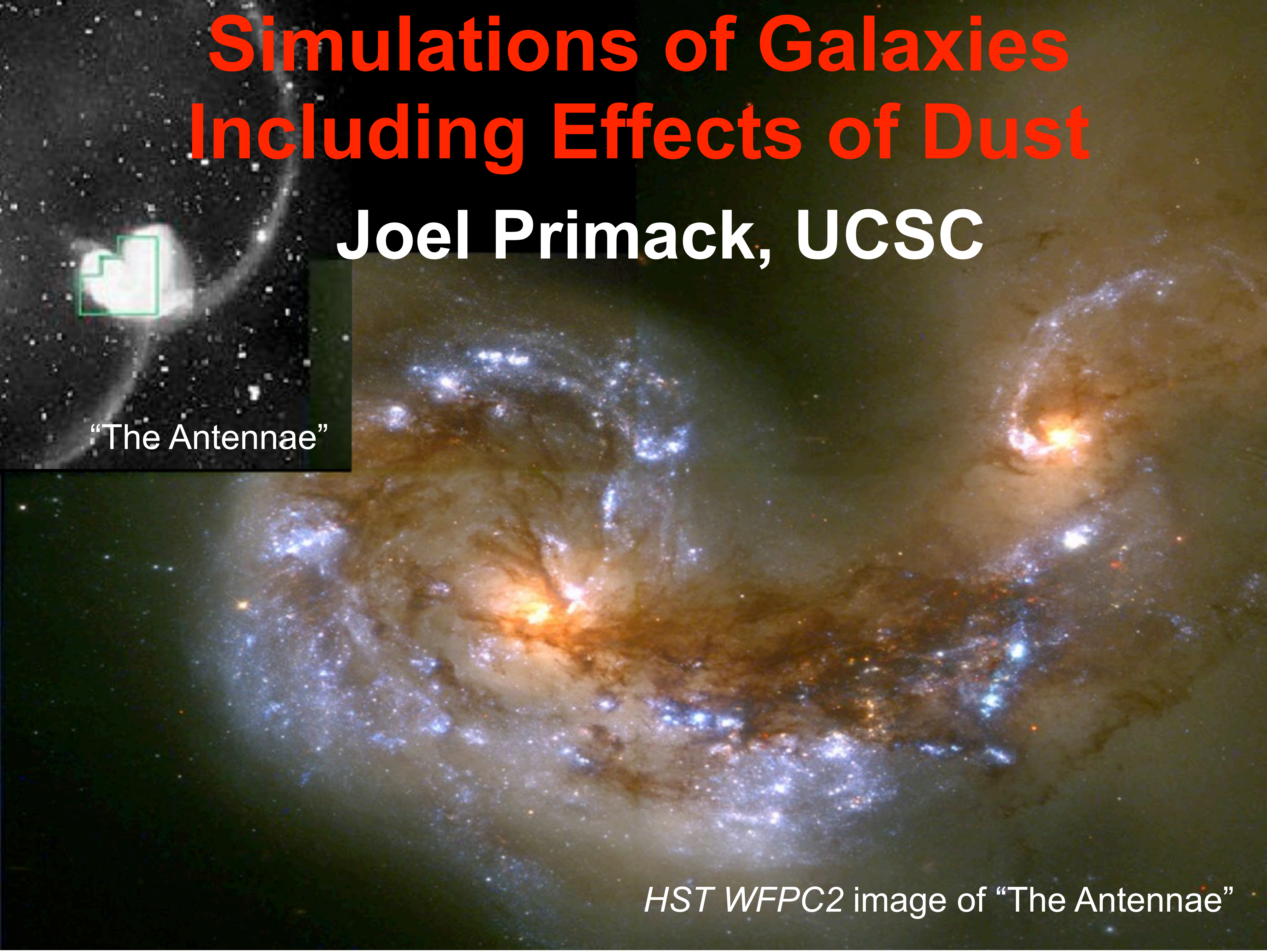
Simulations of Galaxies Including Effects of Dust

Joel Primack, UCSC



“The Antennae”

HST WFPC2 image of “The Antennae”

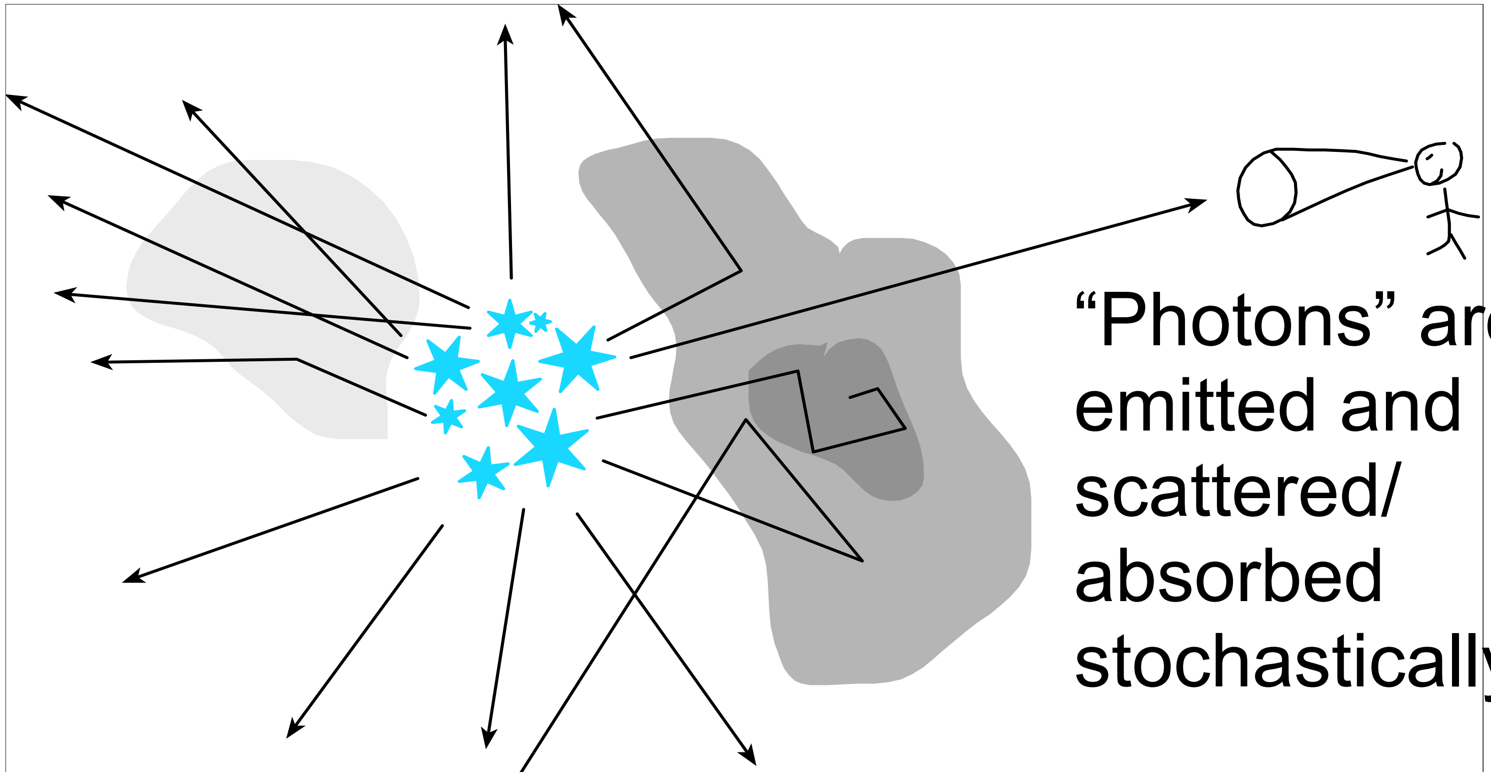
Stellar Evolution and Dust

- Dust in galaxies is important
  - Absorbs about 40% of the local bolometric luminosity
  - Makes brightness of spirals inclination-dependent
  - Completely hides the most spectacular bursts of star formation
  - Makes high-redshift star formation very uncertain
- Dust in galaxies is complicated
  - The mixed geometry of stars and dust makes dust effects geometry-dependent and nontrivial to deduce
  - Needs full radiative transfer model to calculate realistically
- Previous efforts have used 2 strategies
  - Assume a simple, schematic geometry like exponential disks, or
  - Simulate star-forming regions in some detail, assuming the galaxy is made up of such independent regions
  - Have not used detailed information from hydrodynamic simulations
- The *Sunrise* code starts from hydro simulations
- *Sunrise* is open source and adaptable

Sunrise Radiative Transfer Code

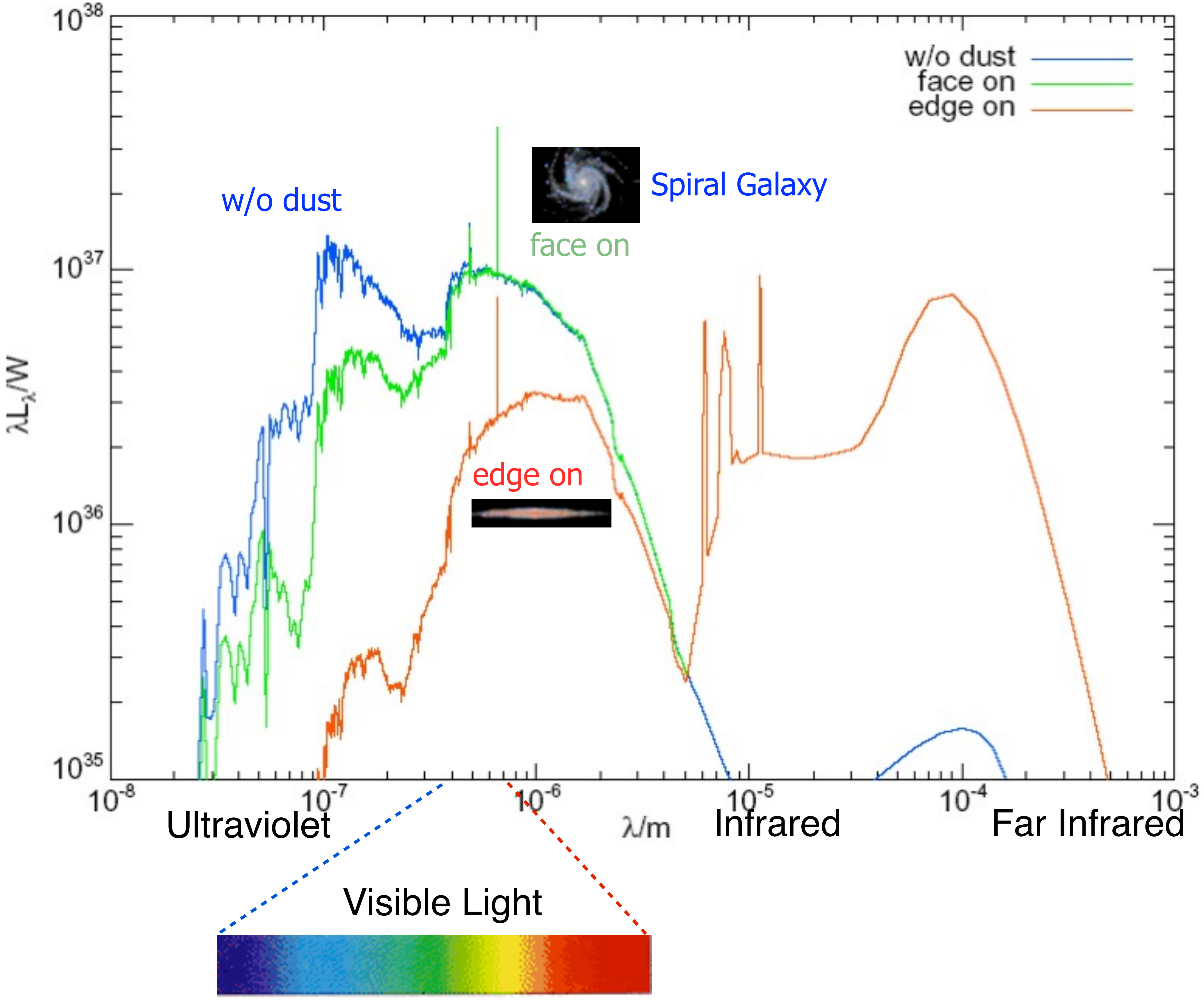
For every simulation snapshot:

- Evolving stellar spectra calculation
- Adaptive grid construction
- MAPPINGS HII region treatment included
- Monte Carlo radiative transfer
- “Polychromatic” rays save 100x CPU time
- Graphic Processor Units give 10x speedup

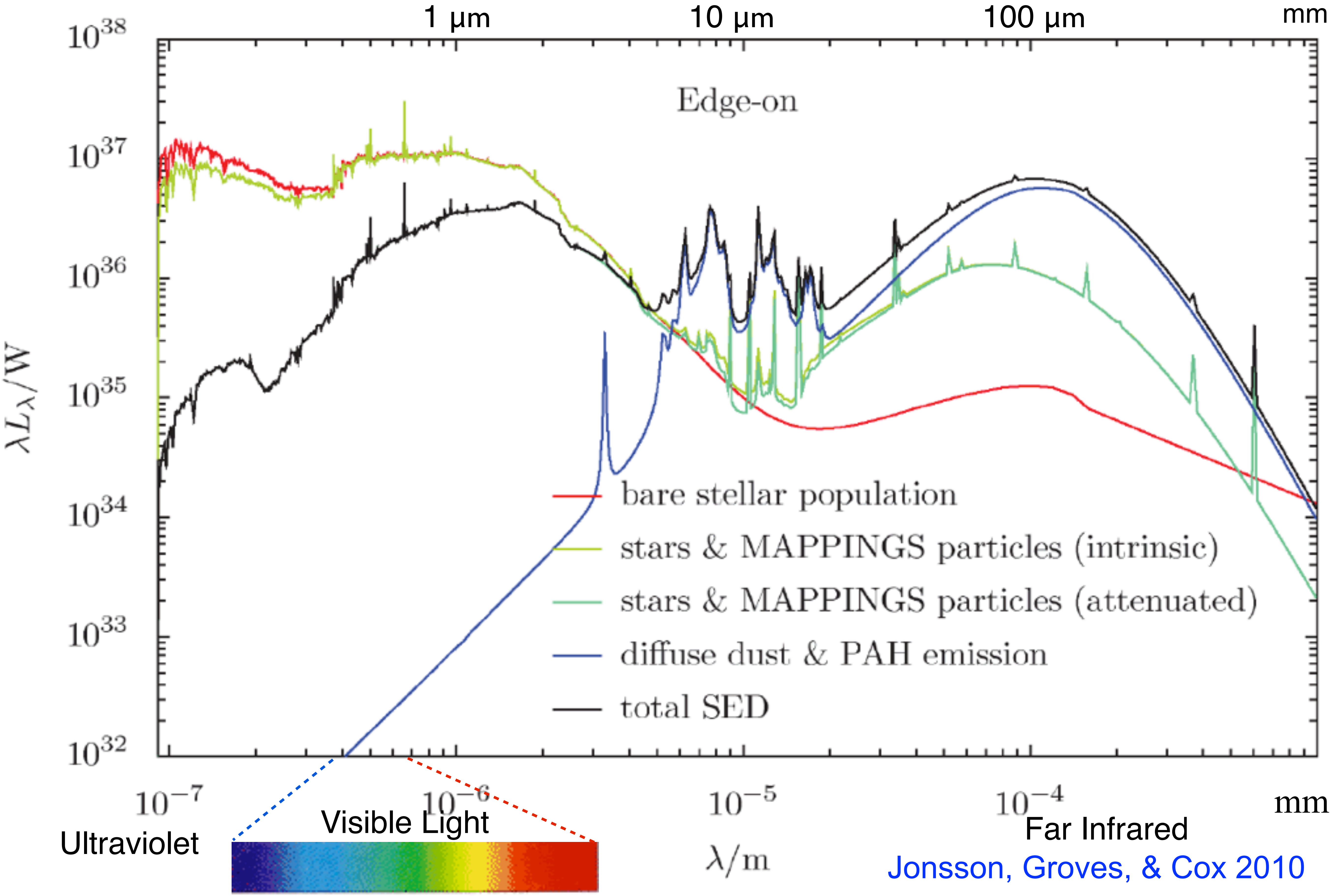


“Photons” are emitted and scattered/ absorbed stochastically

Sunrise Spectral Energy Distribution



Sunrise Spectral Energy Distribution



Jonsson, Groves, & Cox 2010

Accelerating *Sunrise* Dust Temperature Calculations with Graphics Processing Units

Patrik Jonsson, Joel R. Primack

New Astronomy **15**, 509 (2010) (arXiv:0907.3768)

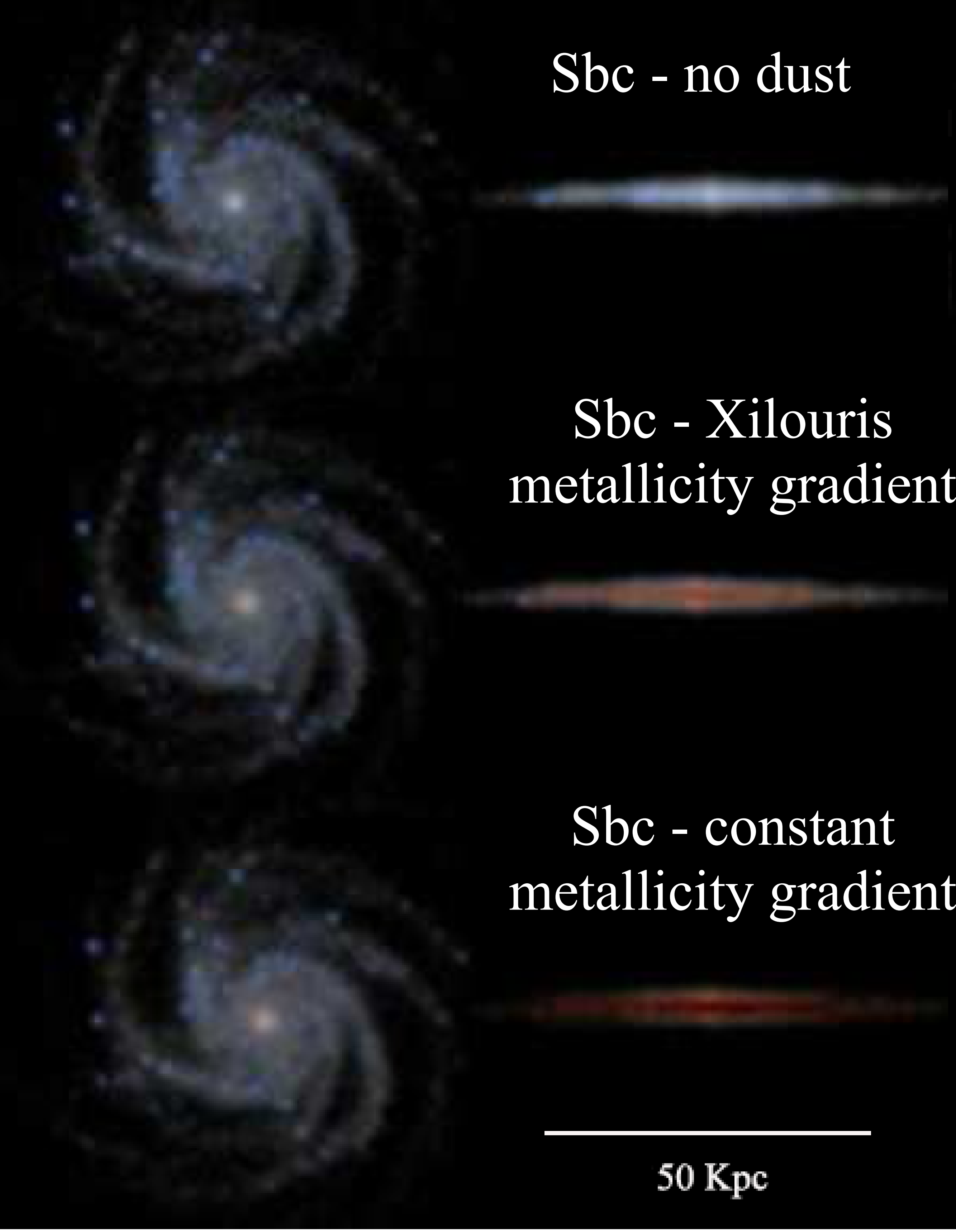
When calculating the infrared spectral energy distributions (SEDs) of galaxies in radiation-transfer models, the calculation of dust grain temperatures is generally the most time-consuming part of the calculation. Because of its highly parallel nature, this calculation is perfectly suited for massively parallel general-purpose Graphics Processing Units (GPUs). This paper presents an implementation of the calculation of dust grain equilibrium temperatures on GPUs in the Monte-Carlo radiation transfer code *Sunrise*, using the CUDA API. The Nvidia Tesla GPU can perform this calculation 55 times faster than 8 CPU cores, showing great potential for accelerating calculations of galaxy SEDs.

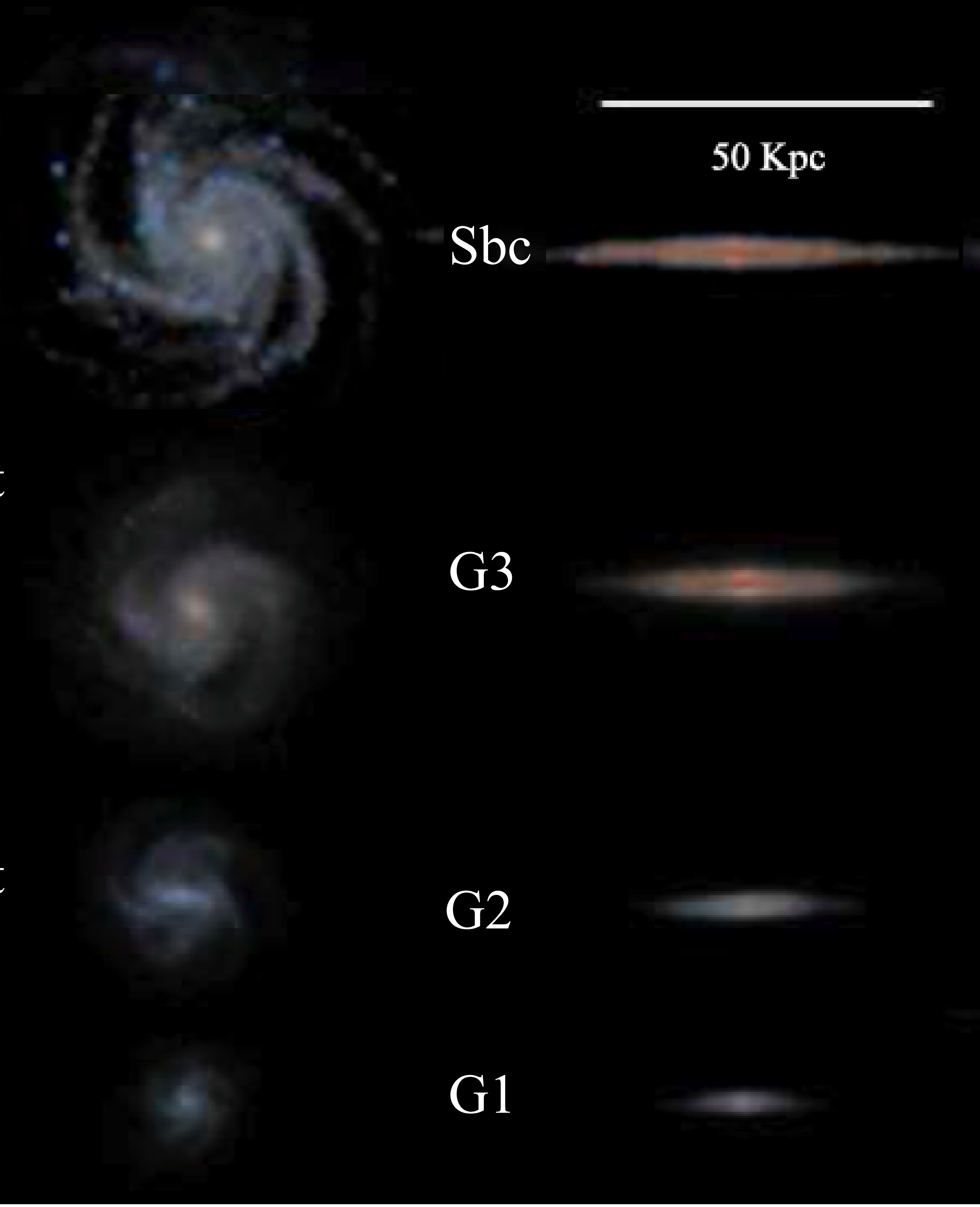
On 64 special NAS Pleiades nodes with 12 Intel cores and an Nvidia 2090 GPU, a 48 hr calculation runs in 4 hr with the GPU. -- Chris Moody

Dust Attenuation in Hydrodynamic Simulations of Spiral Galaxies

Rocha, Jonsson, Primack, & Cox 2008 MN

Right hand side:
Xilouris et al. 1999
metallicity gradient



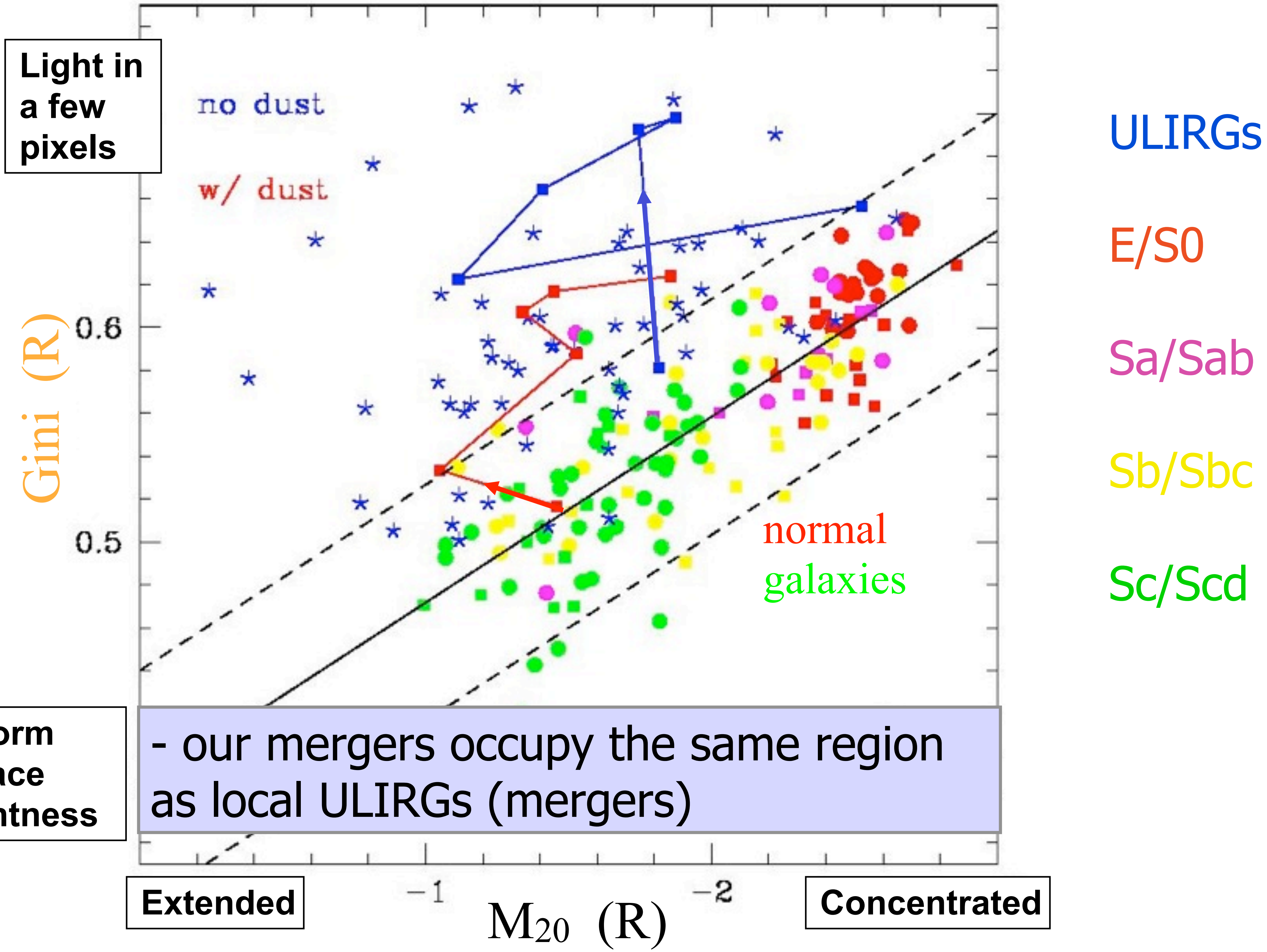


Sunrised Galaxy Merger Simulation

A merger between galaxies like the Milky Way and the Andromeda galaxy. Galaxy mergers like this one trigger gigantic "starbursts" forming many millions of new stars (which look blue in these images). But dust (orange in the video) absorbs up to ~90% of the light, and reradiates the energy at longer wavelengths.

Jonsson, Novak, Primack

Modeling Merger Morphologies



Light in a few pixels

Uniform surface brightness

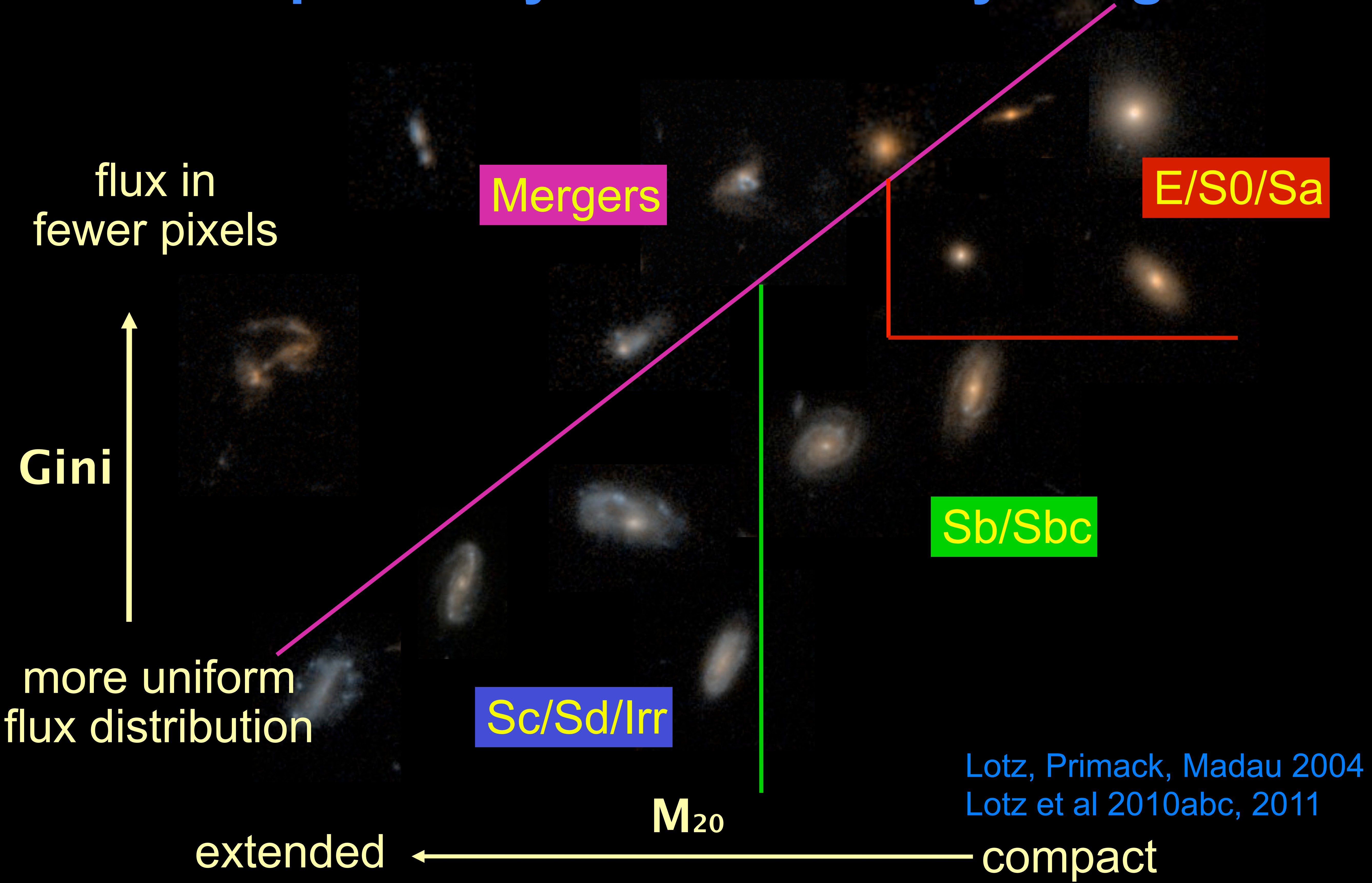
Extended

Concentrated

- our mergers occupy the same region as local ULIRGs (mergers)

Lotz, Primack, Madau 2004; Lotz, Cox, Jonsson, Primack 04-11

G-M_{20} Nonparametric Morphology Measures Can Help Identify $0<z<1.5$ Galaxy Mergers



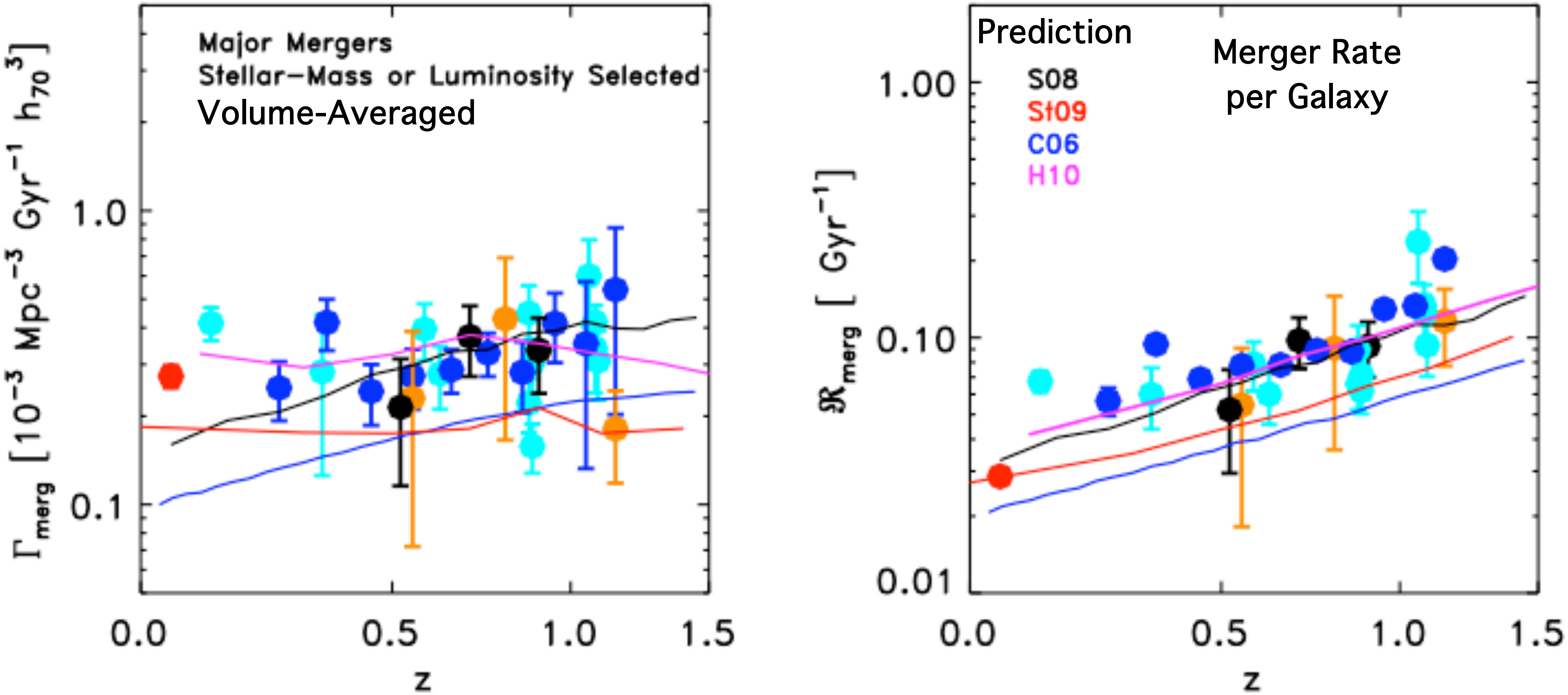
Lotz, Primack, Madau 2004
Lotz et al 2010abc, 2011

THE MAJOR AND MINOR GALAXY MERGER RATES AT Z < 1.5

Jennifer M. Lotz, Patrik Jonsson, T.J. Cox, Darren Croton, Joel R. Primack, Rachel S. Somerville, and Kyle Stewart

Astrophysical Journal 2011

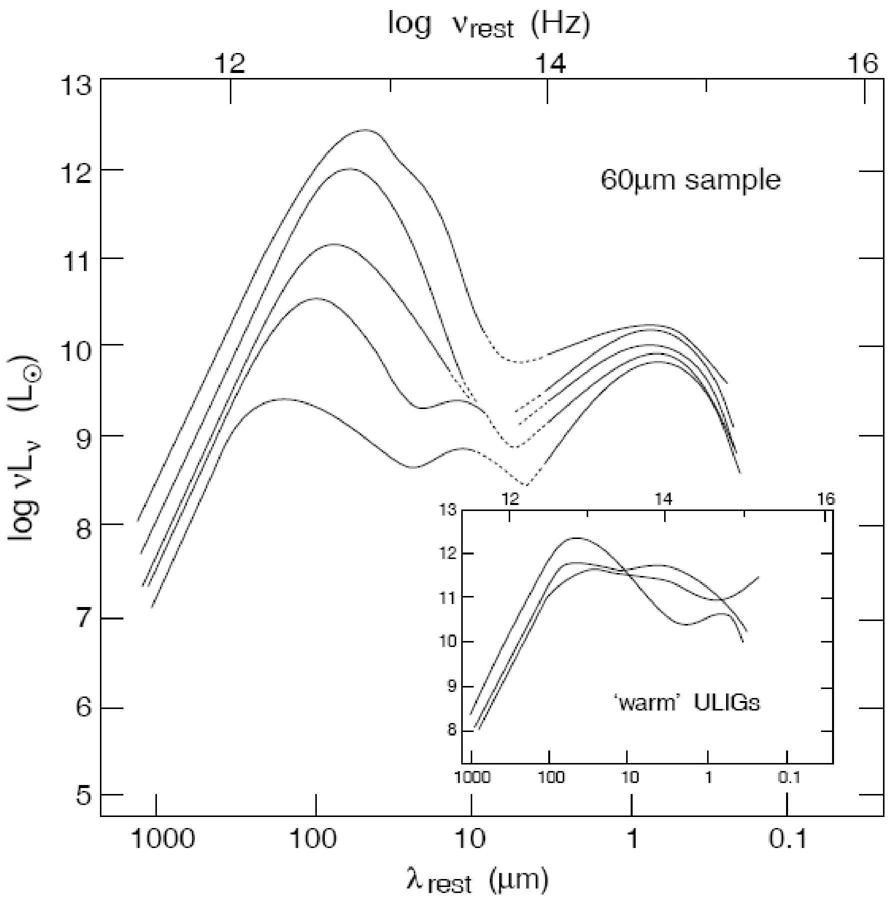
Calculating the galaxy merger rate requires both a census of galaxies identified as merger candidates, and a cosmologically-averaged ‘observability’ timescale $\langle T_{obs}(z)\rangle$ for identifying galaxy mergers. While many have counted galaxy mergers using a variety of techniques, $\langle T_{obs}(z)\rangle$ for these techniques have been poorly constrained. We address this problem by calibrating three merger rate estimators (pairs, asymmetry, and G-M_{20}) with a suite of hydrodynamic merger simulations and three galaxy formation models. When our physically-motivated timescales are adopted, the observed galaxy merger rates become largely consistent. The theoretical predictions are in good agreement with the observed major merger rates.

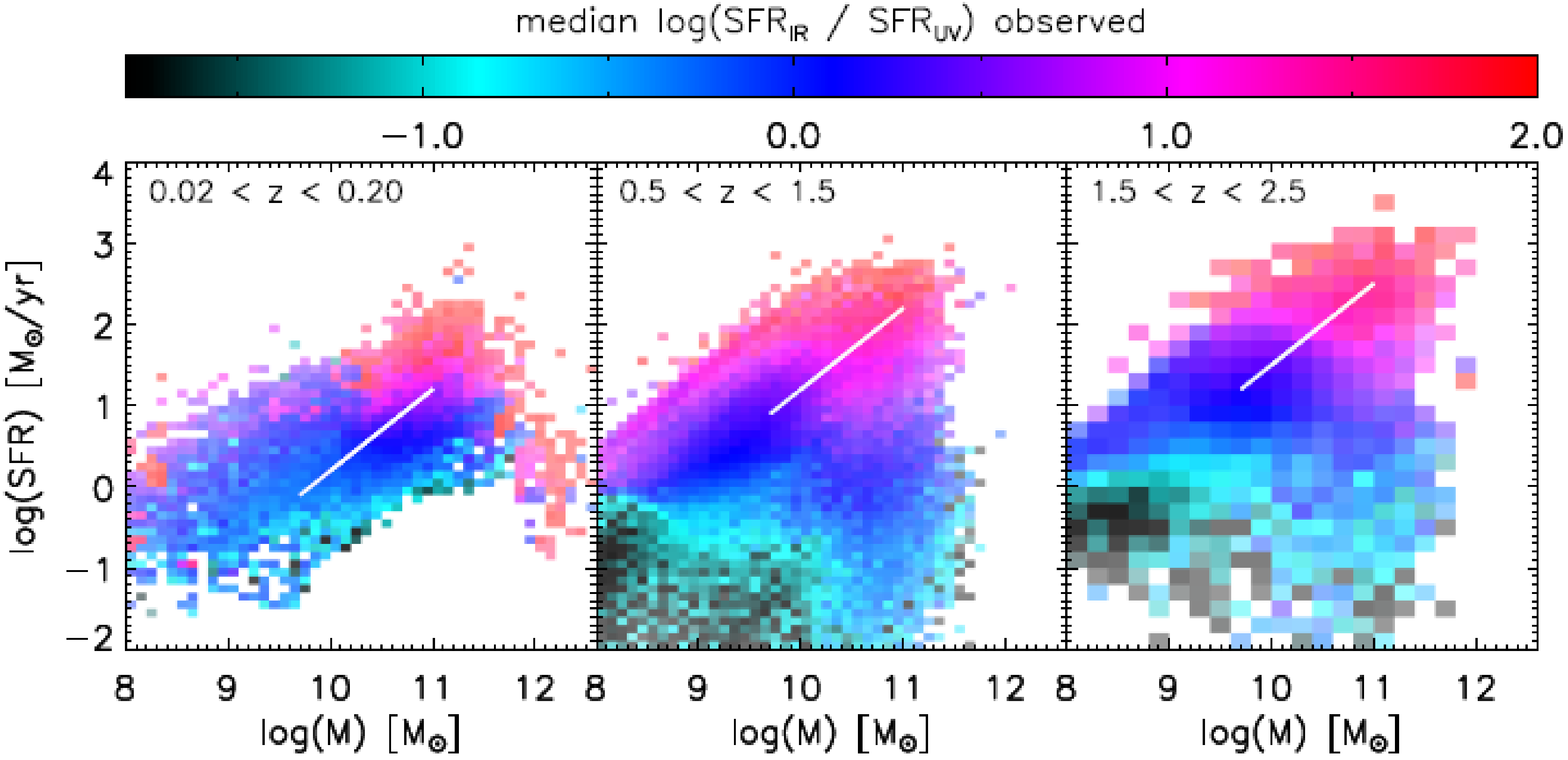


Observed Galaxy Merger Rates v. Theoretical Predictions. The volume-averaged (left) and fractional major merger (right) rates given by stellar-mass and luminosity-selected close pairs are compared to the major merger rates given by the S08 (black lines), St09 (red lines), C06 (blue line), and Hopkins et al. 2010b (magenta lines) models for 1:1 - 1:4 stellar mass ratio mergers and galaxies with $M_{star} > 10^{10}$ $M_{\odot}$.

Correlation between luminosity and dustiness

LIRG: $L_{FIR} \geq 10^{11}L_\odot$ ULIRG: $L_{FIR} \geq 10^{12}L_\odot$ HLIRG: $L_{FIR} \geq 10^{13}L_\odot$



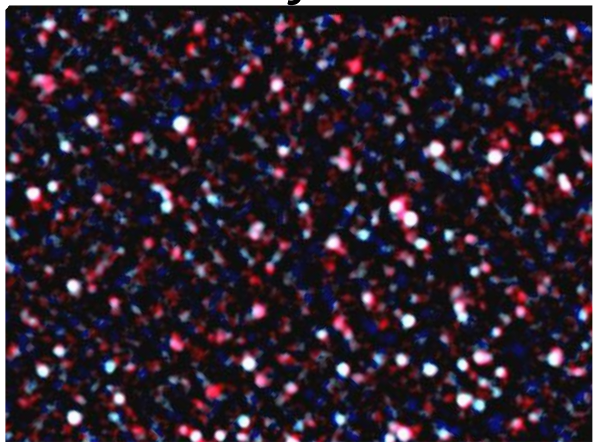


more luminous and massive galaxies are (much) more obscured: for starbursts and (U)LIRGs a de-reddening of the UV-emission does not succeed: the central starburst is behind a 'black screen' and the UV emission comes from a lower obscuration component; even de-reddened Hα fails by about a factor of 10; ULIRGs/starbursts often have 'post-starburst' UV/optical SEDs while the real starburst is completely hidden

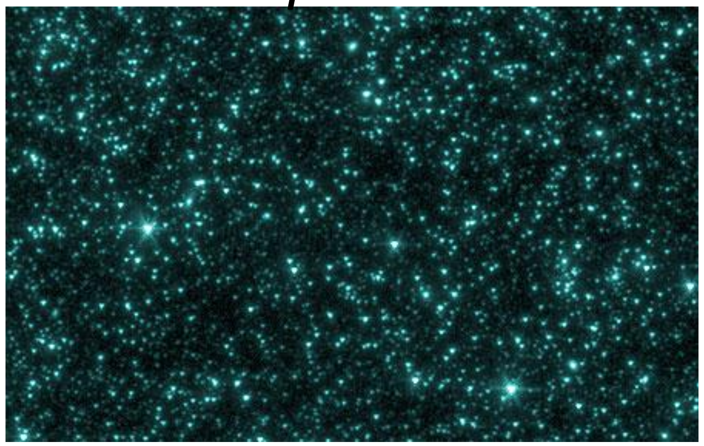
(from Genzel Lecture 2)

Sanders & Mirabel 1996, Meurer et al. 1999, Wuyts et al. 2011

Herschel far-IR

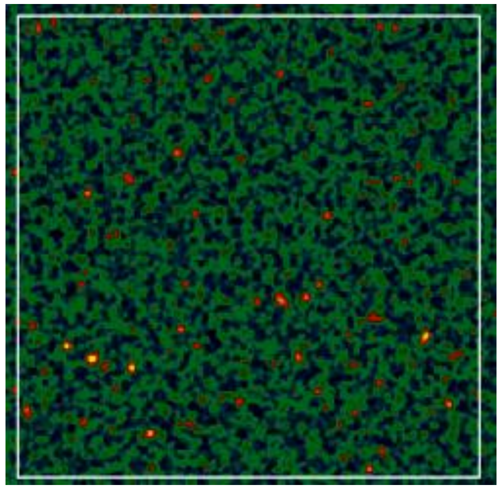


Spitzer mid-IR

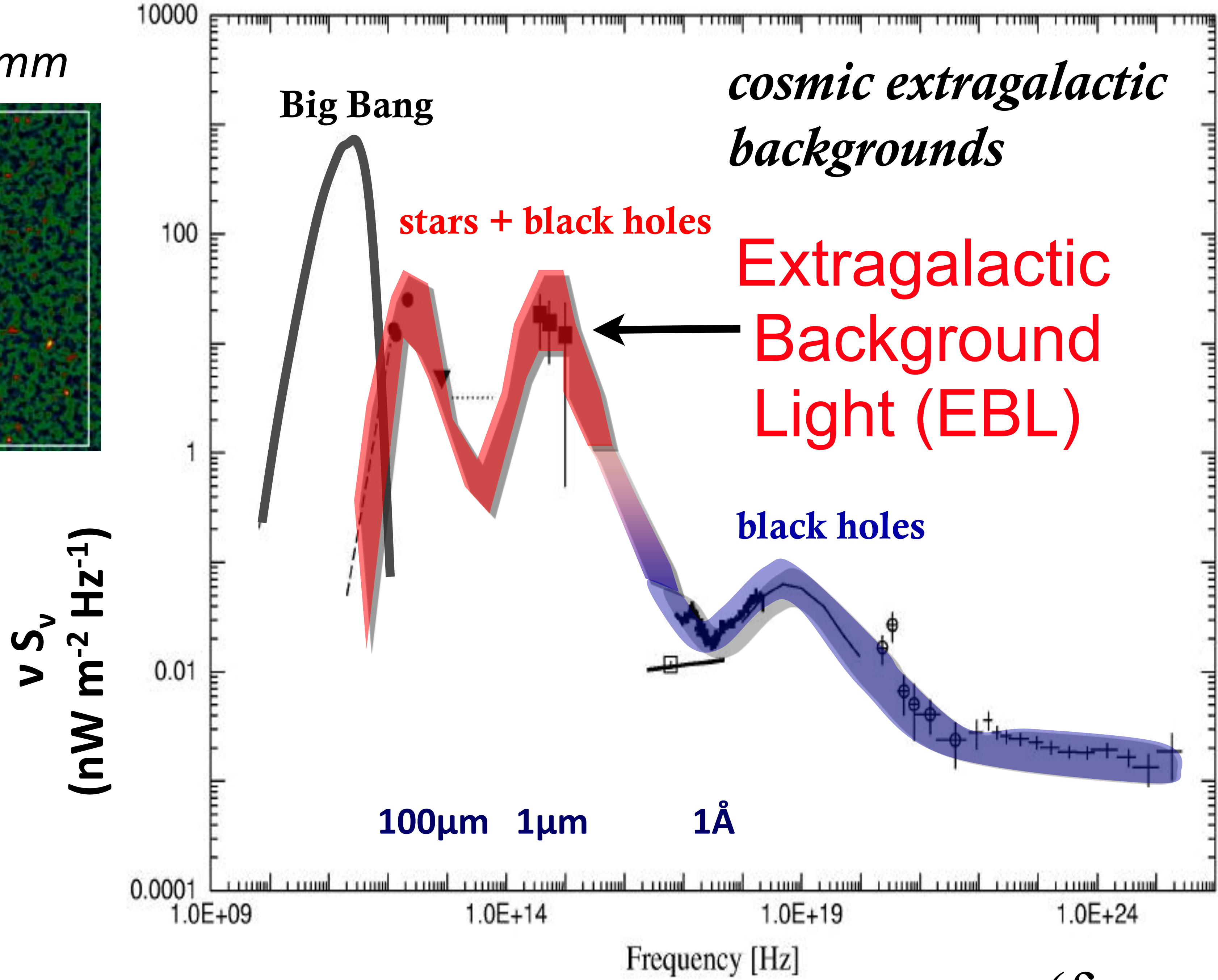


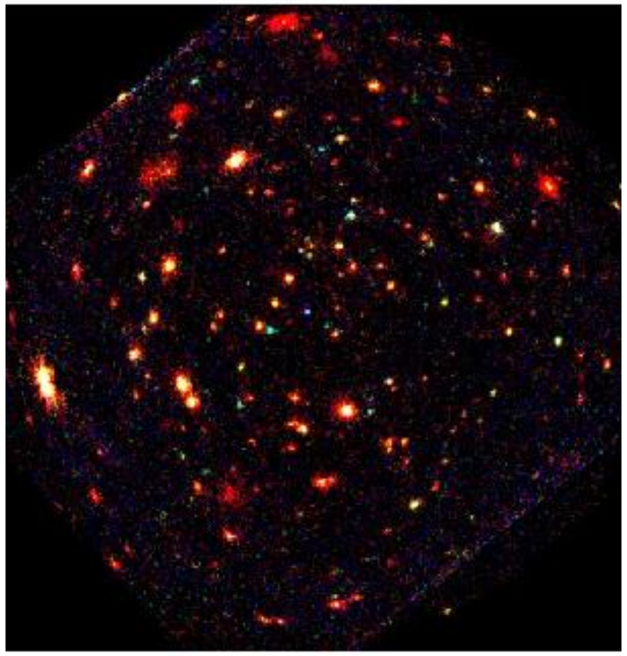
HST-optical/UV

0.850-1.2mm



in the future: ALMA, CCAT..





Chandra/XMM –X-ray

(from Genzel Lecture 2)

Extragalactic Background Light (EBL)

- The usual plot of $\lambda I_\lambda = dI/d \log \lambda$ vs. $\log \lambda$ shows directly the ENERGY DENSITY $\rho_\lambda = (4\pi/c)\, \lambda I_\lambda$ in the EBL:

  $$1\ \mathrm{nW/m^2/sr} = 10^{-6}\ \mathrm{erg/s/cm^2/sr} = 2.6\times10^{-4}\ \mathrm{eV/cm^3}$$

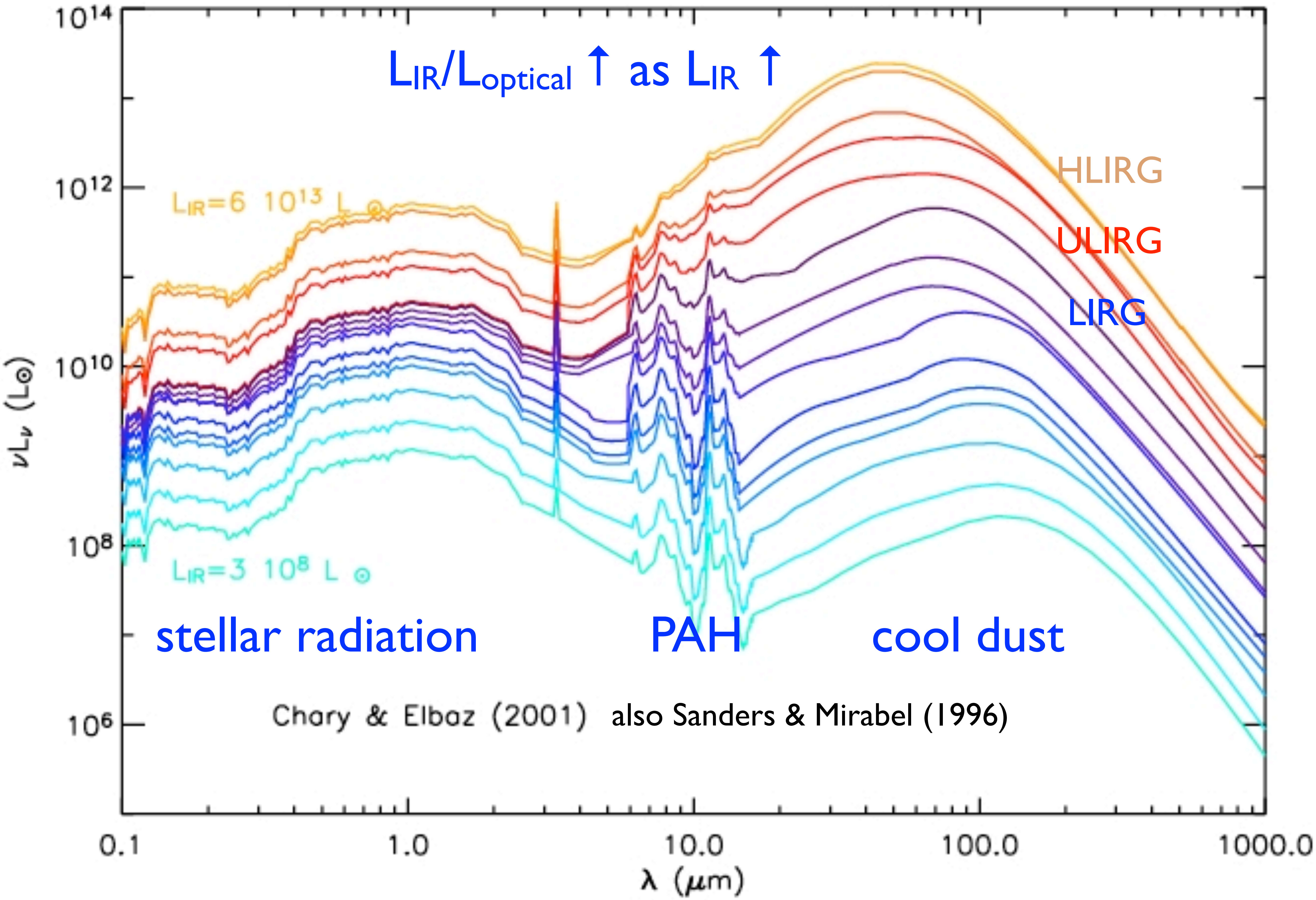
  Total EBL $\Omega_{EBL}{}^{obs} = (4\pi/c)\, I_{EBL}/(\rho_{crit}\, c^2) = 2.0 \times10^{-4}\, I_{EBL}\, h_{70}{}^{-2}$

  The estimated $I_{EBL}{}^{obs} = 60\text{-}100\ \mathrm{nW/m^2/sr}$ translates to

  $$\Omega_{EBL}{}^{obs} = (3\text{-}5) \times10^{-6} \quad (\text{about } 5\% \text{ of } \Omega_{CMB})$$

- Local galaxies typically have $E_{FIR}/E_{opt} \approx 0.3$, while the EBL has $E_{FIR}/E_{opt} = 1\text{-}2$. **This implies that most high-redshift radiation was emitted in the far IR.**

Spectral Energy Distribution vs. L_{IR}



Chary & Elbaz (2001) also Sanders & Mirabel (1996)

Define IR8 ≡ $L_{IR}/L8$

A&A 533, A119 (2011)

$L_{IR}=10^{11}\ L_\odot$ Galaxies:

Main Sequence brighter than Starbursts in PAH and submm

IR8 ≈ 4±1.6 (1σ)

IR8≳8

D. Elbaz et al.: GOODS–*Herschel*: an infrared main sequence for star-forming galaxies

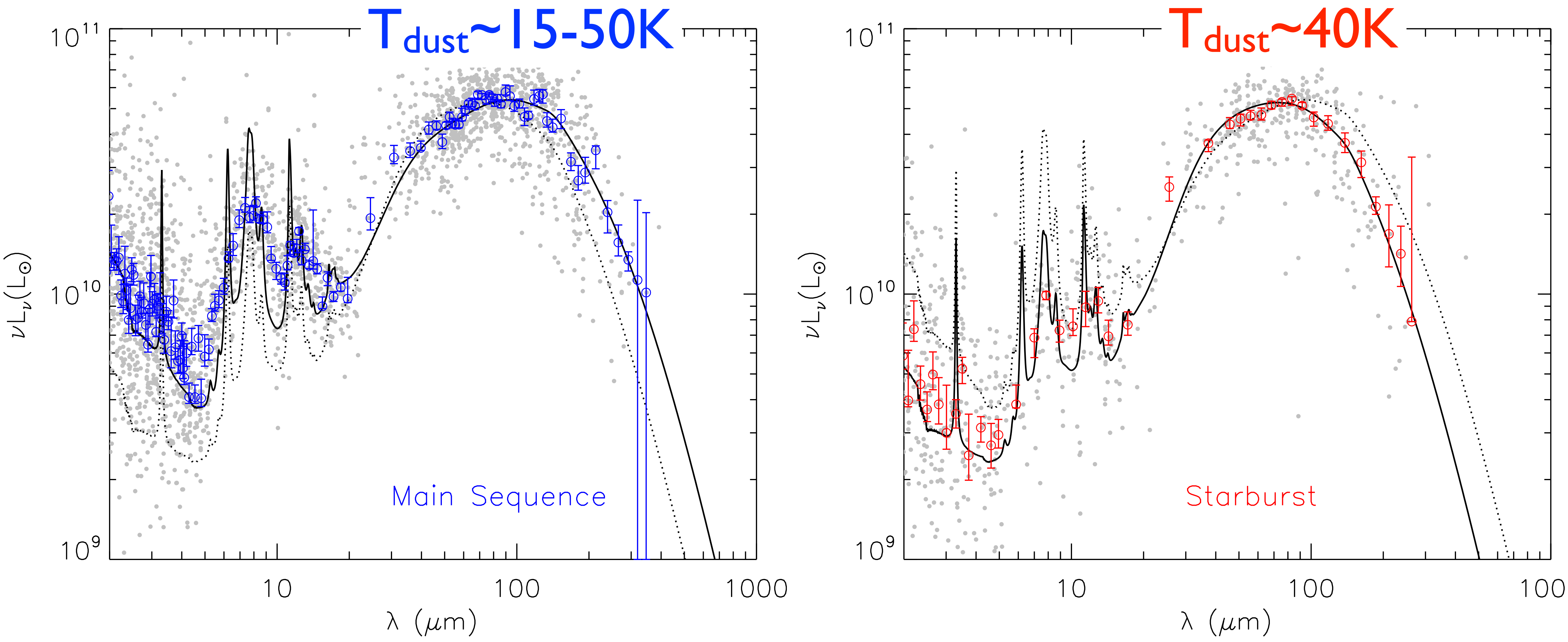


Fig. 21. Composite spectral energy distribution of the typical main sequence galaxy (*left*; IR8 = 4 ± 2, see Eq. (5)) and starburst (*right*; IR8 > 8, i.e., above 2σ). Light grey dots: individual GOODS–*Herschel* galaxies normalized to $L_{\rm IR}^{\rm tot} = 10^{11}\ L_\odot$. The large filled symbols with error bars are the median and associated uncertainty of the MS (*left figure*, blue dots) and SB (*right figure*, red dots) galaxies computed in intervals of wavelengths defined to contain a fixed number of 25 ± 5 galaxies. The uncertainty on the median values is derived from the 16th and 84th percentiles around the median divided by the square root of the number of galaxies. The model fit to each SED is shown with a solid black line while the opposing SED (MS or SB) is shown with a dotted black line for comparison.

See also Magdis+12 for Herschel SED templates

EBL Evolution Calculated from Observations Using AEGIS Multiwavelength Data

Alberto DomÍnguez, Joel Primack, et al. (MNRAS, 2011)

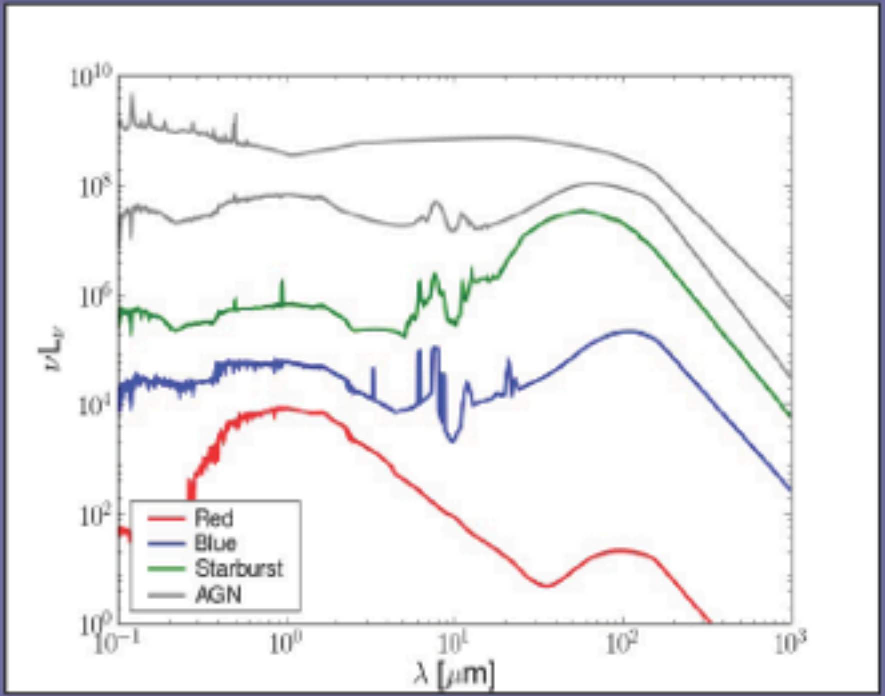
$$j_i(\lambda,z) = j_i^{faint} + j_i^{mid} + j_i^{bright} =$$

$$= \int_{M_1}^{M_2} \underline{\Phi(M_K,z)}\,\underline{f_i}\,\underline{T_i(M_K,\lambda)}\,dM_K +$$

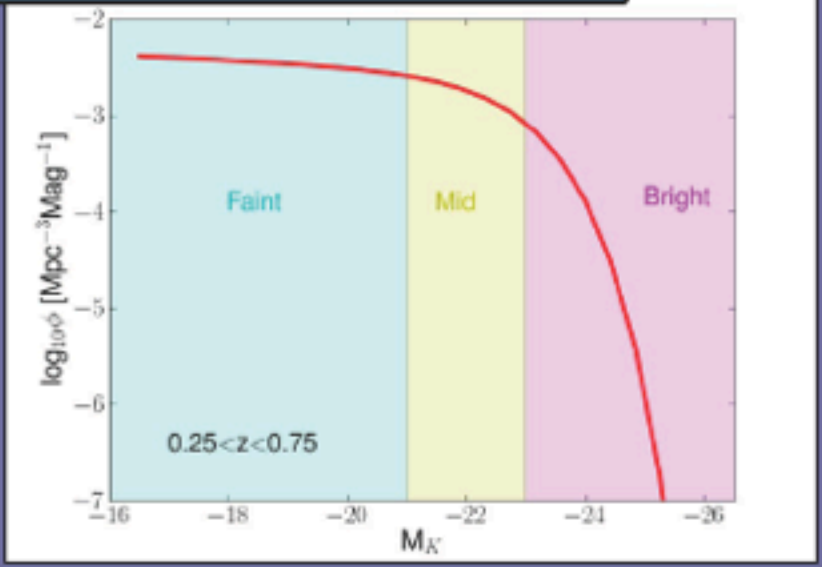
$$+ \int_{M_2}^{M_3} \underline{\Phi(M_K,z)}\,\underline{m_i}\,\underline{T_i(M_K,\lambda)}\,dM_K +$$

$$+ \int_{M_3}^{M_4} \underline{\Phi(M_K,z)}\,\underline{b_i}\,\underline{T_i(M_K,\lambda)}\,dM_K$$

Spectral energy distributions
SWIRE template library, Polletta+ 07



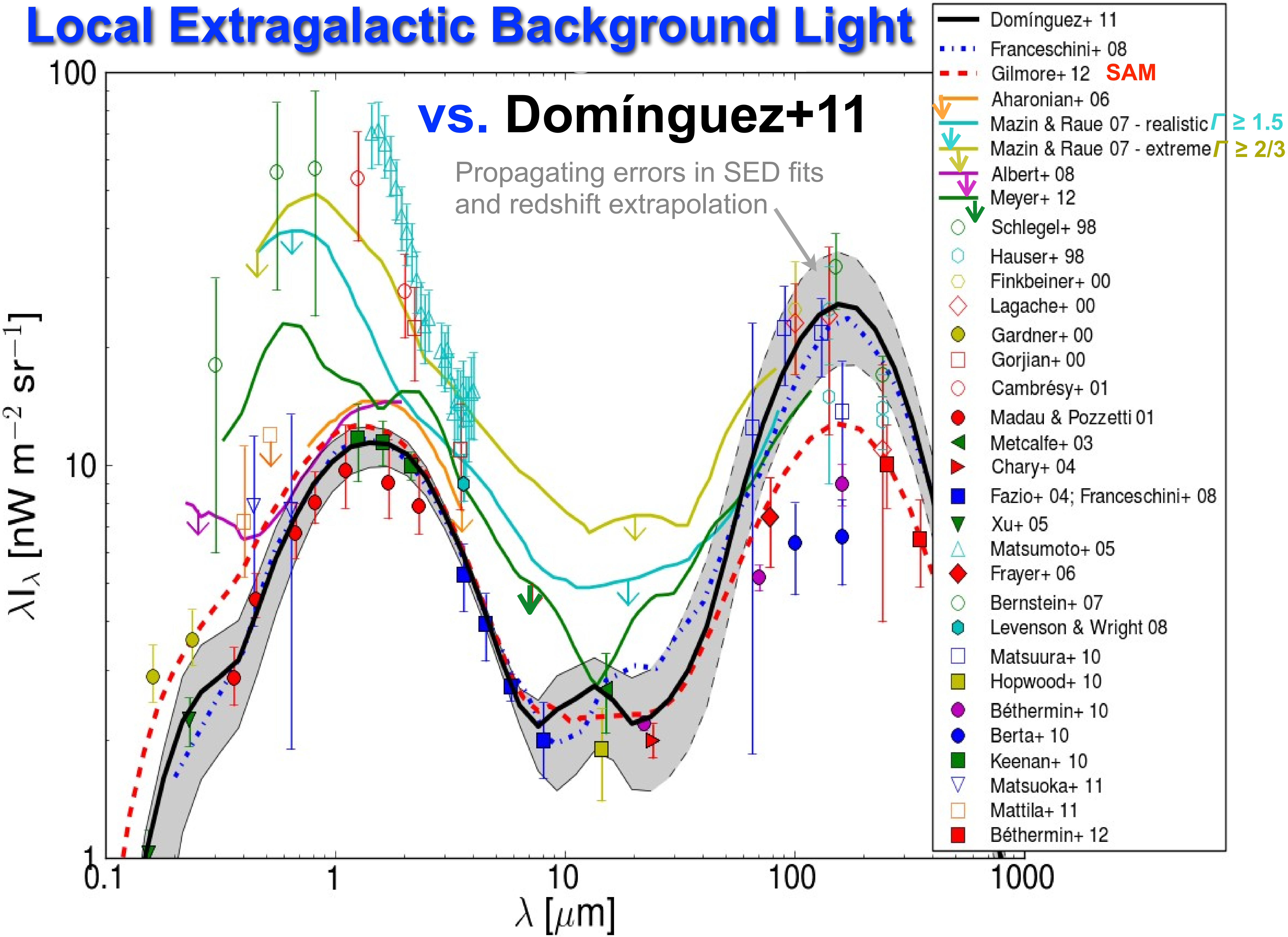
Luminosity function
observed K-band, Cirasuolo+ 09



Spectral-type fractions

$$\lambda I_\lambda(z) = \frac{c}{4\pi}\int_z^{z_{max}} j_{total}[\lambda(1+z)/(1+z'),z']\left|\frac{dt}{dz'}\right|dz'$$

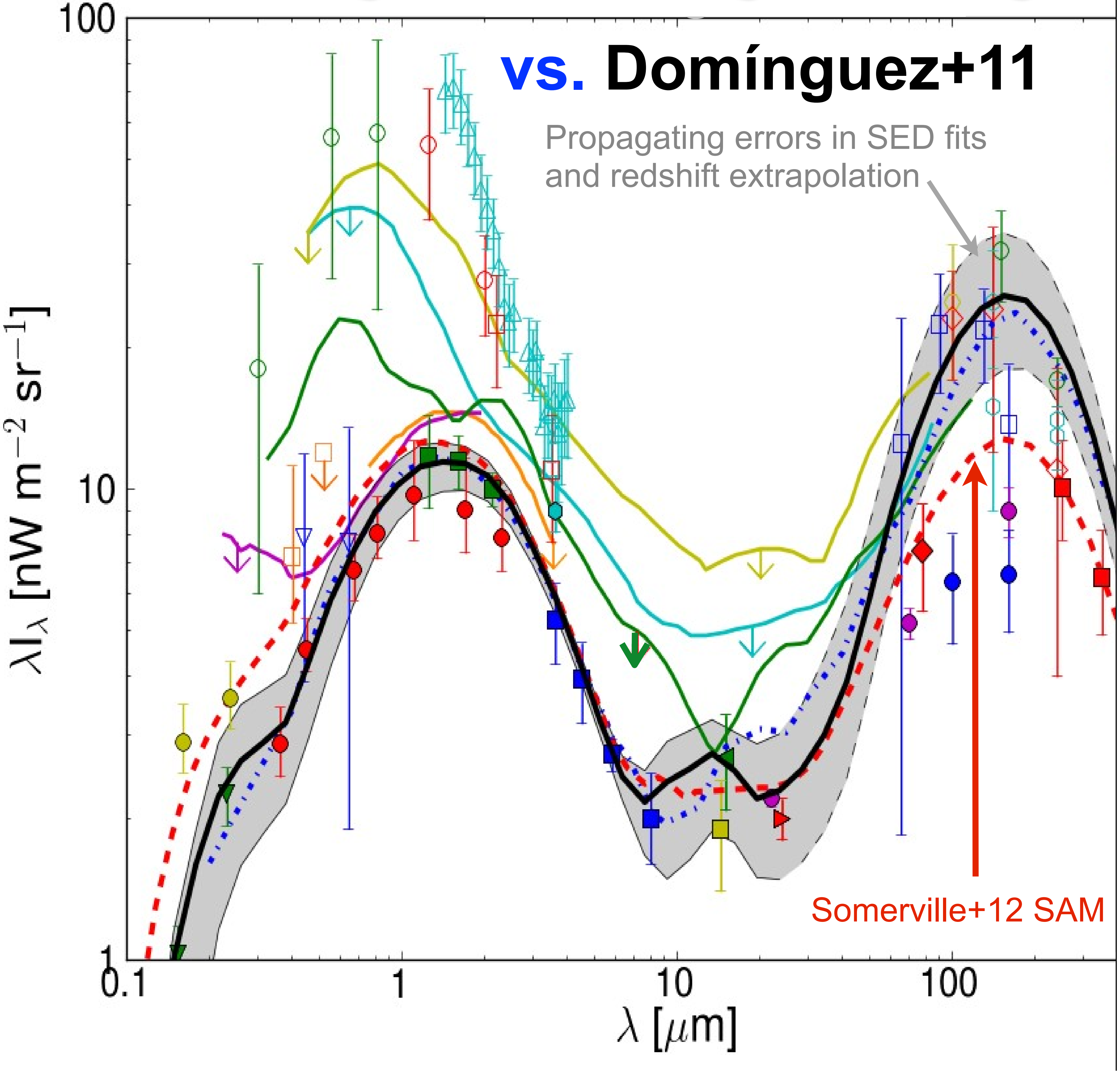
Local Extragalactic Background Light



vs. Domínguez+11

Propagating errors in SED fits and redshift extrapolation

Local Extragalactic Background Light



vs. Domínguez+11

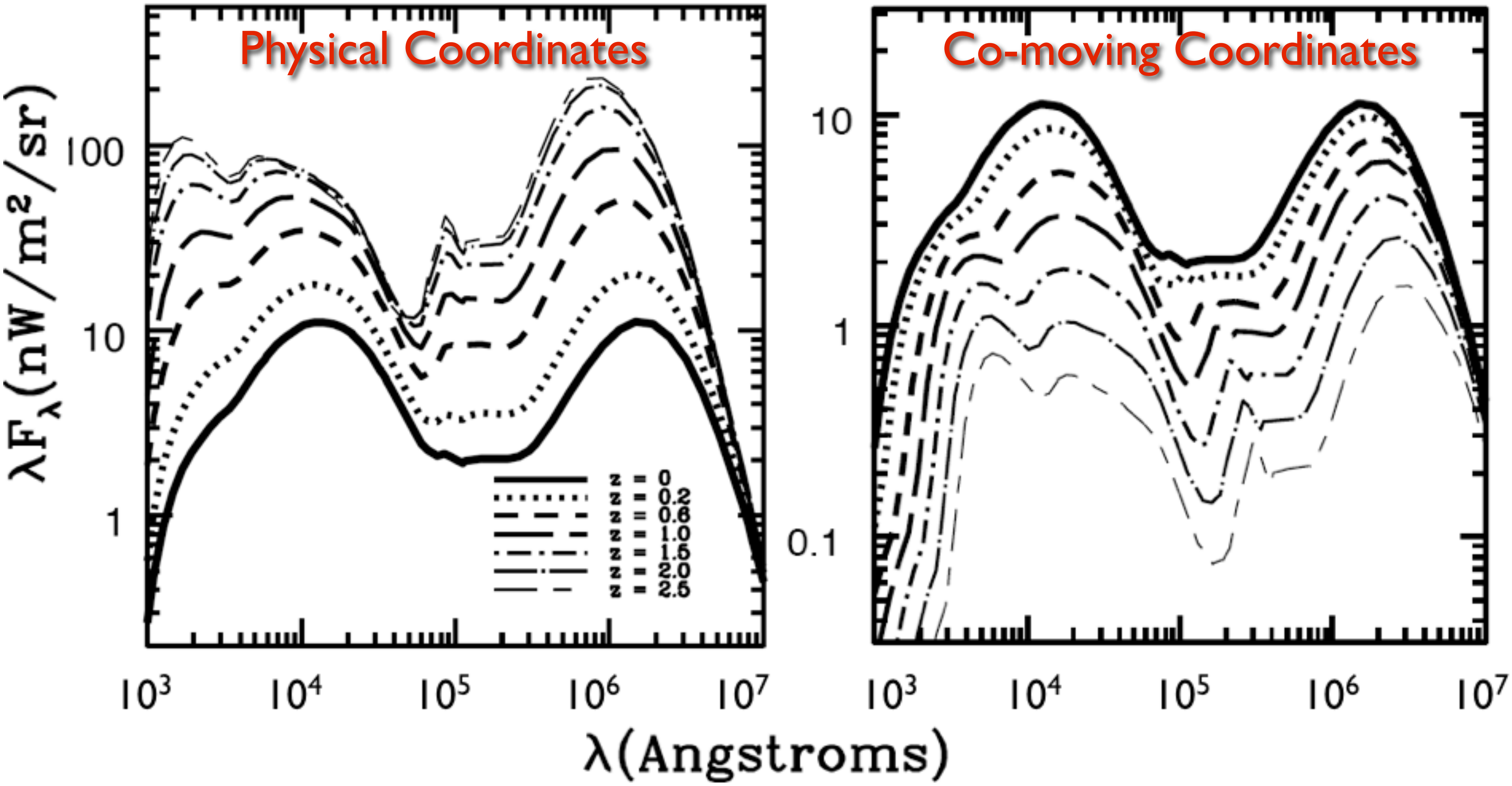
Propagating errors in SED fits and redshift extrapolation

Somerville+12 SAM

Note that the IR EBL is at least as high as the optical EBL. Since few nearby galaxies are strong IR emitters, this IR must have come from higher redshift and been diluted by cosmic expansion. Thus most of the radiation emitted at higher z must have been emitted at long wavelengths by dust.

Note also that the Somerville+12 SAM gives much less Far IR EBL than the direct measurement by Dominguez+11. This SAM's greatest discrepancy compared with observations is at long wavelengths. That should be improved using Chris Hayward's new *Sunrise* modeling of ULIRGs.

Evolution of the EBL



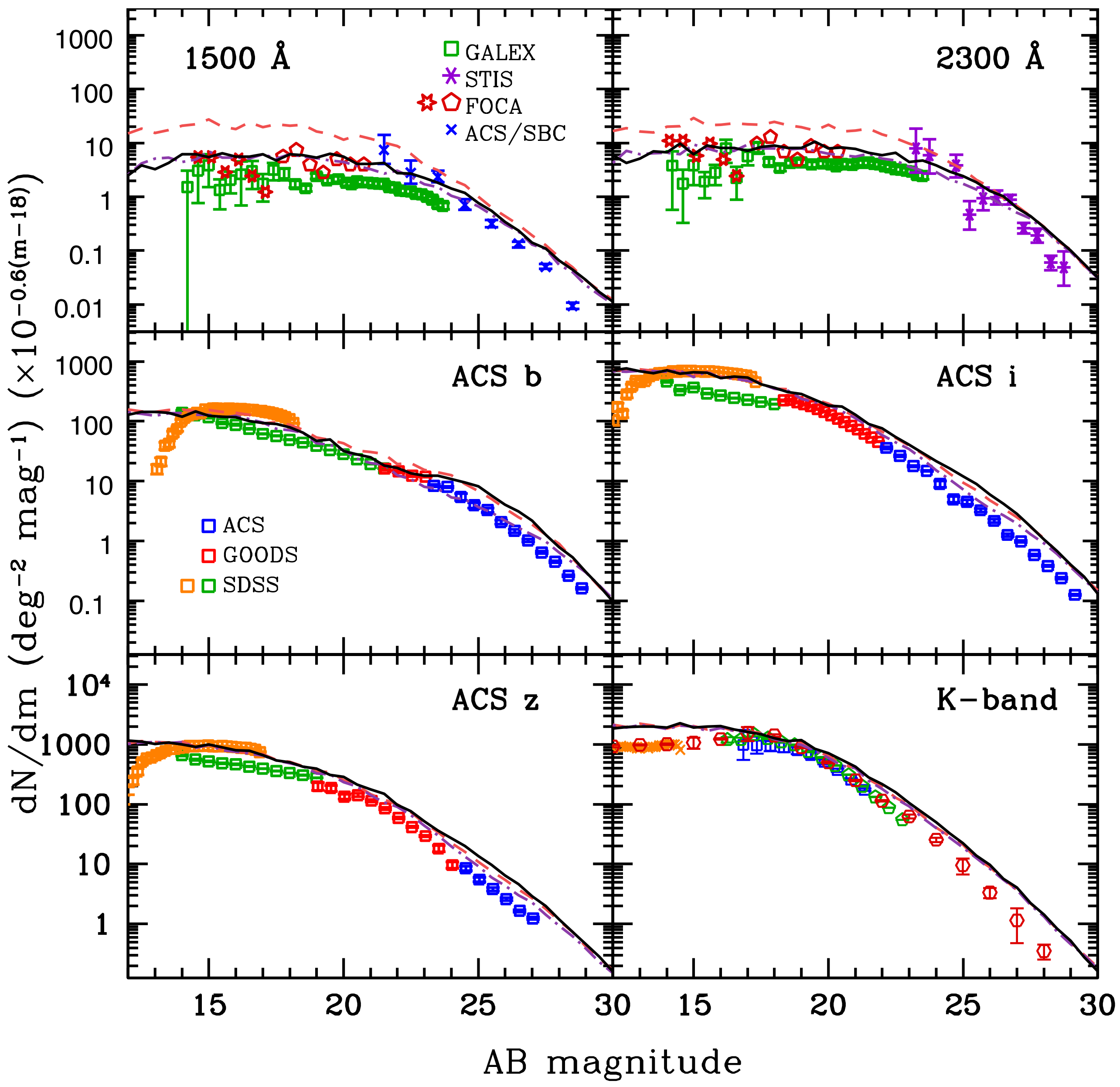
The evolution of the EBL in our WMAP5 Fiducial model. This is plotted on the left panel in standard units. The right panel shows the build-up of the present-day EBL by plotting the same quantities in comoving units. The redshifts from 0 to 2.5 are shown by the different line types in the key in the left panel.

Gilmore, Somerville, Primack, & Domínguez (2012)

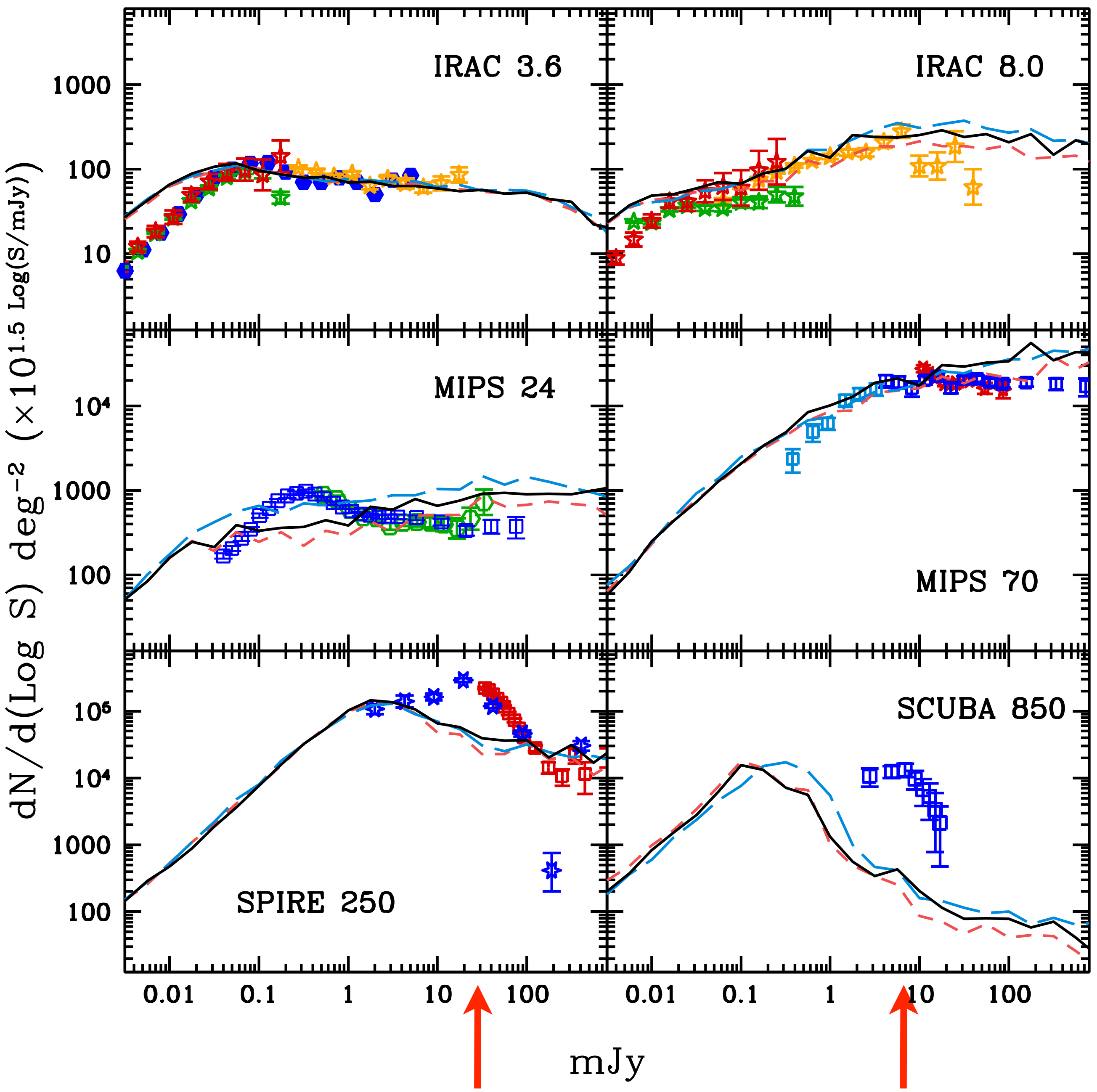
Some Results from Somerville+12 SAM

Number Counts in UV, b, i, z, K Bands

Number Counts in 3.6, 8, 24, 70, 250, & 850 μm Bands



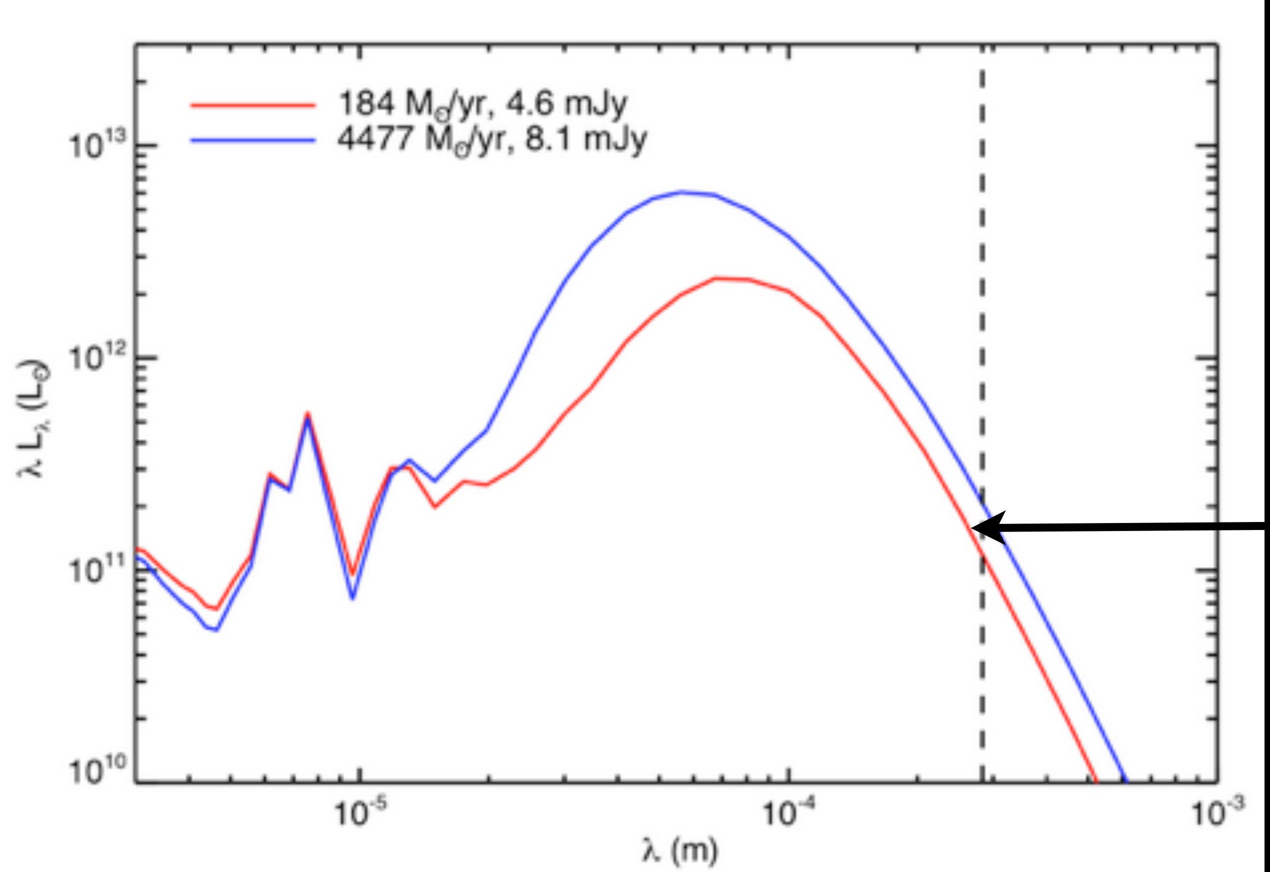
Somerville, Gilmore, Primack, & Dominguez (2012)



Far-IR Underpredictions

Conclusions from Chris Hayward's recent papers based on simulated galaxy mergers with *Sunrise* dust modeling:

- Submm galaxies are a heterogeneous population, including coalescence phase of major gas-rich mergers, but also galaxies with much less star formation and cool dust



https://www.cfa.harvard.edu/~chayward/research.html

submm flux differ by less than a factor of 2

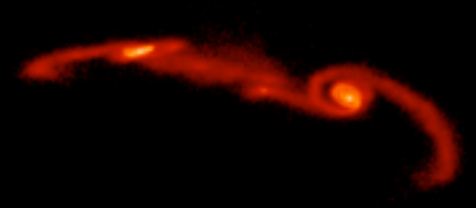
- significant contribution to single-dish counts from blended galaxy pairs

- Counts can be matched with standard IMF

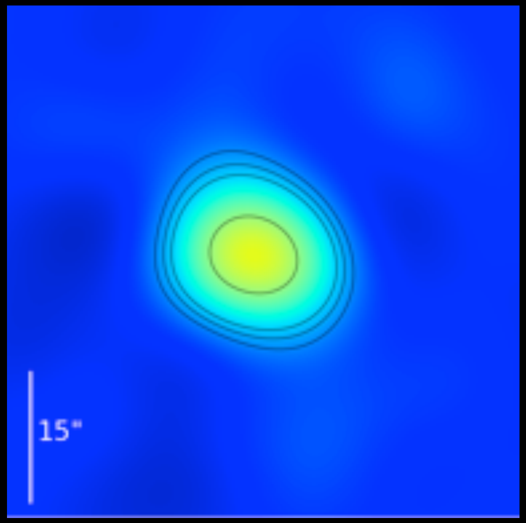
Galaxy pair contribution

Hayward+12

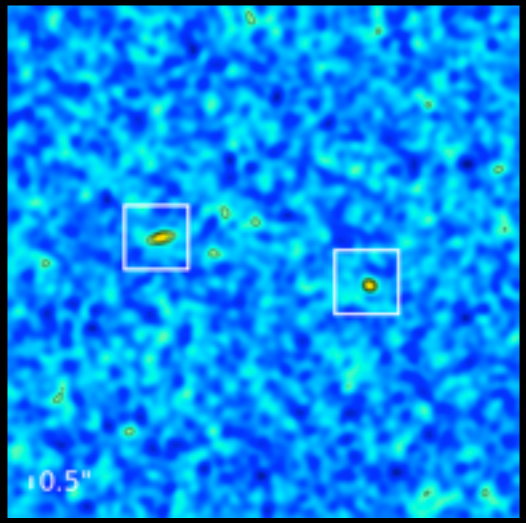
From Chris Hayward's presentation at the JWS



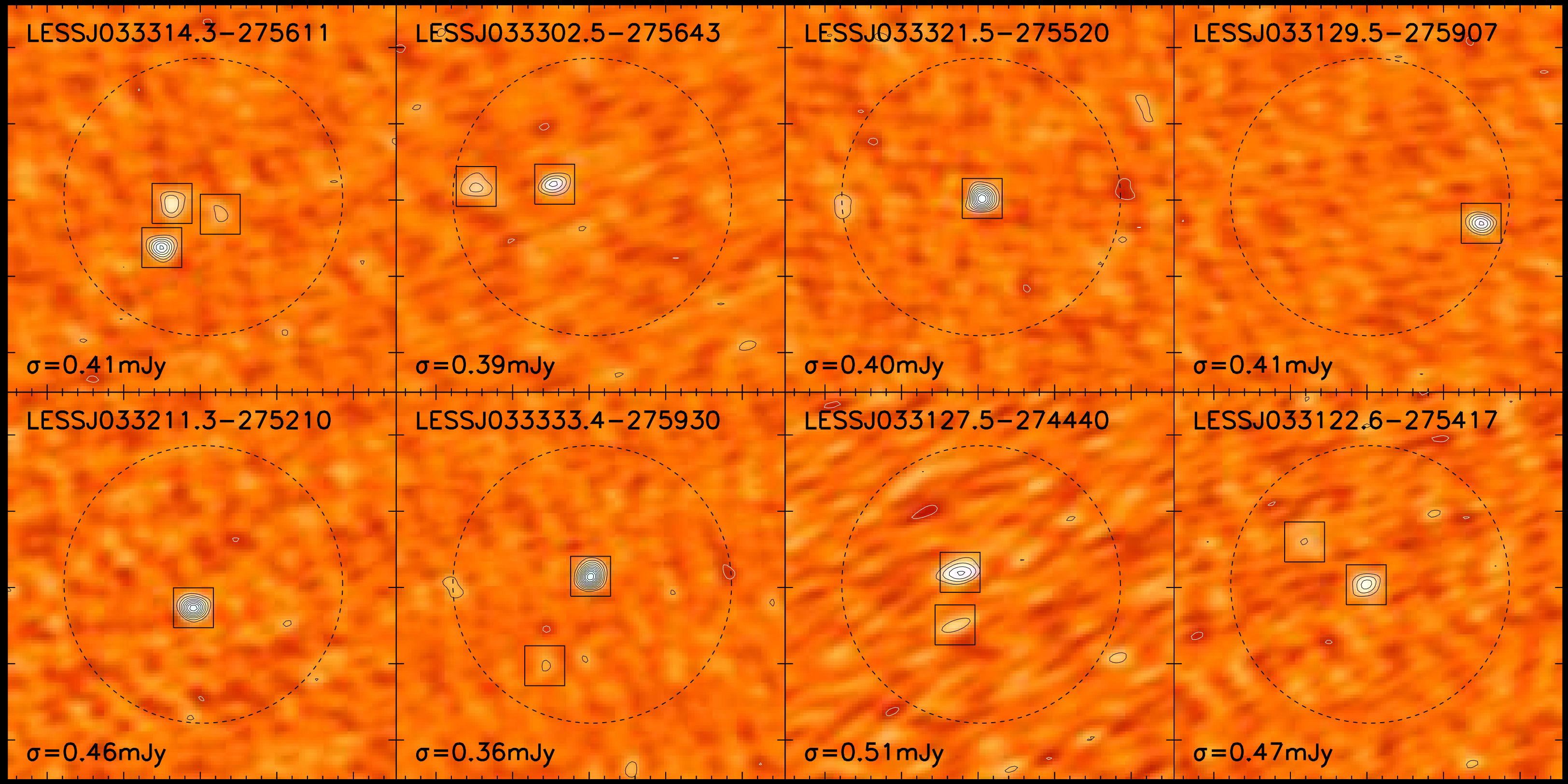
full sim resolution



single-dish



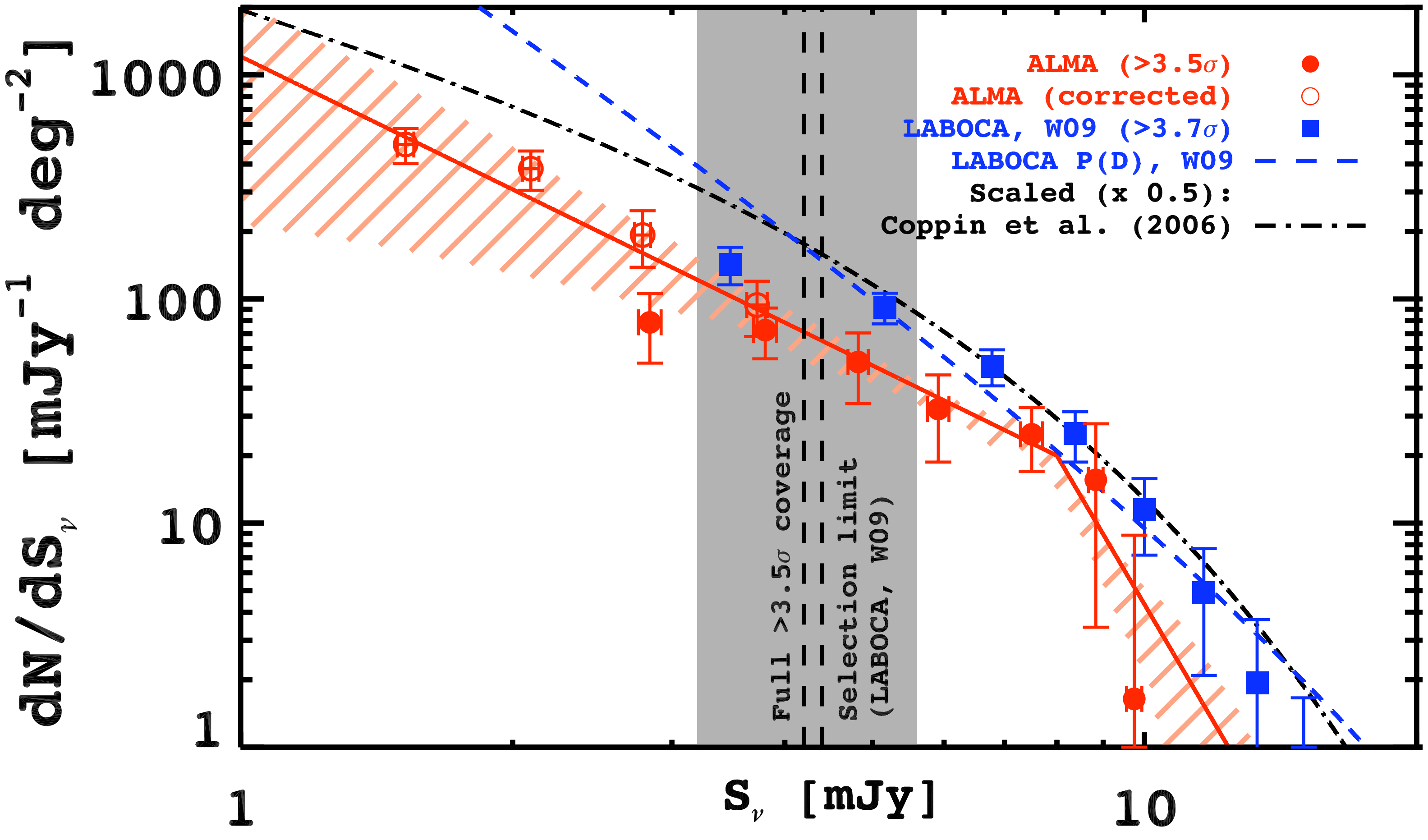
interferometer

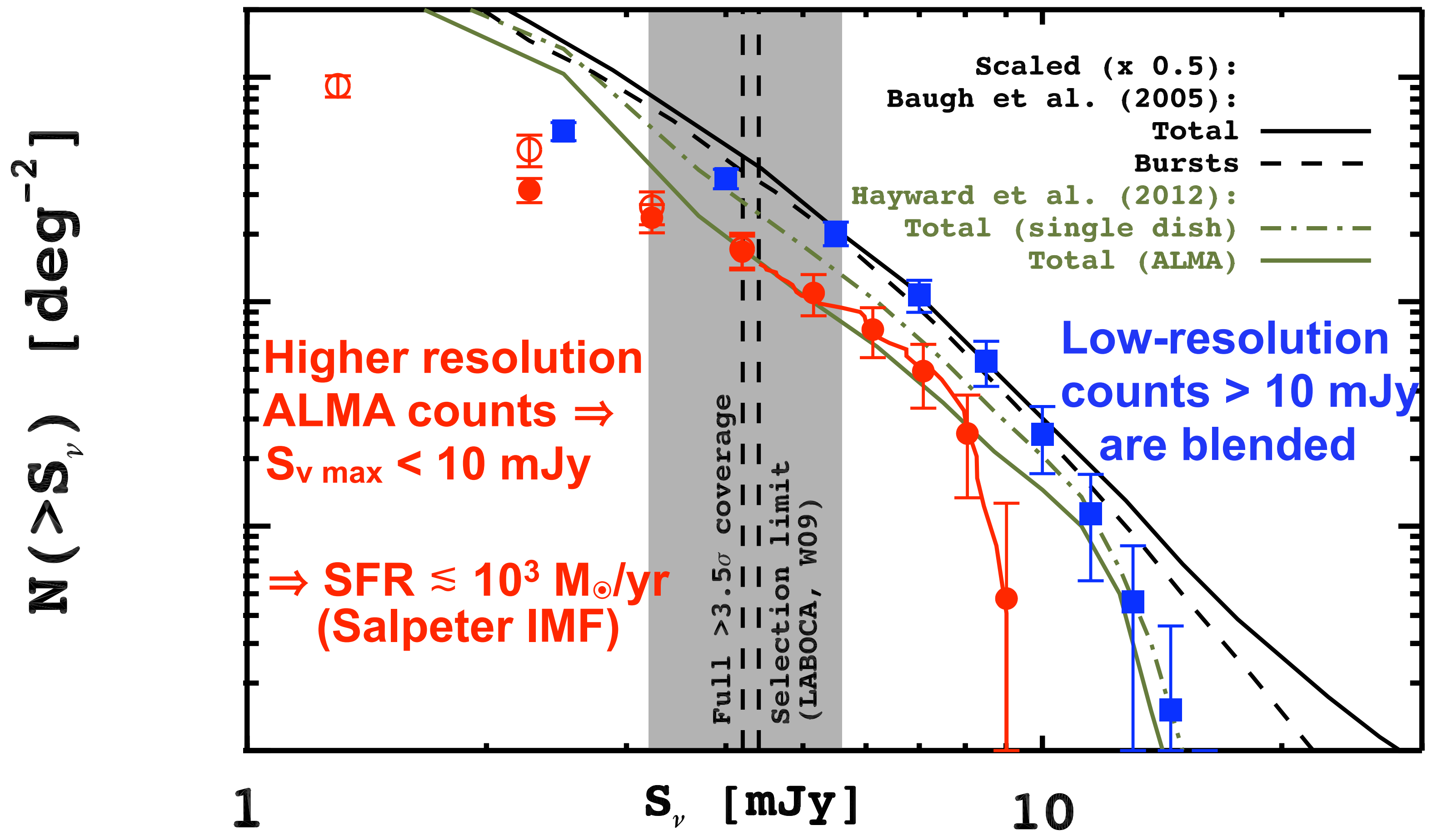


Karim+12

Recently directly confirmed by ALMA

ALMA Observations Compared with Theories





Higher resolution ALMA counts ⇒ $S_{\nu\,\max} < 10$ mJy

⇒ SFR ≲ 10^3 $M_\odot$/yr (Salpeter IMF)

Low-resolution counts > 10 mJy are blended

An ALMA survey of submillimetre galaxies in the Extended Chandra Deep Field South: High resolution 870 μm source counts - Alex Karim et al. arXiv:1210.0249

Alex Karim: "it would be great if you could acknowledge our ALMA/ ECDFS survey (PI Ian Smail, essential Co-I's are Mark Swinbank, Fabian Walter, Jackie Hodge, myself and Axel Weiss (who led the LESS LABOCA parent survey) and refer to my paper as well as Hodge et al. (subm.) when showing our results."

Chris Hayward's recent papers:

How to distinguish starbursts and quiescently star-forming galaxies: the 'bimodal' submillimetre galaxy population as a case study
Christopher C. Hayward, Patrik Jonsson, Dusan Keres, Benjamin Magnelli, Lars Hernquist and T. J. Cox
Mon. Not. R. Astron. Soc. **424,** 951–970 (2012)

Submillimetre galaxies in a hierarchical universe: number counts, redshift distribution and implications for the IMF
Christopher C. Hayward, Desika Narayanan, Dusan Keres, Patrik Jonsson, Philip F. Hopkins, T. J. Cox, and Lars Hernquist
MNRAS **428,** 2529–2547 (2013)

From Chris Hayward's webpage

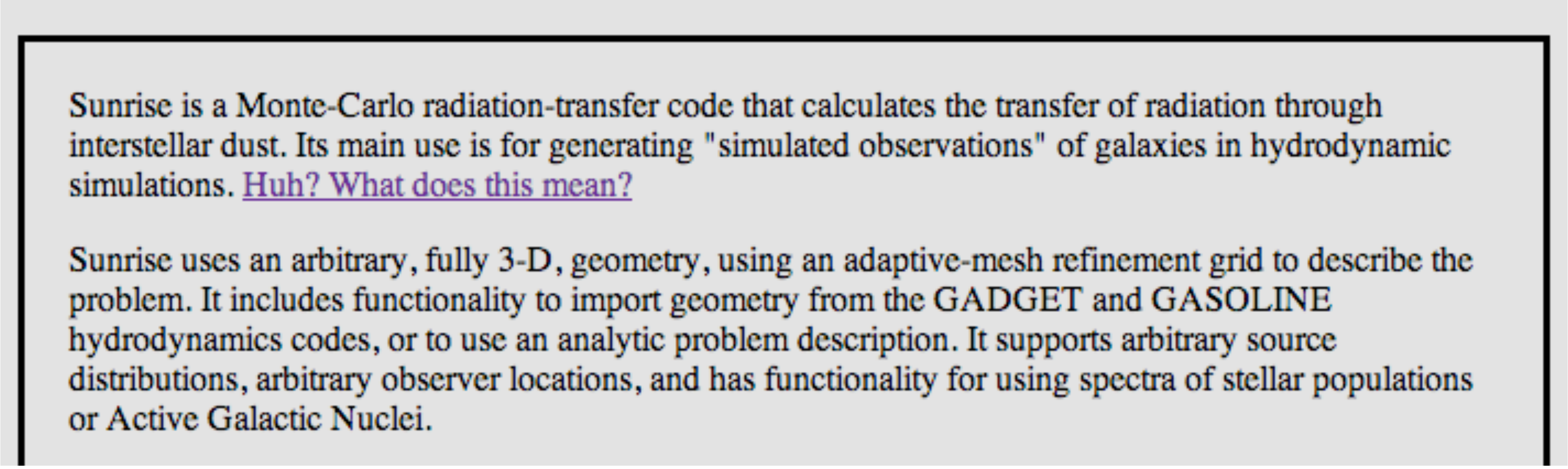
https://www.cfa.harvard.edu/~chayward/research.html

During the hydrodynamical simulations, I regularly save 'snapshots' of the simulated galaxies, typically every 10 million years. Then, I use these snapshots as input for the *Sunrise* 3-D Monte Carlo dust radiative transfer code. *Sunrise* first uses the metal density from the hydrodynamical simulations to determine the dust distribution in the galaxies, which it describes using an adaptive mesh. Then, spectral energy distributions (SEDs) are assigned to the star and black hole particles. After these steps are completed, the Monte Carlo radiative transfer is performed. This means that millions of 'photon packets' are propagated from the sources of radiation through the dusty ISM. The effects of dust absorption, scattering, and re-emission are calculated. The final output of the*Sunrise* calculation is UV-mm SEDs at every camera pixel for multiple viewing angles. To directly compare to observational data, we can use this output to produce monochromatic images in various filters, integrated SEDs and photometry, fiber or slit spectra, etc. For a simple description of*Sunrise*, see Patrik Jonsson's webpage.

Patrik Jonsson's webpage

http://www.familjenjonsson.org/patrik/sunrise

See also Jonsson's lectures at the 2010 HiPACC Summer School on Galaxy Simulations

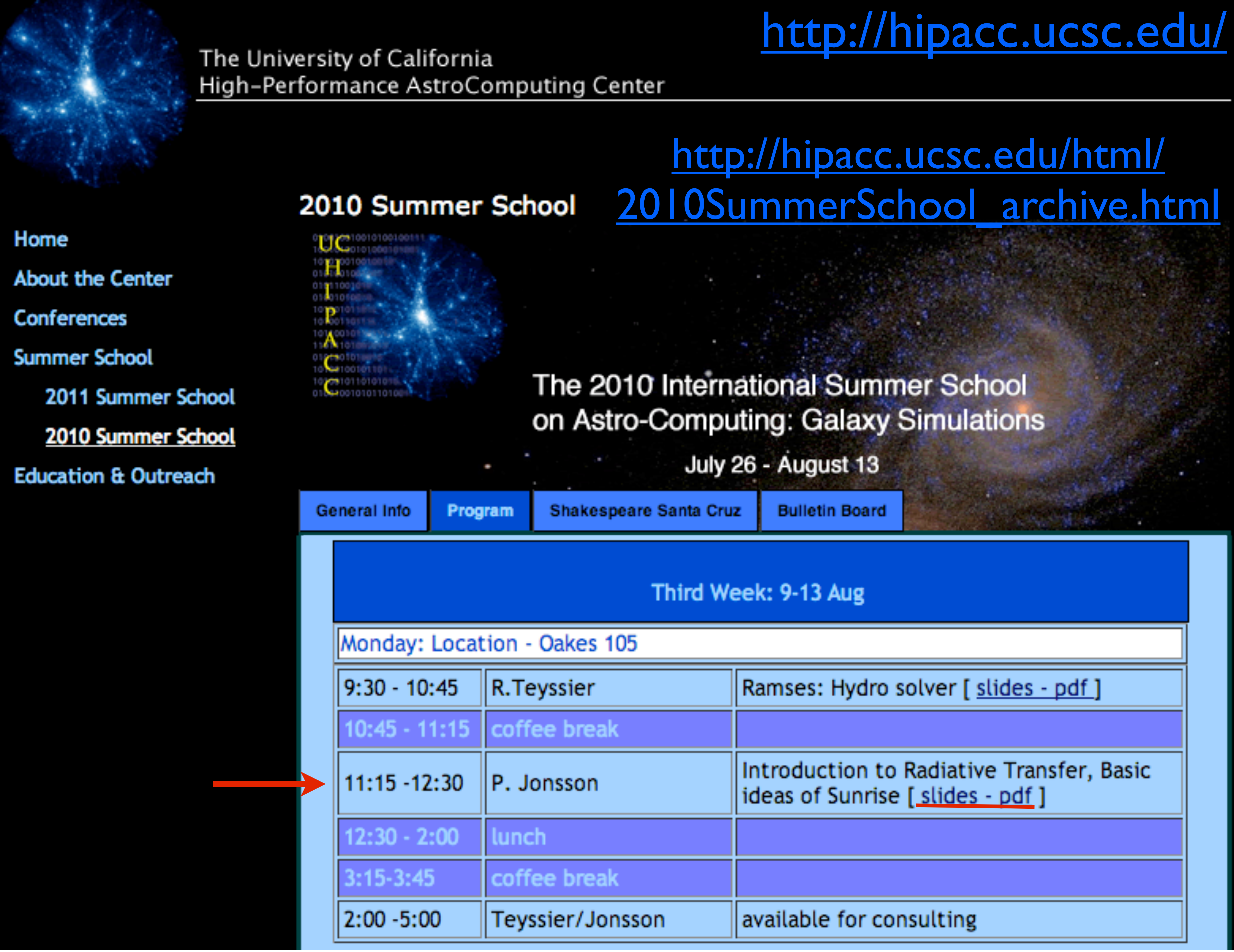


Sunrise is a Monte-Carlo radiation-transfer code that calculates the transfer of radiation through interstellar dust. Its main use is for generating "simulated observations" of galaxies in hydrodynamic simulations. Huh? What does this mean?

Sunrise uses an arbitrary, fully 3-D, geometry, using an adaptive-mesh refinement grid to describe the problem. It includes functionality to import geometry from the GADGET and GASOLINE hydrodynamics codes, or to use an analytic problem description. It supports arbitrary source distributions, arbitrary observer locations, and has functionality for using spectra of stellar populations or Active Galactic Nuclei.

http://hipacc.ucsc.edu/

http://hipacc.ucsc.edu/html/2010SummerSchool_archive.html



The University of California
High-Performance AstroComputing Center

2010 Summer School

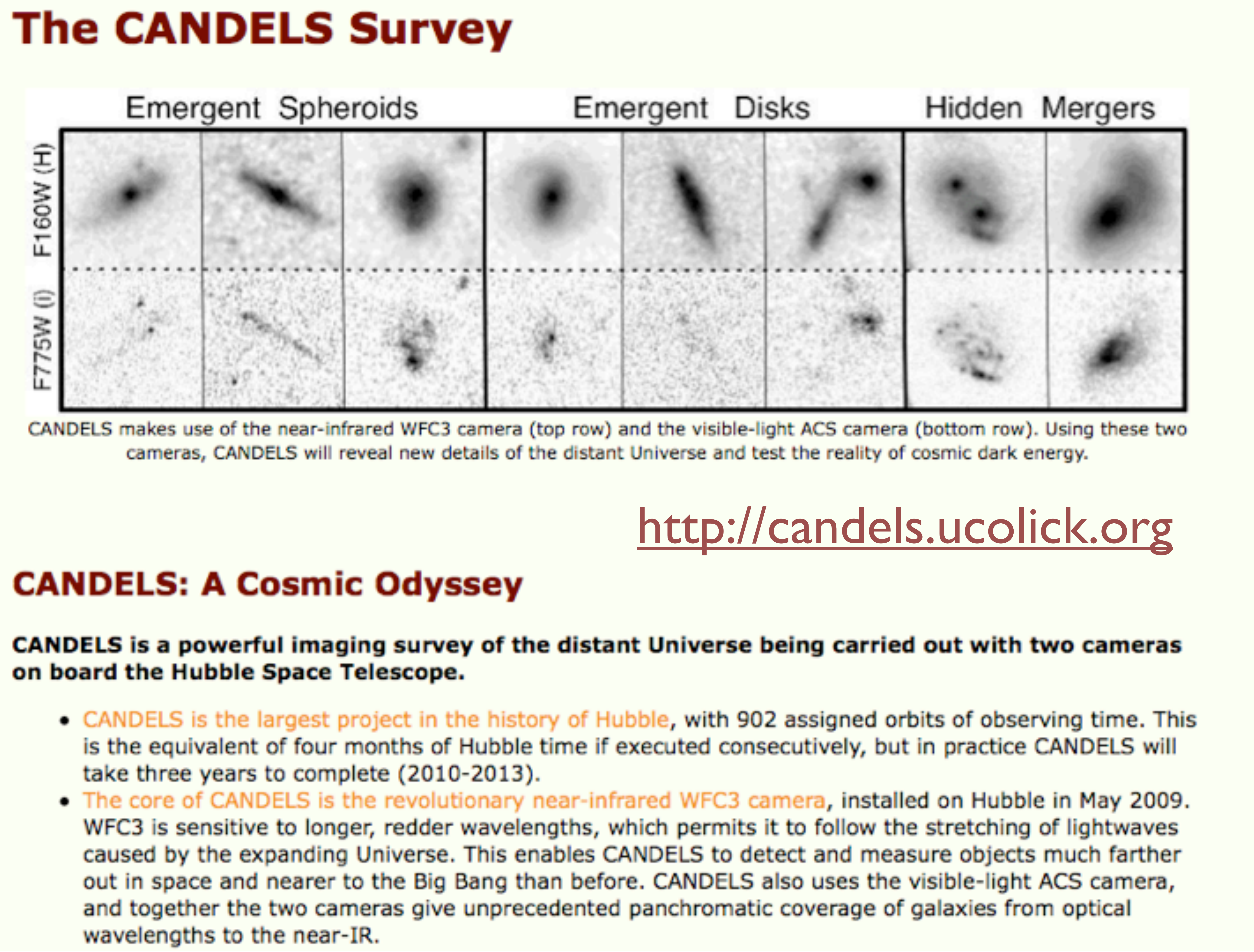
The 2010 International Summer School on Astro-Computing: Galaxy Simulations

July 26 - August 13

Third Week: 9-13 Aug

Monday: Location - Oakes 105

9:30 - 10:45	R.Teyssier	Ramses: Hydro solver [slides - pdf]
10:45 - 11:15	coffee break	
11:15 -12:30	P. Jonsson	Introduction to Radiative Transfer, Basic ideas of Sunrise [slides - pdf]
12:30 - 2:00	lunch	
3:15-3:45	coffee break	
2:00 -5:00	Teyssier/Jonsson	available for consulting



The CANDELS Survey

CANDELS makes use of the near-infrared WFC3 camera (top row) and the visible-light ACS camera (bottom row). Using these two cameras, CANDELS will reveal new details of the distant Universe and test the reality of cosmic dark energy.

http://candels.ucolick.org

CANDELS: A Cosmic Odyssey

CANDELS is a powerful imaging survey of the distant Universe being carried out with two cameras on board the Hubble Space Telescope.

- CANDELS is the largest project in the history of Hubble, with 902 assigned orbits of observing time. This is the equivalent of four months of Hubble time if executed consecutively, but in practice CANDELS will take three years to complete (2010-2013).
- The core of CANDELS is the revolutionary near-infrared WFC3 camera, installed on Hubble in May 2009. WFC3 is sensitive to longer, redder wavelengths, which permits it to follow the stretching of lightwaves caused by the expanding Universe. This enables CANDELS to detect and measure objects much farther out in space and nearer to the Big Bang than before. CANDELS also uses the visible-light ACS camera, and together the two cameras give unprecedented panchromatic coverage of galaxies from optical wavelengths to the near-IR.

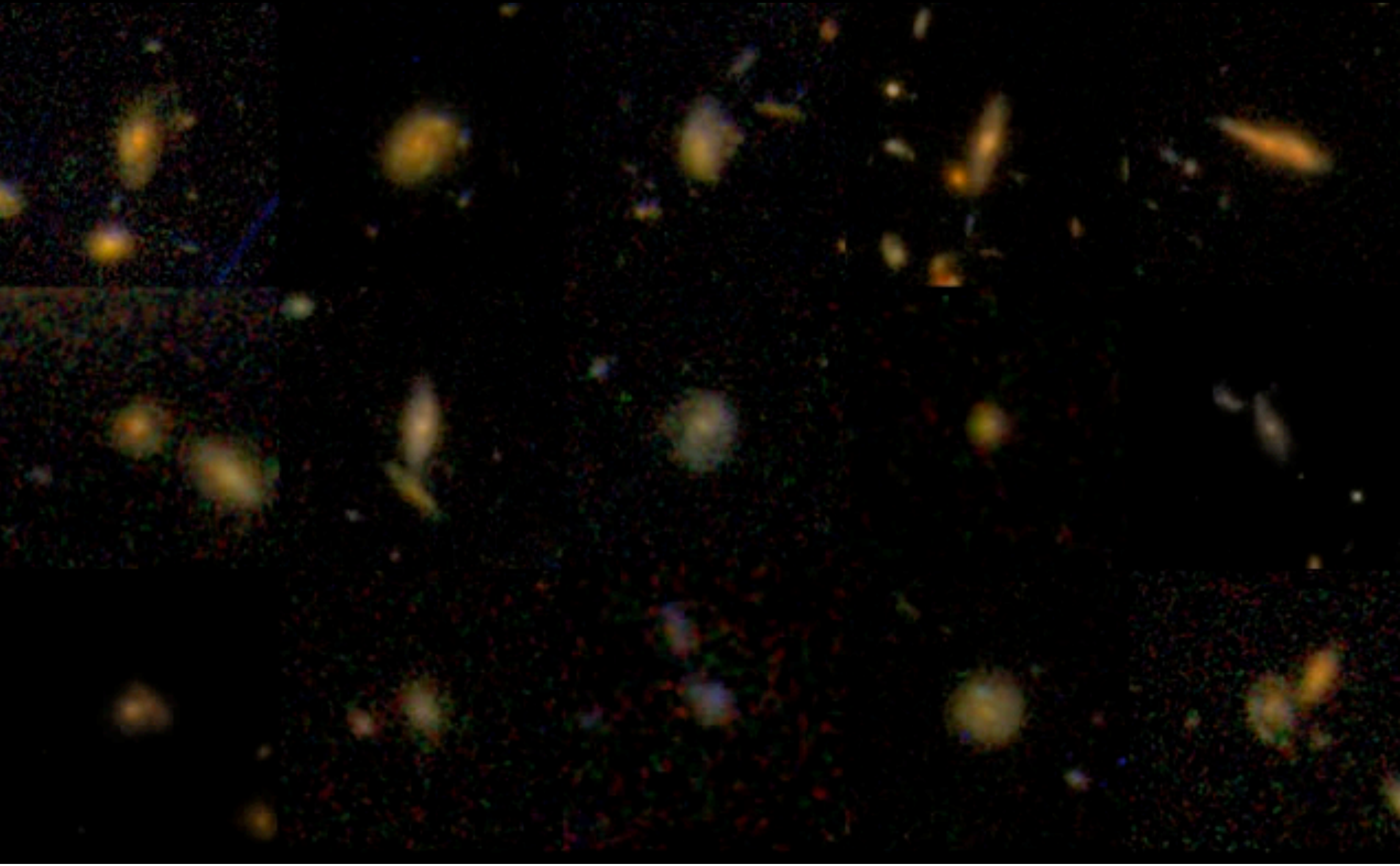
GALAXY ZOO meets CANDELS

For the original Galaxy Zoo project, over one hundred thousand volunteers signed up to classify nearly one million galaxies from the Sloan Digital Sky Survey (SDSS). These volunteers determined whether each of the galaxies was a spiral or an elliptical and if it was a spiral whether it was rotating clockwise, counter-clockwise, or viewed edge on. Galaxy mergers and image artifacts were also options that the classifiers could select. Not only did these citizen scientists quickly take to classifying galaxies, they had fun and learned a lot about galaxies in the process. The Galaxy Zoo webpage hosts a forum where volunteers can post about interesting objects they find and discuss their classifications. One of the exciting aspects of having all of these galaxies looked at individually was the ability to identify rare and unique objects that had not been seen before, such as Hanny's Voowerp. These classifications have provided an incredible data set for Galaxy Zoo scientists and a number of publications have resulted from this tremendous effort.

The Galaxy Zoo project was further expanded with the start of Galaxy Zoo 2, which included a much more detailed look at a subset of galaxies, and Galaxy Zoo Hubble, which asks volunteers to classify galaxies imaged with the Hubble Space Telescope in a number of deep fields. Last month, Galaxy Zoo relaunched in its latest incarnation and now includes reprocessed SDSS images along with HST images from CANDELS. These new images have been discussed in great detail on the Galaxy Zoo blog. This is a unique and exciting project for CANDELS because now galaxies at high redshift with near-infrared data will be classified alongside SDSS galaxies by many people to produce a fantastic data set of classifications.

CANDELS volunteers worked together closely with the Galaxy Zoo team to produce images for the website. Astronomers are used to analyzing images taken with a specific filter, or one very narrow portion of the spectrum. As such, these images are scientifically very useful, but we must look at images taken in different filters in order to study various galaxy properties. Beautiful color astronomical images of galaxies combine several of these filters together. In the CANDELS images being given to Galaxy Zoo, visible colors are assigned to the different near-infrared filters. These images are thus false-colored, but these colors represent real physical properties. The pictures on the next slide highlight what some of these CANDELS galaxies look like in color as they are being classified by Galaxy Zoo volunteers.

A sampling of colorized CANDELS galaxies that are in the newly relaunched Galaxy Zoo



‘CANDELizing’ Simulations

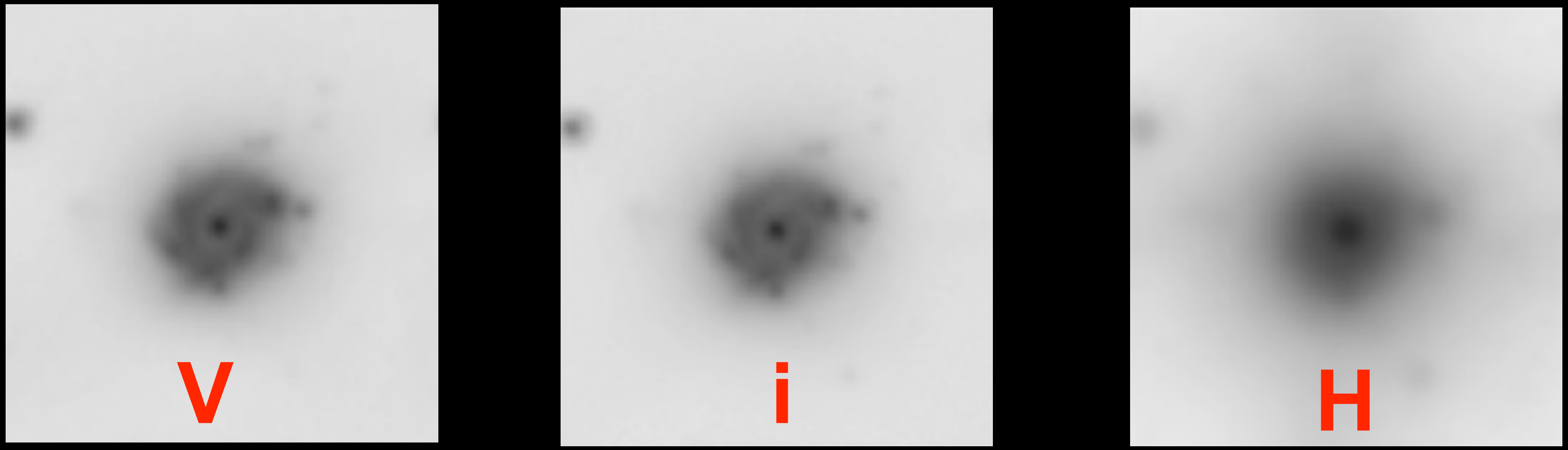
Mark Mozena (UCSC)

Run latest Hydro-ART simulations through SUNRISE

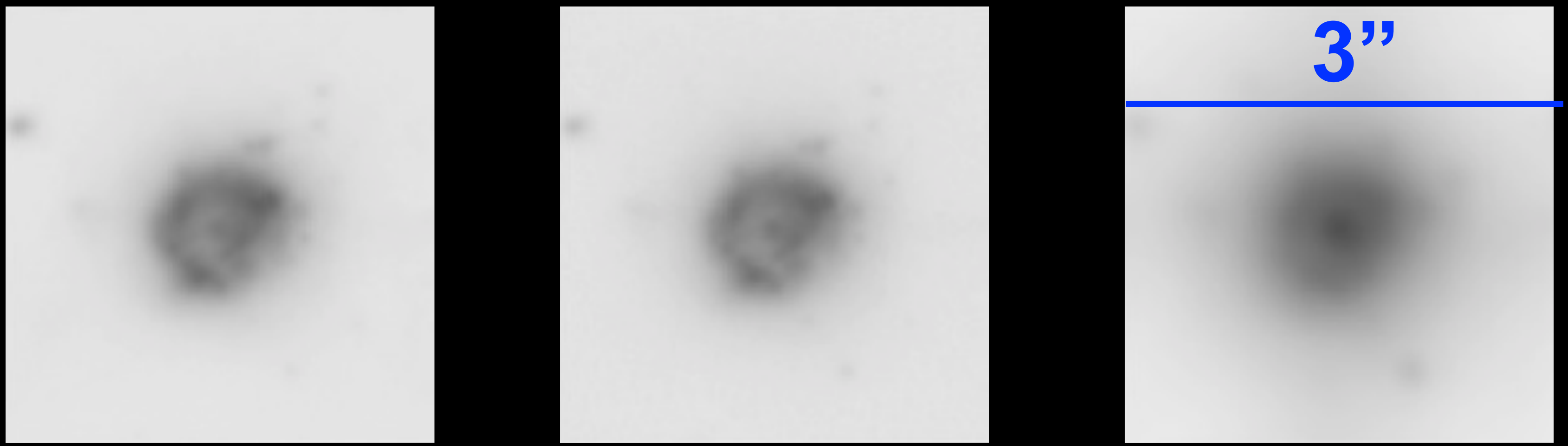
‘CANDELization’ process to reproduce noise, background, pixel scale, psf of observed galaxies

Send simulations through the same CANDELS pipeline to compare them to CANDELS galaxies

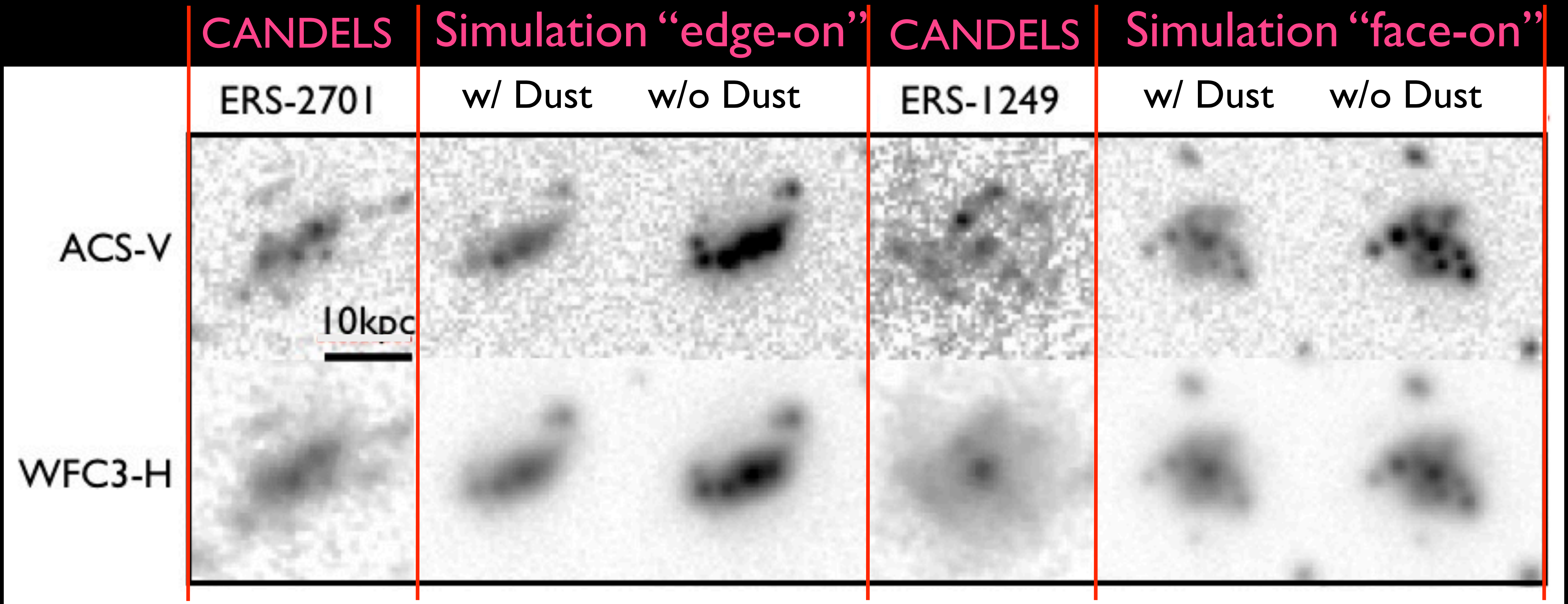
No dust



With dust (SUNRISE)



z~2.33 log(stellar mass) = 11.04



Simulation shown is MW3 at z=2.33 ‘imaged’ to match the CANDELS observations in ACS-Vband and WFC3-Hband

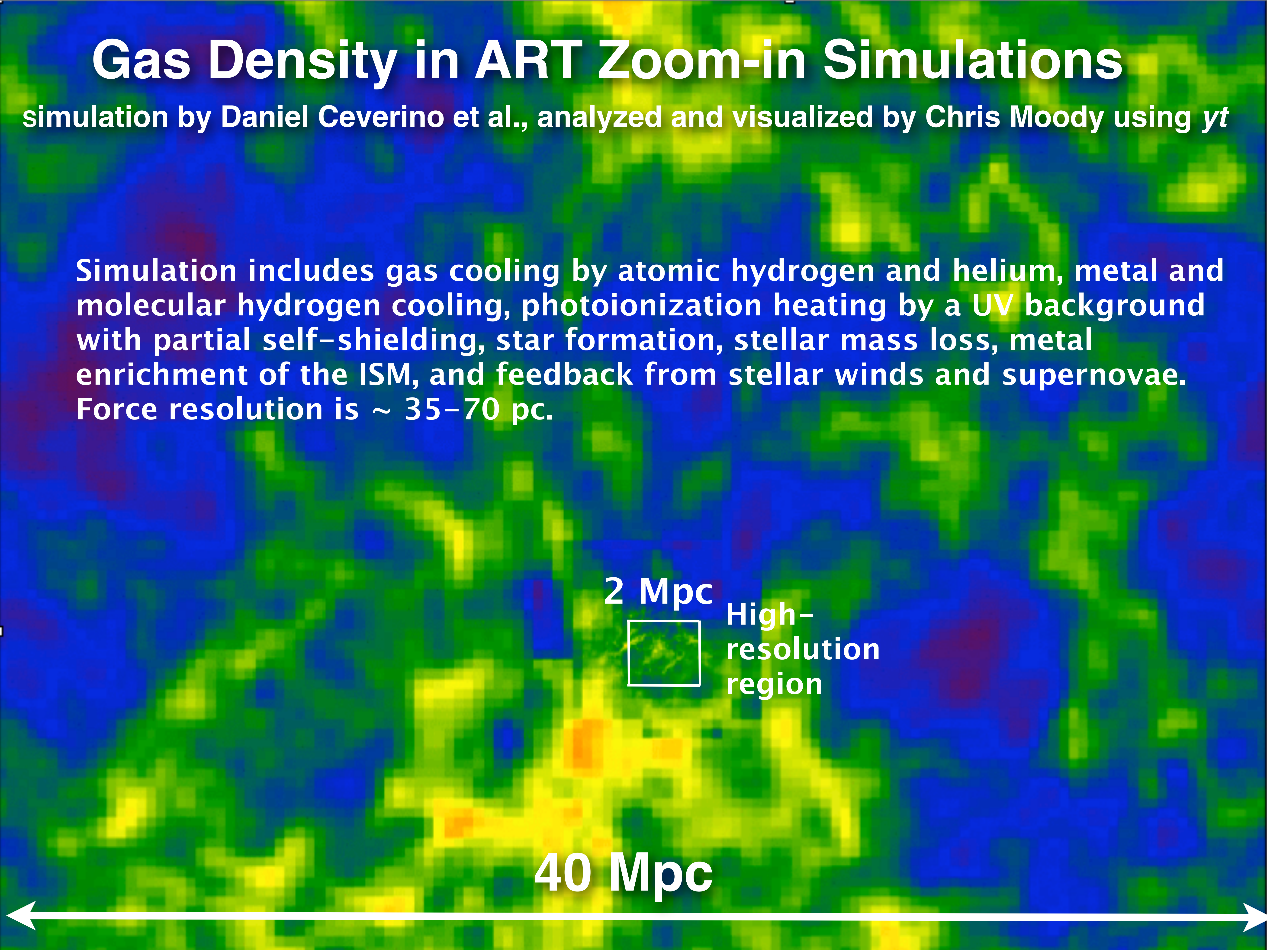
- 0.06” Pixel scale
- convolved with simulated PSFs
- noise and background derived from ERS observations (same field as examples shown)

MW3 was imaged at ‘face-on’ and ‘edge-on’ viewing angles both with and without including dust scattering, absorption, and re-emission

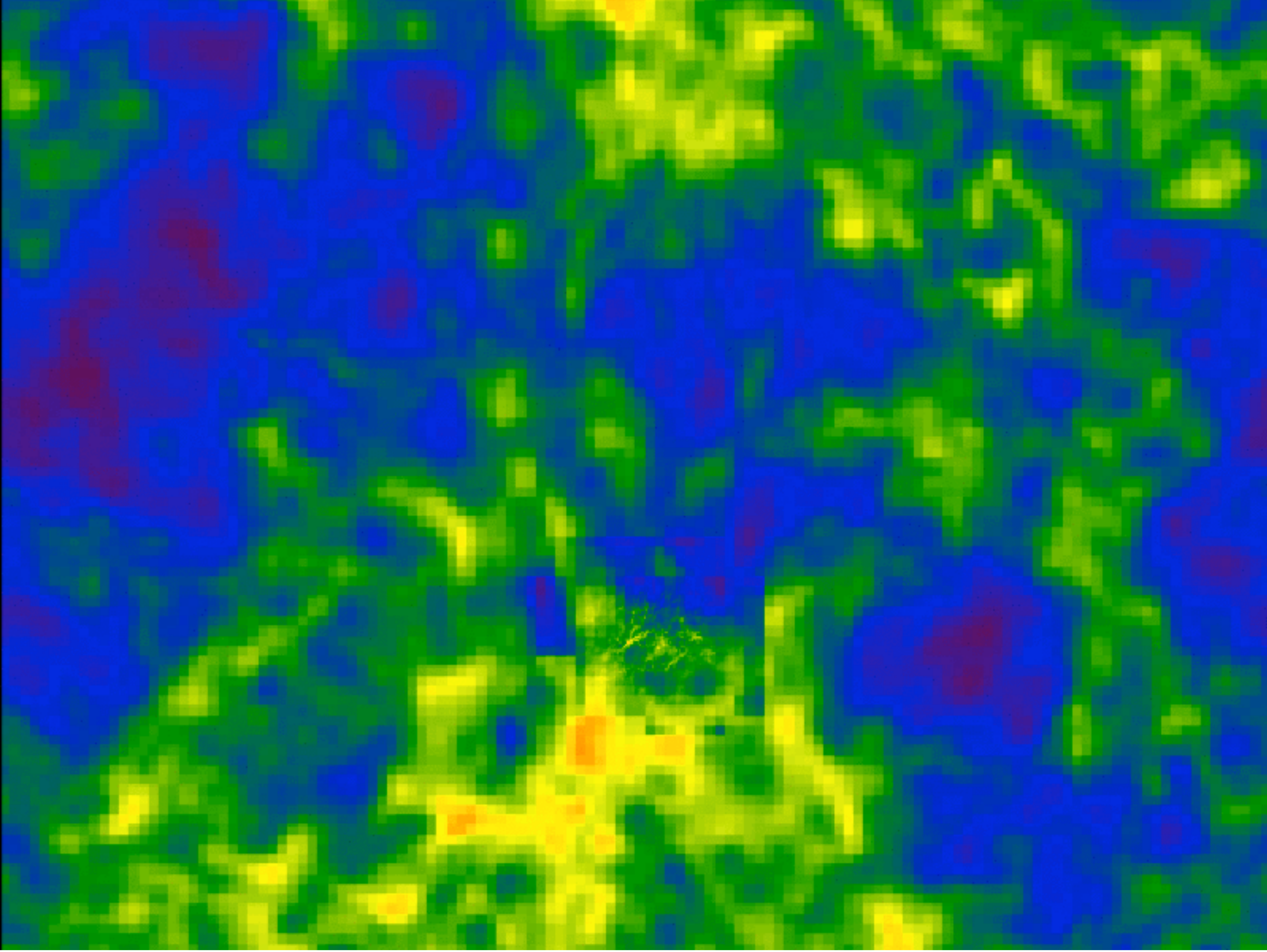
Mark Mozena (UCSC)

Gas Density in ART Zoom-in Simulations

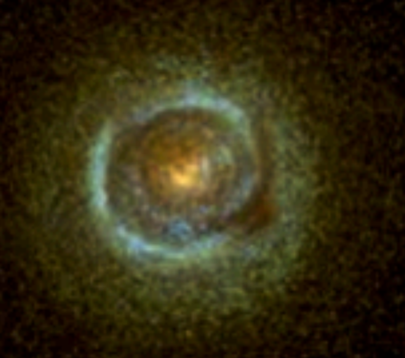
simulation by Daniel Ceverino et al., analyzed and visualized by Chris Moody using *yt*

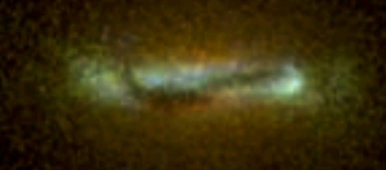


Simulation includes gas cooling by atomic hydrogen and helium, metal and molecular hydrogen cooling, photoionization heating by a UV background with partial self-shielding, star formation, stellar mass loss, metal enrichment of the ISM, and feedback from stellar winds and supernovae. Force resolution is ~ 35-70 pc.



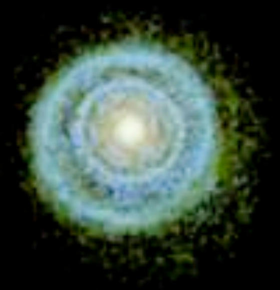
What's the effect of including dust?





with
dust

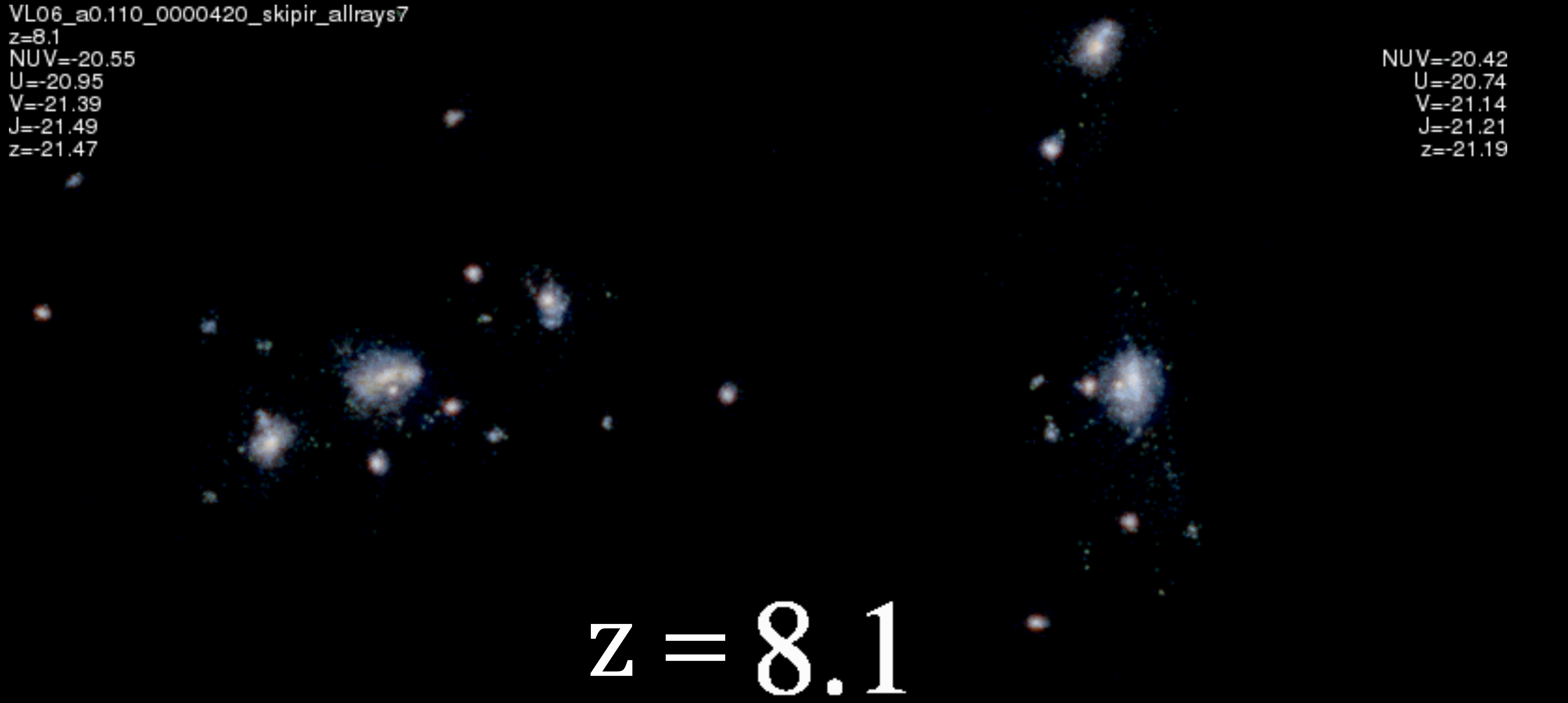
Dramatic effects on
- Appearance
- Half-mass radii (bigger with dust)
- Sersic index (lower with dust)



stars
only

cemoody.imgur.com

Ceverino+ VL6 Cosmological Zoom-in Simulation



Chris Moody

Assembly of Galaxies of Resolved Anatomy

AGORA

High-Resolution Hydrodynamic Galaxy Simulation Comparison Project

www.AGORAsimulations.org

The AGORA High-Resolution Galaxy Simulation Comparison Project: Rationale

Key Earlier Simulation Comparisons

The paper led by Carlos Frenk, “The **Santa Barbara Cluster Comparison Project**: A Comparison of Hydrodynamics Simulations,” ApJ, 525, 554 (1999), which grew out of a workshop at the KITP in Santa Barbara, has now received over 300 citations. A more recent galaxy simulation comparison project resulted in the paper led by Cecilia Scannapieco, “The **Aquila Comparison Project**: The Effects of Feedback and Numerical Methods on Simulations of Galaxy Formation” (MNRAS 2012). The simulations there mostly used the Gadget smooth-particle-hydrodynamics code, and they had typical force resolutions of ~1 kiloparsec, with dark matter particle masses larger than $10^6\ M^{\odot}$ and gas particle masses mostly larger than $0.4\text{x}10^6\ M^{\odot}$. The one adaptive mesh refinement code used for these simulations, RAMSES, was run with relatively poor force resolution of 260 pc and dark matter particle mass $0.2\text{x}10^6\ M^{\odot}$. At these resolutions, all the key physics of star formation and feedback is sub-grid. There were large code-to-code variations in the size, morphology, and stellar and gas masses of the simulated galaxies started from the same initial conditions, and rather poor agreement with observed galaxies. The success of recent higher-resolution simulations such as **Eris** (Javiera Guedes, Simone Gallegari, Piero Madau, & Lucio Mayer 2011, ApJ, 742, 76) in matching observed galaxies encourages us to hope for progress with the high-resolution simulations.

The Aquila comparison Project: The Effects of Feedback and Numerical Methods on Simulations of Galaxy Formation

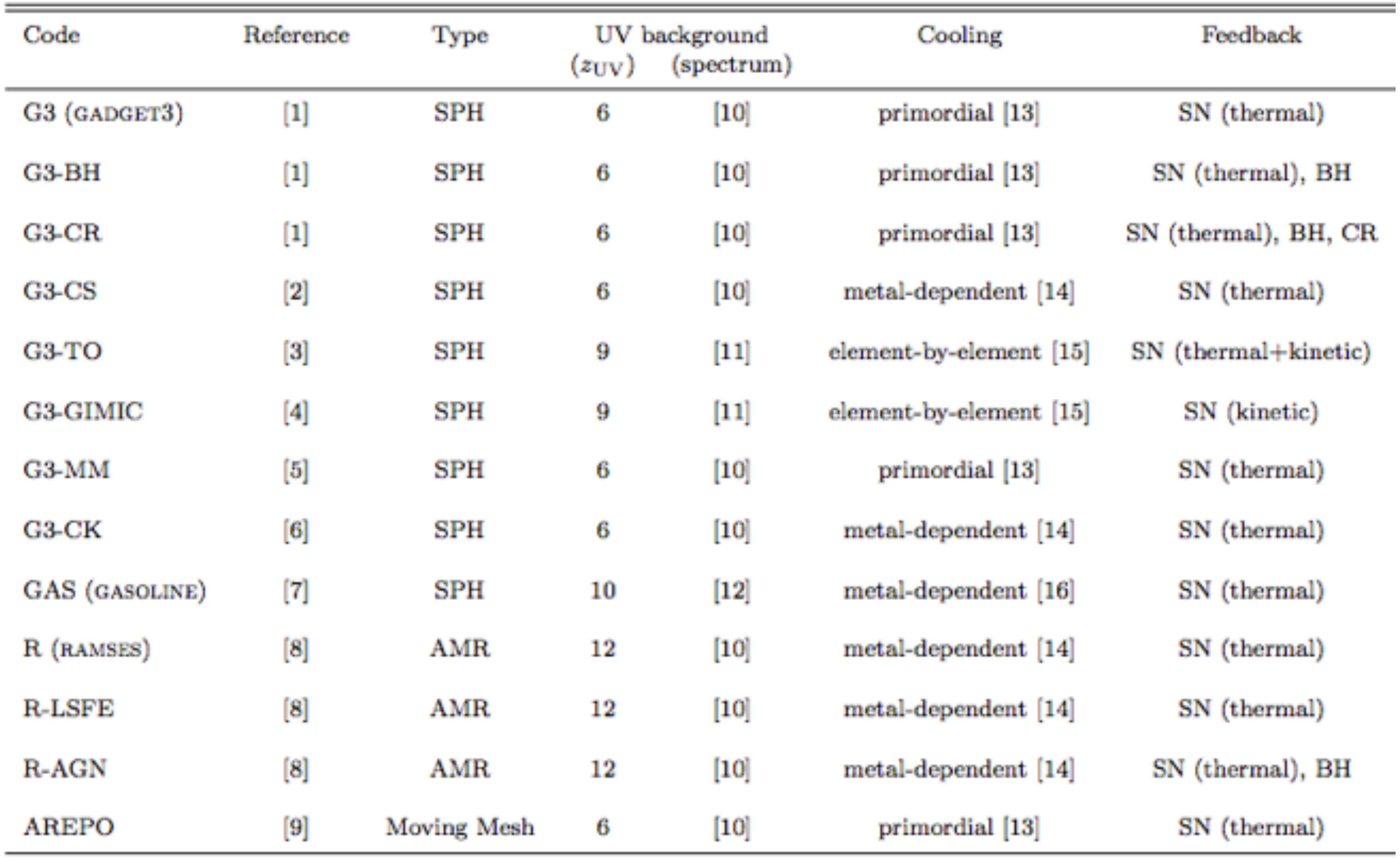
C. Scannapieco,[1] M. Wadepuhl,[2] O.H. Parry,[3,4] J.F. Navarro,[5] A. Jenkins,[3] V. Springel,[6,7] R. Teyssier,[8,9] E. Carlson,[10] H.M.P. Couchman,[11]
R.A. Crain,[12,13] C. Dalla Vecchia,[14] C.S. Frenk,[3] C. Kobayashi,[15,16] P. Monaco,[17,18] G. Murante,[17,19] T. Okamoto,[20] T. Quinn,[10] J. Schaye,[13]
G. S. Stinson,[21] T. Theuns,[3,22] J. Wadsley,[11] S.D.M. White,[2] R. Woods[11]

2012 MNRAS 423, 1726

ABSTRACT

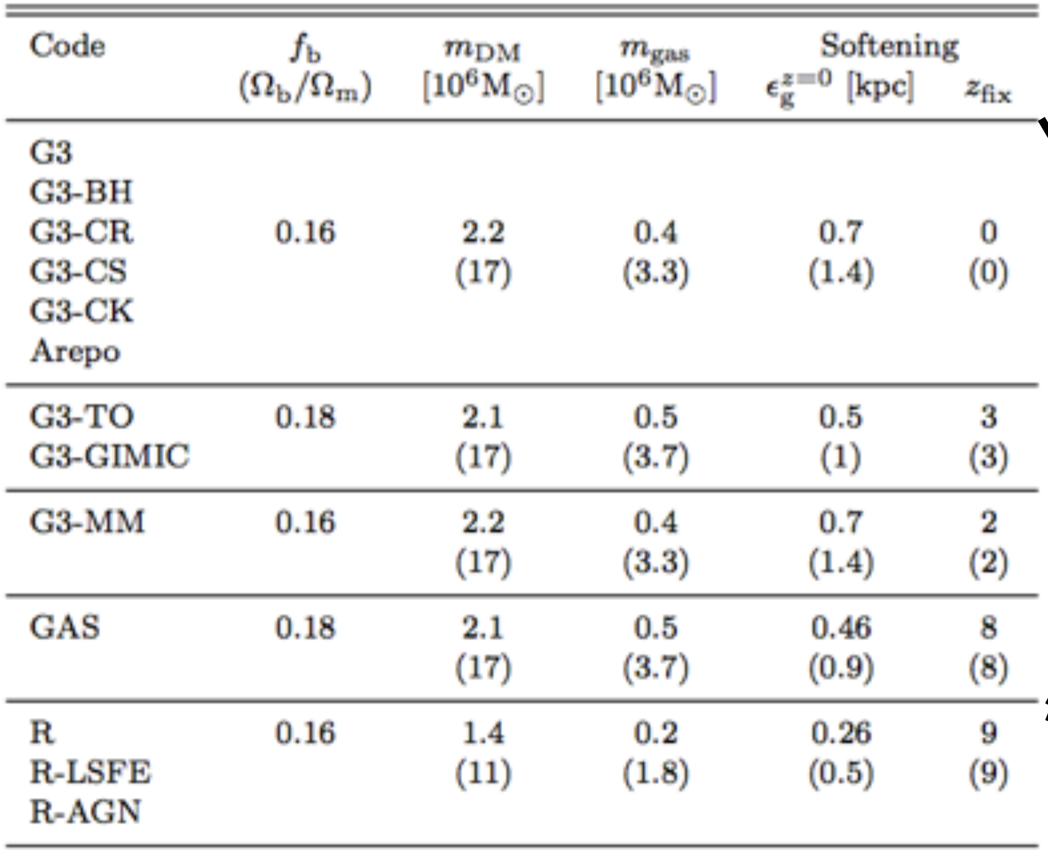
We compare the results of various cosmological gas-dynamical codes used to simulate the formation of a galaxy in the ΛCDM structure formation paradigm. **The various runs** (thirteen in total) differ in their numerical hydrodynamical treatment (SPH, moving-mesh and AMR) but **share the same initial conditions and adopt in each case their latest published model of gas cooling, star formation and feedback.** Despite the common halo assembly history, **we find large code-to-code variations in the stellar mass, size, morphology and gas content of the galaxy at z = 0, due mainly to the different implementations of star formation and feedback**. Compared with observation, **most codes tend to produce an overly massive galaxy, smaller and less gas-rich than typical spirals, with a massive bulge and a declining rotation curve**. A stellar disk is discernible in most simulations, although its prominence varies widely from code to code. There is a well-defined trend between the effects of feedback and the severity of the disagreement with observed spirals. In general, **models that are more effective at limiting the baryonic mass of the galaxy come closer to matching observed galaxy scaling laws, but often to the detriment of the disk component.** Although numerical convergence is not particularly good for any of the codes, our conclusions hold at two different numerical resolutions. Some differences can also be traced to the different numerical techniques; for example, more gas seems able to cool and become available for star formation in grid-based codes than in SPH. However, this effect is small compared to the variations induced by different feedback prescriptions. **We conclude that state-of-the-art simulations cannot yet uniquely predict the properties of the baryonic component of a galaxy, even when the assembly history of its host halo is fully specified. Developing feedback algorithms that can effectively regulate the mass of a galaxy without hindering the formation of high-angular momentum stellar disks remains a challenge.**

The Aquila Comparison Project



Code	Reference	Type	UV background (z_{UV})	(spectrum)	Cooling	Feedback
G3 (GADGET3)	[1]	SPH	6	[10]	primordial [13]	SN (thermal)
G3-BH	[1]	SPH	6	[10]	primordial [13]	SN (thermal), BH
G3-CR	[1]	SPH	6	[10]	primordial [13]	SN (thermal), BH, CR
G3-CS	[2]	SPH	6	[10]	metal-dependent [14]	SN (thermal)
G3-TO	[3]	SPH	9	[11]	element-by-element [15]	SN (thermal+kinetic)
G3-GIMIC	[4]	SPH	9	[11]	element-by-element [15]	SN (kinetic)
G3-MM	[5]	SPH	6	[10]	primordial [13]	SN (thermal)
G3-CK	[6]	SPH	6	[10]	metal-dependent [14]	SN (thermal)
GAS (GASOLINE)	[7]	SPH	10	[12]	metal-dependent [16]	SN (thermal)
R (RAMSES)	[8]	AMR	12	[10]	metal-dependent [14]	SN (thermal)
R-LSFE	[8]	AMR	12	[10]	metal-dependent [14]	SN (thermal)
R-AGN	[8]	AMR	12	[10]	metal-dependent [14]	SN (thermal), BH
AREPO	[9]	Moving Mesh	6	[10]	primordial [13]	SN (thermal)

All simulations share the same initial conditions (ICs), a zoomed-in resimulation of one of the halos of the Aquarius Project (halo “Aq-C”, in the notation of Springel et al. 2008).



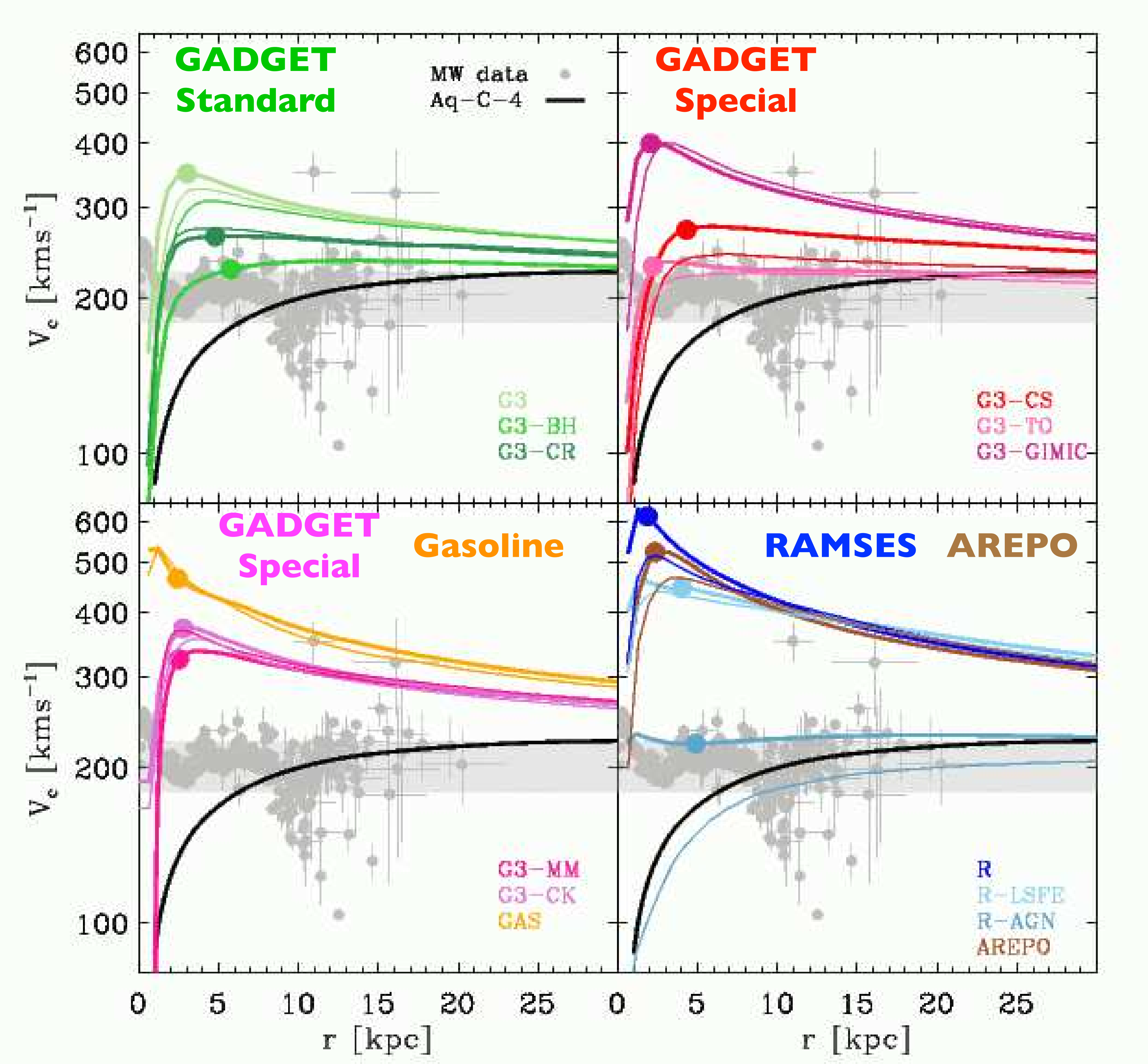
Code	f_b (Ω_b/Ω_m)	m_{DM} [$10^6 M_\odot$]	m_{gas} [$10^6 M_\odot$]	Softening $\epsilon_g^{z=0}$ [kpc]	z_{fix}
G3 G3-BH G3-CR G3-CS G3-CK Arepo	0.16	2.2 (17)	0.4 (3.3)	0.7 (1.4)	0 (0)
G3-TO G3-GIMIC	0.18	2.1 (17)	0.5 (3.7)	0.5 (1)	3 (3)
G3-MM	0.16	2.2 (17)	0.4 (3.3)	0.7 (1.4)	2 (2)
GAS	0.18	2.1 (17)	0.5 (3.7)	0.46 (0.9)	8 (8)
R R-LSFE R-AGN	0.16	1.4 (11)	0.2 (1.8)	0.26 (0.5)	9 (9)

Most stars form in galactic disks, so realistic simulations should resolve disks. The scale height of the MWy disk is about 100 pc. It’s better yet to resolve GMCs, 10s of pc.

Softening is 500 pc or worse (fixed in comoving coordinates at $z = z_{fix}$).

Softening is 260 pc (fixed in comoving coordinates at $z_{fix} = 9$)

Aquila Comparison Project Rotation Curves - Scannapieco+2012



Wednesday, January 9, 13

University of California
High-Performance
AstroComputing Center
(UC-HiPACC)
Joel Primack, Director

University of California
Santa Cruz
Next Telescope Science
Institute (NEXSI)
Piero Madau, Director

AGORA High-Resolution Galaxy Simulation Comparison Project Steering Committee

Piero Madau & Joel R. Primack, UCSC, Co-Chairs
Tom Abel, Stanford
Nick Gnedin, Chicago/Fermilab
Lucio Mayer, University of Zurich
Romain Teyssier, Saclay & Zurich
James Wadsley, McMaster

Ji-hoon Kim, UCSC (Coordinator)

https://sites.google.com/site/santacruzcomparisonproject/

http://www.agorasimulations.org

Project AGORA: High-resolution Galaxy Simulation Comparison

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Sister Workshop

Home

Welcome to Project AGORA: Assembling Galaxies Of Resolved Anatomy! We investigate galaxy formation with high-resolution numerical simulations and compare the results across different platforms, and with observation. Learn what we plan to do by visiting Project Details. We welcome any group or person interested in participating in the project.

We are happy to announce that the Starting Workshop to launch the project was a great success (Aug. 17-19, 2012, UC Santa Cruz). For the consensus reached during the workshop and the working groups formed, please visit here. Please do not hesitate to contact us if you would like to join us or have any question!

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Posted Nov 21, 2012 10:19 PM by Ji-hoon Kim

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Posted Nov 16, 2012 9:54 PM by Ji-hoon Kim

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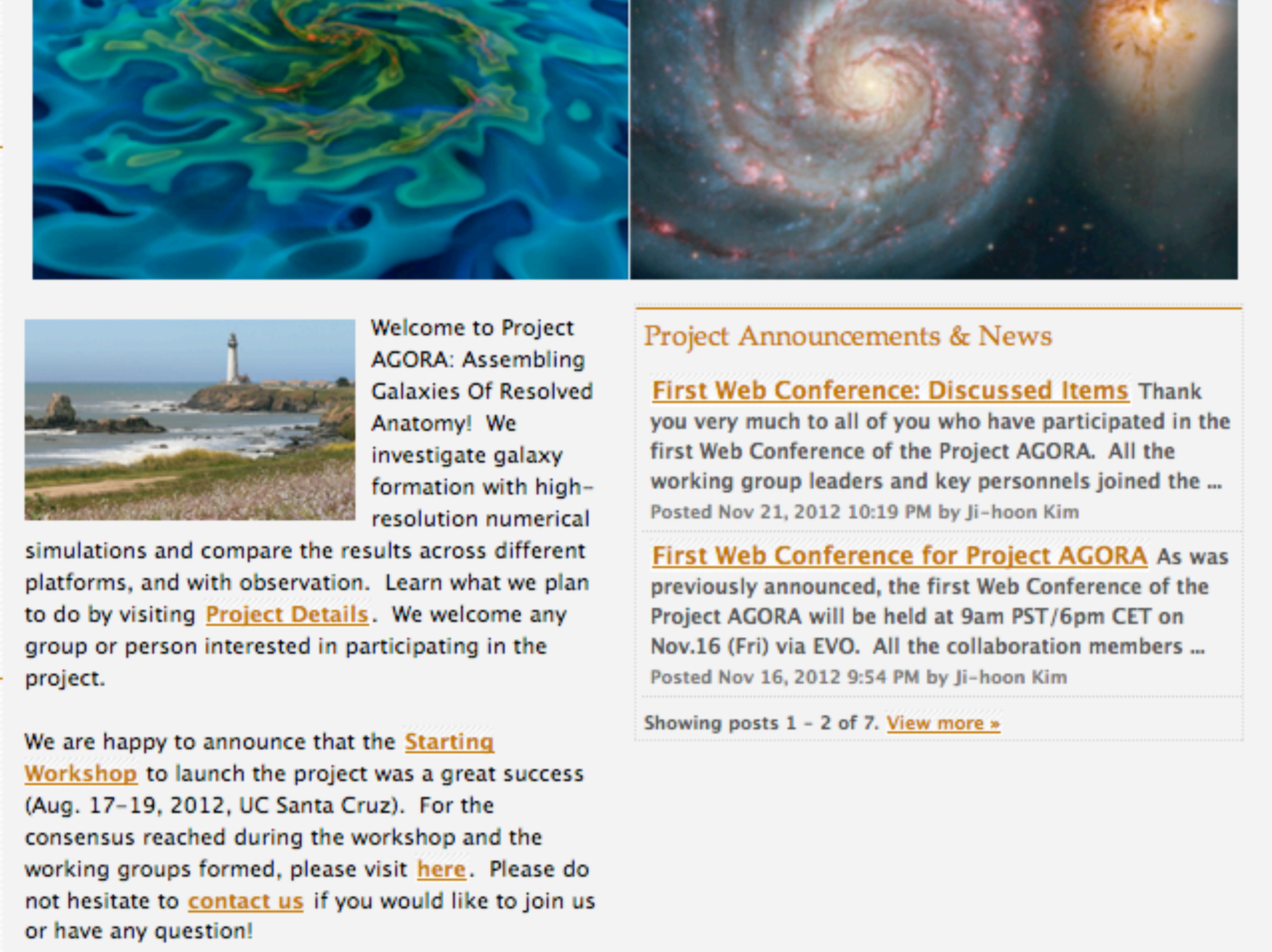

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AGORA Goals

(1) Inaugurate a set of frameworks for comparing high-resolution galaxy simulations (with resolution better than 100 parsecs) across different high-resolution numerical platforms

(2) Establish isolated and cosmological initial conditions so each participating group can run a suite of simulations

(3) Maintain the collaboration online (telecon+webpage) between the in-person meetings

(4) Objectives: produce a set of comparison papers by ~ the end of year 2013

Starting Workshop Results

The **Starting Workshop** of the High-Resolution Galaxy Simulation Comparison (UCSC, Aug. 17-19, 2012) was a success. Most of the main high-resolution simulation codes in the world were represented (in many cases by their leaders), people acted very constructively, and we were able to reach consensus on a wide variety of key issues including initial conditions for cosmological and isolated disk simulations (including separation criteria for the cosmological ICs), ultraviolet background and cooling functions, and common analysis tools (mainly yt - which also serves as input for *Sunrise*).

People have signed up to be key contacts for all the simulation groups, topics of several major papers to be produced by this project were agreed on with at least one person tentatively agreeing to take charge of each, and the first of our follow-up web conferences was Nov. 16 (Fri) at 9am PST, noon EST, and 6pm in Europe; it was well attended.

It is remarkable that we are launching this project at the time when several key technologies have just become available including the simulation codes, the MUlti-Scale Initial Conditions generator (MUSIC) for setting up the simulations, and the yt code for analyzing the outputs from all the simulations in a parallel way. This project will be state-of-the-art, and it will surely advance the entire field of galaxy simulations.

AGORA High-Resolution Simulation Comparison

Initial Conditions for Simulations

MUSIC galaxy masses at *z*~0: ~10^{10}, 10^{11}, 10^{12}, 10^{13} $M_\odot$

with both quiet and busy merging trees

isolation criteria agreed for Lagrangian regions

Isolated Spiral Galaxy at z~1, M ~ 10^{10}, 10^{11}, 10^{12} $M_\odot$

Astrophysics that all groups will include

UV background (Haardt-Madau 2012)

cooling function (based on ENZO and Eris cooling)

Tools to compare simulations based on *yt*, available for all codes used here (work in progress)

Images and SEDs for all timesteps from *yt* ➠ *Sunrise*

Goals of the Project

[1] **Each of the participating code groups is invited** (but not required) **to perform two different types of high-resolution galaxy formation simulations: isolated galaxy and cosmological zoom-in simulations.** These two types of simulations will be run and studied in parallel in the upcoming months. We will analyze and compare the results at several epochs and in multiple dimensions.

[2] **At the end we will go a step further to include comparisons with observational data.** We focus on science-based research, not just code-based comparison. We aim to use this project as a platform to launch many science-oriented studies of high-resolution galaxy simulations.

Point Persons for Participating Codes

CODE	Isolated Galaxy	Cosmological Zoom-in Galaxy
AREPO	Dusan Keres*, Volker Springel*	Dusan Keres, Volker Springel*
ART-NMSU	Sebastian Trujillo-Gomez	Daniel Ceverino
ART-Chicago	Sam Leitner	Sam Leitner
ENZO	Nathan Goldbaum, Ji-hoon Kim	John Wise
GADGET	Dusan Keres, Brant Robertson, Justin Read	Amit Kashi, Justin Read, Phil Hopkins
GADGET-SPHS	Justin Read	Justin Read
GASOLINE	James Wadsley, Lucio Mayer	Sijing Shen
Nyx	Wolfram Schmidt	Wolfram Schmidt
RAMSES	Oscar Agertz, Romain Teyssier	Oscar Agertz, Romain Teyssier

*To be confirmed

Working Groups

We have formed 13 working groups including eight science-oriented working groups primarily focused on performing original research by comparing simulations across different codes and with observations. Most of the Working Groups are led by postdocs.

Task-oriented Working Groups (I-IV)
Working Group I – **Common Physics and Introduction to Project**
Working Group II – **Common ICs: Isolated Low Redshift Disk Galaxy**
Working Group III – **Common ICs: Cosmological Zoom-In**
Working Group IV – **Common Analysis**

Science-oriented Working Groups (V-XIII)
Working Group V – **Isolated Galaxies and Subgrid Physics**
Working Group VI – **Dwarf Galaxies in Cosmological Simulations**
Working Group VII – **Dark Matter Issues**
Working Group VIII – **Satellite Galaxies**
Working Group IX – **Characteristics of Cosmological Galaxies**
Working Group X – **Outflows**
Working Group XI – **High-redshift Galaxies and Reionization**
Working Group XII – **Interstellar Medium**
Working Group XIII – **Black Hole Accretion and Feedback**

plus possible additional science working groups

AGORA Task Oriented Working Groups

To successfully commence the project and ensure the consistent comparison across different codes, four task-oriented working groups are formed. Participants listed below are in an alphabetical order and will be regularly updated according to the most recent results of the sign-up.

(1) Working Group I – Common Physics and Introduction to Project

– Task: Provide a common physics package for cosmological simulations, write a flagship paper introducing the comparison project and its rationale

– Leader: **Piero Madau**

– Participants: Tom Abel, Greg Bryan, Daniel Ceverino, Nick Gnedin, Oliver Hahn, Cameron Hummels, Ji-hoon Kim, Andrey Kravtsov, Mike Kuhlen, Piero Madau, Lucio Mayer, Daisuke Nagai, Ken Nagamine, Jose Onorbe, Brian O'Shea, Joel Primack, Tom Quinn, Brant Robertson, Sijing Shen, Britton Smith, Romain Teyssier, Matthew Turk, James Wadsley, [to be added]

– Description: We will provide a package of common physics for cosmological simulations. Participants to the Project will agree to a minimal set of common input parameters, from the initial stellar mass function to the metal yield, and to the ionizing ultraviolet background. Gas cooling tables as a function of density, temperature, metallicity, and UV background (or redshift) will be provided over the next six weeks or so to all Project participants for code implementation. We also aim to reach the first milestone of this project by publishing a flagship paper on a proposed comparison, common physics, and common analysis, in early 2013. [authored by Piero Madau]

...

(4) Working Group IV – Common Analysis

– Task: Develop a pipeline for common data analysis, write a research article introducing such analysis

– Leader: **Matthew Turk**

– Participants: Nathan Goldbaum, Cameron Hummels, Chris Moody, Daisuke Nagai, Jose Onorbe, Joel Primack, Britton Smith, Robert Thompson, Matthew Turk, [to be added]

– Description: This working group will focus on defining repeatable, quantitative and physically-meaningful comparisons of simulation results. Additionally, tools will be identified and developed to support making these comparisons. [authored by Matthew Turk]

AGORA Science Working Groups

In order to achieve the astrophysics-based comparison of high-resolution galaxy formation simulations, nine science-oriented working groups are formed. Each working group consists of individual volunteers from interested codes. Each group aims to perform original research based on its code comparison, and to produce a standalone journal article. The group leader is responsible for making every effort to initiate and maintain the collaboration within the working group, online and offline. Participants listed below are in an alphabetical order and will be regularly updated according to the most recent results of the sign-up.

(1) Working Group V – Isolated Galaxies and Subgrid Physics

- Science Question: Common vs. favorite physics in isolated galaxy formation simulations
- Leader: **Oscar Agertz** and **Romain Teyssier** (co-leadership)
- Participants: Oscar Agertz, Samantha Benincasa, Daniel Ceverino, Ben Keller, Nick Gnedin, Nathan Goldbaum, Javiera Guedes, Alexander Hobbs, Phil Hopkins, Amit Kashi, Ji-hoon Kim, Andrey Kravtsov, Sam Leitner, Nir Mandelker, Lucio Mayer, Ken Nagamine, Brian O'Shea, Joel Primack, Tom Quinn, Justin Read, Rok Roskar, Wolfram Schmidt, Sijing Shen, Robert Thompson, Dylan Tweed, James Wadsley, [to be added]

(2) Working Group VI – Dwarf Galaxies in Cosmological Simulations

- Science Question: Simulate and compare a 10^{10} M_{sun} galactic halo across *all* participating codes
- Leader: **Jose Onorbe**
- Participants: Kenza Arraki, Greg Bryan, Javiera Guedes, Jason Jaacks, Dusan Keres, Ji-hoon Kim, Mike Kuhlen, Ken Nagamine, Jose Onorbe, Brian O'Shea, Joel Primack, Justin Read, Emilio Romano-Diaz, Sijing Shen, Christine Simpson, Matteo Tomassetti, Sebastian Trujillo-Gomez, Dylan Tweed, John Wise, Adi Zolotov, [to be added]

(3) Working Group VII – Dark Matter

- Science Question: Dark matter profile, distribution, substructure, core-cusp problem, triaxiality, etc.
- Leader: **Mike Kuhlen**
- Participants: Javiera Guedes, Mike Boylan-Kolchin, Mike Kuhlen, Piero Madau, Annalisa Pillepich, Joel Prima
Justin Read, Miguel Rocha, [to be added]

(4) Working Group VIII – Satellite Galaxies

– Science Question: Environmental effects, UV background, tidal disruption, too-big-to-fail, etc.
– Leader: **Adi Zolotov**
– Participants: Javiera Guedes, Mike Boylan-Kolchin, Mike Kuhlen, Piero Madau, Lucio Mayer, Annalisa Pillepich, Joel Primack, Justin Read, Miguel Rocha, Christine Simpson, Adi Zolotov, [to be added]

(5) Working Group IX – Characteristics of Cosmological Galaxies

– Science Question: Surface brightness, disks, bulges, stellar properties, metallicity, images and SEDs generated by SUNRISE/yt, etc.
– Leader: **Javiera Guedes** and **Cameron Hummels** (co-leadership)
– Participants: Oscar Agertz, Daniel Ceverino, Maria Emilia De Rossi, Javiera Guedes, Cameron Hummels, Jason Jaacks, Dusan Keres, Andrey Kravtsov, Sam Leitner, Lucio Mayer, Daisuke Nagai, Ken Nagamine, Brian O'Shea, Joel Primack, Justin Read, Brant Robertson, Emilio Romano-Diaz, Rok Roskar, Sijing Shen, Britton Smith, Robert Thompson, Matteo Tomassetti, [to be added]

(6) Working Group X – Outflows

– Science Question: Galactic outflows, circum-galactic medium, metal absorption systems, the effect of AGN feedback, etc.
– Leader: **Sijing Shen**
– Participants: Greg Bryan, Daniel Ceverino, Colin DeGraf, Michele Fumagalli, Javiera Guedes, Alexander Hobbs, Phil Hopkins, Cameron Hummels, Amit Kashi, Dusan Keres, Sam Leitner, Piero Madau, Ken Nagamine, Justin Read, Wolfram Schmidt, Sijing Shen, Britton Smith, James Wadsley, [to be added]

(7) Working Group XI – High-redshift Galaxies

– Science Question: Cold flows, clumpiness, kinematics, Lyman-limit systems, etc.
– Leader: **Daniel Ceverino**
– Participants: Oscar Agertz, Daniel Ceverino, Maria Emilia De Rossi, Jan Engels, Michele Fumagalli, Nick Gnedin, Javiera Guedes, Jason Jaacks, Dusan Keres, Andrey Kravtsov, Mike Kuhlen, Sam Leitner, Piero Madau, Ken Nagamine, Brian O'Shea, Joel Primack, Brant Robertson, Emilio Romano-Diaz, Sijing Shen, Robert Thompson, Matteo Tomassetti, John Wise, [to be added]

(8) Working Group XII – Interstellar Medium

– Science Question: Interstellar medium, thermodynamics, etc.
– Leader: **Sam Leitner**
– Participants: Oscar Agertz, Daniel Ceverino, Charlotte Christensen, Nick Gnedin, Nathan Goldbaum, Cameron Hummels, Amit Kashi, Dusan Keres, Andrey Kravtsov, Sam Leitner, Piero Madau, Lucio Mayer, Ken Nagamine, Brian O'Shea, Brant Robertson, Emilio Romano-Diaz, Sijing Shen, Robert Thompson, Matteo Tomassetti, James Wadsley, [to be added]

(9) Working Group XIII – Black Hole Accretion and Feedback

– Science Question: Effect of black hole feeding and feedback on the evolution of galaxies (isolated and cosmological) across participating codes, etc.
– Leader: **Alexander Hobbs**
– Participants: Colin DeGraf, Alexander Hobbs, Phil Hopkins, Amit Kashi, Ben Keller, Lucio Mayer, Daisuke Nagai, Brian O'Shea, Justin Read, Romain Teyssier, [to be added]

(10) Tentative Working Group XIV – Lyman alpha absorption and emission

– Science Question: Lyman alpha absorption and emission predicted for simulated galaxies and their environments across participating codes including effects of radiative transfer, including associated metal lines, etc.
– Leader: Michele Fumagalli and Sebastiano Cantalupo (?)
– Participants: [to be added]

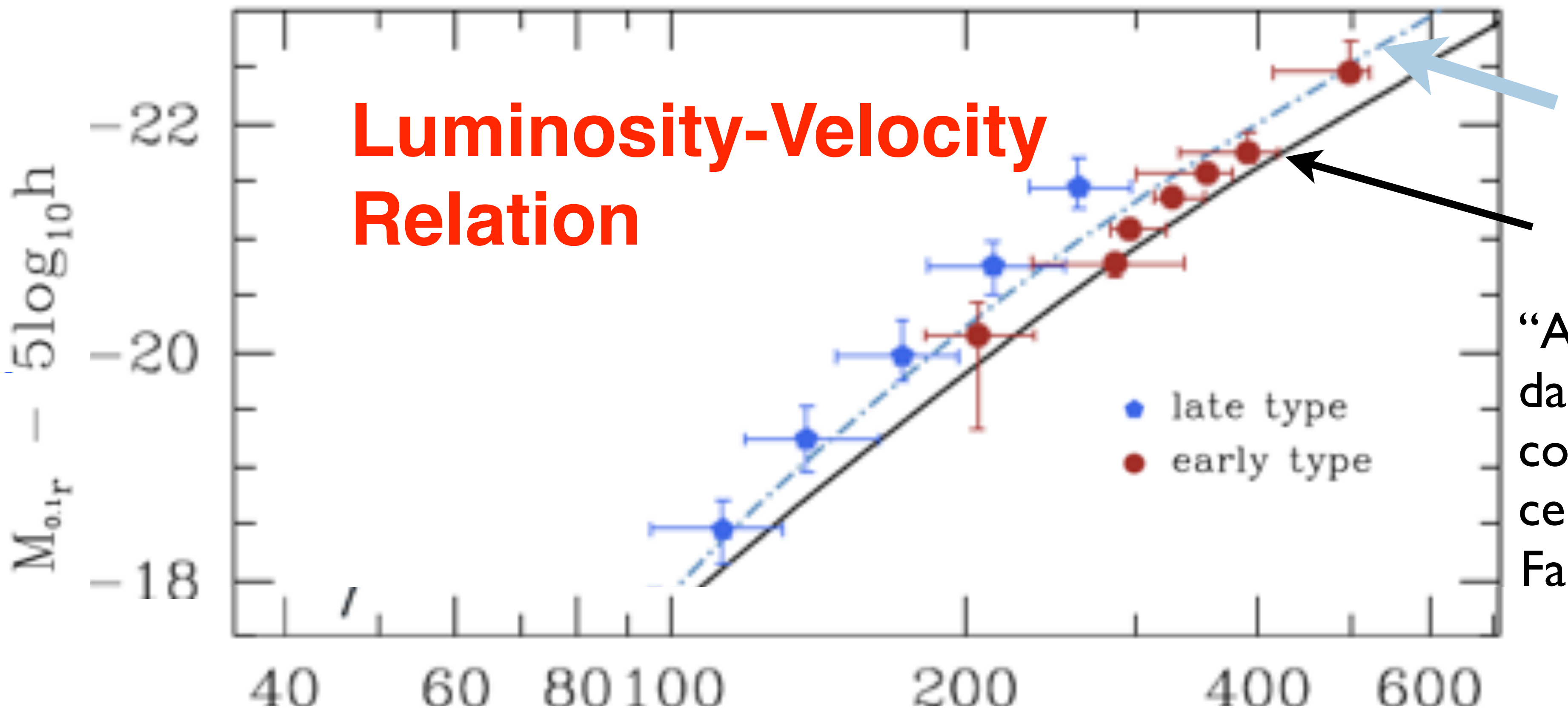
(11) Additional Working Groups – to be organized as needed

Online Collaboration

The leader of each working group is in charge of organizing the online collaboration via Google Sites, Skype, EVO-SeeVogh, etc. **One possible option is the newly-designed "Workspace" page on Google Sites.** In the new Workspace, each working group has its own page, and every registered collaboration member is granted a full access to read and write. This page may be used as a simplest option to share the data.

Examples of galaxy issues to be addressed by AGORA

- Feedback from SF and AGN - effects of different recipes, comparisons with observations such as SF efficiency and high-velocity outflows
- How to solve the too-high SF at high z in intermediate-mass galaxies?
- What quenches star formation in galaxies above a characteristic central density? Radio-mode FB? Cutoff of cold flows above $M_{halo} \sim 10^{12}\ M_\odot$? Environmental effects (satellite quenching)?
- Angular momentum differences between DM and gas, especially after cooling and SF/FB are included?
- Effects of baryons on dwarf galaxies: cusp removal, TBTF problem?
- Why is Adiabatic Contraction important for ETGs but not Spirals?


Luminosity-Velocity Relation

median Vcirc without AC

median Vcirc with AC

"AC" = Adiabatic Contraction of dark matter halos when baryons cool & condense to halo centers, following Blumenthal, Faber, Flores, & Primack 1986

AGORA High-Resolution Galaxy Simulation Comparison Project: Calendar

AGORA Kickoff Meeting: August 17-18-19, 2012, at UCSC

Roughly every two months: AGORA web conference
First web conf. Nov. 16, 2012; next Feb. 1, 2013 (tentatively); ...

Summer 2013:
UC-HiPACC Summer School on Star and Planet Formation
July 22 - August 9, at UCSC, directed by Mark Krumholz (more info http://hipacc.ucsc.edu/ISSAC2013.html - applications due March 16)
Santa Cruz Galaxy Workshop - August 12-16 (by invitation - contact Avishai Dekel or Joel Primack)

AGORA Conference August 19-23 at UCSC