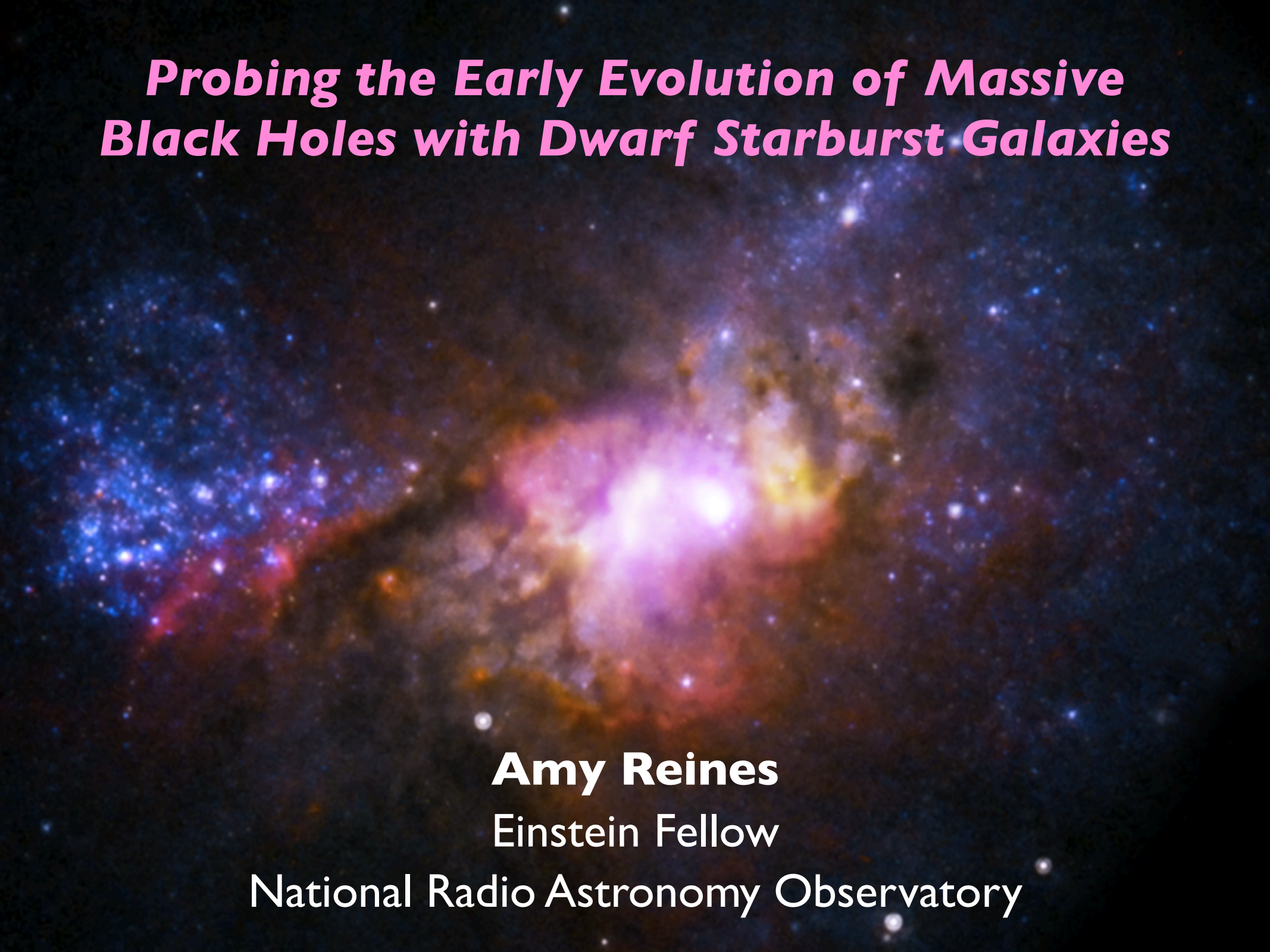


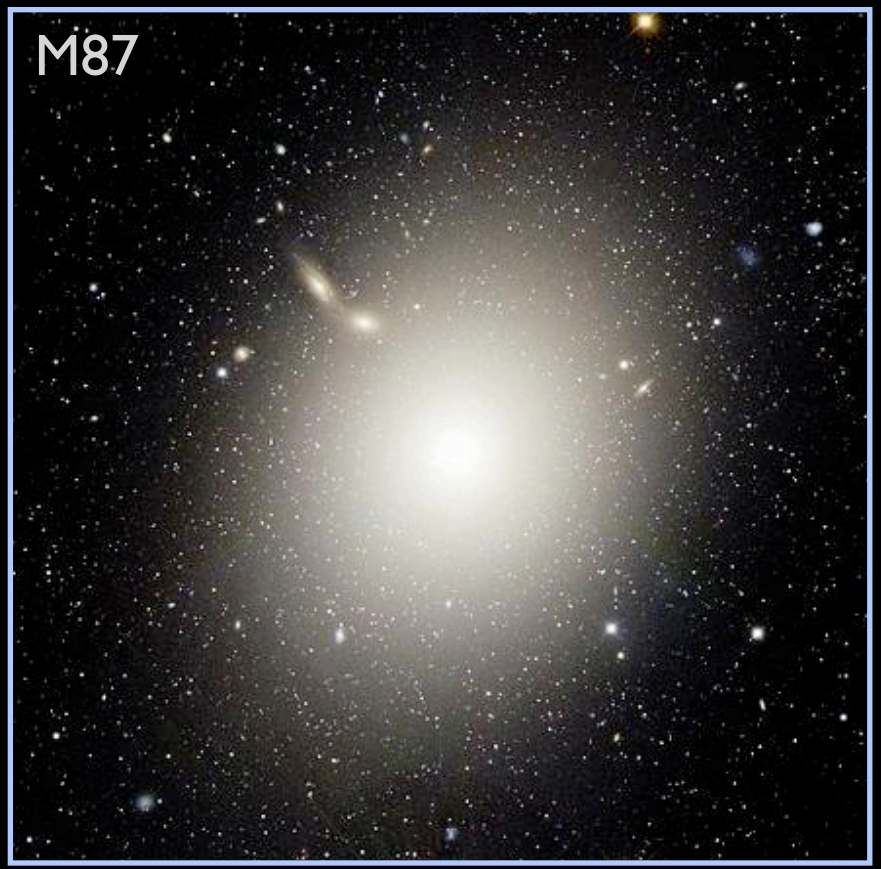
# *Probing the Early Evolution of Massive Black Holes with Dwarf Starburst Galaxies*

**Amy Reines**
Einstein Fellow
National Radio Astronomy Observatory

# Supermassive black holes and galaxy evolution

- Supermassive black holes reside in the nuclei of essentially all massive galaxies with a bulge
(e.g. Kormendy & Richstone 1995; Magorrian et al. 1998; Kormendy 2004)


$M_{BH} \sim 1.4 \times 10^8 M_{sun}$ (Bender et al. 2005)

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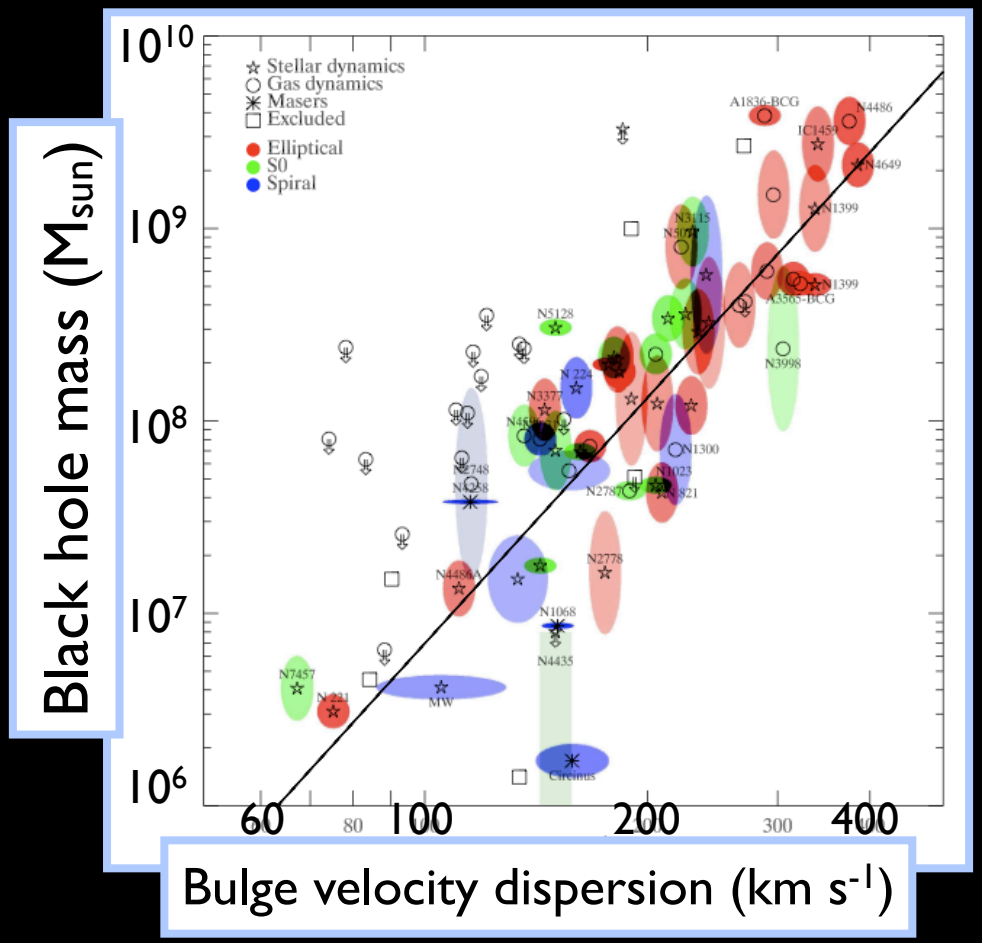


Gültekin et al. (2009)

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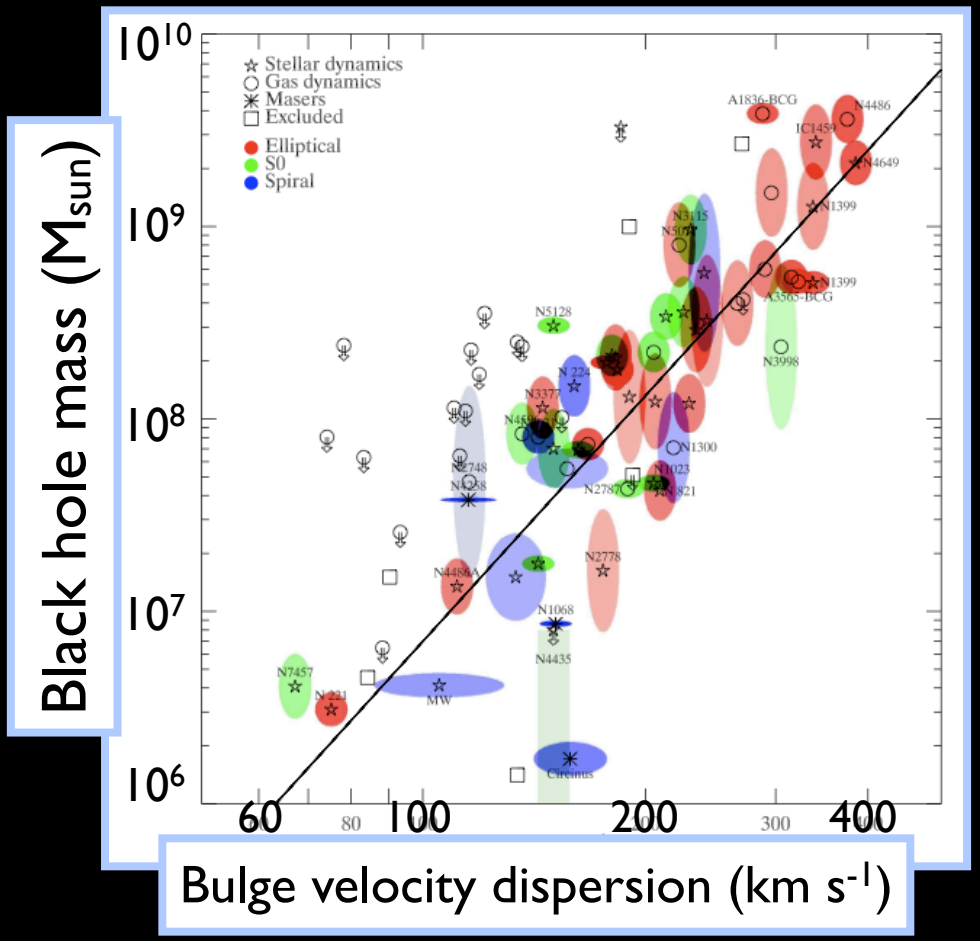


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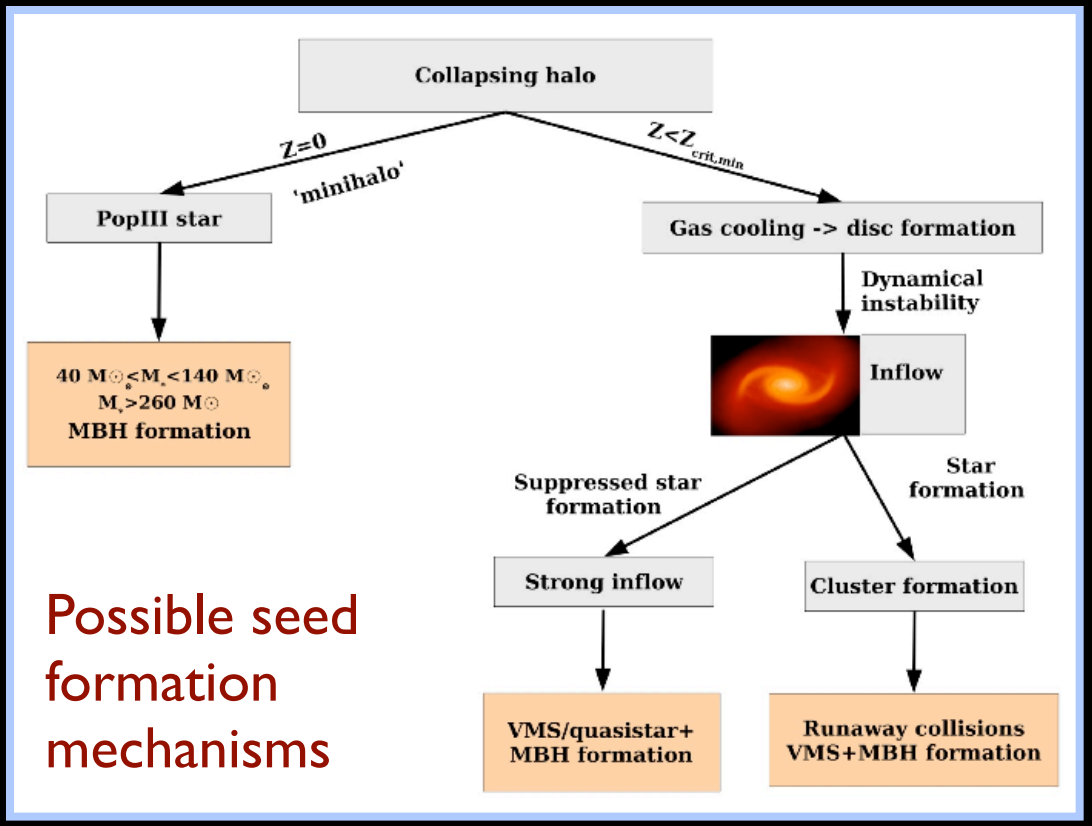


Volonteri (2010)

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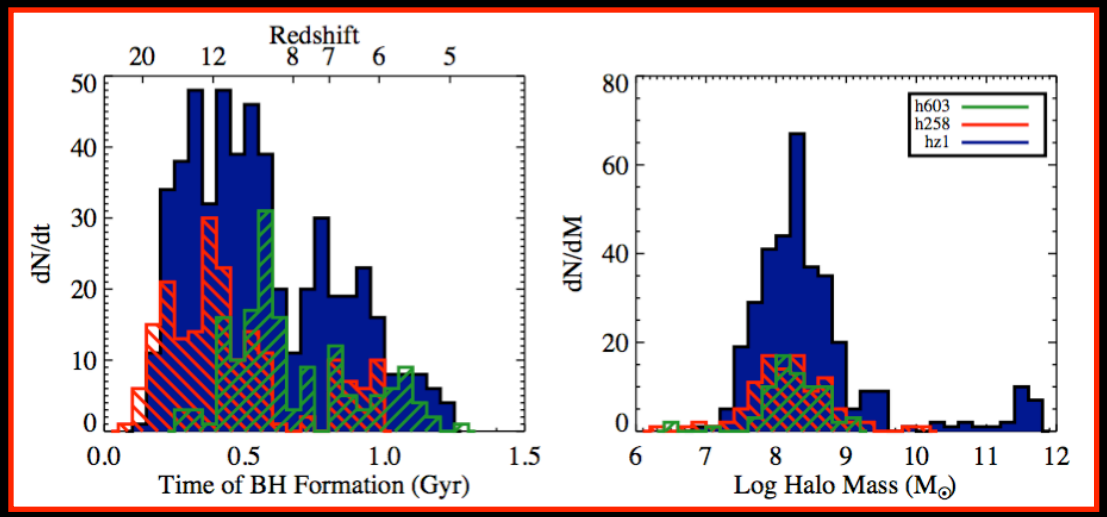


Bellovary et al. (2011)

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- How do the "seeds" of supermassive black holes form?

- When did the seeds form and what types of galaxies did they form in?

- How common are massive black holes in modern bulgeless and dwarf galaxies?


*"An actively accreting massive black hole in the dwarf starburst galaxy Henize 2-10"*

Reines, Sivakoff, Johnson & Brogan 2011, Nature, 470, 66

*"Astrophysics: Big black hole found in tiny galaxy"*

Greene 2011, Nature, 470, 45

# Henize 2-10

- Nearby (D~9 Mpc) dwarf starburst galaxy (Allen et al. 1976)
- Compact (~ 1 kpc), irregular morphology
- Young super star clusters (proto-globular clusters) (e.g. Johnson et al. 2000)

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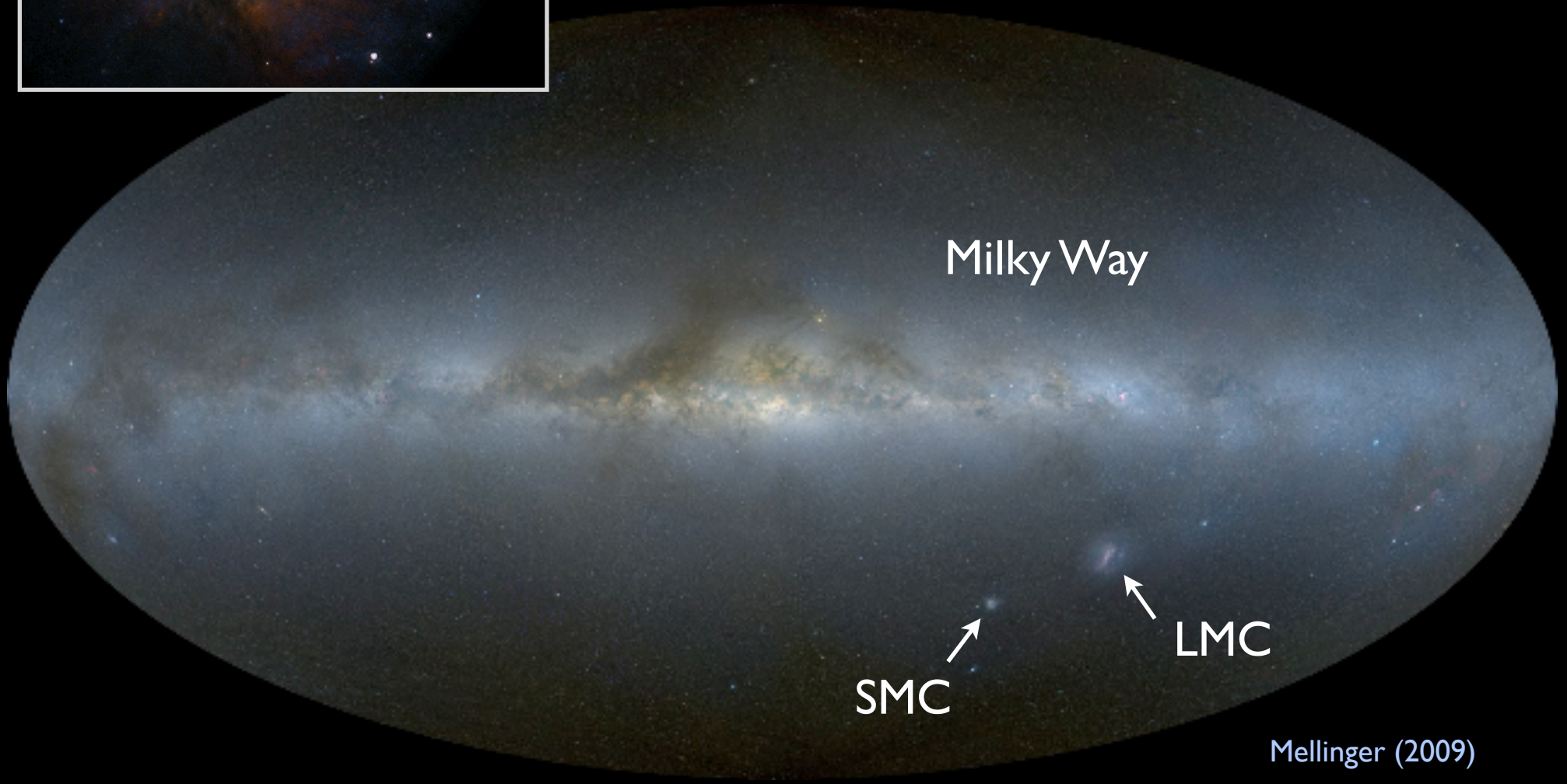
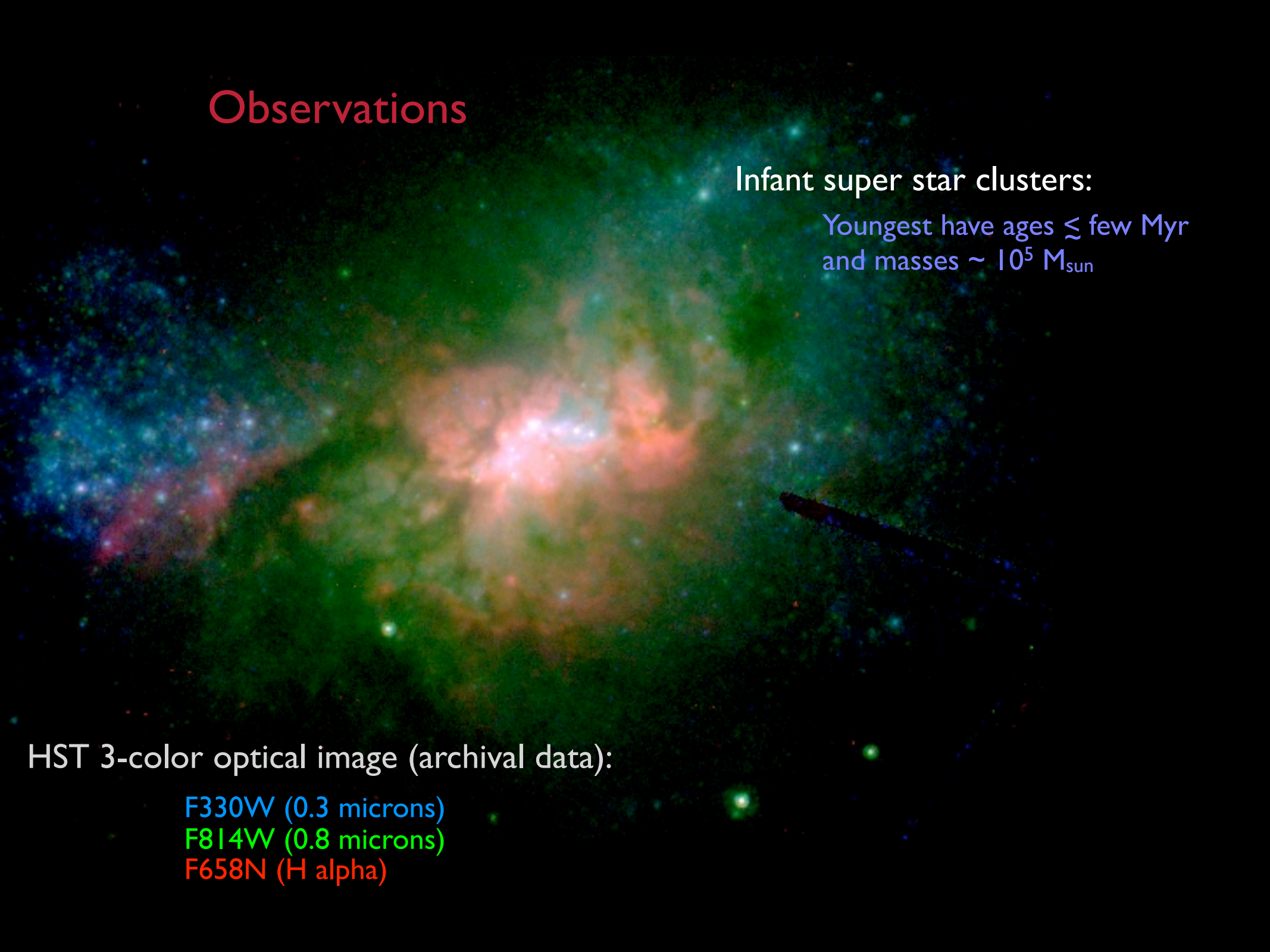
- Nearby (D~9 Mpc) dwarf starburst galaxy (Allen et al. 1976)
- Compact (~ 1 kpc), irregular morphology
- Young super star clusters (proto-globular clusters) (e.g. Johnson et al. 2000)
- Main optical body is about half the size of the SMC
- SFR ~ 10 times the LMC but similar stellar and HI masses




Mellinger (2009)

# Observations

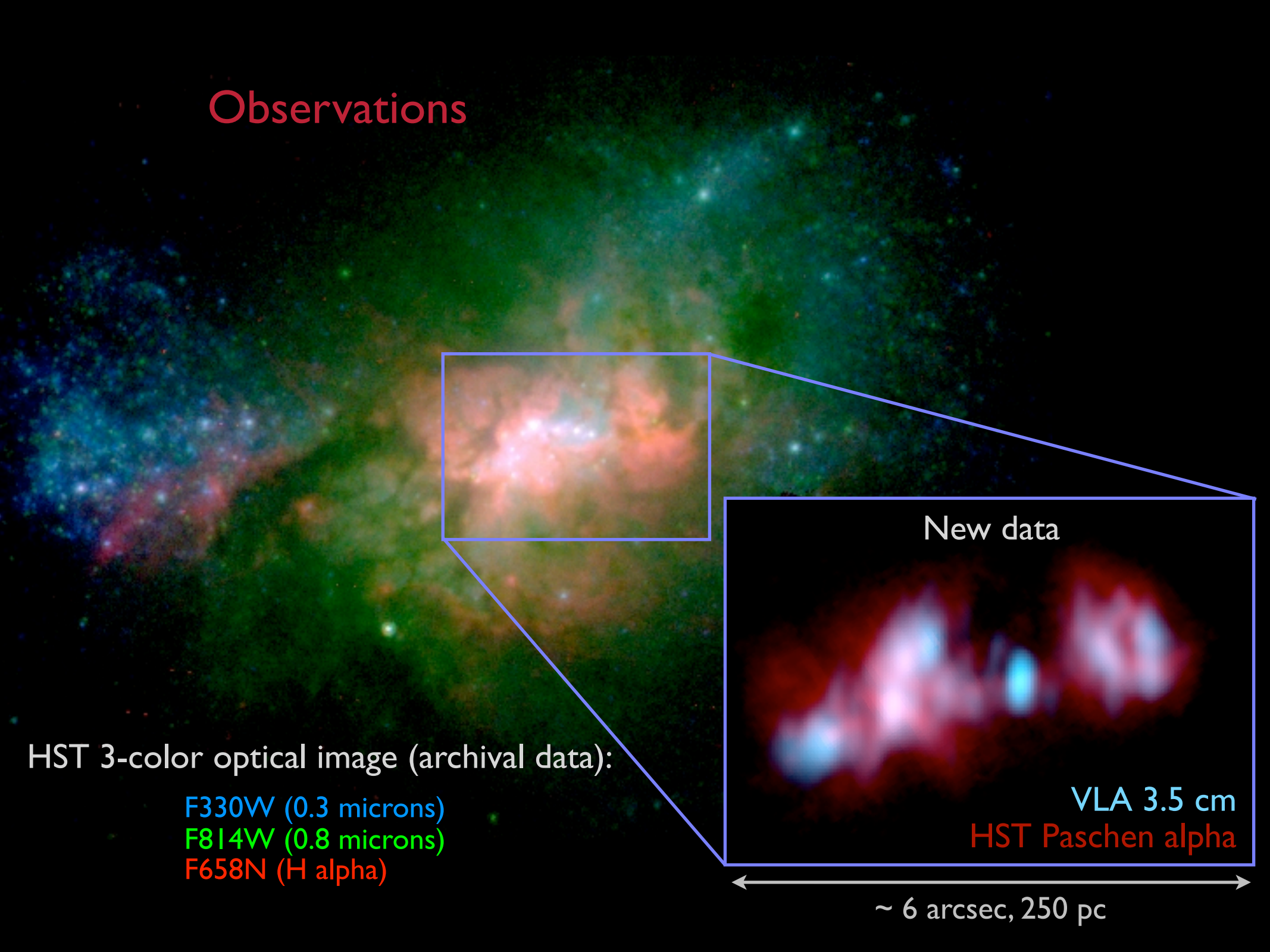


Infant super star clusters:

Youngest have ages $\lesssim$ few Myr
and masses ~ $10^5$ $M_{sun}$

HST 3-color optical image (archival data):

F330W (0.3 microns)
F814W (0.8 microns)
F658N (H alpha)


Observations
New data
HST 3-color optical image (archival data):
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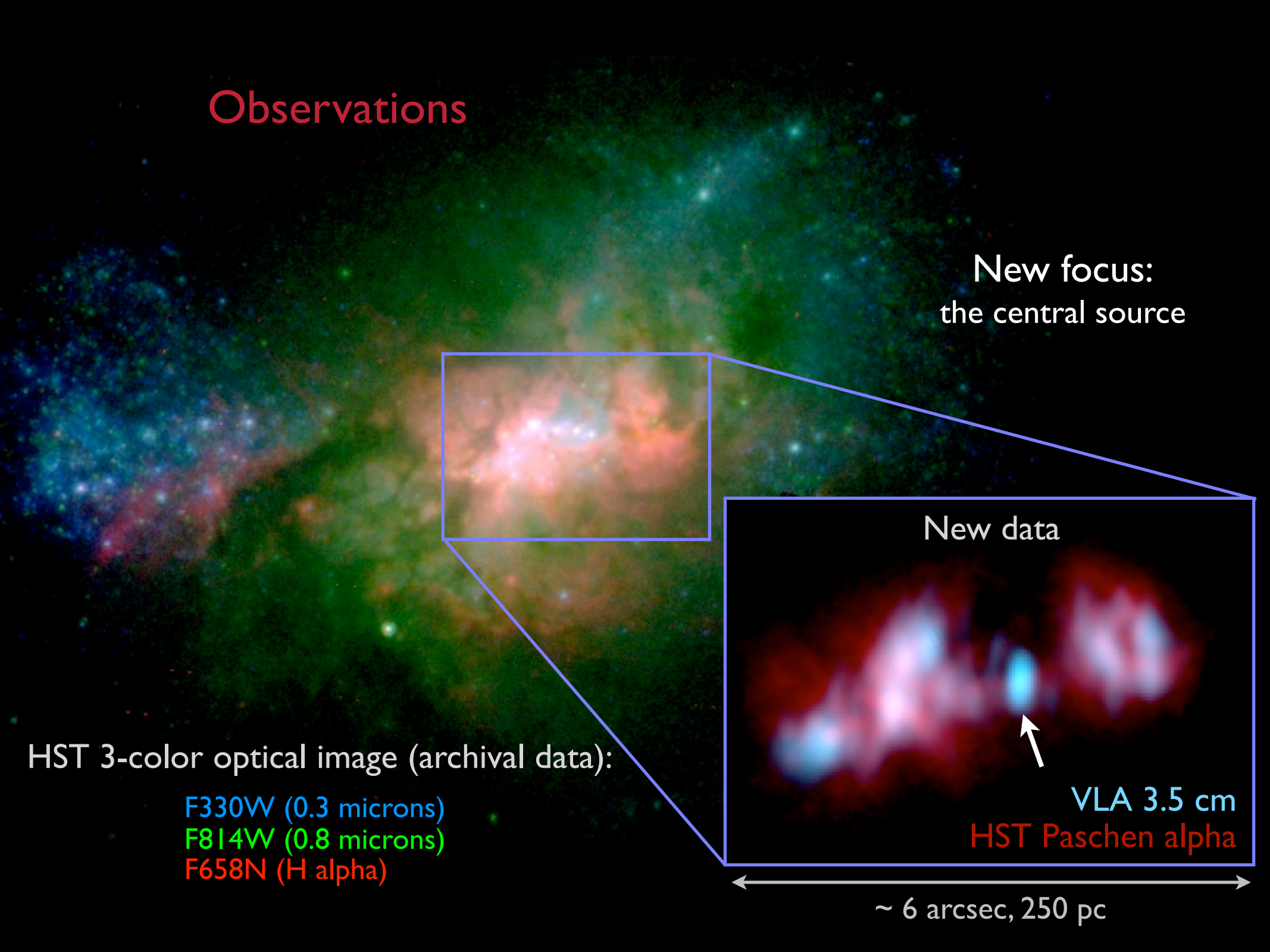
VLA 3.5 cm
HST Paschen alpha
~ 6 arcsec, 250 pc


Observations
New focus:
the central source
New data
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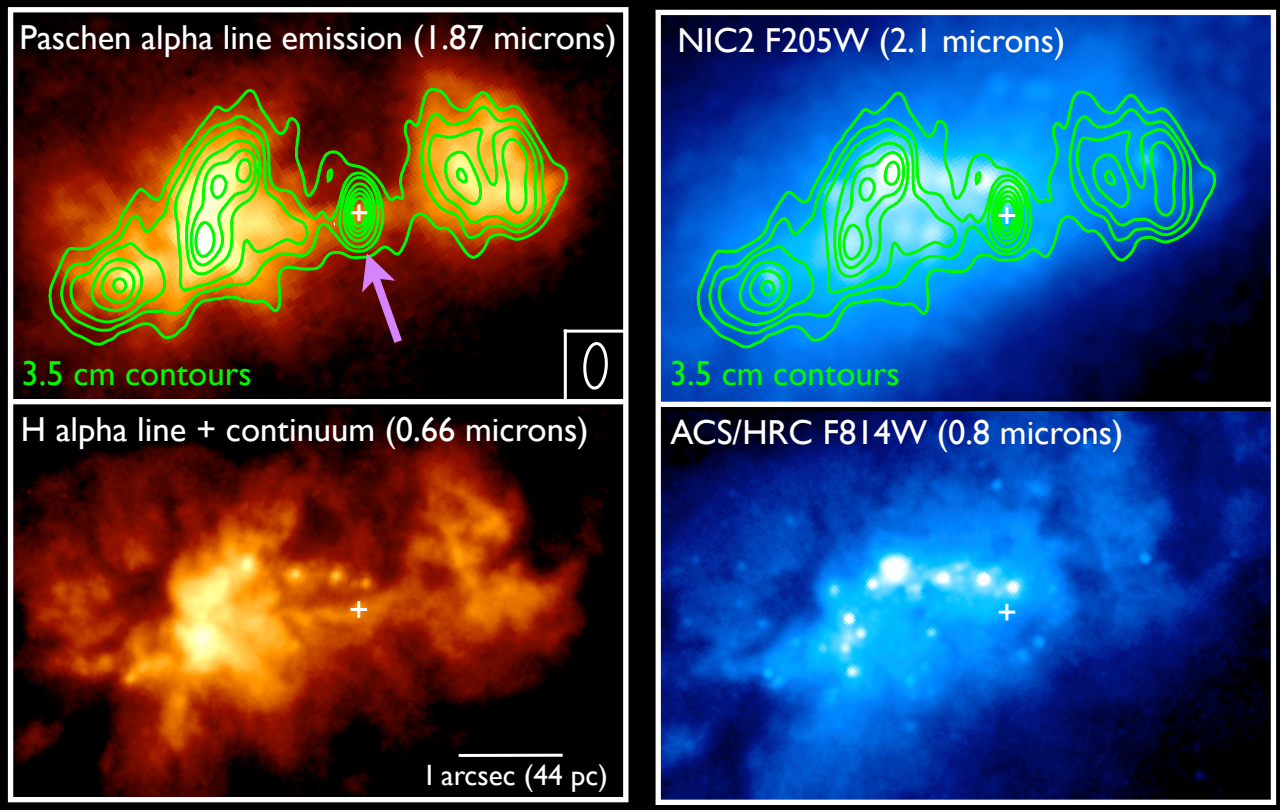
# The central source in Henize 2-10

*Narrow-band imaging (ionized gas)*

*Broad-band imaging (stars)*



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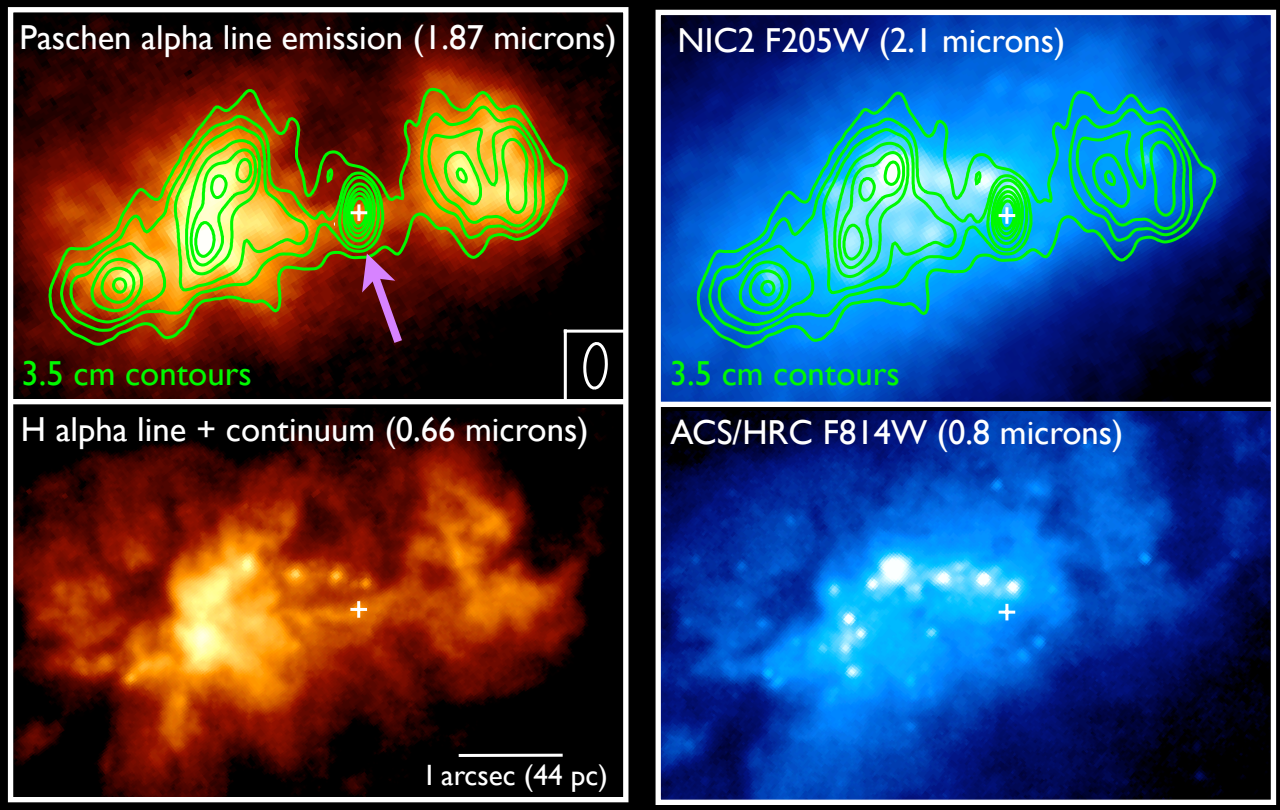


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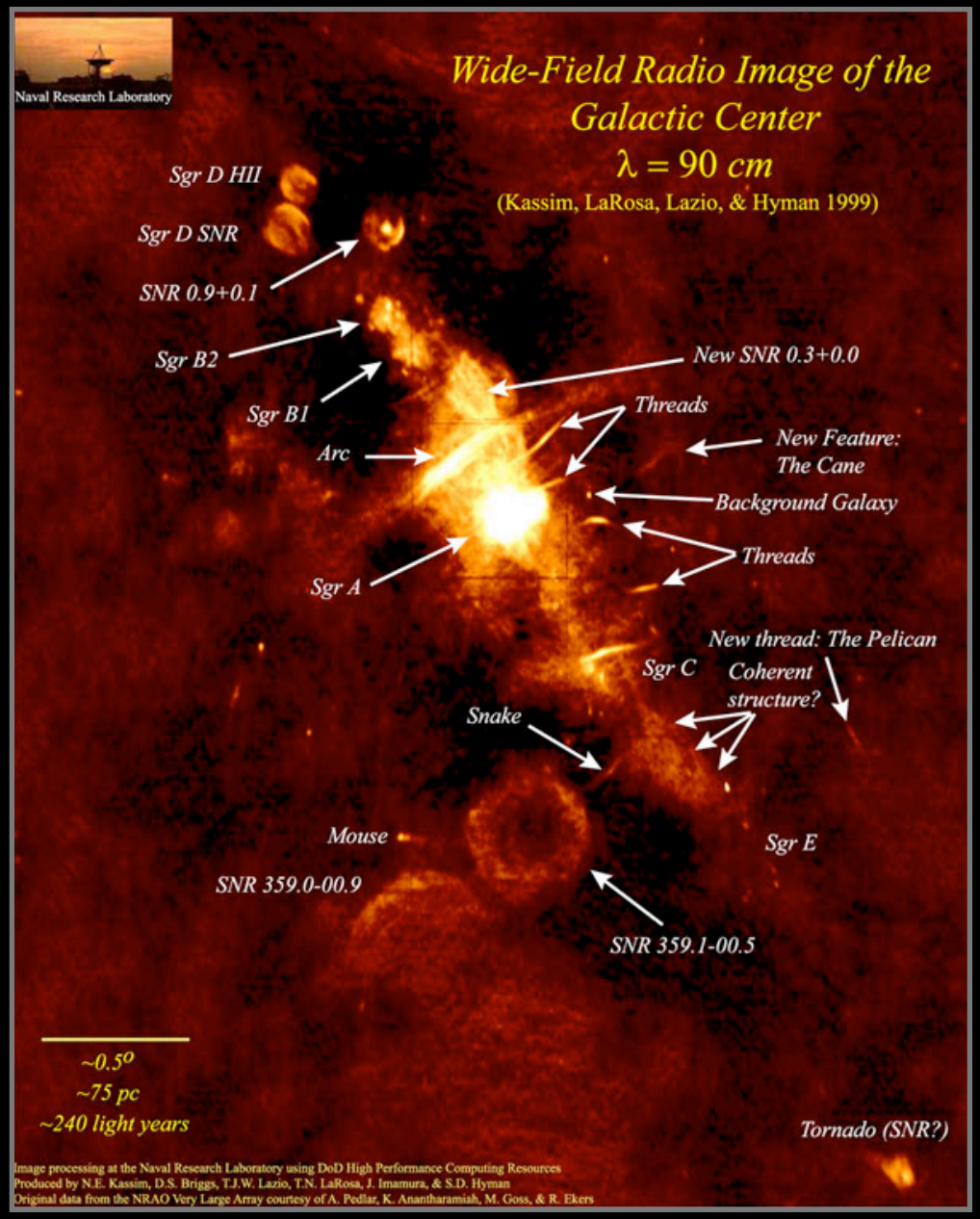


Radio image of
the Galactic Center

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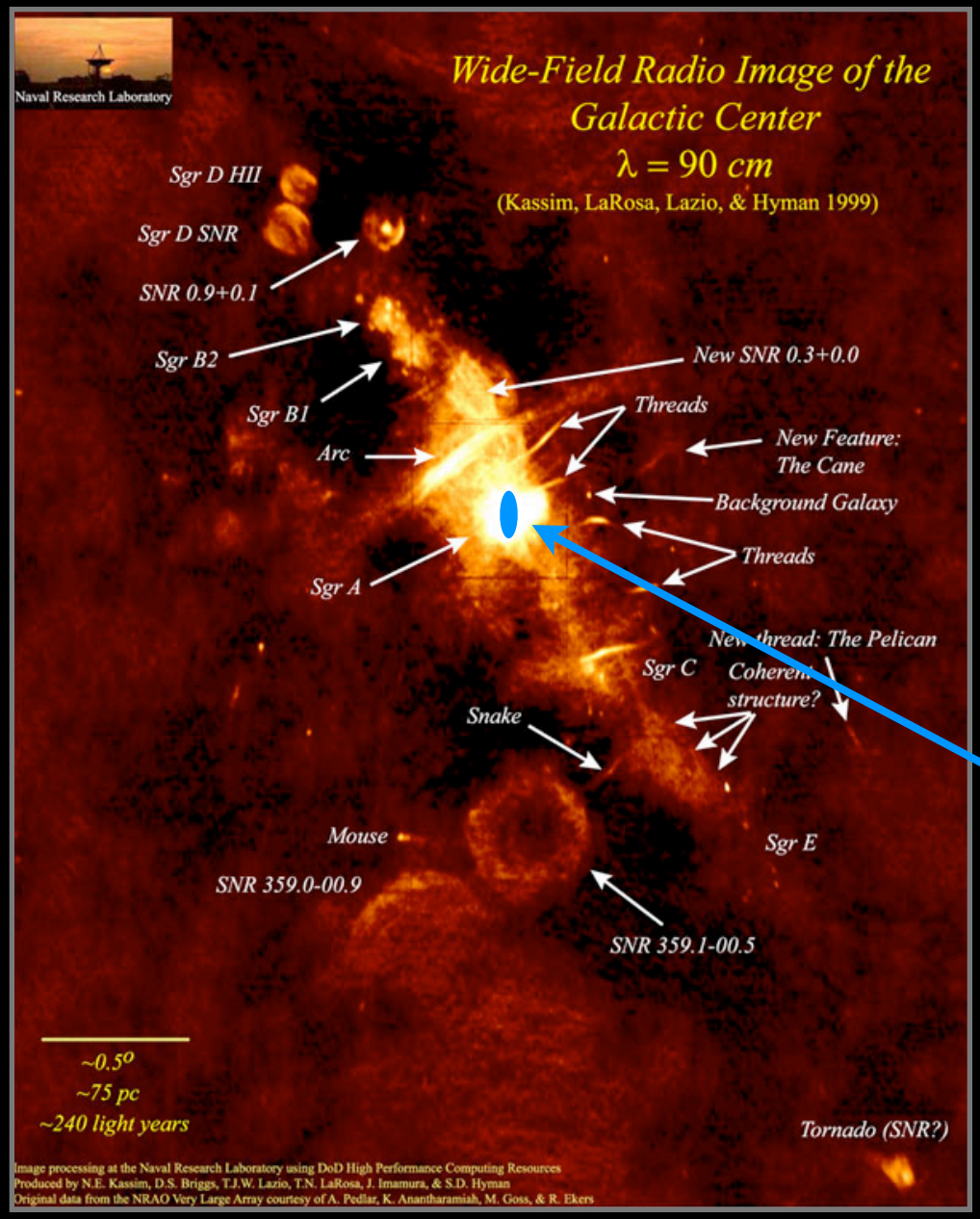


Radio image of the Galactic Center

24 pc x 9 pc beam

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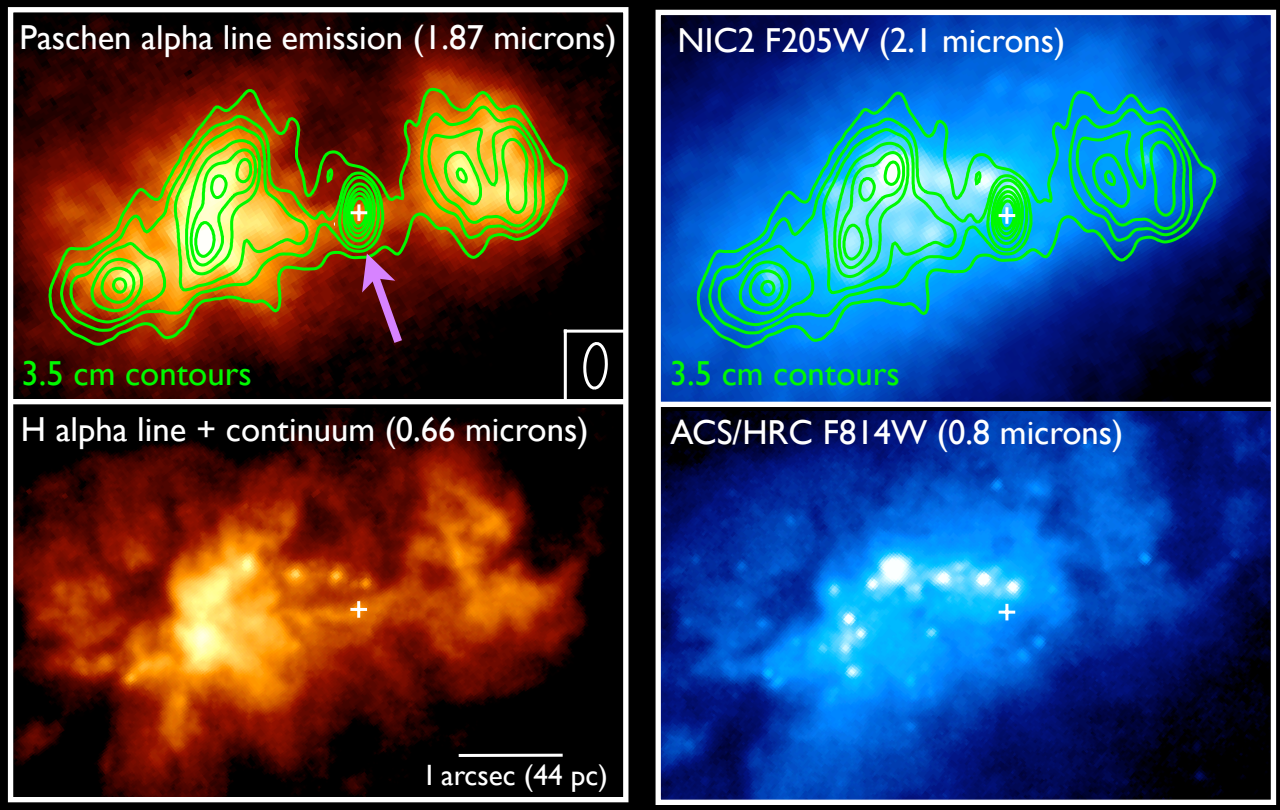


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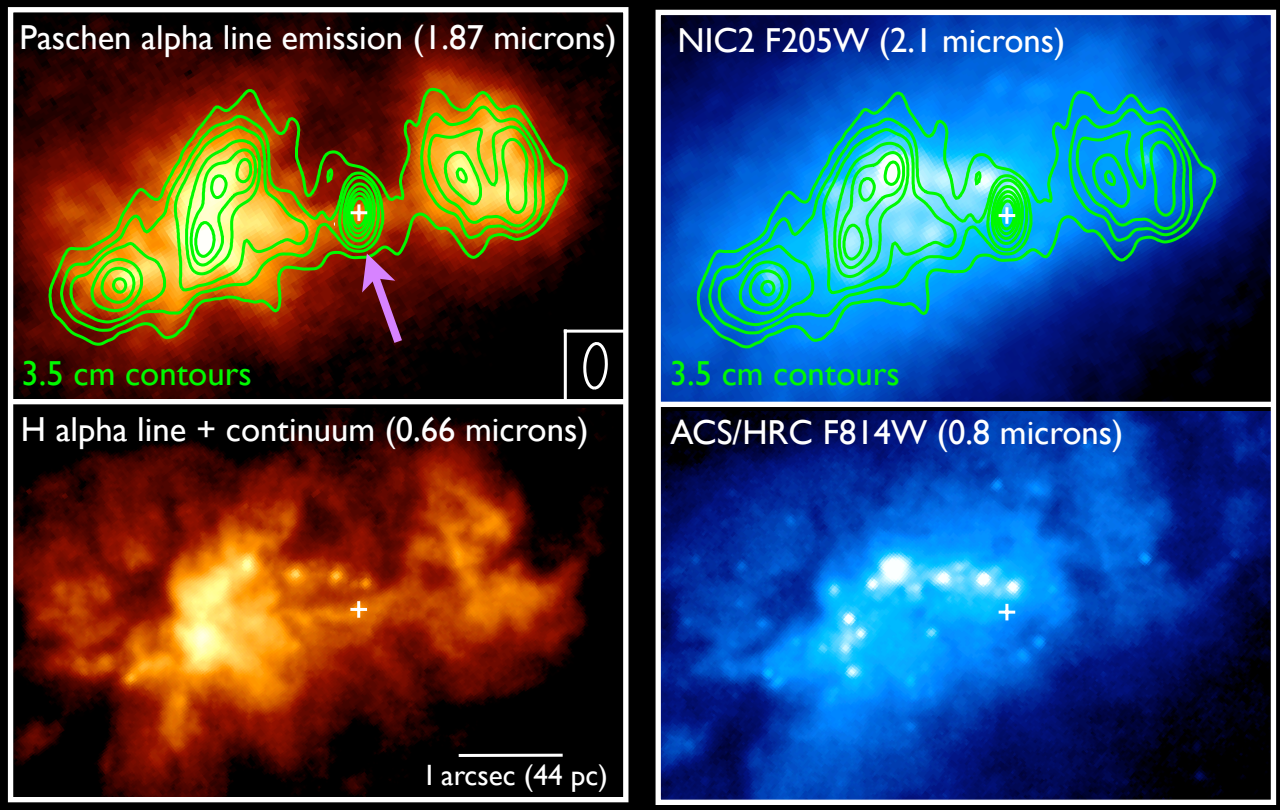


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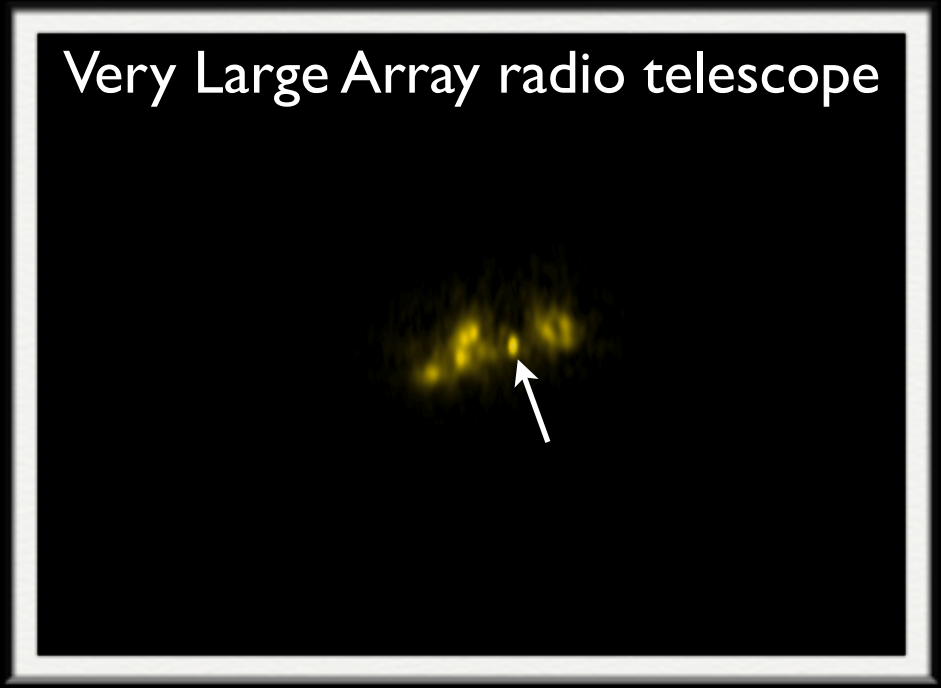
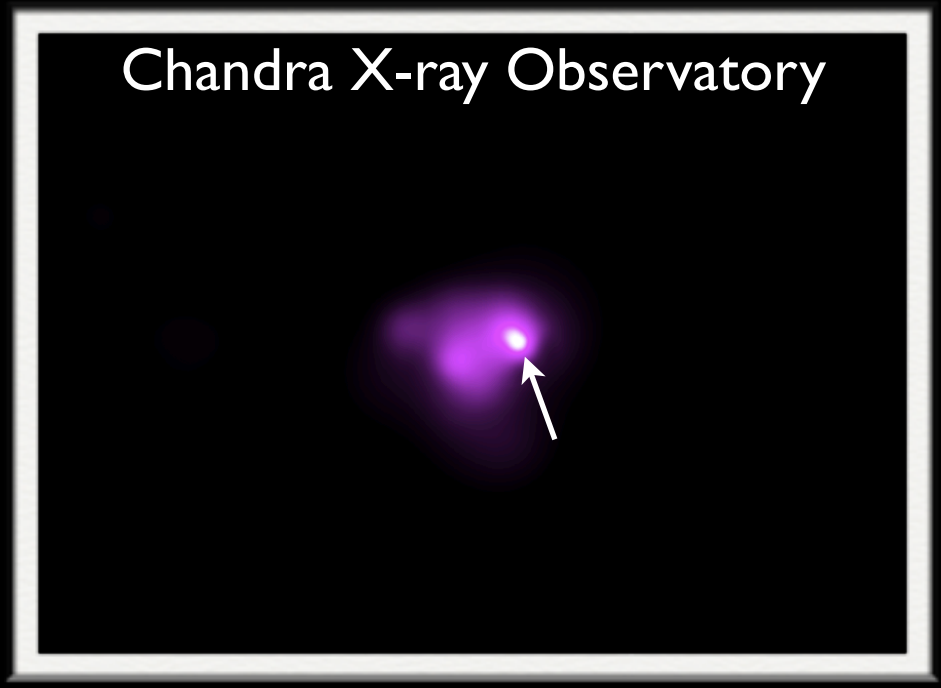
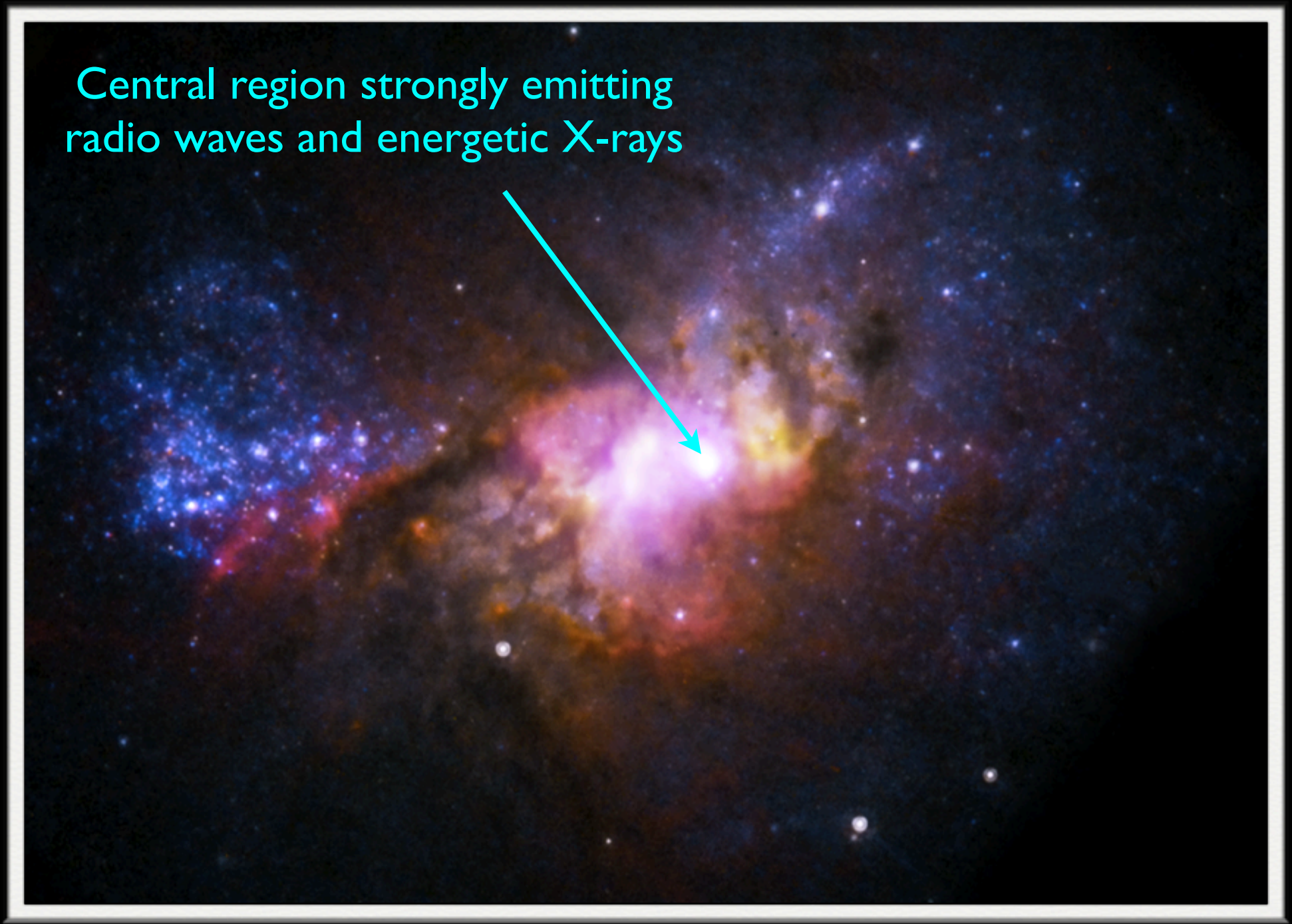



Images from http://chandra.harvard.edu/press

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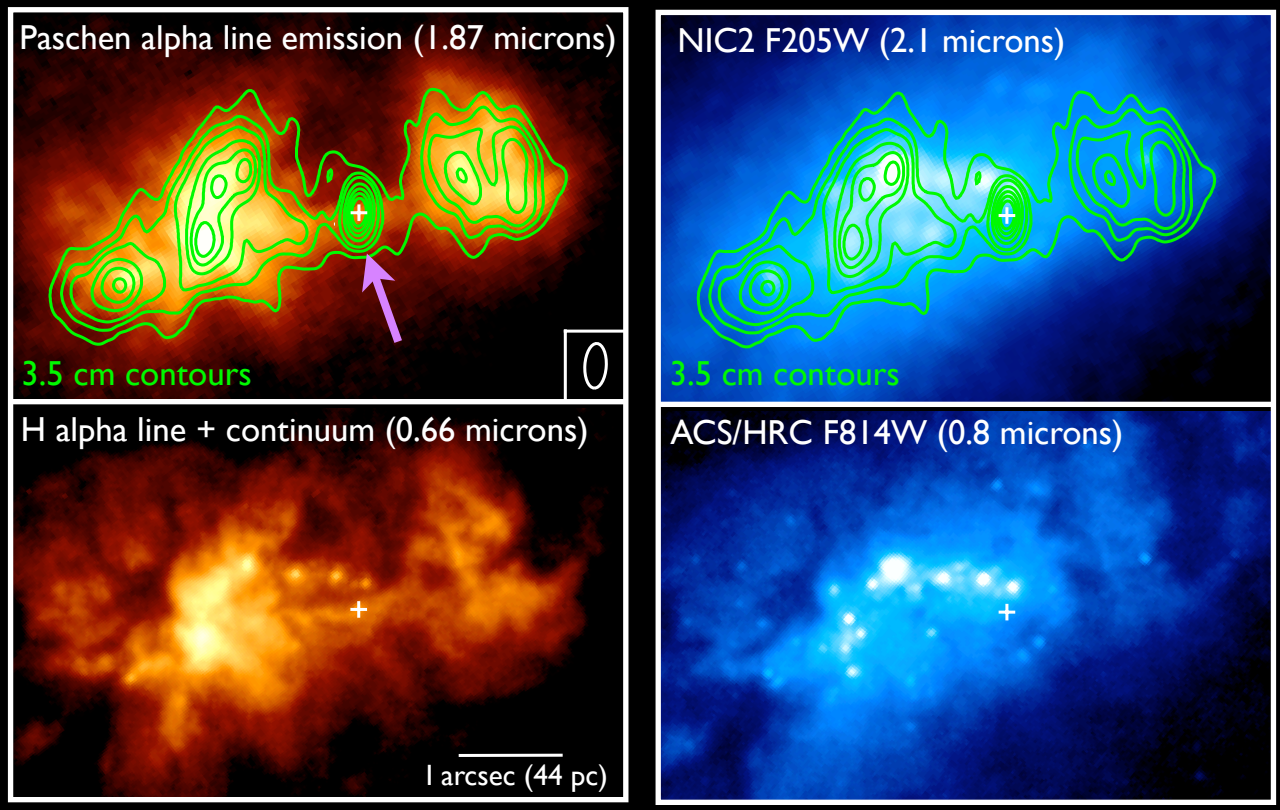


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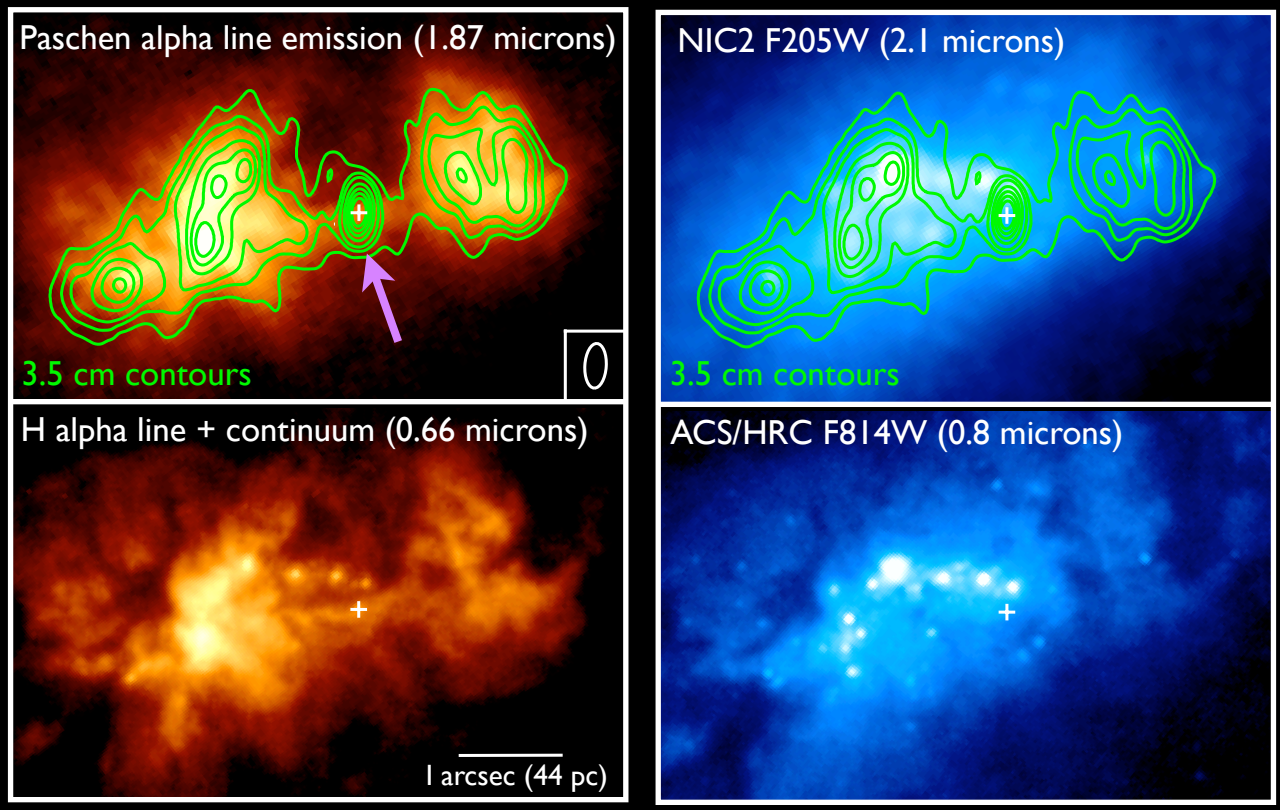


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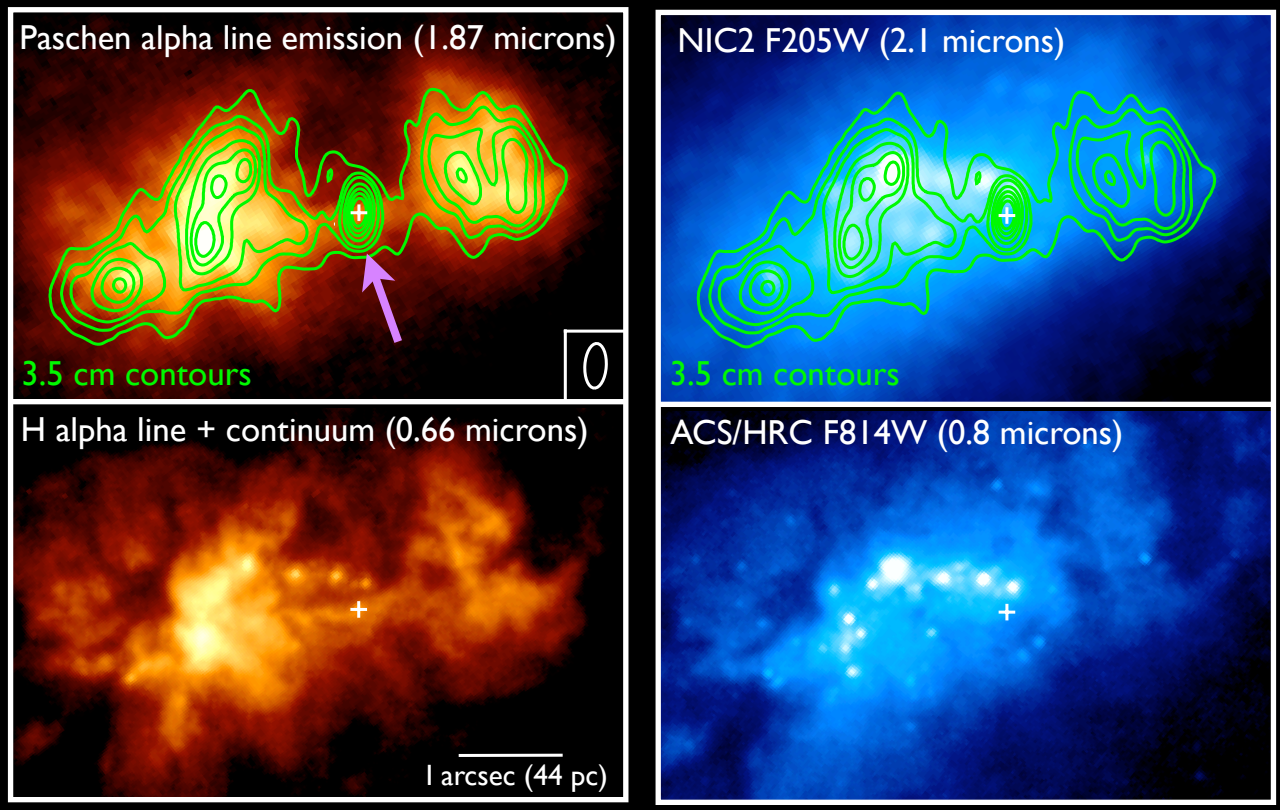


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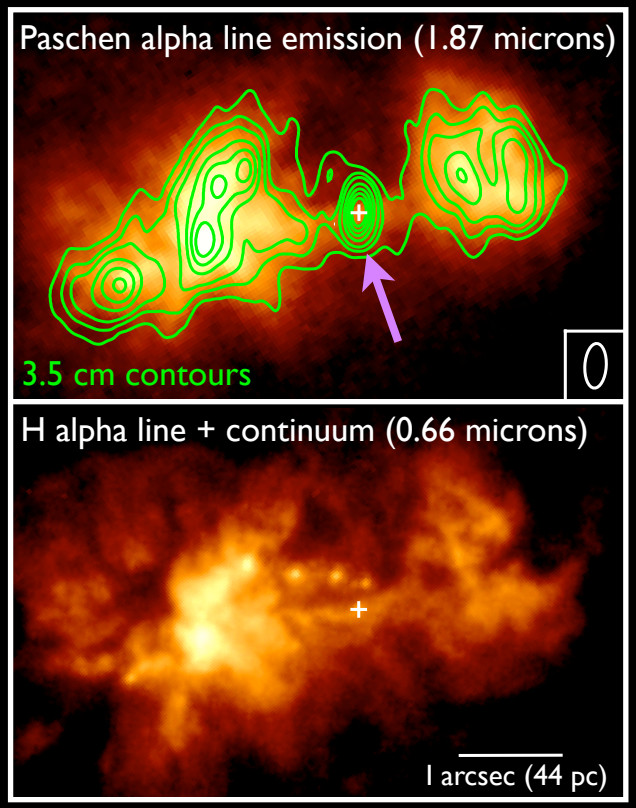


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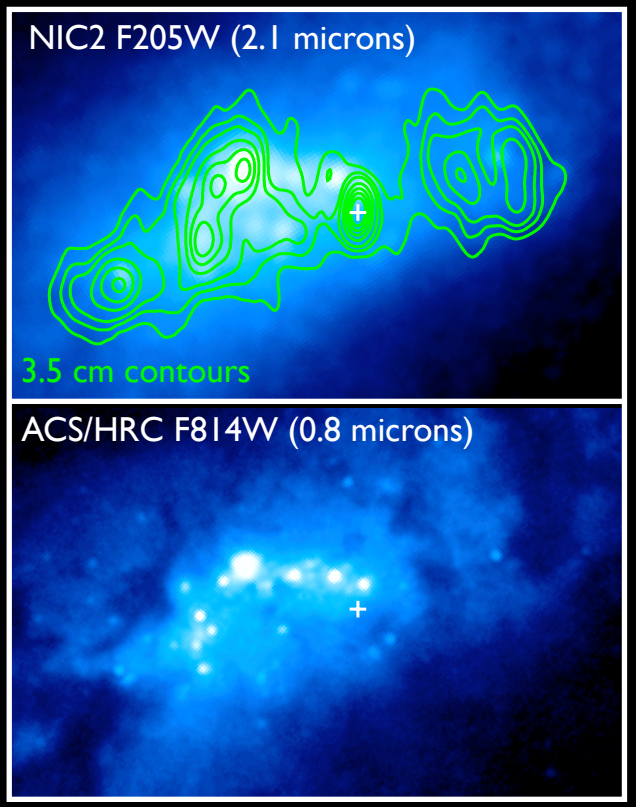


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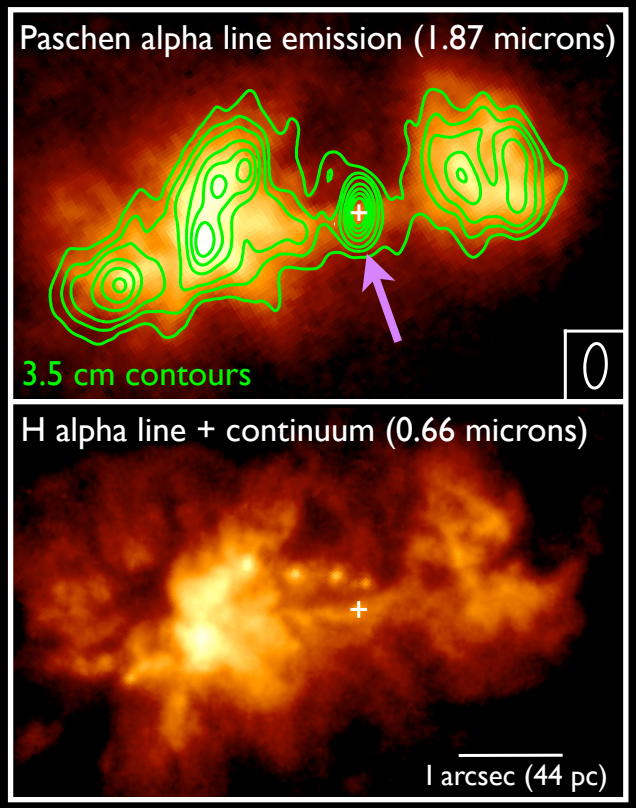


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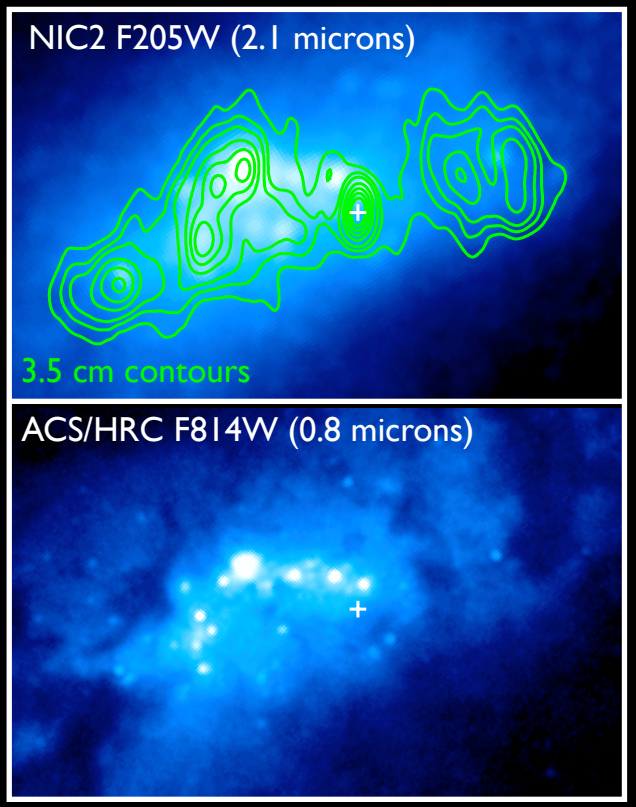


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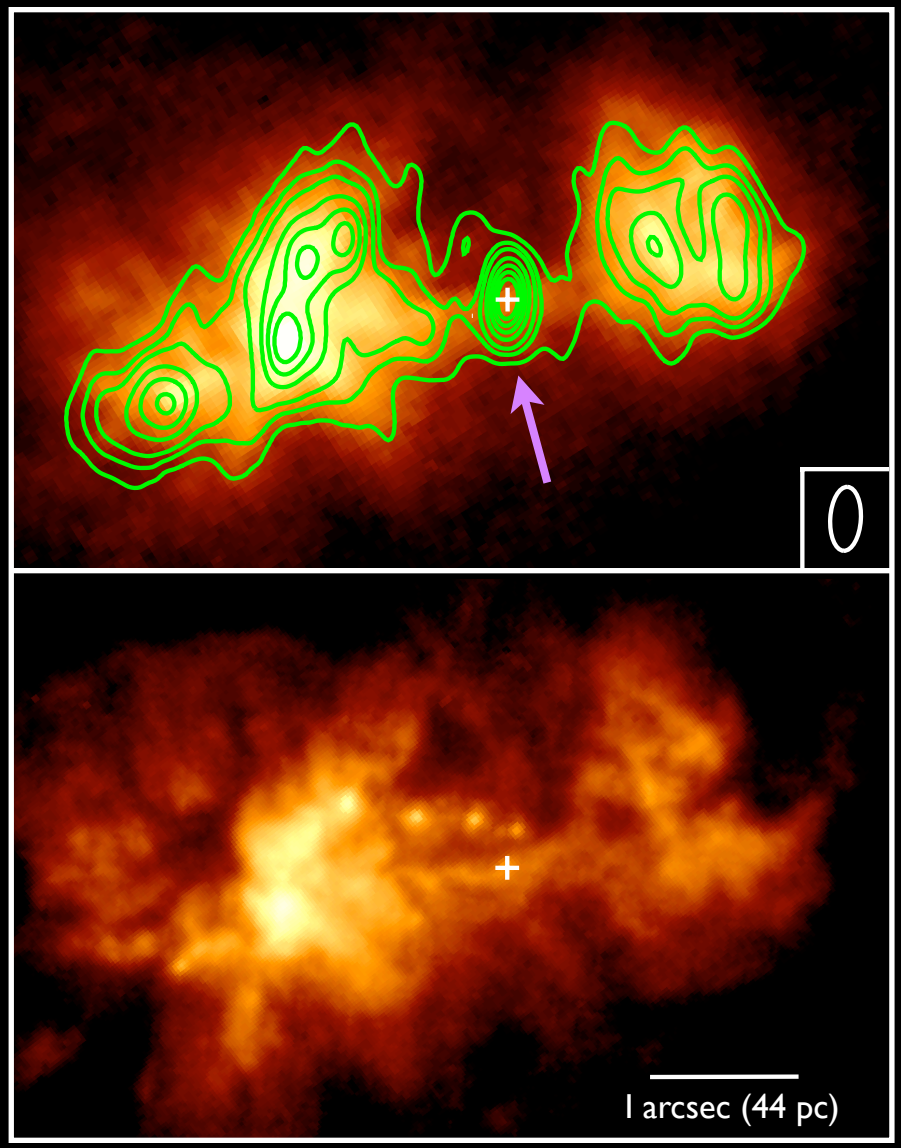
→ Active Galactic Nucleus

# Ruling out alternative explanations

- supernova remnants
- more recently created supernovae
- stellar mass black hole X-ray binaries
- some combination of the above

See Supplementary Information in Reines et al. 2011
at www.nature.com/nature or on astro-ph

# An actively accreting massive black hole



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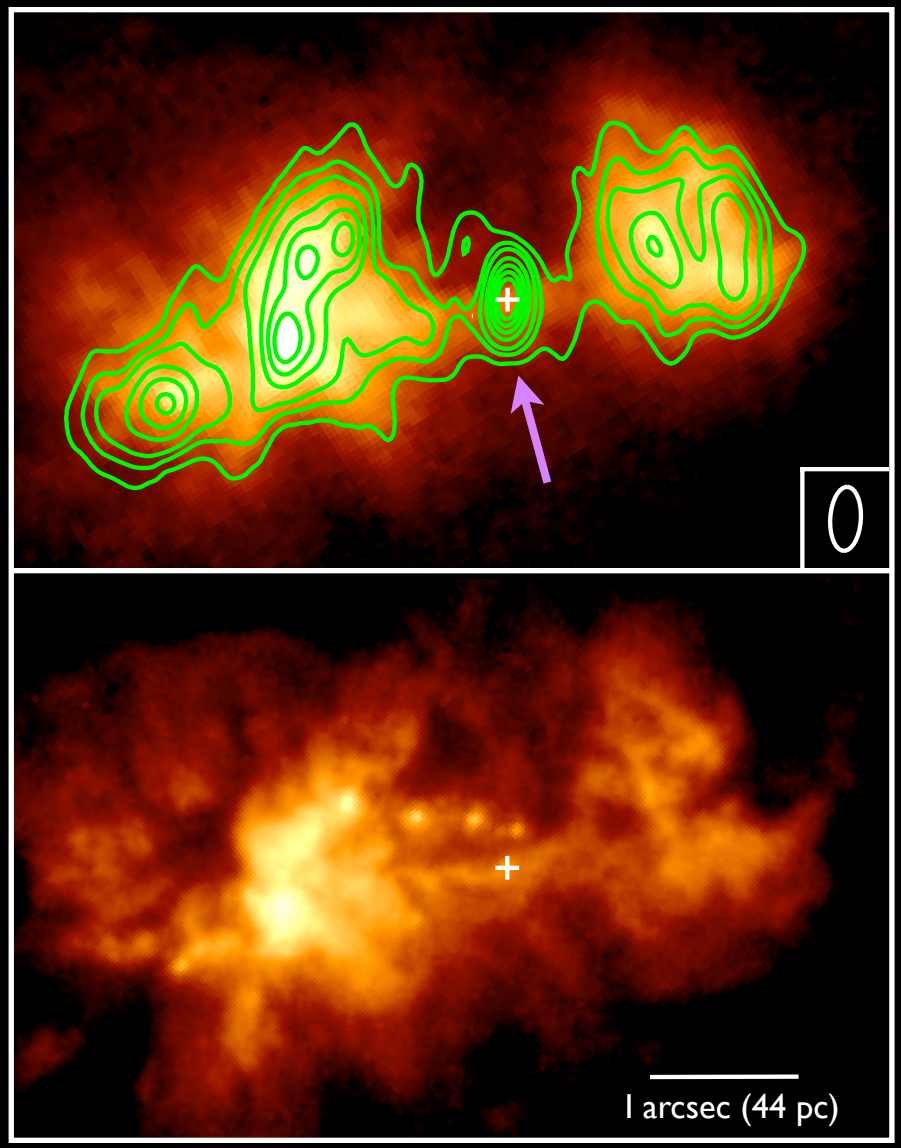
*How massive?*



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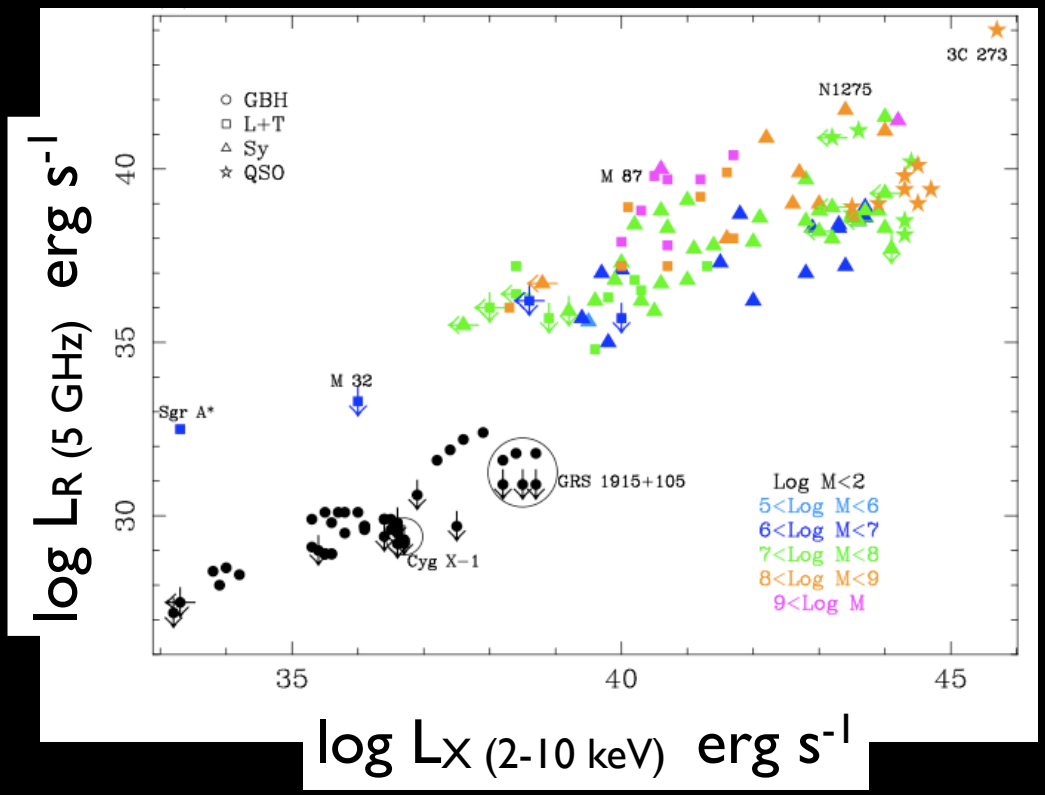

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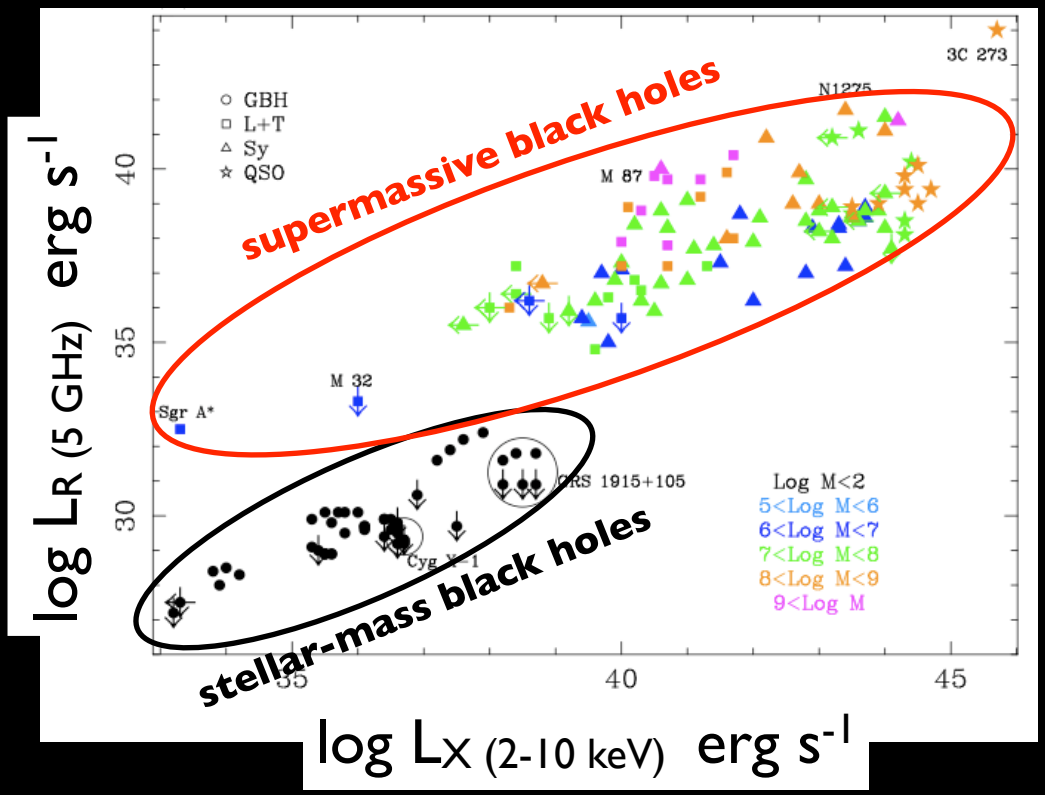

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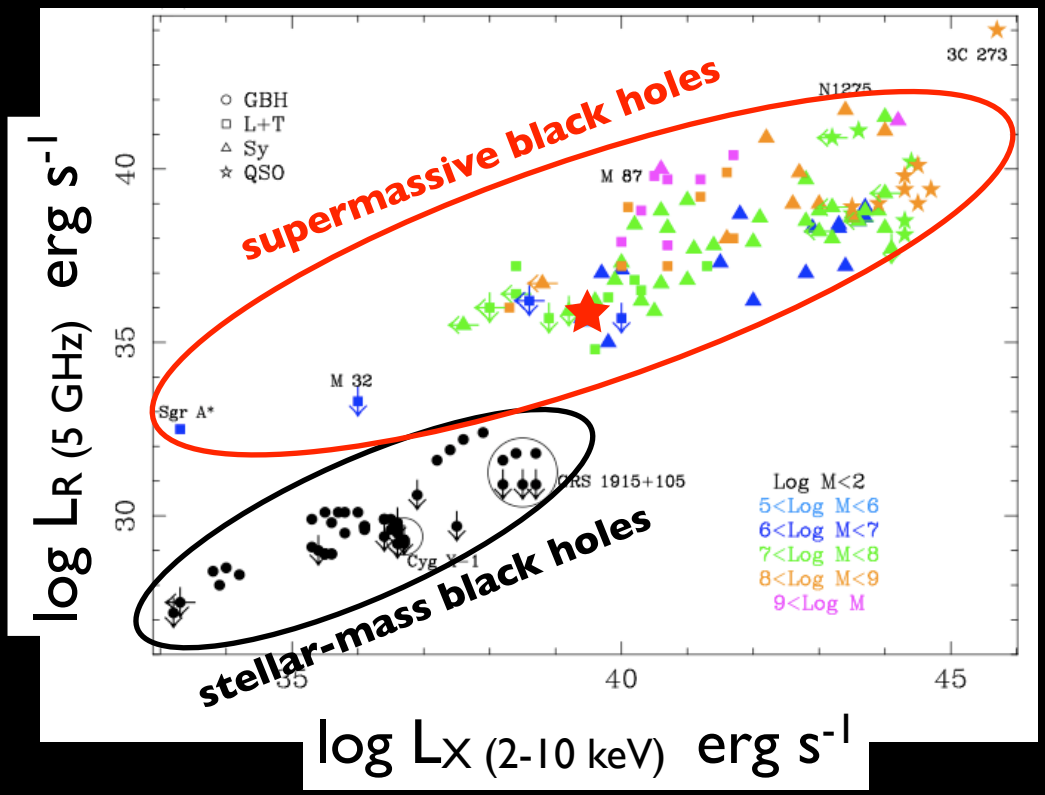

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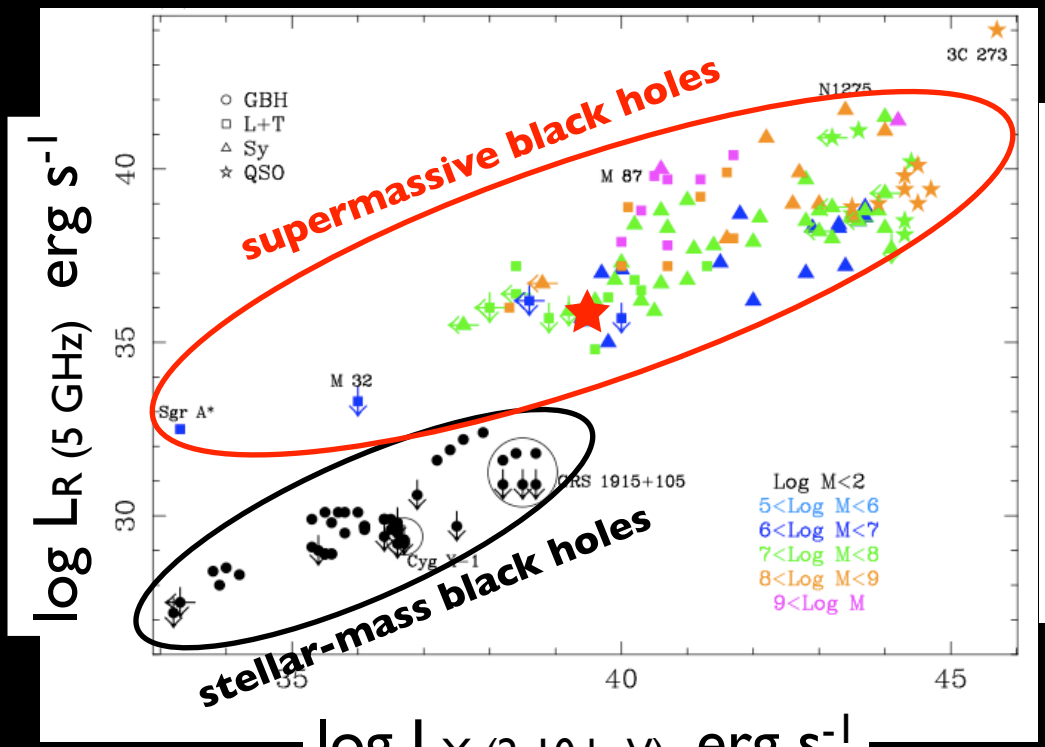


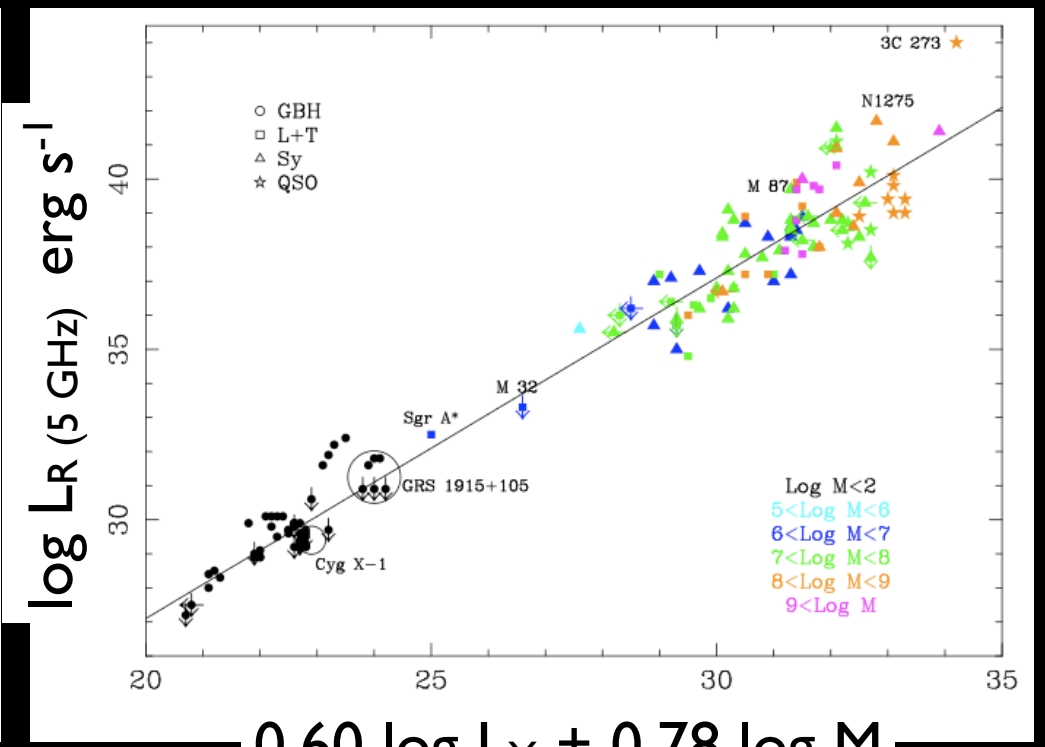


"fundamental plane of black hole activity"

$\log L_R = 0.60 \log L_X + 0.78 \log M + 7.33$

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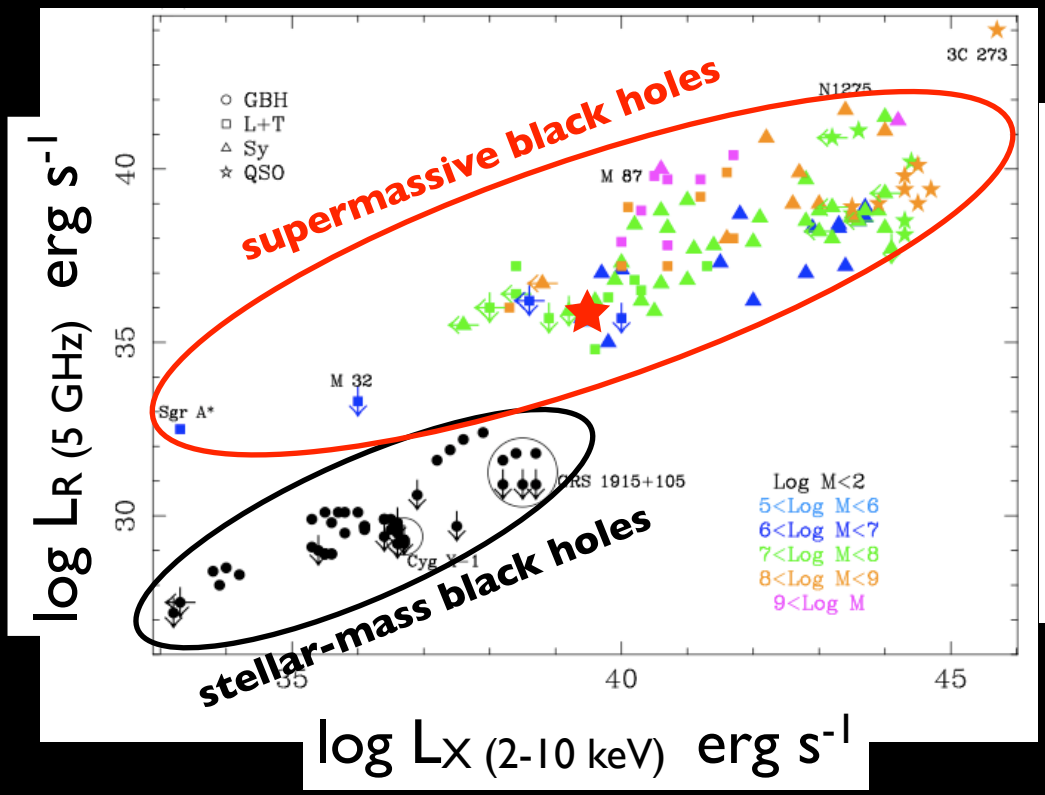
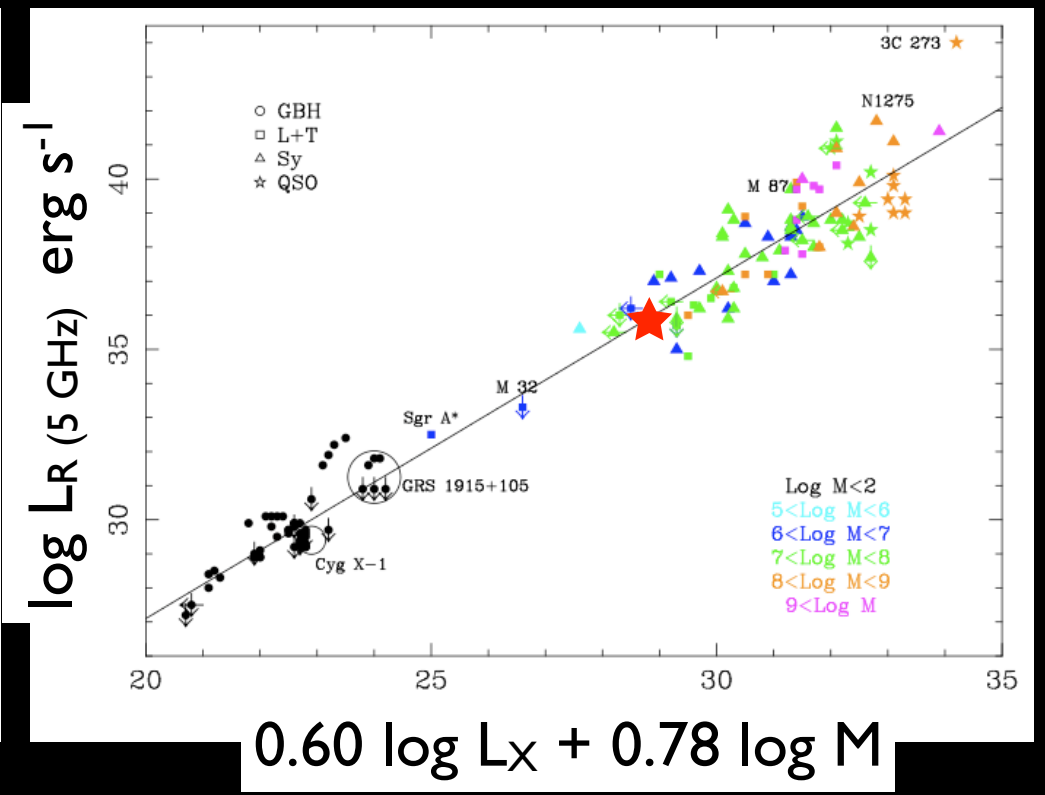
Merloni et al. 2003




"fundamental plane of black hole activity"

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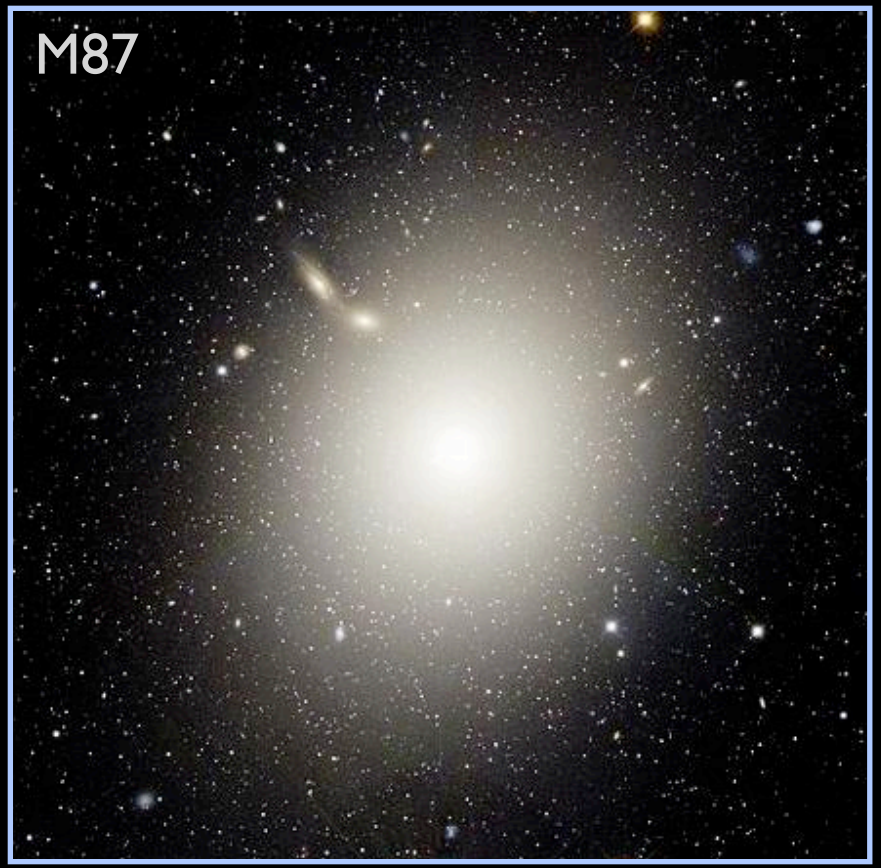
black hole in Henize 2-10 → $\log (M_{BH}/M_{sun}) = 6.3 +/- 1.1$

# Supermassive black holes have typically been found in massive galaxies with bulges


$M_{BH} \sim 1.4 \times 10^8 M_{sun}$ (Bender et al. 2005)

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Supermassive black holes have typically been found in massive galaxies with bulges

*But not always...*


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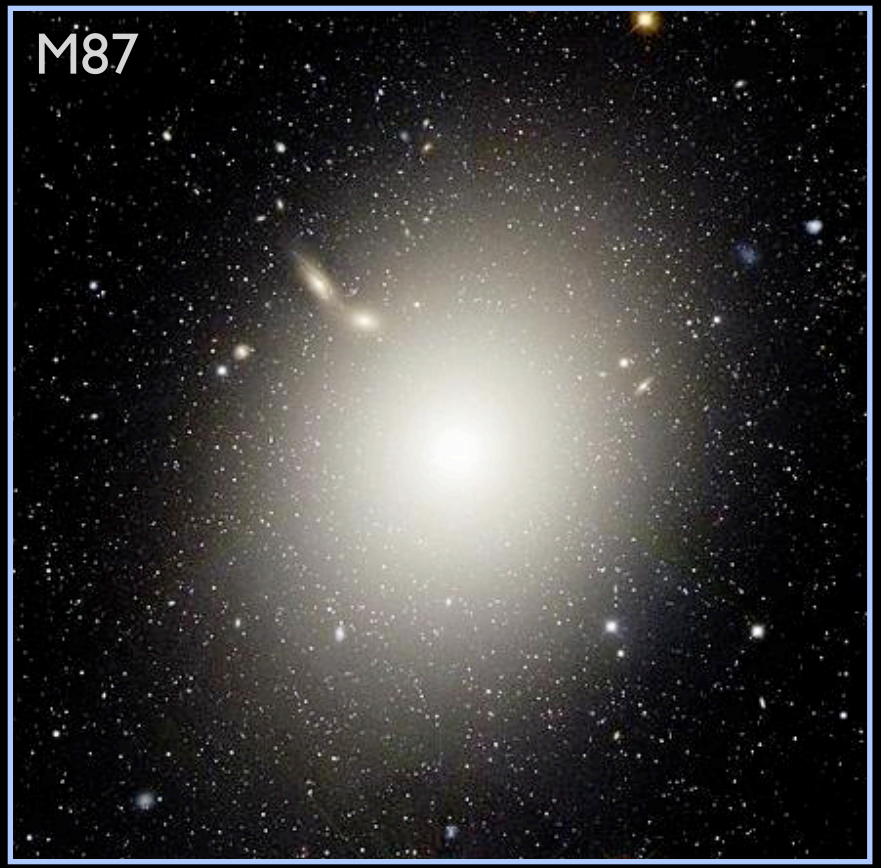


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# The Low-Mass Regime: Putting Henize 2-10 in context

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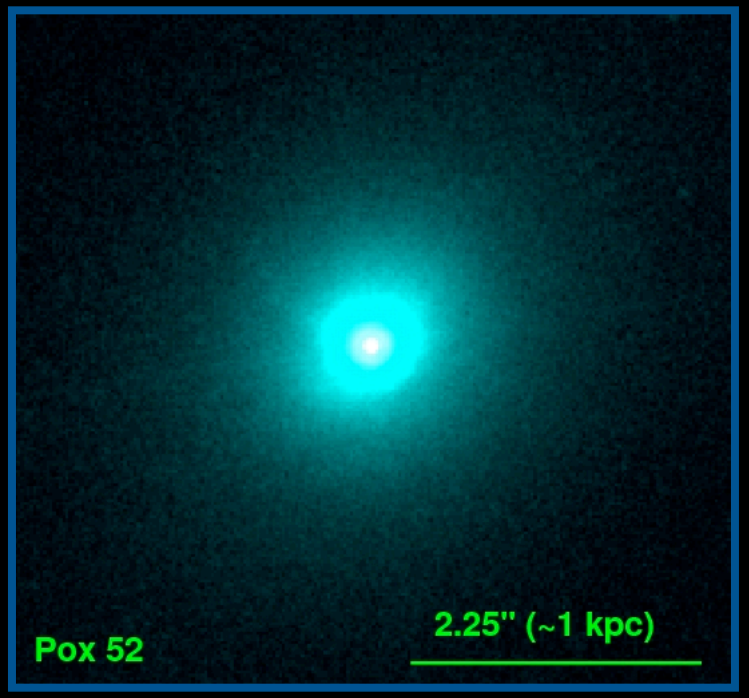
| Name | Type |
|---|---|
| NGC 4395 | Sd |
| Pox 52 | dE |

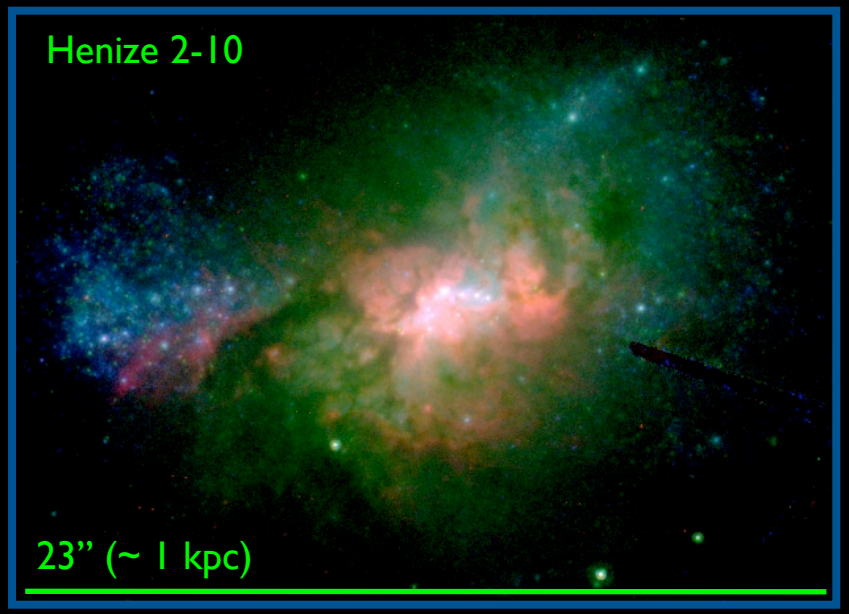

Filippenko & Sargent (1989)
Filippenko & Ho (2003)
Peterson et al. (2005)



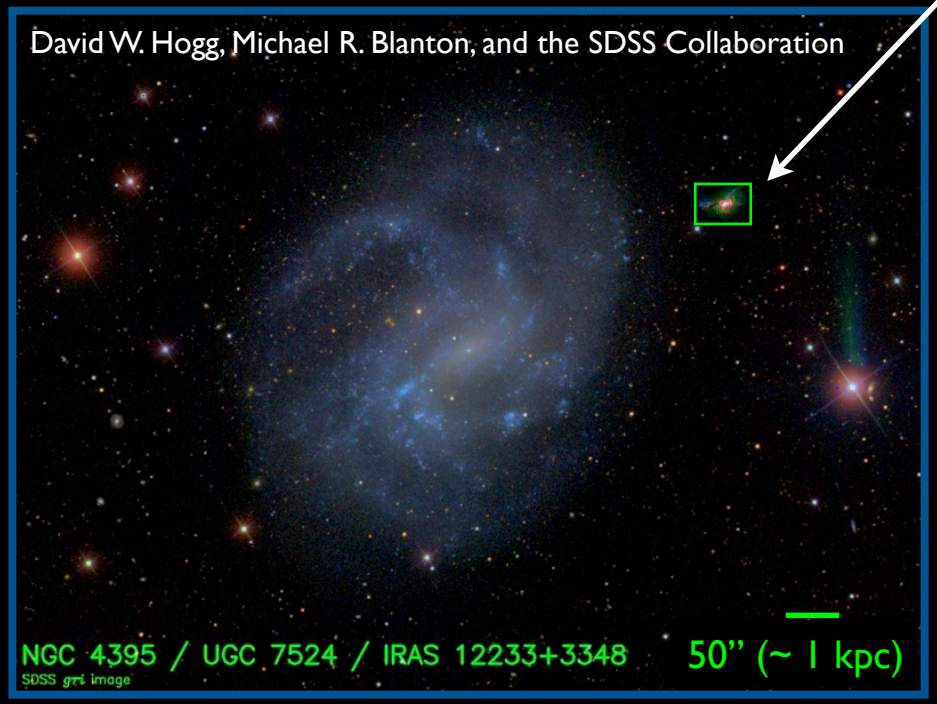

Kunth, Sargent & Bothun (1987)
Barth et al. (2004)
Thornton et al. (2008)

# The Low-Mass Regime

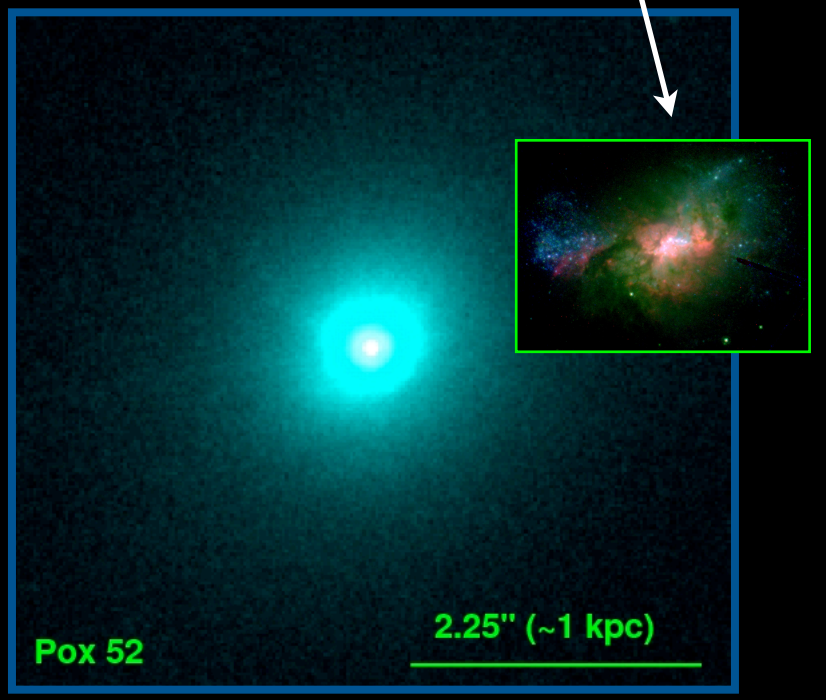
| Name | Type |
|---|---|
| NGC 4395 | Sd |
| Pox 52 | dE |
| Henize 2-10 | Blue Compact Dwarf |




Reines et al. (2011)



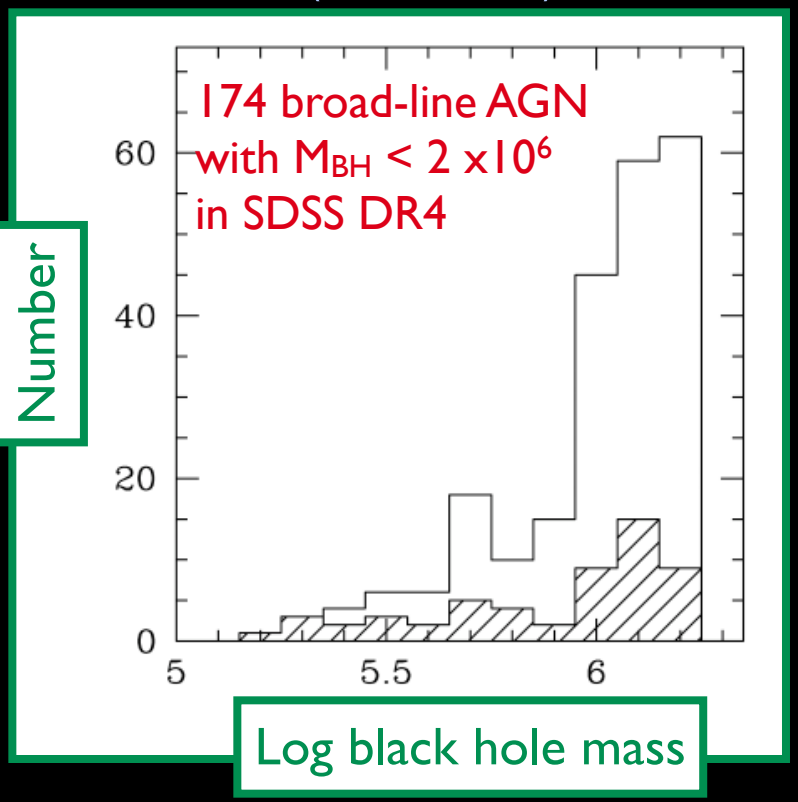

Filippenko & Sargent (1989)
Filippenko & Ho (2003)
Peterson et al. (2005)




Kunth, Sargent & Bothun (1987)
Barth et al. (2004)
Thornton et al. (2008)

# The Low-Mass Regime: Putting Henize 2-10 in context

Greene & Ho (2004, 2007)



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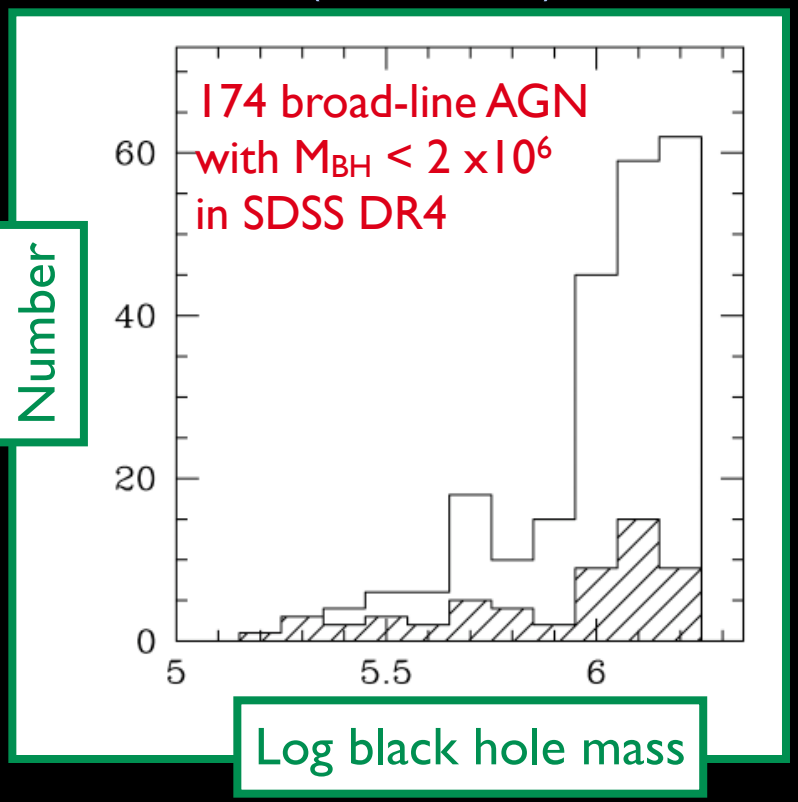
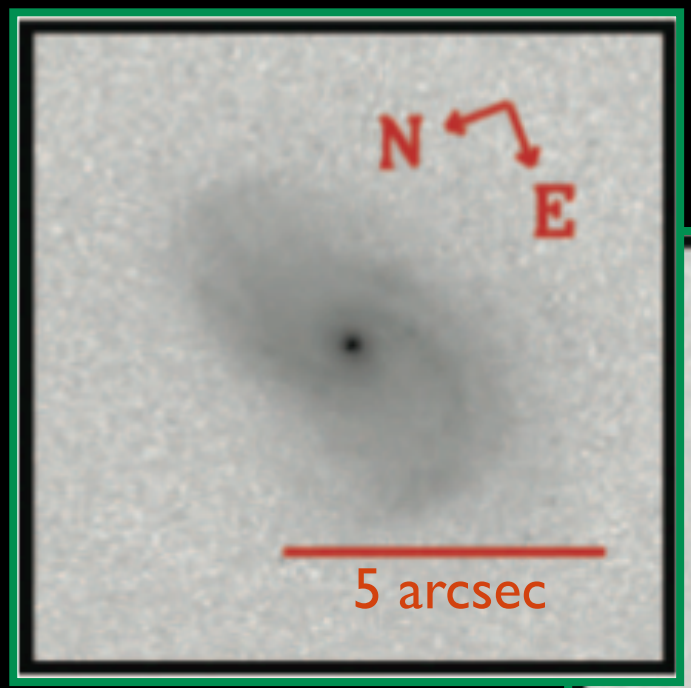
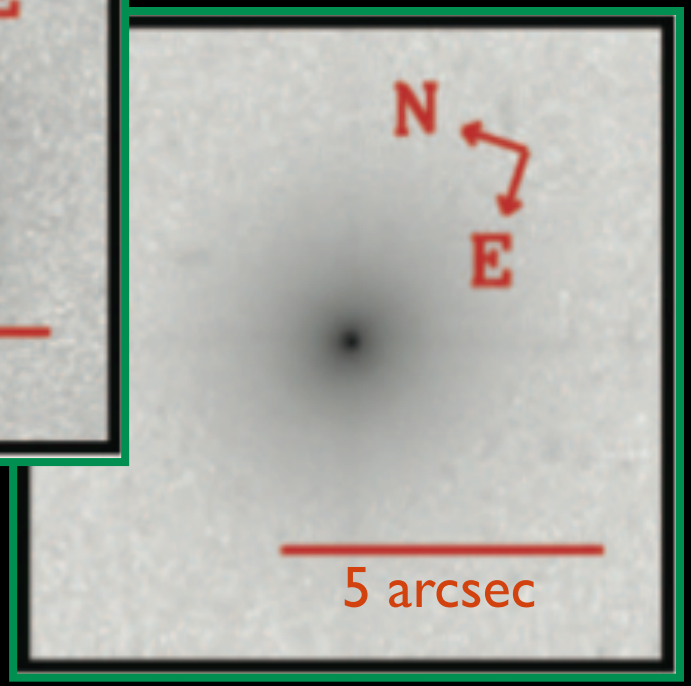



## *Host Galaxies*

- Low-luminosity galaxies, ~ 1 mag below L*
- Well-defined optical nuclei



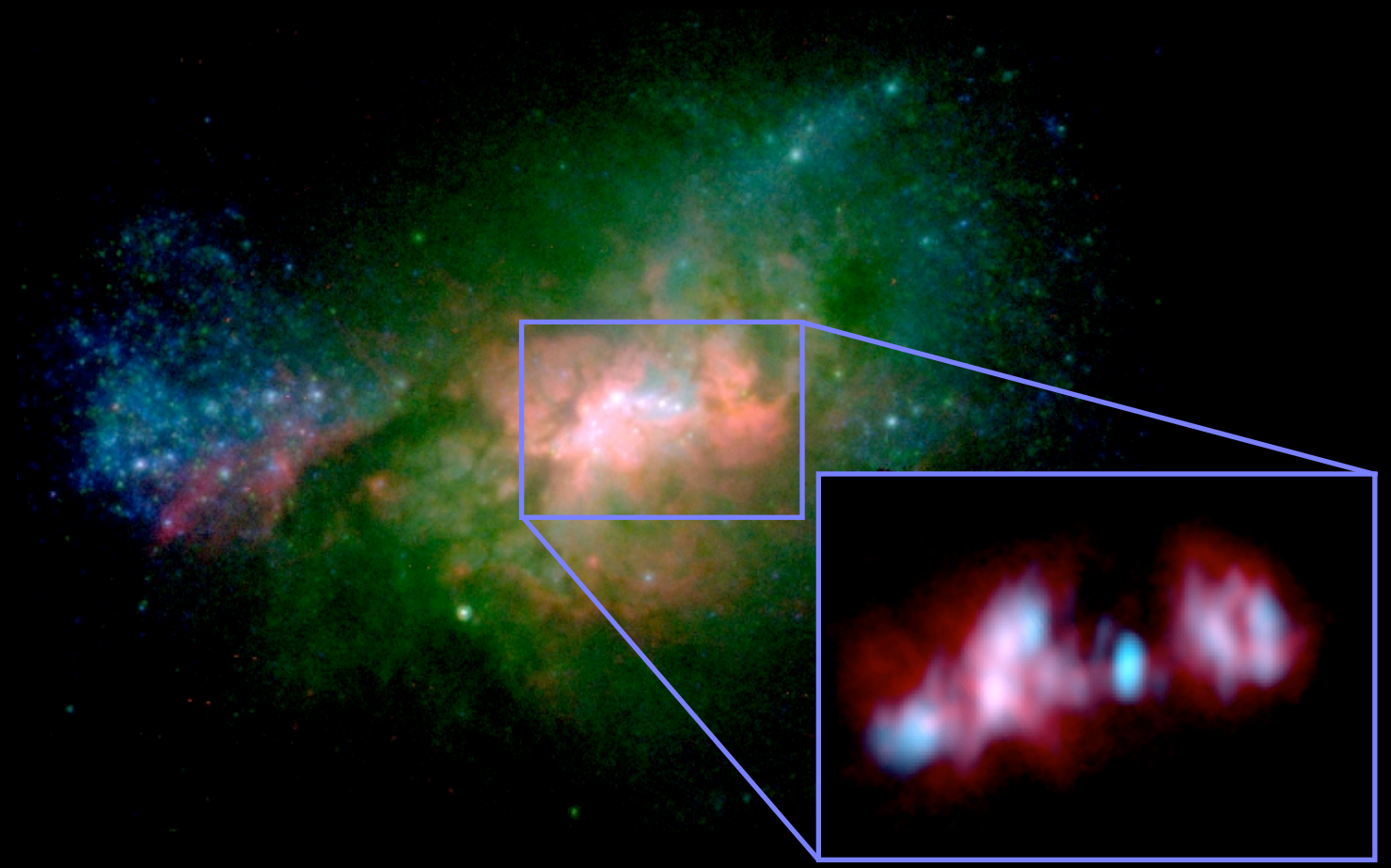

~ 93% extended disks
(with pseudobulges)

~ 7% spheroidals

Greene et al. (2008); Jiang et al. (2011)

# Henize 2-10 is *different*

- Dwarf starburst galaxy with newly formed globular clusters
- Irregular morphology without a well-defined nucleus



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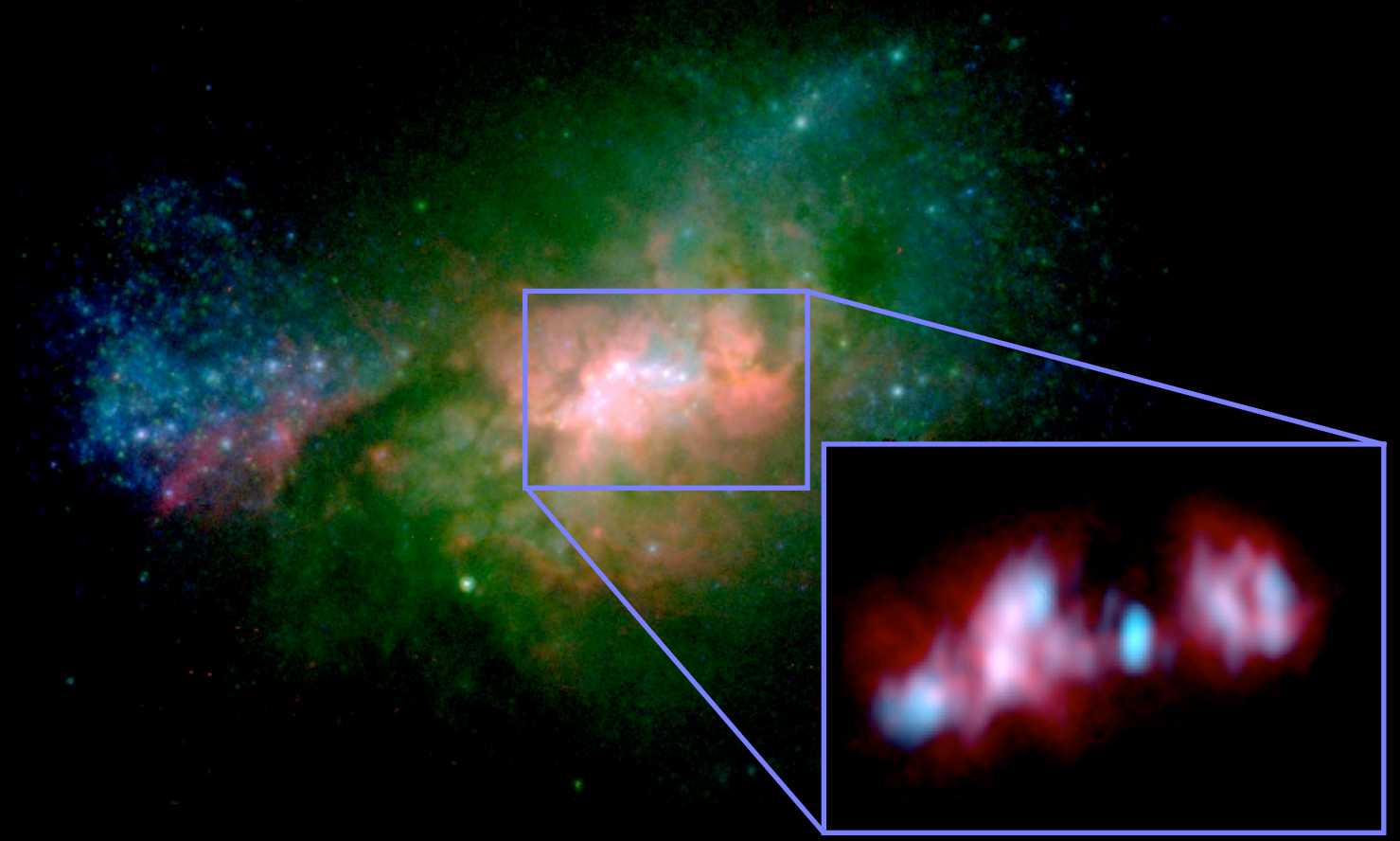

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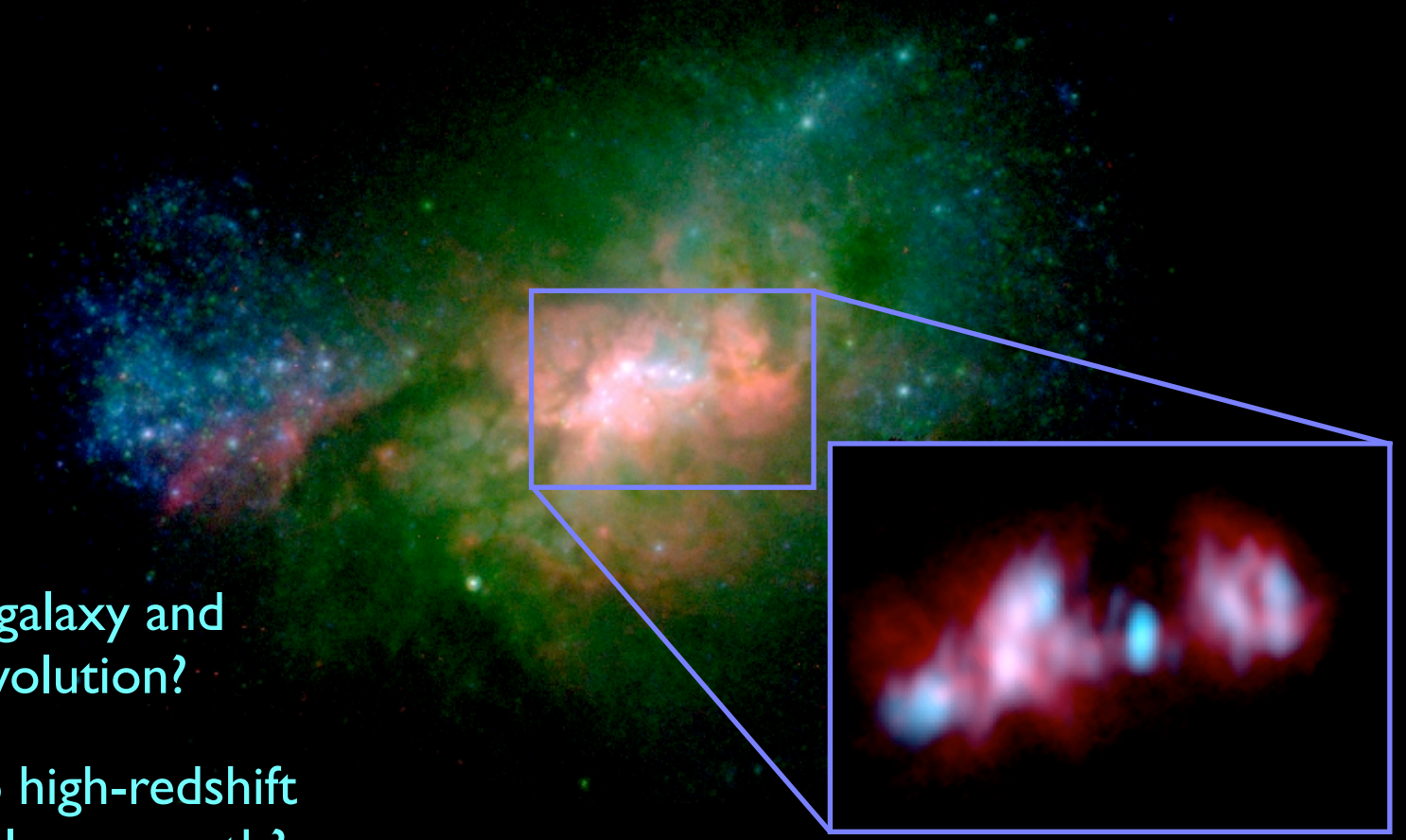
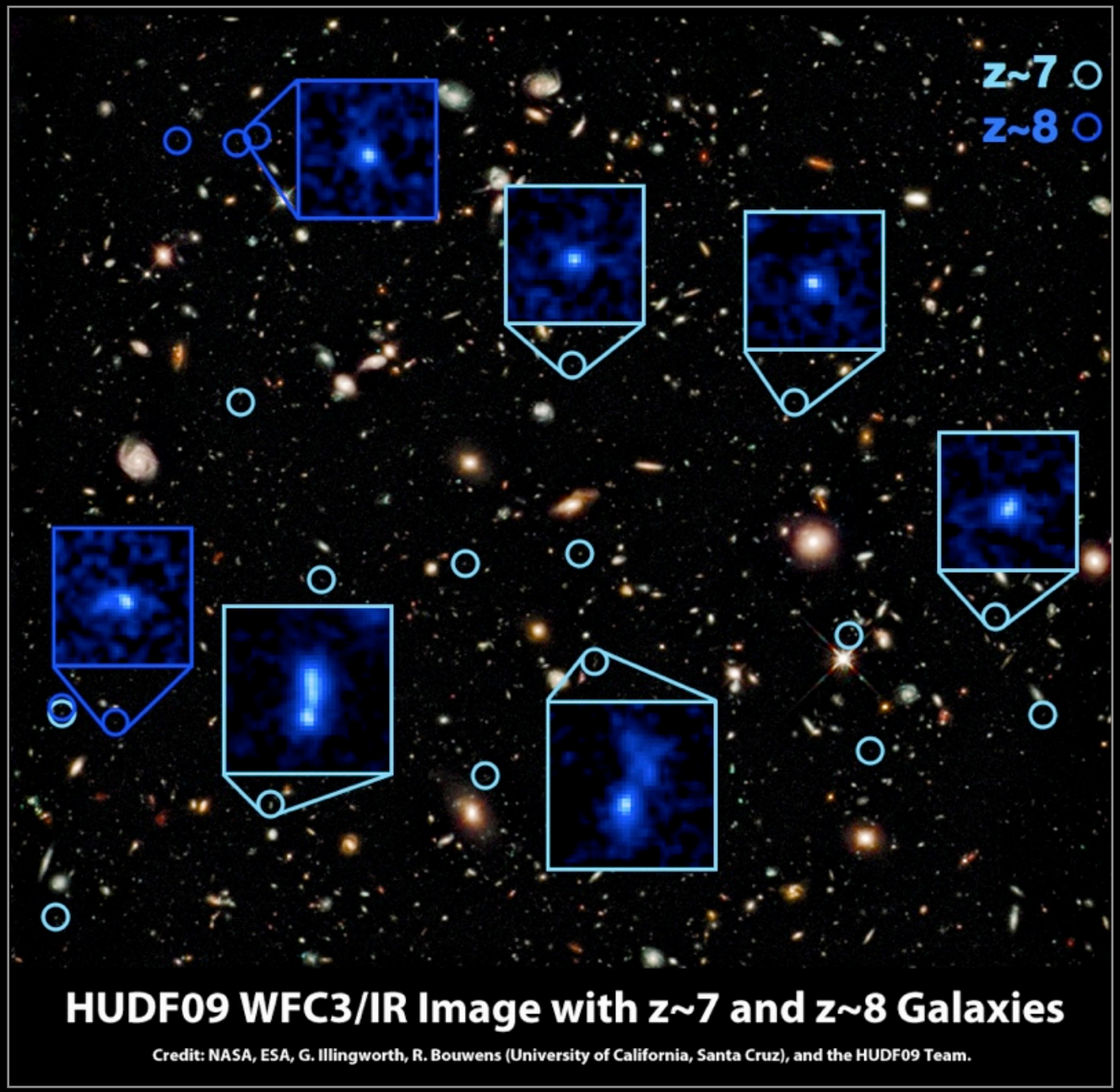


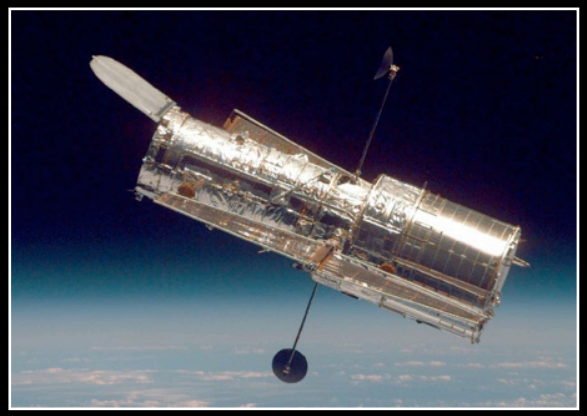
Early stage of galaxy and black hole evolution?

Local analogue to high-redshift black hole and galaxy growth?

# The First Star-Forming Galaxies




- blue, compact galaxies 600-800 Myr after the Big Bang (Bouwens et al. 2010)
- intrinsic sizes $\lesssim$ 1 kpc (Oesch et al. 2010)
- masses ~ $10^9$-$10^{10}$ $M_{sun}$ (Labbé et al. 2010)
- likely forming globular clusters
- likely host massive black holes (Treister et al. 2011)



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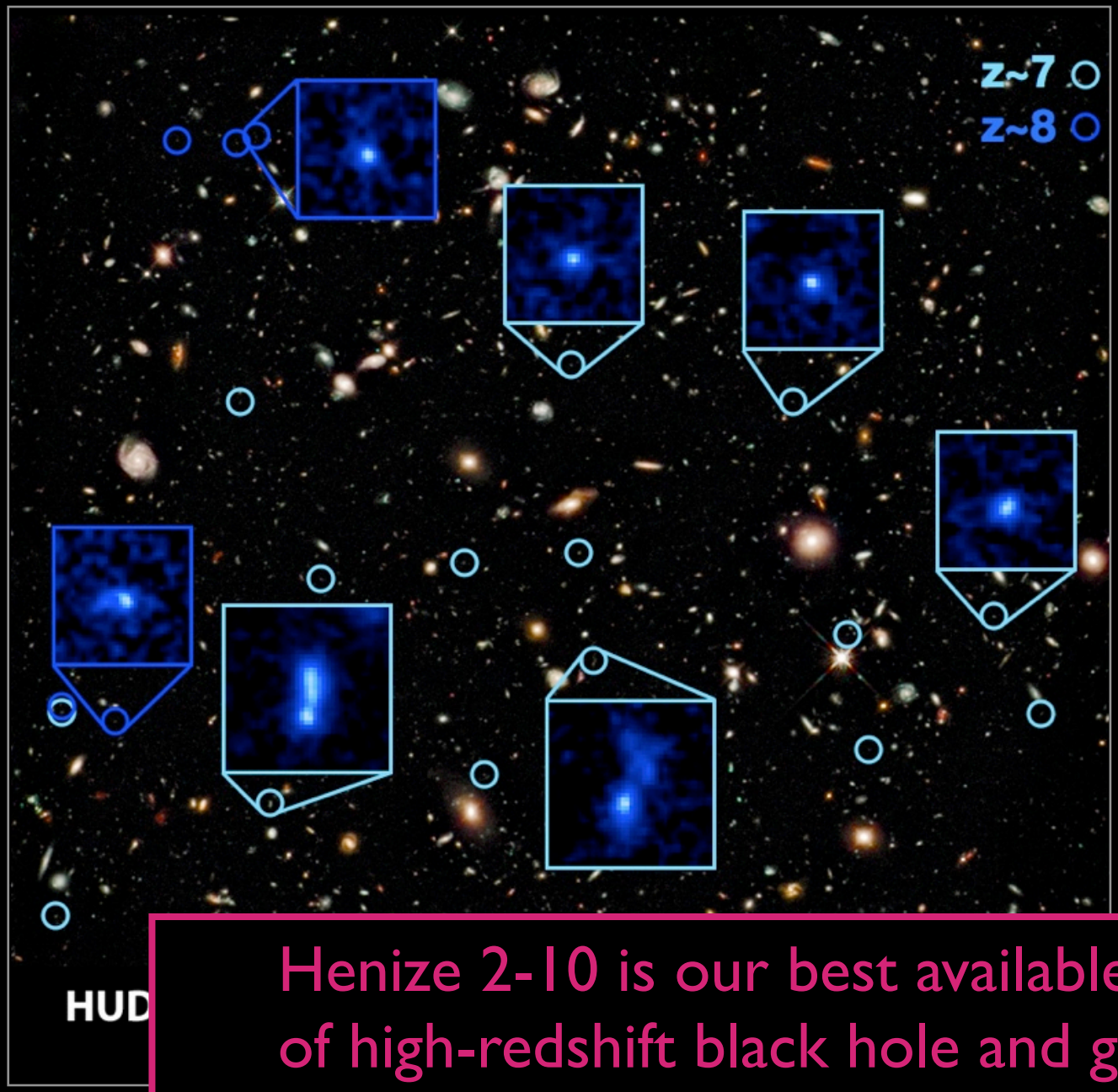


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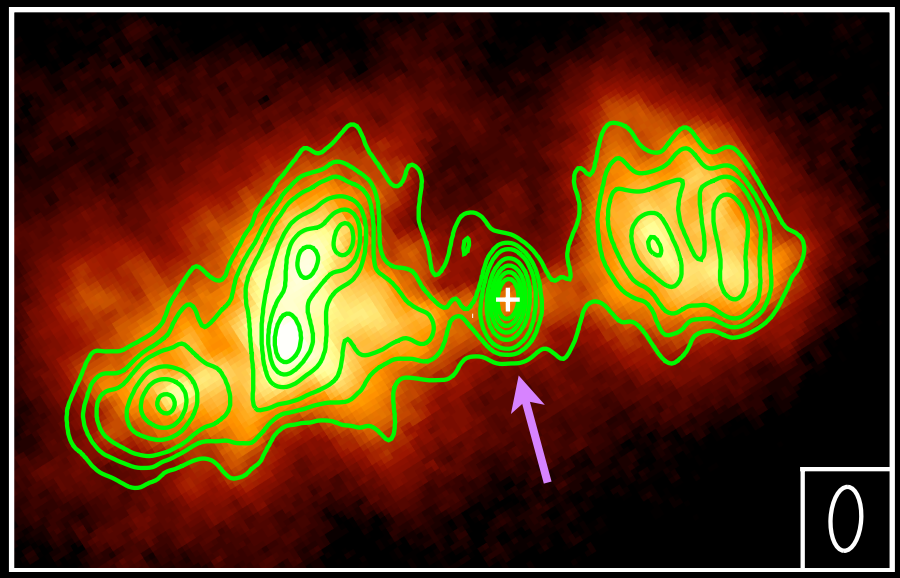
Henize 2-10 is our best available local analog of high-redshift black hole and galaxy growth

# Main take-away points about Henize 2-10

- First example of a massive black hole in a local dwarf starburst galaxy
- Nearby galaxy much like those in the earlier universe
- No discernible bulge - black hole growth can precede the build-up of galaxy spheroids



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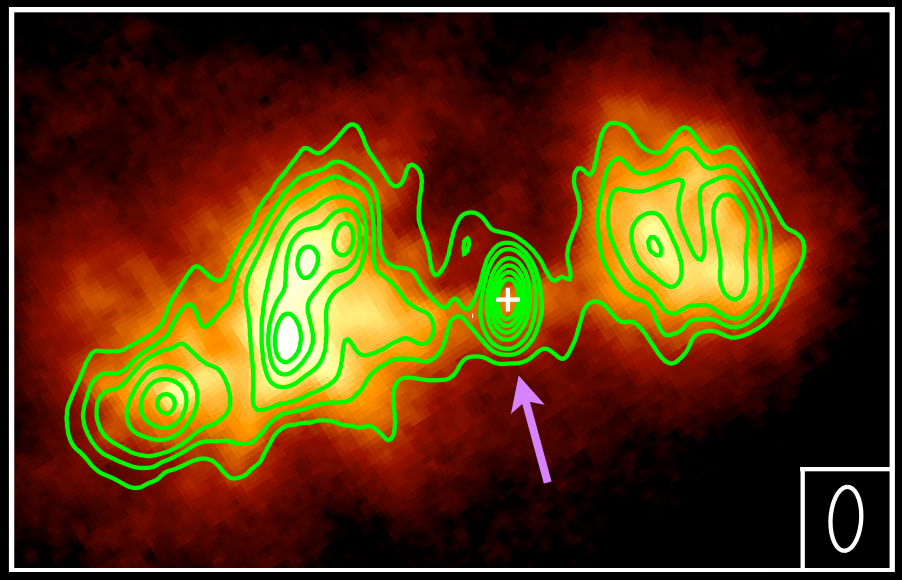
- Nearby galaxy much like those in the earlier universe
- No discernible bulge - black hole growth can precede the build-up of galaxy spheroids
- Opens up a new class of host galaxies in which to search for low-mass black holes!



# The Future:
# Searching for big black holes in little galaxies

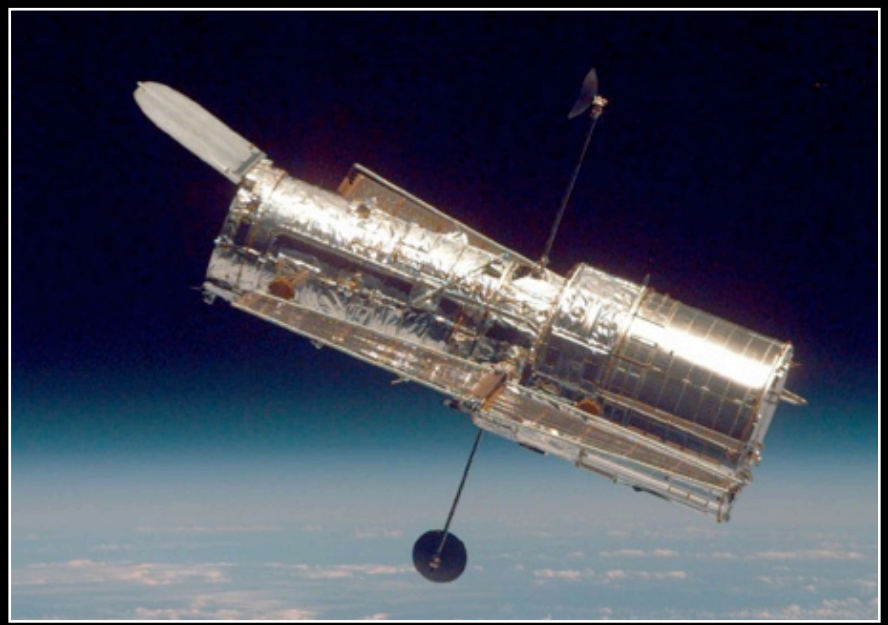
Sensitive, high-resolution radio and X-ray observations of star-forming dwarf galaxies

Accepted Cycle 13 *Chandra* + EVLA proposal

P.I. Reines (w/ Sivakoff, Condon)

# The Future:
# Searching for big black holes in little galaxies

*HST* and ALMA follow-up to study host galaxies



# Follow-up observations of Henize 2-10

## Accepted Proposals

- *HST/STIS* - Kinematics and ionization conditions near AGN
  P.I. Reines (w/ Whittle, Johnson)

- *XMM-Newton* - X-ray follow-up
  P.I. Hickox (w/ Greene, Reines, Sivakoff, Johnson, Alexander)

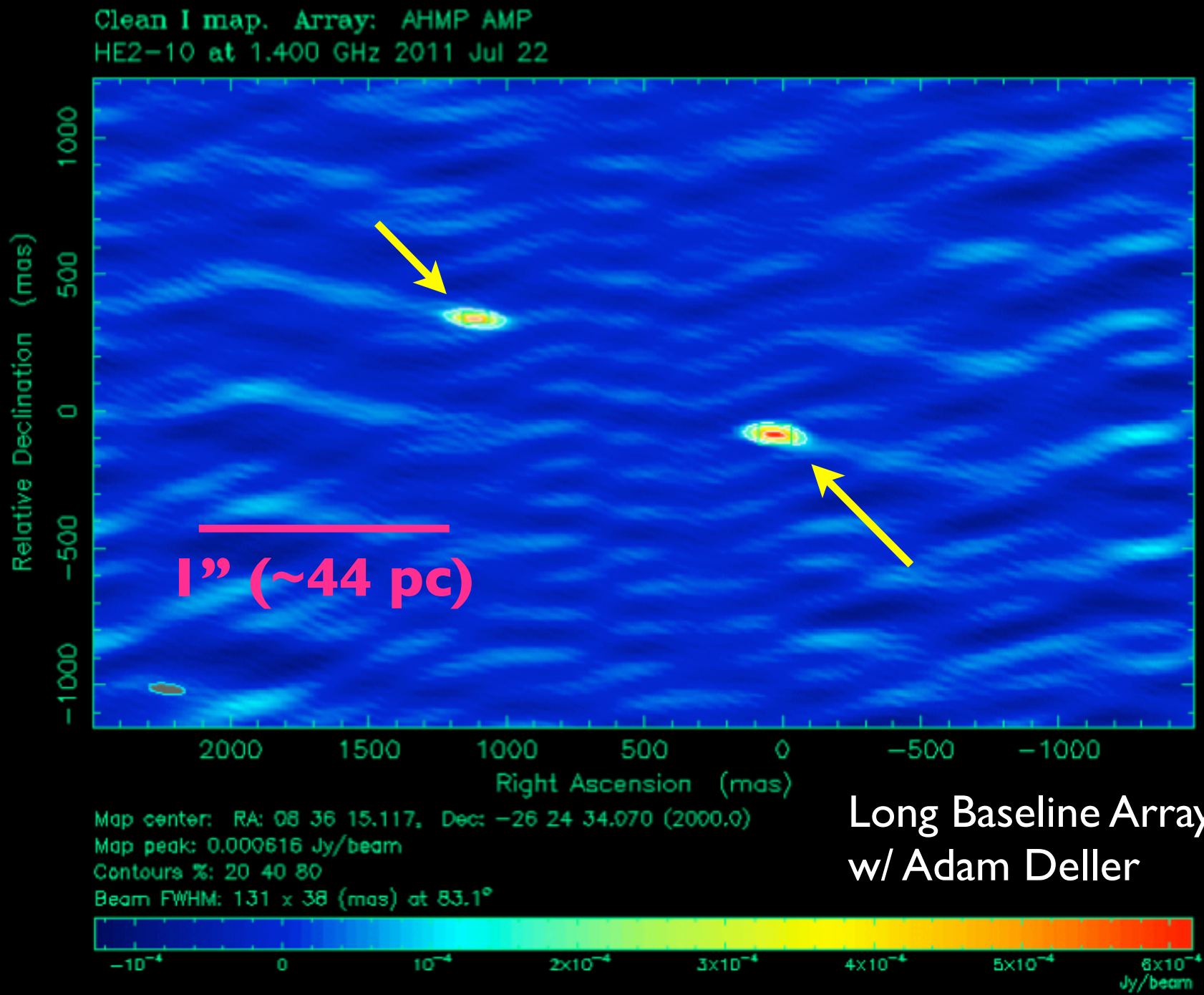
- *VLBI with the Long Baseline Array* - High-resolution observations at 1.4 GHz
  P.I. Reines (w/ Deller, Johnson)

## Submitted Proposals

- *EVLA* - Water maser observations
  P.I. Reines (w/ Darling, Brogan, Johnson)

- *ALMA* - Dense molecular gas
  P.I. Johnson (w/ Reines, Testi, Brogan, Vanzi, Wilner, Chen)

# New VLBI observations of Henize 2-10 at 1.4 GHz




Long Baseline Array (LBA)
w/ Adam Deller

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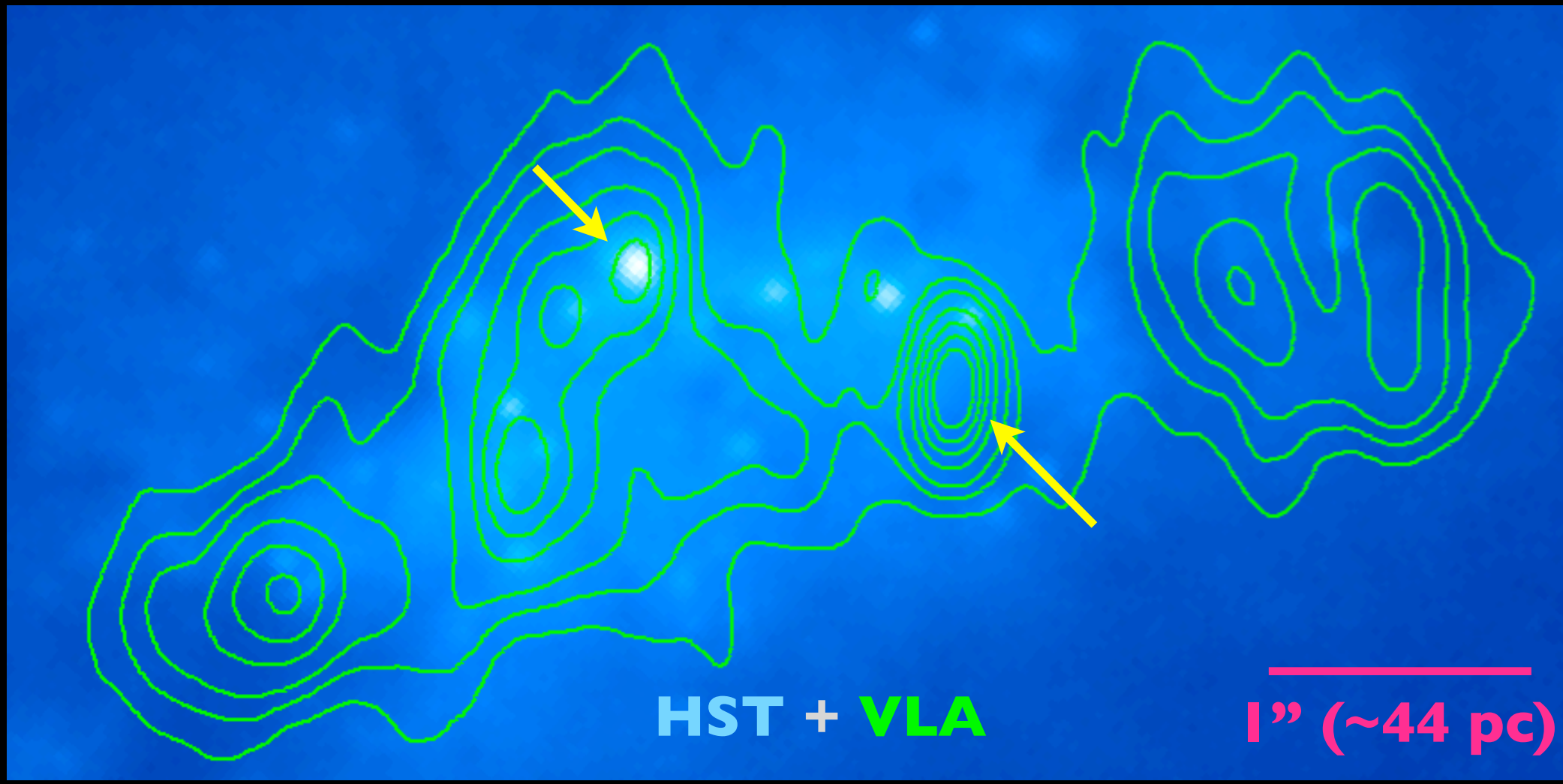

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