All Radiation Backgrounds from Star-Forming Galaxies: A Preview

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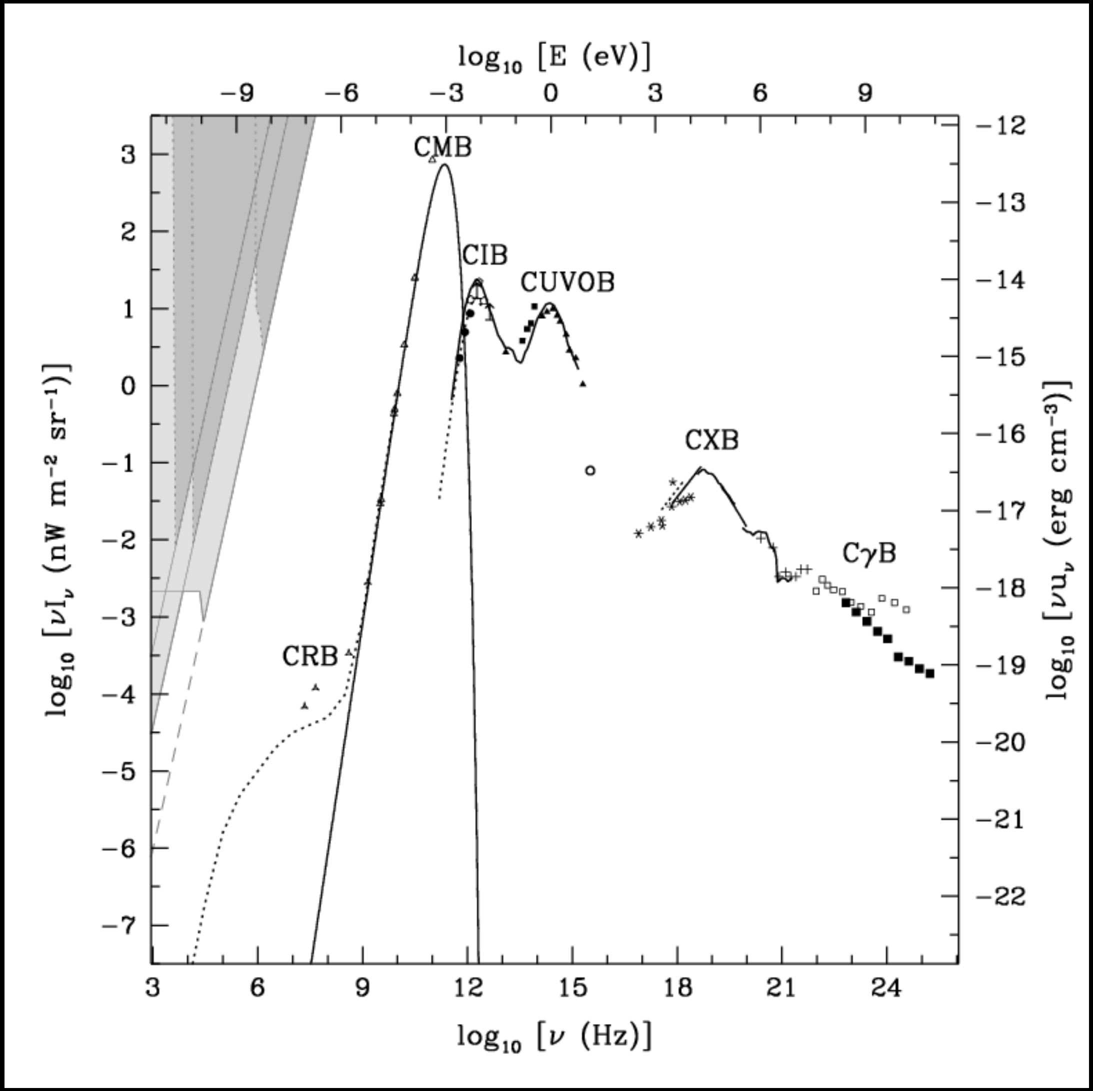
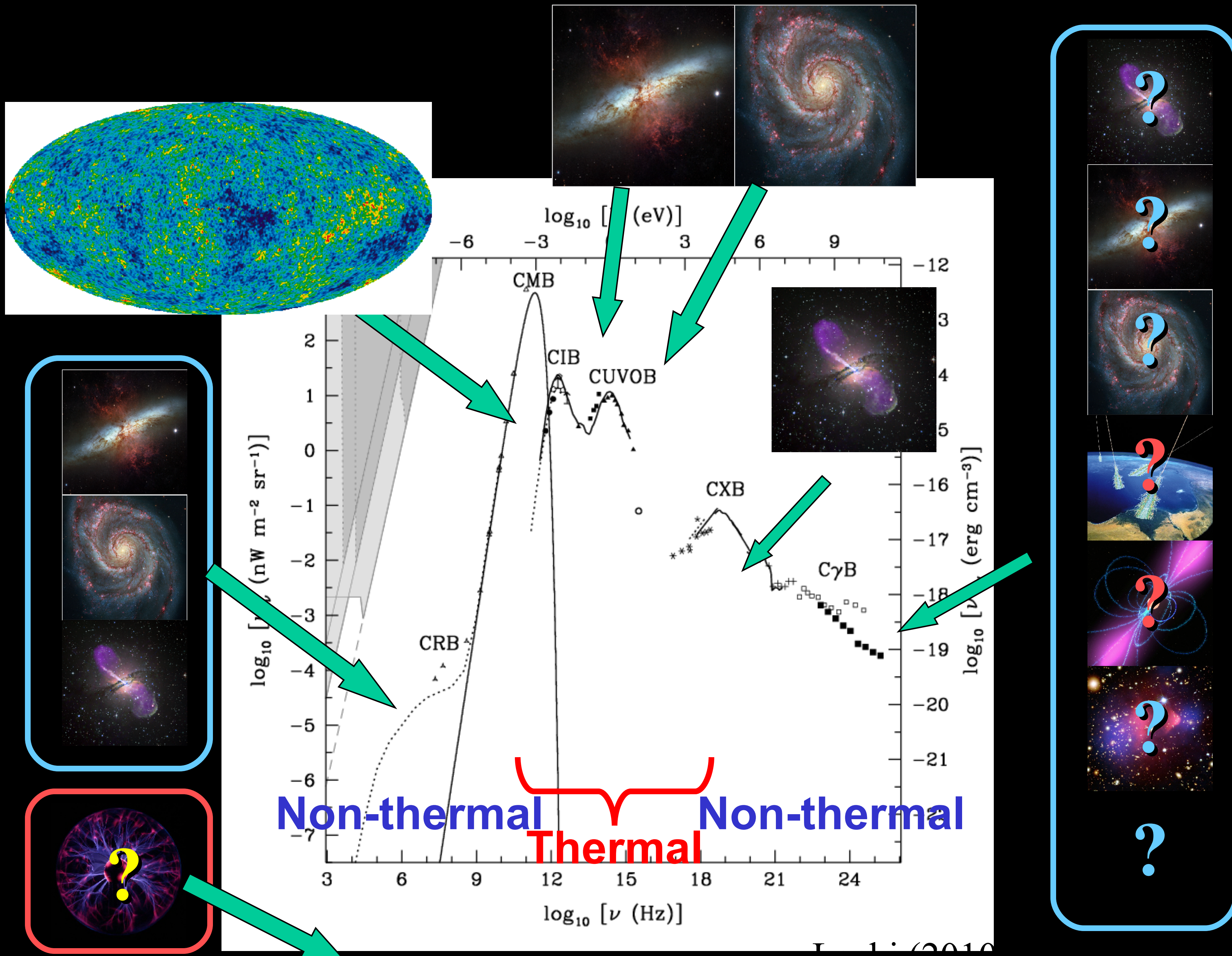
EVERYTHING IS PRELIMINARY!

The Cosmic SED





Credit: Simon Swordy (U. Chicago) / NASA / APoD; Luc Viator

The Motivation

Connect UV/O/IR backgrounds to radio and gamma-rays

- Radio related to IR at GHz
- UV/O/IR emission affects gamma-ray propagation

Radio background poorly understood

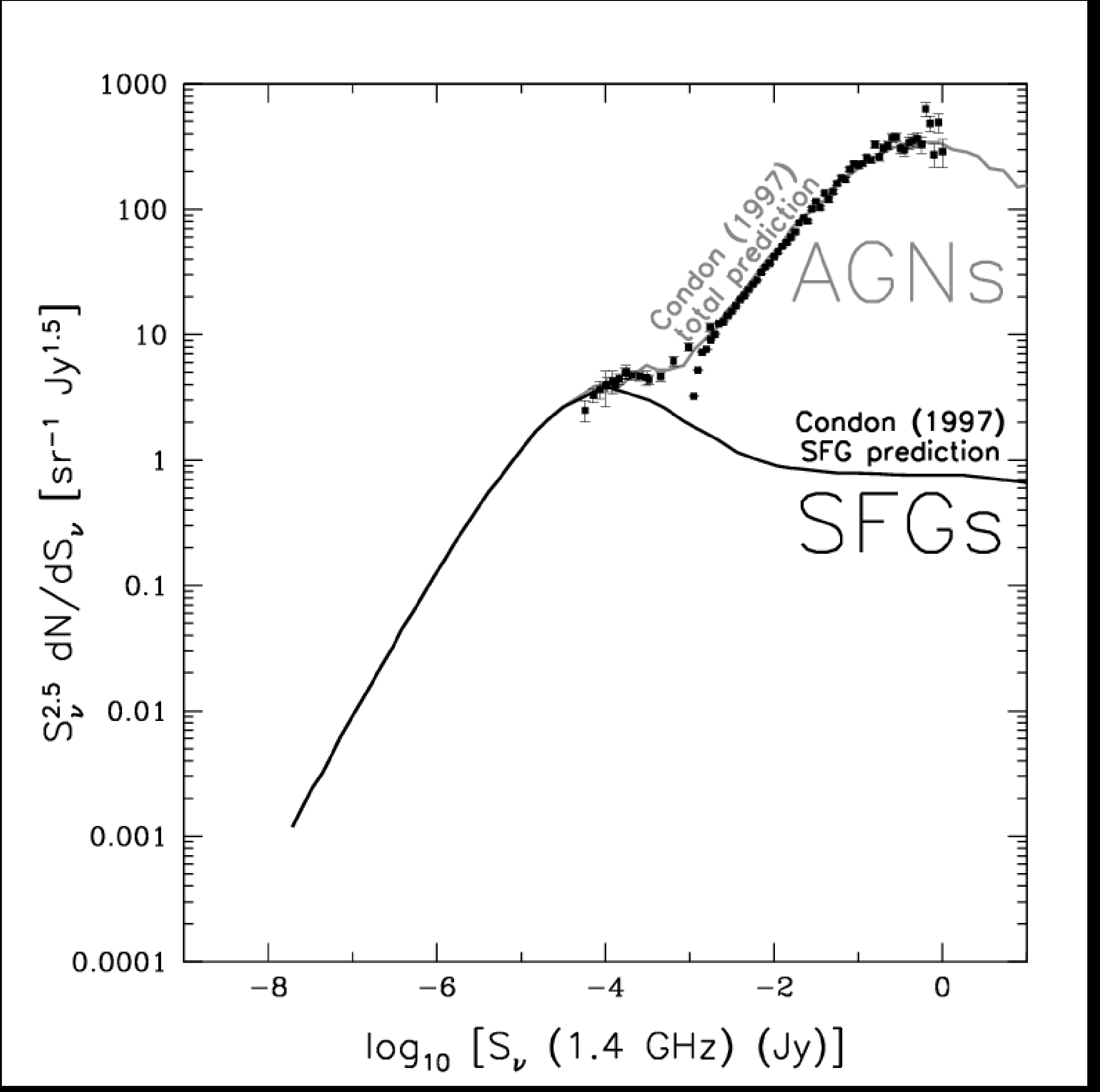
- ARCADE excess
- μJy range probed by JVLA
- Propagation of ultra-high energy CRs

Gamma-ray background also poorly understood

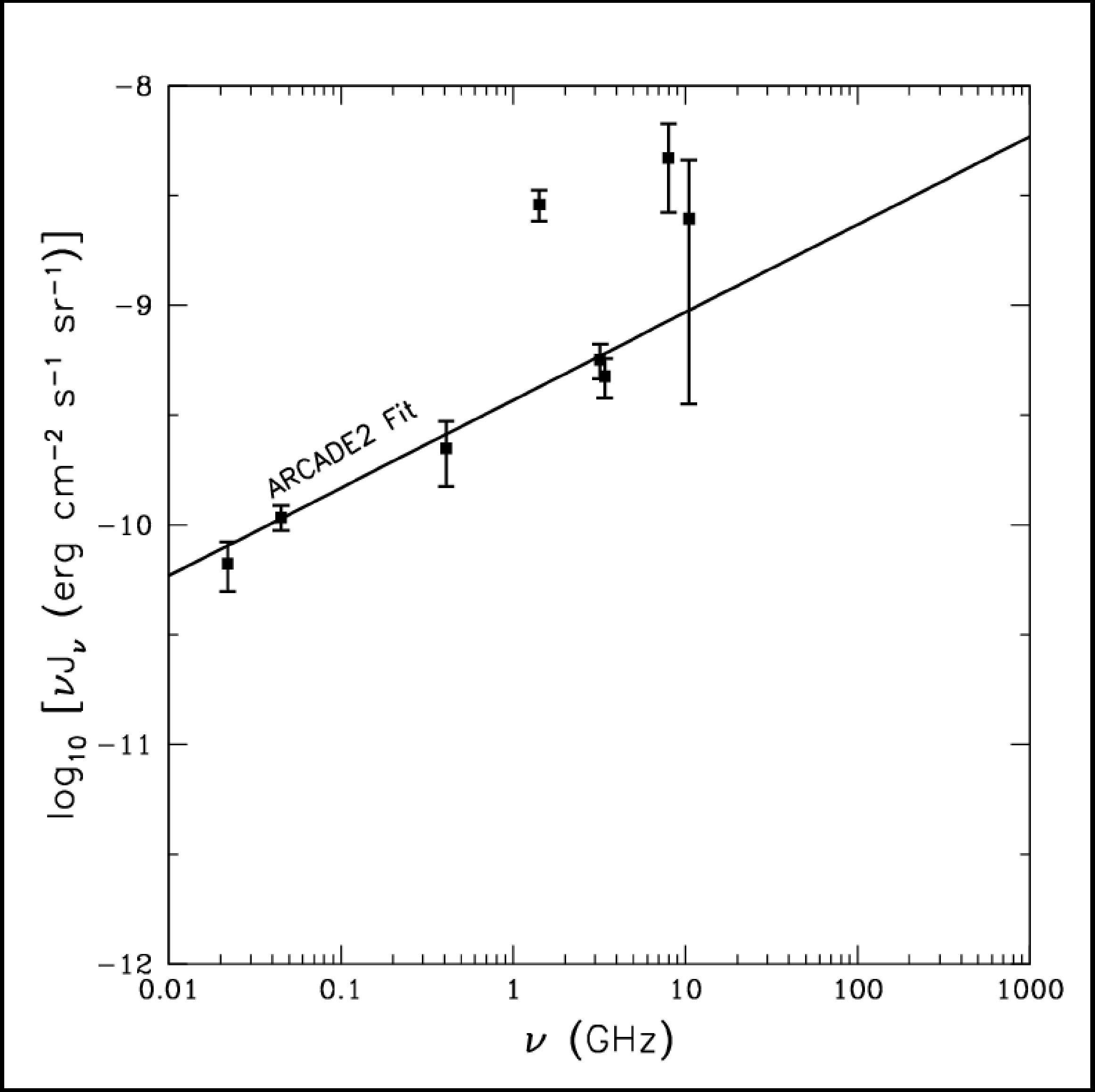
- How does galaxy evolution affect emission?

Foregrounds for other studies

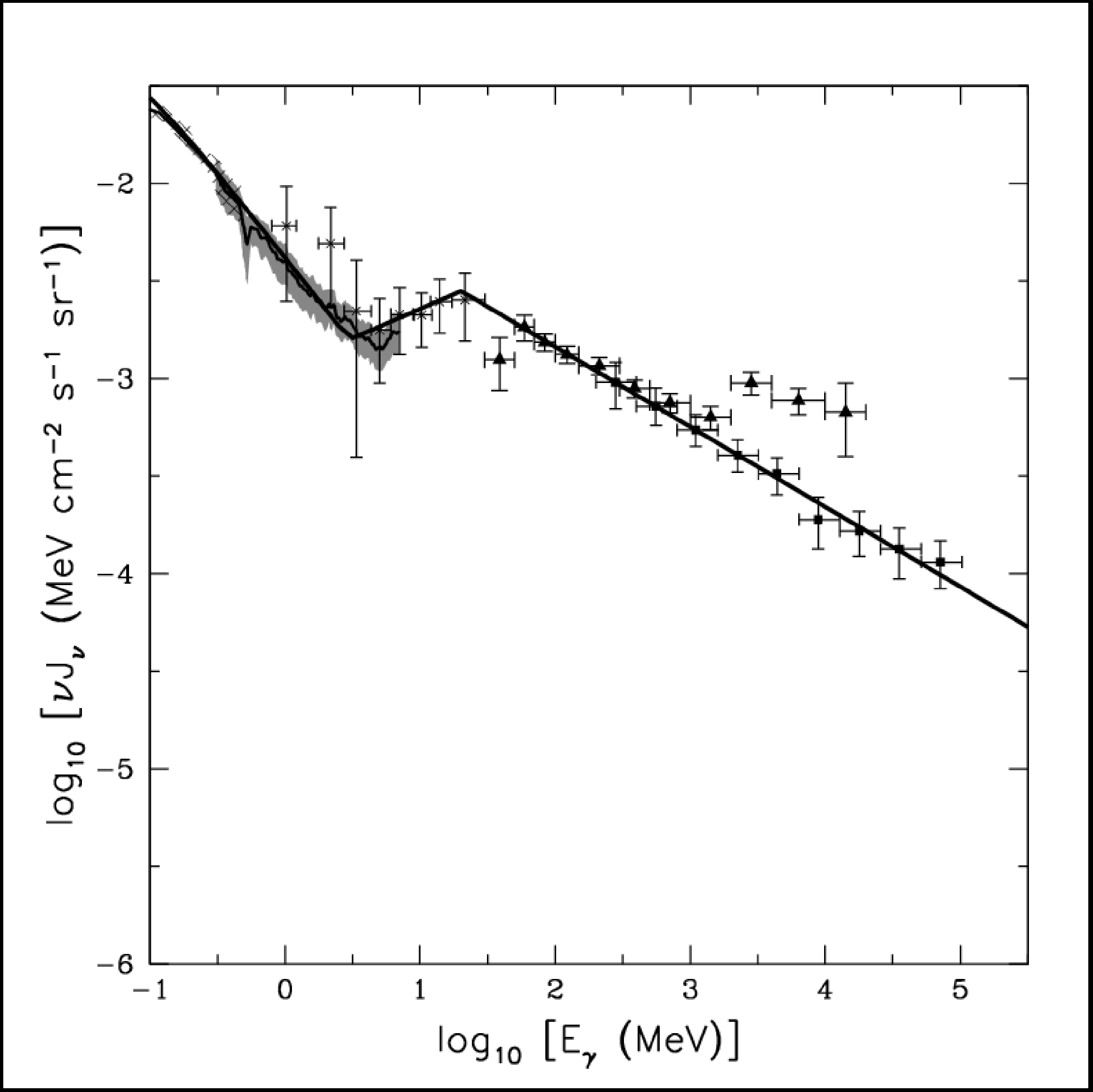
Radio Source Counts



The Radio Background



The Gamma-Ray Background



The Plan

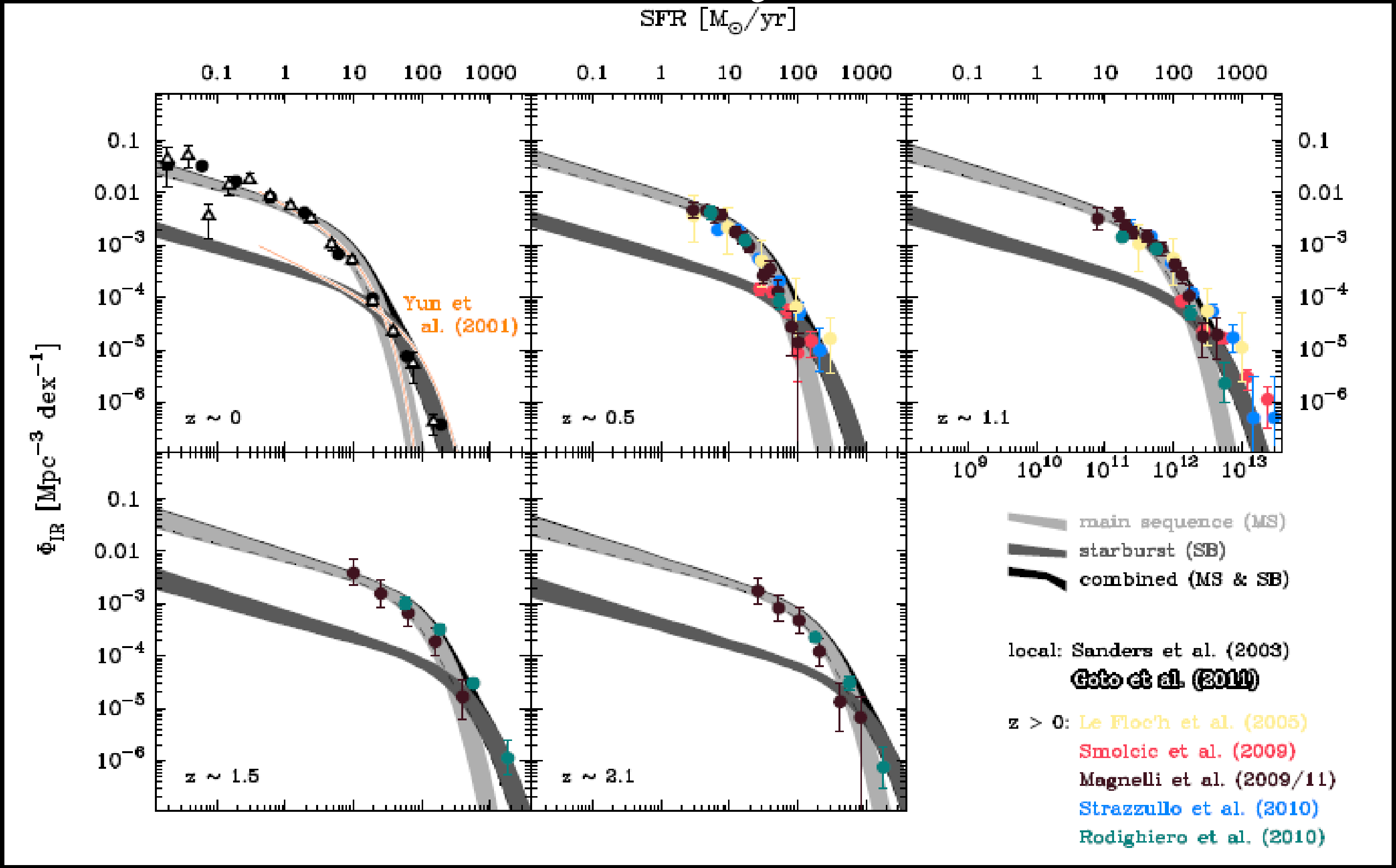
Calculate all EM backgrounds self-consistently with models

- One zone models for simplicity
- Don't assume, e.g., FIR-radio correlation, at all z
- Synthesize what we've learned about galaxies in these models

Thermal emission (UV/O/IR) – starlight, dust emission

Nonthermal emission (radio – γ-rays) – CR emission

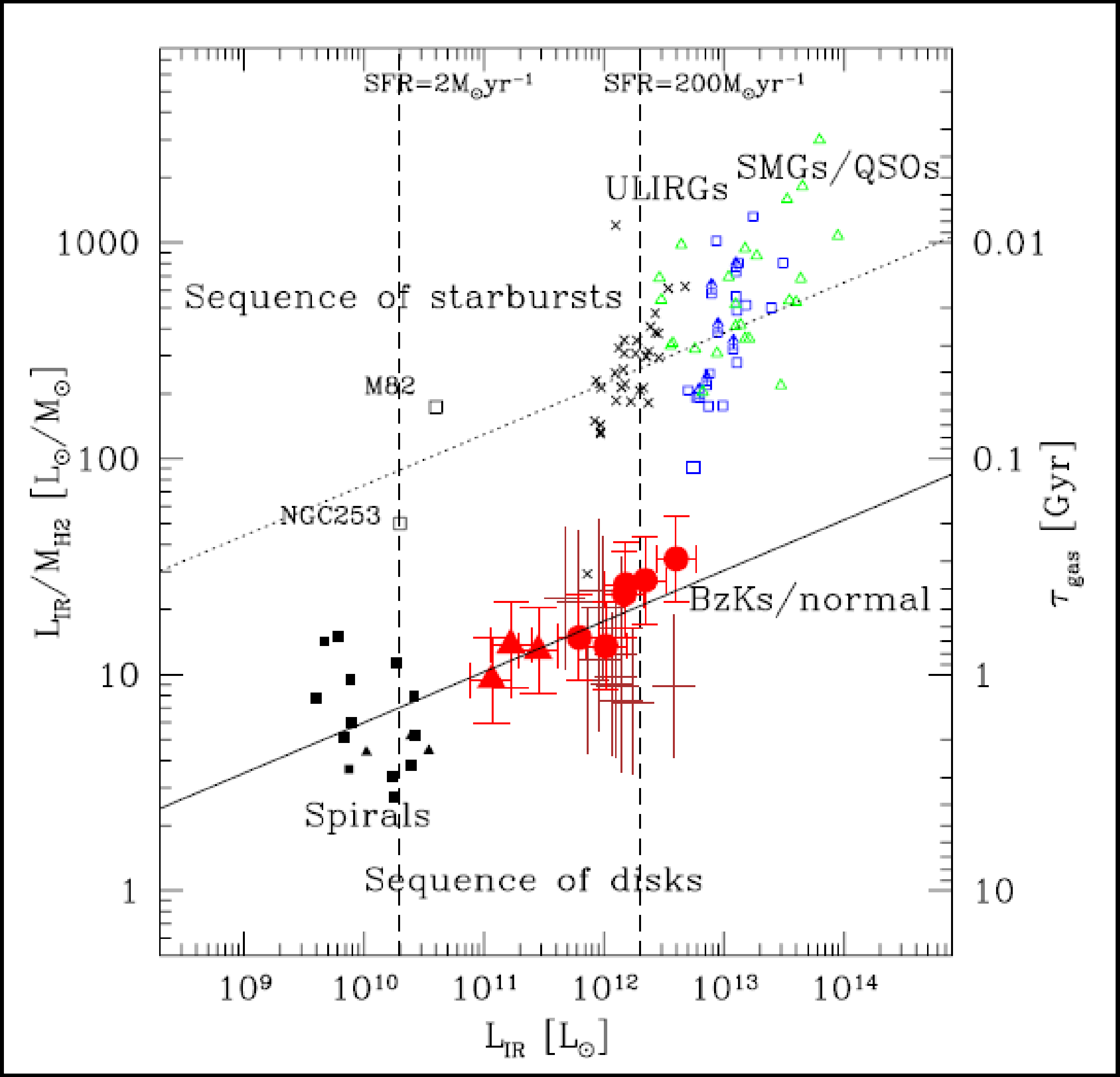
IR Luminosity Functions



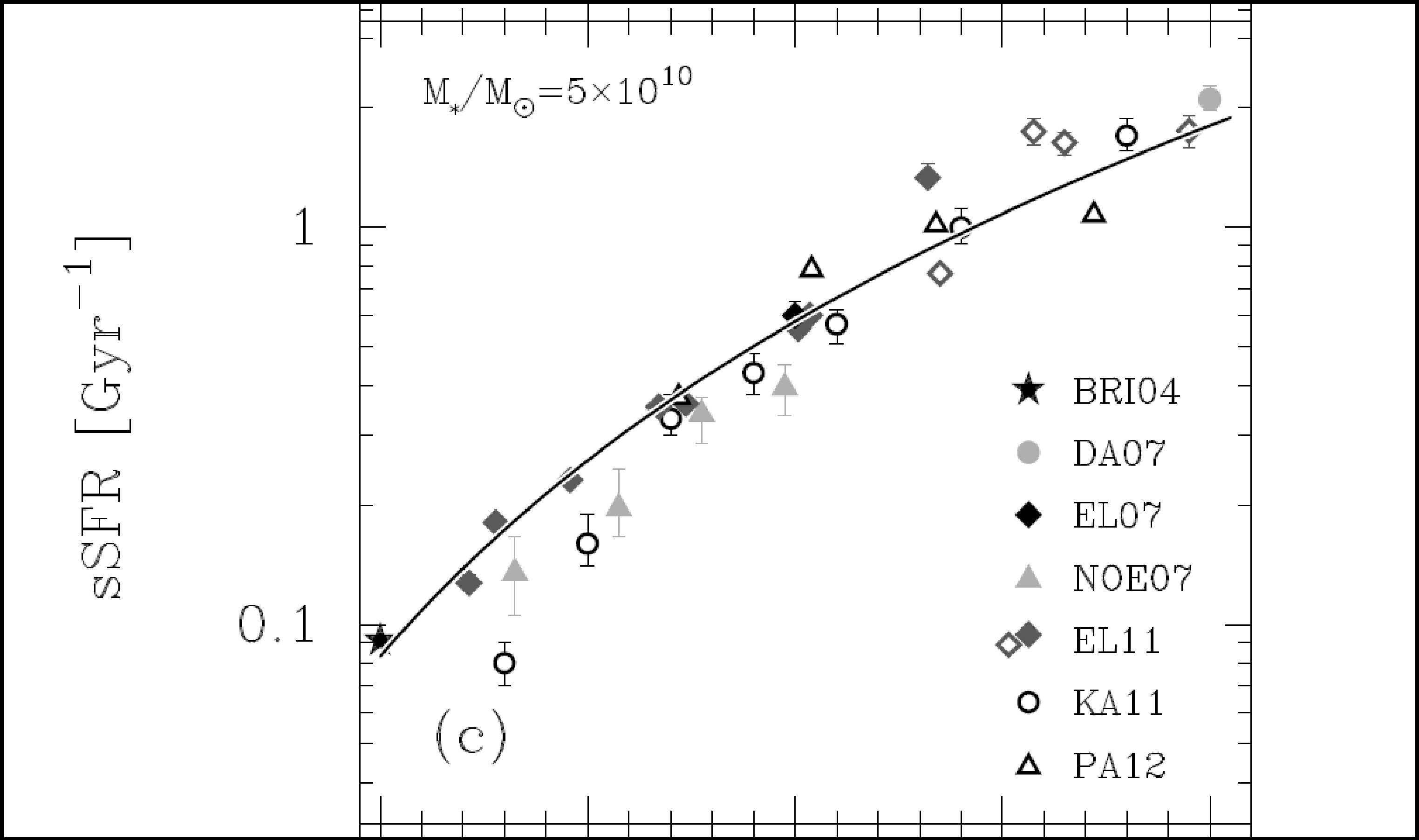
Gives number of galaxies at each redshift with each SFR

Problem: Need gas density, radius, height, magnetic fields, etc. to predict emission

Starbursts vs. the Main Sequence



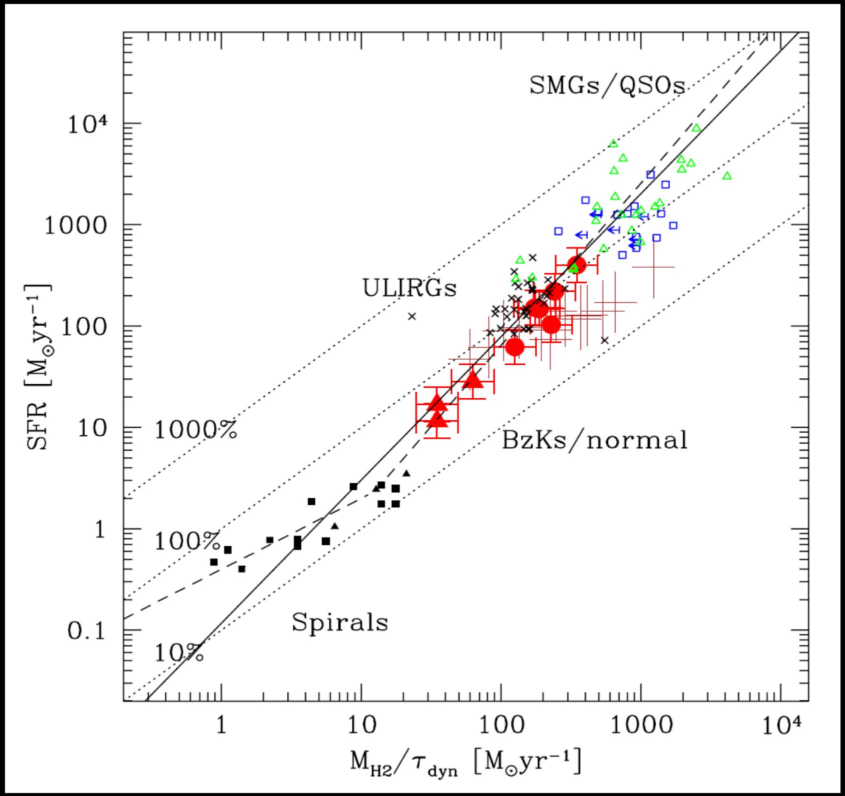
Piece 1: The Main Sequence



Star-forming, non-starburst galaxies at each z have similar SSFR

SSFR = SFR / M*

Piece 2: The Schmidt Law



Gas density related to star-formation rate by dynamical time

$$\mathbf{SFR = \eta\, M_g\, (R/v_{circ})}$$

Assume v_{circ} = 200 km/s

Pieces 1a & 2a: Starbursts

Starbursts have much higher SSFRs, different Schmidt law

$$\tau_{gas} = SFR / M_{gas} = 20 \text{ Myr}$$

$$R = 150 \text{ pc } (1 + z)^2$$

Piece 3: Toomre Q is 1

Toomre Q is near 1 if disks are in equilibrium

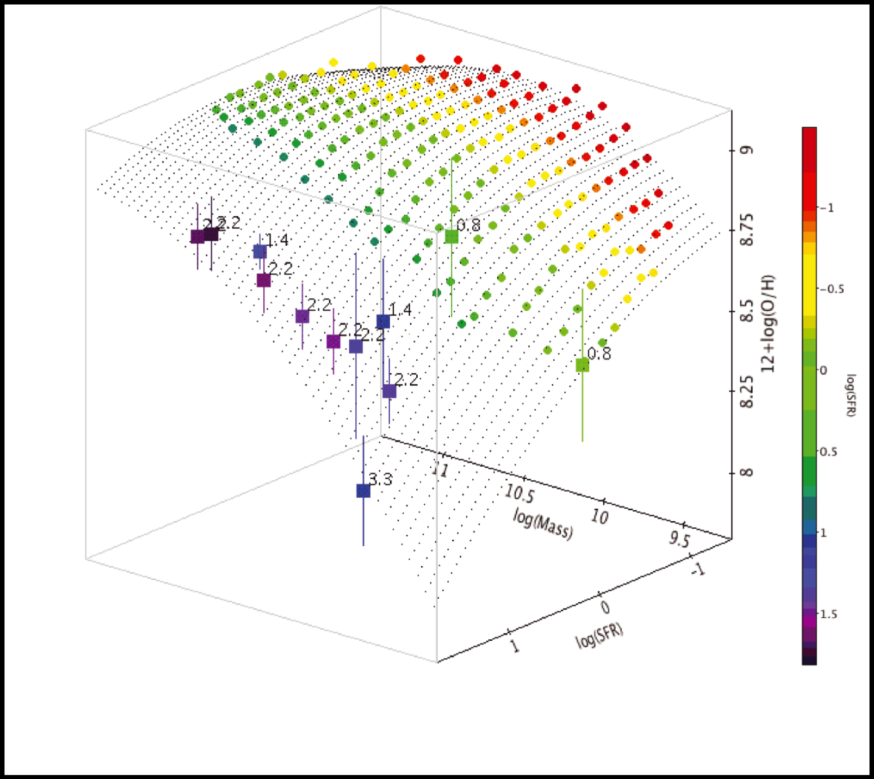
Gives relation between **height** and **radius**

$$\sigma / v_{circ} = h/R = f_{gas} / 2$$

Need relation for turbulent speeds σ

$$\sigma = \min [15 \text{ km/s} (\log_{10} \Sigma_{SFR} + 2), 8 \text{ km/s}]$$

Piece 4: The Fundamental Mass-Metallicity Relation



Relates stellar mass to metallicity at a given redshift

Lower mass galaxies lower metallicity

Metallicity needed for stellar spectra, dust emission

Putting it all Together

SFR	Mode	z	Mstar	Mgas	R	h
0.10	MS	0	5.6e8	4.9e7	1800	72
3.2 (MW)	MS	0	4.2e10	3.7e9	10000	410
10	MS	0	1.8e11	1.5e10	15000	580
3.2	MS	1	3.2e9	6.3e8	2500	230
32 (z~1 LIRG)	MS	1	5.7e10	1.4e10	6100	660
3.2	MS	2	7.0e8	2.5e8	1200	170
320 (z~2 ULIRG)	MS	2	2.2e11	1.1e11	6300	1100
3.2	MS	3	3.9e8	1.7e8	870	140
320	MS	3	1.2e11	7.8e10	4600	930

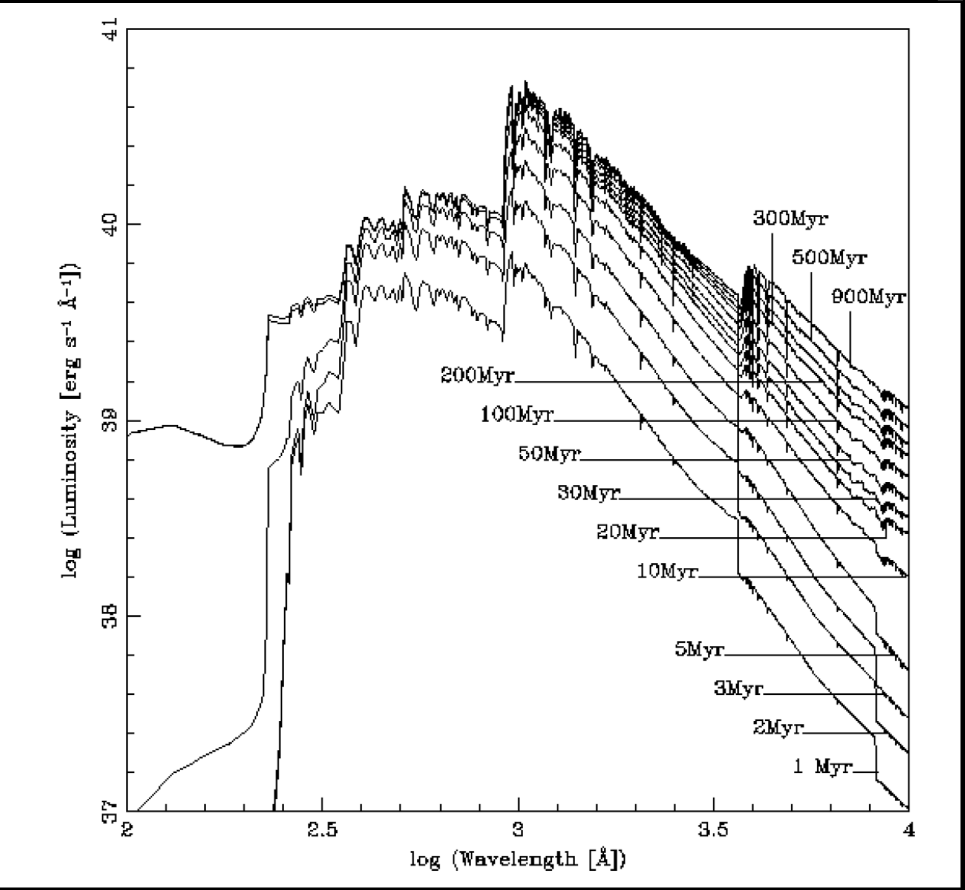
Get reasonable values for galaxy properties

Putting it all Together

SFR	Mode	z	Mstar	Mgas	R	h
3.2 (NGC 253)	SB	0	6.4e7	6.4e7	.150	41
10 (M82)	SB	0	2e8	2e8	150	47
180 (Arp 220)	SB	0	3.6e9	3.6e9	150	61
100	SB	1	2e9	2e9	600	180
1000 (SMG)	SB	2	2e10	2e10	1400	430
1000	SB	3	2e10	2e10	1900	550

Get reasonable values for galaxy properties

The Unabsorbed UV/O/IR Spectra



Starburst99 Spectra

Continuously forming stars for 1/SSFR

Dust Absorption and Emission: One Zone Models

Most star-formation in Universe is heavily extinguished

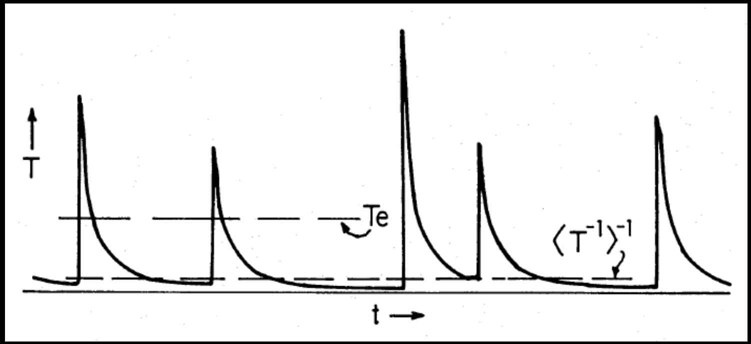
- Dust (1) absorbs UV/O light and (2) emits IR light
- Both are linked: internal SED sets grain temperatures

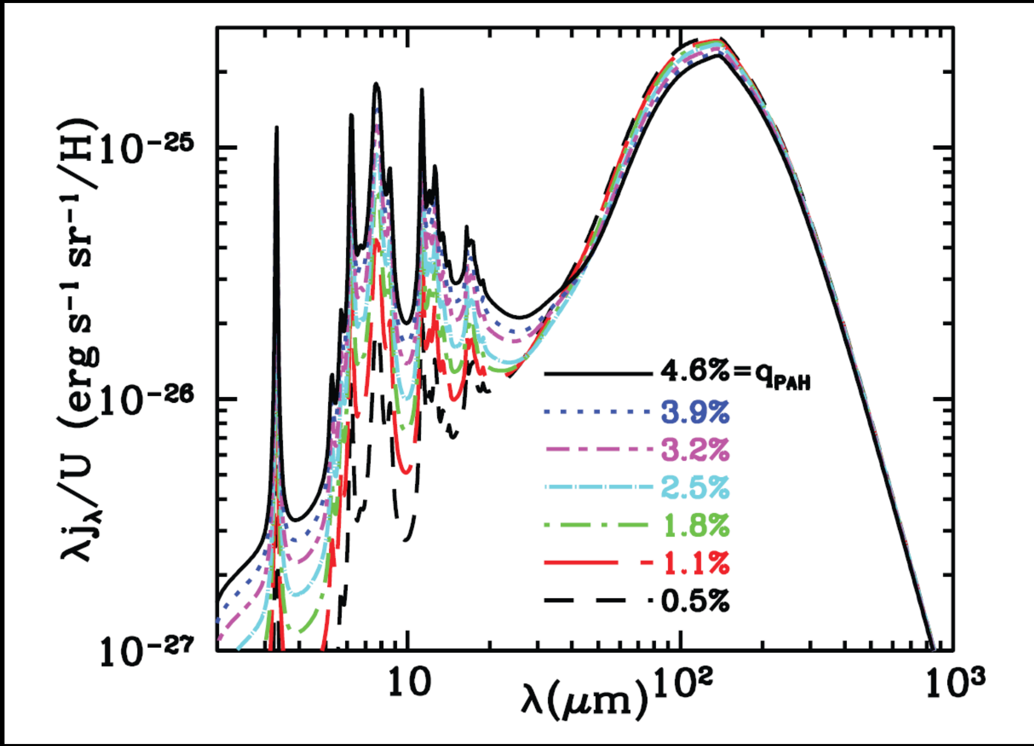
One zone model for internal SED

$$u_\lambda \sim s/c\,(\varepsilon_{stars} + \varepsilon_{dust})$$

Iterative process – guess first u_λ, feed into ε_{dust}, repeat

MIR Emission: Not Just One T





Grains transiently heated by UV light

Cooling responsible for MIR emission

Problem: SEDs can be very different

- Dwarfs: much light in UV – strong MIR
- Starbursts: most light in FIR – weak MIR

The Continous Cooling Approximation

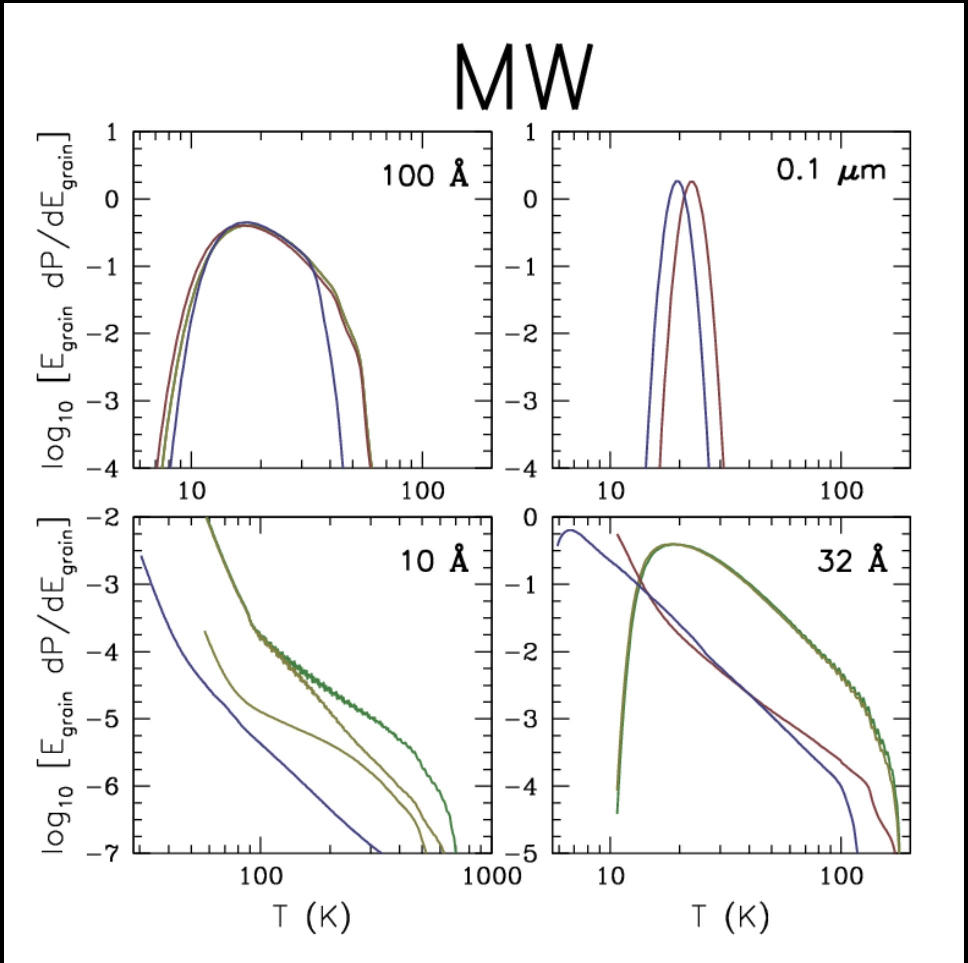
Grains lose energy by emitting one photon at a time

But energy of photons small compared to grain energy

So treat it as continous process

Very simple

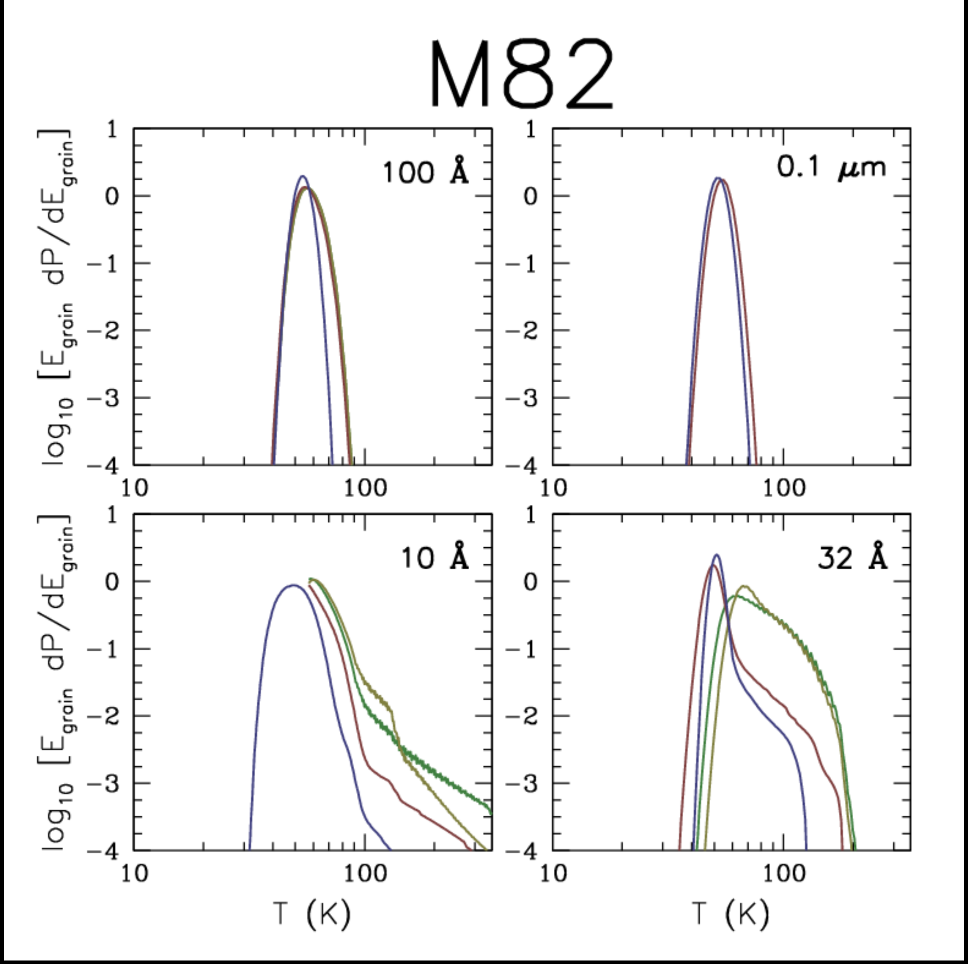
Temperature Distributions: Milky Way



Grains have wide distributions of temperatures

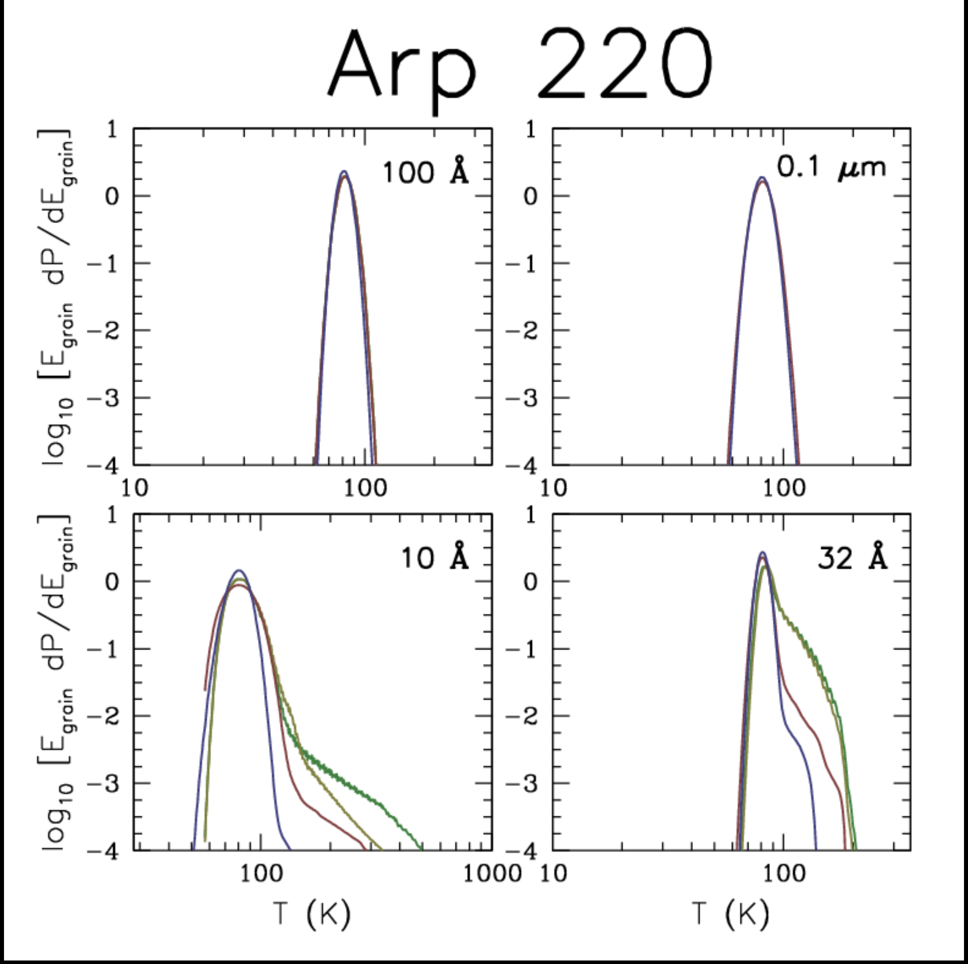
Smaller grains have wider temperature distributions

Temperature Distributions: M82



Relatively hot

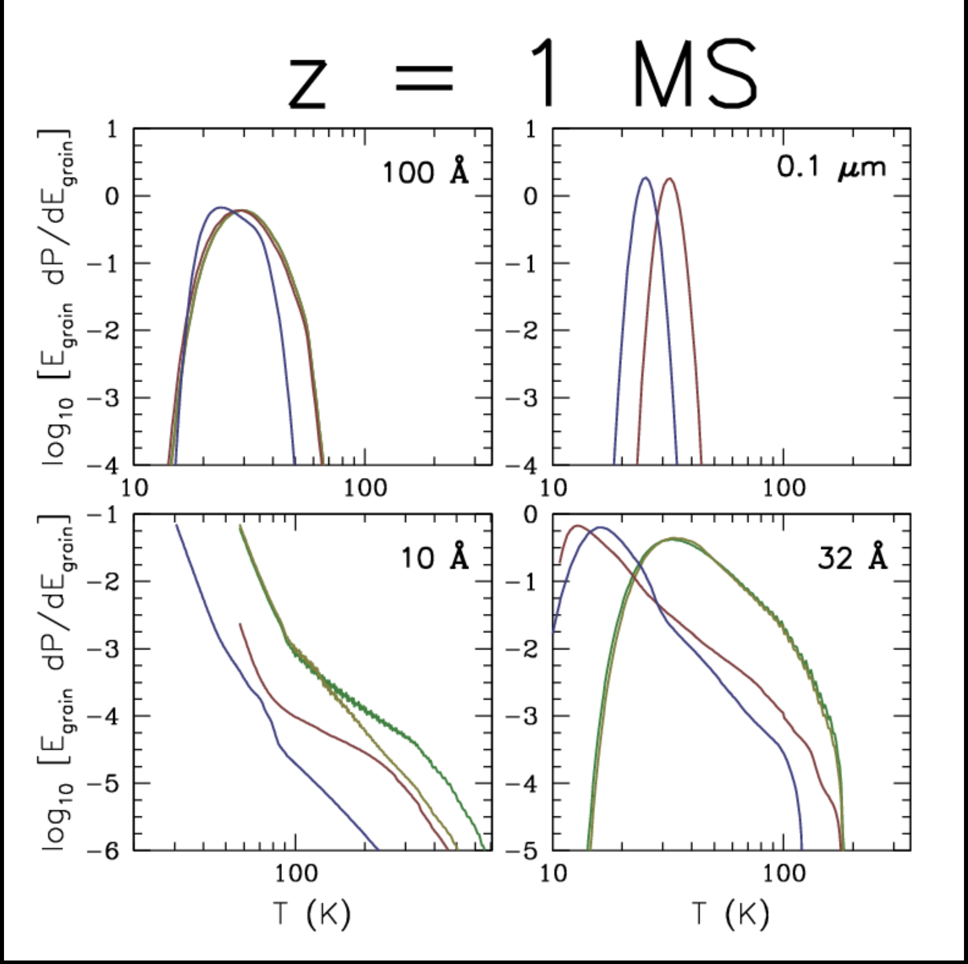
Temperature Distributions: Arp 220



Grains heated by thermal FIR

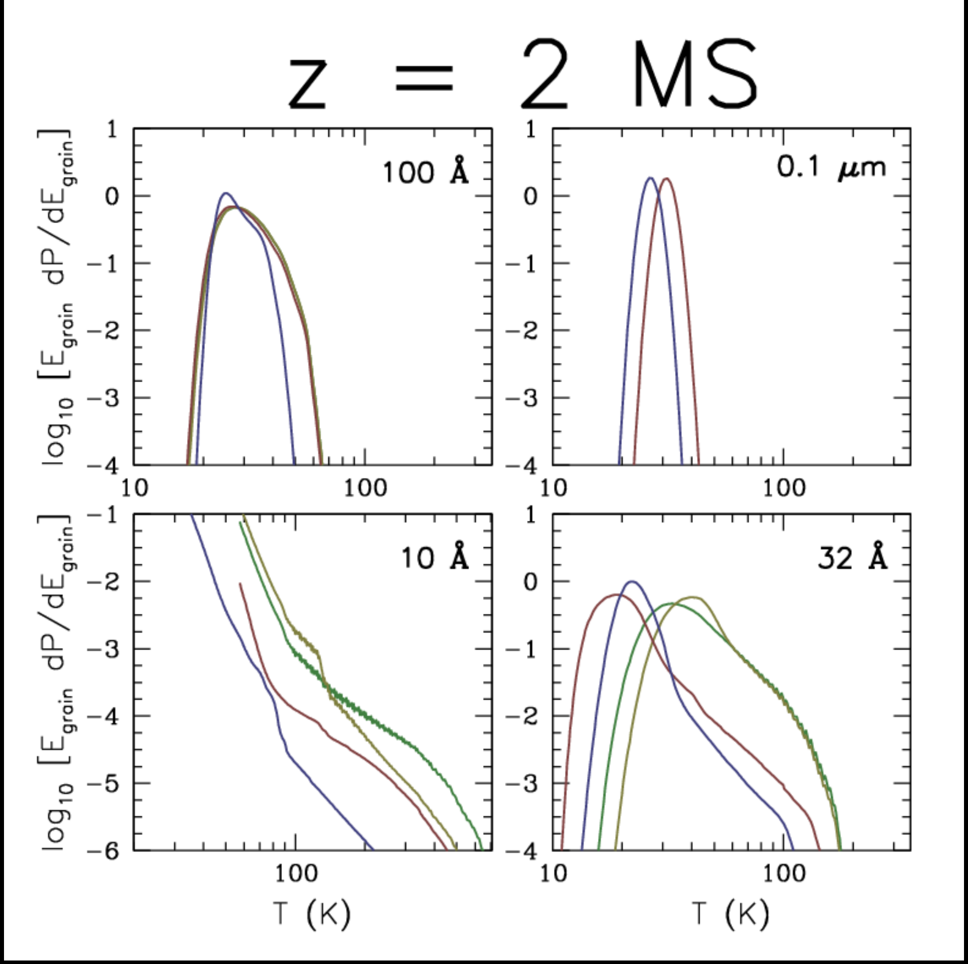
Well-defined temperatures

Temperature Distributions: z ~ 1 MS



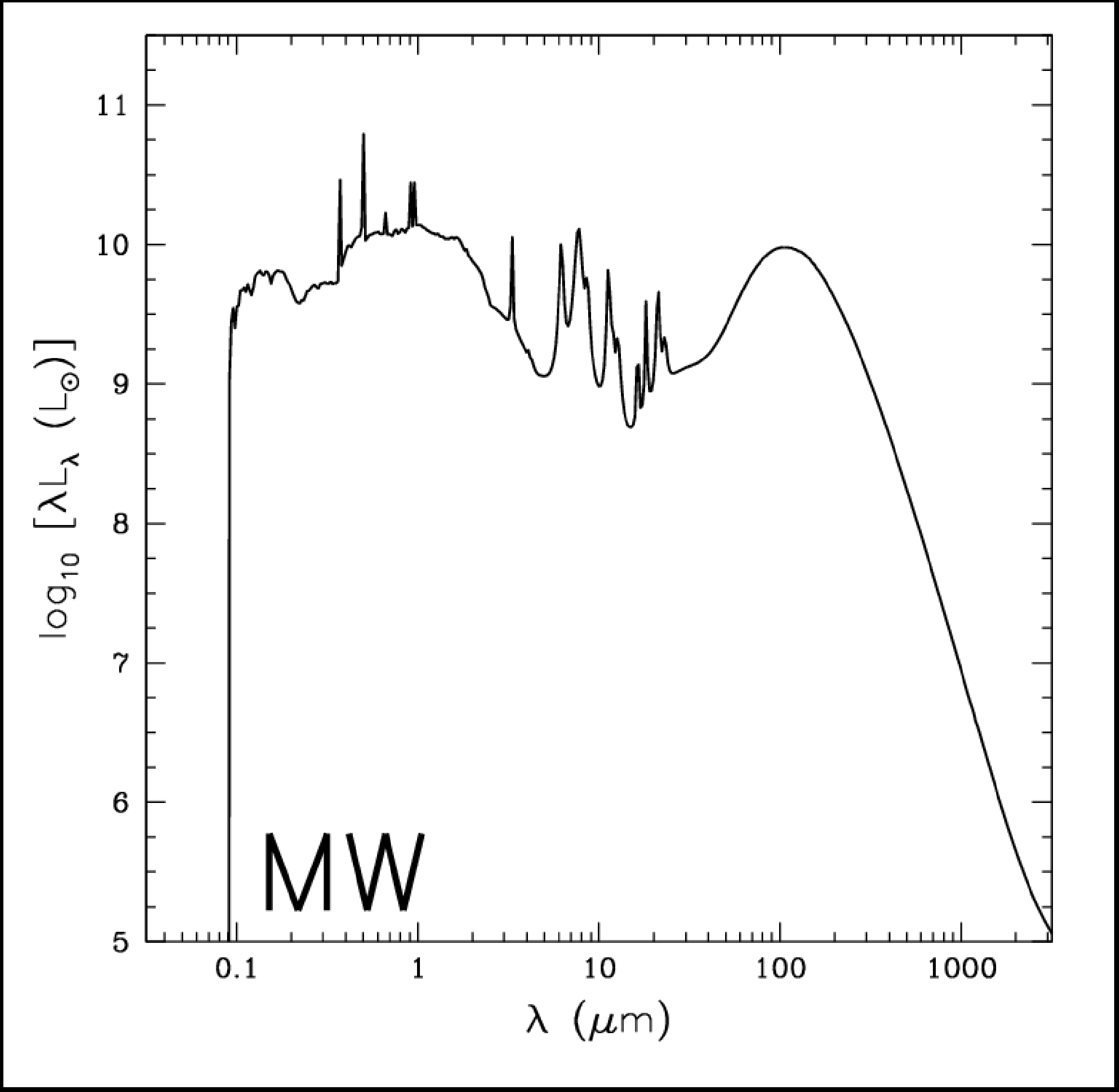
Relatively cold

Temperature Distributions: z ~ 2 MS

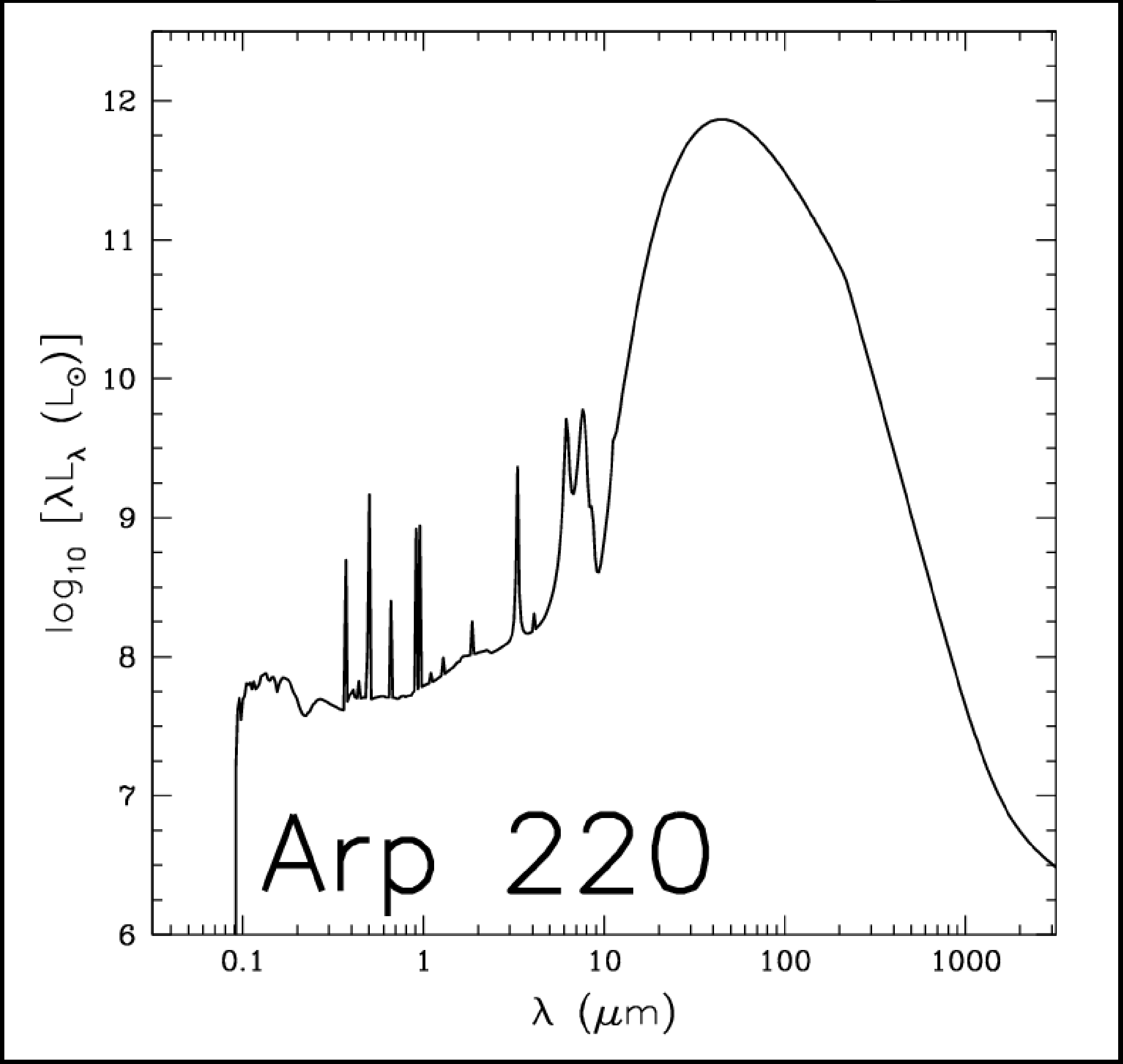


Relatively cold

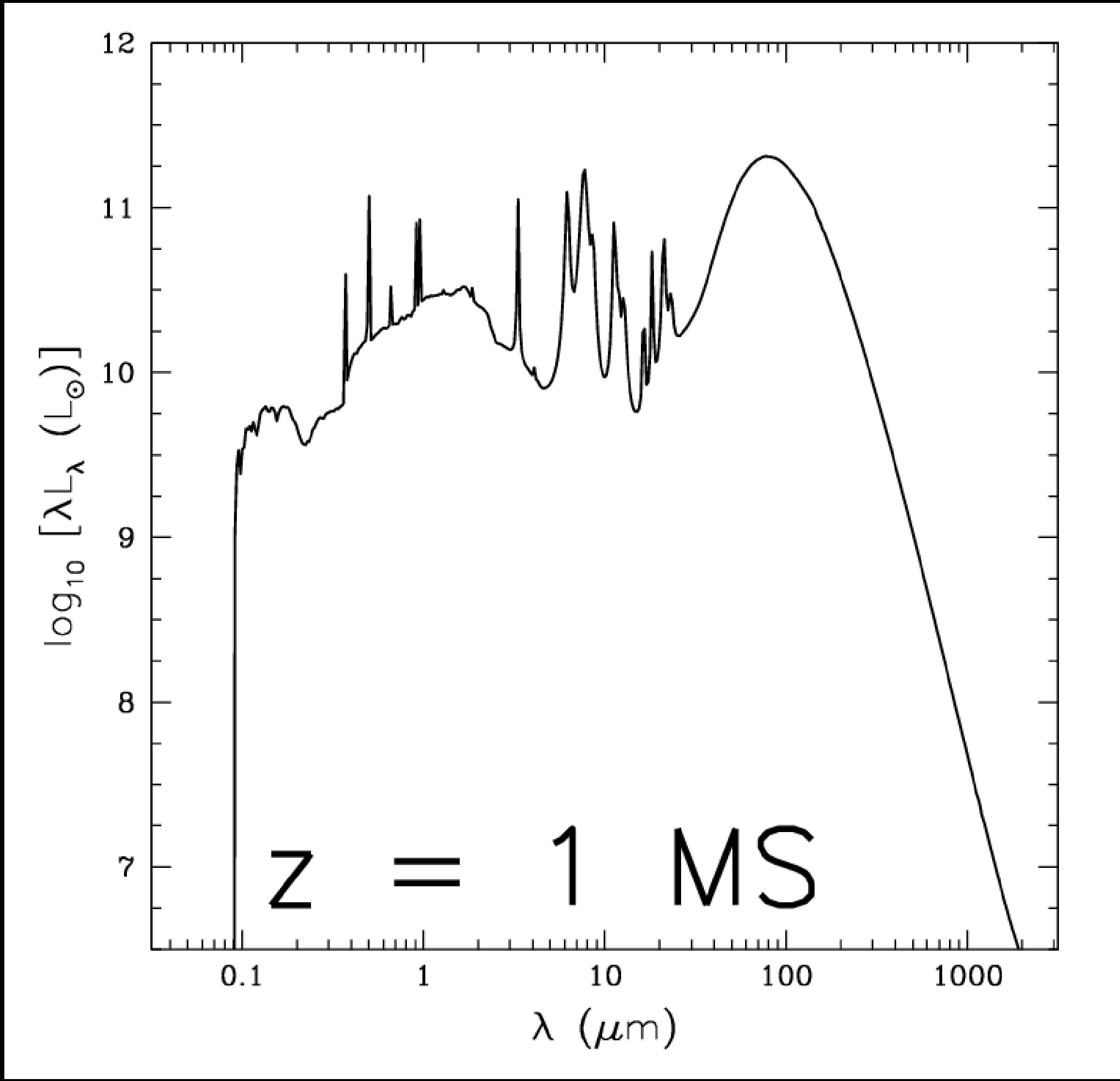
Predicted UV/O/IR Spectra



Predicted UV/O/IR Spectra



Predicted UV/O/IR Spectra



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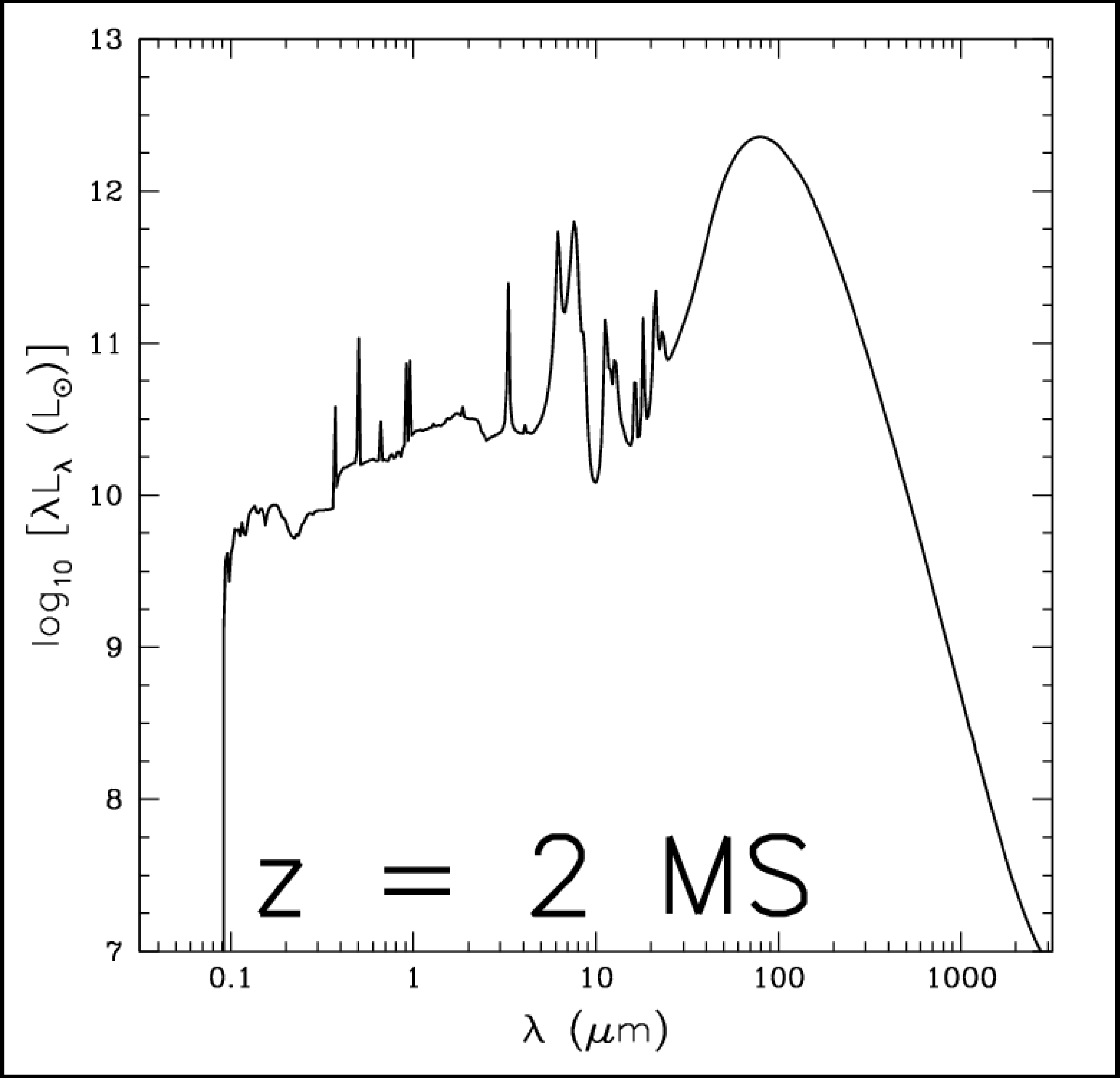
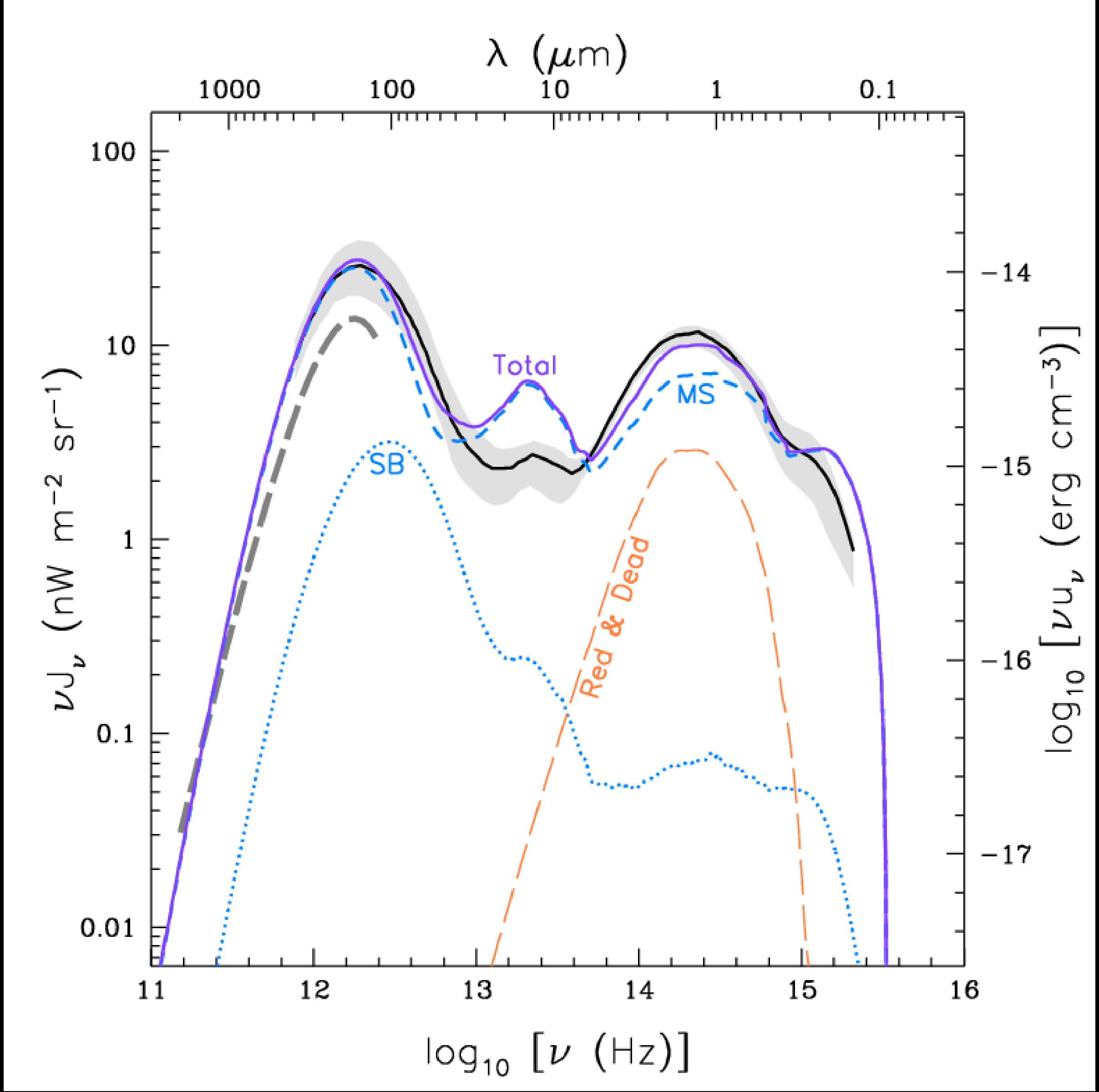


The UV/O/IR Background



CR Populations: The Simplest Version

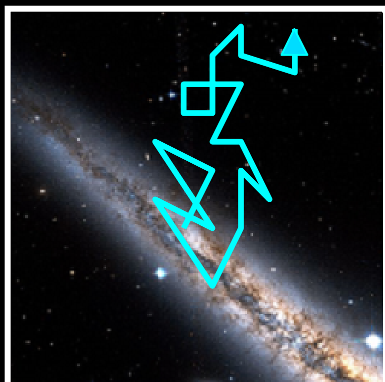
$$Q(E) \times t(E) \sim N(E)$$

Rate at which particles injected at energy E	Time particles survive with energy E	Number of particles with energy E

Shorter t(E) at high E – steeper (softer) spectrum
Shorter t(E) at low E – flatter (harder) spectrum

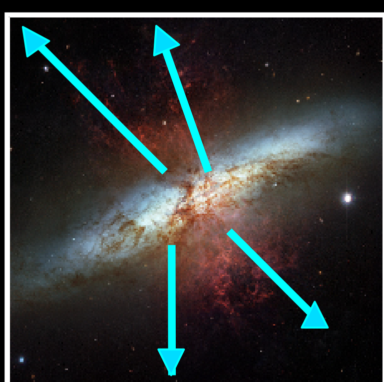
The Life of a CR Electron

Flatten Spectra

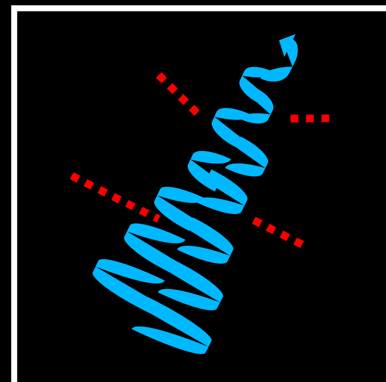


Diffusive Escape

Convective Escape

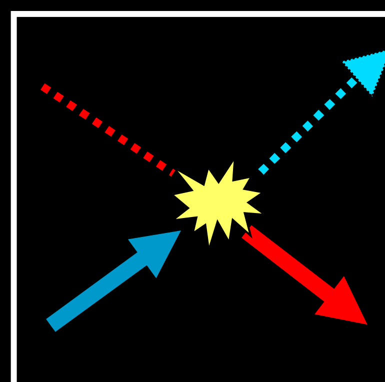


Steepen Spectra

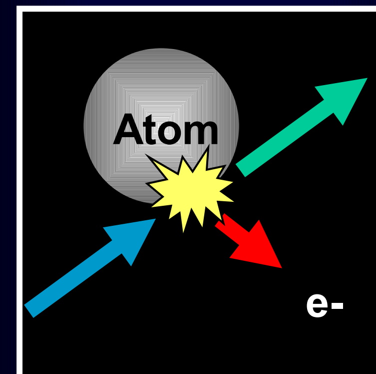


Synchrotron

Inverse Compton

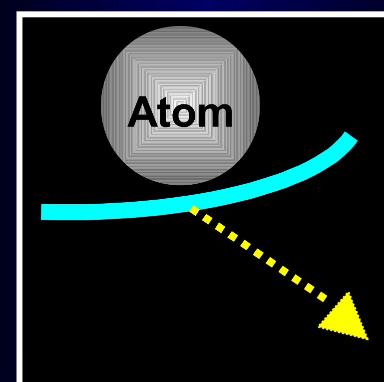


Flatten Spectra

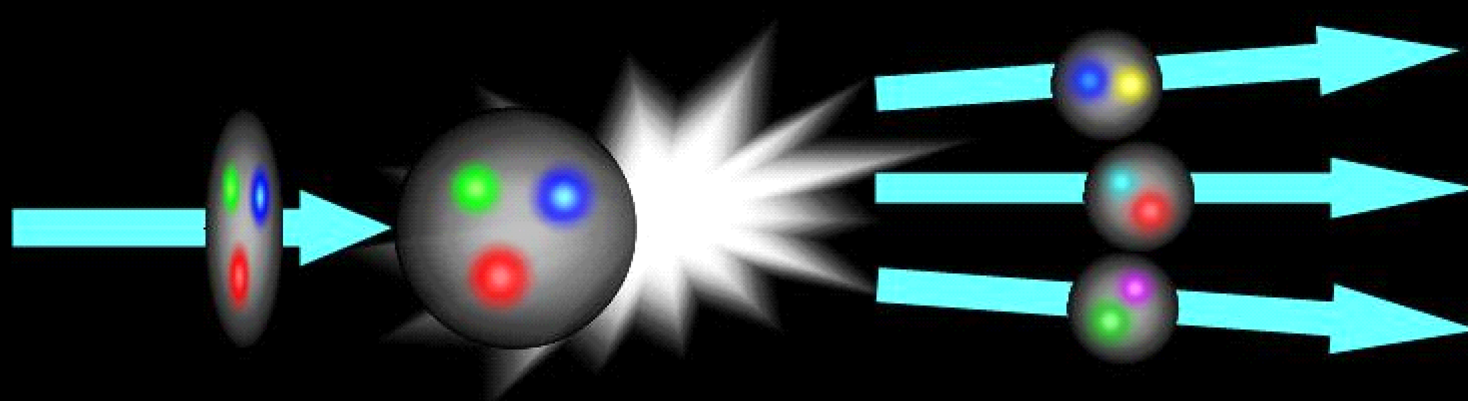


Ionization

Bremsstrahlung



Secondary $e^{+/-}$



Cosmic ray protons hit ISM protons and make pions

$$
\begin{array}{lllllllll}
\pi^+ & \rightarrow & e^+ & + & \nu_e & + & \bar{\nu}_\mu & + & \nu_\mu \\
\pi^- & \rightarrow & e^- & + & \bar{\nu}_e & + & \nu_\mu & + & \bar{\nu}_\mu \\
\pi^0 & \rightarrow & & & \gamma & + & \gamma & &
\end{array}
$$

Secondary e+/e-

Gamma-rays & neutrinos

Magnetic fields

Biggest uncertainty

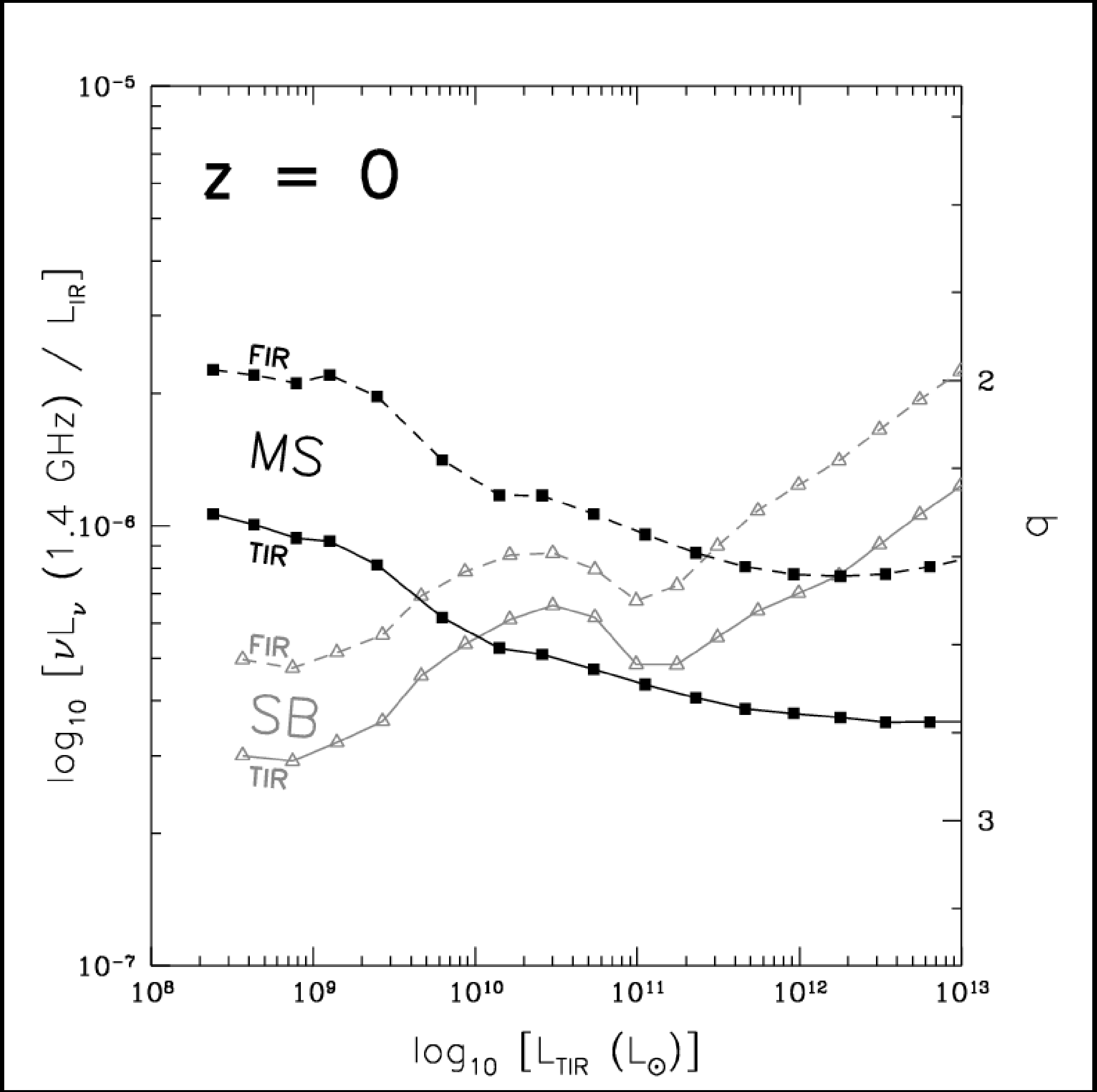
But B ~ SSFR1/2 dependence motivated by FIR-radio correlation

Also SFR-driven turbulence

$$B = 8\ \mu G\ (\Sigma_{SFR} / \Sigma_{SFR,MW})^{1/2}$$ [MS]

$$B = 3\ \mu G\ (\Sigma_{SFR} / \Sigma_{SFR,MW})^{1/2}$$ [SB]

Predicted FIR-Radio Correlation



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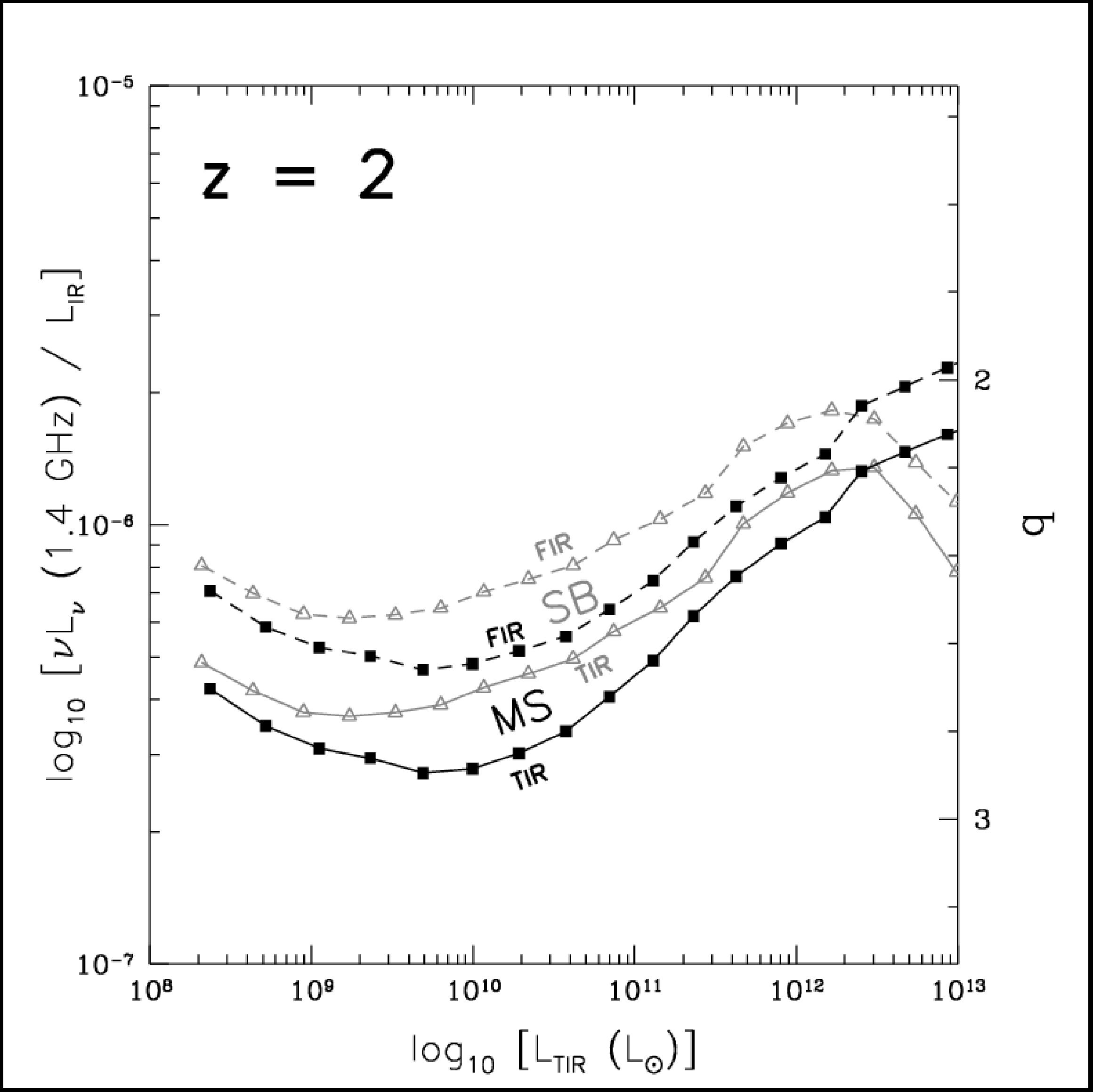
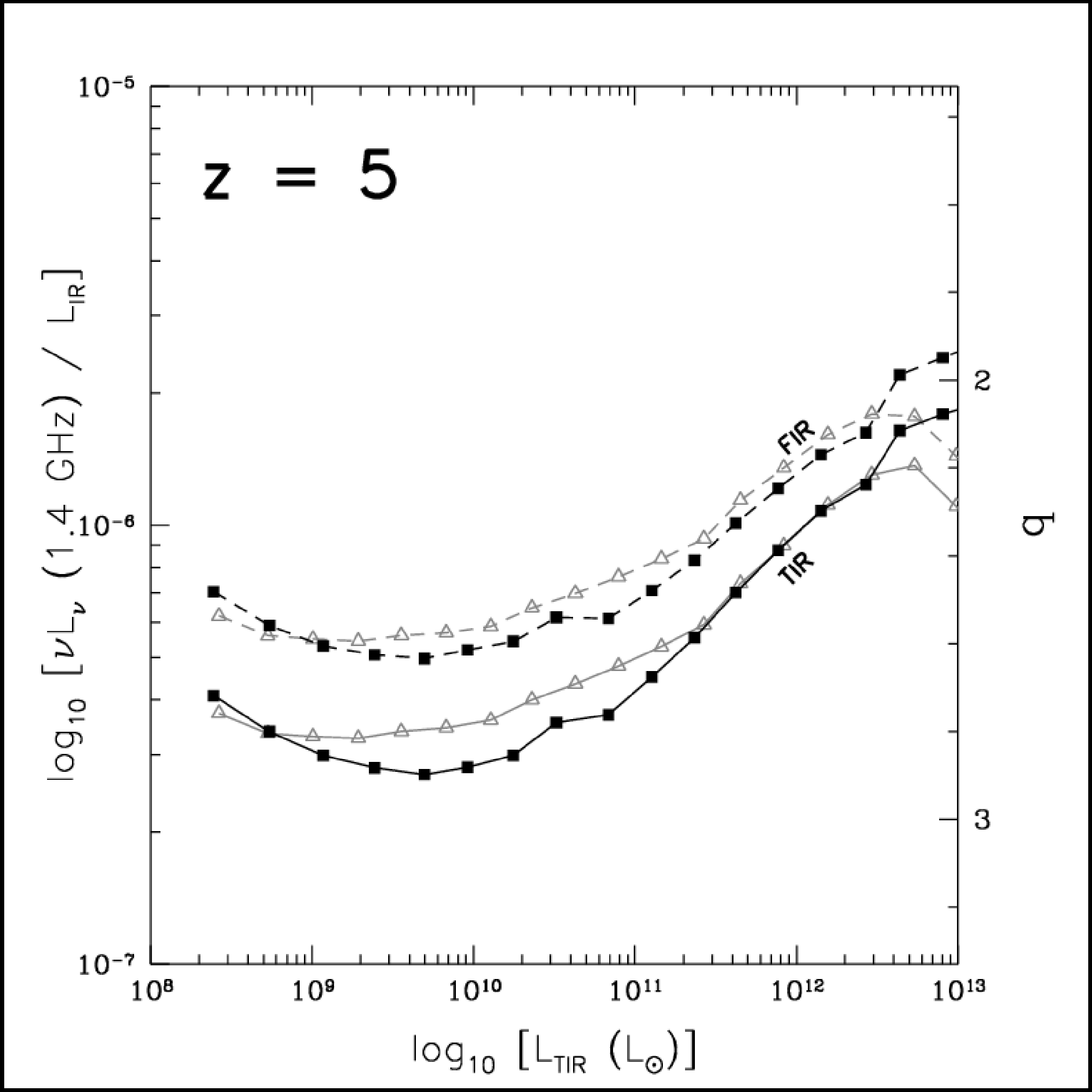
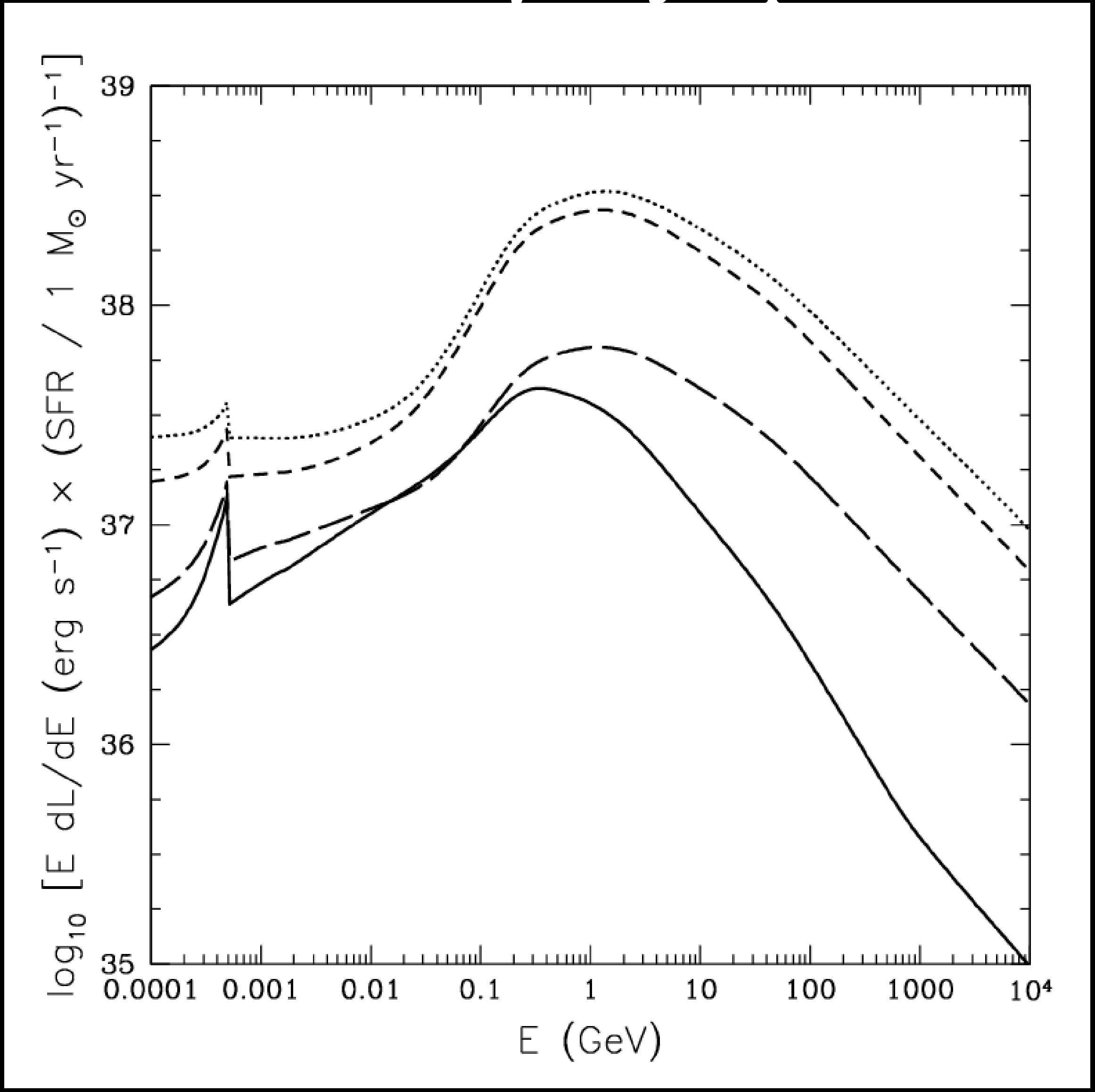


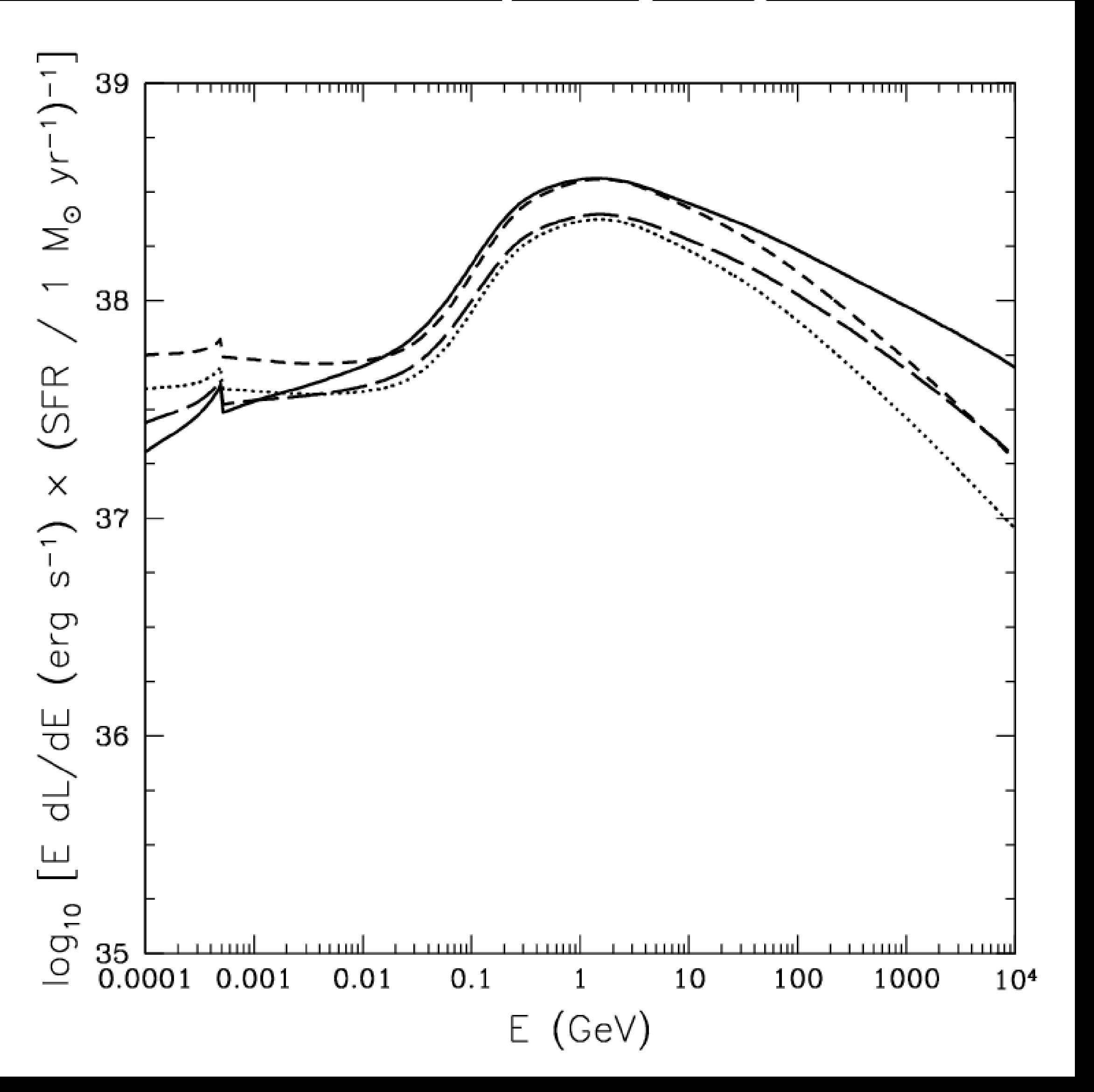
Predicted FIR-Radio Correlation



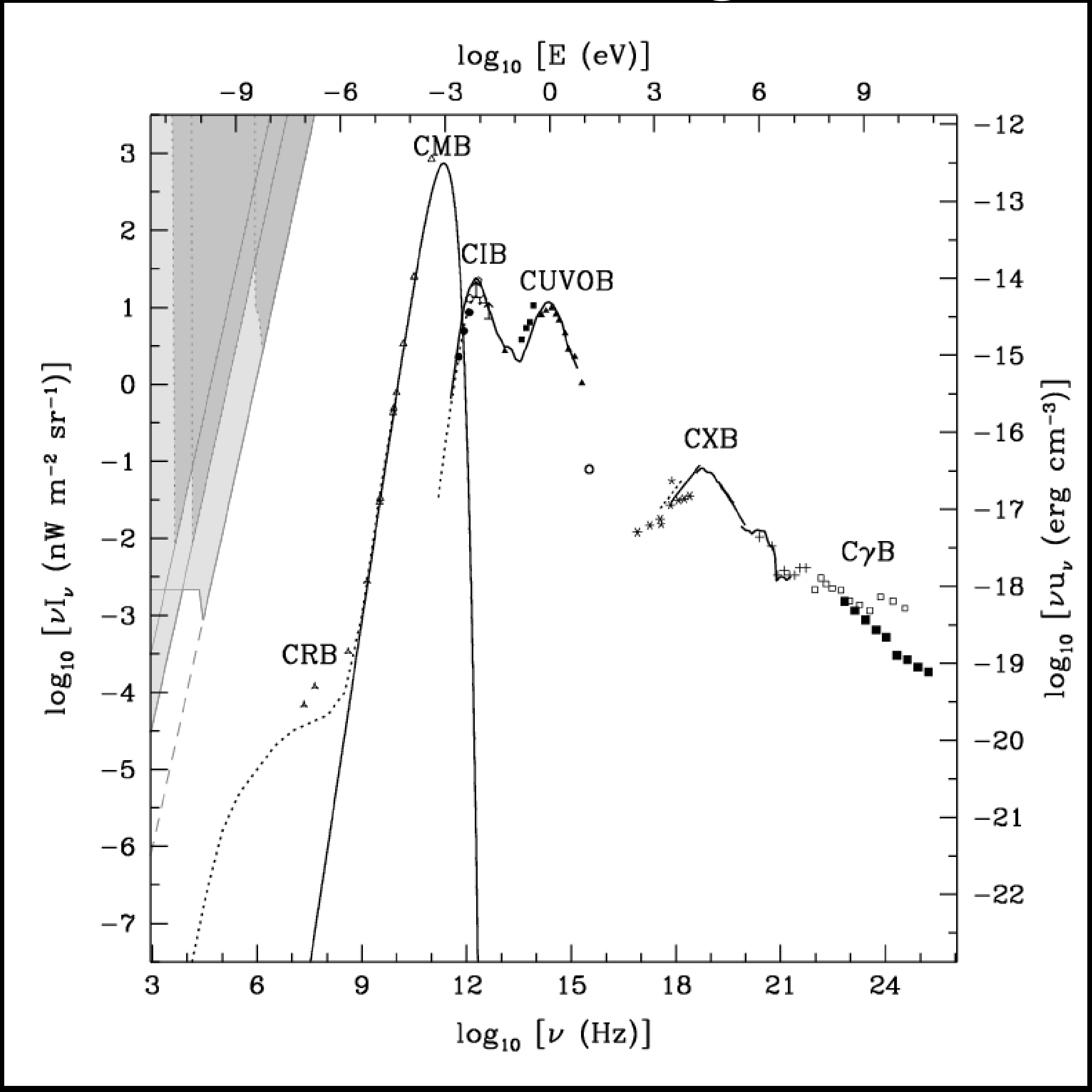
Predicted γ-ray spectra



Predicted γ-ray spectra



(Most) Radiation Backgrounds From Star-Forming Galaxies



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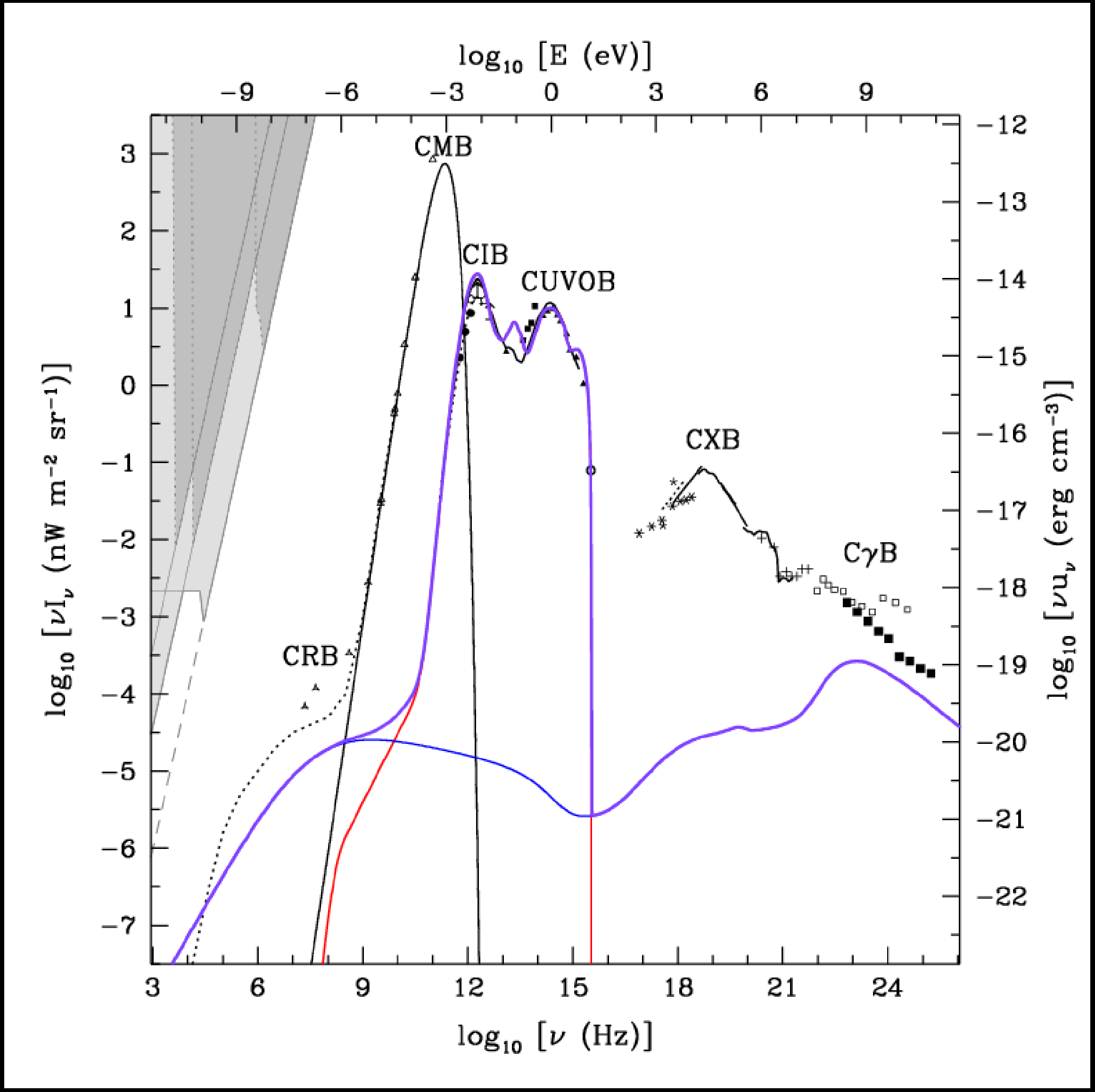
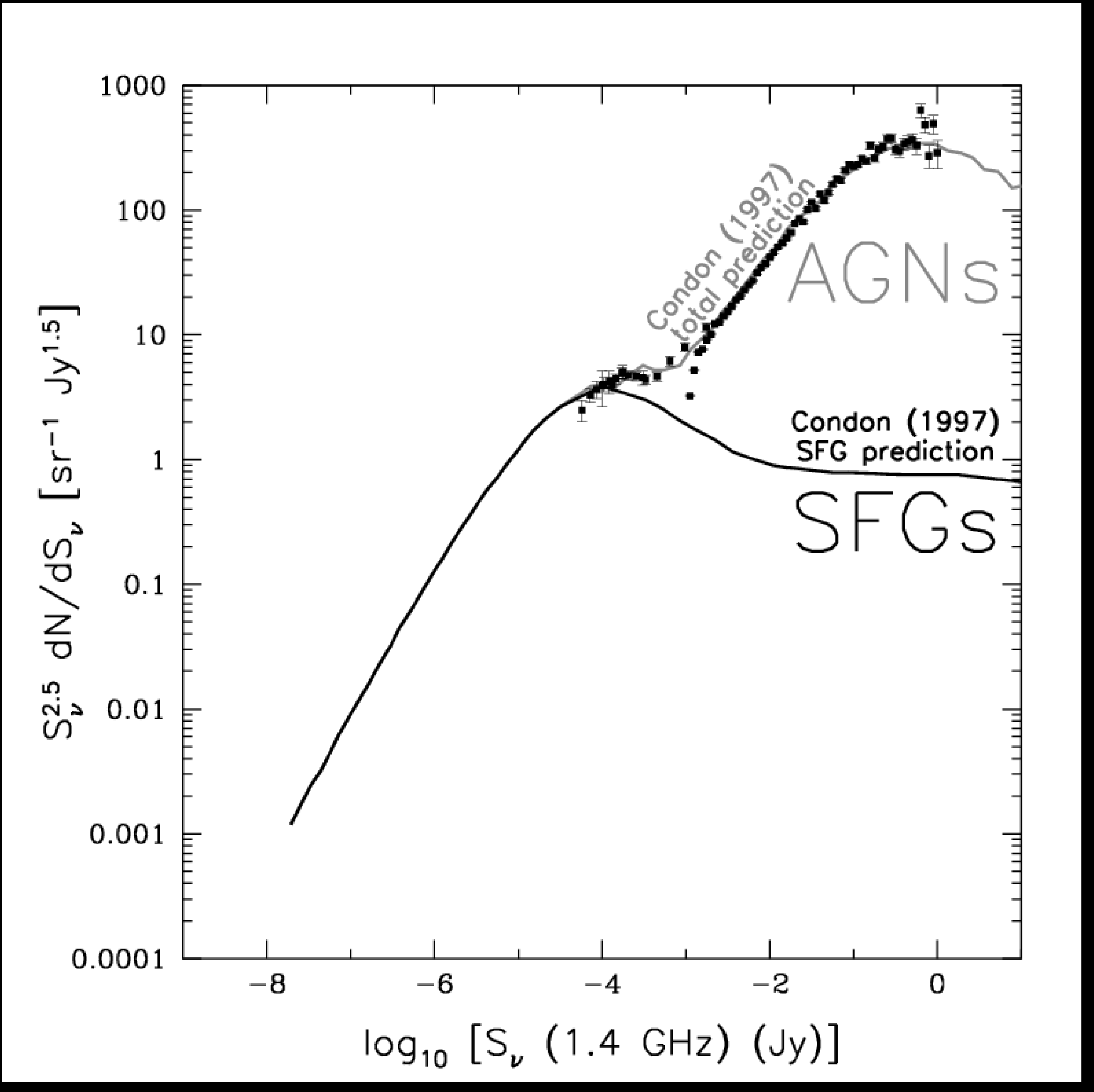
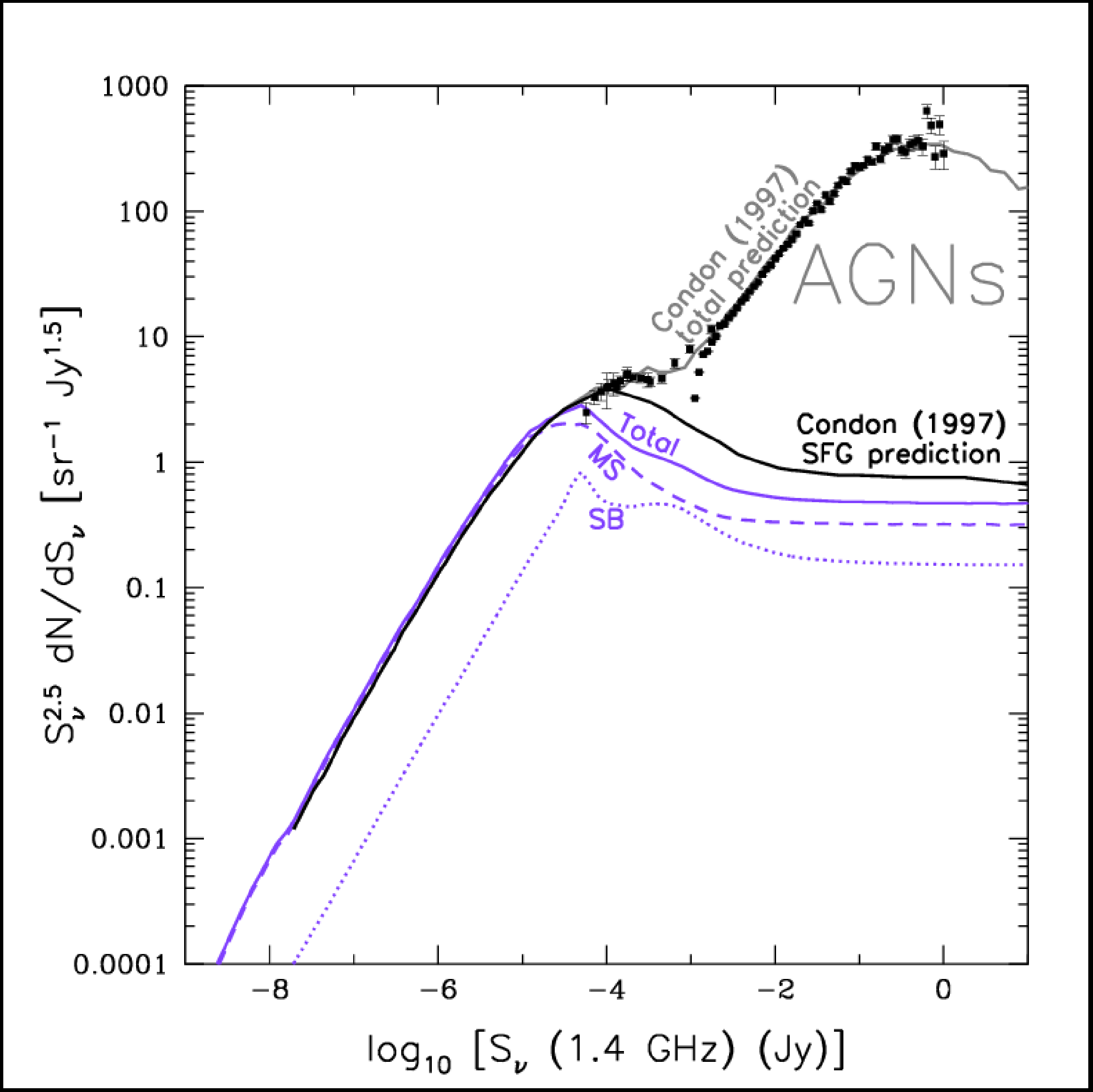


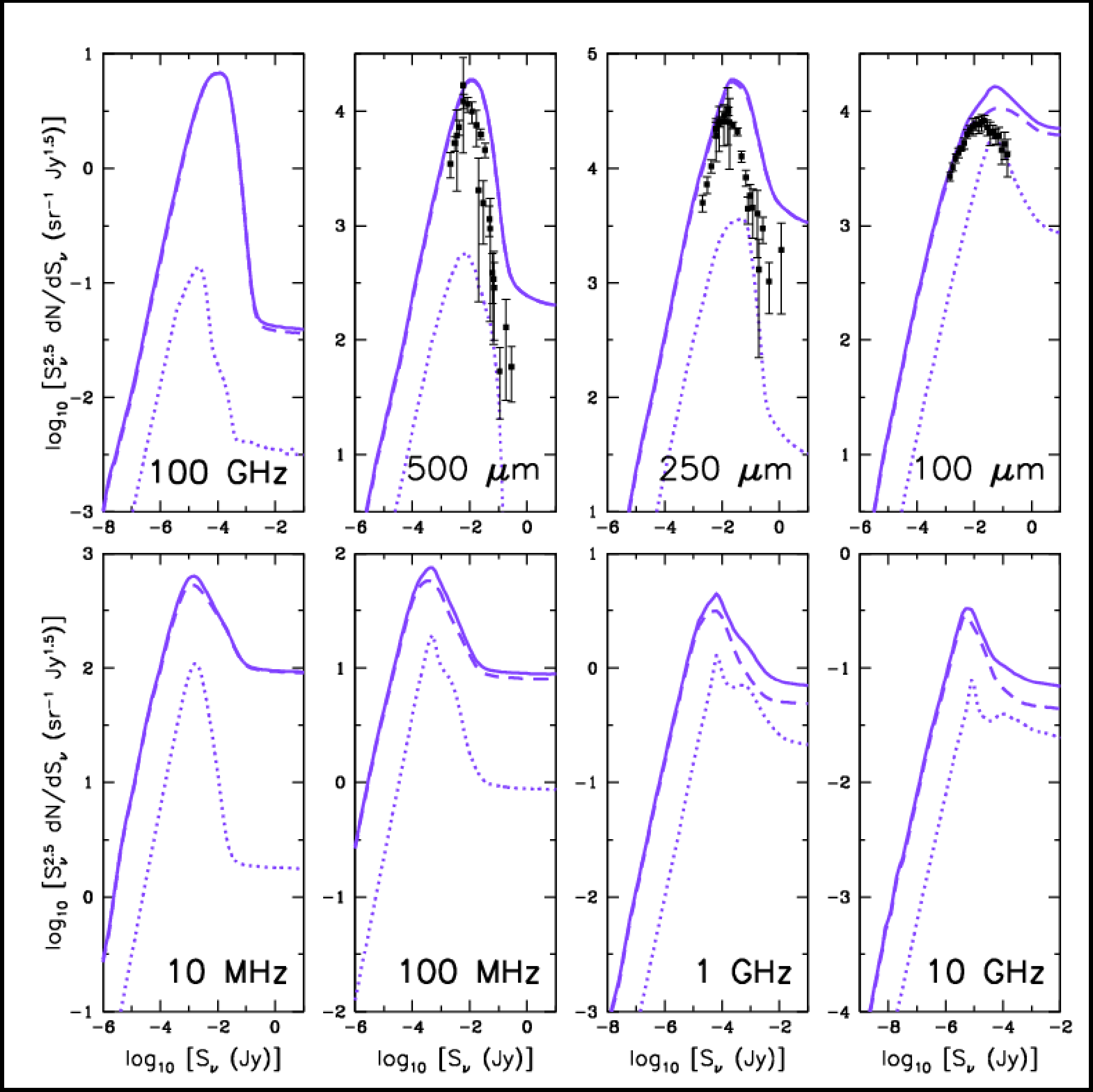
Radio Source Counts



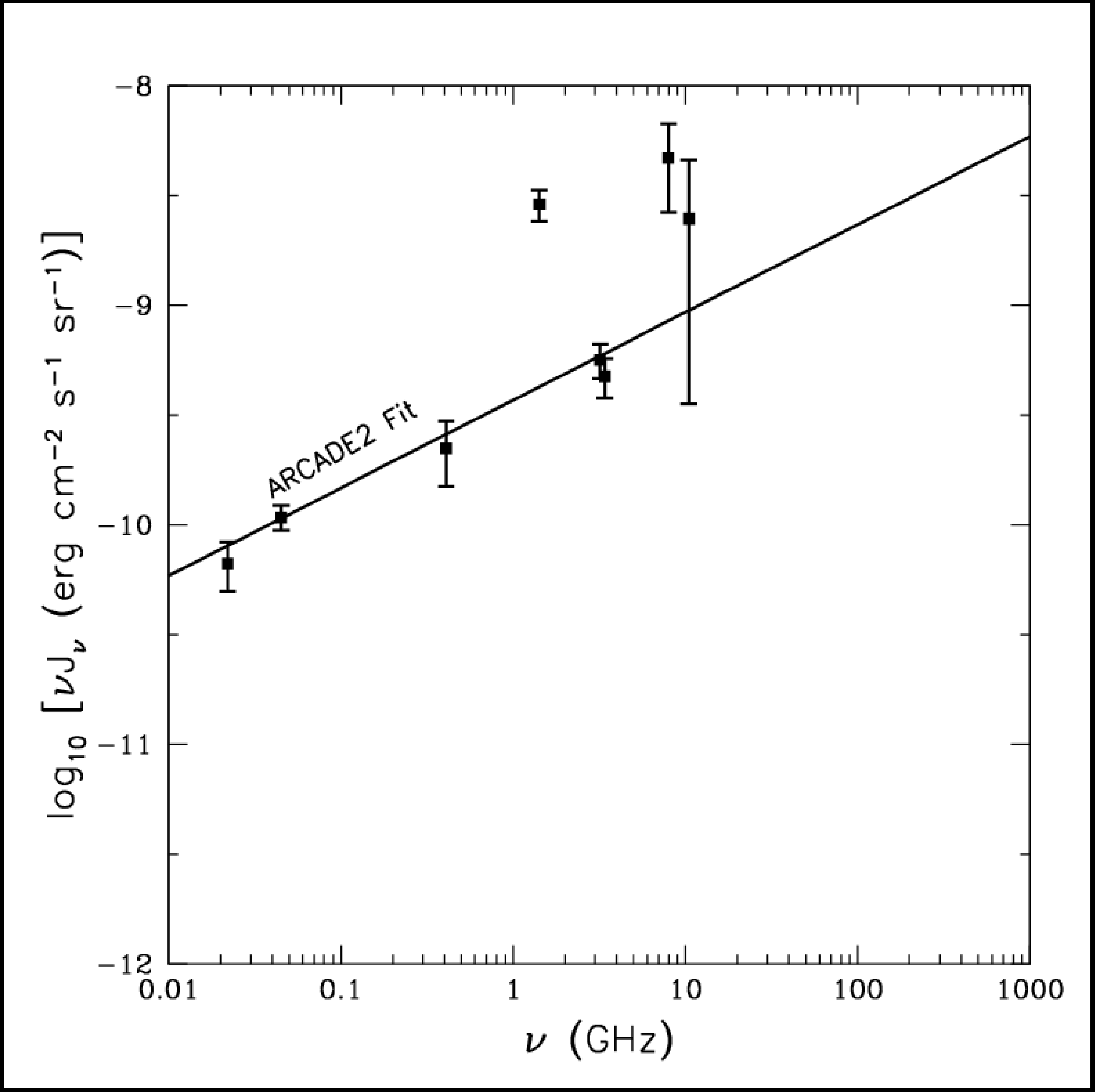
Radio Source Counts



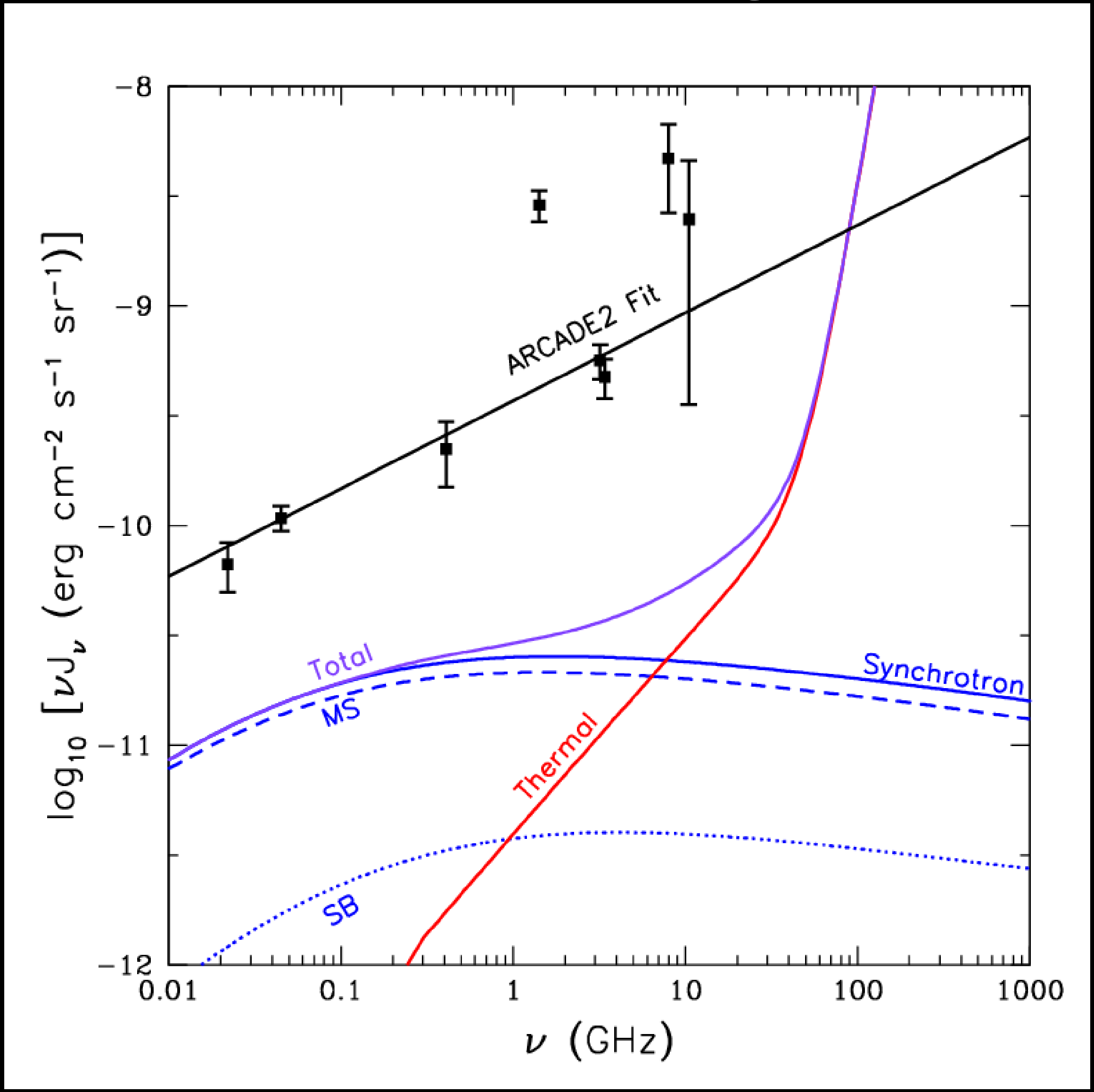
IR Source Counts



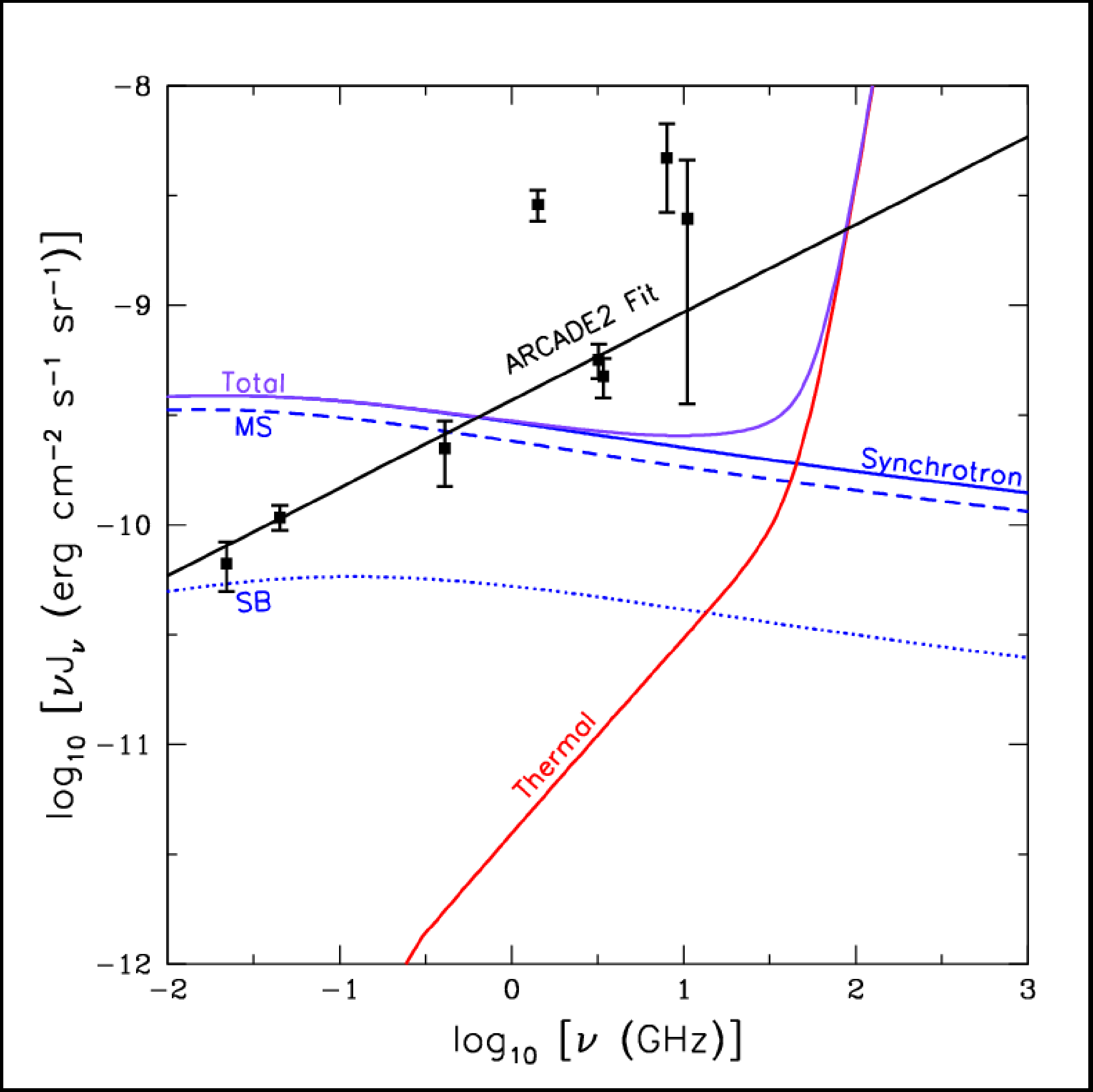
The Radio Background



The Radio Background



No ARCADE Excess



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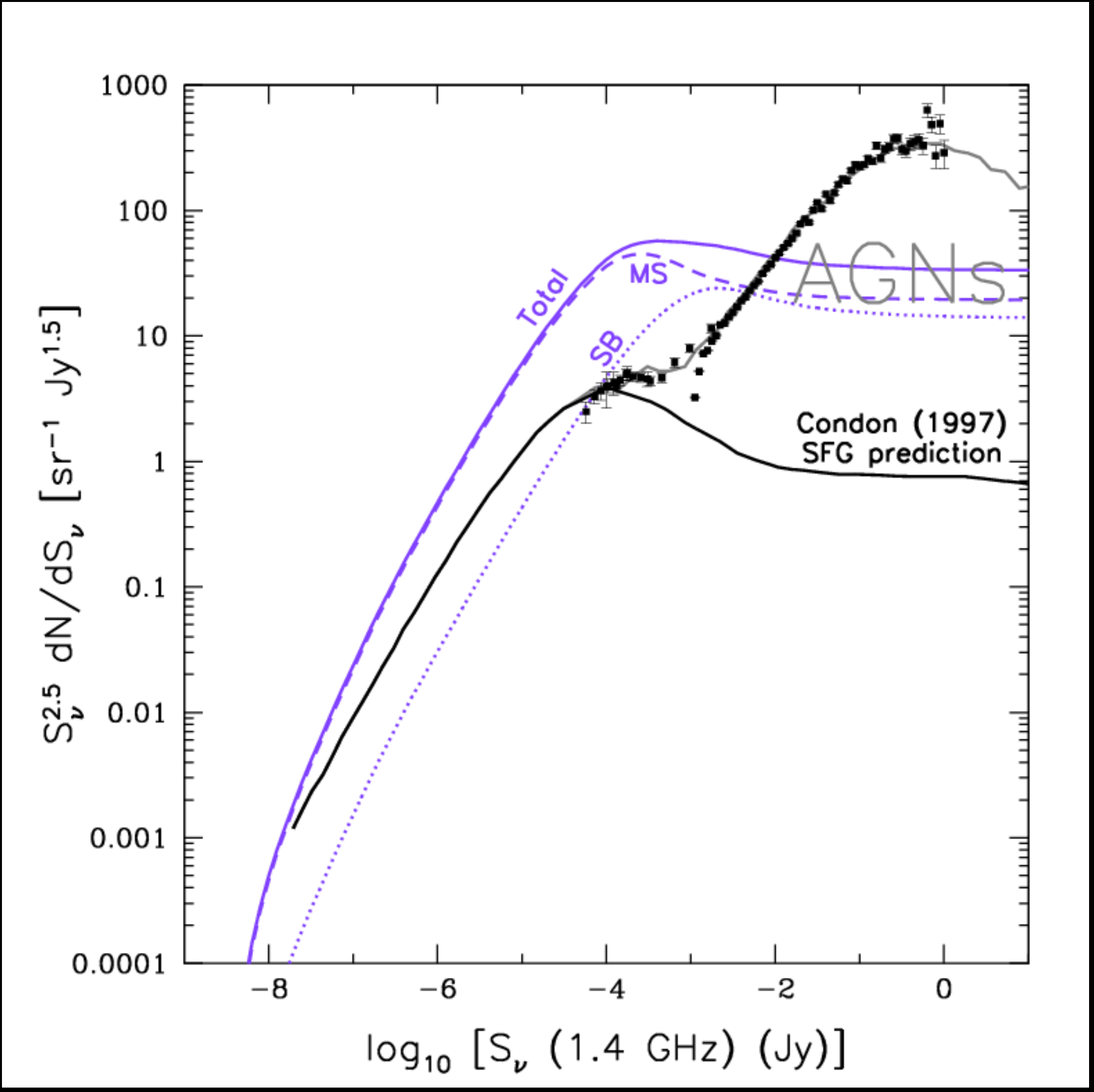
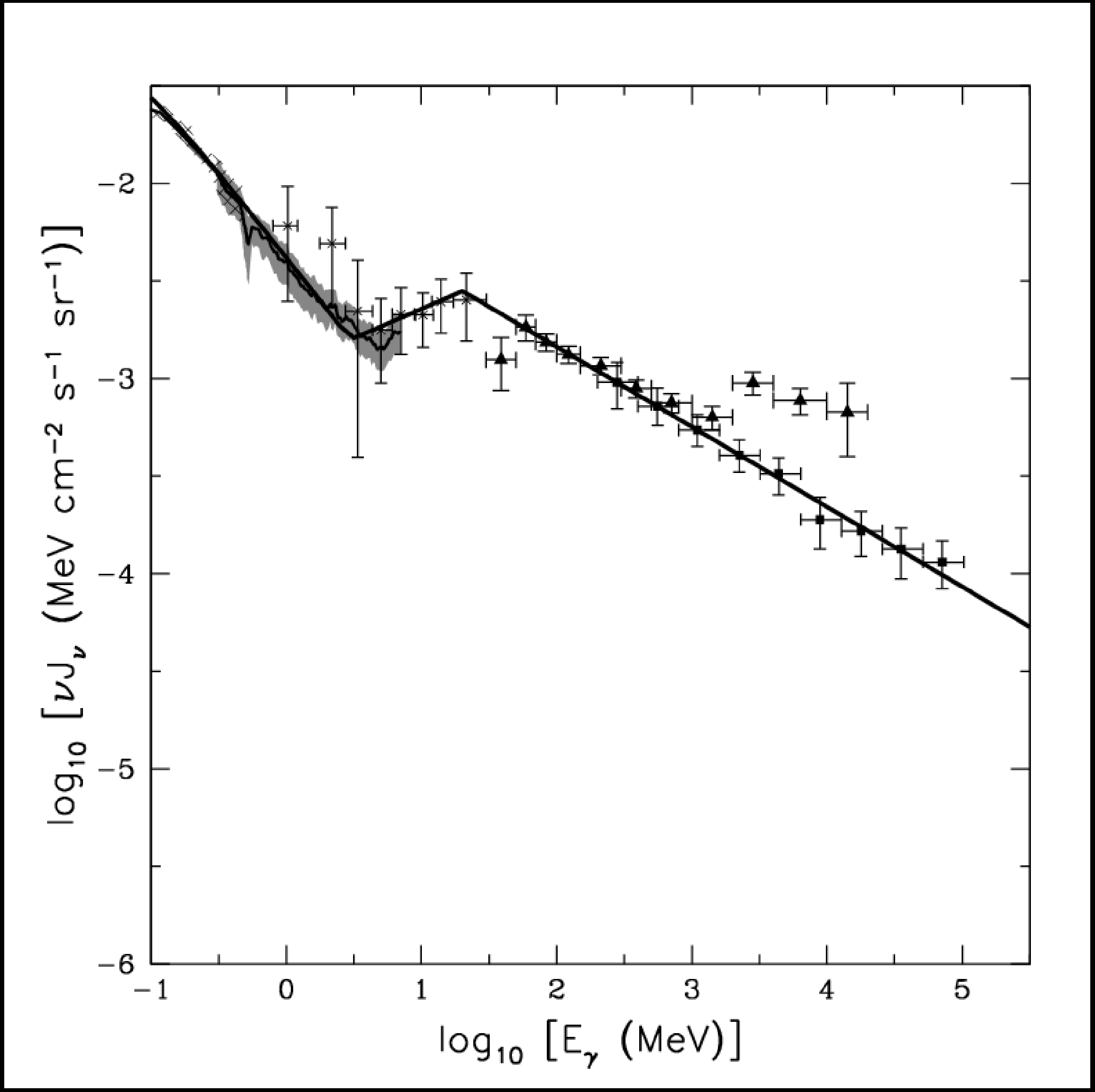
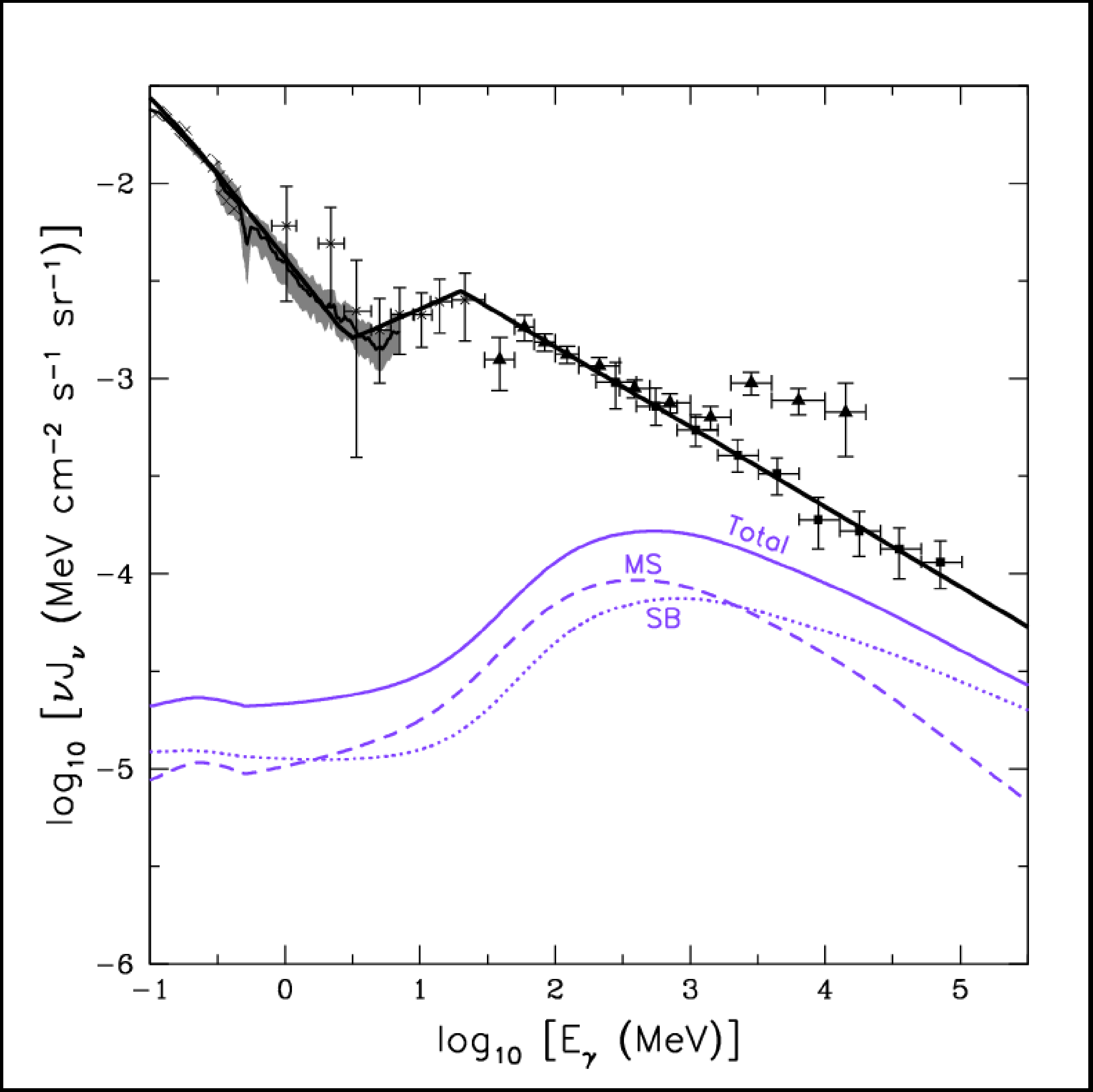


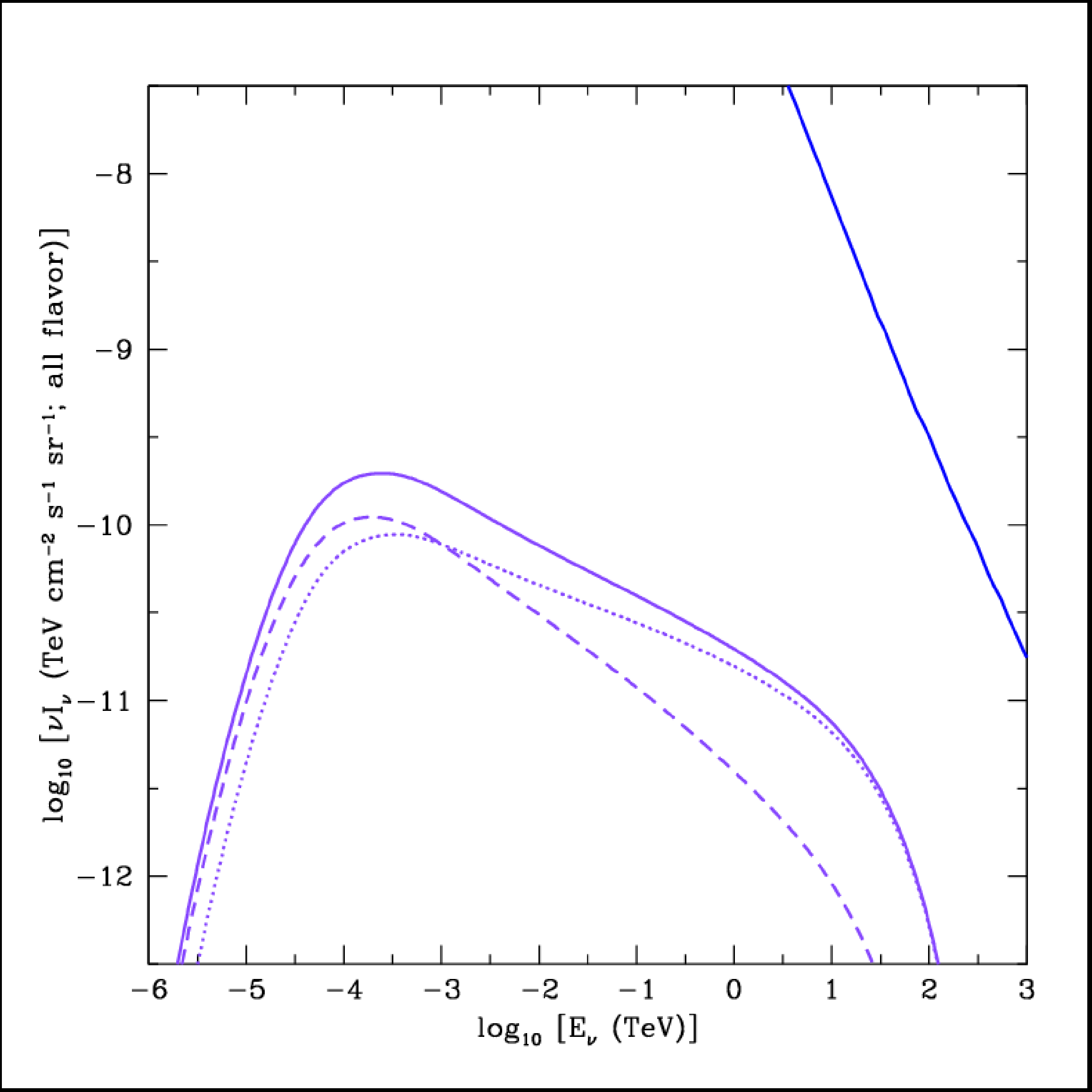
The Gamma-Ray Background



The Gamma-Ray Background



The Neutrino Background



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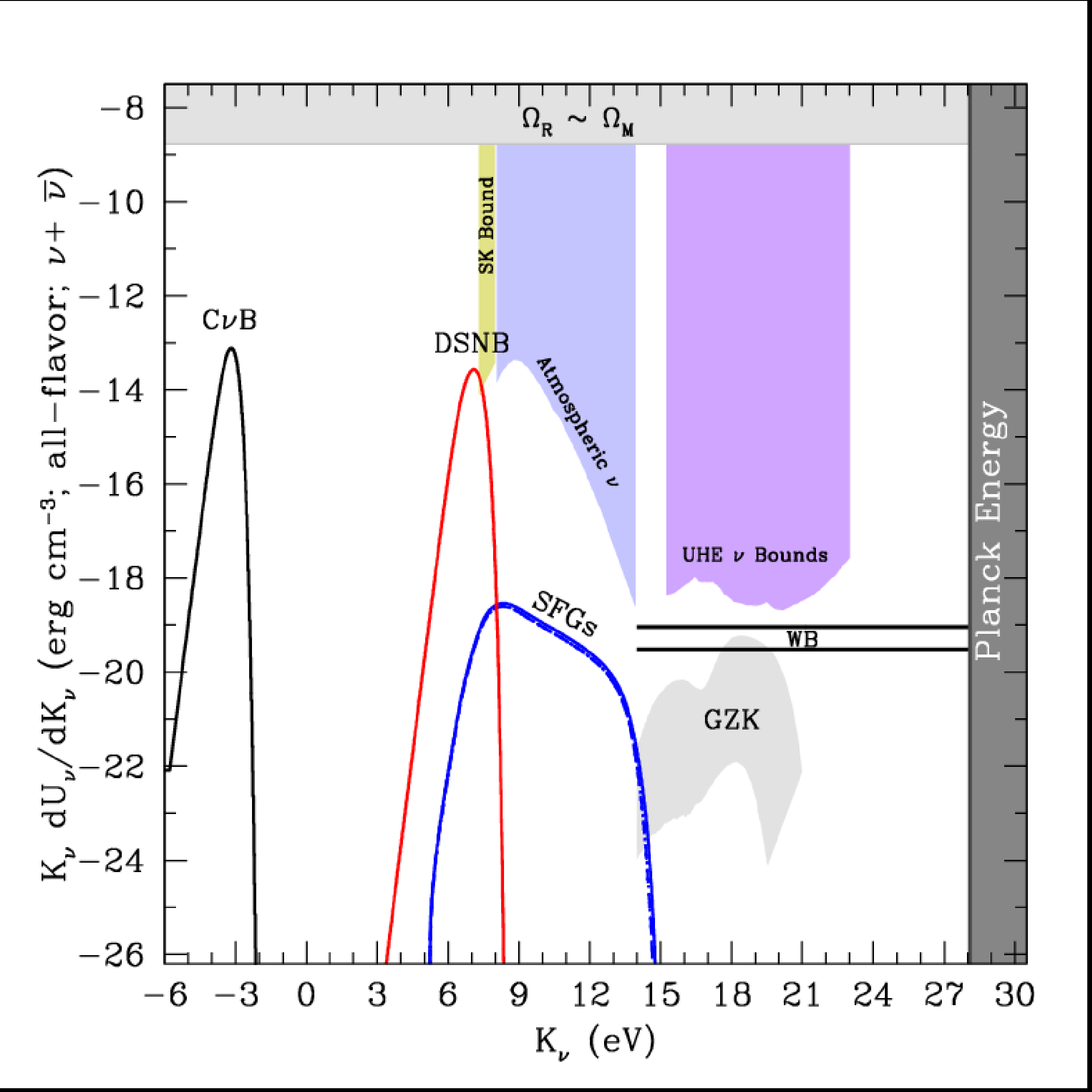

Future Improvements

X-rays

- X-ray binaries for hard X-rays
- Hot gas for soft X-rays

Very low frequency radio

- Free-free absorption from H II regions
- Transition radiation (kHz)

Ultra high energy CRs

- Photo-pion radiation from starbursts?