Physics 343 Lecture # 14:

the Search for Extra-Terrestrial Intelligence

and galactic collisions (mergers)

SETI

Astrobiology: a useful starting point

astrobiology (Lafleur 1941)

cosmobiology (Bernal 1952)

exobiology (Lederberg 1960)

bioastronomy (IAU 2004)

1941 definition by Lafleur: "consideration of life in the universe elsewhere than on earth"

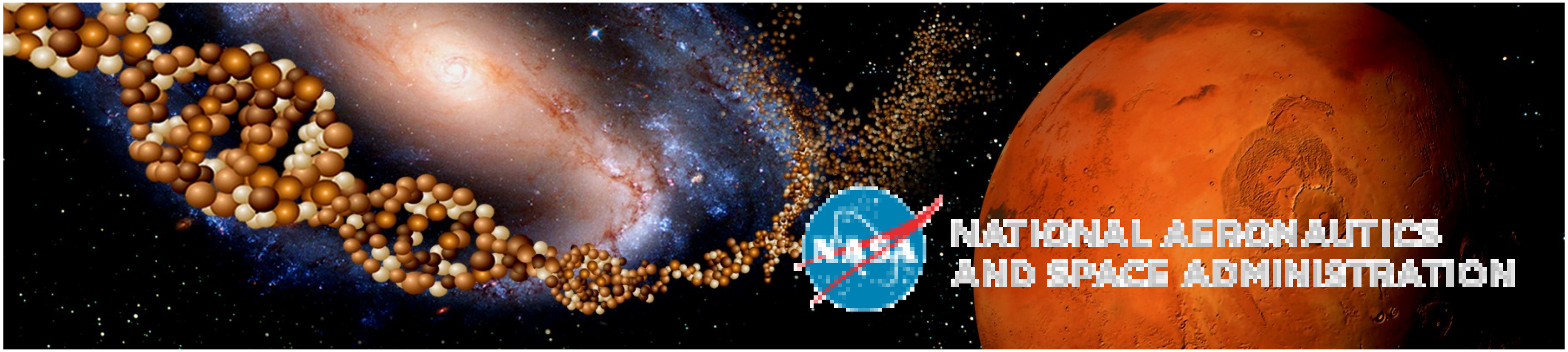
1964 comment by Simpson: "this 'science' has yet to demonstrate that its subject matter exists!"

2008 definition by NASA: "study of the living universe"

Astrobiology vs. SETI

Astrobiology research is funded by NASA.

NASA Astrobiology Institute (http://nai.nasa.gov/) started in 1998 as a virtual institute to coordinate research.



SETI has not been funded by NASA since 1993, when Congress killed the Ames/JPL "High Resolution Microwave Survey."

Should “astrobiology” include life on Earth?

To address many astrobiological questions, we have no choice but to extrapolate from a sample of one.

Is this legitimate?

Copernican principle: our circumstances are not special

anthropic principle: our circumstances are special, because we're here

Relevant to SETI because insights about astrobiology guide our choice of search strategy.

Quantifying our ignorance...

UC Santa Cruz astronomer Frank Drake in Green Bank, WV

November 1960: a secret meeting in WV

Ten scientists met in Green Bank, WV to discuss the prospect for existence and detection of extraterrestrial life.

Location inspired by Drake's first SETI experiment.

Participants included astronomers, biologists, engineers, and a chemist whose Nobel Prize was announced during the meeting; nicknamed themselves "Order of the Dolphins."

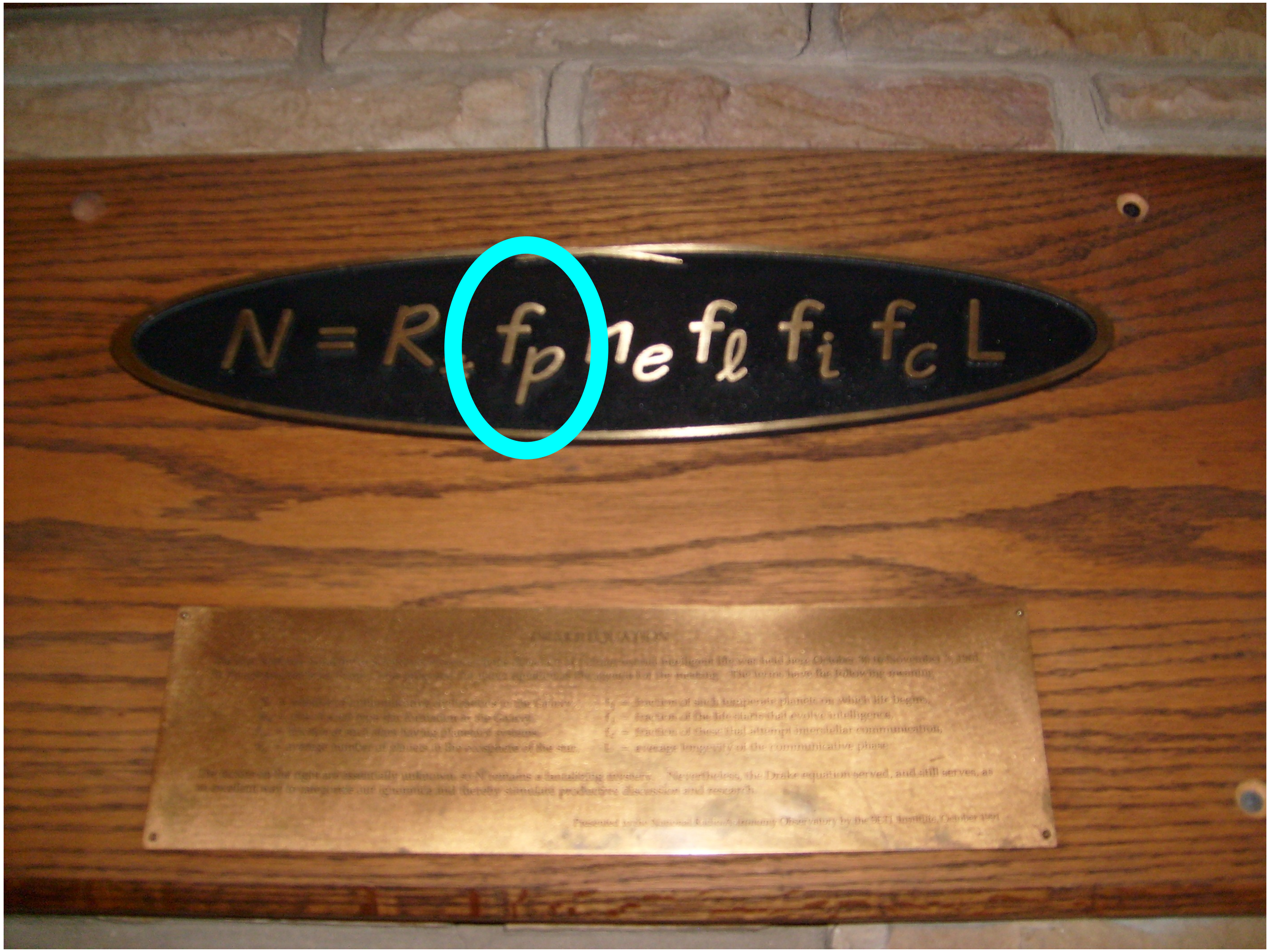
The Drake Equation

***N* = number of transmitting civilizations in the Milky Way**

The Drake Equation

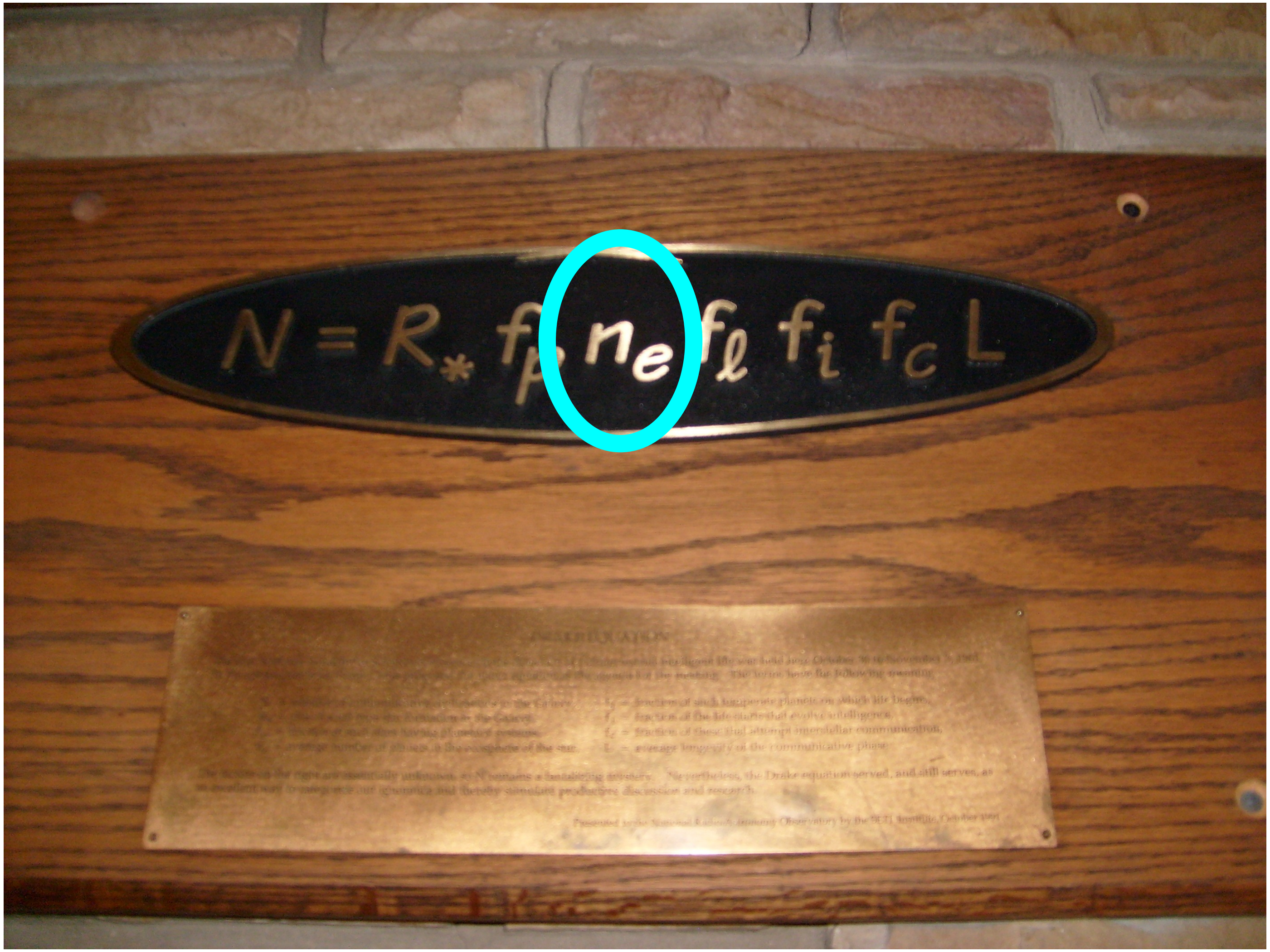
R_* = rate at which suitable stars form in Milky Way (yr^{-1})

The Drake Equation



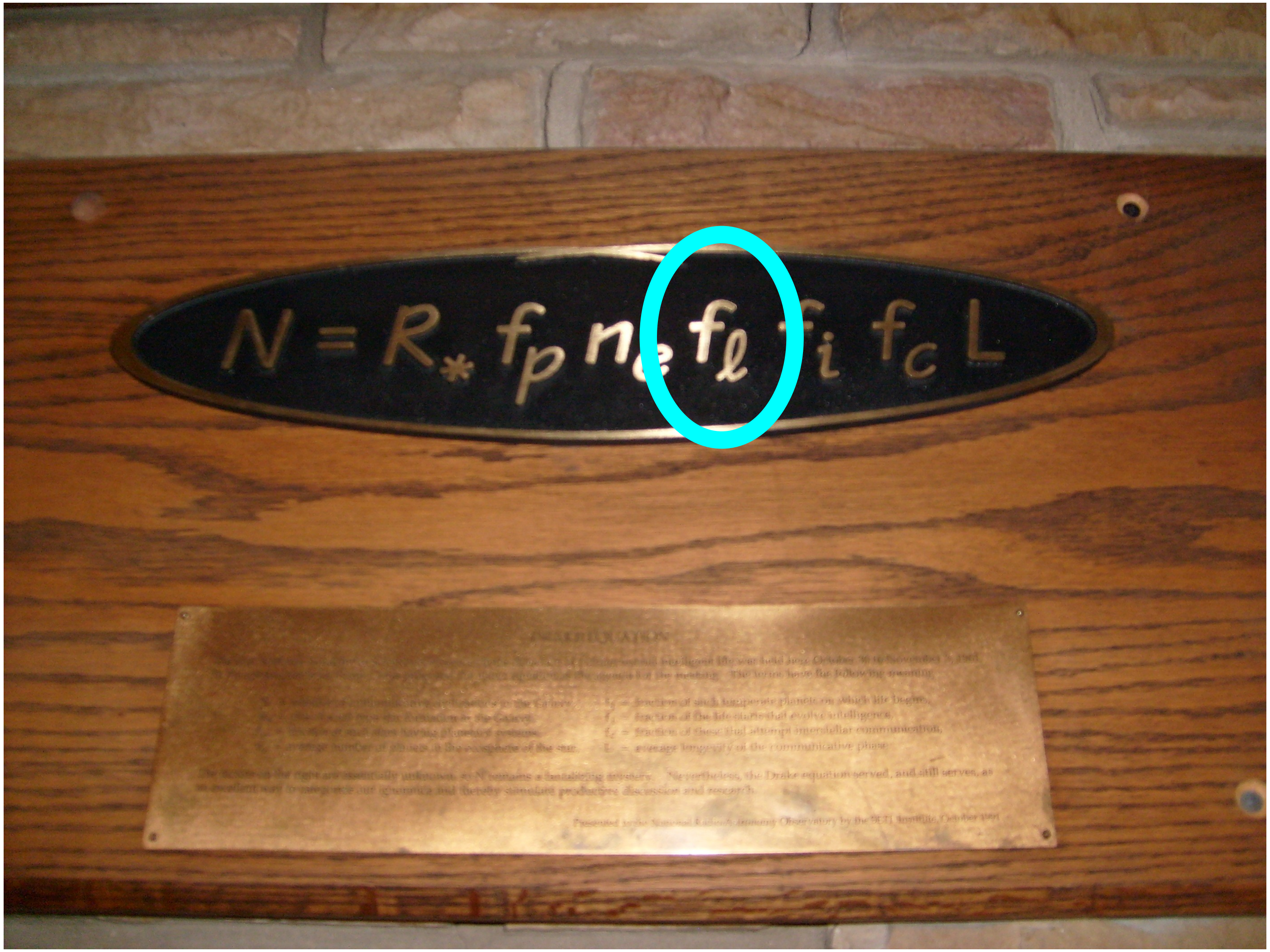
f_p = fraction of such stars that have planets

The Drake Equation



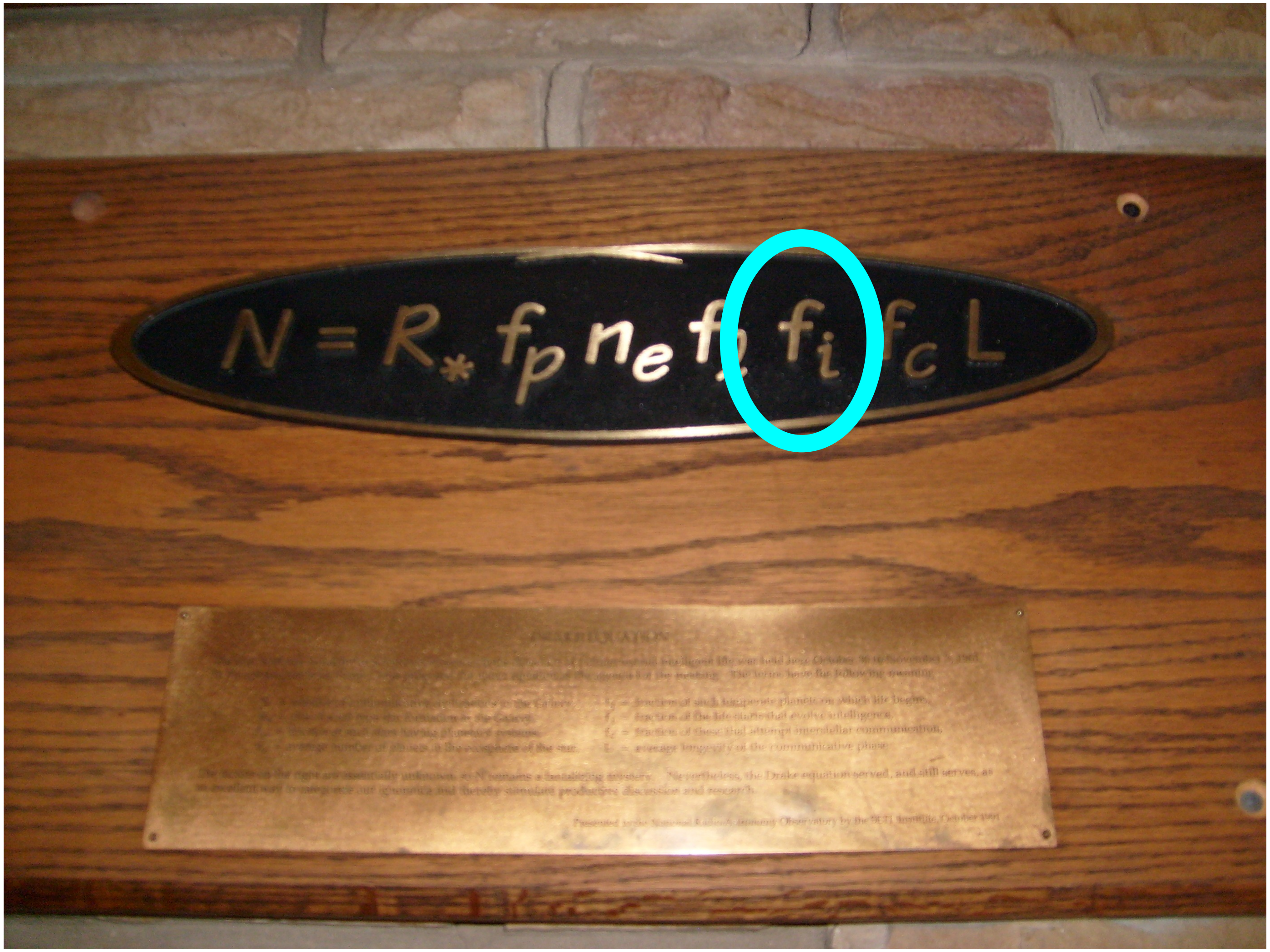
n_e = mean number of planets per solar system that *could* support life

The Drake Equation



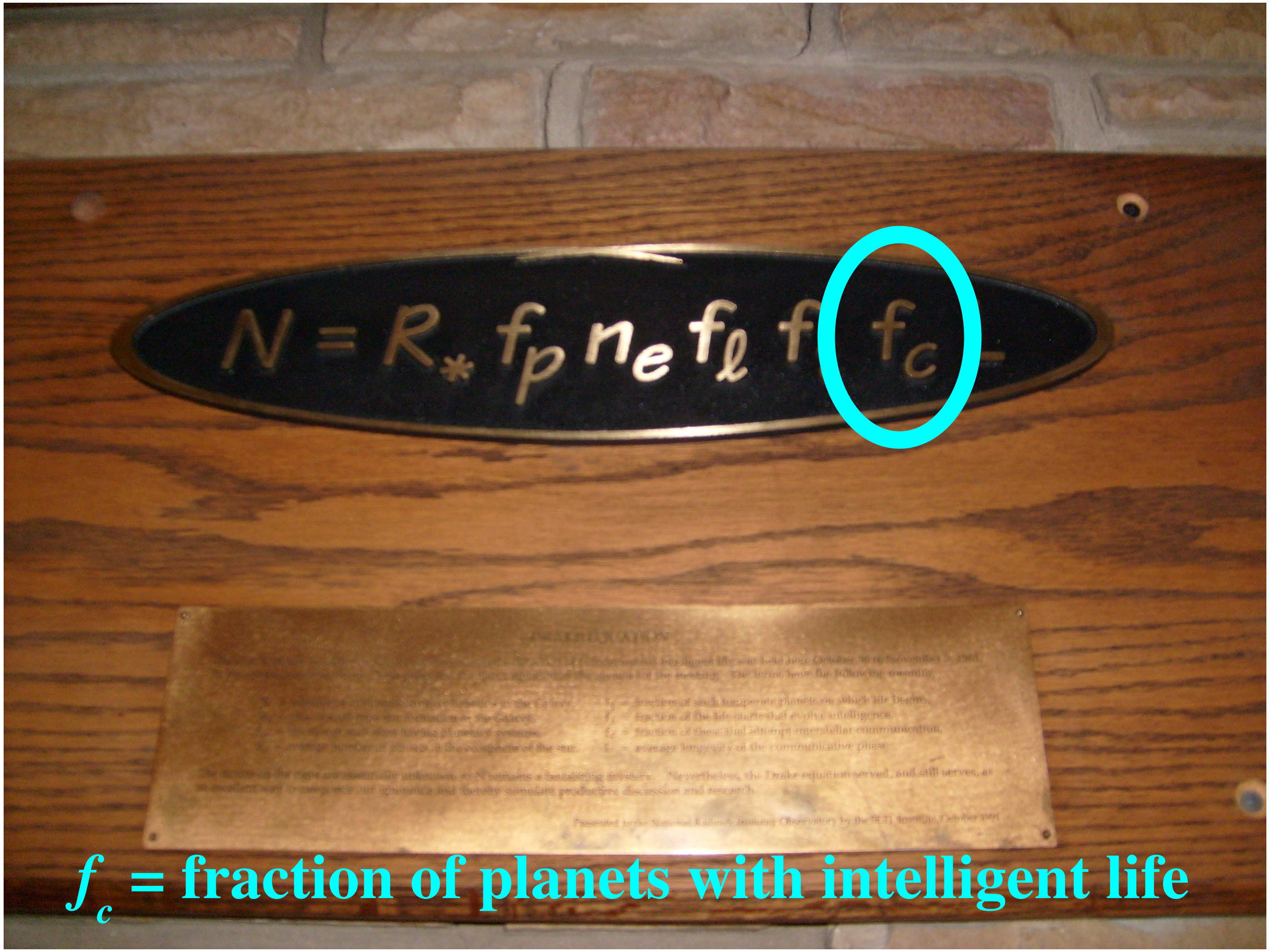
f_l = fraction of habitable planets on which life *did* evolve

The Drake Equation



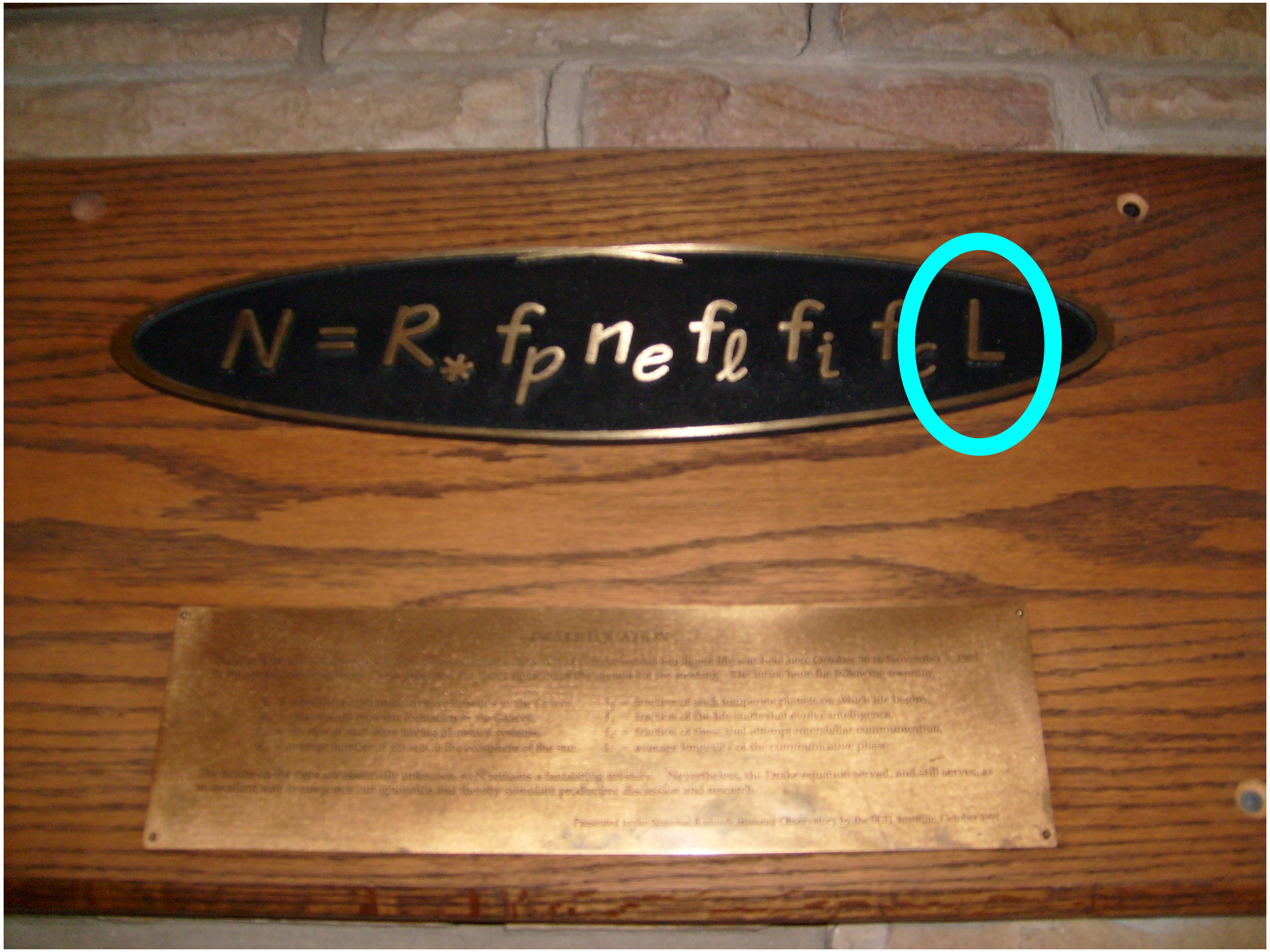
f_i = fraction of planets with life on which intelligence evolved

The Drake Equation



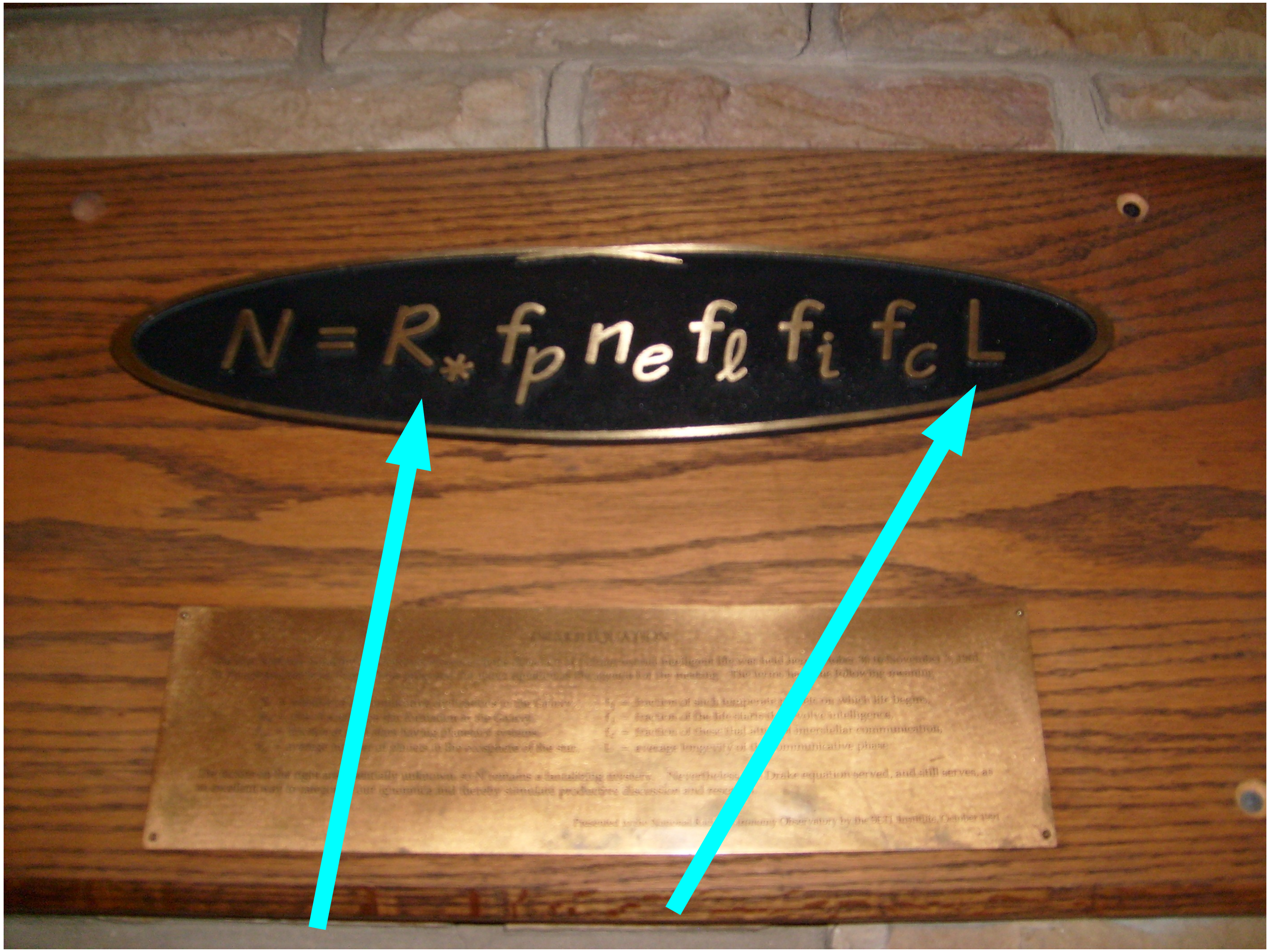
f_c = fraction of planets with intelligent life on which a transmitting *civilization* arises

The Drake Equation



***L* = mean lifetime of a transmitting civilization (yr)**

The Drake Equation



units: $R_* \sim \mathrm{yr}^{-1}$ and $L \sim \mathrm{yr} \Rightarrow N$ is dimensionless

What did Frank Drake guess in 1961?

$R_* \sim 10\ \mathrm{yr}^{-1}$

$f_p \sim 0.5$

$n_e \sim 2$

$f_l \sim 1$ $\Rightarrow N \sim 10$

$f_i \sim 0.01$

$f_c \sim 0.01$

$L \sim 10^4\ \mathrm{yr}$

Key value of the Drake Equation: highlights the fact that some factors are less certain than others!

Quiz

Overall strategy for contacting ETI

If we want to get in touch with ETI, should we

(a) send messages?

(b) listen for messages?

(c) wait to be visited?

The relative youth of our technological civilization argues that (b) is better than (a), but also begs the question of why we have not already been visited!

Latter question is known as the Fermi Paradox. Possible answers: they don't exist, they're far away, or they're hiding.

The listening strategy for SETI: details

Two key questions:

(1) Where do we look on the sky?

(2) Where do we look in the electromagnetic spectrum?

Most straightforward answers draw from our own experience:

(1) Look near stars like the Sun, which could have planetary systems like our solar system.

(2) Look in the radio, where interstellar dust and a planetary atmopshere will not absorb/scatter a signal.

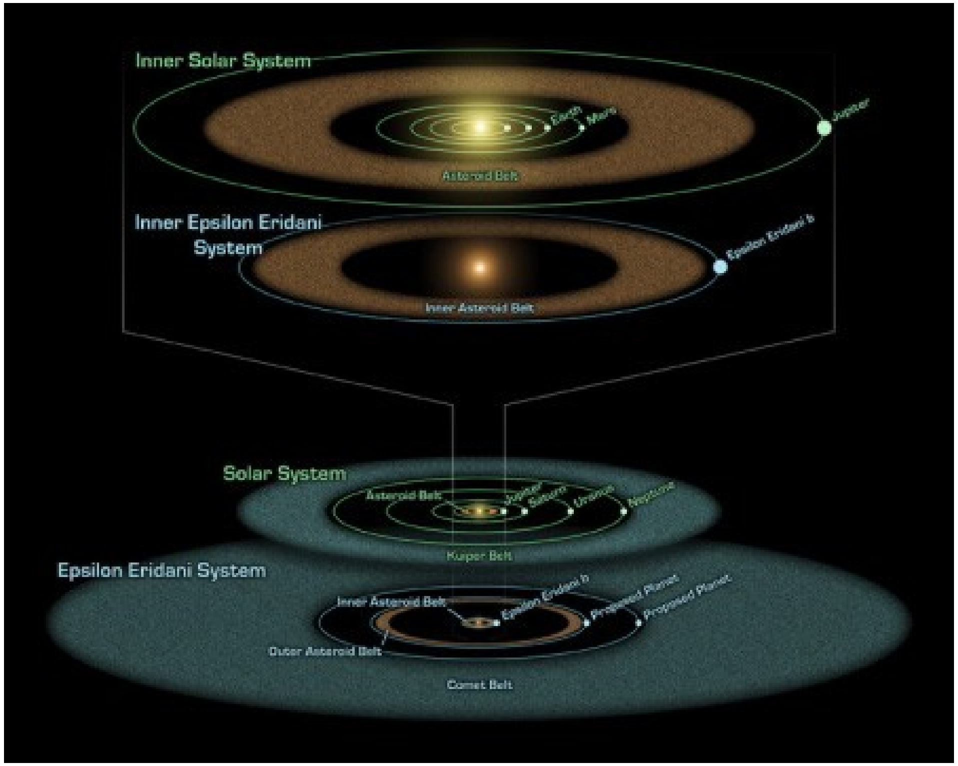
Project Ozma

1960: Frank Drake used the 85 foot telescope in Green Bank to observe two nearby stars at $\nu \sim 1420.4$ MHz (a single 100 Hz channel scanned 400 kHz of bandwidth; compare to mode 1 of SRT receiver, which obtains 500 kHz at 7.8125 kHz resolution). Frequency was chosen for cheap cost ($2000). Strip chart and tape recorder stored data. Observed 150 hrs.

Targets chosen to be like the Sun: Epsilon Eridani (3.22 pc) and Tau Ceti (3.65 pc). No astronomical signals detected.

Epsilon Eridani: the picture today

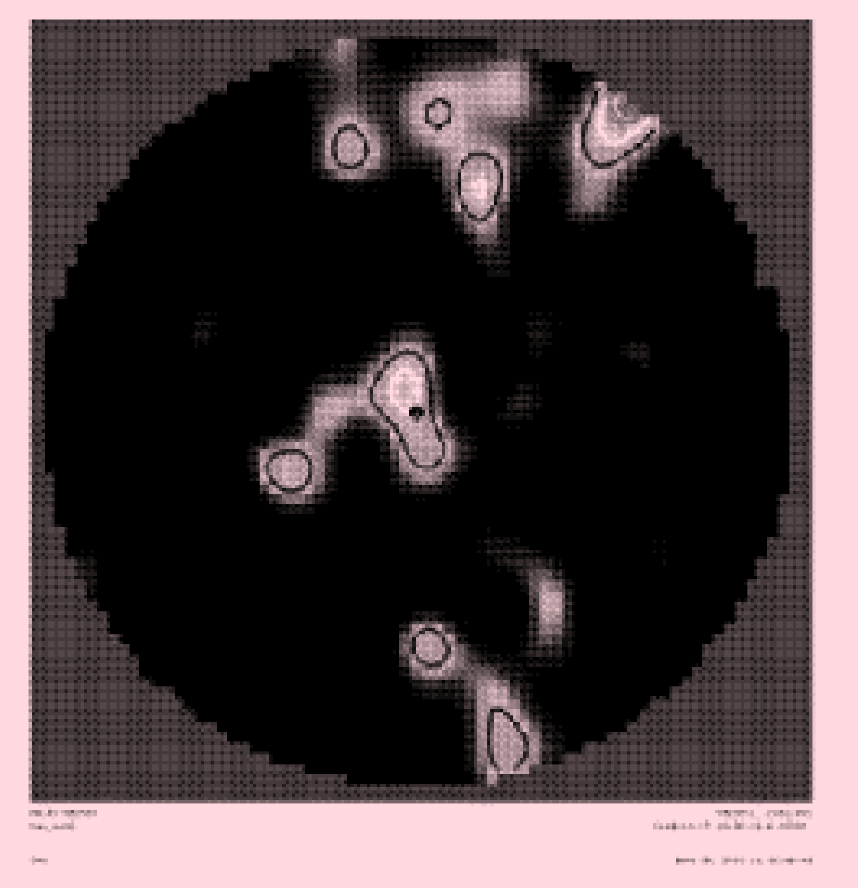
Bumps in dust spectrum imply existence of two asteroid belts confined by three planets (one also seen in radial velocities) and an icy quasi-"Kuiper belt"... but only 850 Myr old, so no time for intelligent life to develop (Backman et al. 2008).



Courtesy NASA/JPL.

Tau Ceti: the picture today

No evidence for planets in radial velocity searches, but submillimeter photometry indicates a debris disk ten times as massive as our Kuiper belt... which presumably implies a ten-times-higher rate of major impacts than what the Earth suffers.



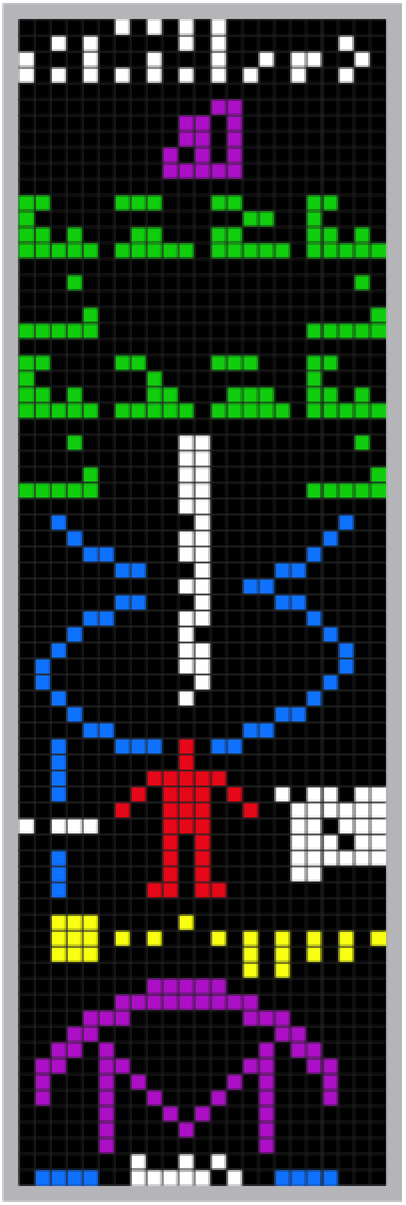
Greaves et al. (2004)

What sort of signals are expected?

What sort of signals have we (deliberately) sent?

1974 Arecibo Message: 23 × 73 sequence of pulses at two different frequencies, to suggest arrangement into a 2D array.

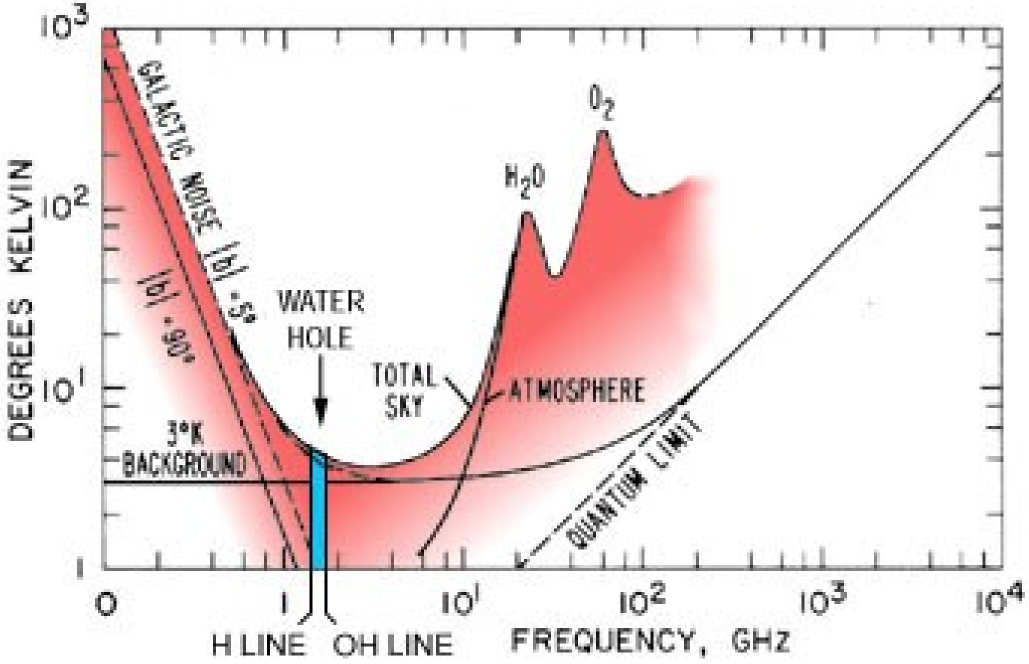
This was beamed towards the globular cluster M13, which will move out of its path before the 25,000 year travel time has elapsed!



Where might we look in frequency?

Close to the 21cm HI line, which is an obvious point of reference for all radio astronomers (Morrison & Cocconi 1959).

1420 MHz through 1662 MHz (frequency of strong OH lines) defines the low-background "water hole" (B. Oliver), which might be appealing to species with a common biology.



Signal frequency unlikely to be stationary

Search strategies need to check for repeatability but allow for Doppler drift: transmissions from a planet or a satellite in orbit will in general reflect line-of-sight motions.

Conclusion: want to search wide frequency ranges at very high frequency resolution.

Post-Ozma searches from Green Bank

Later programs could take advantage of the 140 ft and 300 ft telescopes at NRAO Green Bank.

1971-72: "Ozpa" searches towards 9 nearby stars (including allowance for Doppler drift) over a meager 13 hours

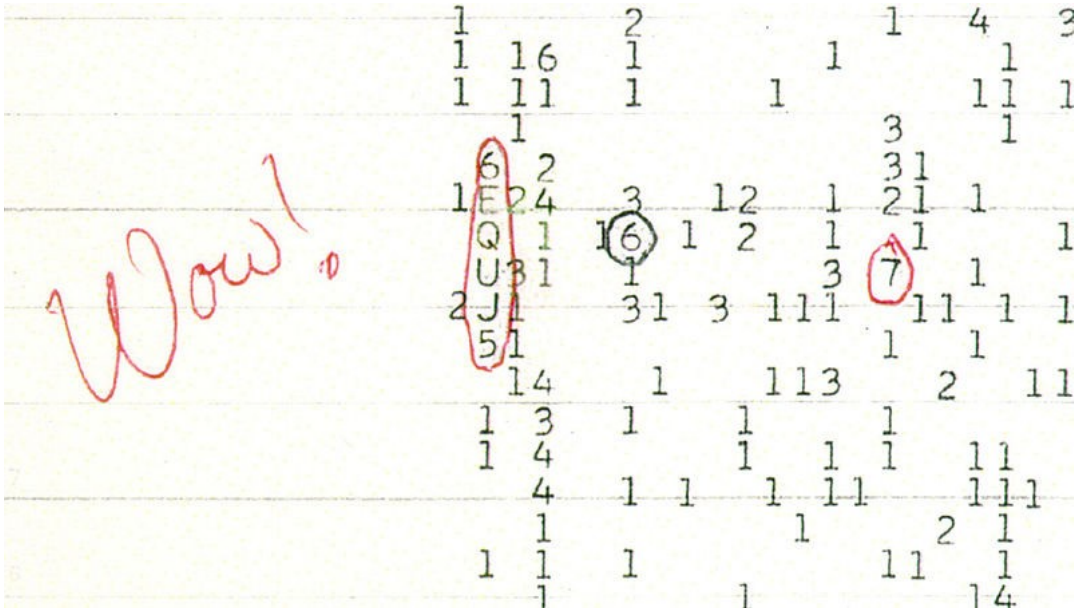
1972-76: "Ozma II" searches towards 674 stars over 500 hours; target stars selected to be between F5 and K4, to avoid short stellar lifetimes and small habitable zones

The first university-based SETI effort

Ohio State's “Big Ear” (1963-1998): drift field telescope with feed horns on a cart at base of flat reflector. SETI work began in 1973 and continued over two decades.

August 15, 1977: the “wow” signal

While observing in the direction of Sagittarius, Big Ear detected a strong, narrow-band signal in one of its two feed horns that was not repeated. Nevertheless, Jerry Ehman was quite enthusiastic!



Wow!

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1     2        1  4  3
1 16  1      1     1
1 11  1    1      11 1
  1            3   1
 6 2           31
1E24  3  12   1 21 1
 Q 1 16 1 2  1  1    1
 U31  1      3 7  1
2J1   31 3 111  11 1 1
 51            1  1
  14   1   113   2  11
 1 3  1   1    1
 1 4      1  1 1  11
   4  1 1  1 11   111
   1        1    2 1
 1 1  1        11   1
   1      1       14
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1979: NASA gets on board

NASA established the "Microwave Observing Program" (MOP) to pursue a mixture of targeted and all-sky searches.

This attracted mixed attention from Congress: Sen. William Proxmire (D-WI) gave it a "Golden Fleece" award in 1979, and succeeded in killing funding in 1982.

Funding reestablished in 1983 after Carl Sagan and others paid Sen. Proxmire a visit...

MOP observations: 1992-93

MOP surveys began in 1992 at Arecibo (305m, targeted, 800-1000 stars, led by NASA Ames) and Goldstone (34m, all-sky, led by NASA JPL).

Renamed the "High Resolution Microwave Survey".

HRMS signal processing

Targeted survey:

searched 1 – 3 GHz in 20 MHz chunks, each divided into 20 million channels, for 1 – 28 Hz bandwidth signals

All-sky survey:

searched 1 – 10 GHz in 320 MHz chunks, each divided into 16 million channels

Compare to early “Big Ear” searches of 50 channels at a time!

Funding killed by Sen. Richard Bryan (D-NV) in 1995.

Onward via private support

- First private funding of SETI: The Planetary Society (1980 – present, http://www.planetary.org/), which funnelled donations from Steven Spielberg and others into the Sentinel (131 kchan), META (8.4 Mchan), and BETA (250 Mchan + rapid retuning) projects on the 26m telescope in Harvard, MA.

- Alas: the 26m telescope was blown over by strong winds in 1999...

Project Phoenix

Resuscitation of HRMS targeted search under the leadership of Dr. Jill Tarter of the SETI Institute.

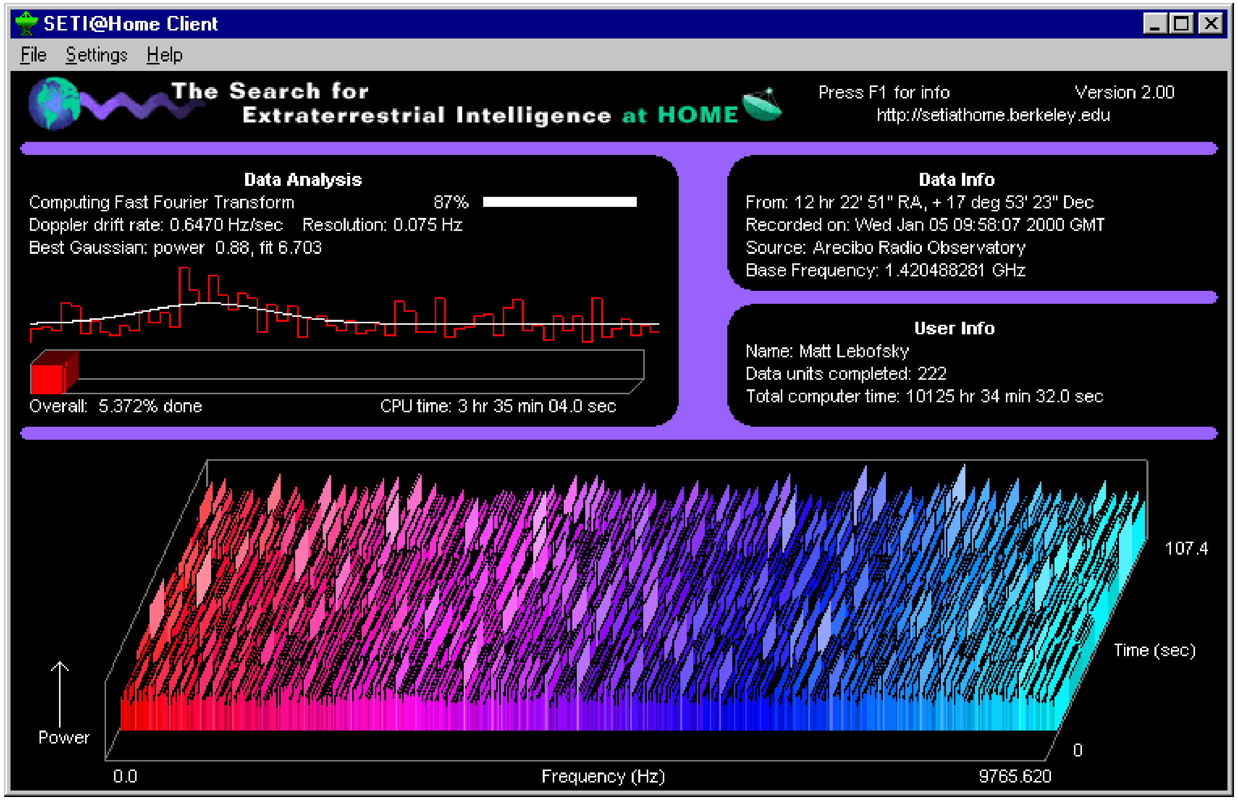
Used 64m Parkes radio telescope in Australia (1995 – 1996) + Green Bank 140 foot (1996 – 1998) + Arecibo (1998 – 2004) to survey 800 stars within 200 light-years of earth over 1 – 3 GHz range.

Targeted search requires (temporary) control of the telescope.

SERENDIP

Like the Sentinel/META/BETA efforts, SERENDIP targets an all-sky survey, but in this case by piggybacking on science observations with Arecibo.

SERENDIP IV data are analyzed by the SETI@home program.



Press F1 for info
Version 2.00
http://setiathome.berkeley.edu

Data Analysis
Computing Fast Fourier Transform 87%
Doppler drift rate: 0.6470 Hz/sec Resolution: 0.075 Hz
Best Gaussian: power 0.88, fit 6.703
Overall: 5.372% done
CPU time: 3 hr 35 min 04.0 sec

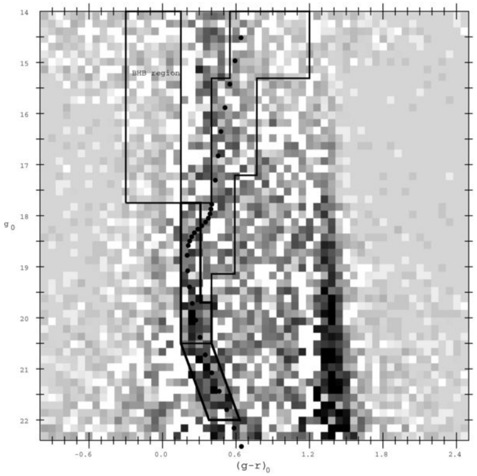
Data Info
From: 12 hr 22' 51" RA, + 17 deg 53' 23" Dec
Recorded on: Wed Jan 05 09:58:07 2000 GMT
Source: Arecibo Radio Observatory
Base Frequency: 1.420488281 GHz

User Info
Name: Matt Lebofsky
Data units completed: 222
Total computer time: 10125 hr 34 min 32.0 sec

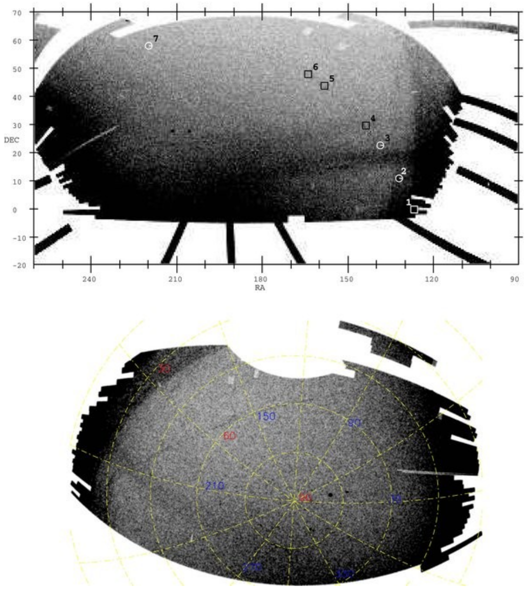
GALAXY MERGERS

Evidence of merging in the Milky Way: I

Tidal streams and halo moving groups are fossil evidence of prior episodes of galactic cannibalism (typical victim = globular cluster or dwarf galaxy).



stream in color-magnitude diagram

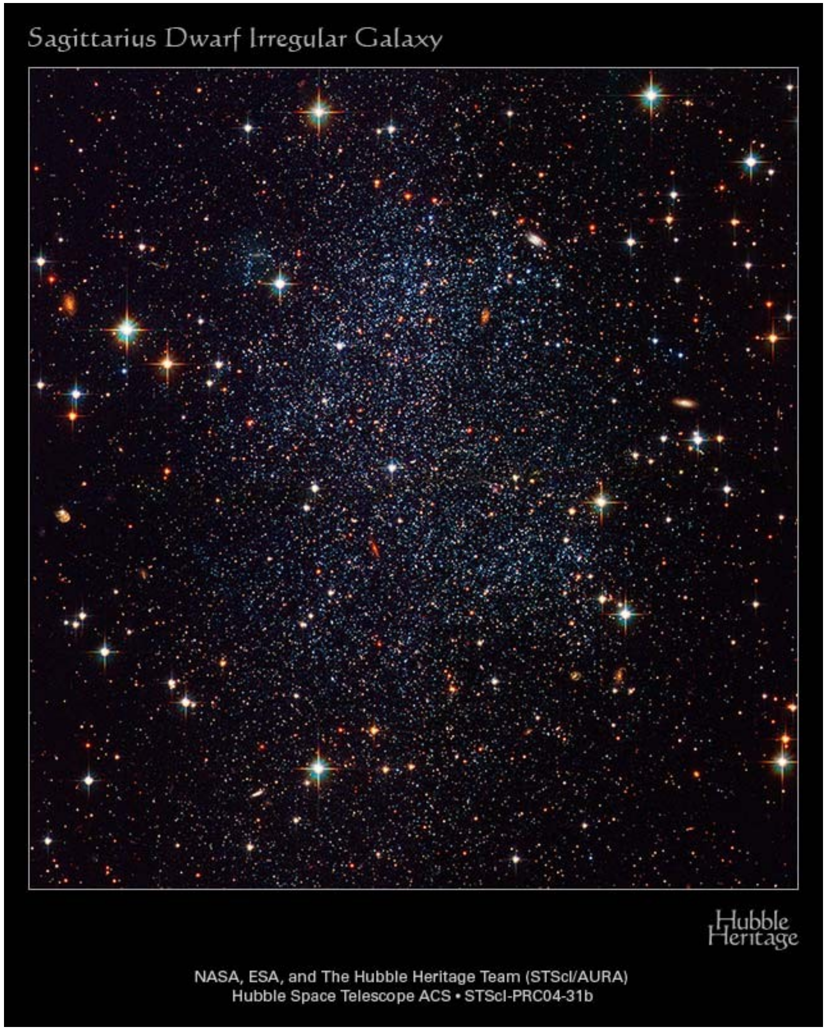


stream in RA + Dec, Galactic polar coordinates

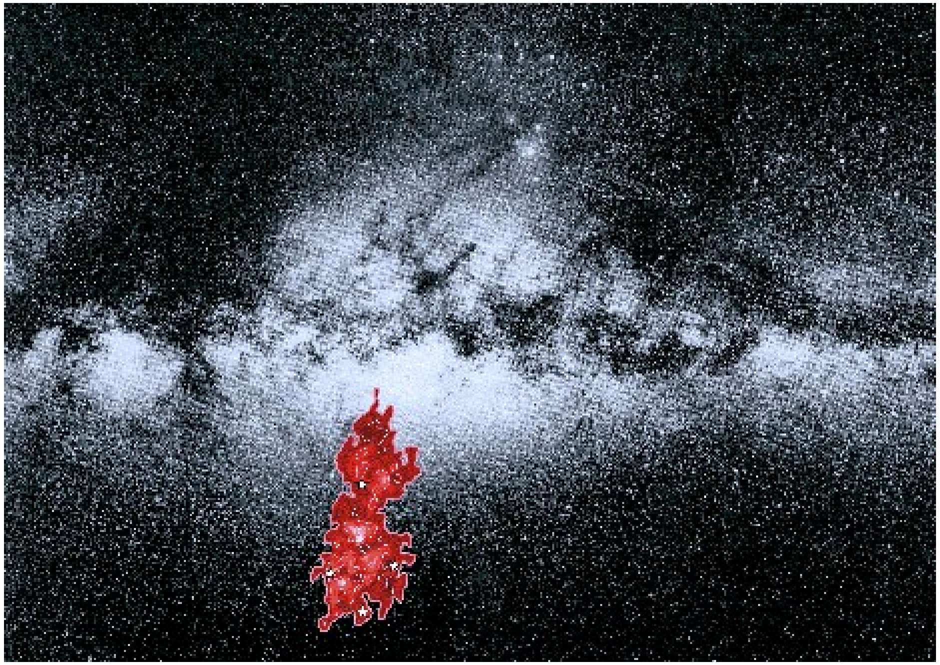
Grillmair & Dionatos (2006); Willett et al. (2009)

Evidence of merging in the Milky Way: II

The Sagittarius Dwarf is being ripped apart in front of us.

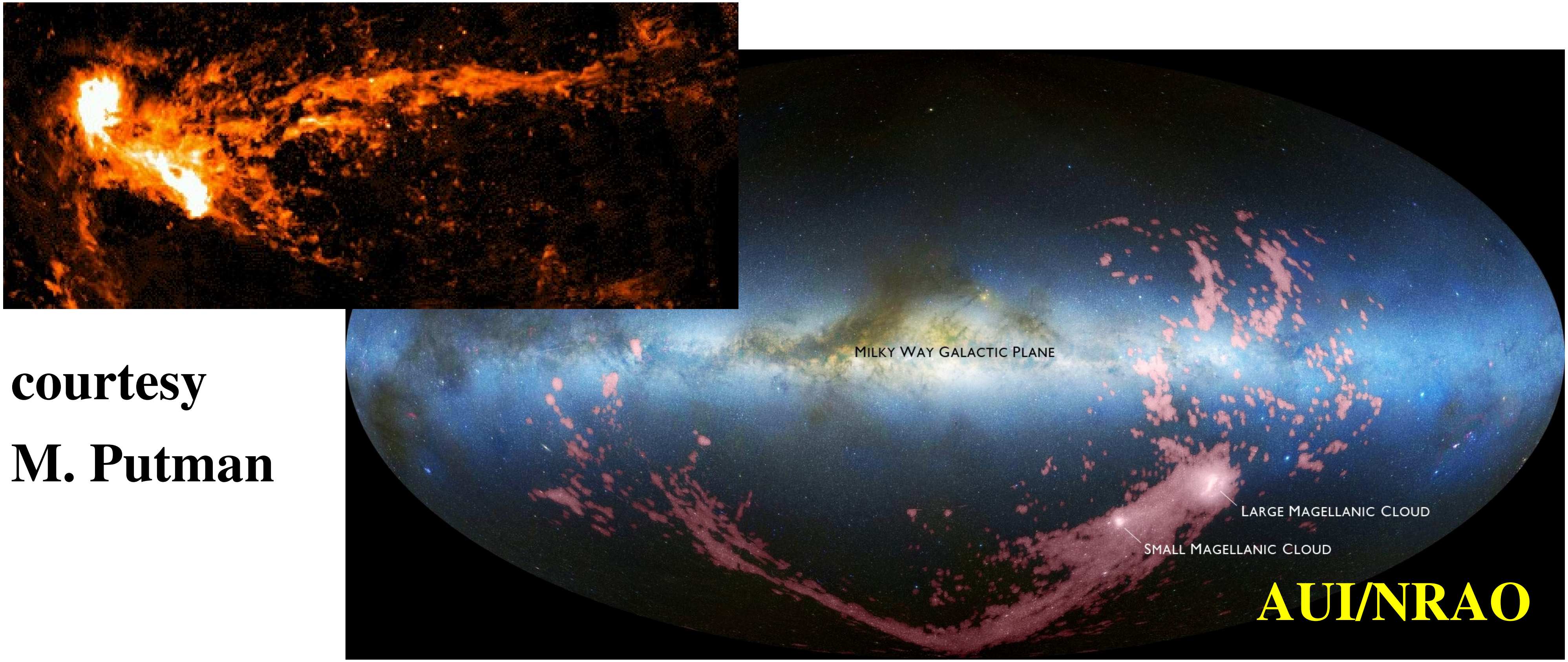

Sagittarius Dwarf Irregular Galaxy

NASA, ESA, and The Hubble Heritage Team (STScI/AURA)
Hubble Space Telescope ACS • STScI-PRC04-31b



Evidence of merging in the Milky Way: III

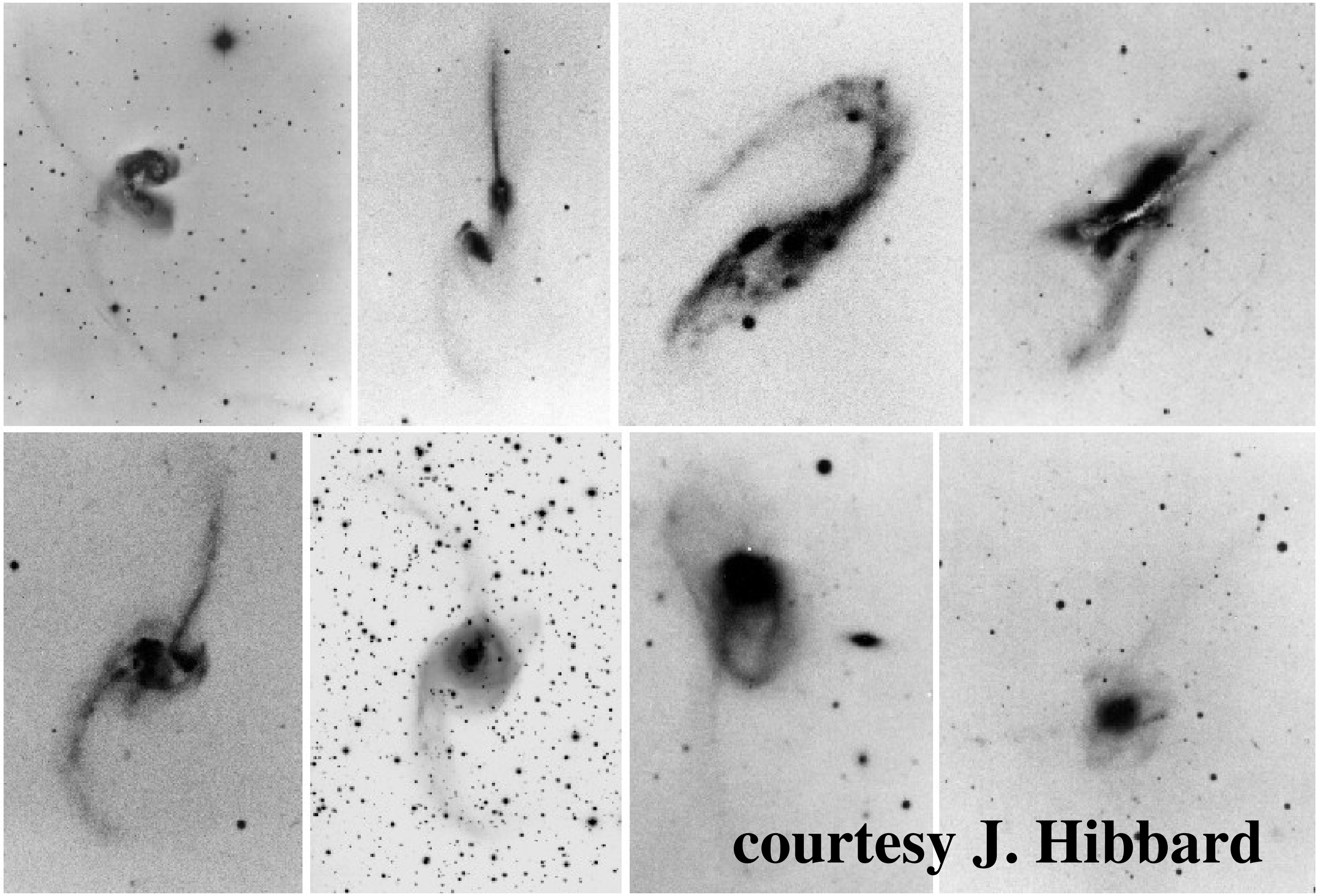
The Magellanic Stream (neutral hydrogen) is being ripped out of the Large and Small Magellanic Clouds, through a combination of tidal torques and stripping.



courtesy
M. Putman

The Toomre sequence

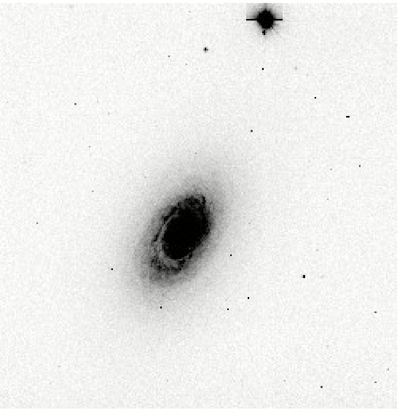
A. Toomre (1977, in “The Evolution of Galaxies and Stellar Populations”): proposed an evolutionary sequence for mergers.



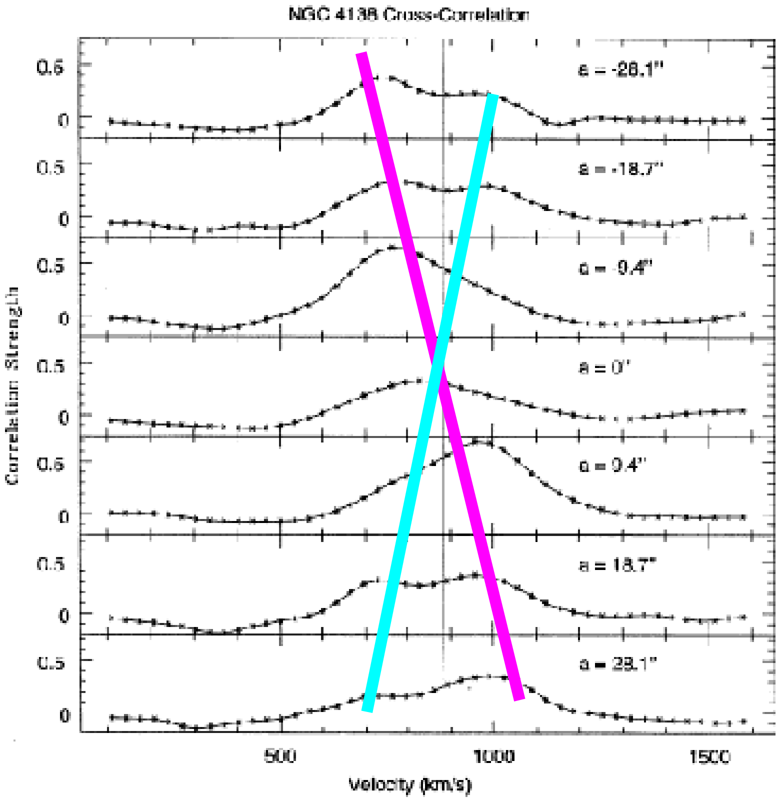
courtesy J. Hibbard

Fossil evidence in “normal” galaxies

NGC4138: normal Sa in *B*-band...

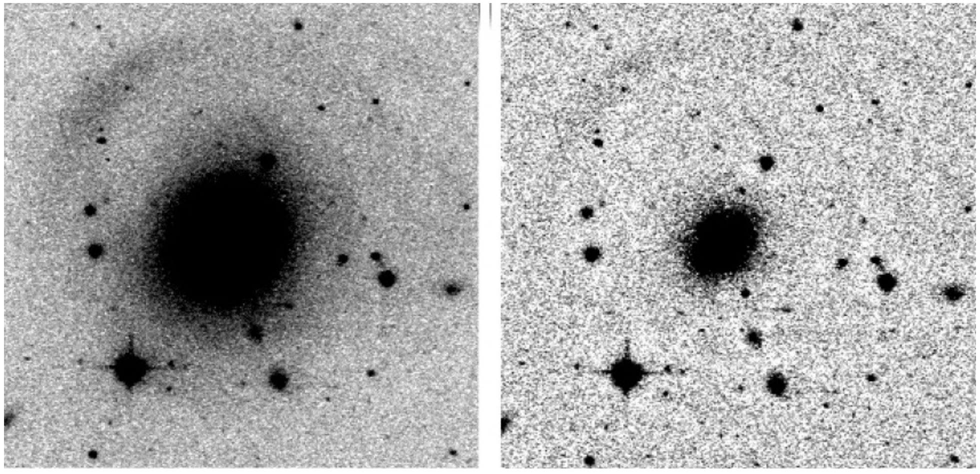


but contains two counterrotating stellar disks (Jore et al. 1996)!



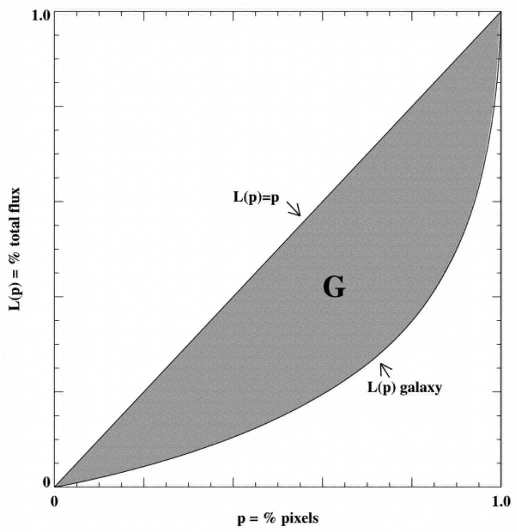
NGC3332: normal, isolated E...

but reveals multiple shell features after unsharp marking is applied (Colbert et al. 2001)!

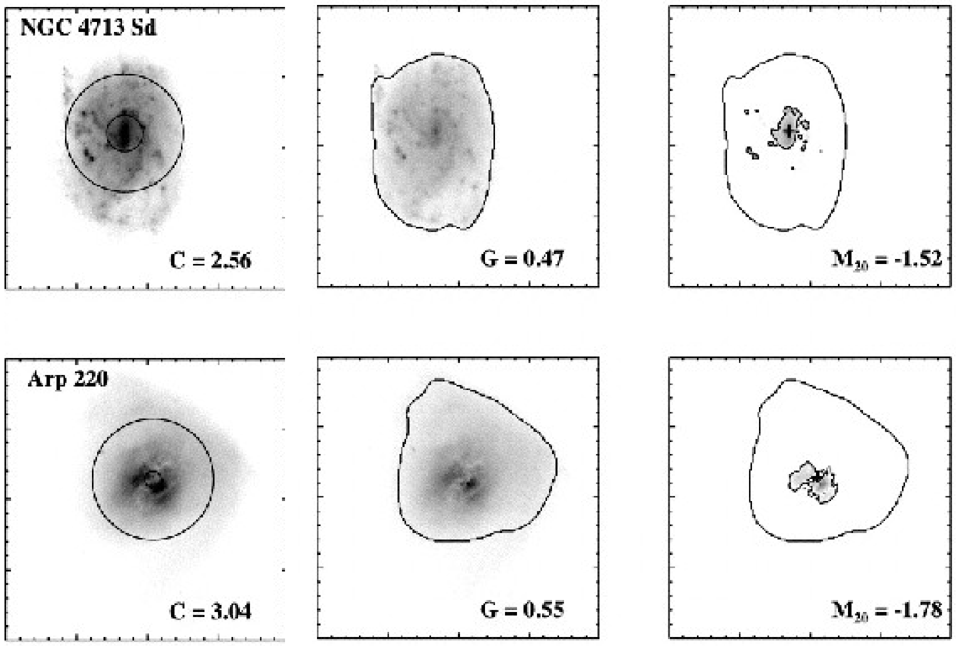


Identification of mergers: morphology

Gini coefficient = measure of “inequality” of a galaxy's pixels (area of shaded region/area under $y = x$)



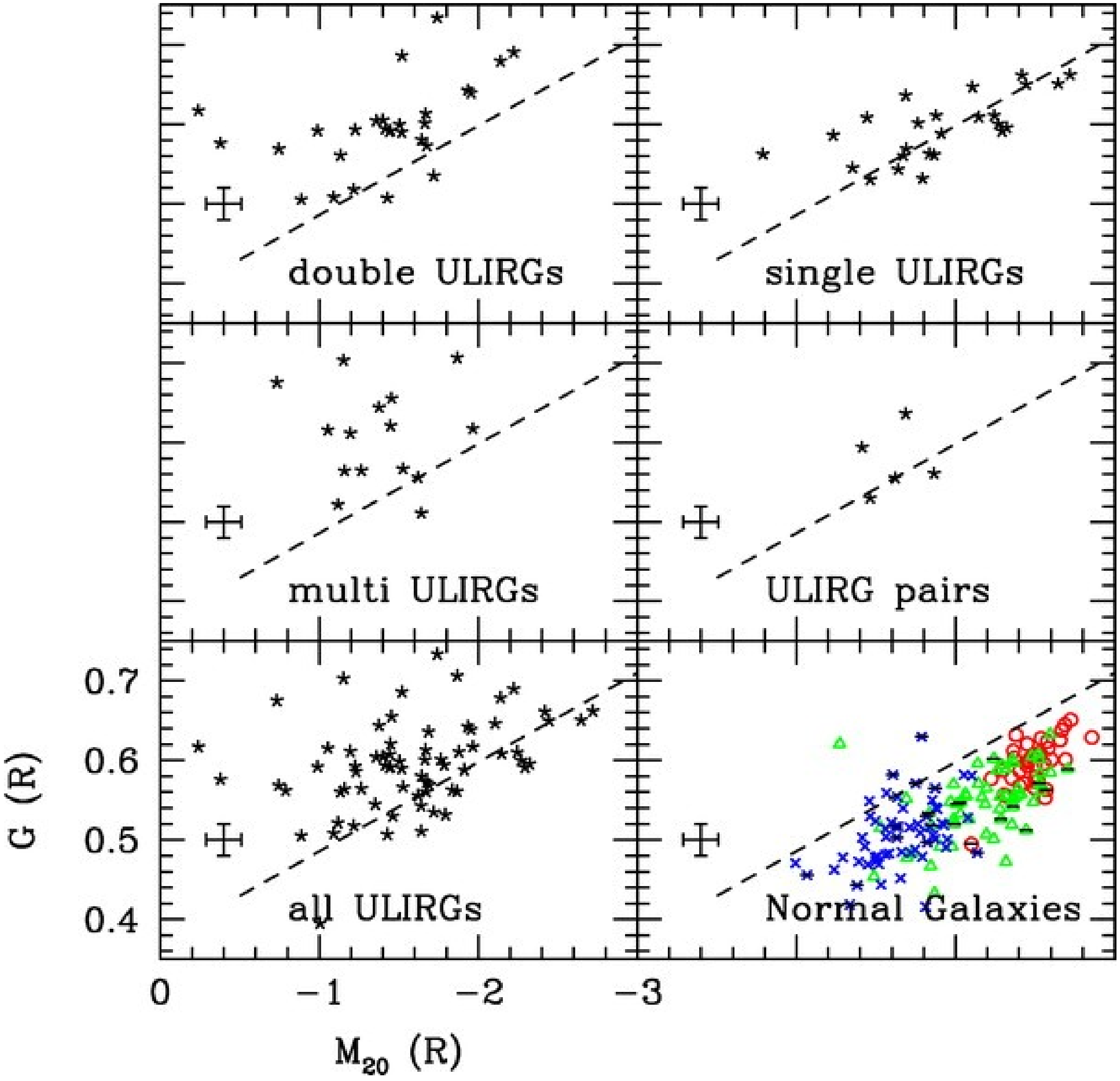
M_{20} = logarithm of (normalized) second-order moment of brightest 20% of a galaxy's pixels



Lotz et al. (2004)

Mergers in Gini vs. *M*$_{20}$ space

In 6500 Å images, mergers have higher Gini and *M*$_{20}$ than normal galaxies.



Lotz et al. (2004)

Key concepts in discussing mergers

I. major vs. minor

major: 1:1 to ~2:1

minor: ~3:1 to ~10:1

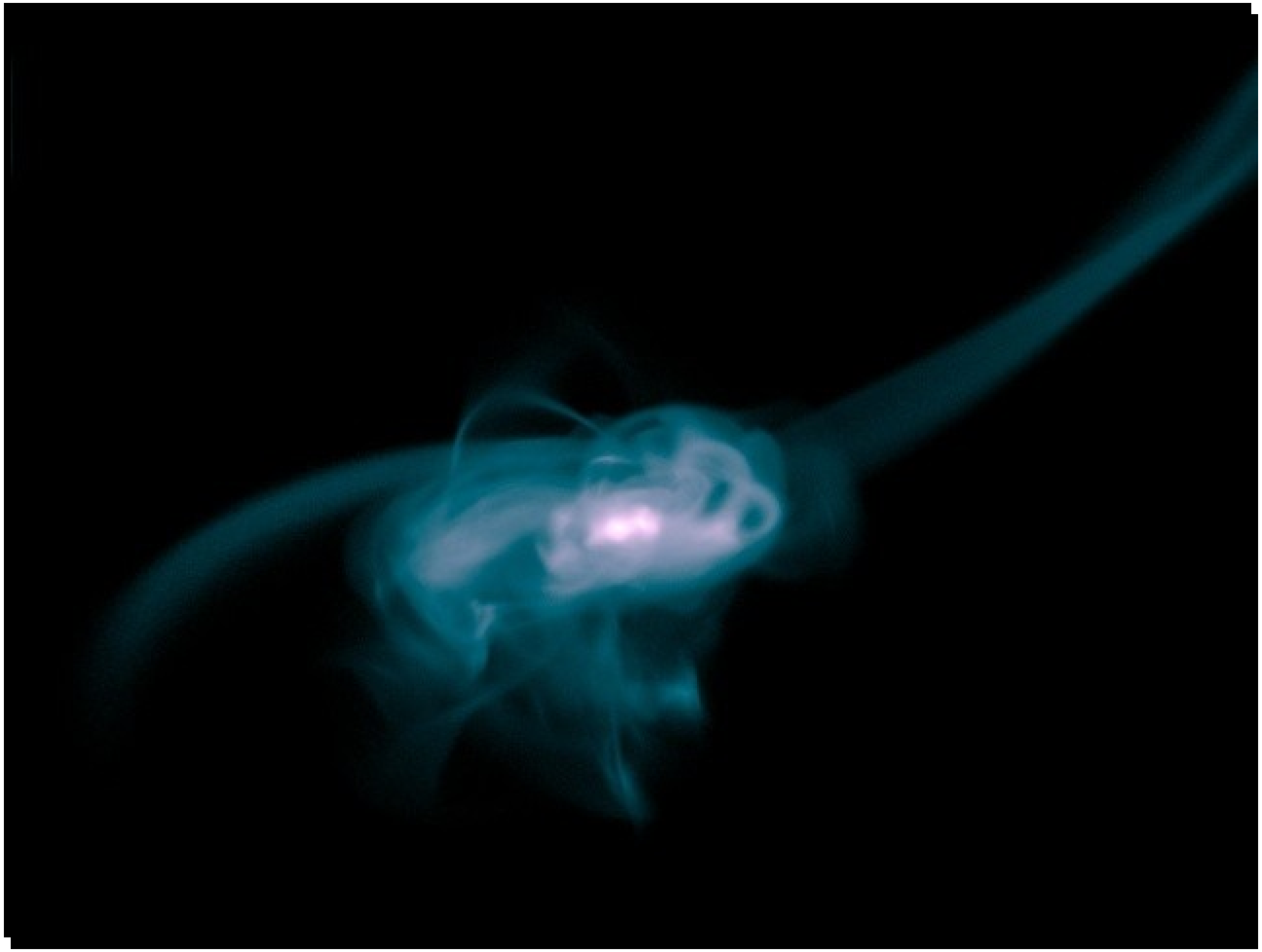
II. wet vs. dry

wet: both galaxies involved are gas-rich

dry: both galaxies involved are gas-poor

When one galaxy has gas and the other doesn't, a merger is "wet-dry", "damp", etc.

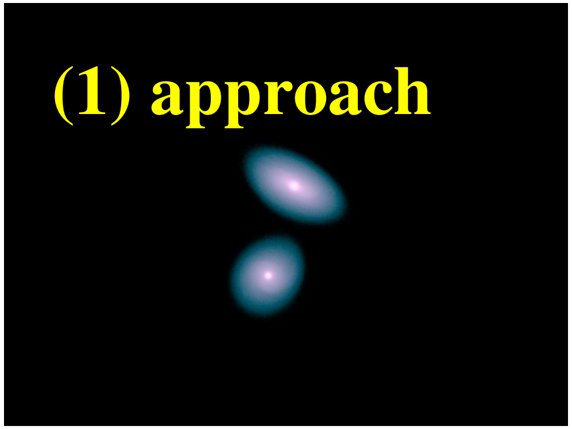
Simulation of a Milky Way/M31 merger

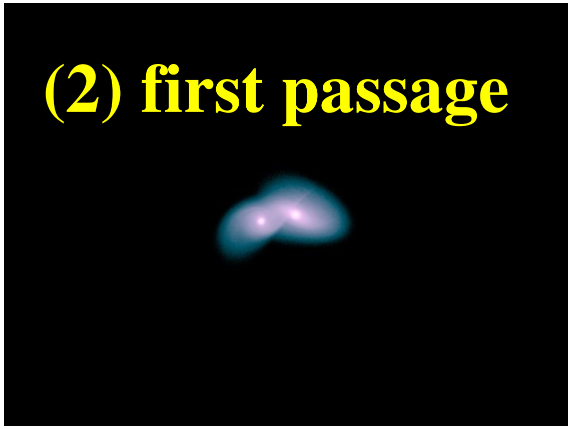


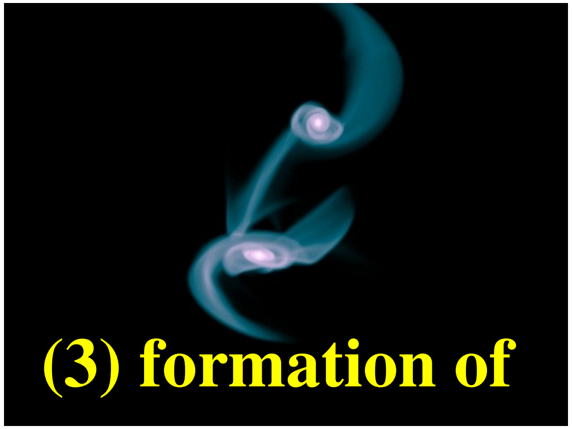
2 × (40M stellar + 10M dark matter particles); Δt = 90 Myr.

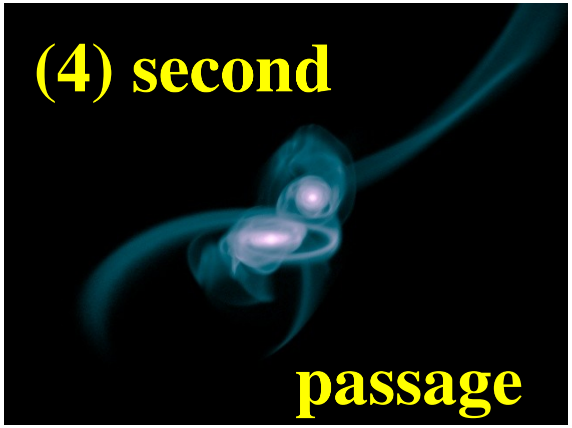
Taken from J. Dubinski, http://www.galaxydynamics.org/.

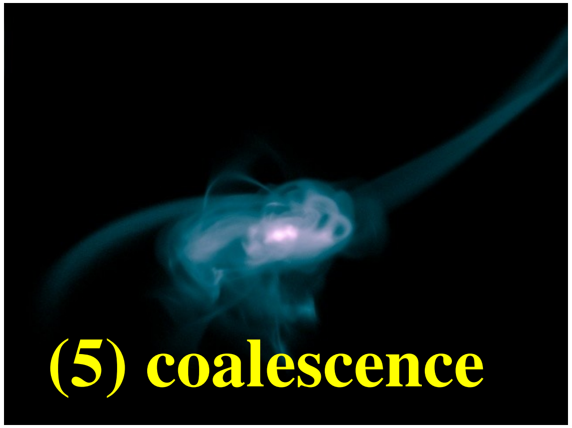
Key stages in a major merger


(1) approach


(2) first passage


(3) formation of tidal bridges/tails

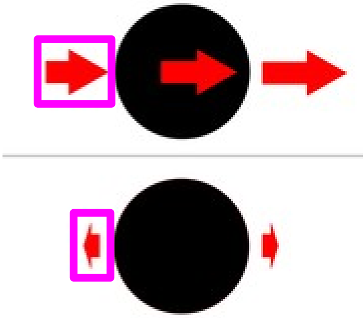

(4) second passage


(5) coalescence and violent relaxation

Dynamical friction of dark matter haloes drives the merger process.

images from J. Dubinski

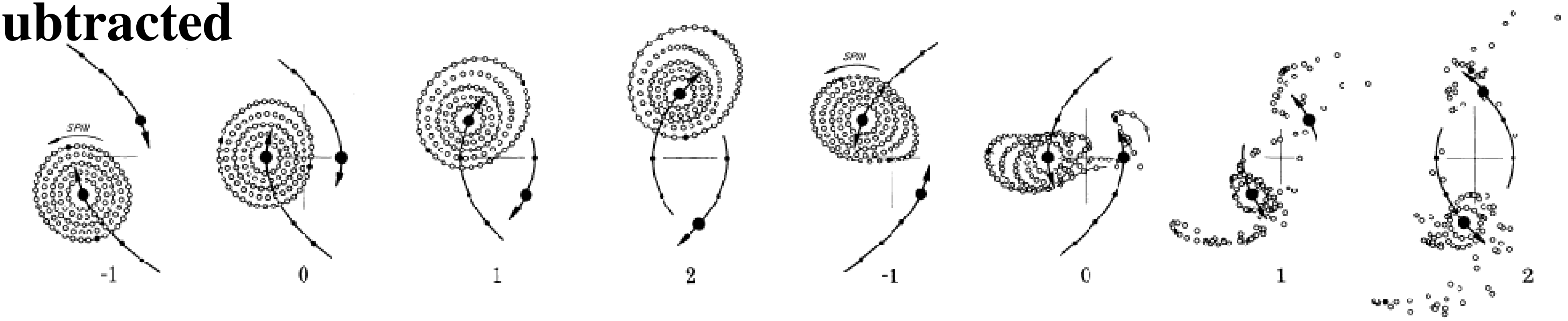
Tidal bridges and tails



with mean subtracted

Tidal features are formed because the gravitational field is stronger (weaker) on the near (far) side.

Encounter geometry affects the strength of the effect.

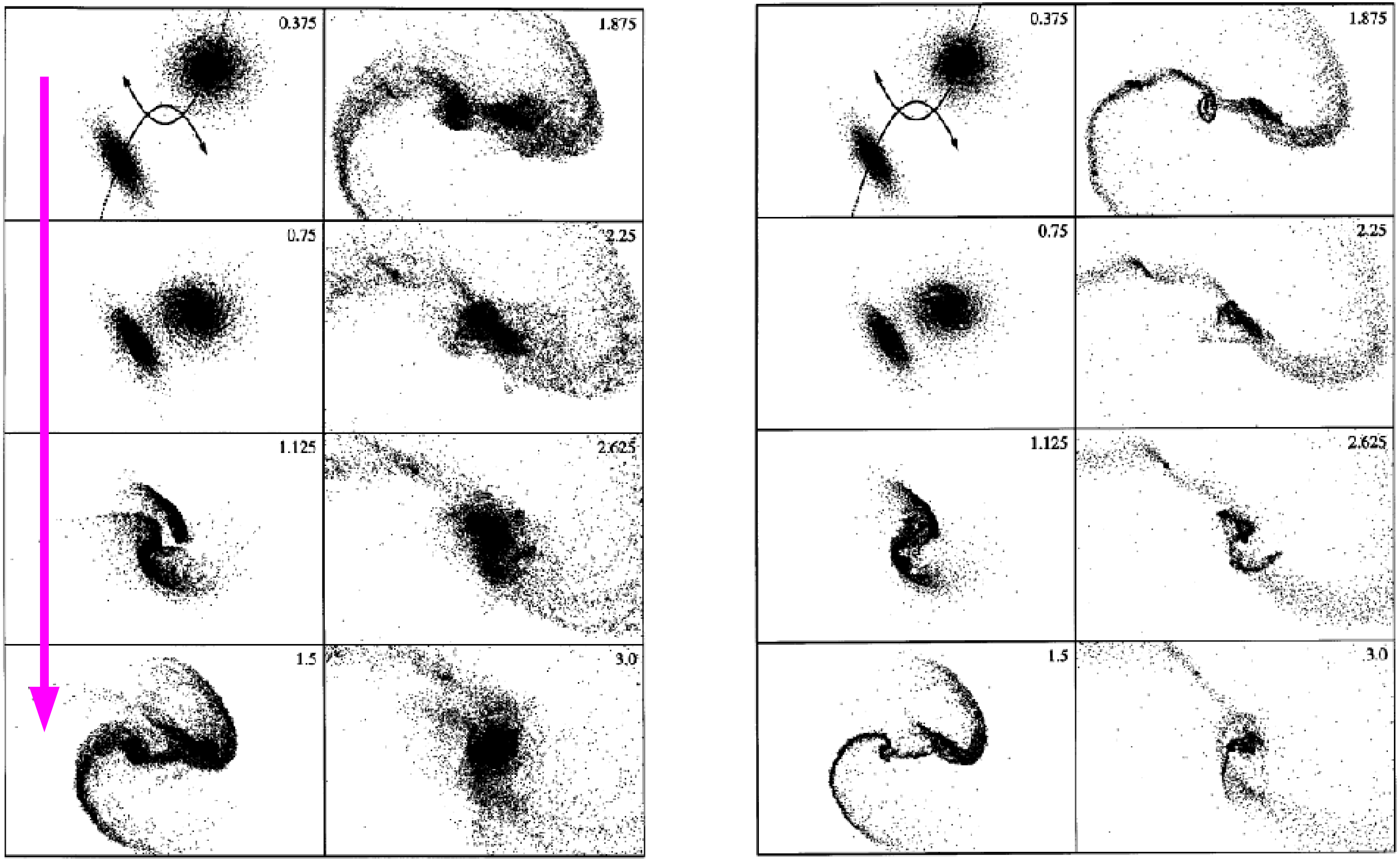


retrograde encounter **prograde encounter**

Toomre & Toomre (1972)

How does *gas* behave in a major merger?

Barnes & Hernquist (1996): simulated stars (left) and gas (right).



Why gas and stars behave differently

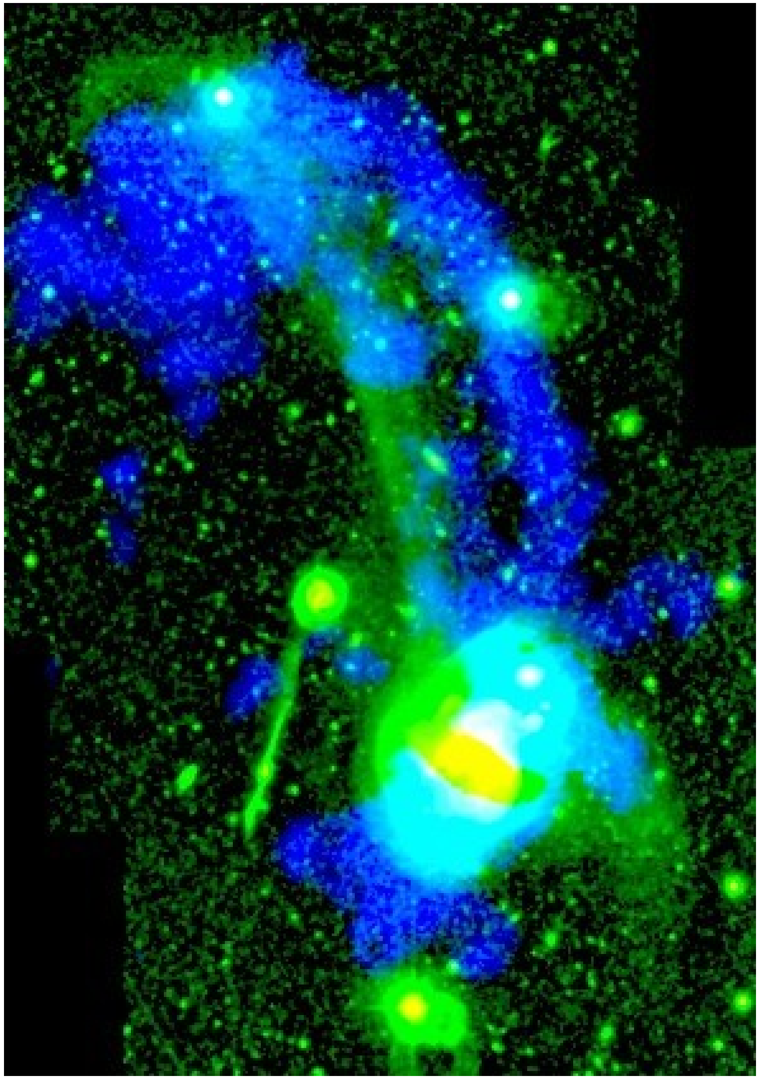
Stars and gas both feel gravitational attraction. However, while stars and dark matter particles can persist on intersecting (and self-intersecting) orbits, gas cannot.

⇒ gas makes the progenitors' disks more susceptible to bar instabilities (although massive bulges will stabilize the disks against bar formation)

⇒ gas loses ("dissipates") energy and angular momentum more quickly, so is concentrated in the center of each progenitor and (eventually) the remnant

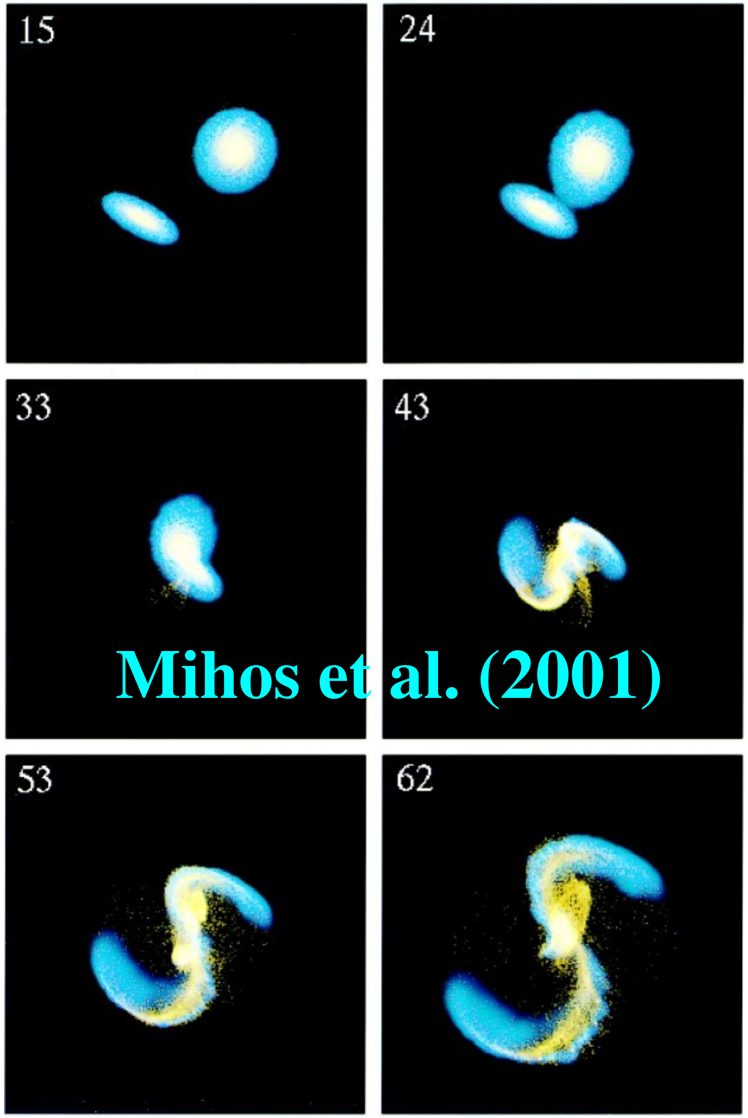
Offsets between gas and stellar tidal tails

Some mergers show offsets between gas and stellar tidal tails – why?



Arp 299: HI vs. stars (J. Hibbard)

Offset tails are seen in simulations if gas starts at larger radii than stars!



Mihos et al. (2001)

The fate of gas in (wet) major mergers

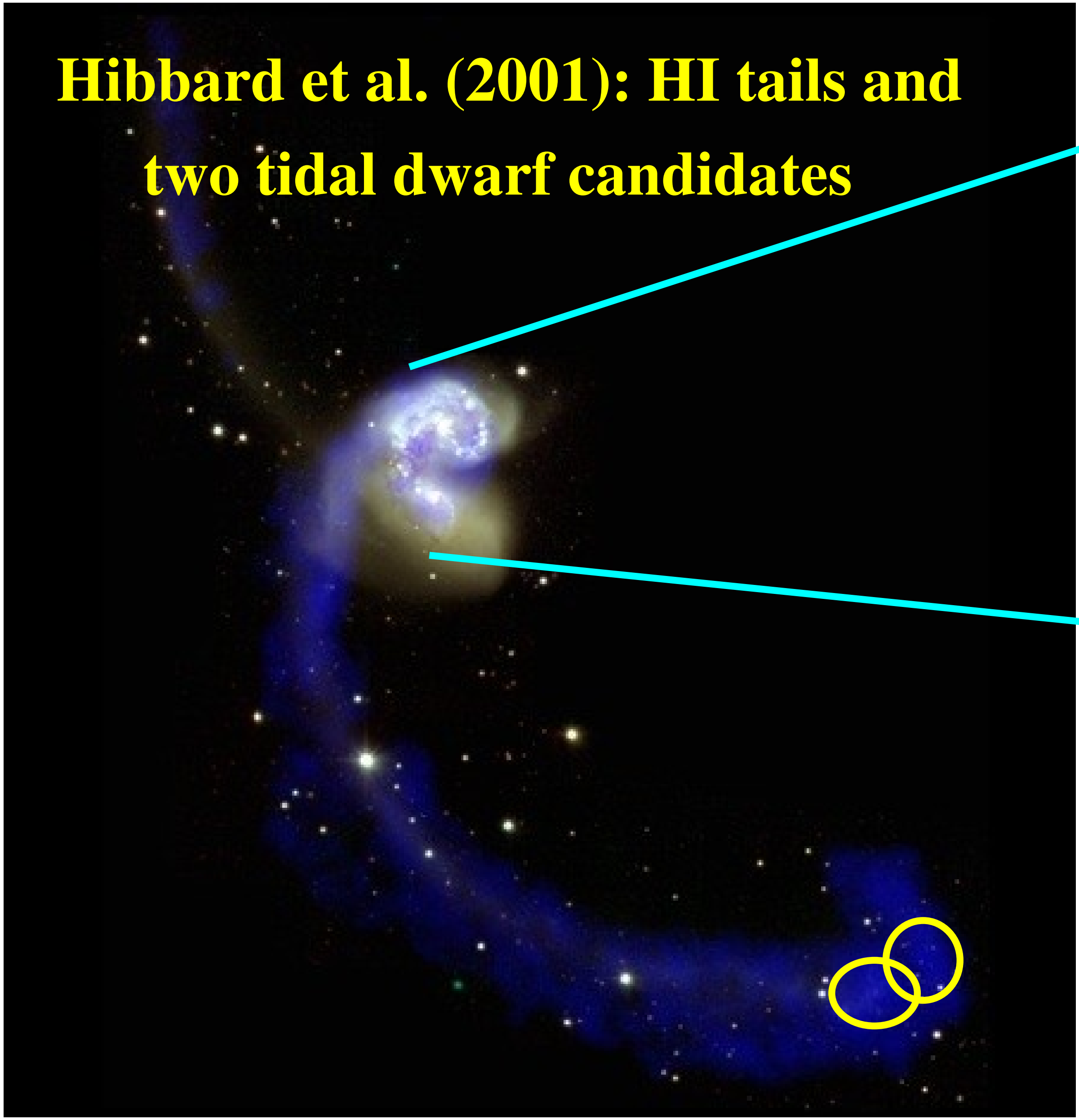
Simulation results:

+ 50–90% of the gas in the progenitors rapidly coalesces into a massive central condensation in the remnant

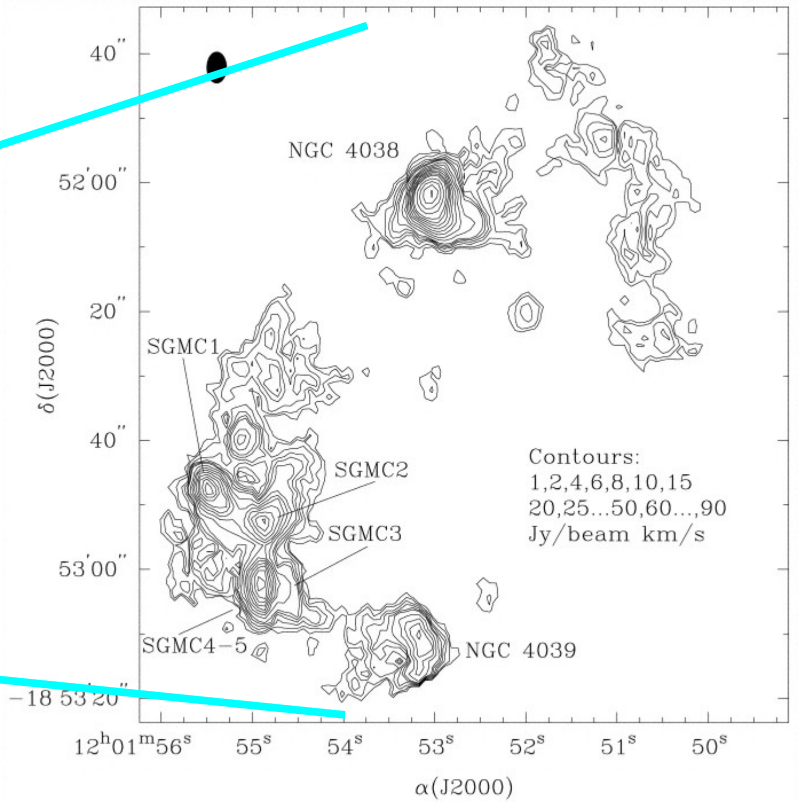
+ most of the rest falls back into the center on longer timescales, from extended tidal tail/bridge features

+ a modest amount can end up in gravitationally bound tidal dwarf galaxies

An observational example: the “Antennae”



Hibbard et al. (2001): HI tails and two tidal dwarf candidates



Wilson et al. (2000): CO(1–0) tracing dense gas in progenitors and “overlap region”

Forming ellipticals: the merger hypothesis

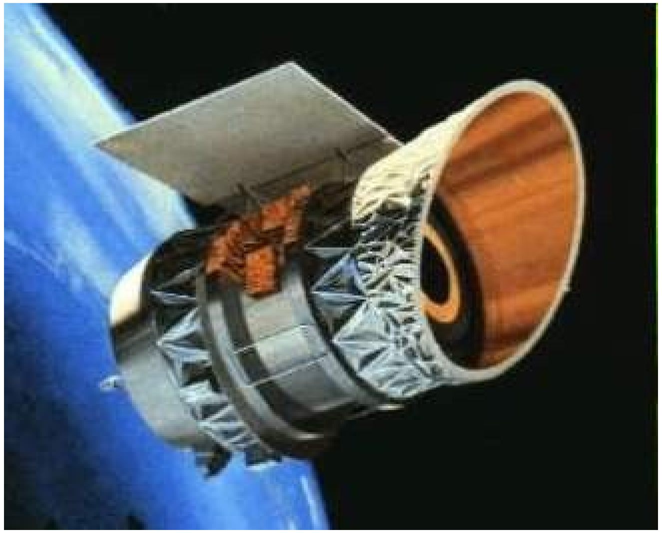
Toomre (1977) proposed that the end state of a merger between two gas-rich spirals is an elliptical. This was a provocative suggestion: ellipticals have higher phase space density and greater orbital anisotropy than spirals.

+ violent relaxation makes stellar orbits more anisotropic (although it does not change phase space density)

+ large central gas mass can form new stars, leading to a higher phase space density than in the progenitors

Testing the merger hypothesis: gas-rich systems

The best way to identify gas-rich mergers is to look for the central burst of star formation that the gas inflow triggers!



Infrared Astronomical Satellite (IRAS)

in 1983 mapped 96% of the sky

at 12, 25, 60, and 100 μm,

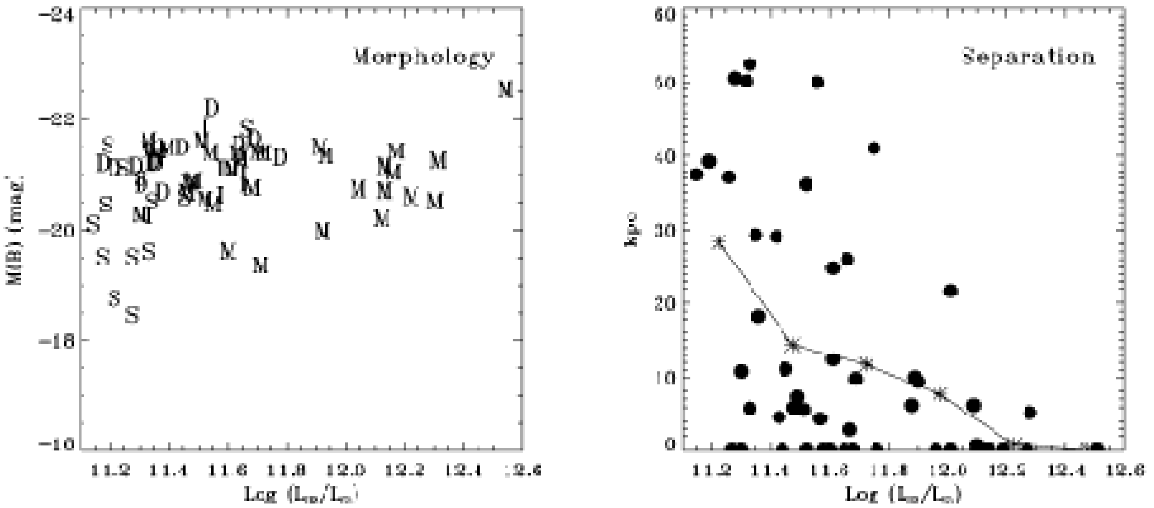
and recognized a new category

of infrared-luminous galaxies.

L_{IR}(8–1000 μm) > 10^{11} $L_{\odot}$: luminous infrared galaxy (LIRG)

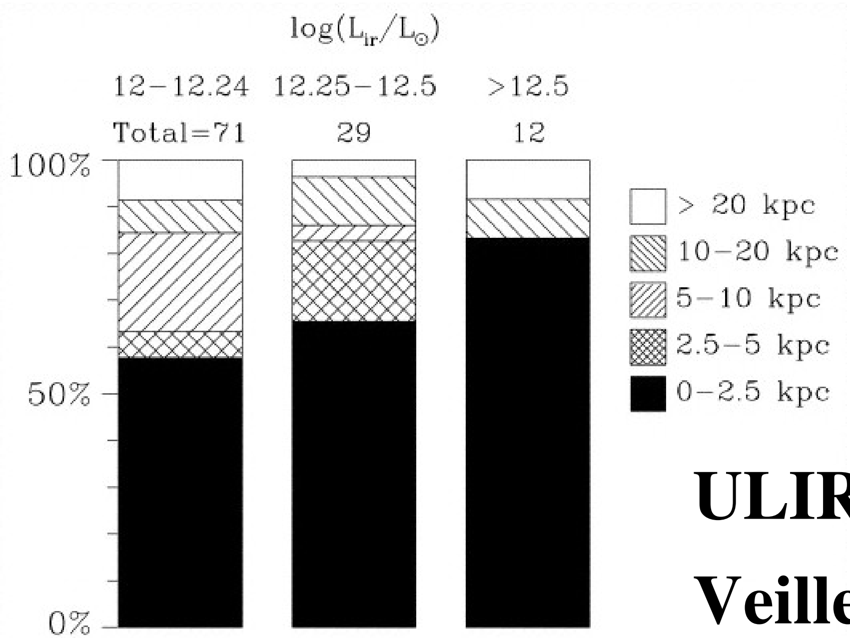
L_{IR}(8–1000 μm) > 10^{12} $L_{\odot}$: ultraluminous infrared galaxy (ULIRG)

LIRG and ULIRG morphologies



LIRG sample:

Sanders & Ishida (2004)



As L_{IR} increases, we see

+ a higher fraction of mergers

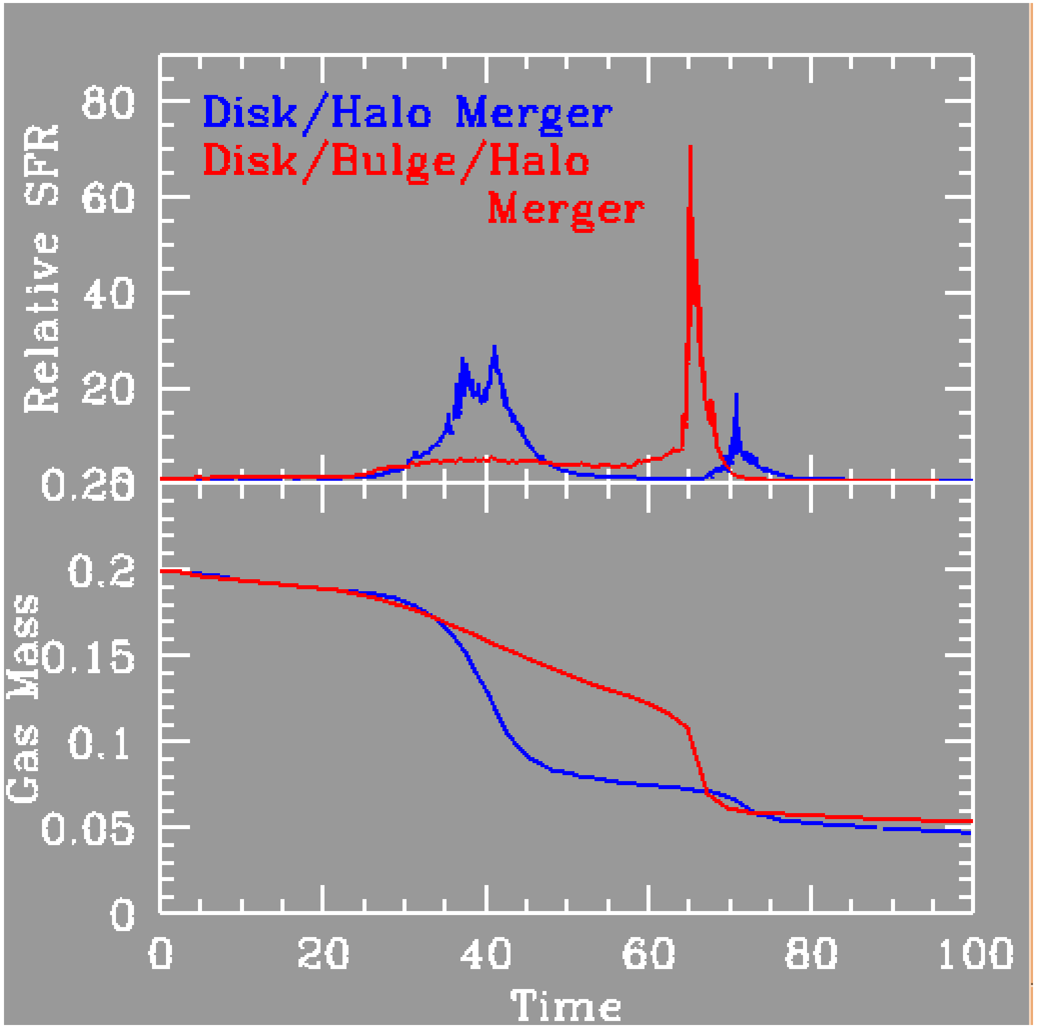
(100% for ULIRGs), and

+ smaller separations.

ULIRG sample:

Veilleux et al. (2002)

Star formation during a major merger

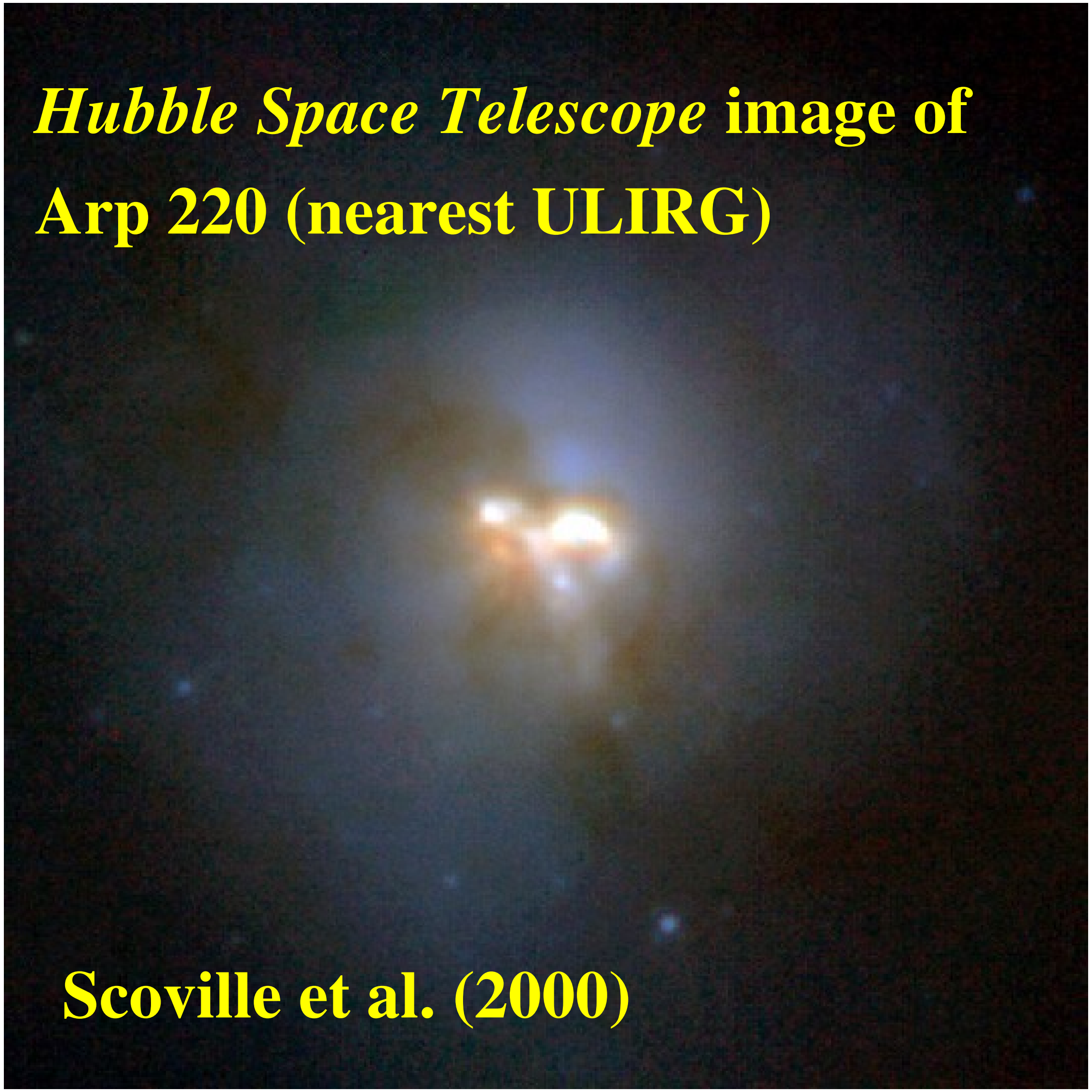


courtesy J. C. Mihos

Sharp peaks in star formation rate (therefore, L_{IR}) occur at first passage if progenitors do not have bulges, but are delayed until final coalescence if progenitors do have bulges.

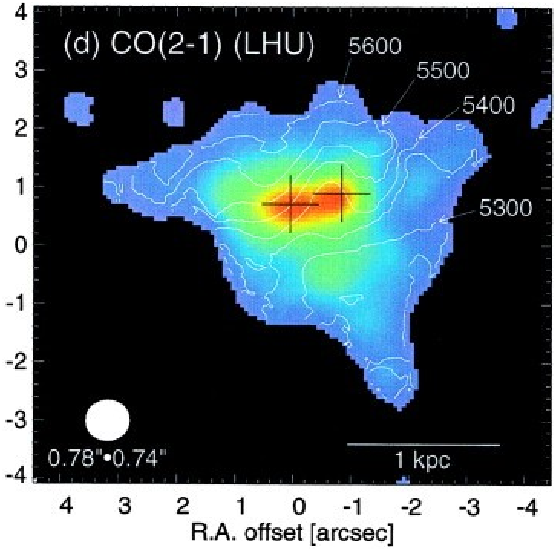
ULIRGs are more likely to be late-stage mergers.

Large central gas masses



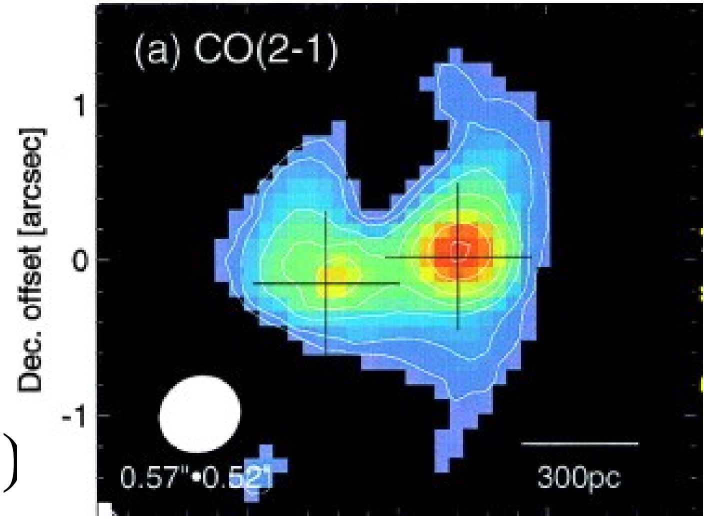
***Hubble Space Telescope* image of Arp 220 (nearest ULIRG)**

Scoville et al. (2000)



CO(2–1) mapping reveals

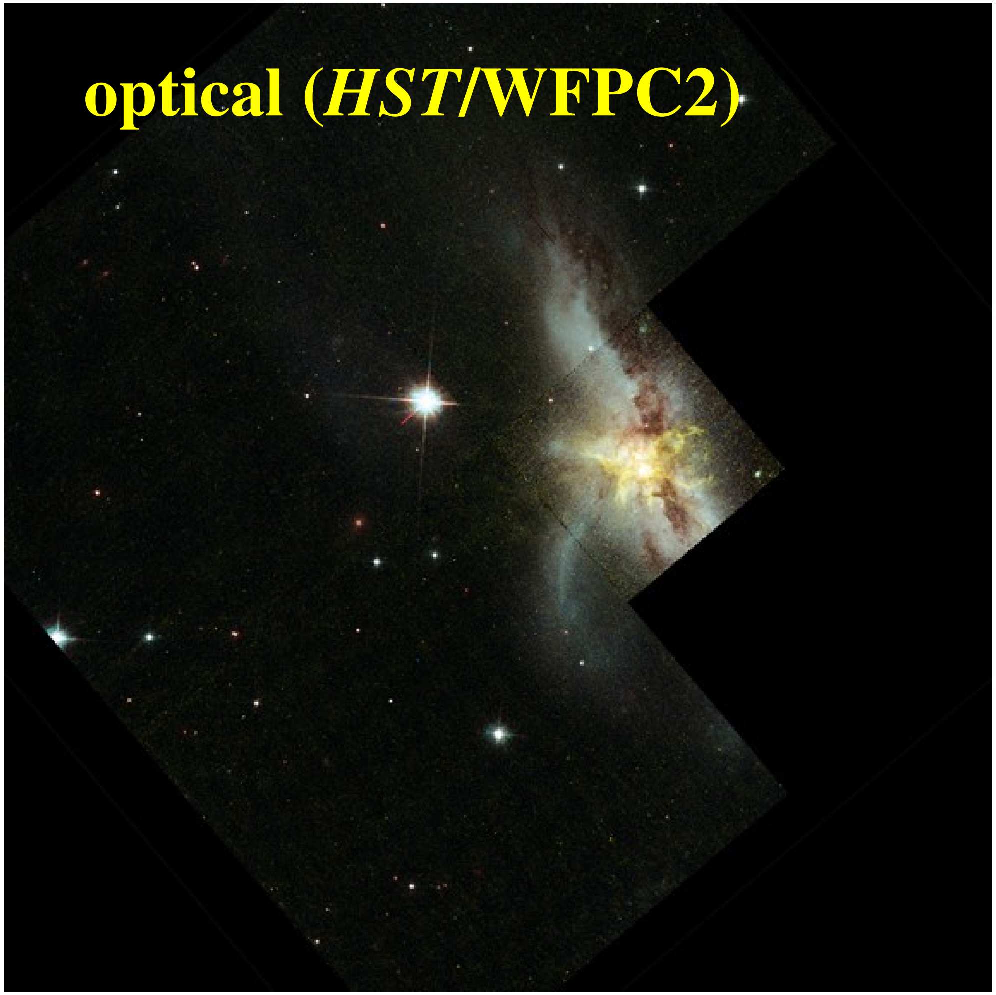
$M_{\mathrm{gas}} \sim 9 \times 10^9\, M_\odot$.

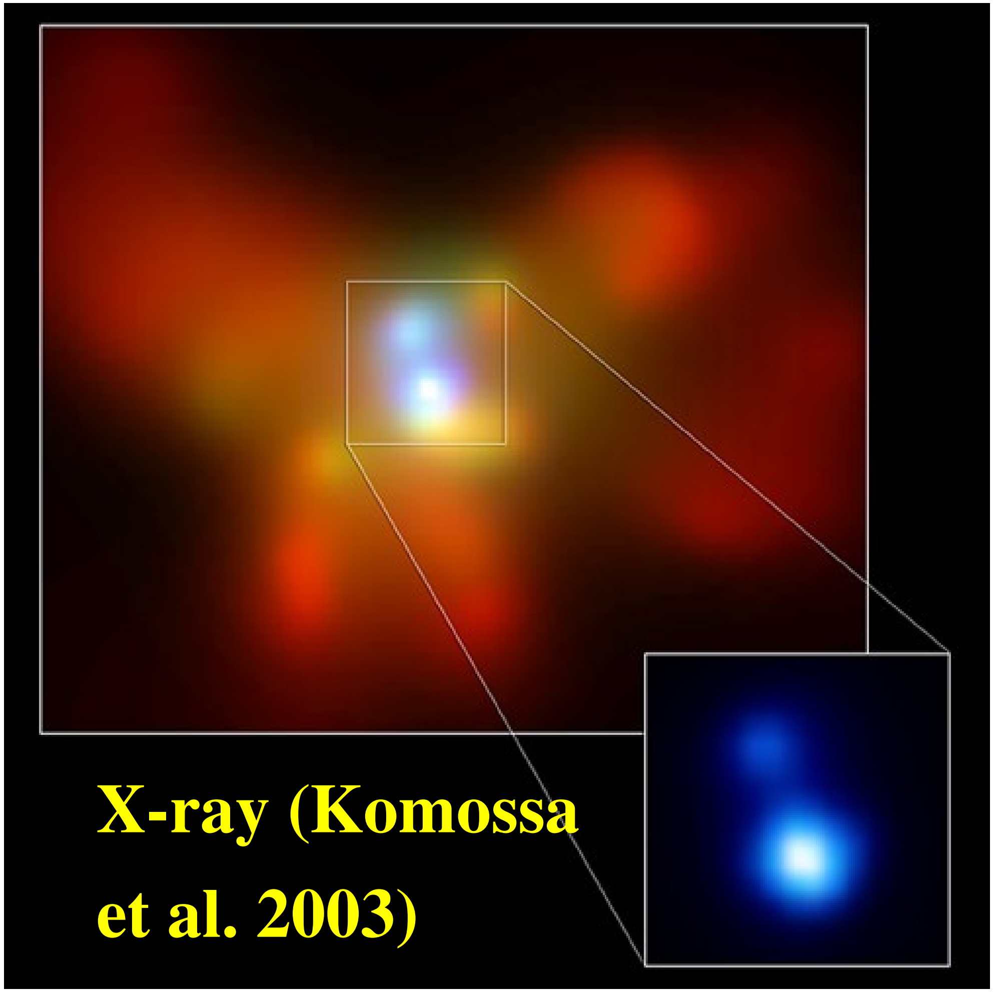


Sakamoto et al. (1999)

Double AGN buried in NGC6240

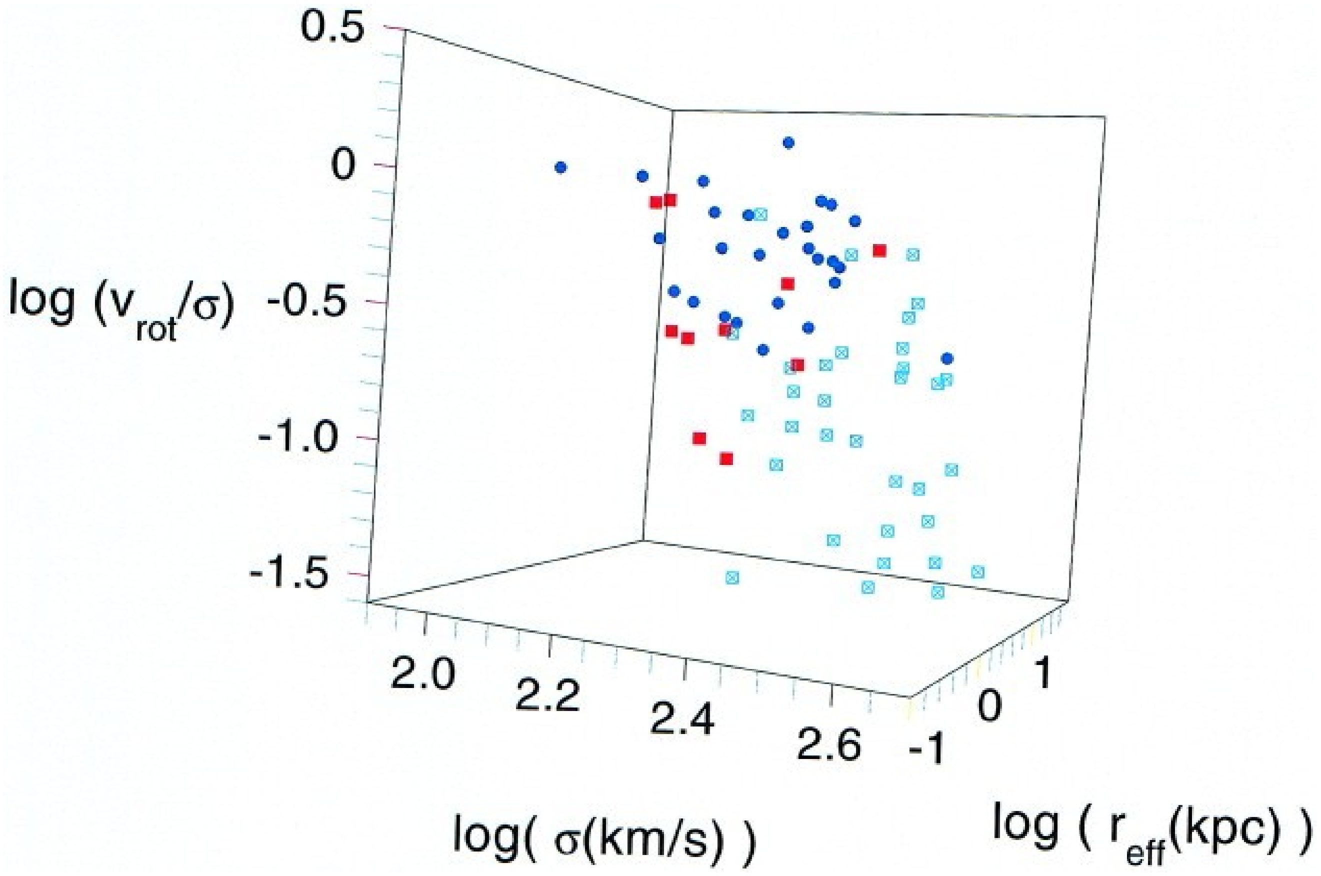
NGC6240: a messy merger at the LIRG/ULIRG boundary...





...whose $L_{\rm IR}$ is mostly powered by two highly obscured AGN.

Merger hypothesis: rotational support



ULIRGs have high *v*/σ (i.e., rotational support) more similar to intermediate-mass, disky ellipticals than to giant, boxy ellipticals (Genzel et al. 2001).

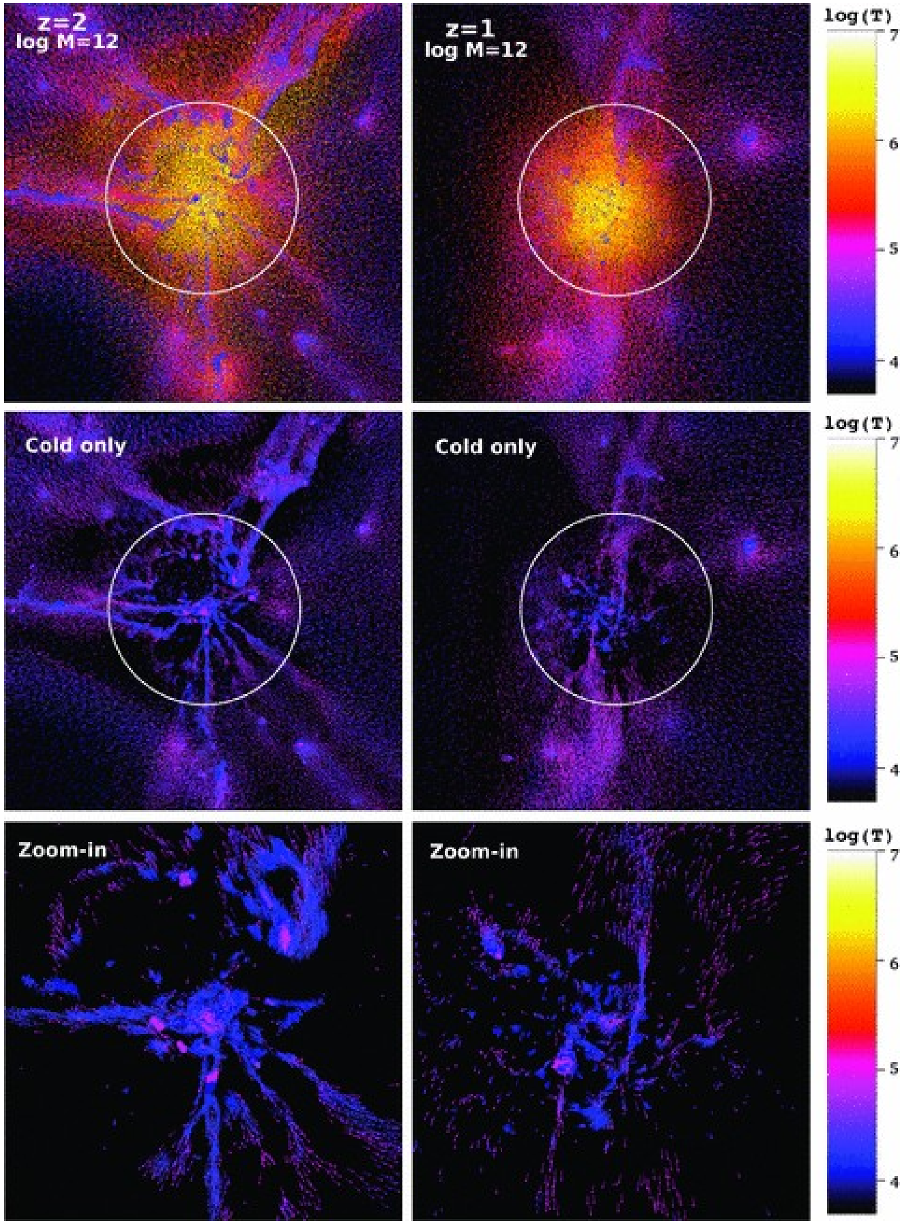
The origin of BCG/cD ellipticals?

Giant, boxy ellipticals that lie at the centers of clusters do not appear to be formed in wet, ULIRG-like mergers: they have higher σ and lower v/σ (greater anisotropy) than ULIRGs.


Gravitational Lens in Galaxy Cluster Abell 1689 HUBBLESITE.org

A likely formation scenario: multiple dry mergers, with tidal capture of other galaxies' globular clusters explaining their high specific frequency (S_N).

Minor mergers



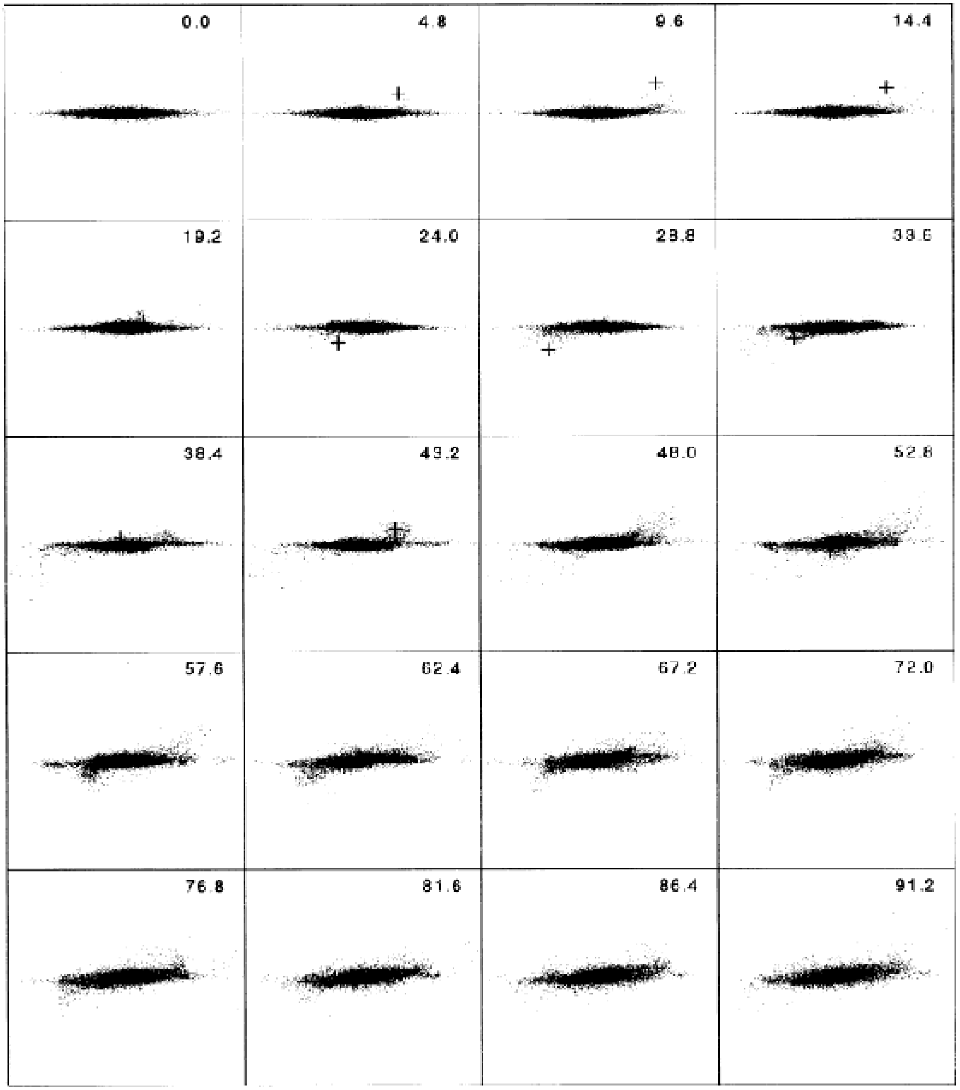
Compared to major mergers, minor mergers are

- **+ more frequent**
- **+ less destructive**
- **+ more difficult to identify or distinguish from "cold accretion" of intergalactic gas.**

Kereš et al. (2009)

Effects of minor mergers on disks

Minor mergers are likely to dynamically heat a disk (increasing its vertical scale height), and if one partner is gas-rich, to trigger a LIRG-scale burst of star formation.



Hernquist & Mihos (1995): disk thickened by a 10:1 minor merger