The Hunt for the Most Luminous Galaxies with WISE

Chao-Wei Tsai

The Hunt for the Most Luminous Galaxies

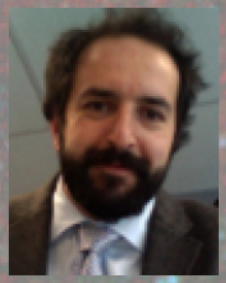
Chao-Wei Tsai (UCLA)

Peter Eisenhardt (JPL)

Jingwen Wu (**NAOC**)

Andrew Blain (**Leicester**)

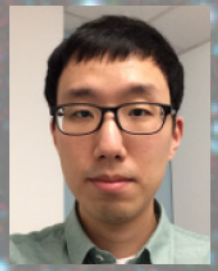
Ned Wright (UCLA)



Daniel Stern (JPL)

Roberto Assef (**Diego Portales**)

Tanio Santos-Diaz (**Diego Portales**)



Hyunsung Jun (**KASi**)

JPL
- Leonidas Moustakas
- Fengchuan Liu
- Amy Mainzer
- Carrie Bridge

Caltech
- Jack Sayers

UCLA
- Ian McLean

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**)

WISE

UCLA Graduate students, 2017, August (~ 10 years + 1 week ago)
Around 5:00 pm

Mike McElwain
(GSFC)

Chris Howard
(Google)

Emily Rice
(CSI/CUNY)

Ryan Mallery
(Rebellion Photonics)

Erin Smith
(GSFC/Ames)

Kathy Kornei
(OMSI)

Louis Levenson
(McDermott Will & Emery)

Jessica Lu
(UC Berkeley)

Alex Jarvis
(Disney)

Carl Melis
(UCSD)

Claire Tsai
(Castillero Middle)

Alaina Henry
(GSFC)

Chao-Wei Tsai
(UCLA)

Eugene Chen
(Adobe)

Shelley Wright
(UCSD)

Quinn Konopacky
(UCSD)s

Tuan Do
(UCLA)

Sylvana Yelda
(Gravity)

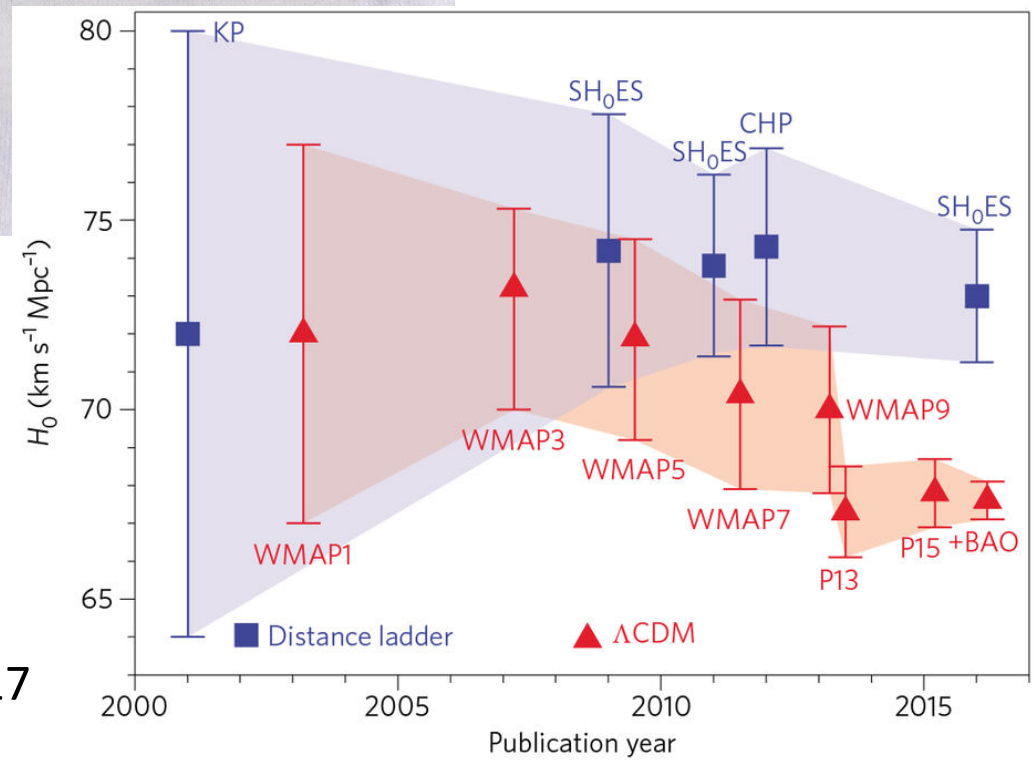
Xi Chen
(Caltech)

Chun Ly
(MMT)

Today

"Well, there are sort of two classes of people in the world — those that know that H_o has always been really uncertain and those that were born too late."

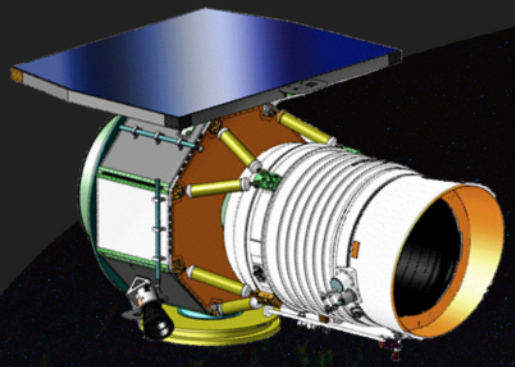
-Ned Wright



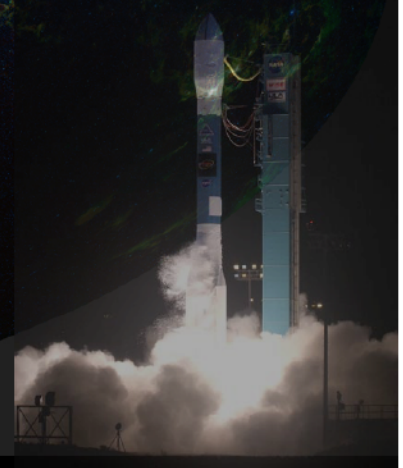
Wendy Freeman
Nature Astronomy, 2017

WISE

Wide-field Infrared Survey Explorer



Launched on December 14 2009,
WISE mapped the sky in infrared light, searching for
the nearest and coolest stars,
the origins of stellar and planetary systems,
and **the most luminous galaxies in the Universe**.



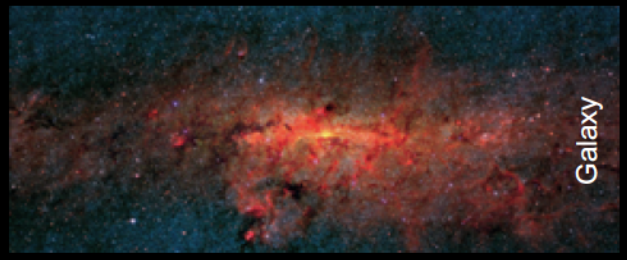
WISE delivered to the scientific community:

Over 1.5 million images covering the whole sky in
4 infrared wavelengths: **3.4, 4.6, 12, 22 micron**

Catalogs of ≈ **750 million objects seen in these 4 wavelengths**


asteroids


brown dwarfs

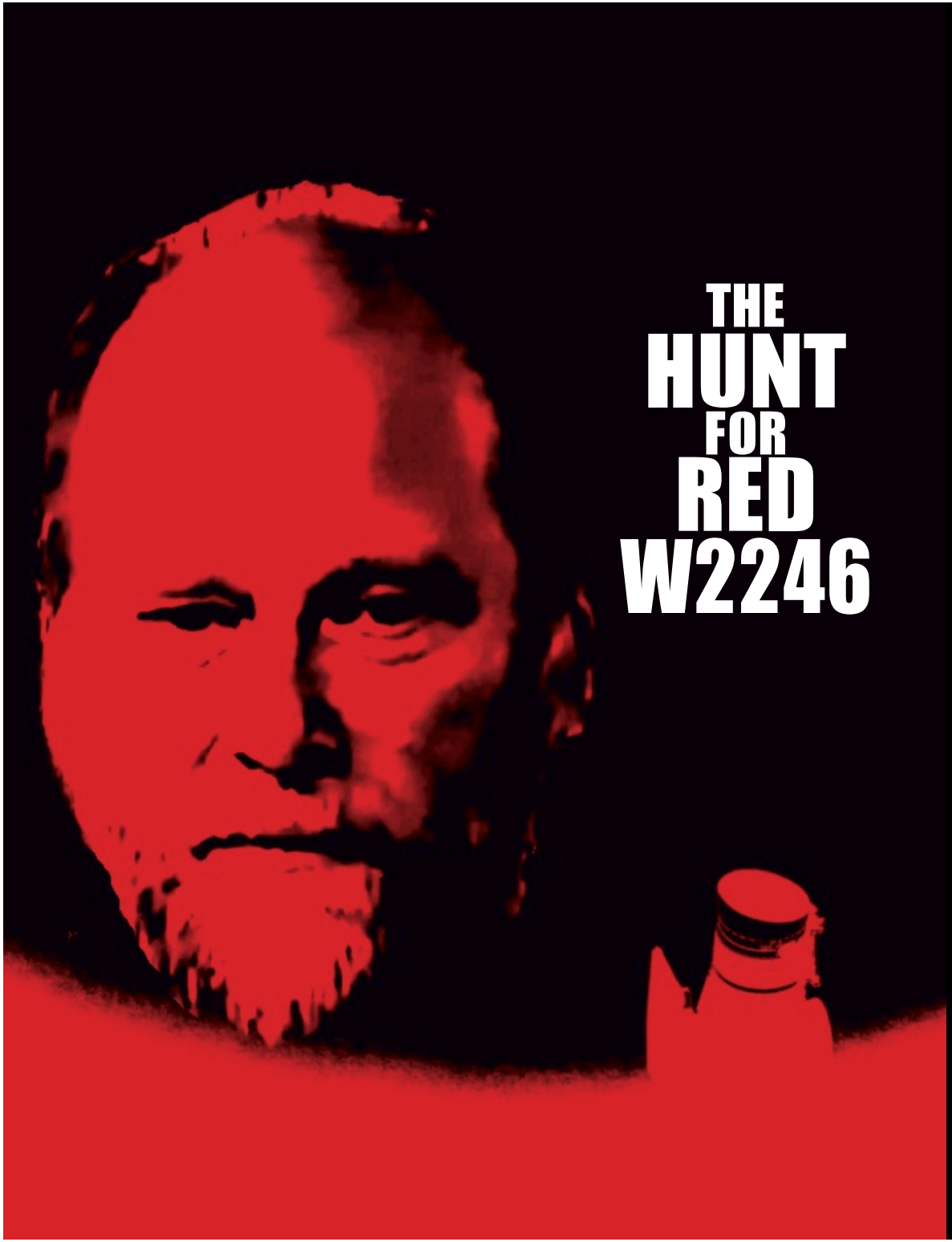

Galaxy


ULIRGs

wise.astro.ucla.edu

WISE All-Sky Data Release

WISE Science Data Center
IPAC, Caltech
March 14, 2012



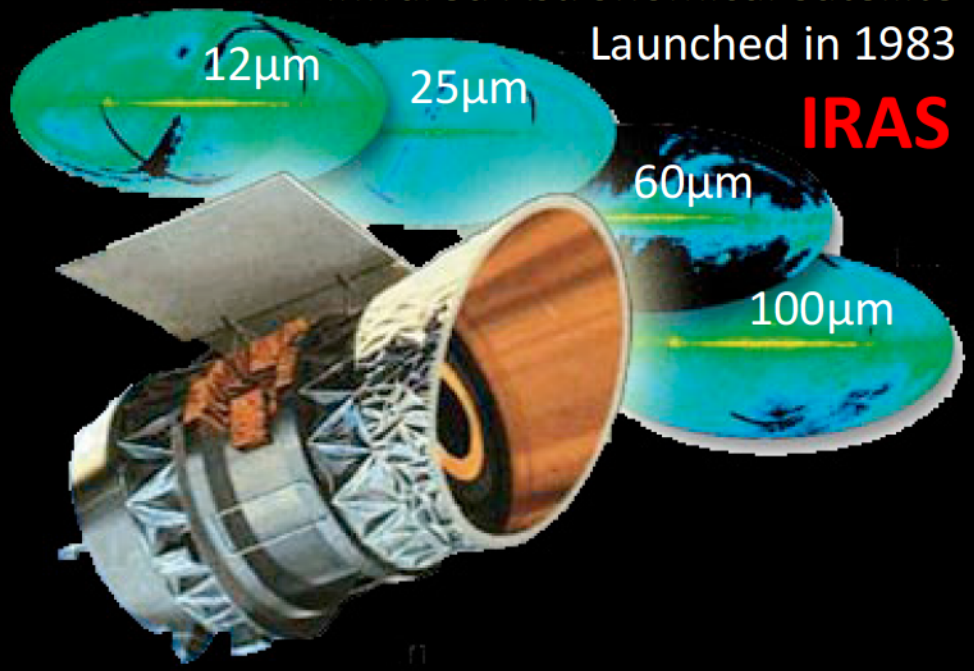
THE HUNT FOR RED W2246

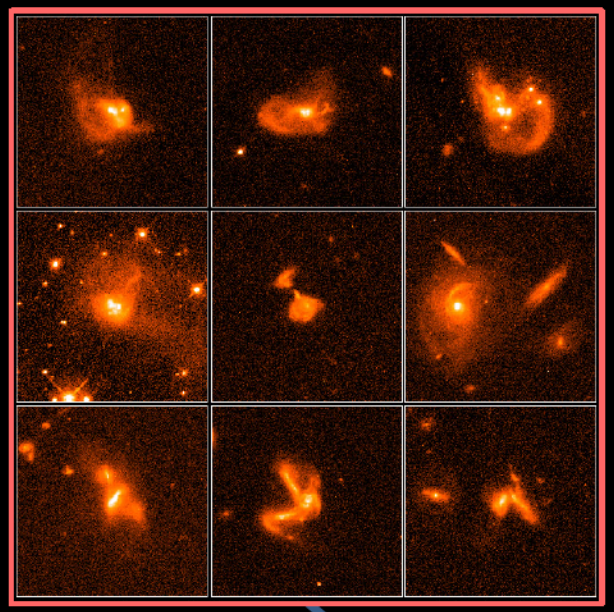
THE HUNT FOR THE MOST LUMINOUS GALAXY IS DONE.


THE
HUNT
FOR
RED
W2246
THE
HUNT
FOR
RED
OCTOBER
Paramount Pictures
(1990)

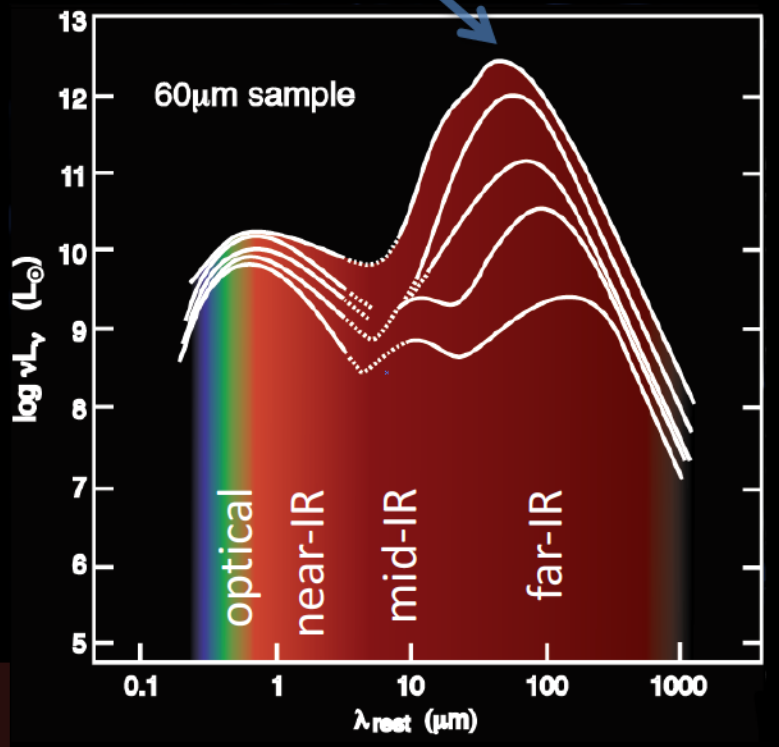
Infrared Astronomical Satellite
Launched in 1983

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

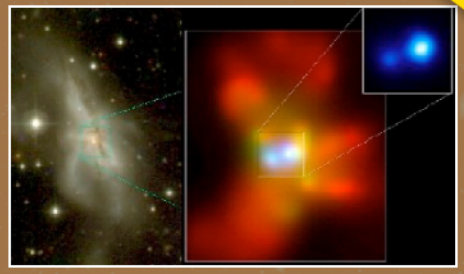
A bit of history – 1983

Merger Driven Galaxy Evolution

Galaxy Merger

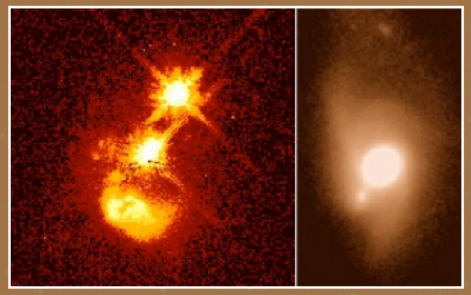
- gas-rich merger

Coalescence/ULIRG



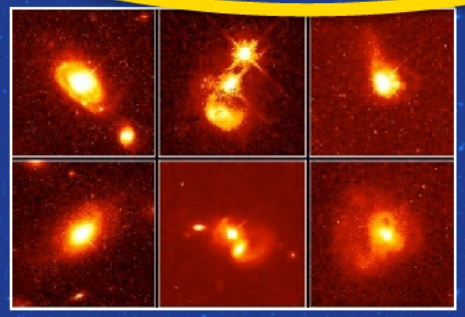
- gas inflows to center
- star formation triggered
- dusty starburst dominates luminosity

"Blowout"



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

Quasar



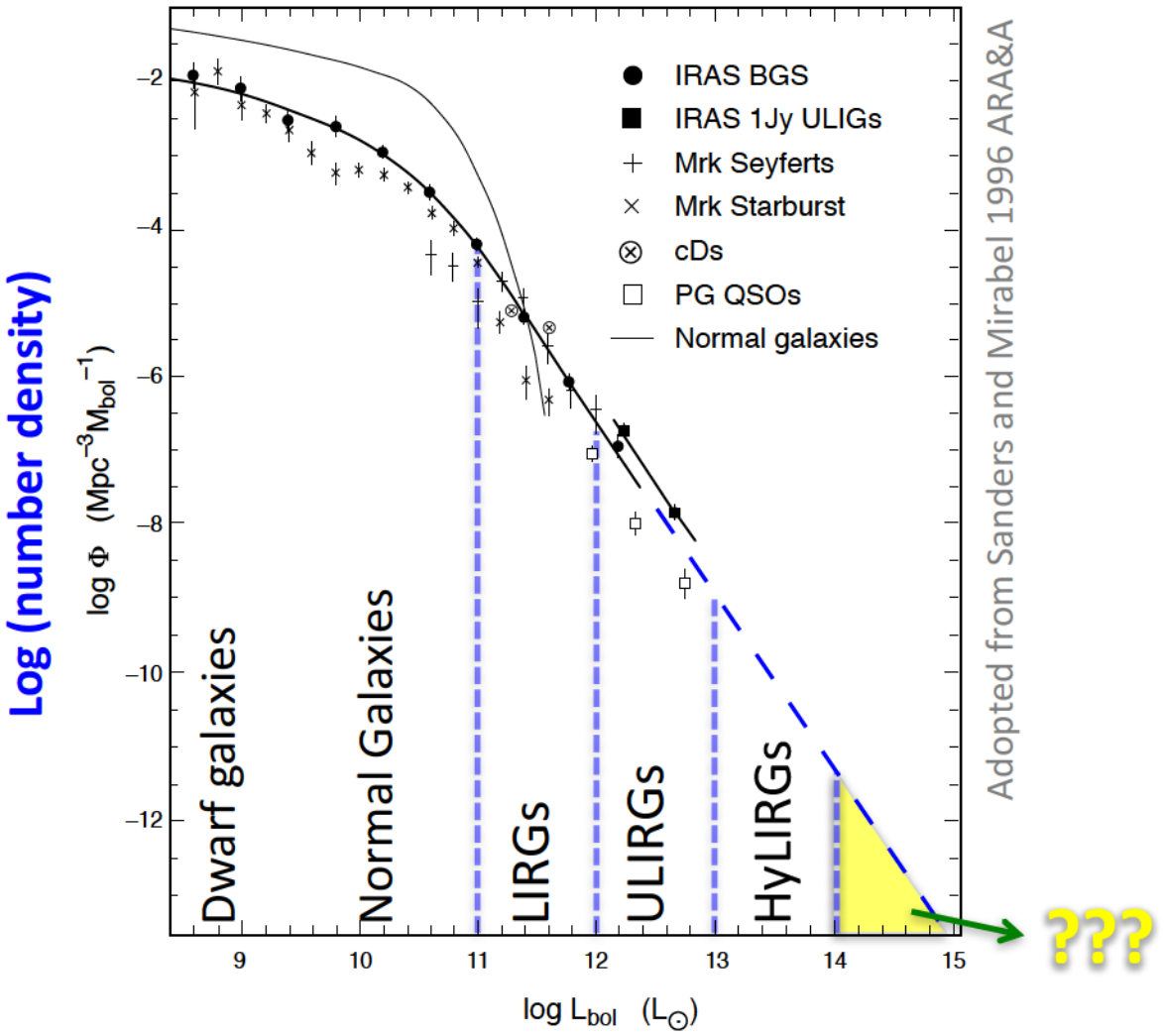
- dust removed
- traditional optical QSO

Elliptical

- red and dead

Sanders et al. (1988)
Hopkins et al. (2008)

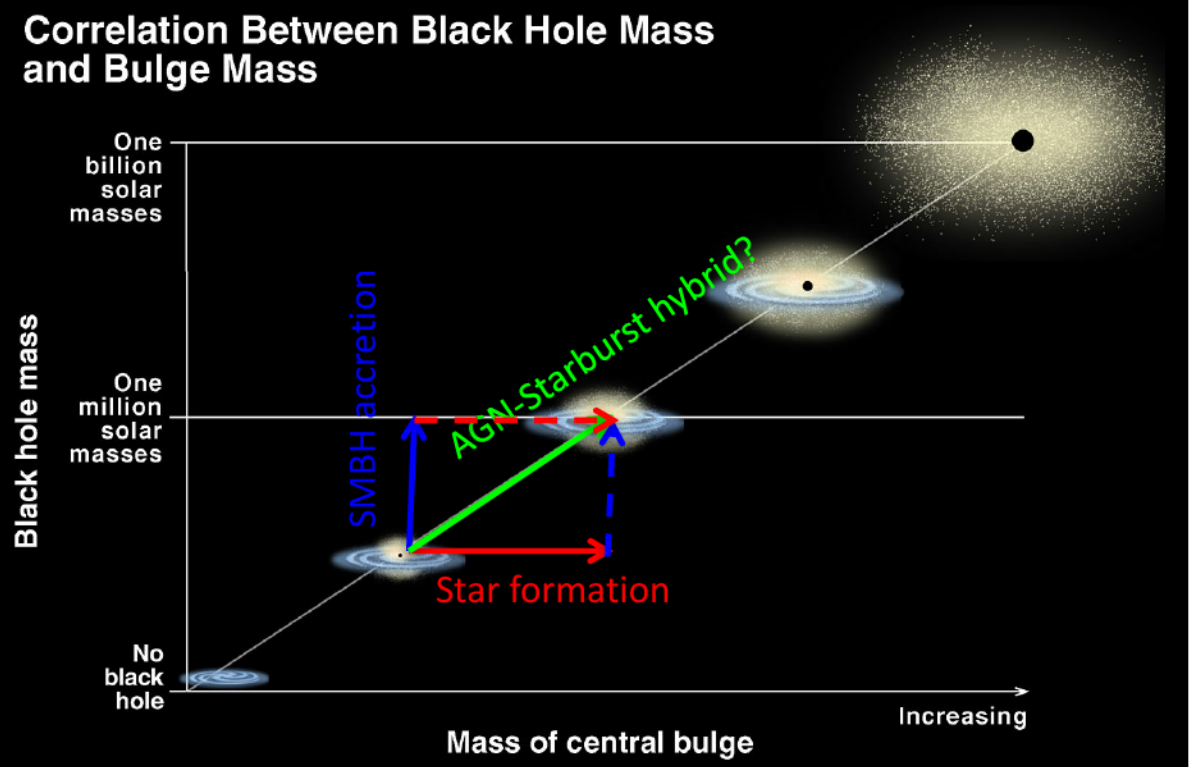
Tip of the Luminosity Function



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!

Tip of the Luminosity Function

THE ASTROPHYSICAL JOURNAL, 424:L65–L68, 1994 April 1

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

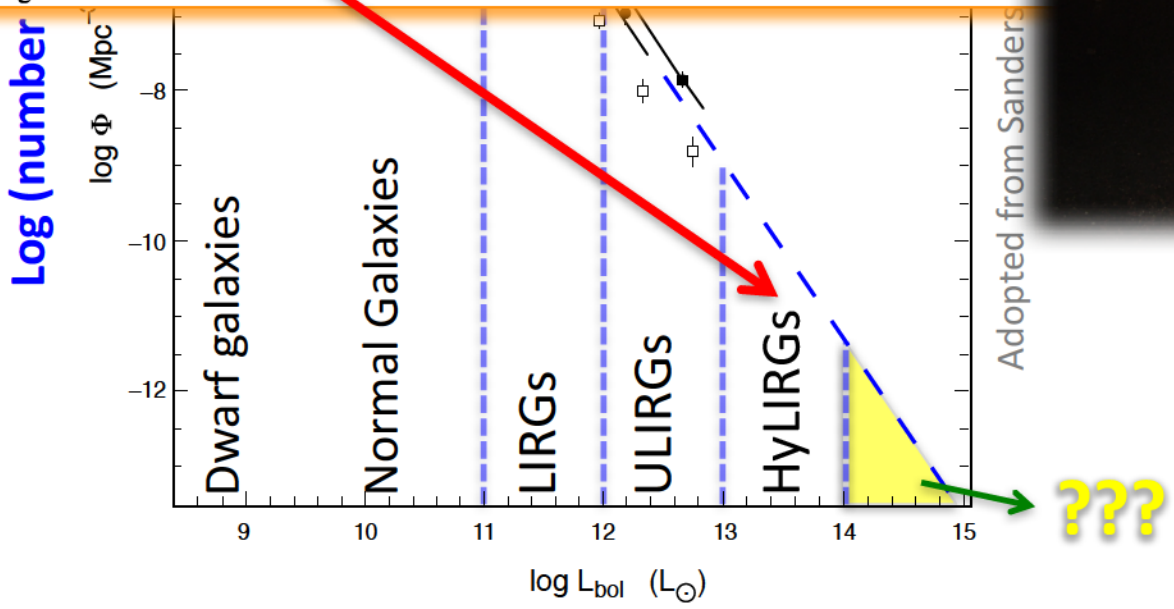
ROC M. CUTRI,[2] JOHN P. HUCHRA,[3] FRANK J. LOW,[2] ROBERT L. BROWN,[4] AND PAUL A. VANDEN BOUT[4]

Received 29 October 1993; accepted 1994 January 6

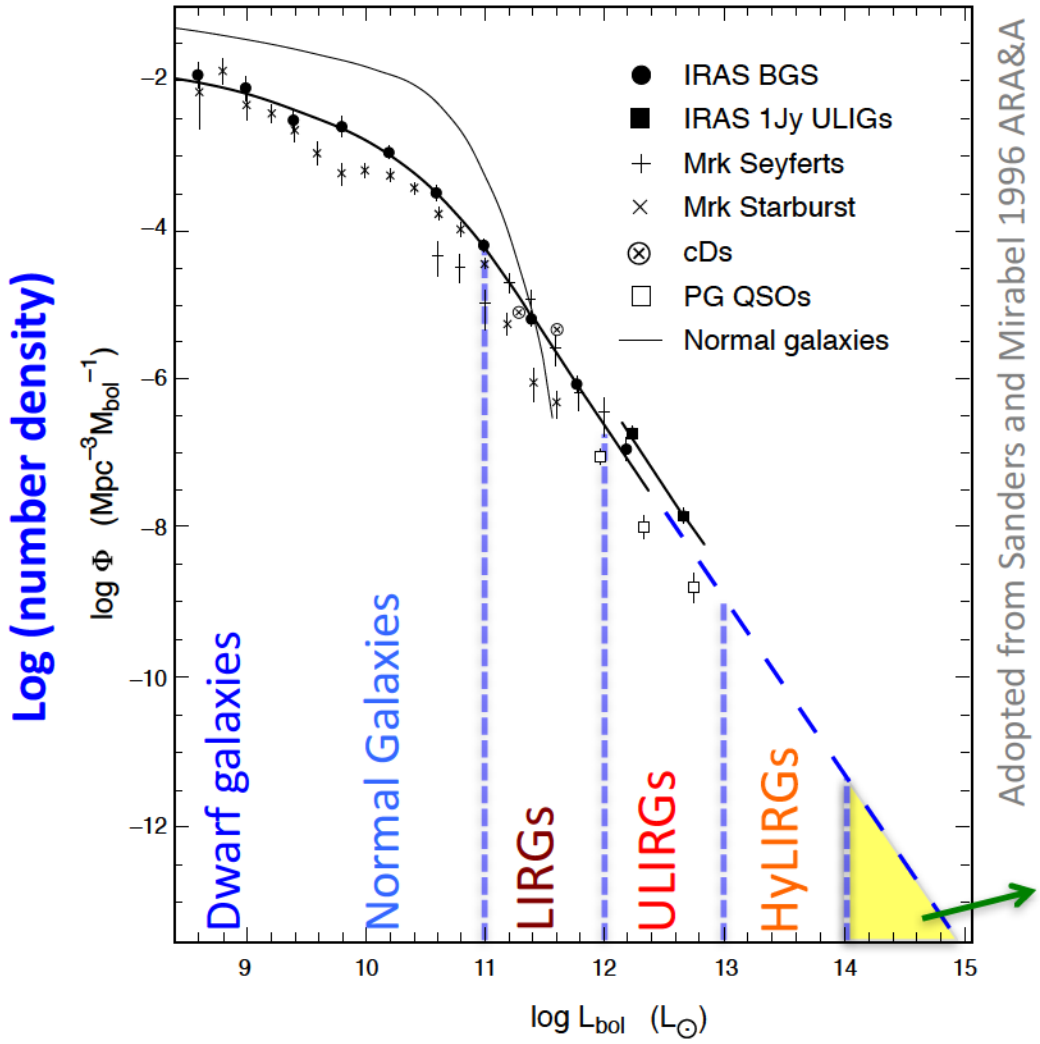
ABSTRACT

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 – Extreme Luminous Infrared Galaxies (**ELIRGs**)

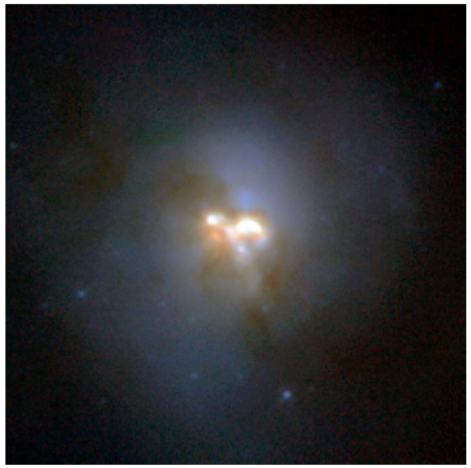


Extremely Luminous InfraRed Galaxies

ELIRGs

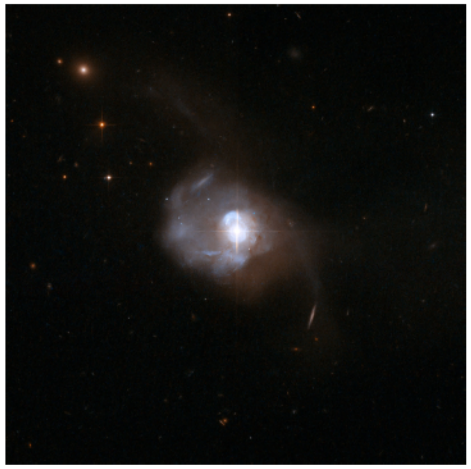
Hunt for ELIRGs – with WISE

Starburst Dominated

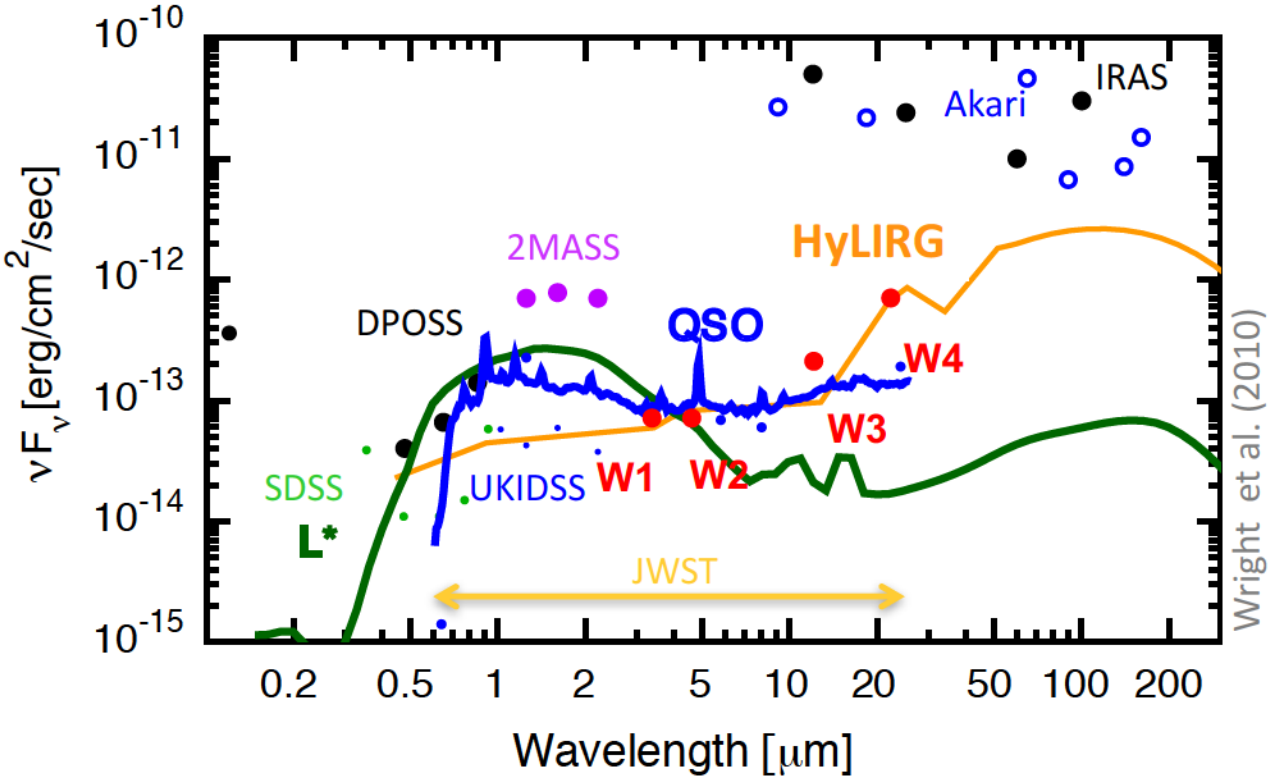


Arp220 x **100**?

AGN dominated



Mrk231 x **100**?



L* at z = 0.33

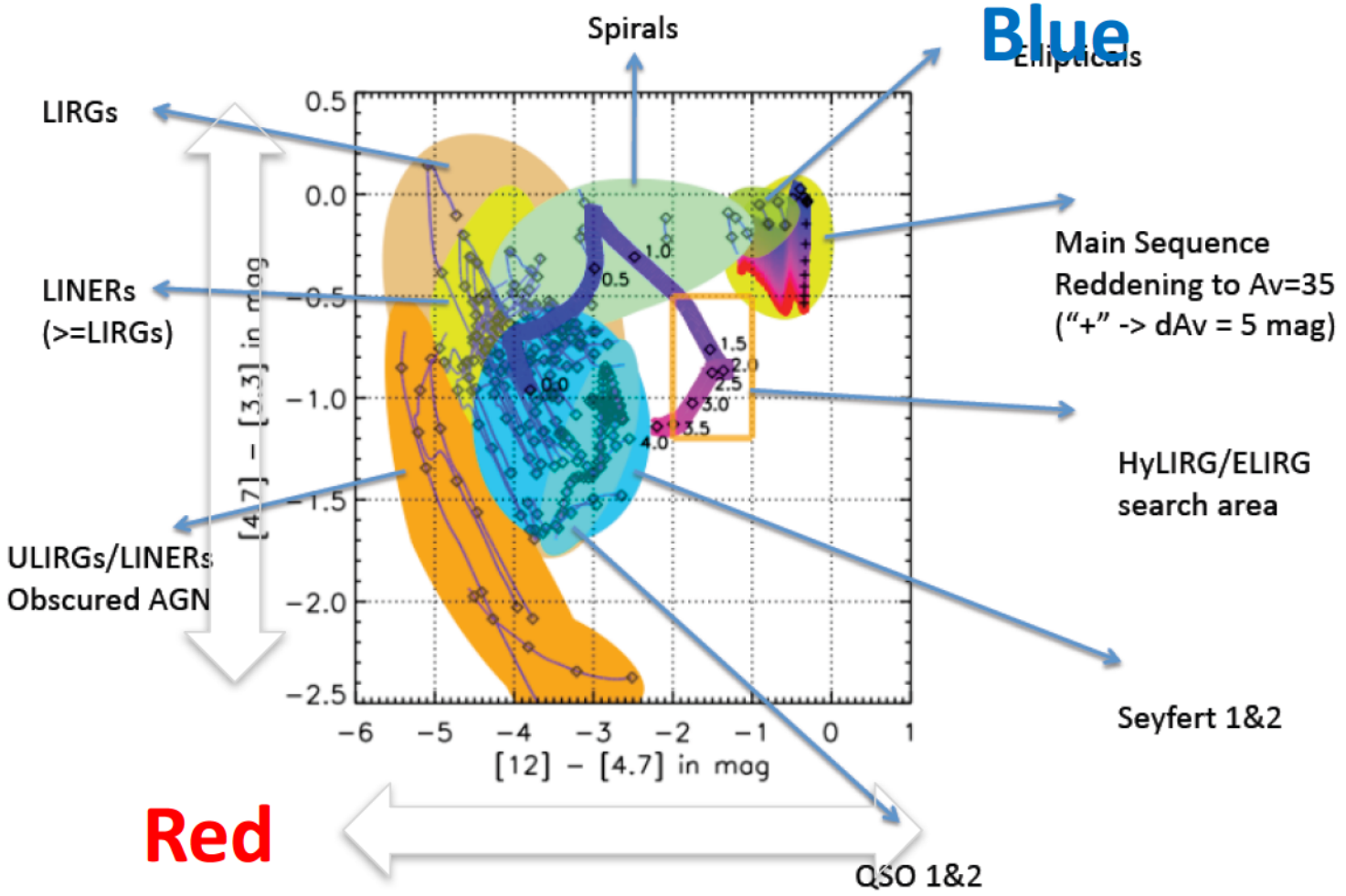
QSO J1148+5251 at z = 6.4

HyLIRG: FSC 15307+3253 at z = **3**

Real SED **x 3**, L = 6x10^{13} L_{Sun}

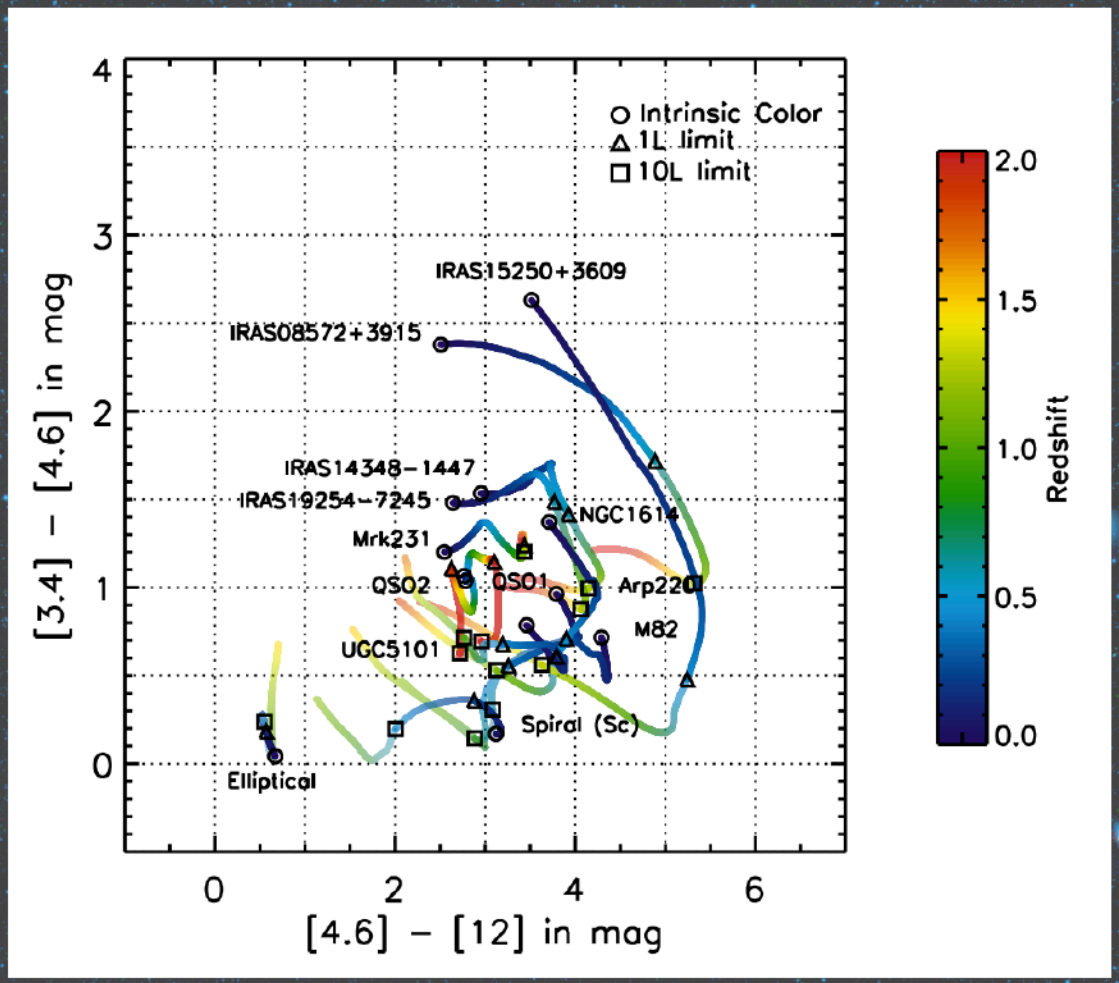
Ah… How to Identify ELIRGs?

WISE Colors of U/Hy/E LIRGs



Based on GRASIL SED models and SWIRE SED templates

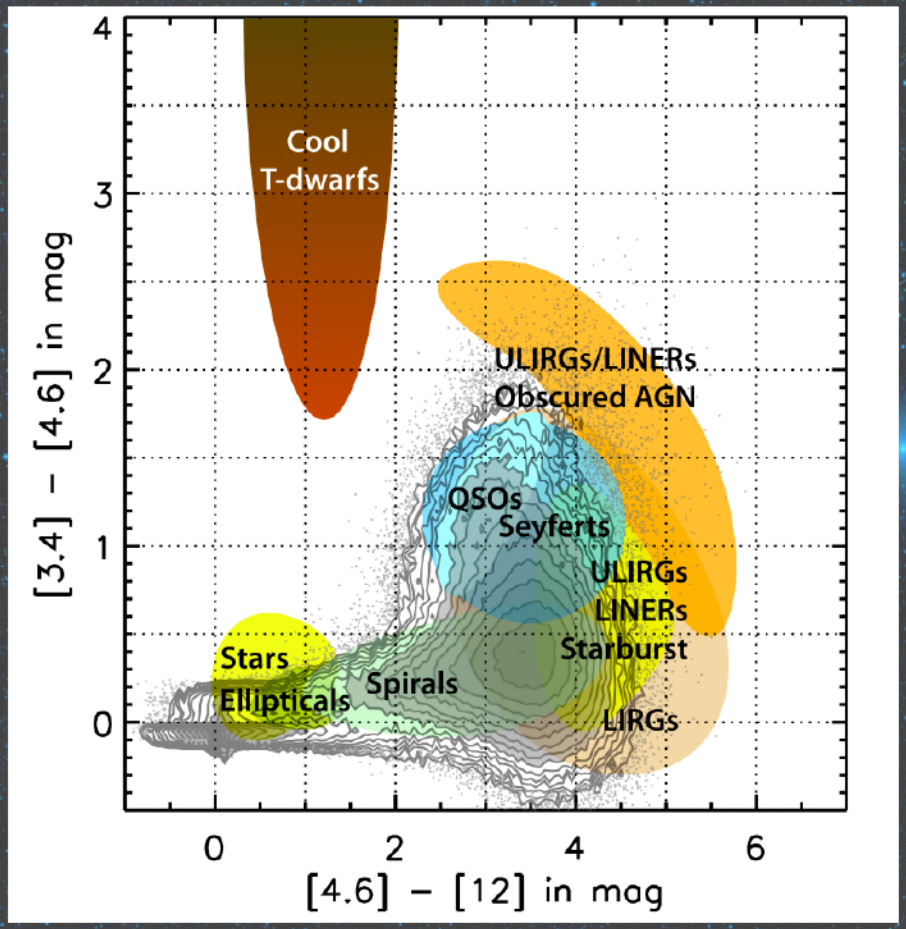
Ah… How to Identify ELIRGs?



Hundred millions of WISE sources!

How to find the most luminous galaxies??

Inhabitants of WISE Color Space



Hundred millions of WISE sources!

How to find the most luminous galaxies??

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

The Astronomical Journal, 140:1868–1881, 2010 December doi:10.1088/0004-6256/140/6/1868

THE WIDE-FIELD INFRARED SURVEY EXPLORER (WISE): MISSION DESCRIPTION AND INITIAL ON-ORBIT PERFORMANCE

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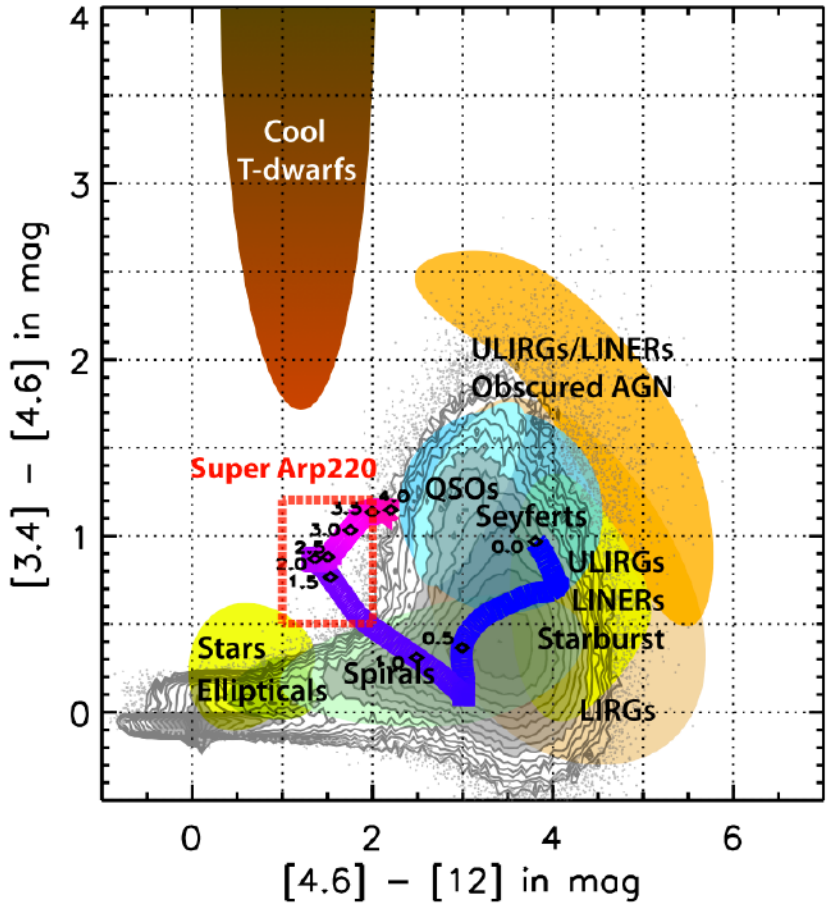
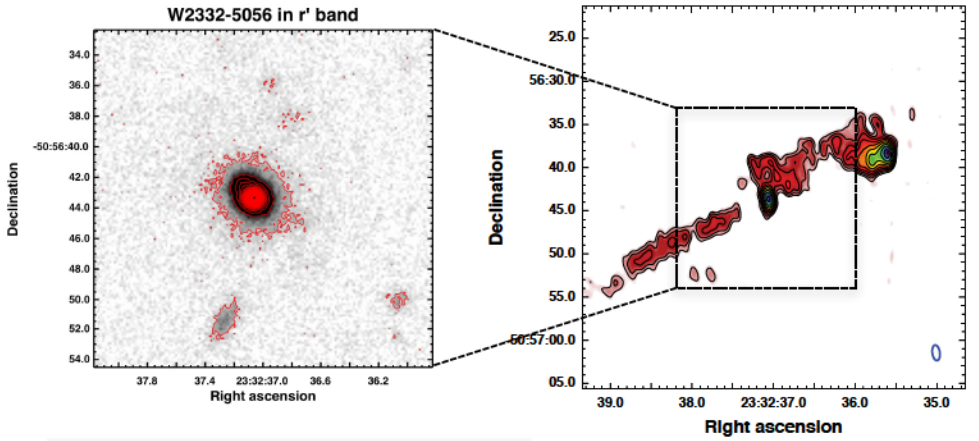
Received 2010 July 25; accepted 2010 September 22; published 2010 November 9

Searching for Most Luminous Galaxies

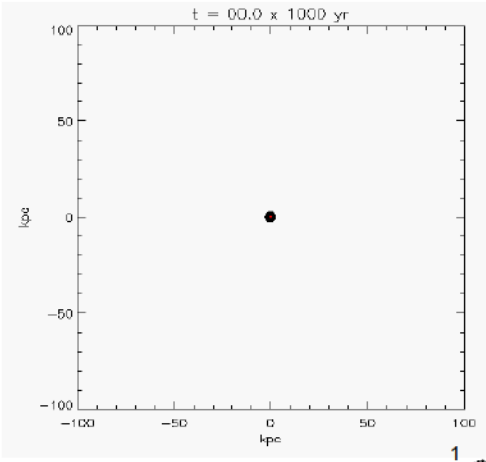


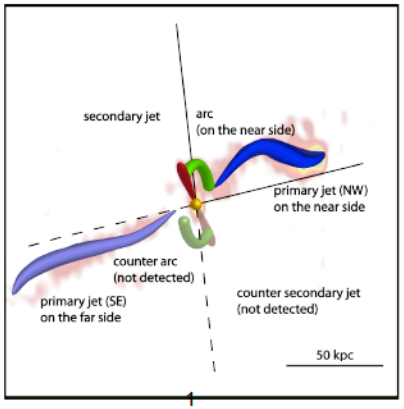
Based on SEDs

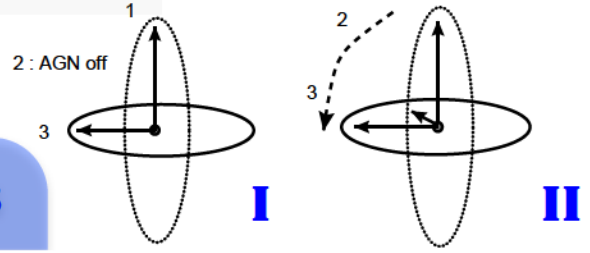
9 GHz Continuum



Tsai, Jarrett et al. (2013)



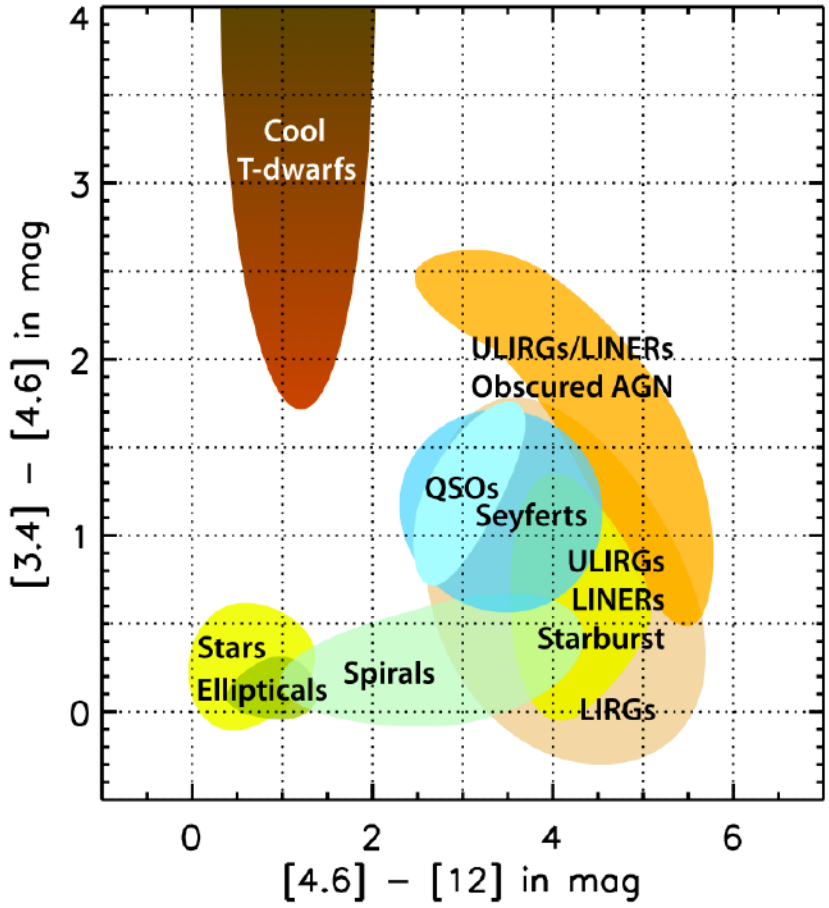


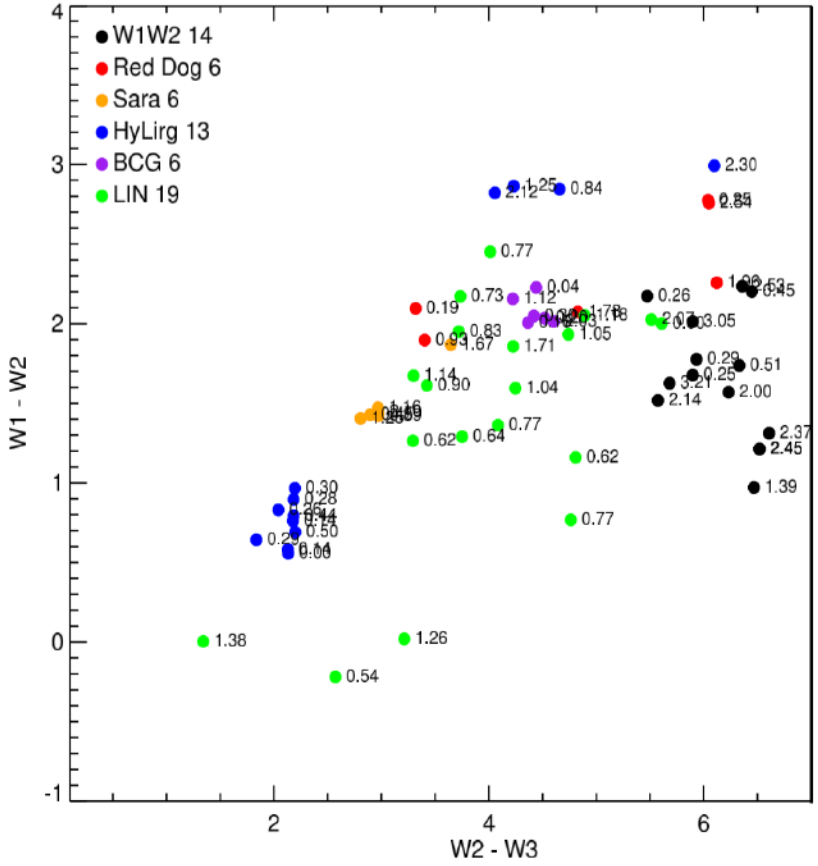


Possible Scenarios

Dennett-Thorpe+ 02

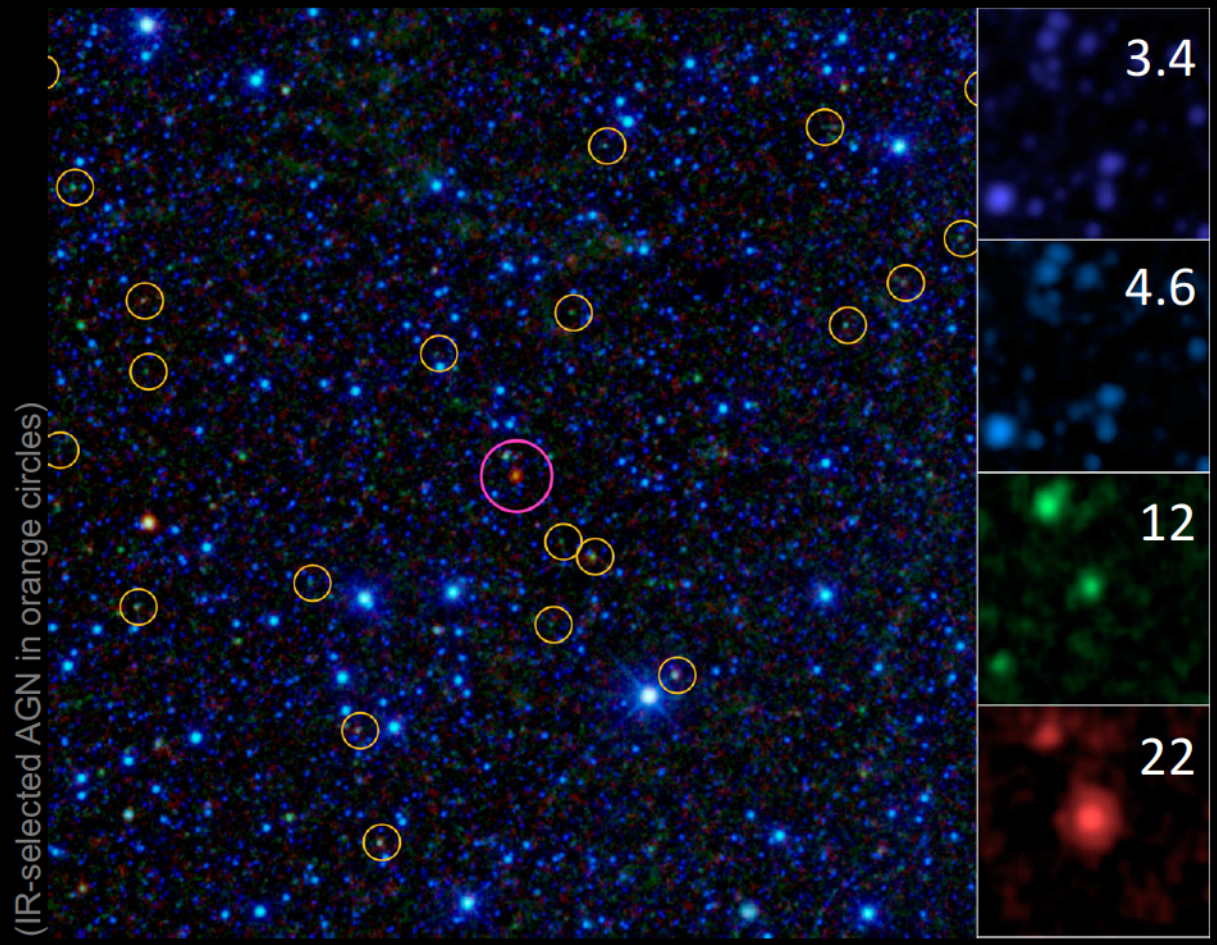
Inhabitants of WISE Color Space





Results from October 2010
Keck LRIS Optical Spectroscopic Follow-up

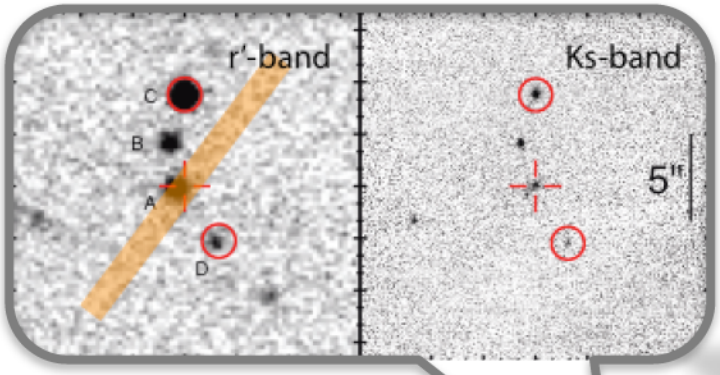
W1W2 Dropouts

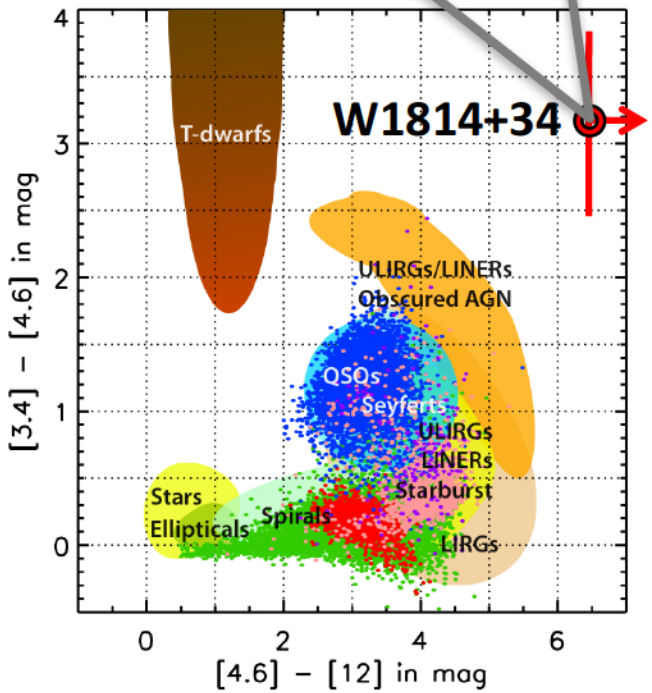


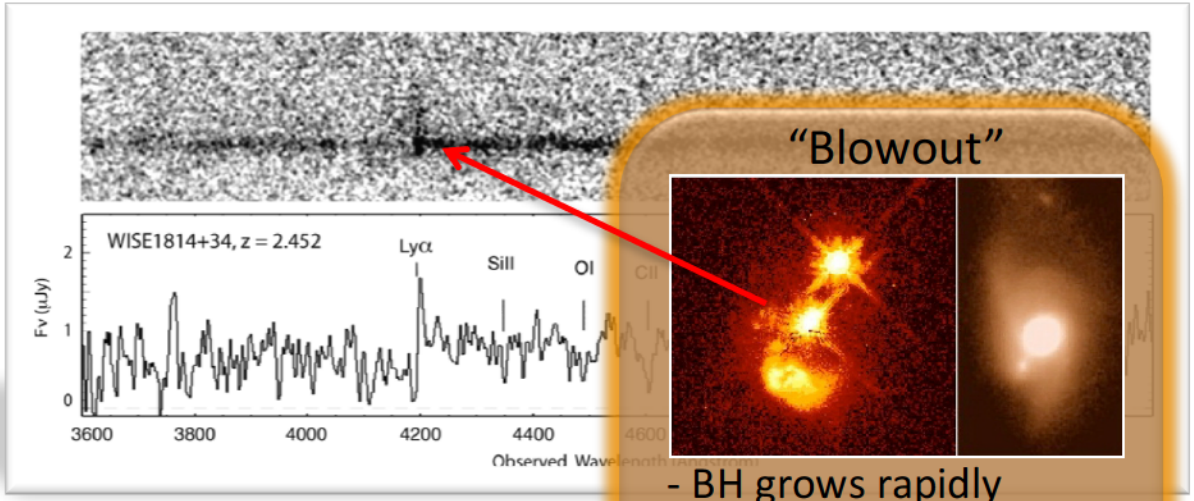
WISE objects well detected at **12 µm** and **22 µm**

faint or invisible at **3.4 µm** and **4.6 µm**

First HyLIRG Discovered by WISE







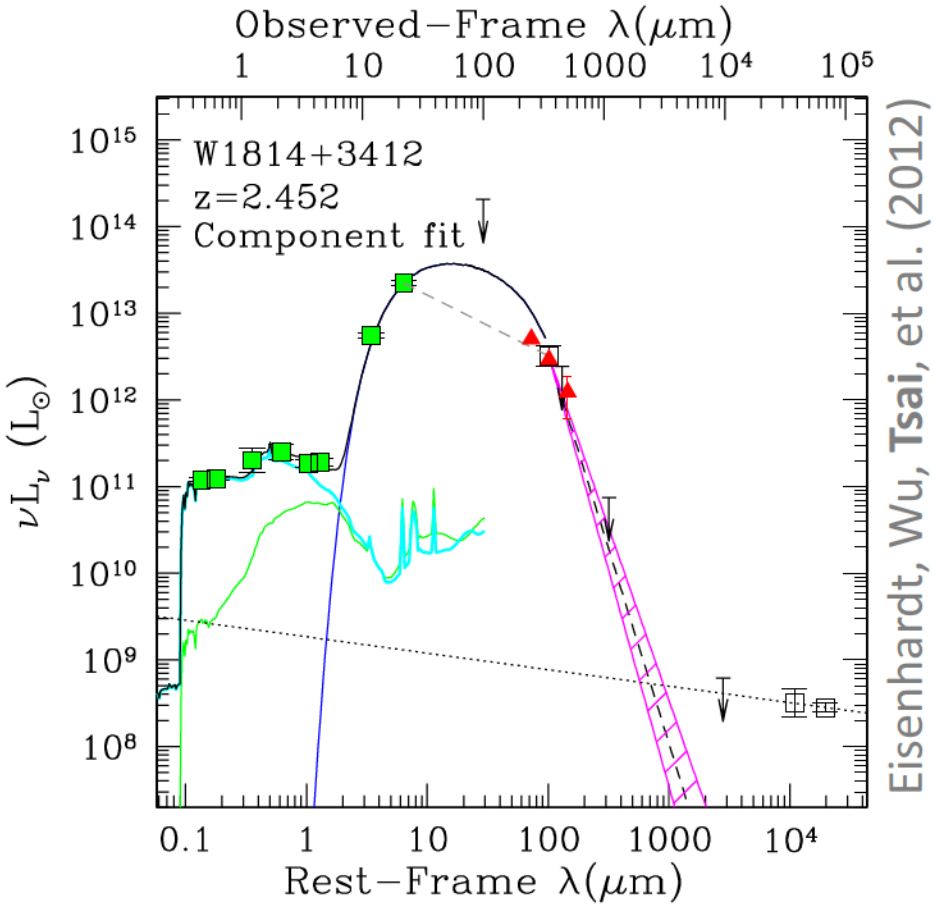
- BH grows rapidly
- Highly dust reddened
- dust/gas expelled

W1814+34

- **at z=2.452**
- (Eisenhardt et al. including Ned Wright 2012)
- Extended hydrogen gas emission ~100,000 light-years
- (Bridge et al. including Ned Wright 2013)

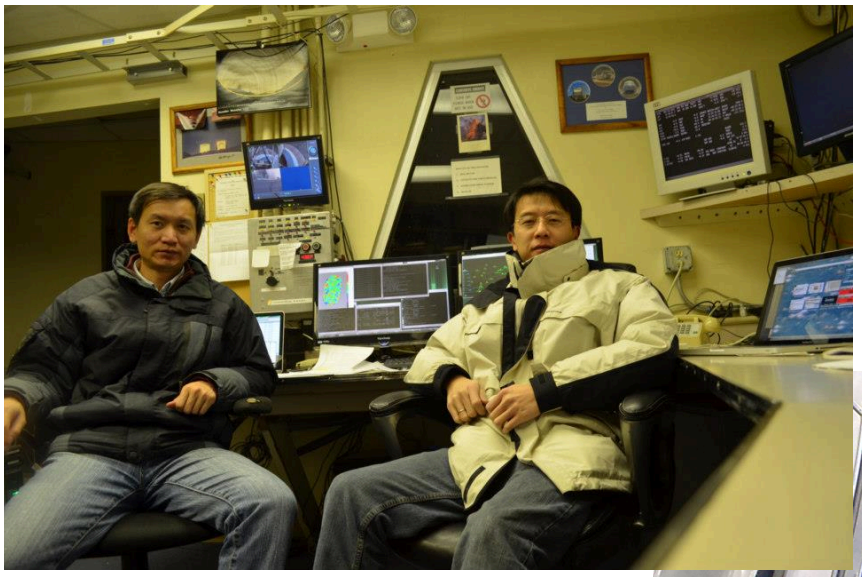
SED Decomposition of W1814+34

- 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



Follow-up Observation Programs

X-ray	UV –Optical	Near-IR	Mid-IR	Far-IR	Sub-mm – mm	Radio
NuSTAR	HST	HST	WISE & NEOWISE	Herschel	CSO	VLA
Chandra	Keck	Keck	Spitzer		JCMT	ATCA
XMM	VLT	VLT			SMA	GBT
Suzaku	Gemini N/S	Gemini N/S				
	Palomar	Palomar			CARMA	
	SOAR	SOAR			IRAM30m	
	WYIN	WYIN			PdBI	
	Lick	Lick			ALMA	
	Magellan	Bok				

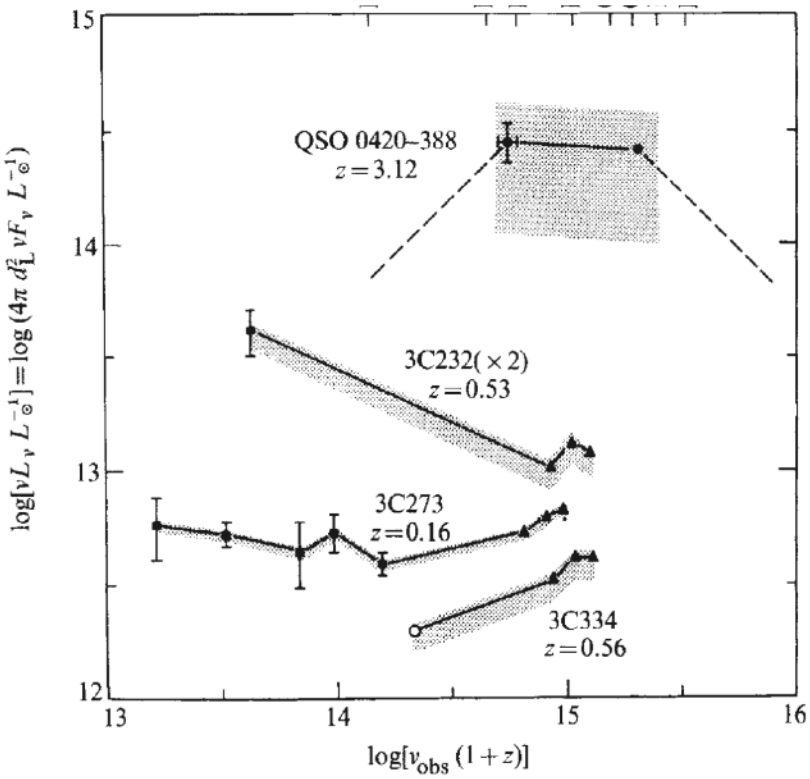


2010-2012
CSO submillimeter Follow-up

Often getting the optical
spectroscopic data
from Keck at the same time

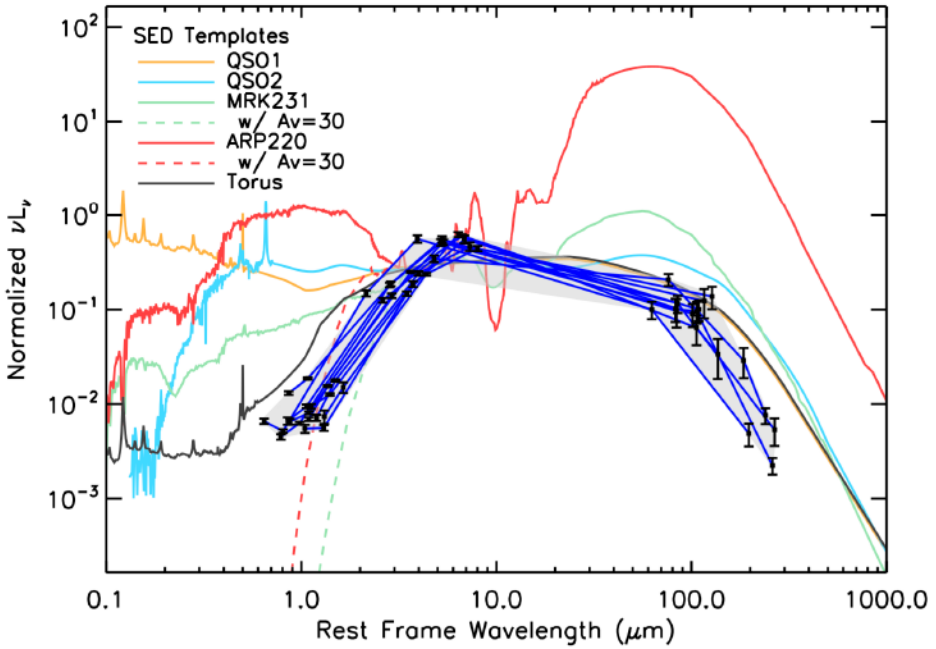
Far-IR Follow-up on W1W2 Dropouts

Infrared observations of the most luminous quasar



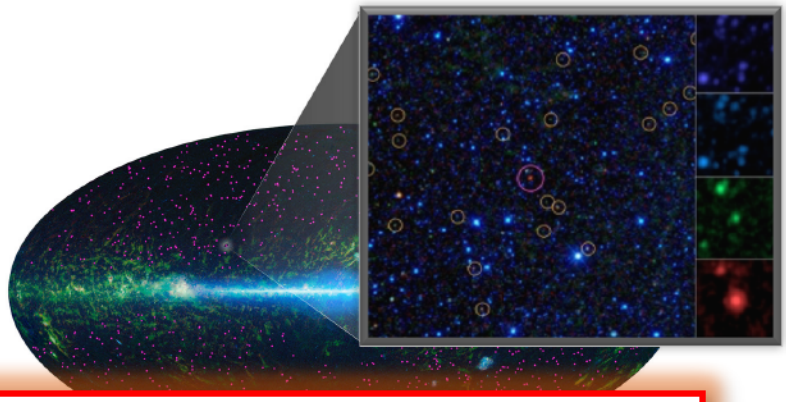
Wright and Kleinmann (1978, Nature)

Submm follow-up of WISE-selected Hyperluminous Galaxies



Wu et al. including Ned Wright (2012)

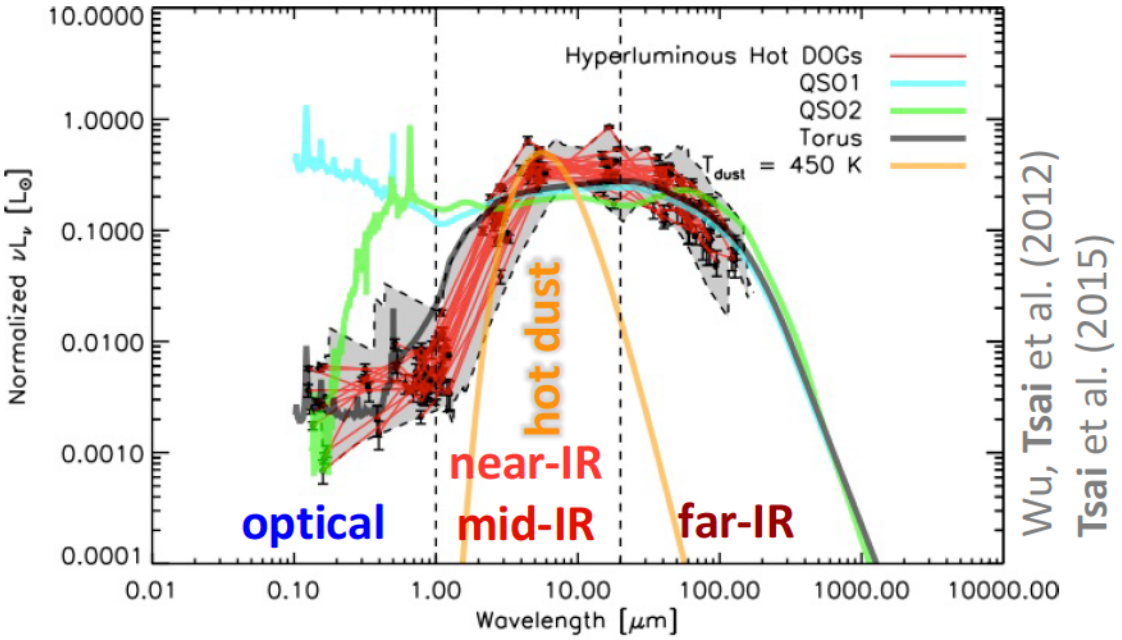
Far-IR Follow-up on W1W2 Dropouts



Hot Dust Obscured Galaxies

– Hot DOGs

(Dog Haus Pasadena)



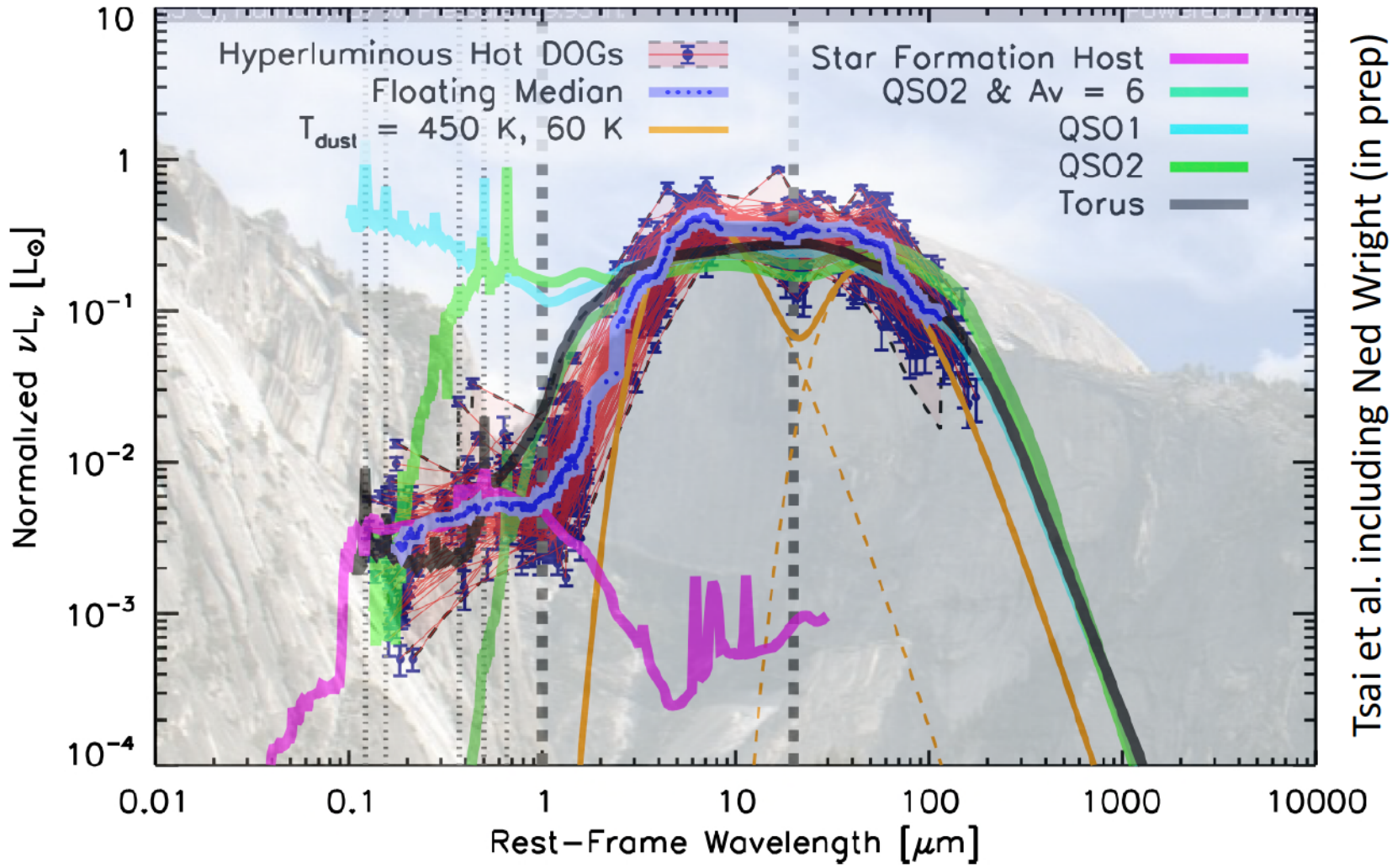
Wu, Tsai et al. (2012)
Tsai et al. (2015)

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

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

  (Hot DOGs)

Far-IR Follow-up on W1W2 Dropouts

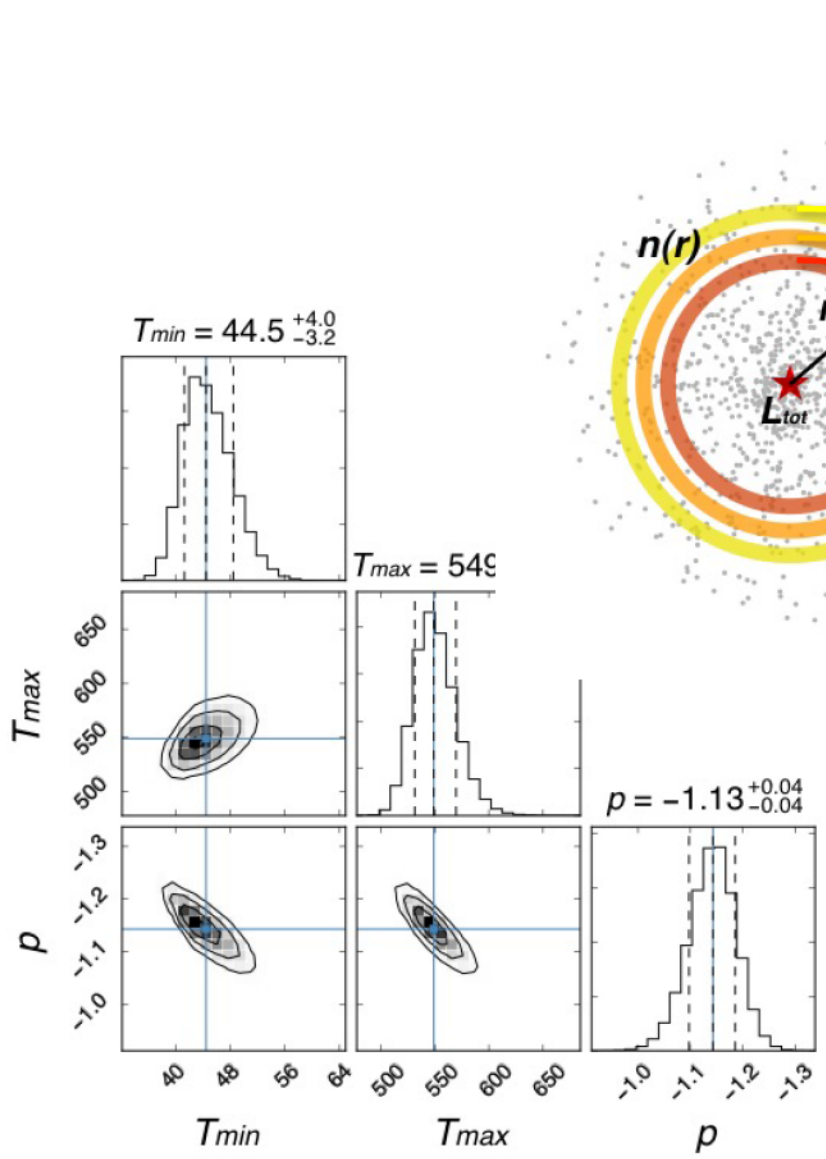


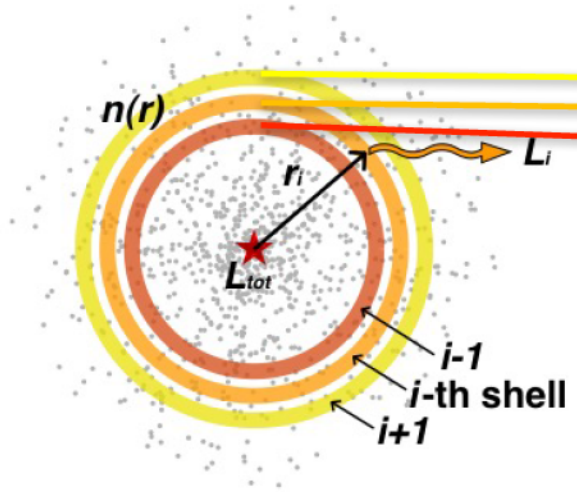
Yosemite "Half-Dome" shaped SED

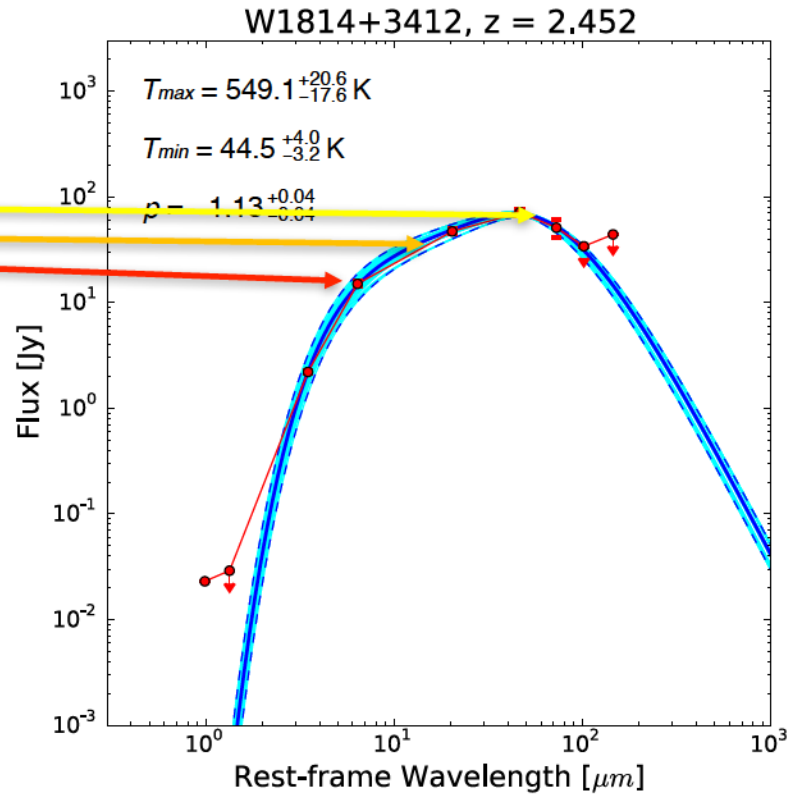
Far-IR Follow-up on W1W2 Dropouts

Yosemite "Half-Dome" shaped SED

Far-IR Follow-up on W1W2 Dropouts





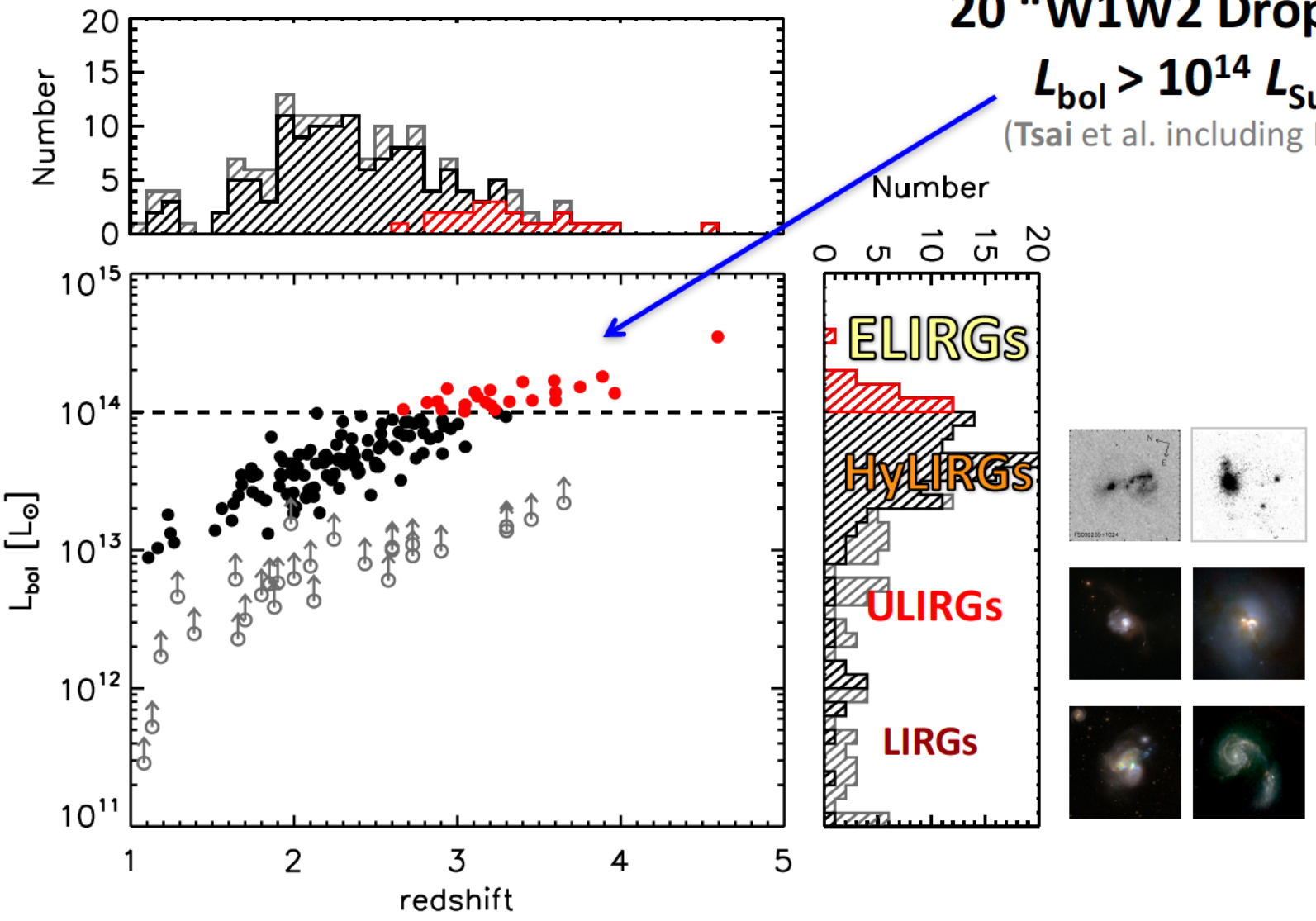


Tsai et al.
(in preparation)

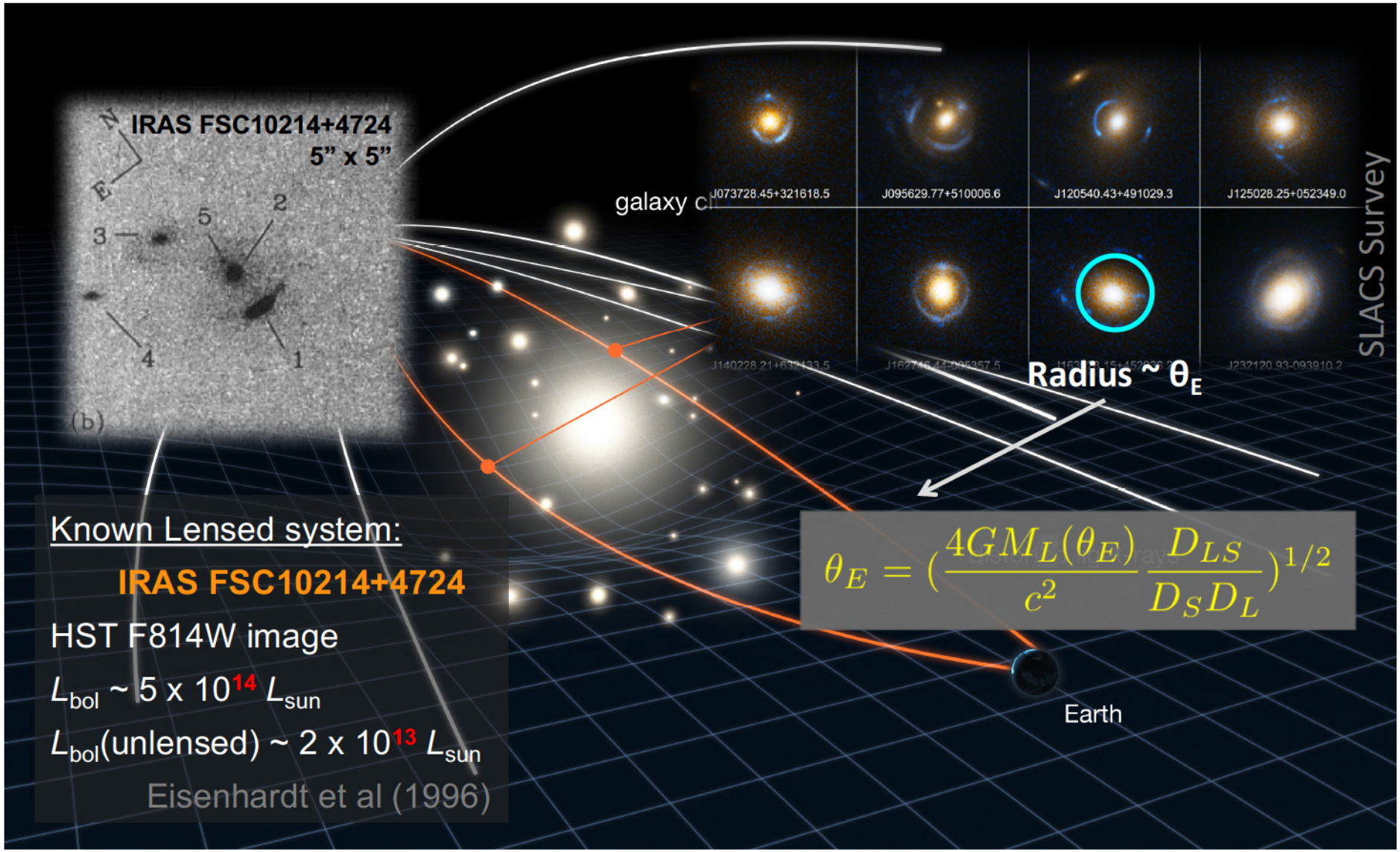
Mission Accomplished!

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

(Tsai et al. including Ned Wright 2015)

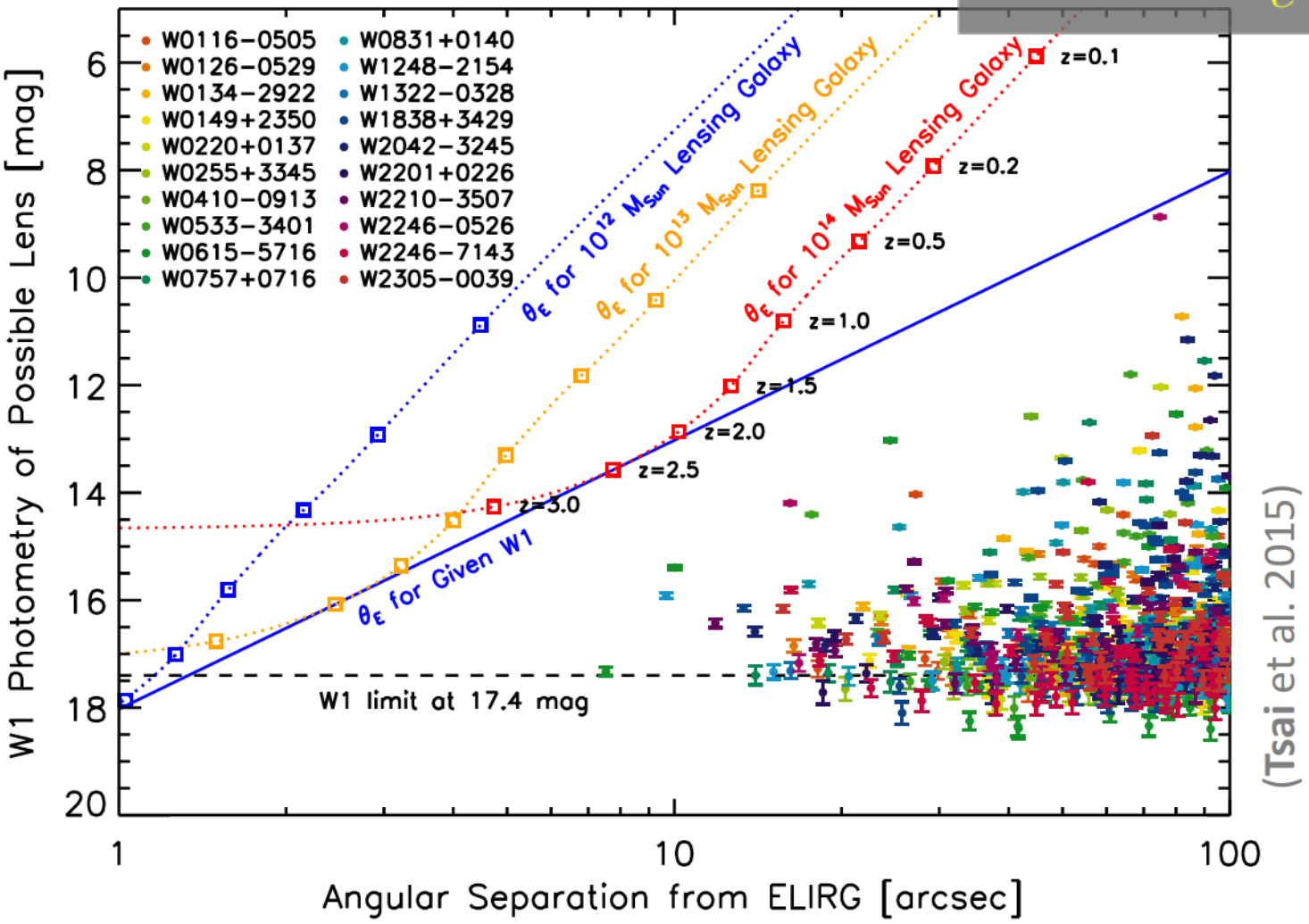


Gravitationally lensed?



Possible Foreground Lensing Galaxies at Separation > WISE W1 Resolution

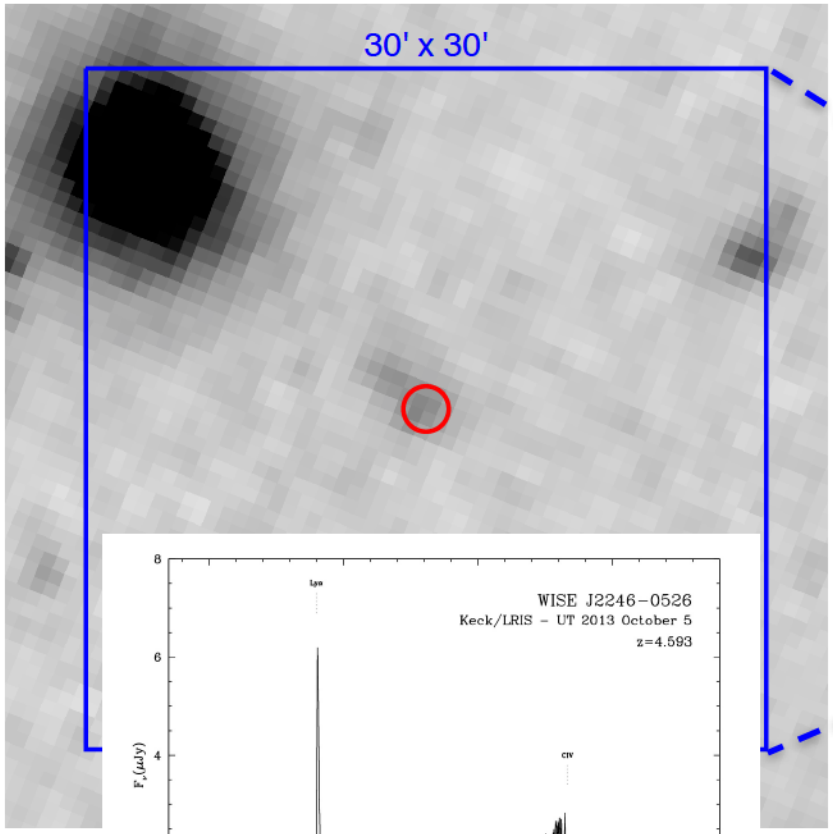
$$\theta_E = \left(\frac{4GM_L(\theta_E)}{c^2}\frac{D_{LS}}{D_S D_L}\right)^{1/2}$$



(Tsai et al. 2015)

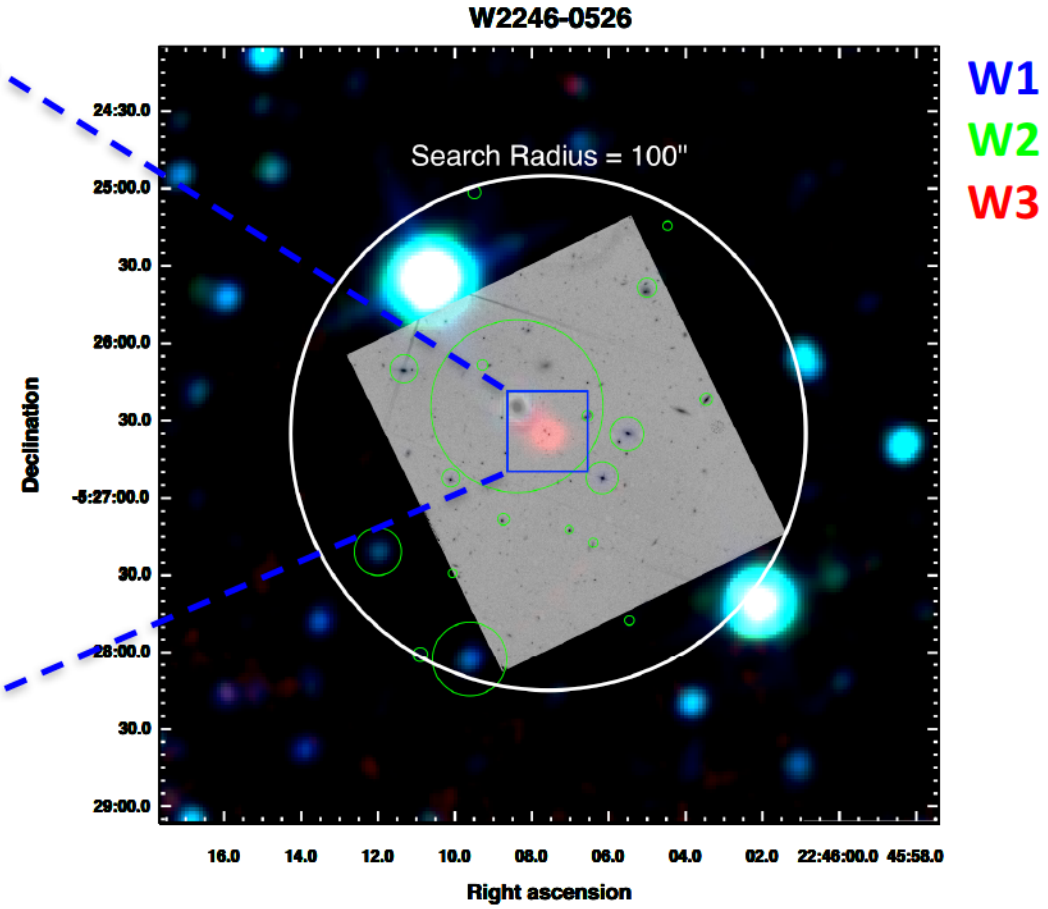
Most Luminous Galaxy – W2246-0526

HST F160W image



Tsai et al. (2015)

Con 8



If θ_E ~

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

Friday, May 22, 2015 » MORE AT FACEBOOK.COM/PASADENASTARNEWS AND TWITTER.COM/PASSTARNEWS pasadenastarnews.com

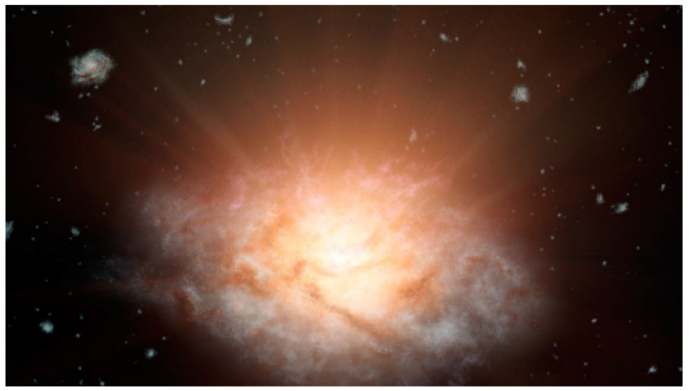
JET PROPULSION LABORATORY DISCOVERY

The most luminous galaxy found

LA CAÑADA FLINTRIDGE » A distant galaxy sizzling with light from more than 300 trillion stars has been named the most luminous galaxy, NASA's Jet Propulsion Laboratory announced Thursday.

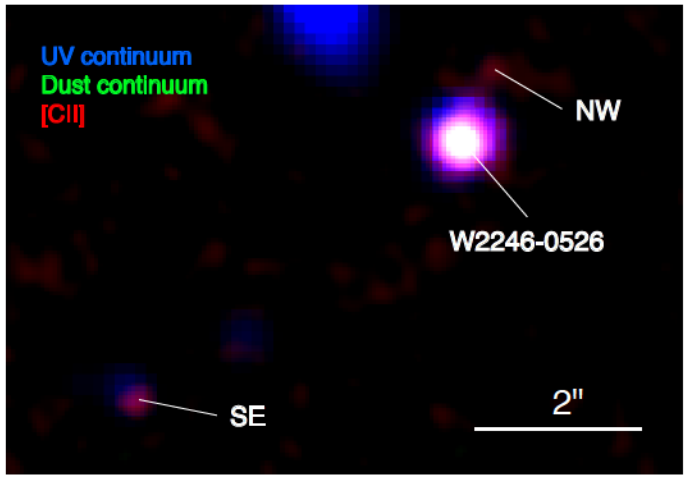
NASA's Wide-field Infrared Survey Explorer spacecraft, managed and operated by JPL, discovered the bright galaxy, which belongs to a new class of objects called extremely luminous infrared galaxies. The light may originate from a major growth spurt of the galaxy's black hole, said Chao-Wei Tsai of JPL and lead author of a report published Friday.

by Zen Vuong, Pasadena Star-News
Based on NASA Press-Release 15-095
and **Tsai et al. 2015, ApJ**



NASA/JPL-CALTECH

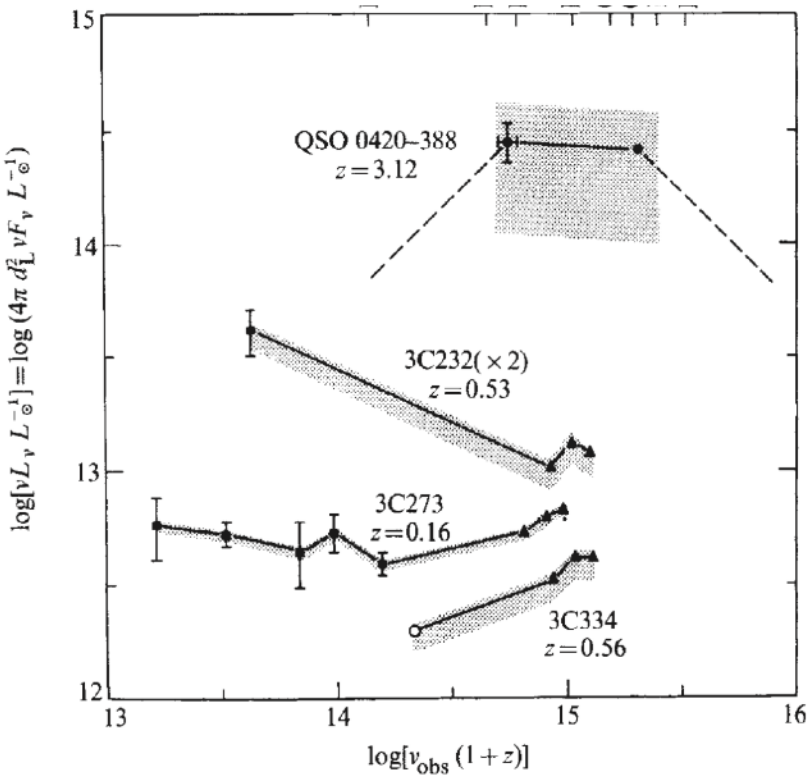
This artist's concept depicts the current record holder for the most luminous galaxy in the universe. The galaxy, WISE J224607.57-052635.0, is erupting with light equal to more than 300 trillion suns. It was discovered using data from NASA's WISE mission.



ALMA and HST images of **W2246-0526**
Diaz-Santos et al. 2016, ApJL

About 40 Years Ago

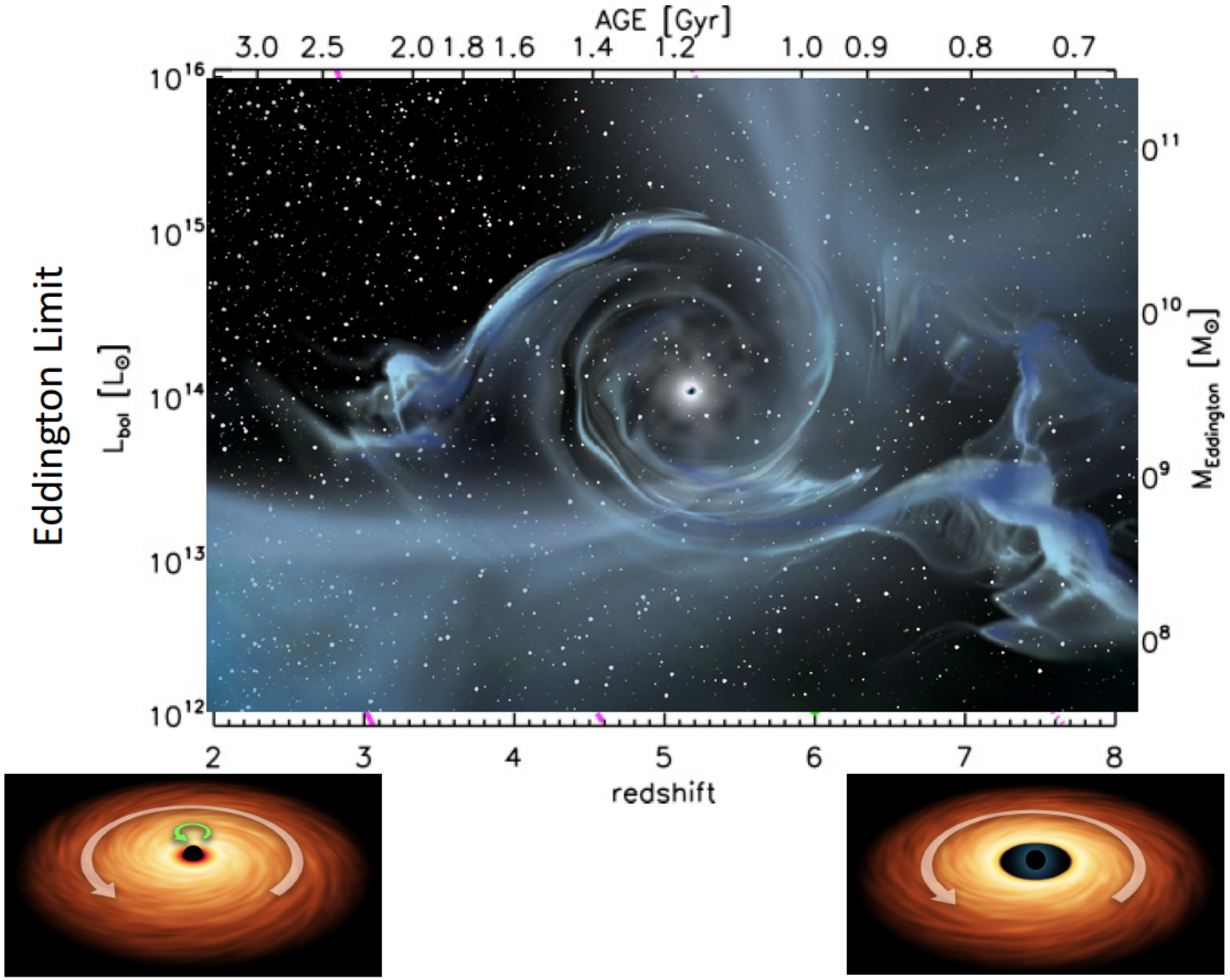
Infrared observations of the most luminous quasar



Wright and Kleinmann (1978, Nature)

- With an assumed spectral index and moderm cosmology:
  - Lbol ~ 3.0 x 10^{14} L_{Sun}
  - LIR ~ 1.7– 4 x 10^{14} L_{sun}
  - Could qualify as an ELIRG.
- After adding WISE data, the conservative estimate:
  - L_{bol} ~ 1.2 x 10^{15} L_{sun}
  - L_{IR} (8-1000μm) ~ 2.0 x 10^{14} L_{Sun}
  - No Far-IR data available
  - It IS an ELIRG!!

SMBH Accretion History

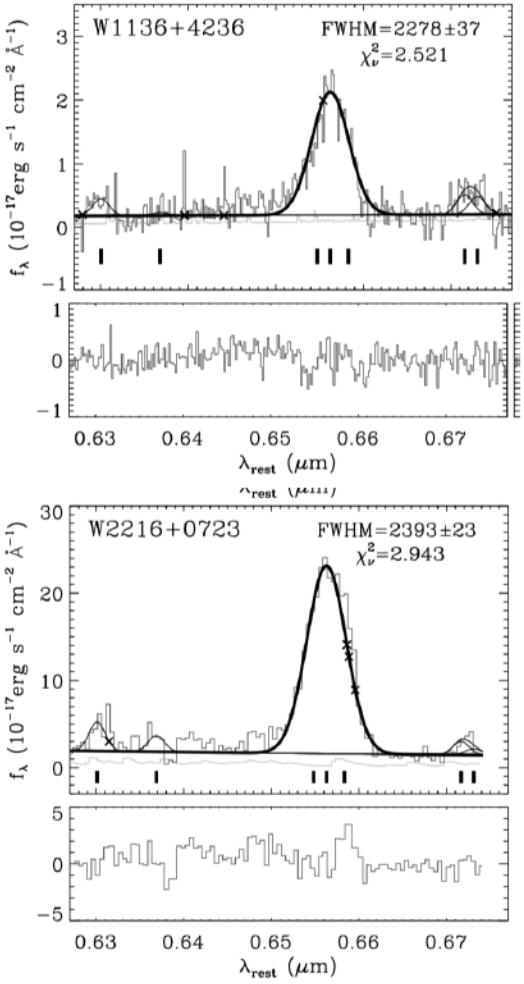


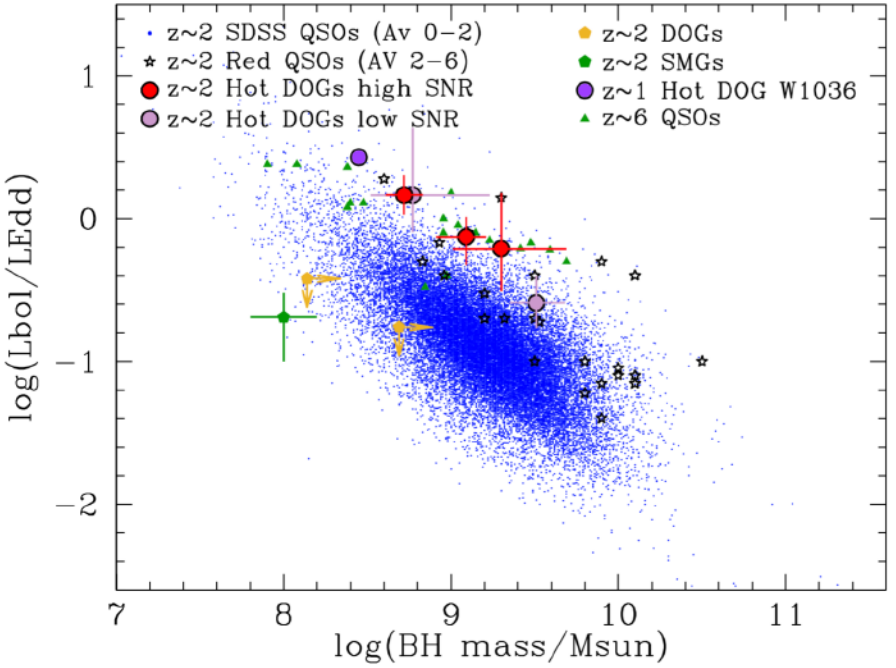
Averaged
$\eta < 0.15$

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

SMBH Mass and Eddington Ratios

Keck MOSFIRE and Gemini FLAMINGO2 spectra of Hα



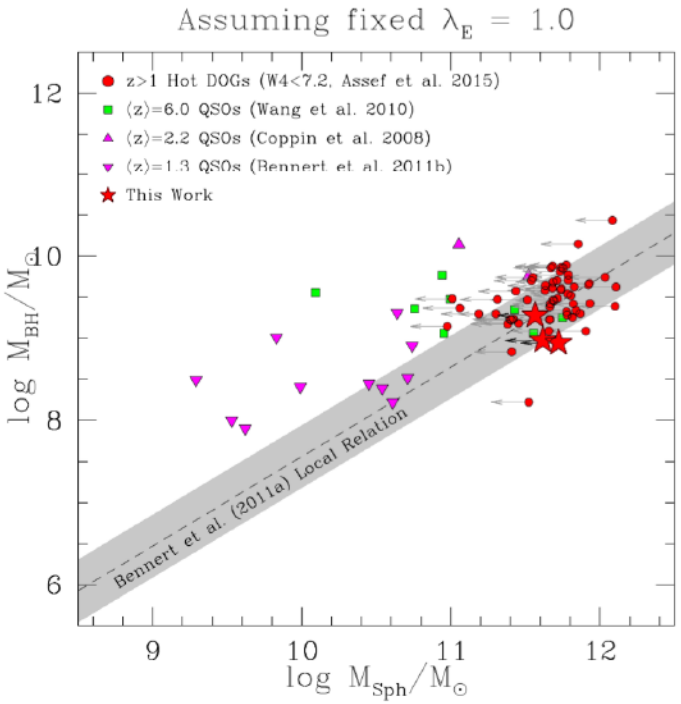


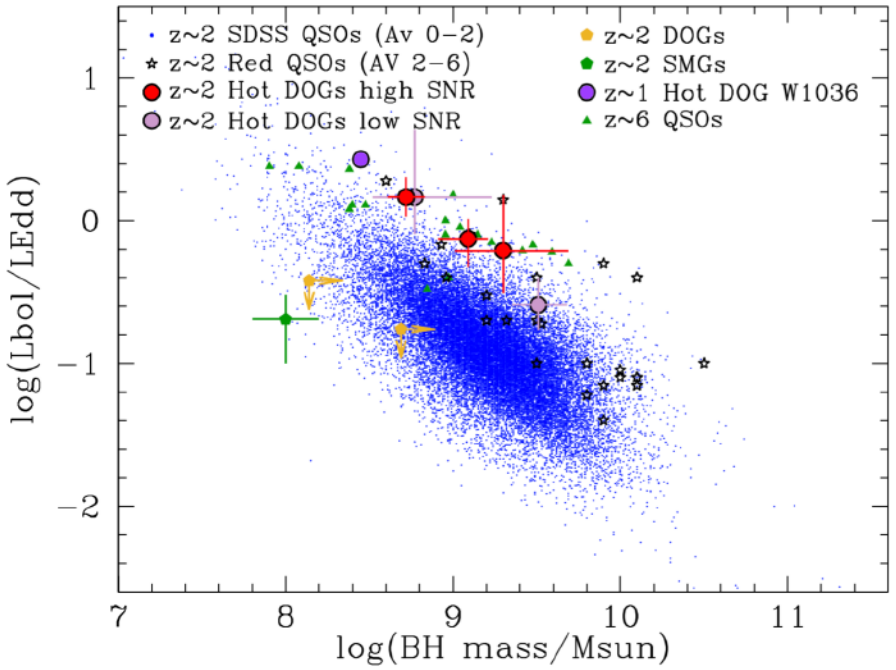
$$M_{\rm BH} \propto \sigma_{BL}^2 \, L_{\rm BL}^{1/2}$$

Wu et al. including Ned Wright (submitted)

SMBH Mass and Eddington Ratios

Keck MOSFIRE and Gemini FLAMINGO2 spectra of Hα

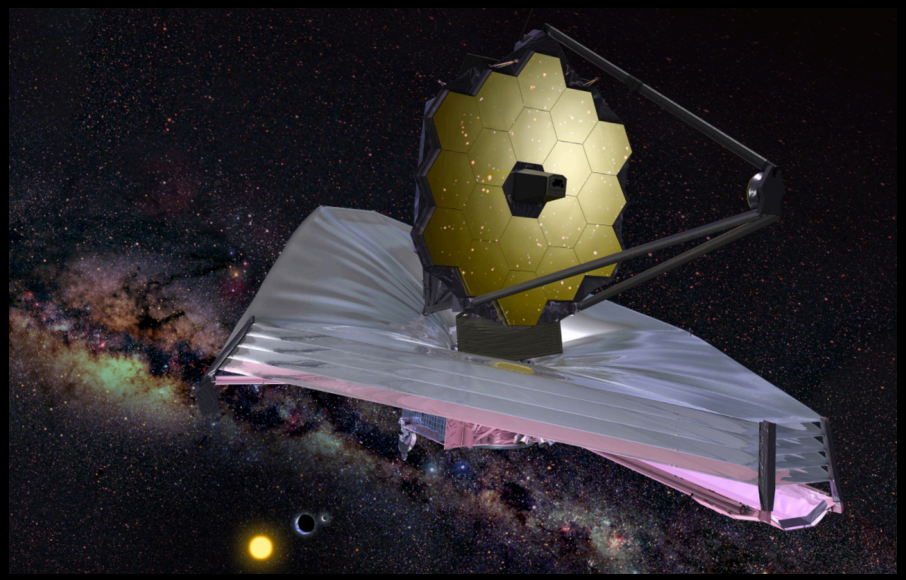




$$M_{\rm BH} \propto \sigma_{BL}^2 \, L_{\rm BL}^{1/2}$$

Wu et al. including Ned Wright (submitted)

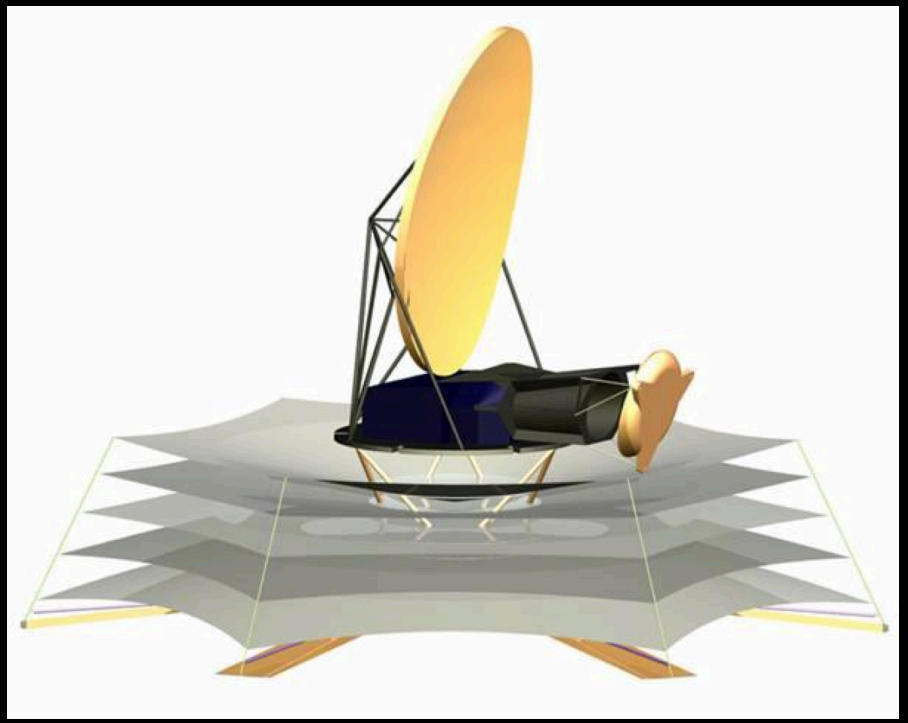
In the Future



JWST

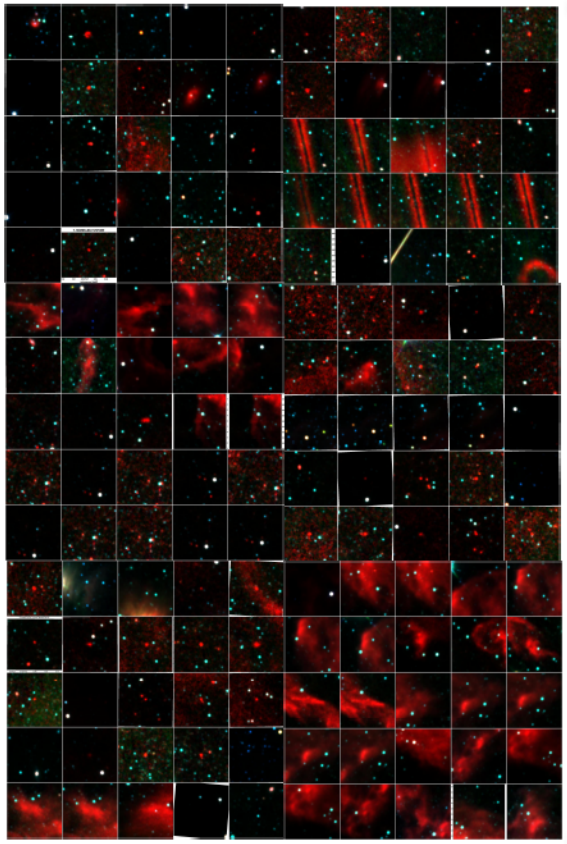
Far-IR Surveyor

CALISTO concept
for 2020 Decadal



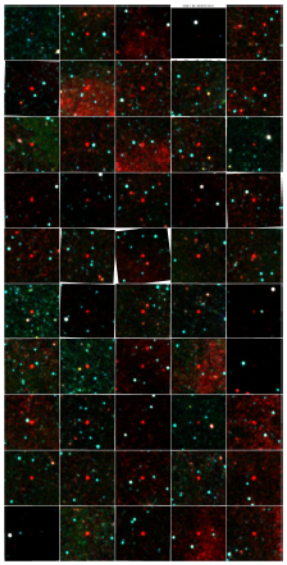
What's Next?

Broadening the Selection Criteria



Roger Griffith

Visual Inspection

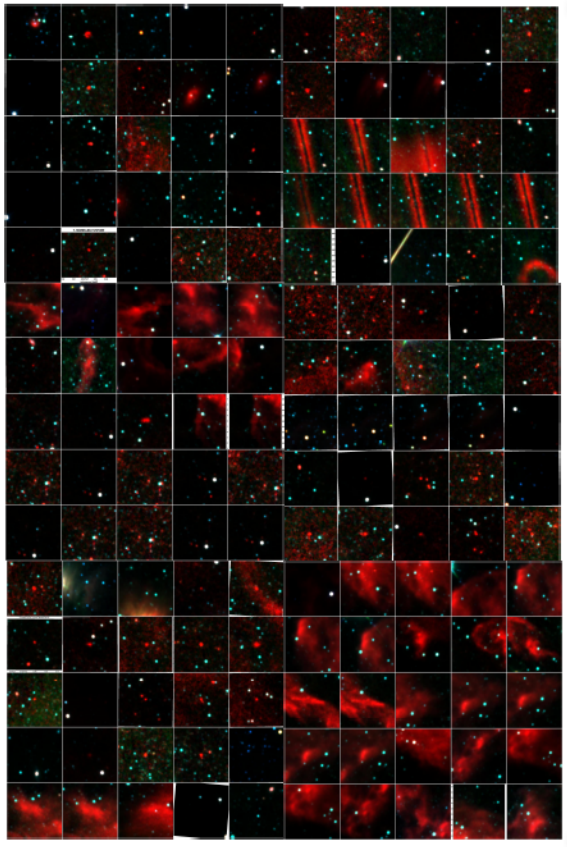


Archival Selection Results

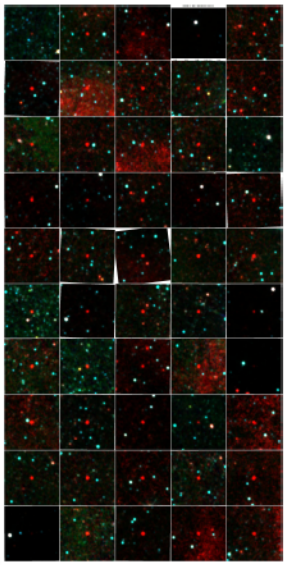
Good ELIRG candidates

What's Next?

Broadening the Selection Criteria



Visual Inspection



Archival Selection Results

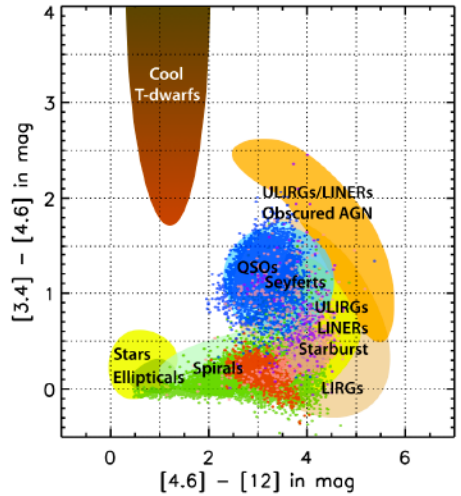
T-800

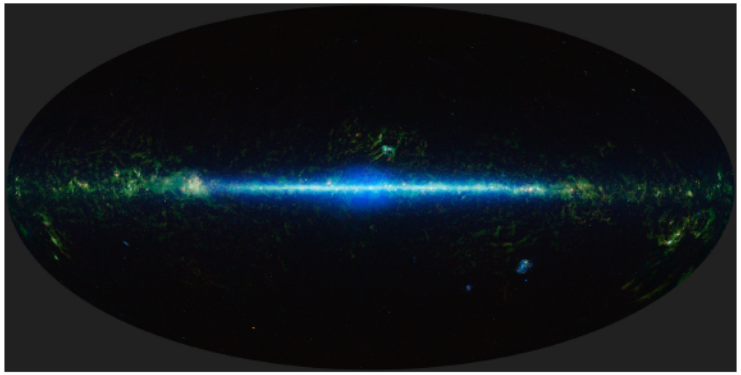
Good ELIRG candidates

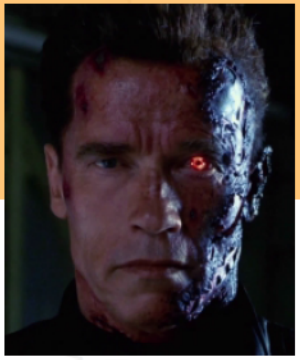
Because – What can go wrong?!

The Terminator, Orion Pictures (1984)

Inhabitants of WISE Color Space

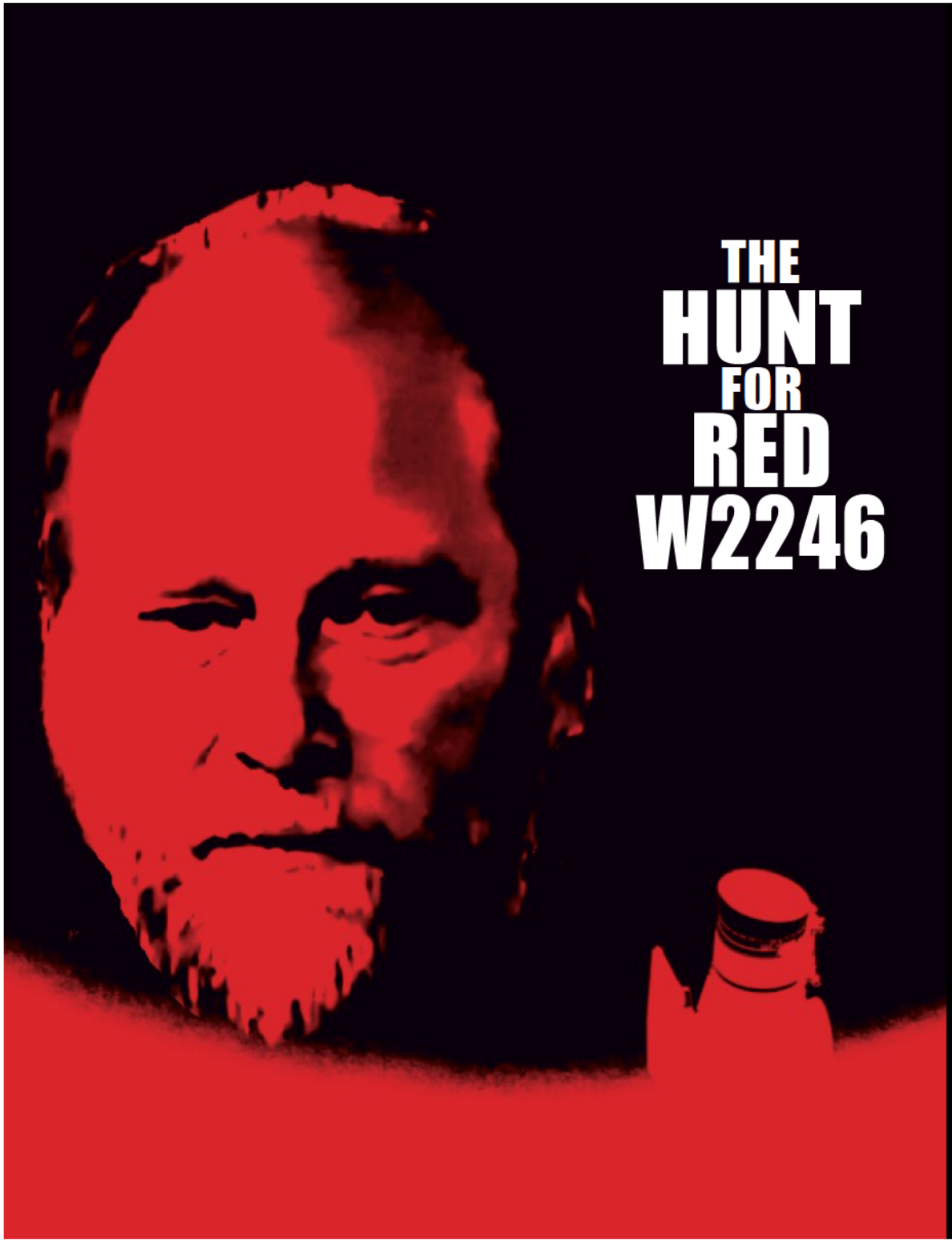






T-800

- QSO
- E/Hy/ULIRGs
- Elliptical
- Spiral
- Stars
- BDs



THE HUNT FOR RED W2246

THE HUNT FOR THE MOST LUMINOUS GALAXY IS ~~DONE~~ ON.

WISE One-Year-in-Orbit Party

Peter Eisenhardt's House in Altadena, CA

2010/12/15

Salt Lick BBQ
Driftwood, Texas (right outside Austin)
2012/01/12, AAS meeting

Ned's 60th Birthday Party

Happy Birthday, Ned!