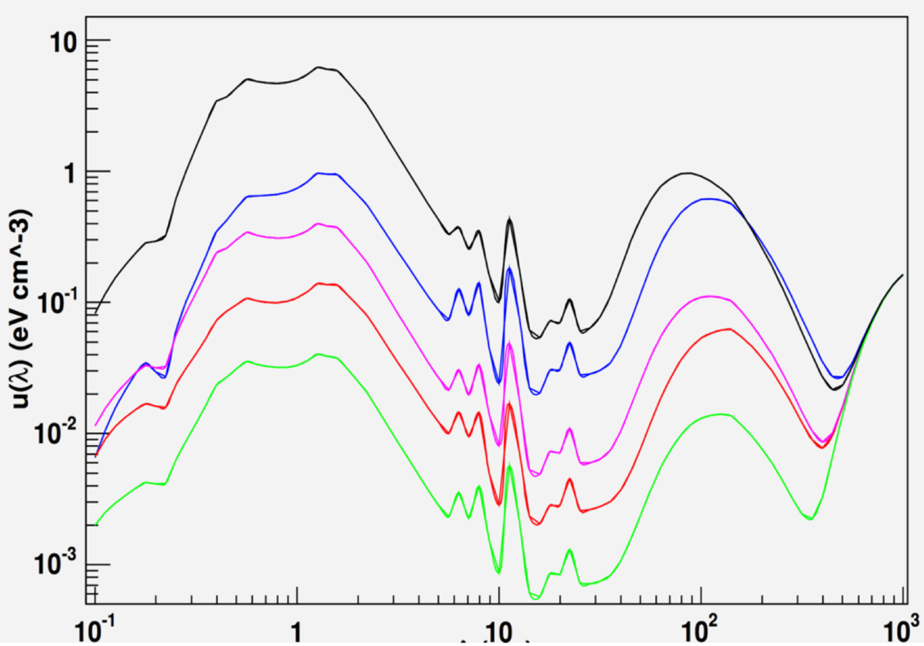
Element	Atomic Wt	number	mass	I	II	III
1 H	1.008	12	12	13.598		
2 He	4.003	10.99	11.59	24.587	54.416	
8 O	15.999	8.72	9.92	13.618	35.117	54.934
6 C	12.011	8.56	9.64	11.26	24.383	47.887
10 Ne	20.18	8.09	9.34	21.564	40.962	63.45
7 N	14.007	8.05	9.19	14.534	29.601	47.448

- O is neutral whenever H is neutral
- C, Na, Mg, Al, Si, S, Ca, Fe, Ni can all be easily ionized by background starlight (Ca doubly), providing a floor for the relative electron abundance
- Among the most 6 abundant elements ($\log N_X / \log N_H > -4$), only C can be (singly) ionized in regions where H is neutral
- OIII traces very energetic UV fields
- Abundances provide constraints on dust composition

What is the interstellar radiation field?



Wavelength [μm]



Wavelength [μm]

Local radiation field as modelled by Porter and Strong (2005) *Solid black line* total radiation field, including CMBR. *Dashed black line:* total optical. *Dotted black line:* total scattered optical. *Dash-dot black line:* total infra-red.
Data: *thick red solid line*: Apollo; *thick blue solid line*: DIRBE; *thick green solid line*: FIRAS.

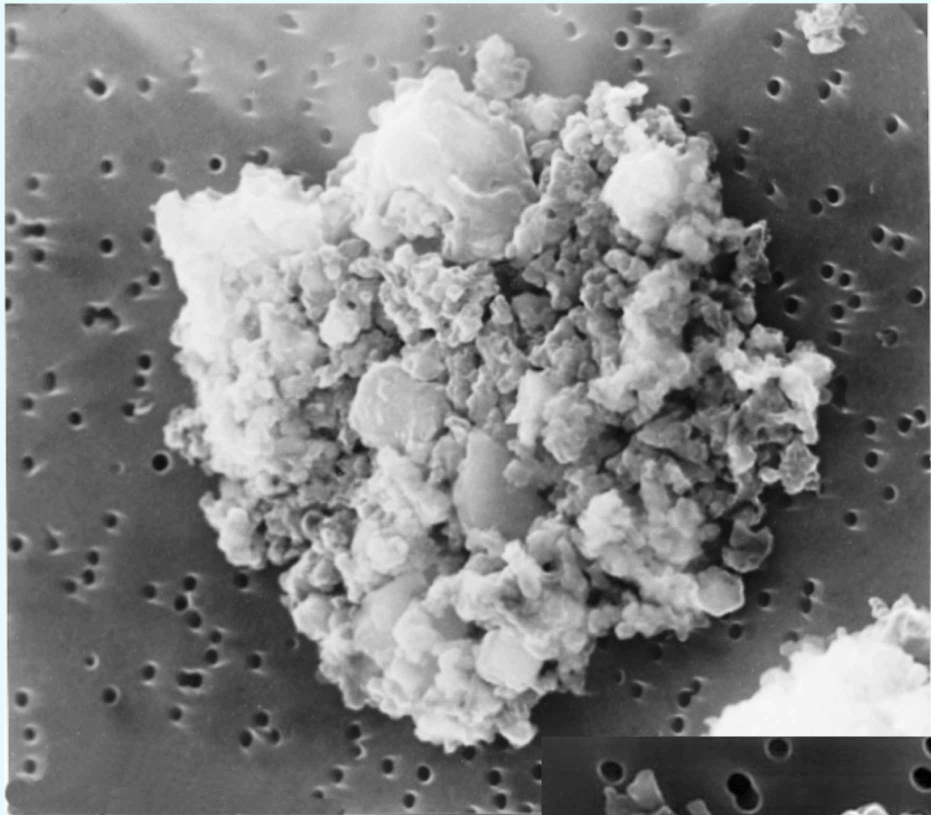
Spatial variation of the total radiation field as a function of galactocentric distance.

black:	R = 0 kpc, z = 0
blue:	R = 5 kpc, z = 0
magenta:	R = 0 kpc, z = 5 kpc
red:	R= 12 kpc, z = 0
green:	R=20 kpc, z = 0

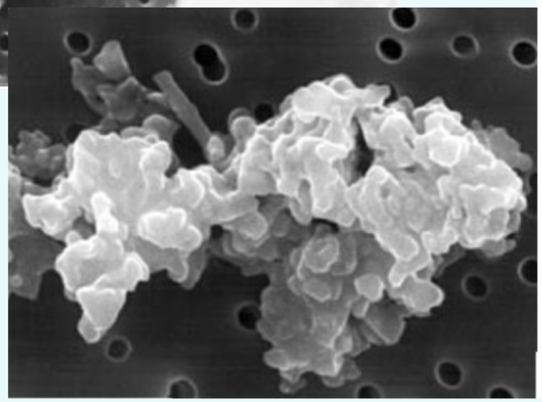
Want do we want to know about interstellar grains?

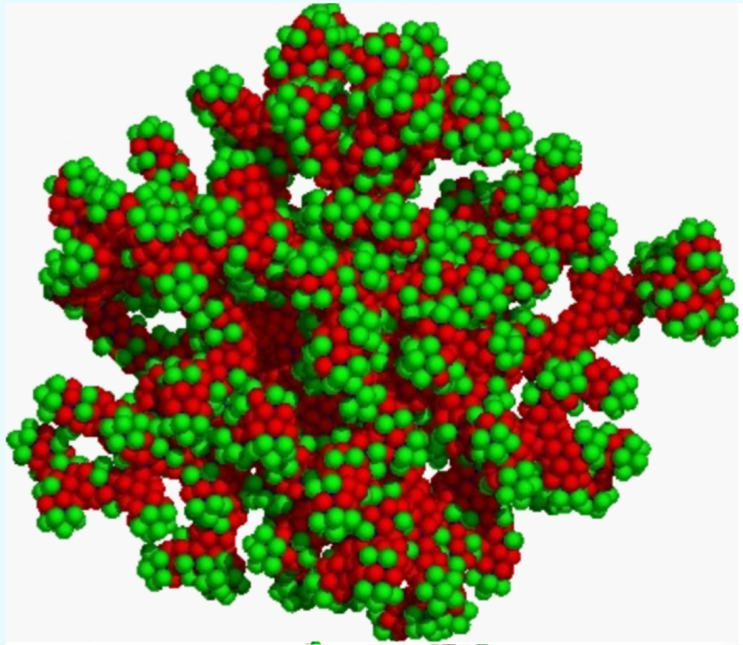
- Their composition
  - Consistent with observed abundances (comparison between stellar and interstellar abundances: depletion)
  - Consistent with the solid-state physics (condensation sequence, thermodynamic stability of the components, structural changes)
  - Constrained by solid state absorption/emission features (specific to the solid, its structure)
  - Should be the precursors of pre-solar (meteoritic) grains
- Their size distribution
  - Can be constrained from: Extinction
  - Emission (shape of the emission features)
- How they interact with light
  - Scattering properties (polarization, when aligned)
  - Absorption (and emission) properties
- Their role in the thermodynamics (heating/cooling) of the gas
- Their role in surface chemistry and adsorption of species
- Their role in the hydrodynamics of the gas

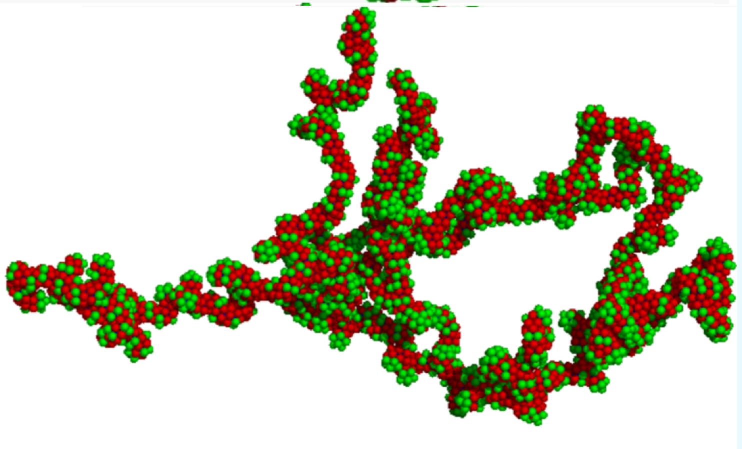
(Un)fortunately, grains are not spheres



IDP Image Credit NASA



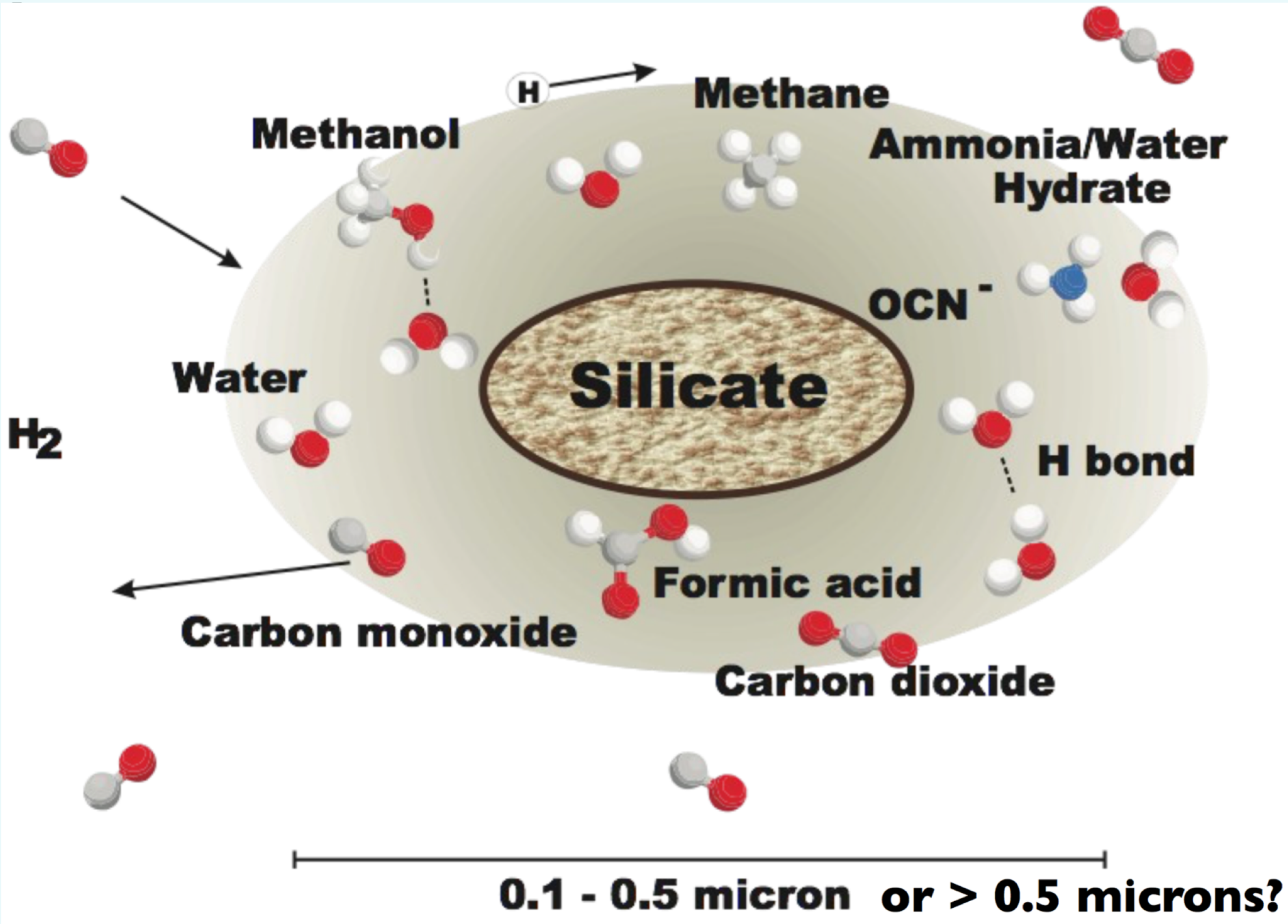




Typical Dust Model

- There cannot be much more dust than 0.01 M_H, because that uses up all elements
- Typical model:
  - 2/3 of carbon used for carbonaceous material
  - Essentially all Mg, Fe, Si and 20% of O in $(Mg,Fe)_2SiO_4$ consistent with the observational depletion pattern and the physics of solid condensation
  - Some SiC if grains are formed in carbon-rich environments
  - May include mantel of “dirty ices” (volatiles)

Icy dust models (mantel mostly H_2O)



Large variety of solid structures

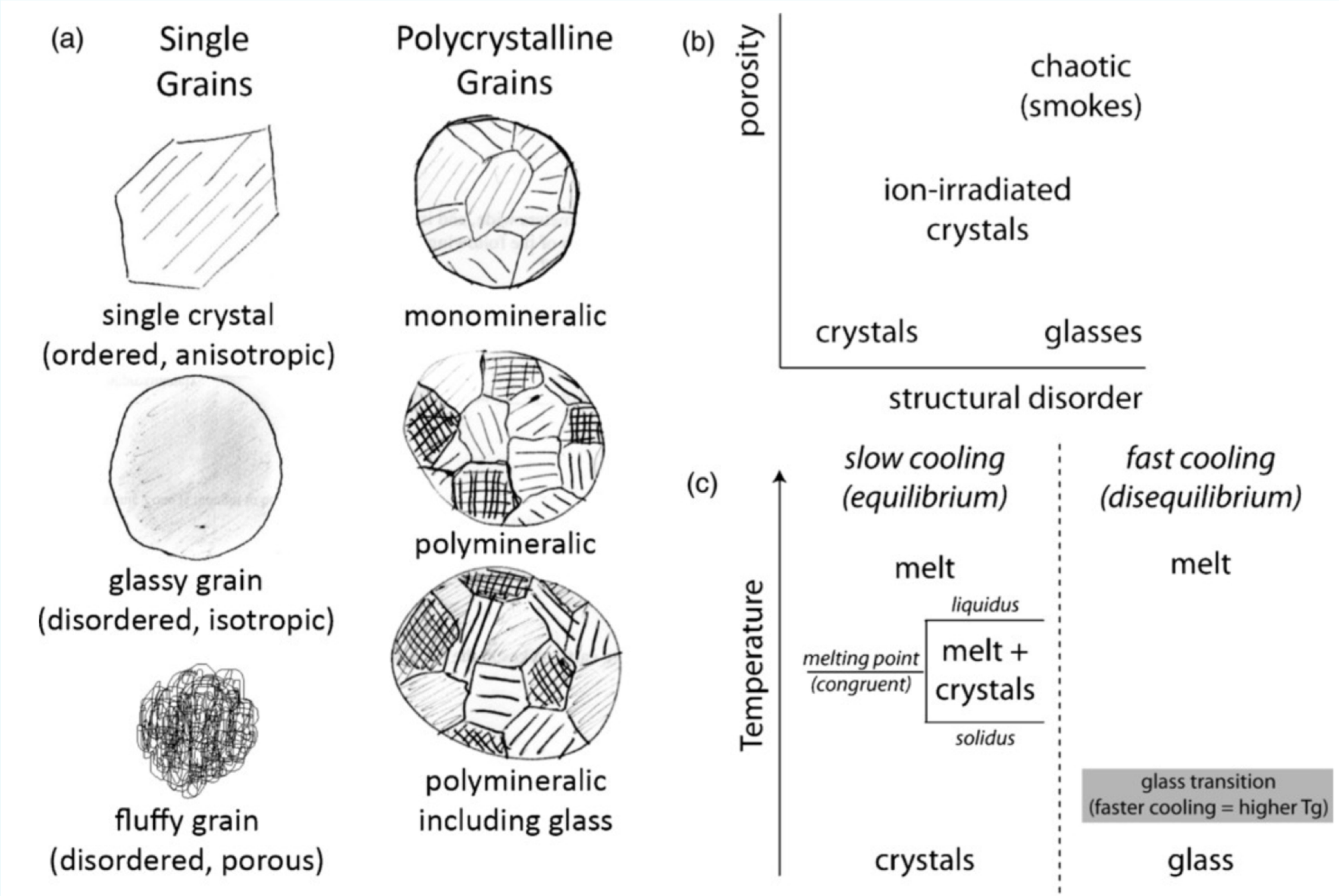
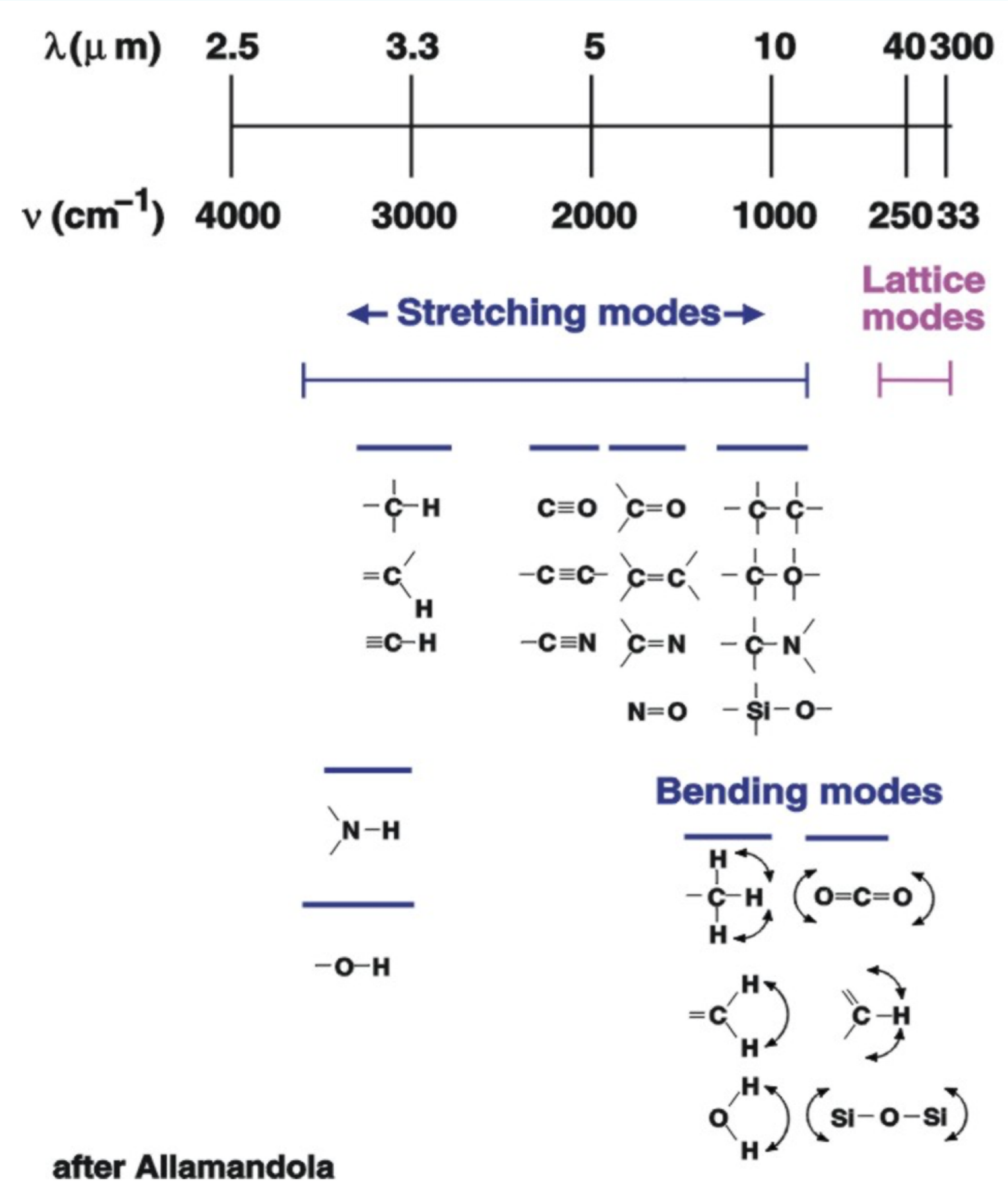


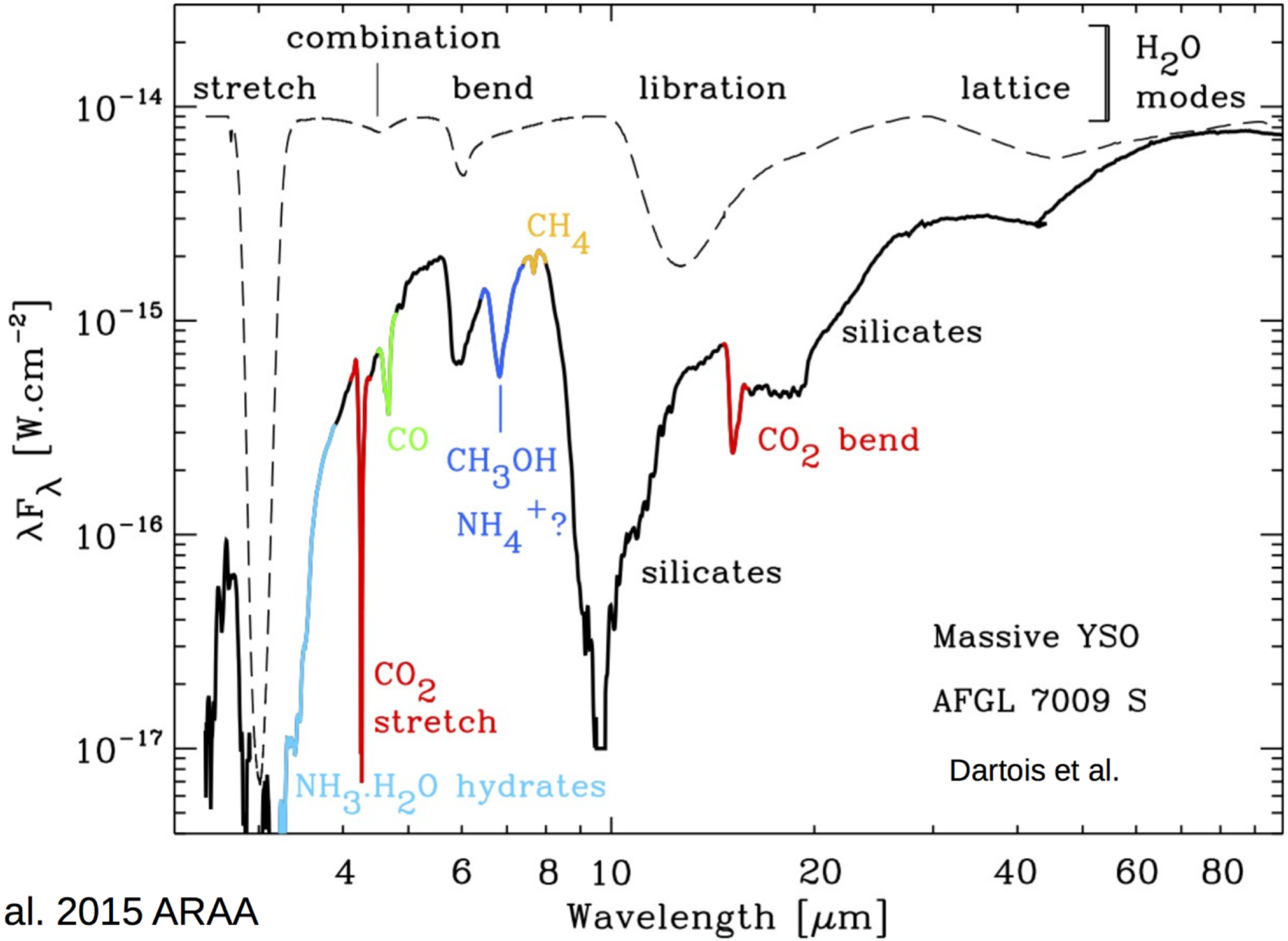
Figure 1 from Disordered Silicates in Space: A Study of Laboratory Spectra of "Amorphous" Silicates Angela K. Speck et al. 2011 ApJ 740 93

Molecular vibrations in the infrared



- Stretching & bending modes occur in both amorphous and crystalline solids
- Lattice (phonon) modes exist only in crystalline solids

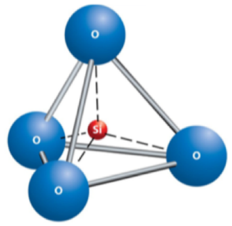
Interstellar ice absorption



Boogert et al. 2015 ARAA

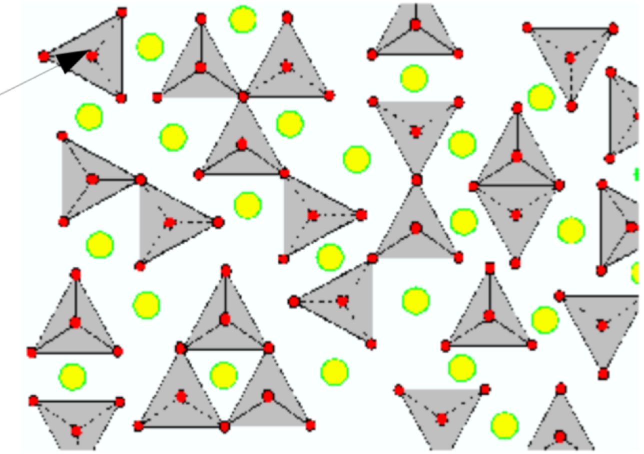
Amorphous vs Crystalline silicate: structure and spectral signatures

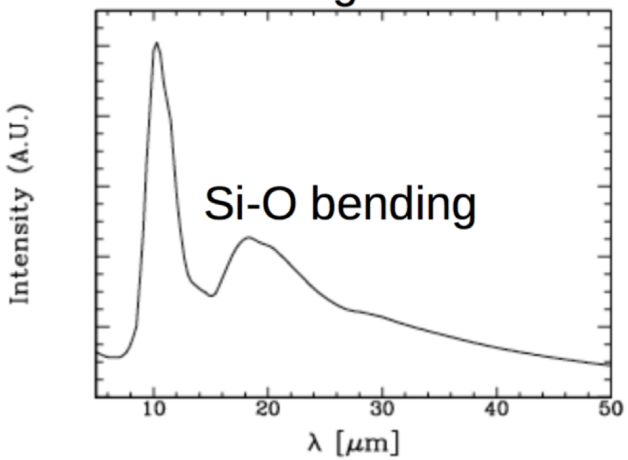
Amorphous structure



Henning T. 2010. Annu. Rev. Astron. Astrophys. 48:21–46

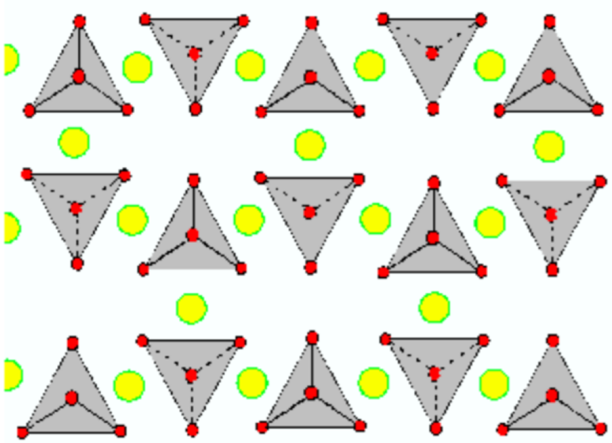
SiO_4

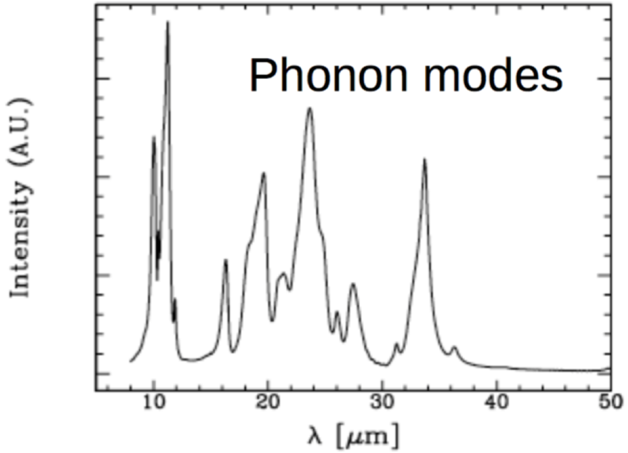




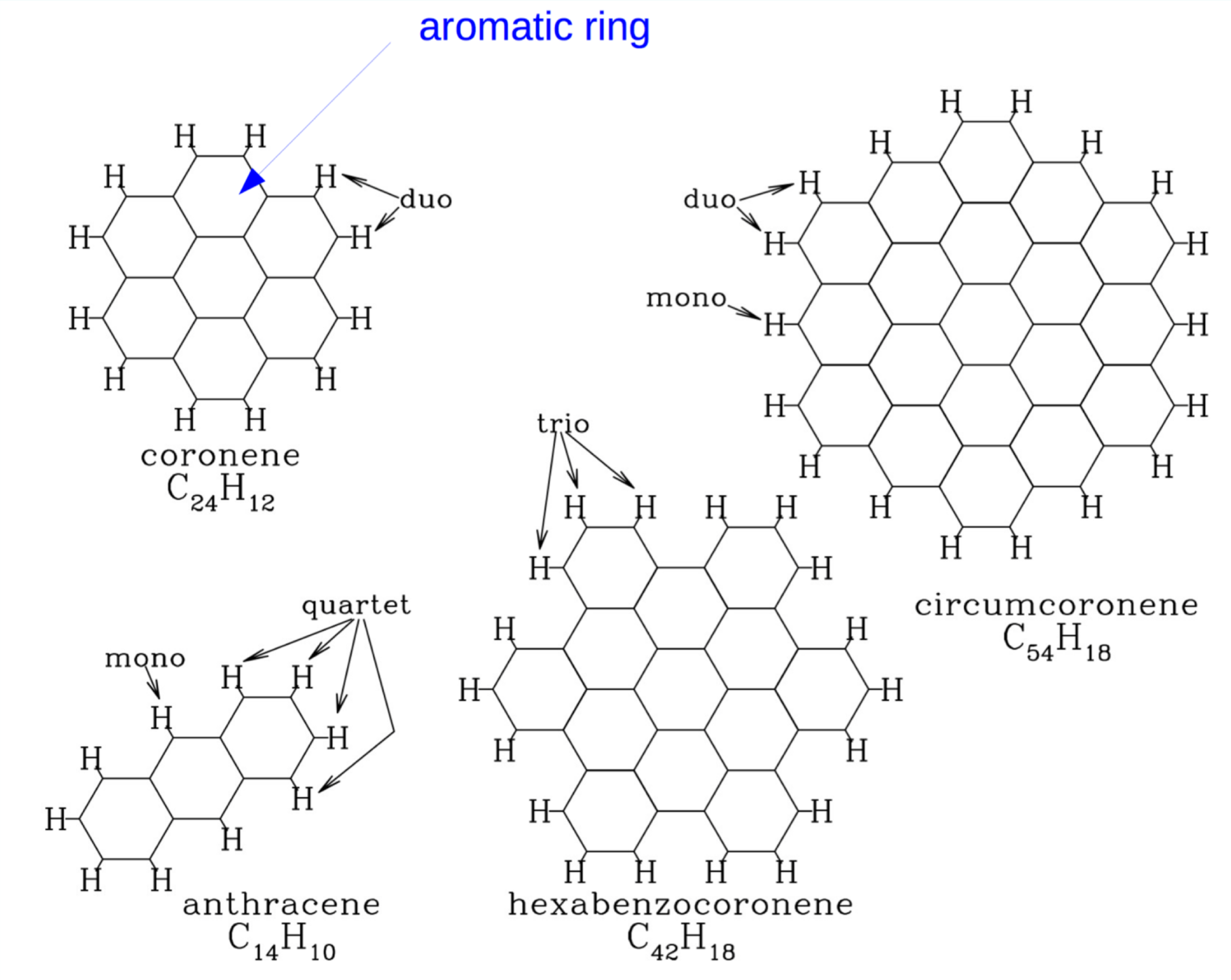
Molster et al. 2005

Crystalline structure

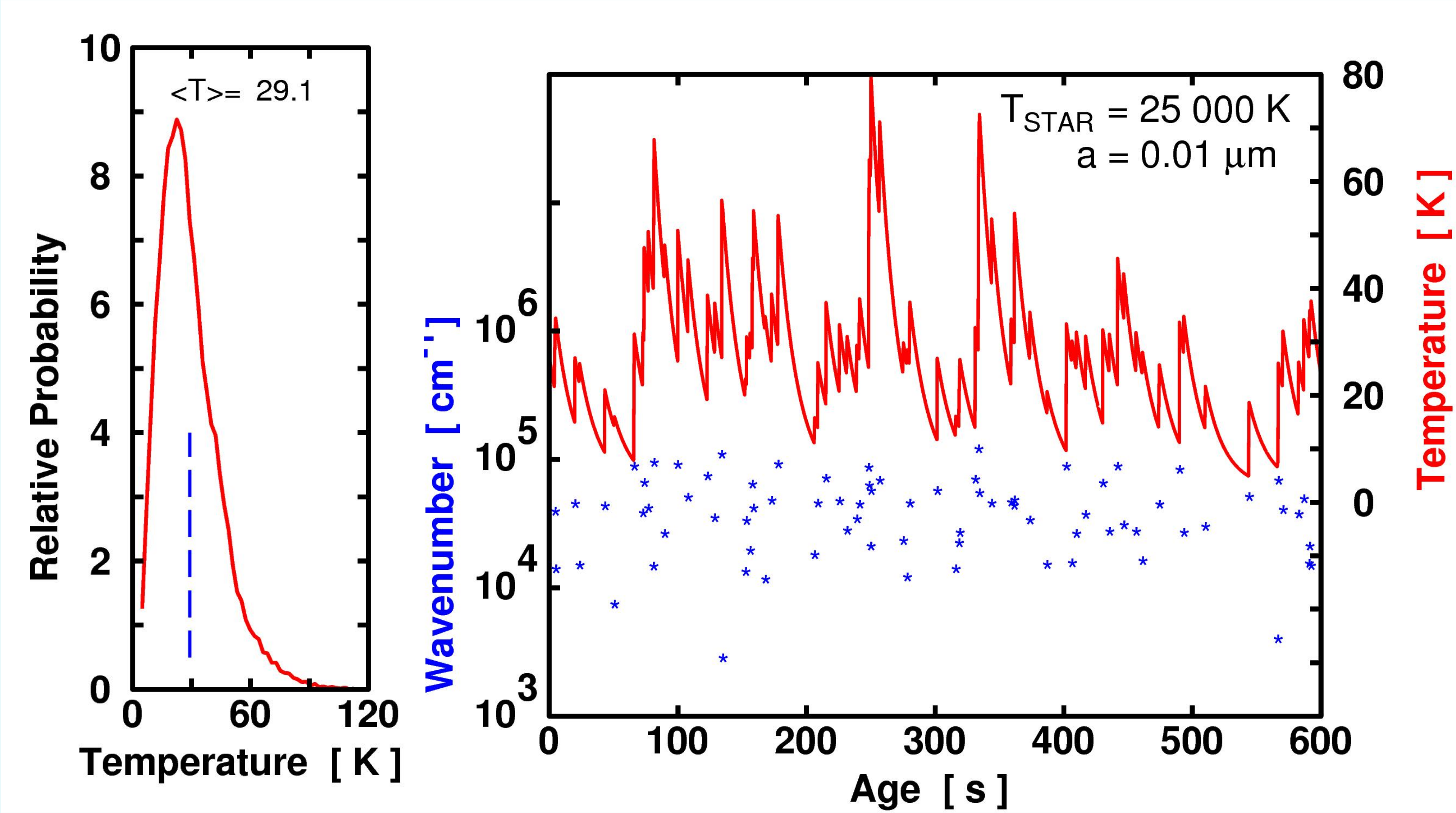




Polycyclic Aromatic Hydrocarbons



Stochastic heating of small grains



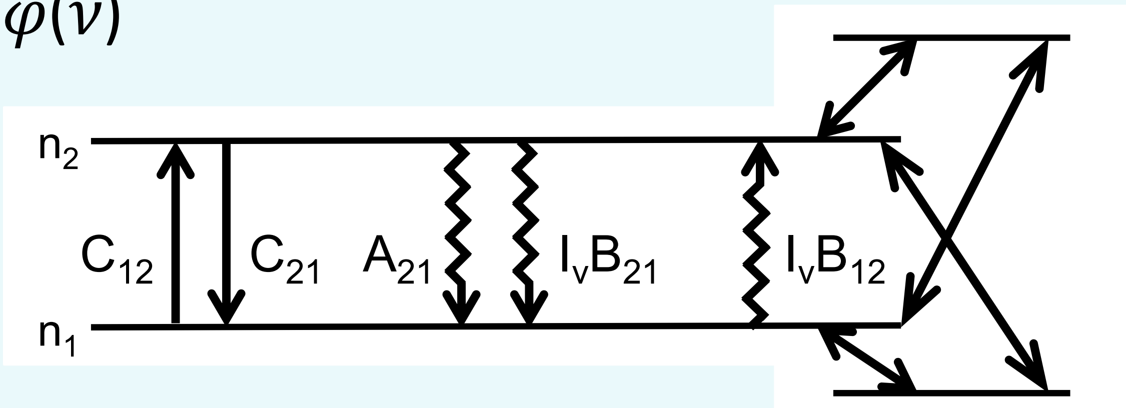
Line Radiation Transfer

Basic Equation: $d/ds(I_\nu) = -\sigma_\nu^C(I_\nu - S_\nu^C) - \sigma_\nu^L(I_\nu - S_\nu^L)$

detailed physics more detailed physics

$\sigma_\nu^L = n_1 B_{12} h\nu_0/4\pi\ [1 - n_2 g_1/n_1 g_2]\ \varphi(\nu)$

$\sigma_\nu^L S_\nu^L = n_2 A_{21} h\nu_0/4\pi\ \varphi(\nu)$



A_{21}, B_{21}, B_{12} are Einstein coefficients

$\varphi(\nu)$ is the line profile (includes thermal doppler broadening)

The multi-level case

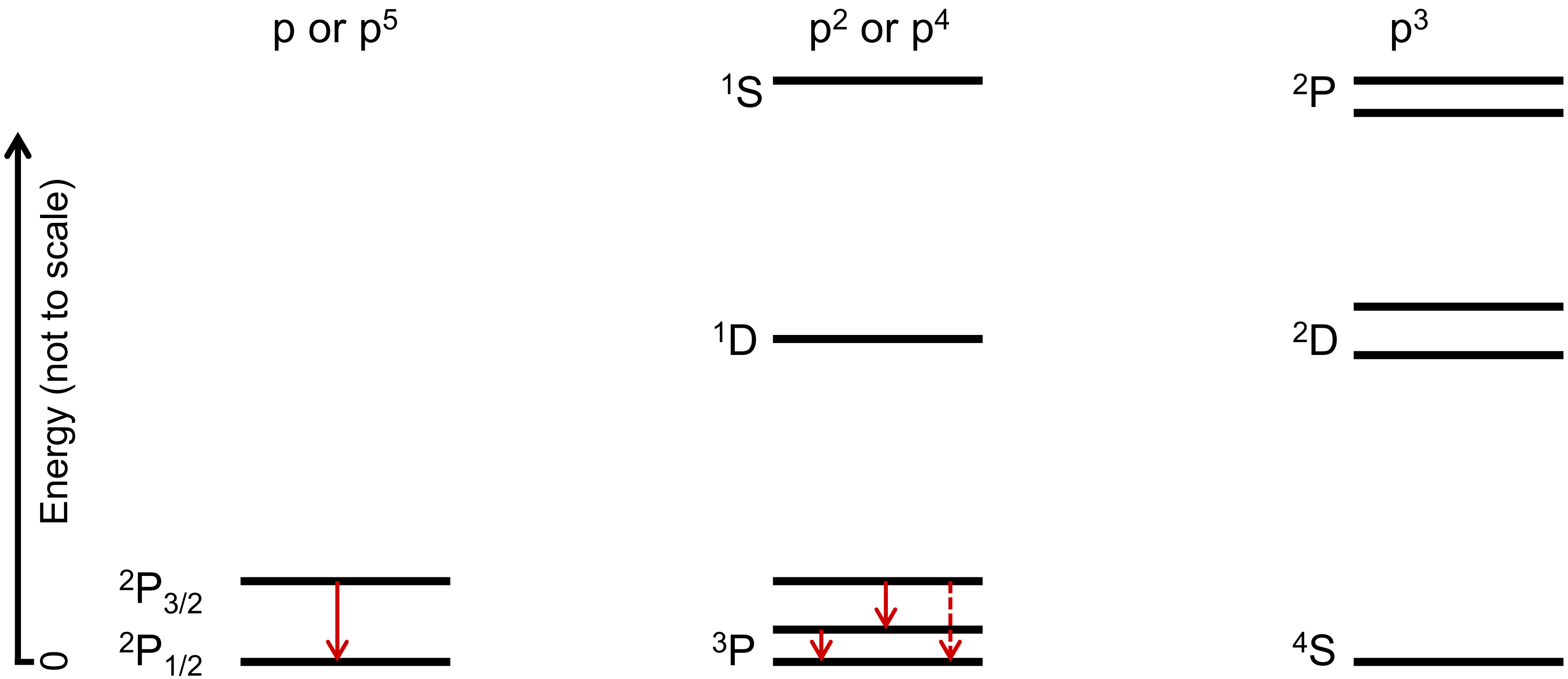
$$n_i \left(\sum_{j<i} A_{ij} + \sum_{j\neq i} B_{ij}\, u_{ij} + \sum_{j\neq i} C_{ij}\right) = \sum_{j>i} A_{ji}\, n_j + \sum_{j\neq i} B_{ji}\, u_{ij}\, n_j + \sum_{j\neq i} C_{ij}\, n_j$$

where $u_{ij} = \int_{4\pi} I(\nu_{ij})\, d\Omega$ is the radiation density

and $\sum_i n_i$ = density of species

Fine Structure Line Emission

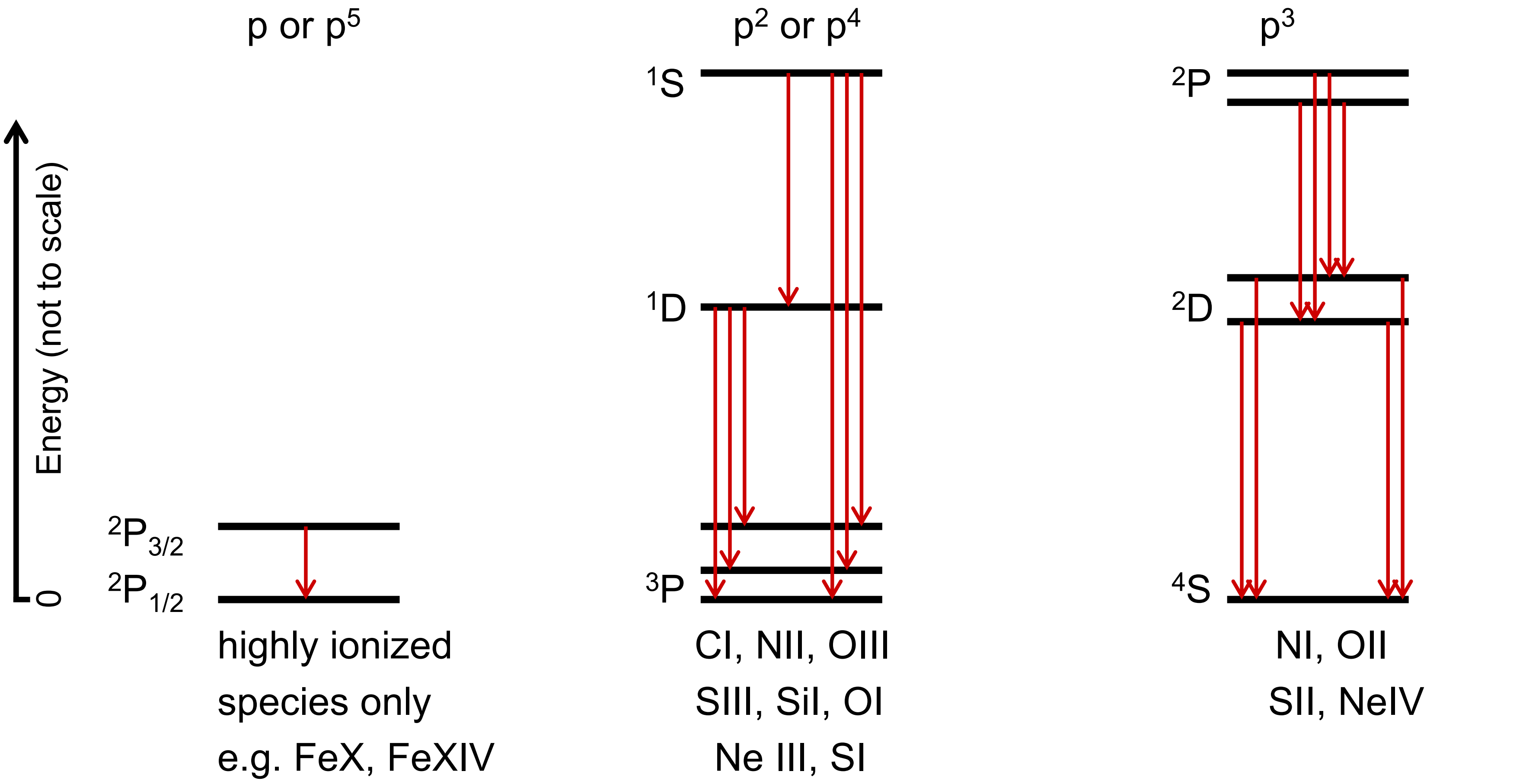
L-S coupling for ions with one to five p electrons: (far)IR transitions



p or p^5	p^2 or p^4	p^3
CII (158)	CI (610,370,230)	OI (63,146,44)
NIII (57)	NII (205,122, 76)	NeIII (36,16,11)
OIV (26)	OIII (88, 52, 33)	SI (56, 25, 17)
NeII (13)	SIII (33, 19, 12)	
SiII (35)	SiI (130, 68, 45)	

Fine Structure Line Emission

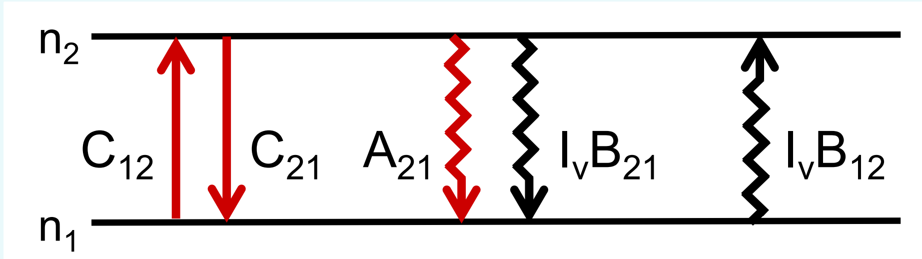
L-S coupling for ions with one to five p electrons: transitions in visible



The two level case

$C_{12}/C_{21} = g_2/g_1 \exp(-\Delta E/kT)$

$n_1 C_{12} = n_2(C_{21}+\beta_{21}A_{21})$



$n = n_1 + n_2$, where n is the density of coolant available

The cooling rate from this transition is: $\Lambda_{21} = \Delta E\, n_2\, A_{21}\, \beta_{21}$

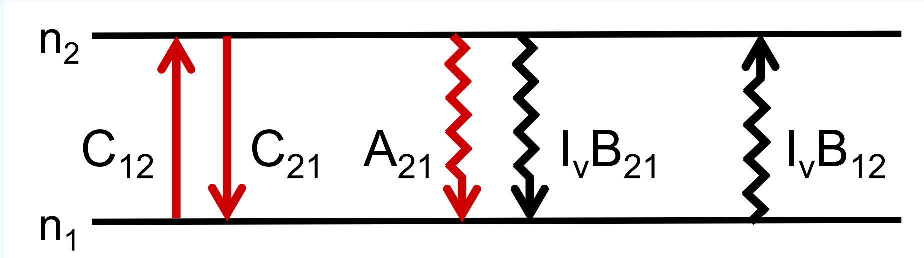
β_{21} is the "escape probability", i.e. the likelihood that the emitted photon can actually leave the volume without being reabsorbed. Often one uses the simple expression $\beta_{21} \sim (<[1 - \exp(-\tau_{21})]/\tau_{21}>$, where τ_{21} is the line center optical depth

$$\Lambda_{21} = \Delta E\, n\, A_{21}\, \beta_{21} \frac{g_2/g_1 \exp(-T_{ex}/T)}{1 + g_2/g_1 \exp(-T_{ex}/T) + n_{ncrit}/n_{coll}},$$

where $n_{crit} = n_{coll} A_{21} \beta_{21} / C_{21} = A_{21} \beta_{21} / <v\sigma>_{21}$ is the "critical density" and n_{coll} is the density of the exciting collider

The two limiting cases

$n_{coll} << n_{crit}$ and $n_{coll} >> n_{crit}$



$$\Lambda_{21} = \Delta E \; n \; A_{21} \; \beta_{21} \; \frac{g_2/g_1 \exp(-T_{ex}/T)}{1 + g_2/g_1 \exp(-T_{ex}/T) + n_{ncrit}/n_{coll}}$$

$n_{coll} << n_{crit}$ (subthermal)

$$\Lambda_{21} = \Delta E \; n \; n_{coll} <v\sigma>_{21}$$

$n_{coll} >> n_{crit}$ (thermalized)

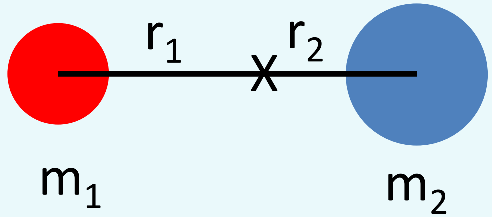
$$\Lambda_{21} = \Delta E \; n \; A_{21} \; \beta_{21} \; \frac{g_2/g_1 \exp(-T_{ex}/T)}{1 + g_2/g_1 \exp(-T_{ex}/T)}$$

Examples (subthermal):

$$\Lambda_{CII}(158\mu m) = (6.67x10^{-20} \, n_e \, T^{-1/2} + 1.77x10^{-23} \, n_{HI} \, T^{1/2}) \, n_{CII} \exp(-92K/T)$$
$$\Lambda_{OI}(63\mu m) = 6.43x10^{-24} \, n_{HI} \, n_{OI} T^{1/2} \exp(-228K/T)$$
$$\Lambda_{OI}(147\mu m) = 4.7x10^{-24} \, n_{HI} \, n_{OI} T^{1/2} \exp(-326K/T)$$

A simple diatomic model (rigid rotator)

Assume two nuclei, m_1 & m_2 separated by distance d



$r_1 + r_2 = d$

$m_1 r_1 = m_2 r_2$

$r_1 = d\, m_2 /(m_1+m_2)$

$r_2 = d\, m_1 /(m_1+m_2)$

$E = ½\, [m_1(r_1\omega)^2 + m_2(r_2\omega)^2]$

$E = ½\, L\, \omega$

$L = m_1(r_1)^2\, \omega + m_2(r_2)^2\, \omega$

$L = \mu\, d^2\, \omega$ with $\mu = m_1\, m_2 /(m_1+m_2)$

"Quantum" ansatz: $L_n = n\hbar$ => $E_n = n^2 \frac{\hbar^2}{2\mu d^2}$

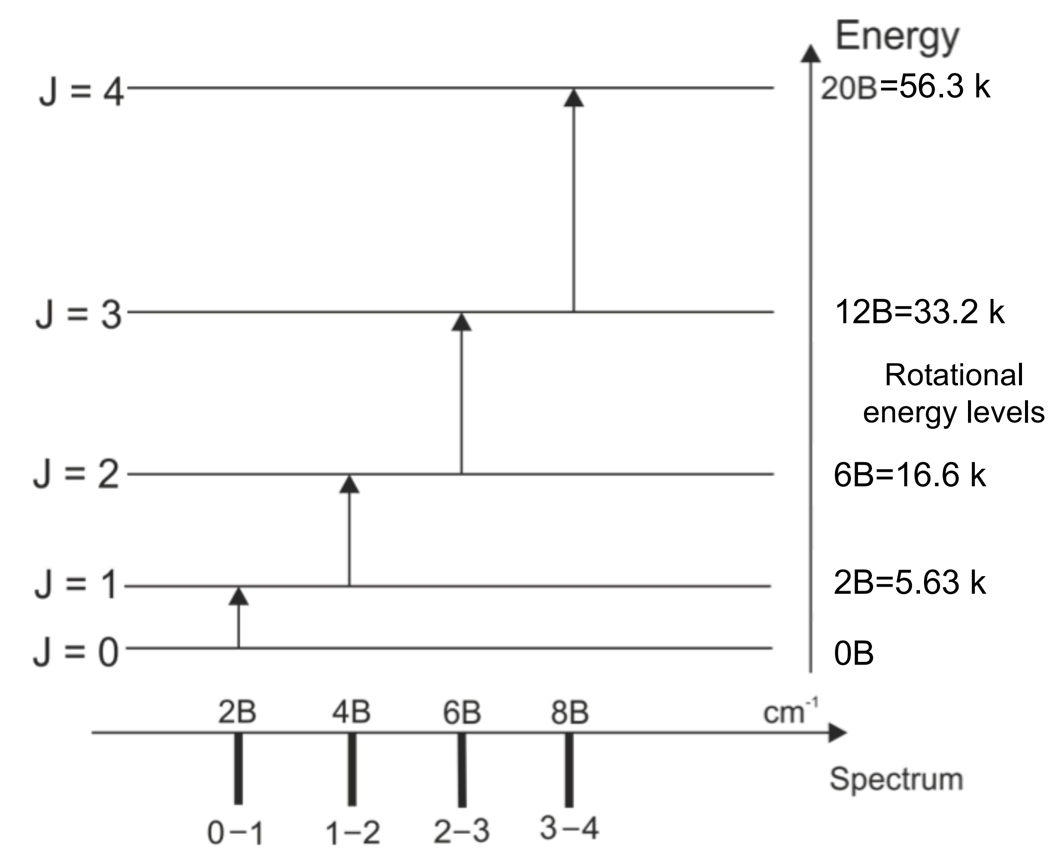
Actually, $E_J = J\,(J+1) \frac{\hbar^2}{2\mu d^2} = J\,(J+1)\, B$

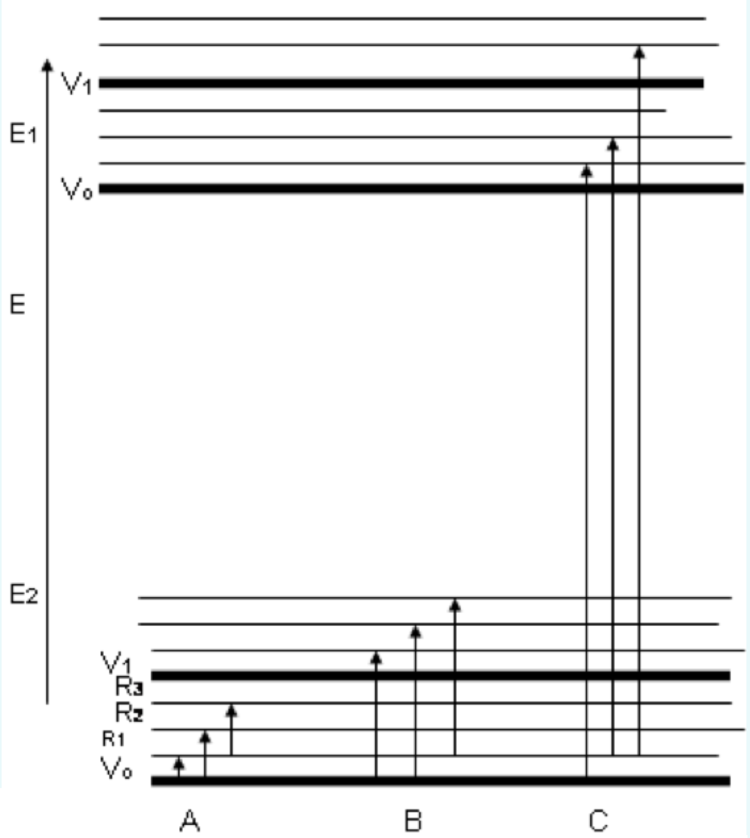
Example: The carbon monoxide molecule (CO) consists of a carbon atom and an oxygen atom separated by a distance of $d=1.13 \times 10^{-10}$ m (from Google).

$\mu = 6.86\, m_H$ => $B = 2.77\, k_B = 57.6$ GHz h = 0.00024 eV

CO Emission

- CO rotation energy levels $E_J = J(J+1)B$, where $\Delta J = \pm 1$
  - $B \approx$ const. = 2.77 k = 57.6 GHz h = 0.00024 eV (Actually, d gets larger with J)





The CO v=1->0 rot-vib transitions occur at ~5µm ($T_{ex} \approx$ 3000 k)

pure rotation | vibro-rotation | electronic transitions

The H_2 molecule

- Because H_2 has no dipole moment, J=1 –> J=0 is not allowed.
- The lowest transition is: J=2 -> J=0 (para-hydrogen)
- The next lowest is: J=3 -> J=1 (ortho-hydrogen)
- $d = 7.414 \times 10^{-11}$ m (from Google); $\mu = 0.5\ m_H$

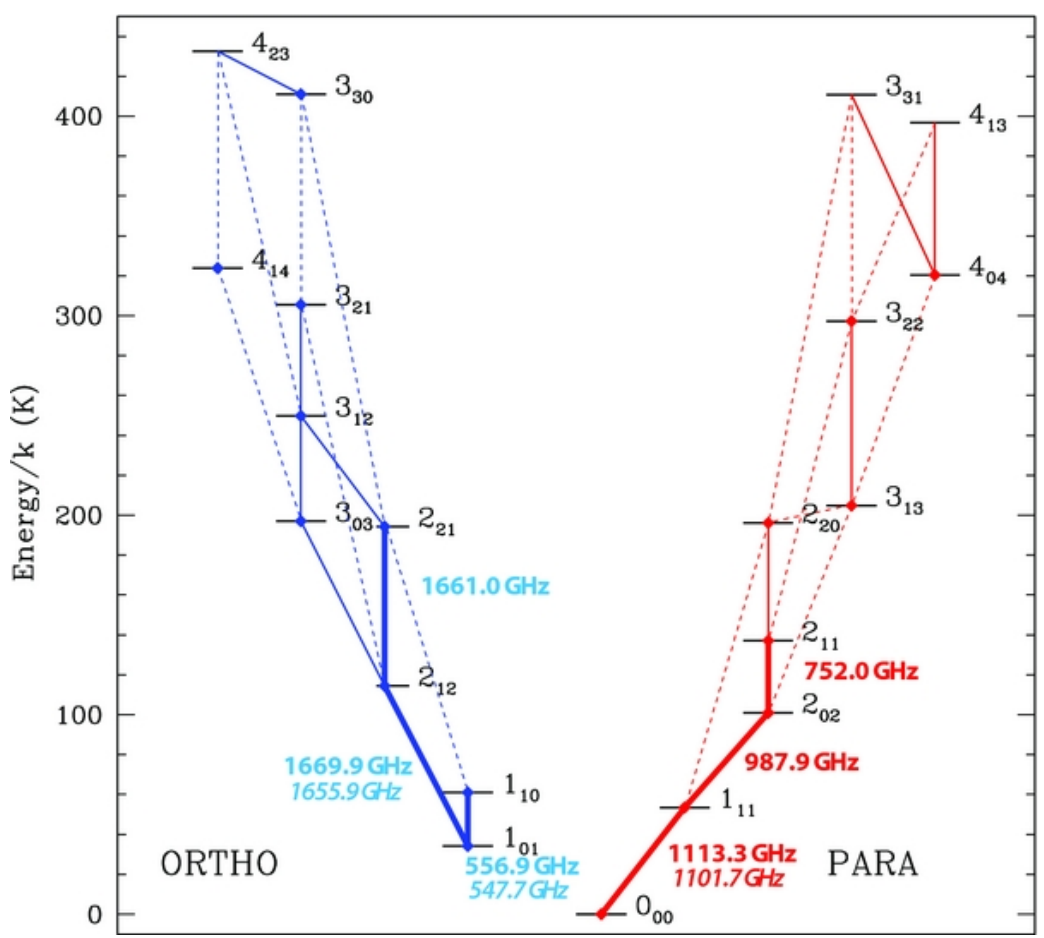
$$E_J = J\,(J+1)\,\frac{\hbar^2}{2\mu d^2} = J\,(J+1)\,B$$

=> λ (2-0) = 28 μm; λ (3-1) = 17 μm

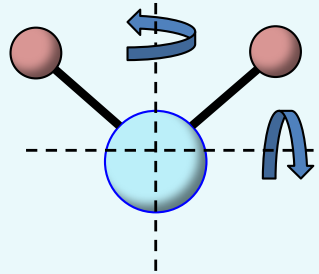
- Similarly for hydrides, XH, where X=C, N, O, … ; the ground state lines lie in the far infrared.
  - Estimate: $d \sim 10^{-10}$ m; $\mu = A_X/(A_X+1)\ m_H \sim m_H$ => B~500 GHz h
  - Lowest transition at 2B: $\lambda(1\text{-}0) \sim 300\mu m[\mu/m_H][d/\text{Å}]^2$

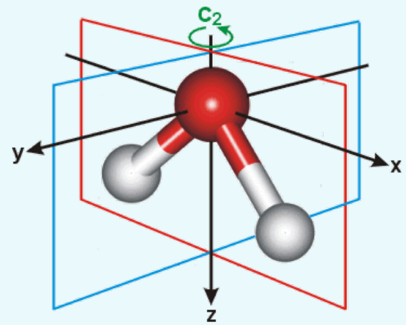
Water Emission

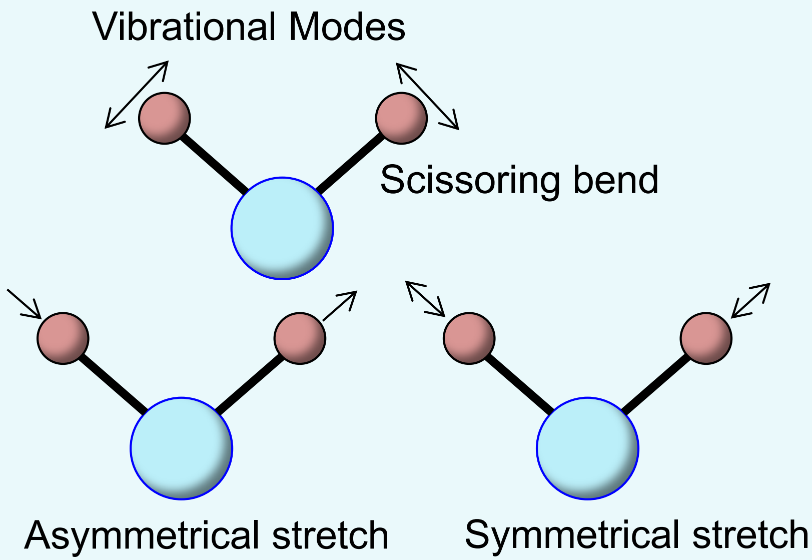
- H_2O Cooling: H_2O quantum numbers J, K_{+1}, K_{-1}, $\Delta J = \pm 1$, $\Delta K = \pm 1, \pm 3$
  - If K_{+1}, K_{-1} have same parity => “para” state, otherwise “ortho” state



Credit: Flagey, et al. 2013, ApJ 762, 11

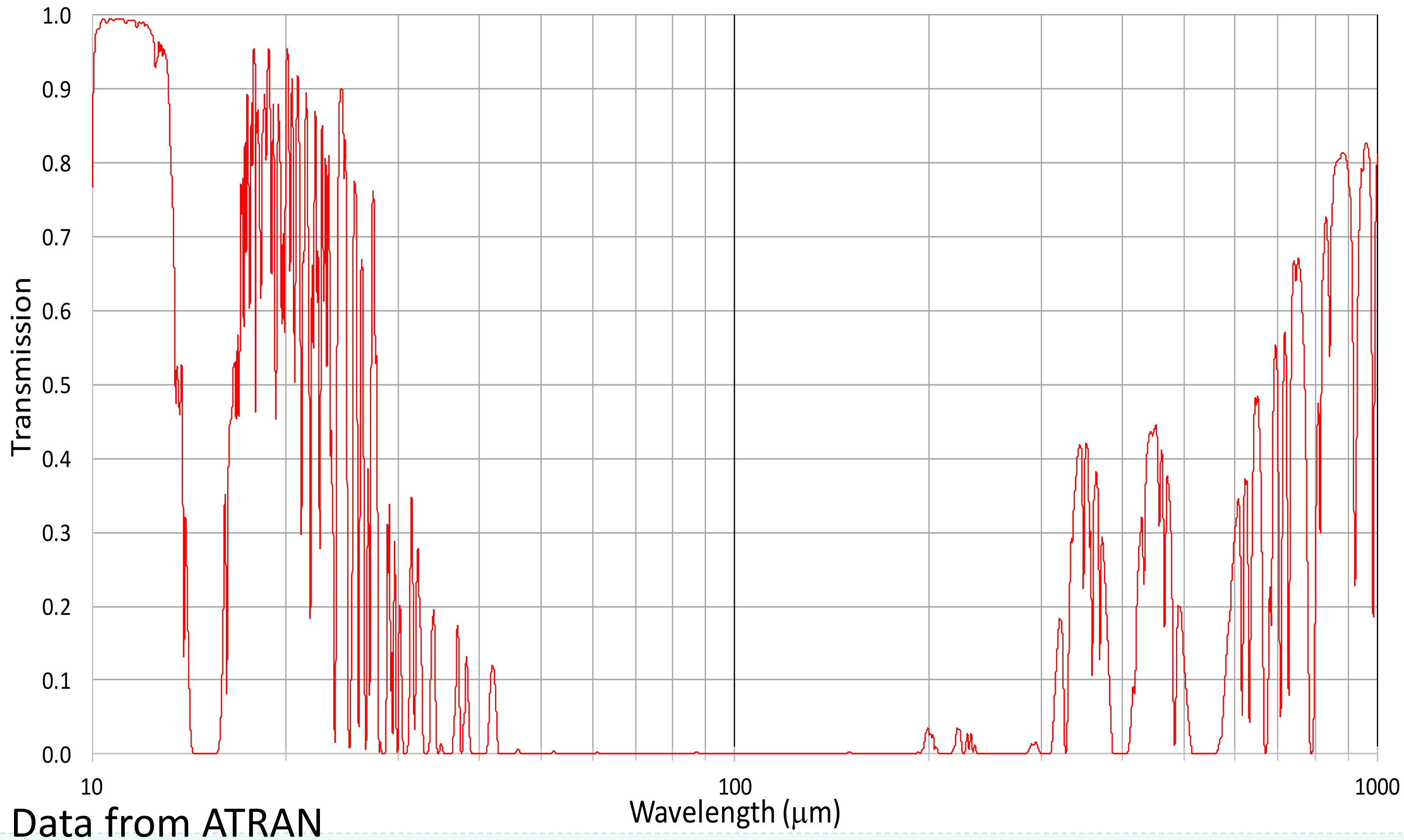






Water vapor makes the atmosphere opaque in the Far IR

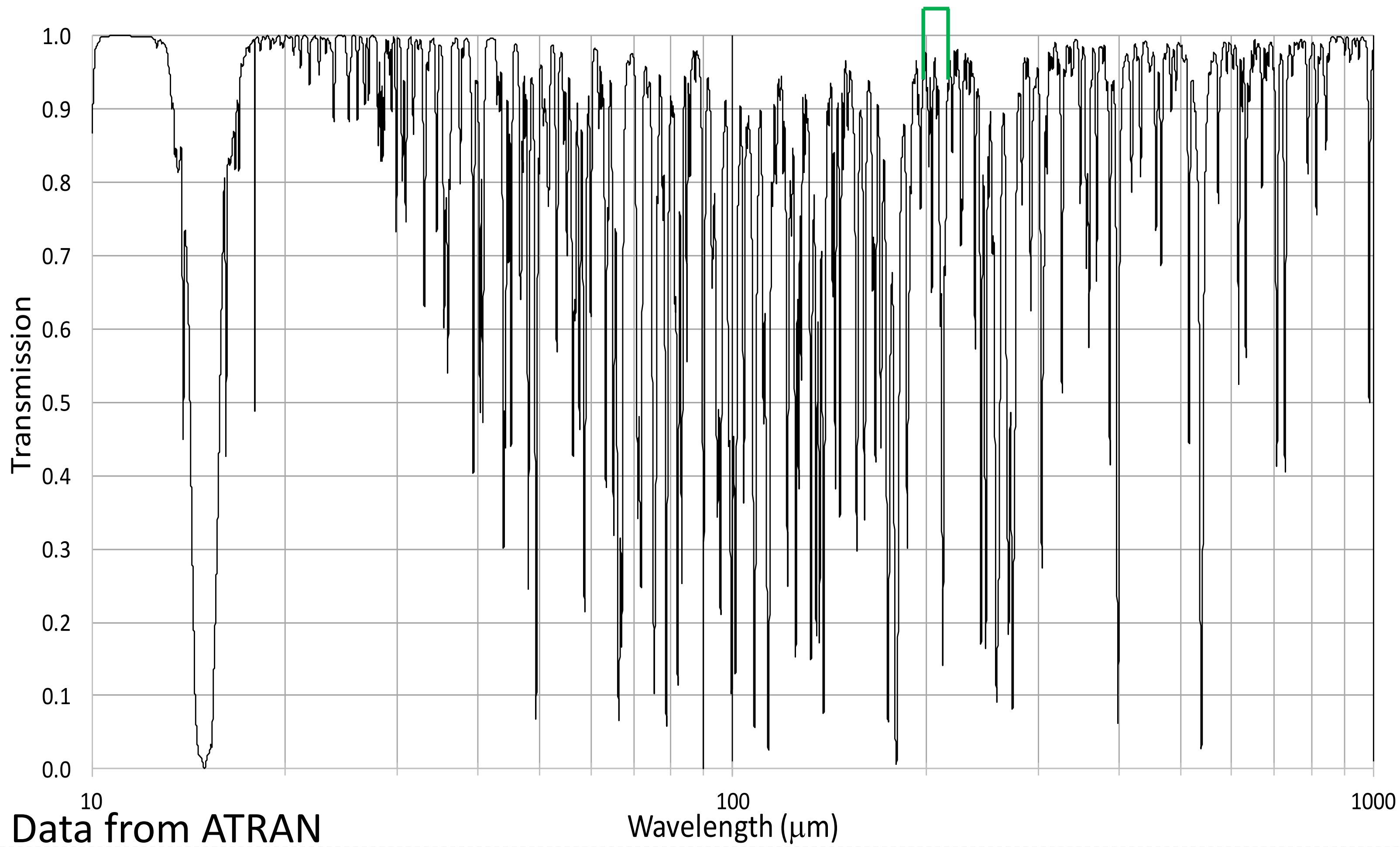
- Good night at ALMA ~700 μm water vapor column



Data from ATRAN

Water vapor in the atmosphere

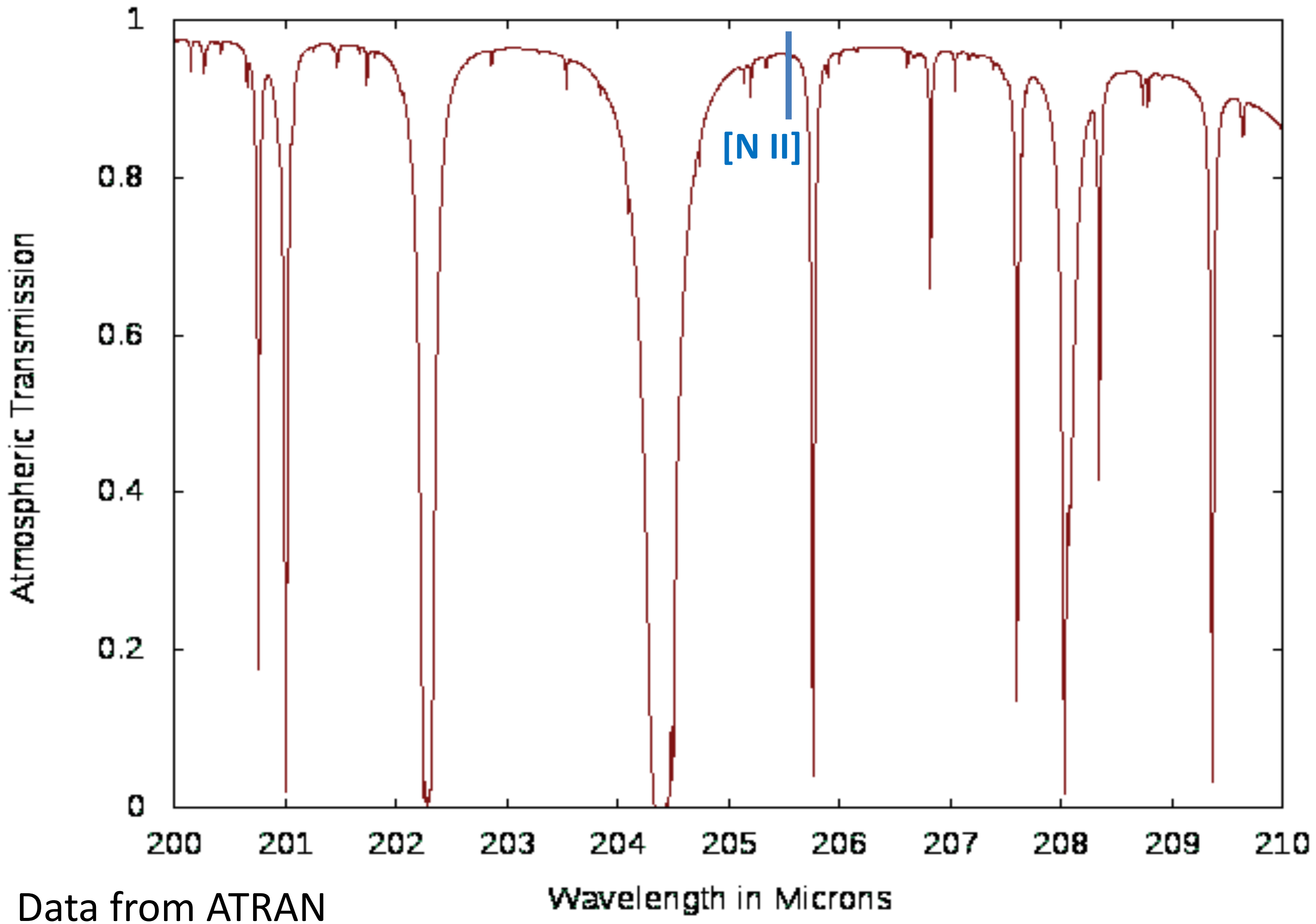
- Good night on SOFIA ~10 μm water vapor



Data from ATRAN

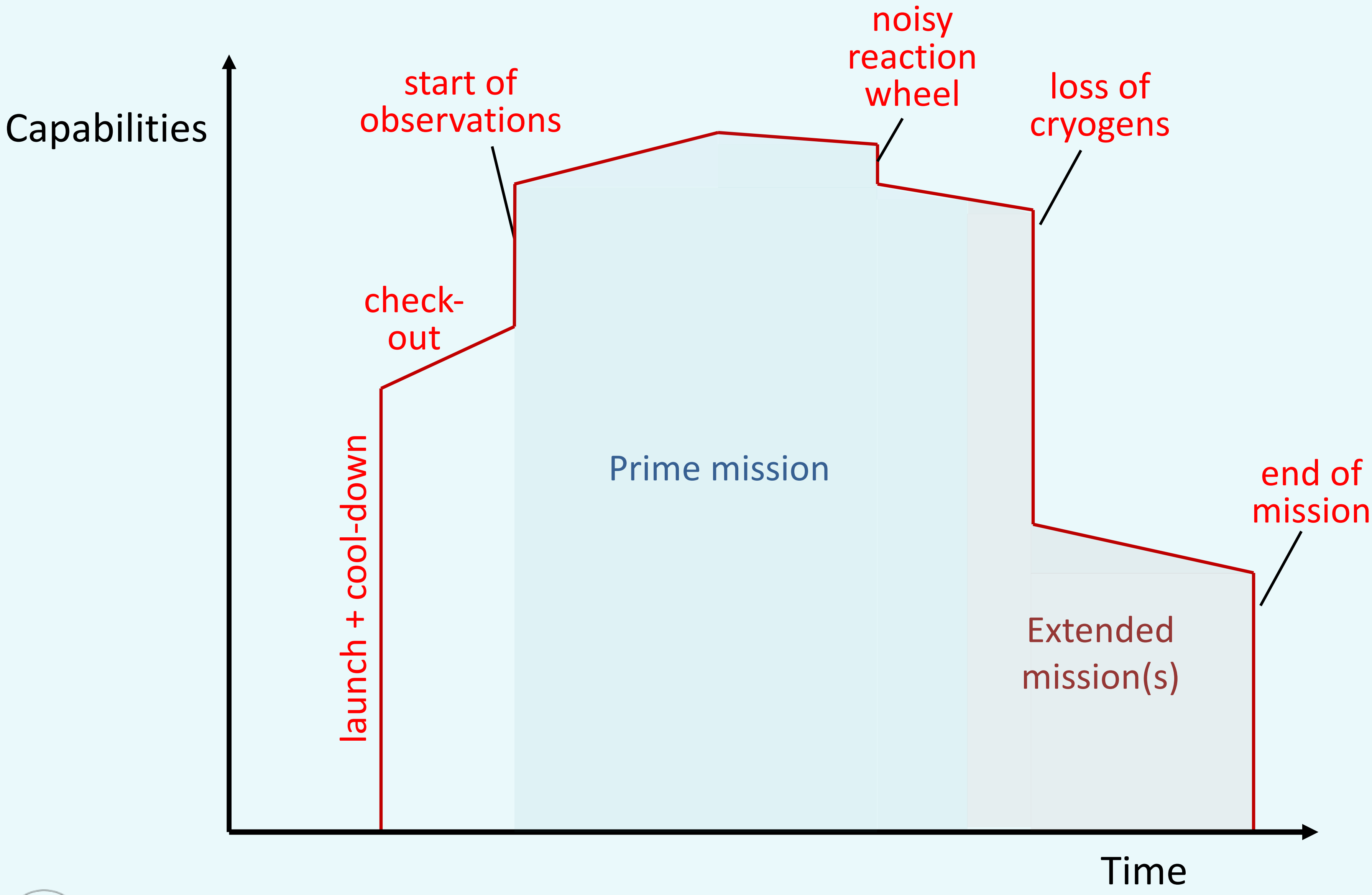
Water vapor in the atmosphere

- Good night on SOFIA ~10 μm water vapor



Data from ATRAN

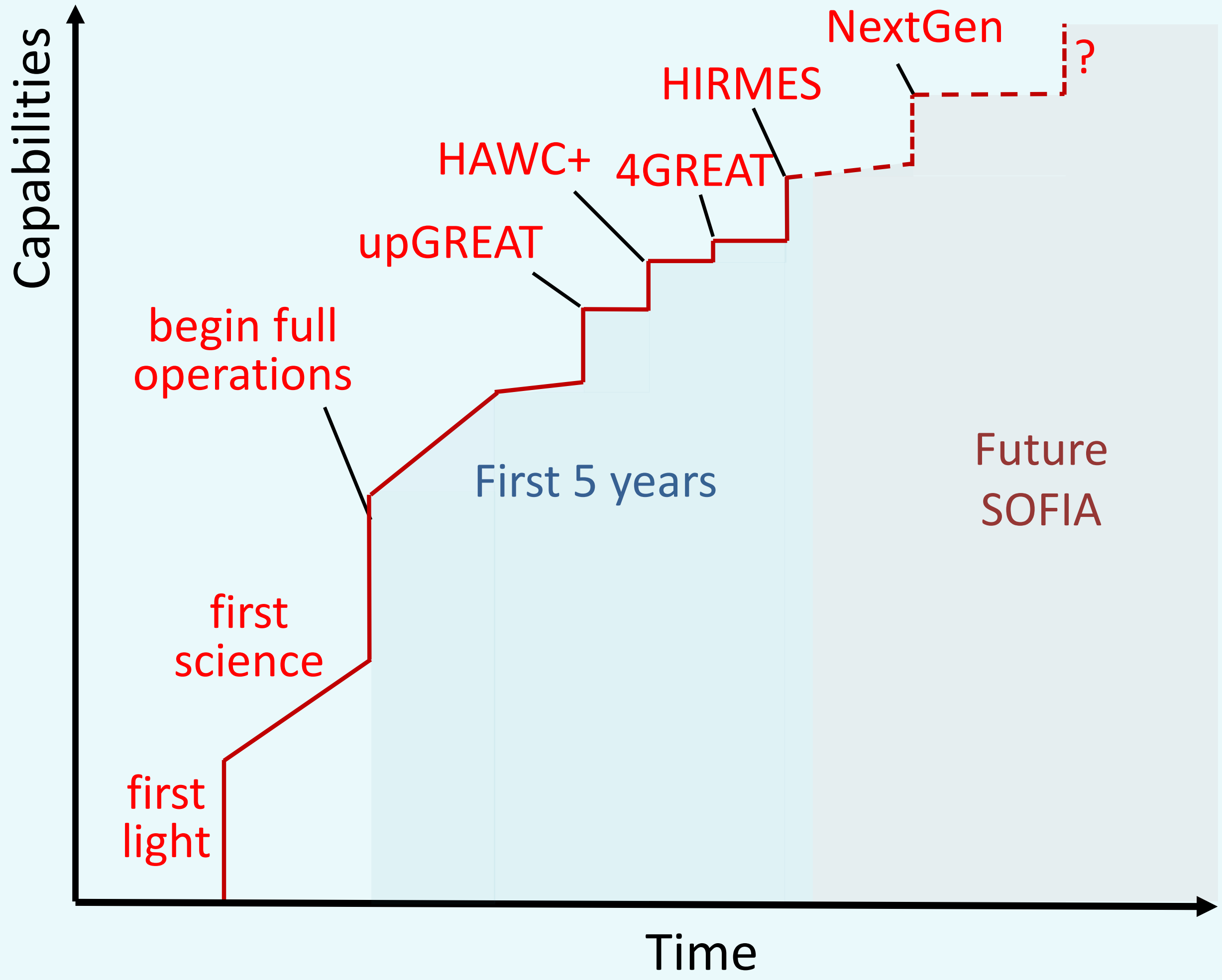
The evolution of capabilities of space missions



The evolution of SOFIA capabilities

SOFIA is not a space mission

- Hardware repairs & updates are possible on a relatively short time scale
- New instruments can be added to address current relevant science questions
- SOFIA tomorrow is much more capable than SOFIA today which is more capable than SOFIA yesterday



SOFIA is unique…

- SOFIA is the only observatory with access to infrared wavelengths above 99% Earth's water vapor
  - Its unique capabilities are necessary for quantitative answers to key science questions.
  - Through the development of new instruments, new science themes can be quickly addressed.
- SOFIA is an outstanding on-sky laboratory for development of future space-based instruments
  - Ample power, weight, 4K cooling, and computing facilities as well as personnel on board allow lower TRL instruments to be designed, built, flown, debugged, used, and perfected before adapting and qualifying for space.

SOFIA is unique…

- SOFIA maintains a working far-infrared community in preparation for a future space mission in the 2030s.
  - Need to maintain experts in dust physics, far- infrared spectroscopy and heating/cooling of gas and dust.
  - Far-infrared detectors are not commercially available; need technologists to continue advancing this field.


http://www.sofia.usra.edu