
A Global View on Dust Evolution(s)
from Nearby Galaxies
Frédéric Galliano (AIM, CEA/Saclay, France)
Eli Dwek (NASA/GSFC, USA)
Anthony Jones (IAS, Orsay, France)
Pierre Chanial (Imperial College, UK)

Content of the Talk

1) A Quick Sweep of the Dusty Universe
   - Basic dust physics, the models and their constraints
   - Step by step building of a spectral energy distribution (SED)
   - Observed SED evolution of galaxies

Content of the Talk

1) A Quick Sweep of the Dusty Universe
   - Basic dust physics, the models and their constraints
   - Step by step building of a spectral energy distribution (SED)
   - Observed SED evolution of galaxies

2) The Dust Evolution Cycle and the Observed Dust Budget in Galaxies
   - Open questions about dust evolution: sites of formation, efficiency of destruction
   - Difficulties to interpret an observed galaxy's SED

Content of the Talk

1) A Quick Sweep of the Dusty Universe
   - Basic dust physics, the models and their constraints
   - Step by step building of a spectral energy distribution (SED)
   - Observed SED evolution of galaxies

2) The Dust Evolution Cycle and the Observed Dust Budget in Galaxies
   - Open questions about dust evolution: sites of formation, efficiency of destruction
   - Difficulties to interpret an observed galaxy's SED

3) Bridging the Gap Between the Distant Universe and Nearby Galaxies
   - A multiphase SED model
   - A consistent dust and elemental evolution model
   - The distinct evolution of PAHs and SN-condensed dust as a function of time

Content of the Talk

1) A Quick Sweep of the Dusty Universe
   - Basic dust physics, the models and their constraints
   - Step by step building of a spectral energy distribution (SED)
   - Observed SED evolution of galaxies

2) The Dust Evolution Cycle and the Observed Dust Budget in Galaxies
   - Open questions about dust evolution: sites of formation, efficiency of destruction
   - Difficulties to interpret an observed galaxy's SED

3) Bridging the Gap Between the Distant Universe and Nearby Galaxies
   - A multiphase SED model
   - A consistent dust and elemental evolution model
   - The distinct evolution of PAHs and SN-condensed dust as a function of time

Summary & Conclusion

Content of the Talk

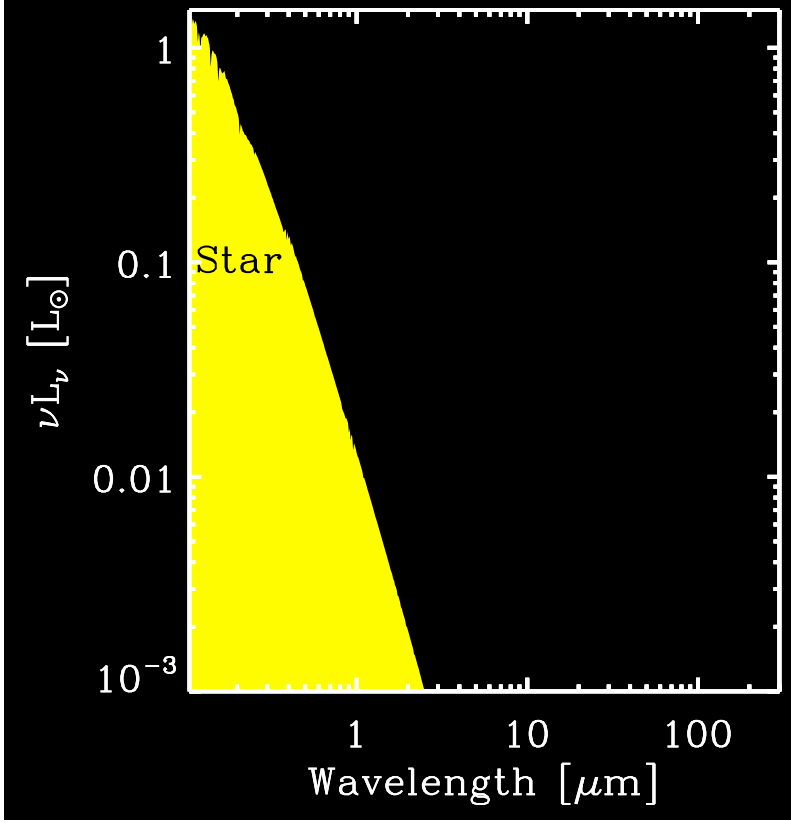
1) A Quick Sweep of the Dusty Universe
   - Basic dust physics, the models and their constraints
   - Step by step building of a spectral energy distribution (SED)
   - Observed SED evolution of galaxies

2) The Dust Evolution Cycle and the Observed Dust Budget in Galaxies
   - Open questions about dust evolution: sites of formation, efficiency of destruction
   - Difficulties to interpret an observed galaxy's SED

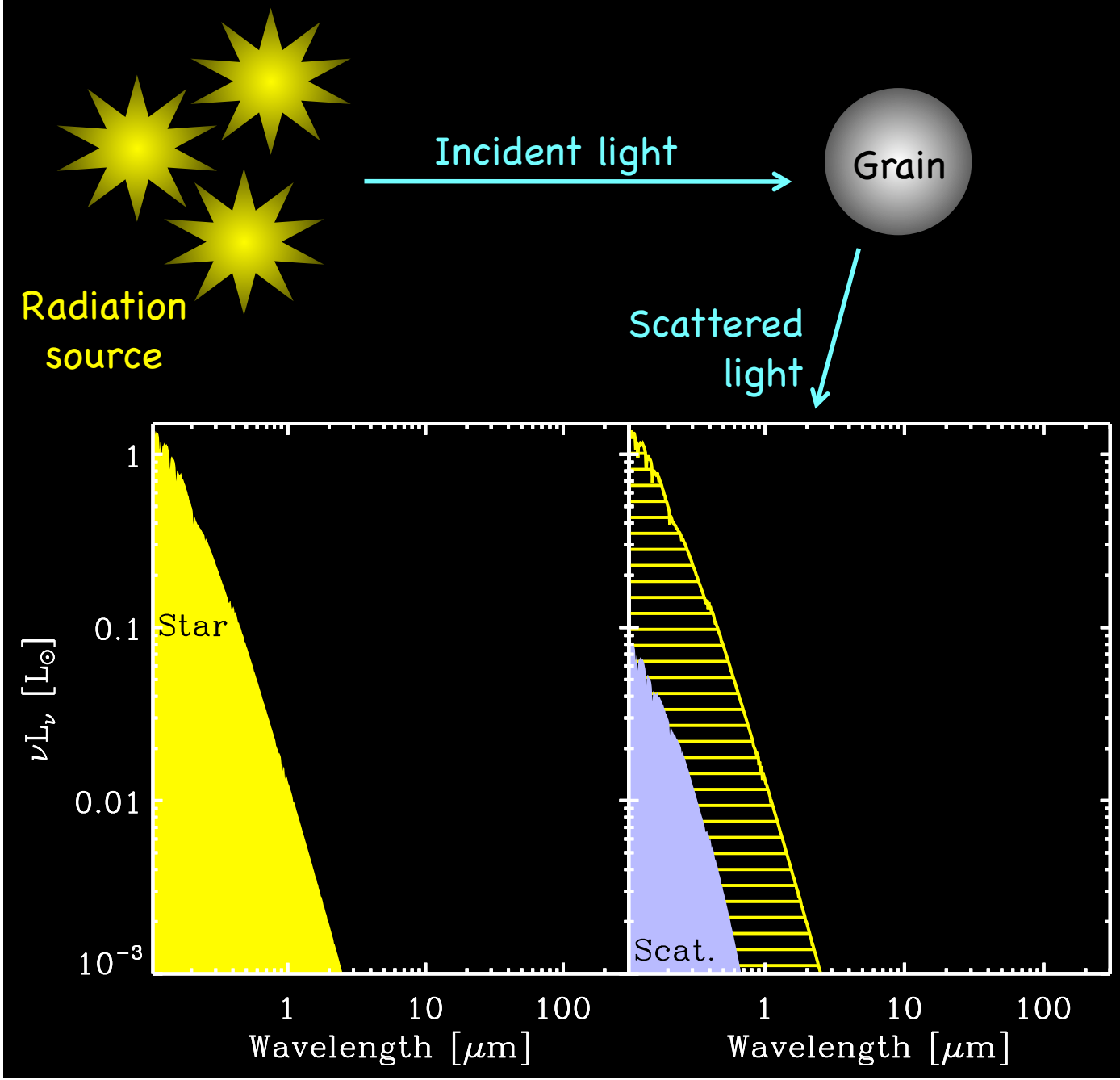
3) Bridging the Gap Between the Distant Universe and Nearby Galaxies
   - A multiphase SED model
   - A consistent dust and elemental evolution model
   - The distinct evolution of PAHs and SN-condensed dust as a function of time

Summary & Conclusion

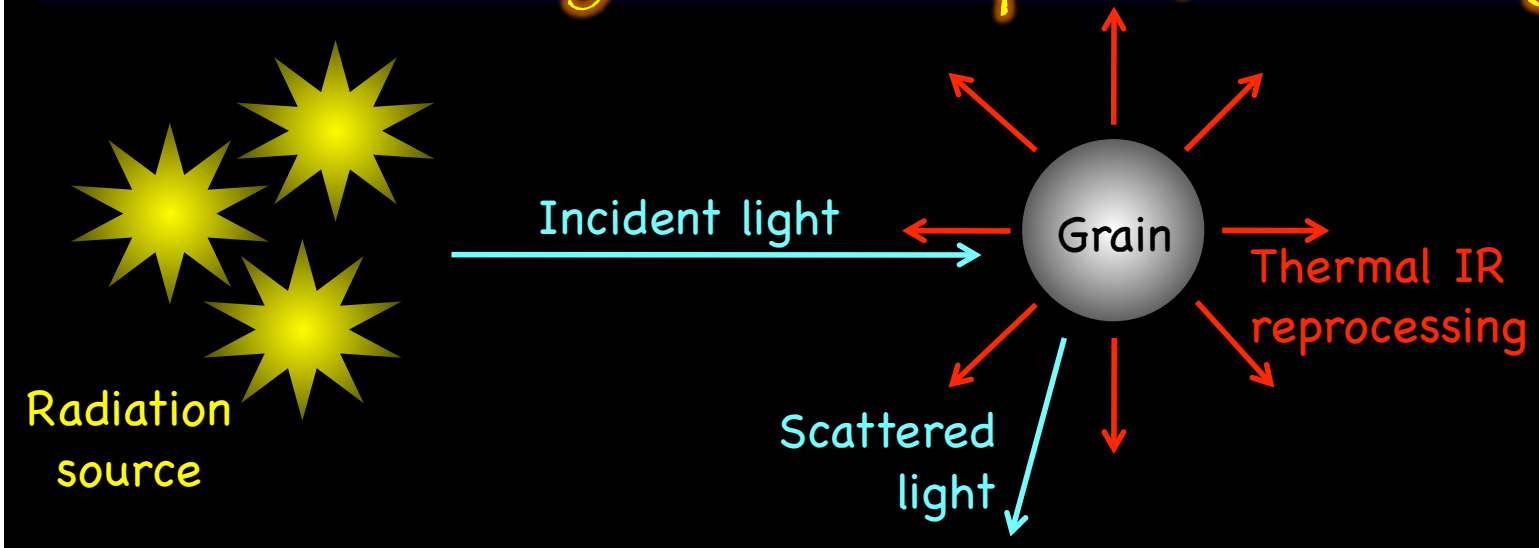
Basic Dust Physics: Absorption, Scattering, Emission

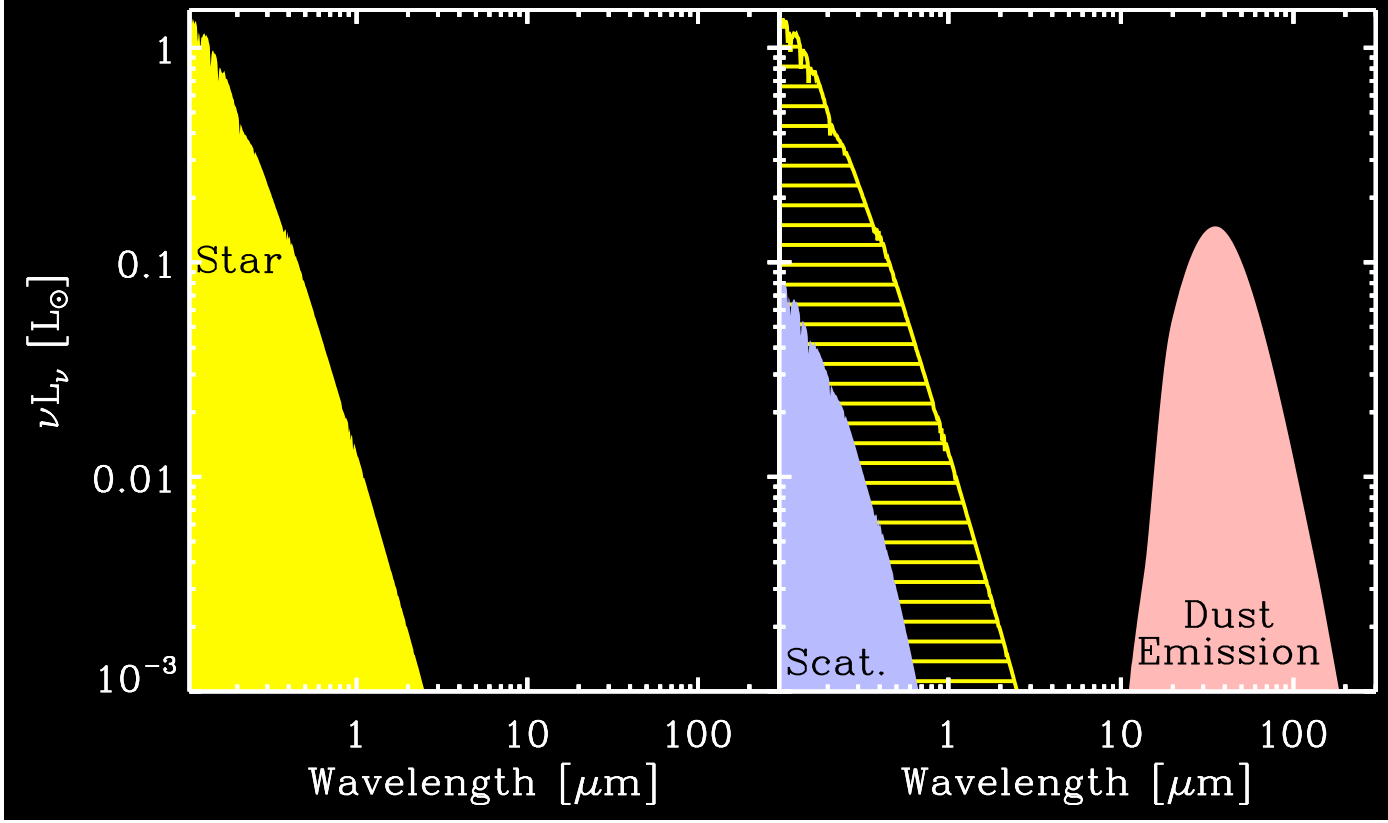


Basic Dust Physics: Absorption, Scattering, Emission

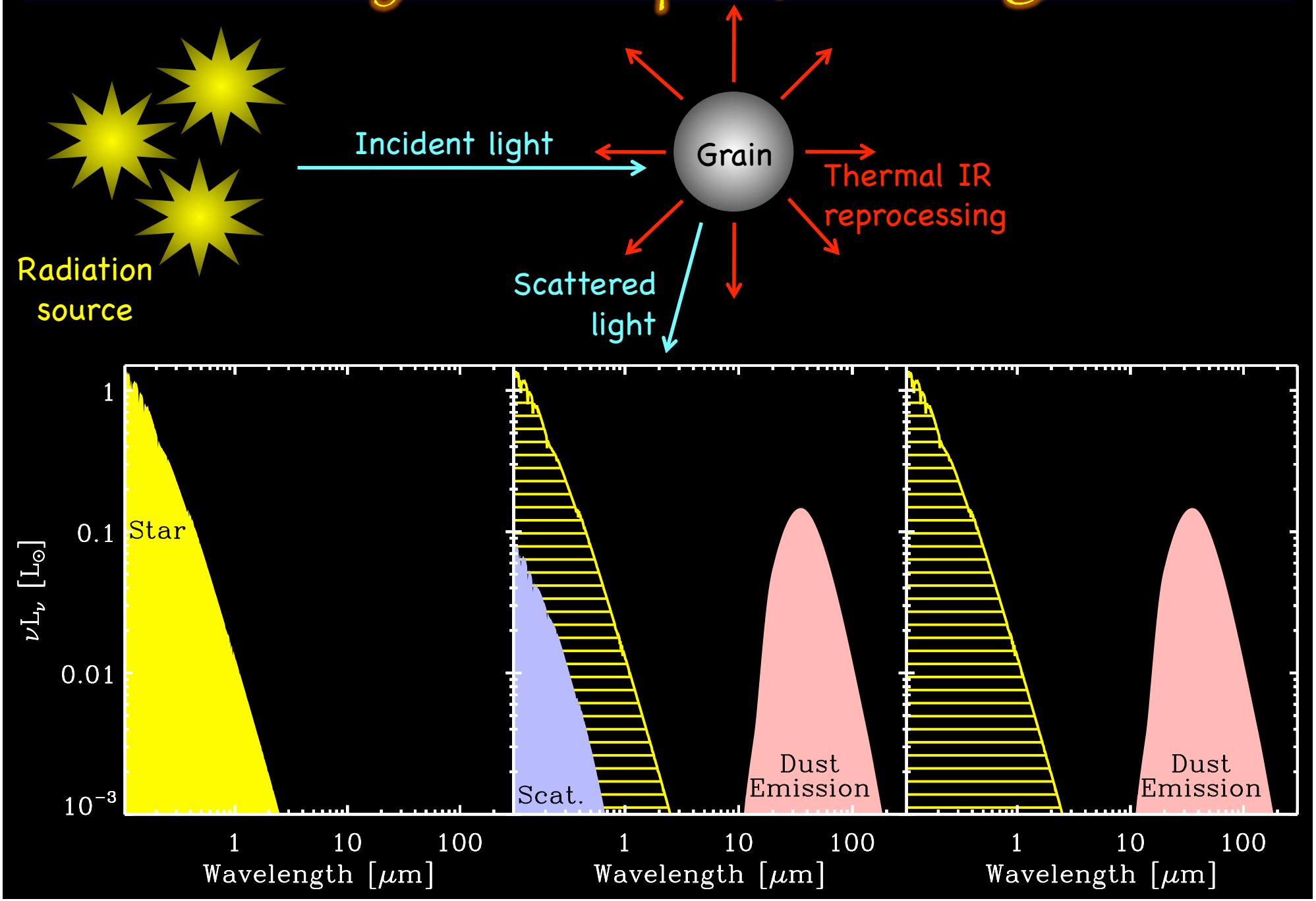


Basic Dust Physics: Absorption, Scattering, Emission

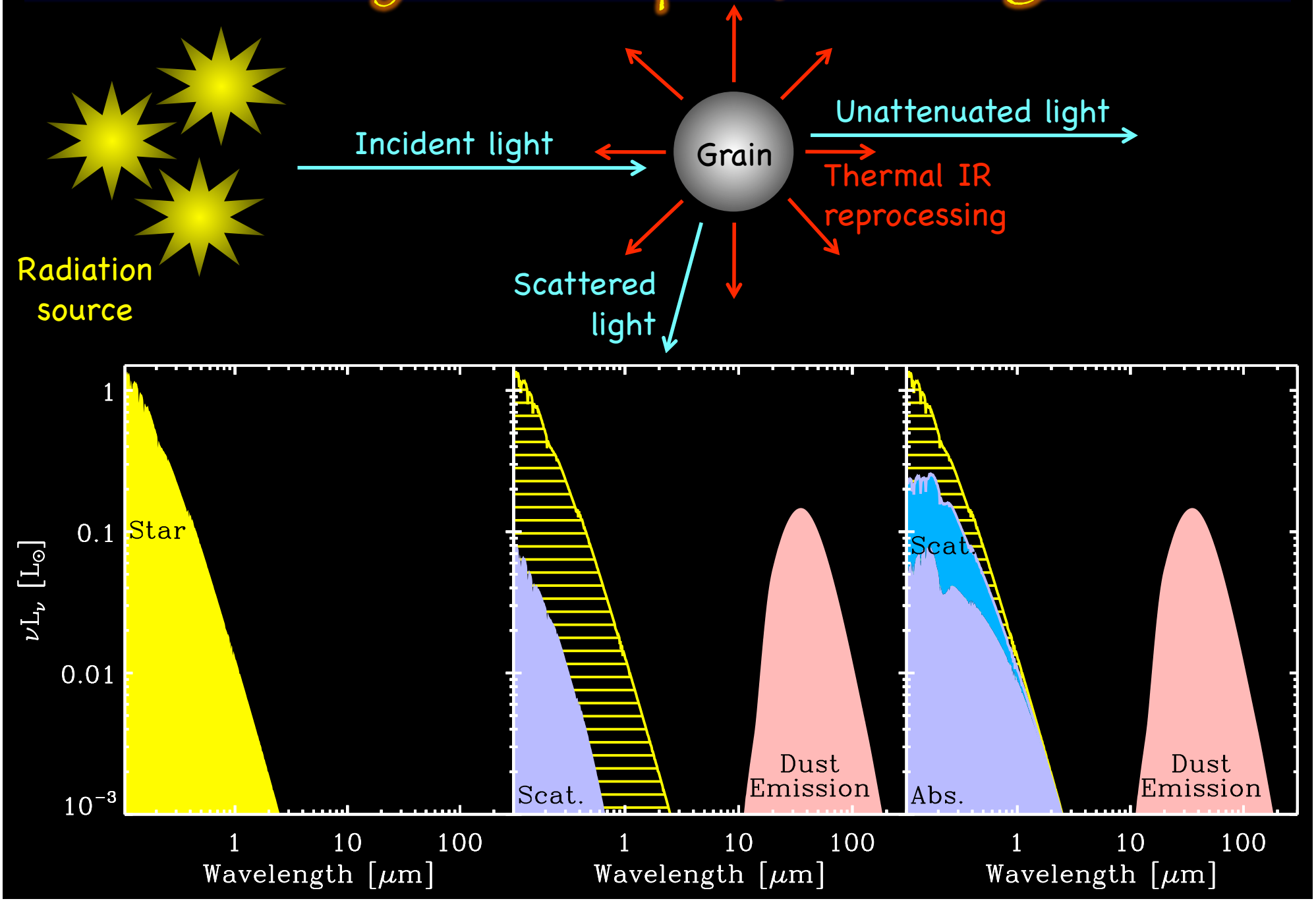




Basic Dust Physics: Absorption, Scattering, Emission



Basic Dust Physics: Absorption, Scattering, Emission



A Few Facts About Dust

- It is ubiquitous. At first order, its mass abundance is ≈1/3 of the metals
  => $M_{dust}/M_{gas} \approx 1/100 \times Z/Z_{\odot}$.

A Few Facts About Dust

- It is ubiquitous. At first order, its mass abundance is ≈1/3 of the metals
  => $M_{dust}/M_{gas} \approx 1/100 \times Z/Z_{\odot}$.
- In our Galaxy, it reprocesses ≈30 % of the stellar power. In a starburst, it is ≈99 % (embedded star formation).

A Few Facts About Dust

- It is ubiquitous. At first order, its mass abundance is ≈1/3 of the metals
  => $M_{dust}/M_{gas} \approx 1/100 \times Z/Z_{\odot}$.
- In our Galaxy, it reprocesses ≈30 % of the stellar power. In a starburst, it is ≈99 % (embedded star formation).
- It has a crucial role in the cooling and heating of the photodissociation regions: photoelectric effect => far-IR fine structure line pumping.

A Few Facts About Dust

- It is ubiquitous. At first order, its mass abundance is ≈1/3 of the metals => $M_{dust}/M_{gas} \approx 1/100 \times Z/Z_{\odot}$.
- In our Galaxy, it reprocesses ≈30 % of the stellar power. In a starburst, it is ≈99 % (embedded star formation).
- It has a crucial role in the cooling and heating of the photodissociation regions: photoelectric effect => far-IR fine structure line pumping.
- It plays a role of catalysts in many chemical reactions. H_2 is formed on grain surfaces.

A Few Facts About Dust

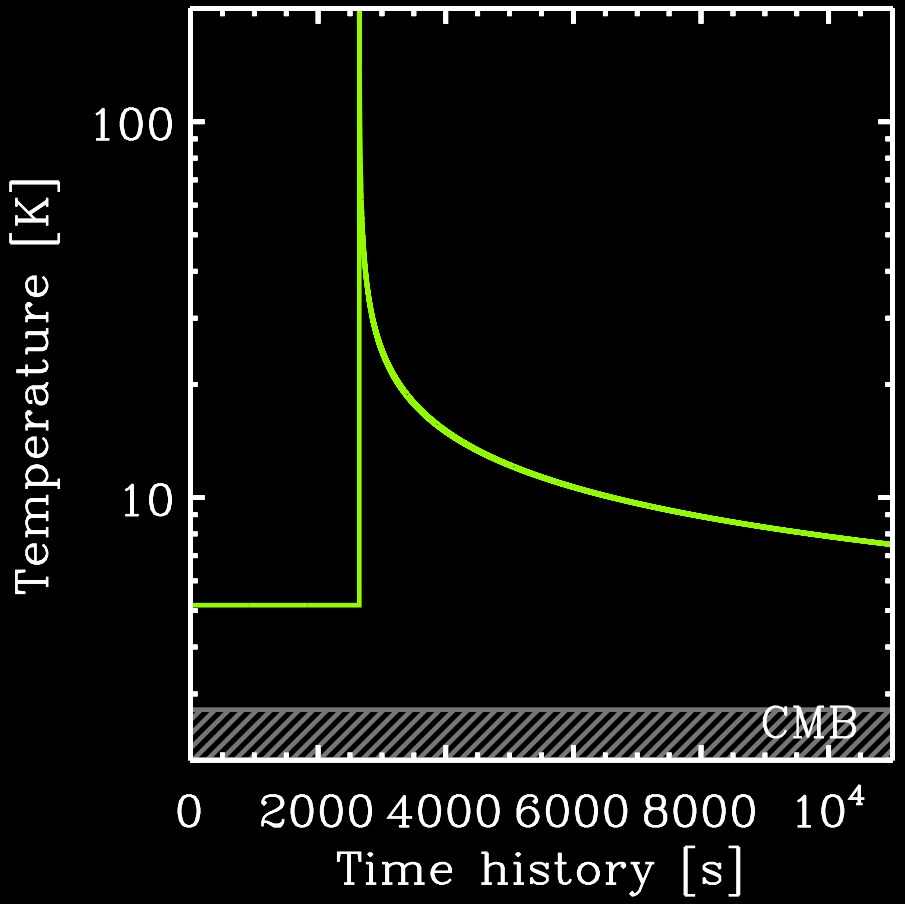
- It is ubiquitous. At first order, its mass abundance is ≈1/3 of the metals
  => $M_{dust}/M_{gas} \approx 1/100 \times Z/Z_{\odot}$.
- In our Galaxy, it reprocesses ≈30 % of the stellar power. In a starburst, it is ≈99 % (embedded star formation).
- It has a crucial role in the cooling and heating of the photodissociation regions: photoelectric effect => far-IR fine structure line pumping.
- It plays a role of catalysts in many chemical reactions. H_2 is formed on grain surfaces.
- The most accurate dust models are currently constrained from observations of the Galactic diffuse ISM. They account for the following constraints:
  — the IR-to-mm emission (Zubko et al. 2004; Draine & Li 2007);
  — the UV-to-near-IR extinction curve (Zubko et al. 2004; Draine & Li 2007);
  — the elemental depletions (Zubko et al. 2004);
  (— the X-ray scattering halos; Dwek et al. *in prep*).
  => abundance & size distribution of the various dust types.

Stochastic Heating: Temperature Fluctuations

Very small grains (radius < 0.01 μm) are out of equilibrium with the radiation field.

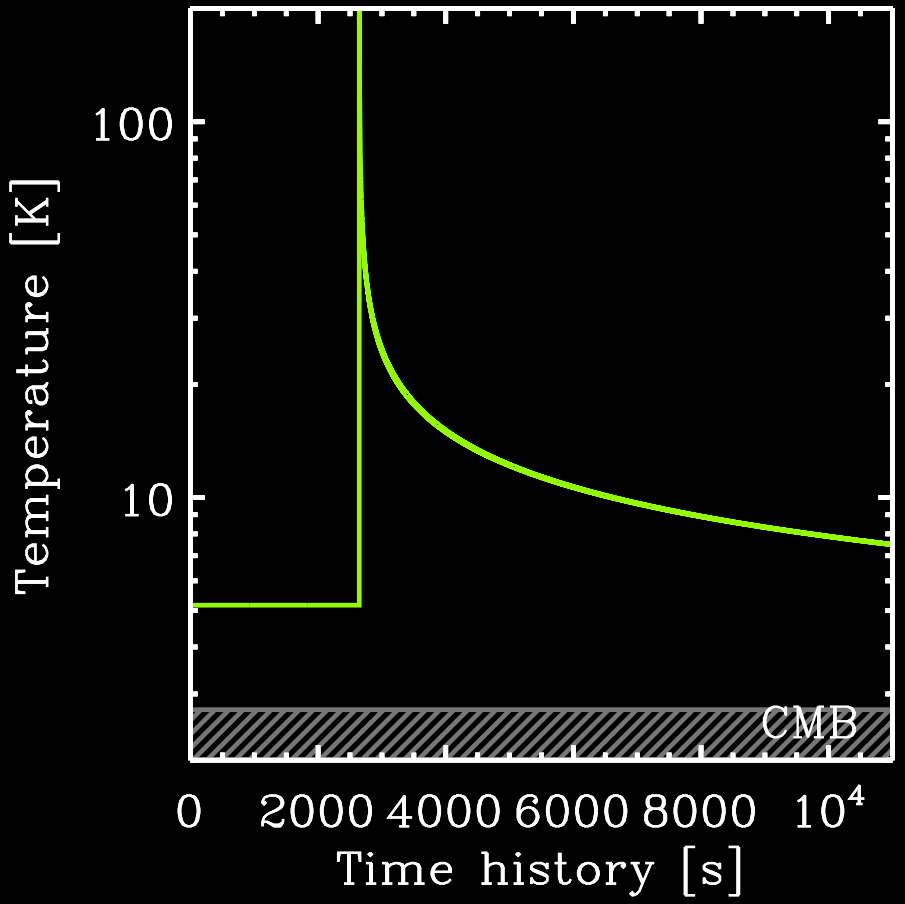
Stochastic Heating: Temperature Fluctuations

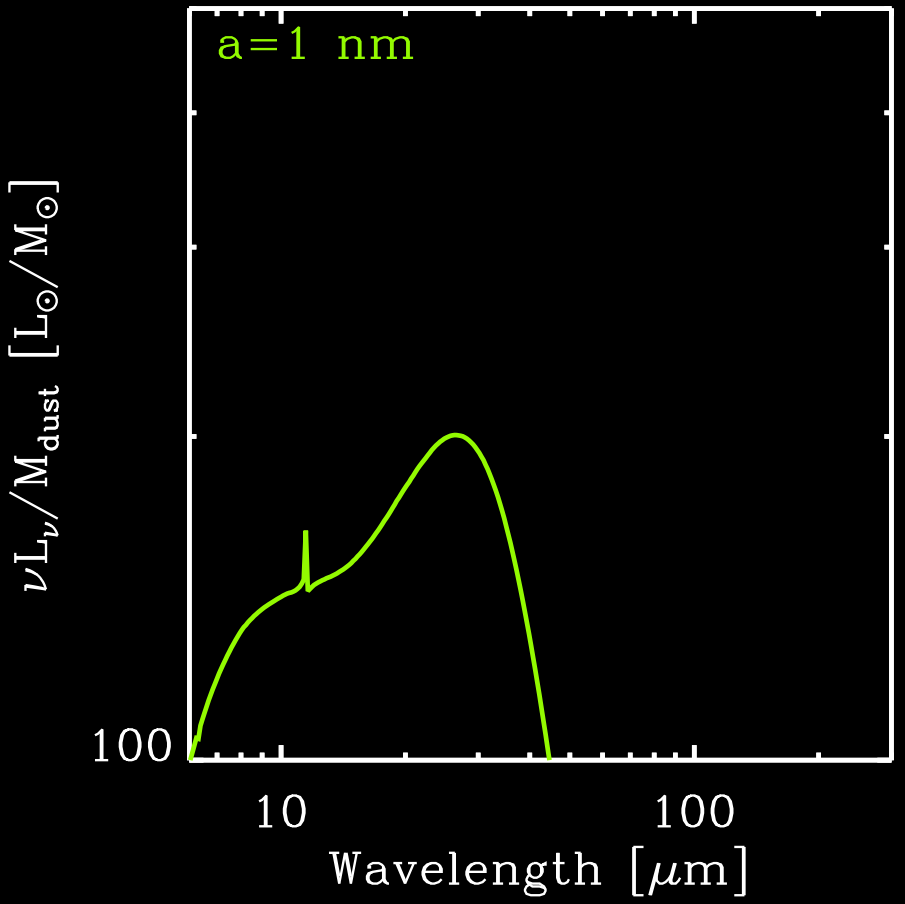
Very small grains (radius < 0.01 μm) are out of equilibrium with the radiation field.



Stochastic Heating: Temperature Fluctuations

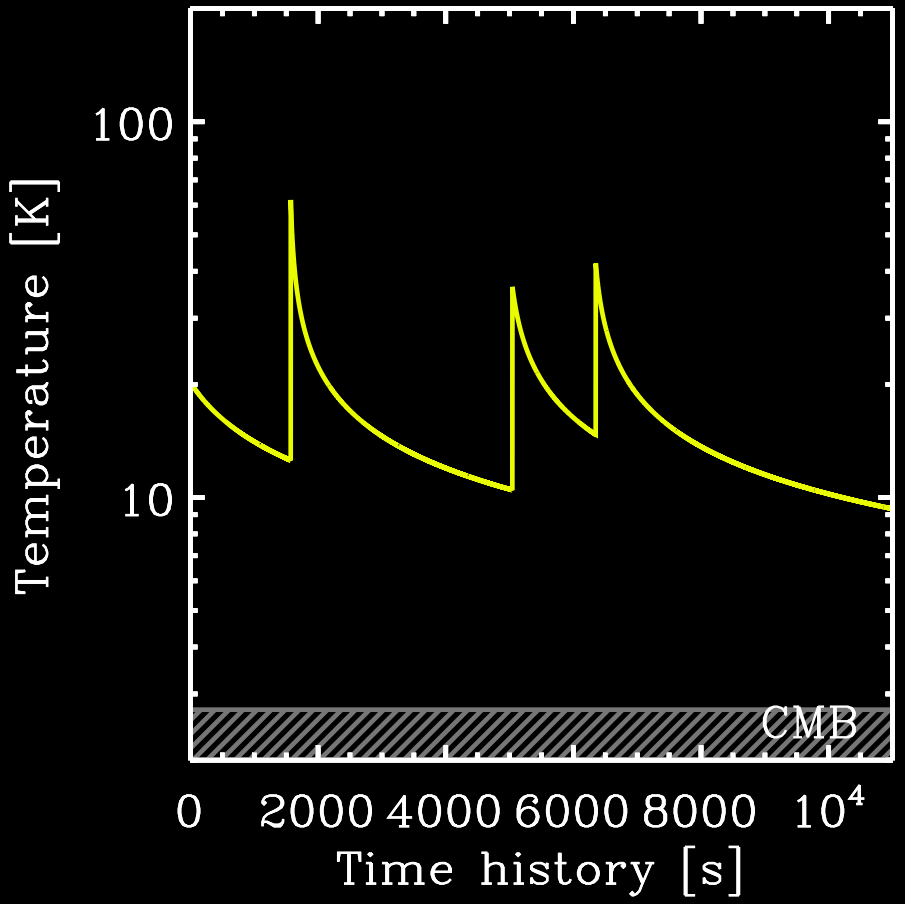
Very small grains (radius < 0.01 μm) are out of equilibrium with the radiation field.

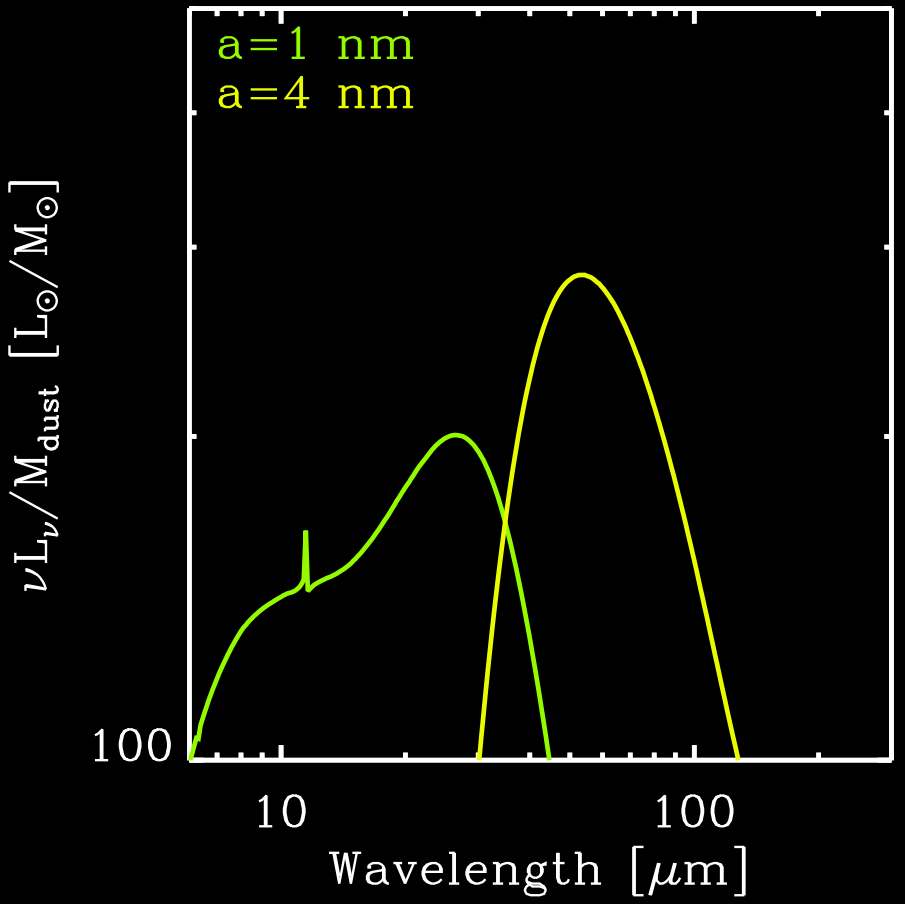




Stochastic Heating: Temperature Fluctuations

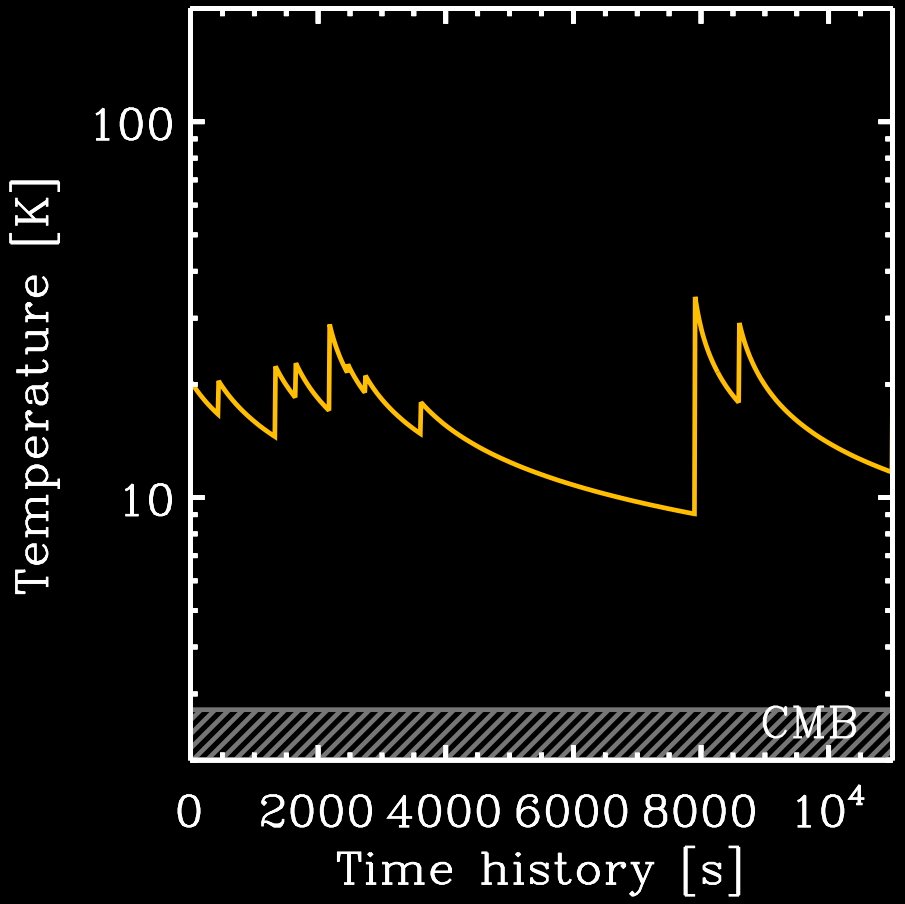
Very small grains (radius < 0.01 μm) are out of equilibrium with the radiation field.

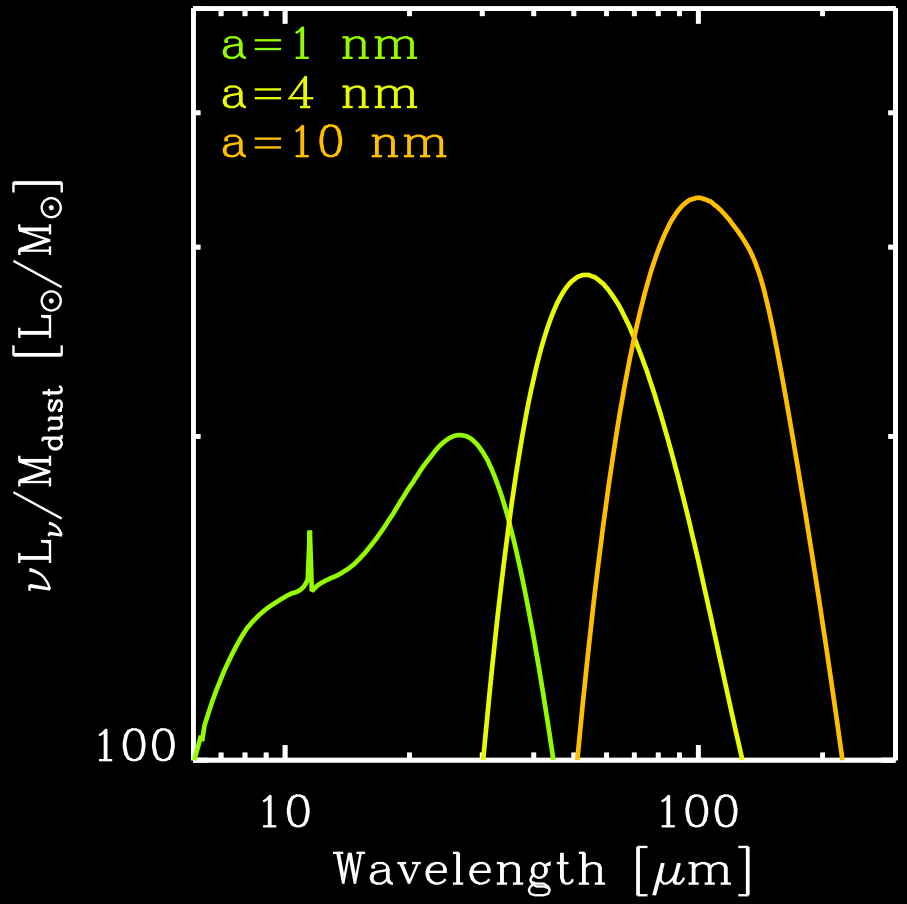




Stochastic Heating: Temperature Fluctuations

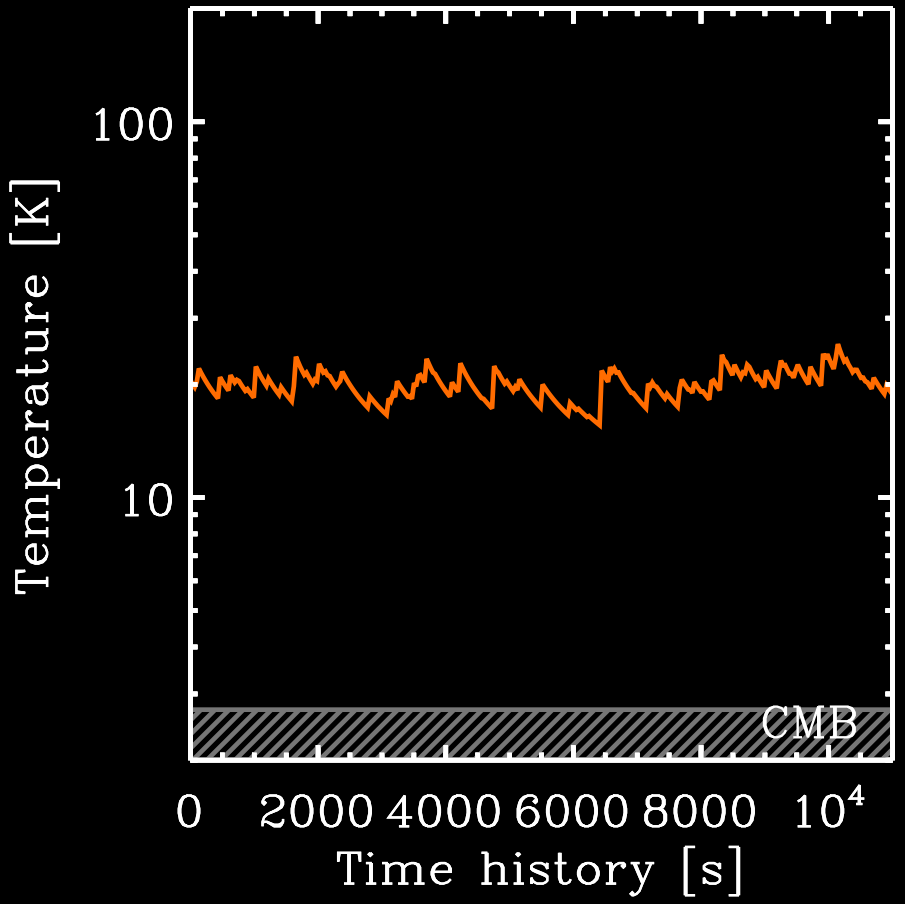
Very small grains (radius < 0.01 μm) are out of equilibrium with the radiation field.

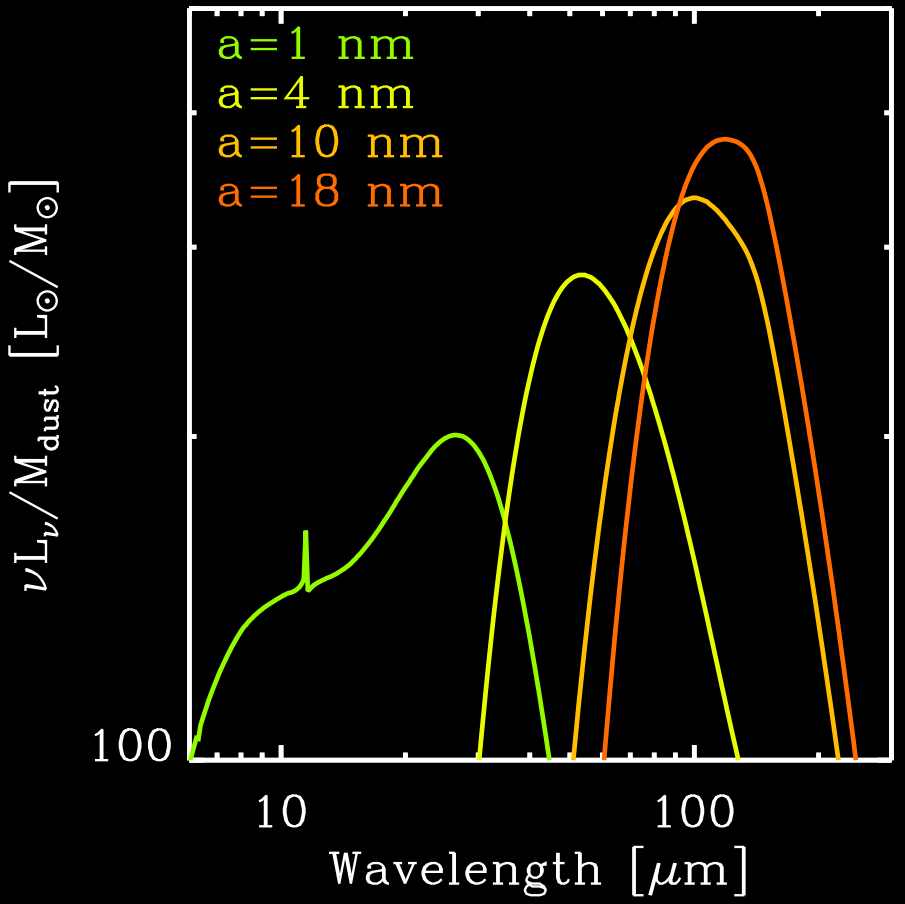




Stochastic Heating: Temperature Fluctuations

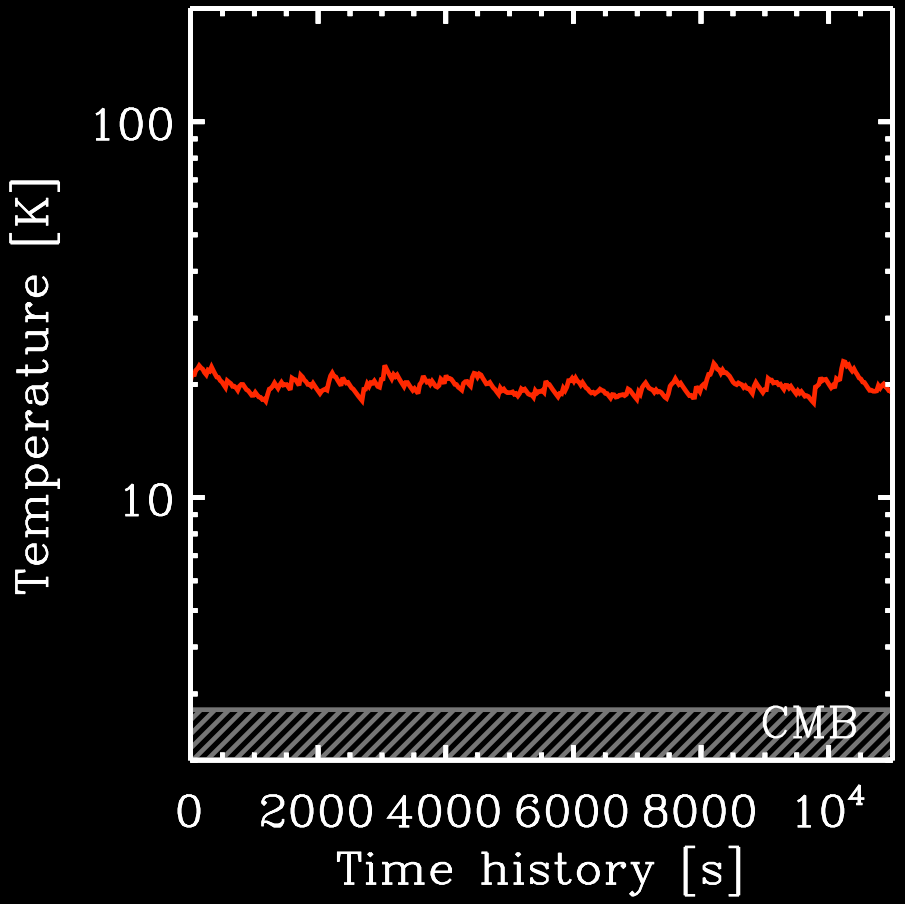
Very small grains (radius < 0.01 μm) are out of equilibrium with the radiation field.

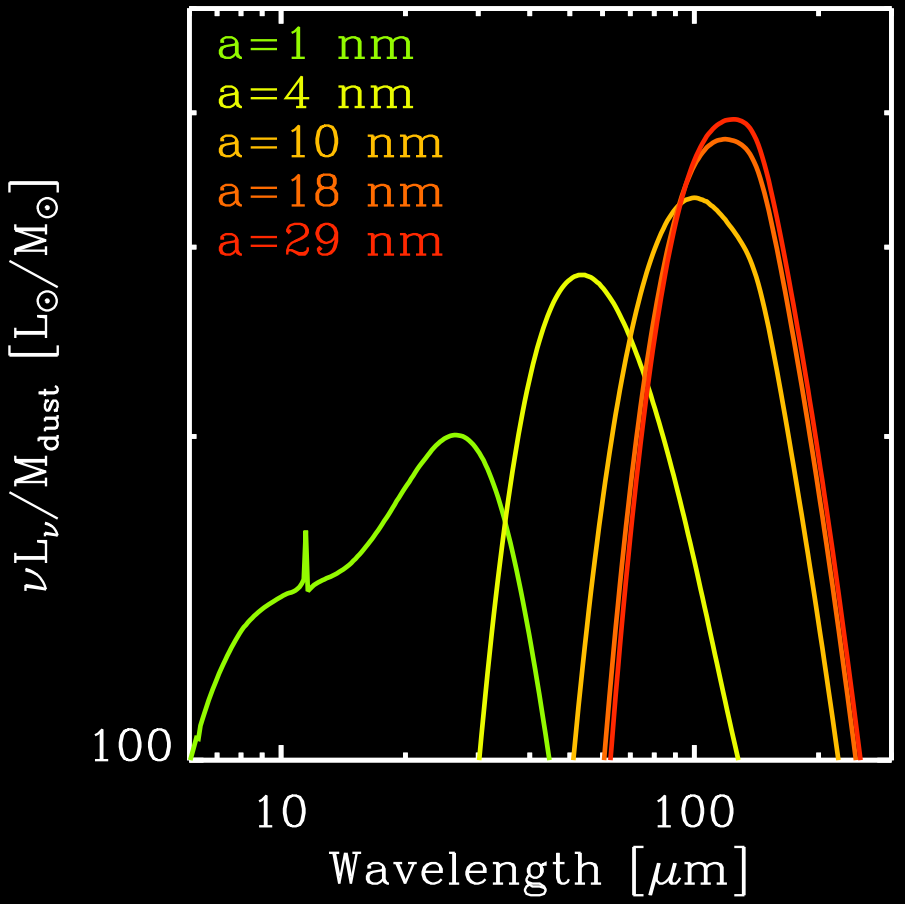




Stochastic Heating: Temperature Fluctuations

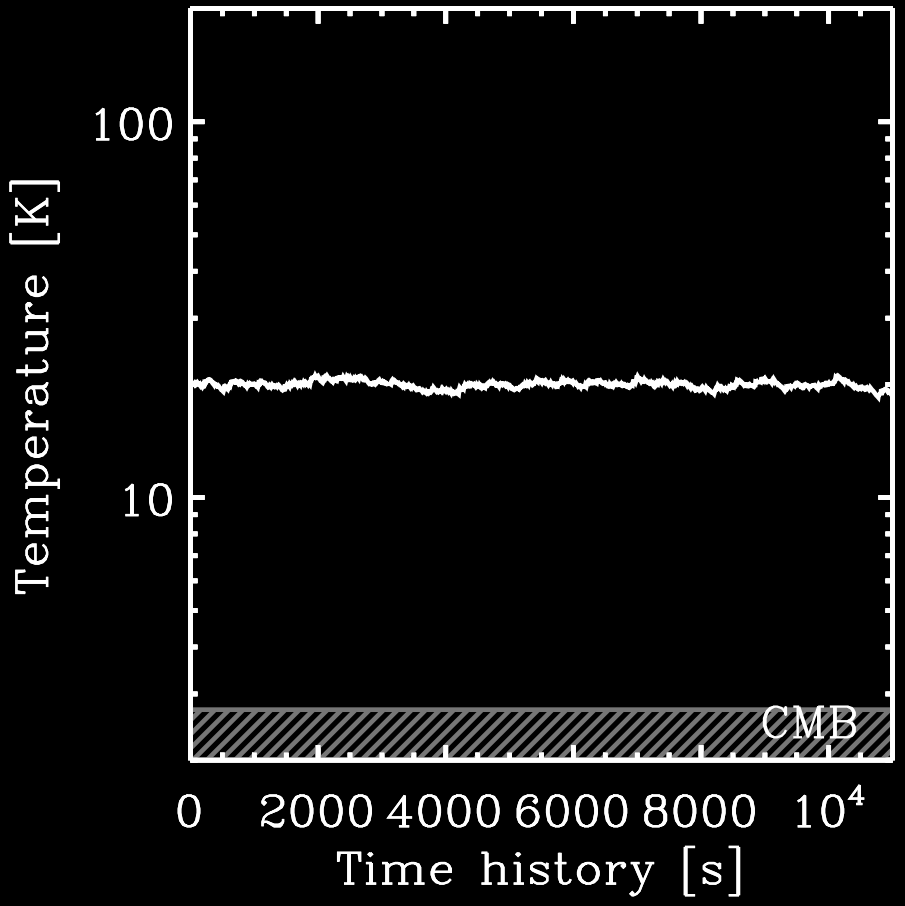
Very small grains (radius < 0.01 μm) are out of equilibrium with the radiation field.

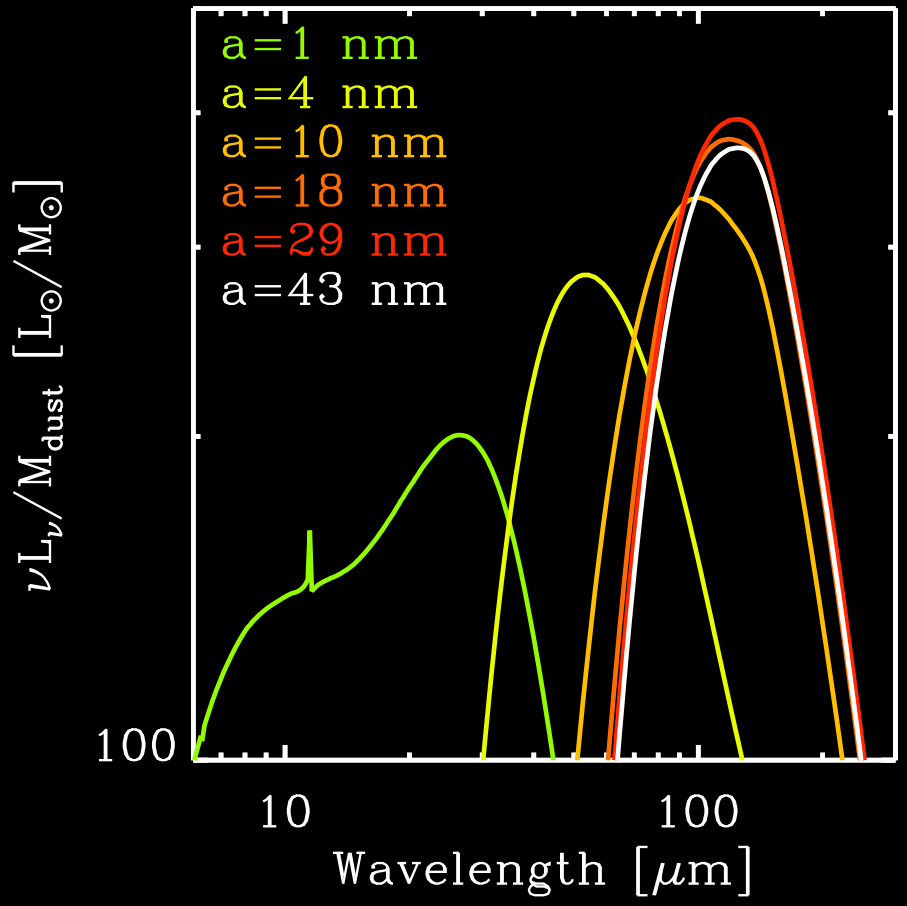




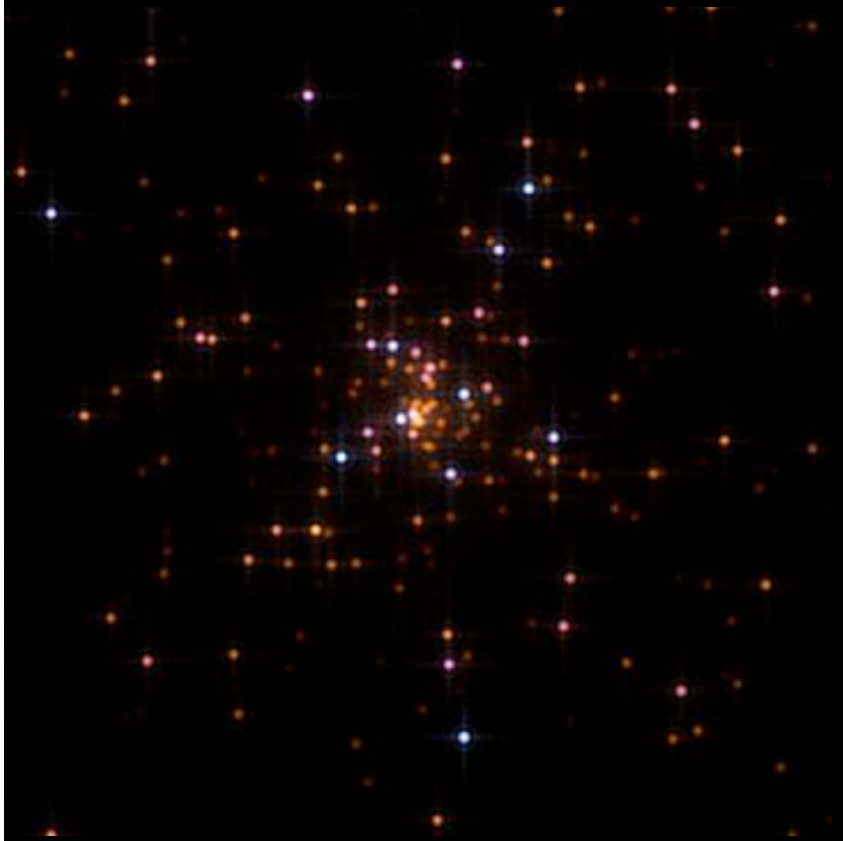
Stochastic Heating: Temperature Fluctuations

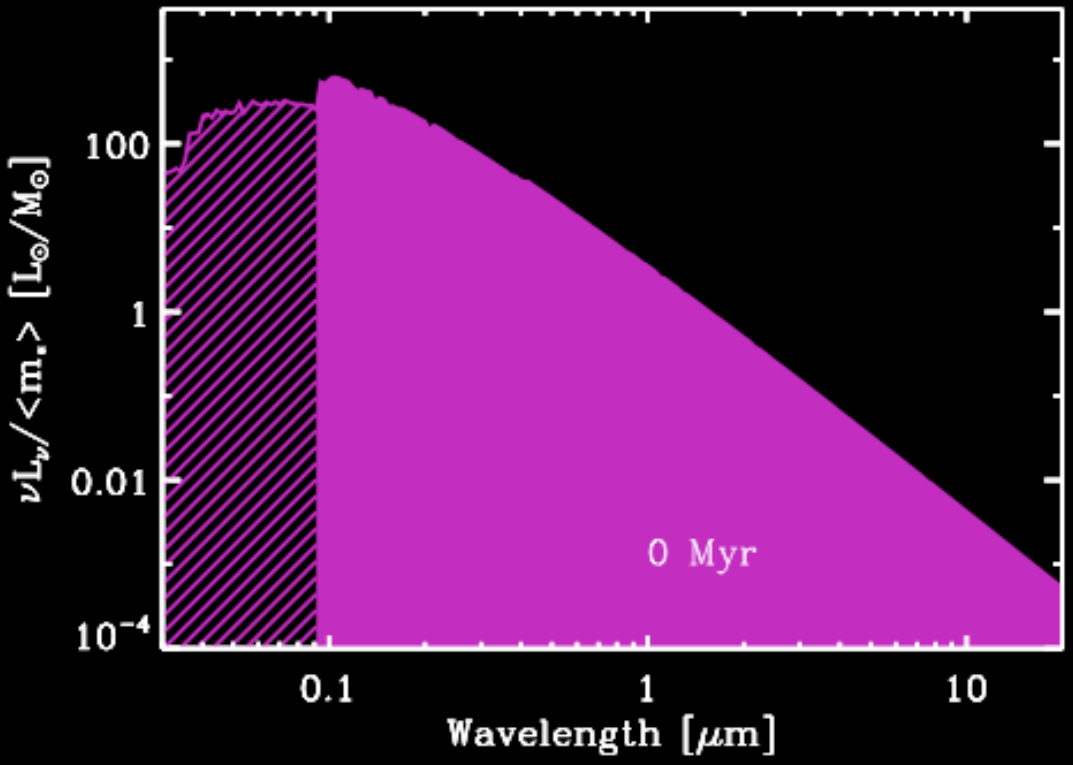
Very small grains (radius < 0.01 μm) are out of equilibrium with the radiation field.



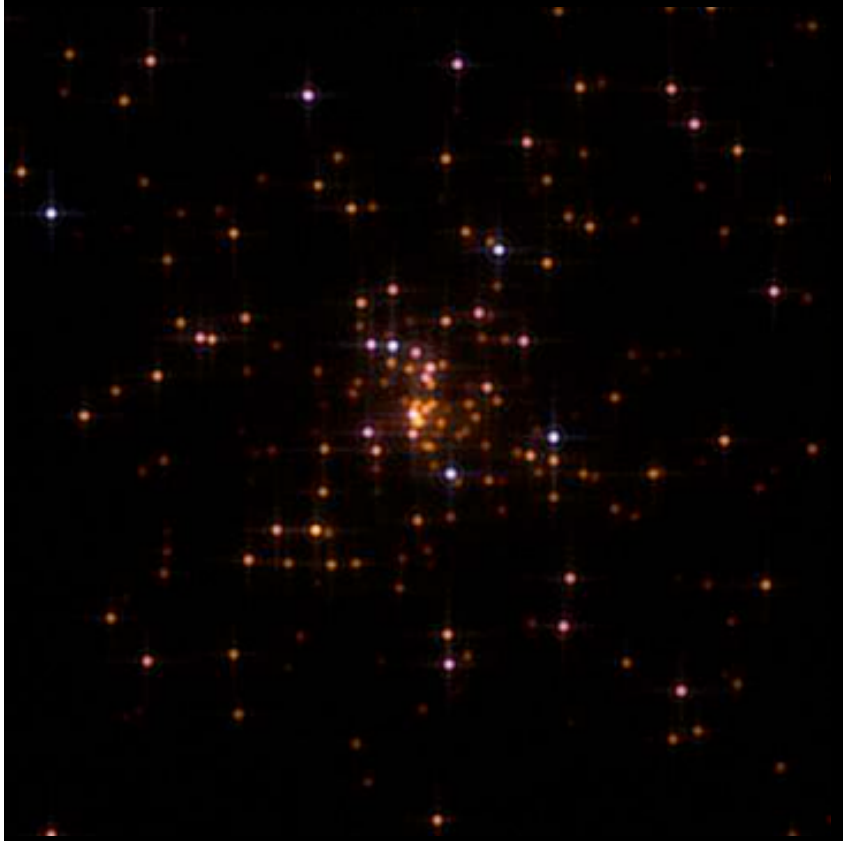


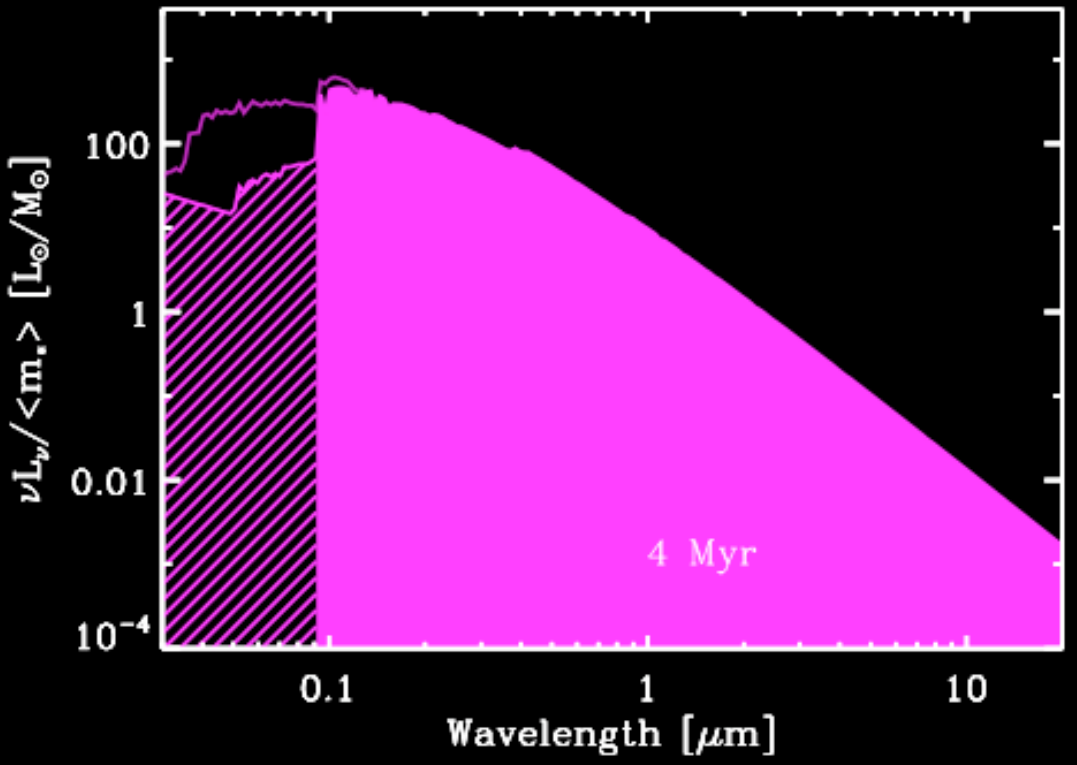
Stellar Evolutionary Synthesis



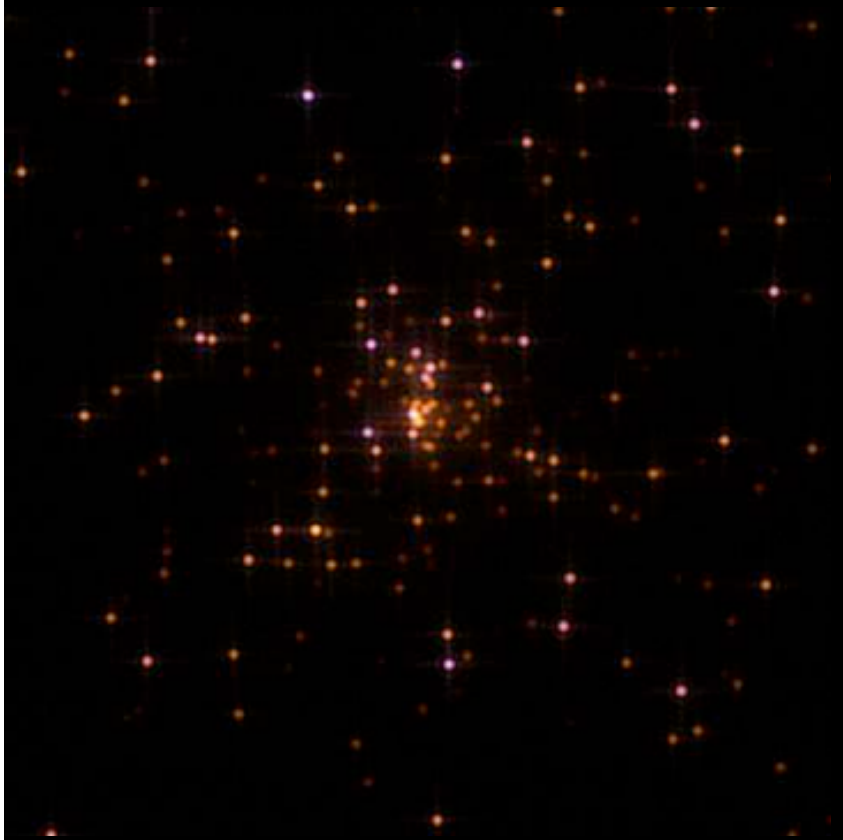


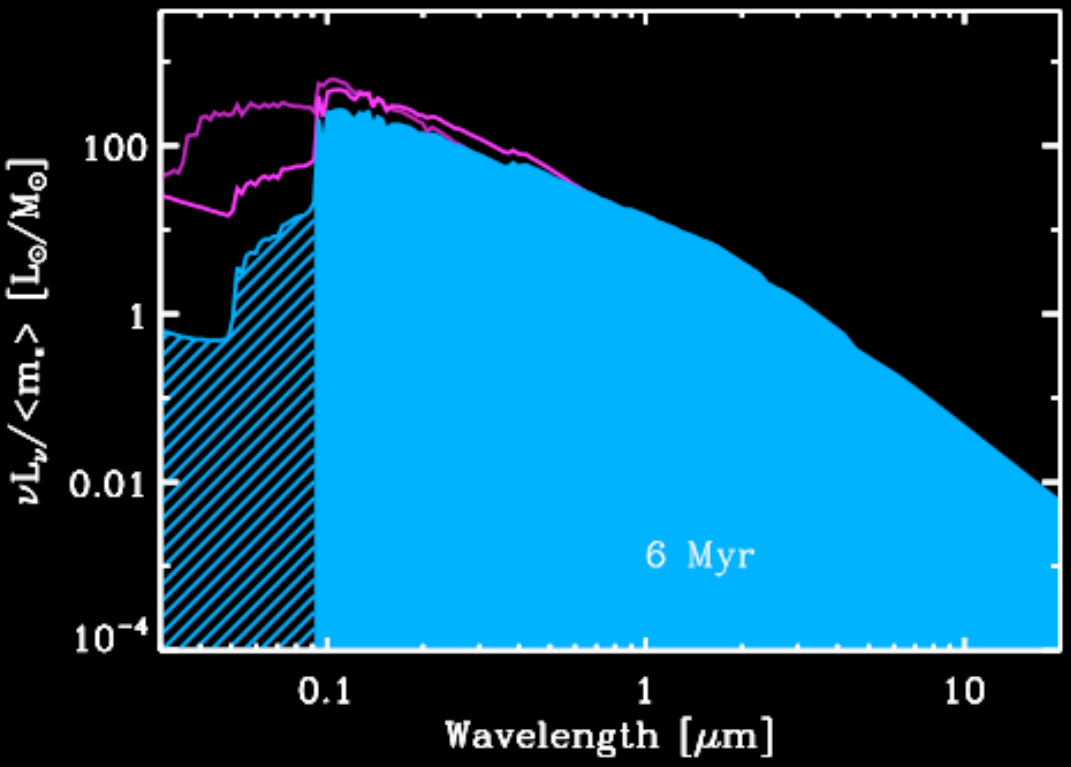
Stellar Evolutionary Synthesis



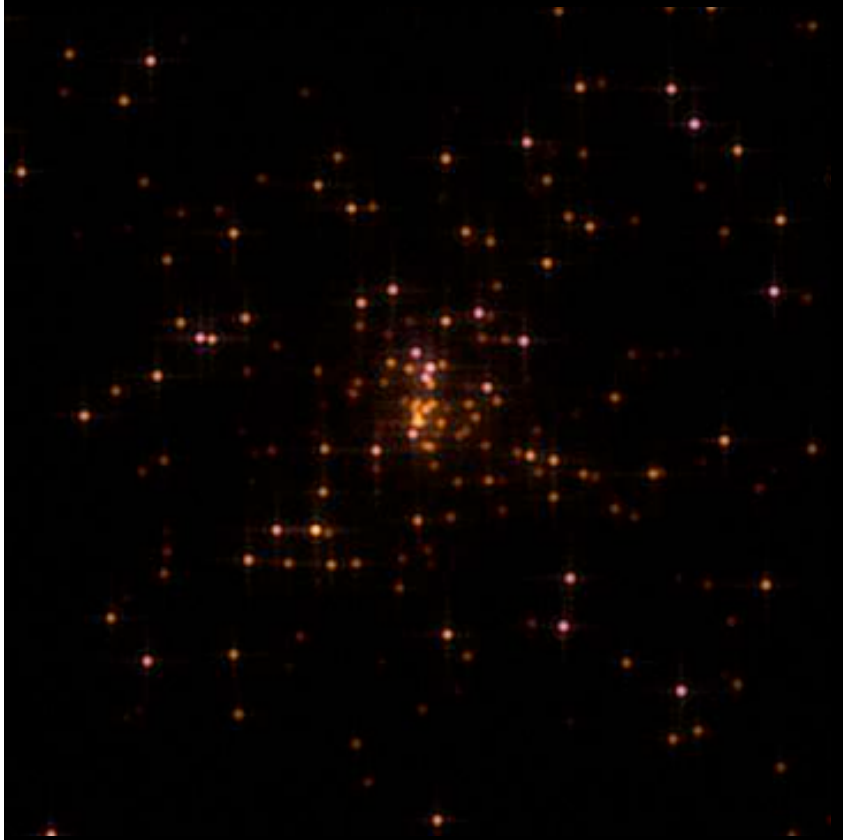


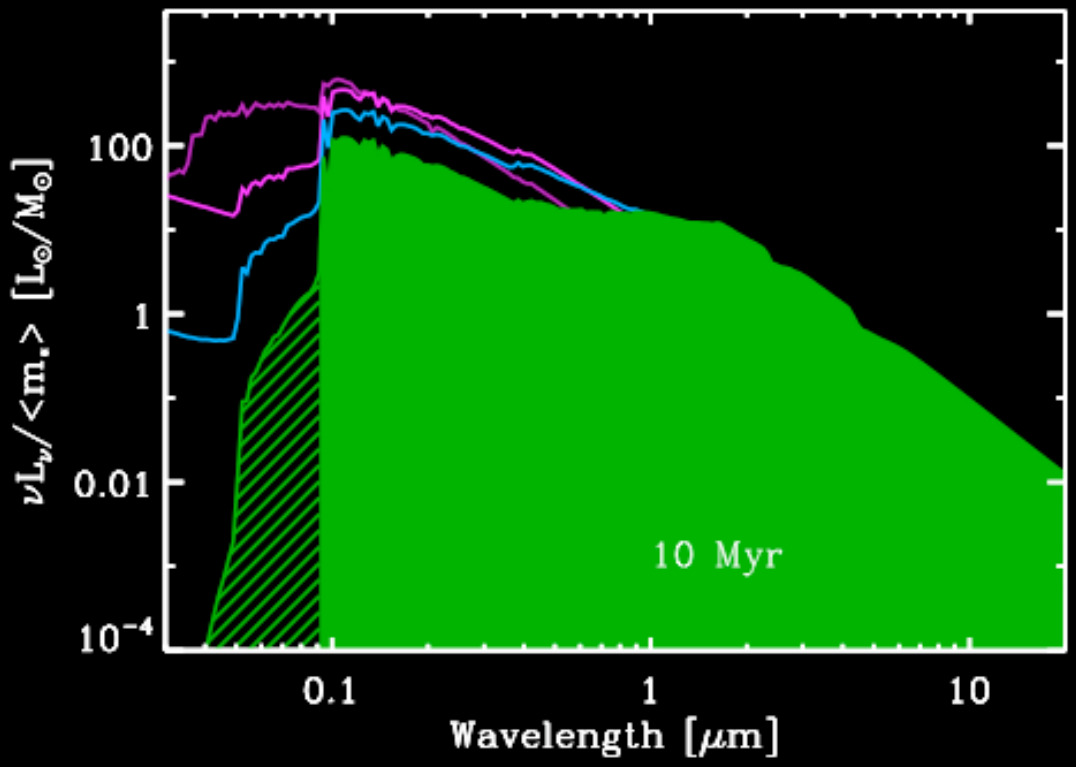
Stellar Evolutionary Synthesis



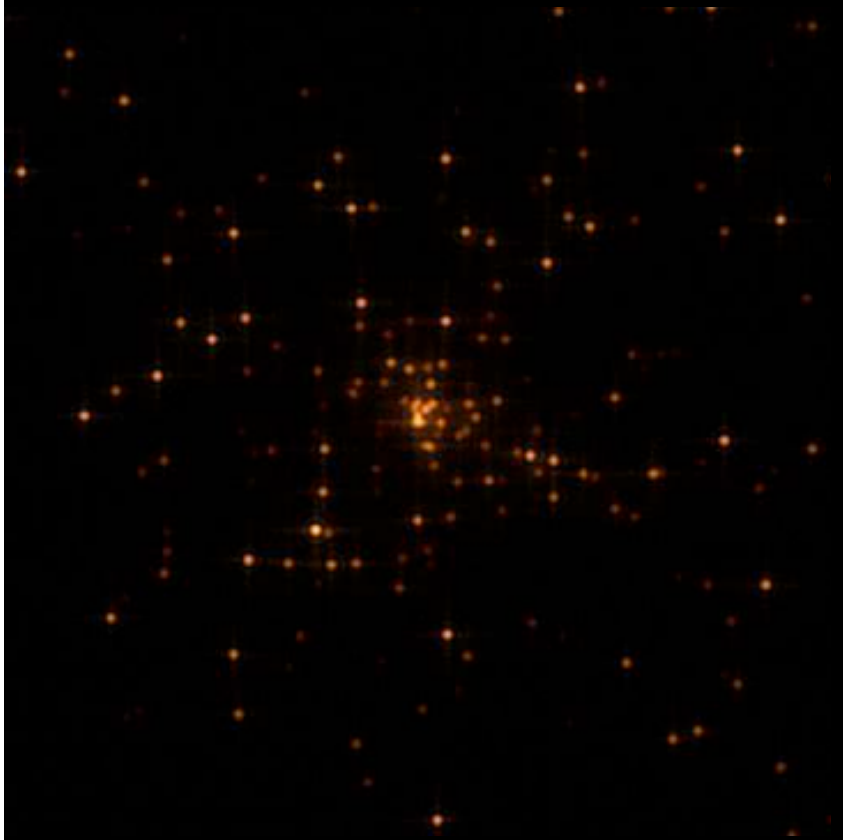


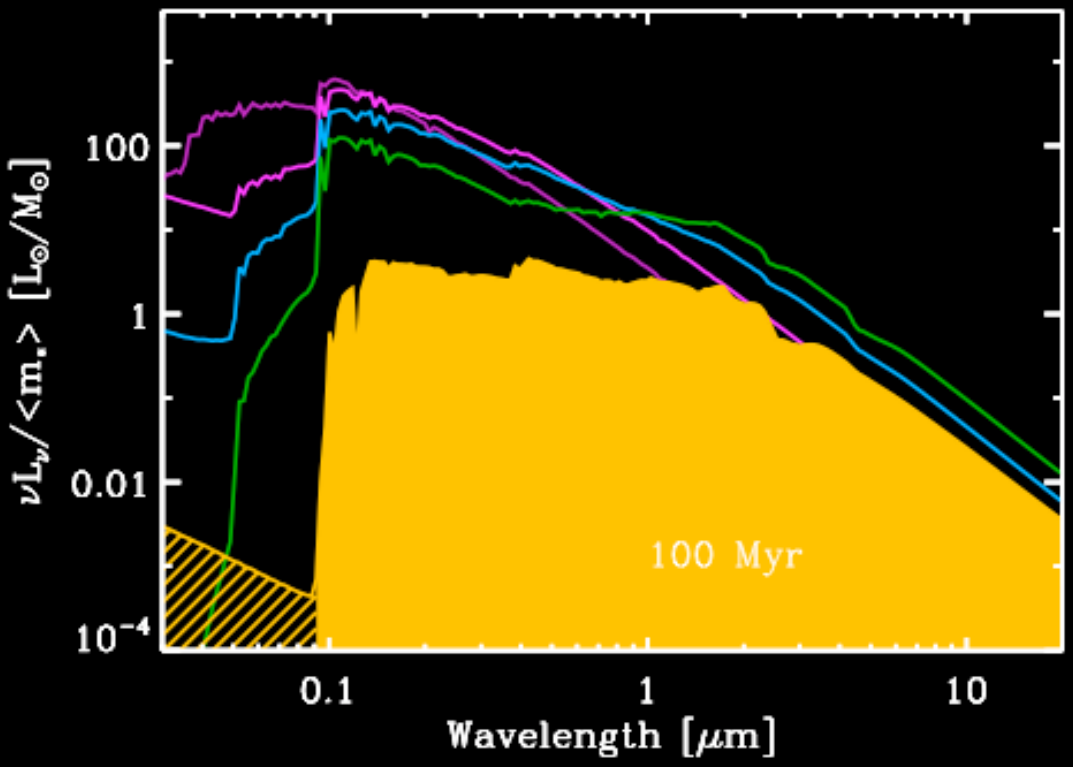
Stellar Evolutionary Synthesis



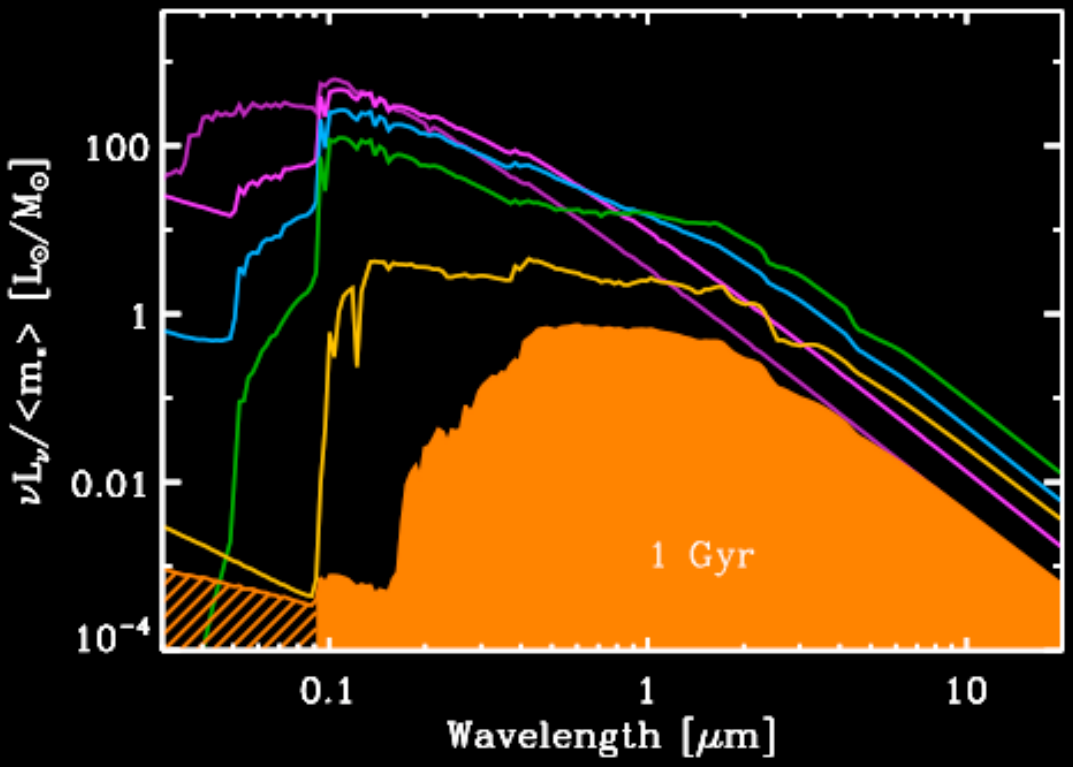


Stellar Evolutionary Synthesis

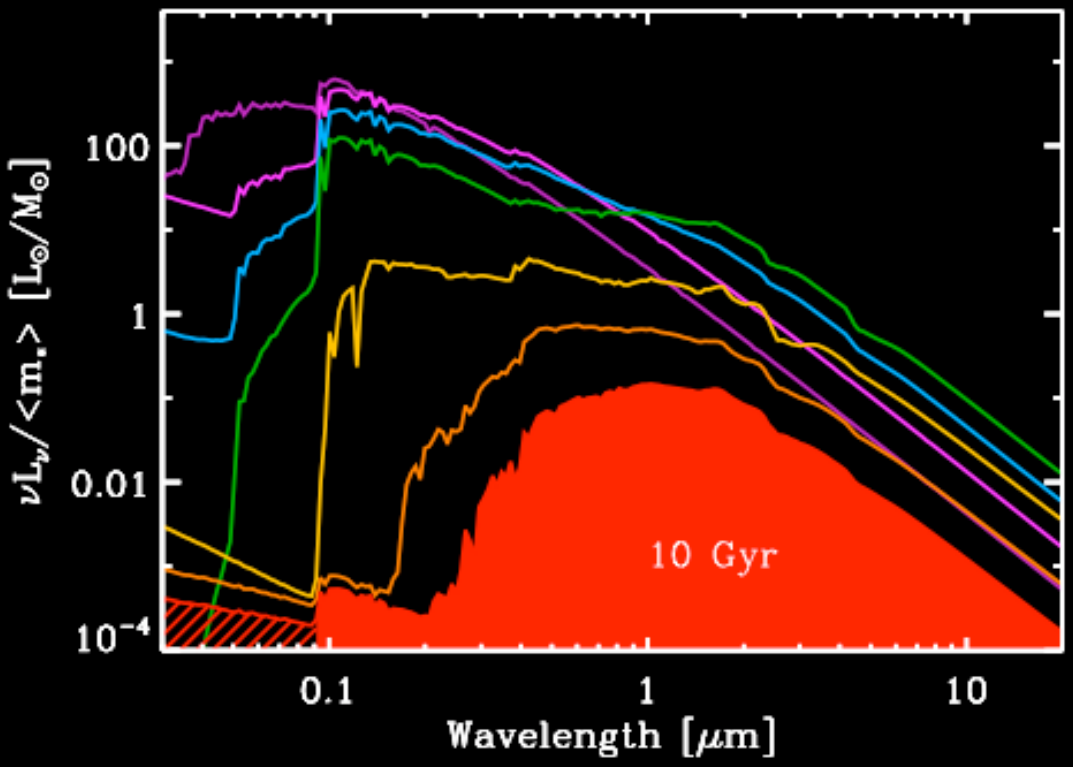




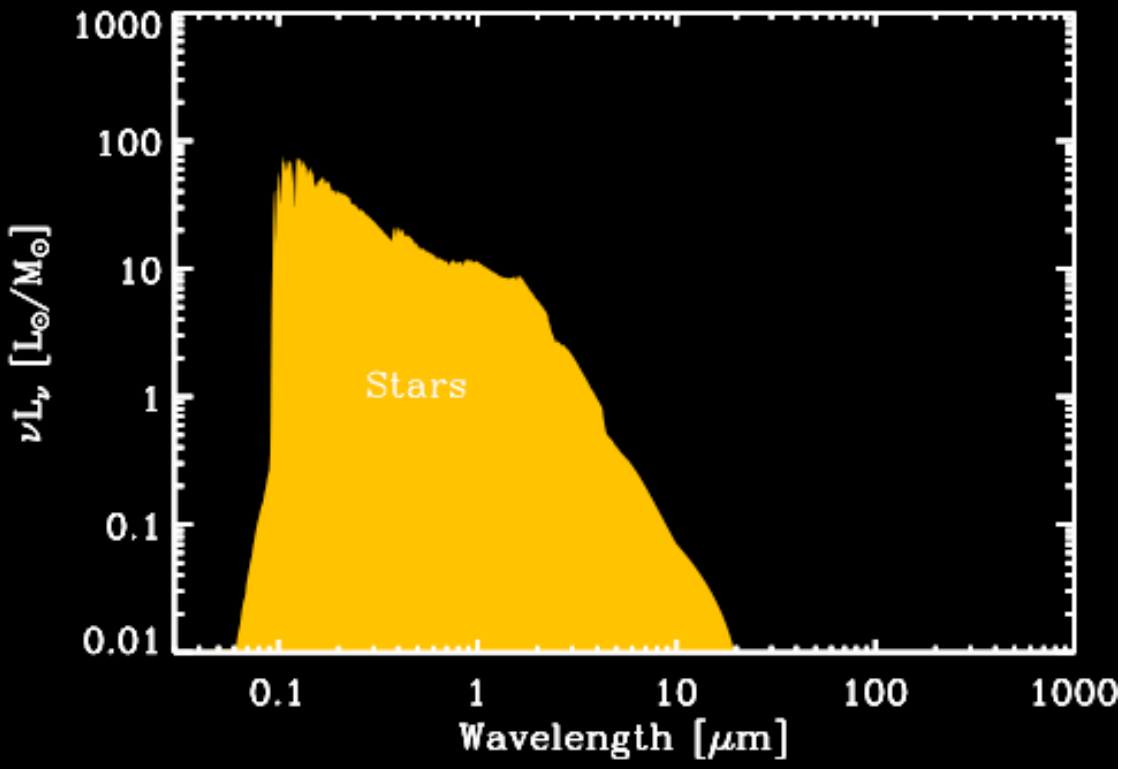
Stellar Evolutionary Synthesis



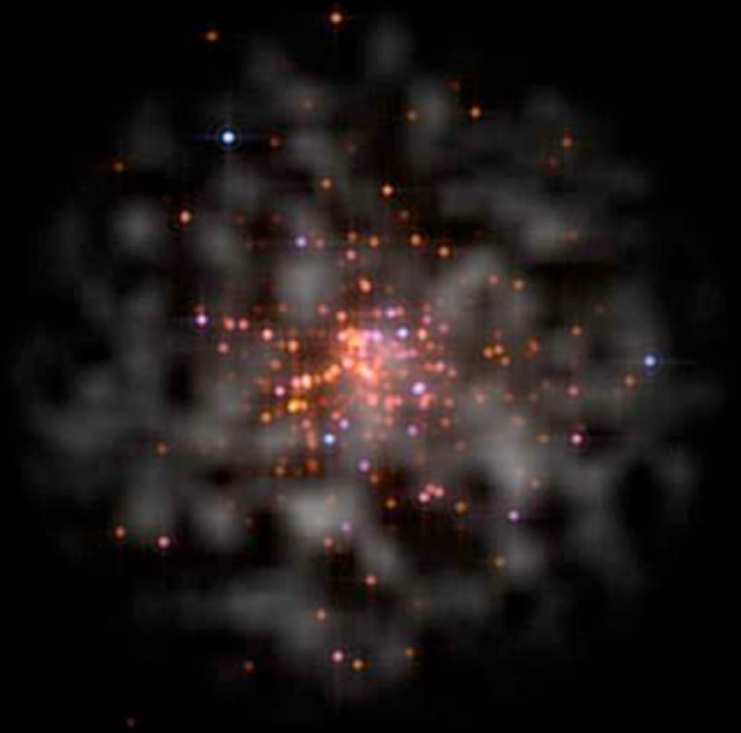
Stellar Evolutionary Synthesis

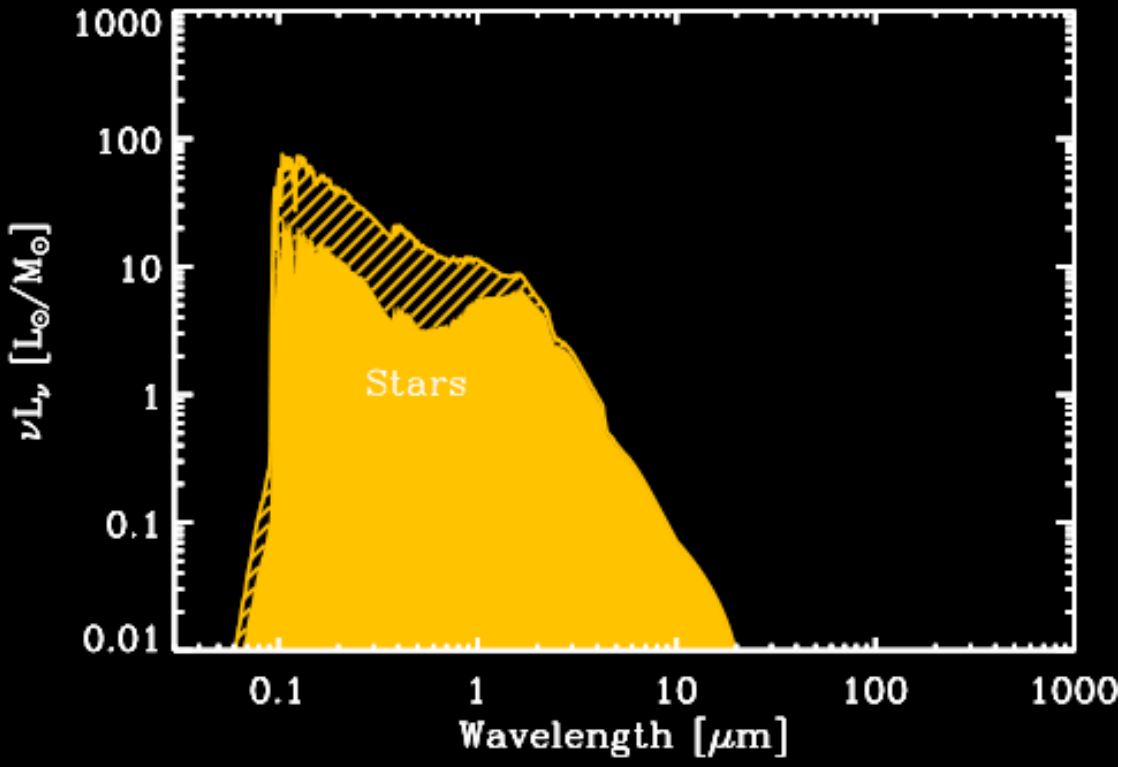


Dust Properties & Spectral Energy Distributions

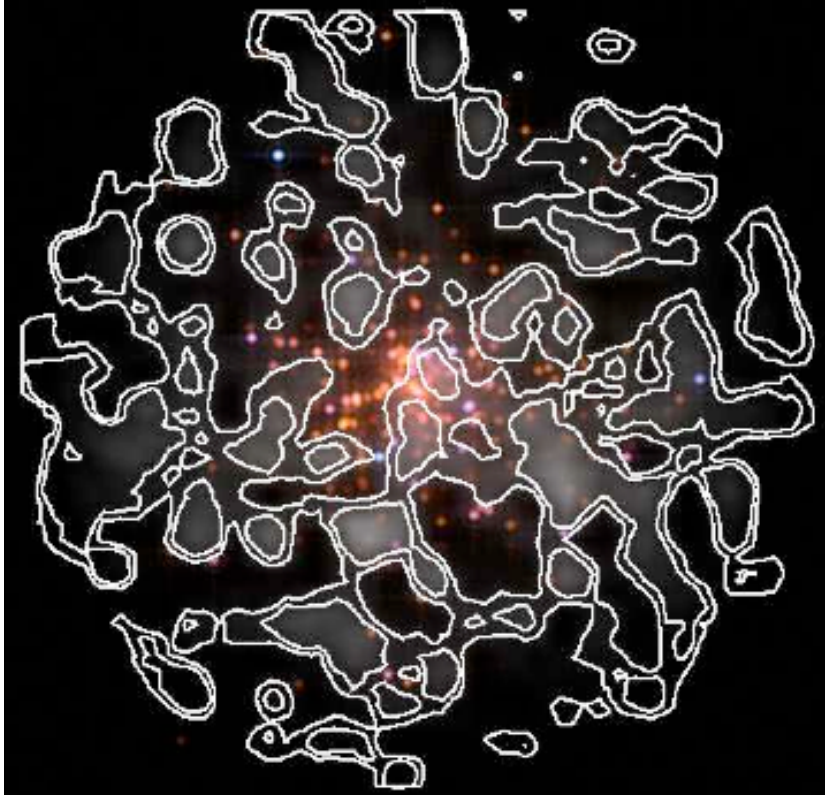


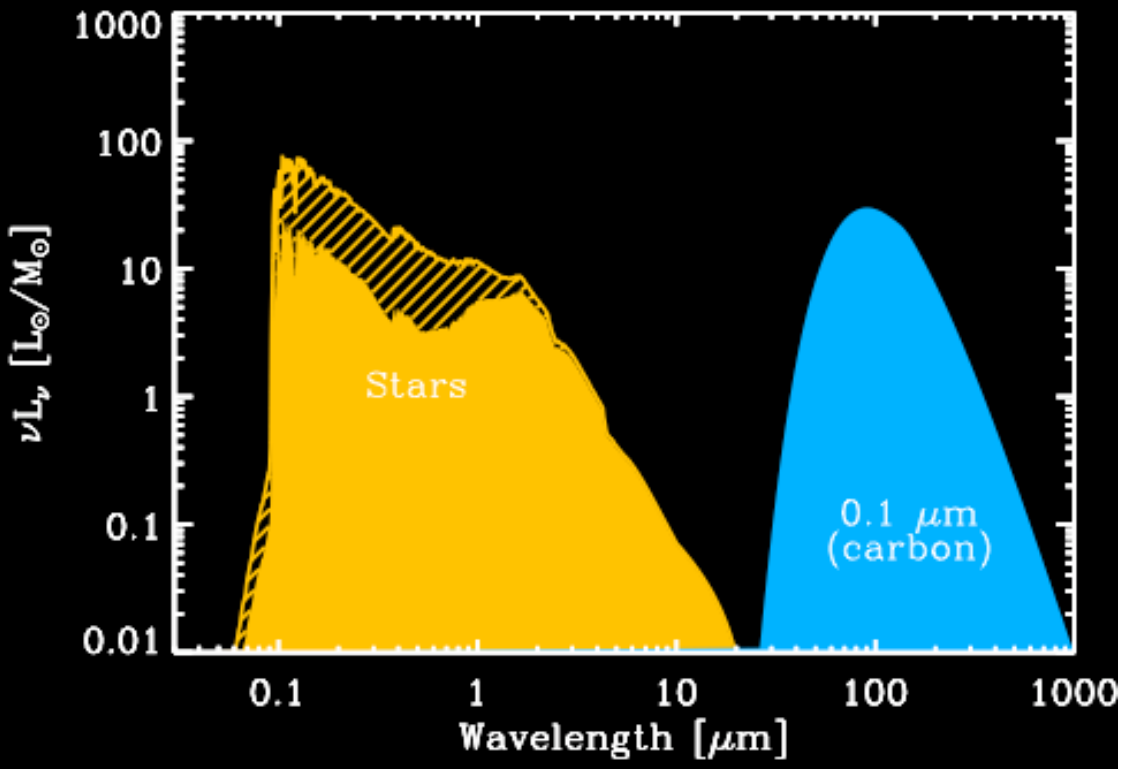
Dust Properties & Spectral Energy Distributions



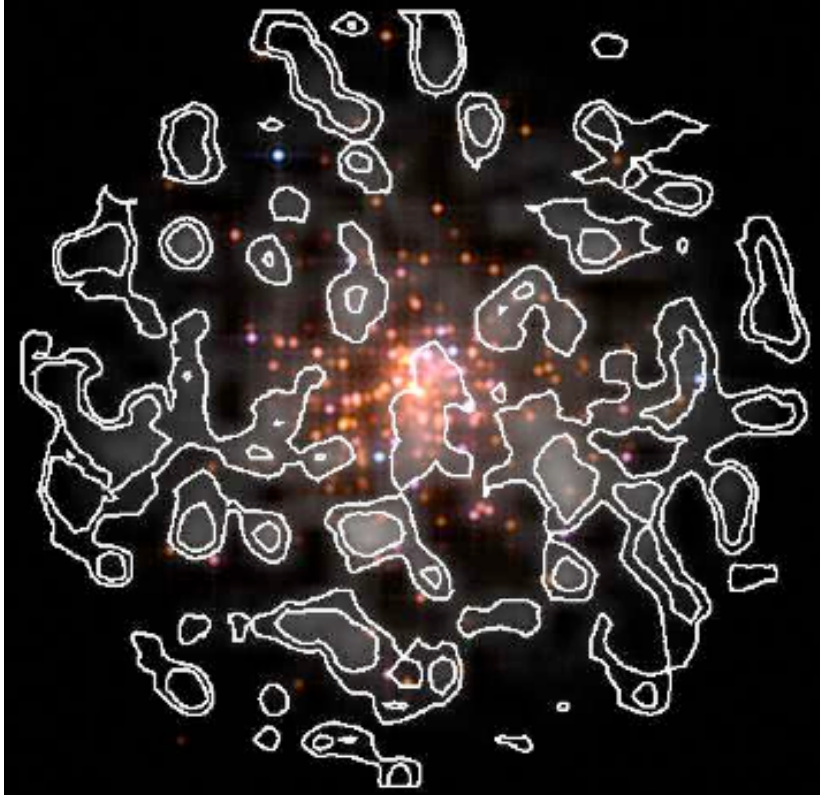


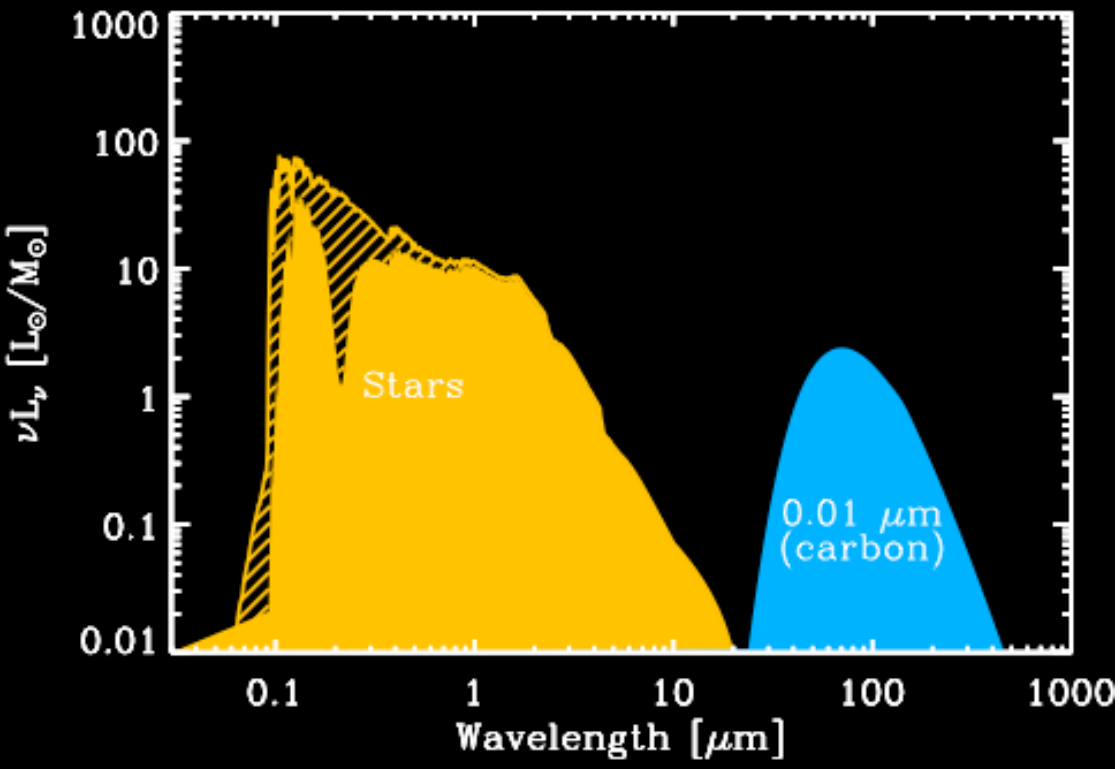
Dust Properties & Spectral Energy Distributions



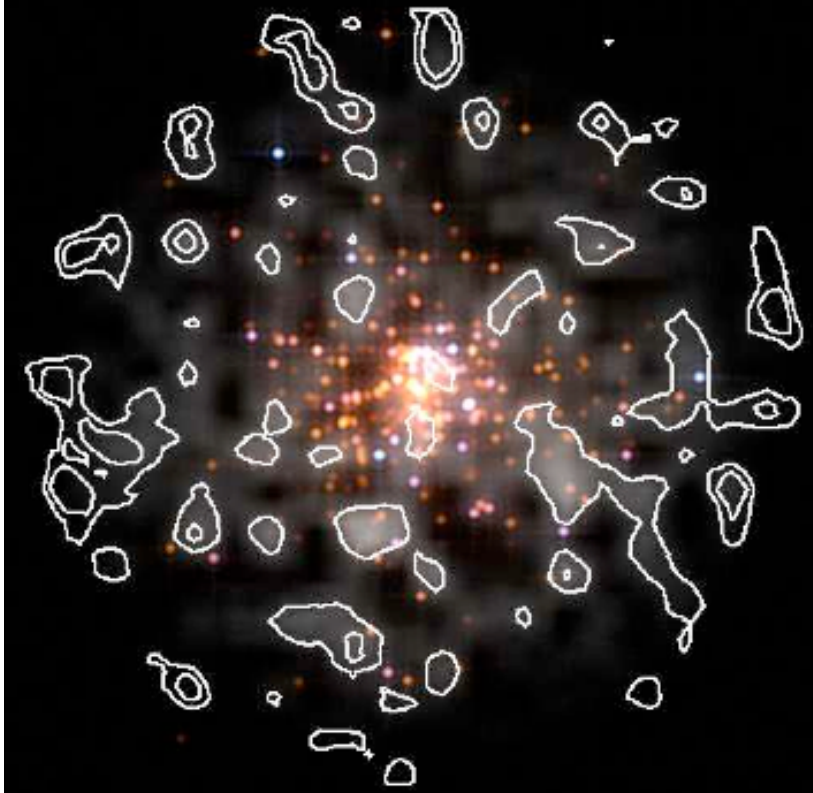


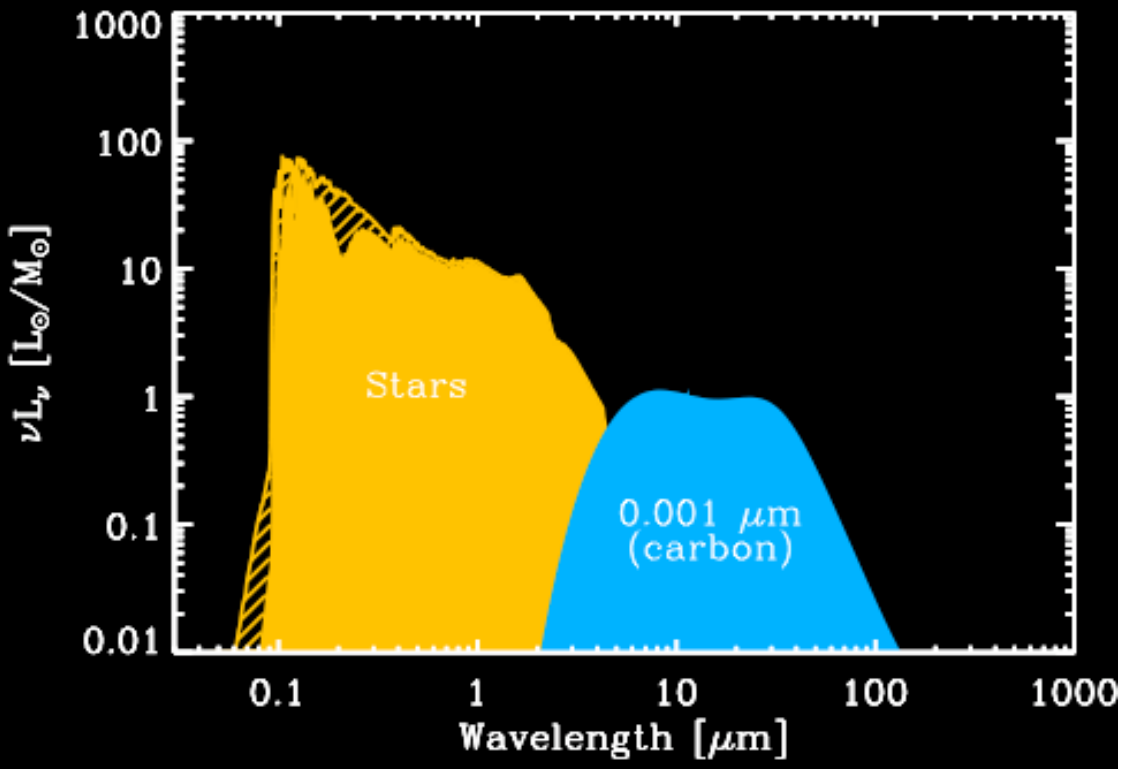
Dust Properties & Spectral Energy Distributions



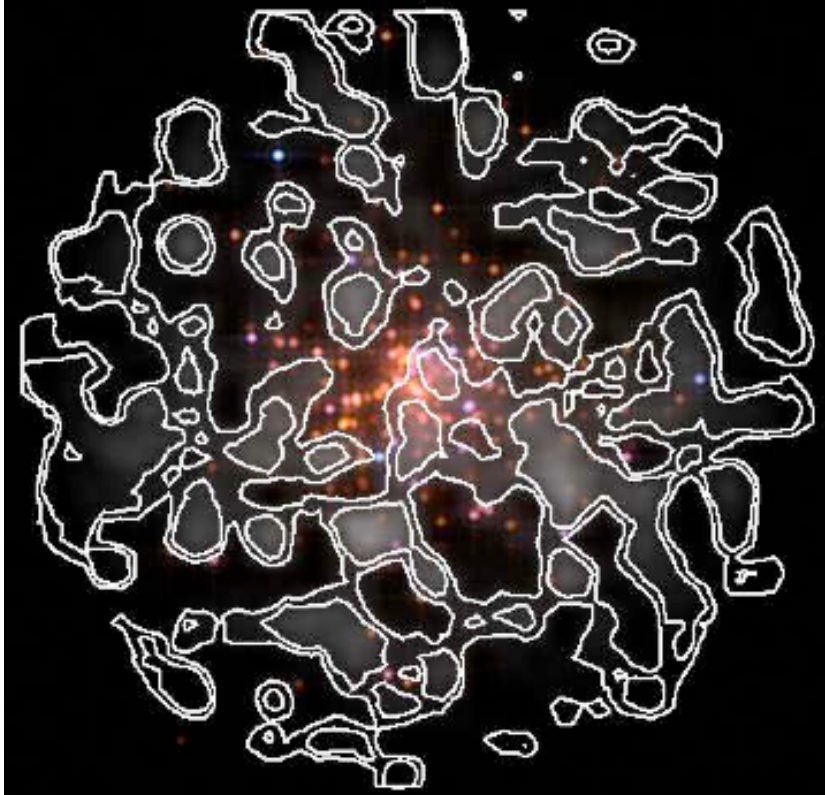


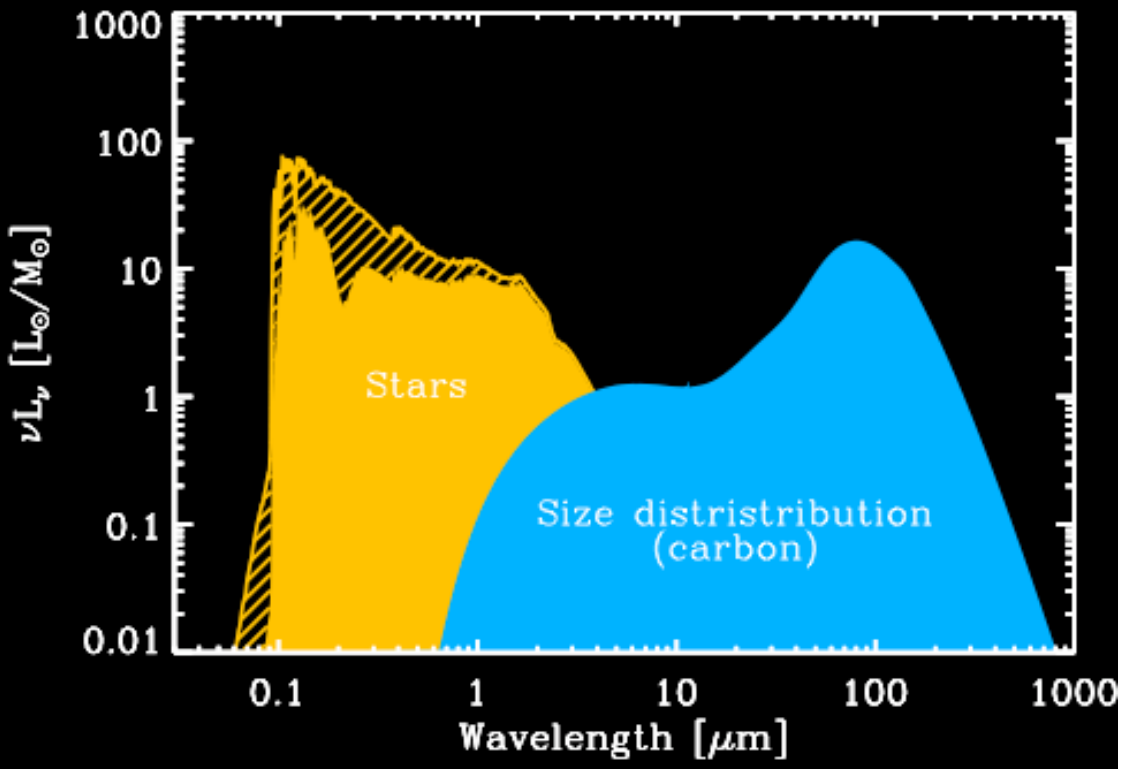
Dust Properties & Spectral Energy Distributions



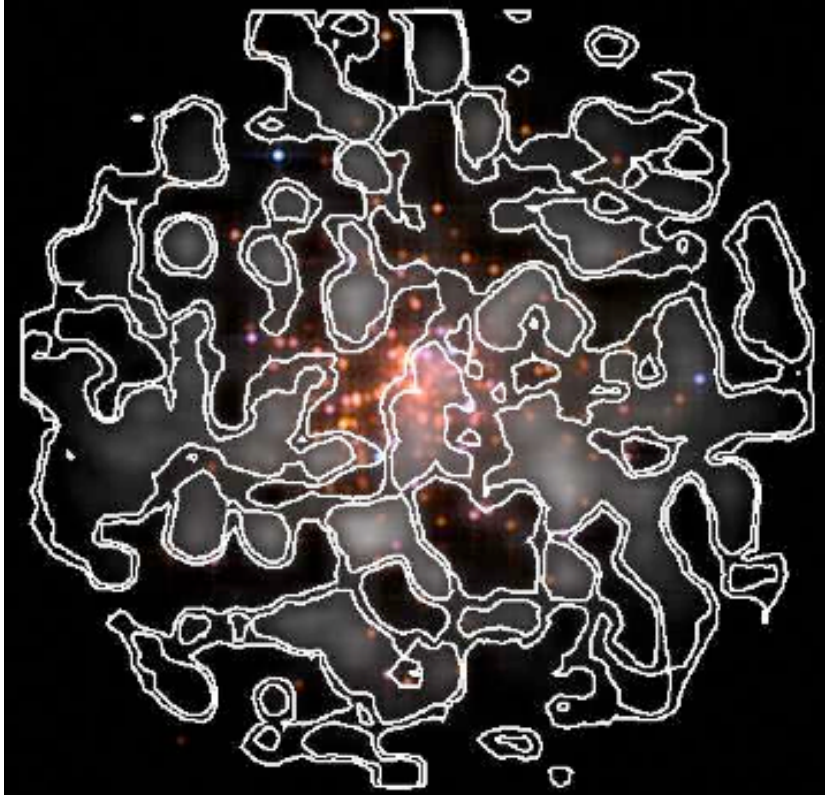


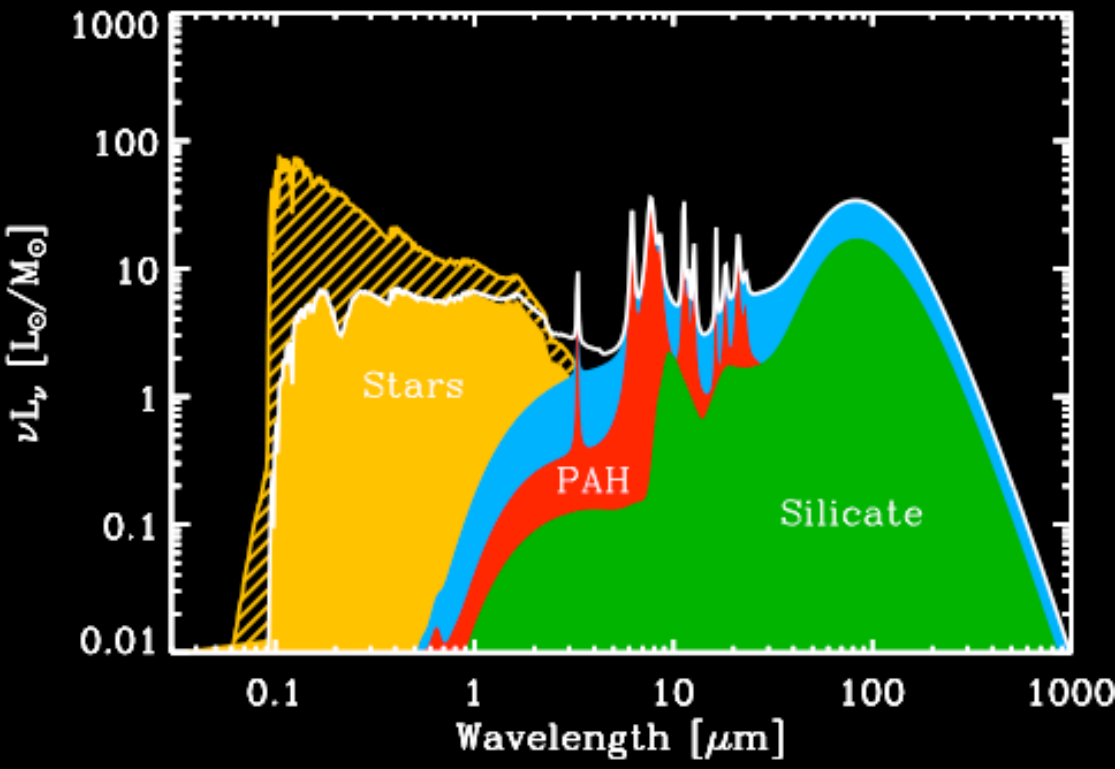
Dust Properties & Spectral Energy Distributions



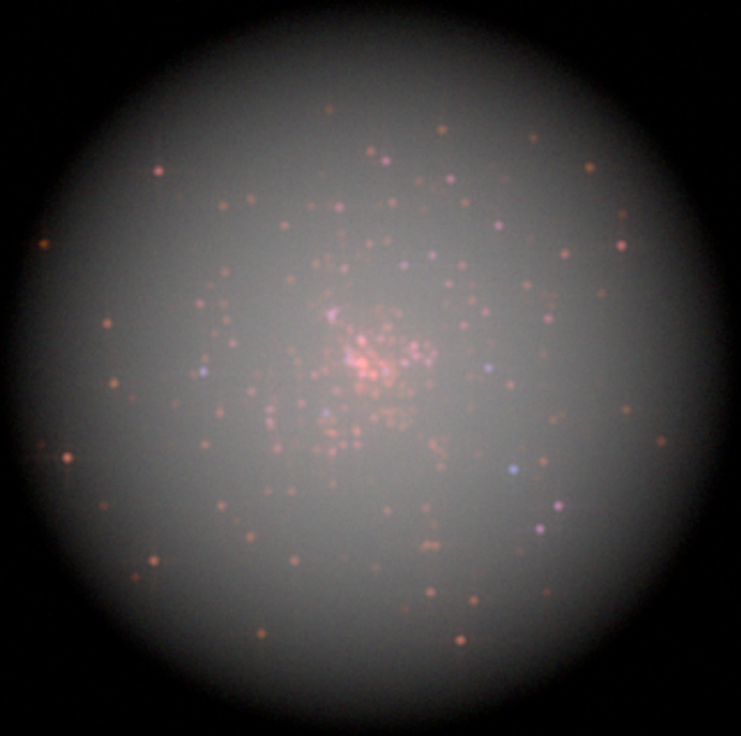


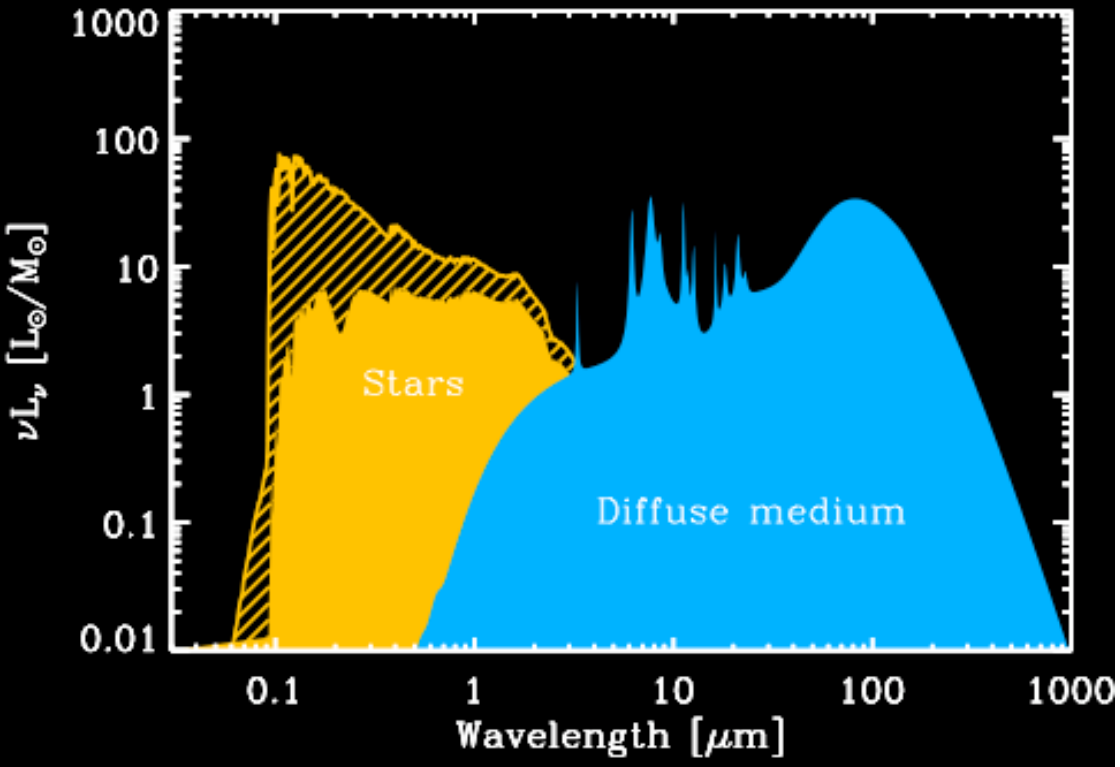
Dust Properties & Spectral Energy Distributions



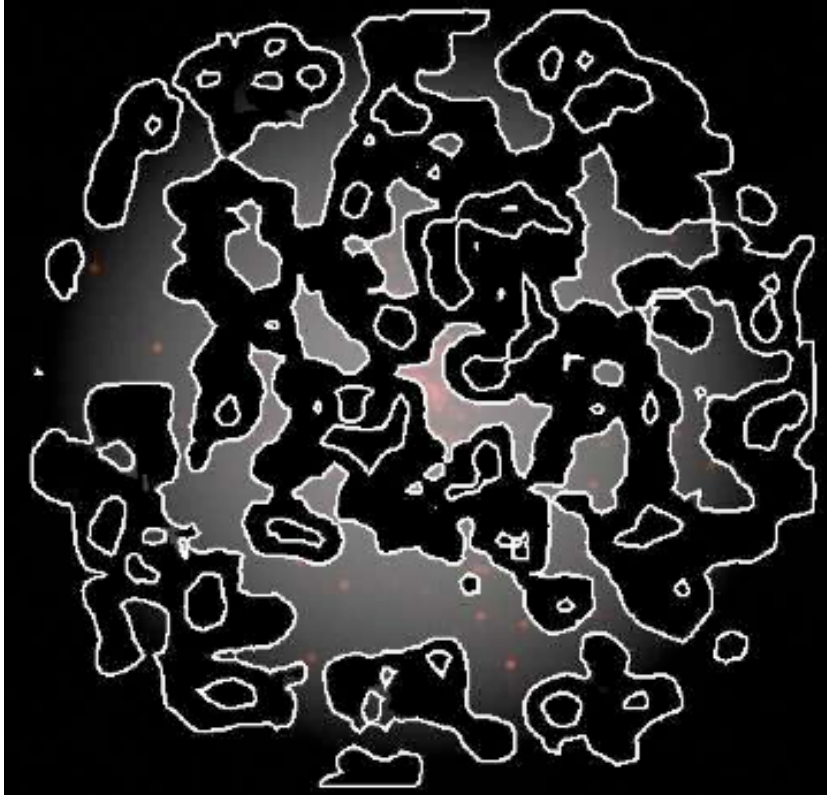


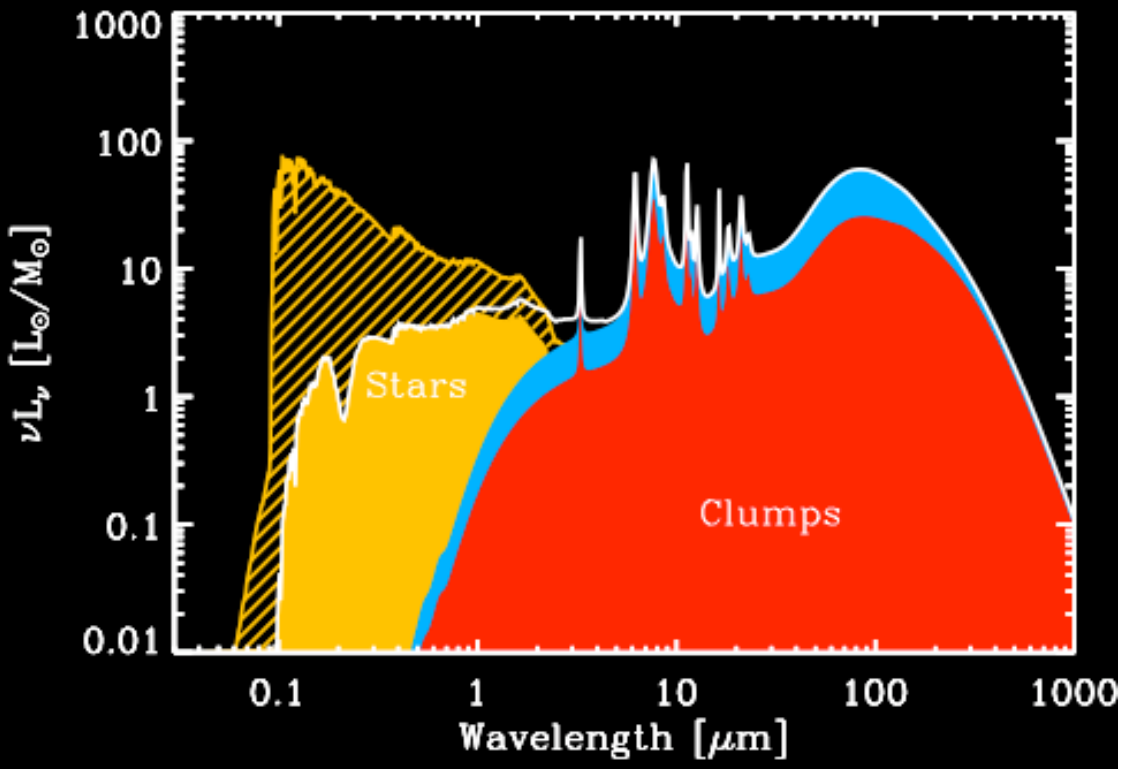
Effects of the Morphology of the ISM



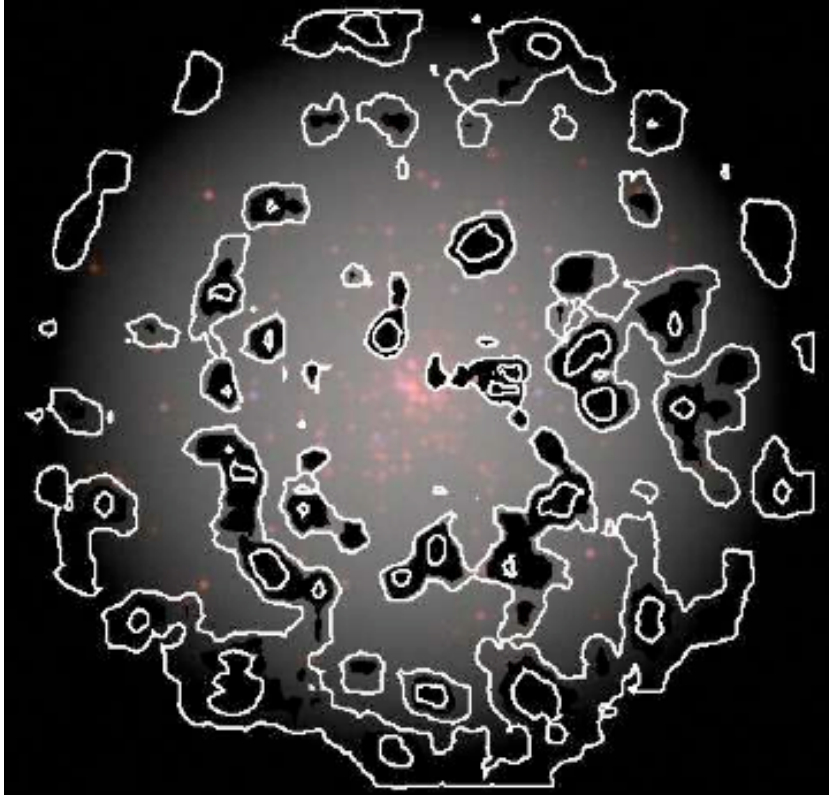


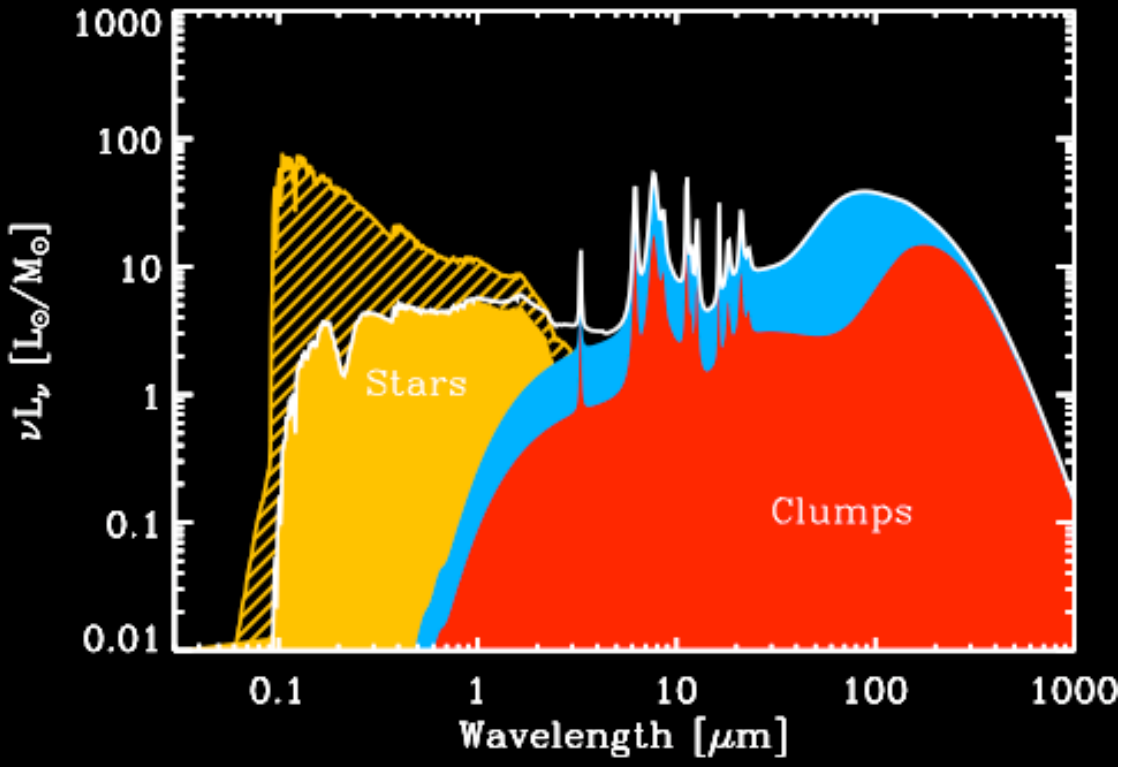
Effects of the Morphology of the ISM





Effects of the Morphology of the ISM





Content of the Talk

1) A Quick Sweep of the Dusty Universe
- Basic dust physics, the models and their constraints
- Step by step building of a spectral energy distribution (SED)
- Observed SED evolution of galaxies

2) The Dust Evolution Cycle and the Observed Dust Budget in Galaxies
- Open questions about dust evolution: sites of formation, efficiency of destruction
- Difficulties to interpret an observed galaxy's SED

3) Bridging the Gap Between the Distant Universe and Nearby Galaxies
- A multiphase SED model
- A consistent dust and elemental evolution model
- The distinct evolution of PAHs and SN-condensed dust as a function of time

Summary & Conclusion

Motivation: Cosmic Dust Evolution

- To *constrain dust evolution* models: need measure of the variation of dust abundances with time.

Motivation: Cosmic Dust Evolution

- To *constrain dust evolution* models: need measure of the variation of dust abundances with time.

- *Nearby galaxies* are crucial: wide range of metallicity and physical conditions

Motivation: Cosmic Dust Evolution

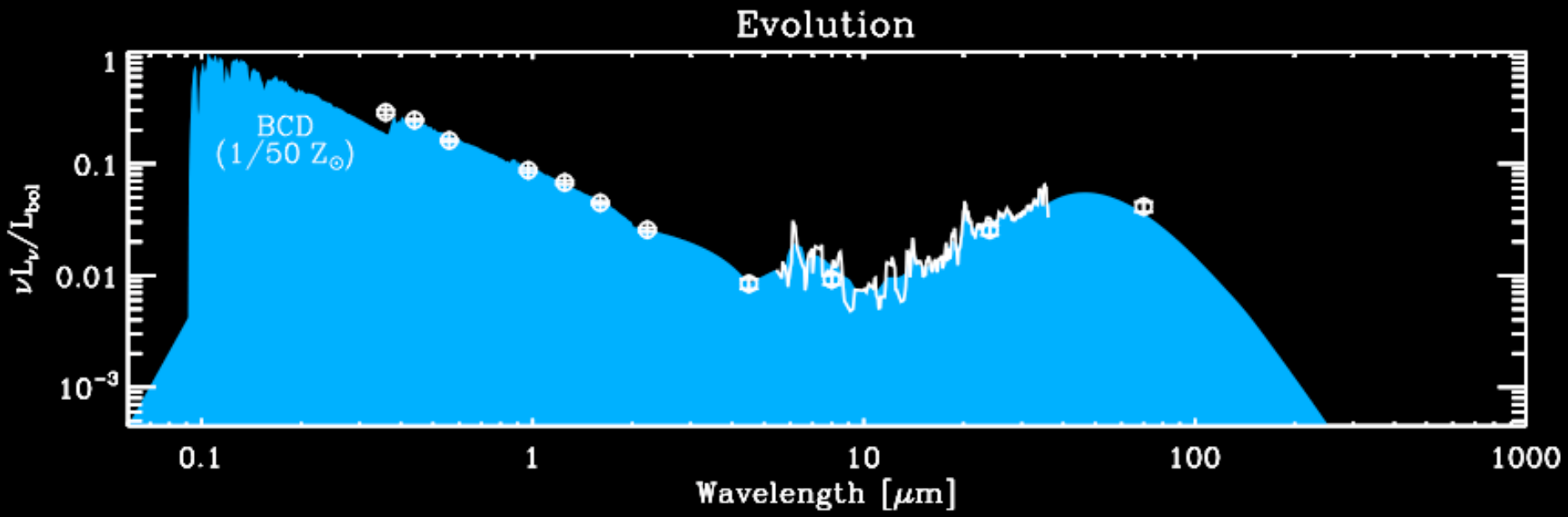
- To *constrain dust evolution* models: need measure of the variation of dust abundances with time.

- *Nearby galaxies* are crucial: wide range of metallicity and physical conditions

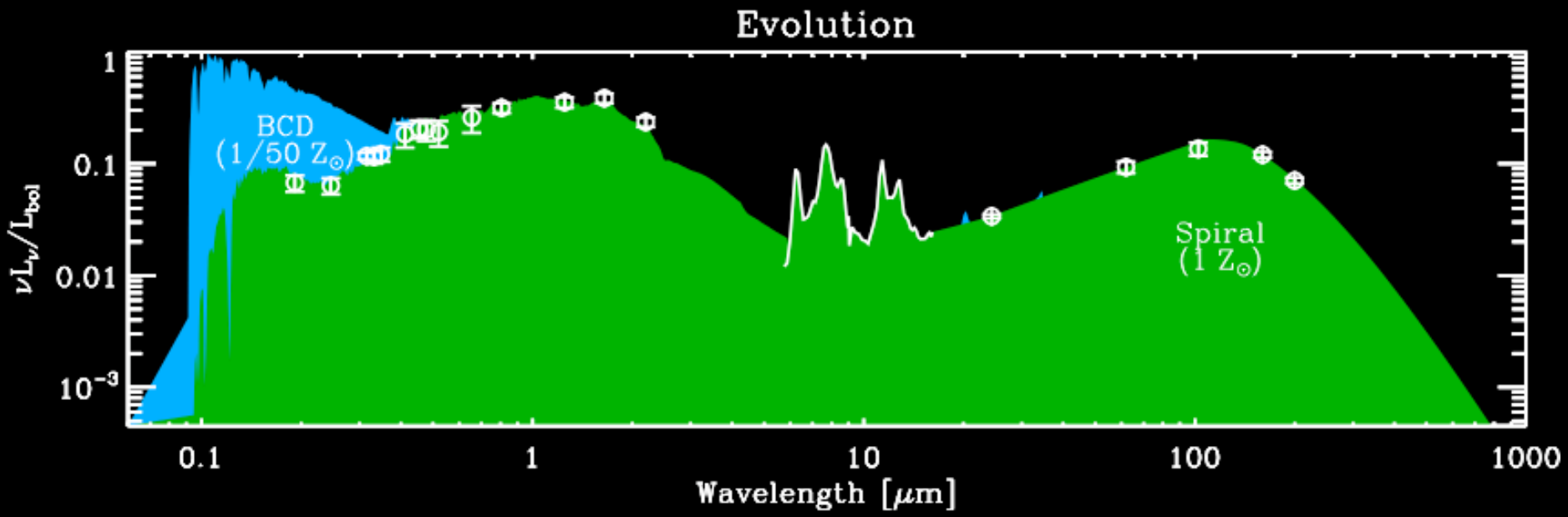
- However, the global SED of a galaxy is the *intricate combination* of different phenomena:

  1. *Long timescale* processes (≈ 1 Gyr): elemental enrichment, evolution of the stellar populations (traced by Z_{gas});
  2. *Short timescale* processes (≈ 10 Myr): massive stars, SN blast waves, HII region evolution (traced by L_{IR}).

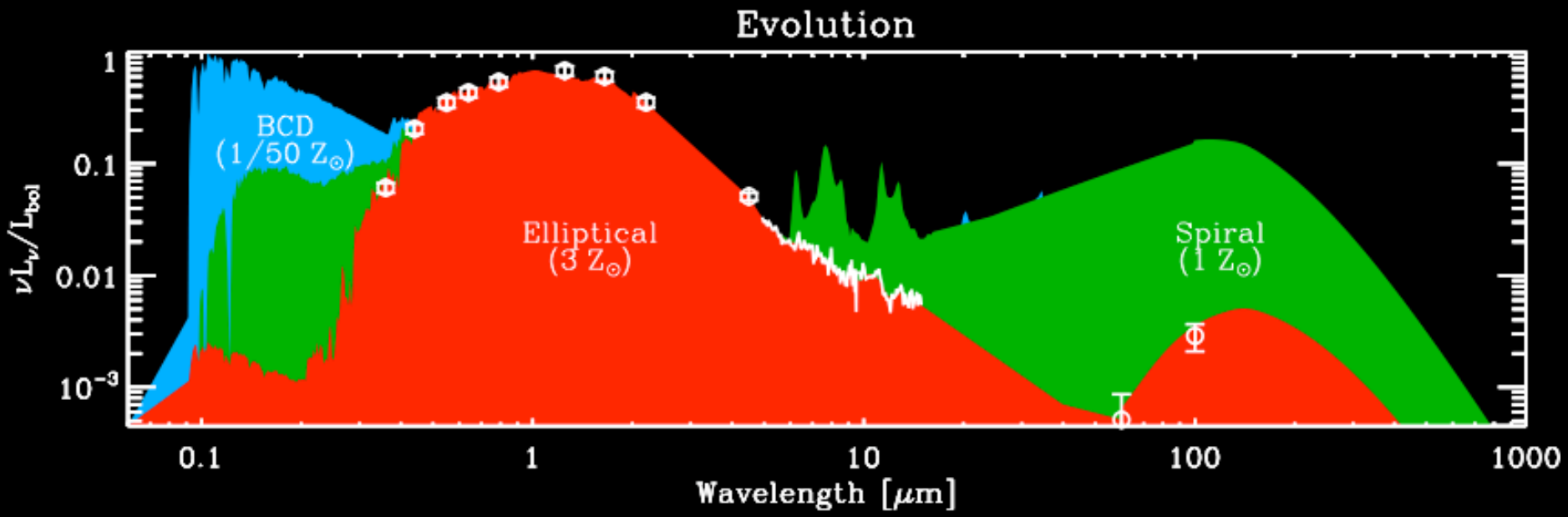
Real Life SEDs of Galaxies



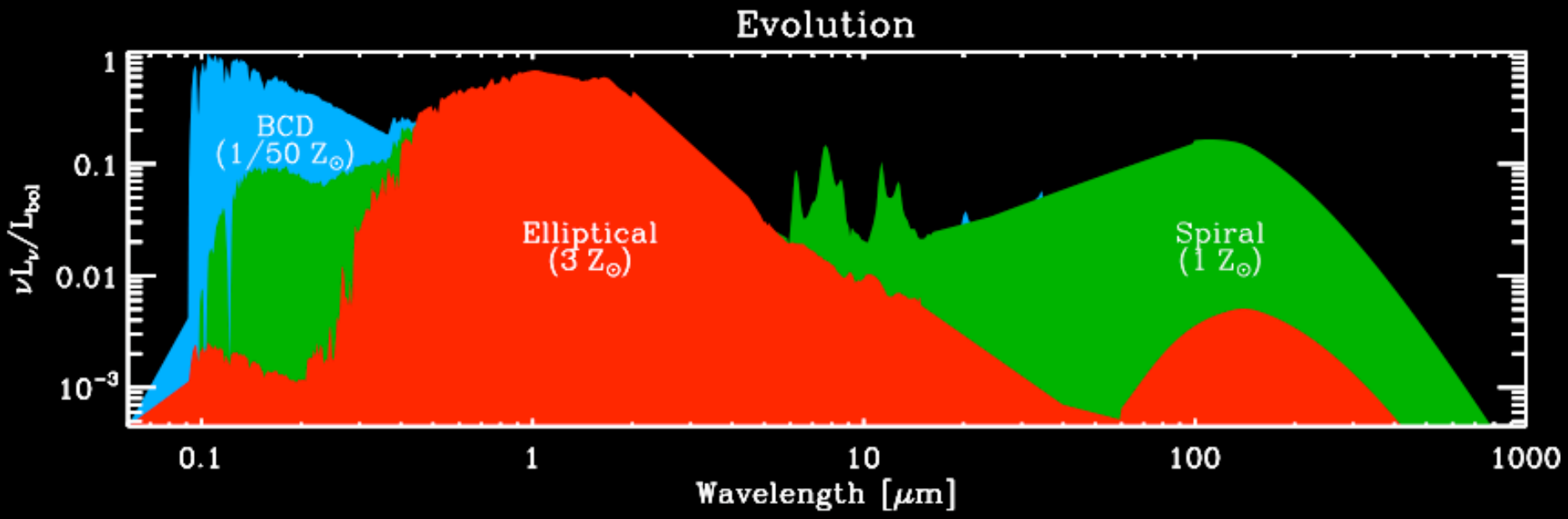
Real Life SEDs of Galaxies



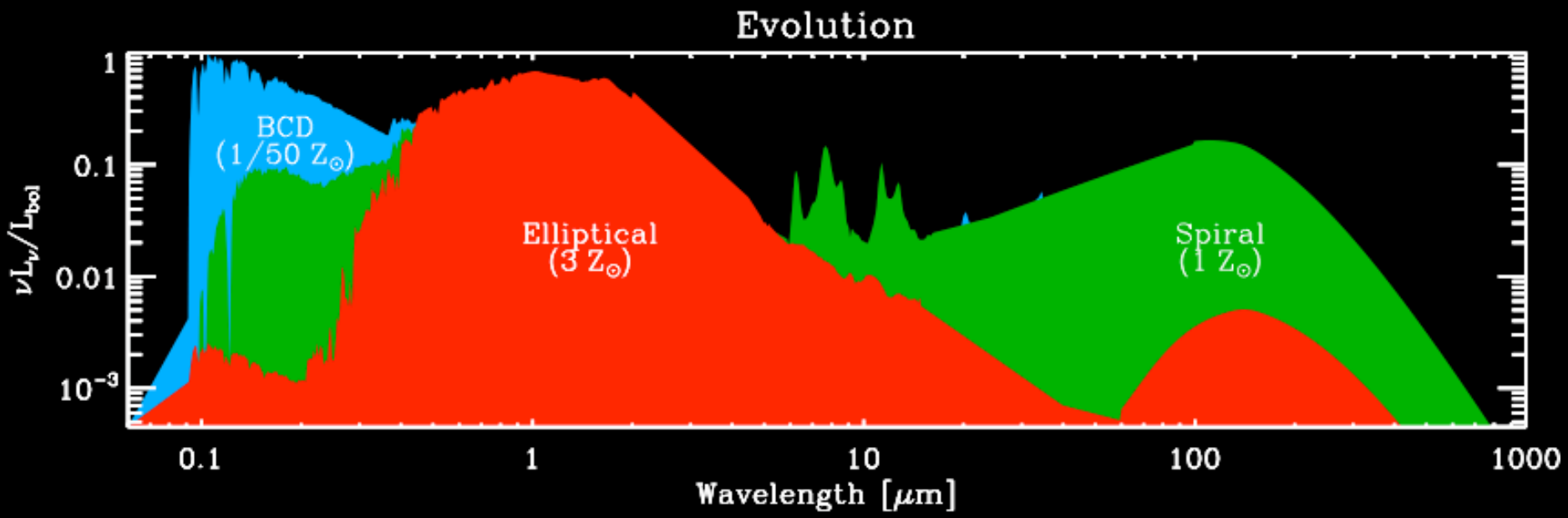
Real Life SEDs of Galaxies

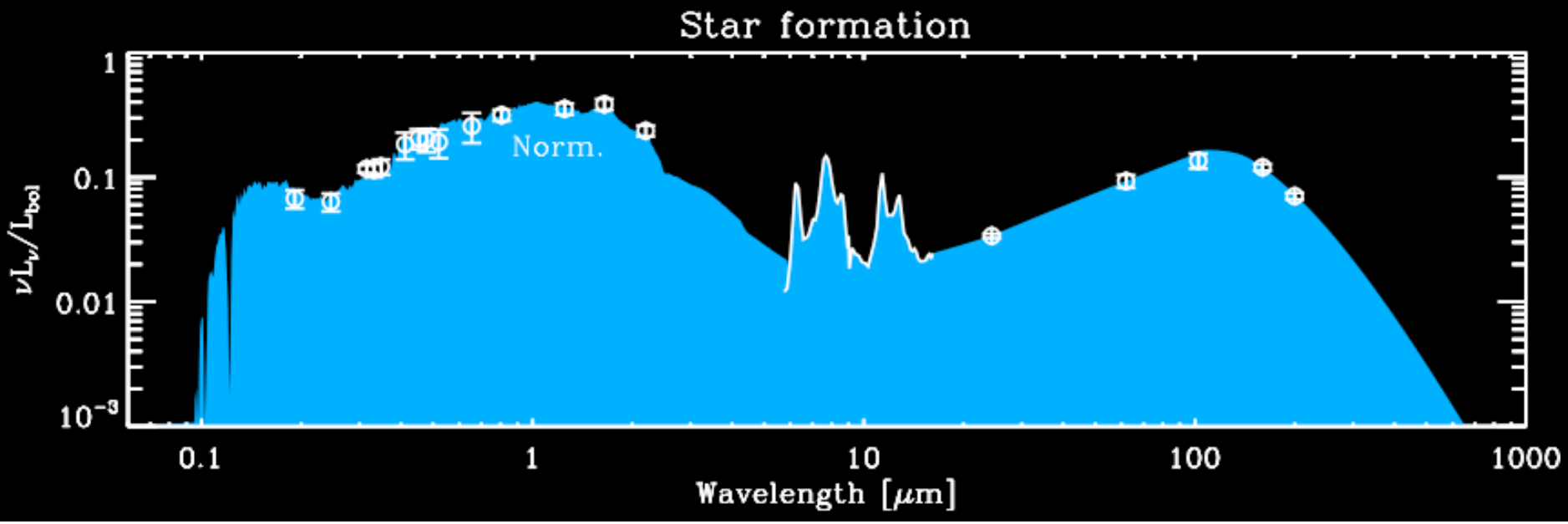


Real Life SEDs of Galaxies

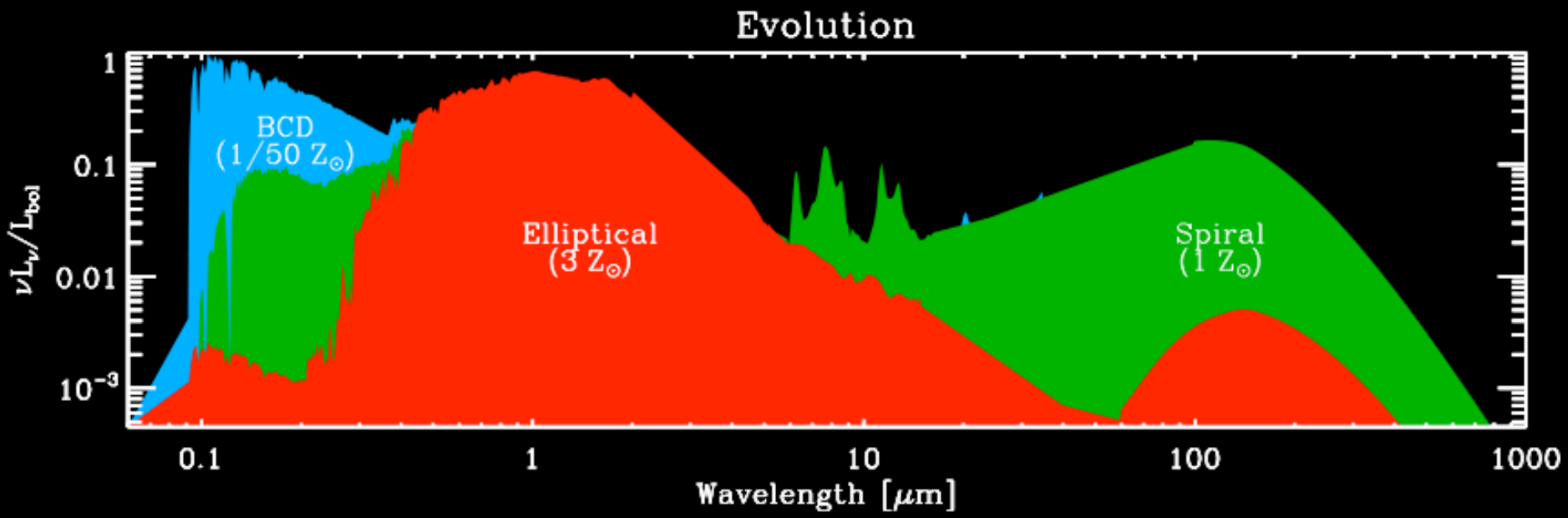


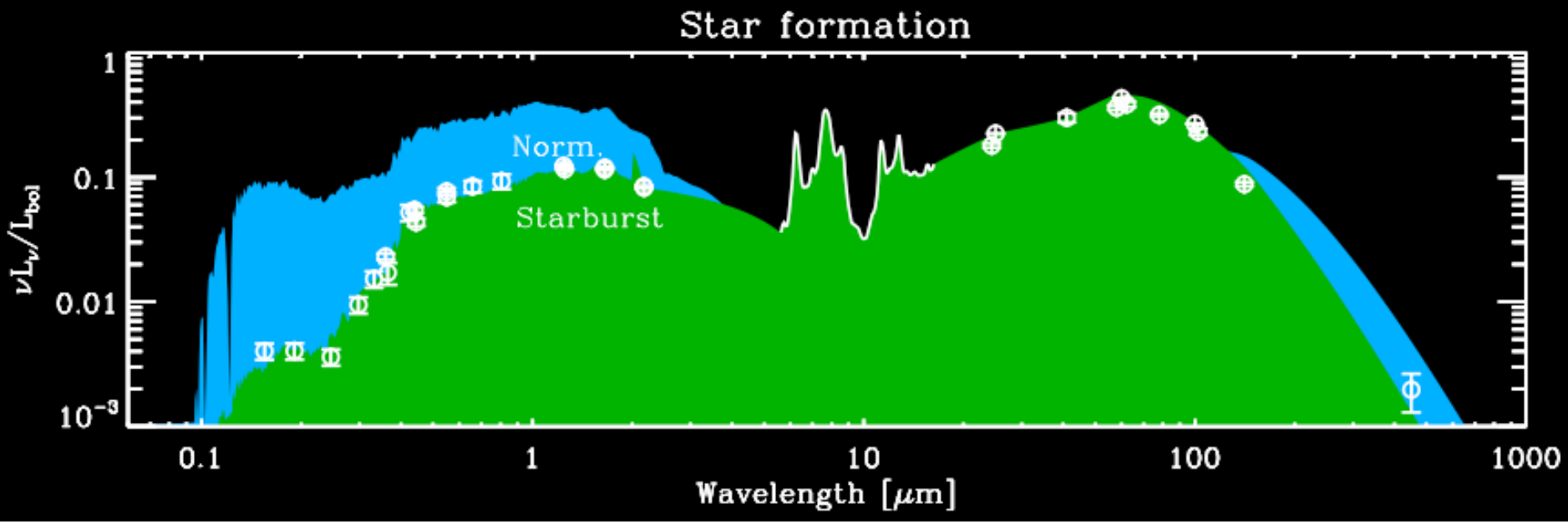
Real Life SEDs of Galaxies



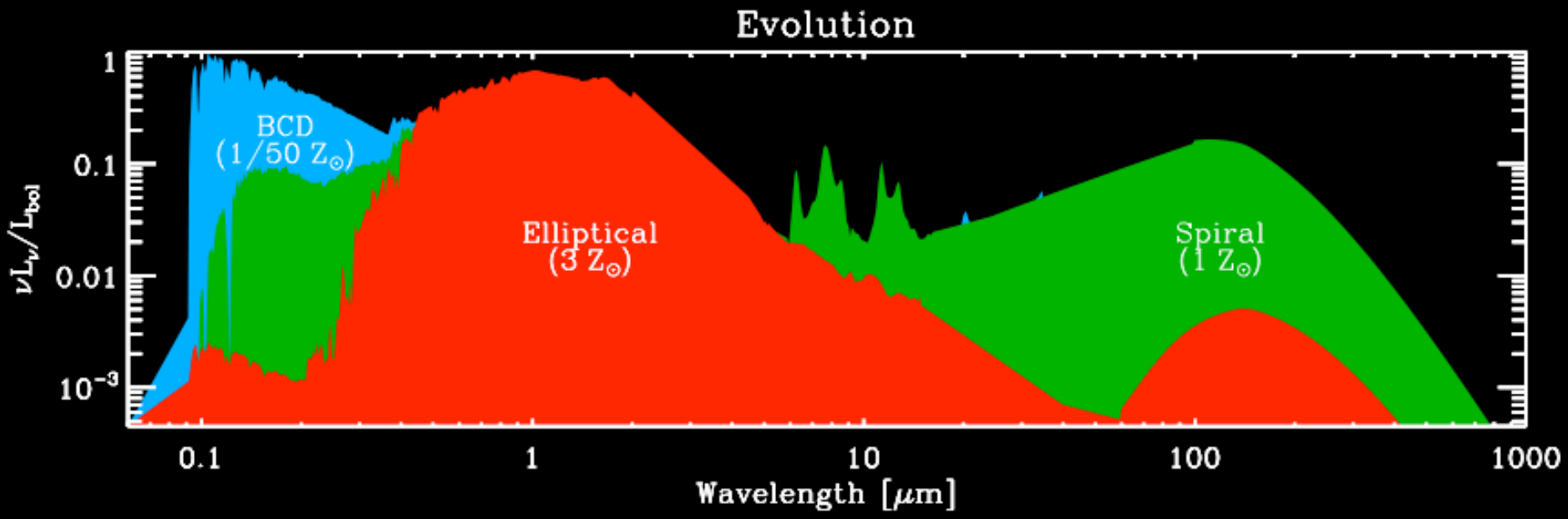


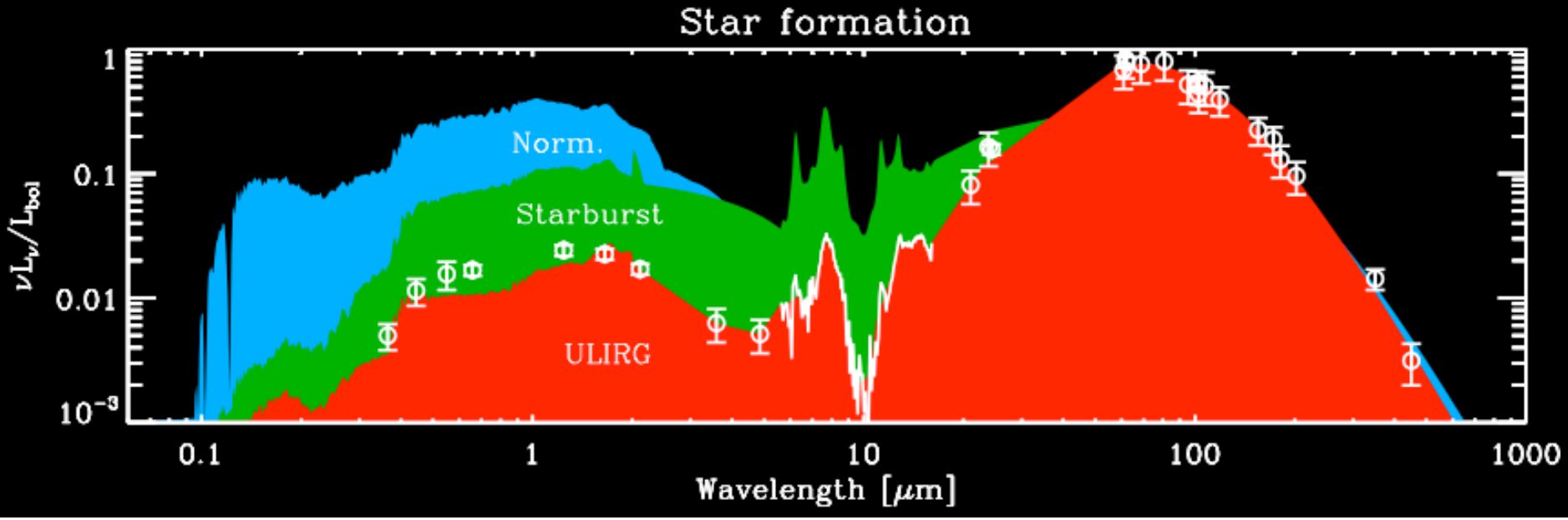
Real Life SEDs of Galaxies



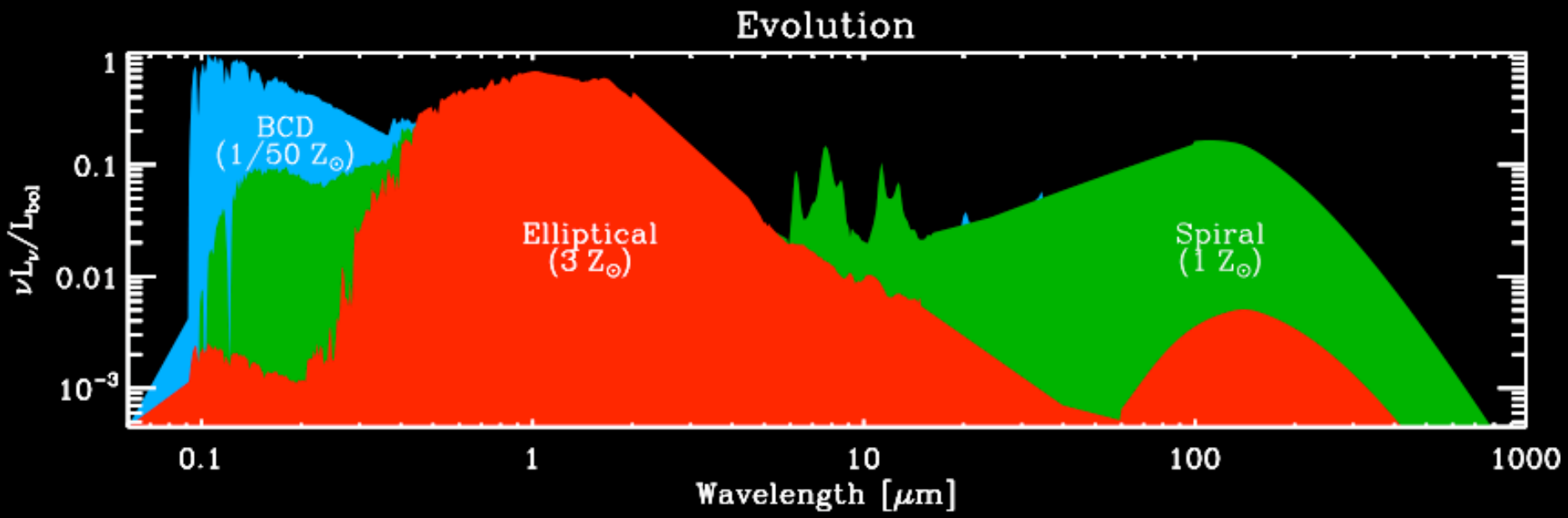


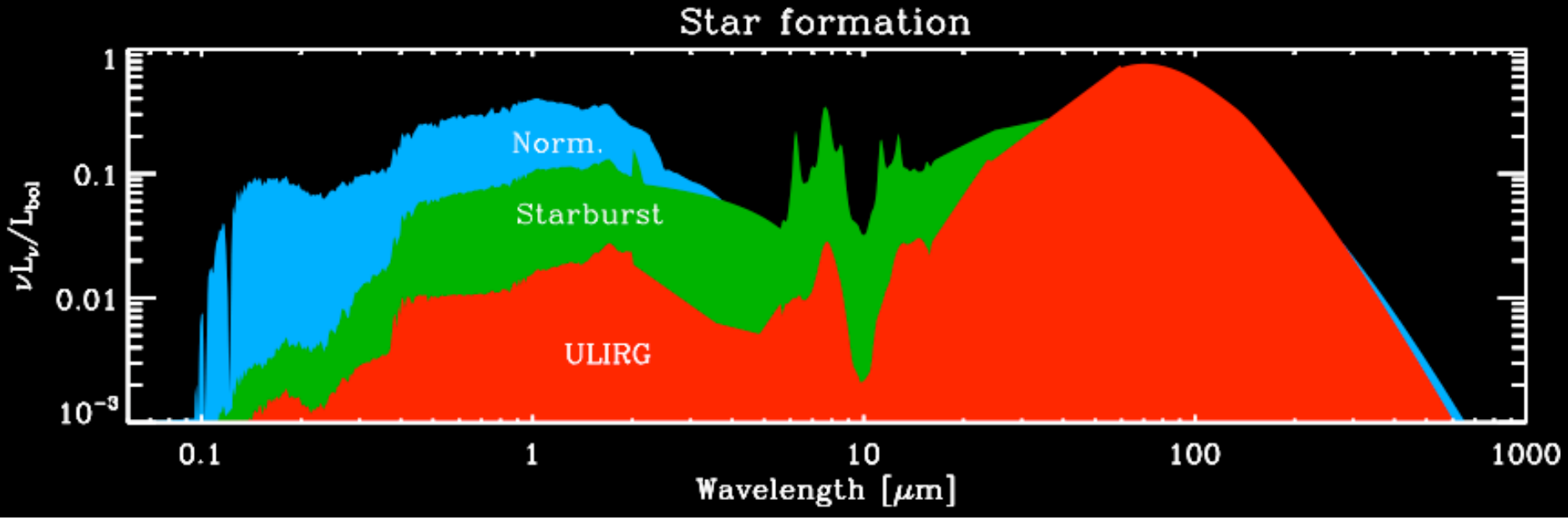
Real Life SEDs of Galaxies





Real Life SEDs of Galaxies





Open Questions About Dust Evolution

- Dust formation by supernovae:

  1) Individual SNe: ≈ 10^{-2} $M_{\odot}$/SN (Sugerman et al. 2006; Rho et al. 2008).

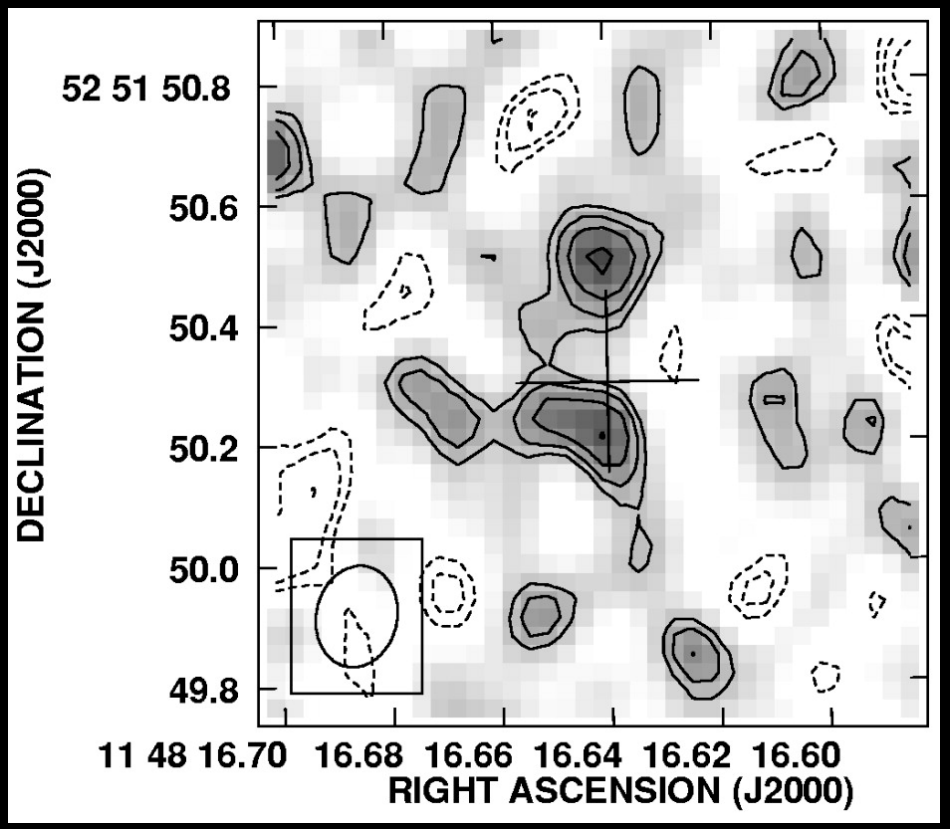
  2) From the distant universe: SDSS J1148+5251 at z=6.42

Open Questions About Dust Evolution

- Dust formation by supernovae:

  1) Individual SNe: ≈ 10^{-2} $M_{\odot}$/SN (Sugerman et al. 2006; Rho et al. 2008).

  2) From the distant universe: SDSS J1148+5251 at z=6.42



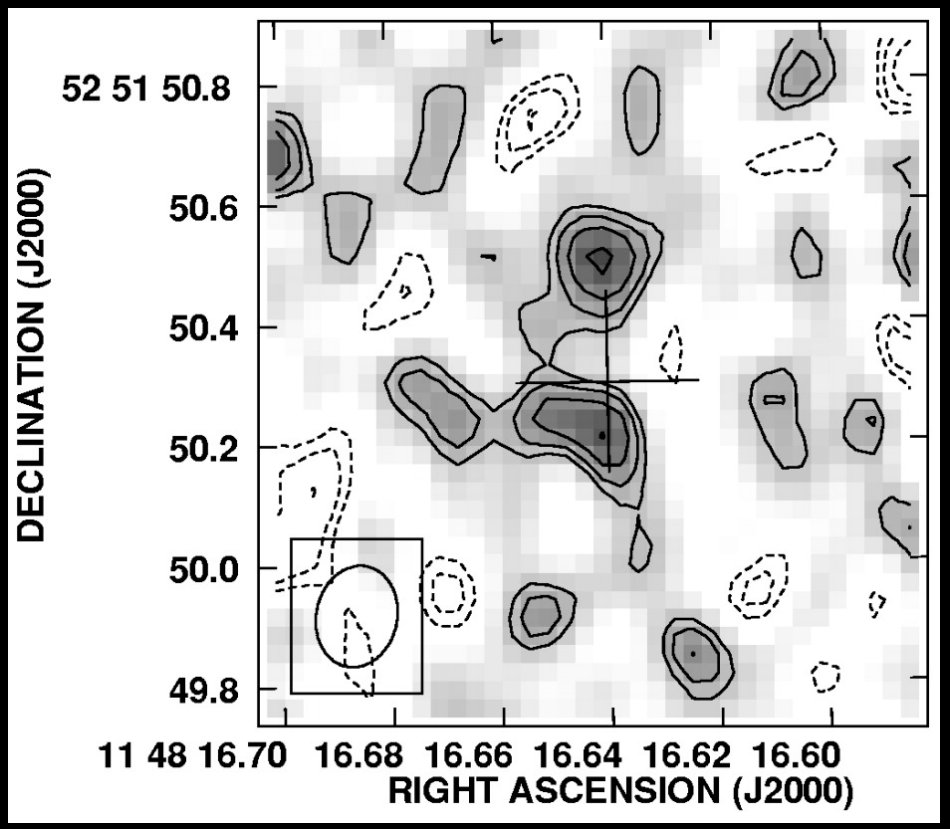
(Walter et al. 2004)

Open Questions About Dust Evolution

- Dust formation by supernovae:

  1) Individual SNe: ≈ 10^{-2} $M_\odot$/SN (Sugerman et al. 2006; Rho et al. 2008).

  2) From the distant universe: SDSS J1148+5251 at z=6.42



- Age ≈ 400 Myr
- L(IR) ≈ (1-2) × 10^{13} $L_\odot$
- Mdust ≈ (1-5) × 10^{8} $M_\odot$
- M(H_2) ≈ 2 × 10^{10} $M_\odot$
- SFR(L_{IR}) ≈ 3000 $M_\odot$/yr

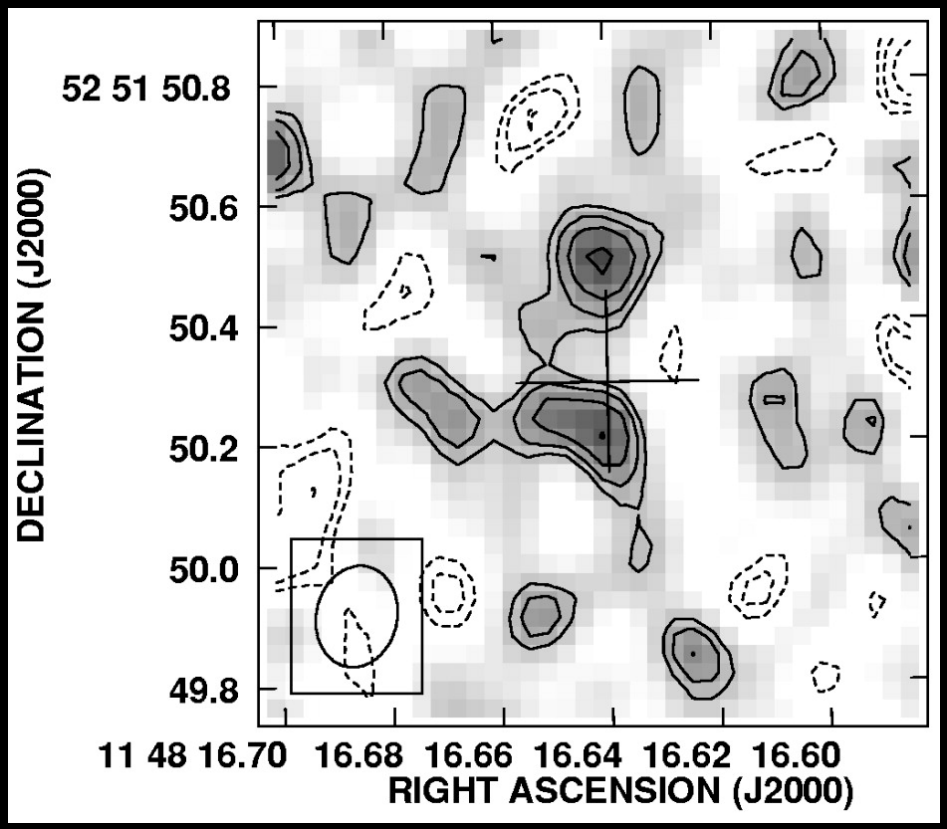
(Walter et al. 2004)

Open Questions About Dust Evolution

- Dust formation by supernovae:

  1) Individual SNe: ≈ 10^{-2} $M_\odot$/SN (Sugerman et al. 2006; Rho et al. 2008).

  2) From the distant universe: SDSS J1148+5251 at z=6.42



(Walter et al. 2004)

- Age ≈ 400 Myr
- L(IR) ≈ (1-2) × 10^{13} $L_\odot$
- Mdust ≈ (1-5) × 10^{8} $M_\odot$
- M(H_2) ≈ 2 × 10^{10} $M_\odot$
- SFR(L_{IR}) ≈ 3000 $M_\odot$/yr

=> Dust yield ≈ 1 $M_\odot$/SN

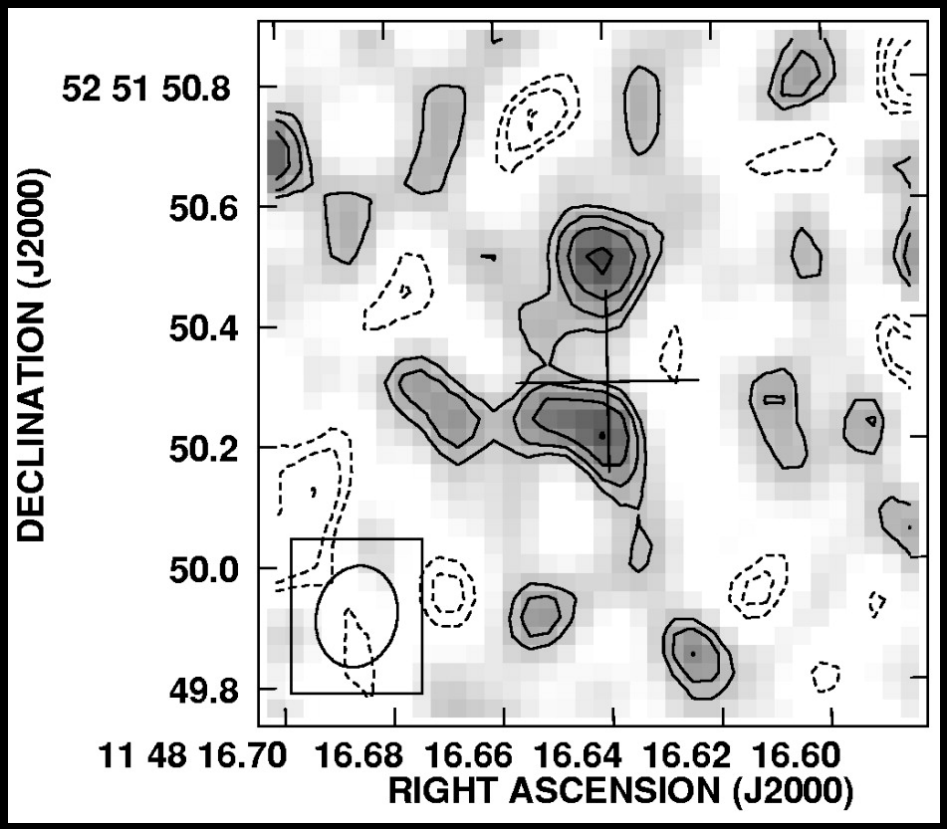
(Dwek, Galliano & Jones 2007)

Open Questions About Dust Evolution

- Dust formation by supernovae:

  1) Individual SNe: ≈ 10^{-2} $M_\odot$/SN (Sugerman et al. 2006; Rho et al. 2008).

  2) From the distant universe: SDSS J1148+5251 at z=6.42



(Walter et al. 2004)

- Age ≈ 400 Myr
- L(IR) ≈ (1-2) × 10^{13} $L_\odot$
- Mdust ≈ (1-5) × 10^{8} $M_\odot$
- M(H_2) ≈ 2 × 10^{10} $M_\odot$
- SFR(L_{IR}) ≈ 3000 $M_\odot$/yr

=> Dust yield ≈ 1 $M_\odot$/SN

(Dwek, Galliano & Jones 2007)

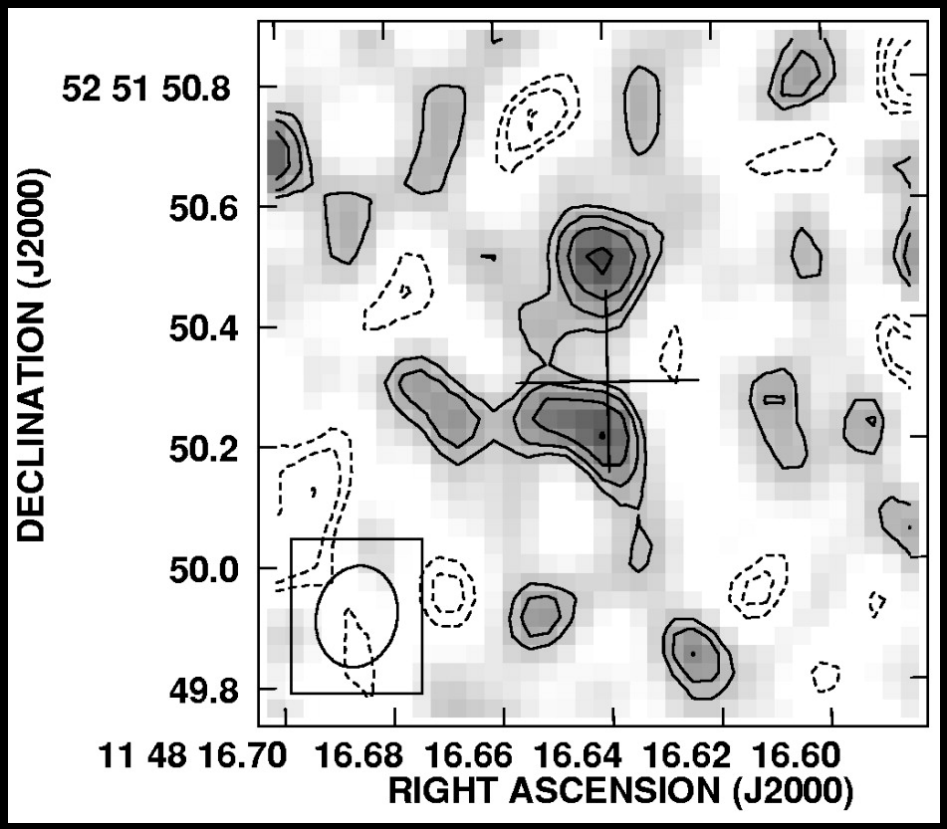
- Dust condensation in dense regions of the ISM: short timescales (10^5 yr).

Open Questions About Dust Evolution

- Dust formation by supernovae:

  1) Individual SNe: ≈ 10^{-2} $M_\odot$/SN (Sugerman et al. 2006; Rho et al. 2008).

  2) From the distant universe: SDSS J1148+5251 at z=6.42



- Age ≈ 400 Myr
- L(IR) ≈ (1–2) × 10^{13} $L_\odot$
- Mdust ≈ (1–5) × 10^{8} $M_\odot$
- M(H_2) ≈ 2 × 10^{10} $M_\odot$
- SFR(L_{IR}) ≈ 3000 $M_\odot$/yr

=> Dust yield ≈ 1 $M_\odot$/SN

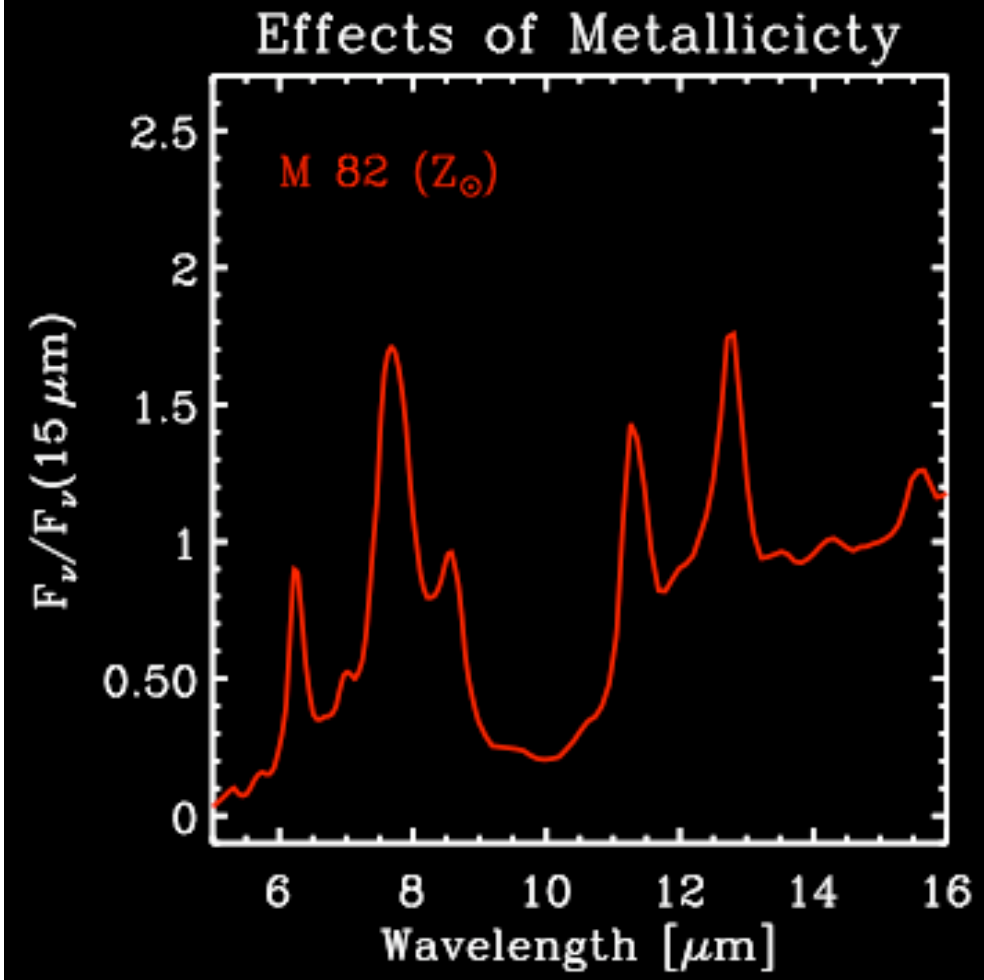
(Dwek, Galliano & Jones 2007)

(Walter et al. 2004)

- Dust condensation in dense regions of the ISM: short timescales (10^5 yr).
- The lack of PAHs in low-metallicity environments...

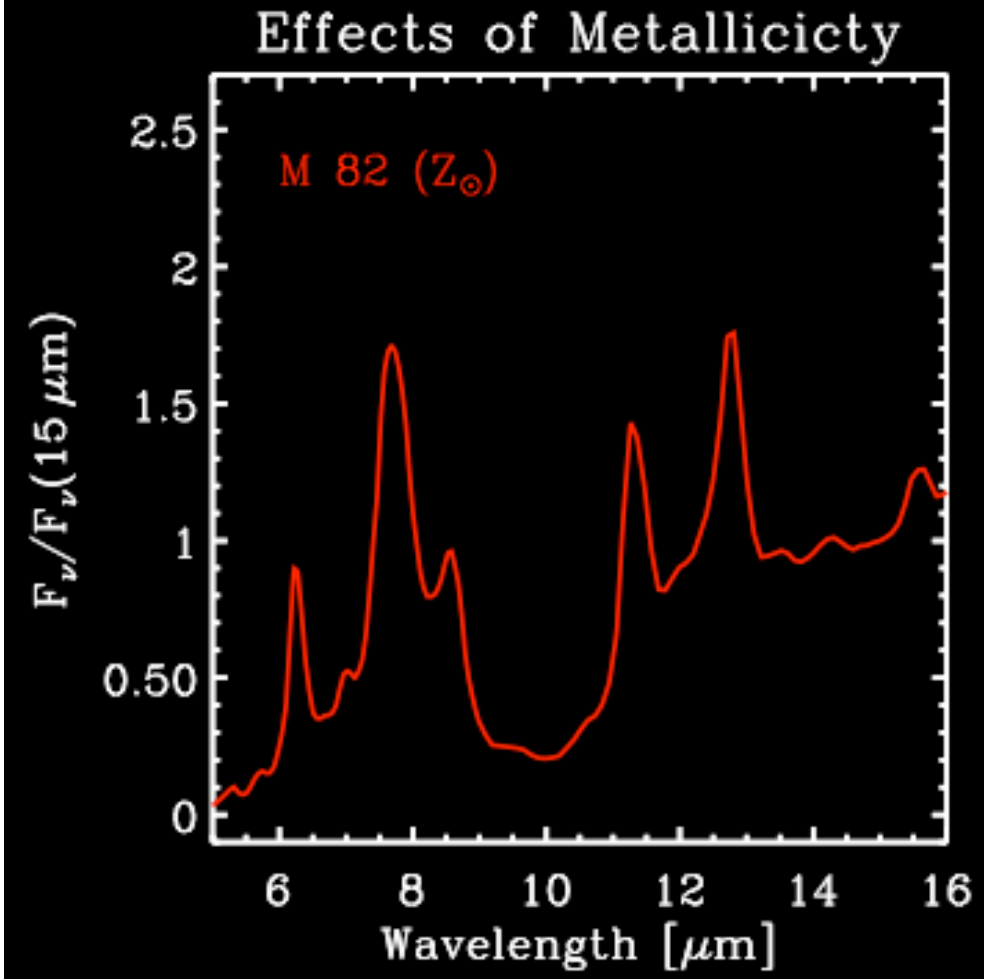
Differential Dust Evolution: PAHs vs. Dust

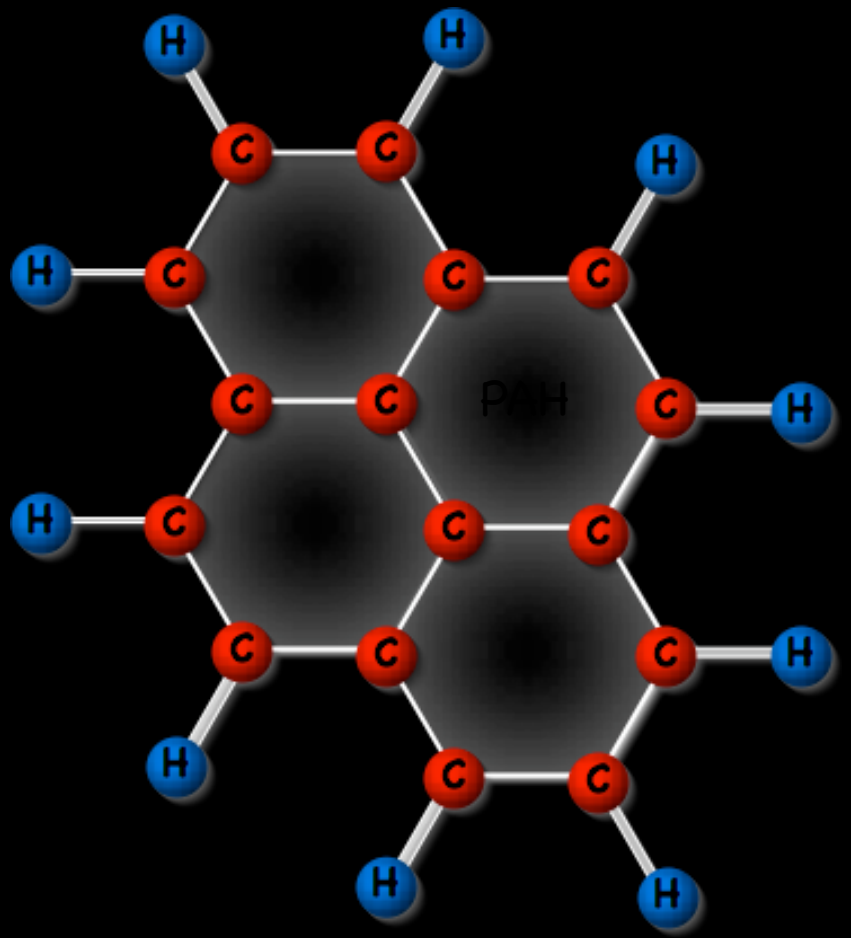
Paucity of PAHs in low-metallicity environments



Differential Dust Evolution: PAHs vs. Dust

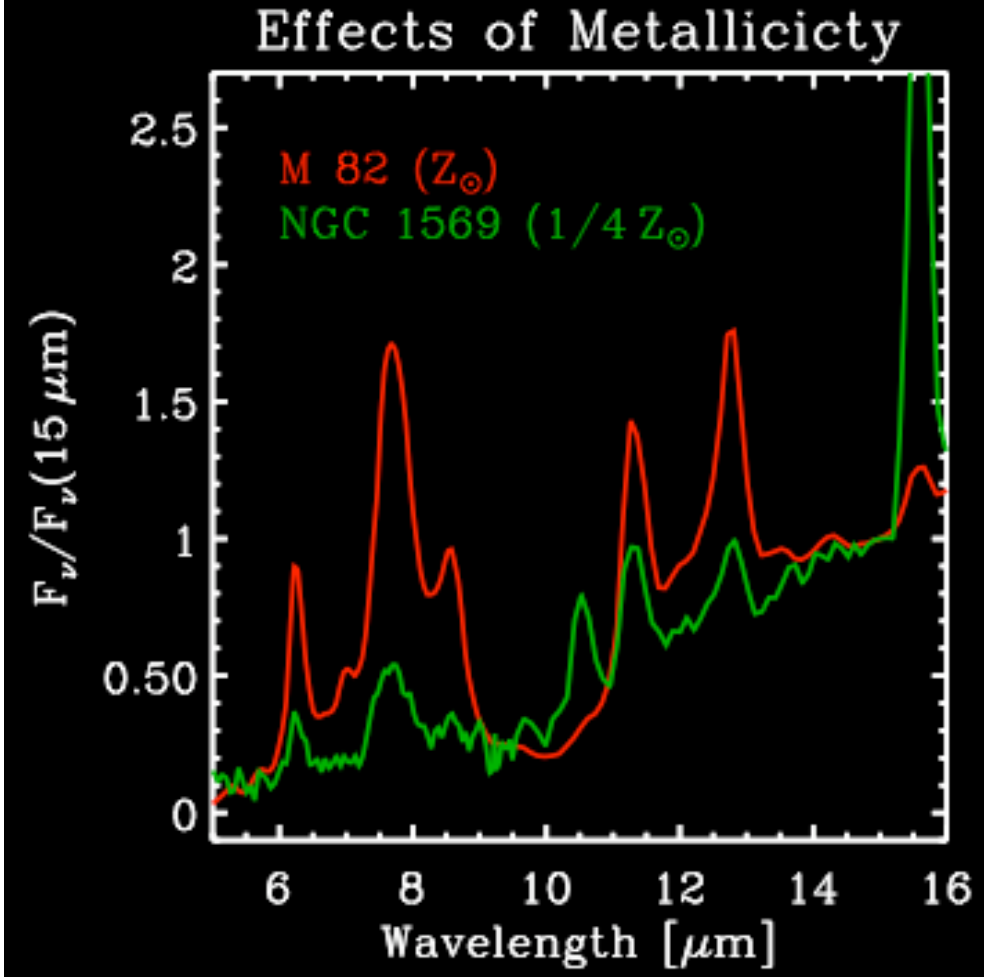
Paucity of PAHs in low-metallicity environments

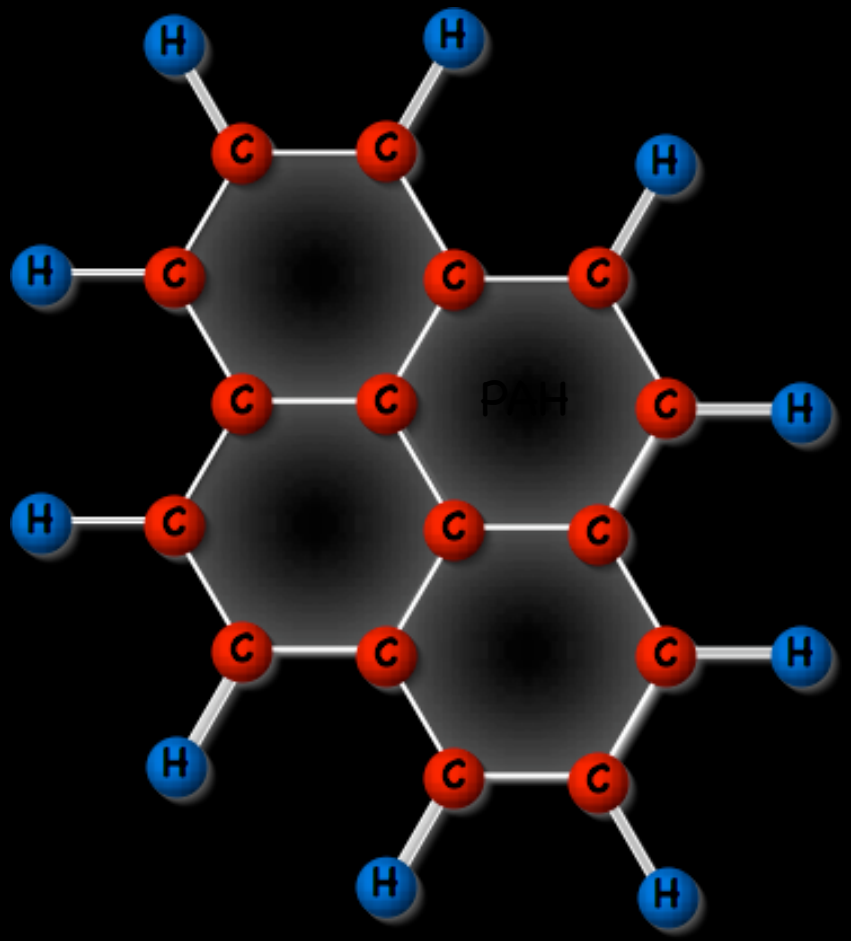




Differential Dust Evolution: PAHs vs. Dust

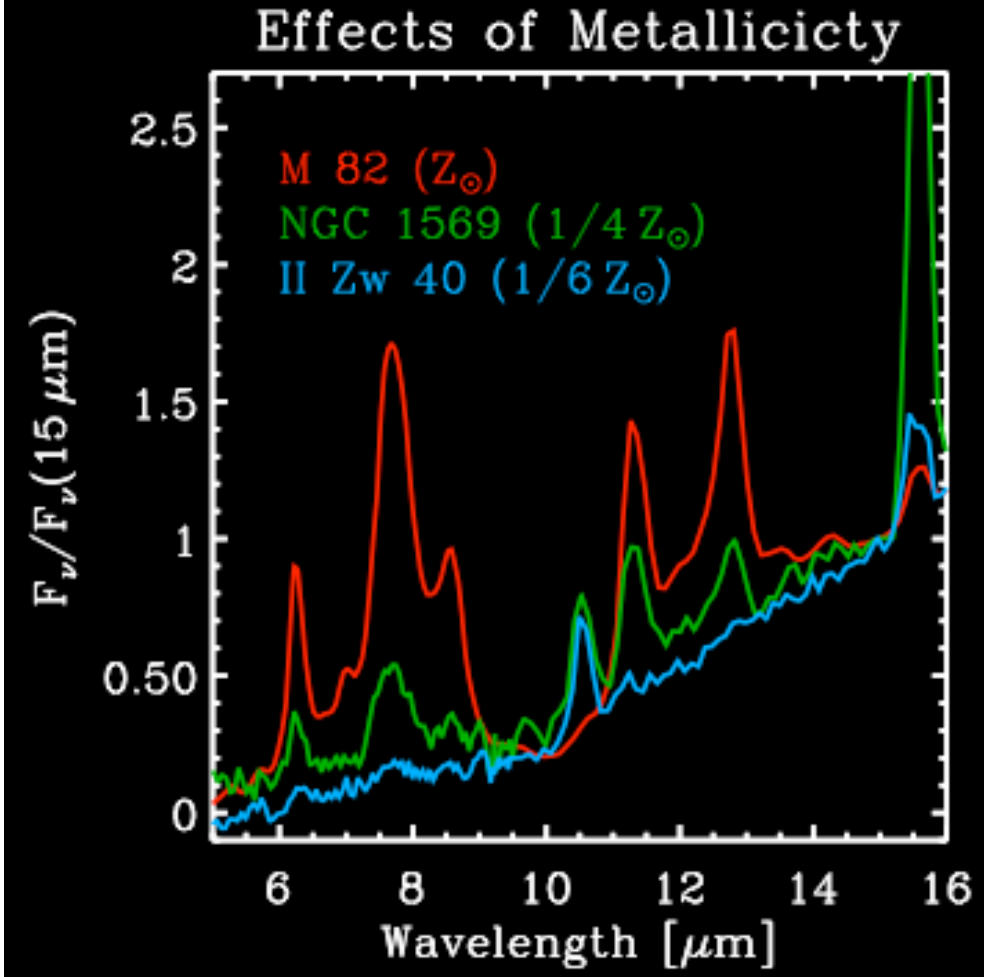
Paucity of PAHs in low-metallicity environments

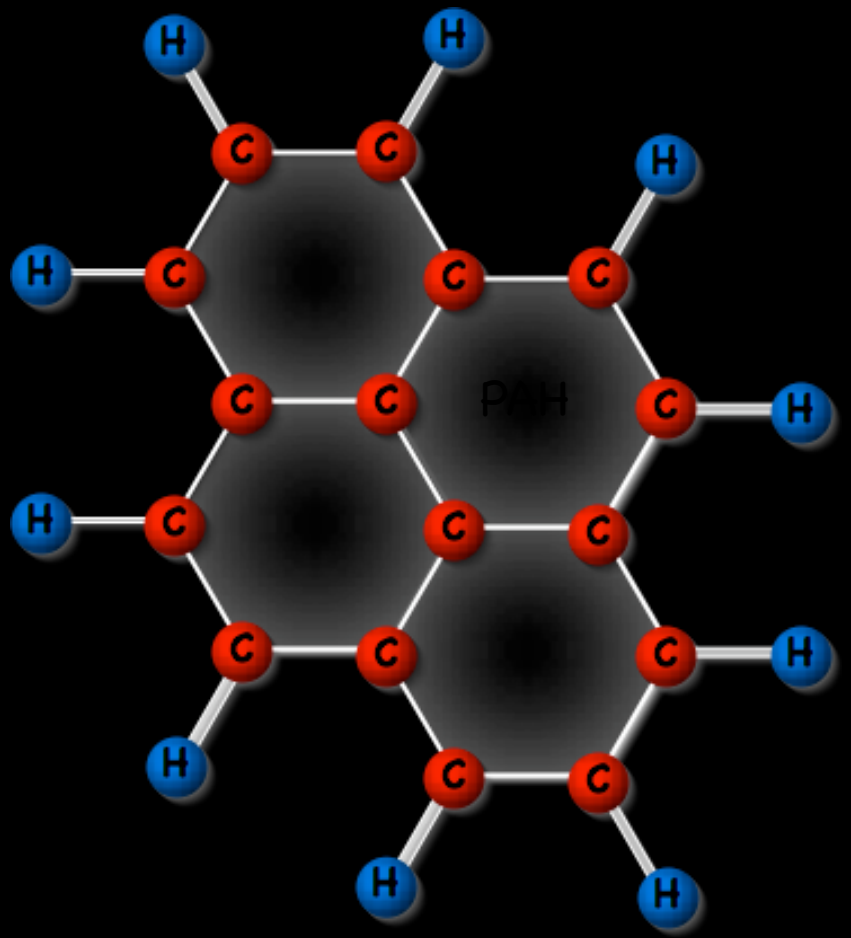




Differential Dust Evolution: PAHs vs. Dust

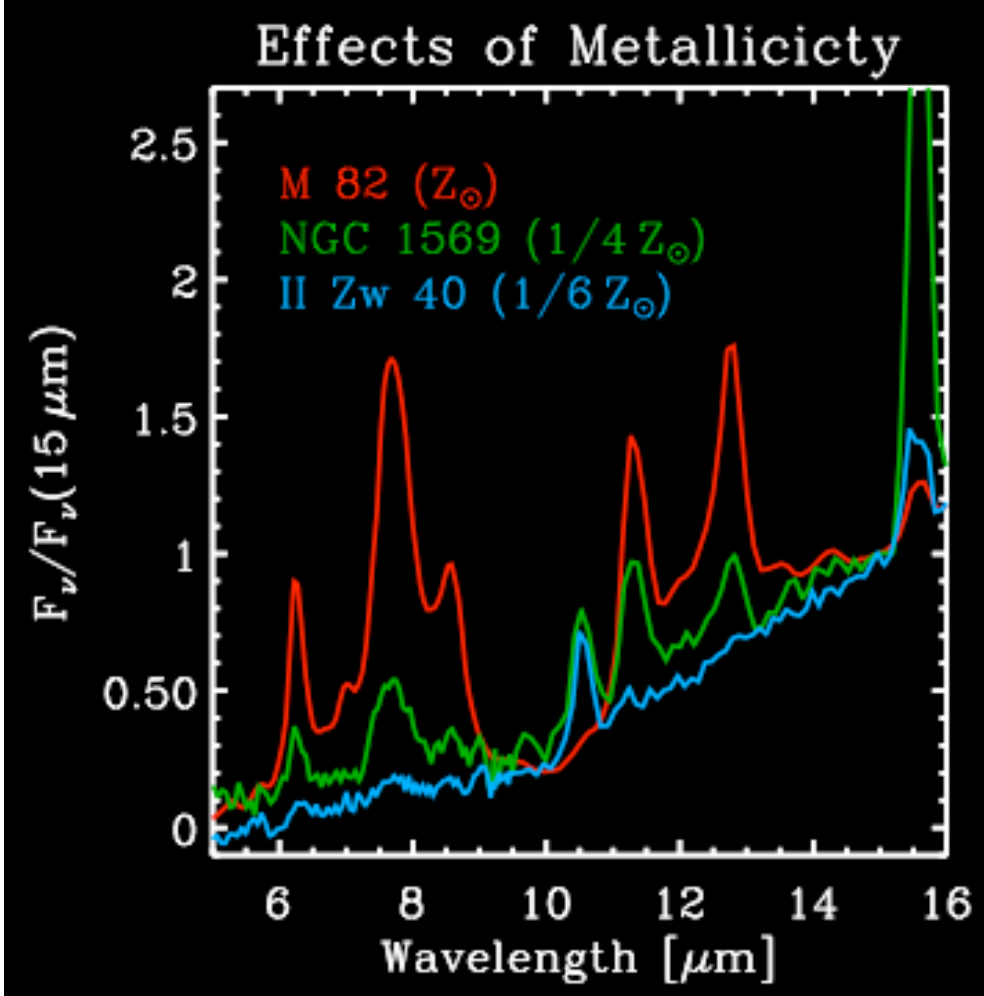
Paucity of PAHs in low-metallicity environments

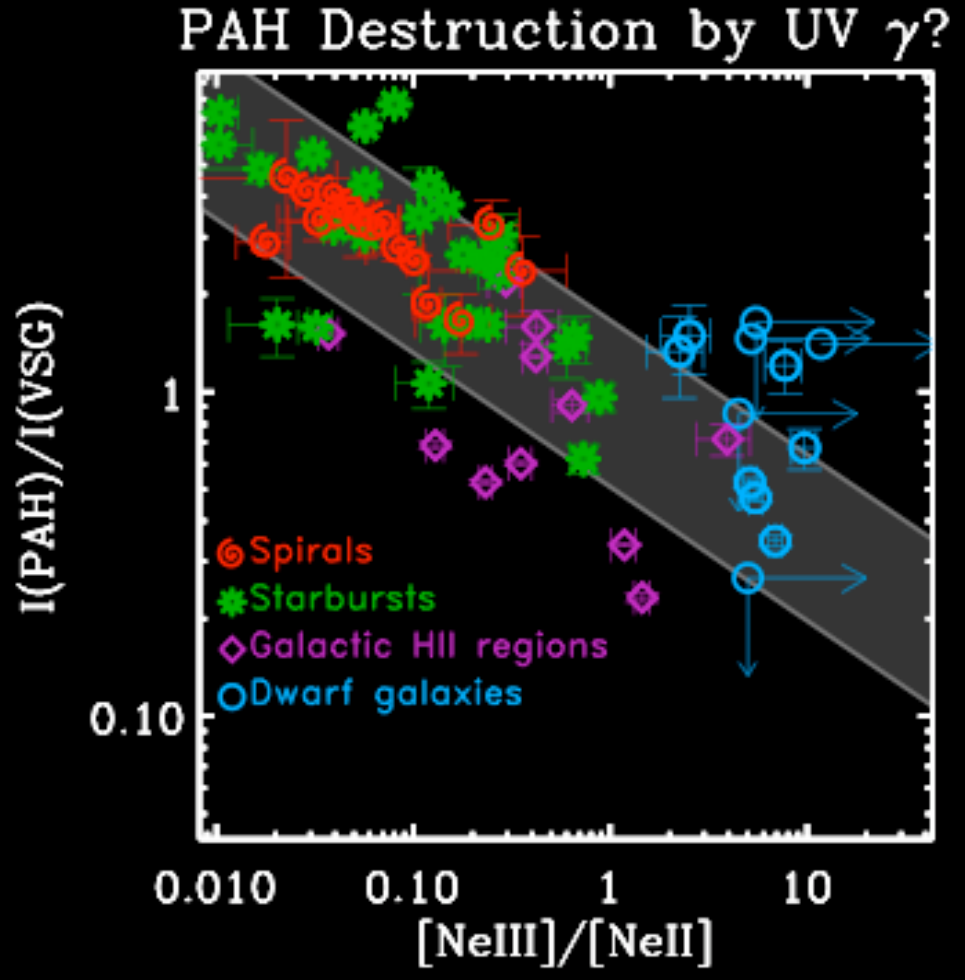




Differential Dust Evolution: PAHs vs. Dust

Paucity of PAHs in low-metallicity environments

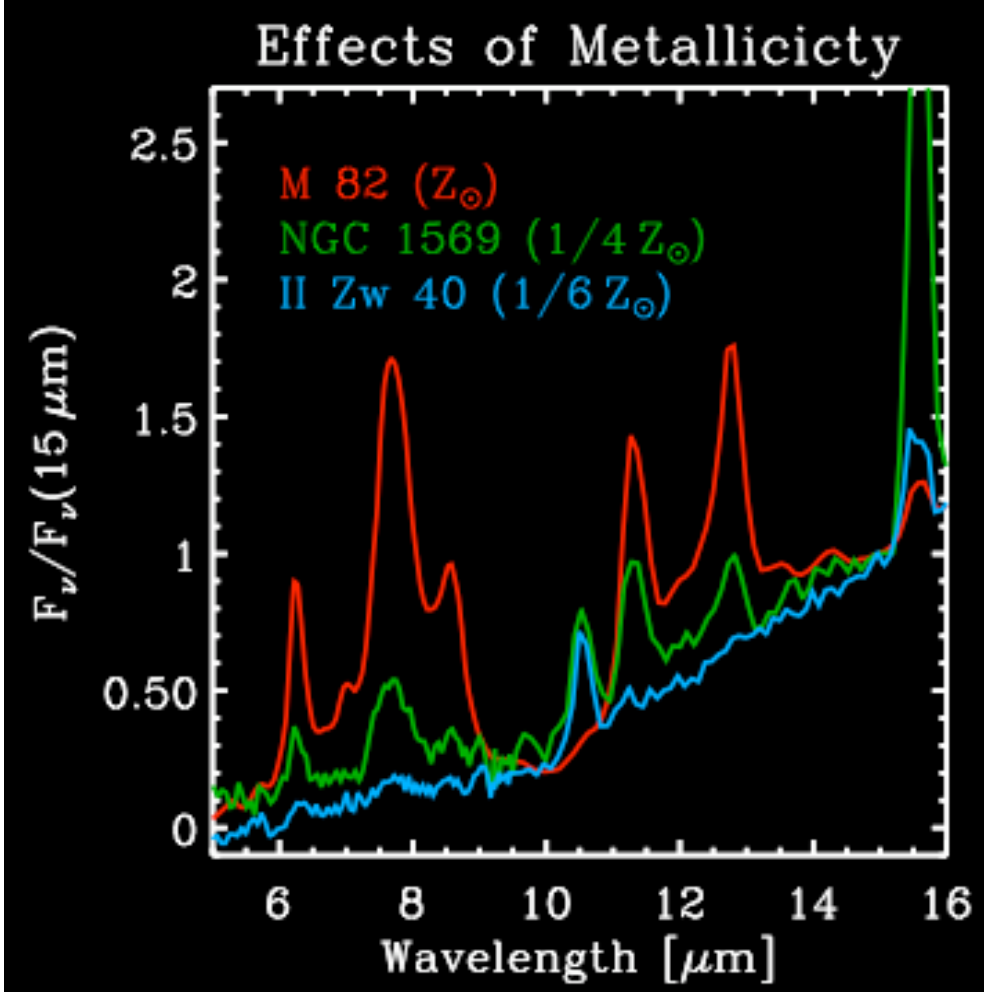


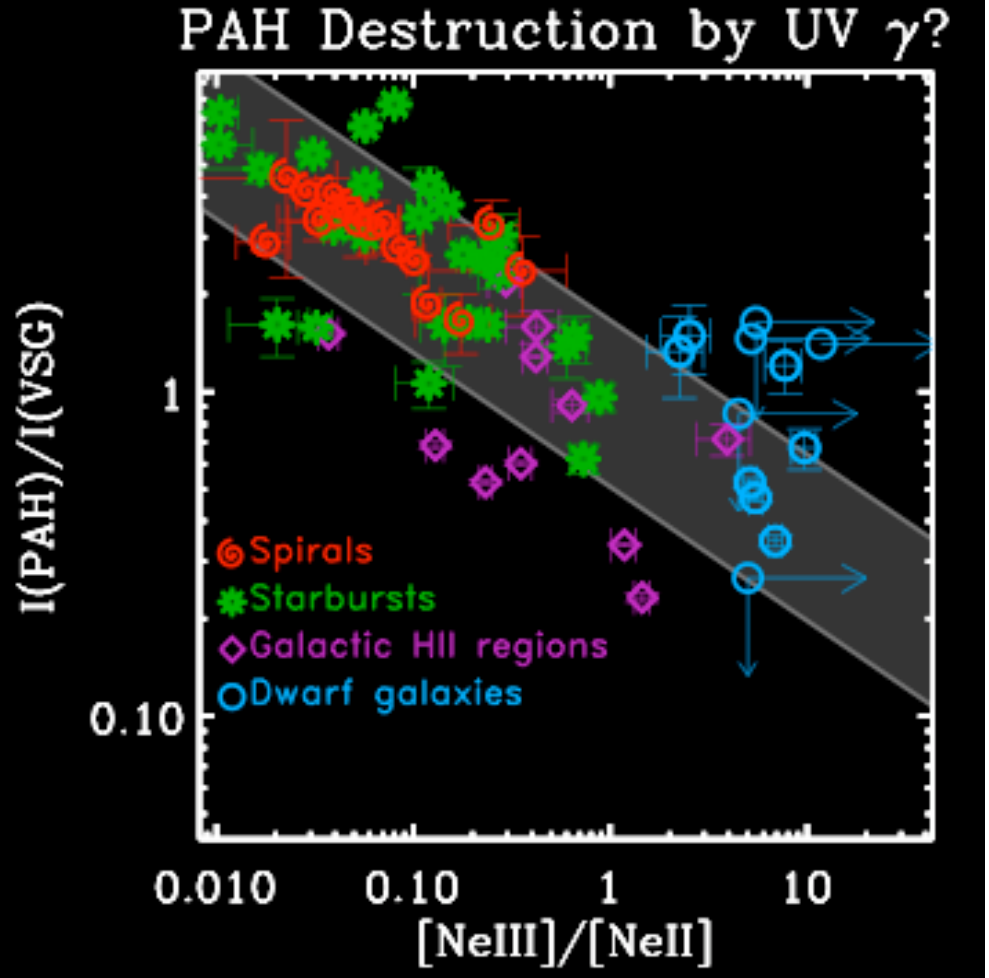


(Madden, Galliano et al. 2006, A&A, 446, 877)

Differential Dust Evolution: PAHs vs. Dust

Paucity of PAHs in low-metallicity environments





(Madden, Galliano et al. 2006, A&A, 446, 877)

=> Need a SED model taking into account PAH destruction in HII regions

Content of the Talk

1) A Quick Sweep of the Dusty Universe
   - Basic dust physics, the models and their constraints
   - Step by step building of a spectral energy distribution (SED)
   - Observed SED evolution of galaxies

2) The Dust Evolution Cycle and the Observed Dust Budget in Galaxies
   - Open questions about dust evolution: sites of formation, efficiency of destruction
   - Difficulties to interpret an observed galaxy's SED

3) Bridging the Gap Between the Distant Universe and Nearby Galaxies
   - A multiphase SED model
   - A consistent dust and elemental evolution model
   - The distinct evolution of PAHs and SN-condensed dust as a function of time

Summary & Conclusion

Physical Ingredients of the Model

- General interstellar radiation field: population synthesis;

Physical Ingredients of the Model

- General interstellar radiation field: population synthesis;
- Radiative transfer: HII regions, PDR;

Physical Ingredients of the Model

- General interstellar radiation field: population synthesis;
- Radiative transfer: HII regions, PDR;
- Dust model: stochastic heating, realistic optical properties for PAH^+, PAH^0, graphite, silicate (Zubko et al. 2004; Draine & Li 2007);

Physical Ingredients of the Model

- General interstellar radiation field: population synthesis;
- Radiative transfer: HII regions, PDR;
- Dust model: stochastic heating, realistic optical properties for PAH^+, PAH^0, graphite, silicate (Zubko et al. 2004; Draine & Li 2007);
- Self-consistency: energy conservation;

Physical Ingredients of the Model

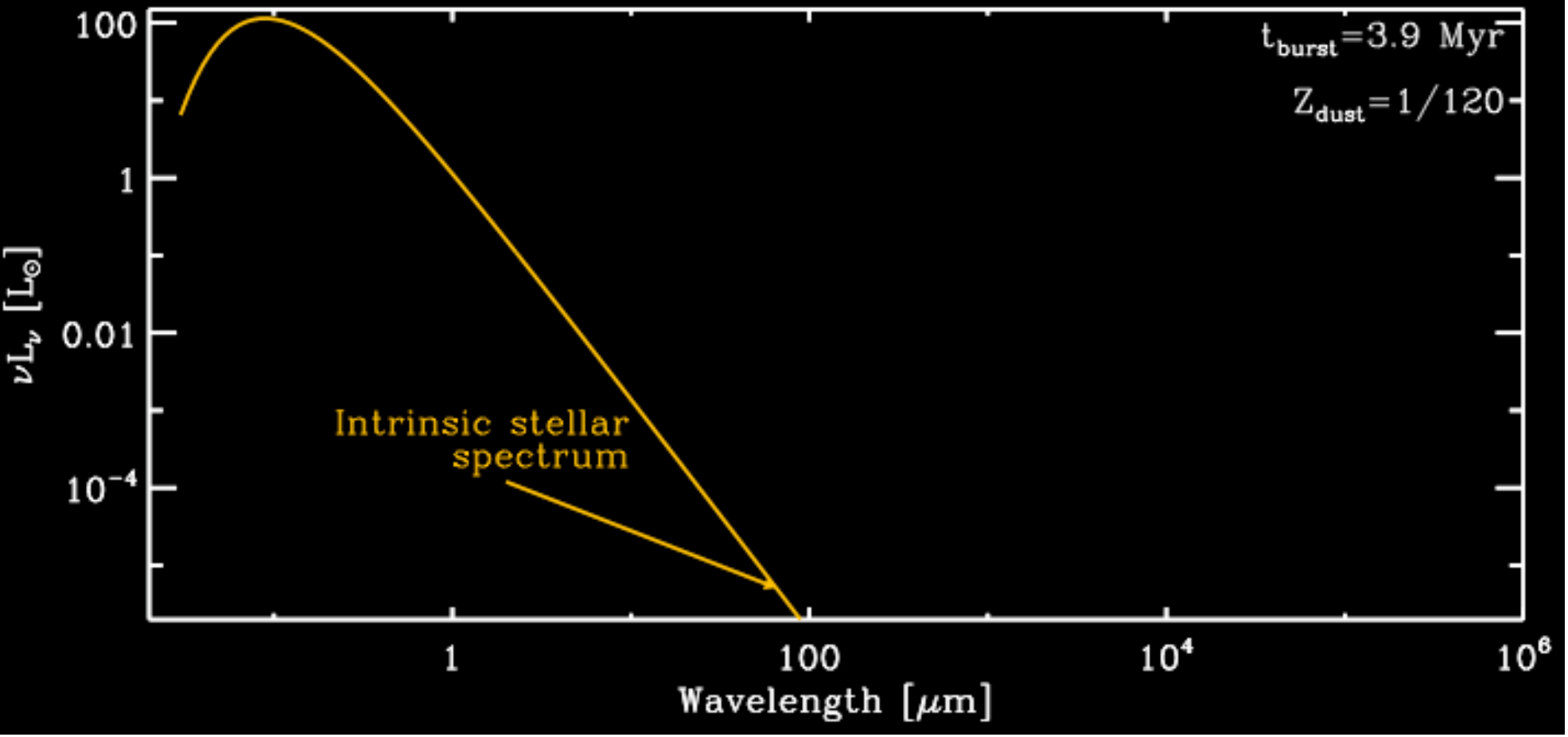
- General interstellar radiation field: population synthesis;
- Radiative transfer: HII regions, PDR;
- Dust model: stochastic heating, realistic optical properties for PAH^+, PAH^0, graphite, silicate (Zubko et al. 2004; Draine & Li 2007);
- Self-consistency: energy conservation;
- Each model parameter is constrained by the global panchromatic observed SED of 35 nearby galaxies.

SEDs of H II Regions

- Homogeneous spherical HII regions: constant G2D, no PAHs
- Radiative transfer: competition between gas and dust for absorption of ionizing photons.

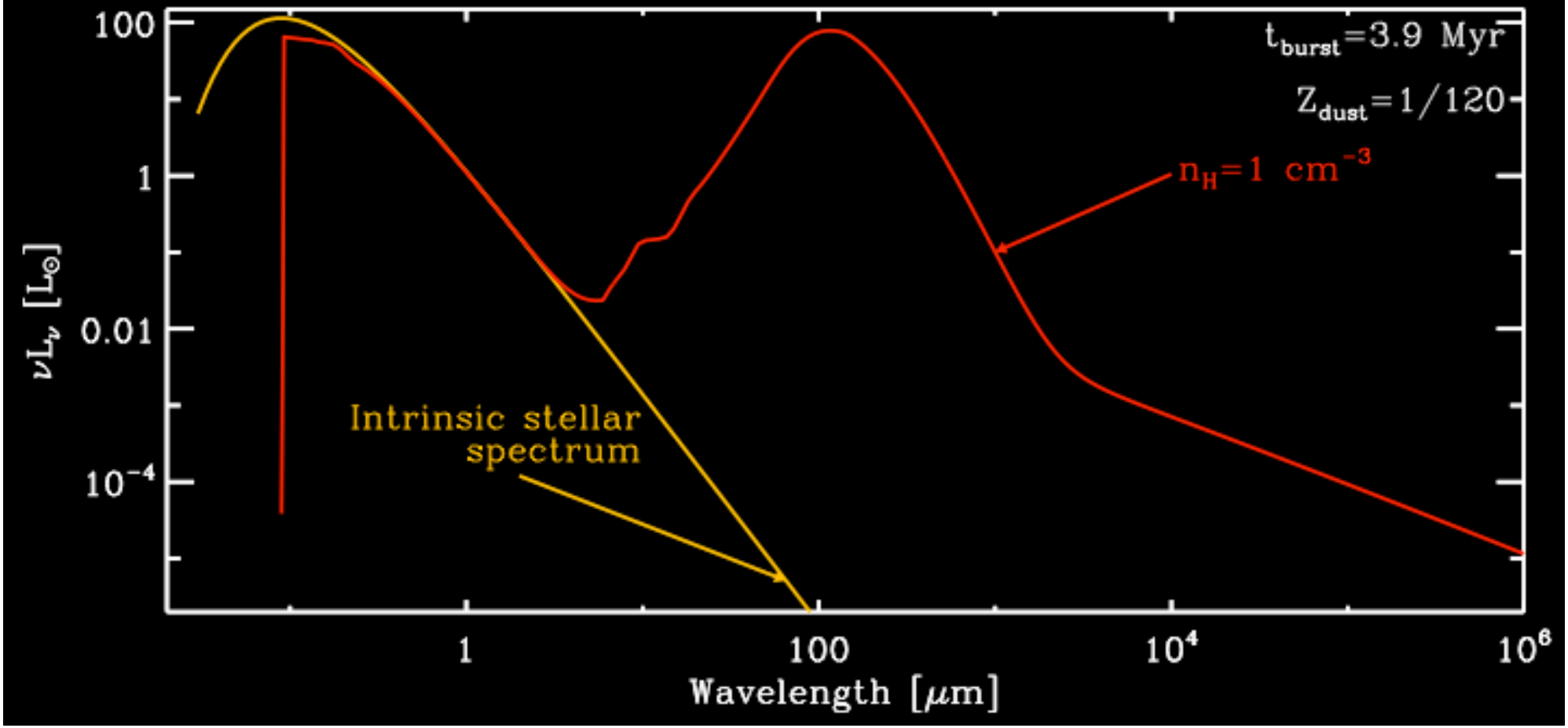
SEDs of H II Regions

- Homogeneous spherical HII regions: constant G2D, no PAHs
- Radiative transfer: competition between gas and dust for absorption of ionizing photons.



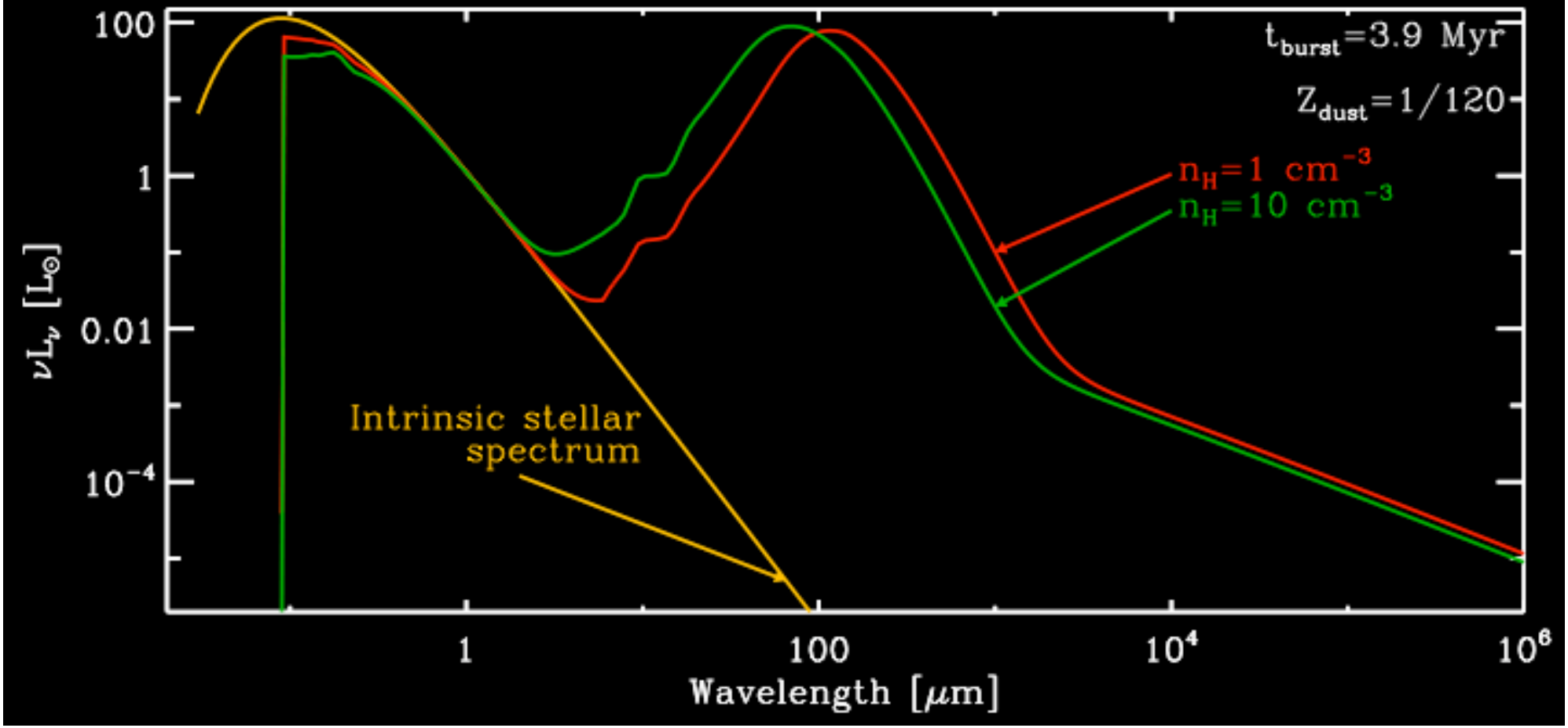
SEDs of H II Regions

- Homogeneous spherical HII regions: constant G2D, no PAHs
- Radiative transfer: competition between gas and dust for absorption of ionizing photons.



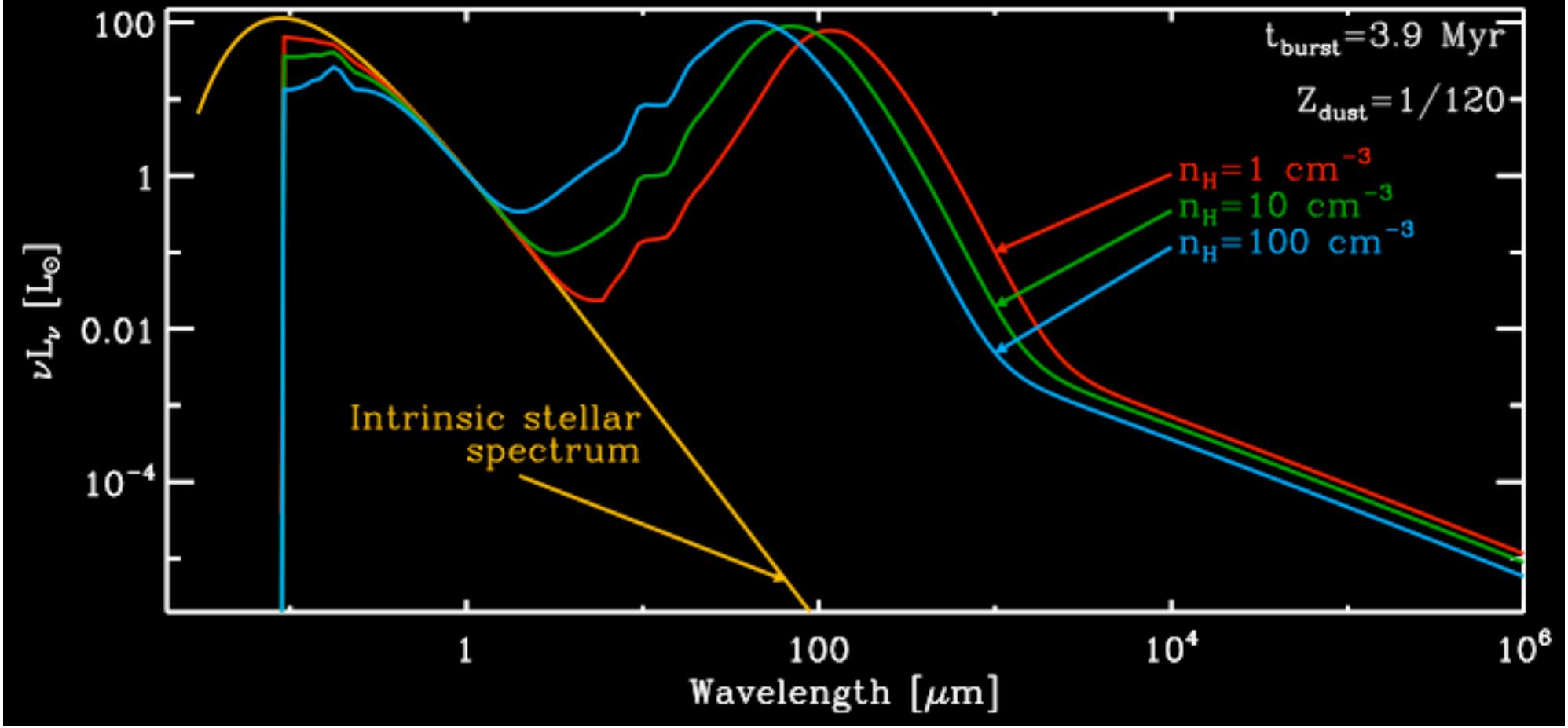
SEDs of H II Regions

- Homogeneous spherical HII regions: constant G2D, no PAHs
- Radiative transfer: competition between gas and dust for absorption of ionizing photons.



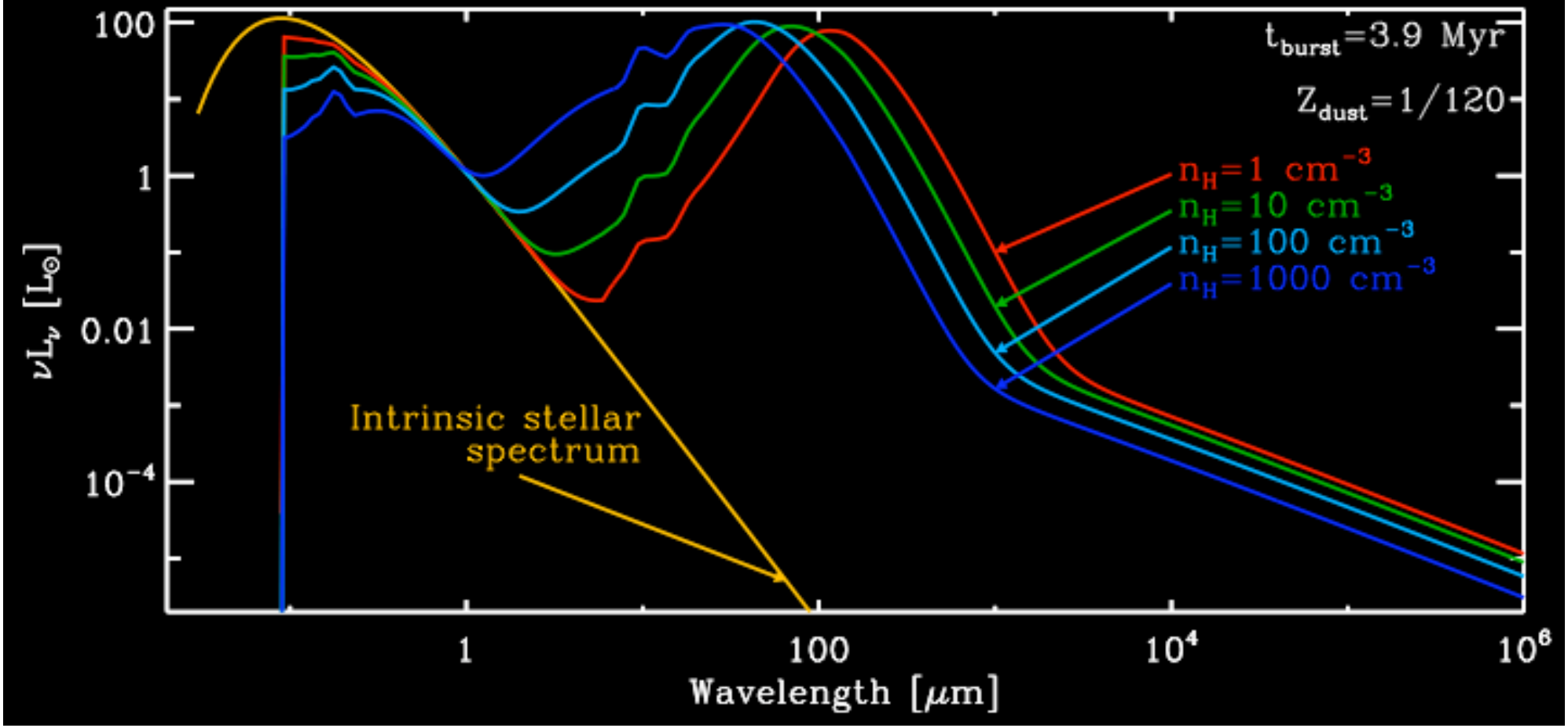
SEDs of H II Regions

- Homogeneous spherical HII regions: constant G2D, no PAHs
- Radiative transfer: competition between gas and dust for absorption of ionizing photons.



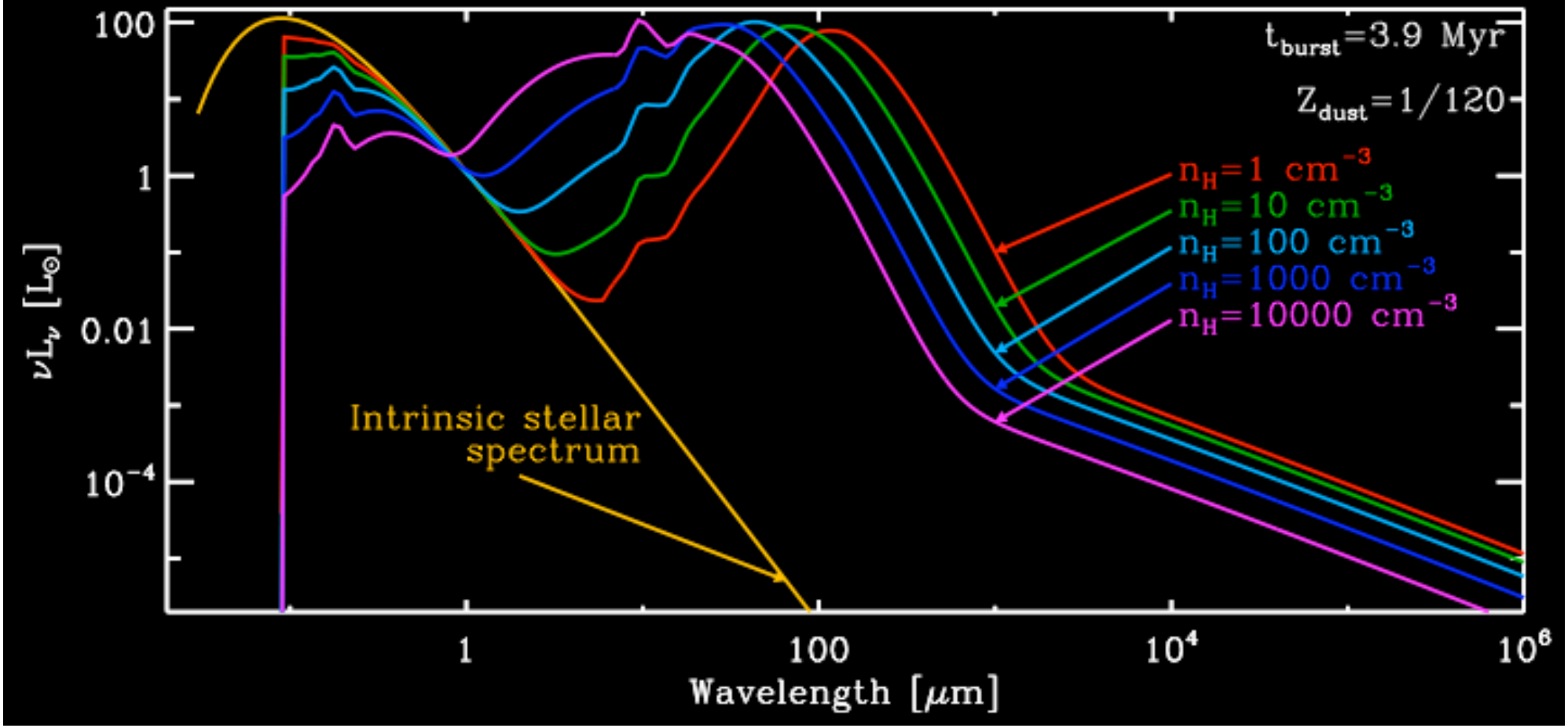
SEDs of H II Regions

- Homogeneous spherical HII regions: constant G2D, no PAHs
- Radiative transfer: competition between gas and dust for absorption of ionizing photons.



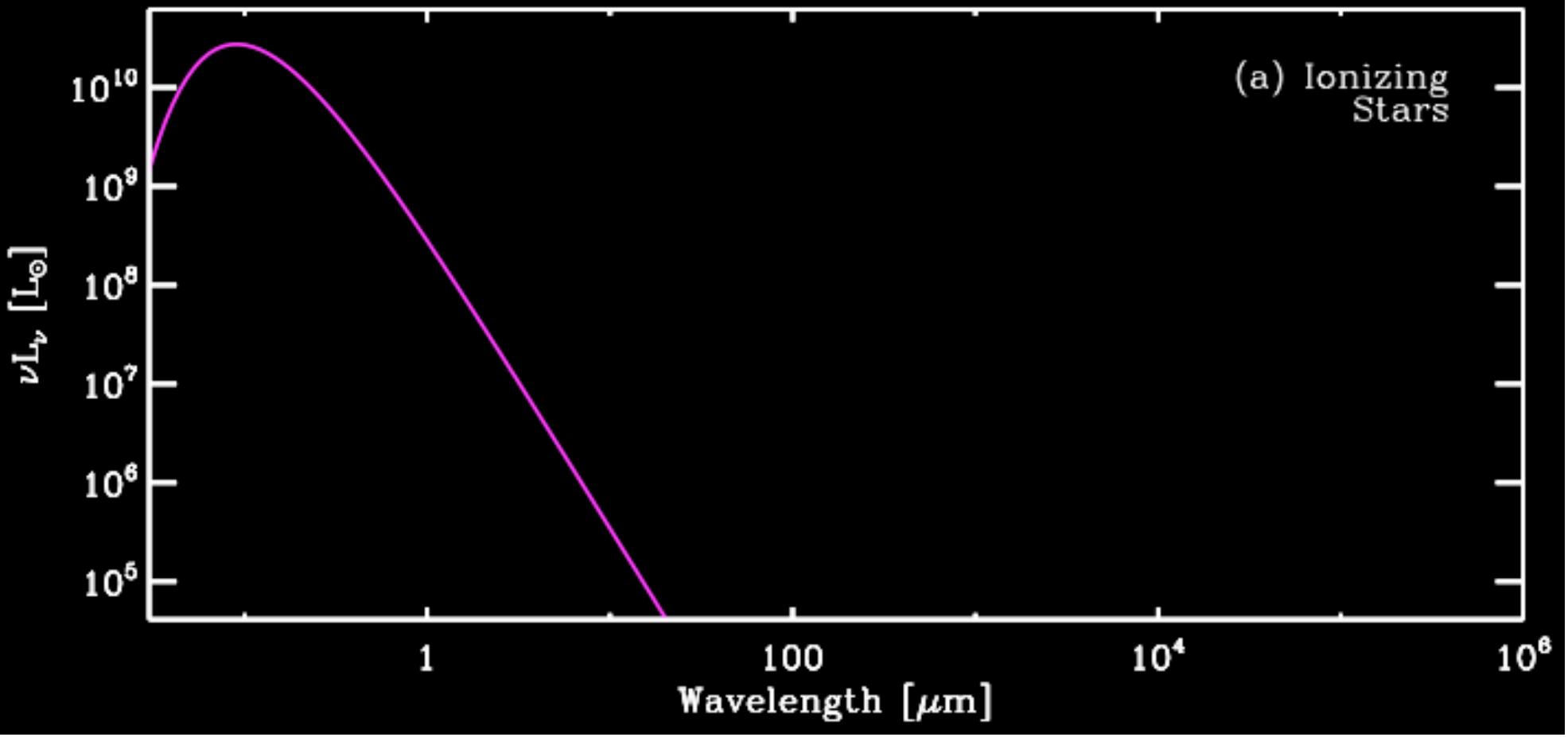
SEDs of H II Regions

- Homogeneous spherical HII regions: constant G2D, no PAHs
- Radiative transfer: competition between gas and dust for absorption of ionizing photons.



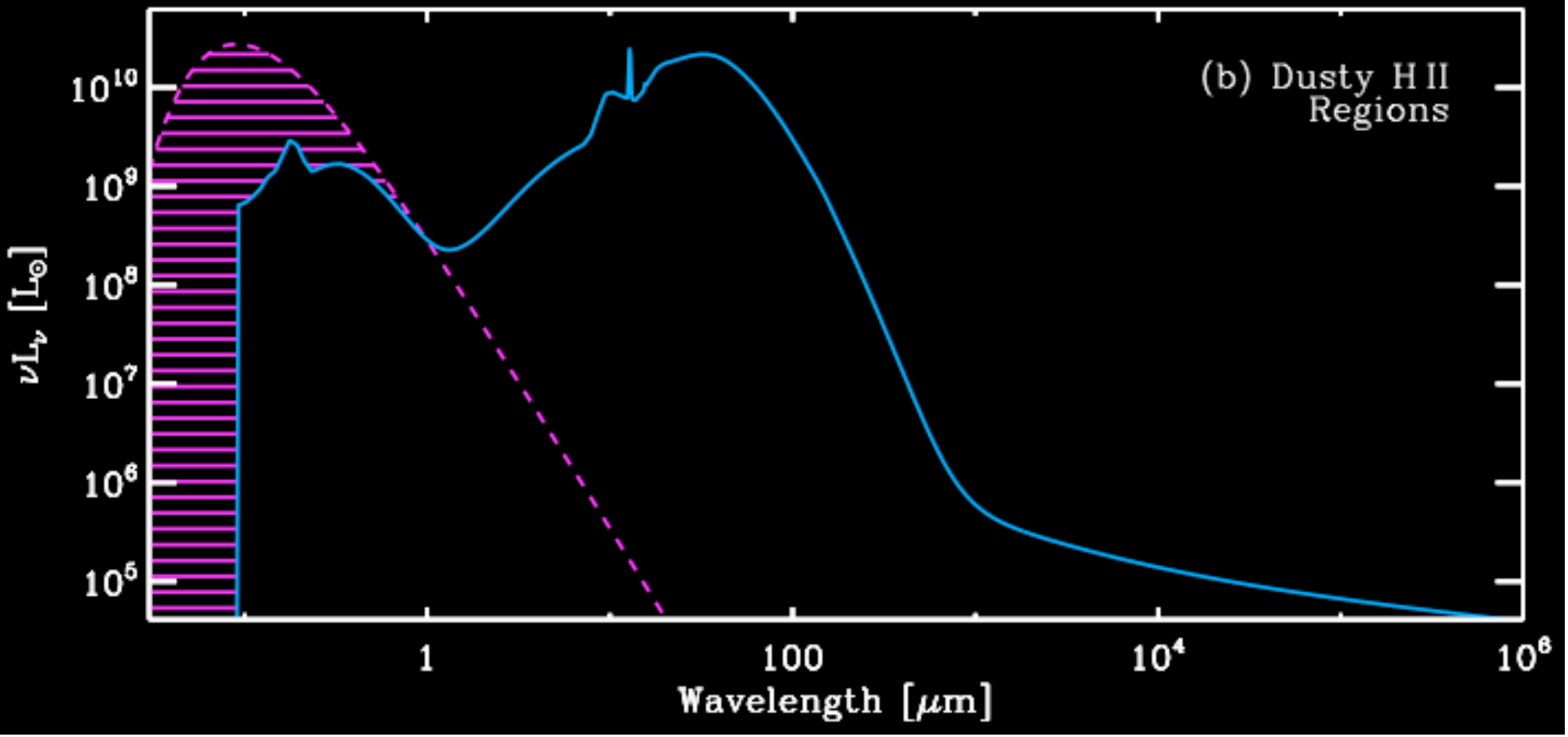
Schemtaic of the SED Model

- ✓ HII regions: constraints on the density from free-free.
- ✓ "PDR": molecular clouds & diffuse ISM.



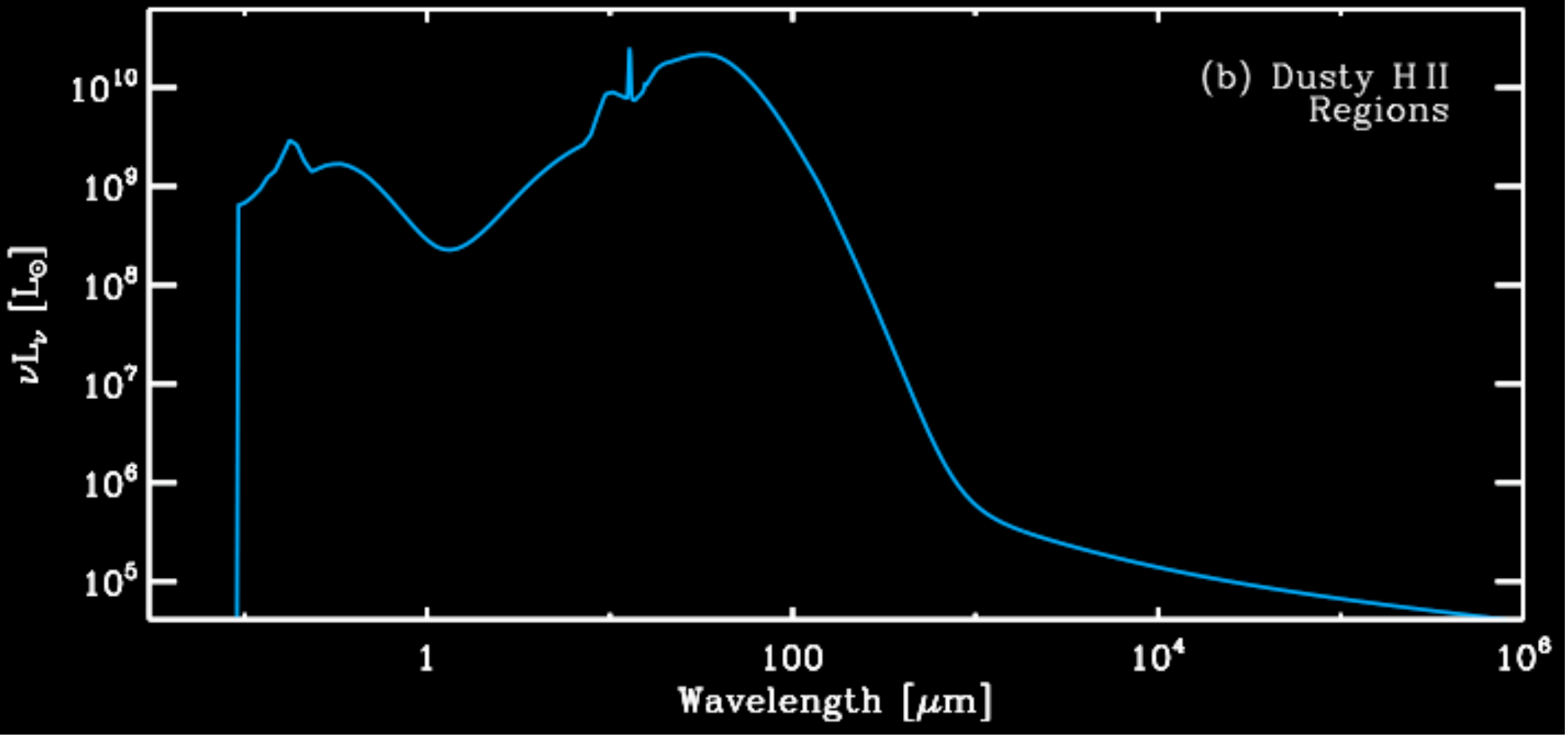
Schemtaic of the SED Model

- ✓ HII regions: constraints on the density from free-free.
- ✓ "PDR": molecular clouds & diffuse ISM.



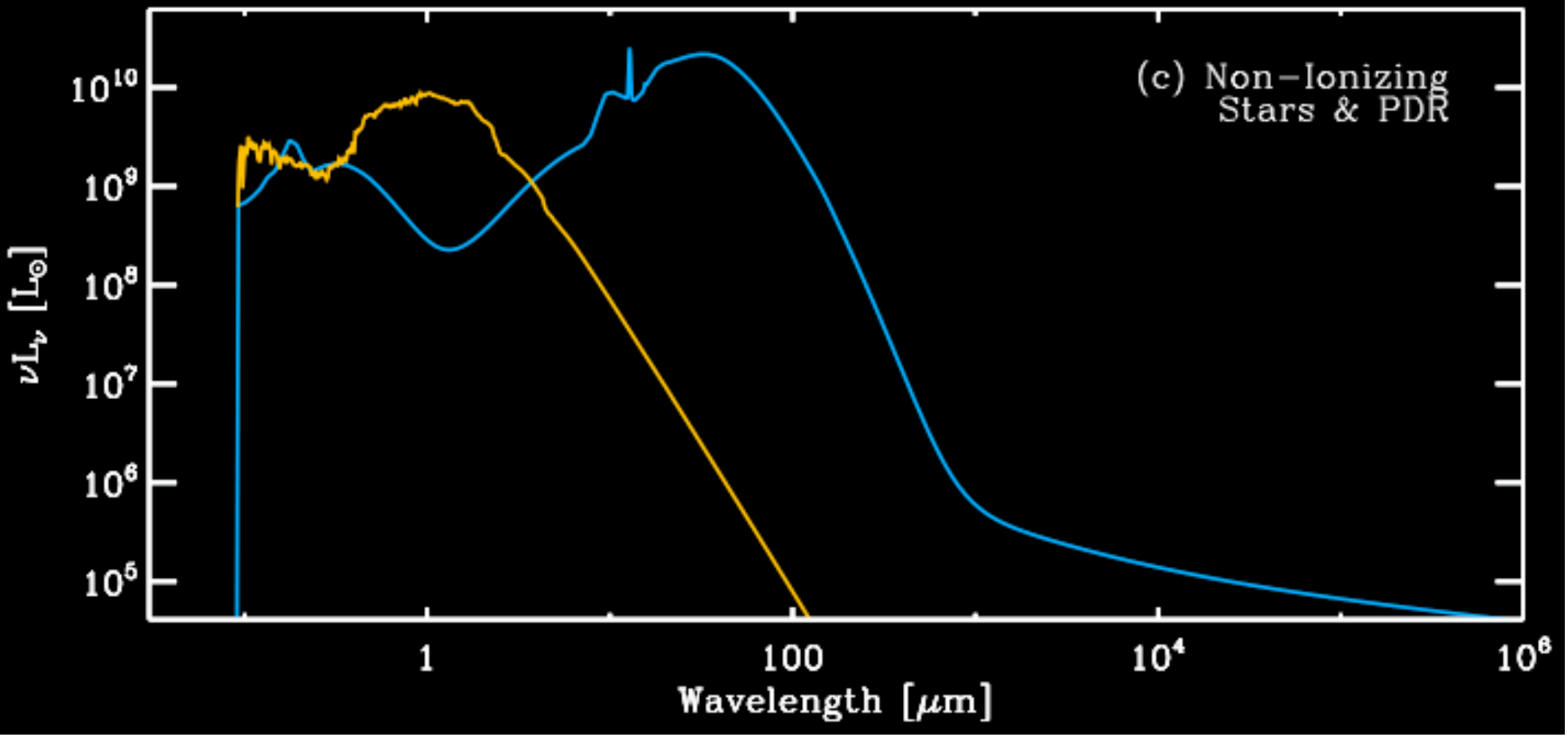
Schemtaic of the SED Model

- ✓ HII regions: constraints on the density from free-free.
- ✓ "PDR": molecular clouds & diffuse ISM.



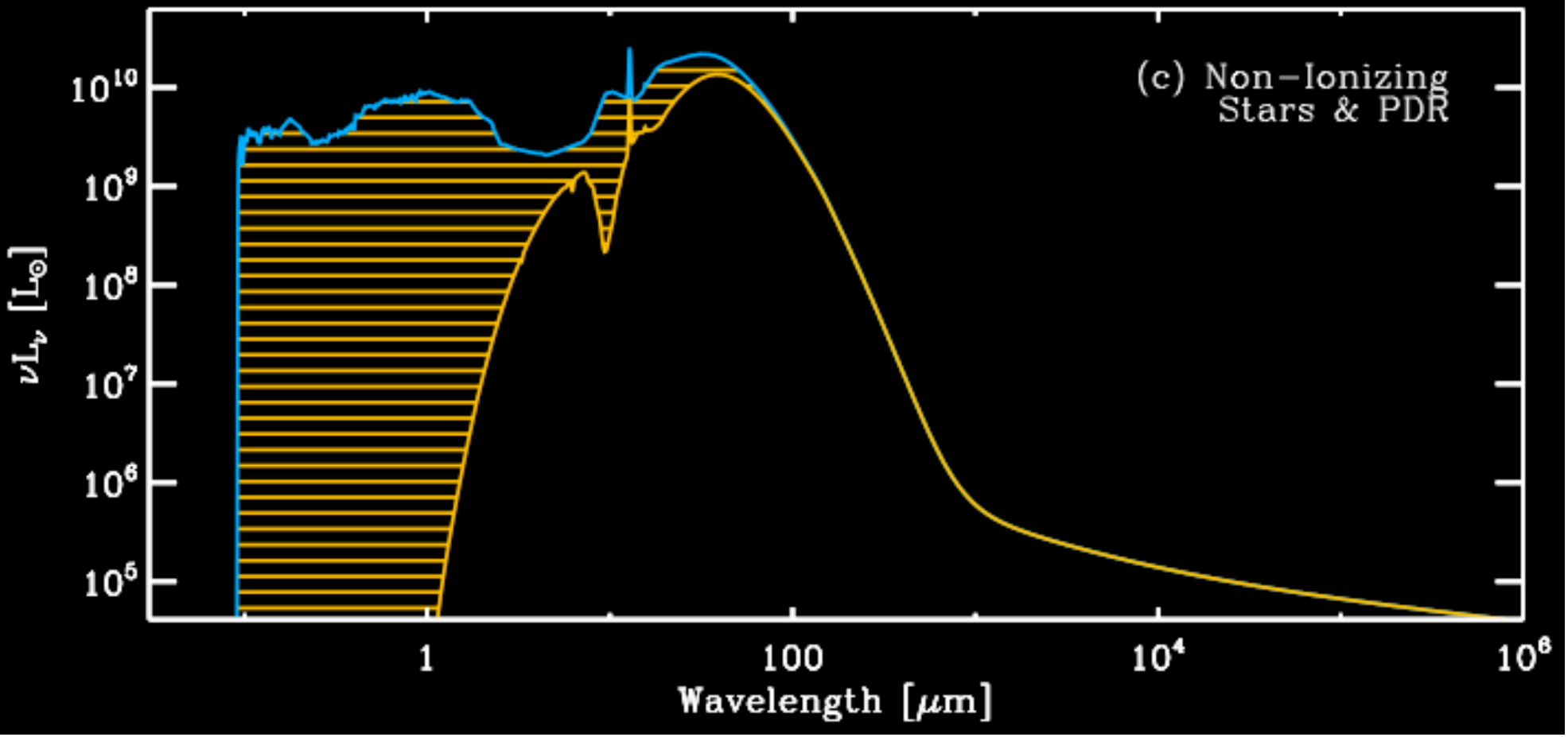
Schemtaic of the SED Model

- ✓ HII regions: constraints on the density from free-free.
- ✓ "PDR": molecular clouds & diffuse ISM.



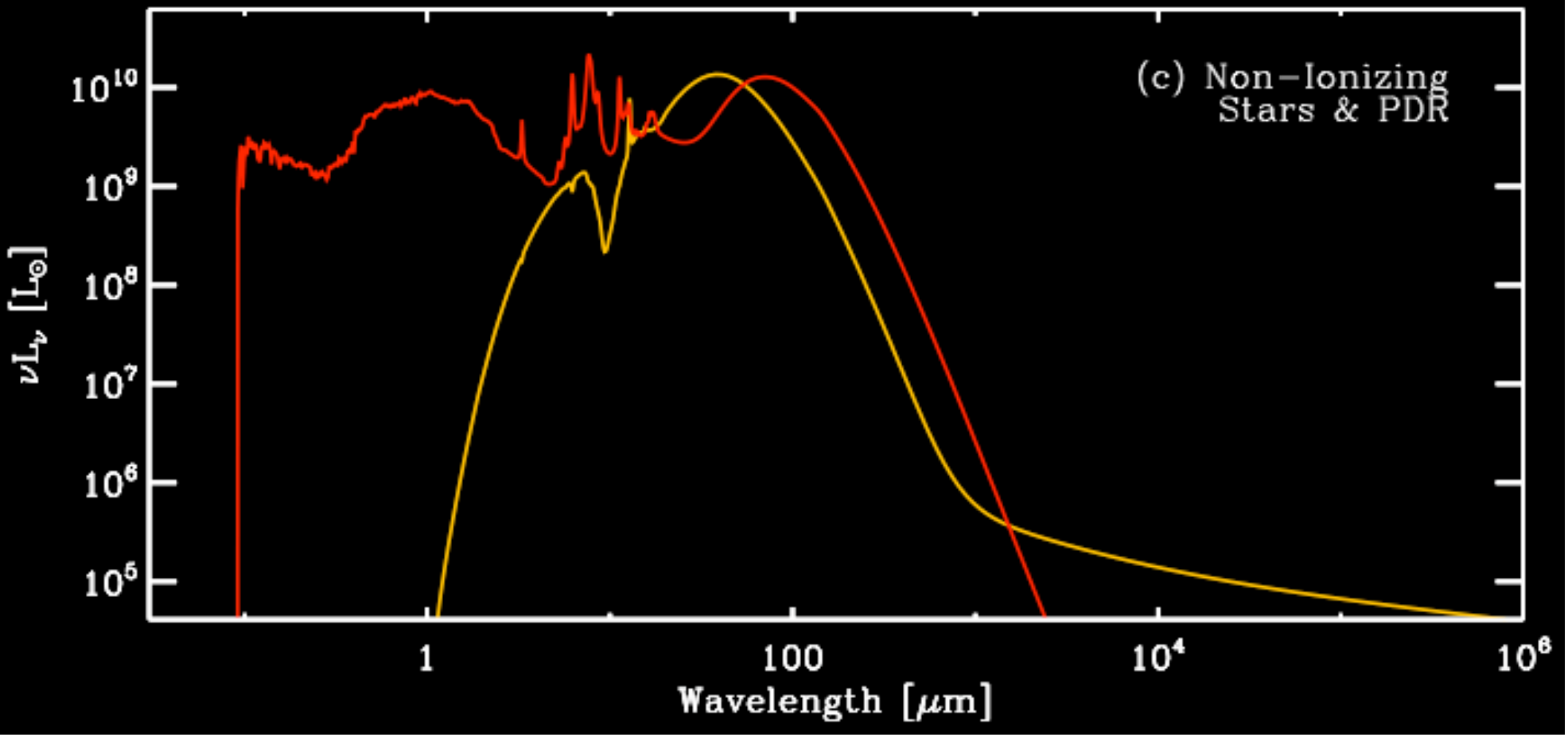
Schemtaic of the SED Model

- ✓ HII regions: constraints on the density from free-free.
- ✓ "PDR": molecular clouds & diffuse ISM.



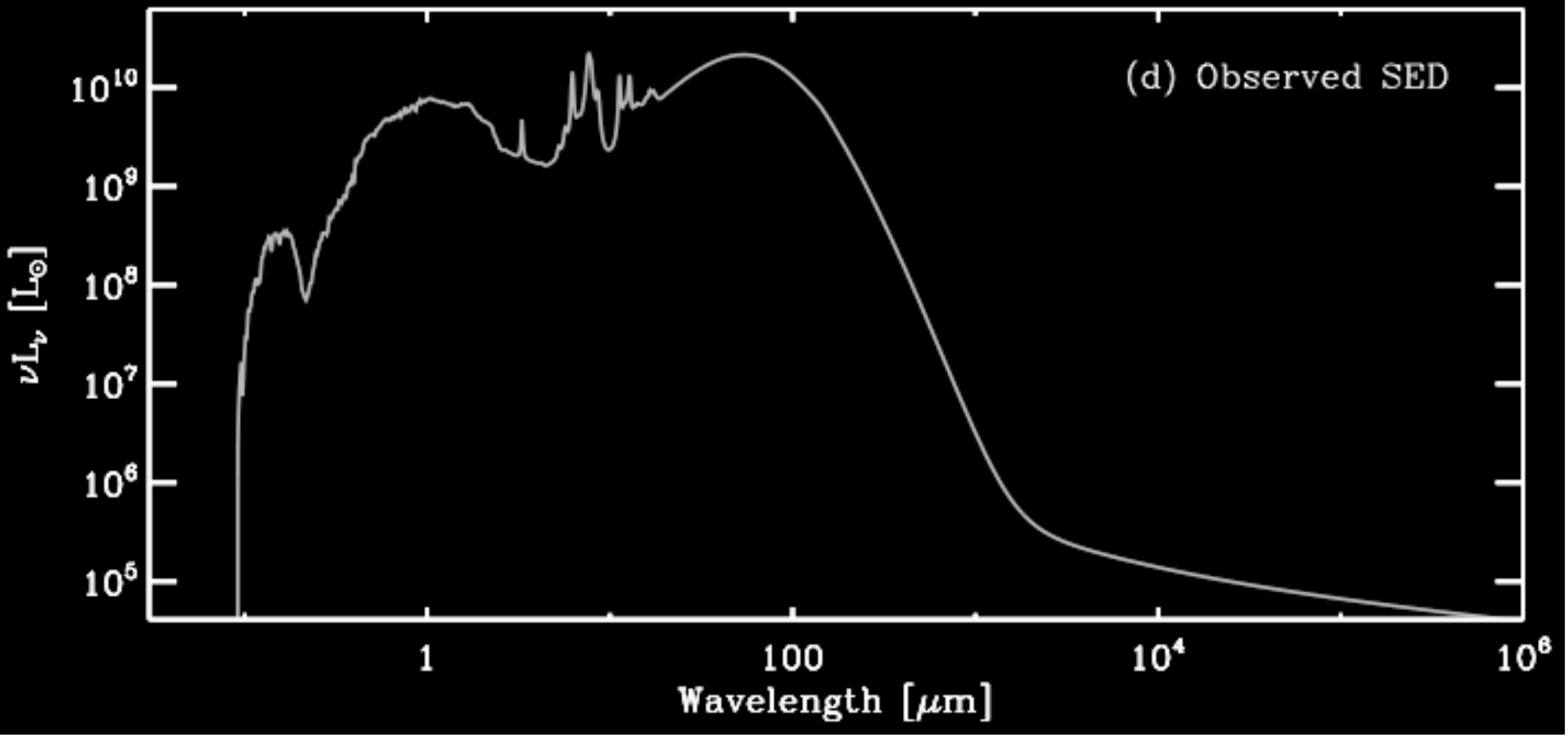
Schemtaic of the SED Model

- ✓ HII regions: constraints on the density from free-free.
- ✓ "PDR": molecular clouds & diffuse ISM.

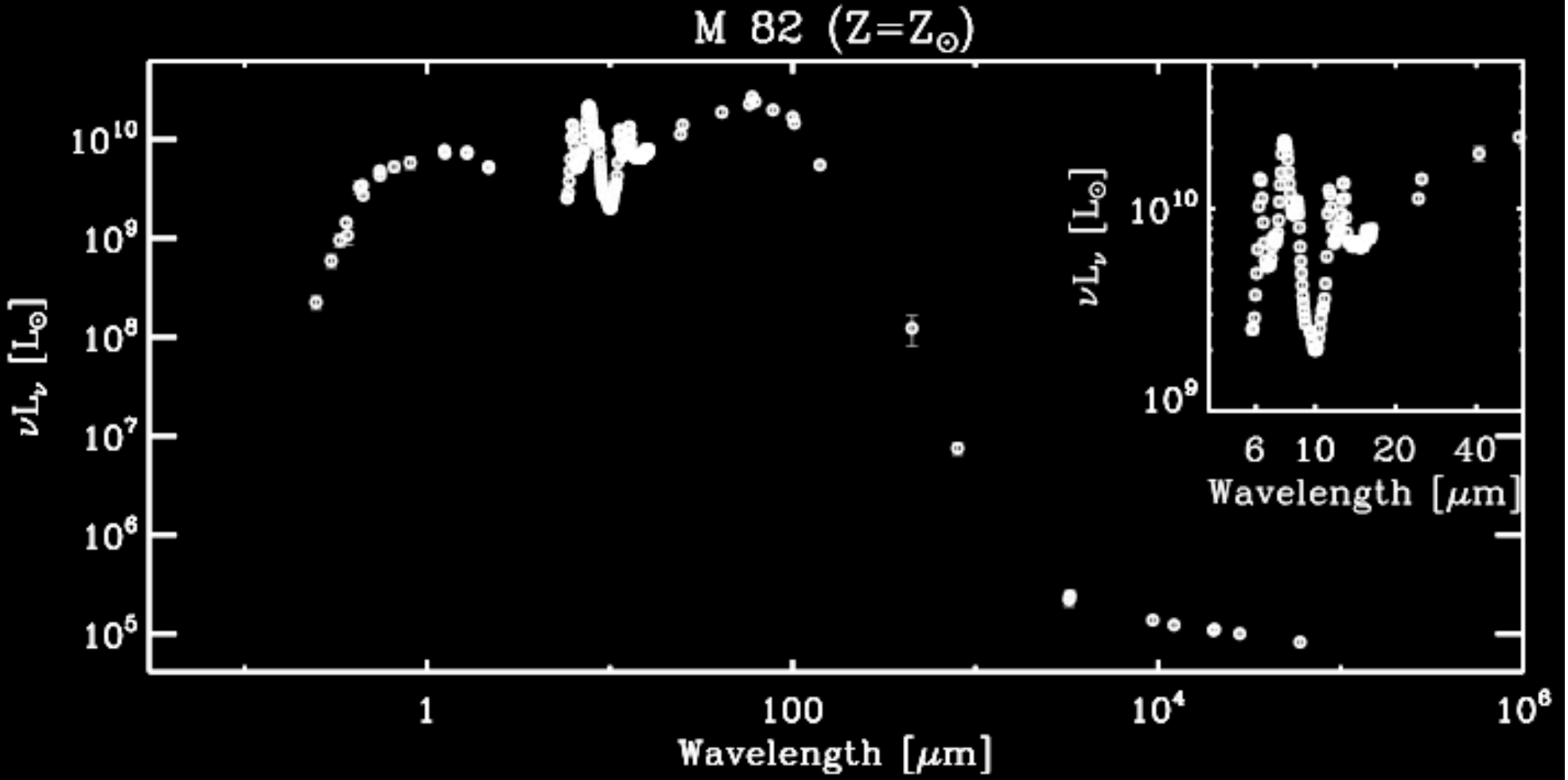


Schemtaic of the SED Model

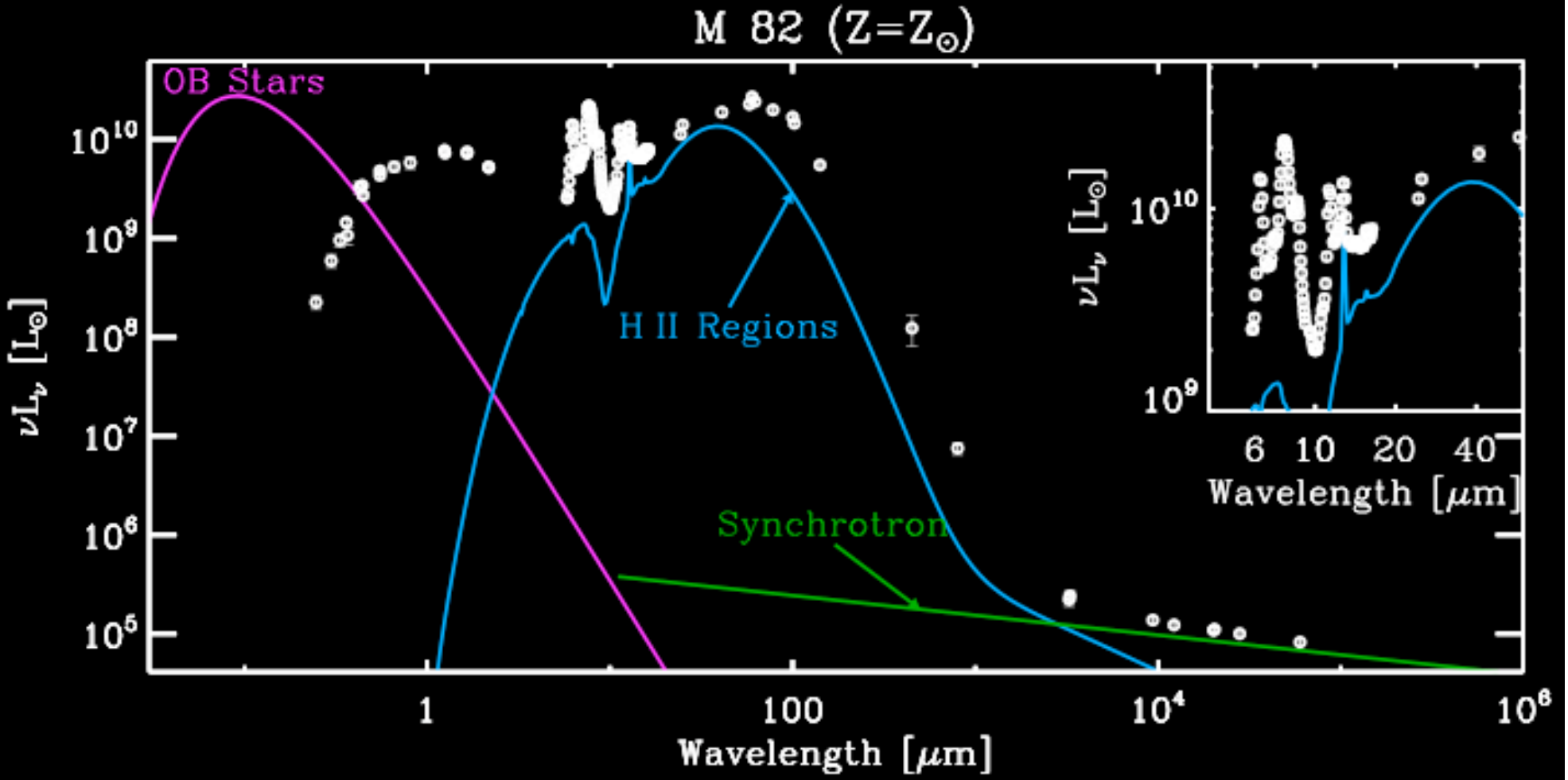
- ✓ HII regions: constraints on the density from free-free.
- ✓ "PDR": molecular clouds & diffuse ISM.



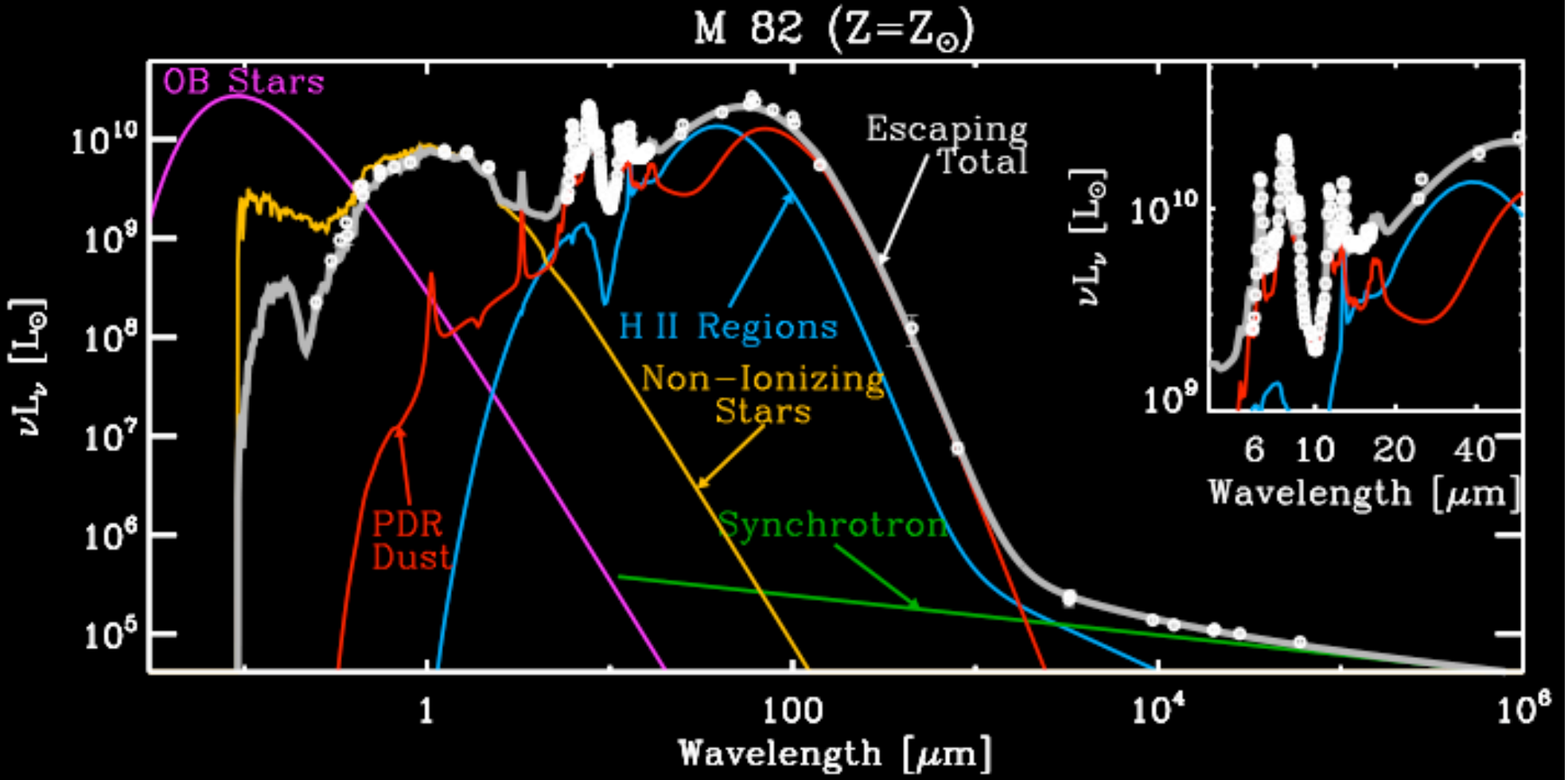
Panchromatic SEDs of Select Objects (1/2)



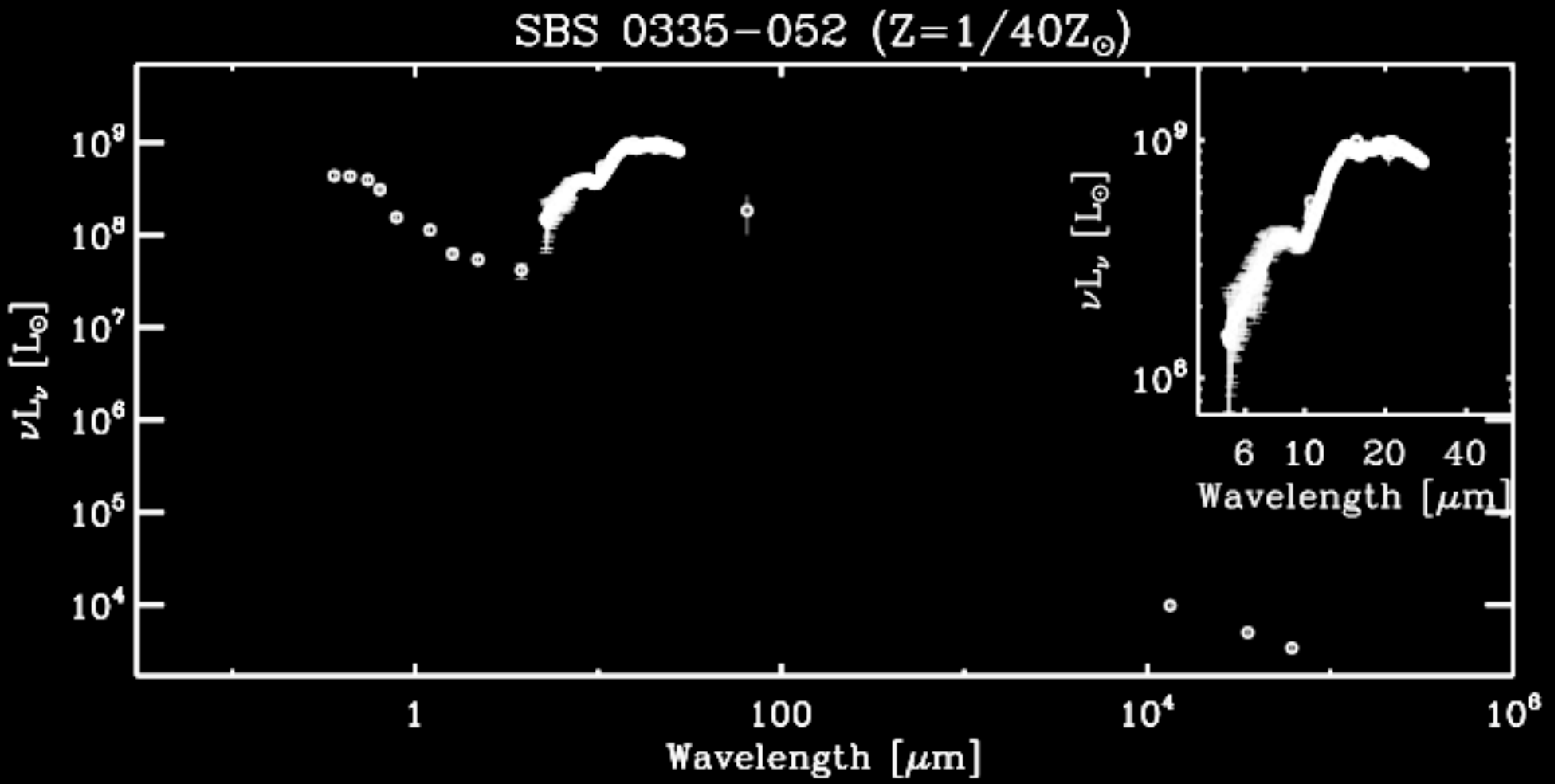
Panchromatic SEDs of Select Objects (1/2)



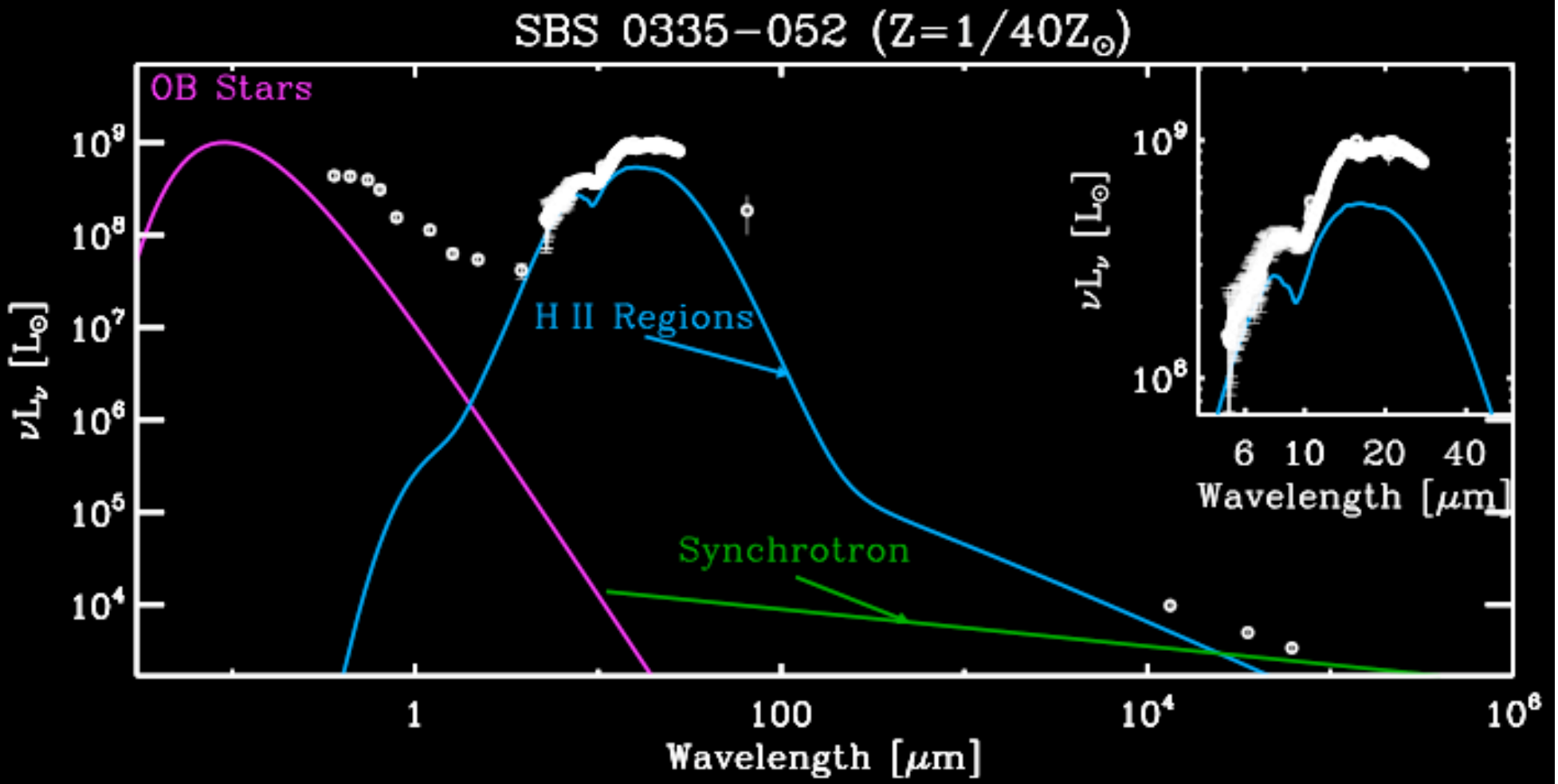
Panchromatic SEDs of Select Objects (1/2)



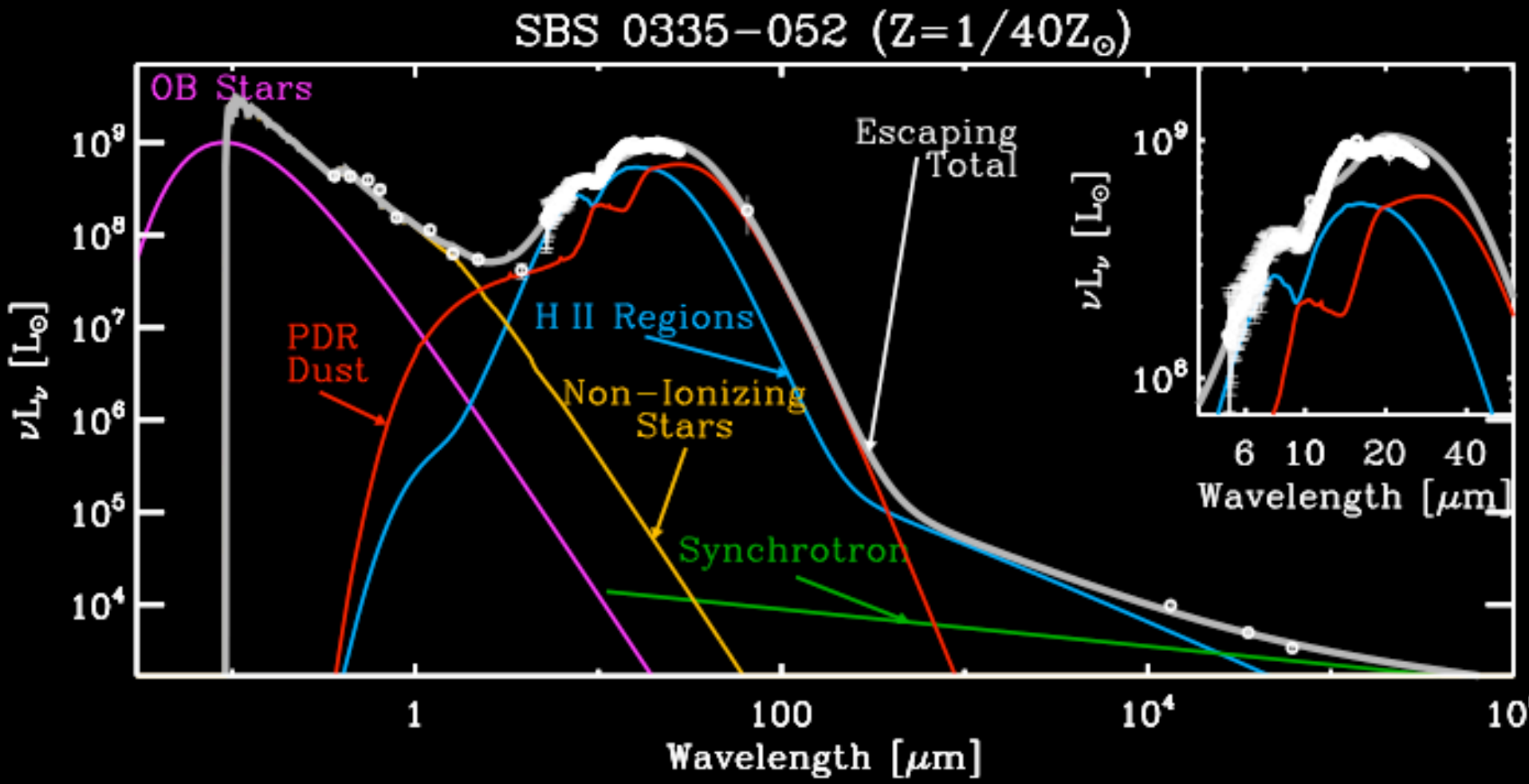
Panchromatic SEDs of Select Objects (2/2)



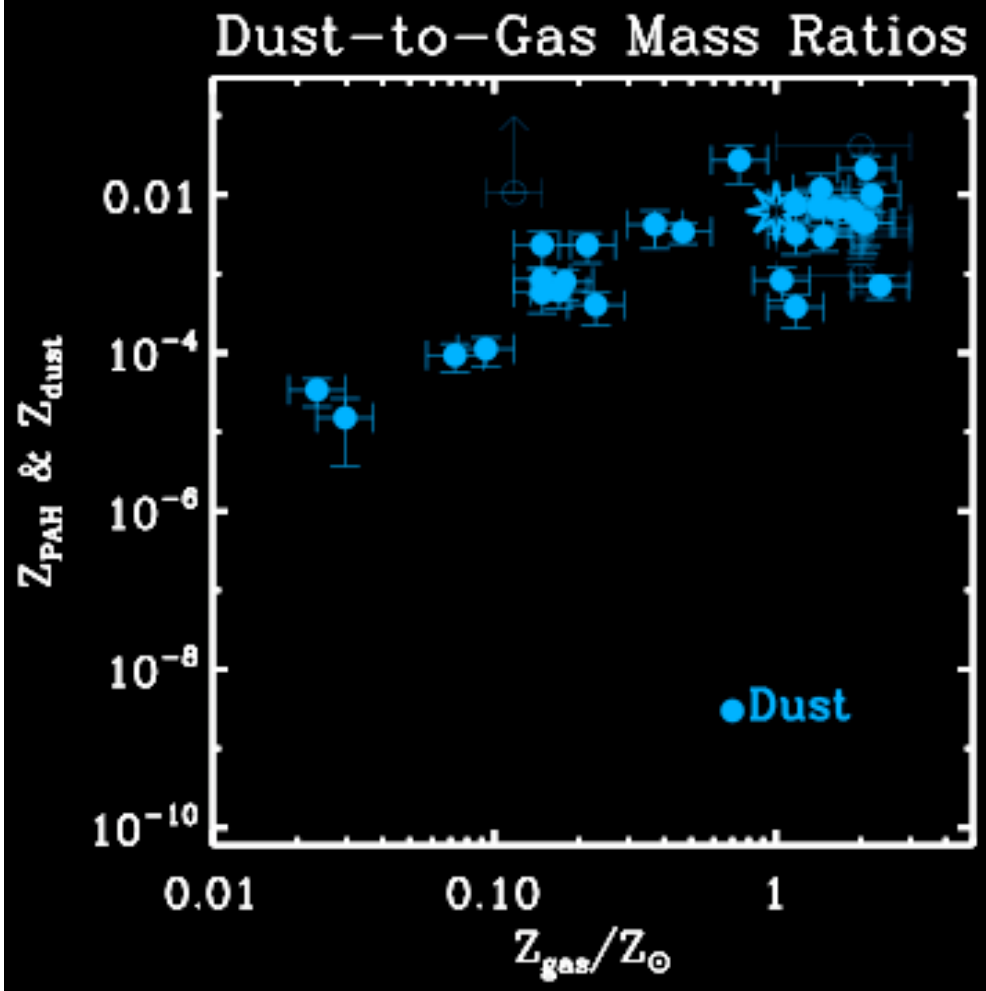
Panchromatic SEDs of Select Objects (2/2)



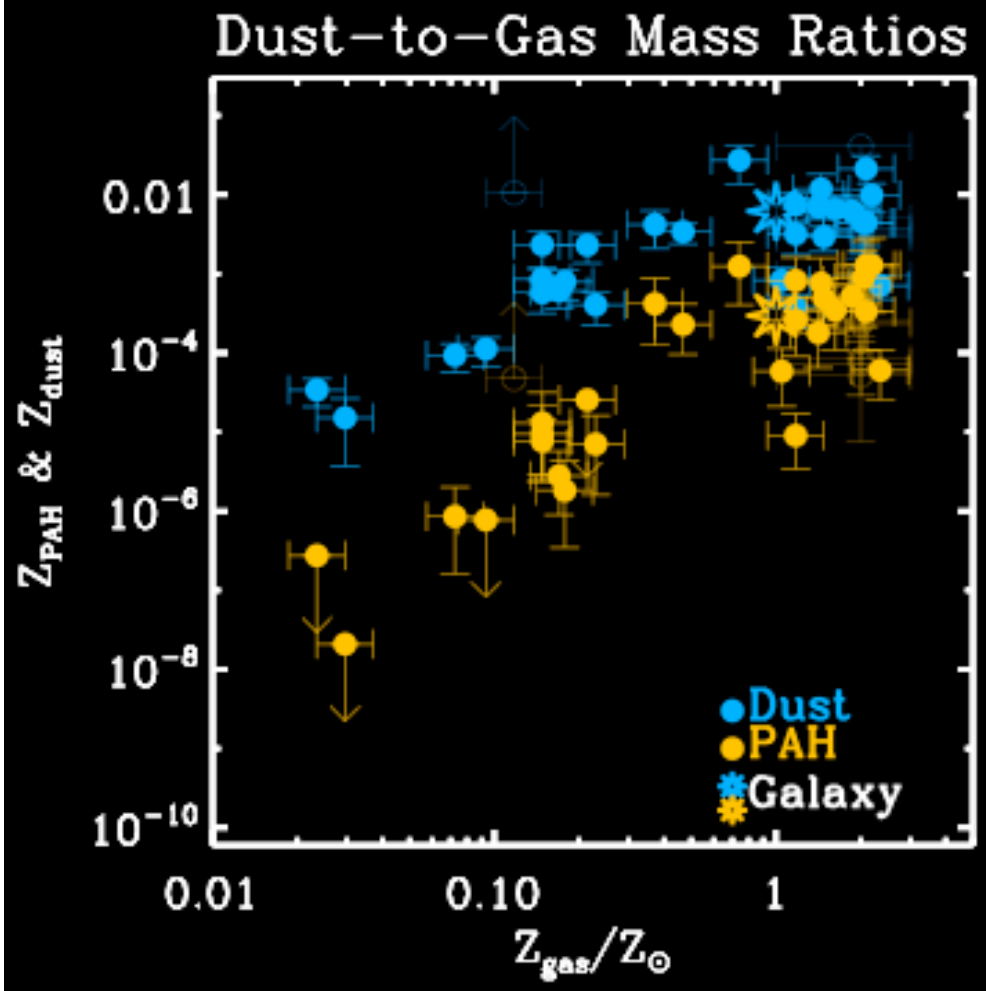
Panchromatic SEDs of Select Objects (2/2)



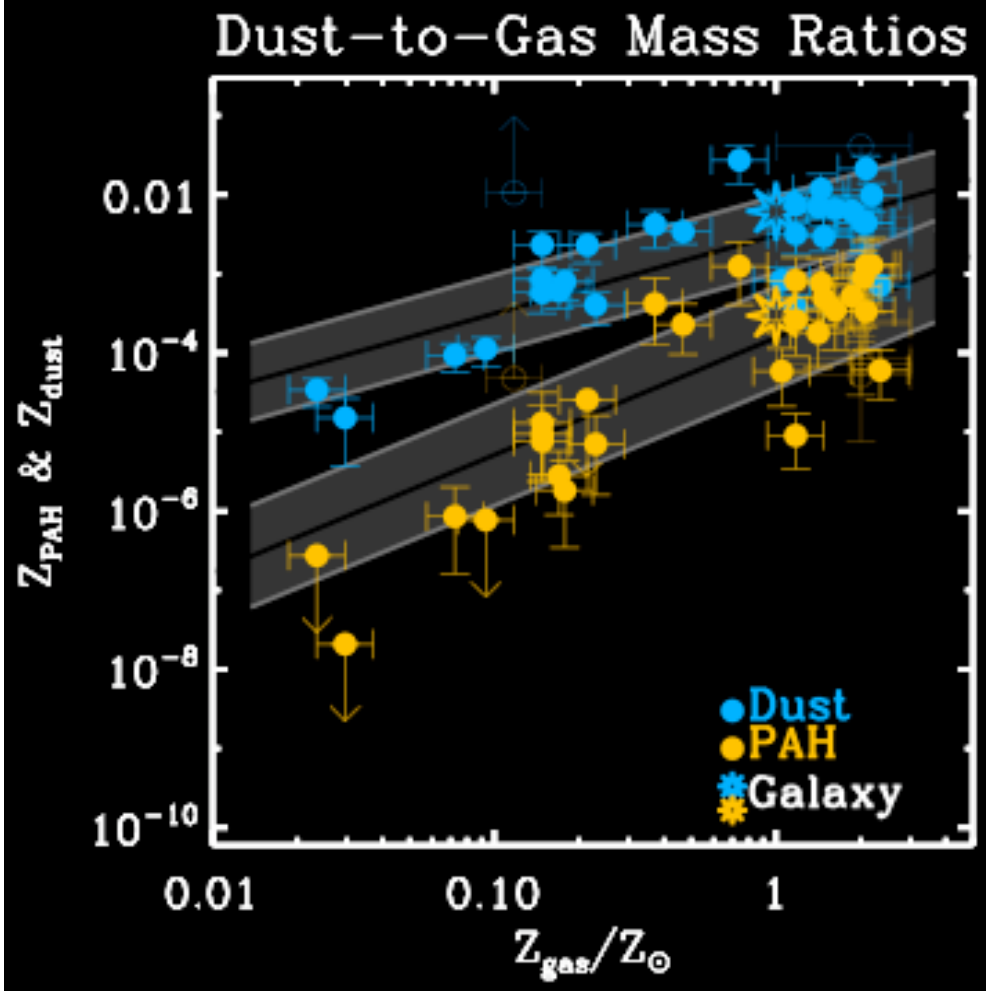
Evolution of the PAH and Dust Abundances



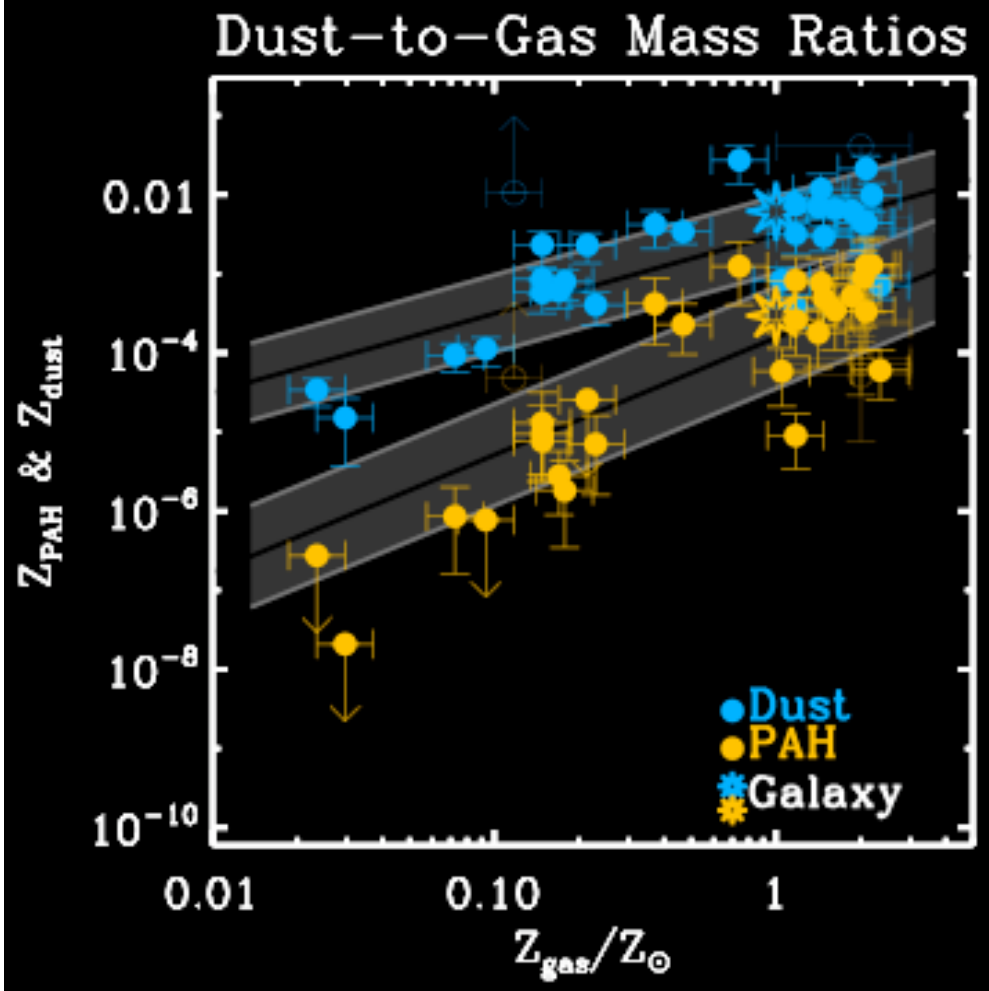
Evolution of the PAH and Dust Abundances

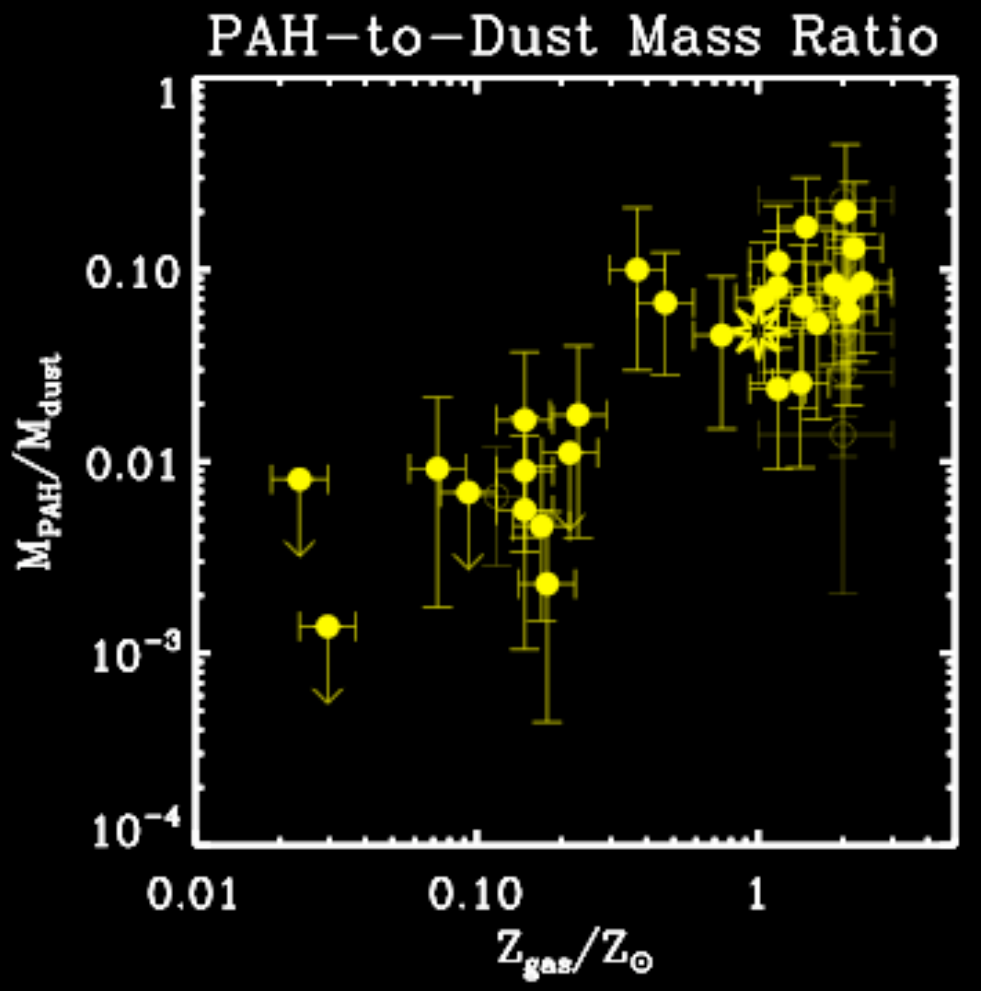


Evolution of the PAH and Dust Abundances

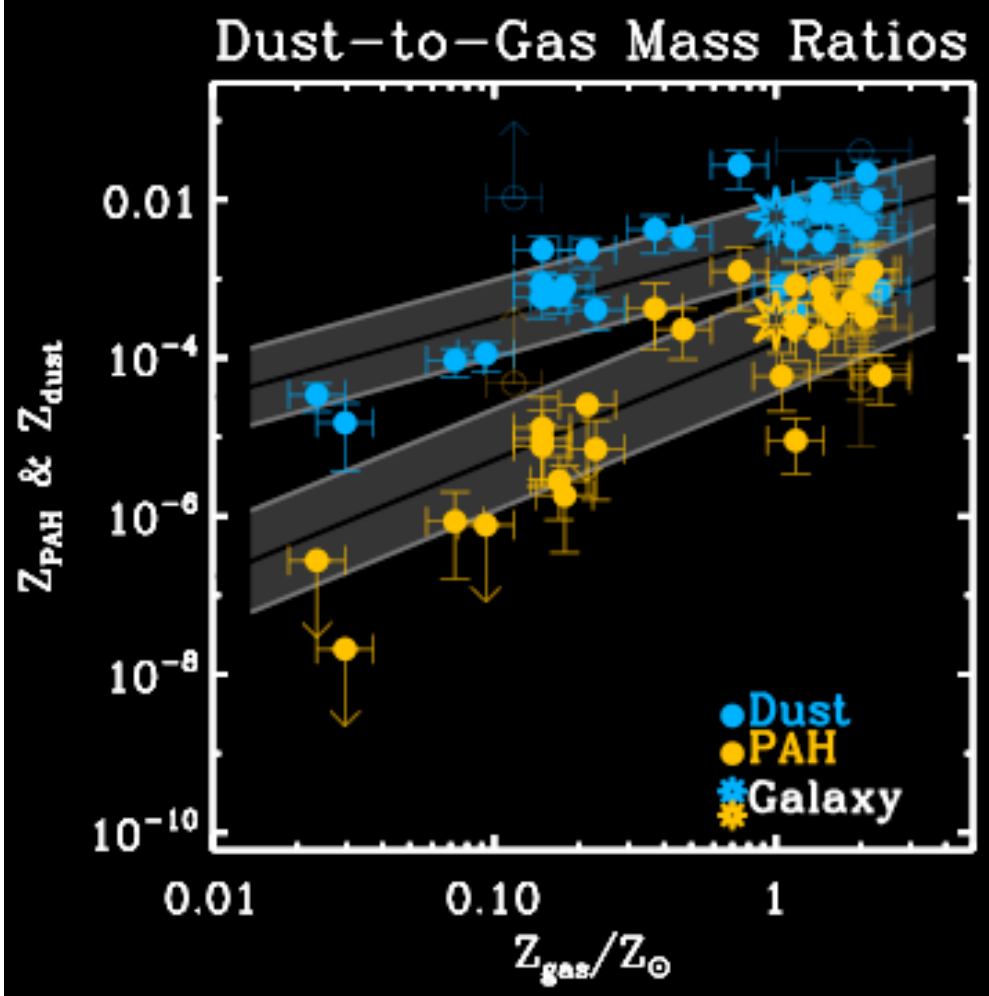


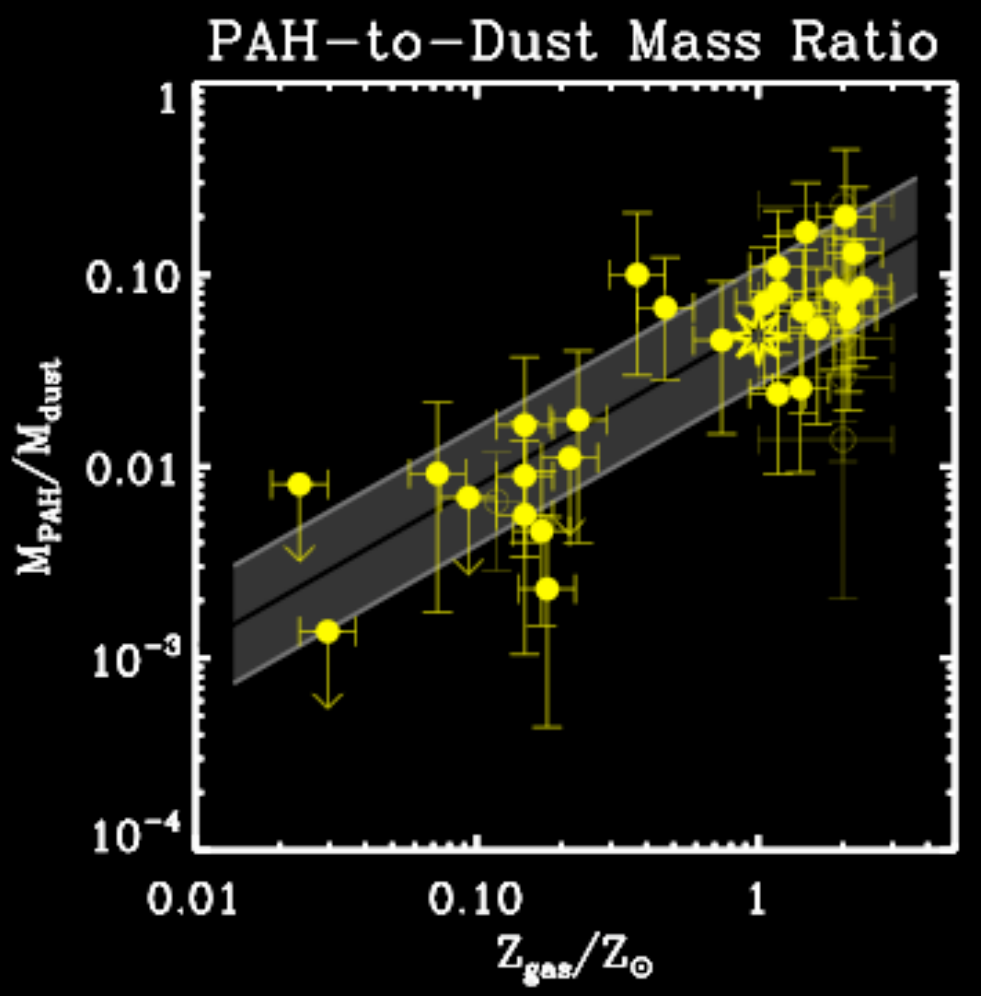
Evolution of the PAH and Dust Abundances



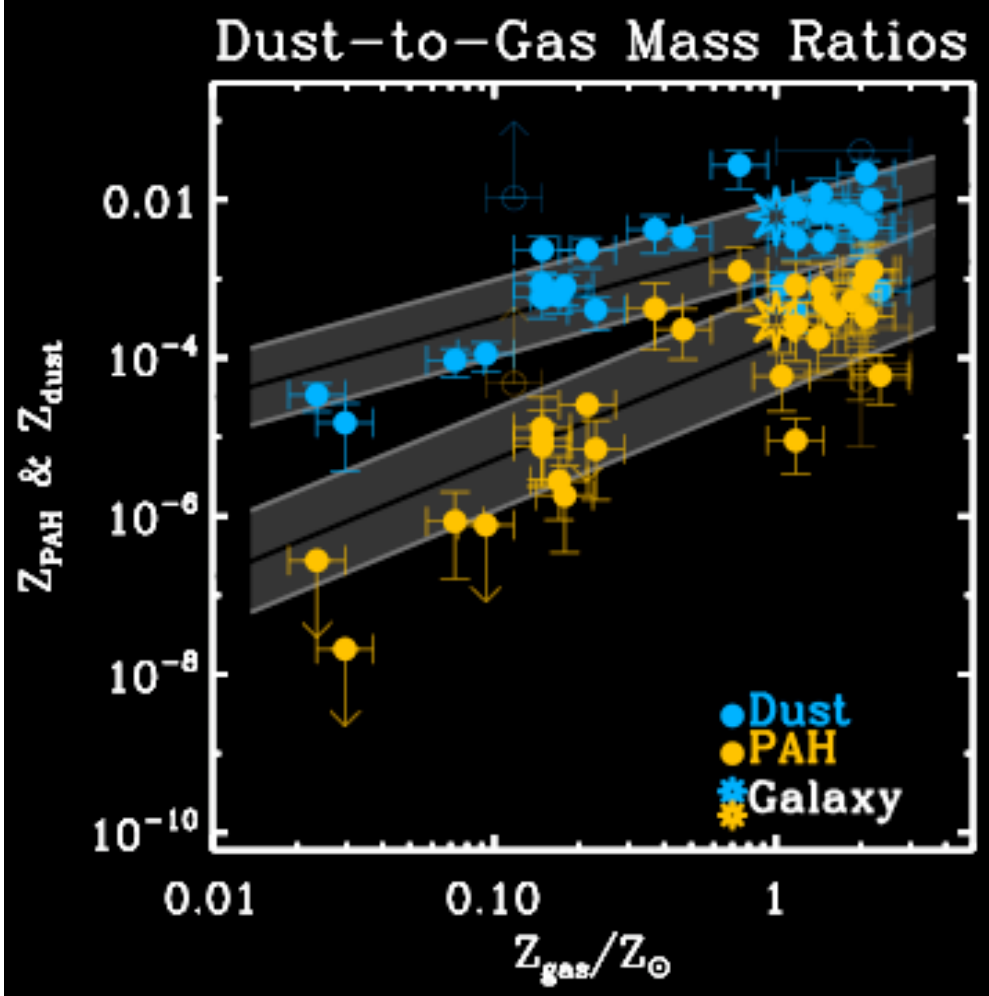


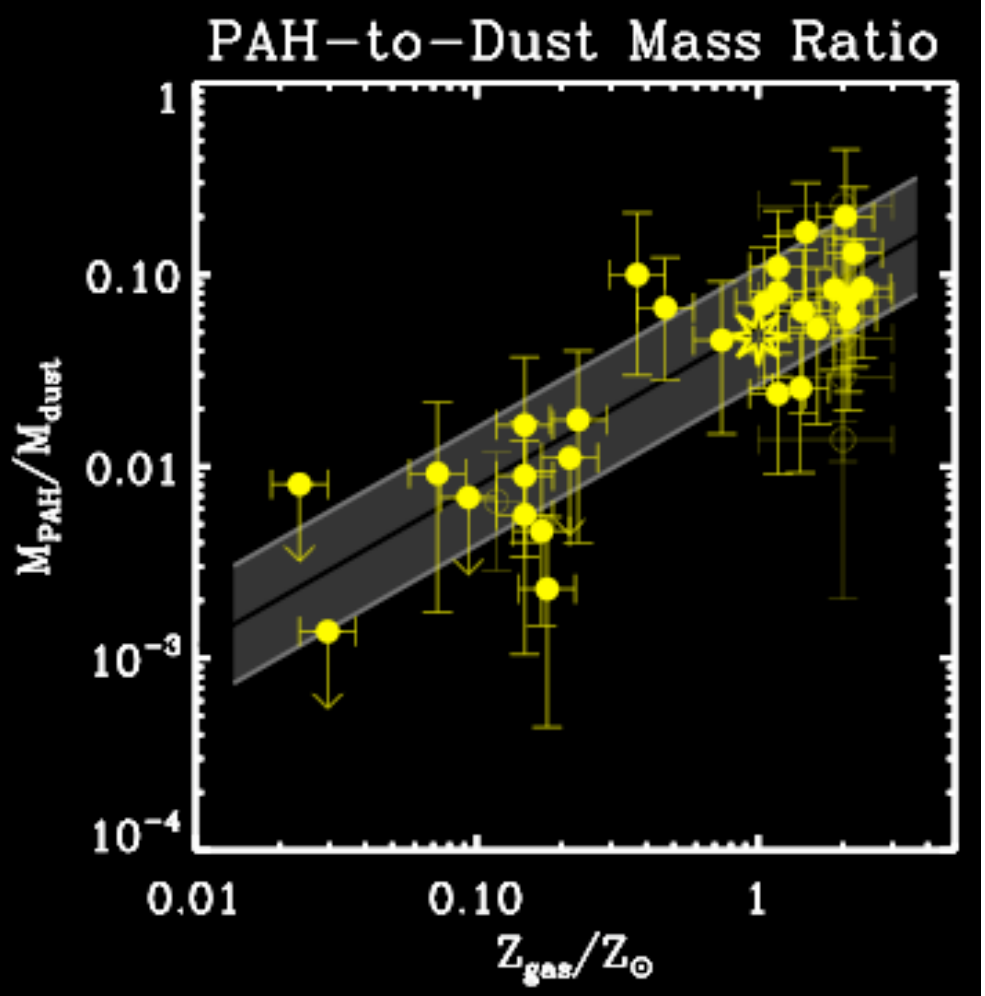
Evolution of the PAH and Dust Abundances





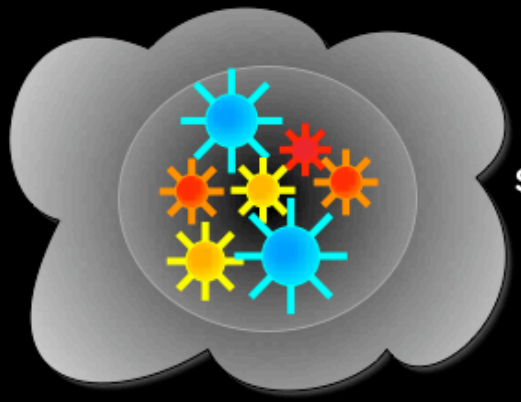
Evolution of the PAH and Dust Abundances





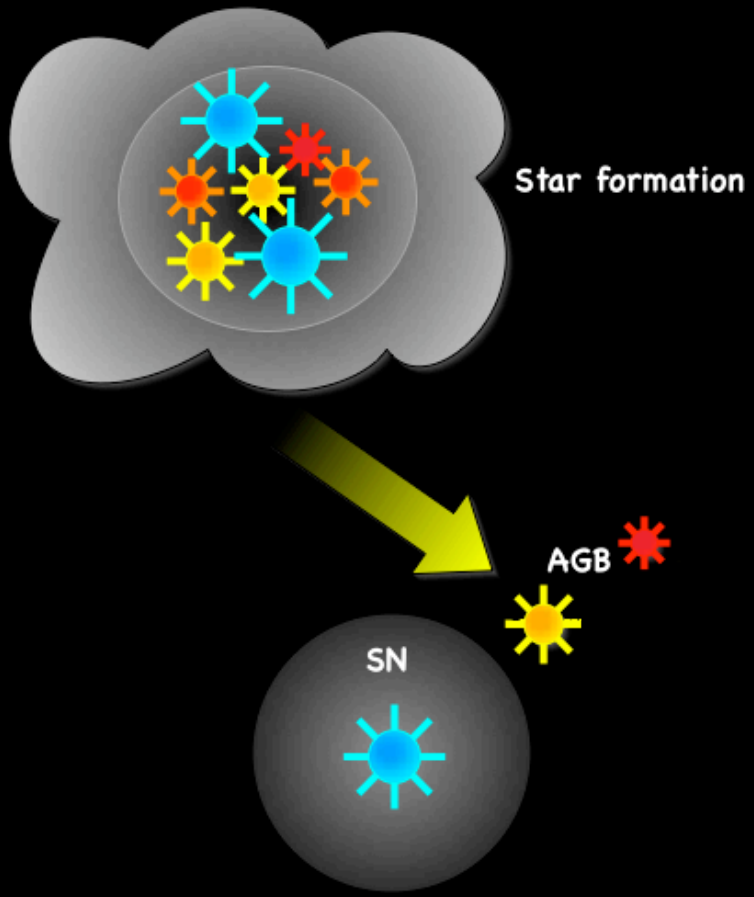
- Distinct evolutionary trends between PAHs and Dust.
- Benchmark for evolution models: comparison with theory.

A Model for the Evolution of Elements and Dust

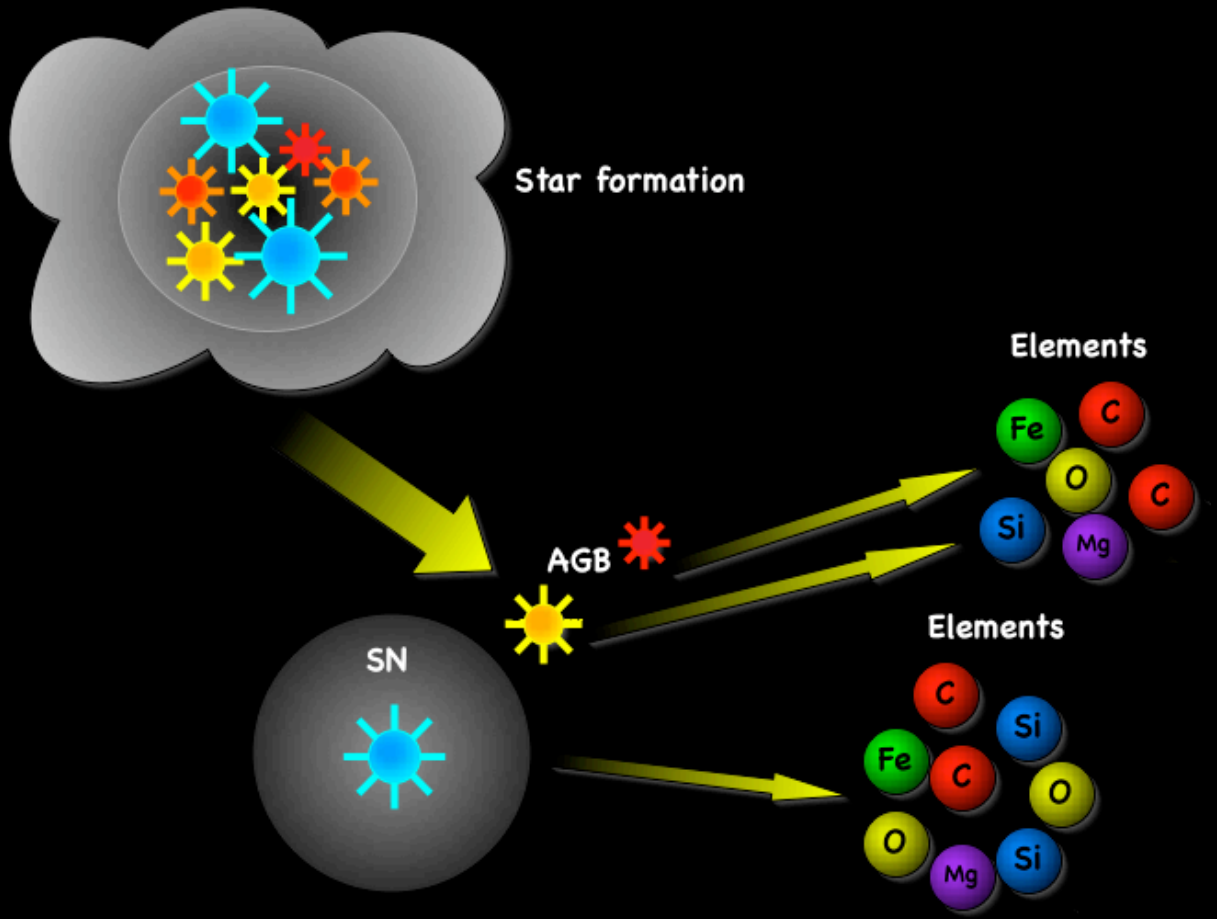


Star formation

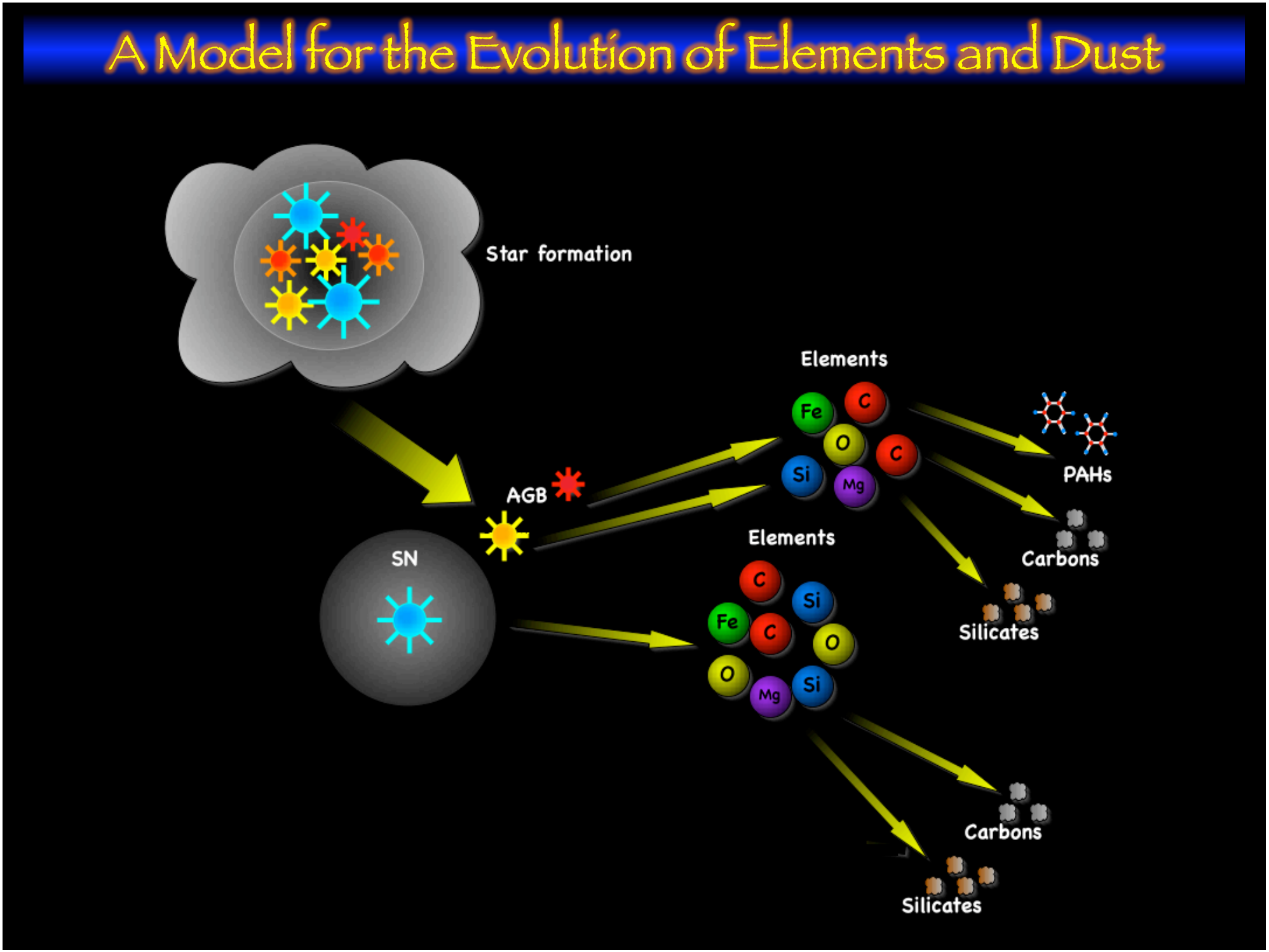
A Model for the Evolution of Elements and Dust



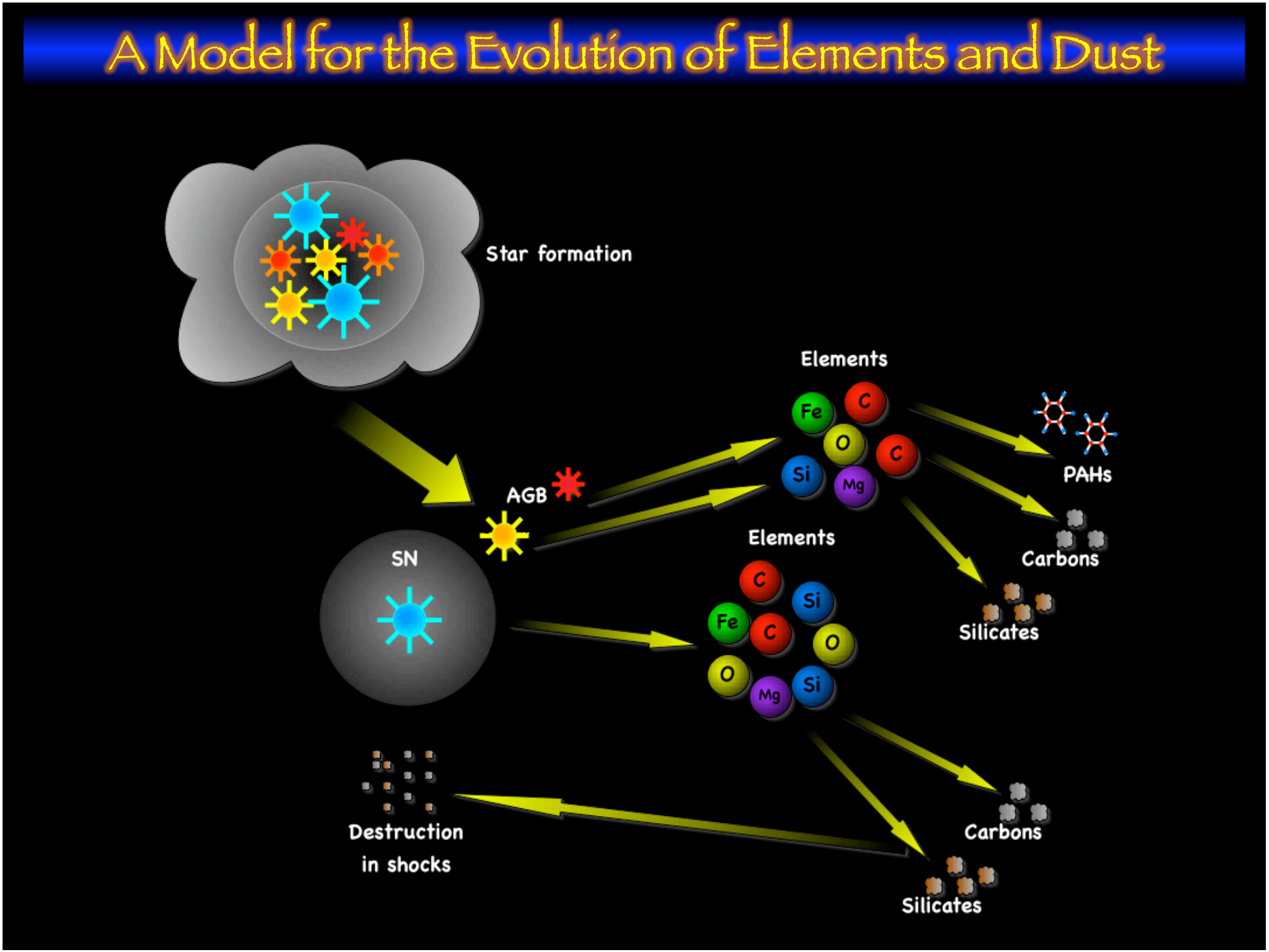
A Model for the Evolution of Elements and Dust



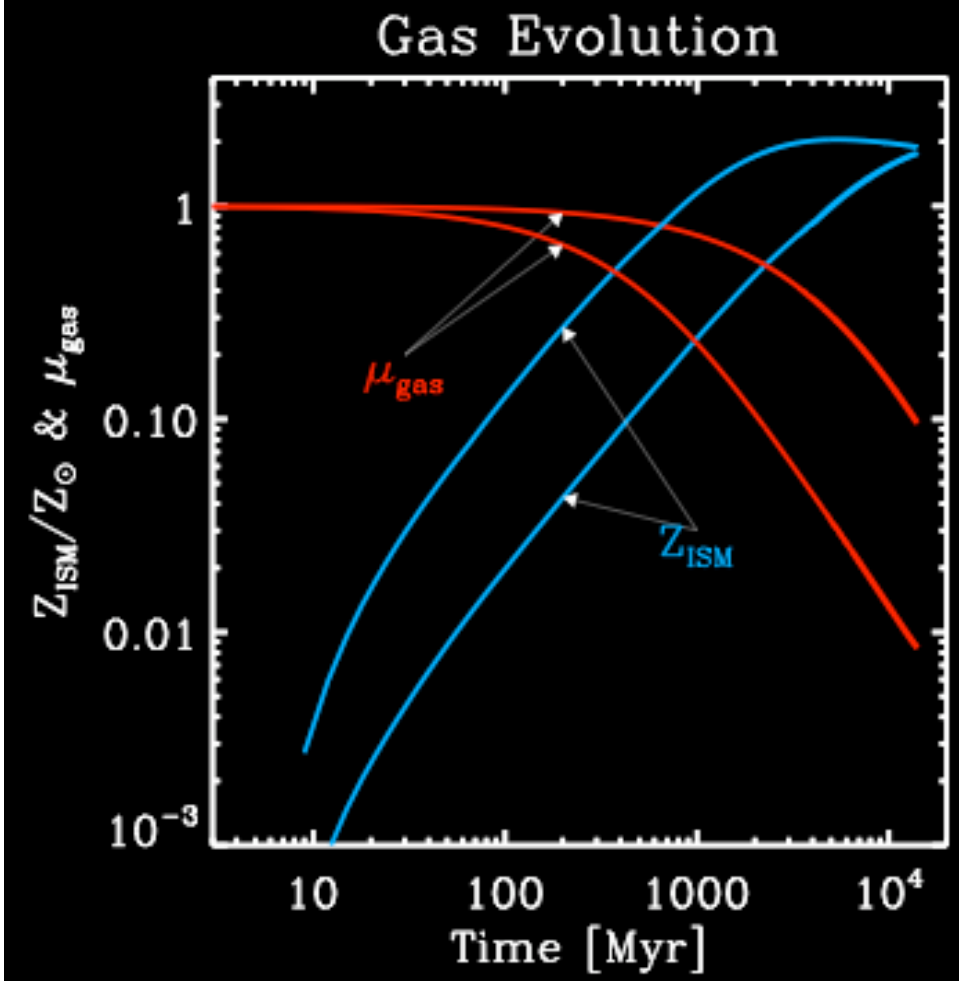
A Model for the Evolution of Elements and Dust



A Model for the Evolution of Elements and Dust

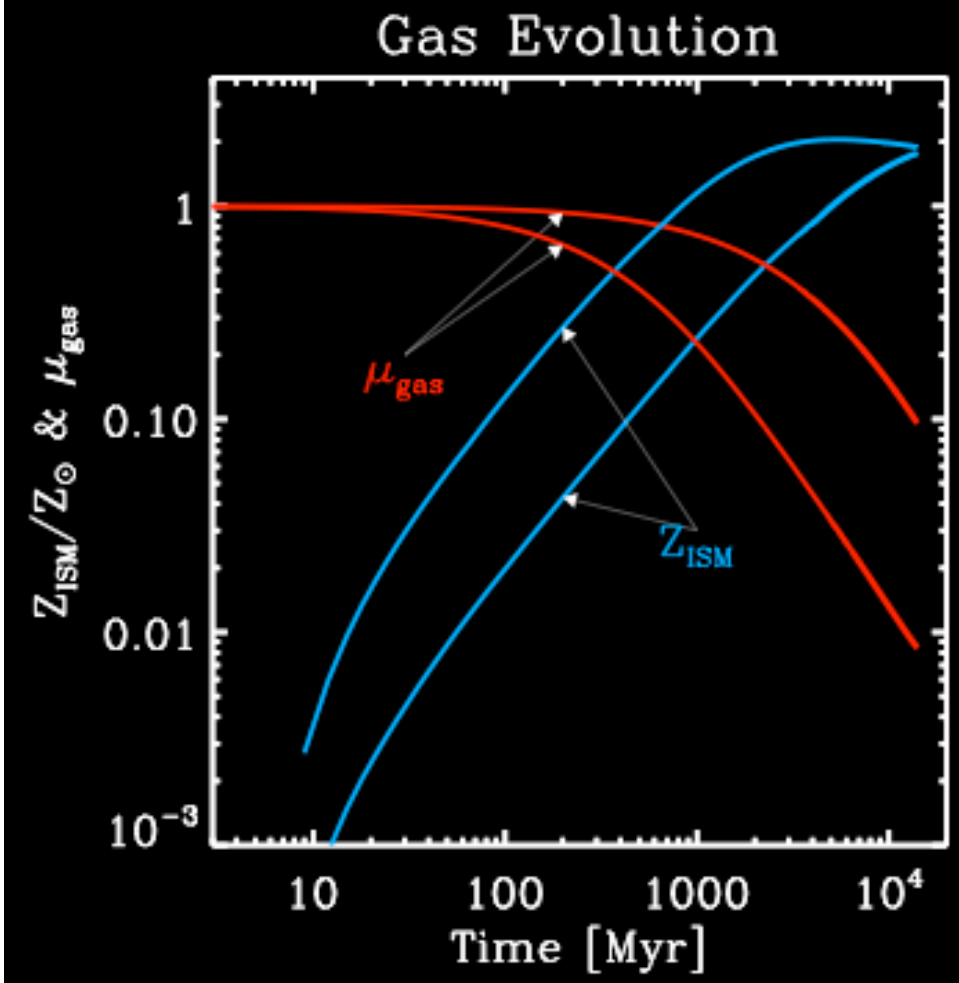


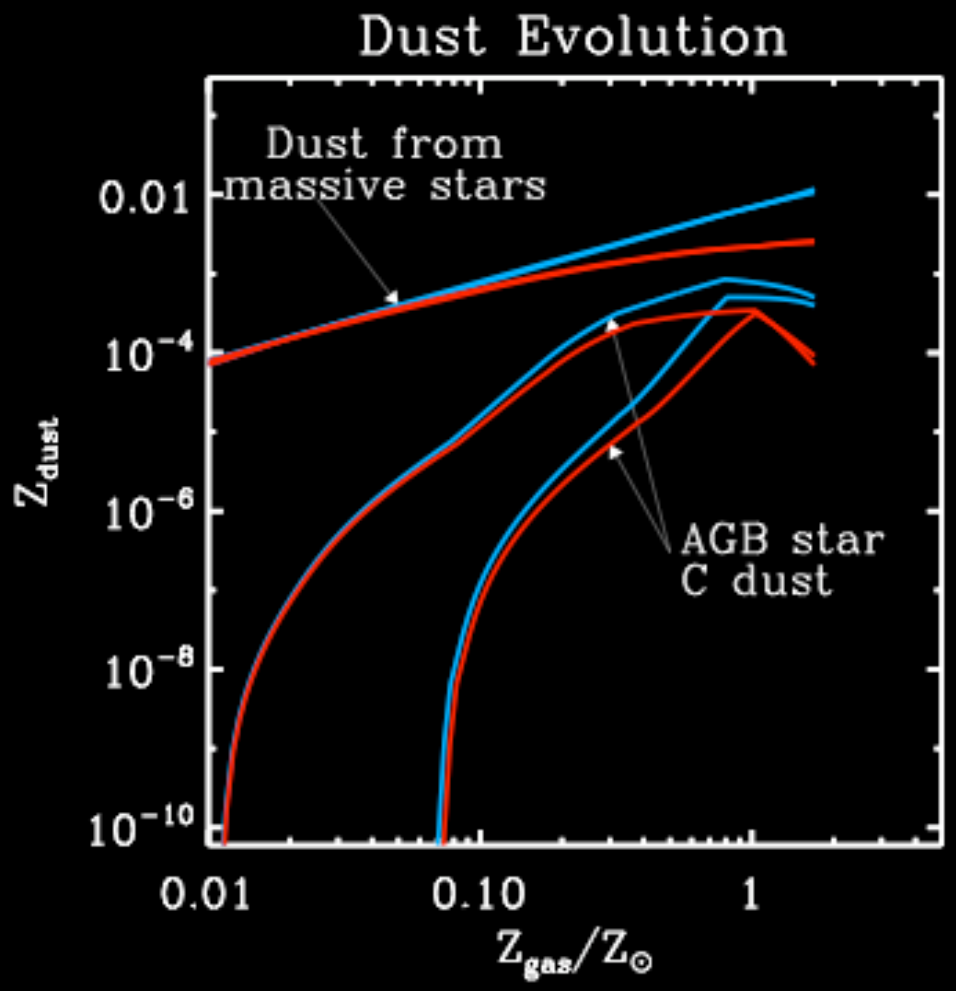
Gas and Dust Evolution: Different Progenitors



(Galliano, Dwek & Chanial 2008, ApJ, 672, 214)

Gas and Dust Evolution: Different Progenitors



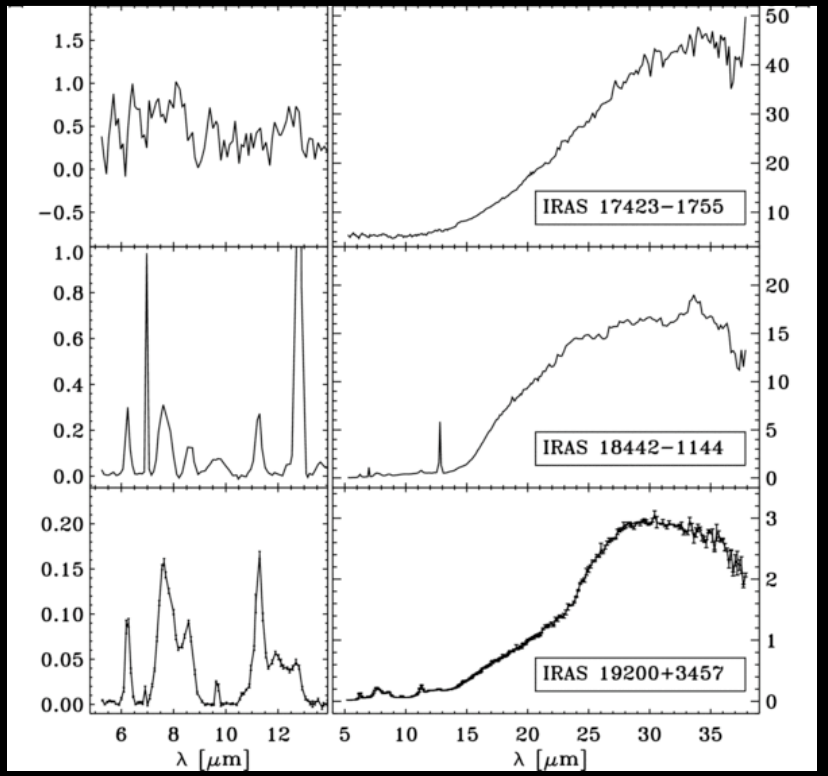


(Galliano, Dwek & Chanial 2008, ApJ, 672, 214)

Are the Hypotheses of the Model Reasonable?

Production of PAHs by post-AGB stars?

- Evidence from mid-IR observations
- In other progenitors, the physical conditions are not appropriate.

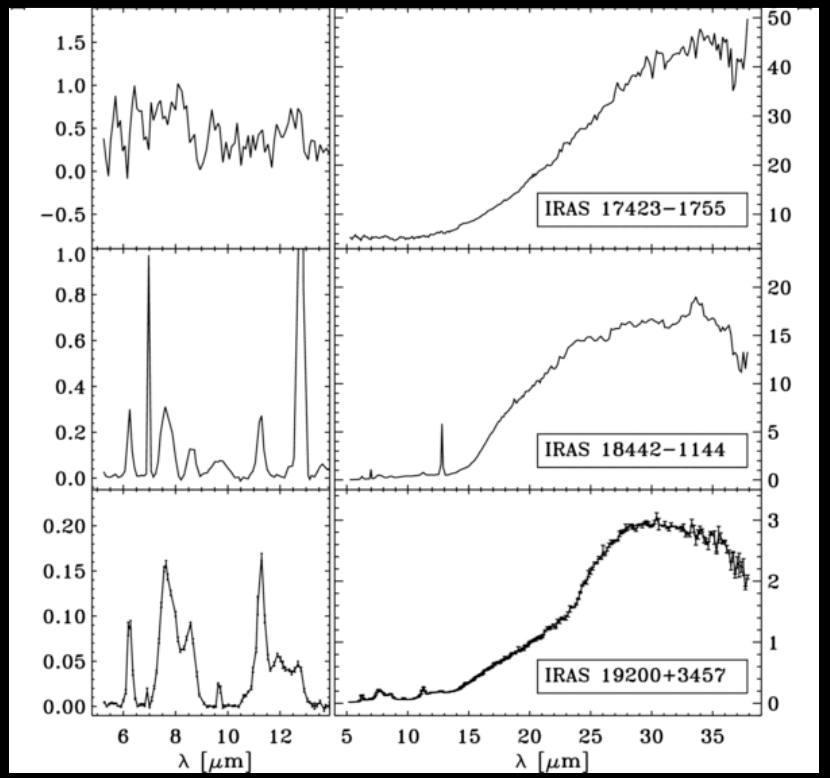


Cerrigone et al. (2009)

Are the Hypotheses of the Model Reasonable?

Production of PAHs by post-AGB stars?

- Evidence from mid-IR observations
- In other progenitors, the physical conditions are not appropriate.



Cerrigone et al. (2009)

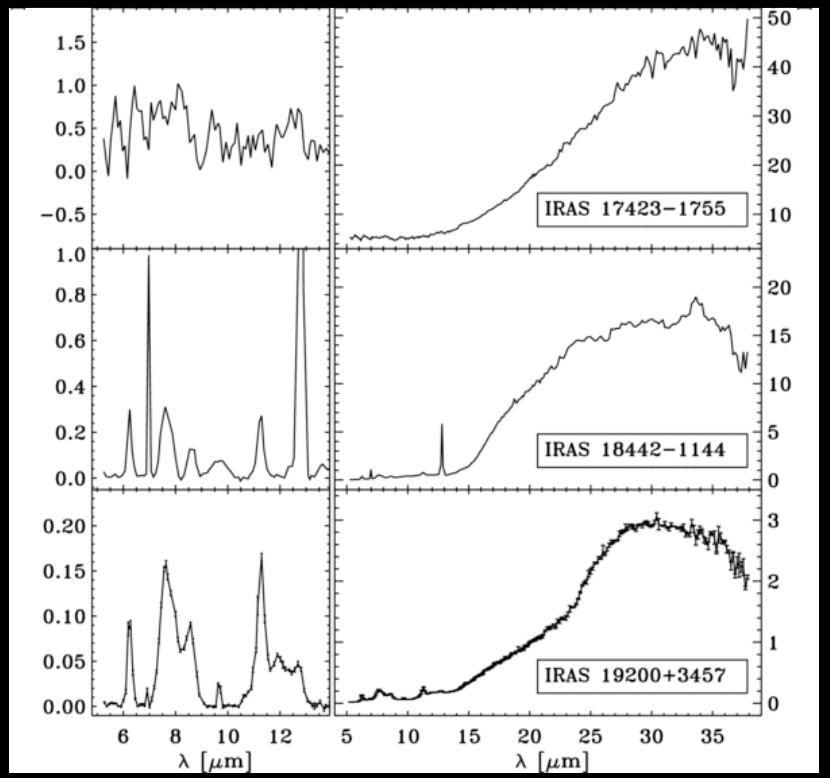
Is a continuous star formation history realistic?

=> Survey of the dwarf galaxies of the local volume *(Lee et al. 2009)*, starbursts are responsible for only a quarter of the star formation over the history of the galaxy.

Are the Hypotheses of the Model Reasonable?

Production of PAHs by post-AGB stars?

- Evidence from mid-IR observations
- In other progenitors, the physical conditions are not appropriate.



Cerrigone et al. (2009)

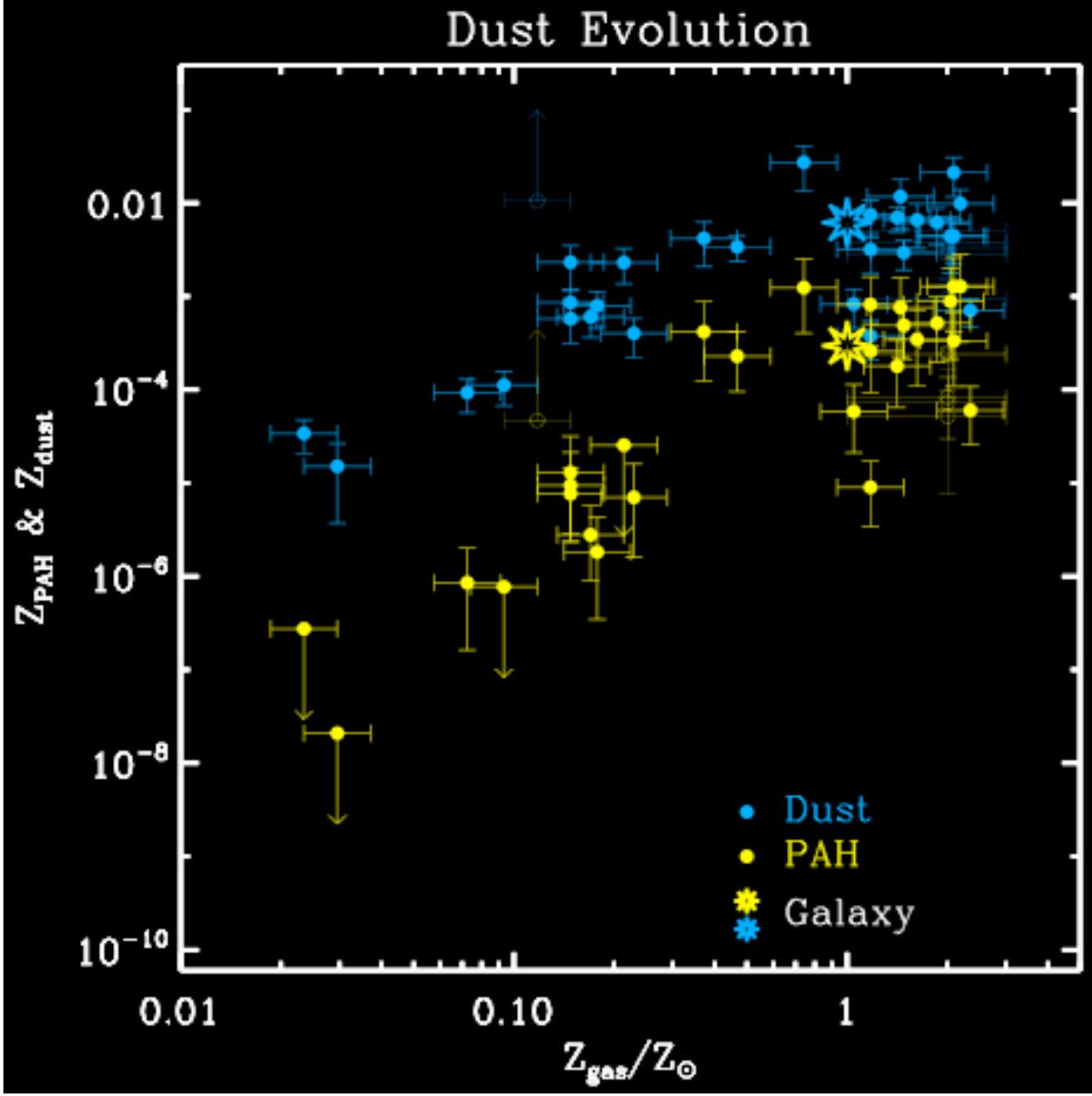
Is a continuous star formation history realistic?

=> Survey of the dwarf galaxies of the local volume *(Lee et al. 2009)*, starbursts are responsible for only a quarter of the star formation over the history of the galaxy.

How relevant is the dust production by stellar progenitors?

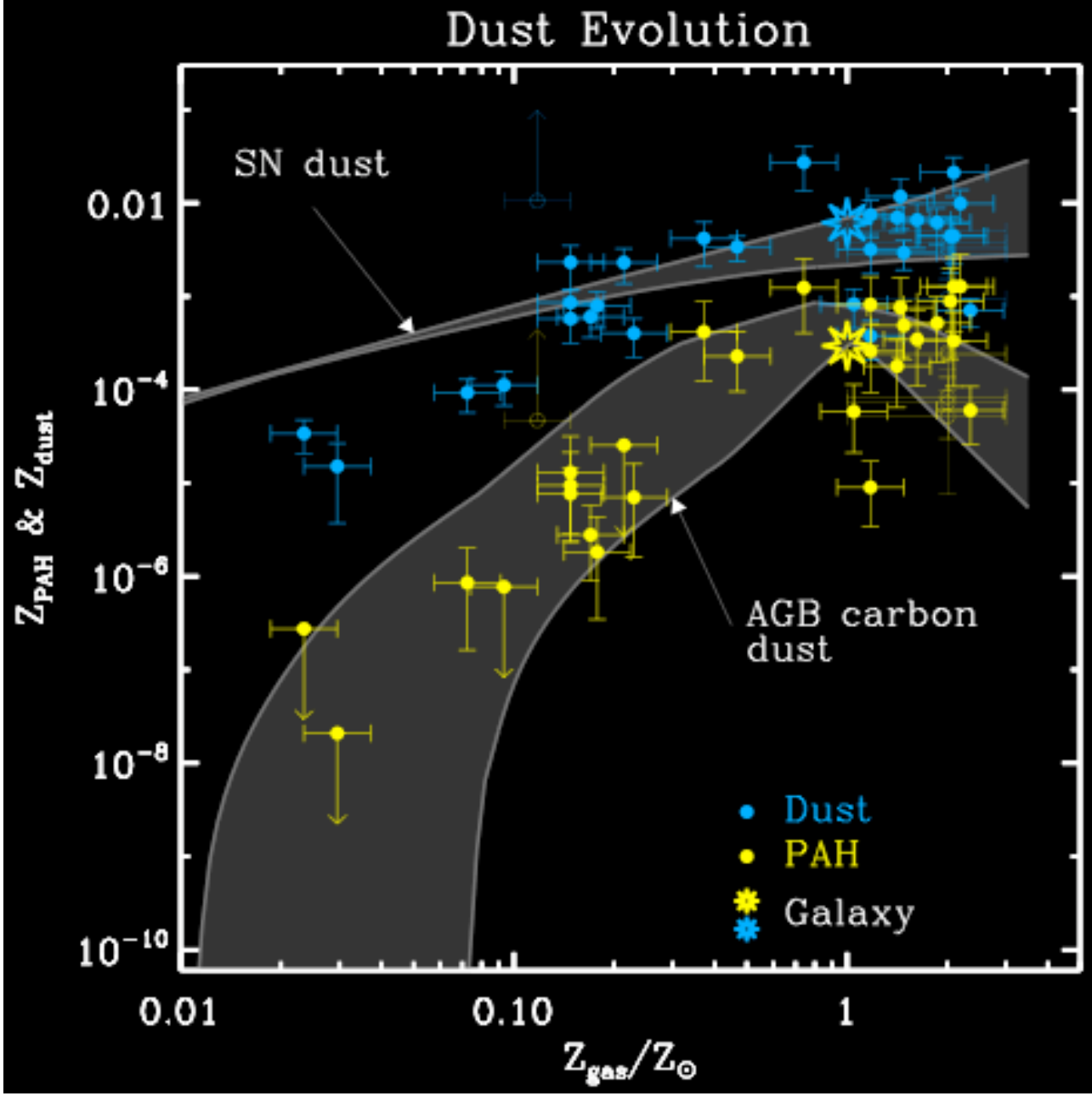
Dust condensation in molecular clouds in $\approx 10^5$ yr => indistinct

Dust Evolution: Delayed Injection of PAHs



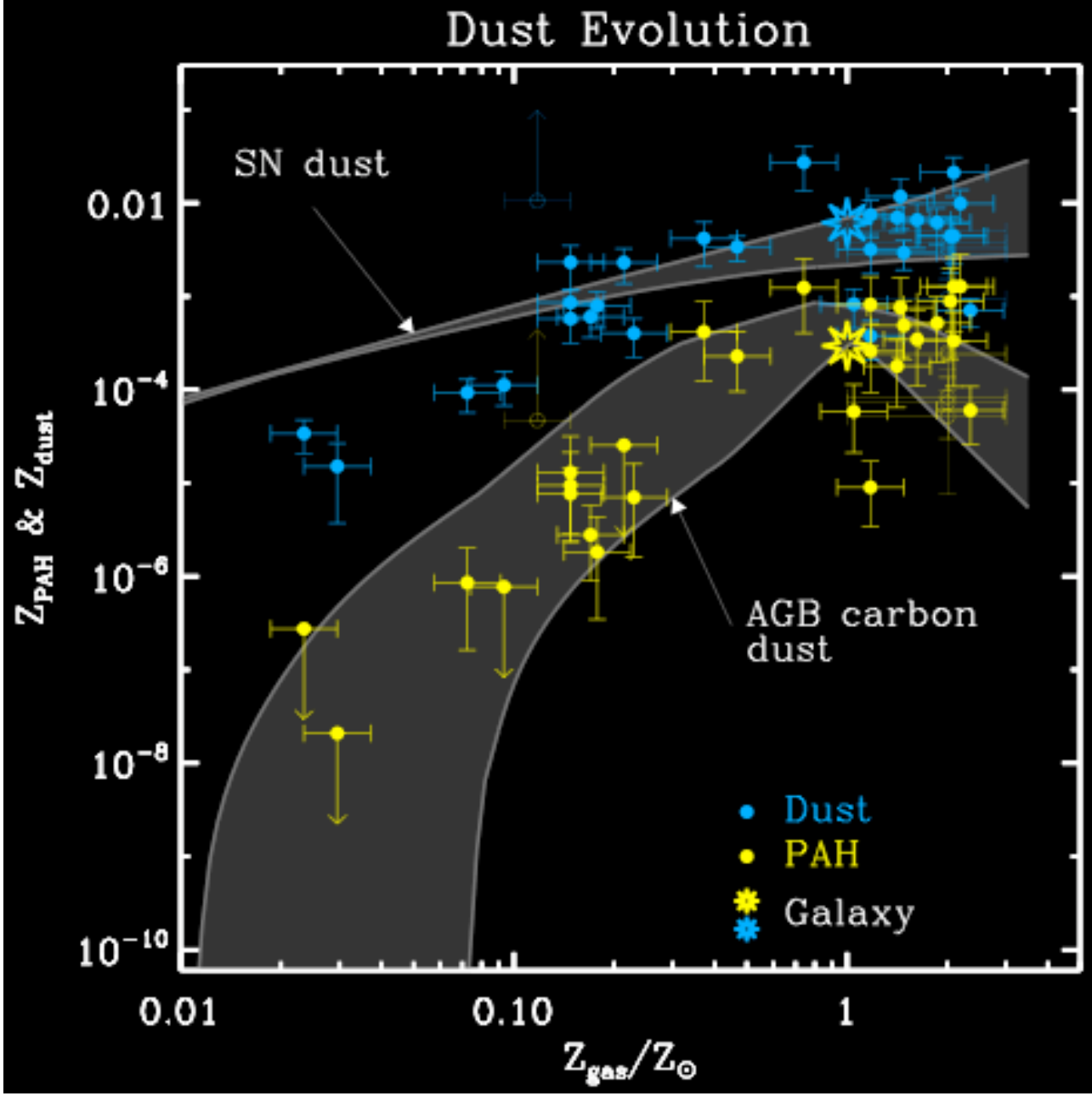
(Galliano, Dwek & Chanial 2008, ApJ, 672, 214)

Dust Evolution: Delayed Injection of PAHs



(Galliano, Dwek & Chanial 2008, ApJ, 672, 214)

Dust Evolution: Delayed Injection of PAHs

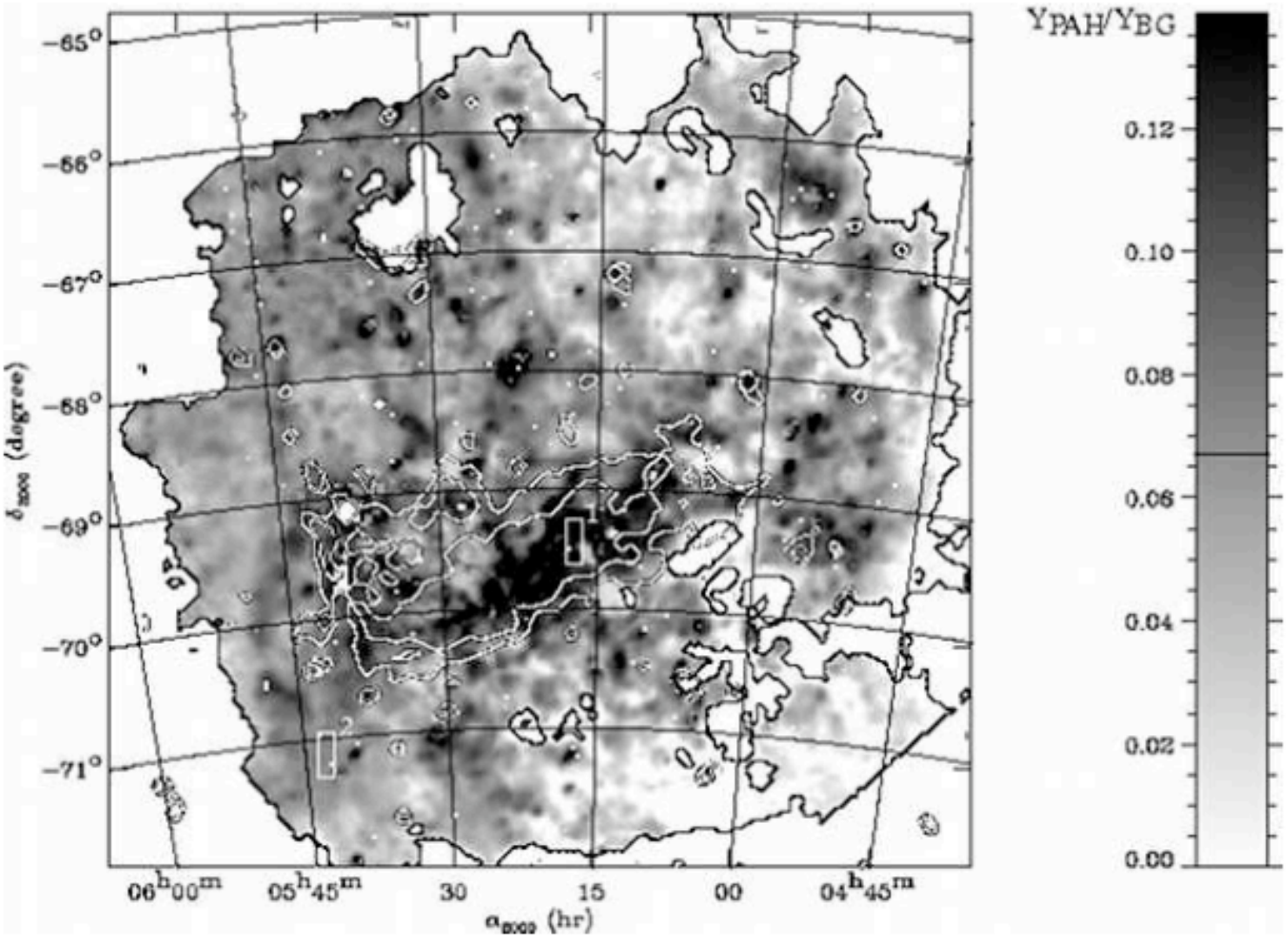


- ✓ Paucity of PAHs in low-Z: delayed injection of carbon dust condensed in AGB stars.
- ✓ Bulk of the dust emission: SN-condensed dust.
- ✓ Outlyers: very cold dust or chaotic star formation history?

(Galliano, Dwek & Chanial 2008, ApJ, 672, 214)

Confirmation at Resolved Spatial Scales?

SAGE: *Spitzer* survey of the LMC: PAH enhancement spatially associated with AGB stars *(Paradis et al. 2009)*.



Content of the Talk

1) A Quick Sweep of the Dusty Universe
   - Basic dust physics, the models and their constraints
   - Step by step building of a spectral energy distribution (SED)
   - Observed SED evolution of galaxies

2) The Dust Evolution Cycle and the Observed Dust Budget in Galaxies
   - Open questions about dust evolution: sites of formation, efficiency of destruction
   - Difficulties to interpret an observed galaxy's SED

3) Bridging the Gap Between the Distant Universe and Nearby Galaxies
   - A multiphase SED model
   - A consistent dust and elemental evolution model
   - The distinct evolution of PAHs and SN-condensed dust as a function of time

Summary & Conclusion

Summary & Conclusion

- Phenomenological model for global UV-to-radio SEDs of galaxies:
  1. Determine the contribution of HII regions to the total SED;
  2. Take into account stellar evolution;
  3. Self-consistency (energy balance).

Summary & Conclusion

- Phenomenological model for global UV-to-radio SEDs of galaxies:
    1. Determine the contribution of HII regions to the total SED;
    2. Take into account stellar evolution;
    3. Self-consistency (energy balance).
- Distinct evolutionary trends between PAHs and Dust.
- Dust abundance correlated with SN-dust production: consistent with high-z QSO, although dust formation in the ISM can not be excluded.
- Paucity of PAHs in low-Z: delayed injection by AGB stars.

Summary & Conclusion

- Phenomenological model for global UV-to-radio SEDs of galaxies:
  1. Determine the contribution of HII regions to the total SED;
  2. Take into account stellar evolution;
  3. Self-consistency (energy balance).
- Distinct evolutionary trends between PAHs and Dust.
- Dust abundance correlated with SN-dust production: consistent with high-z QSO, although dust formation in the ISM can not be excluded.
- Paucity of PAHs in low-Z: delayed injection by AGB stars.

Prospectives

- better mass estimates => longer wavelengths & resolving the ISM (*Herschel*).
- better constraints on individual formation/destruction processes (ISM studies => measure production rates).