SOAR 2018: Galaxies

Aileen A. O'Donoghue
Priest Associate Professor of Physics

ST. LAWRENCE UNIVERSITY

Photo by Marc Staves 2011

Galaxies

- ☆ 9/4/18
  - Milky Way Galaxy Contents & Motions
- ☆ 9/11/18
  - Milky Way Environment & the Local Group
- ☆ 9/18/18
  - Other Galaxies & Clusters of Galaxies
- ☆ 9/30/18
  - Expansion, History & Evolution of the Universe

SOAR: Galaxies

The Milky Way Environment & the Local Group

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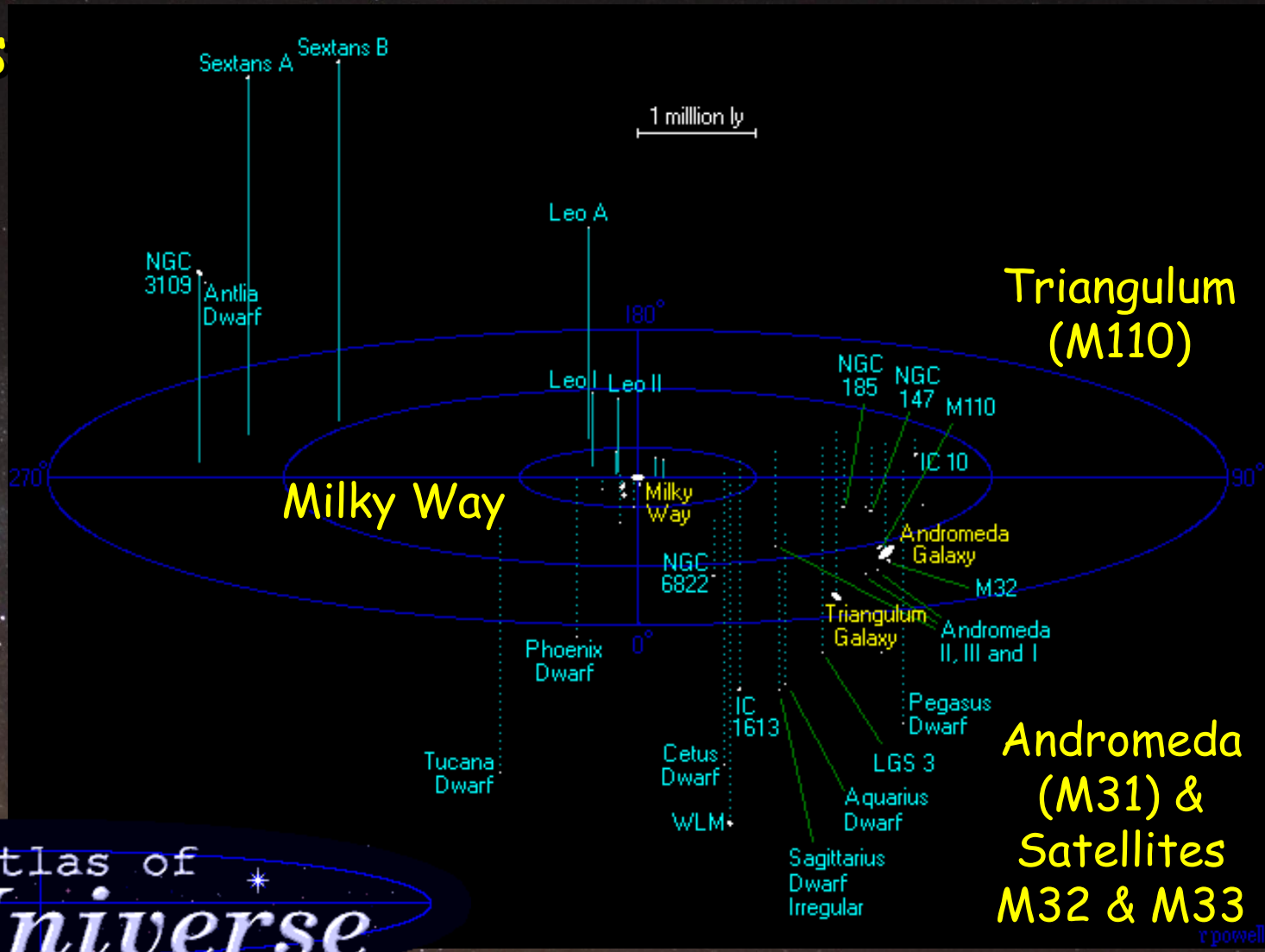
Photo by Marc Staves 2011

The Local Group

☆ The Milky Way's Galaxy Cluster

- > 54 galaxies within 5 million light years



An Atlas of The Universe

Photo by Mar

The 'Hood

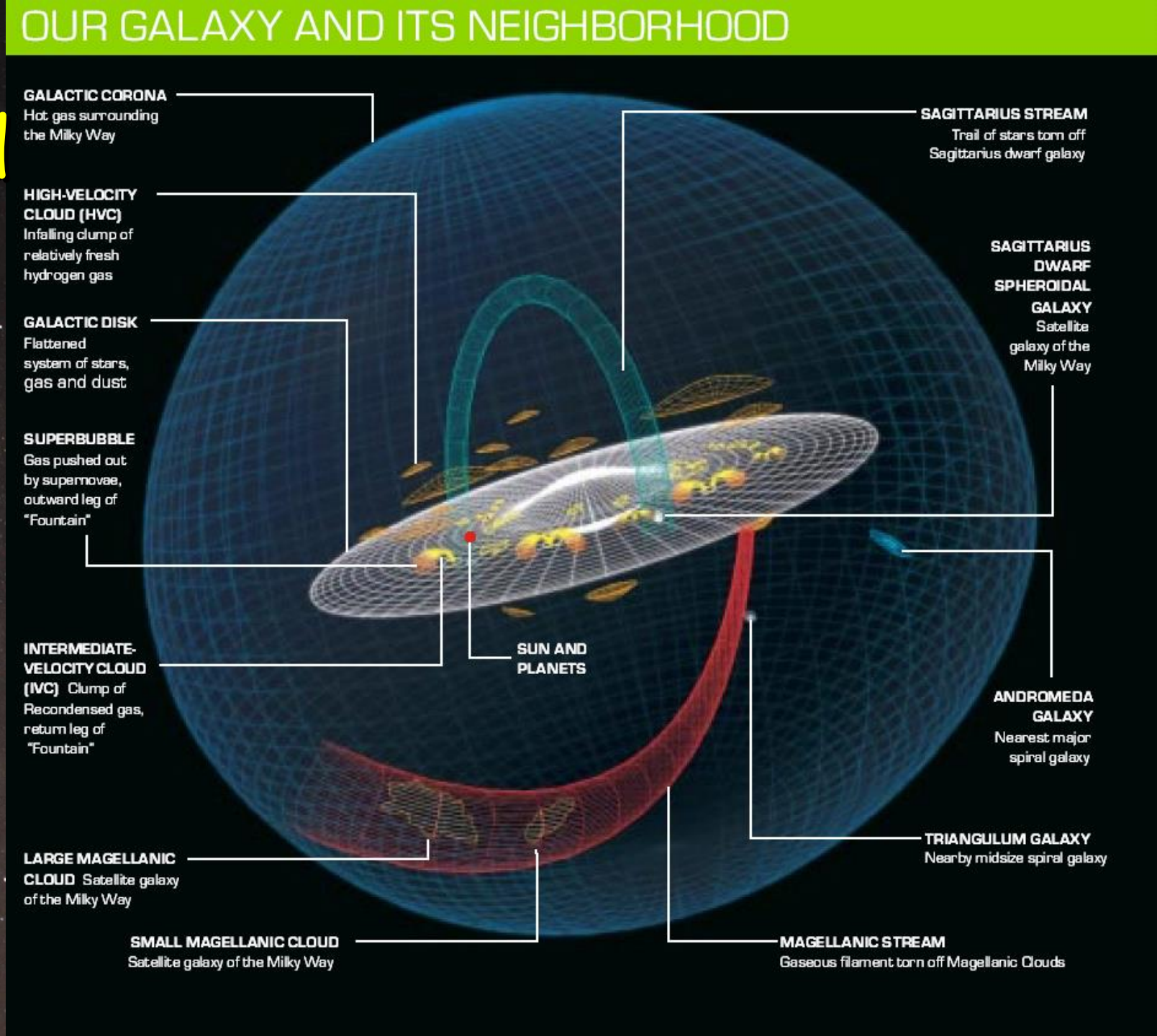
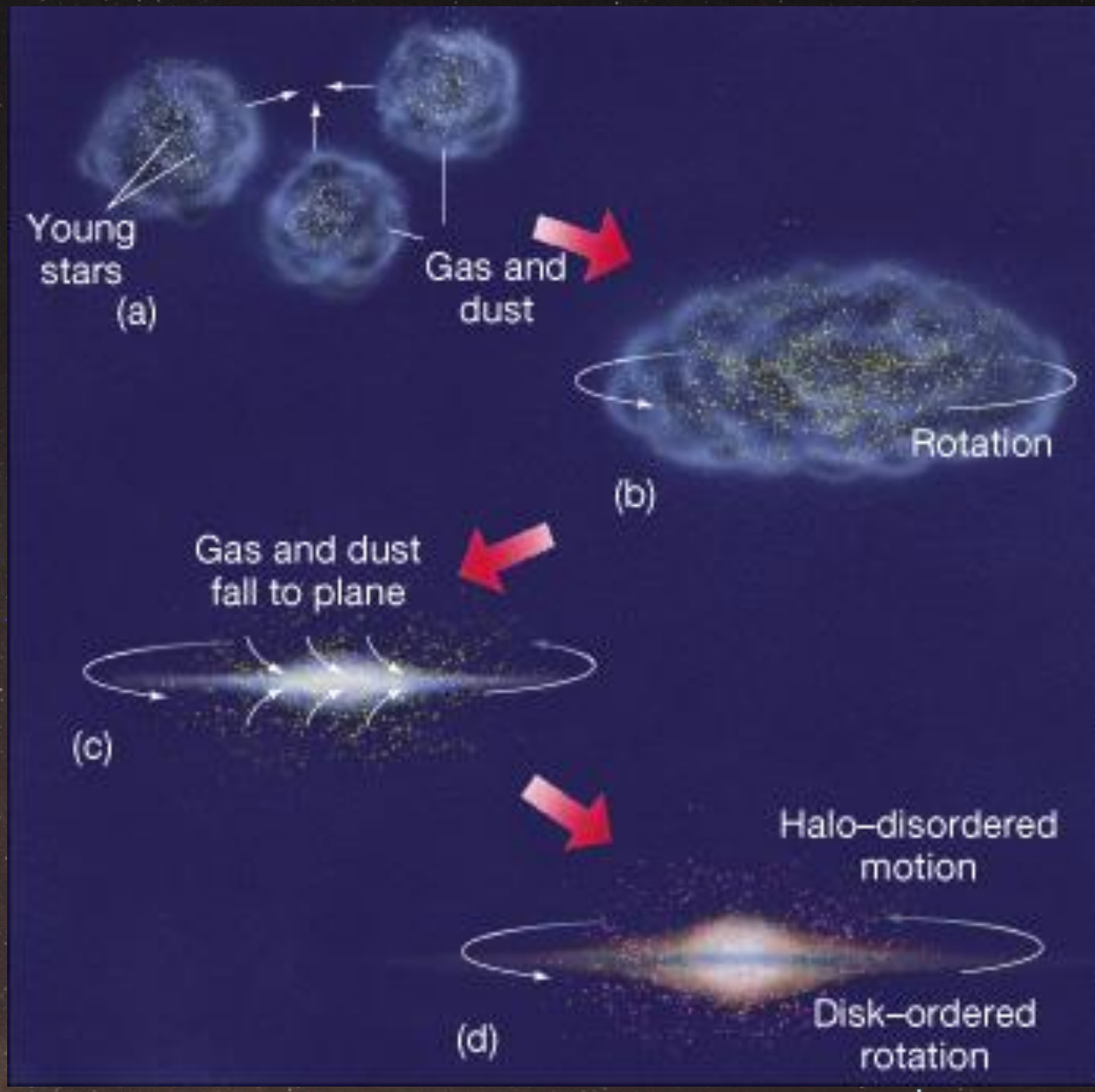


Photo by Marc Staves 2011

Milky Way's Environment

IntraCluster Medium (ICM)

Did galaxies form from this gas?

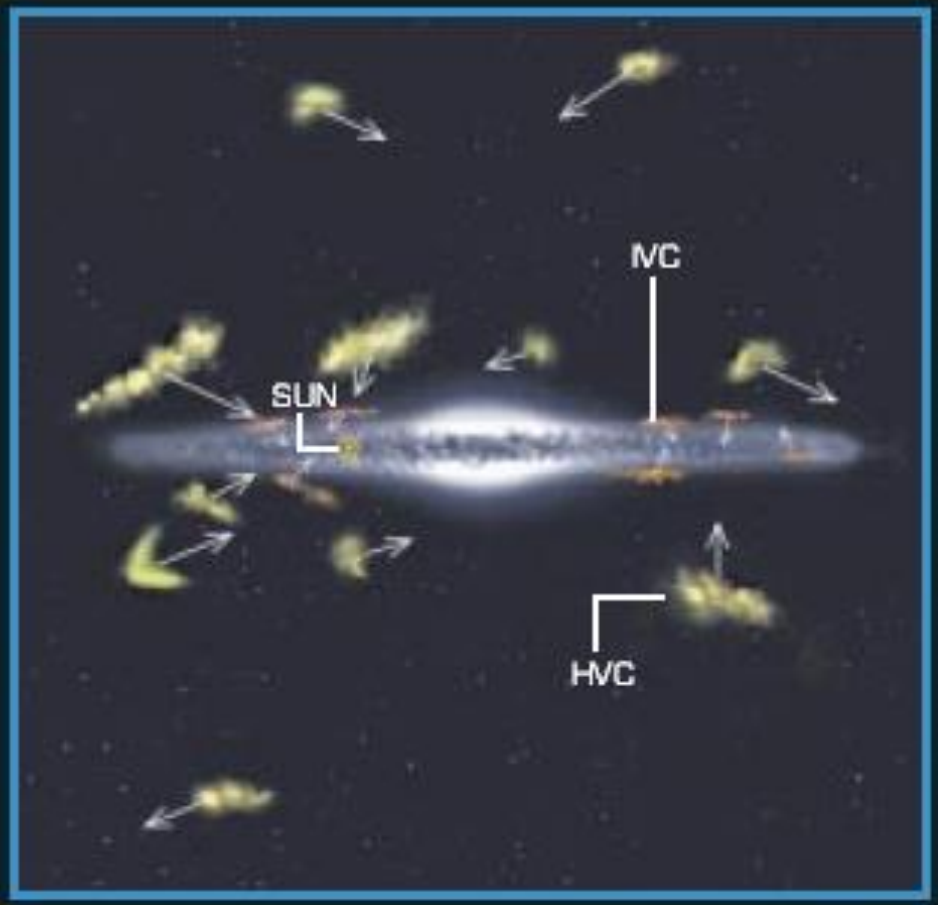


Milky Way's Environment

☆Galaxies emit and absorb gas

GALACTIC FOUNTAIN: Intermediate-velocity clouds are probably the return leg of a vast cycle of gas. Clusters of supernova explosions generate bubbles of hot gas (blue) that break through the surrounding cold gas (yellow) and feed a hot corona. Chunks of the gas cool and fall back to the disk.

GAS INFALL: Many of the high-velocity clouds (yellow) are gas raining onto the Milky Way, continuing its formation nearly 12 billion years after it started. Such gas could provide fresh fuel for star formation. Observationally, they are easily confused with the intermediate-velocity clouds (orange).



Milky Way's Environment

- ☆ Milky Way's Lumpy Halo
  - 🌎 Stars, Globular Clusters, Gas, Dwarf Galaxies

Being studied by RAdial Velocity Experiment by Institutions from 11 nations

RAVE
RADIAL VELOCITY EXPERIMENT

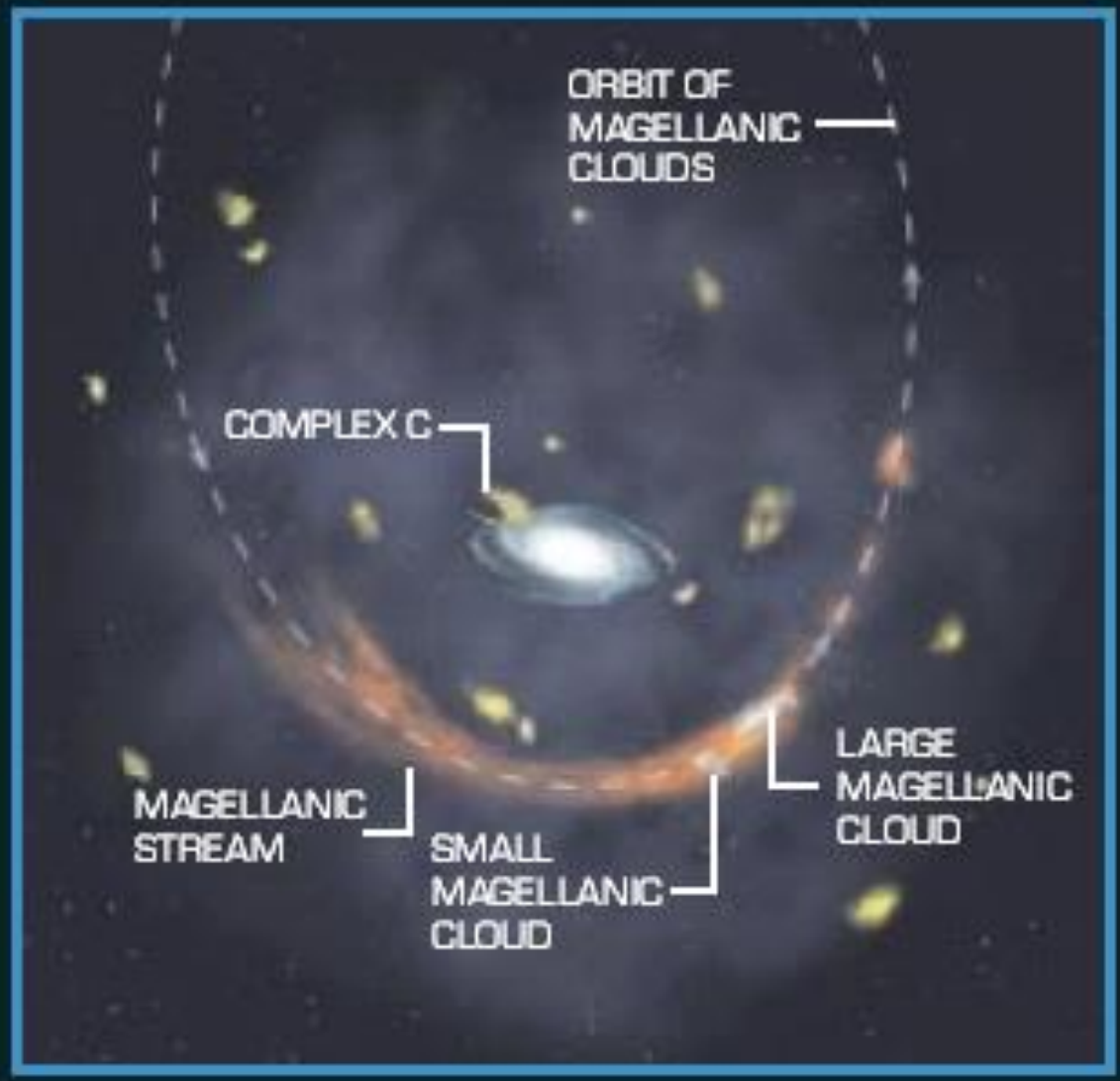
Photo by Marc Staves 2011

Galactic Cannibalism

- ☆ Galaxies grow by eating their neighbors
- ☆ MW has 9 dwarf companion galaxies
- ☆ Halo stars from disrupted dwarfs

Photo by Marc Staves 2011

GALACTIC CANNIBALIZATION: The Milky Way is ripping gas from two of its satellite galaxies, the Large and Small Magellanic Clouds. Along their orbits astronomers see the Magellanic Stream (orange). Other, unrelated high-velocity clouds (yellow), possibly condensing out of a hot corona, float in the same space

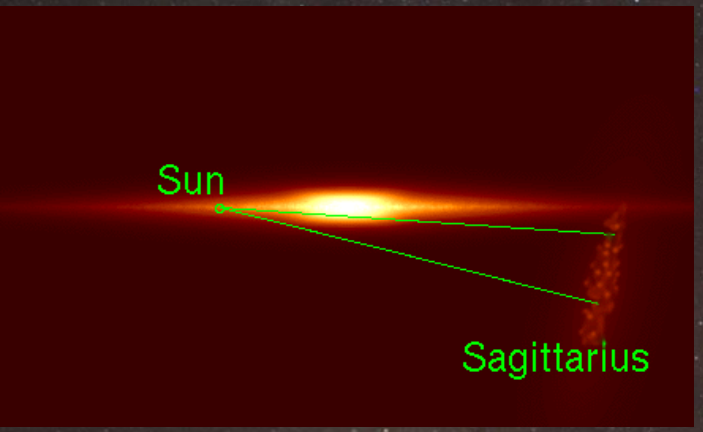


The Milky Way Growing?

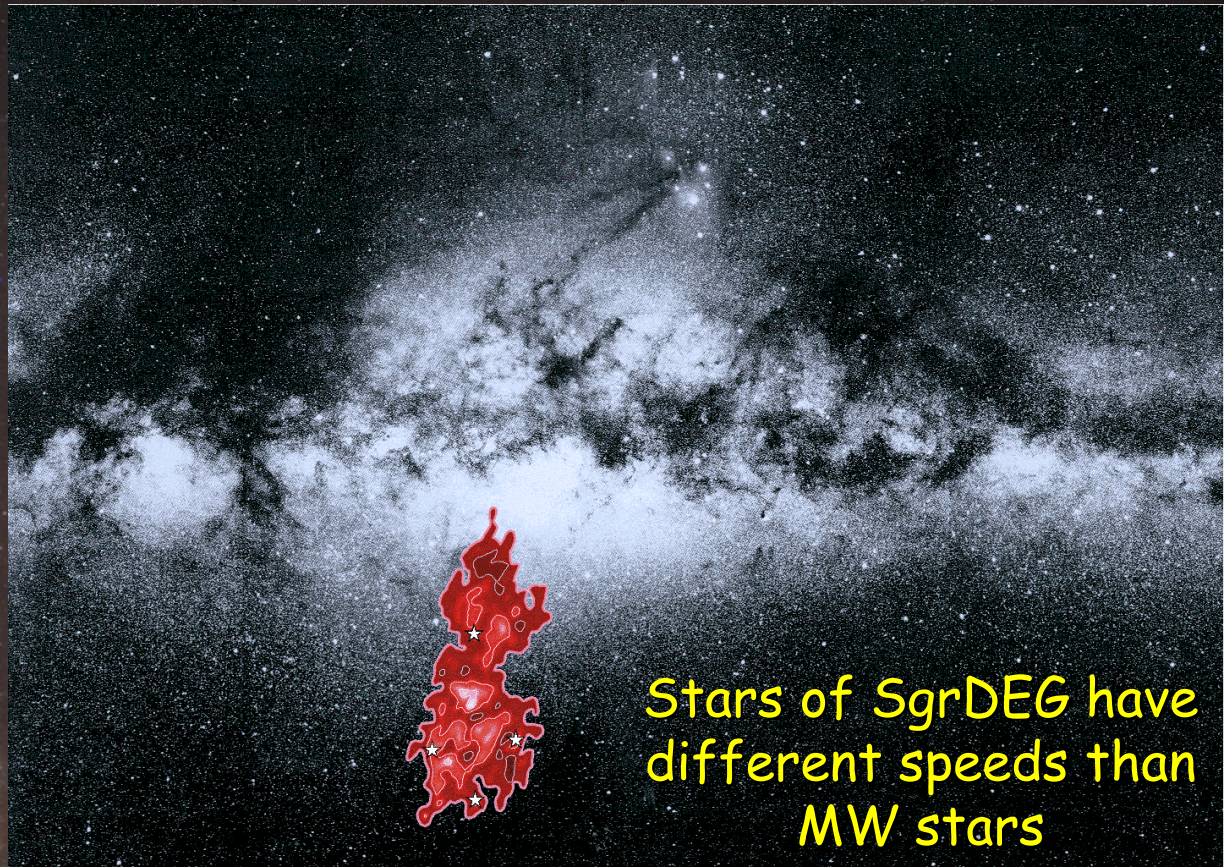
- ☆ Galaxies merge with other galaxies
  - "Galactic Cannibalism"
- ☆ Milky Way has two known merging galaxies
  - Dwarf Elliptical Galaxy in Sagittarius
  - Dwarf Galaxy in Canis Minor
    - ☽ Closest galaxy in process of merging
- ☆ Researchers expect to find more!

Sagittarius Dwarf Elliptical

- ☆ Part of the "Sagittarius Stream" of gas & stars
  - 52 kly from galactic center
  - Has passed through MW 10 times
    - ☽ Dark Matter indicted by lack of disruption!



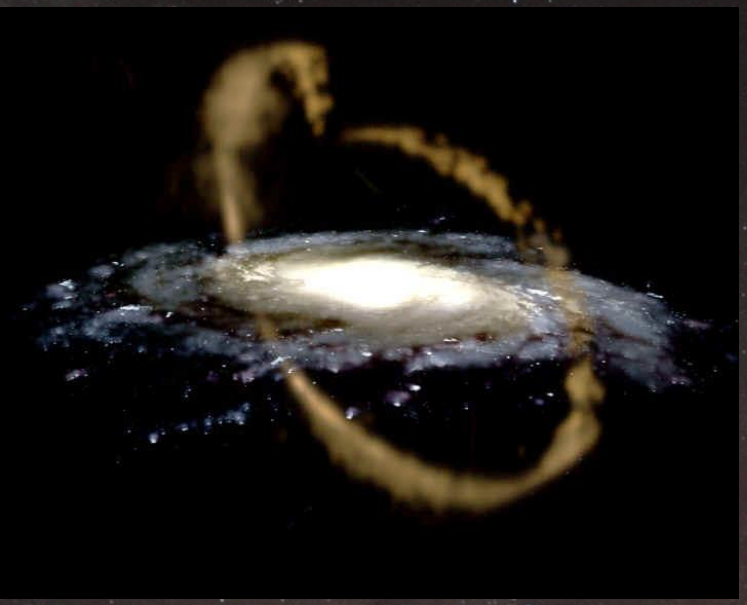
SgrDEG on far side of galactic center



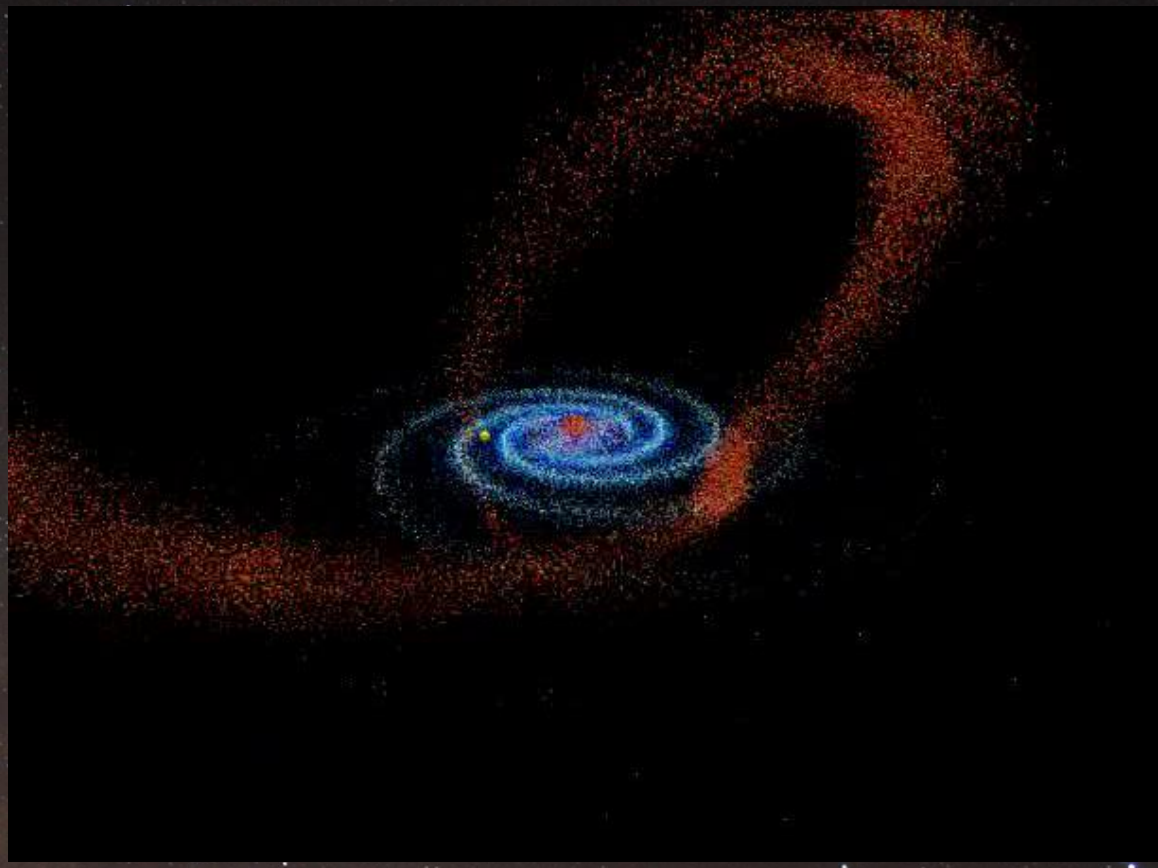
Stars of SgrDEG have different speeds than MW stars

Sagittarius Stream

☆ Stars & gas stripped from SgrDEG



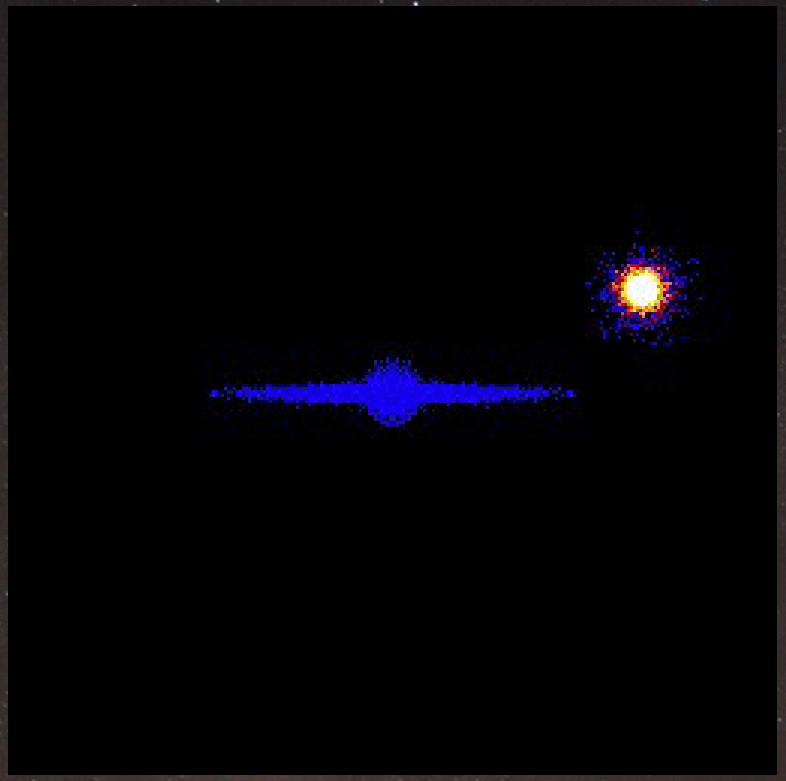
APOD image of Sagittarius Stream



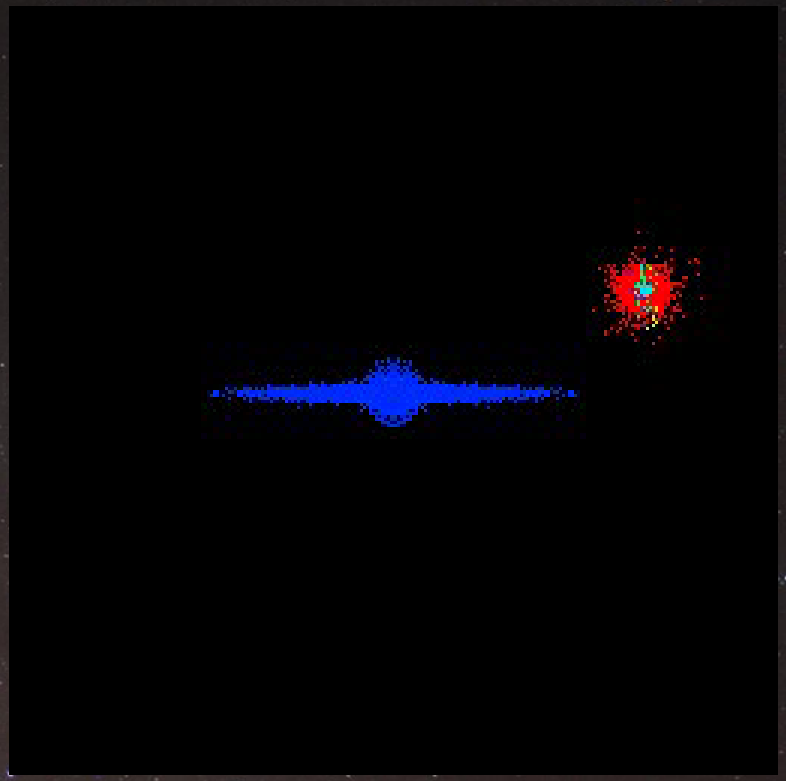
"Flyaround" of Milky Way with Sagittarius Stream

Sagittarius Stream

☆ Simulations of tidal stripping of SgrDEG
~ 2 billion BCE to 500 million CE



Color indicates stellar density



Color indicates time of tidal stripping

Simulations by Kathryn V. Johnston, Wesleyan University

Canis Minor Dwarf

☆Discovered in 2003, 25 kly from MW center

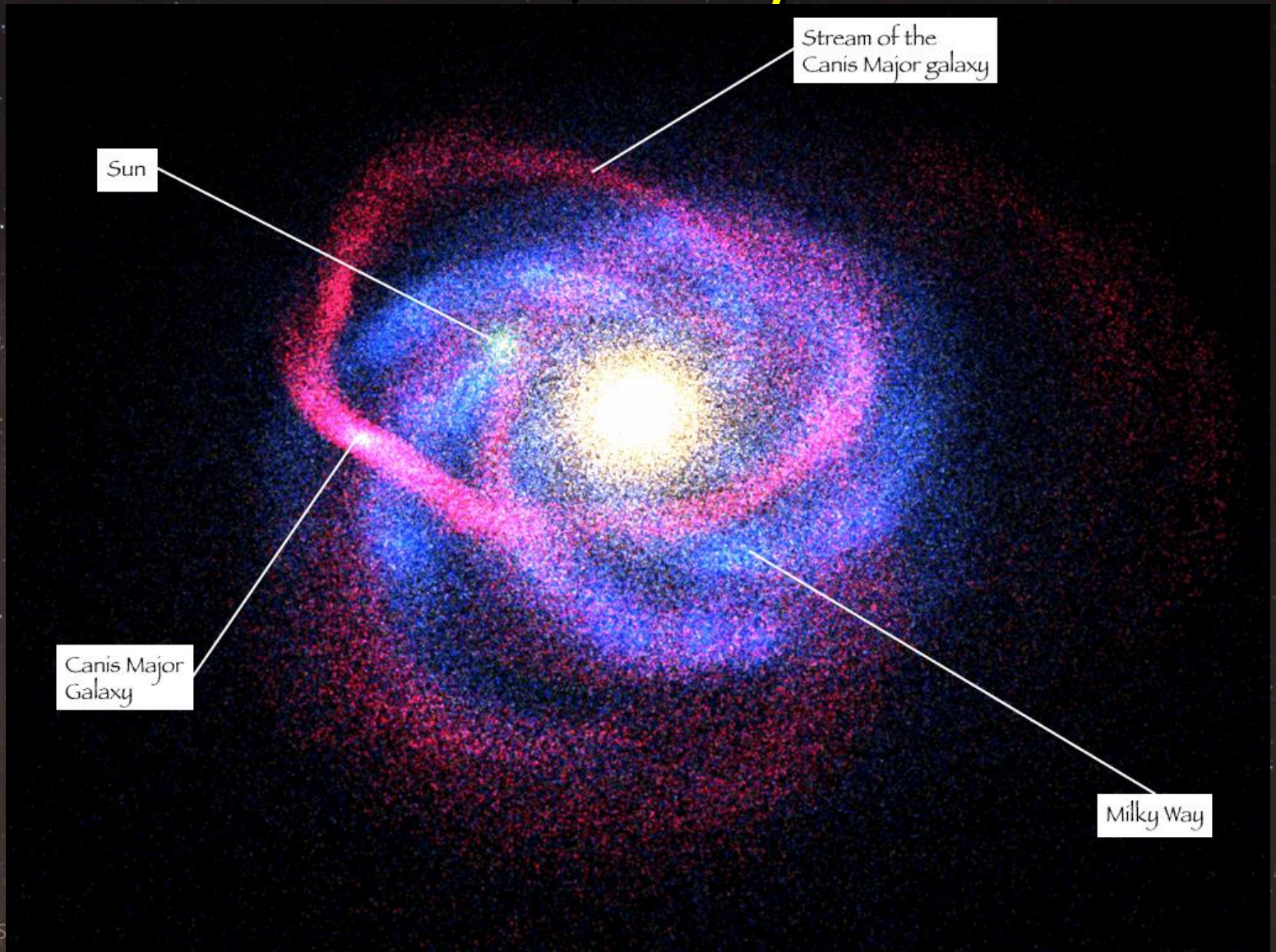


Photo by Marc S

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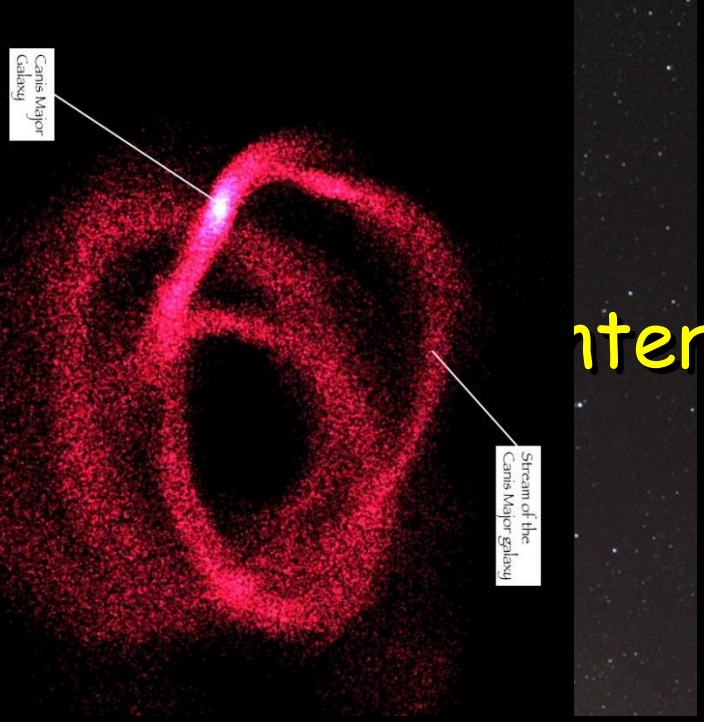
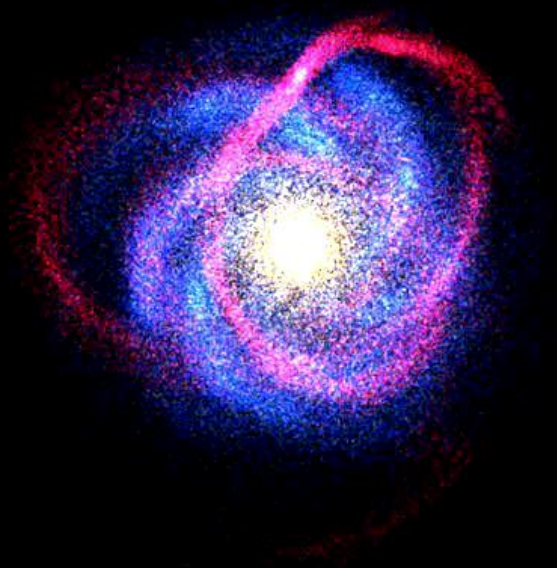
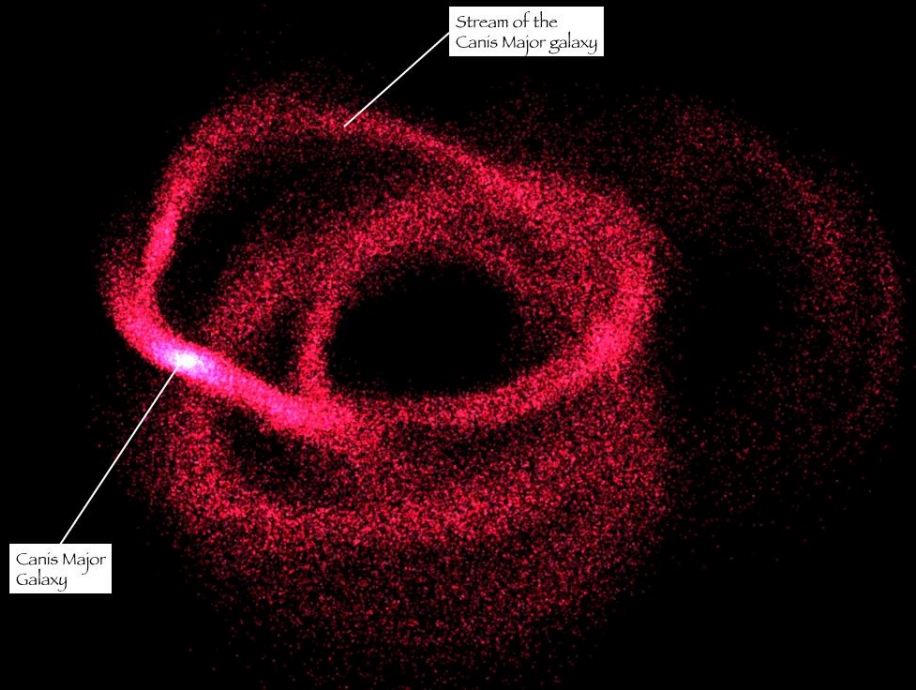

Canis Major Galaxy
Stream of the Canis Major galaxy




Stream of the Canis Major galaxy
Canis Major Galaxy

Milky Way Ring

- ☆ Thick ring of stars beyond disk

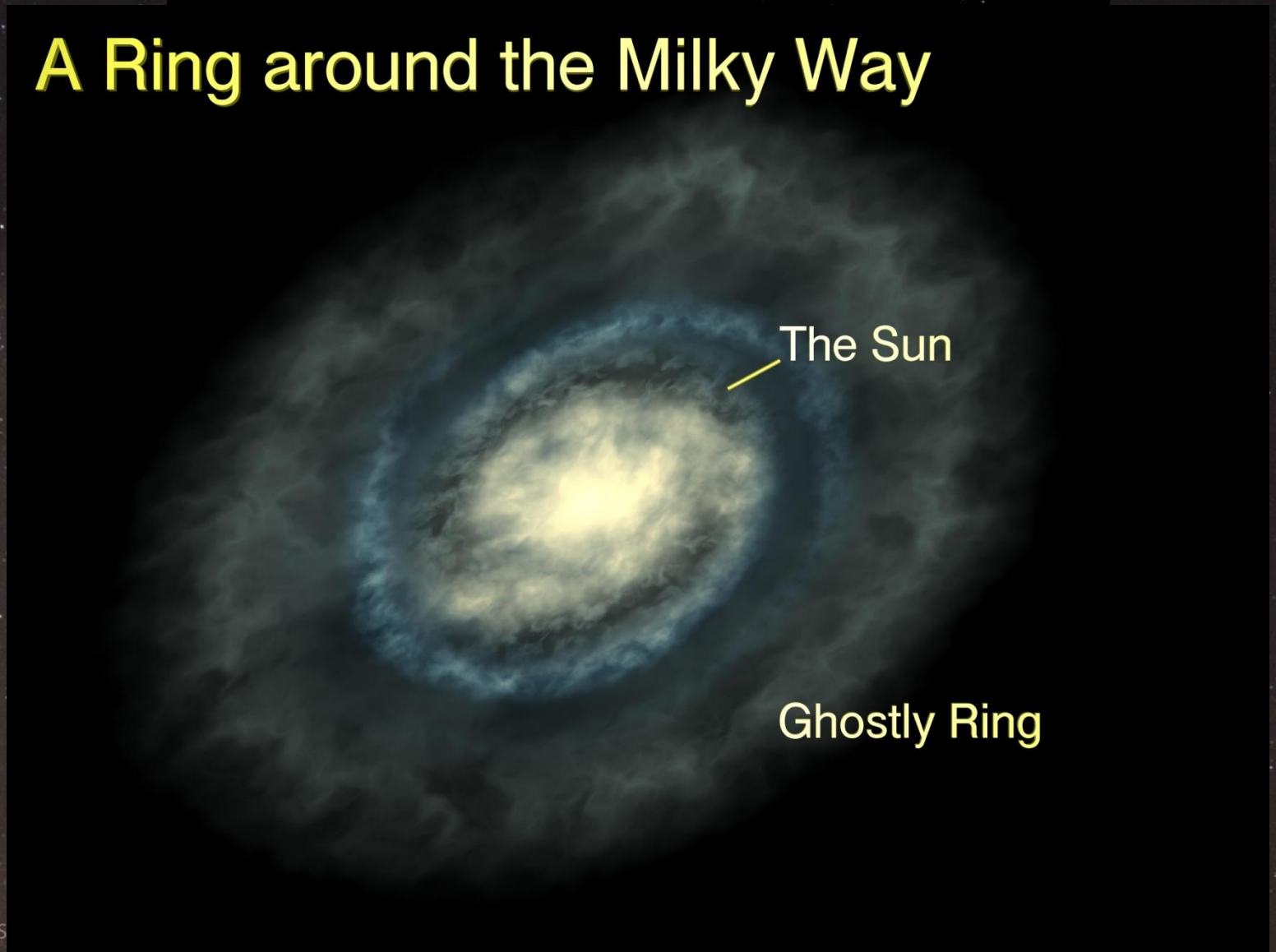


Photo by Marc S

Milky Way Ring

- ☆ Due to past galactic collision?

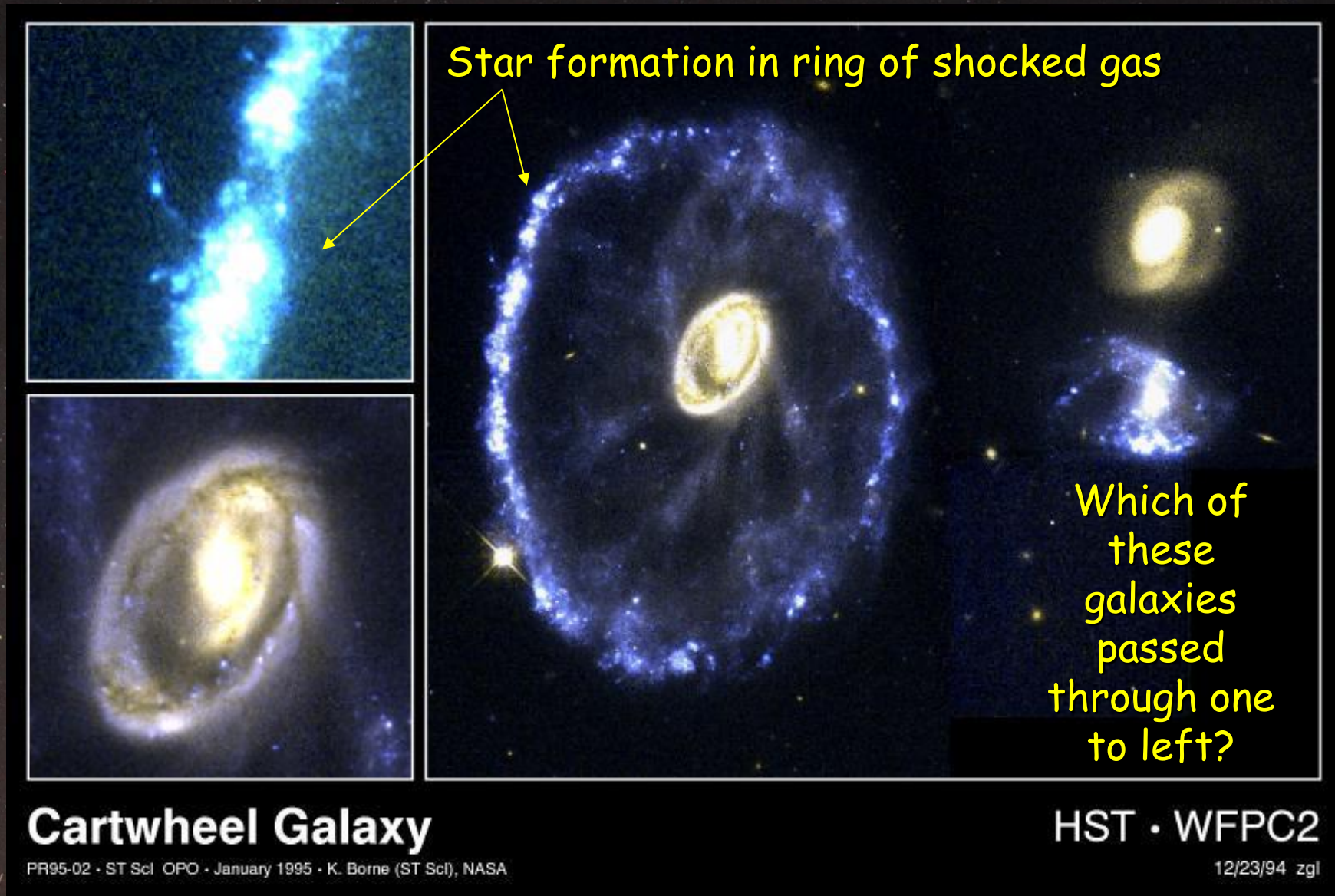


Photo by

The Local Group

- ☆ More than 54 galaxies
  - Mostly dwarfs, including those merging with the Milky Way
- ☆3 Major spiral galaxies
  - Milky Way, Andromeda & Triangulum

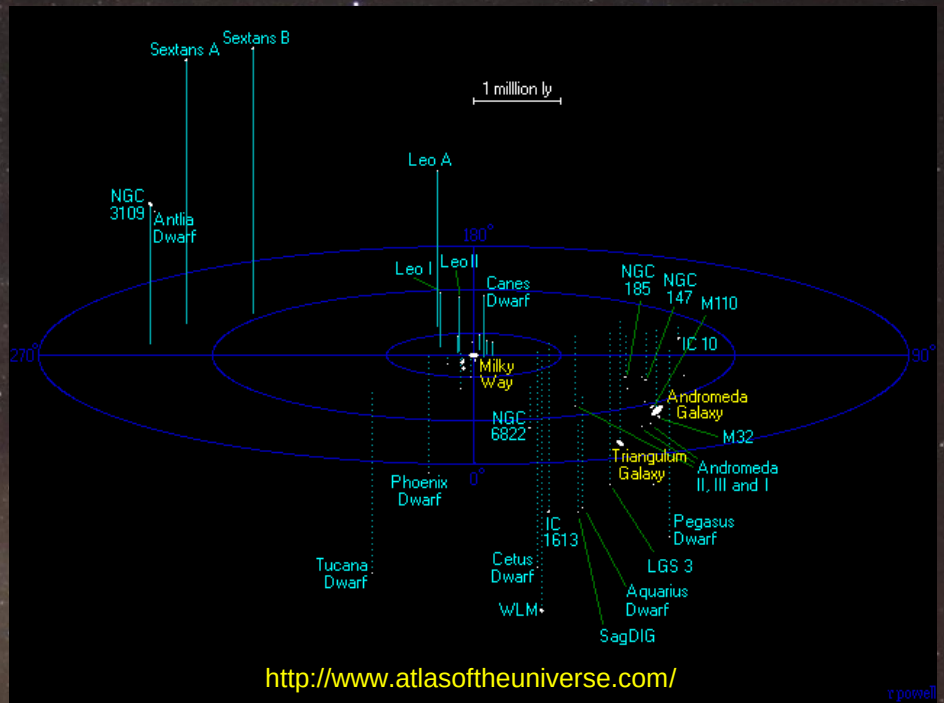
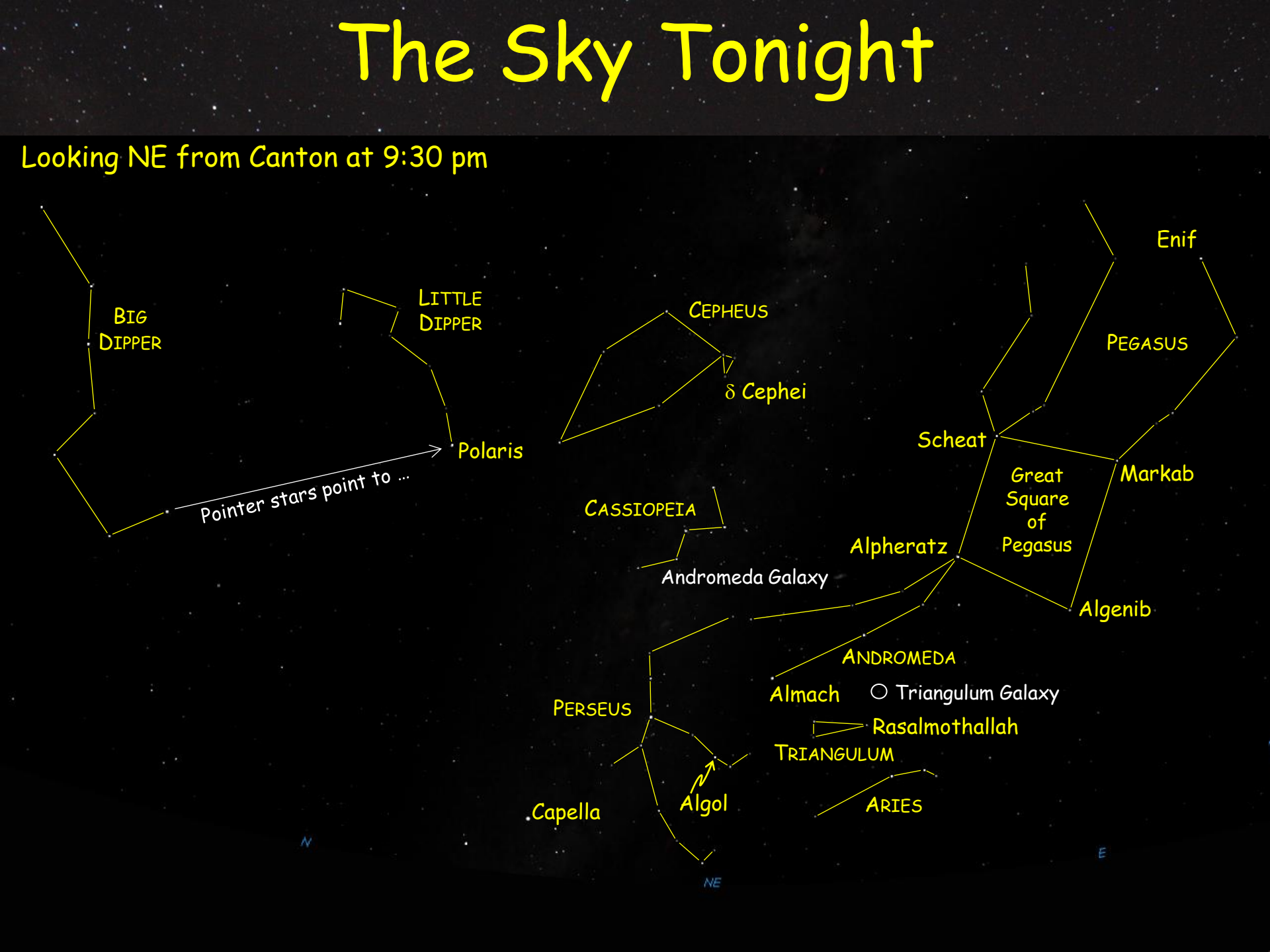


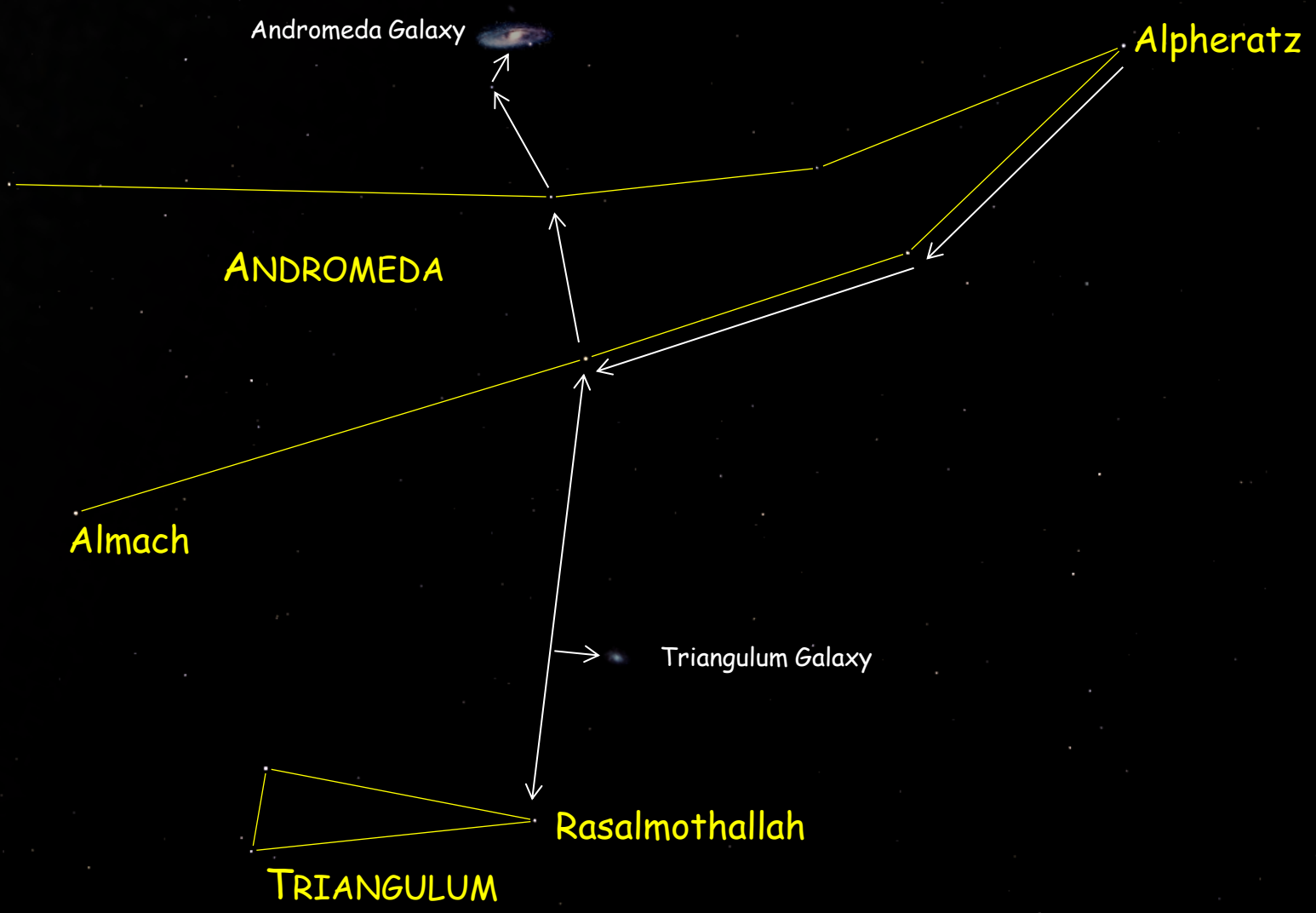
Photo by Marc Staves 2011

The Sky Tonight

Looking NE from Canton at 9:30 pm



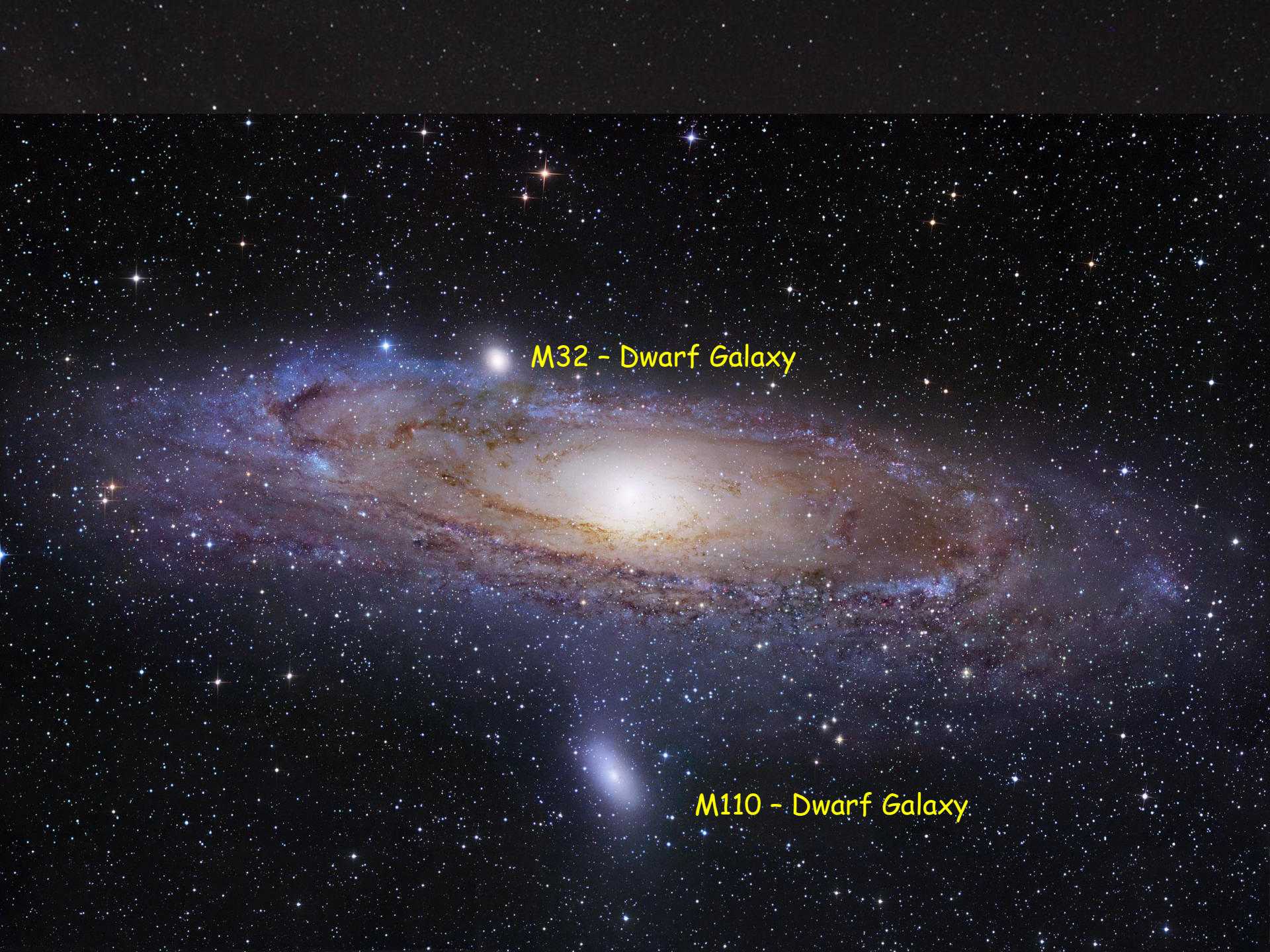
Finding Galaxies



Andromeda Galaxy

- ☆ Local Group's Largest Galaxy
  - One Trillion Stars (10^{12})
  - 2.5 million light-years away
    - 1.5×10^{19} mi (1 ly = 5.88×10^{12} miles ~ 6 trillioin)
  - 200,000,000 $M_\odot$ black hole in center
  - Approaching us at 300 km/s (190 miles/sec)
    - Should collide with Milky Way in ~4 billion years

Photo by Marc Staves 2011


M32 – Dwarf Galaxy
M110 – Dwarf Galaxy

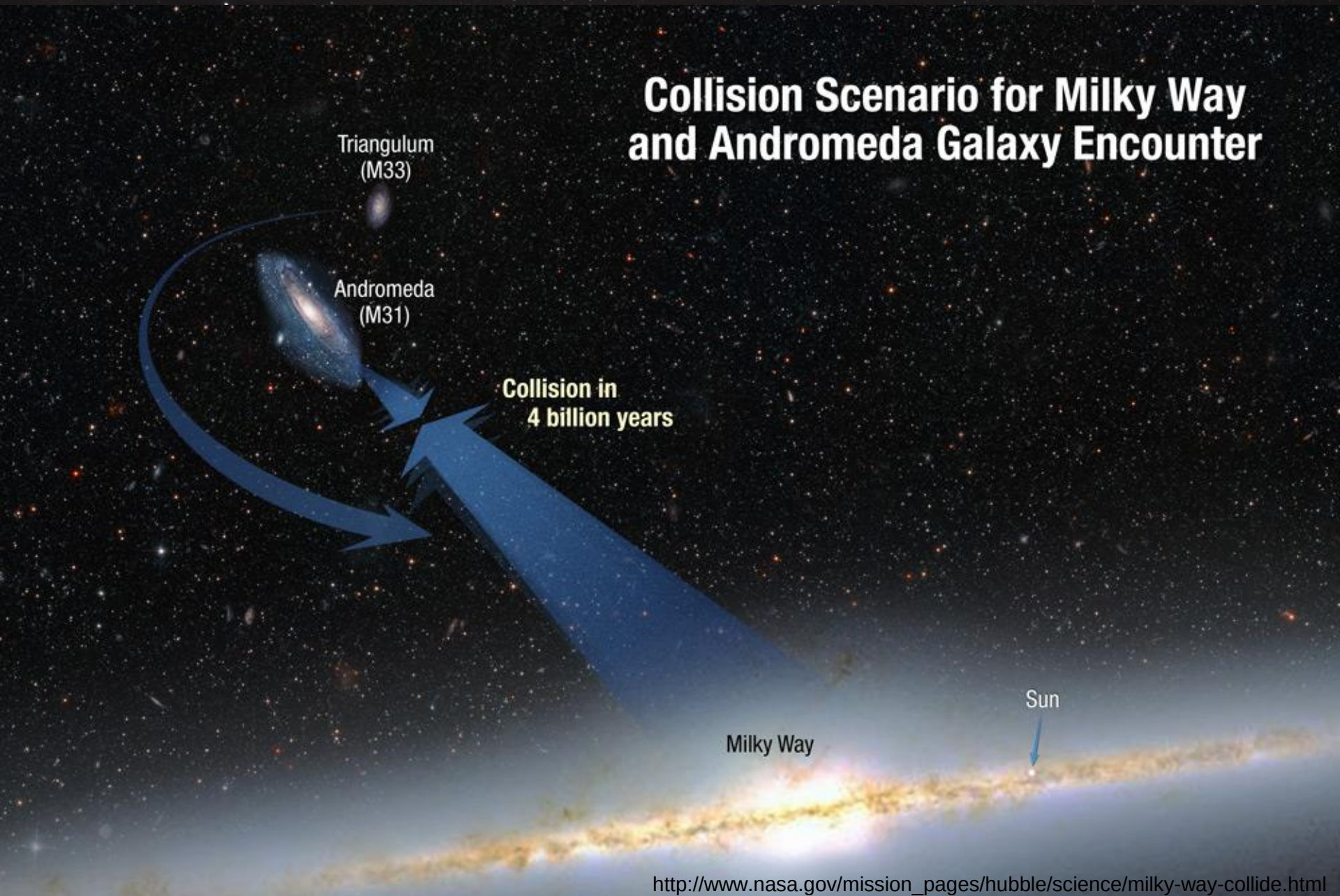
Triangulum Galaxy

- ☆ Pinwheel Galaxy (M 101)
  - 40 Billion Stars (10^{10})
  - 3 million light-years away
    - 1.5×10^{19} mi (1 ly = 5.88×10^{12} miles ~ 6 trillioin)
  - Linked to Andromeda by streams of stars and neutral hydrogen
    - ⇒ interacted with Andromeda 2-8 by ago
    - ⇒ will have more violent interaction in 2.5 my
    - ⇒ may participate in collision with MW

http://www.nasa.gov/topics/universe/features/molecule-fingerprints.html

Photo by Marc Staves 2011

The Coming Collision



http://www.nasa.gov/mission_pages/hubble/science/milky-way-collide.html

Clusters of Galaxies

- ☆ Gravitationally bound galaxy groups
  - Require dark matter
    - ☽ galaxies move too fast for glowing matter
    - ⇒ map the distribution of dark matter!
- ☆ Range in size and Richness
  - Local Group = 54 members
  - Virgo Cluster (nearest) = 1,300 – 2,000 mem.
  - El Gordo (largest) = 1,000,000 members


Virgo Cluster of Galaxies seen from Kitt Peak, Arizona
https://commons.wikimedia.org/wiki/File:ESO-M87.jpg


El Gordo Cluster of
Galaxies image from
Hubble Space Telescope
https://www.space.com/39424-el-gordo-galaxy-cluster-hubble-image.html

Clusters of Galaxies

- ☆ Galaxies emit gas, dust, cosmic rays
  - stellar explosions, collisions, etc.
- ☆ Galaxy clusters have atmospheres
  - Intracluster Medium (ICM)
    - ☽ Glows in X-Rays due to electrons zipping by protons

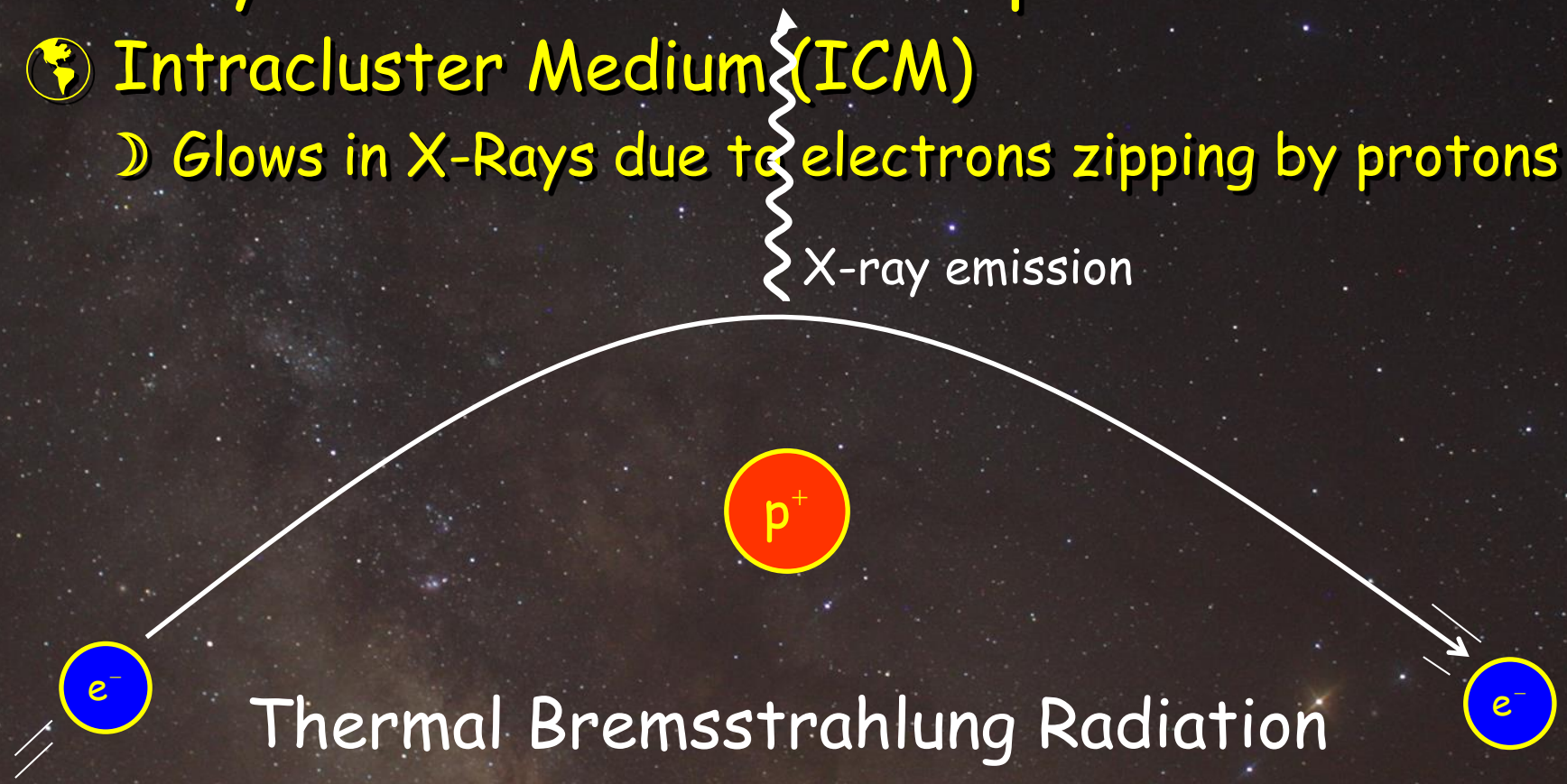
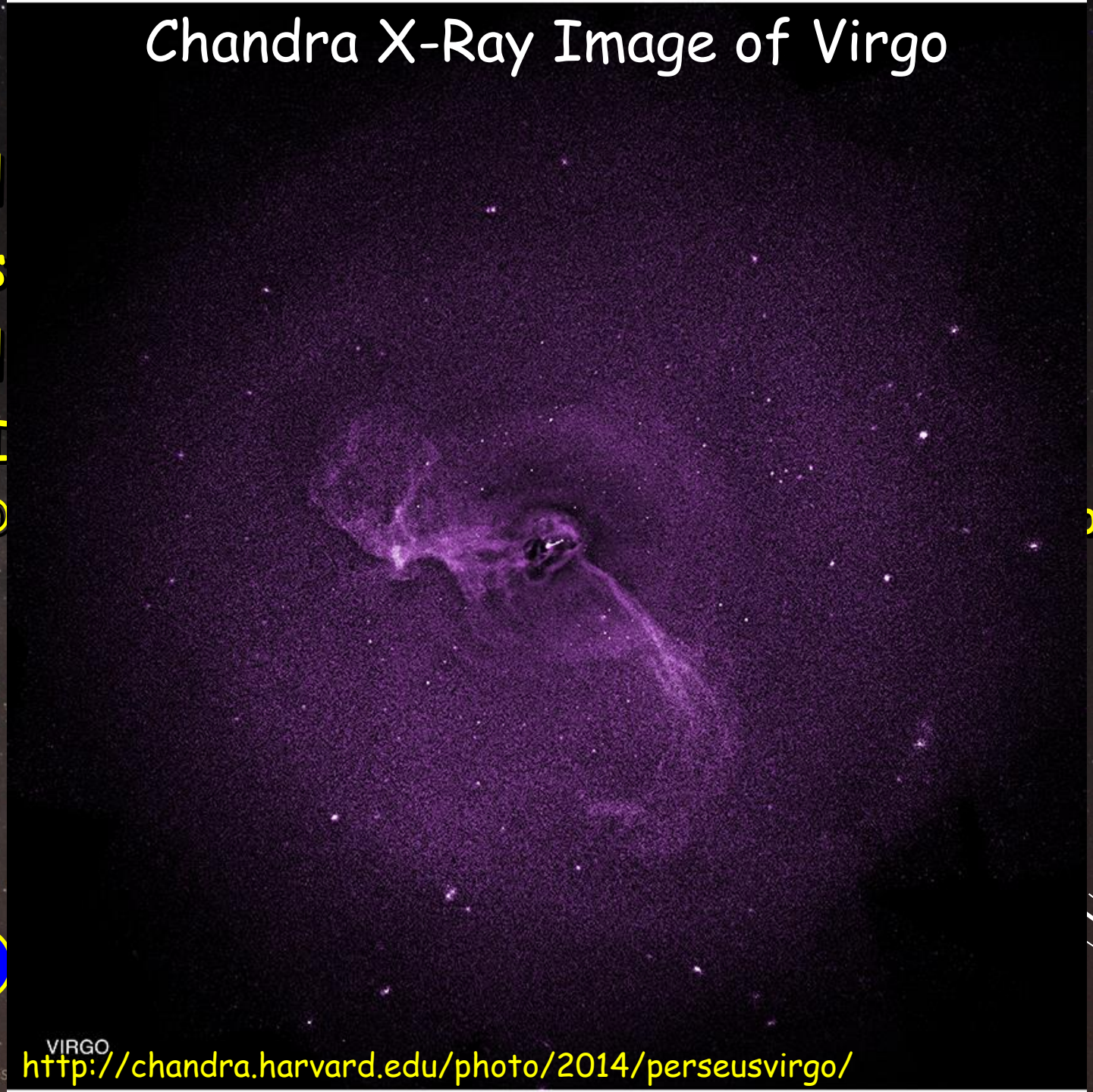


Photo by Marc Staves 2011

Chandra X-Ray Image of Virgo



http://chandra.harvard.edu/photo/2014/perseusvirgo/

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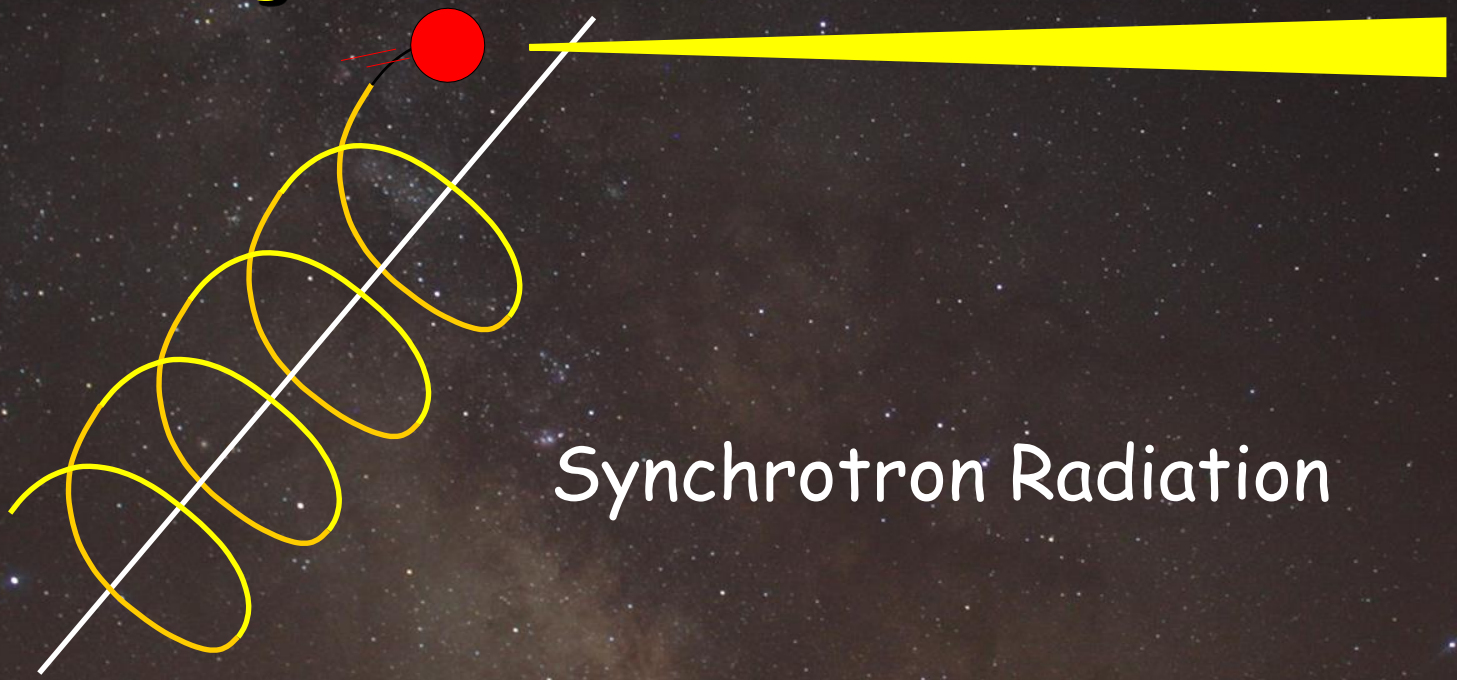
Photo by Marc Staves

Clusters of Galaxies

- ☆ Galaxies emit gas, dust, cosmic rays
  - stellar explosions, collisions, etc.
- ☆ Galaxy clusters have atmospheres
  - Glows in Radio due to electrons zipping along magnetic field lines.

$f_{radiation} \propto E_{electron}$



Synchrotron Radiation


Perseus A in the Perseus Cluster of Galaxies
Visible Hubble images with
Violet shells of X-ray gas
Pink jets and lobes of radio-luminous plasma

ALFALFA

Seeing Dark Galaxies: The ALFALFA Survey

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UNIVERSITY OF DENVER 1864

ST. LAWRENCE UNIVERSITY

ALFALFA

- Arecibo Fast ALFA Survey
  - Arecibo
  - ALFA
  - L-Band
  - Radio Galaxies
    - Continuum Sources
    - Spectral Line Sources
  - ALFALFA Observations
  - Some ALFALFA Results

Arecibo Observatory

- National Astronomy & Ionosphere Center
  - Funded by NSF, administered by Cornell University
- Arecibo, Puerto Rico
  - Karst Topography
    - Subsurface limestone ⇒ sink holes
    - Like Gulin, China

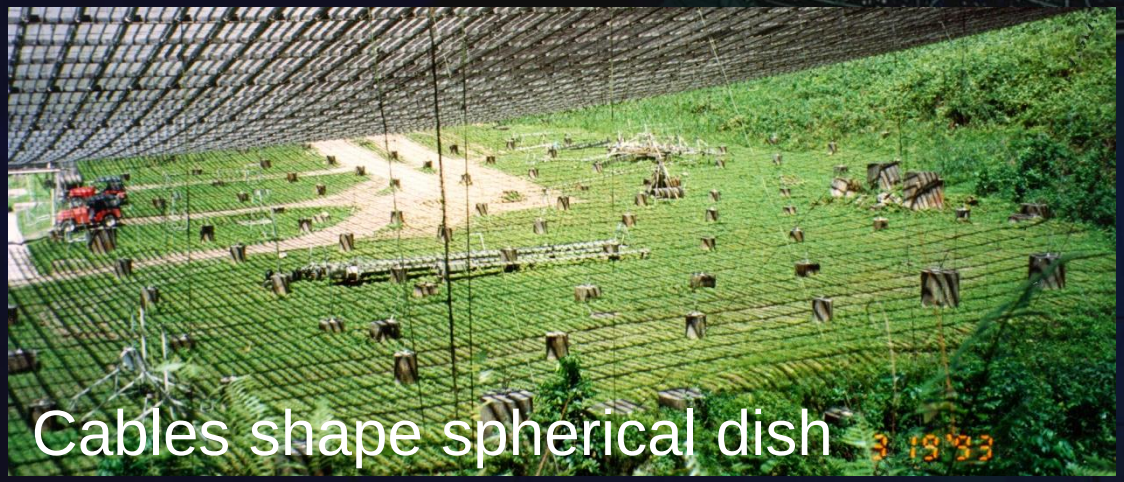
Arecibo Observatory

- Largest Single-dish radio telescope
  - diameter = 305 m = 1000 ft
  - depth = 167 ft (870 ft sphere)
  - 40,000 3 x 5 aluminum panels

Arecibo Observatory

- Largest Single-dish radio telescope

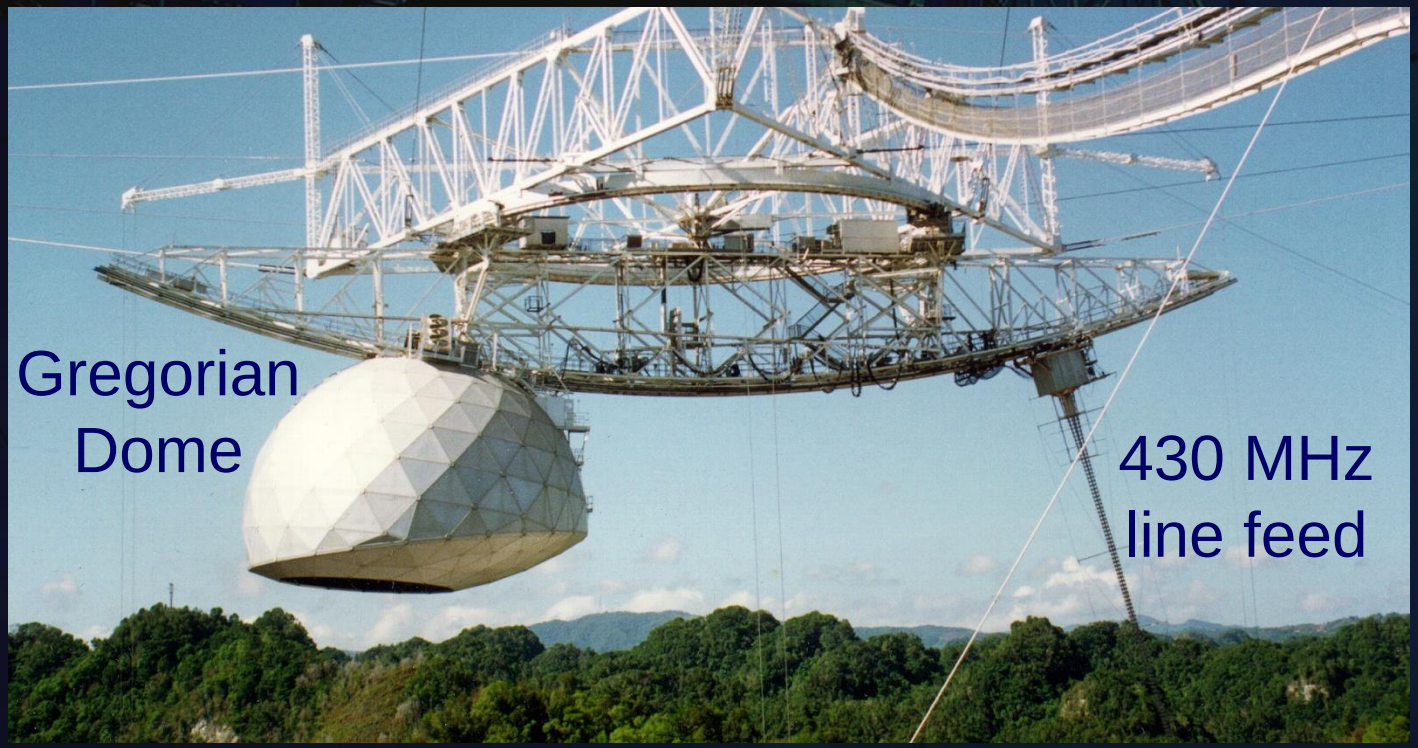
Tie-downs keep platform steady



Cables shape spherical dish

Arecibo Observatory

- Instrument Platform
  - weight = 900 tons, 18 supporting cables
  - height = 450 ft above dish
  - azimuth arm length = 328 ft

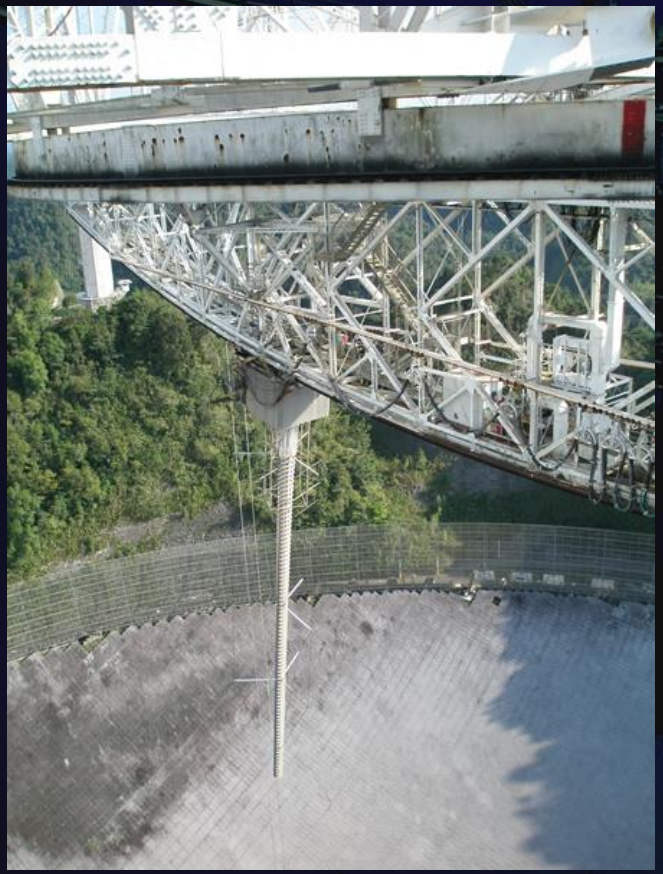


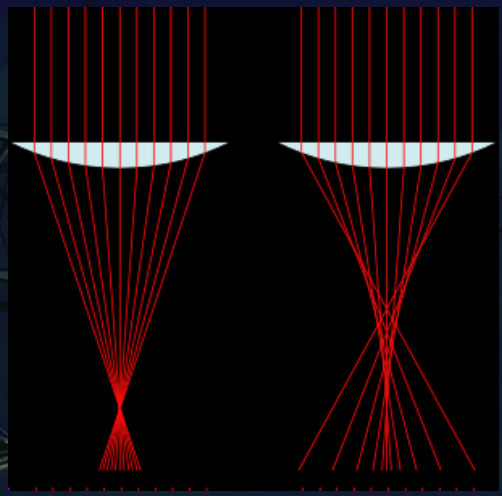
On The Platform

Jamie on the
azimuth arm

Arecibo Observatory

- Instruments
  - Line feed counters spherical aberration

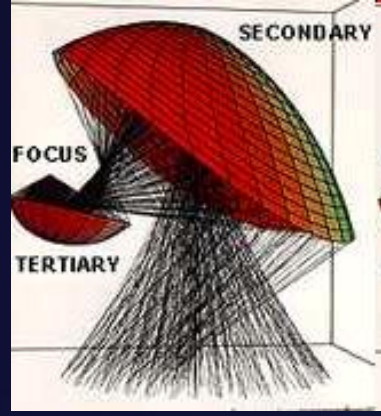




Different parts of dish focus to different heights

430 MHz line feed (70 cm)

Arecibo Observatory

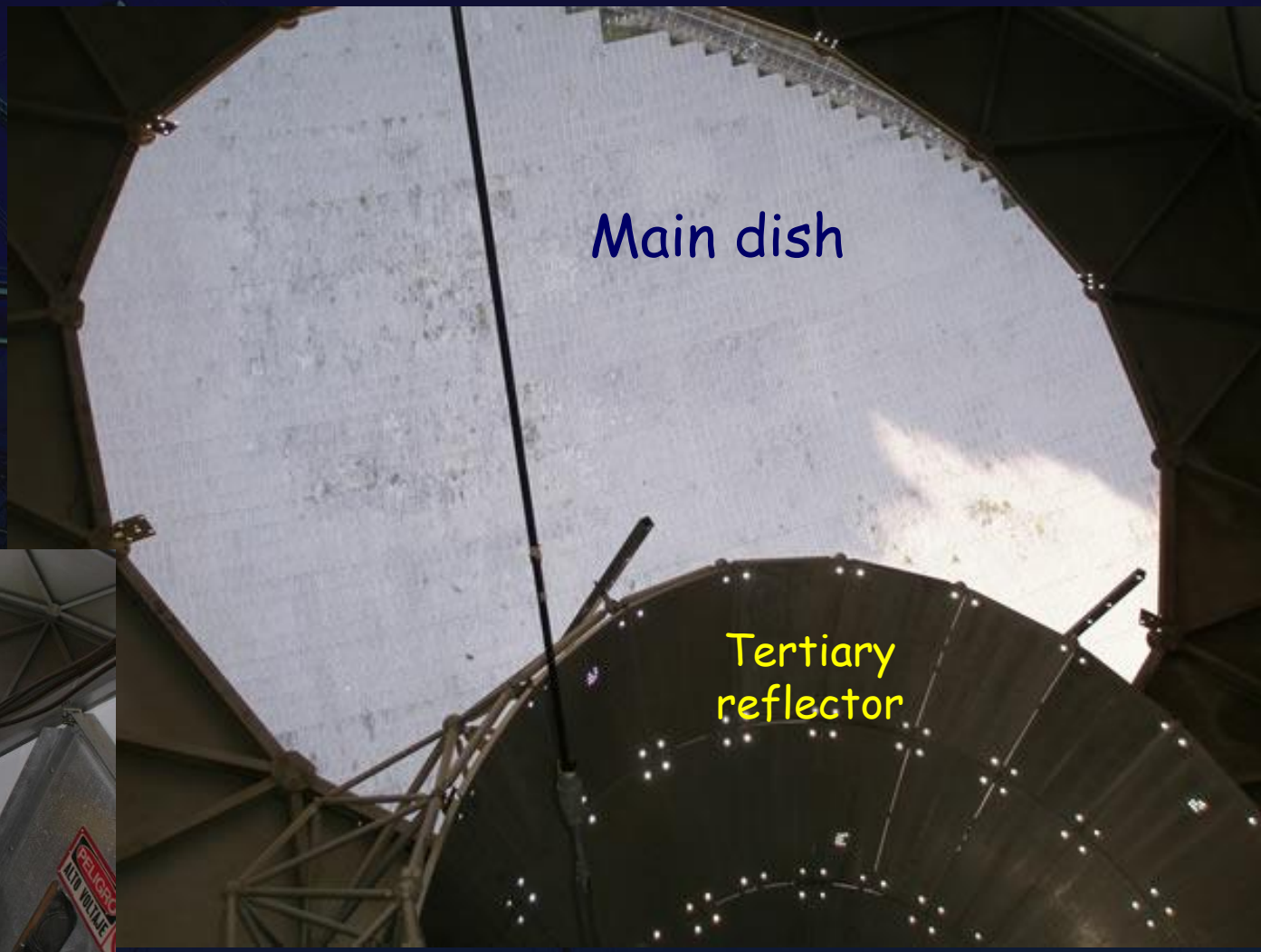


- Instruments
  - Gregorian dome houses instruments
    - "gregorian" ⇒ secondary behind primary focus

Gregorian Dome

Odd Puerto Rican berry!

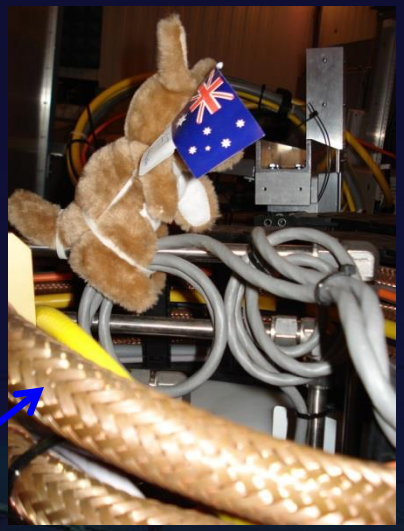
Inside the Gregorian Dome



Inside of dome is secondary reflector

ALFA

- Arecibo L-Band Feed Array
  - Seven feeds in hexagonal array



Made in Aust-ralia

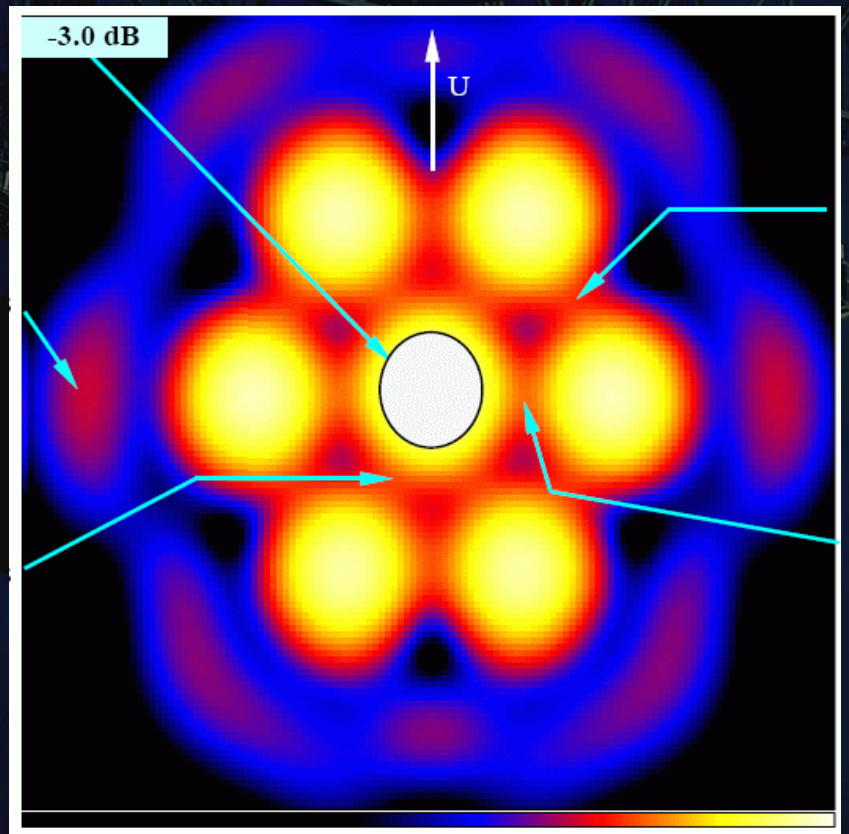
ALFA receivers

ALFA apertures

… and SLU student

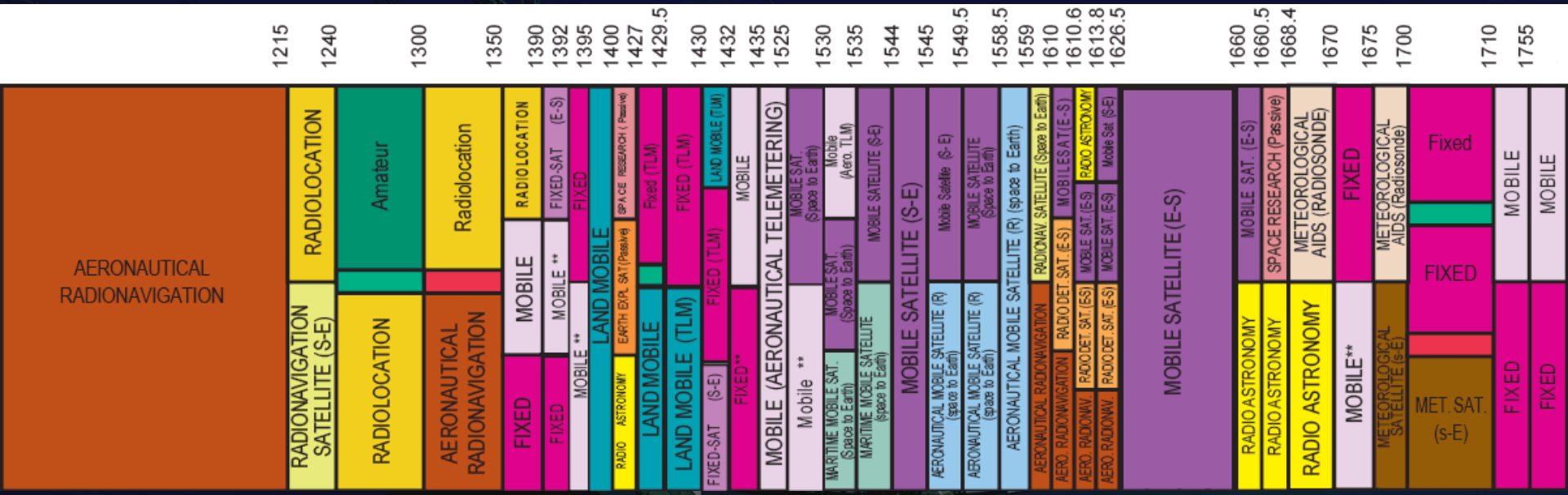
ALFA

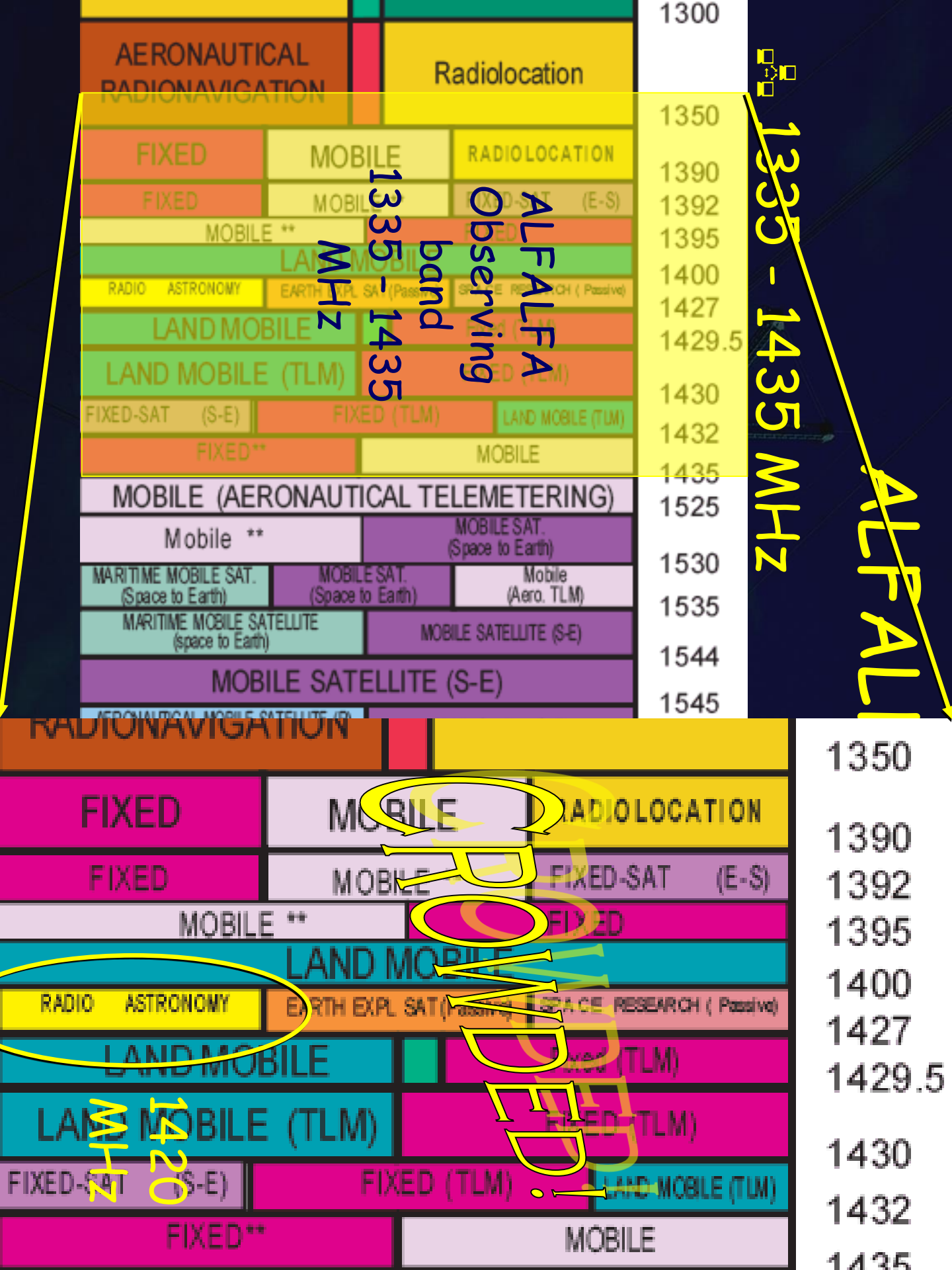
- Point Spread Function
  - Multiple beams & asymmetries alias sources
  - Combining beams into one image requires careful processing



L Band

- 1200 – 1800 MHz




AERONAUTICAL RADIONAVIGATION
Radiolocation
1300
1350
FIXED
MOBILE
RADIOLOCATION
1390
FIXED
MOBILE
FIXED-SAT (E-S)
1392
MOBILE **
1395
LAND MOBILE
1400
RADIO ASTRONOMY
EARTH EXPL SAT (Passive)
SPACE RESEARCH (Passive)
1427
LAND MOBILE
1429.5
LAND MOBILE (TLM)
1430
FIXED-SAT (S-E)
FIXED (TLM)
LAND MOBILE (TLM)
1432
FIXED**
MOBILE
1435
MOBILE (AERONAUTICAL TELEMETERING)
1525
Mobile **
MOBILE SAT. (Space to Earth)
1530
MARITIME MOBILE SAT. (Space to Earth)
MOBILE SAT. (Space to Earth)
Mobile (Aero. TLM)
1535
MARITIME MOBILE SATELLITE (space to Earth)
MOBILE SATELLITE (S-E)
1544
MOBILE SATELLITE (S-E)
1545
1335 - 1435 MHz
ALFALFA Observing band
1335-1435 MHz
ALFALFA
RADIONAVIGATION
1350
FIXED
MOBILE
RADIOLOCATION
1390
FIXED
MOBILE
FIXED-SAT (E-S)
1392
MOBILE **
1395
LAND MOBILE
1400
RADIO ASTRONOMY
EARTH EXPL SAT (Passive)
SPACE RESEARCH (Passive)
1427
LAND MOBILE
1429.5
LAND MOBILE (TLM)
1430
FIXED-SAT (S-E)
FIXED (TLM)
LAND MOBILE (TLM)
1432
FIXED**
MOBILE
1435
1420 MHz
PROVIDED!

ALFALFA

- 1335 - 1435 MHz
  - 100 MHz, 4096 channels
    - $\Rightarrow$ 24.4 kHz/channel

$$v_{\text{recession}} = \frac{f_0 - f}{f} c$$

- Recessional Velocities

$$v_{\text{channel}} = \frac{0.0244}{(1435+1335)/2} 2.998\times10^5 = 5.3 \ km/s$$

$$v_{\text{max}} = \frac{1420-1335}{1335} 2.998\times10^5 = 19,200 \ km/s$$

$$v_{\text{min}} = \frac{1420-1485}{1485} 2.998\times10^5 = -3050 \ km/s$$

ALFALFA

- Distances
  - Hubble Constant

    Currently 72 km/s/Mpc = 2.33 x 10^{18} s^{-1}

    Gives the age of the universe as 13.6 By
  - Cosmological Distances (local)

$$r = \frac{v}{H_0} \qquad H_0 = \frac{v}{r} \sim \frac{km/s}{Mpc}$$

  - ALFALFA's far view

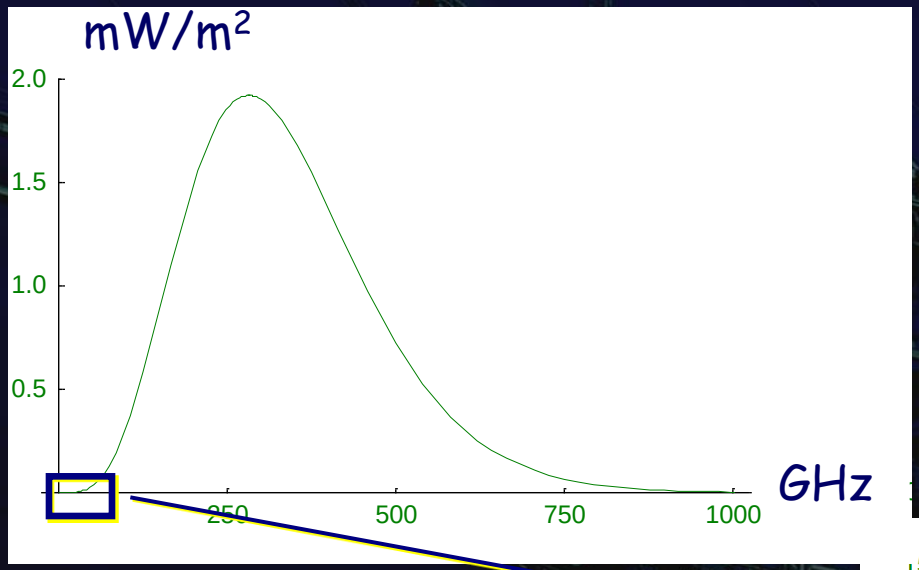
$$r_{max} = \frac{v_{max}}{H_0} = \frac{19{,}179 \ km/s}{72 \ km/s/Mpc} = 266 \ Mpc = 870 \text{ million ly}$$

Radio Sources

- Continuum Sources
  - Thermal radiation
  - Synchrotron radiation
- Spectral Line Sources
  - Cool H!
  - Some molecules

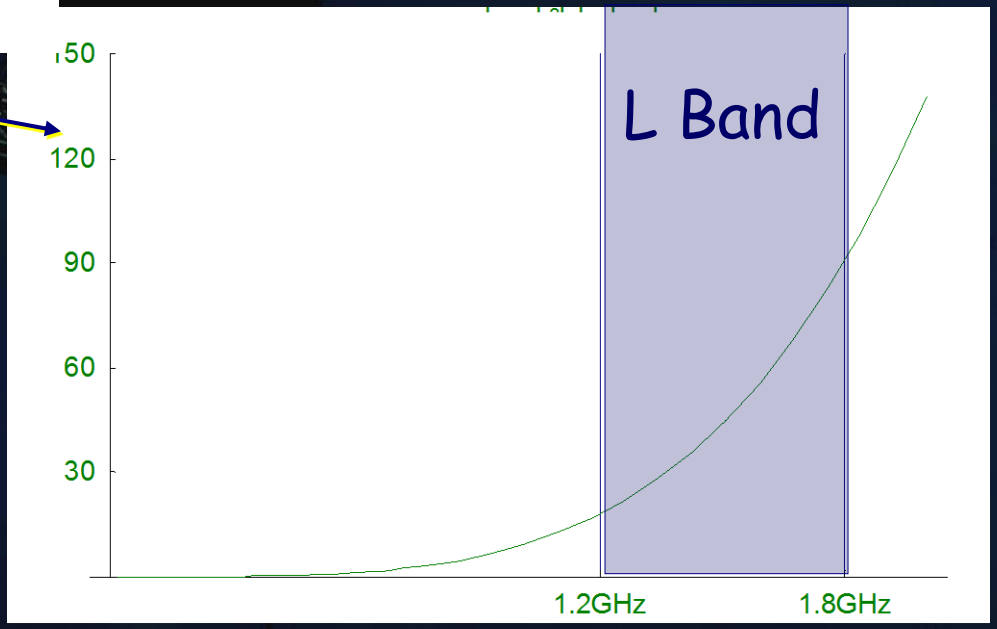
Continuum Radio Emission

- Thermal emission minimal



Wein's Law:
for λ_{max} = 21 cm
T = 13.8 mK

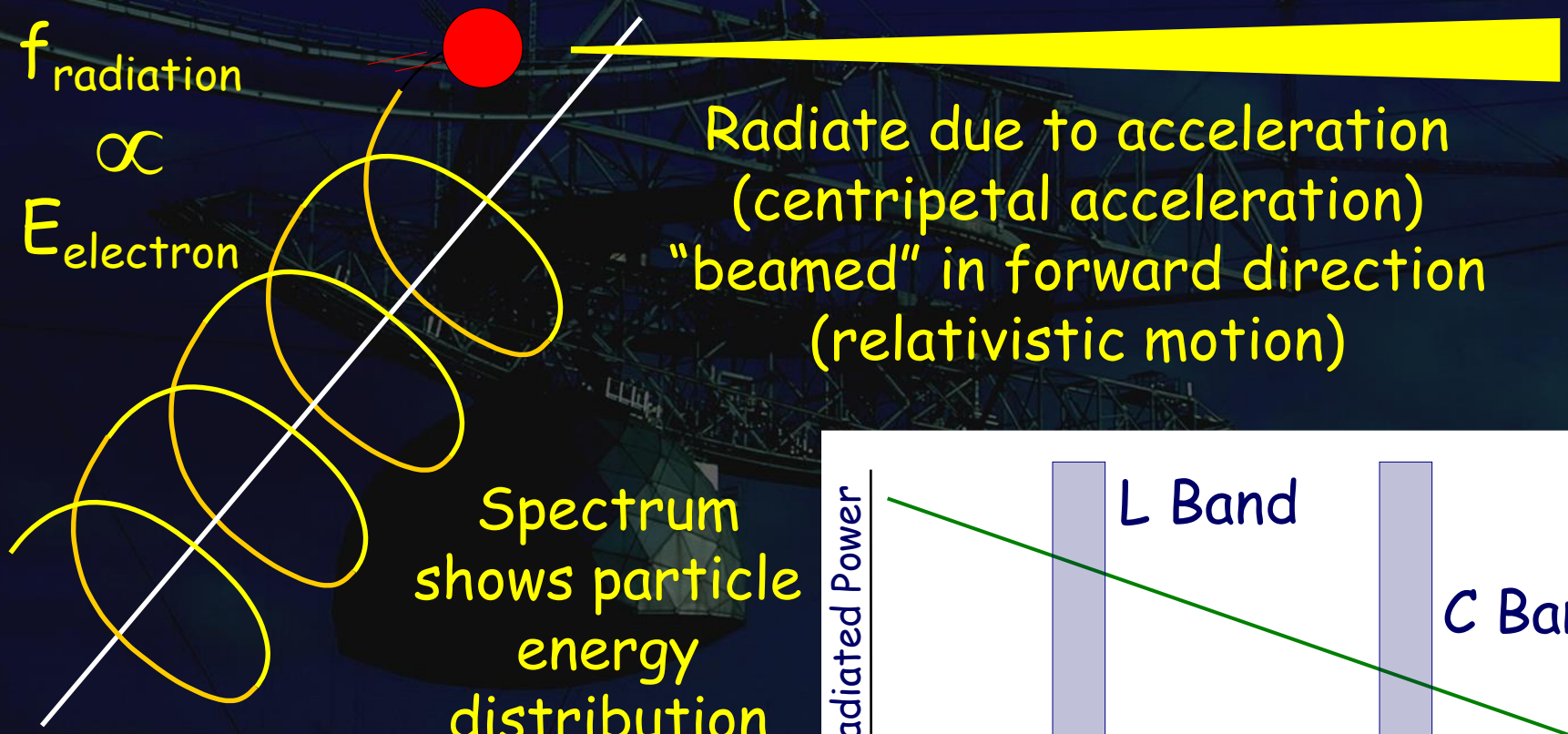
Planck Curve
for 2.725K



Continuum Radio Emission

- Continuum Radiation: Synchrotron
  - e- spiral along magnetic fields

$f_{radiation} \propto E_{electron}$



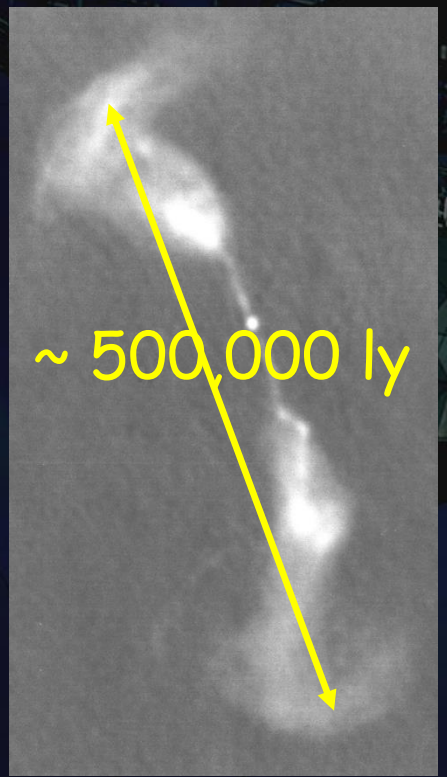
Radiate due to acceleration
(centripetal acceleration)
"beamed" in forward direction
(relativistic motion)

Spectrum shows particle energy distribution
(*ie.* Power Law)

Continuum Radio Galaxies

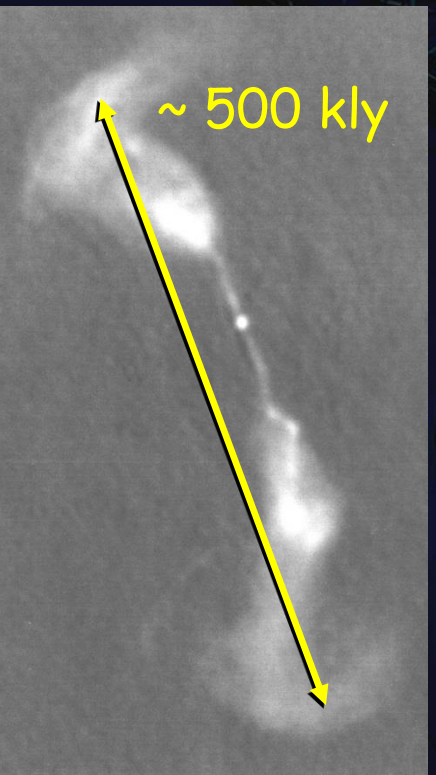
Wide Angle Tailed Radio Galaxies

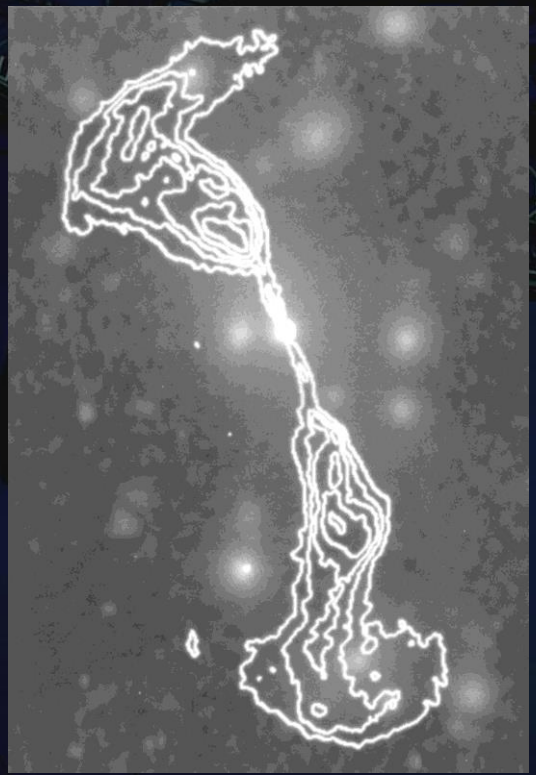
- C-shaped radio emissions
- shaped by "winds" due to smaller clusters of galaxies merging together …
- Even galaxies clusters are still evolving!



Continuum Radio Galaxies

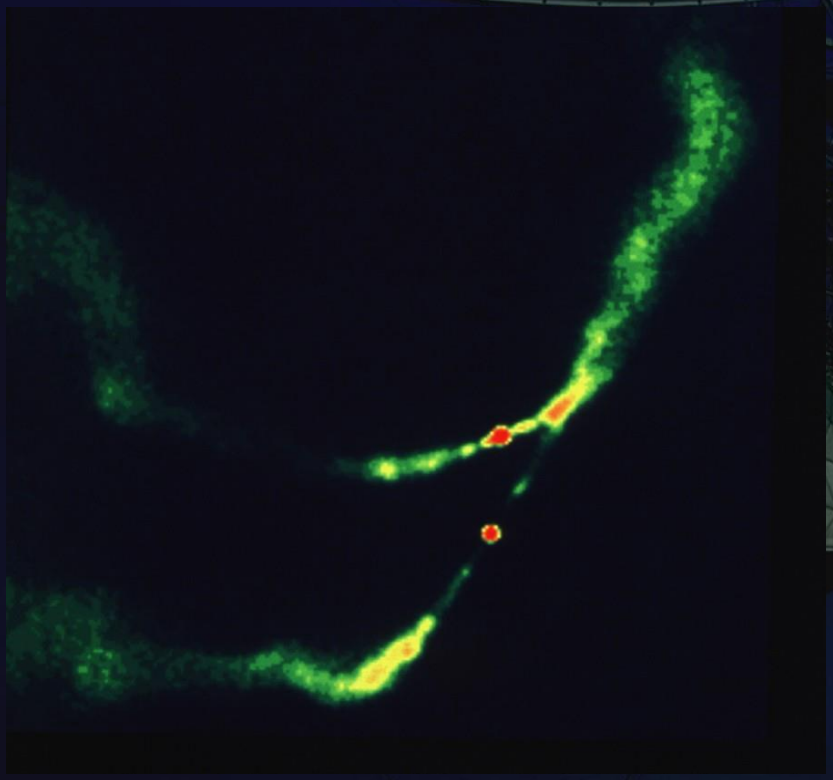
- Attached to cD galaxies
  - cluster Dominant galaxies
    - HUGE ellipticals in centers of galaxy clusters
      - got big by eating neighbors
      - some not done … multiple nuclei

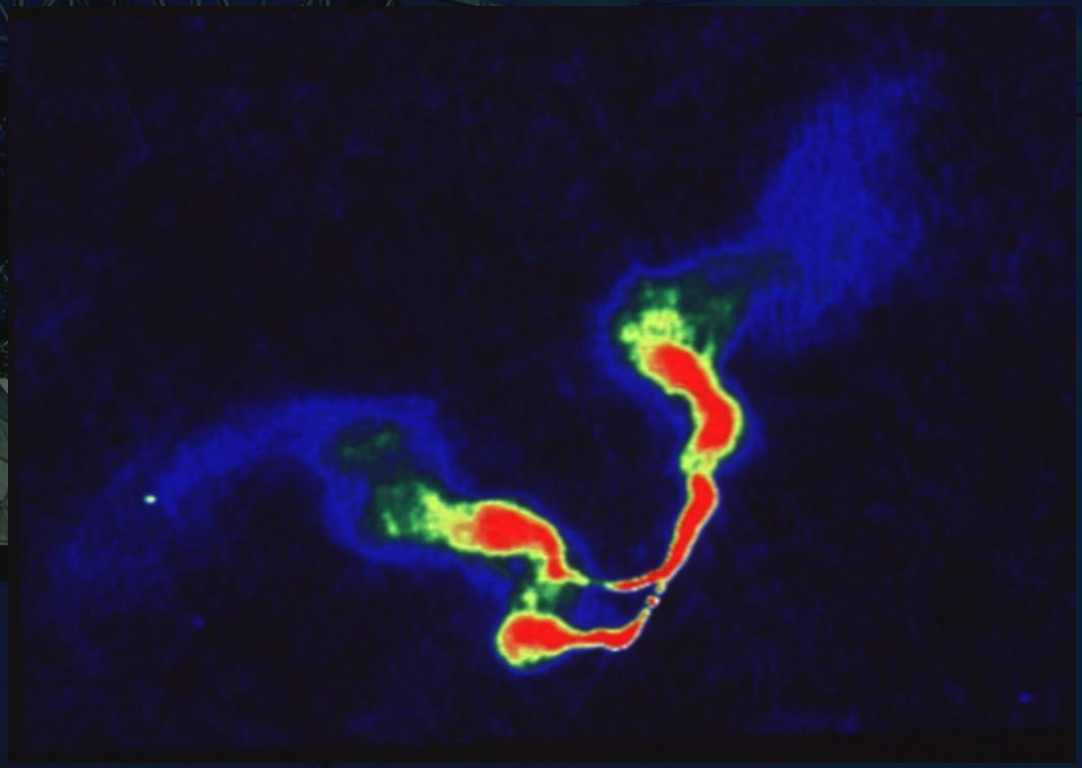




Radio Galaxies

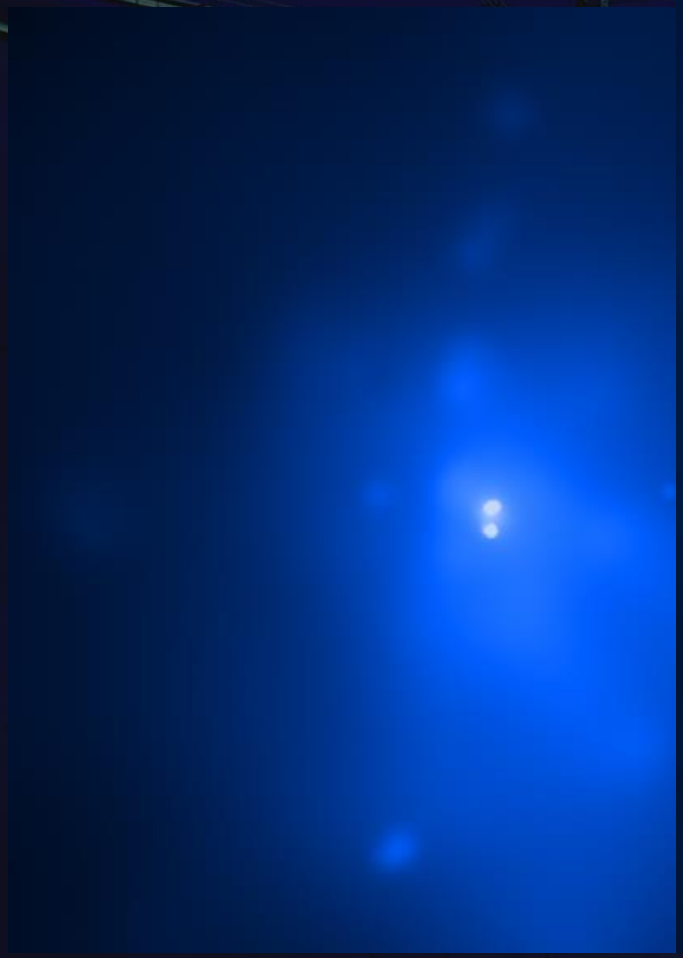
- 3C 75
  - Dual radio galaxies
    - two radio sources from same galaxy
      - two nuclei

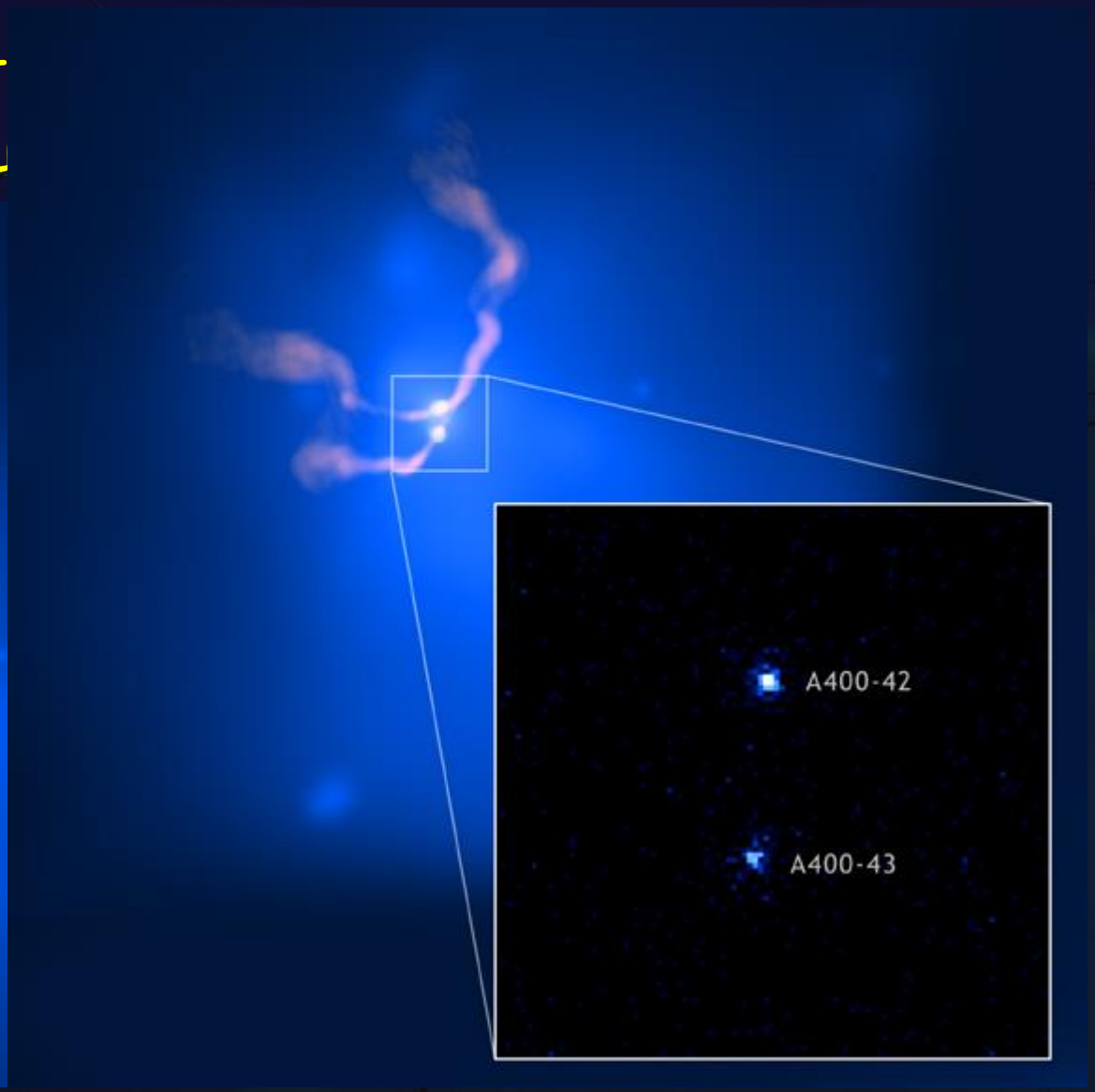




Radio Galaxies

- 3C 75
  - Cluster in X-
    - shows two nu



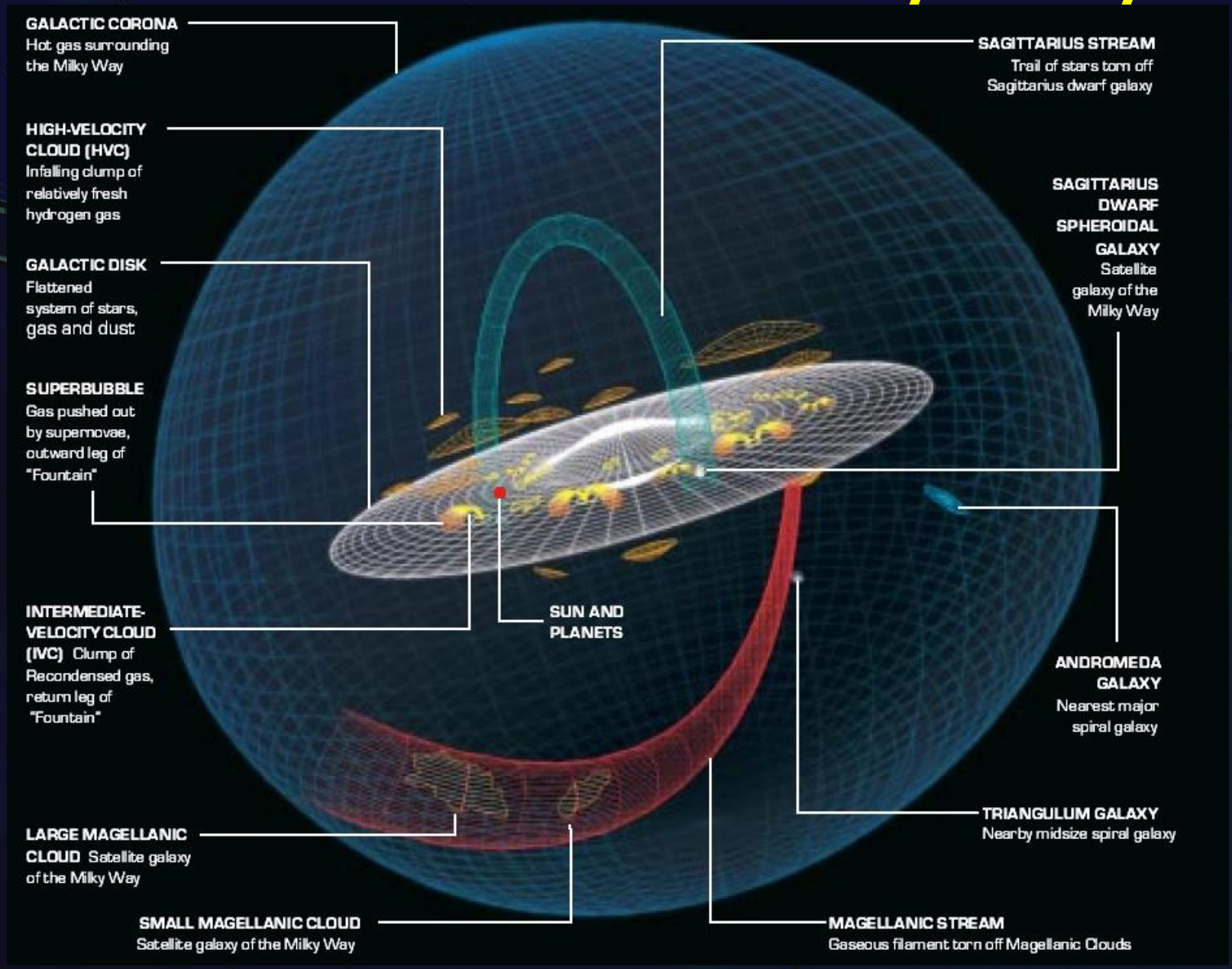


Spectral Radio Emission

- Spectral Line Radiation
  - Hydrogen hyperfine structure

- Spin-flip transition
  - Emits radiation at 1.420405 GHz
    21.106 cm
  - Spontaneous flip ~ 11 million years
  - Collisional flip ~ 400 years

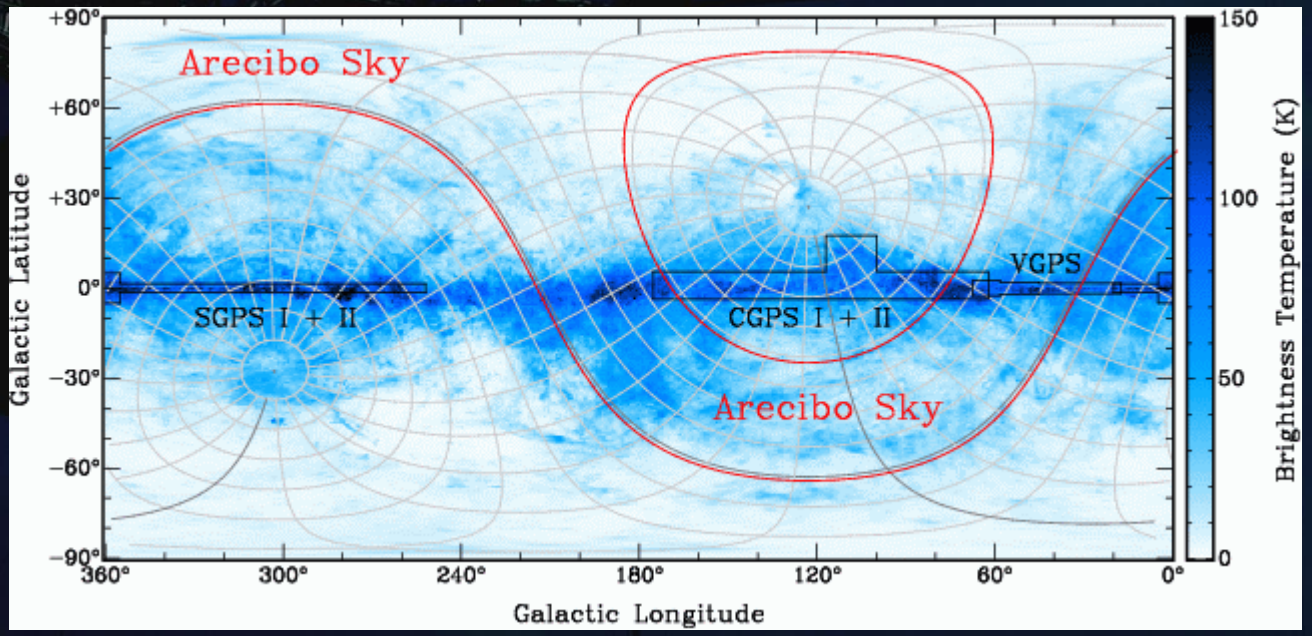
Cool HI in the Milky Way



Cool HI in the Milky Way

- GALFA – Galactic ALFA
  - Galactic HI in star-forming complexes
  - Small-scale structure of Galactic HI
  - Disk-Halo interferences
  - Halo clouds and cloud-halo interactions

Surveys in the International Galactic Plane Survey

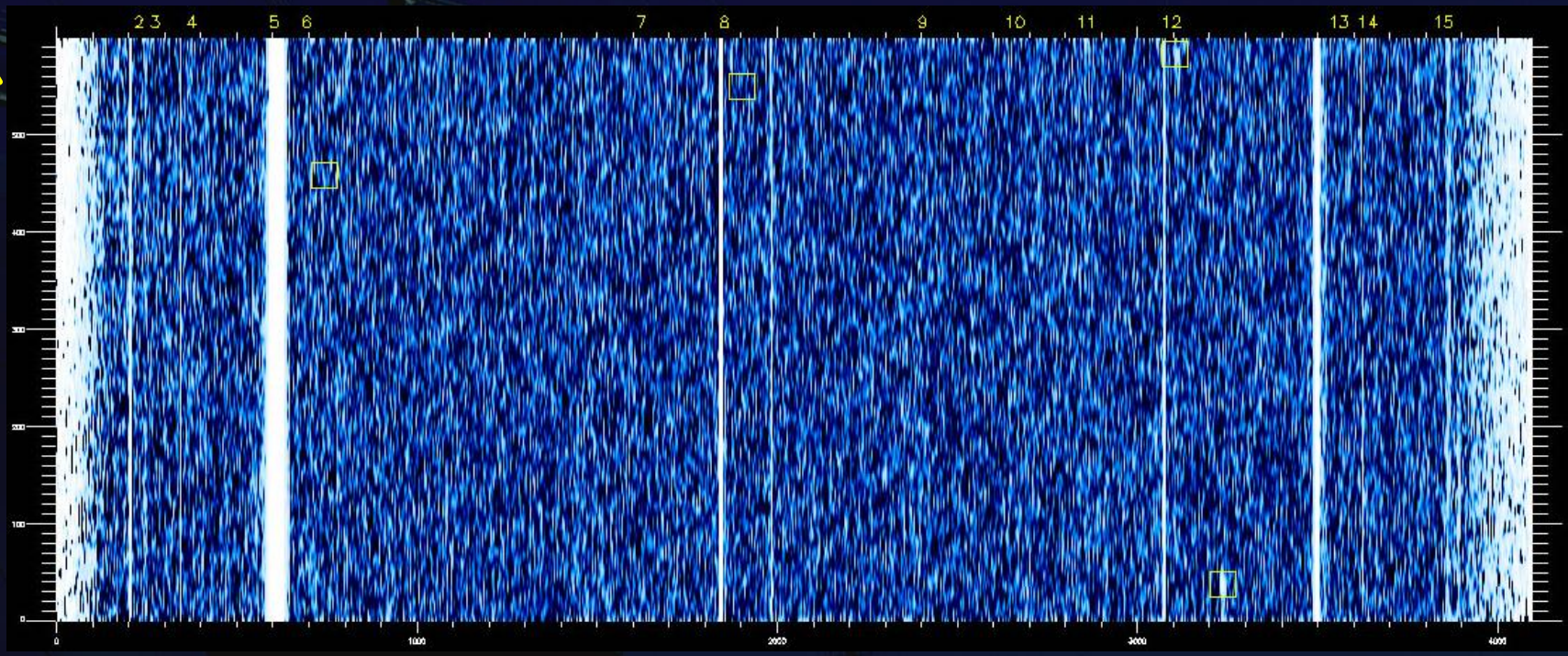


Extragalactic Cool HI

- ALFALFA Science
  - Expected to detect 25,000 objects
    - Local low-mass HI dwarfs ($\geq 10^6$ $M_\odot$)
    - Gas-rich massive galaxies ($\leq 10^{10.8}$ $M_\odot$)
  - HI spectra provide
    - Redshifts
    - HI cloud masses
    - HI disk populations & rotation rates
    - History of tidal events
    - Potential for future star formation
  - Blind survey not prejudiced toward bright or interesting objects … offers surprises!

ALFALFA Data

- Raw Data
  - 14 Spectra per second (7 feeds, 2 polarizations)

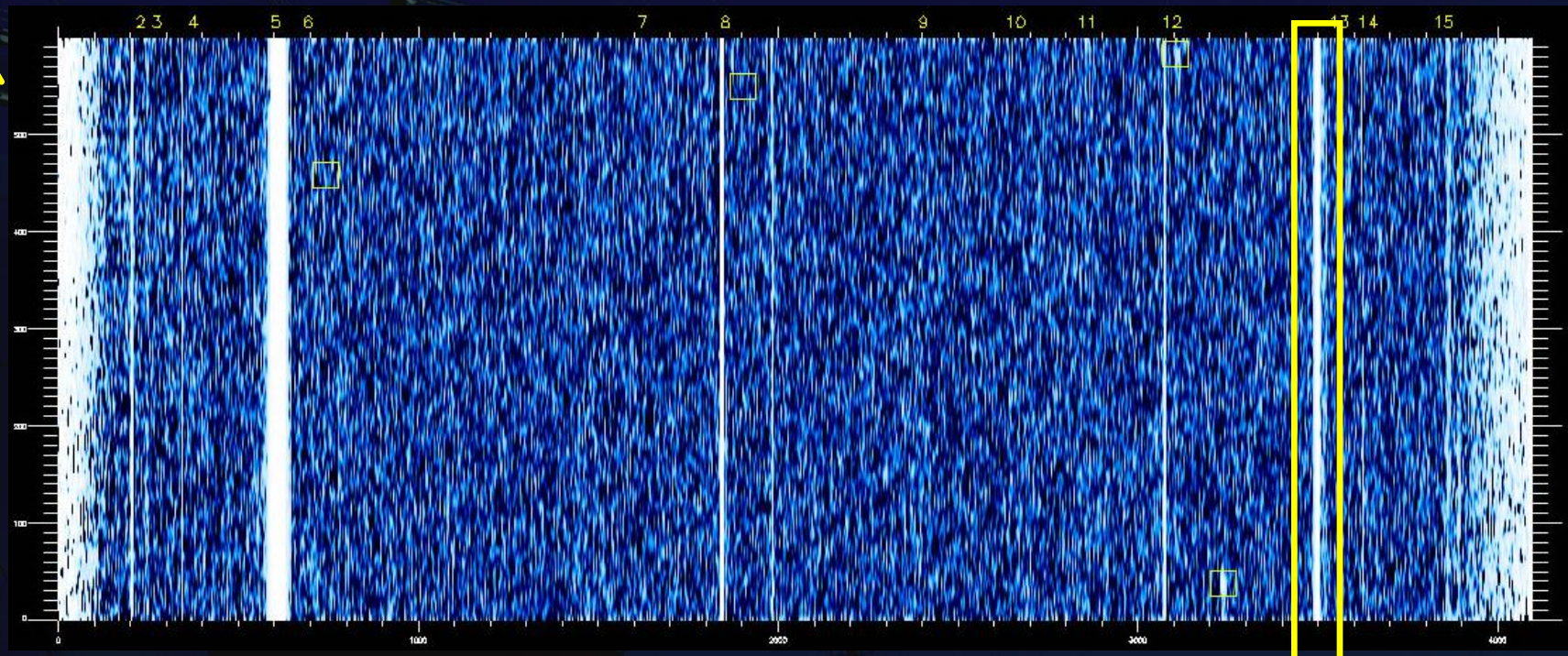


Time (RA)

ν Frequency

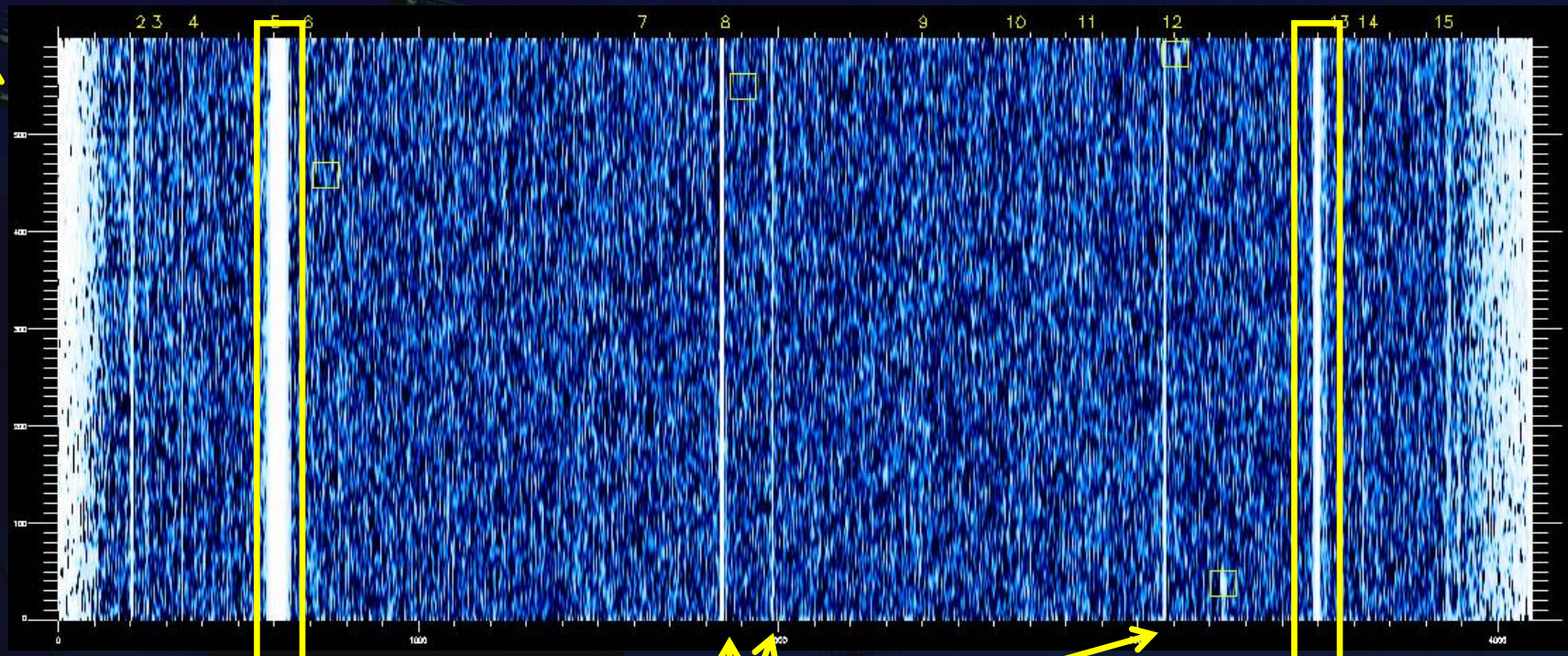
ALFALFA Data

- Raw Data
  - 14 Spectra per second (7 feeds, 2 polarizations)



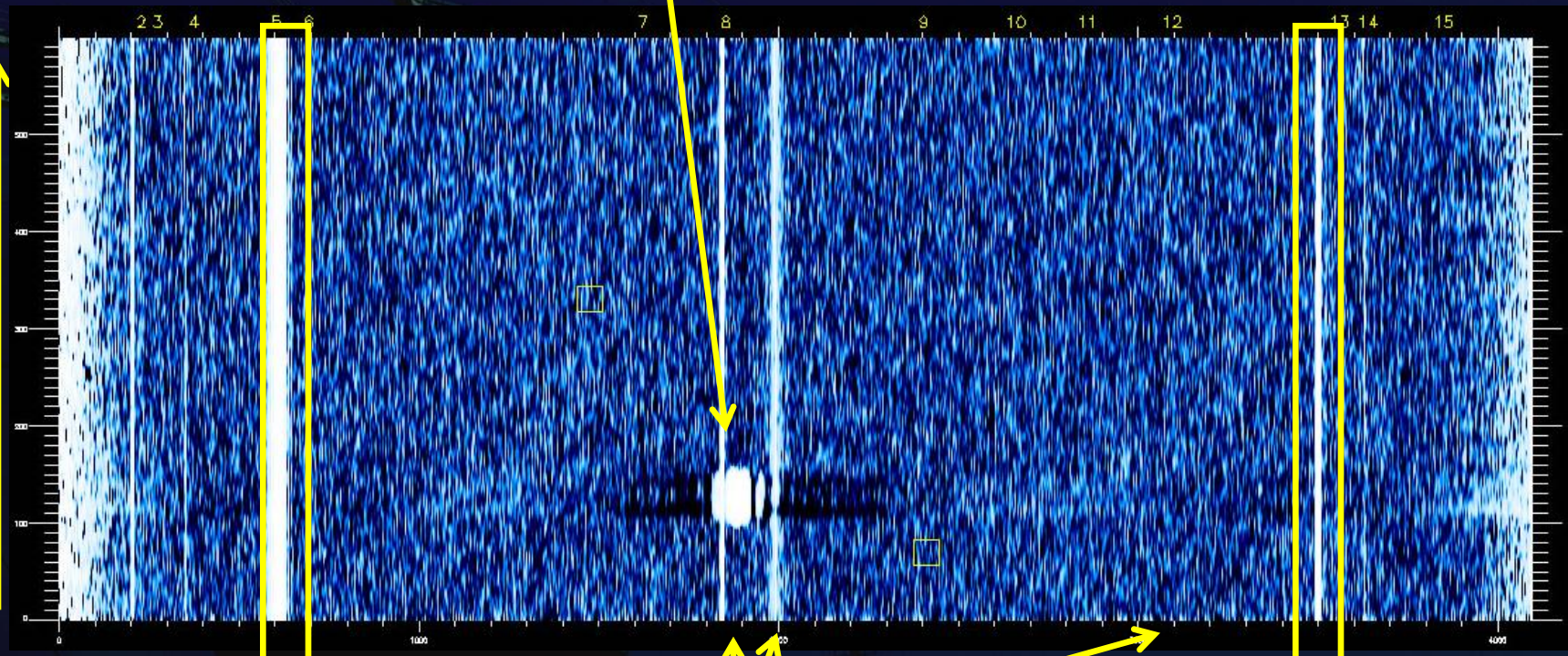
ALFALFA Data

- Raw Data
  - RFI: Radar



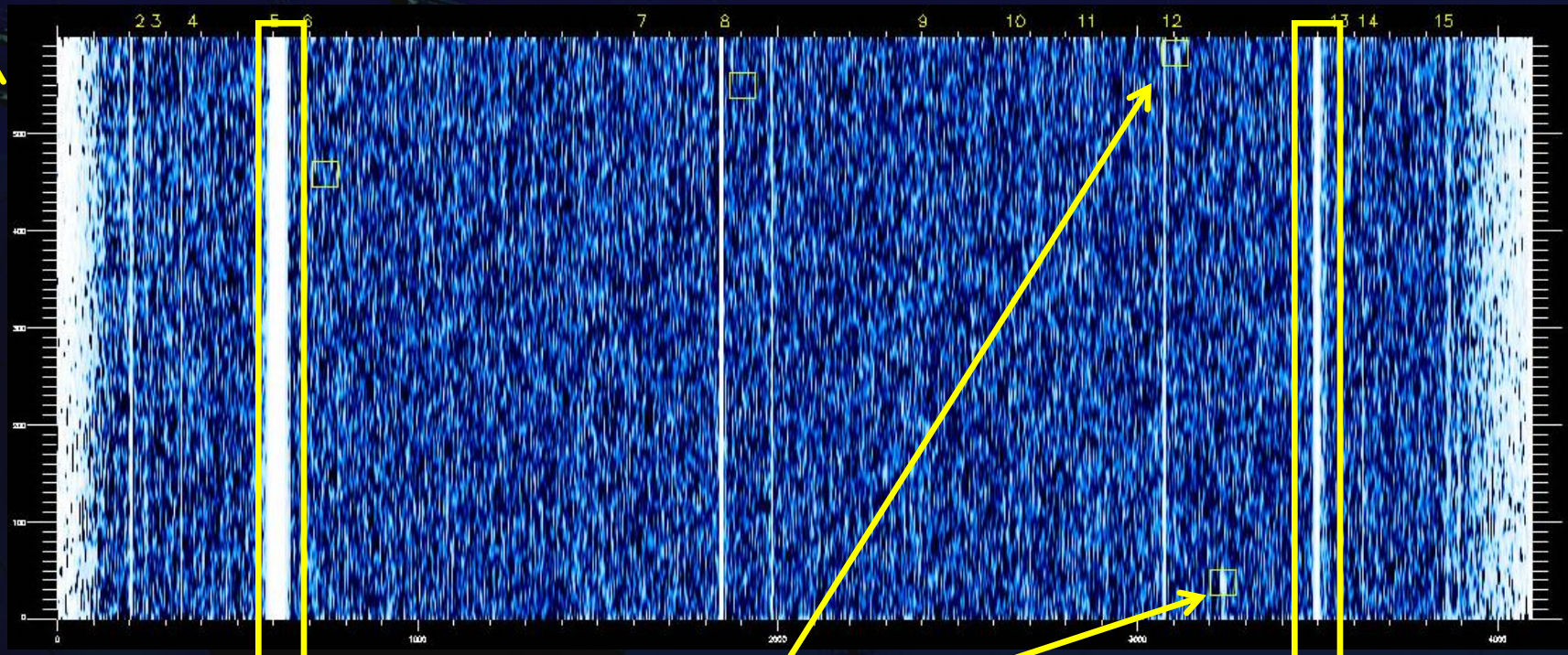
ALFALFA Data

- Raw Data
  - RFI: Radar … and GPS bursts



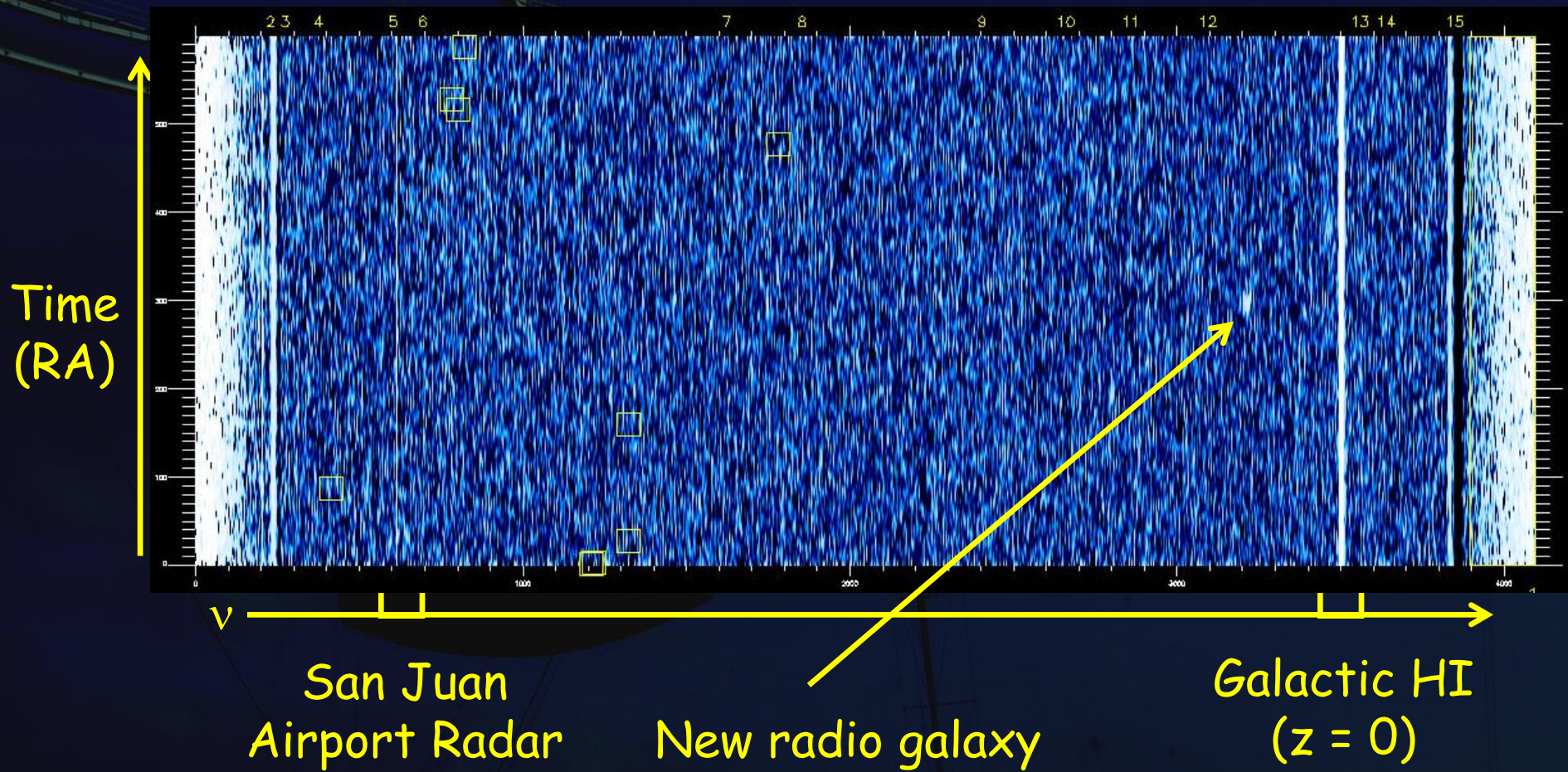
ALFALFA Data

- Raw Data
  - Galaxies: Known



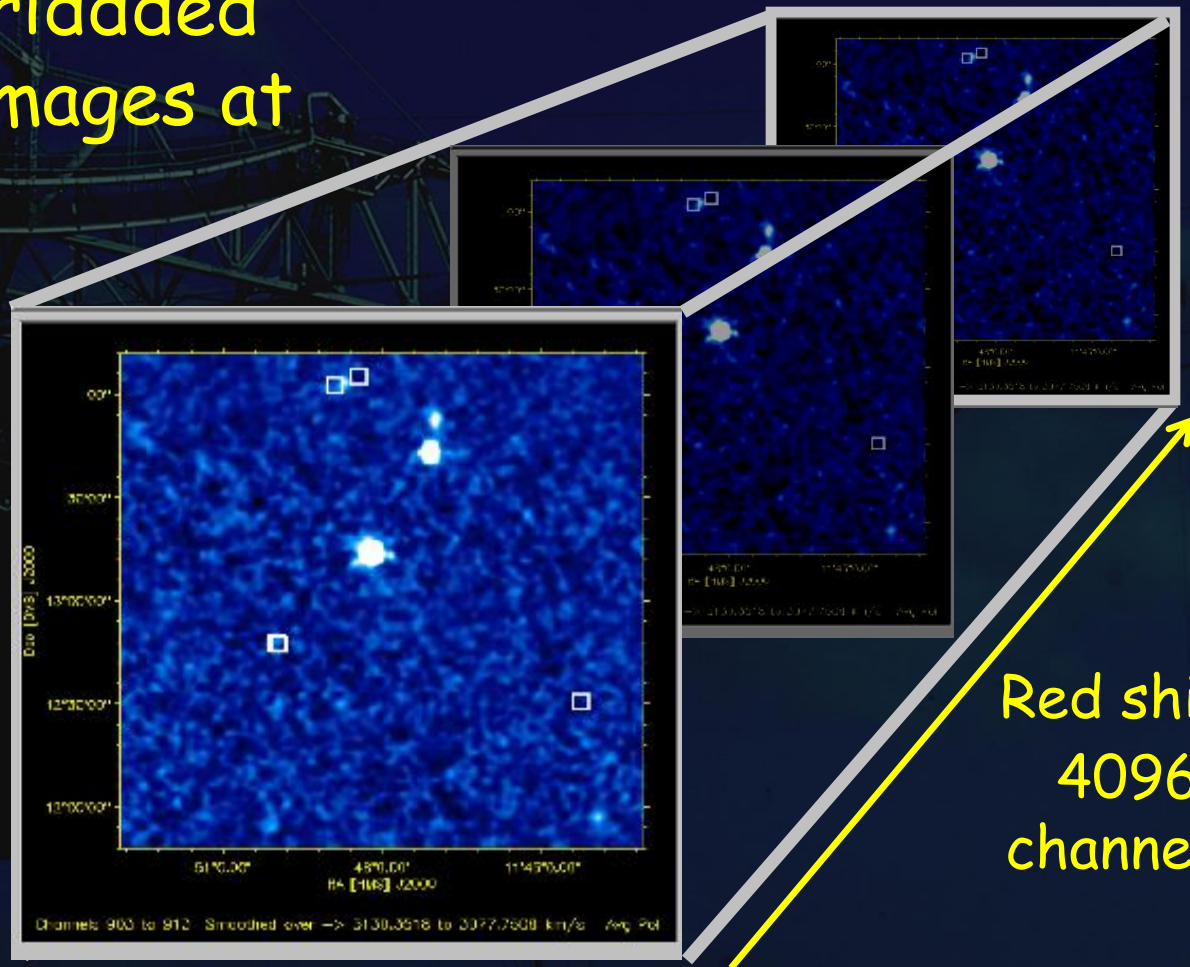
ALFALFA Data

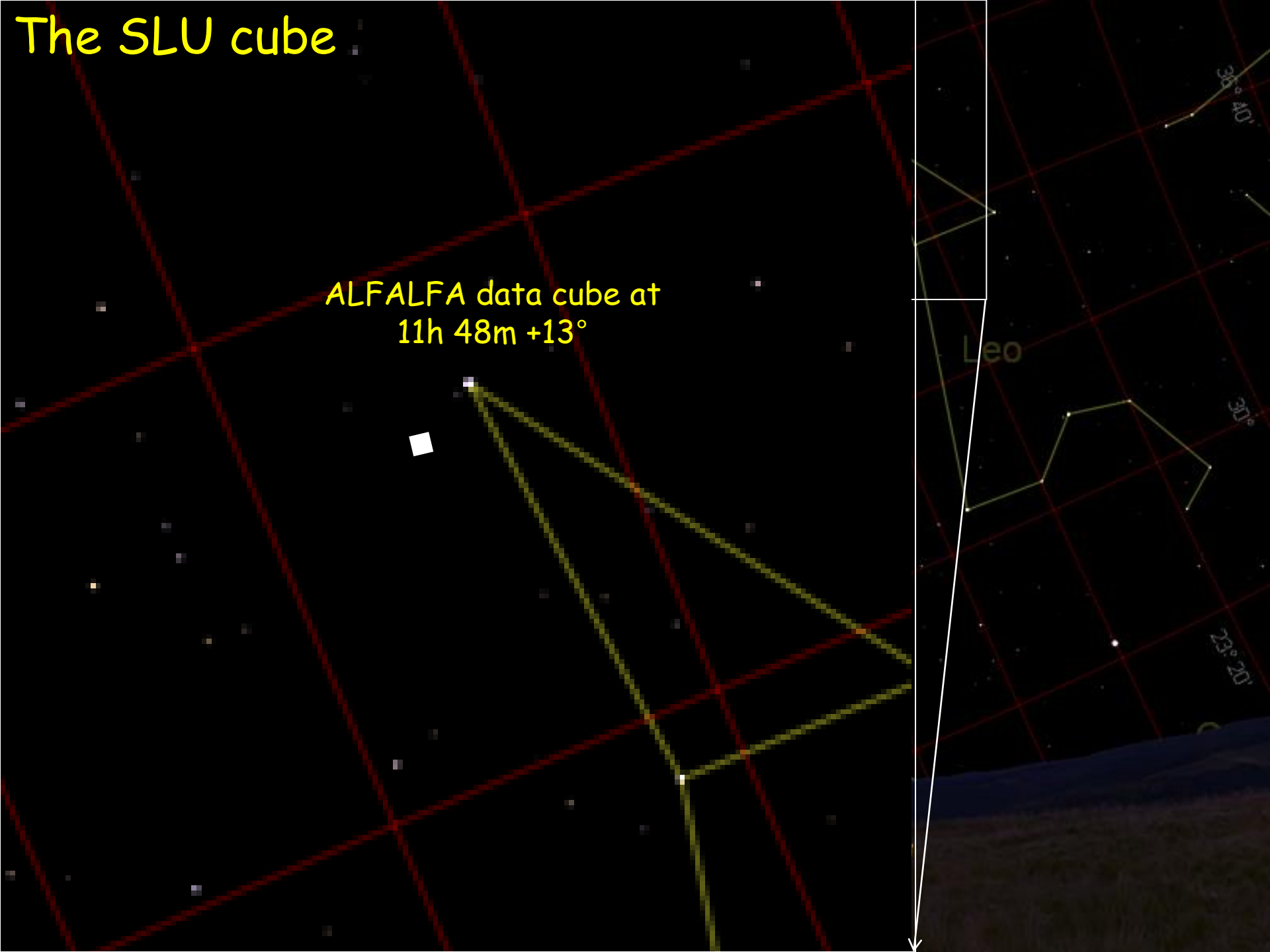
- Raw Data
  - Galaxies: Known and Unknown



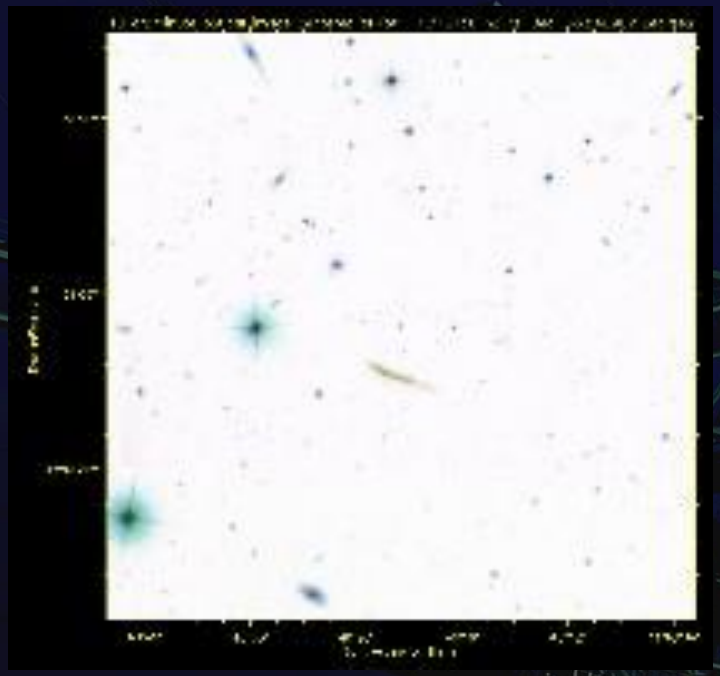
ALFALFA Data

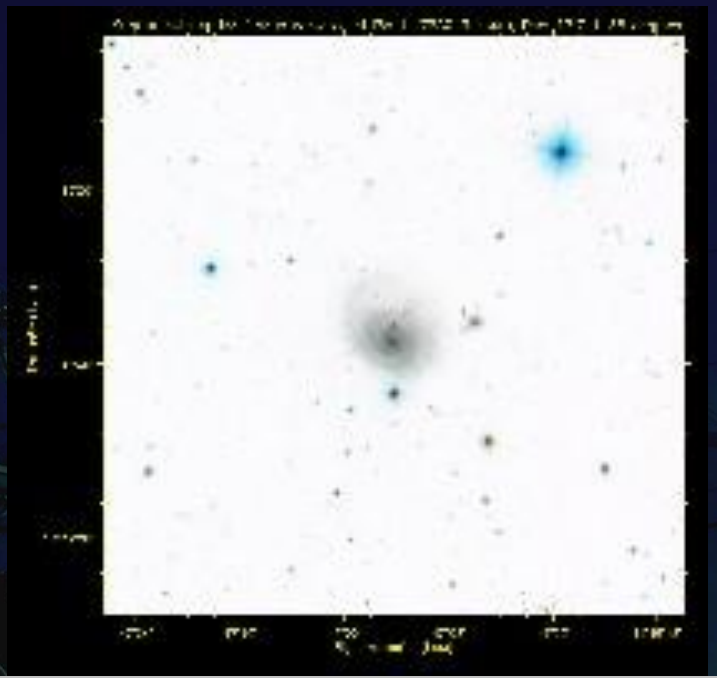
- Cubes
  - Spectra "griddded" into spatial images at increasing red shifts

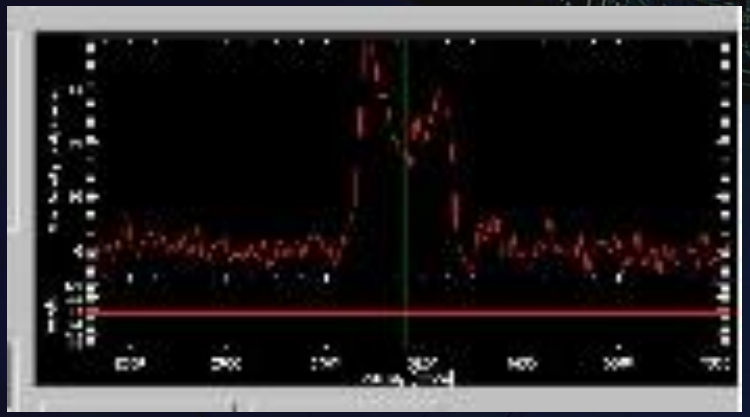


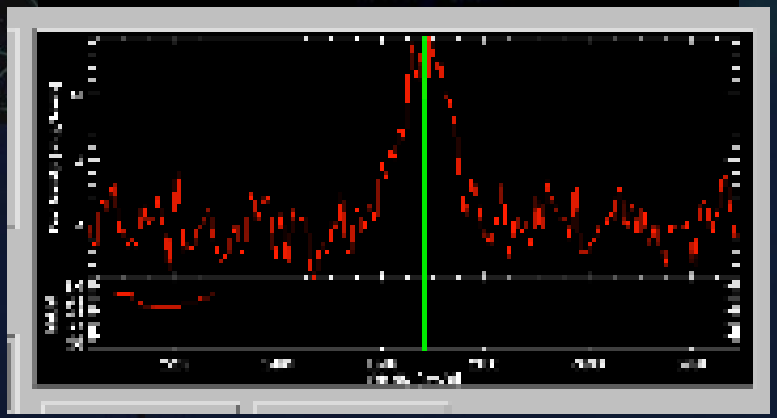

The SLU cube
ALFALFA data cube at
11h 48m +13°
Leo
30°
23° 20'

1148+13 Optical Images and Spectra







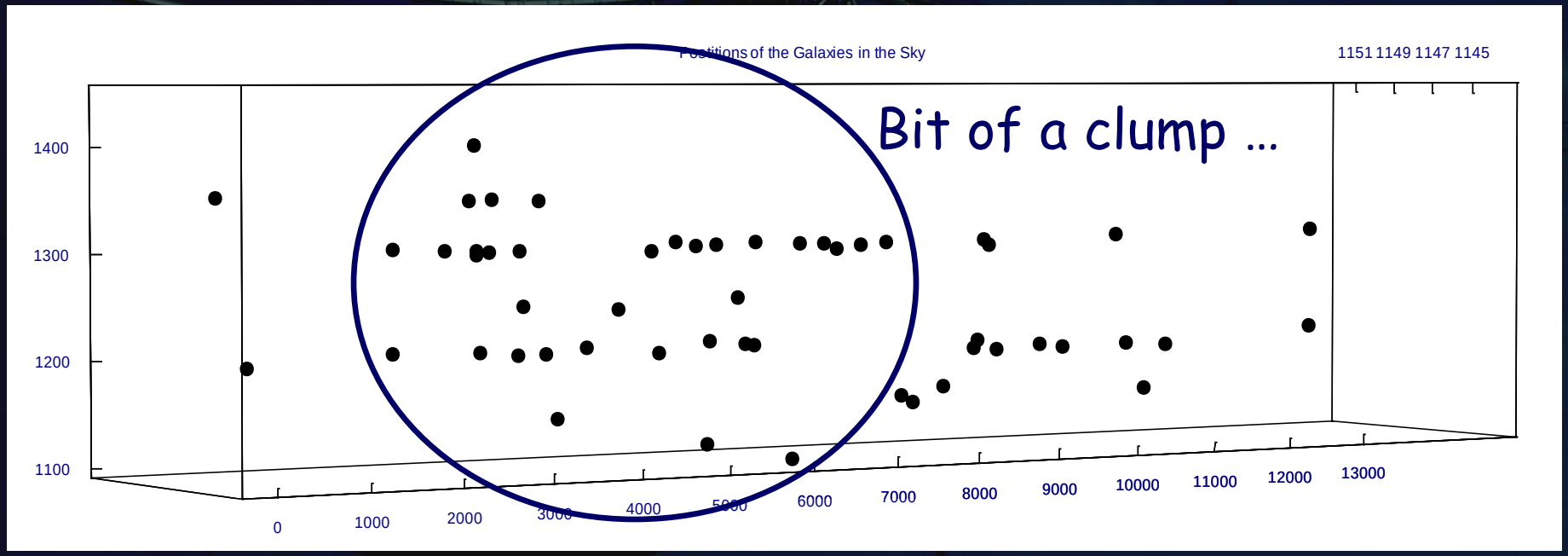


Double humped
spectrum for edge-on

Single humped
spectrum for face-on

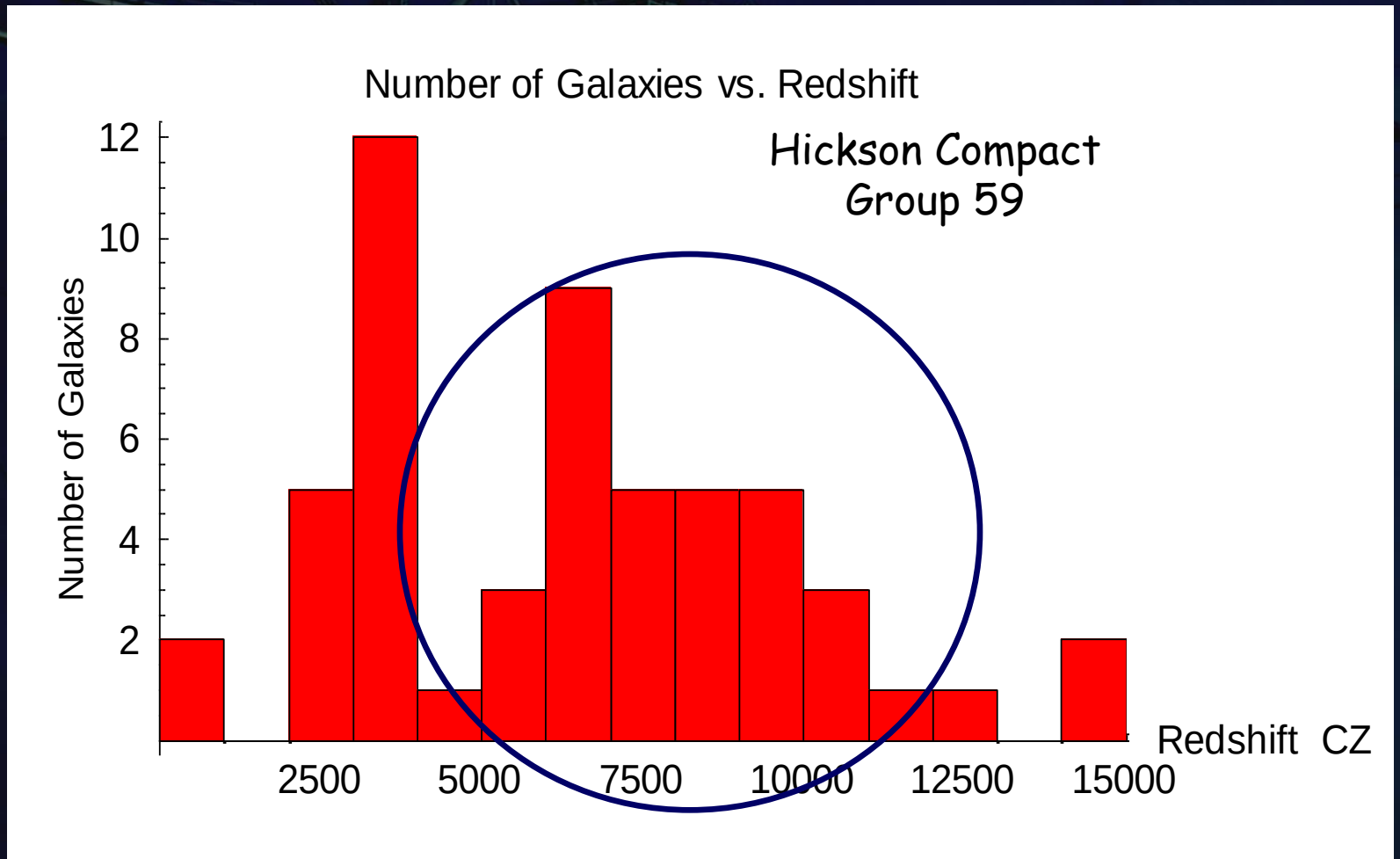
1148+13

- 3-D plot of galaxies in the SLU cube



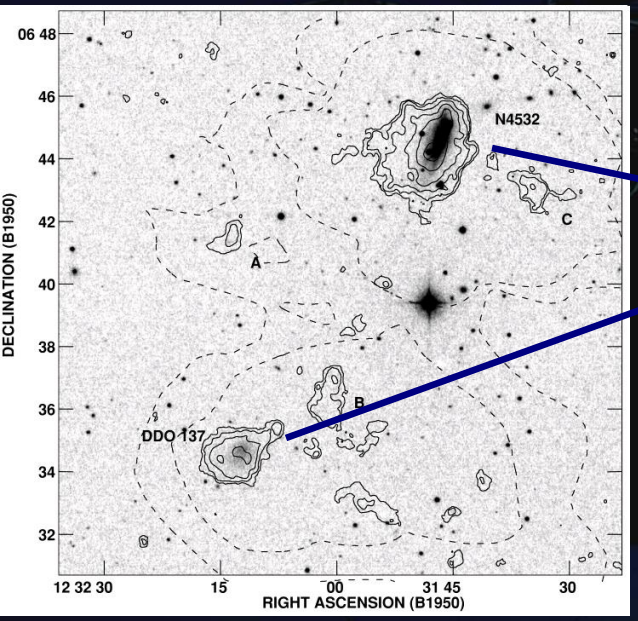
1148+13

- Distribution of Galaxies
  - Hickson Compact Group



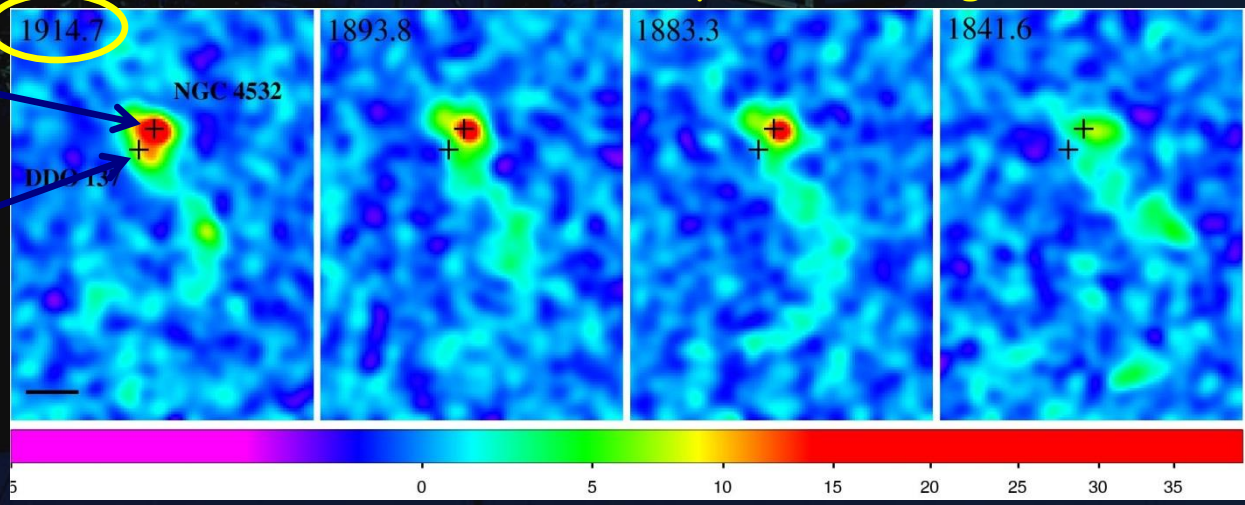
Other ALFALFA Results

- Tidal Stream in Virgo Cluster
  - 500 kpc, ~ 7 x 10^7 $M_\odot$ (~10% of system mass)
    - Seems to be remnant of a NGC 4532 and DDO 137 interaction



G. Lyle Hoffman, et al, 1999 *AJ* **117** 811-825

km/s, blue shifted with respect to the galaxies

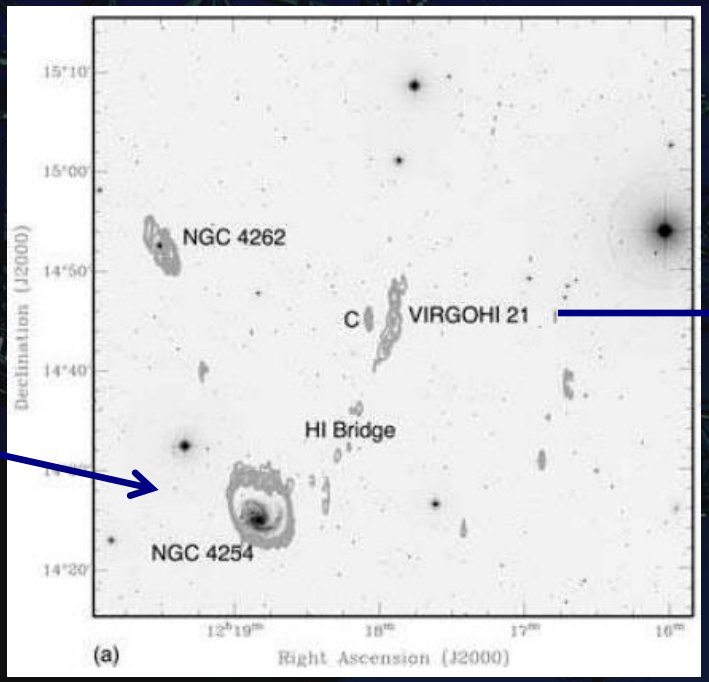


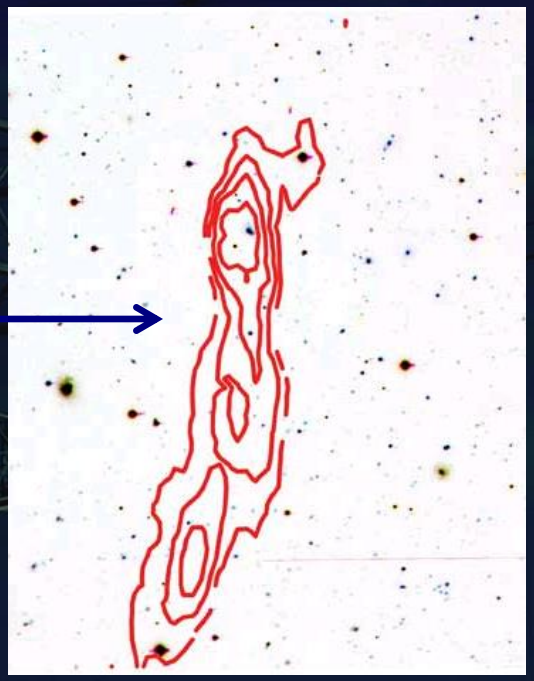
Koopmann, R.A., et al, 2008, *ApJL* **682**, L85

Other ALFALFA Results

- Virgo HI21 near Pinwheel galaxy (M99)
- Rotating HI cloud … First Dark Galaxy?

NGC 4254 showing extended spiral arm.



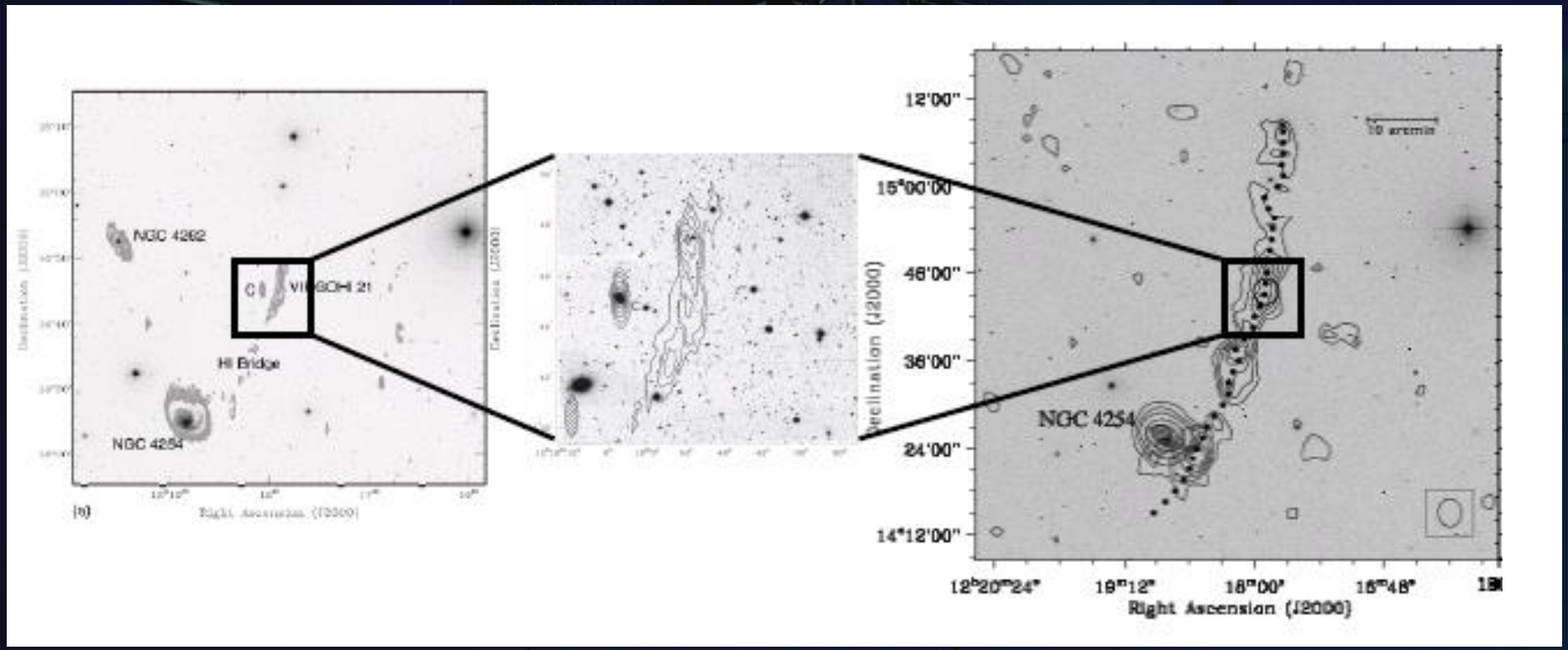


Minchin, R., et al, 2007, ApJ, in Press
http://arxiv.org/abs/0706.1586

University of Alabama
http://www.astr.ua.edu/Galleries.html

Other ALFALFA Results

- Debunking the Dark Galaxy
  - "An Act of Harassment"
    - Part of a larger tidal stream from NGC 4254



Haynes, M. P., et al, 2007, *ApJL* **665**, L19


The adventure continues ...