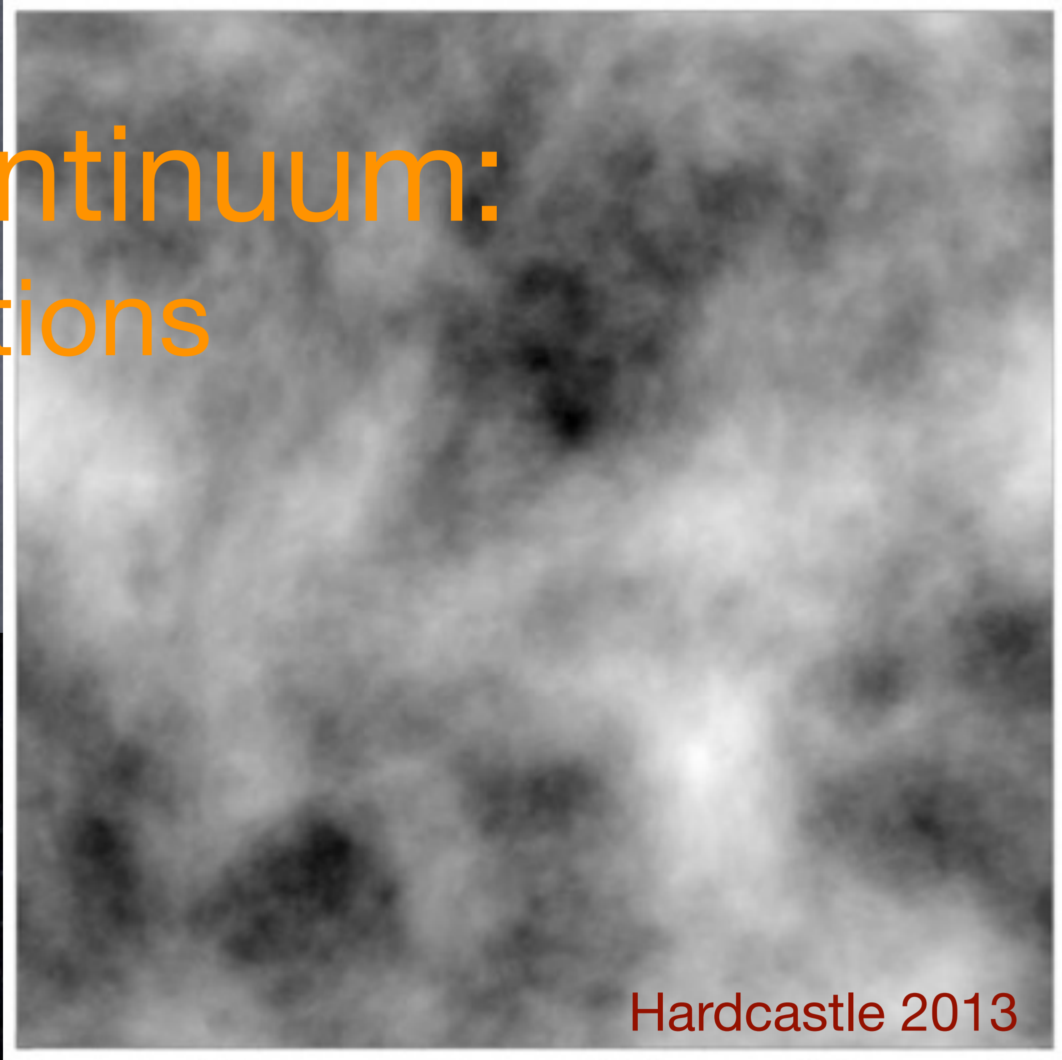
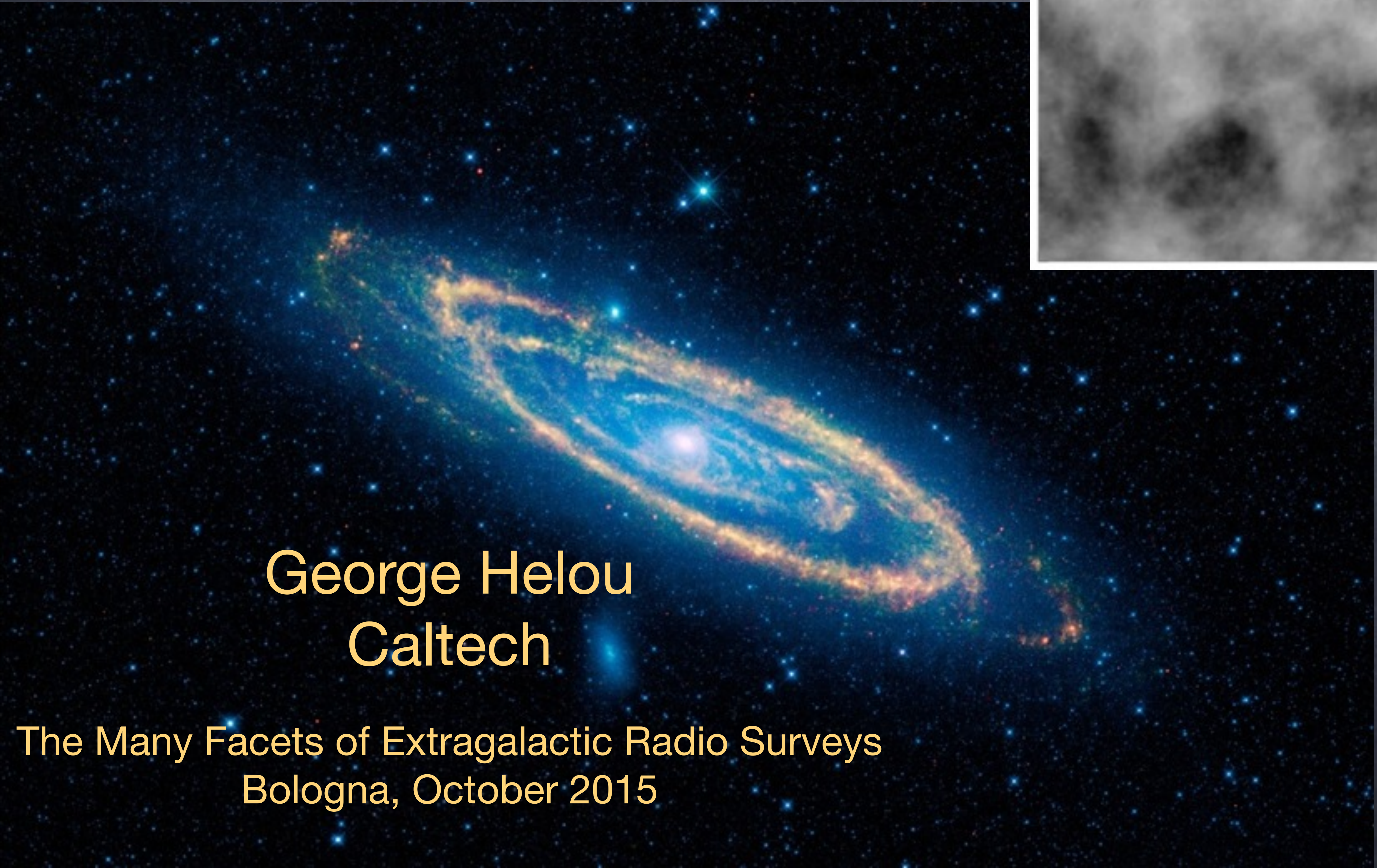
Star Formation & Radio Continuum:

Astrophysics, Theory, Open Questions



Hardcastle 2013



George Helou
Caltech

The Many Facets of Extragalactic Radio Surveys
Bologna, October 2015

A bit of history

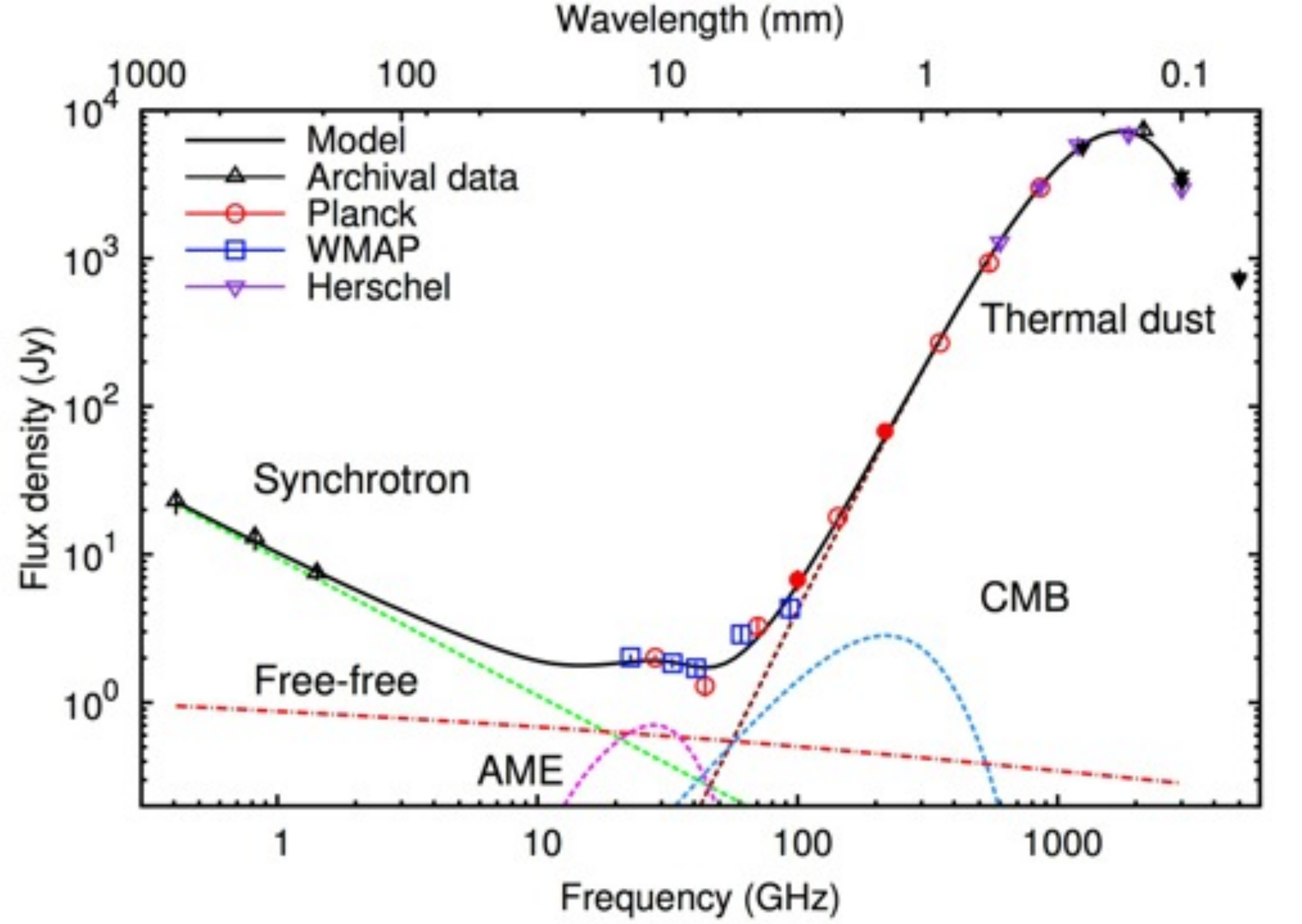
- In 1980s, synchrotron emission from galaxies was associated with «old stars»
  - ✳ Similarity of radial profiles; **diffuse shock acceleration**
- Radio thermal was thought the best measure of SFR
  - ✳ Sparse data on galaxies; **physics of ionized regions**
- Today, we accept synchrotron is driven by SF, with
  - ✳ Longer time constant than other SF tracers
  - ✳ Greater scale length (in disk) than other SF tracers
- This was the result of radio-IR studies

OUTLINE

- Galaxy-scale radio emission, relation to Star Formation
- Galaxy-scale infrared emission, relation to SF
- The relation of radio and infrared: beyond SF
- Testing and improving the framework
- Open questions, opportunities

Framework: radio emission

- Main components of galaxy radio emission linked to SF
  - ✳ SN-> CRe + **B**-> Synchrotron
  - ✳ Ionizing stars + H-> Thermal
  - ✳ Uncertain origin-> AME
  - ✳ Scaling relations well modeled (e.g. Murphy 2009)
- Astrophysics framework has
  - ✳ micro-physics
  - ✳ system physics
  - ✳ environmental modifiers
- Framework still not robust



M31: Planck Consortium 2015

Framework: synchrotron emission

- Synchrotron: Cosmic Ray electrons (CRe) and **B** field
  - ✳ Galaxy-wide scaling of B, CRe other sources/reacceleration, propagation & confinement, secondary CRe/CRp+... uncertain
- Galaxy-scale phenomenology understood (Murphy+ 2006, 2007; Tabatabaei+ 2007, 2013; Heesen+ 2014)
  - ✳ Synchrotron spreads wider than SF sites
- Few physical models (e.g. Völk 1989; Helou+ 1993; Lacki+ 2010; Niklas & Beck 1997)
  - ✳ Driven by relation with IR, gamma-rays
  - ✳ Global galaxy properties/scaling critical: SF intensity, ISM density, scale-height, geometry
  - ✳ Open question: Are galaxies calorimeters or smart filters?

Galaxy Synchrotron Energy Budgets

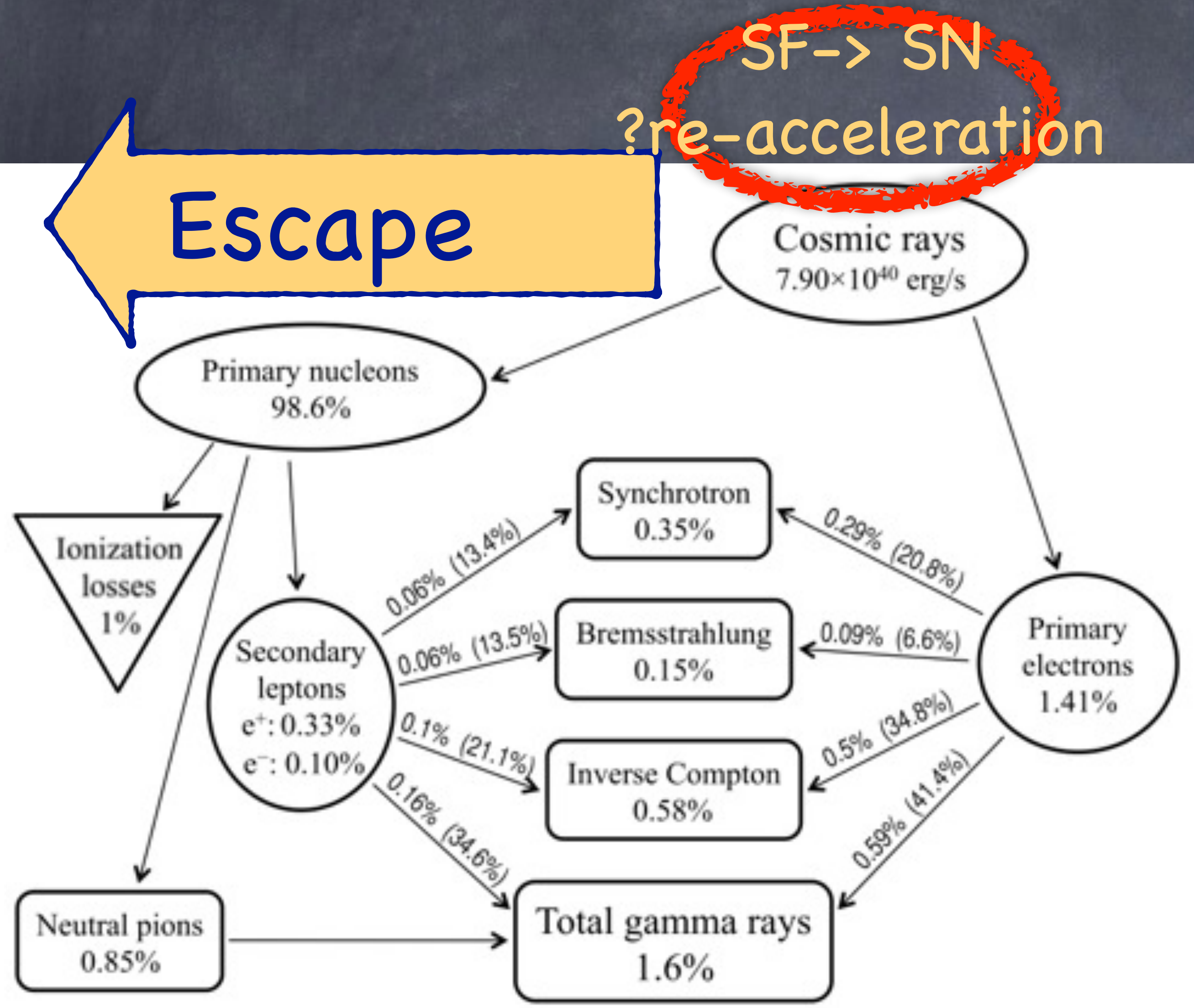


Figure 2. Luminosity budget of the MW for DR propagation model with $z_h = 4$ kpc. The percentage figures are shown with respect to the total injected luminosity in CRs, 7.9×10^{40} erg s^{-1}. The percentages in brackets show the values relative to the luminosity of their respective lepton populations (primary electrons, secondary electrons/positrons).

Strong+ 2010

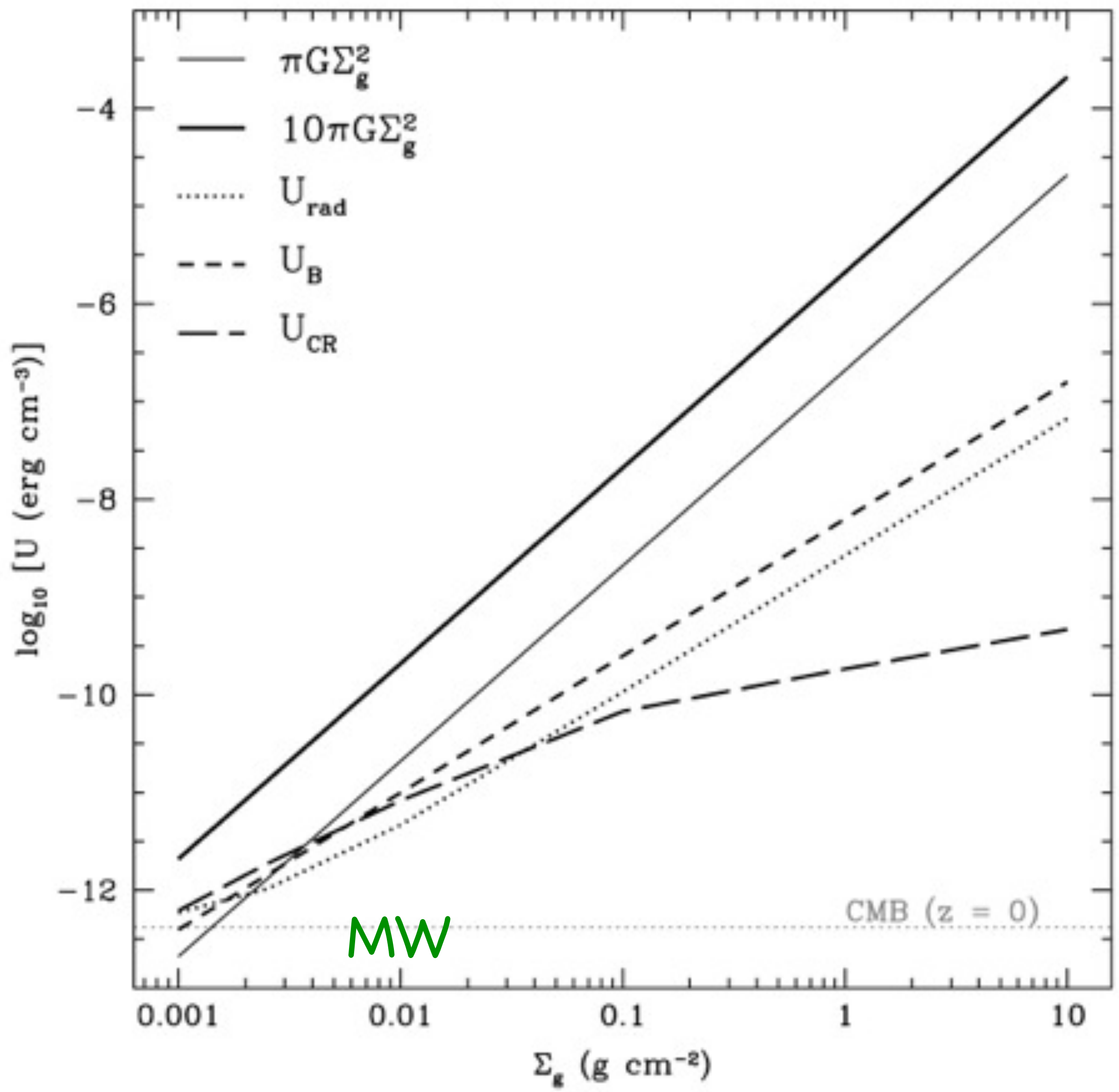
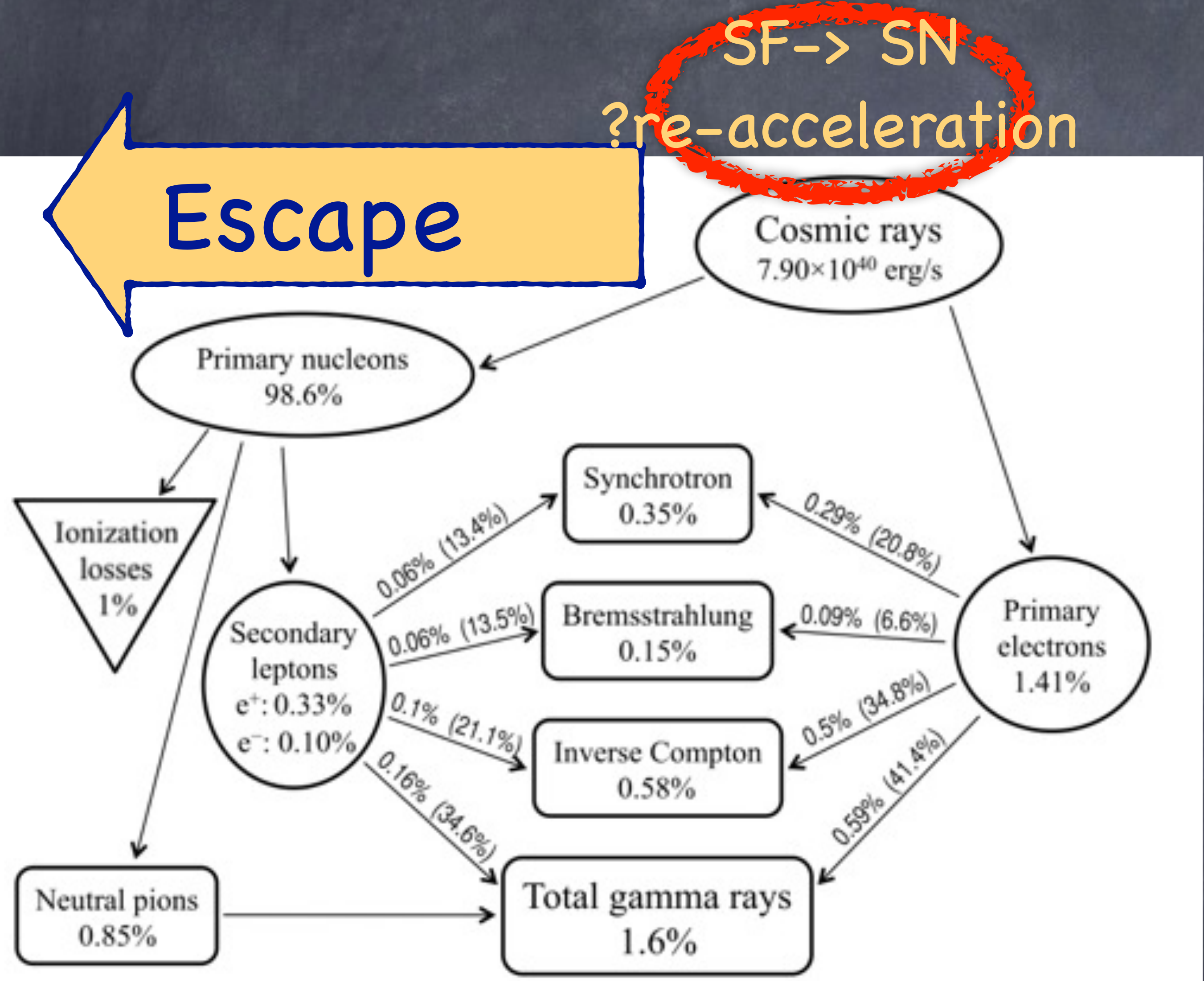


Figure 15. Importance of magnetic, radiation, and CR pressures compared to the hydrostatic pressure needed to support a galactic disk. The hydrostatic pressure needed to support the gas alone is $\pi G\Sigma_g^2$. In low-density galaxies, the mass of the stars implies that $P_{\rm hydro} = 10\pi G\Sigma_g^2$ (see the discussion in Section 5.6). The cosmic ray energy density does not increase as quickly as radiation and magnetic field energy densities in starburst galaxies. None of the three components provides enough pressure to support starburst galaxies.

Lacki+ 2010

Galaxy Synchrotron Energy Budgets



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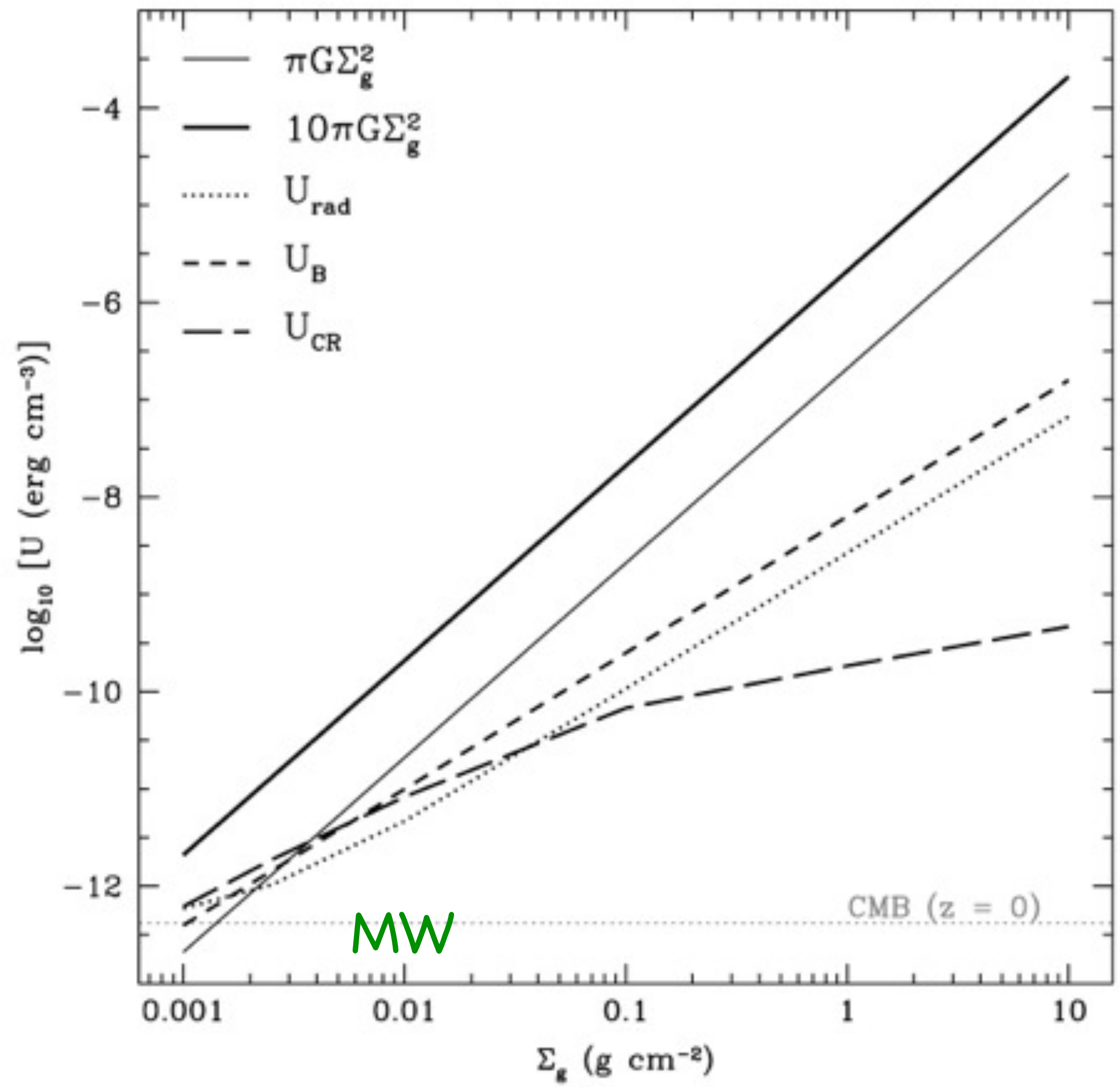
Strong+ 201



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st galaxies.

Lacki+ 2010

Models differ significantly, driven by input data from radio, IR, gamma-rays. Empirical constraints needed on estimates

Framework: infrared emission (1)

- $\overrightarrow{\mathrm{IR}(\lambda)} = [T_{\mathrm{ISM}}] \cdot \overrightarrow{\mathrm{Heating}(\lambda)}$
- Heating(λ) is the input heating spectrum from all stars (neglecting AGN)
- IR(λ) is the Infrared SED, i.e. Dust Cooling
  - ✳ allow for escaping starlight; ignore gas cooling
- T is a matrix with all the coupling terms between Heating and Cooling
  - ✳ Cross-sections, opacities, etc
  - ✳ Geometry(local, initial), geometry(age), geometry(d/g), geometry(morphology), etc

Framework: infrared emission (2)

- $\overrightarrow{IR(\lambda)} = [T_{ISM}]\cdot\overrightarrow{Heating(\lambda)}$ — simplifications:
- Most drastic approximation is "$L(IR) \simeq k\cdot SFR$"
- More useful for extracting information:
  - ✳ $Heating = \Sigma\ IUV(>13.6eV)+FUV(>6eV)+NUV+Vis+NIR$
    - Σ is taken over stars in various age groups
  - ✳ $IR(\lambda) = \Sigma$ SED(dust species, U range, λ)
    - Dust {VSG, Aromatics, LG} at $U \simeq 0.1$--$10^6 G_0$
  - ✳ $[T_{ISM}]$ links star populations to dust emission via ISM phases
- Biggest challenge is geometry, but galaxy size helps!

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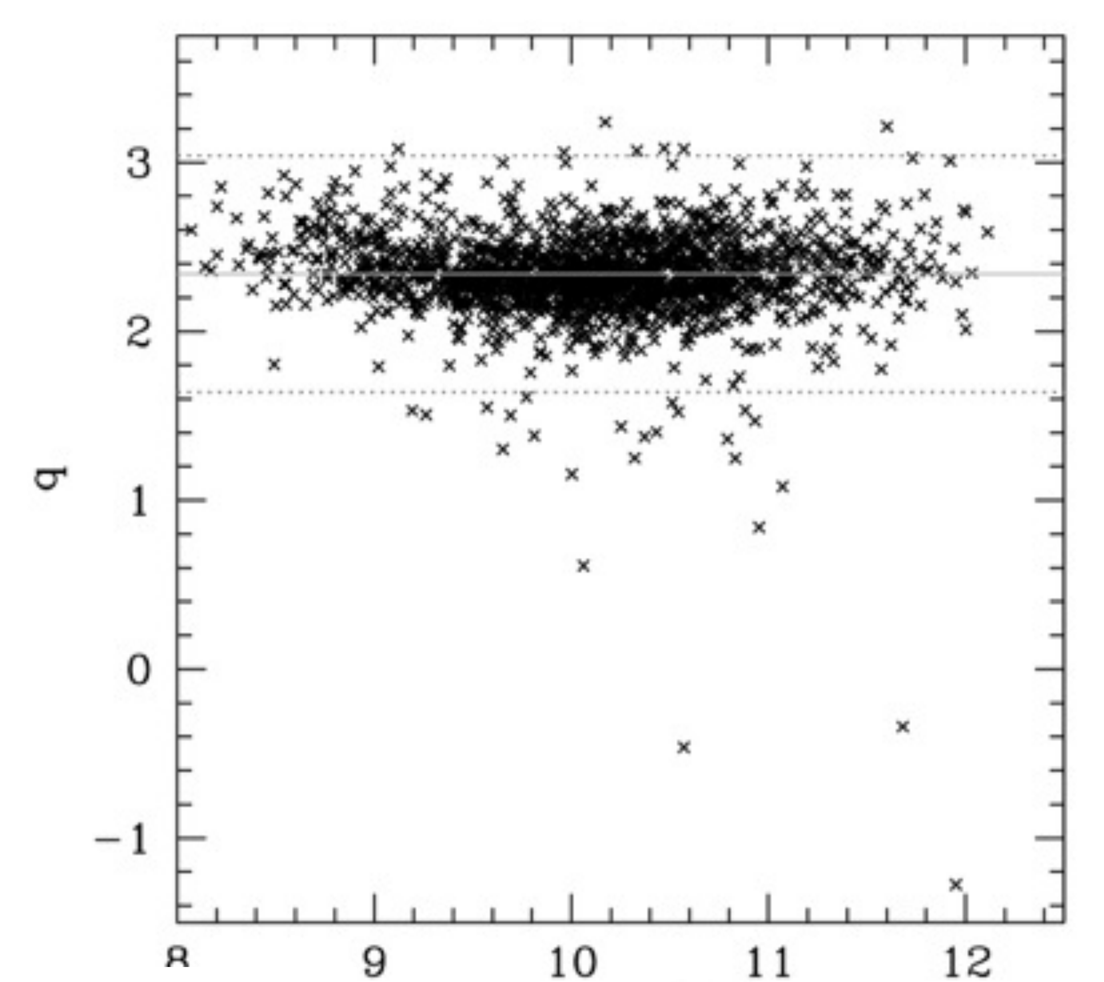
Framework: radio-infrared relation 1

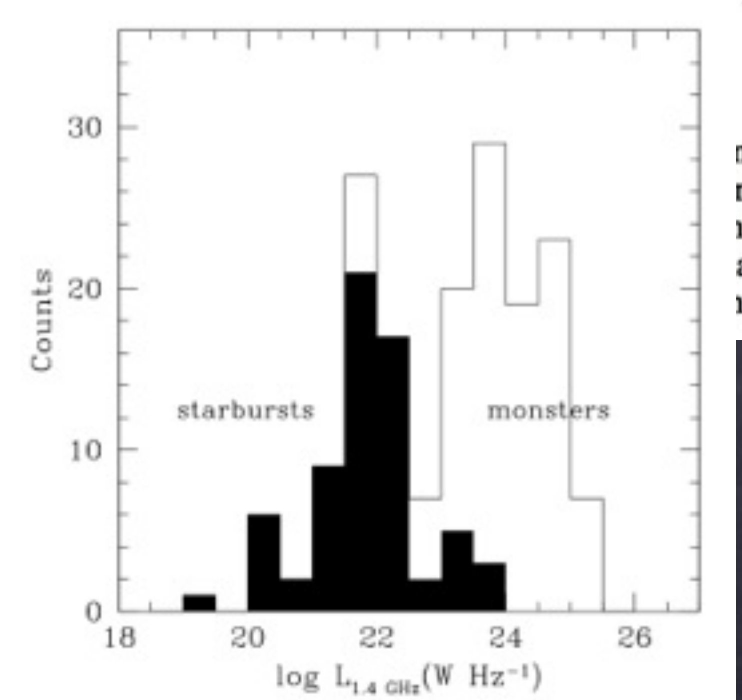
- Strong linear relation radio-IR in spite of complexity in each, great variation in galaxy ISM properties, SFR, geometry, etc

- Note: Luminosity range maps into ranges of SF intensity, ISM gas density, ISRF intensity, B; mapping is NOT 1-to-1



n of q-values plotted as a function of *IRAS* 60 μm ne marks the average value of $q = 2.34$, while the ie "radio-excess" (*below*) and "IR-excess" (*above*) aving 5 times larger radio and IR flux density than ı the linear radio-FIR relation, respectively.

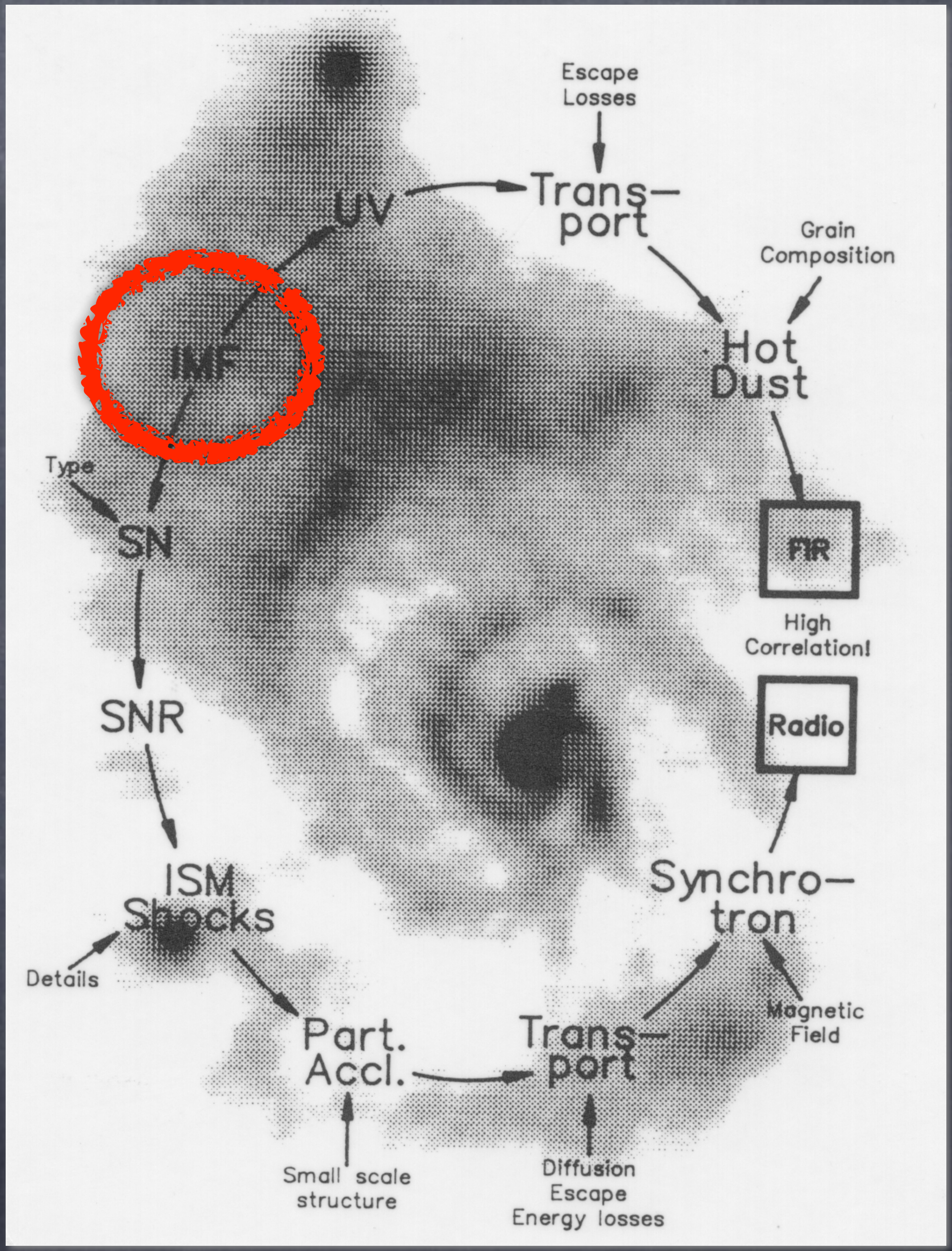
e.g. Yun+ 2001



e.g. Helou+ 1985

Framework: radio-infrared relation 2

- Strong linear relation radio-IR in spite of complexity in each, great variation in galaxy ISM properties, SFR, geometry, etc
- "Conspiracy" recognized early; all models require at least some physical parameters to be linked (Helou & Bicay 1993; Lacki+ 2010), but linkages vary among models



Ekers 1991 (attr.)

Calorimeters or smart filters? (1)

- This is about "system physics": A universal ratio (common origin) of CR and UV/Vis photons does not guarantee constant IR/radio, even in calorimeter case

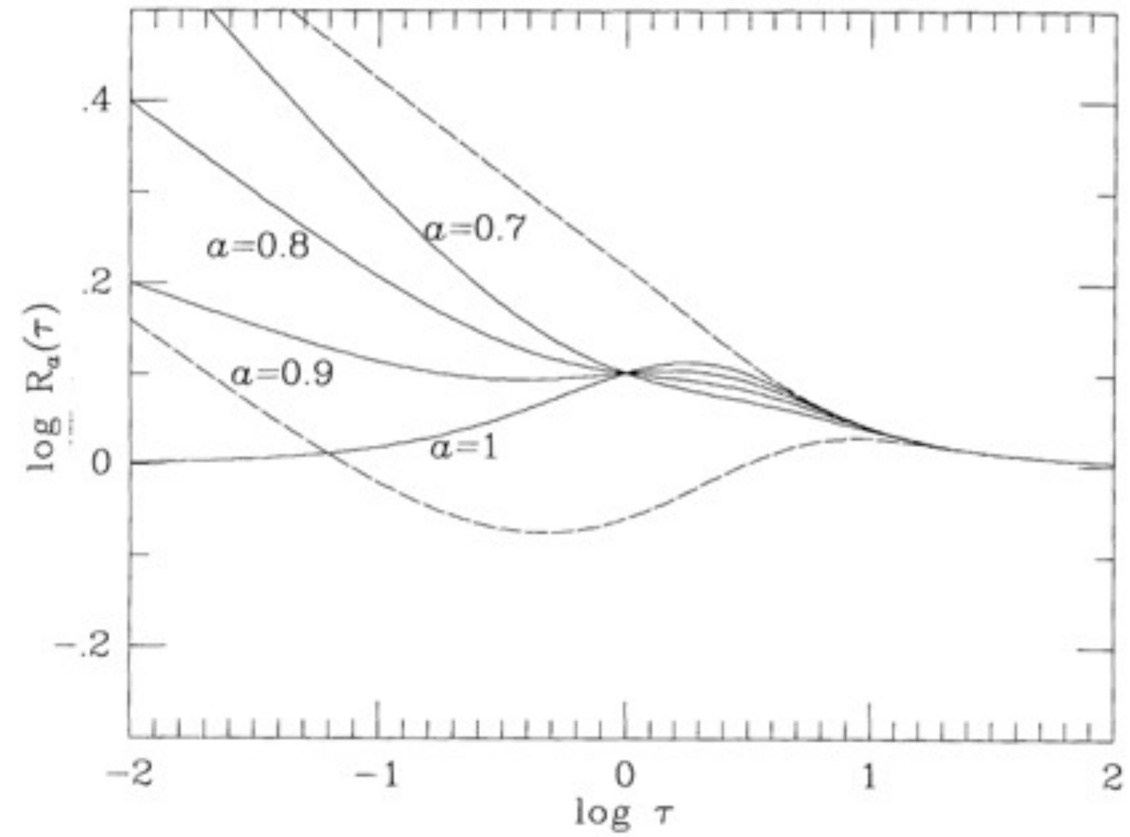


FIG. 1.—The ordinate $R_a(\tau) = [1 - \exp(-\tau_0^a)]/[t_x(1 + t_x)^{-1}]$ is the ratio of effective optical depths of the galaxy to optical radiation and cosmic-ray electrons. The solid lines show the behavior for various values of a for $\tau = t_x$, as discussed in § 3. The dashed lines represent the value that would be assumed by $R_{0.8}(\tau)$ for each of the cases $\tau = 0.5t_x$, and $\tau = 2t_x$.

Helou+ 1993

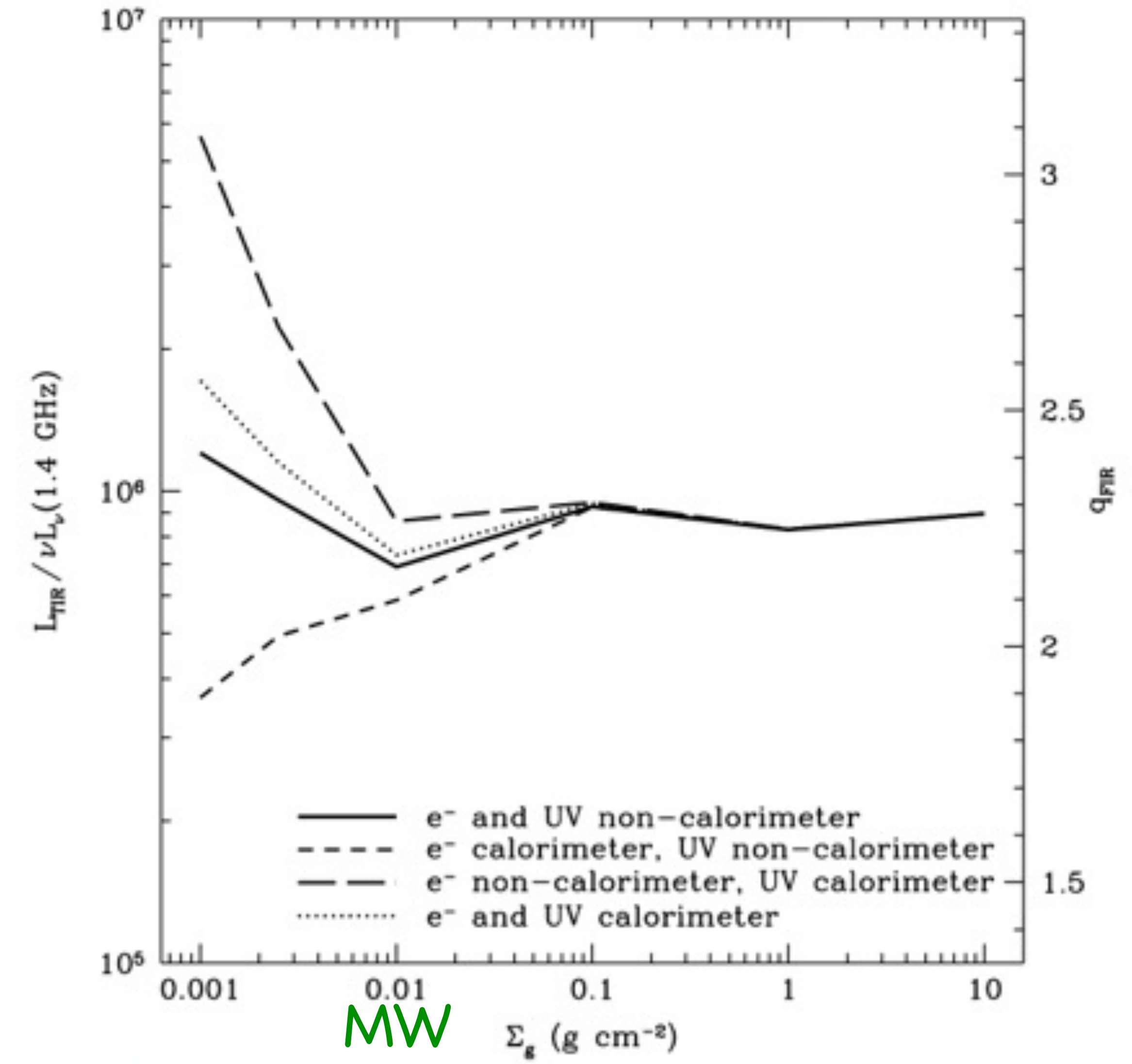
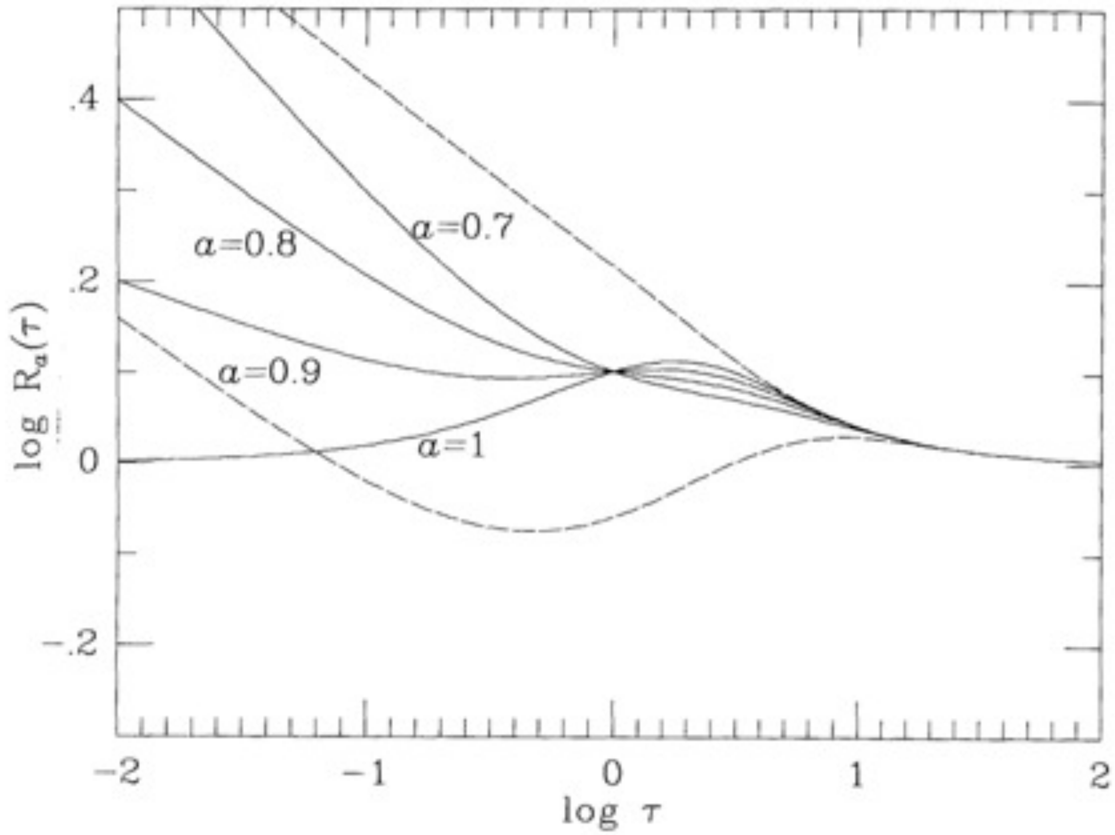


Figure 1. Non-thermal FRC, as reproduced in our standard model ($p = 2.3$, $f = 1.5$, $a = 0.7$, $\delta = 5$, $\xi = 0.023$). While low CR escape times and low UV optical depth on their own would break the correlation at low surface densities the two effects cancel each other out, creating a largely line

Lacki+ 2010

Calorimeters or smart filters? (2)

- This is also about what "micro-physics" and what associated parameters are assumed



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Helou+ 1993

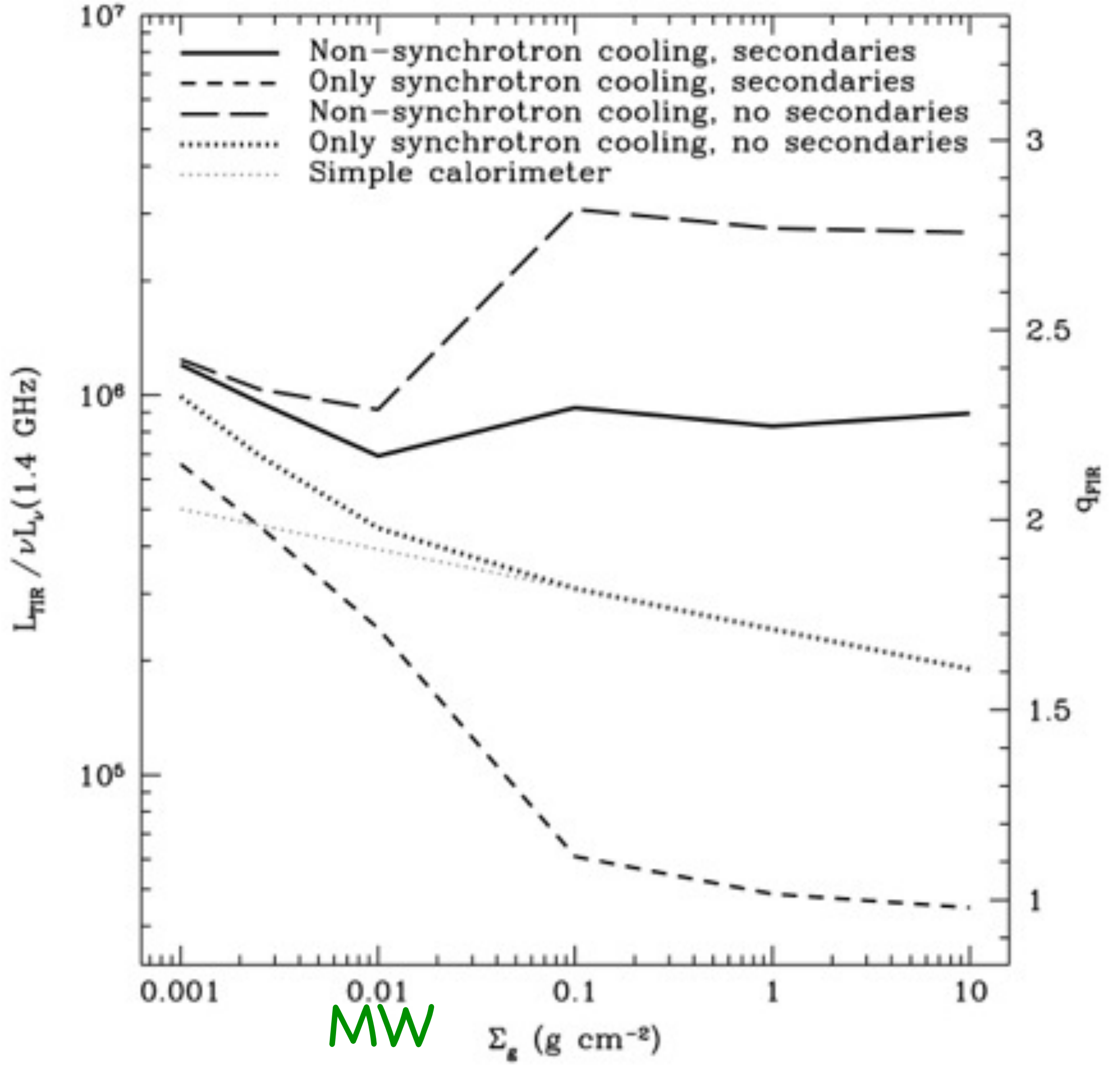

Figure 9. High-Σ_g conspiracy in our standard model ($p = 2.3$, $f = 1.5$, $a = 0.7$, $\tilde{\delta} = 48$, $\xi = 0.023$). The simple calorimeter model has perfect UV calorimetry and electron calorimetry, with only synchrotron cooling and no secondaries. Non-synchrotron cooling and secondaries broken FIR–radio correlation, but conspire to make it linea

Lacki+ 2010

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The framework to higher redshift

- Predictions focus on radio fading at increasing z and on q(high-z) as test of models
  - ✳ Fading because of IC losses by CRe against CMB photons
  - ✳ Dependence on z of ISM/SFR parameters and relations

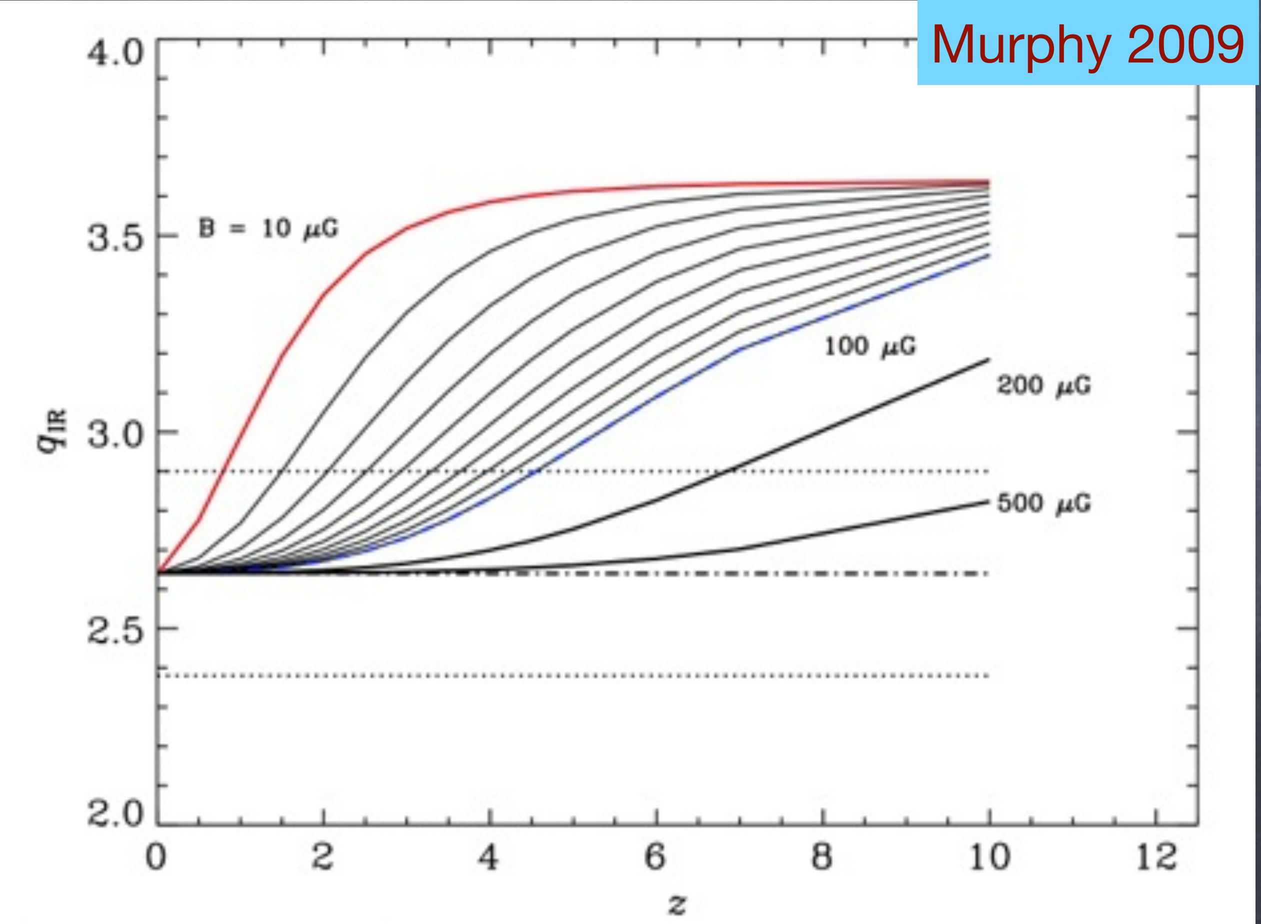
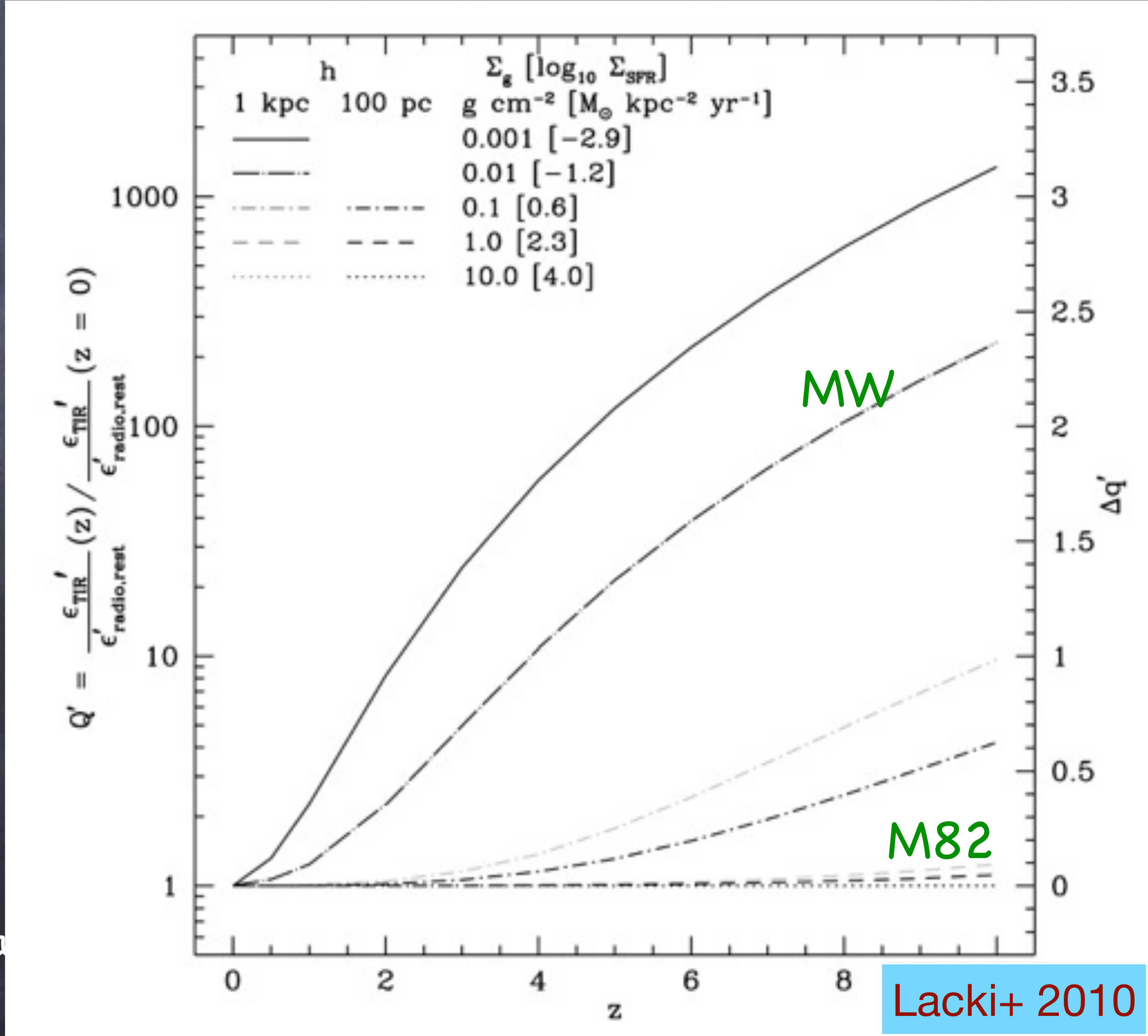

Murphy 2009

Figure 5. Expected rest-frame IR/radio ratios for a galaxy having $q_{IR} = 2.64$ at $z = 0$ as IC losses off of the CMB become increasingly important as a function of redshift. Each track corresponds to a different internal magnetic field strength for the galaxy. As $U_{CMB} \gg U_B$, the IR/radio ratio approaches the limit where only thermal (free–free) radiation contributes to the observed radio continuum emission. The average local q_{IR} values (2.64 dex; dot-dashed line) and the ±1σ scatter (dotted-line) are shown.


Lacki+ 2010

The framework to higher redshift

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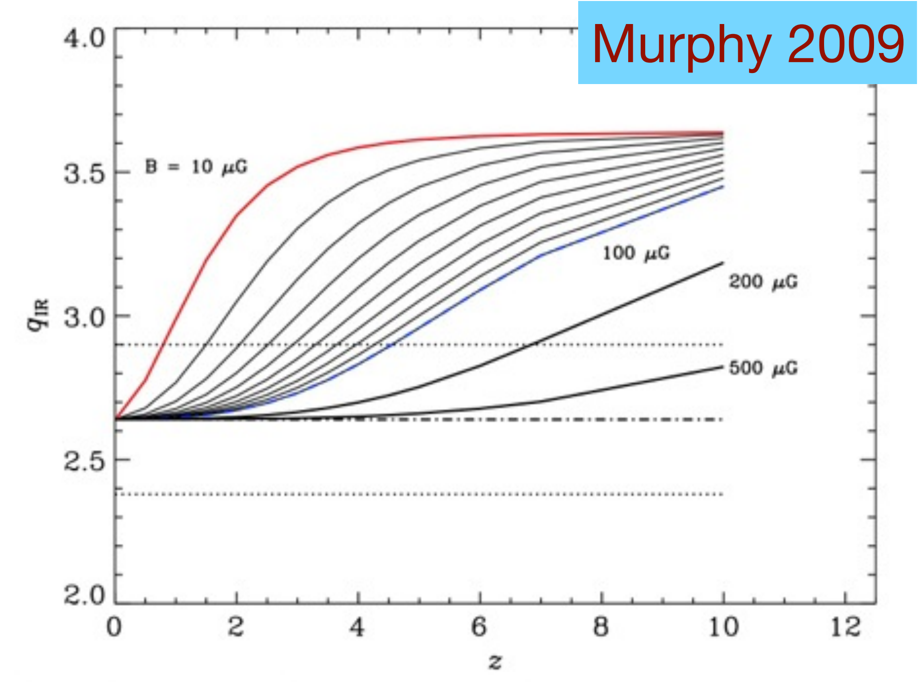
  - ✳ Fading because of IC losses by CRe against CMB photons
  - ✳ Dependence on z of ISM/SFR parameters and relations
- Differences reflect model complexity, CRe loss channels, assumptions on galaxy properties, e.g. compactness vs luminosity



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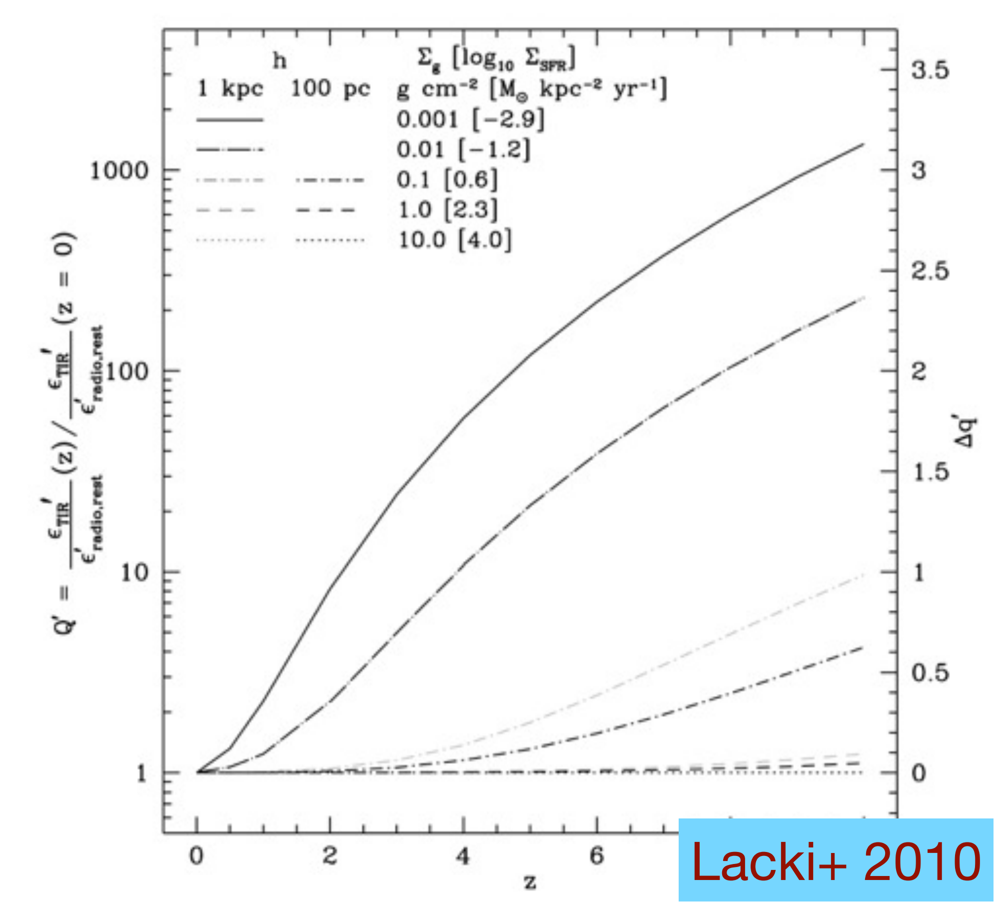

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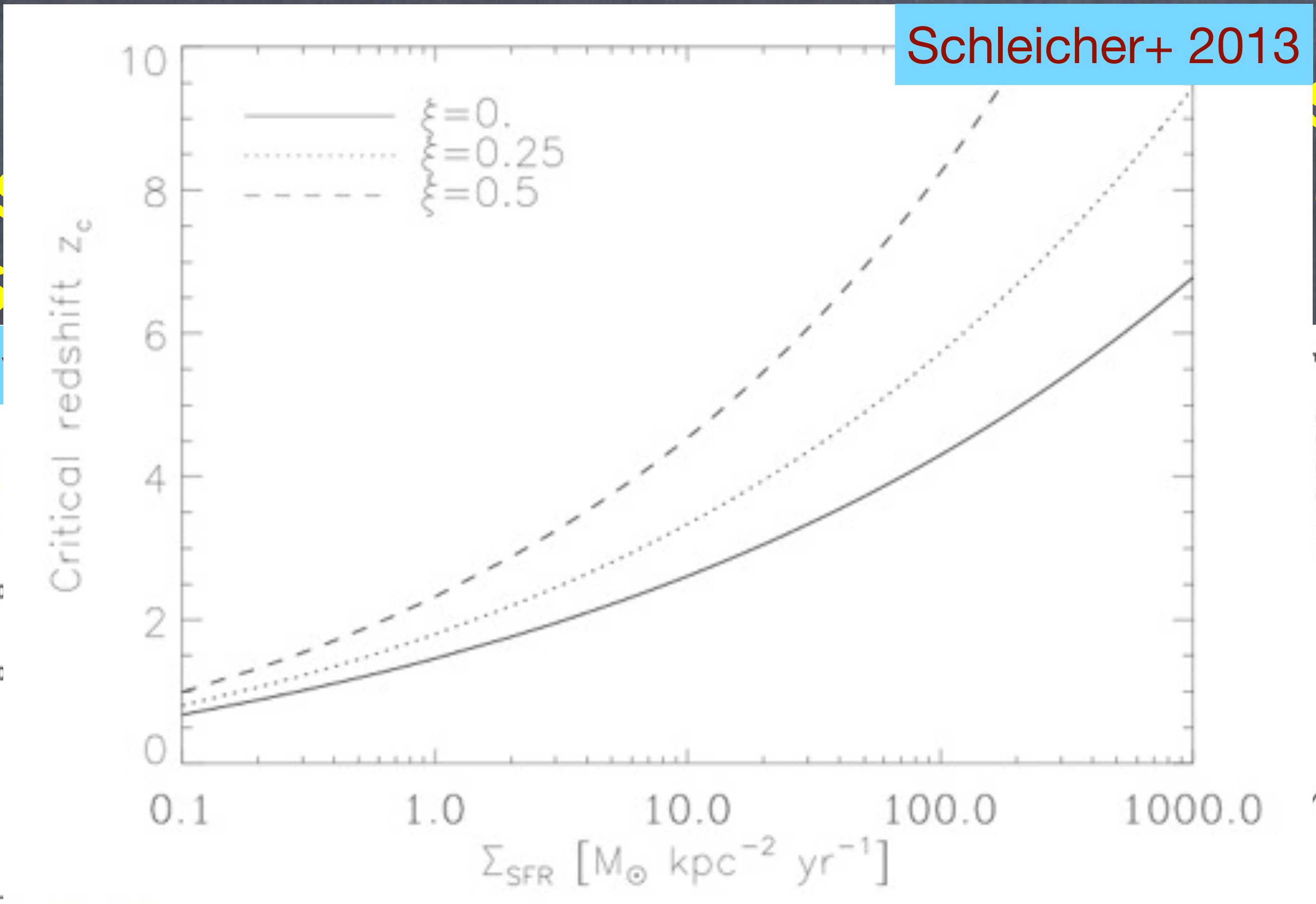
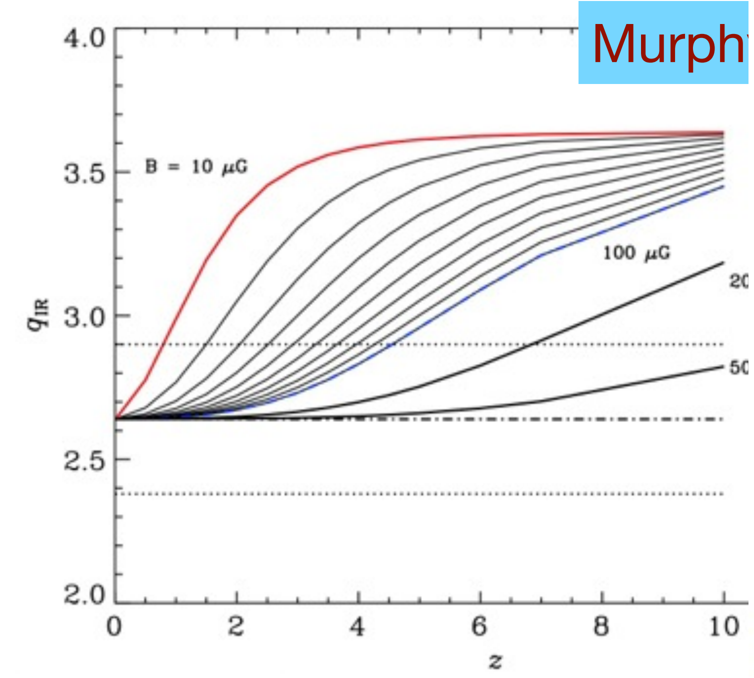


Schleicher+ 2013

Fig. 11. Redshift where the far-infrared – radio correlation breaks down as a function of star formation rate, for different values of $\xi = \alpha/6$, where the parameter α describes the evolution of typical ISM densities with redshift, i.e. $n_{\rm ISM} = n_0(1+z)^\alpha$. We assume here that observations are pursued at the effective frequency as given in Eq. (25).



Murph

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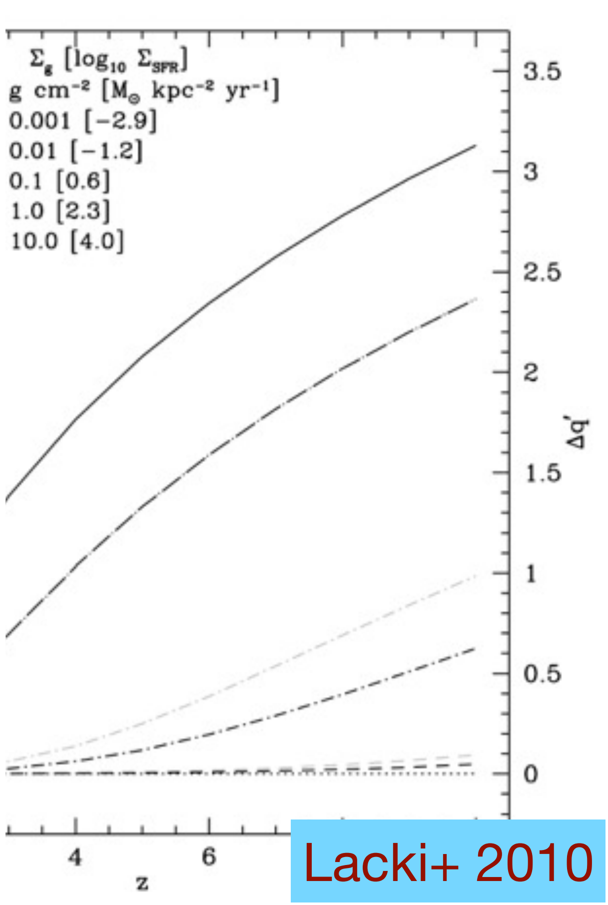
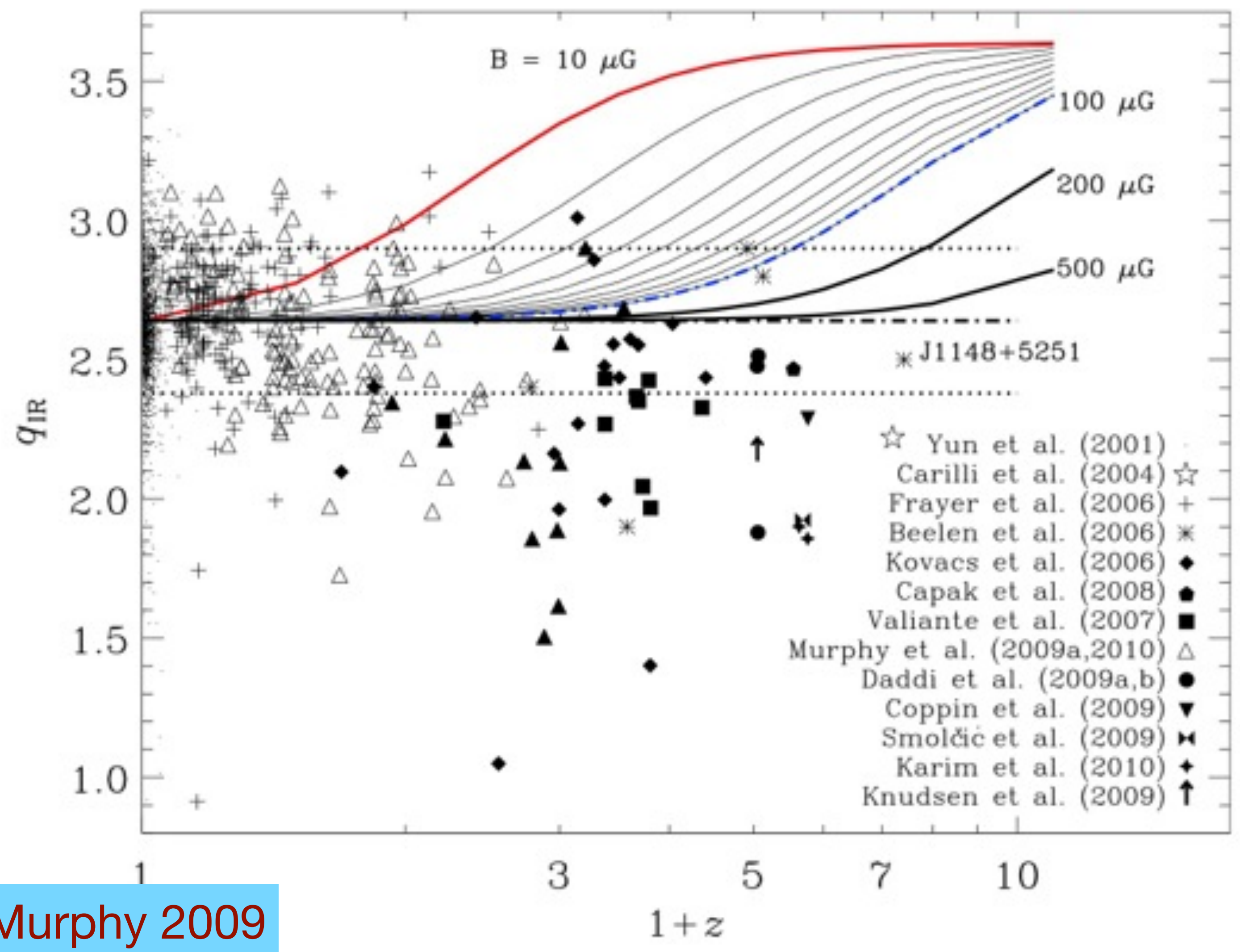


Lacki+ 2010

The Data at higher redshift

- Out to z≈2-3 q=IR/radio appears unchanged, or decreasing(?)
- Sparse data, analysis biases



Murphy 2009

No difference between LIRG & ULIRG

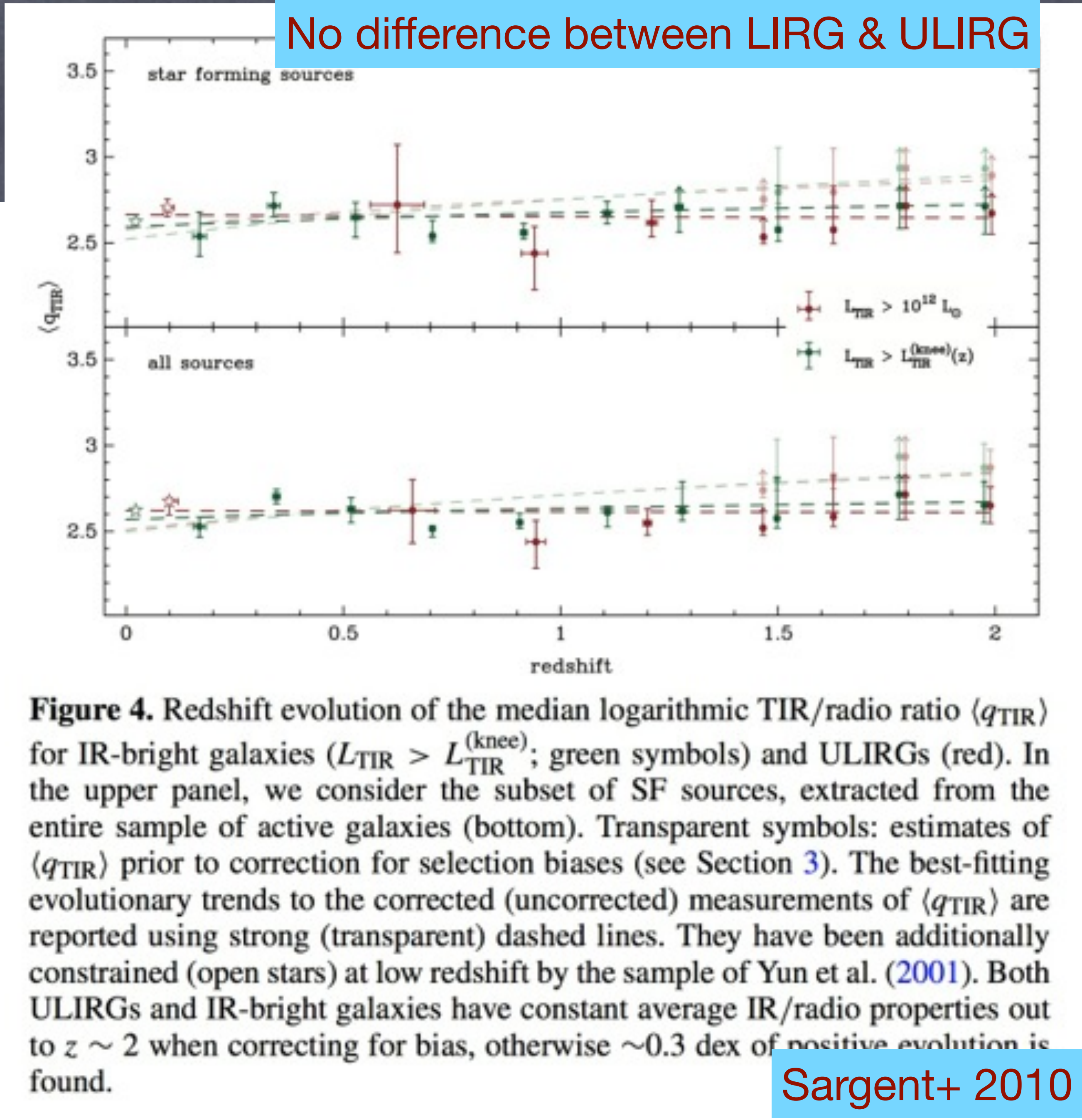


Figure 4. Redshift evolution of the median logarithmic TIR/radio ratio $\langle q_{TIR} \rangle$ for IR-bright galaxies ($L_{TIR} > L_{TIR}^{(knee)}$; green symbols) and ULIRGs (red). In the upper panel, we consider the subset of SF sources, extracted from the entire sample of active galaxies (bottom). Transparent symbols: estimates of $\langle q_{TIR} \rangle$ prior to correction for selection biases (see Section 3). The best-fitting evolutionary trends to the corrected (uncorrected) measurements of $\langle q_{TIR} \rangle$ are reported using strong (transparent) dashed lines. They have been additionally constrained (open stars) at low redshift by the sample of Yun et al. (2001). Both ULIRGs and IR-bright galaxies have constant average IR/radio properties out to $z \sim 2$ when correcting for bias, otherwise ~0.3 dex of positive evolution is found.

Sargent+ 2010

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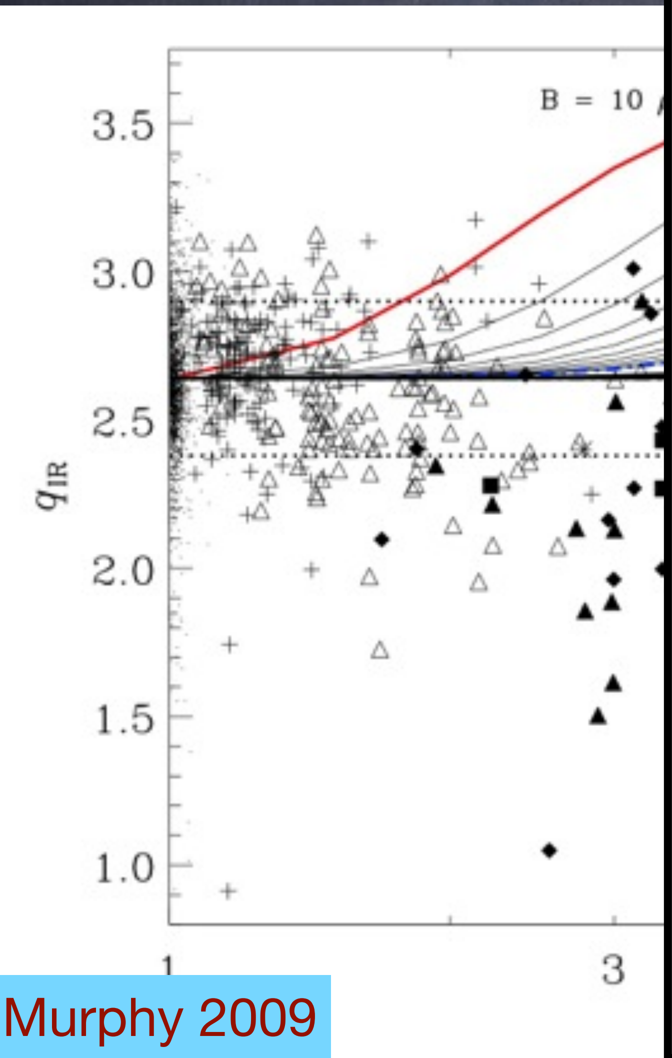
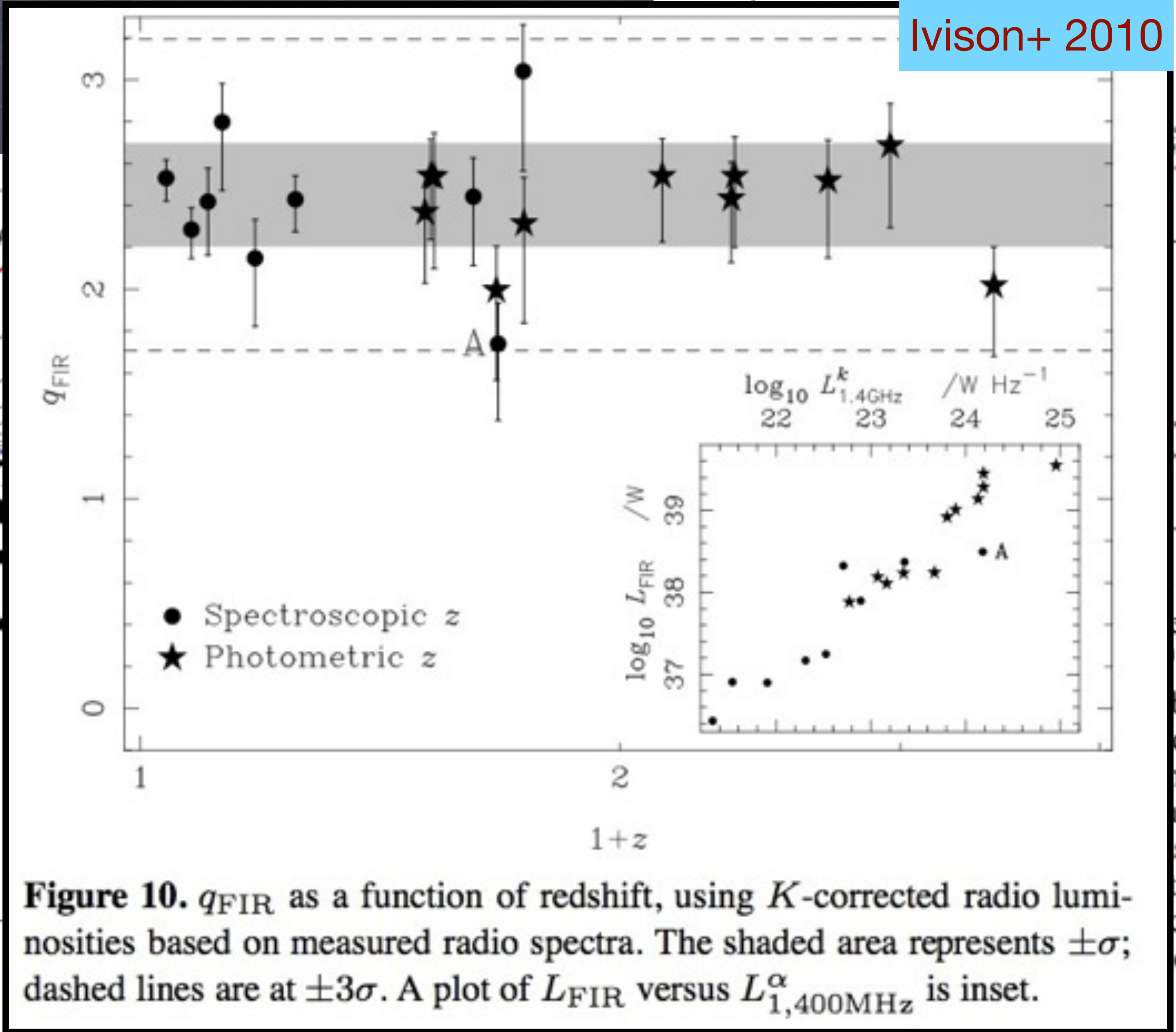
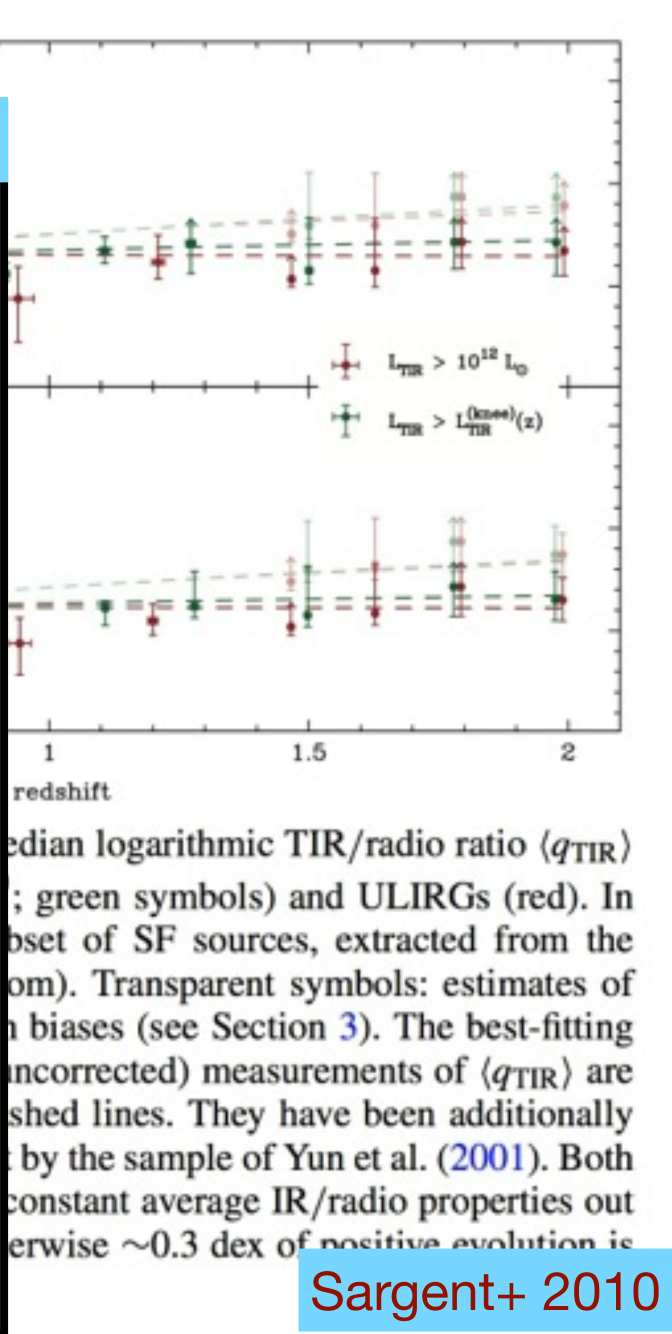


Murphy 2009



Ivison+ 2010

Figure 10. $q_{\rm FIR}$ as a function of redshift, using K-corrected radio luminosities based on measured radio spectra. The shaded area represents $\pm\sigma$; dashed lines are at $\pm3\sigma$. A plot of $L_{\rm FIR}$ versus $L^{\alpha}_{1,400{\rm MHz}}$ is inset.



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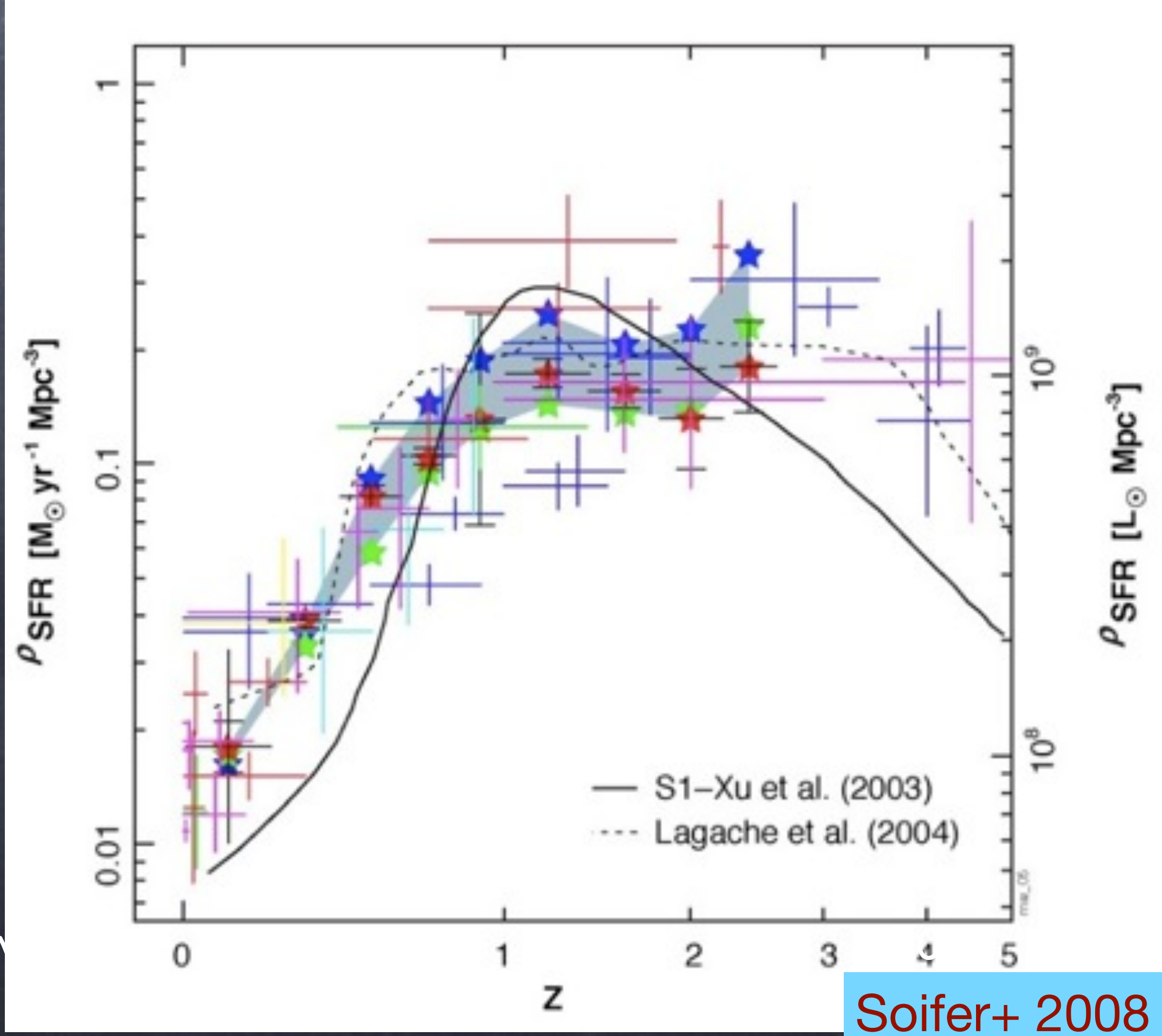
Other effects at high redshift?

- SFR co-moving density, radiation increases with z
  - ✳ Concomitant increase in intergalactic CR is very likely
- Galaxies will capture some of these CR, adding to synchrotron emission
  - ✳ Captured IG CR diffuse much more slowly inside galaxies



Soifer+ 2008

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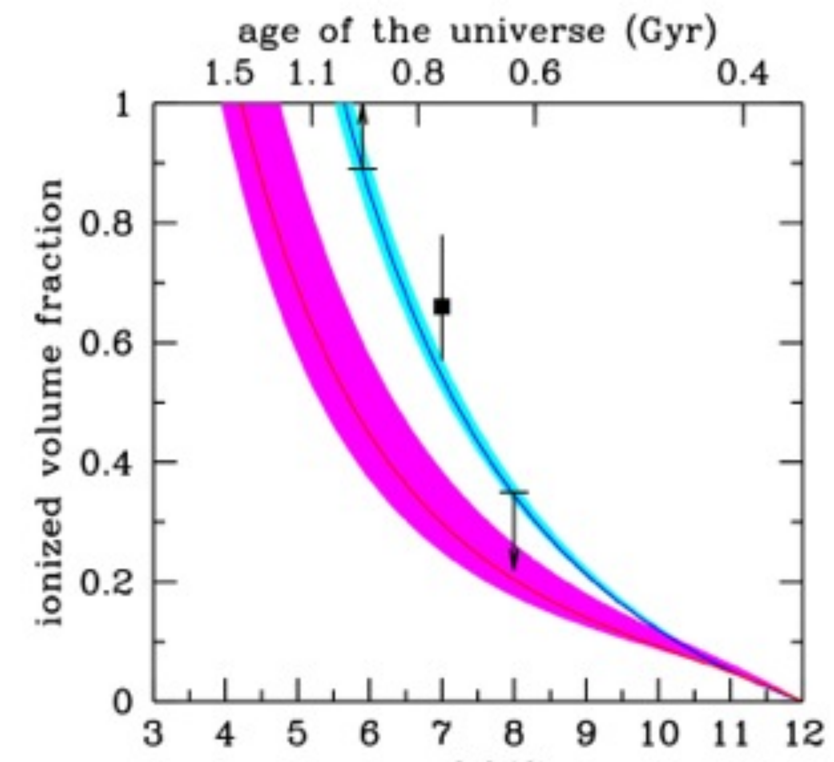
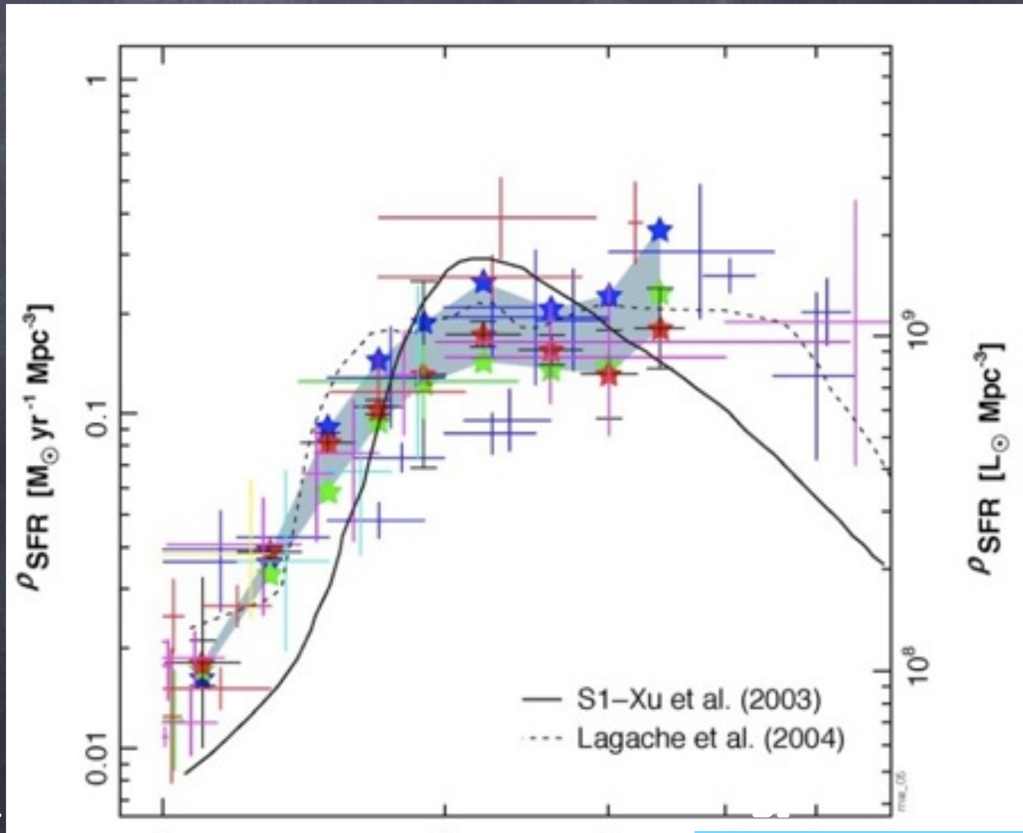


Madau & Haardt 2015

FIG. 2.— Reionization history for our AGN-dominated scenario.



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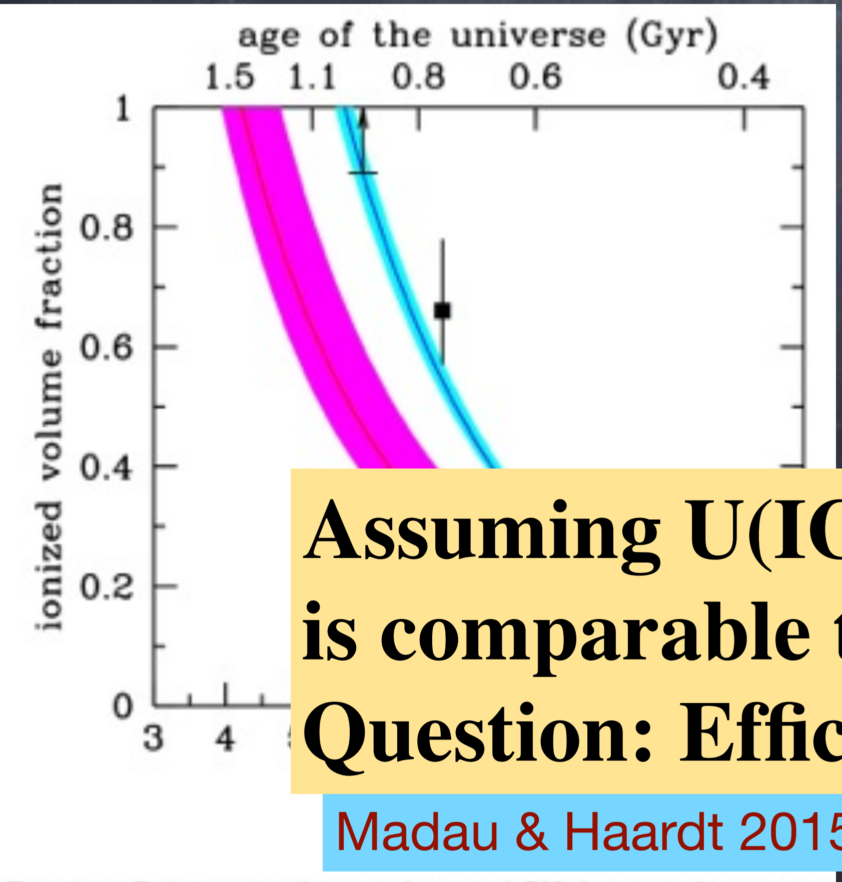

Madau & Haardt 2015

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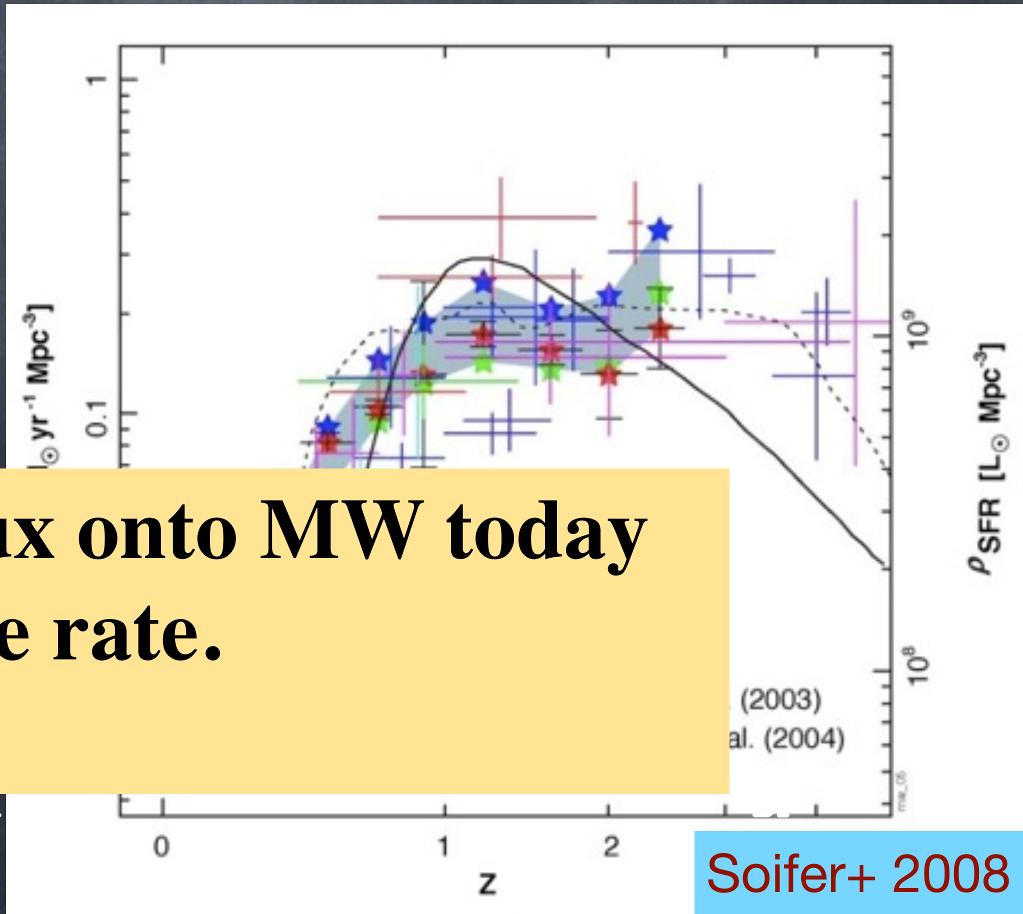


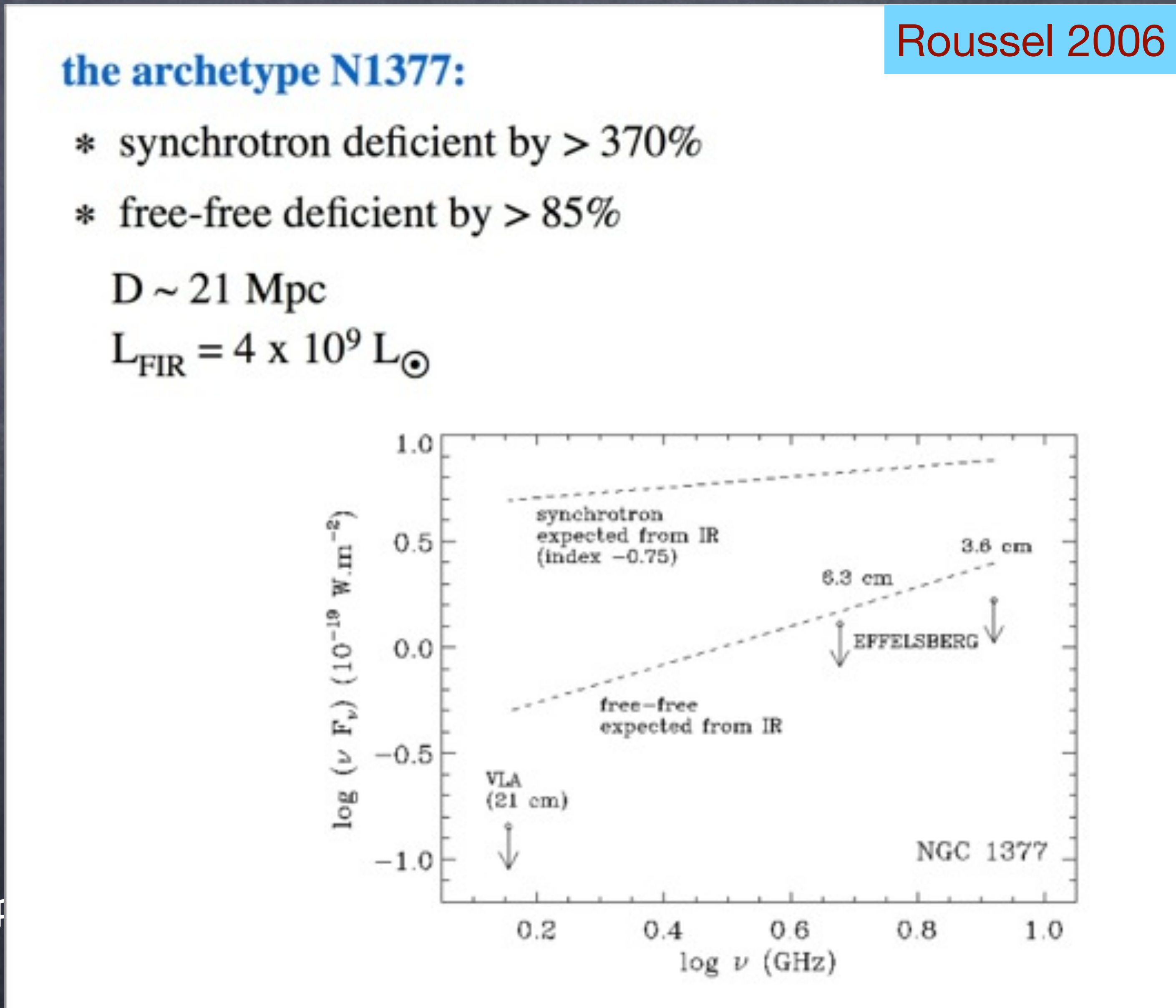
Soifer+ 2008

Assuming U(IGCR)~U(CIB), IGCR flux onto MW today is comparable to SN-derived CR source rate.
Question: Efficiency of CR capture?

The framework to extremes

- Outlier objects in correlations hold useful clues
  - ✳ Are all radio-loud galaxies AGN?
  - ✳ Radio-quiet galaxies still not fully understood (Roussel+ 2003, 2006): Nascent starbursts or something else?

- ~1% populations valuable
  - ✳ Hide easily in surveys



Roussel 2006

the archetype N1377:

- ∗ synchrotron deficient by > 370%
- ∗ free-free deficient by > 85%

D ~ 21 Mpc

$L_{FIR} = 4 \times 10^9 L_\odot$

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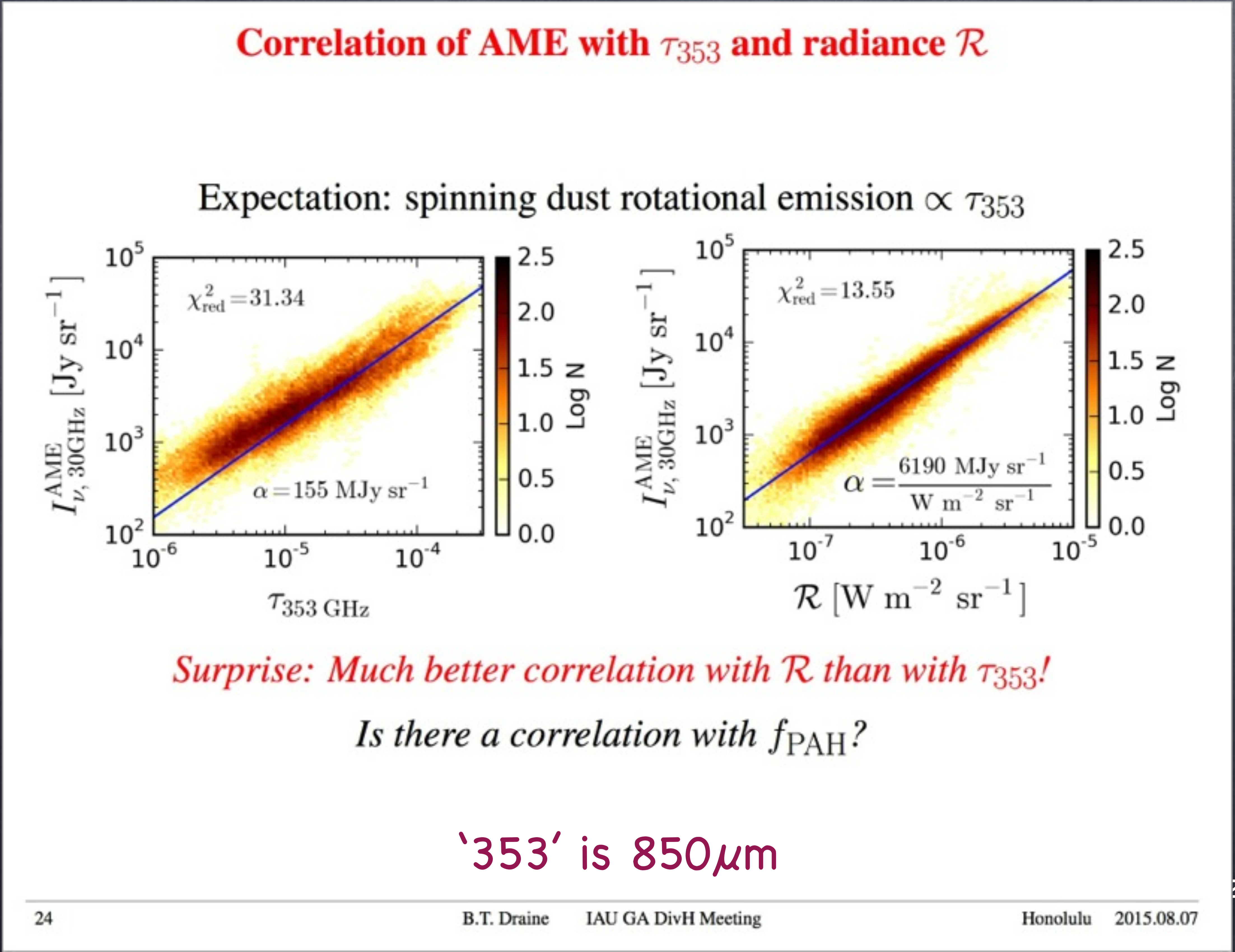
Questions on physics, other agents

- Understanding dynamics between U(CR), U(B), U(gas), U(ISRF), and possibly other U’s
- Understanding magnetic field, its scalings, geometry
- Understanding CR confinement, other behavior
  - ✳ Detailed simulations may be needed, e.g. Hardsastle 2013
- What role for intergalactic CR?
- Wild card: AME
  - ✳ Spinning PAH hypothesis is in difficulty
  - ✳ AME close in energy importance to synchrotron!



Correlation of AME with τ_{353} and radiance $\mathcal{R}$

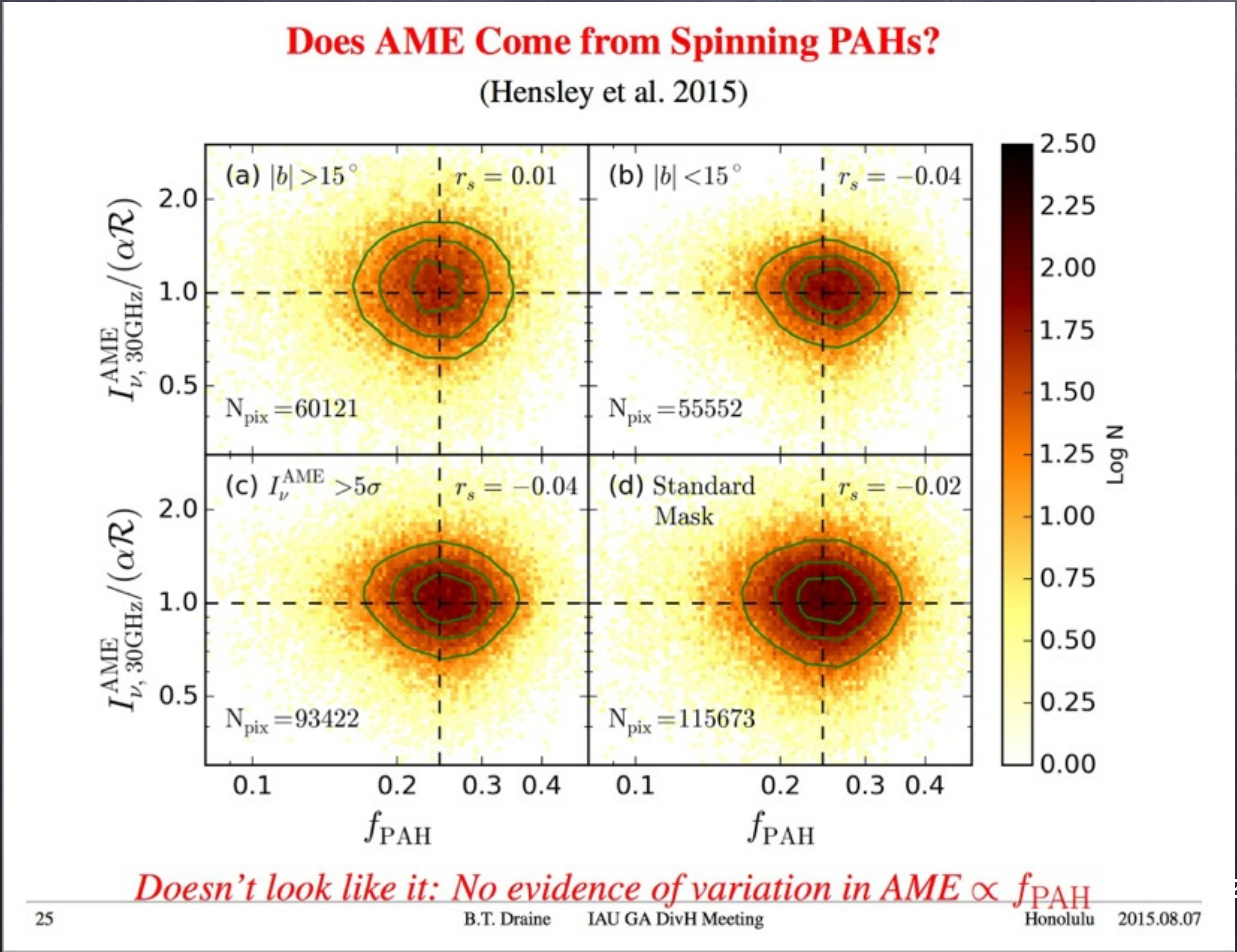
Expectation: spinning dust rotational emission $\propto \tau_{353}$

Surprise: Much better correlation with $\mathcal{R}$ than with τ_{353}!

Is there a correlation with $f_{\rm PAH}$?

24 B.T. Draine IAU GA DivH Meeting Honolulu 2015.08.07

'353' is 850μm



Does AME Come from Spinning PAHs?

(Hensley et al. 2015)

Doesn't look like it: No evidence of variation in AME ∝ $f_{\rm PAH}$

Parting Thought

- "Astronomy is data-driven" - Roger Blandford
  - Radio astronomy is no exception
  - "Theory a mnemonic device" — Martin Schwarzschild (attr.)
- This is the best argument for surveying the sky with powerful new instruments such as SKA or precursors!