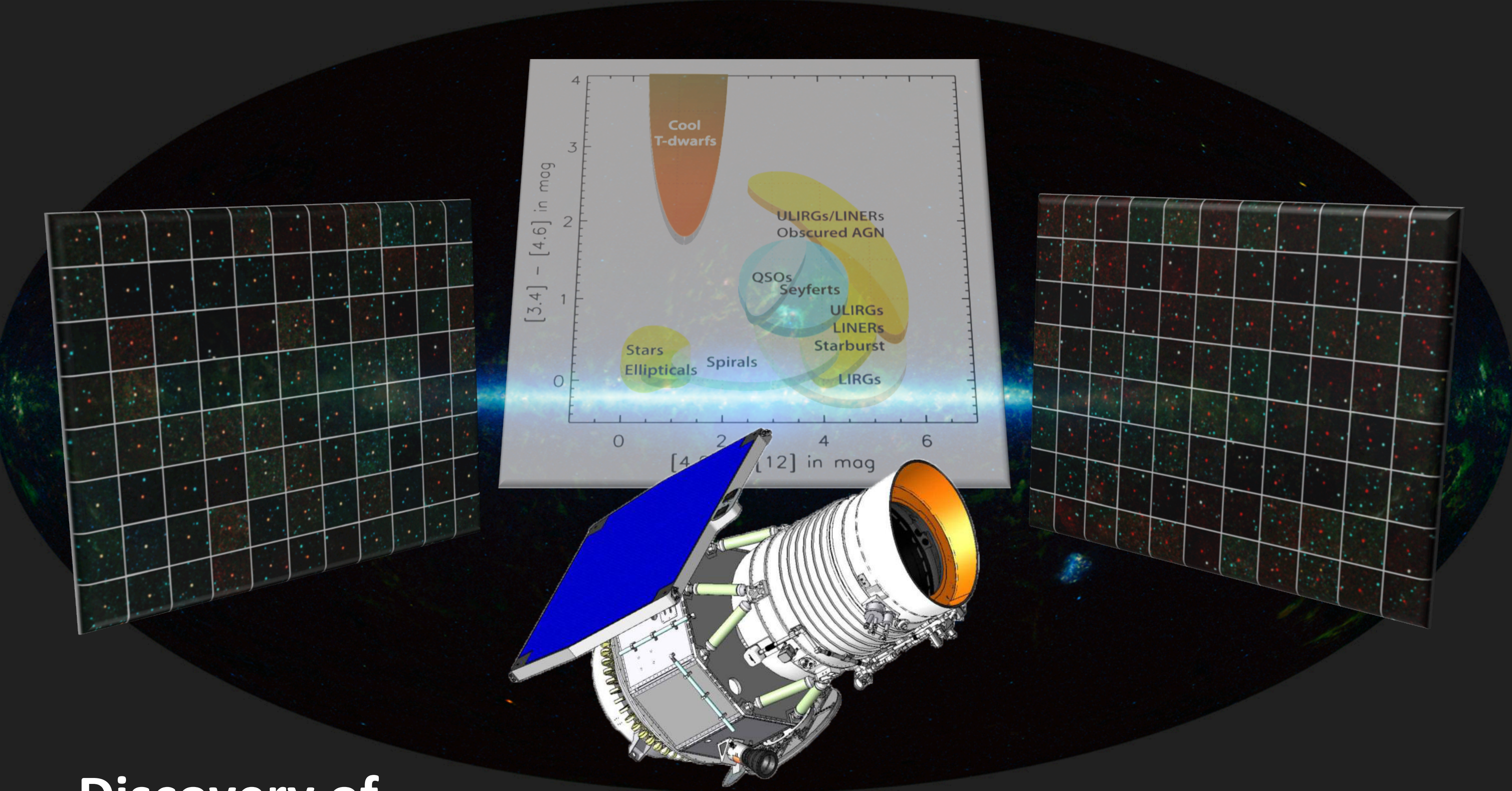
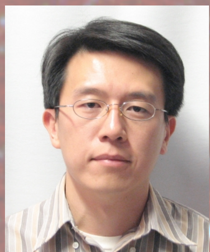


Discovery of the Most Luminous Galaxies in the Universe with WISE

Chao-Wei Tsai (JPL)

Discovery of the Most Luminous Galaxies



Chao-Wei Tsai (JPL)

Peter Eisenhardt (JPL)

Jingwen Wu (UCLA)

Daniel Stern (JPL)

Roberto Assef (**U.Diego Portales**)

Andrew Blain (**Leicester**)

JPL

- Leonidas Moustakas
- Fengchuan Liu
- Amy Mainzer

Caltech

- Carrie Bridge
- Jack Sayers

UCLA

- Ian McLean
- **Ned Wright (P.I. of WISE)**

IPAC/Caltech

- Charles Beichman
- Roc Cutri
- Chris Gelino
- Frank Masci
- Lin Yan

GSFC

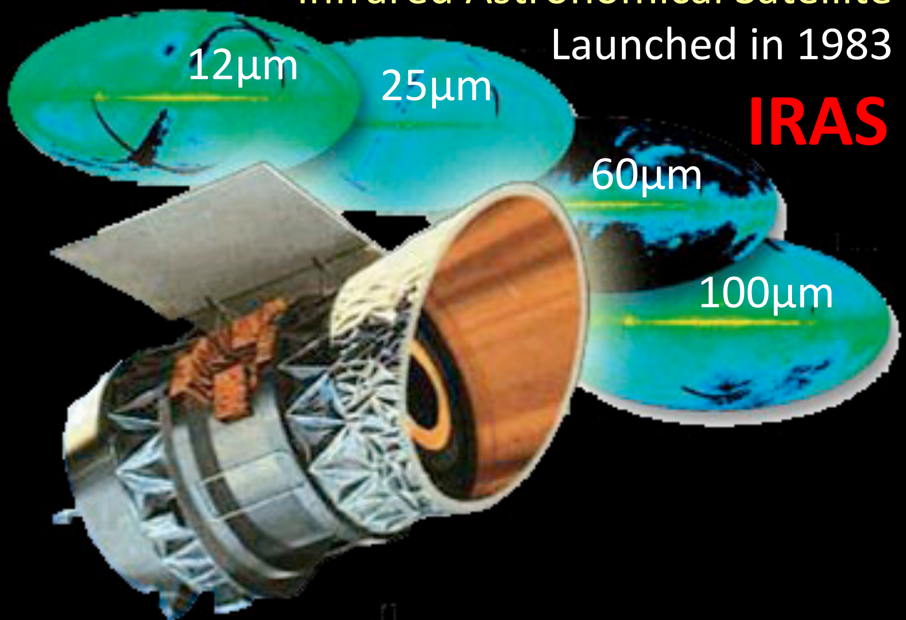
- Dominic Benford
- David Leisawitz
- Deborah Padgett

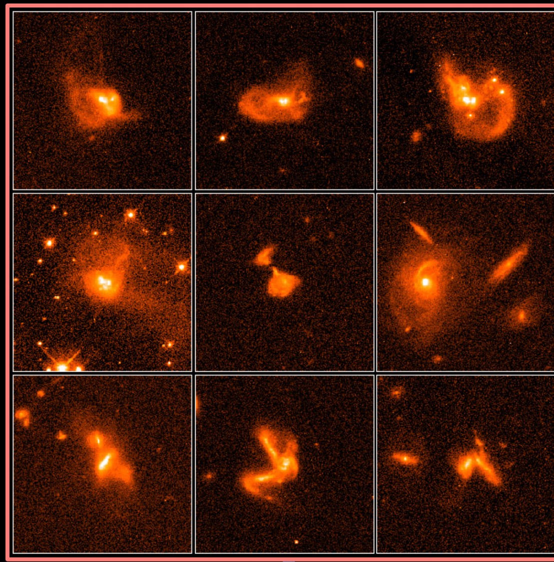
Roger Griffith (**Penn State**)
Adam Stanford (**UCDavis**)
Tom Jarrett (**U Cape Town**)
Carol Lonsdale (**NRAO**)
Sara Petty (**Va Tech**)
Michael Skrutskie (**UVa**)
Stéphanie Juneau (**CEA-Saclay**)

Infrared Astronomical Satellite

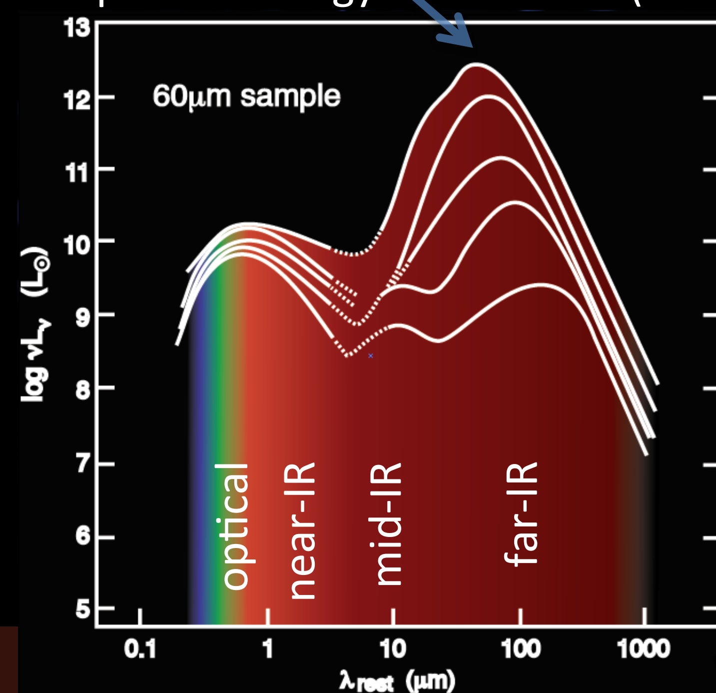
Launched in 1983

IRAS





Spectral Energy Distribution (SED)



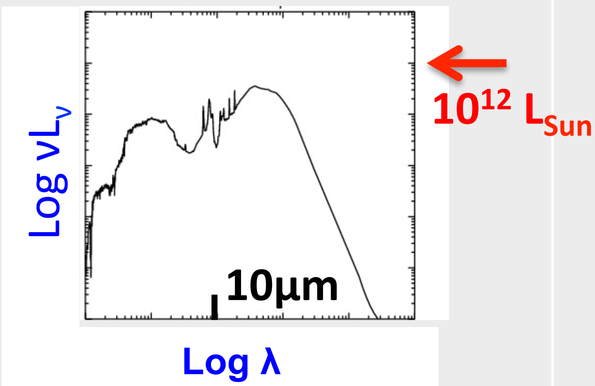
Discovery of Luminous Infrared Galaxies

- ~ 90 % of energy emitted at infrared wavelengths
- Total luminosities are ~ 10x - 100x of Luminosity of Milky Way

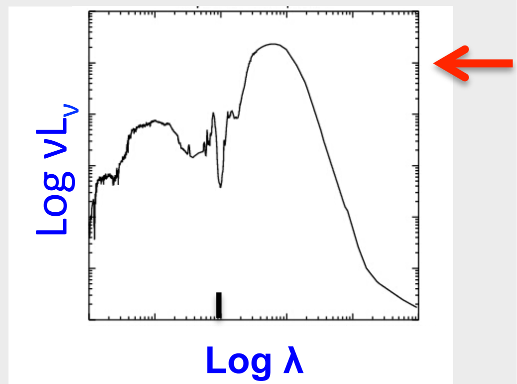
A bit of history – 1983

Luminous InfraRed Galaxies

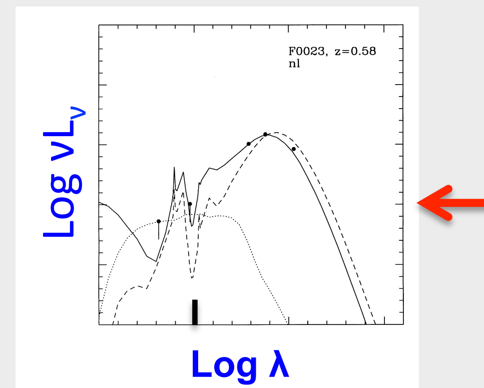
LIRGs	Ultra-LIRGs	Hyper-LIRGs
($10^{11} < L_{IR}/L_{Sun} < 10^{12}$)	($10^{12} < L_{IR}/L_{Sun} < 10^{13}$)	($10^{13} < L_{IR}/L_{Sun} <$??)



NGC6090 (3×10^{11} L_{Sun})

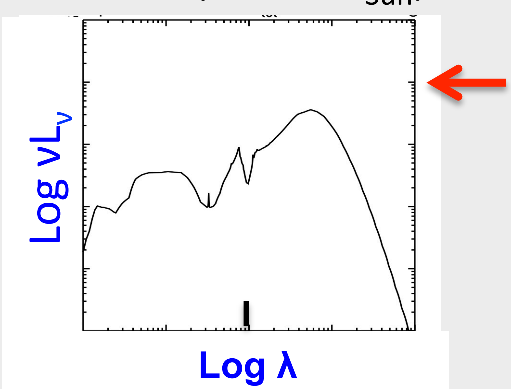


Arp220 (2×10^{12} L_{Sun})

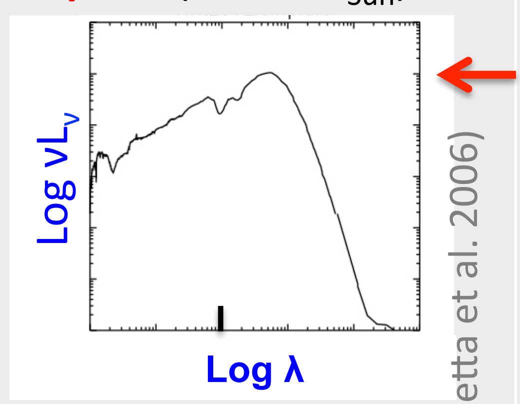


F00235+1024 (2×10^{13} L_{sun})

(Rowan-Robinson 2000)



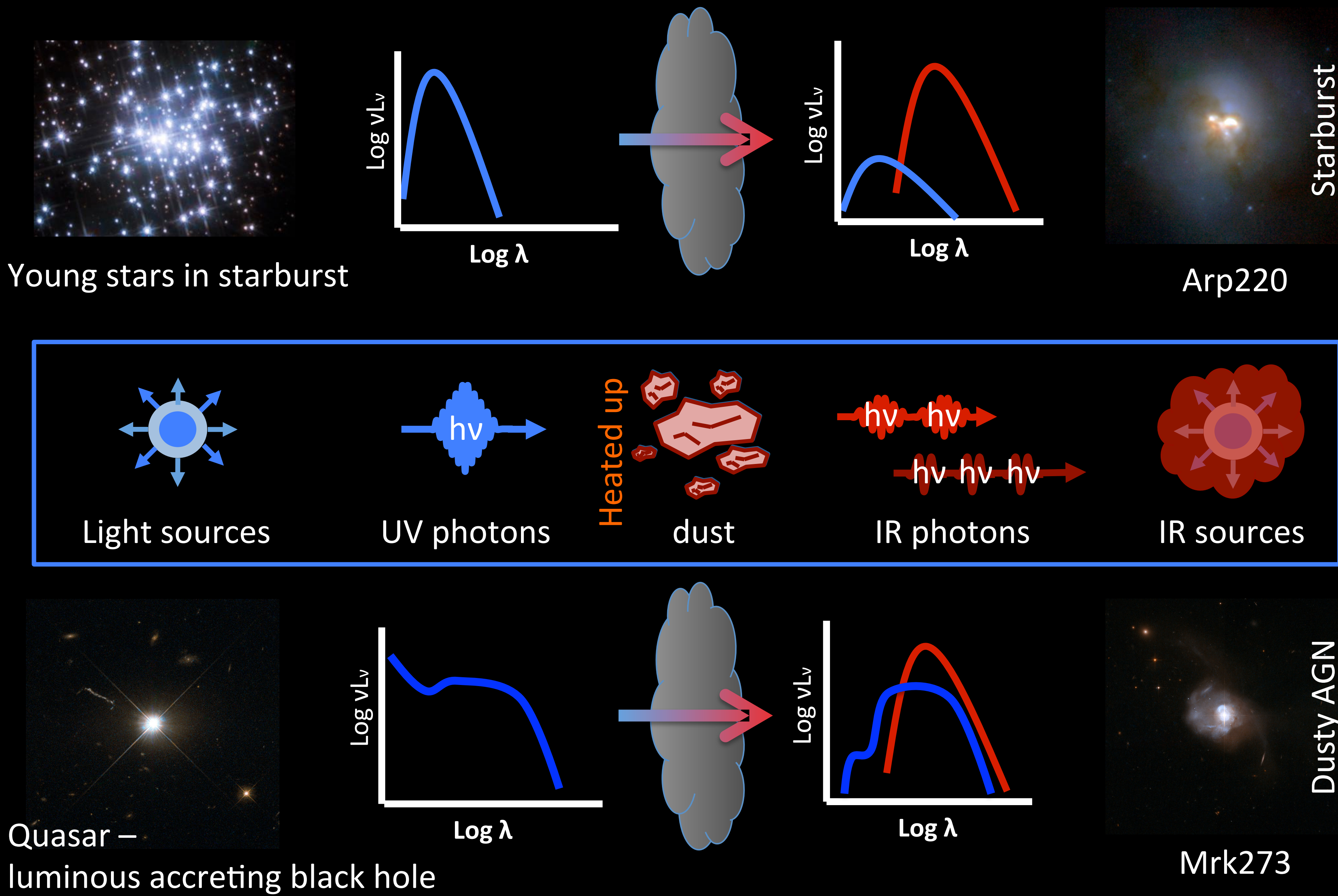
Arp299 (6×10^{11} L_{Sun})



Mrk231(3×10^{12} L_{sun})

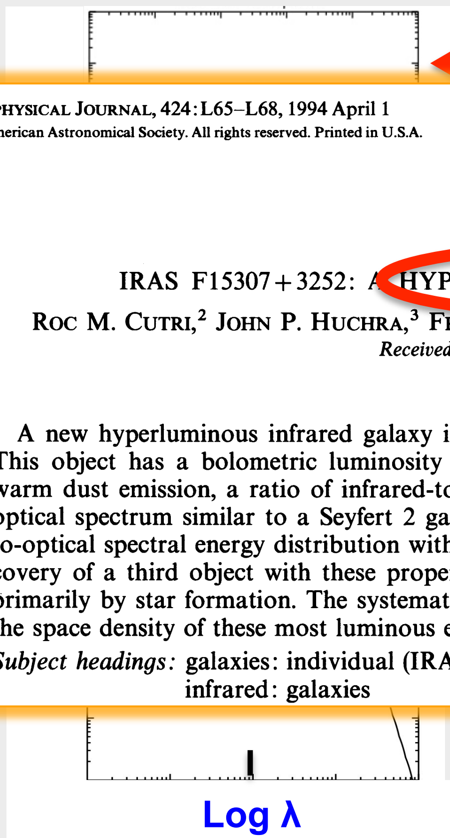
(Polletta et al. 2006)

Infrared Luminosity Comes from Dust Emission

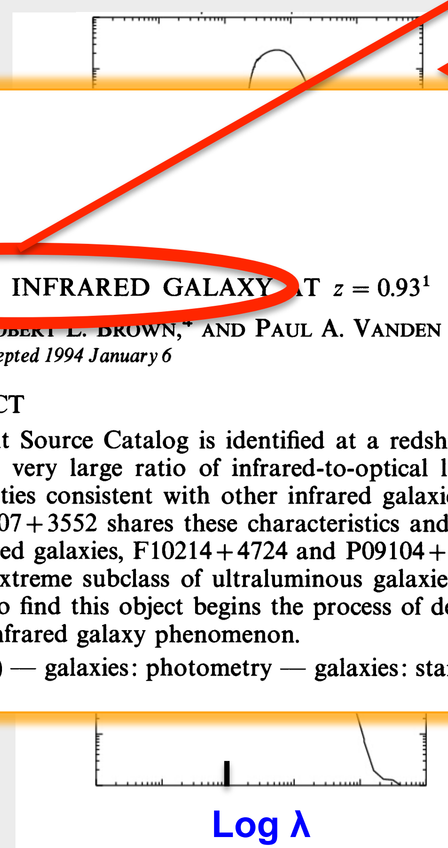


Luminous InfraRed Galaxies

LIRGs	Ultra-LIRGs	Hyper-LIRGs
$(10^{11} < L_{IR}/L_{Sun} < 10^{12})$	$(10^{12} < L_{IR}/L_{Sun} < 10^{13})$	$(10^{13} < L_{IR}/L_{Sun} < ??)$

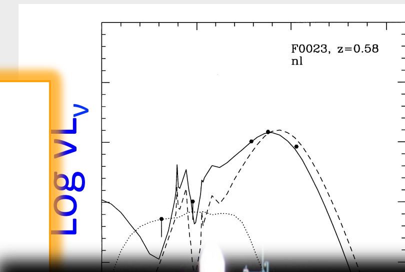


Arp299 $(6 \times 10^{11}\ L_{Sun})$



Mrk231 $(3 \times 10^{12}\ L_{sun})$

(Polletta et a



(Rowan-Robinson 2000)

The Astrophysical Journal, 424:L65–L68, 1994 April 1

IRAS F15307+3252: A HYPERLUMINOUS INFRARED GALAXY AT $z = 0.93$[1]

Roc M. Cutri,[2] John P. Huchra,[3] Frank J. Low, Robert L. Brown,[4] and Paul A. Vanden Bout[4]

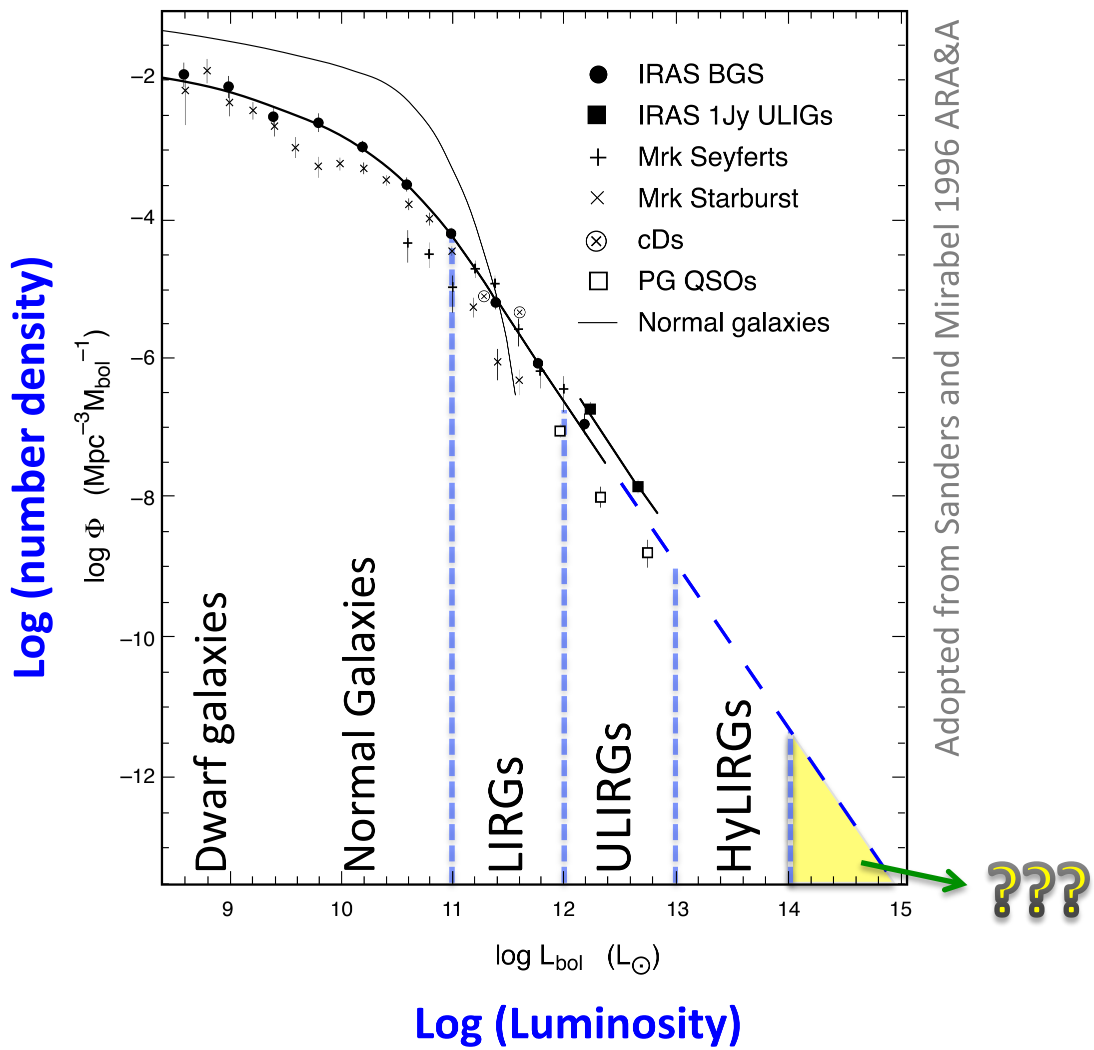
Received 29 October 1993; accepted 1994 January 6

ABSTRACT

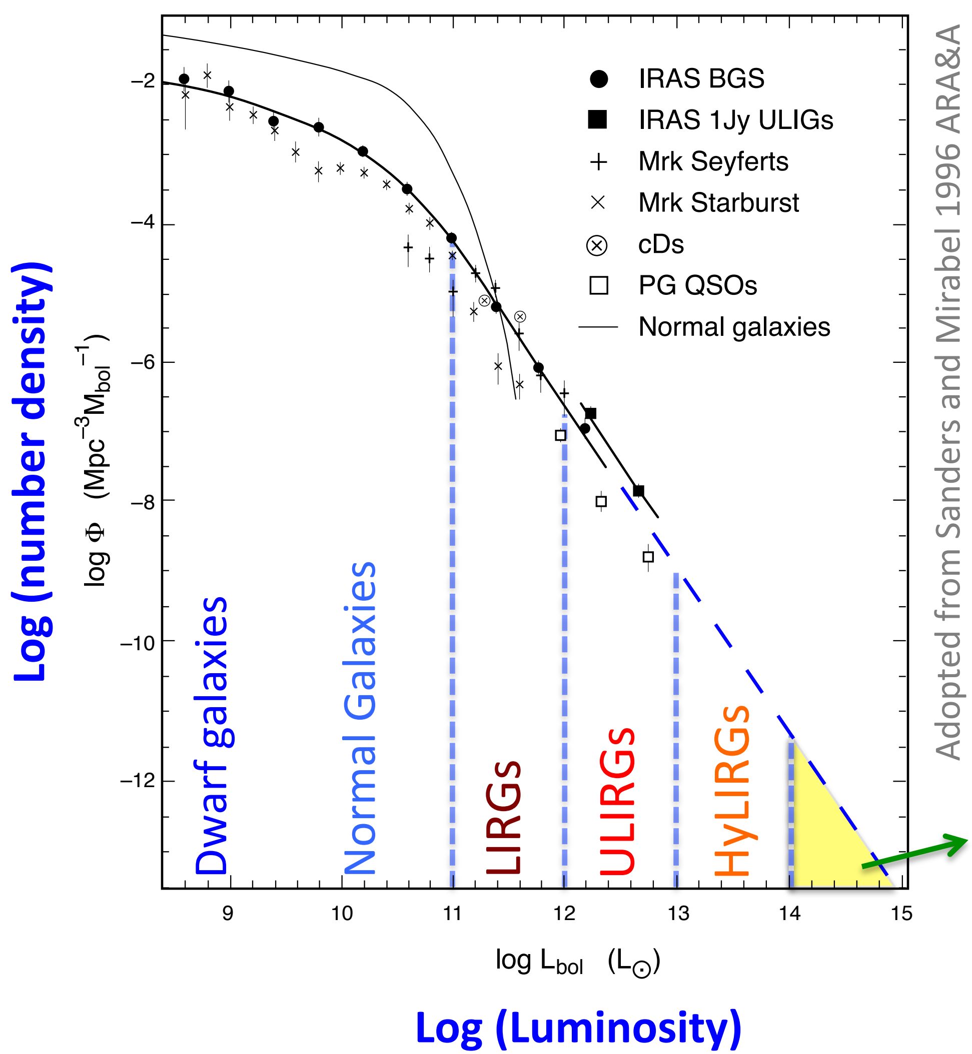
A new hyperluminous infrared galaxy in the *IRAS* Faint Source Catalog is identified at a redshift of 0.93. This object has a bolometric luminosity of $\sim 10^{13}\ L_\odot$, a very large ratio of infrared-to-optical luminosity, warm dust emission, a ratio of infrared-to-radio flux densities consistent with other infrared galaxies, and an optical spectrum similar to a Seyfert 2 galaxy. IRAS F15307+3552 shares these characteristics and its radio-to-optical spectral energy distribution with two other infrared galaxies, F10214+4724 and P09104+4109. Discovery of a third object with these properties defines an extreme subclass of ultraluminous galaxies powered primarily by star formation. The systematic method used to find this object begins the process of determining the space density of these most luminous examples of the infrared galaxy phenomenon.

Subject headings: galaxies: individual (IRAS F15307+3252) — galaxies: photometry — galaxies: starburst — infrared: galaxies

Tip of the Luminosity Function



Tip of the Luminosity Function – Extreme Luminous Infrared Galaxies (**ELIRGs**)



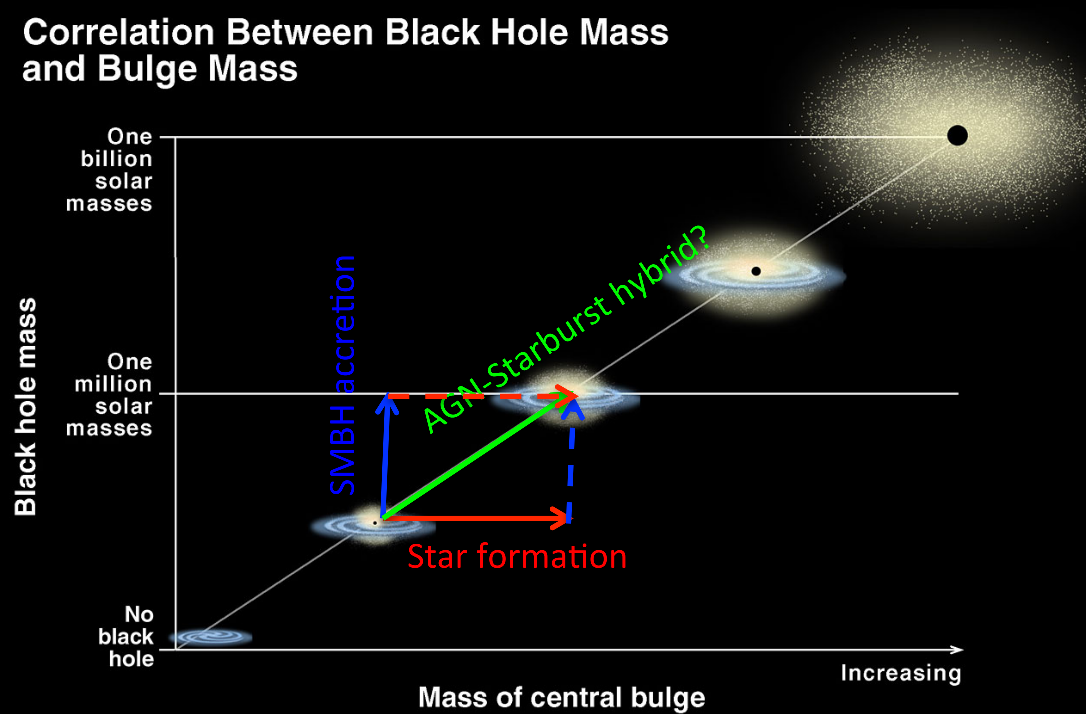
Extremely Luminous InfraRed Galaxies

ELIRGs

Big Mystery of Galaxy Evolution

High luminosity –
rapid mass growth phase

- **Starburst** dominated
  - Rapid and violate **star formation**
- **AGN** dominated
  - Powerful **supermassive black hole accretion**



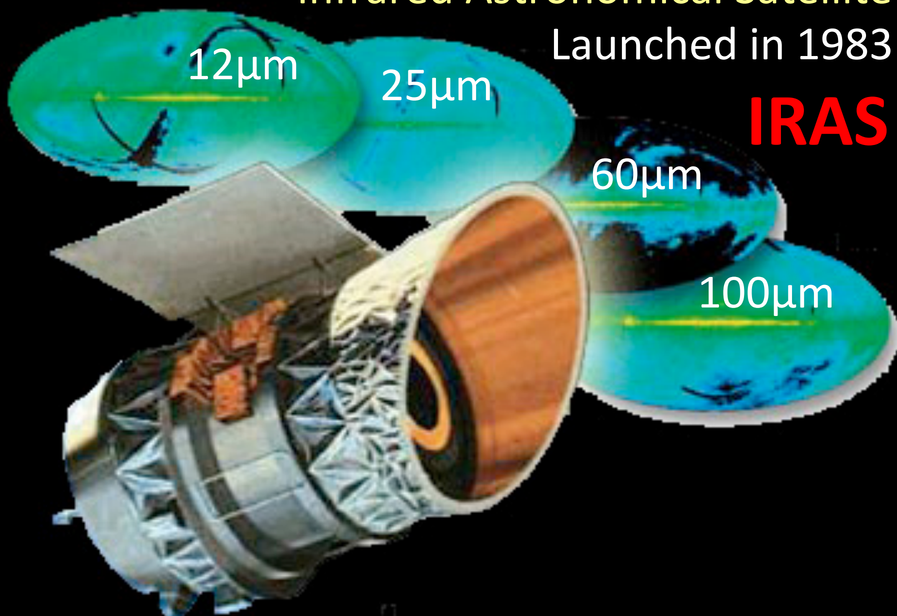
In the Most Luminous Galaxies,
mass of host galaxy or super massive black hole (SMBH) can

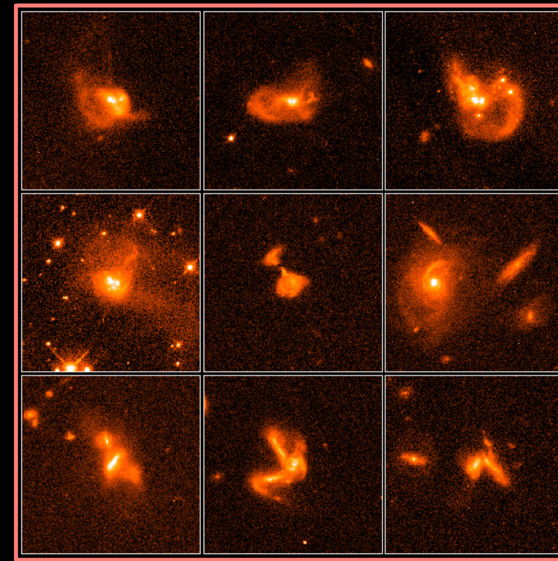
increase by a factor of 10
in ~ 100 - 300 Myr!

Infrared Astronomical Satellite

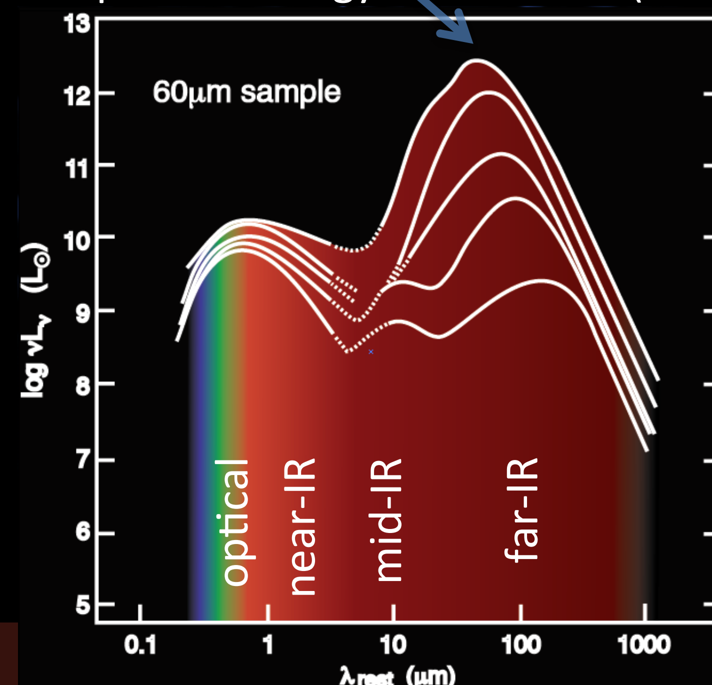
Launched in 1983

IRAS





Spectral Energy Distribution (SED)

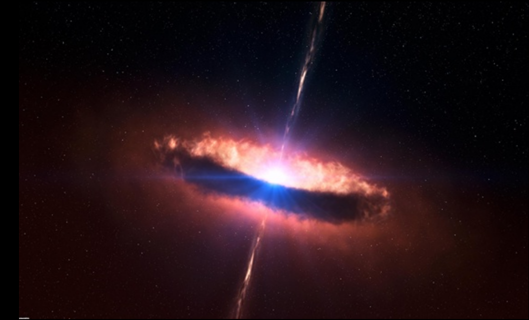


Discovery of Luminous Infrared Galaxies

- ~ 90 % of energy emitted at infrared wavelengths
- Total luminosities are ~ 10x - 100x of Luminosity of Milky Way
- **Galaxy Evolution is hidden behind the dust!**

A bit of history – 1983

Measuring Masses of Super Massive Black Holes (SMBHs) : <u>Eddington Limit</u>

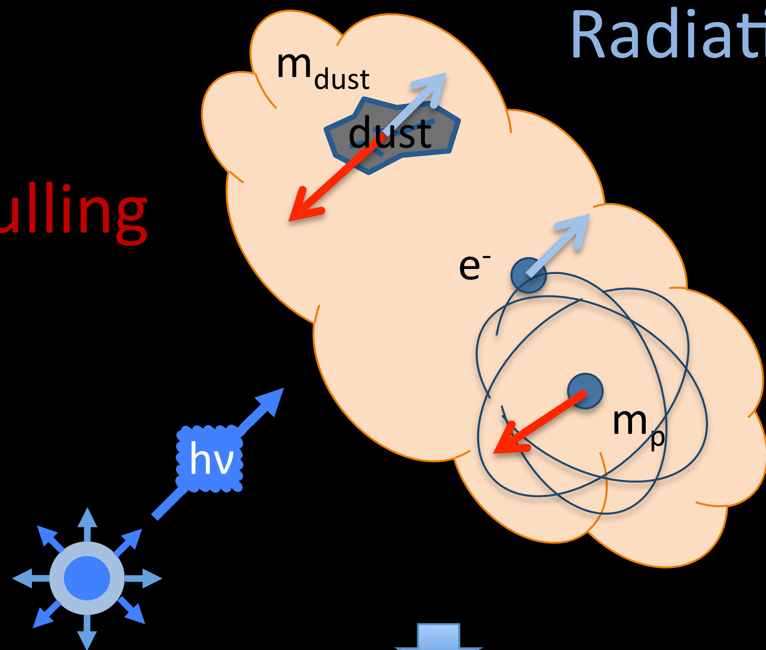


Radiation Pressure × Cross-section

$$\frac{L\,\sigma_{\rm cross}}{4\pi R^2 c}$$

Gravitational Pulling

$$\frac{GMm}{R^2}$$



Light source (accreting black hole) Mass M

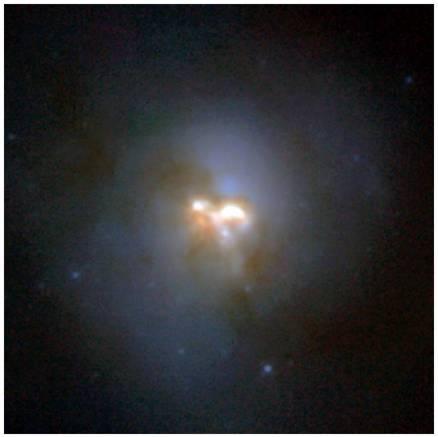
Lower Mass Limit (for given observed luminosity)

If Gravity is winning (=> continuous accretion) :

$$M > \frac{L_{\rm observed}\,\sigma_{\rm Thomson}}{4\pi c G m_p} = 1\,M_{\rm Sun} \times \frac{L_{\rm observed}}{3.2 \times 10^4\,L_{\rm Sun}}$$

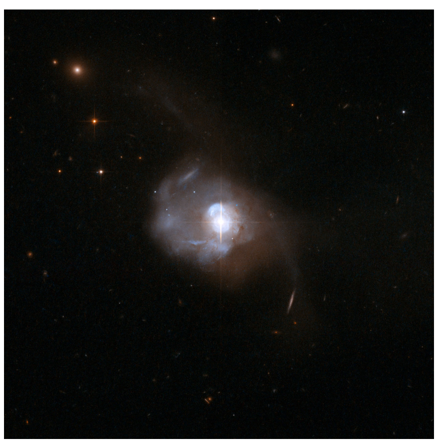
Hunt for ELIRGs – with WISE

Starburst Dominated

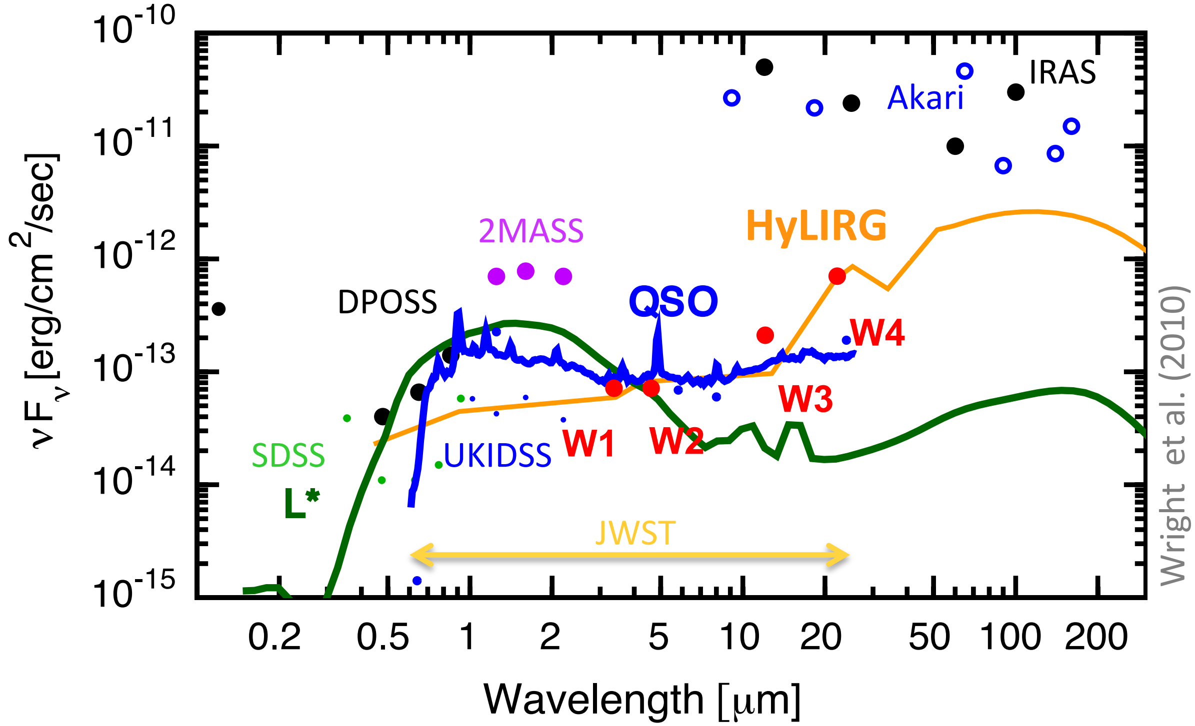


Arp220 x **100**?

AGN dominated



Mrk231 x **100**?



L* at z = 0.33

QSO J1148+5251 at z = 6.4

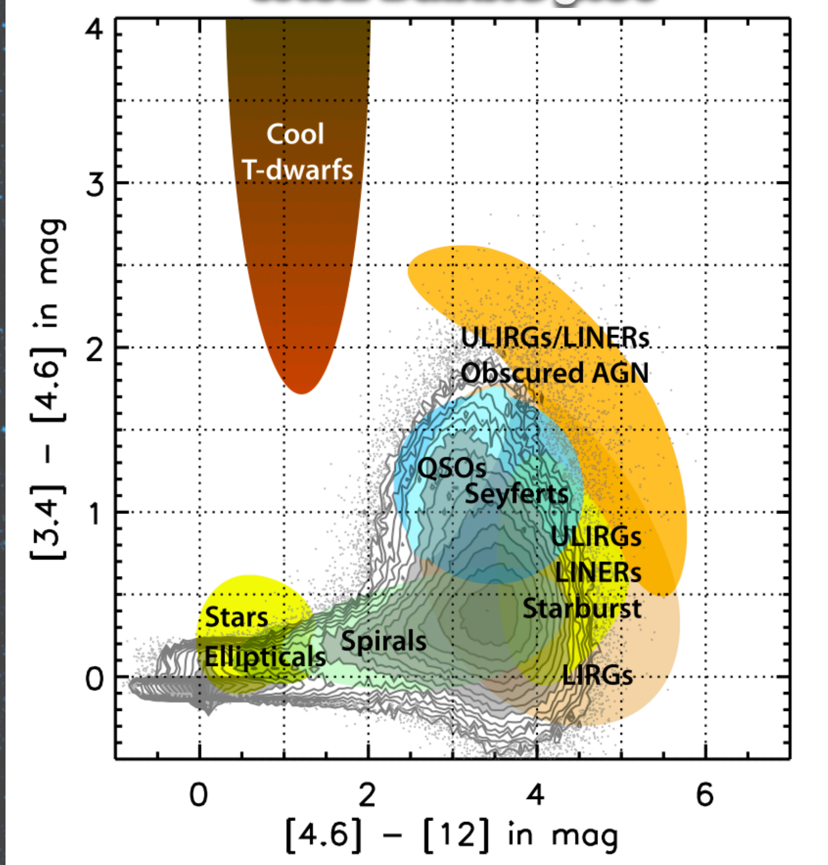
HyLIRG: FSC 15307+3253 at z = 3

Real SED x 3, $L = 6\times10^{13}\ L_{Sun}$

Inhabitants of WISE Color Space

Ah… How to Identify ELIRGs?

Chao-Wei's Color-Color WISE Bubble plot



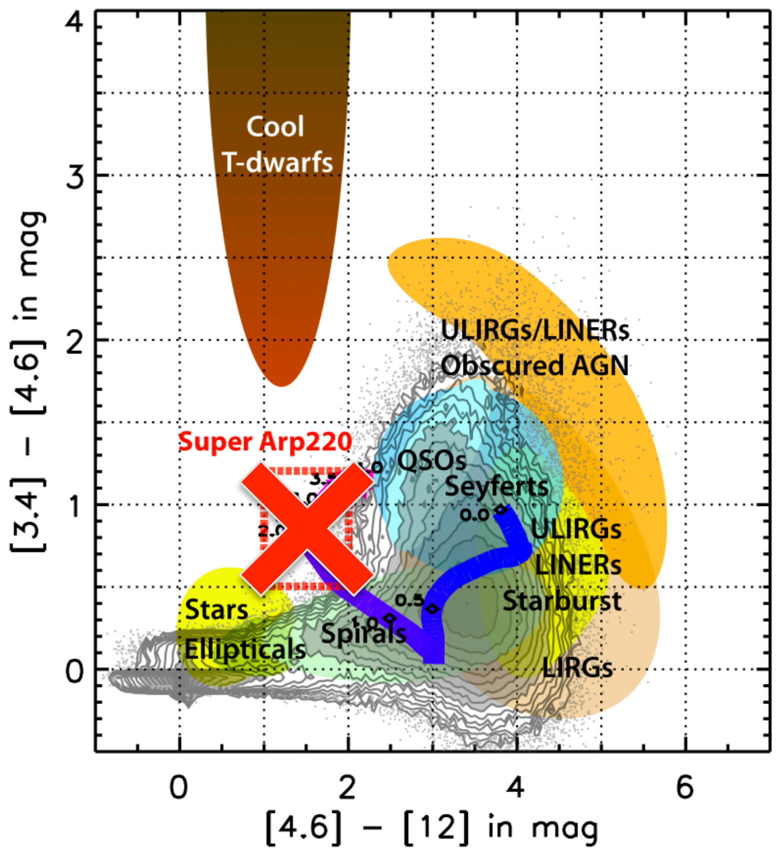
Wright et al. (2010) AJ
Jarrett et al. (2011) ApJ

Hundred millions of WISE sources!

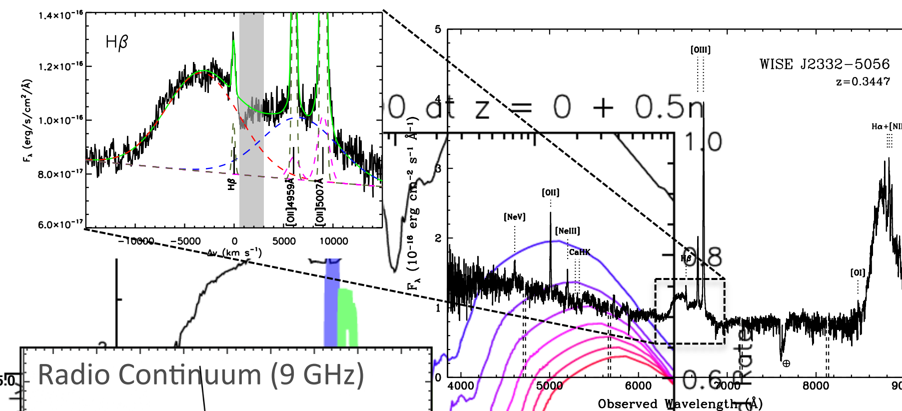
How to find the most luminous galaxies??

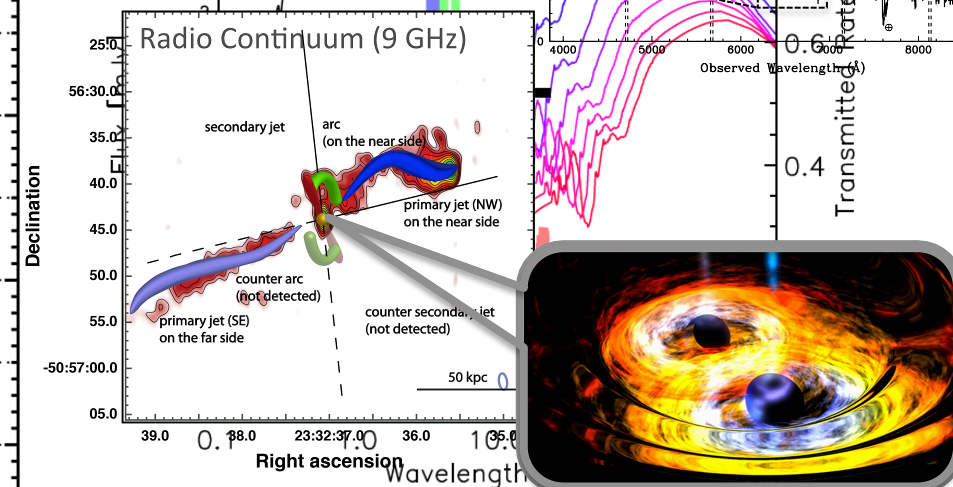
Searching for Most Luminous Galaxies

Chao-Wei's Color-Color WISE Bubble plot



Based on SEDs





10 σ detection by WISE

Radio Galaxy W2332-5056 with

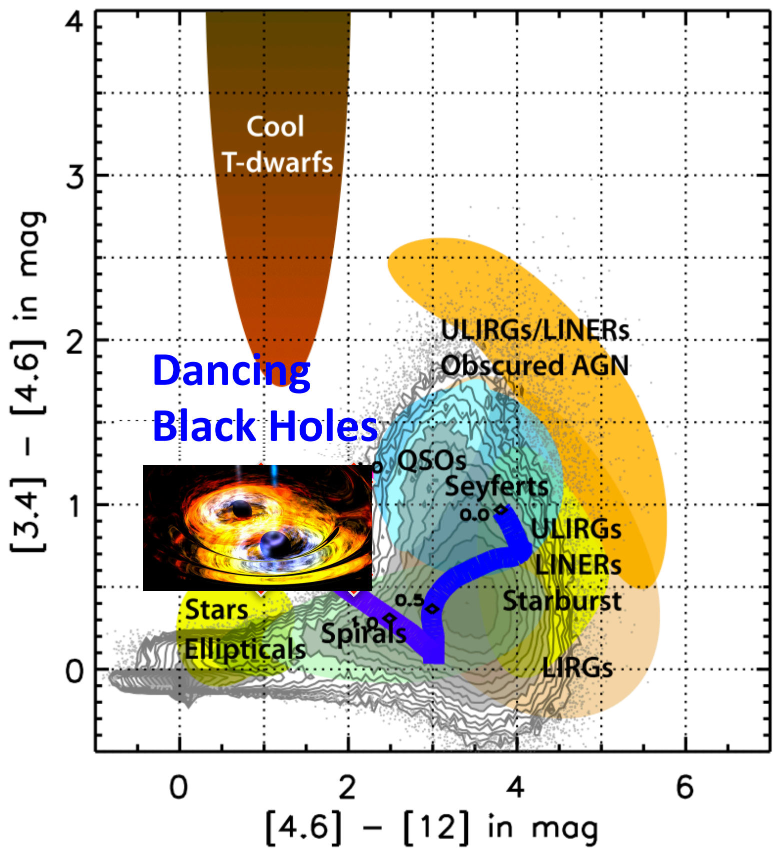
Wiggle jets and double-peaked Hα/Hβ lines

- SMBH binary candidate

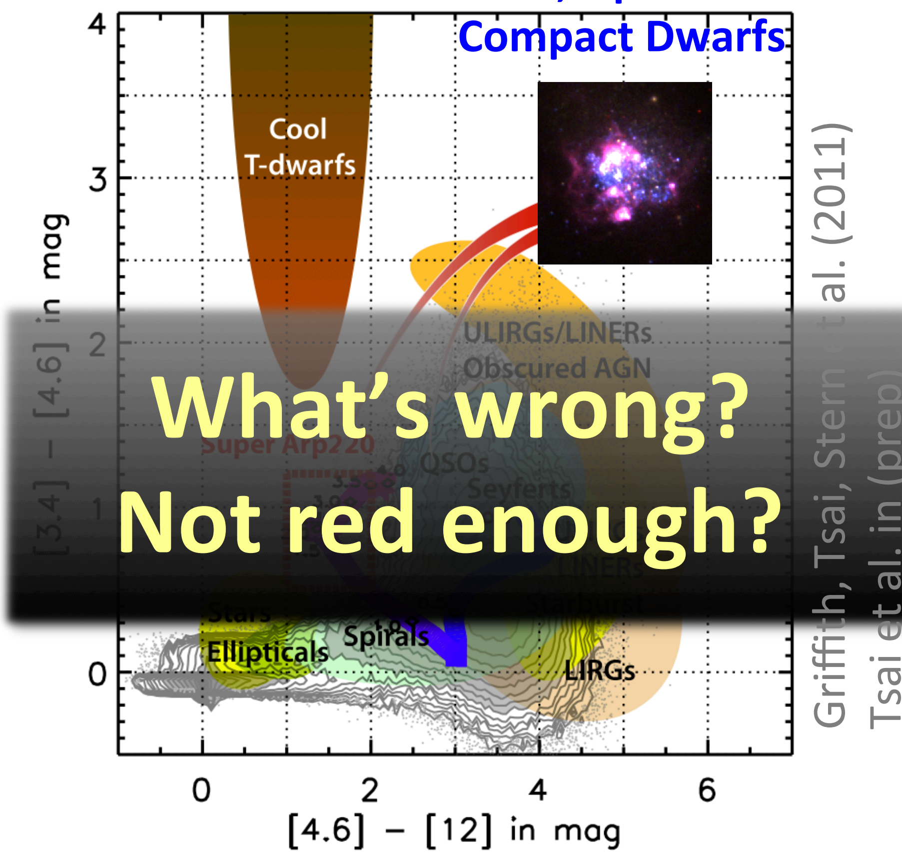
Tsai, Jarrett, Stern et al. (2013)

Searching for Most Luminous Galaxies

Chao-Wei's Color-Color WISE Bubble plot



Based on SEDs

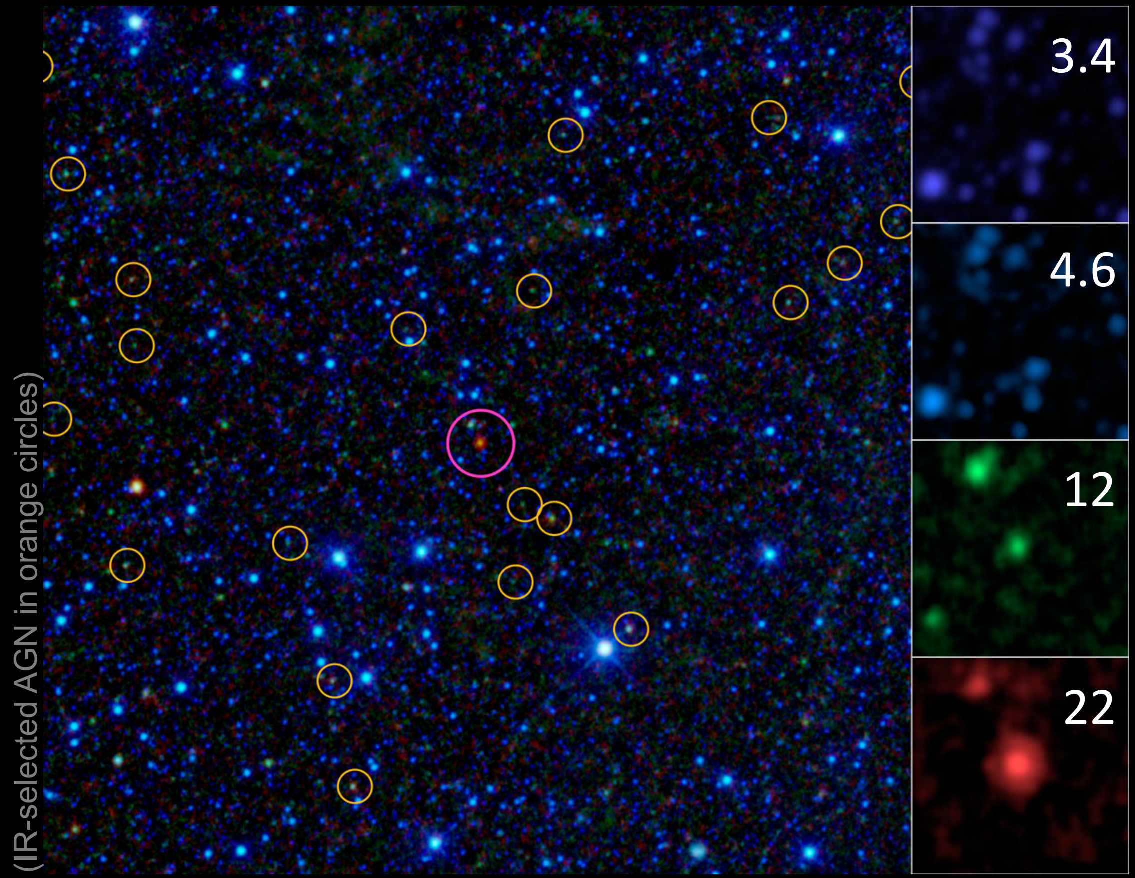


What's wrong?
Not red enough?

Griffith, Tsai, Stern et al. (2011)
Tsai et al. in (prep)

Based on assumption of High extinction

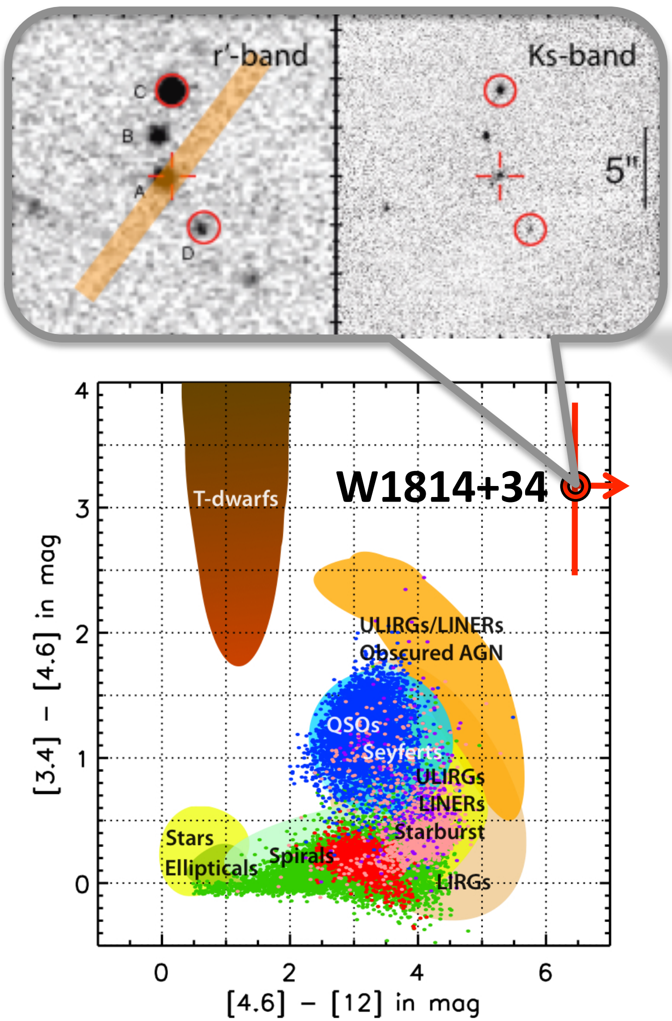
W1W2 Dropouts

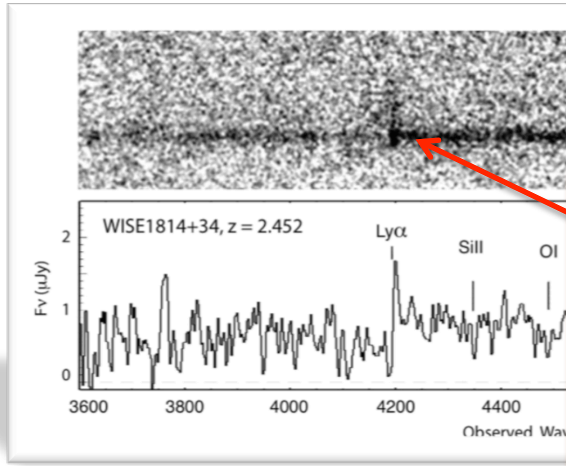


WISE objects well detected at 12 μm and 22 μm

faint or invisible at 3.4 μm and 4.6 μm

First HyLIRG Discovered by WISE





"Blowout"

- BH grows rapidly
- Highly dust reddened
- dust/gas expelled

W1814+34

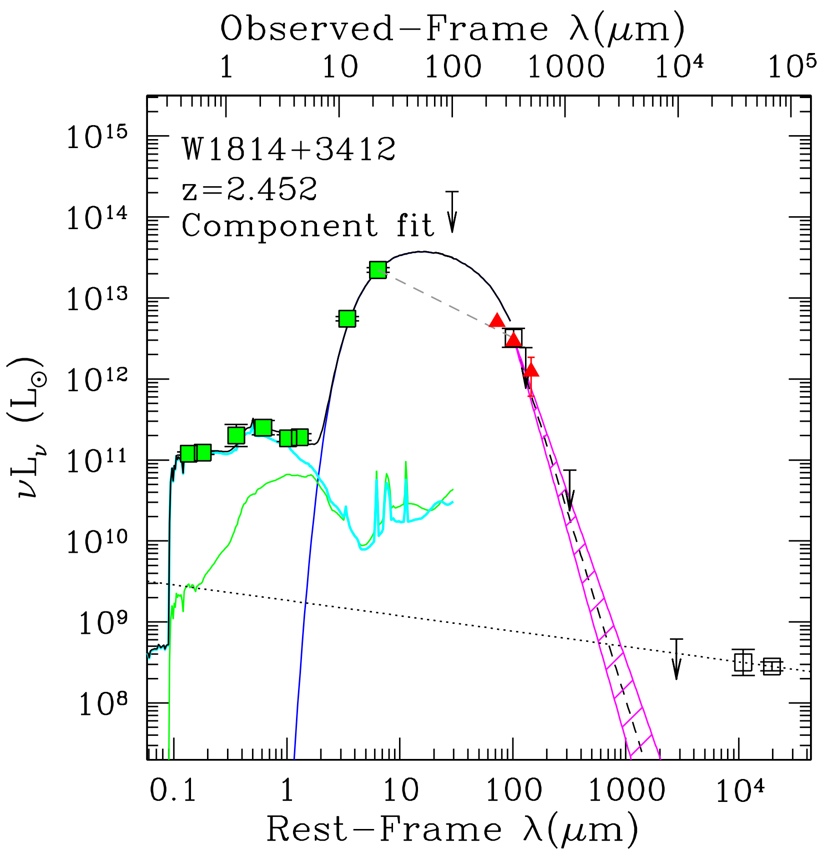
- **at z=2.452**

(Eisenhardt, Wu, **Tsai** et al 2012)

- Extended hydrogen gas emission ~100,000 light-years (Bridge et al. in 2013)

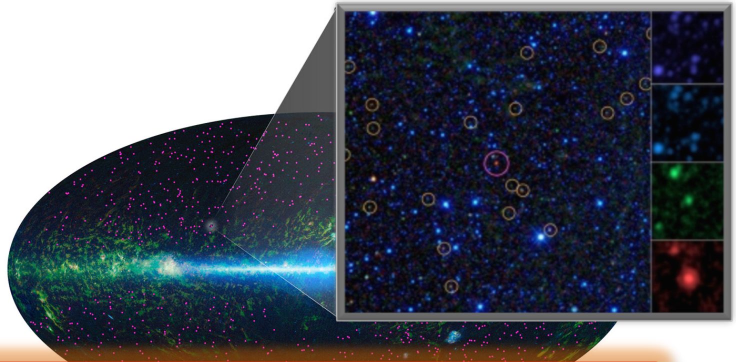
SED Decomposition of W1814+34

- L_{tot} = 4 – 8 x 10^{13} $L_\odot$
  - Very difficult to be powered by starburst
  - Implies supermassive black hole (~ 10^9 $M_\odot$)
- **Obscured AGN**
  - i.e. visible light obscured by dust
- **Starburst**
  - SFR ~ 500 $M_\odot$/yr (10% of L_{bol})
- **Spiral Galaxy**
  - Faint compared to AGN
  - Implies relatively **low ratio of star mass to black hole mass** compared to today



Eisenhardt, Wu, Tsai, et al. (2012)

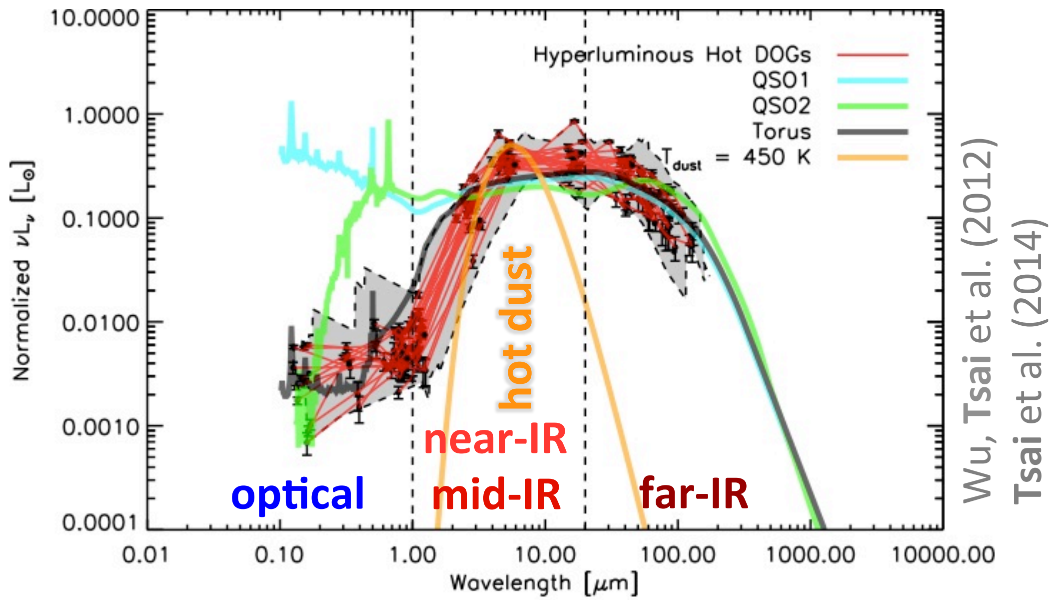
Far-IR Follow-up on W1W2 Dropouts



Hot Dust Obscured Galaxies

– Hot DOGs

(Dog Haus Pasadena)



- Hyperluminous: $L > 10^{13}\ L_{Sun}$
- mid-IR excess:

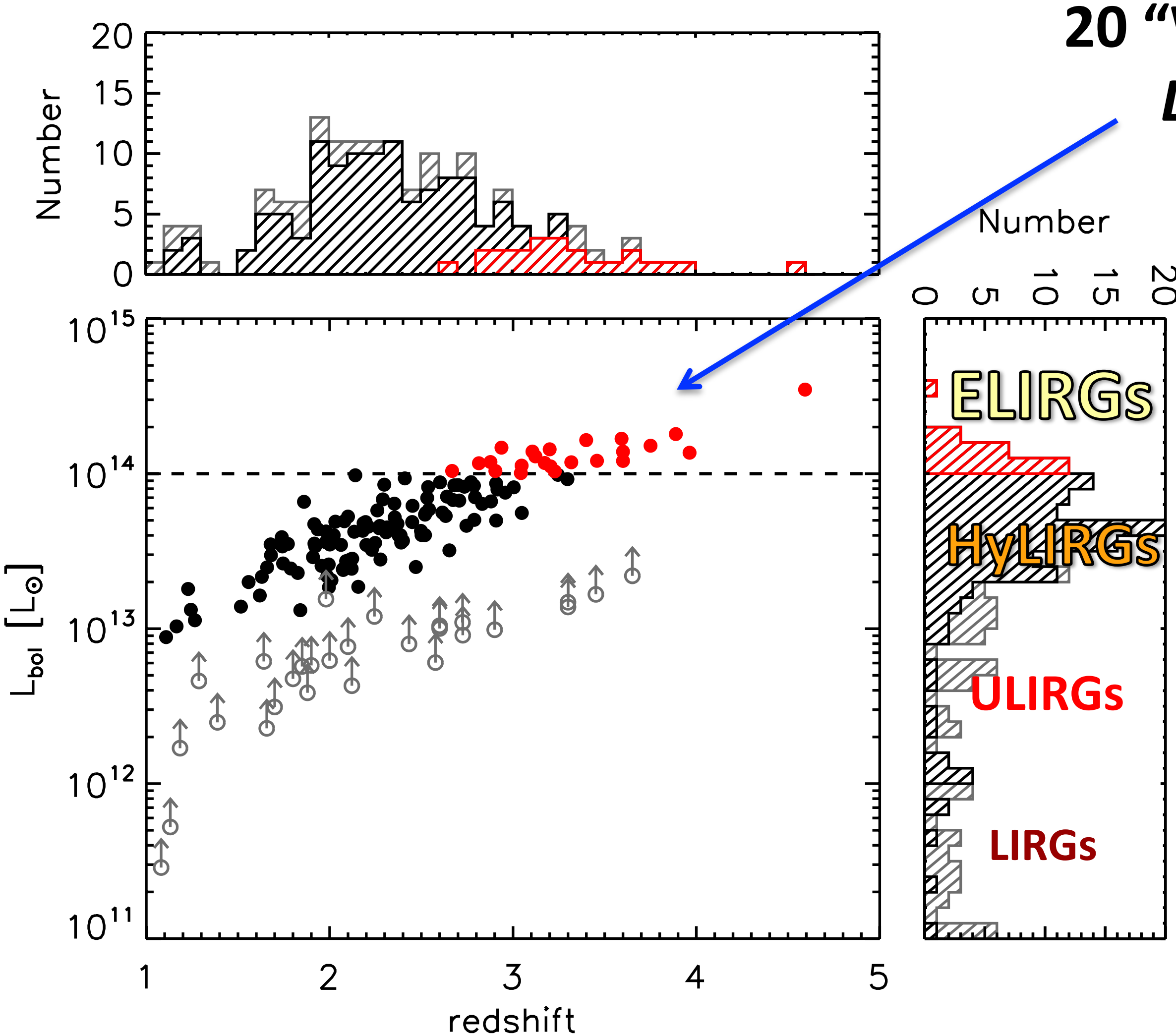
  hot dust emission (T_D ~ 450 K)
- **Hot Dust Obscured Galaxies**

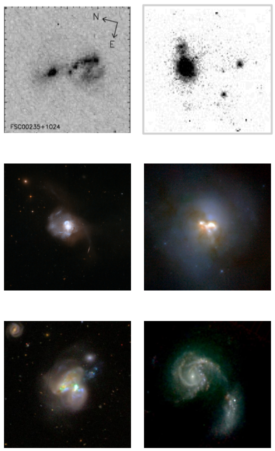
  (Hot DOGs)

Mission Accomplished!

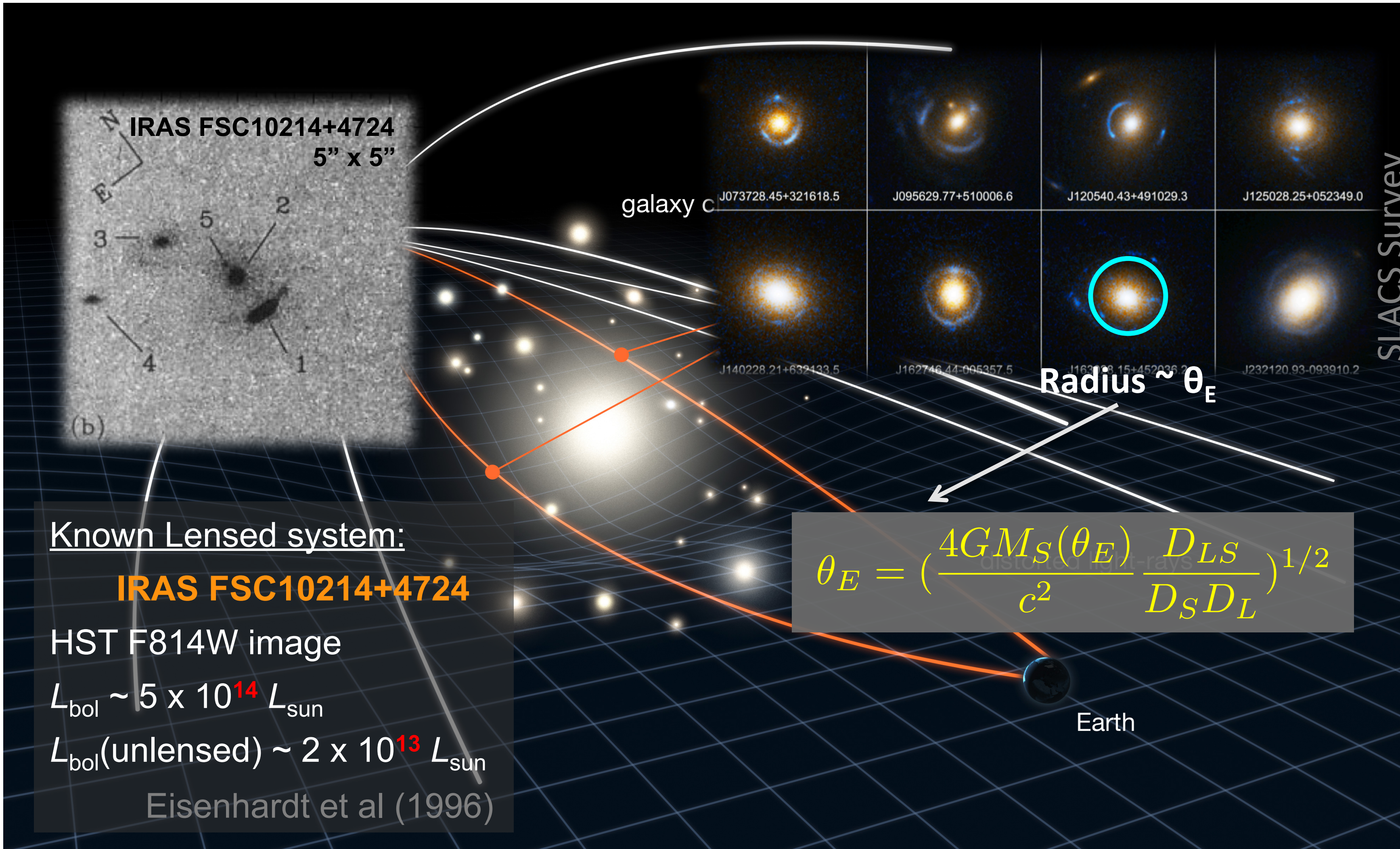
20 "W1W2 Dropouts" have $L_{bol} > 10^{14}\ L_{Sun}$ (ELIRGs!!)

(**Tsai** et al. 2014)

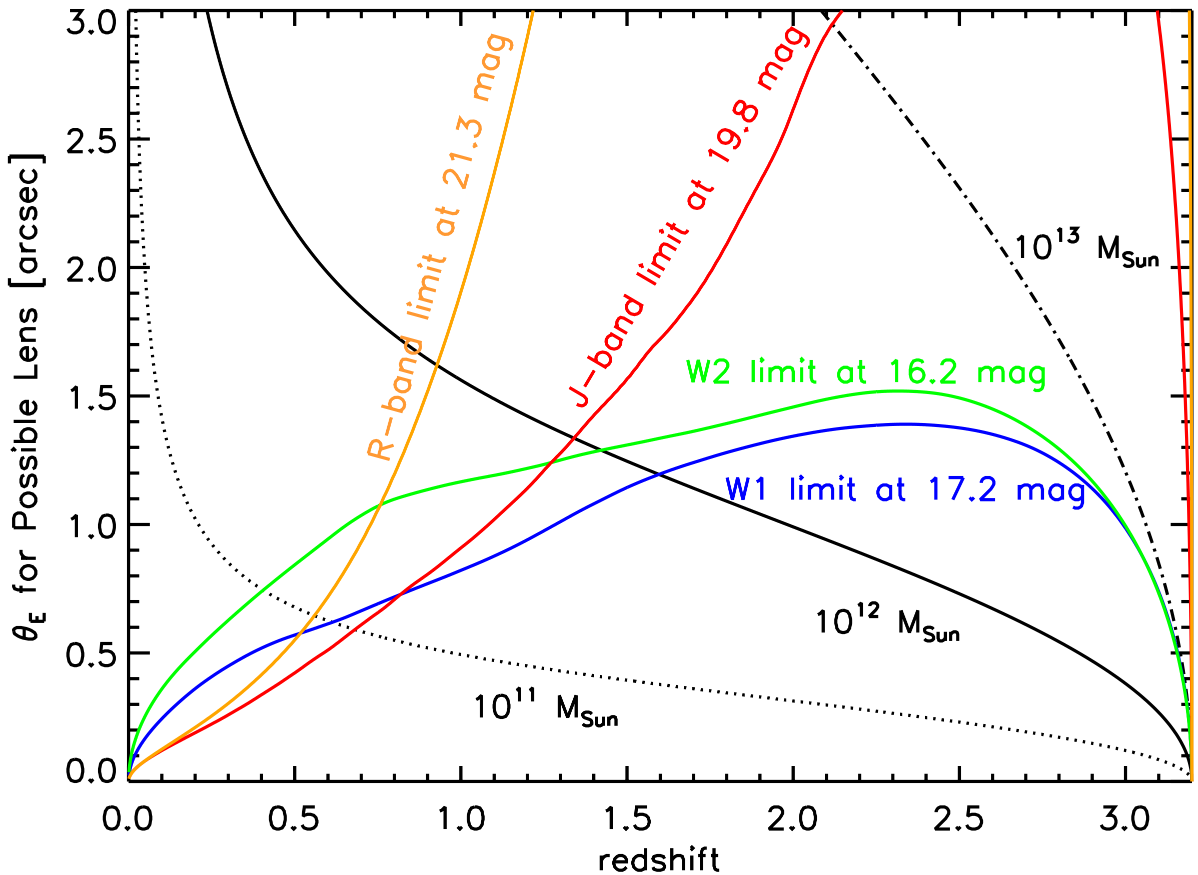




Intrinsic Luminosity – Gravitationally lensed?

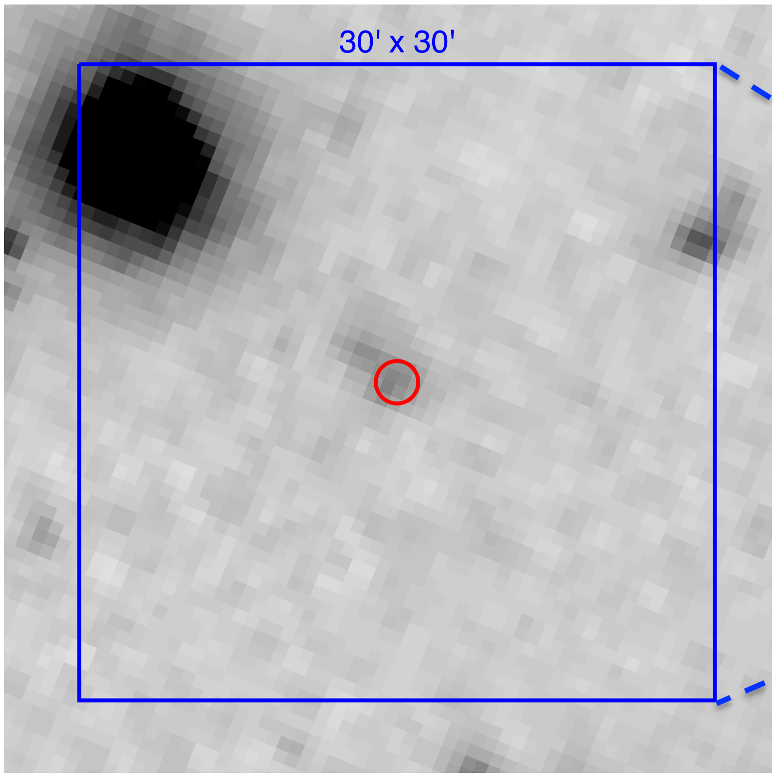


Gravitational Lensing – High Magnification at ~ θ_E



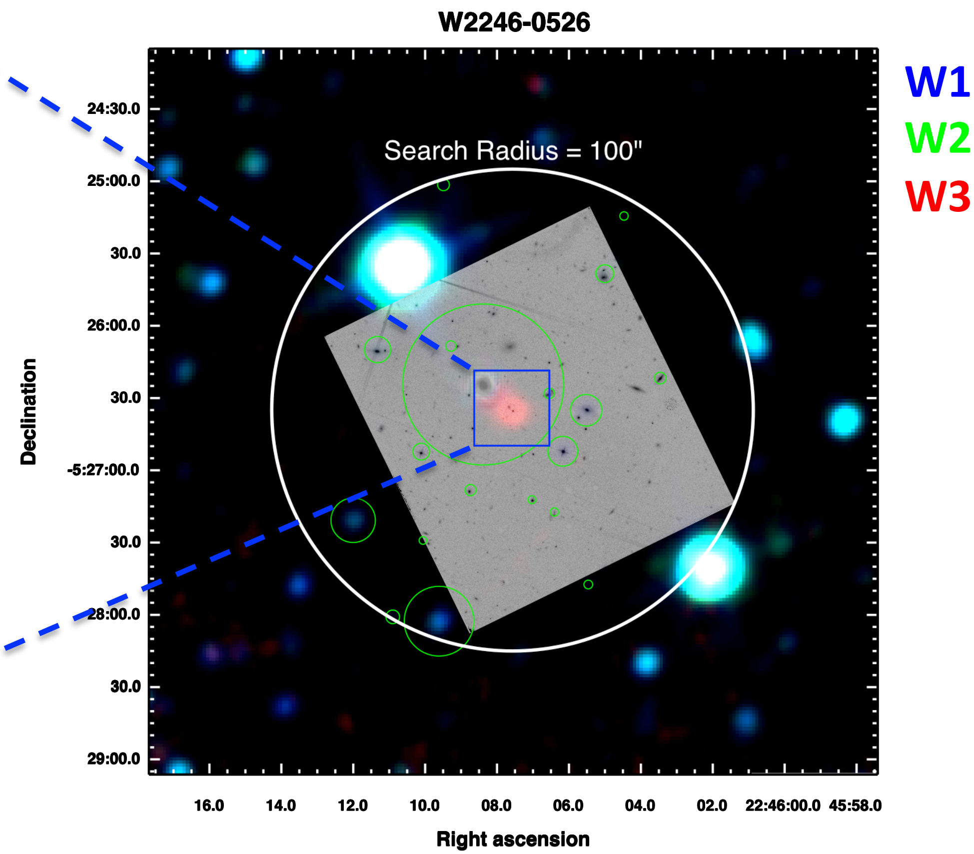
Assuming lensed source at z ~ 3.2

Most Luminous Galaxy – W2246-0526



Tsai et al. (2014)

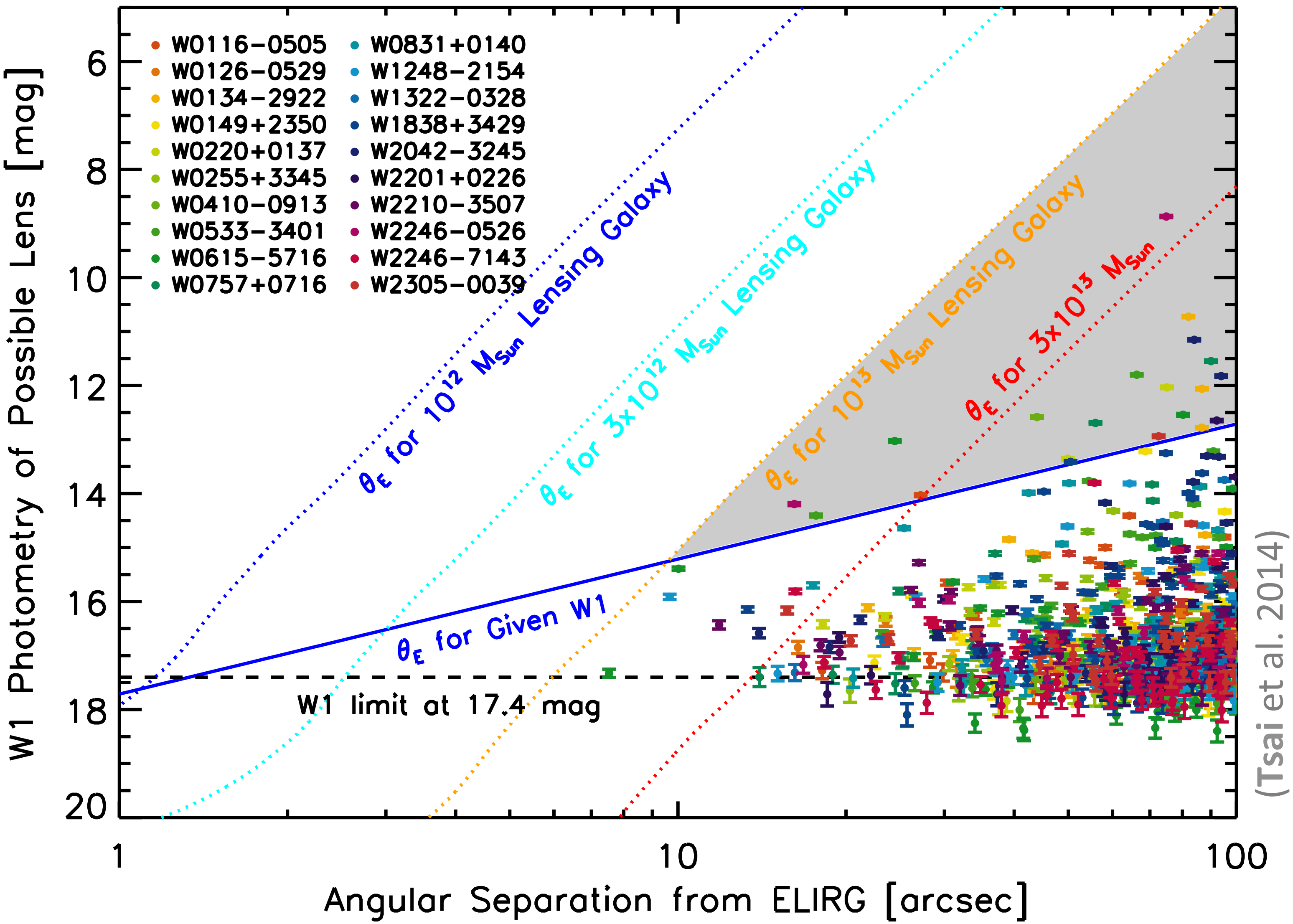
Companion at ~ 2.5" away, z ~ 1.358



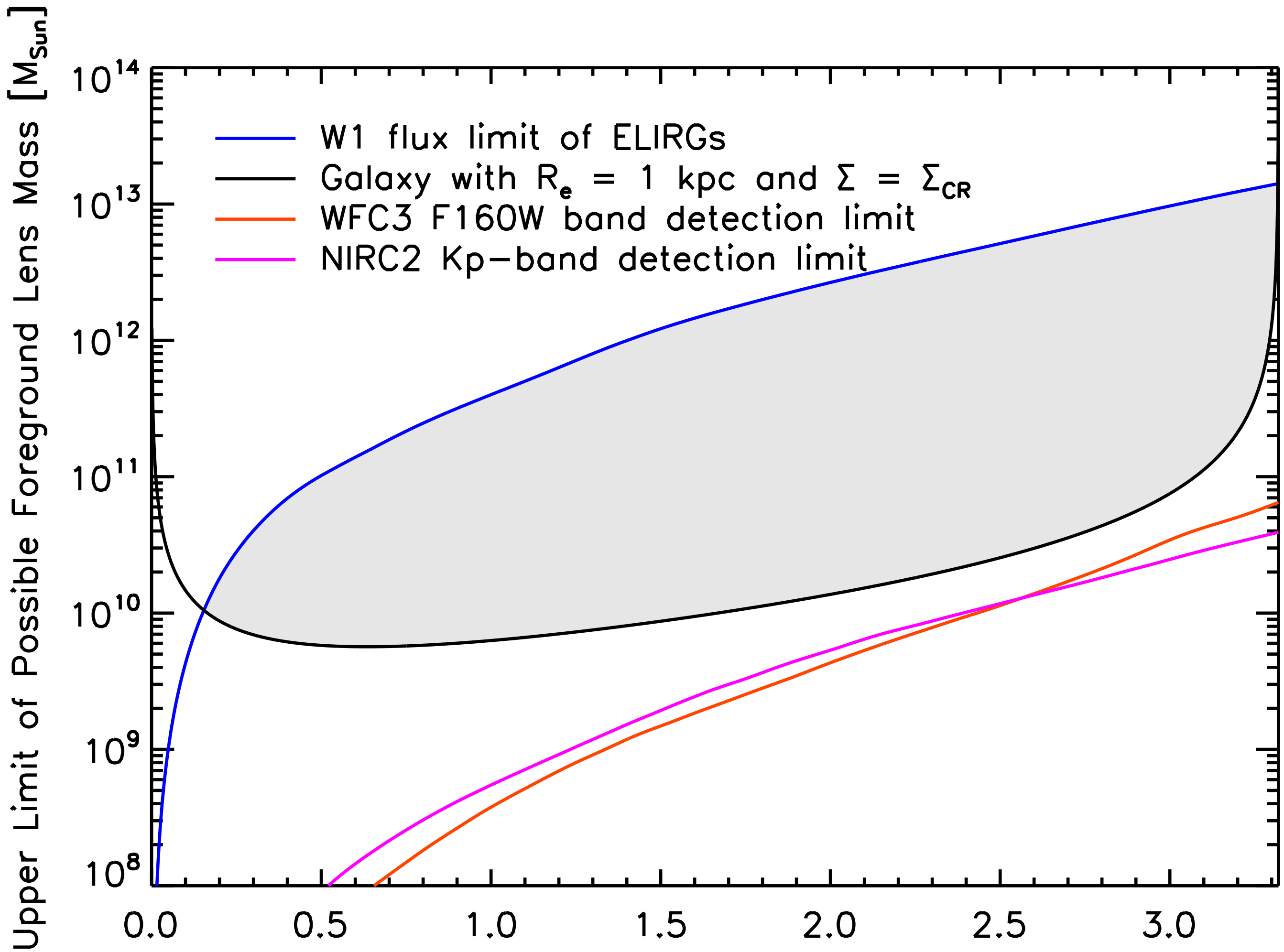
If θ_E ~ 2.5, and lens at z = 1.358

-> require lens mass ~ 4×10^{12} $M_\odot$ and W1 < 16.4 mag (but 17.5 mag is observed)

Possible Foreground Lensing Galaxies at Separation > WISE W1 Resolution

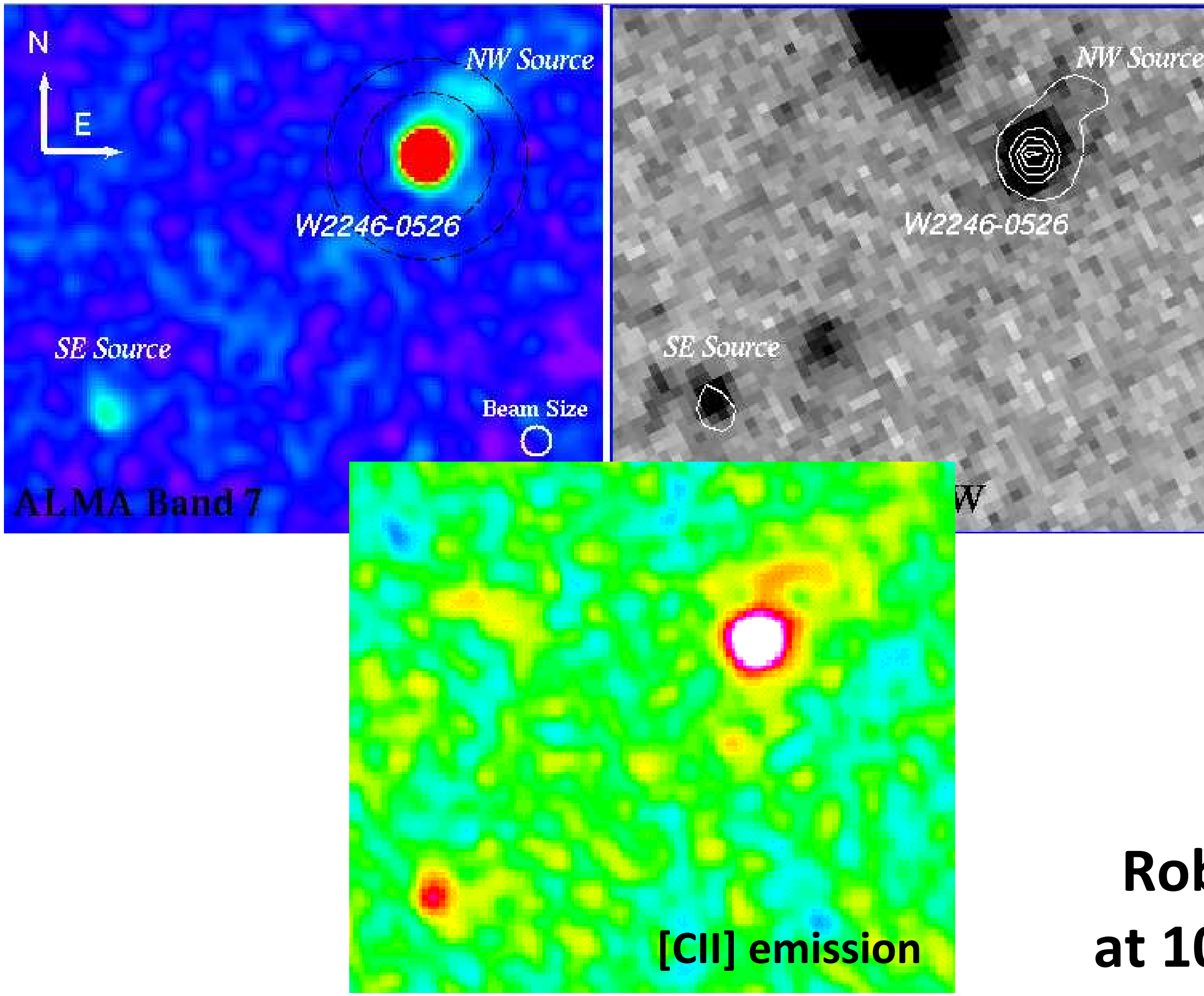


If Putative Foreground Lensing Galaxy and ELIRG are Blended within W1 Resolution



(Tsai et al. 2014)

ALMA



Stay tuned for Roberto Assef's talk at 10:00 on Thursday

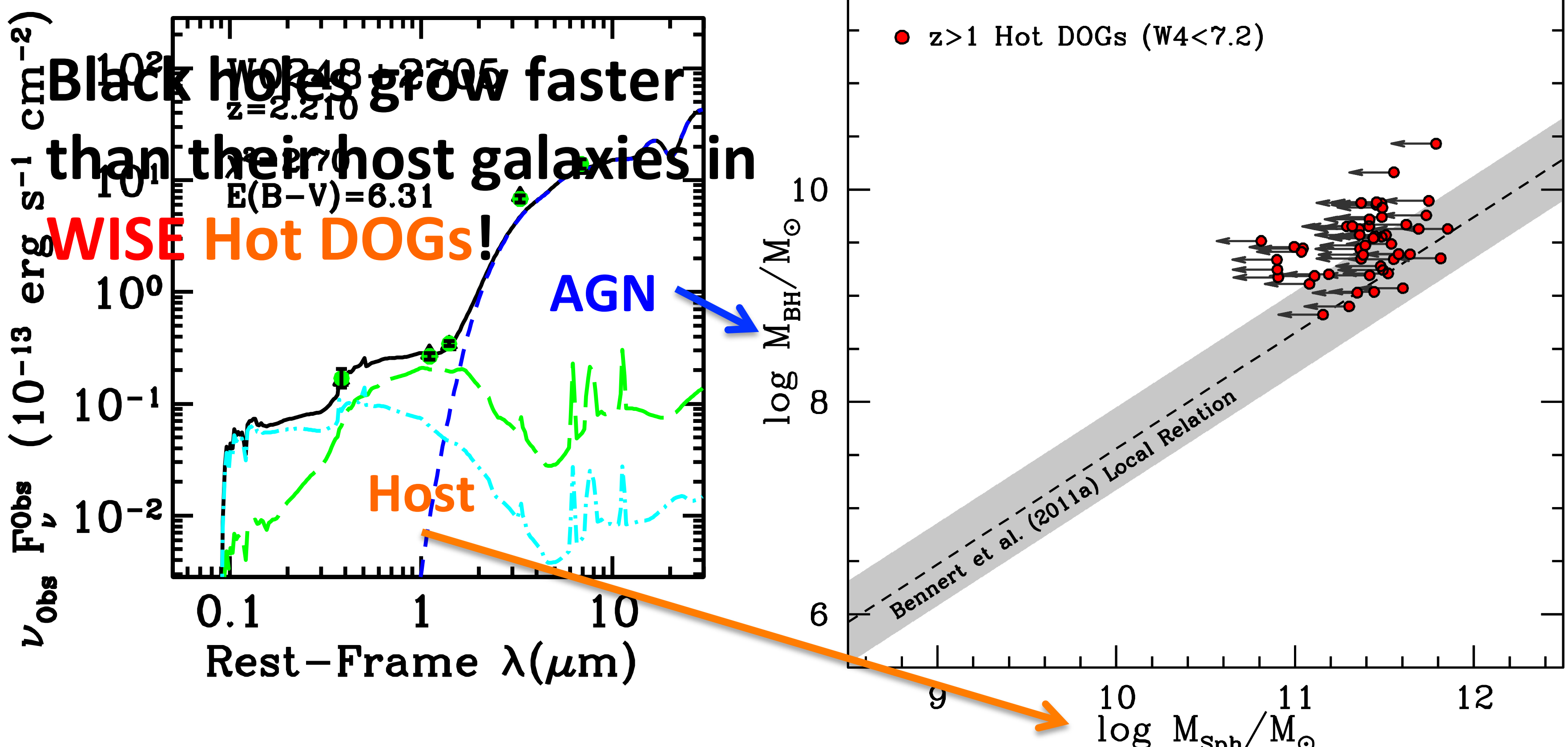
Diaz-Santos, Assef et al. (in prep)

SMBH Mass and Eddington Ratios

Black holes grow faster than their host galaxies in WISE Hot DOGs!

SED Decomposition of Selected Hot DOGs

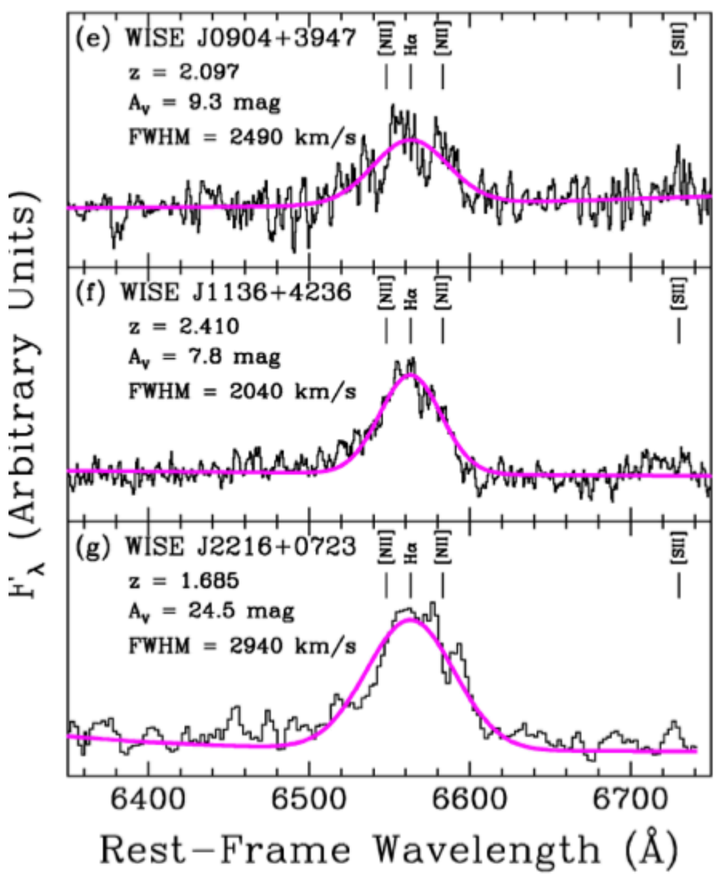
Assuming Eddington Ratio = 1

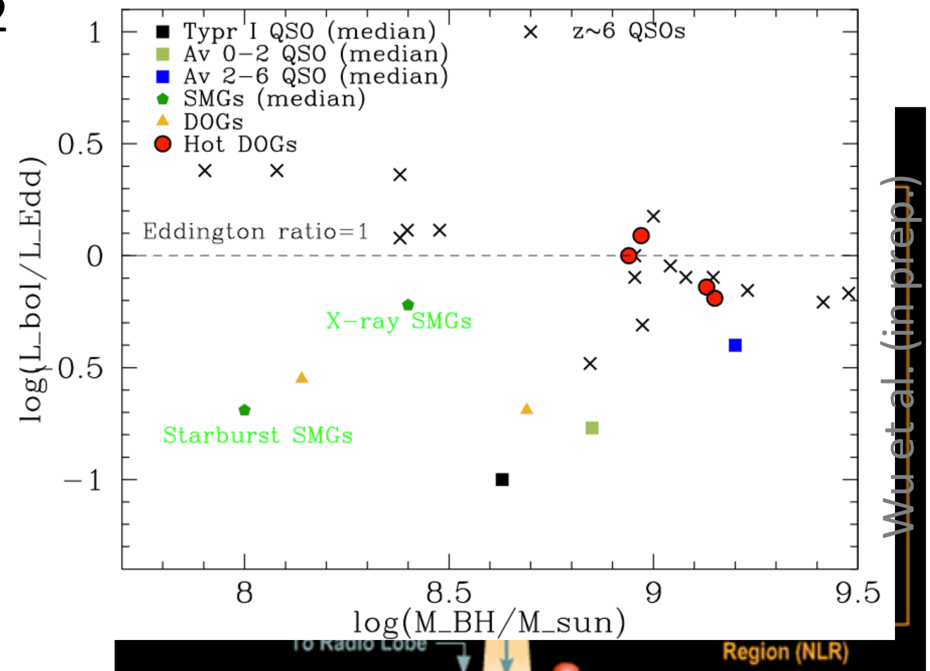


Modified from Assef et al (2014)

SMBH Mass and Eddington Ratios

Keck MOSFIRE and Gemini FLAMINGO2 spectra of Hα





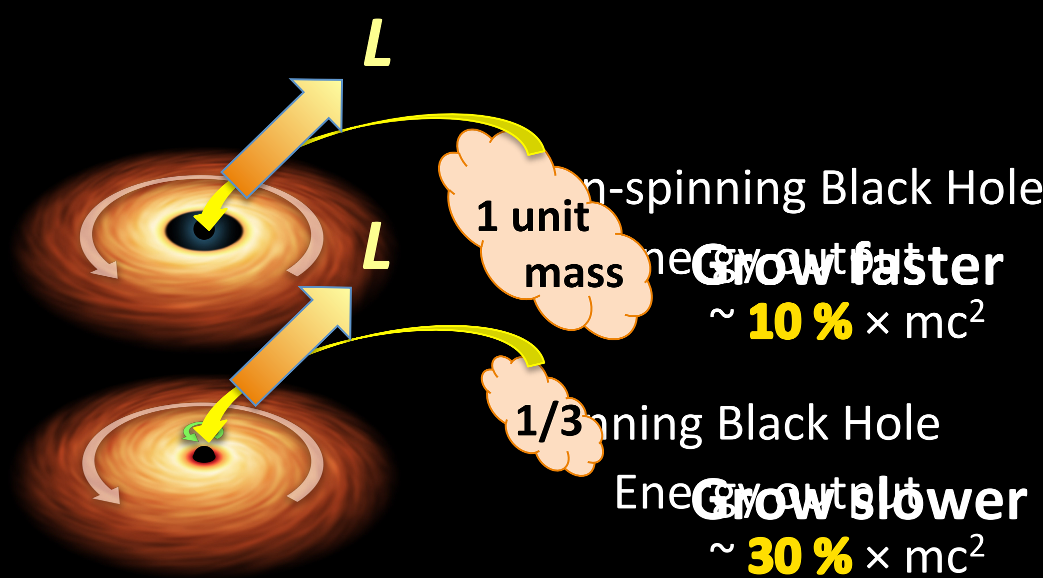
$$M_{BH} \sim M_{Eddington} = \frac{L_{total}}{3.3\times10^4\, L_{Sun}}\, M_{Sun}$$

$$M_{BH} \propto \sigma^2 L^{1/2}$$

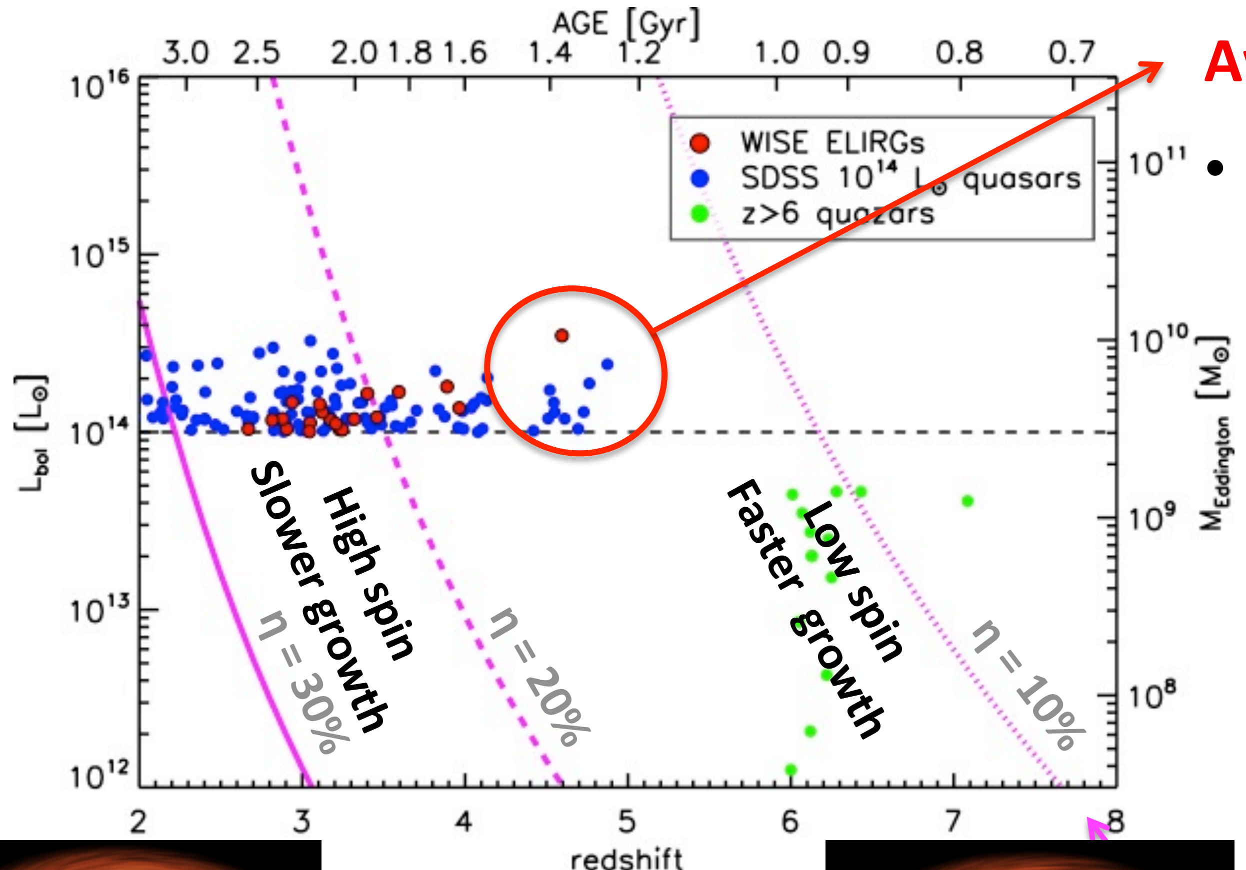
(See Jingwen Wu's poster #37)

SMBH Accretion History

- Spinning black holes can radiate more efficiently (η ~ **30%**)
- Spinning black holes accrete mass at low rate
- **Spinning black holes grow slower than non-spnning black holes**

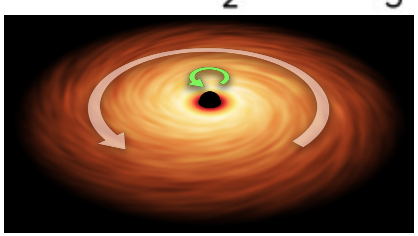


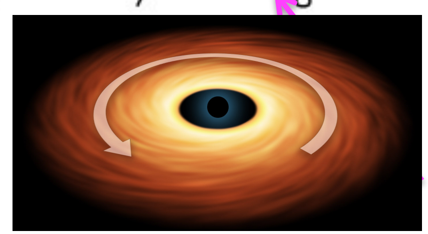
SMBH Accretion History



Averaged η < 15%

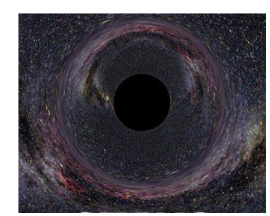
- Black holes in ELIRGs are constantly at **low spin!**





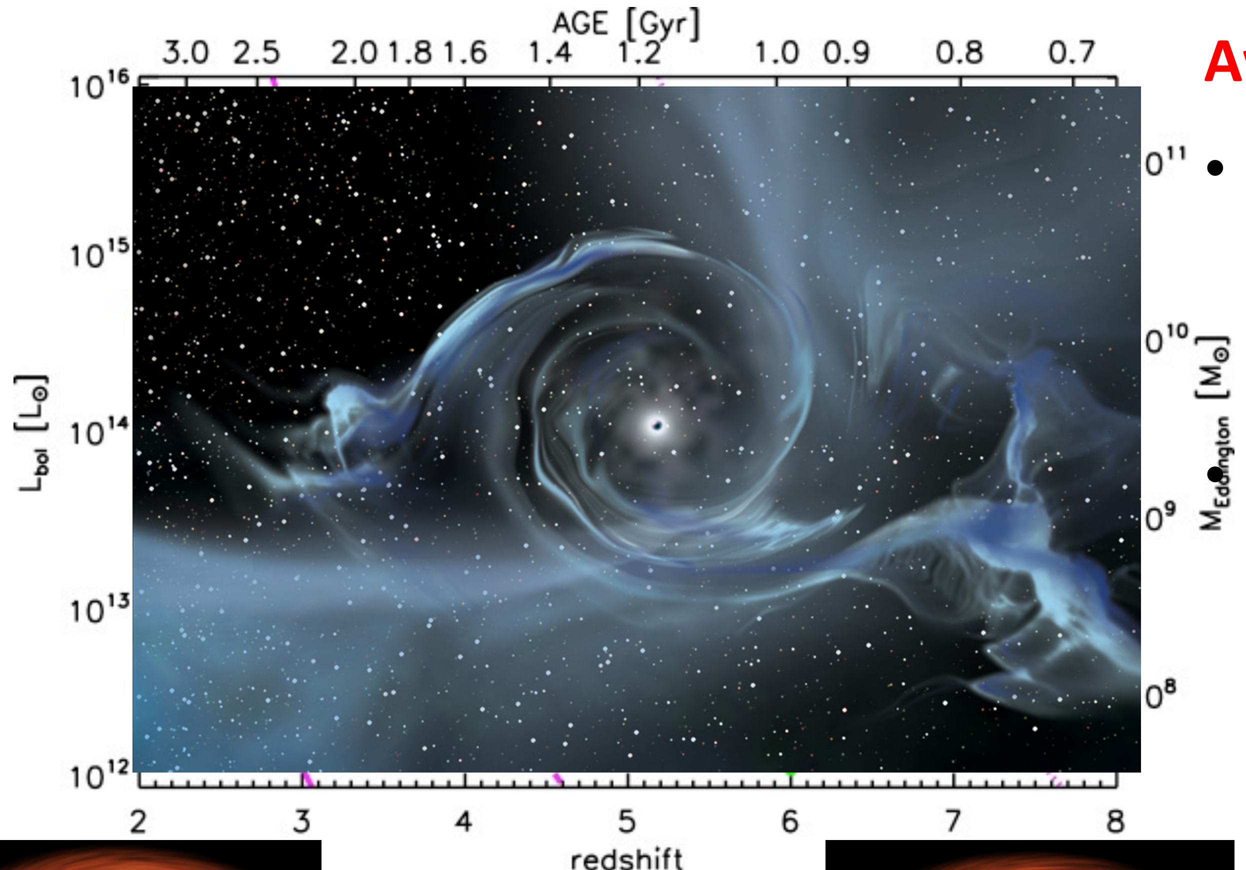
Age of Universe
~ 200 Myr

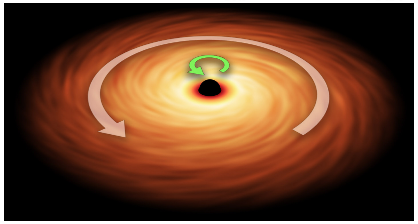
Black Hole Seed

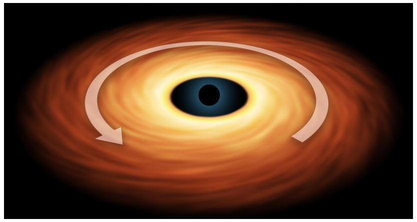


M_{Seed} ~ 1000 M_{Sun}

SMBH Accretion History







Averaged η < 0.15

- Black holes in ELIRGs are constantly at **low spin!**
- **Chaotic accretion history**

Summary

- We have discovered **"Hot Dust Obscured Galaxies"**, or **Hot DOGs**
  - Selected from "W1W2 Dropout" selection criteria
  - They are intrinsically luminous (HyLIRGs, $L_{bol} > 10^{13}\ L_{\odot}$), and their infrared luminosity comes from hot dust emission
  - They are radiating at Eddington limit (Jingwen Wu's Poster #37)
  - They are have comparable number densities as luminous quasars population (Roberto Assef's talk on Thursday!)
- We have found **the Most Luminous Infrared Galaxies**!
  - Total **20 Extremely Luminous Infrared Galaxies (ELIRGs)** in Hot DOG sample
  - **W2246-0526** has intrinsic $L_{bol} = 3.5 \times 10^{14}\ L_{\odot}$, making it the most luminous galaxy discovered in our search
  - ELIRGs are likely to be powered by **black holes with mass > 3×10^{9} M_{Sun}**
- For the most luminous ELIRGs, their black holes seems to have low spin and **chaotic accretion history**