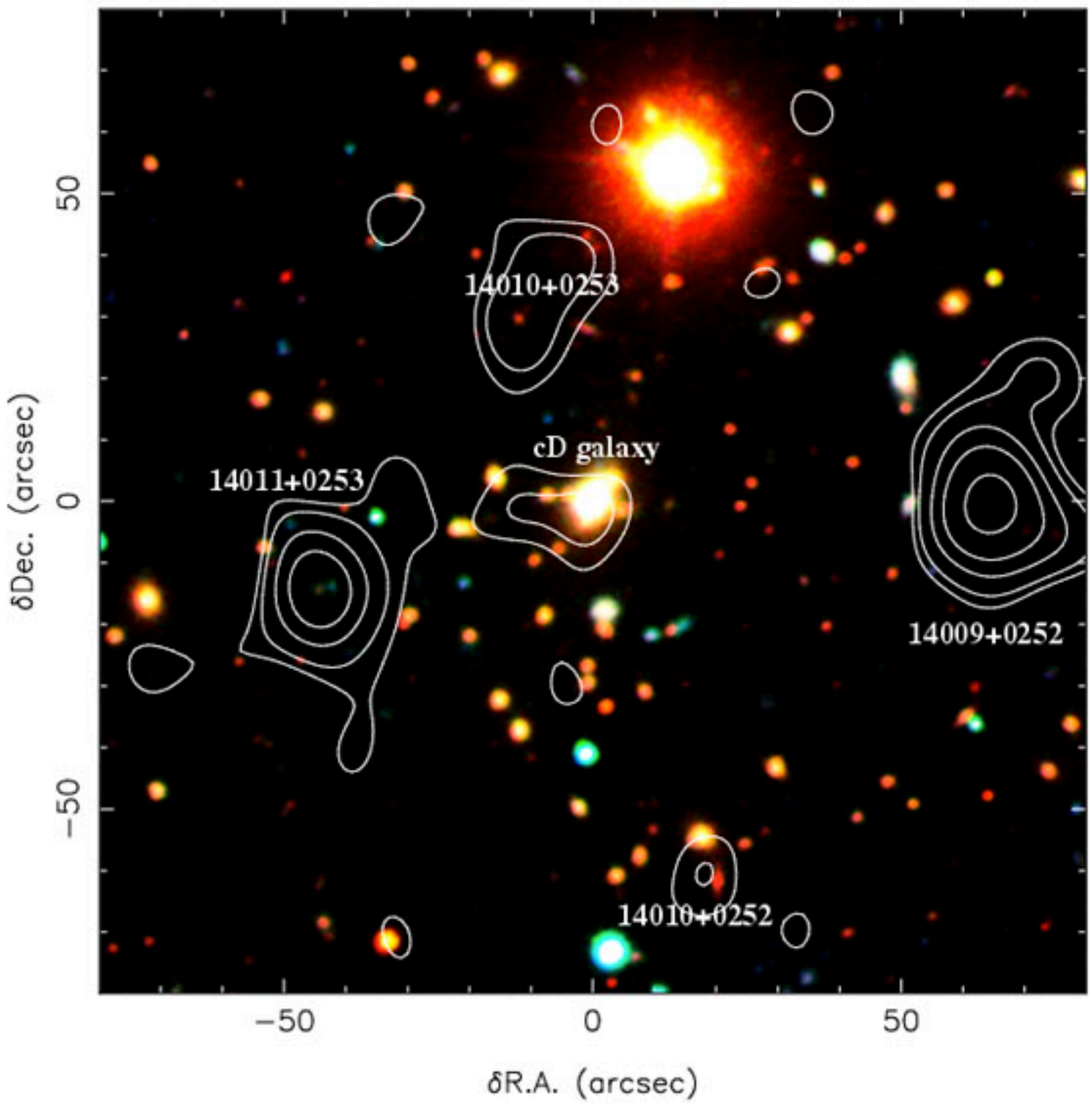
Recap on Dust

- Dust is responsible for extinction (IR to UV) and shape the SED of galaxies
  - Absorption by dust explains the $1/\lambda$ slope of the extinction curve
- Galaxies are bright at IR due to dust emission
  - This is reprocessed emission from star forming regions

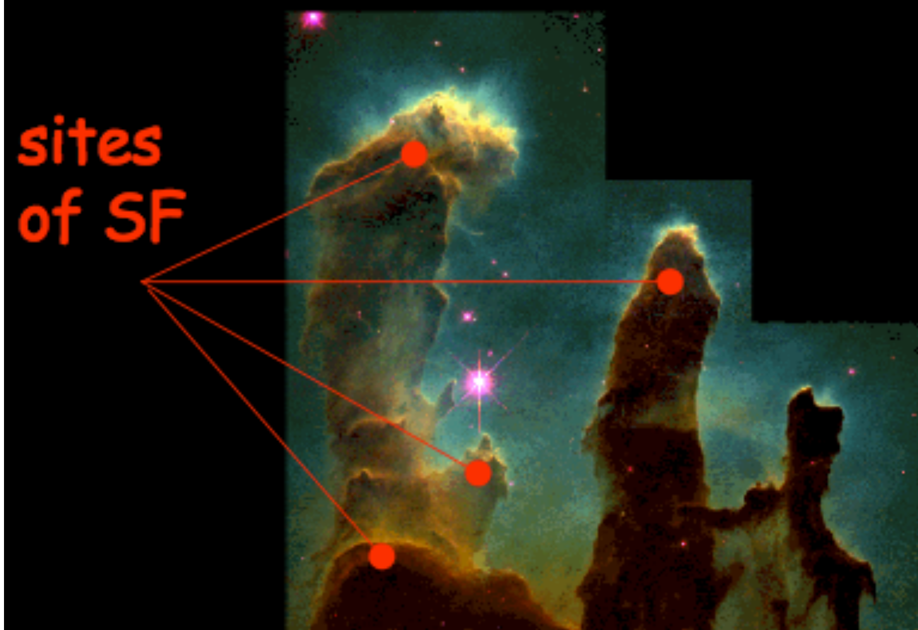
- Dust comes in many sizes: power law $a^{-3.5}$
  - Interpretation of extinction curve, scattering

- Dust is made by a mix of grains: graphites, silicates, ice
  - PAHs, temperature map of the Galaxy, polarization vs extinction

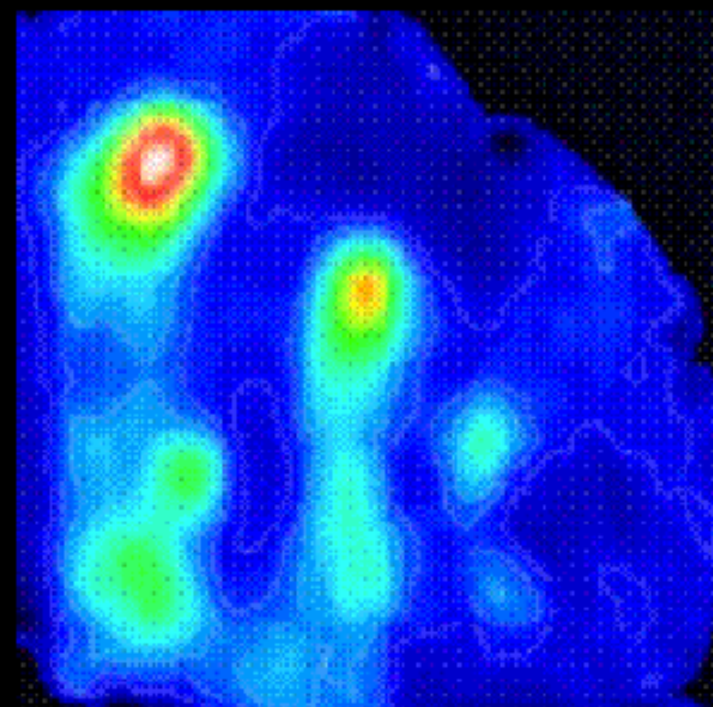
- Dust grains are aligned by the magnetic field:
  - Polarization


14010+0253
cD galaxy
14011+0253
14009+0252
14010+0252
50
0
−50
δDec. (arcsec)
δR.A. (arcsec)

Observing optically-obscured (hidden) star-formation with submm observations



optical HST



sub-mm 450μm

Sub-mm Astronomy

- Two sources of radiation:
  - Emission from dust (99% of all emission in sub-mm)
  - Molecular transitions (CO) in ISM (like MC)
- Emission from dust at T~20K peaks at ~150 μm
- Emission from dust at T~50K peaks at ~58 μm

Typical spectrum can be expressed as : $F(\nu) = B(\nu,T) \cdot \varepsilon$

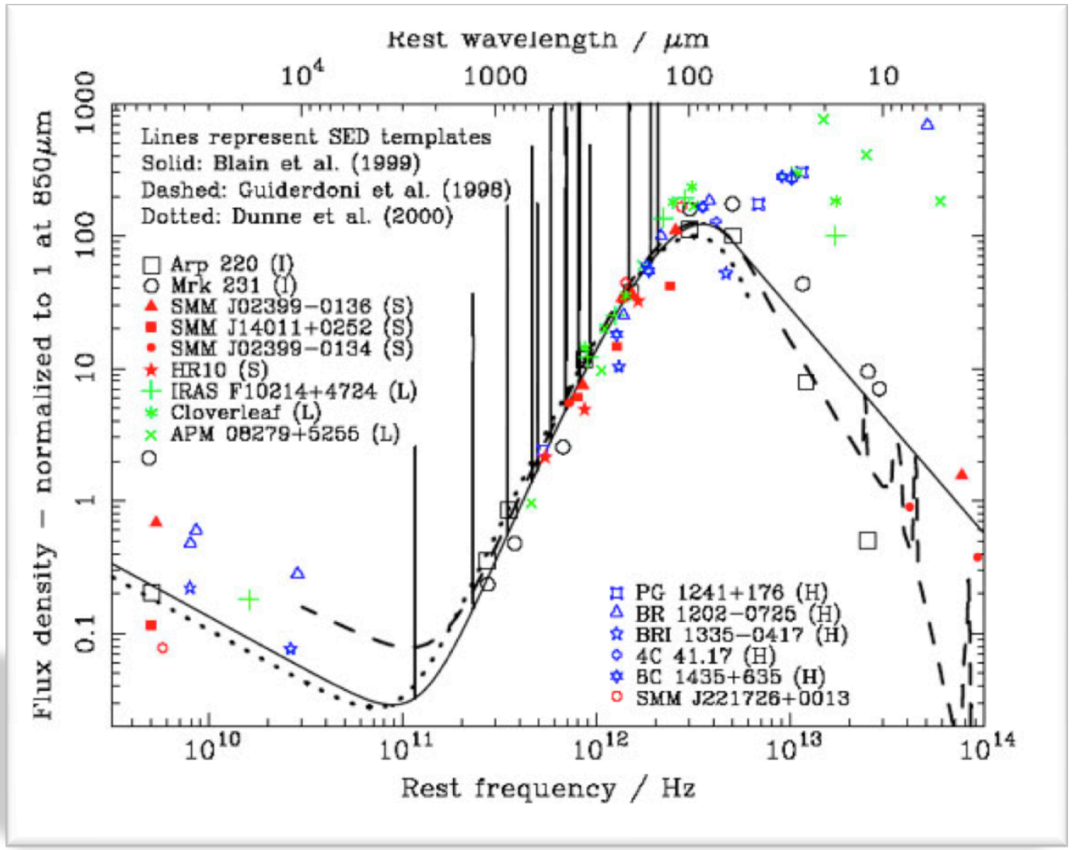
Where $\varepsilon = \nu^{\beta}$ with β~1.5 and T ~40 K

At low freq, R-J approximation:

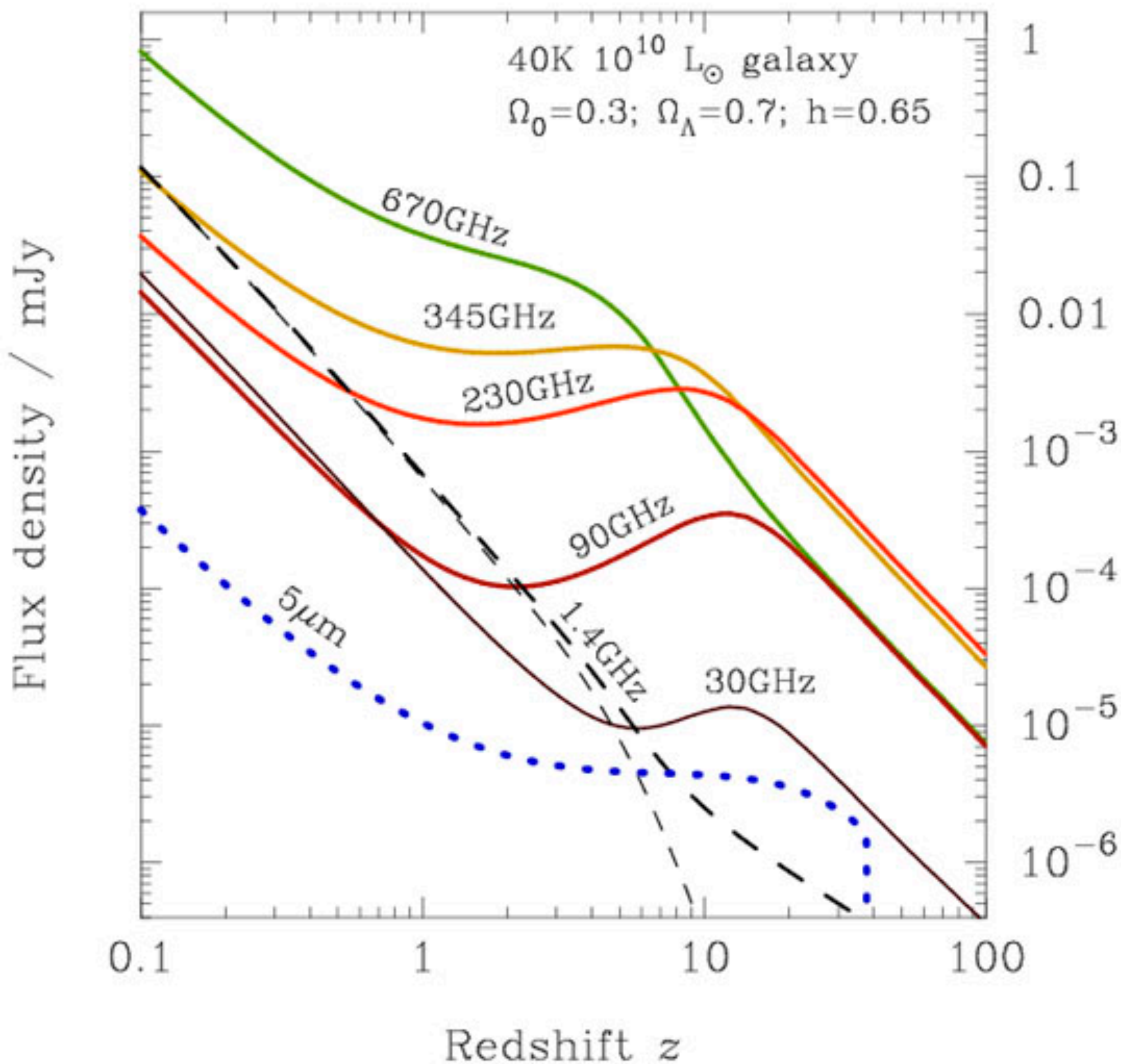
$$B(\nu,T) = 2\nu^2 kT / c^2$$

At high freq, Wien's approx.:

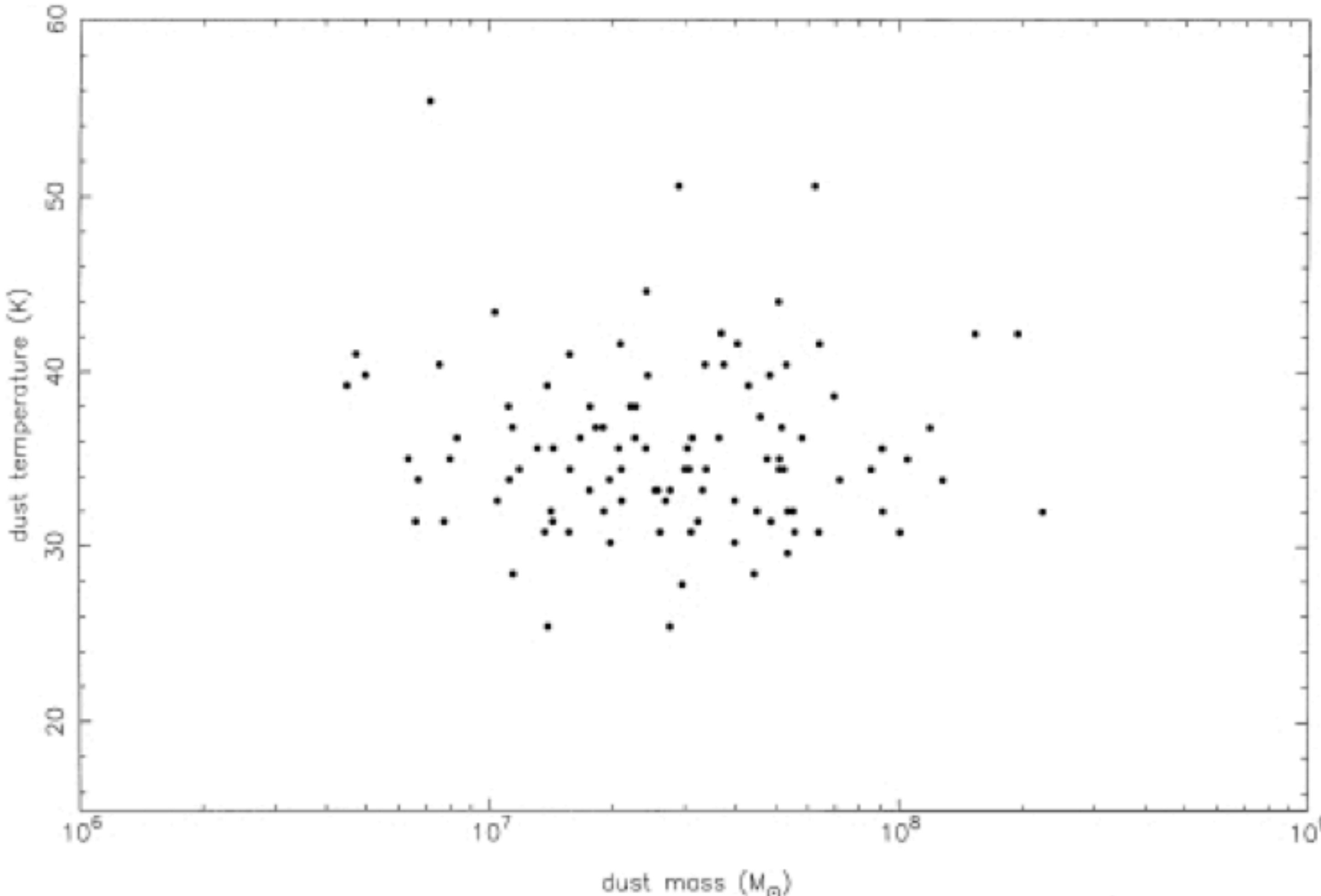
$$B(\nu,T) = 2h\nu^3 kT / c^2 \exp(-h\nu / kT)$$



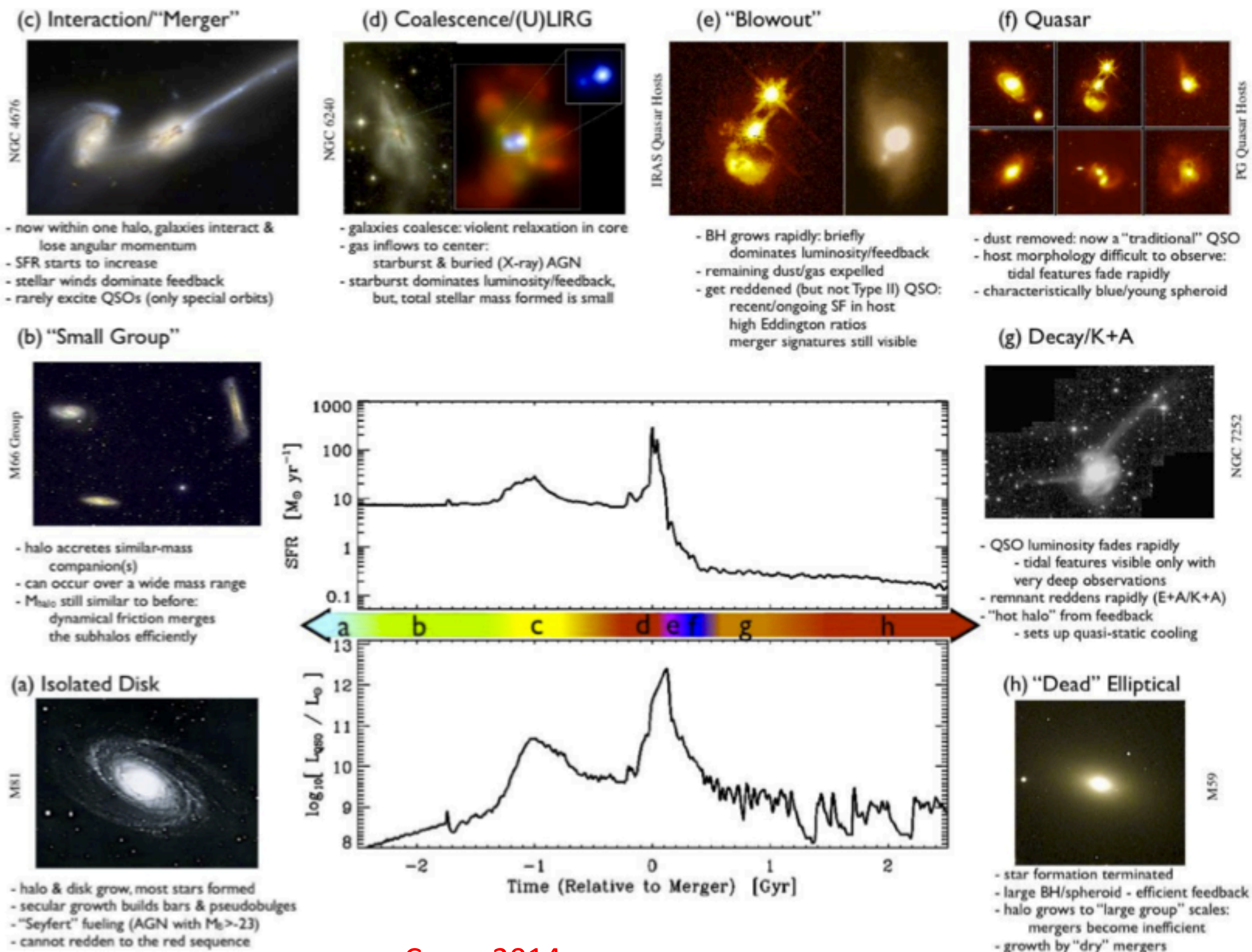
Variation of flux with z for sub-mm observations



Dust Temperatures in Spiral Galaxies in the nearby Universe



Dunne et al. 2000, 2001

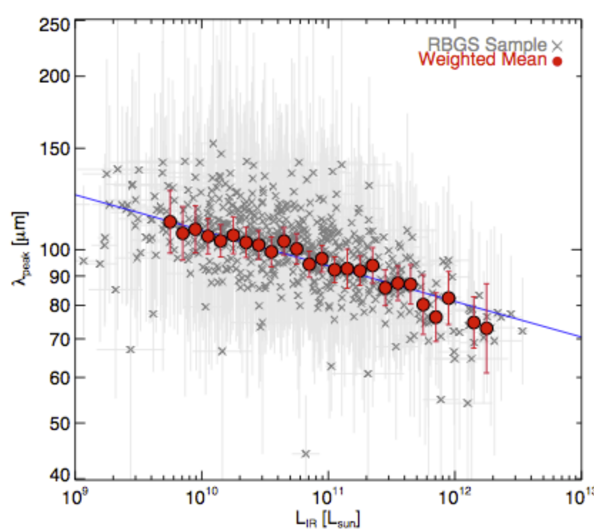


(c) Interaction/"Merger"
NGC 4676
- now within one halo, galaxies interact & lose angular momentum
- SFR starts to increase
- stellar winds dominate feedback
- rarely excite QSOs (only special orbits)
(d) Coalescence/(U)LIRG
NGC 6240
- galaxies coalesce: violent relaxation in core
- gas inflows to center: starburst & buried (X-ray) AGN
- starburst dominates luminosity/feedback, but, total stellar mass formed is small
(e) "Blowout"
IRAS Quasar Hosts
- BH grows rapidly: briefly dominates luminosity/feedback
- remaining dust/gas expelled
- get reddened (but not Type II) QSO: recent/ongoing SF in host high Eddington ratios merger signatures still visible
(f) Quasar
PG Quasar Hosts
- dust removed: now a "traditional" QSO
- host morphology difficult to observe: tidal features fade rapidly
- characteristically blue/young spheroid
(b) "Small Group"
M66 Group
- halo accretes similar-mass companion(s)
- can occur over a wide mass range
- M_{halo} still similar to before: dynamical friction merges the subhalos efficiently
(g) Decay/K+A
NGC 7252
- QSO luminosity fades rapidly
- tidal features visible only with very deep observations
- remnant reddens rapidly (E+A/K+A)
- "hot halo" from feedback
- sets up quasi-static cooling
(a) Isolated Disk
M81
- halo & disk grow, most stars formed
- secular growth builds bars & pseudobulges
- "Seyfert" fueling (AGN with M_B>-23)
- cannot redden to the red sequence
(h) "Dead" Elliptical
M59
- star formation terminated
- large BH/spheroid - efficient feedback
- halo grows to "large group" scales: mergers become inefficient
- growth by "dry" mergers
SFR [$M_\odot$ yr^{-1}]
1000
100
10
1
0.1
a b c d e f g h
$\log_{10}$[L_{QSO} / $L_\odot$]
13
12
11
10
9
8
-2 -1 0 1 2
Time (Relative to Merger) [Gyr]

Casey 2014

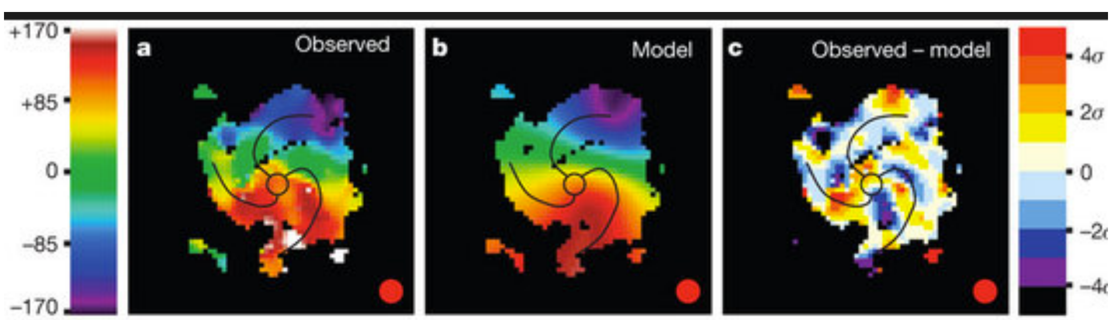
Dusty Star-forming Galaxies

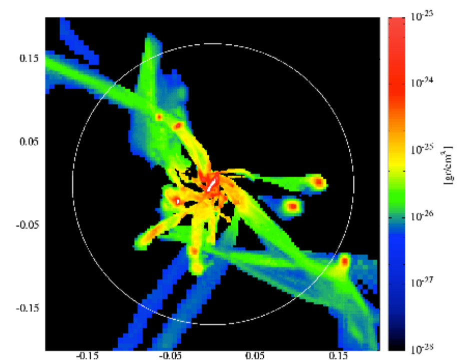
- Dust enshrouded galaxies detected at high redshift (avg z ~2) with SFR of up to ~1000 $M_\odot$/year
  - MW is ~2 $M_\odot$/year
- Some of these galaxies are known to host a SMBH enshrouded by dust and gas
  - DSFG might be precursors of very bright quasars, serving as a precursor when the SMBH grows rapidly up to $10^9 M_\odot$
- DSFG have short depletion timescales (molecular gas mass/SFR)
- High L galaxies have warmer dust



Star Formation at high-z

- Genzel+06 (Nature) reported the presence of massive rotating SF disks in z>2-3 galaxies
  - Large star formation, not the effect of merging activity
- Simulations showed that cold gas can be accreted by a galaxy and form a thick disk (Dekal+08)
  - Gas-rich, turbulent disks are unstable, would fragment, and the form massive star-forming clumps of gas in agreement with observations3. Dynamical friction then forces the clumps to spiral rapidly into the centre of the galaxy, forming a central bulge surrounded by a remnant disk, whose present-day relic may be the old 'thick disk' component seen in nearby galaxies (Genzel+09, Nature).
  - Gas accreted is older and thus metal poor->massive disk should have lower metallicity of the outside part of the galaxy (Cresci+10, Nature)

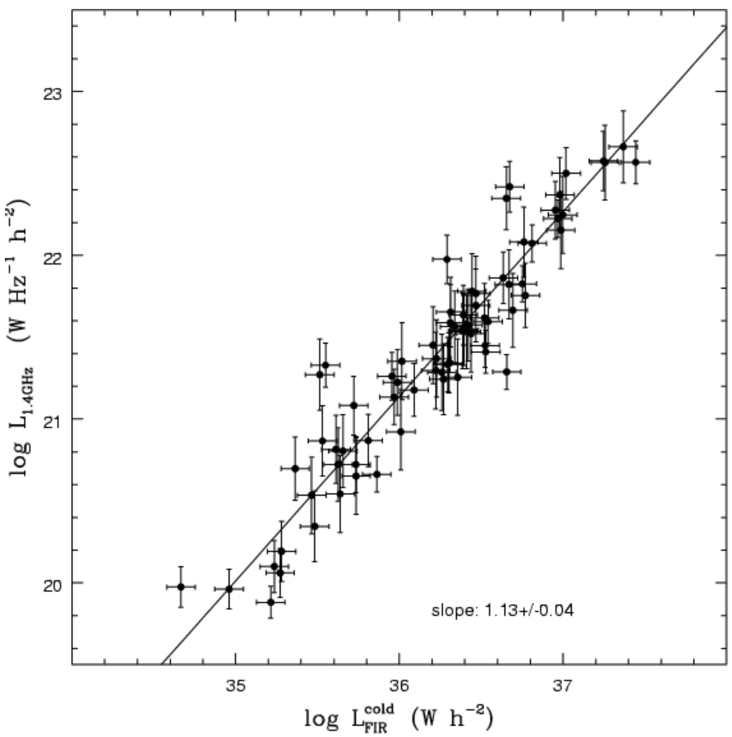




Far IR to radio correlation

- Tight correlation on FIR-radio emission from galaxies:
  - All due to star formation
  - FIR is due to dust heated by massive stars
  - Radio emission is due to CRs e^- accelerated in SNRs

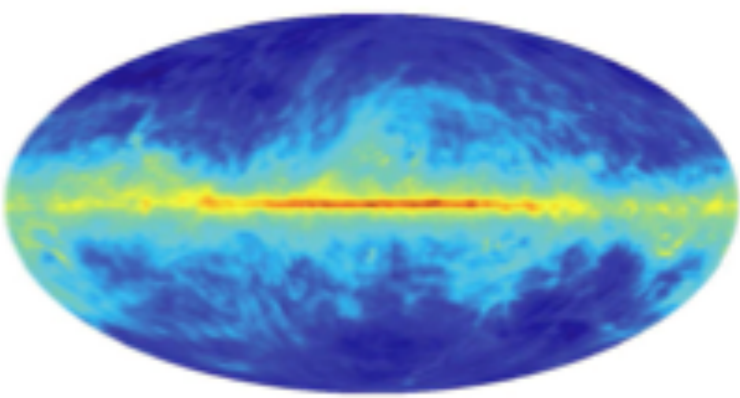
$$\mathrm{SFR}\ (M_\odot\ yr^{-1}) = 4.5 \times 10^{-44}\ L_{FIR}\ (\mathrm{ergs\ s^{-1}}) \quad (starbursts),$$

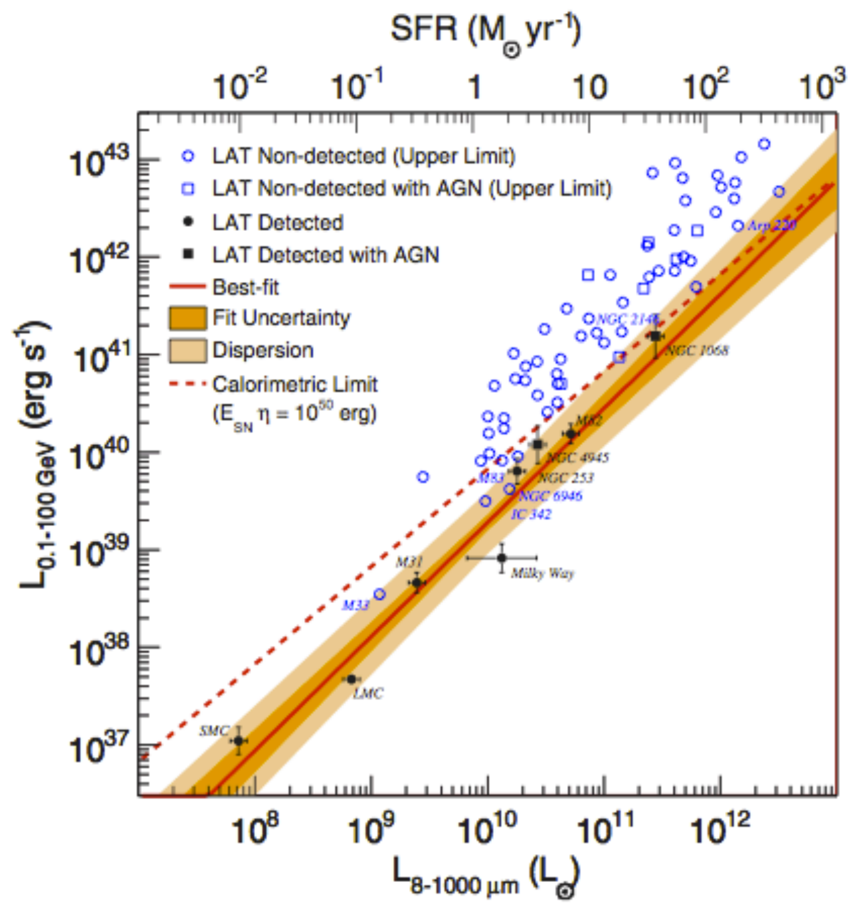


L_{FIR} is a good tracer of star formation (Kennicutt98)

Gamma-rays from the Galaxy

- Galactic diffuse emission at gamma-ray is produced by CRs interaction
- Total IR luminosity and g-ray L are well correlated

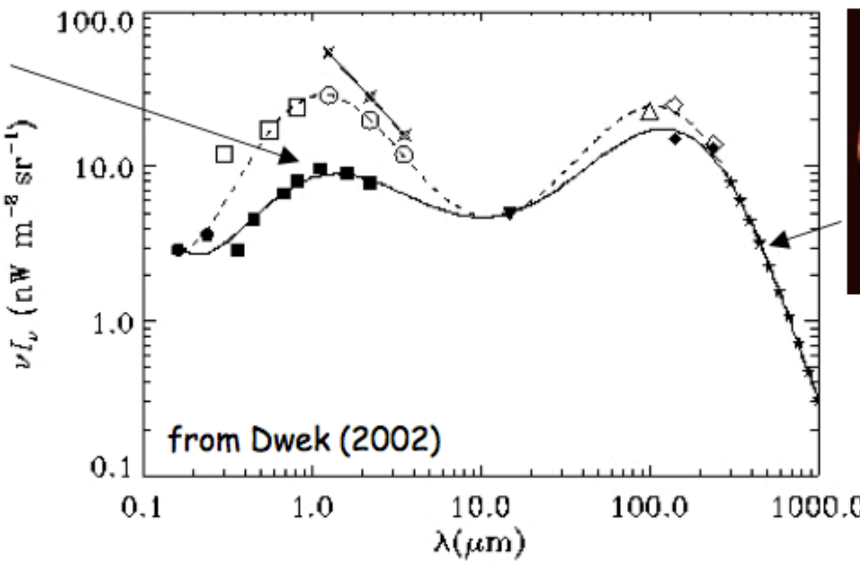


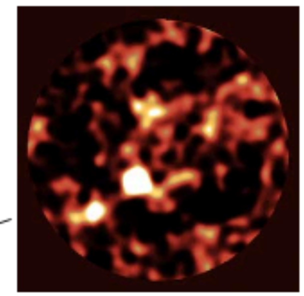


Extragalactic Background Light

Optical/UV survey will miss ~50% of the star formation activity of the Universe

HST HDF
optical survey



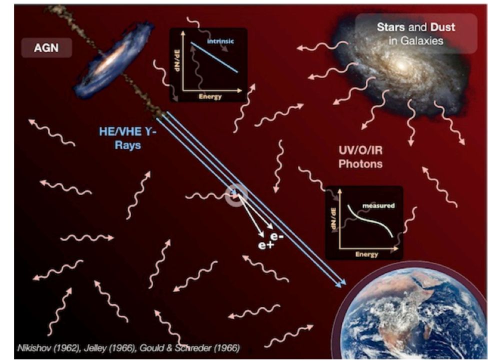


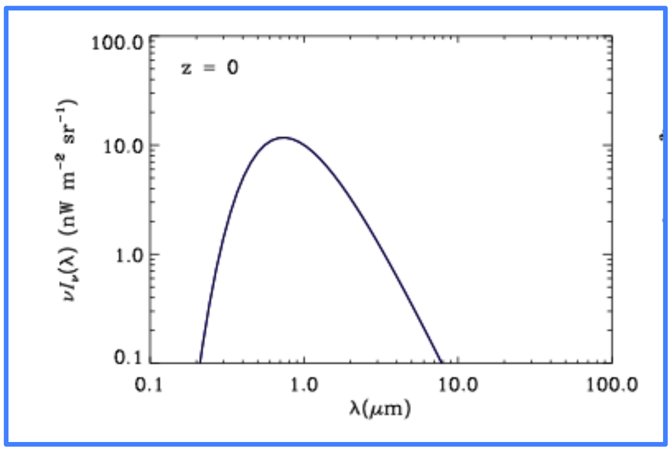
SCUBA HDF
850um survey

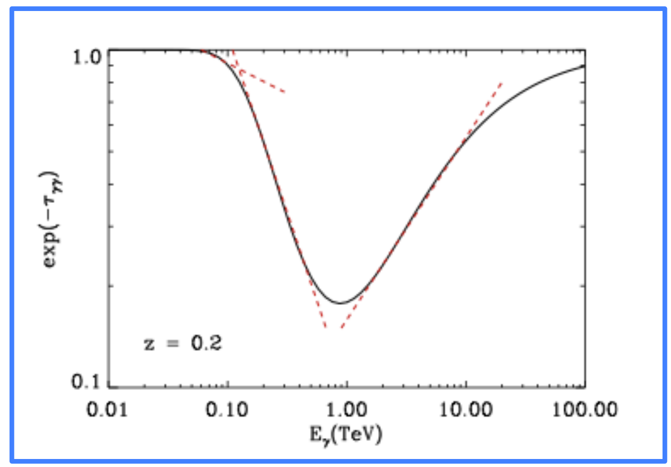
Extragalactic background radiation: energy output at FIR-mm wavelengths is comparable in strength to the optical background, yet < 1 sq. degree (0.002%) of the submm sky has been mapped, and < 50% of submm/mm background has been resolved

Background gamma-ray sources

- 2 Photons convert into an electron-positron pair if :
  - $E\gamma \times E_{EBL} \geq 2(m_e c^2)^2$







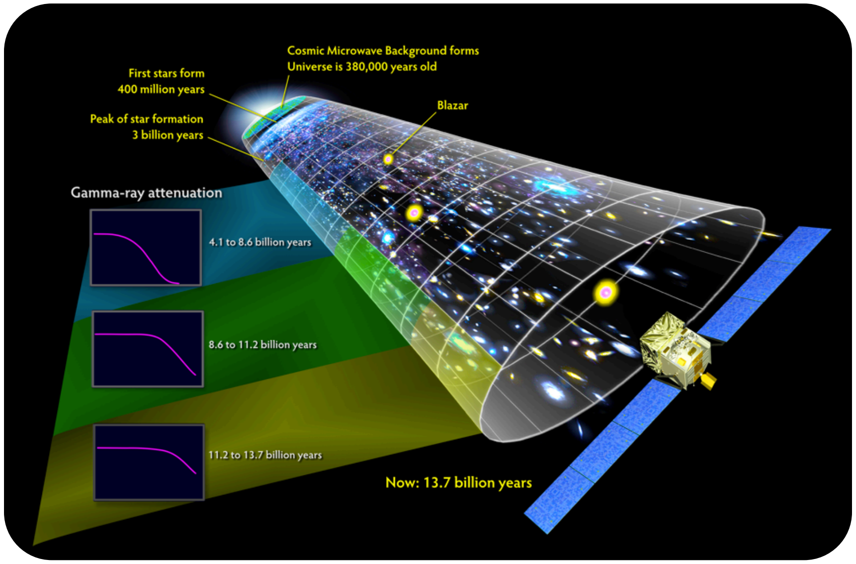
Intrinsic spectrum is attenuated

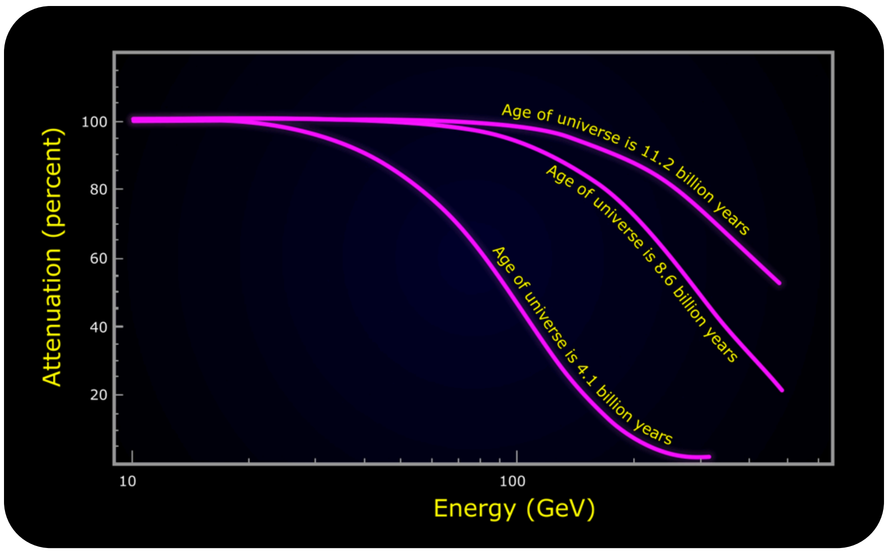
$$\frac{dN_{obs}}{dE} = \frac{dN_{int}}{dE} \times e^{-\tau_\gamma(E,z)}$$

Optical Depth

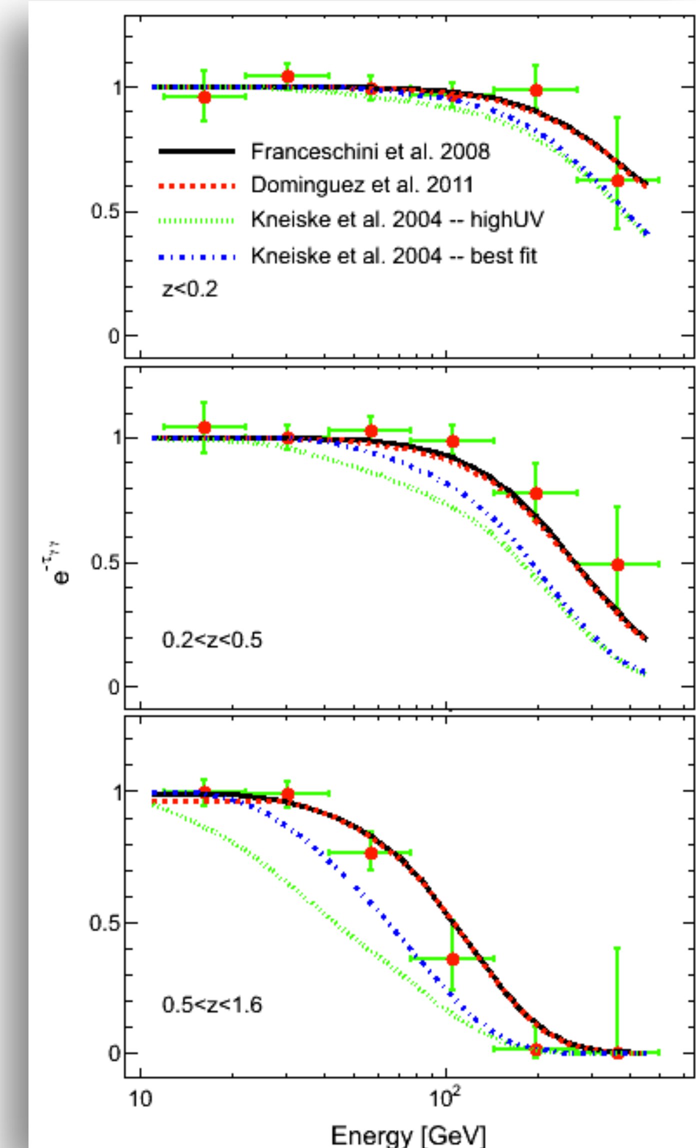
$$\tau_\gamma = \int_0^z d\ell(z) \int_{-1}^{+1} d\mu \frac{1-\mu}{2} \int_{\epsilon'_{thr}}^{\infty} d\epsilon' \frac{dn_{bkg}}{d\epsilon} \sigma_{\gamma\gamma}(E', \epsilon', \mu)$$

EBL Absorption at different redshift





Ajello, Bühler & Reimer for the LAT collab. 2012, Science,338



Useful References

- Casey et al. 2014 (review of sub-mm astronomy)
- Sanders & Mirabel 1996 (luminous IR galaxies)
- Kennicutt 1998 (star formation in galaxies along the Hubble sequence)