Cosmic rays and the far infrared-radio correlation

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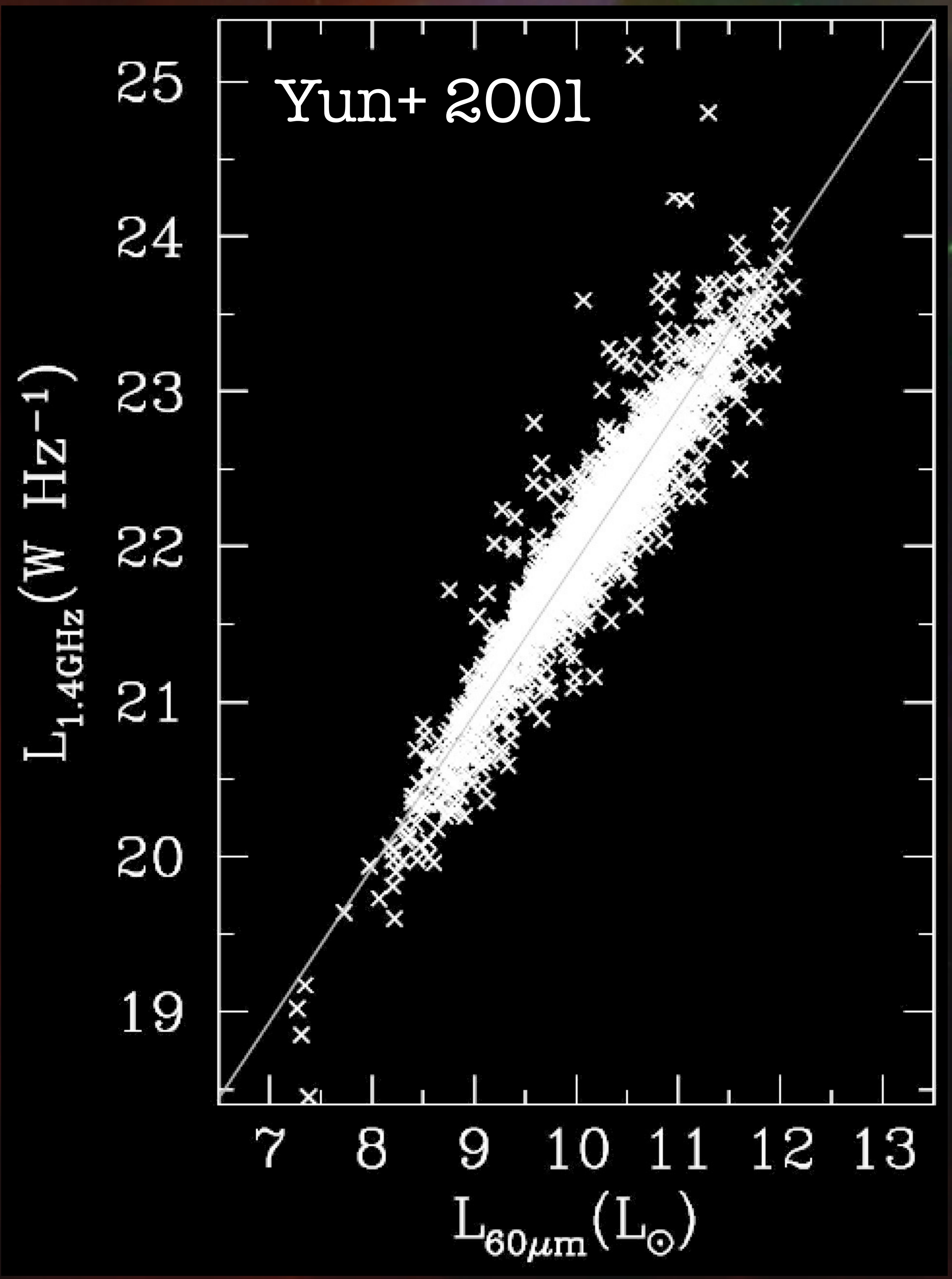
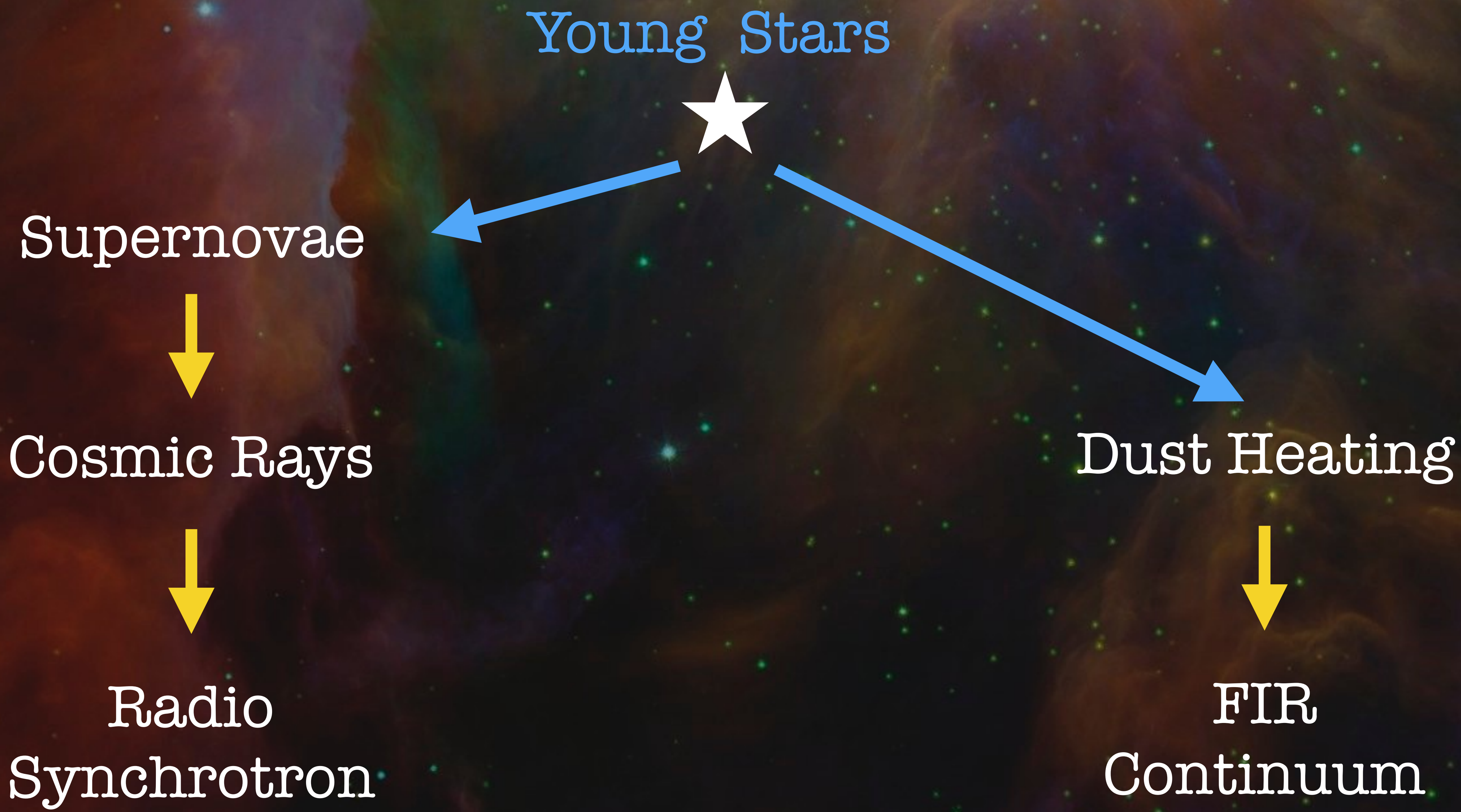
(Manly Astrophysics)

FIR - Radio correlation(s) of galaxies

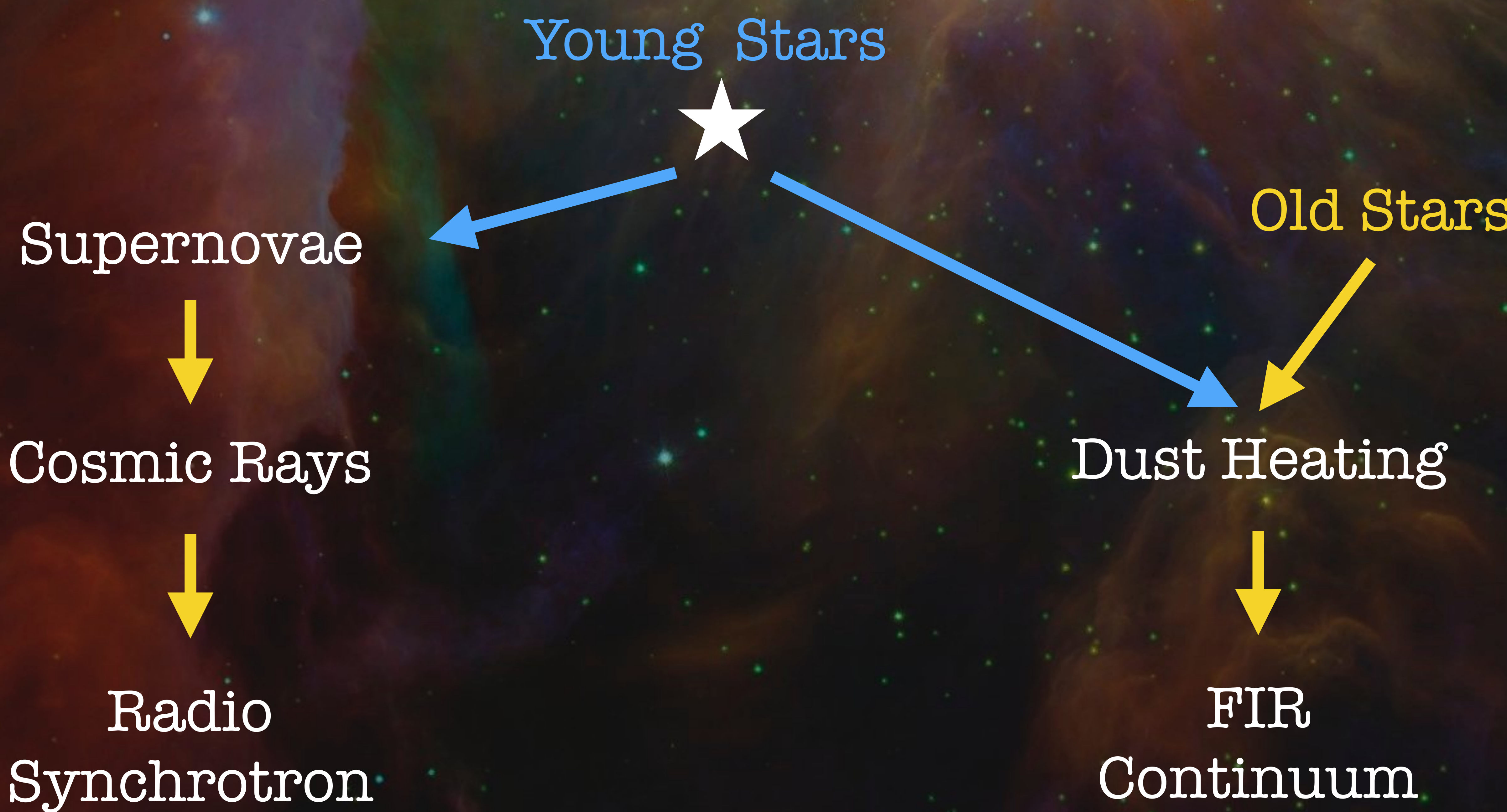


- Tight global correlation
  - Linear
  - No evolution with redshift
  - Dwarfs. Giants. ULIRGs.
    - Not AGN
- Spatially resolved correlation
  - Scales above ~ 40 pc
- FIR-synchrotron, and FIR-thermal bremsstrahlung
- Also correlate with cooling lines: CO, HCN ...

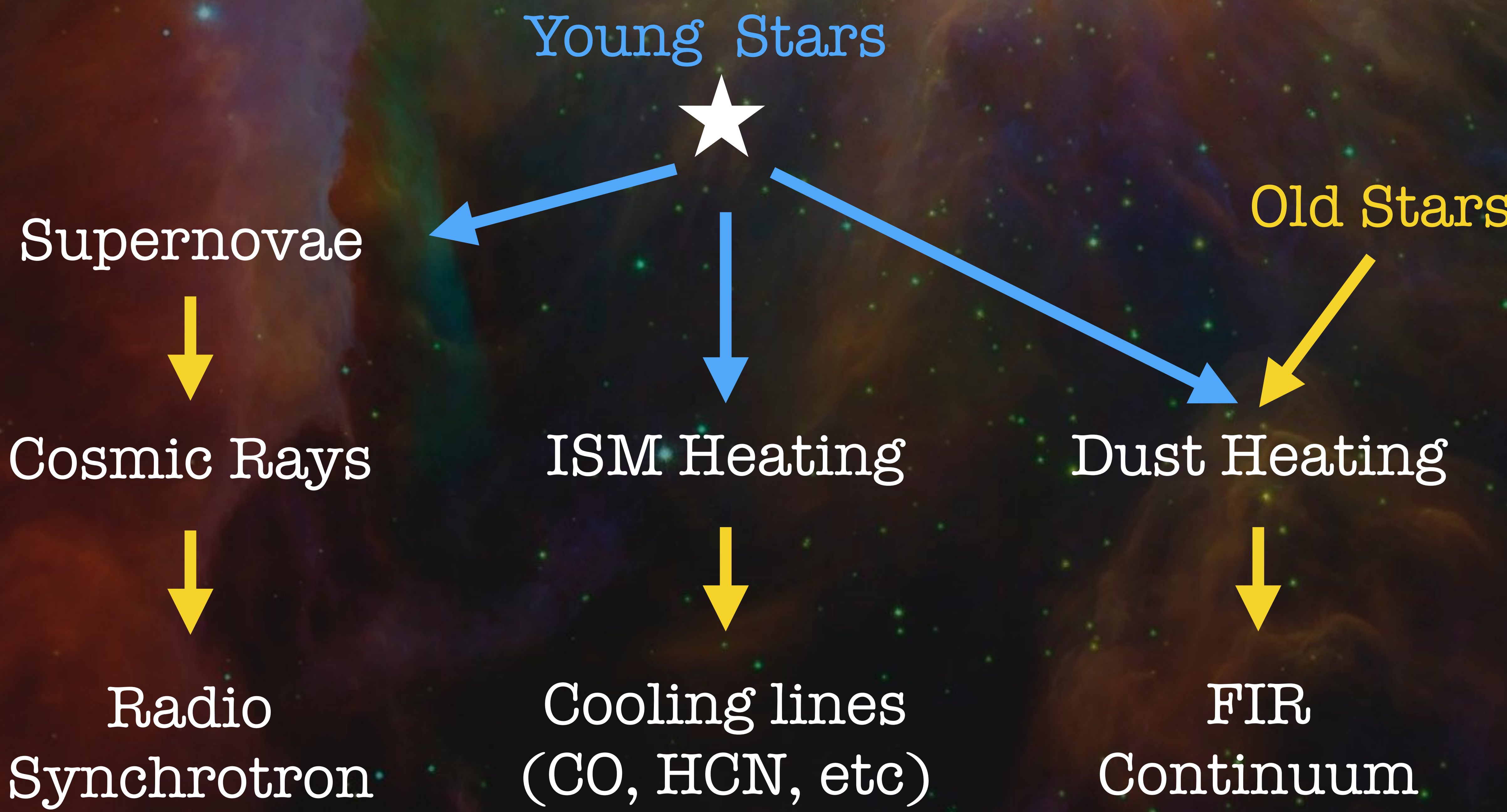
FIR & Radio: conventional picture



FIR & Radio: conventional picture



FIR & Radio: conventional picture



Is a simpler picture possible?

$\boxed{\text{Cosmic Rays}}$ → ISM Heating → Dust Heating

Cosmic Rays ↓ Radio Synchrotron

Dust Heating ↓ FIR Continuum

Is a simpler picture possible?

Cosmic Rays → ISM Heating → (> 90%) Dust Heating

Cosmic Rays ↓ Radio Synchrotron

ISM Heating ↓ (< 10%) Cooling lines (CO, HCN, etc)

Dust Heating ↓ FIR Continuum

Beautiful but problematic

∴ Need 10^{43} erg/s
CR Acceleration

Cosmic Rays → ISM Heating → Dust Heating

↓ Radio Synchrotron

↓ Cooling lines (CO, HCN, etc)

↓ FIR Continuum

Problem 1: 10^{43} erg/s in Galaxy

Beautiful but problematic

∴ Need 10^{43} erg/s
CR Acceleration

Problem 2:
Avoid the
starlight

Cosmic Rays → ISM Heating → Dust Heating

Cosmic Rays ↓ Radio Synchrotron

ISM Heating ↓ Cooling lines (CO, HCN, etc)

Dust Heating ↓ FIR Continuum

Problem 1:
10^{43} erg/s
in Galaxy

Beautiful but problematic

Problem 3:
Heat the dust
$\dot{E} \sim U \sigma v$

Problem 2:
Avoid the
starlight

∴ Need 10^{43} erg/s
CR Acceleration

Cosmic Rays → ISM Heating → Dust Heating

Radio
Synchrotron

Cooling lines
(CO, HCN, etc)

FIR
Continuum

Problem 1:
10^{43} erg/s
in Galaxy

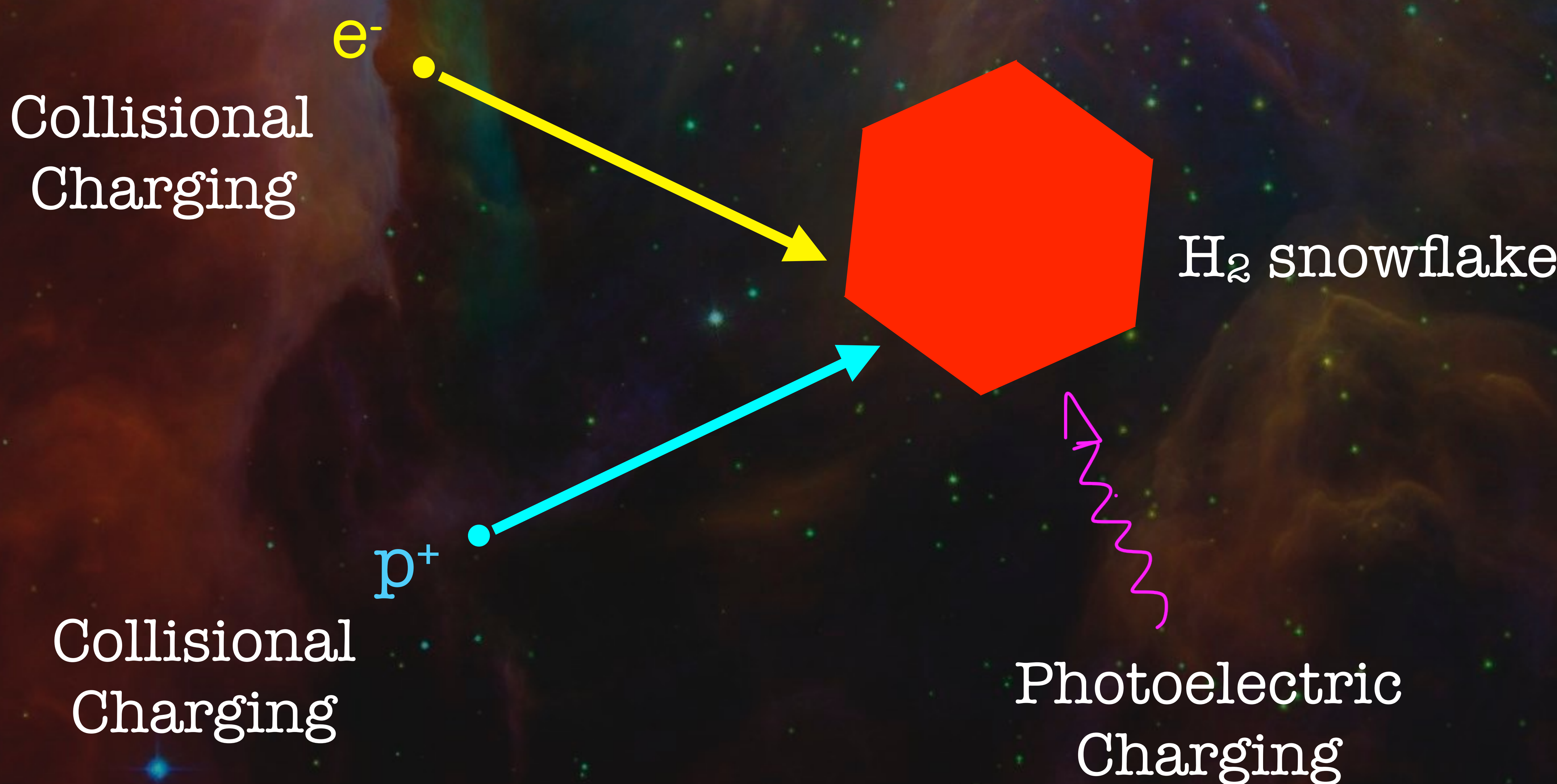
Problems 2 & 3 disappear

if the dust grains are H_2 snowflakes

Why consider solid H_2 dust?

- Hydrogen is the most abundant element
  - No "abundance crisis"
- Very cold, dense molecular clouds may be abundant, but undetected (Pfenniger and Combes 1994)
  - H_2 close to its saturation pressure
    - H_2 snowflakes injected into diffuse ISM via stripping, and via cloud destruction
- Uncharged H_2 grains sublimate rapidly (Field 1969, Greenberg & de Jong 1969). But charged H_2 grains are more durable (MW 2013)

Grain charging in the ISM



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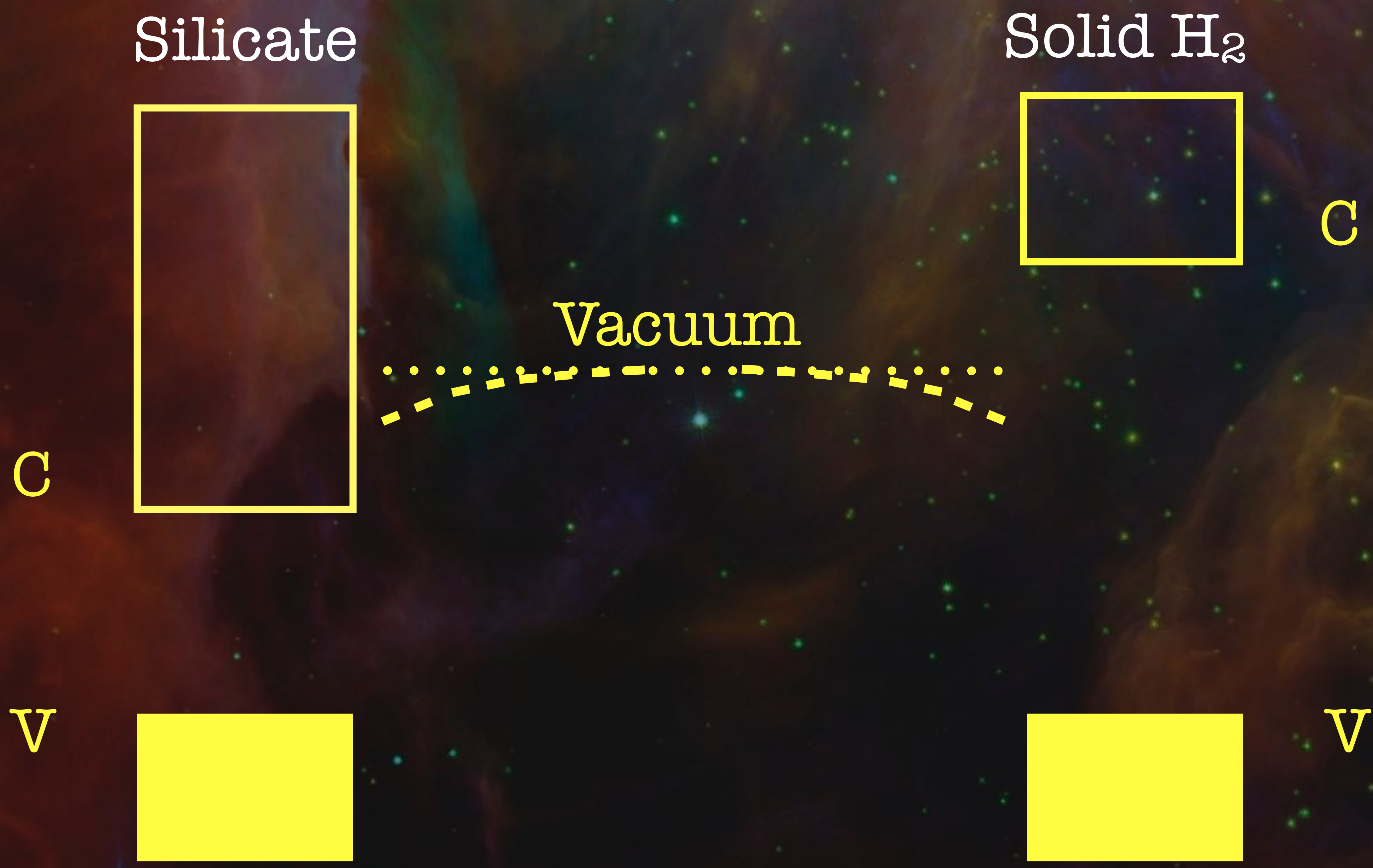
Electronic band structure



Cole 1974 RevModPhys

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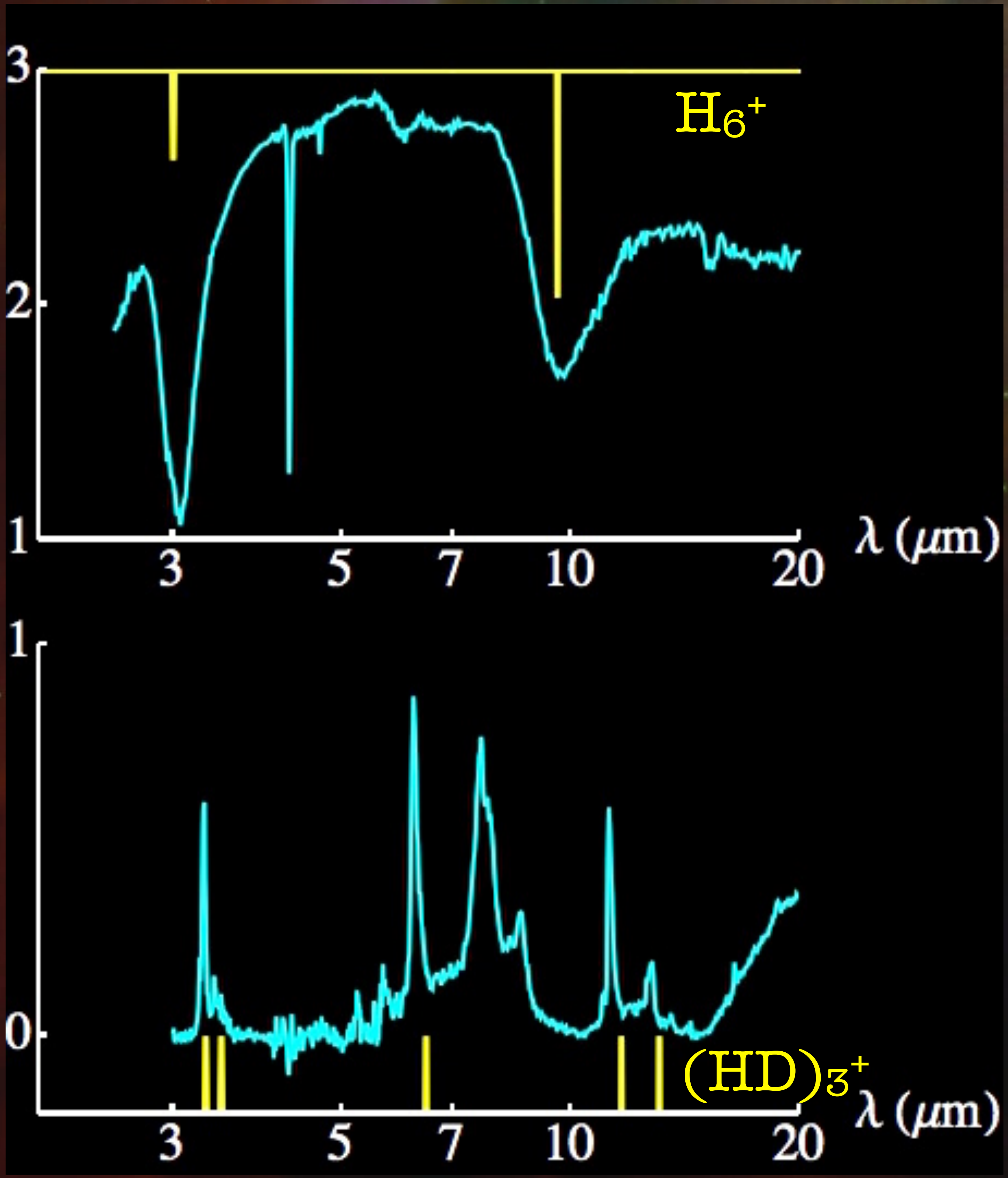
- Uncharged H_2 grains sublimate rapidly (Field 1969, Greenberg & de Jong 1969).
  But charged H_2 grains are more durable (MW 2013)
- Ionisation of condensed H_2 yields H_6^+ and $(HD)_3^+$

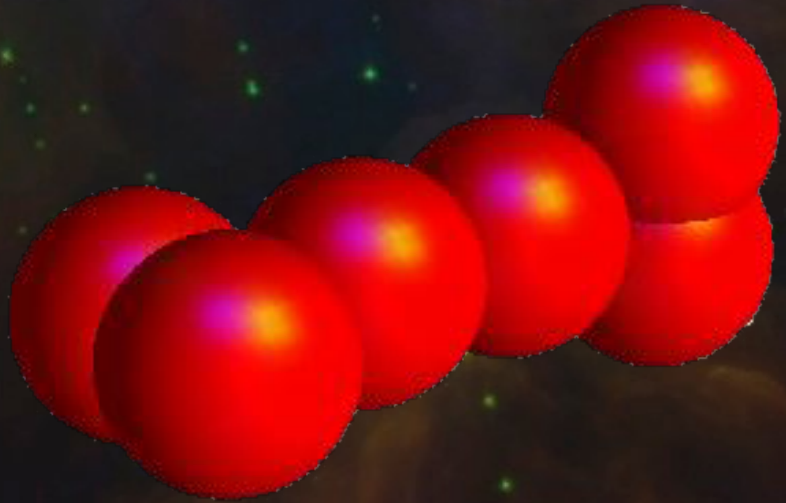
Vibrational transitions of H_6^+



Lin, Gilbert & MW 2011

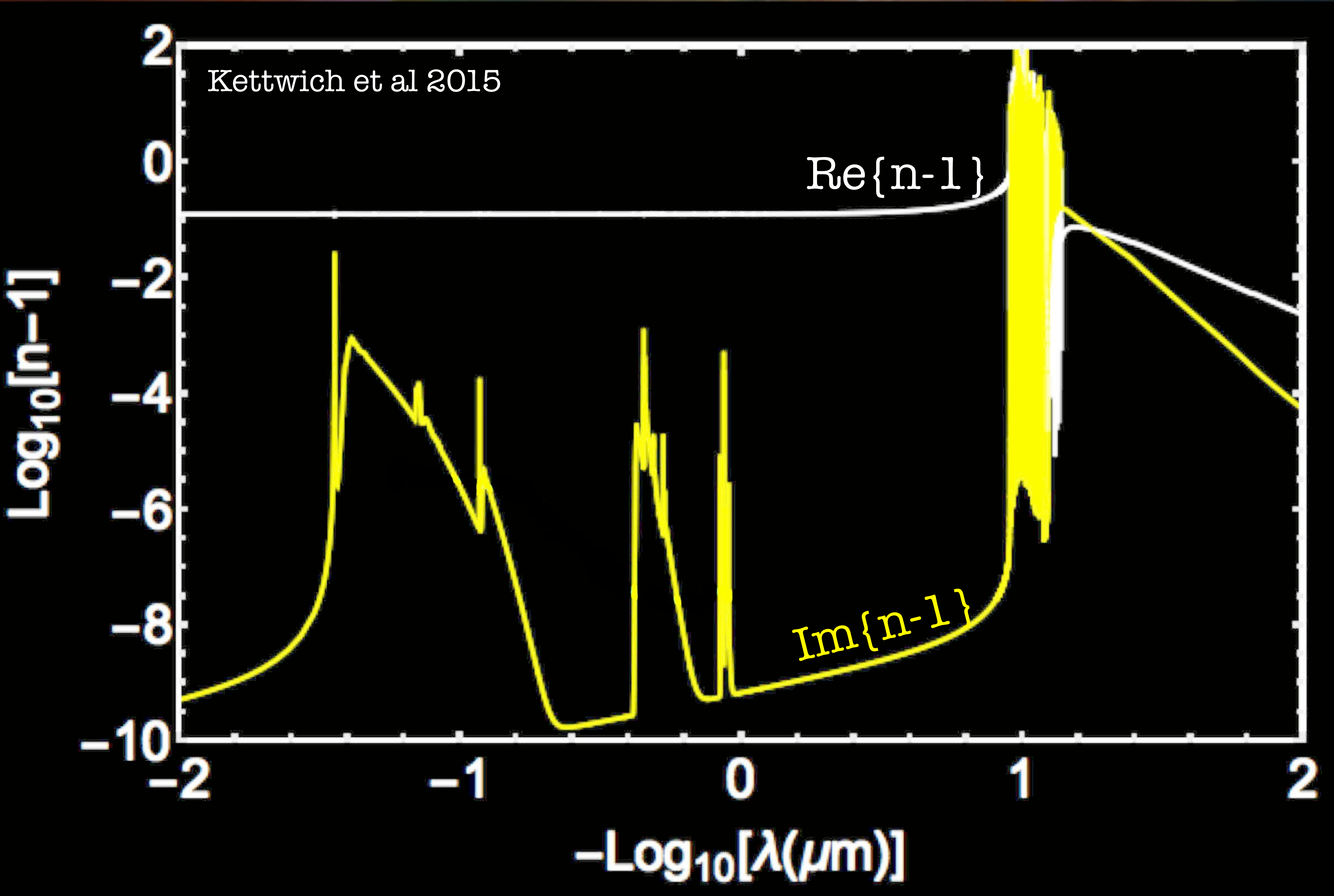
Ab initio quantum theory.

Five modes characterised



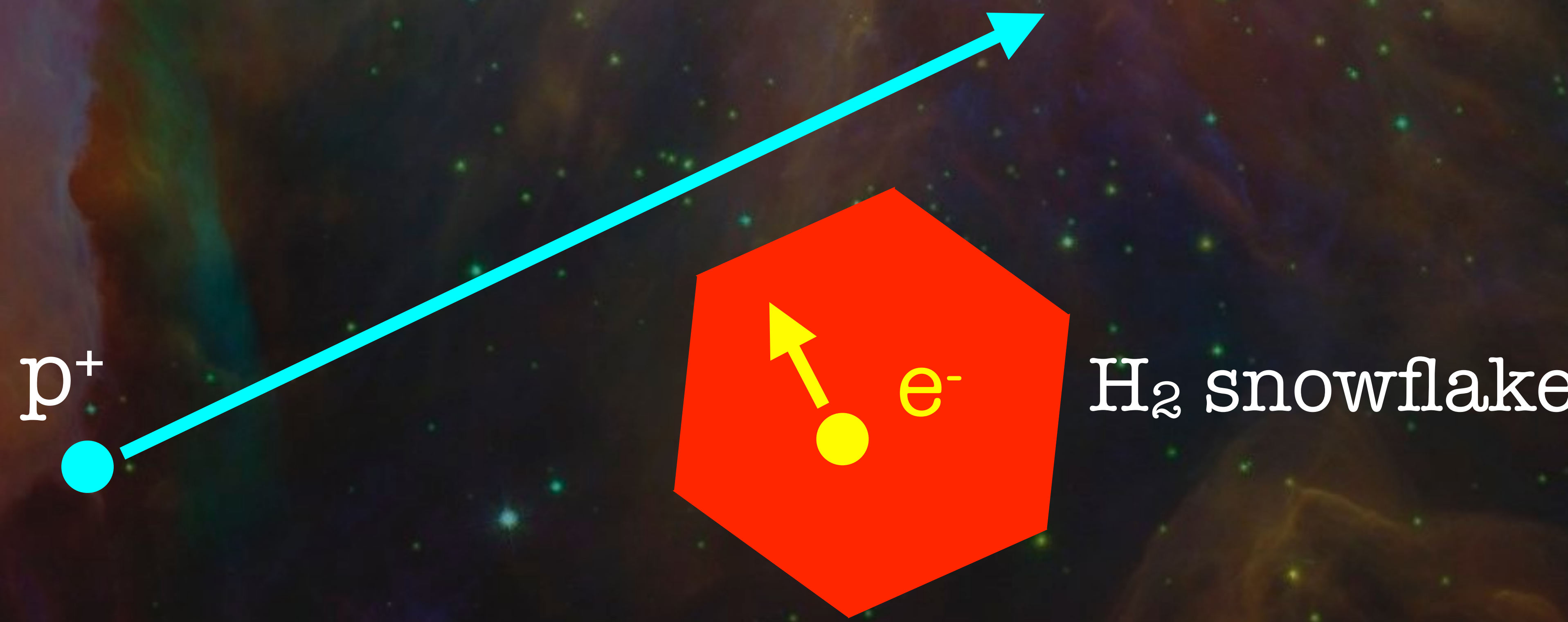
Why problem 2 disappears if the dust grains are H_2 snowflakes

Optical constants of solid H_2

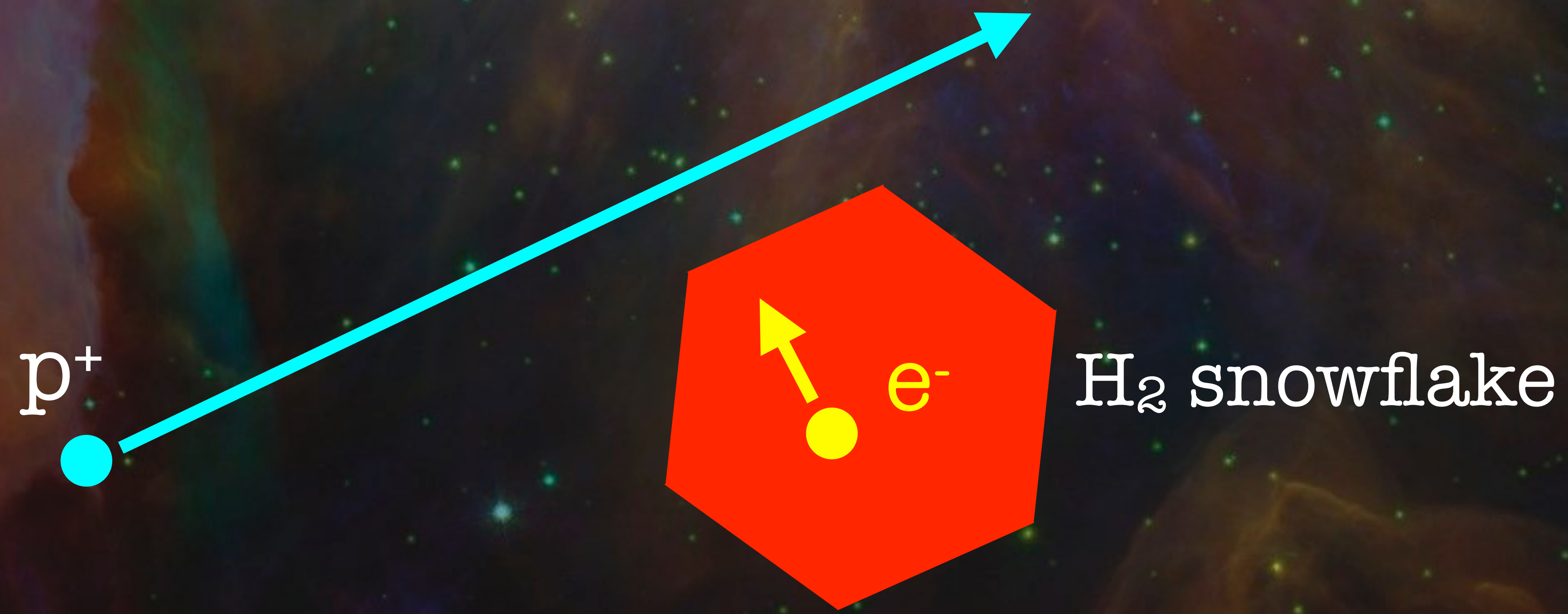


Why problem 3 disappears if the dust grains are H_2 snowflakes

Surface state electrons heated by Coulomb collisions



Surface state electrons heated by Coulomb collisions

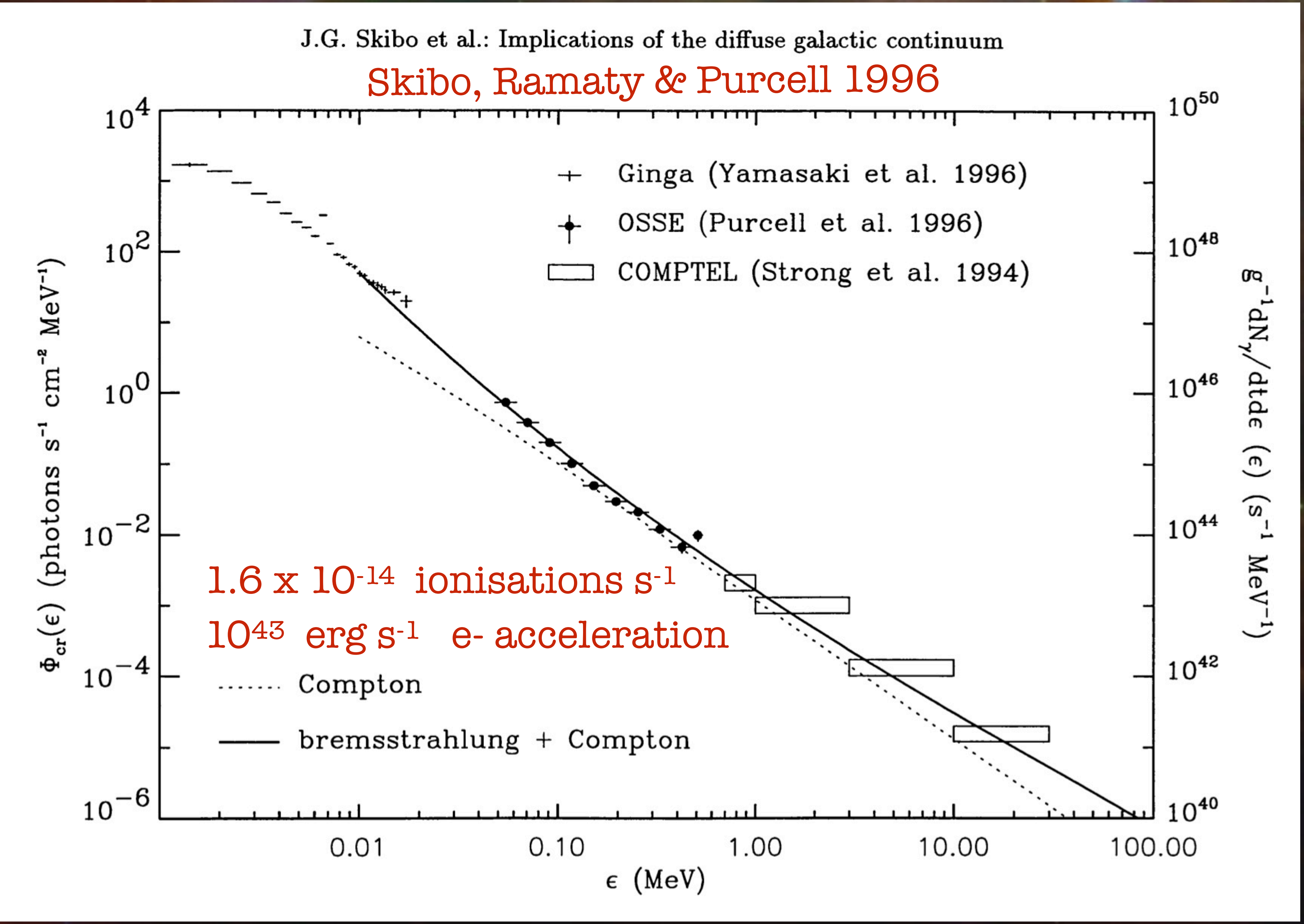


Thermal particles more effective than CRs.
∴ CRs heat plasma, and plasma heats dust.

Problem #1: 10^{43} erg s^{-1} in CR

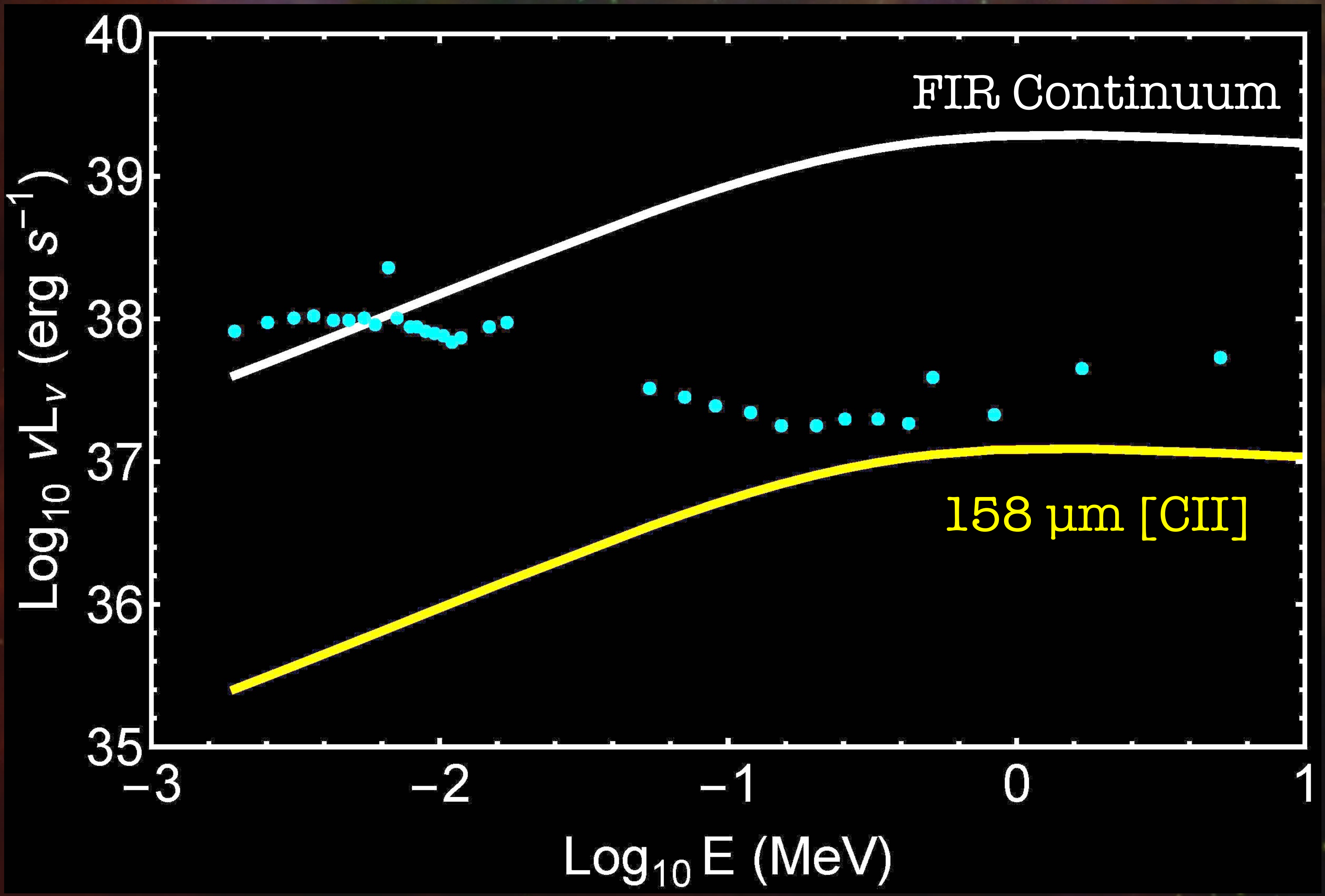
- Supernovae in our Galaxy:
  - 1 SN per 30 years => 10^{-9} Hz * 10^{51} erg
    - Only ~ 10^{42} erg s^{-1} mechanical
- Help! Need other, more powerful accelerators.
- Accelerator wish-list:
  - 10^{43} erg s^{-1}
  - Power flows into e-
    - Radio synchrotron from energetic e-
      FIR from low energy e- via heating of ISM
  - Peak power dissipation at E ~ 0.01 MeV

Galactic Ridge hard X-ray spectrum



NB: many possible origins of Galactic Ridge hard X-rays.

Observed cooling constrains Bremsstrahlung X-radiation



Summary

- FIR-Radio = Universal, tight, linear correlation for star-forming galaxies
  - Suggests a close link between CRs and dust heating
    - Conventionally, these two are remote
- Physics of H_2 snowflakes is largely unexplored, but interesting
  - "New" hydrogen molecule: H_6^+
  - Surface-state electrons
- H_2 snowflakes are largely transparent to starlight
  - Heating via Coulomb collisions with surface-state electrons
- H_2 snowflakes + $LECR_e$ heating of ISM would provide a close link between FIR and radio synchrotron (and subsidiary correlations)
  - But huge $LECR_e$ power requirement - too much for SNe
    - Similar to bremsstrahlung models of Galactic Ridge hard X-rays
    - More than enough ionisations to keep the chemists happy