Extragalactic Astrophysics

Instructor of Record: Prof. Dr. Marcus Brüggen

When? Mo 14.00-15.30, Tue 16.00-16.45

Where? SemRm1

Assessment: grade is based on (i) a single one-hour written exam held at the end of the course (100%) and (ii) homework (pass/fail per sheet) (20%). Full marks can be achieved with the exam. The homework can yield up to 20% bonus points.

Summary: This course gives an elementary introduction to astrophysics on the scales of galaxies and beyond. Much of the material will be presented on a blackboard which means that attendance is strongly recommended. The lecture will be held in English. There will be an emphasis on solving problems and the course will conclude with a written exam.

Books: P. Schneider: Extragalactic Astronomy and Cosmology: An Introduction
S. Rosswog, M. Brüggen: Introduction to High-Energy Astrophysics

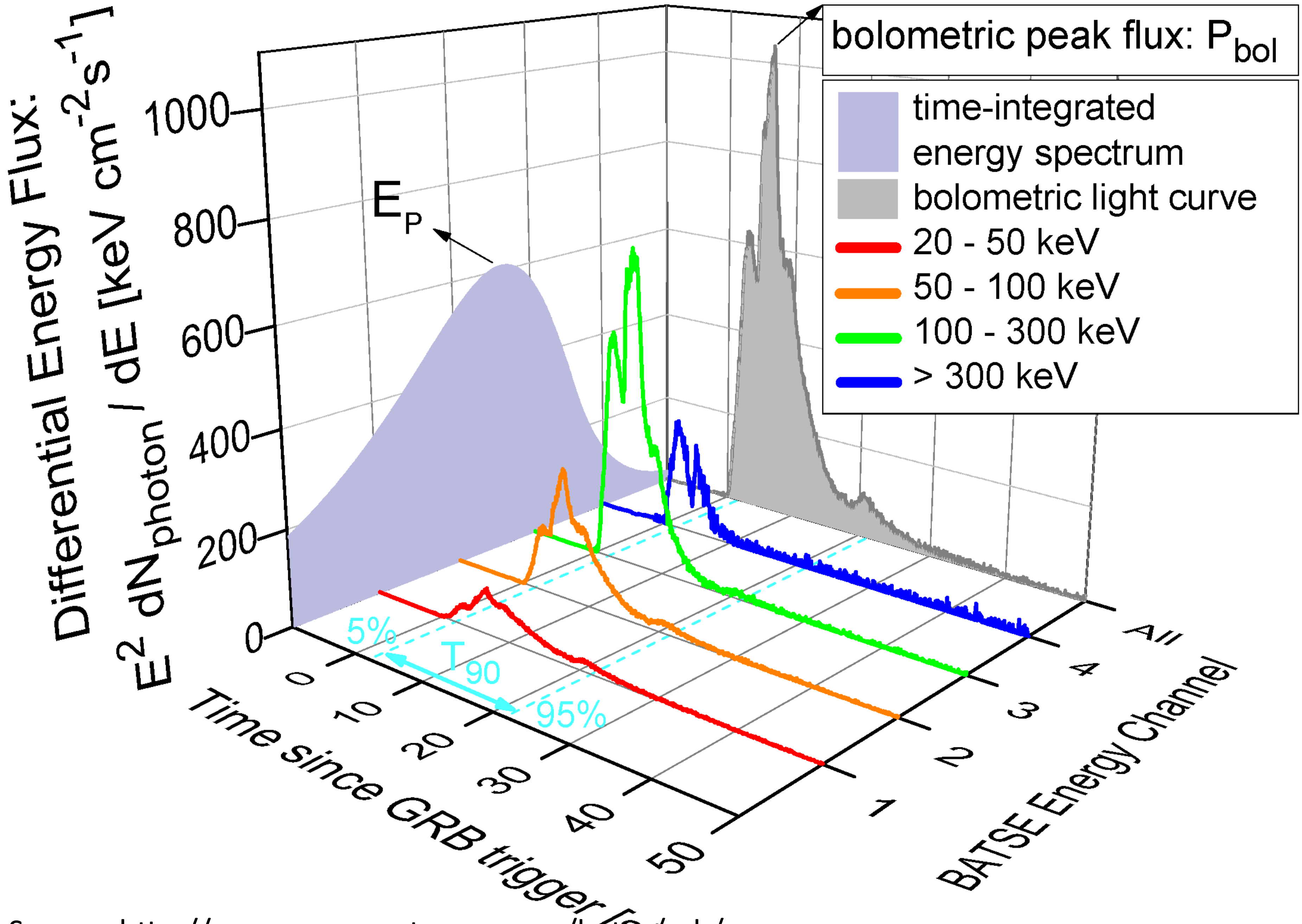
Lecture Notes (excerpt):

Will be posted here.

Problem sheets

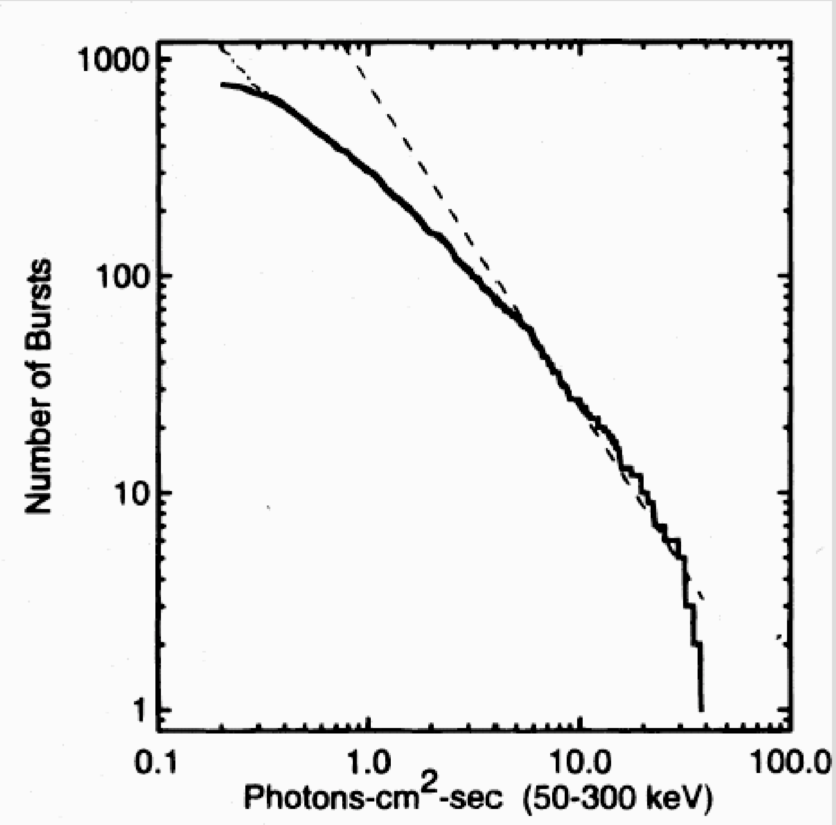
Problem Sheet 1 due 21.10.2014

Links: Ned Wright's Cosmology Tutorial



Source: http://gammaray.nsstc.nasa.gov/batse/grb/

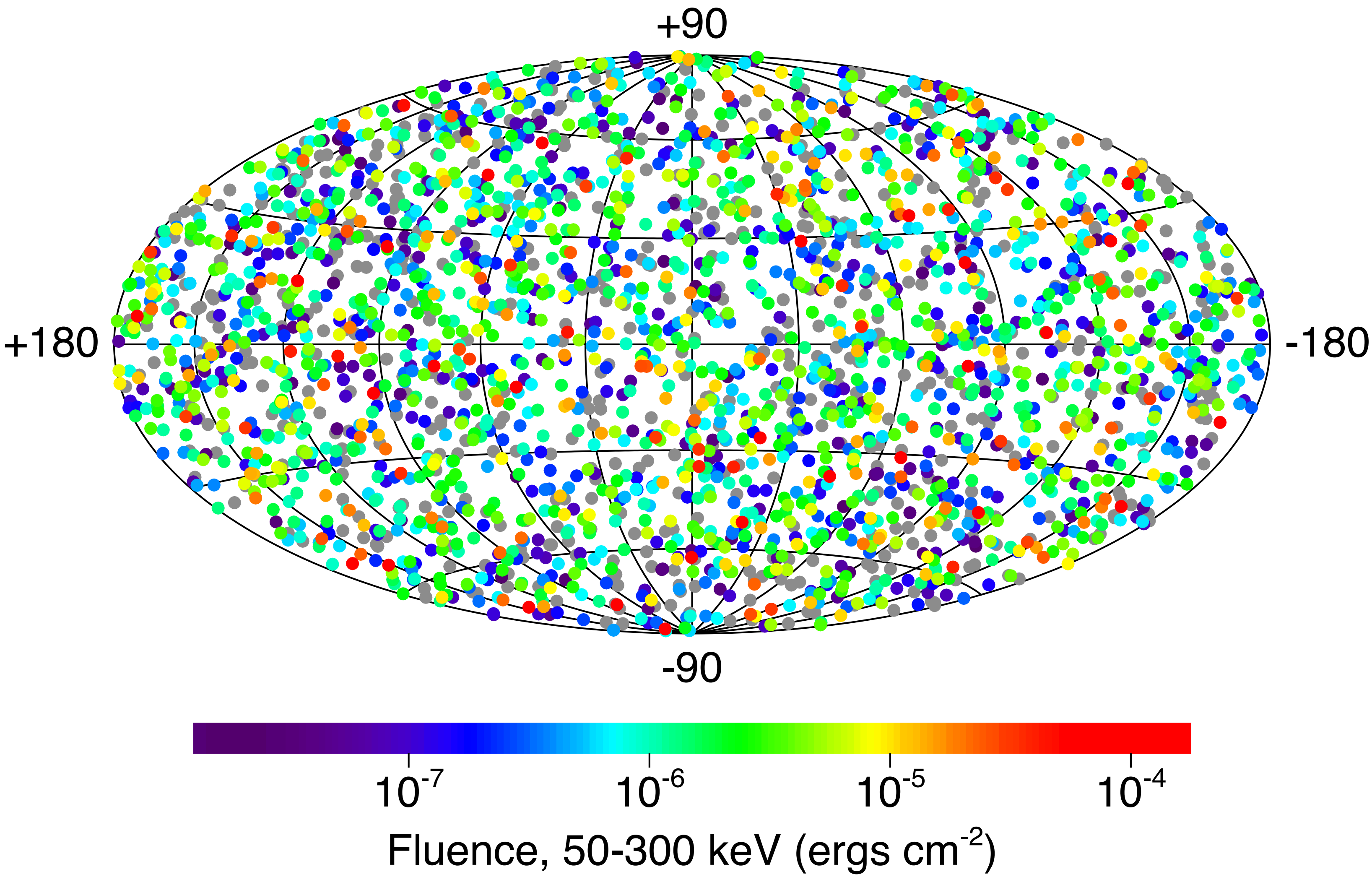
log N - log S test for GRBs



BATSE results showed that a slope of -1.5 fit the distribution of the brightest bursts, but that there were **fewer** faint bursts.

We can see the `edge' of the distribution.

2704 BATSE Gamma-Ray Bursts



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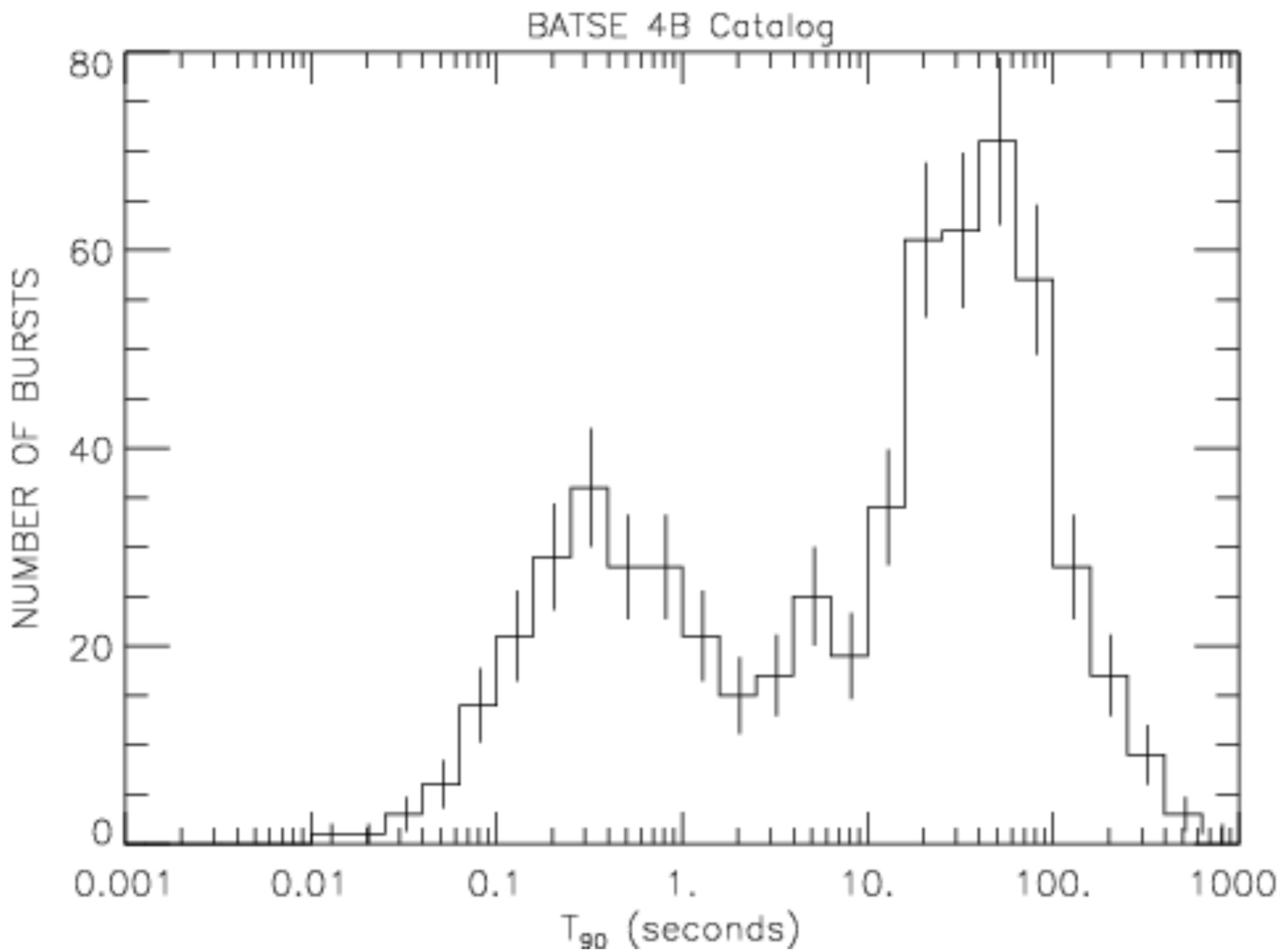

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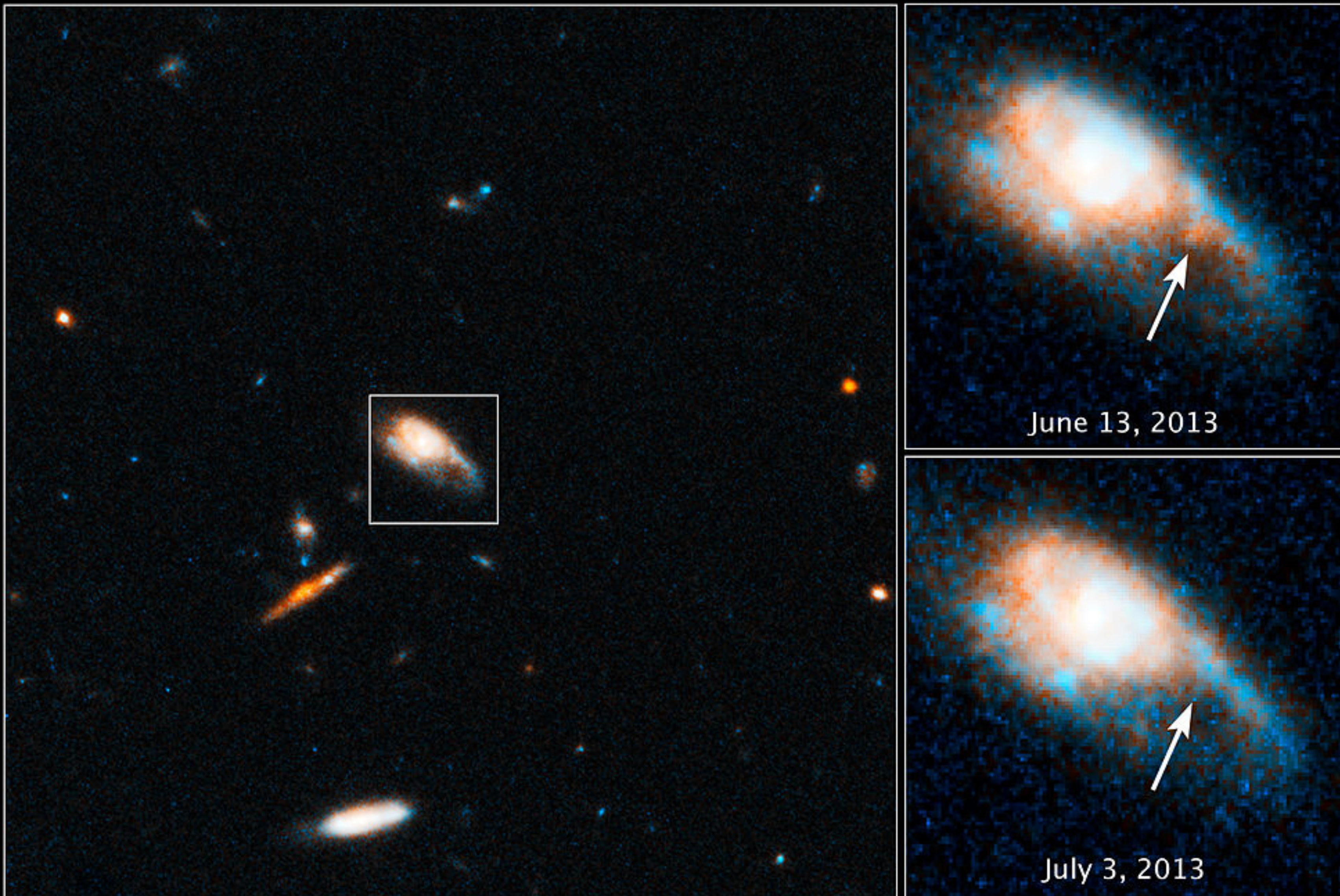
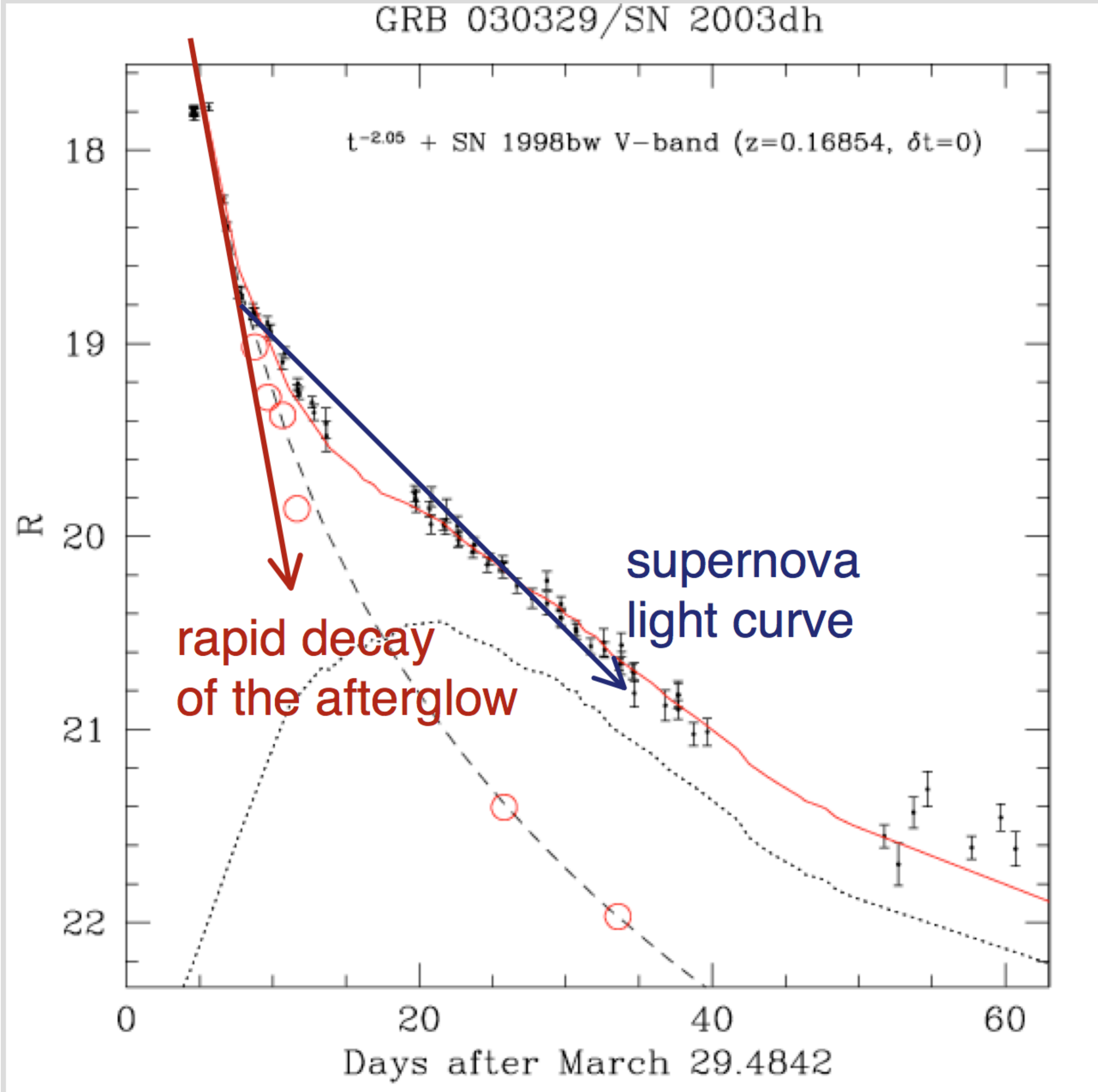


Gamma-ray Burst GRB 130603B
Hubble Space Telescope ▪ ACS/WFC3

NASA and ESA

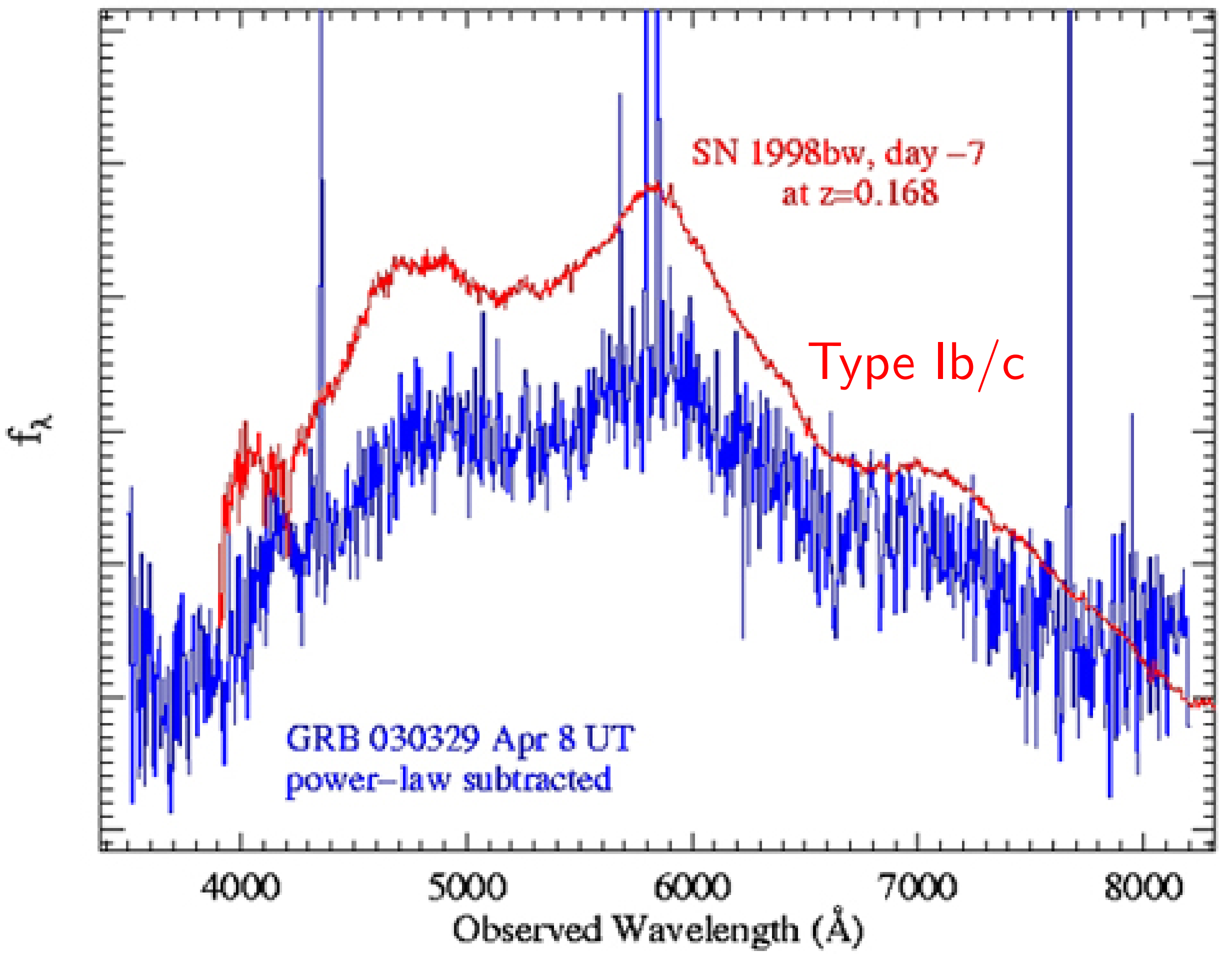
STScI-PRC13-29a

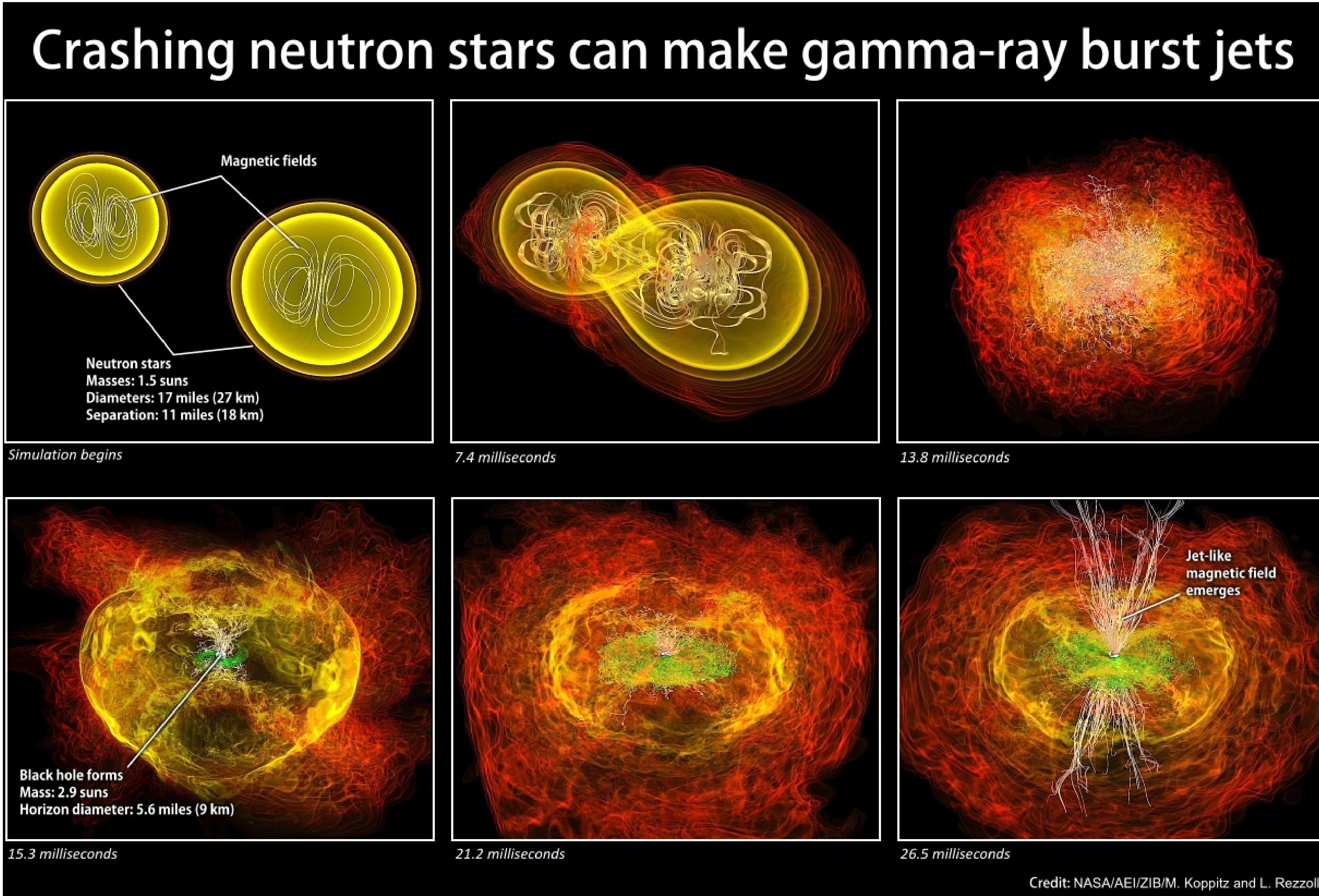


Matheson et al. 2003

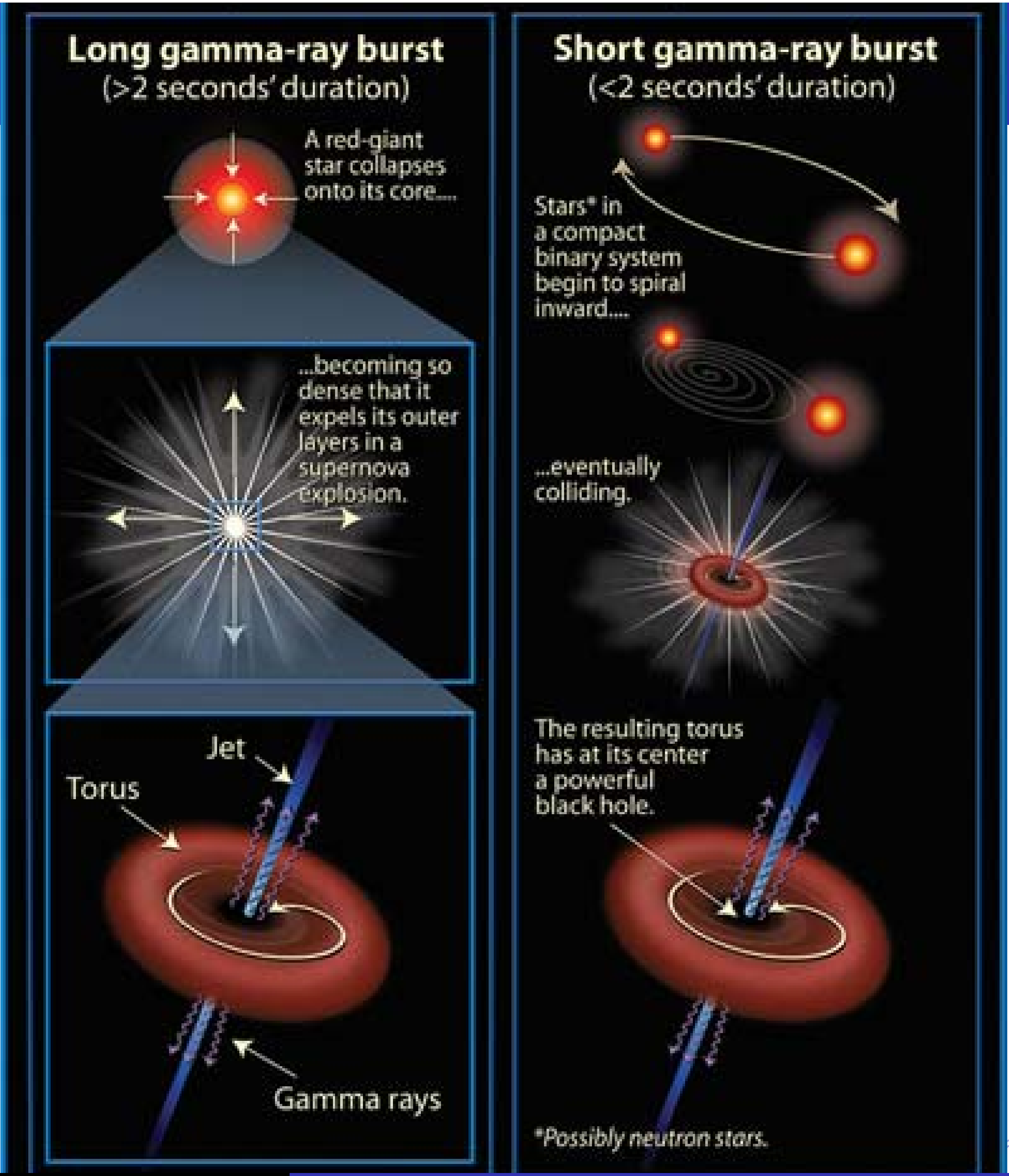
GRBs and Supernovae

Della Valle et al. 2003



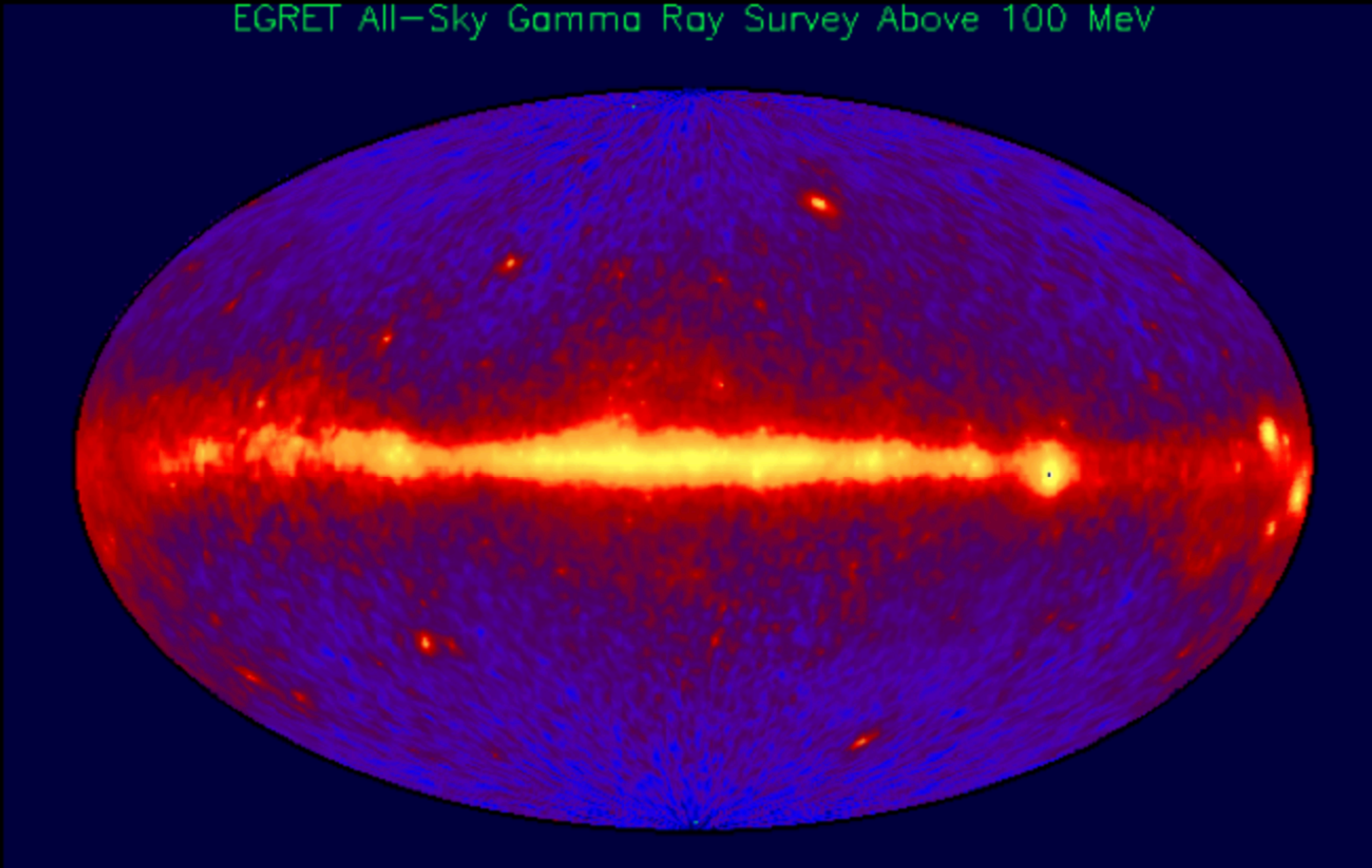

Crashing neutron stars can make gamma-ray burst jets
Magnetic fields
Neutron stars
Masses: 1.5 suns
Diameters: 17 miles (27 km)
Separation: 11 miles (18 km)
Simulation begins
7.4 milliseconds
13.8 milliseconds
Black hole forms
Mass: 2.9 suns
Horizon diameter: 5.6 miles (9 km)
15.3 milliseconds
21.2 milliseconds
Jet-like
magnetic field
emerges
26.5 milliseconds
Credit: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla

GRB Models

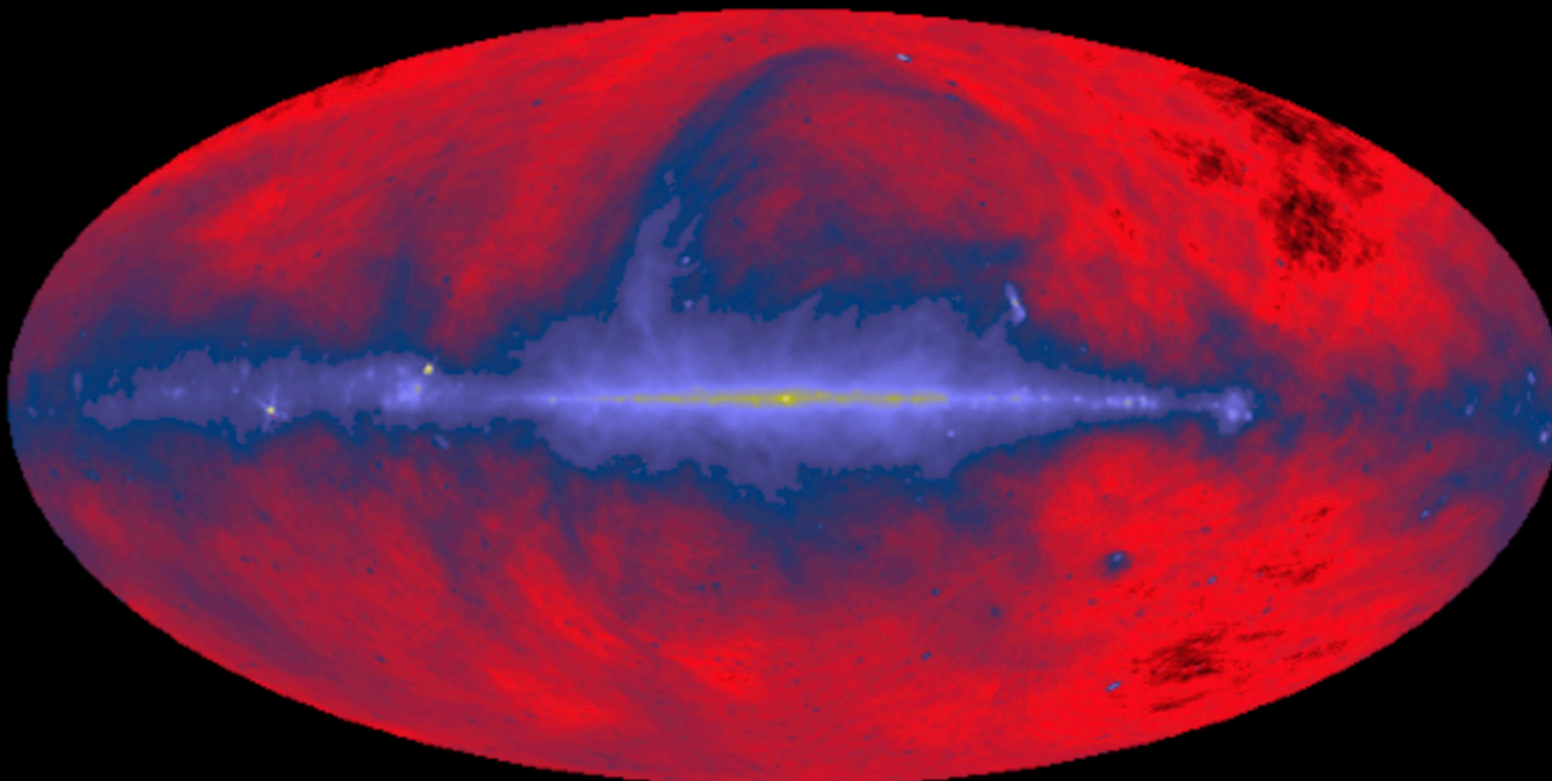


The Encylopedia of Science

Gamma-Ray Sky



Milky Way at 408 MHz



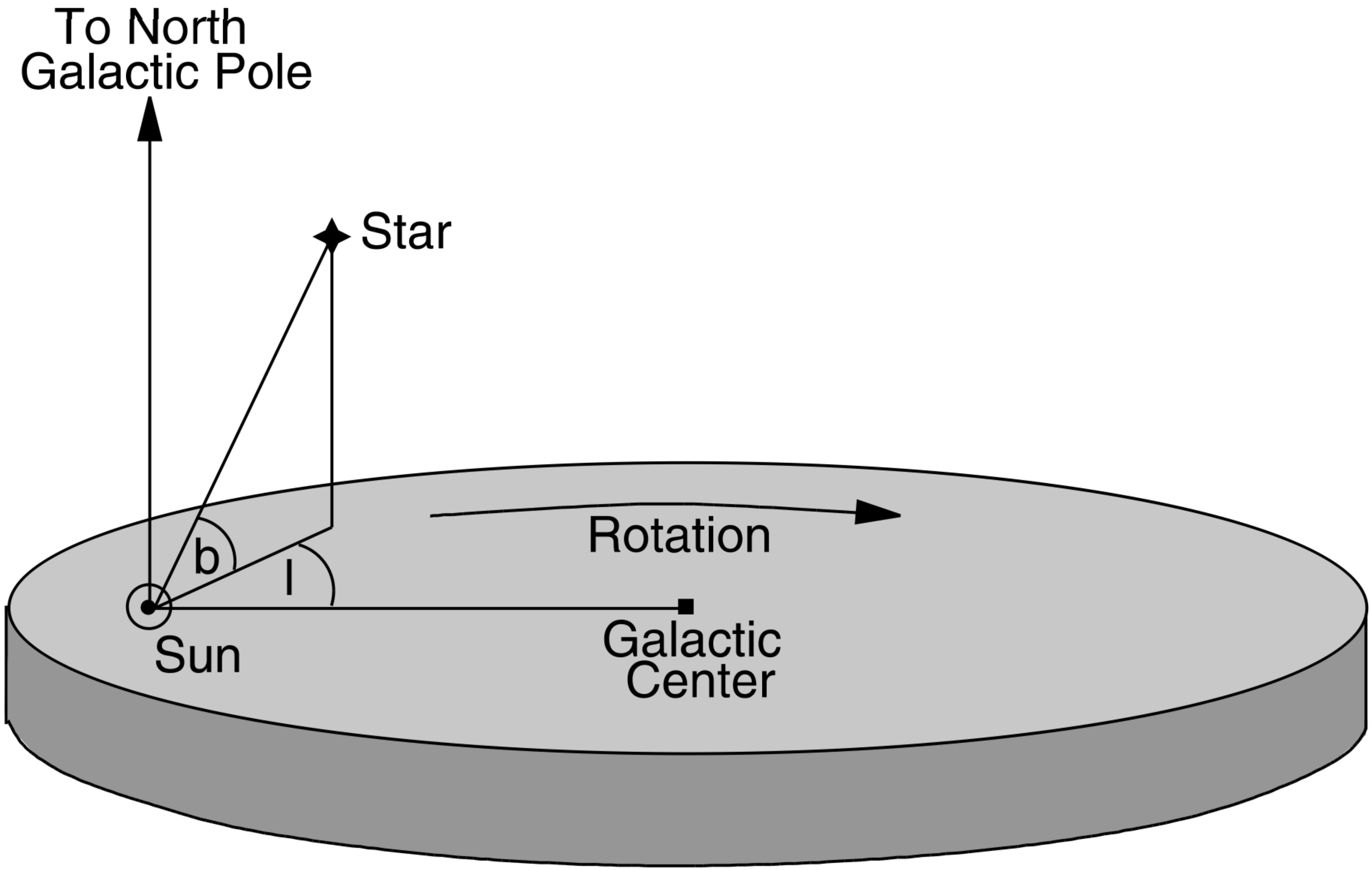


Fig. 2.2. The Sun is at the origin of the Galactic coordinate system. The directions to the Galactic center and to the North Galactic Pole (NGP) are indicated and are located at $\ell = 0°$ and $b = 0°$, and at $b = 90°$, respectively

Spiral Galaxy M64

Hubble Heritage

NASA and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope WFPC2 • STScI-PRC04-04

Whirlpool Galaxy • M51

Hubble Heritage

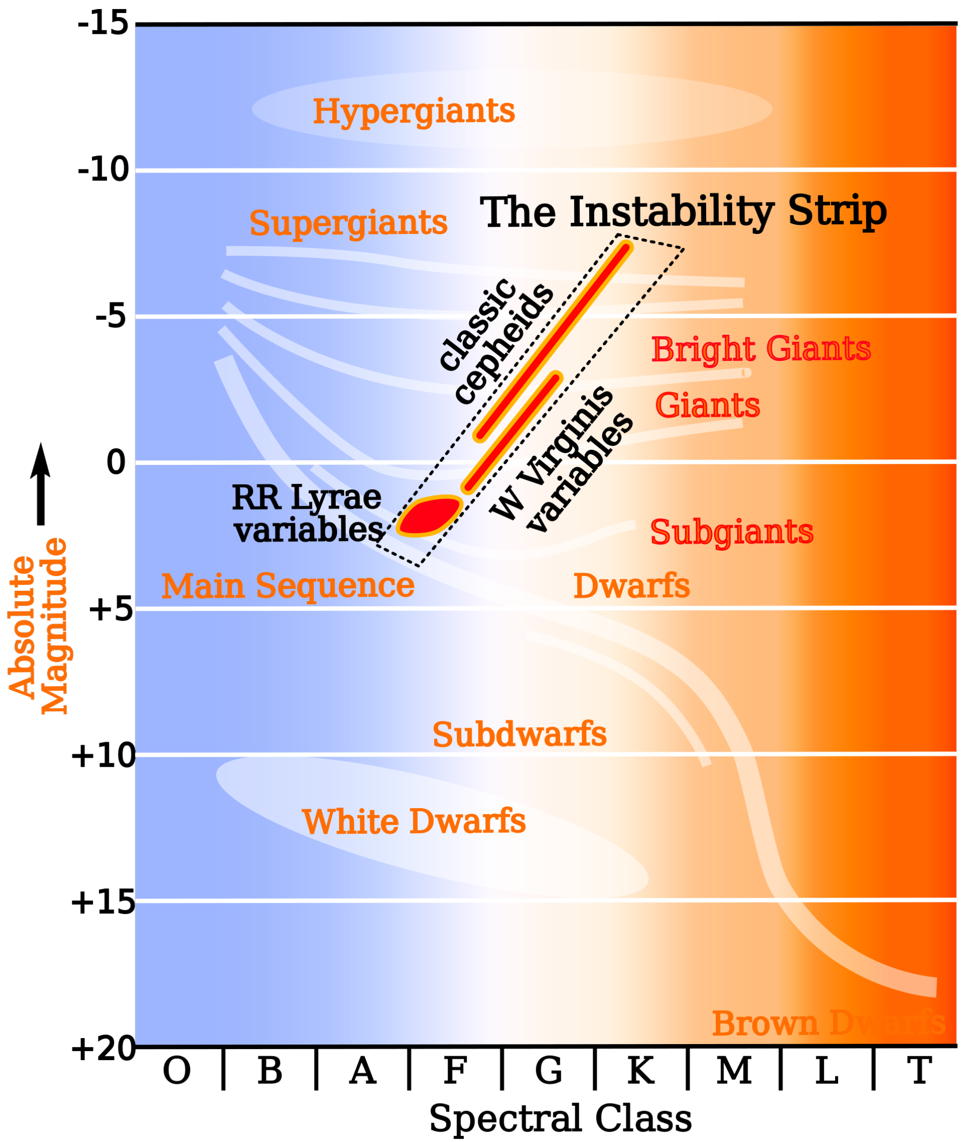
NASA and The Hubble Heritage Team (STScI/AURA)
Hubble Space Telescope WFPC2 • STScI-PRC01-07

Globular Cluster NGC 6093

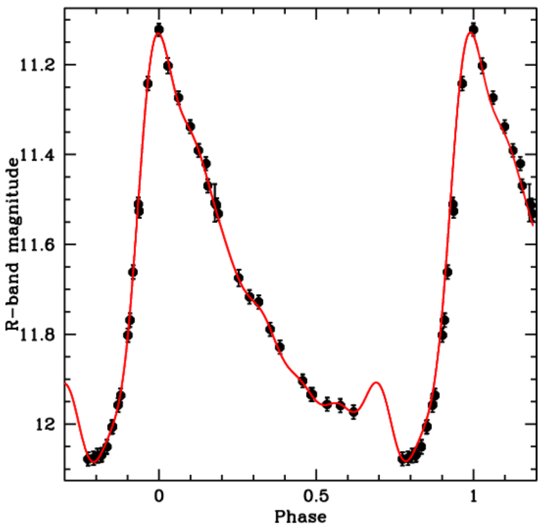
Hubble Heritage

PRC99-26 • Space Telescope Science Institute • Hubble Heritage Team (AURA/STScI/NASA)

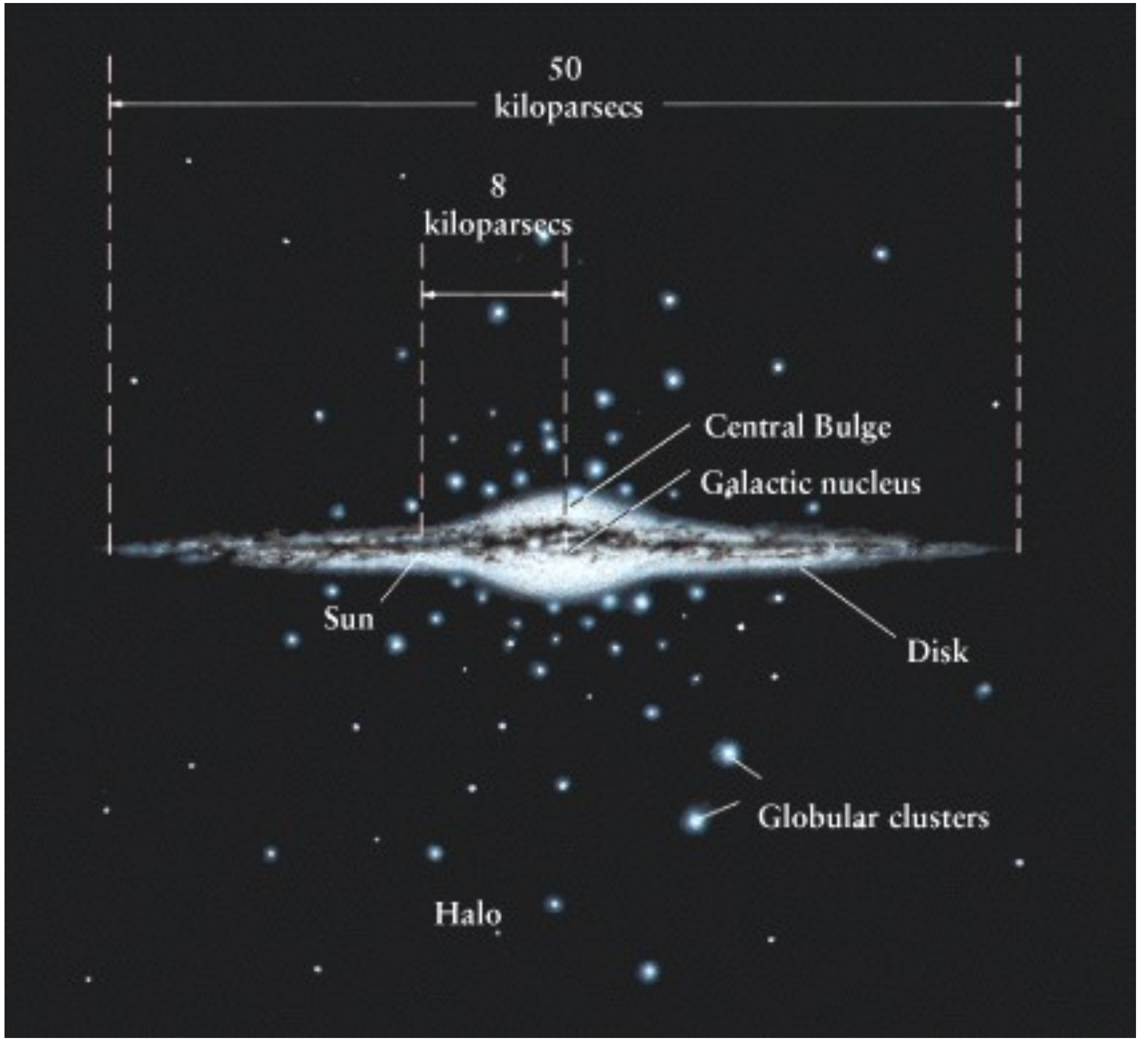
RR Lyrae

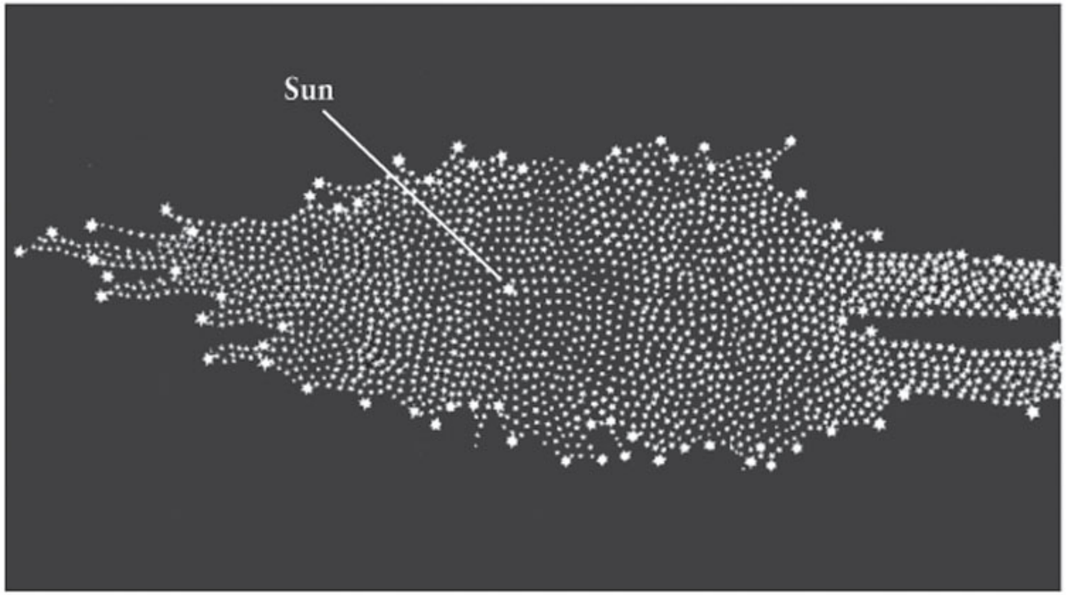


The Instability Strip
Hypergiants
Supergiants
classic cepheids
Bright Giants
Giants
W Virginis variables
RR Lyrae variables
Subgiants
Main Sequence
Dwarfs
Subdwarfs
White Dwarfs
Brown Dwarfs
Absolute Magnitude
-15
-10
-5
0
+5
+10
+15
+20
O B A F G K M L T
Spectral Class



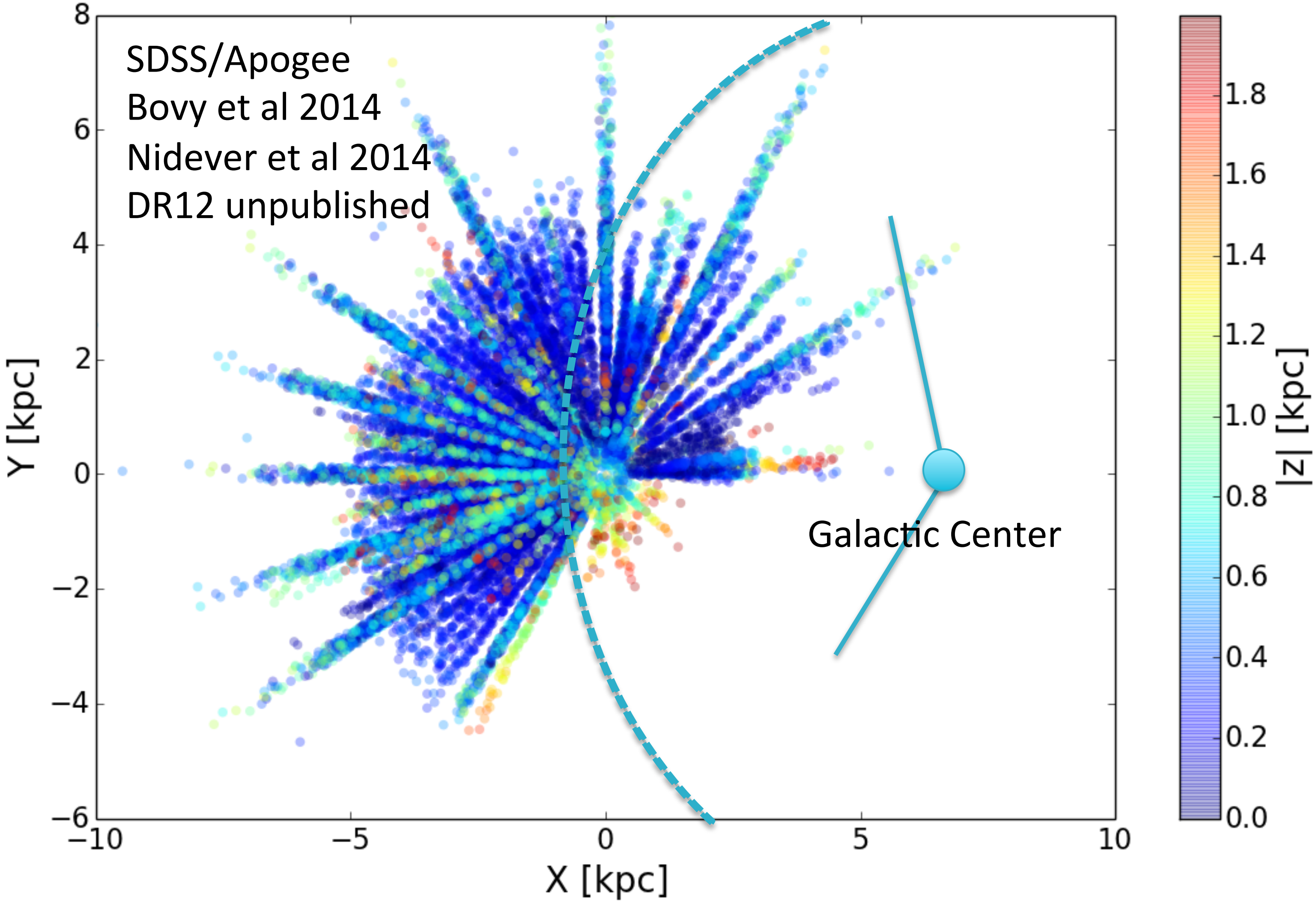
R-band magnitude
11.2
11.4
11.6
11.8
12
0
0.5
1
Phase

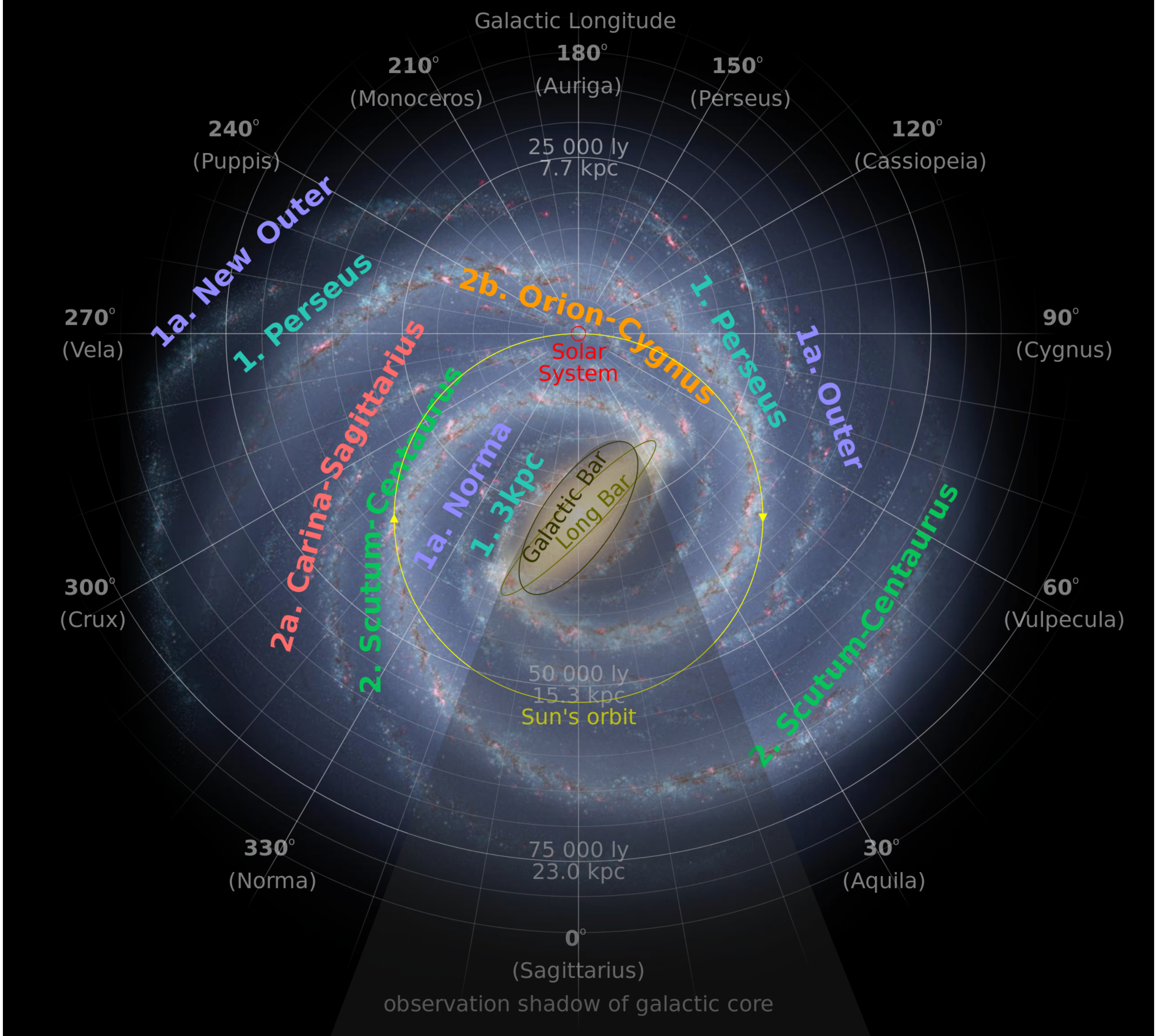

50
kiloparsecs
8
kiloparsecs
Central Bulge
Galactic nucleus
Sun
Disk
Globular clusters
Halo



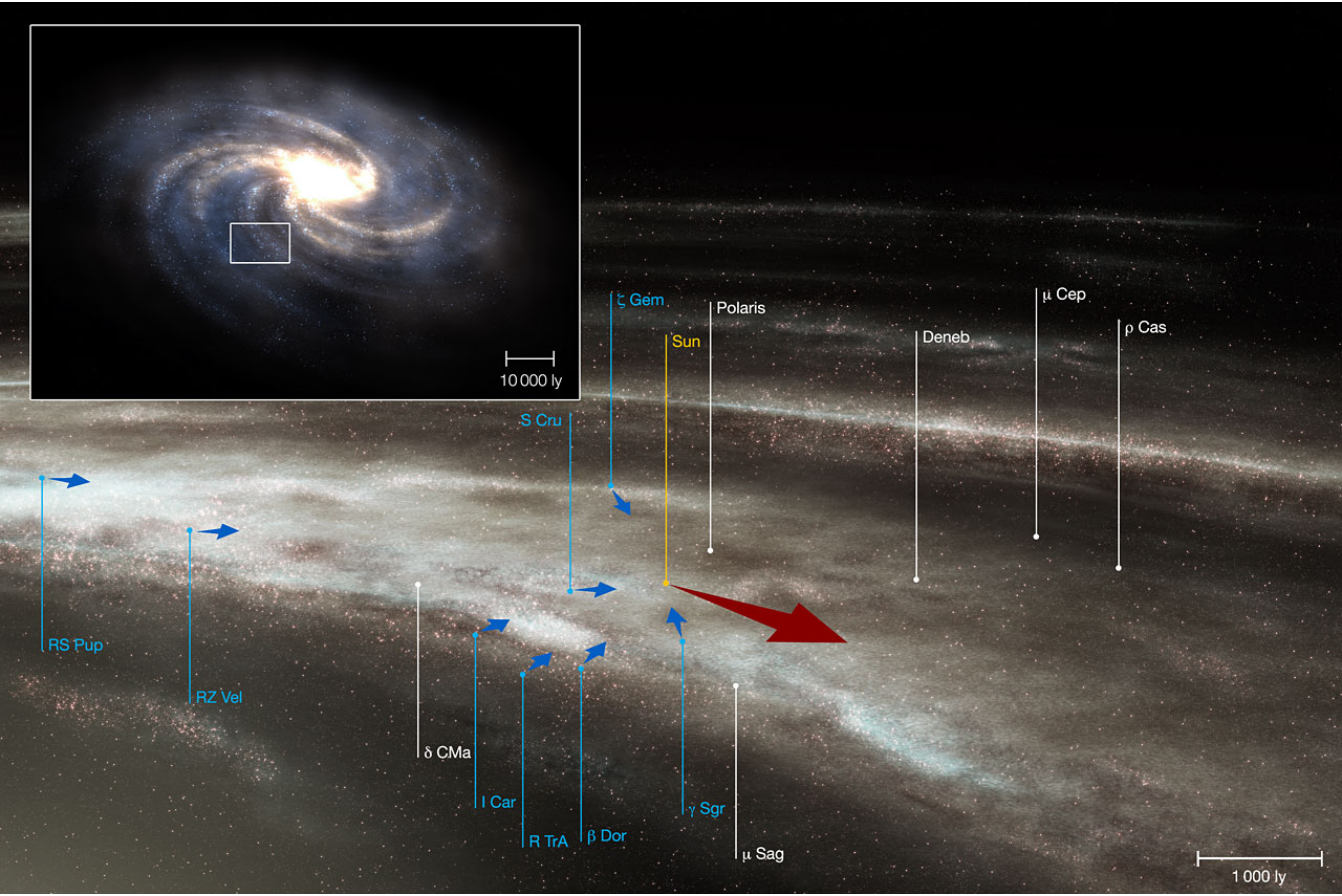
Herschel's map of the Galaxy

Now the Galaxy is being covered systematically with spectra



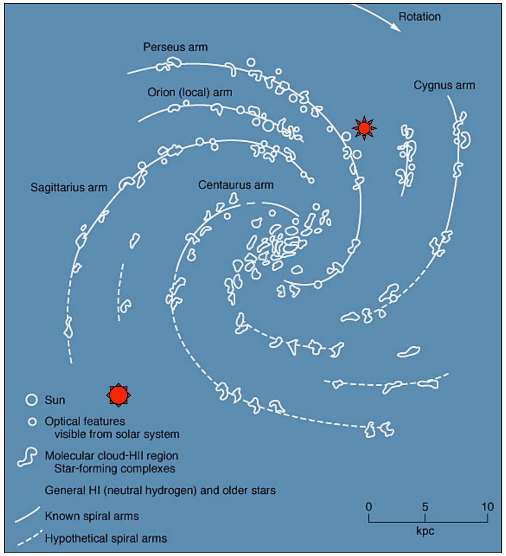


Galactic Longitude
180°
(Auriga)
210°
(Monoceros)
150°
(Perseus)
240°
(Puppis)
120°
(Cassiopeia)
270°
(Vela)
90°
(Cygnus)
300°
(Crux)
60°
(Vulpecula)
330°
(Norma)
30°
(Aquila)
0°
(Sagittarius)
observation shadow of galactic core
25 000 ly
7.7 kpc
50 000 ly
15.3 kpc
75 000 ly
23.0 kpc
Sun's orbit
Solar System
1a. New Outer
1. Perseus
2b. Orion-Cygnus
1. Perseus
1a. Outer
2a. Carina-Sagittarius
2. Scutum-Centaurus
1a. Norma
1. 3kpc
Galactic Bar
Long Bar
2. Scutum-Centaurus



10 000 ly
ζ Gem
Polaris
Sun
μ Cep
ρ Cas
Deneb
S Cru
RS Pup
RZ Vel
δ CMa
l Car
R TrA
β Dor
γ Sgr
μ Sag
1 000 ly

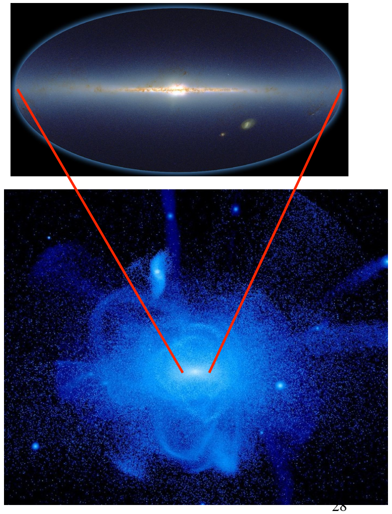
Map of the Milky Way Galaxy



The map has been using HI velocity data sec 2.3.1 in S+G

Theorists View of Dynamics of Stars in MW

- In cold dark matter theories of structure formation many mergers have occurred - it takes a VERY long time for the orbits to 'relax' and thus there should be dynamical signatures of the mergers
- Only in MW and LMC/SMC is there any chance to determine the 3-D distribution of velocities and positions to constrain such models in DETAIL.
- Look for signs of assembly of MW galaxy in our stellar halo (and thin/ thick disk)
  - Stellar halo is conceivably all accreted material
  - Stellar streams in the solar neighborhood



H Rix

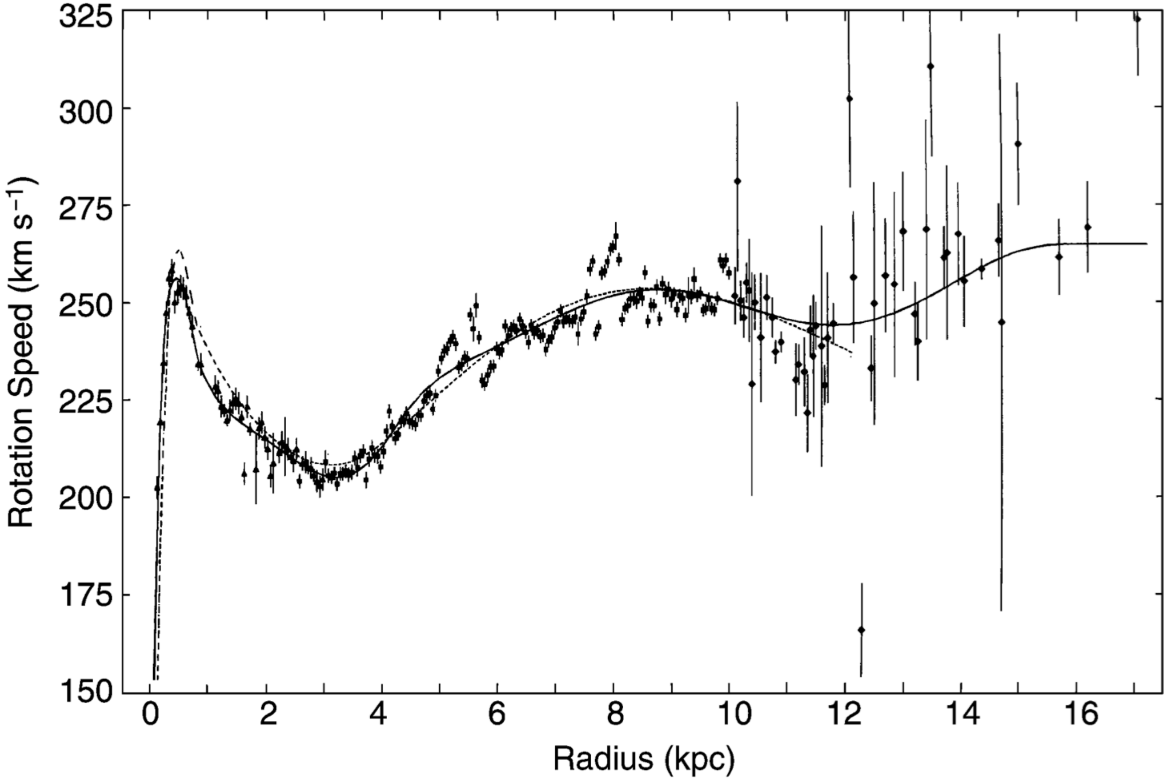


Fig. 2.20. Rotation curve of the Milky Way. Inside the "Solar circle", that is at $R < R_0$, the radial velocity is determined quite accurately using the tangent point method; the measurements outside have larger uncertainties

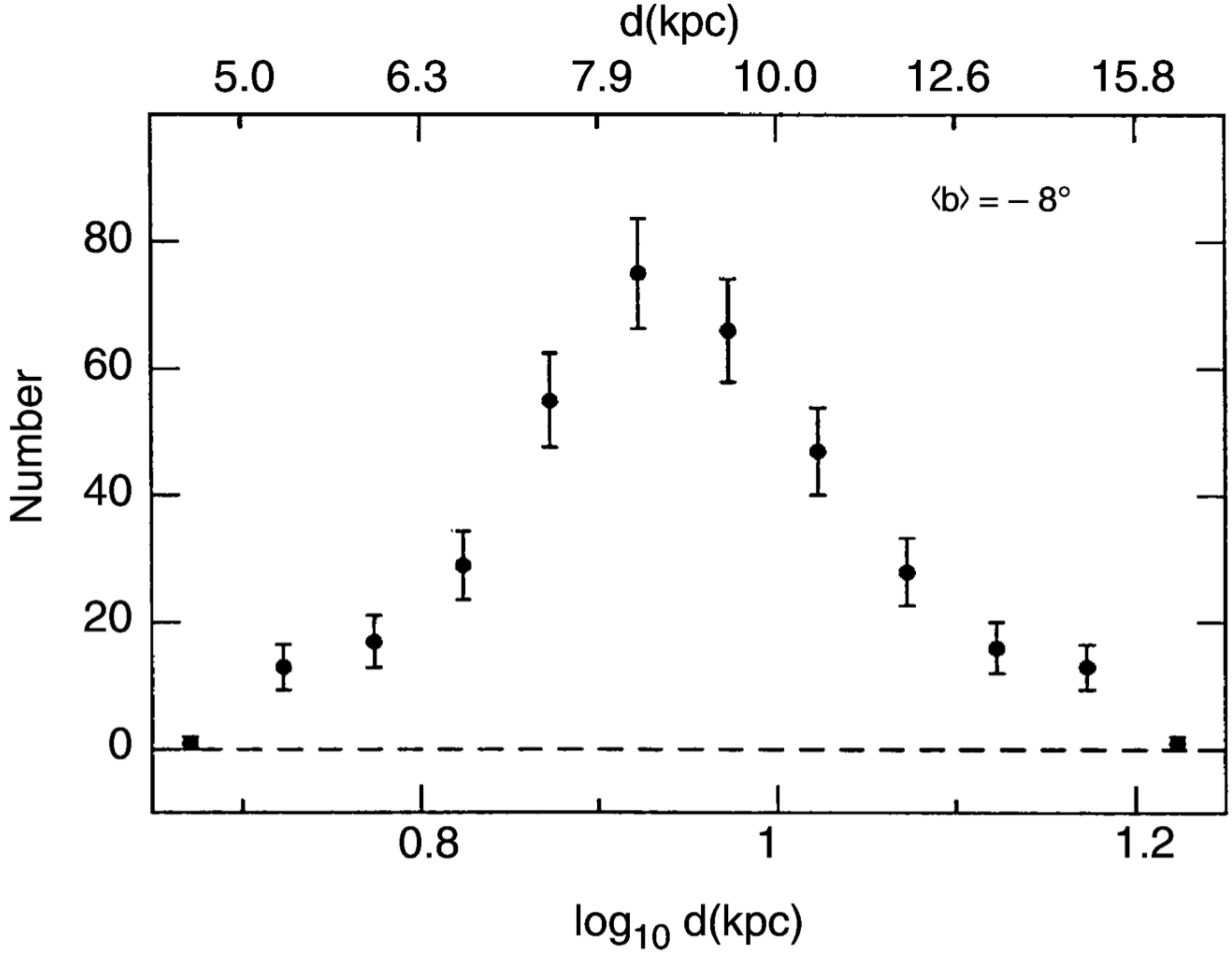


Fig. 2.12. The number of RR Lyrae stars as a function of distance, measured in a direction that closely passes the Galactic center, at $\ell = 0°$ and $b = -8°$. If we assume a spherically symmetric distribution of the RR Lyrae stars, concentrated towards the center, the distance to the Galactic center can be identified with the maximum of this distribution

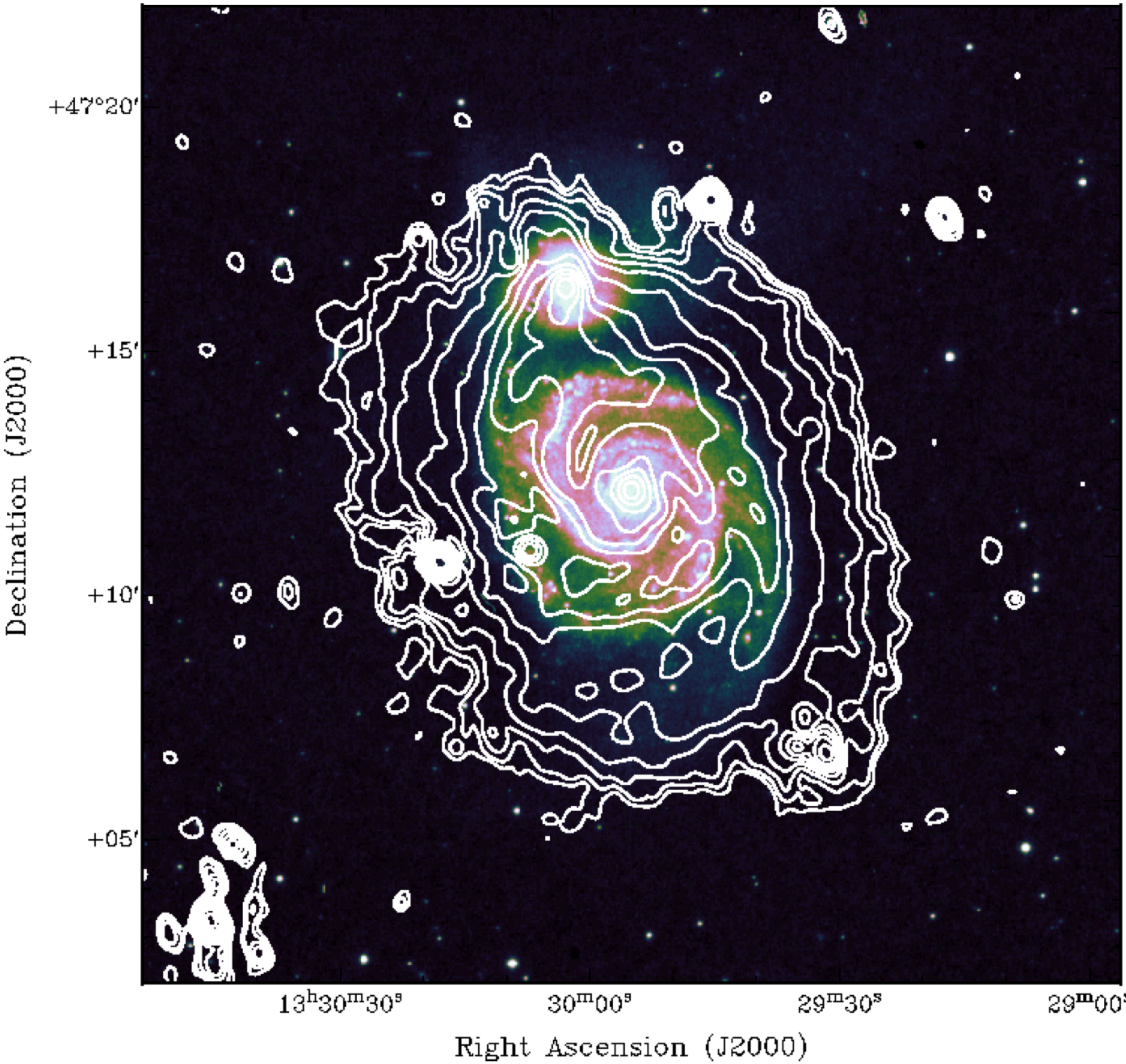


Fig. 3. M51 at a central frequency of 151 MHz with a bandwidth of **47.7 MHz** overlayed onto an optical DSS image. The resolution is 20″ and a robust weighting of −0.5 was used. Here the extended disk is seen clearly. The contours start at 1 mJy/beam and increase by a factor 1.5.

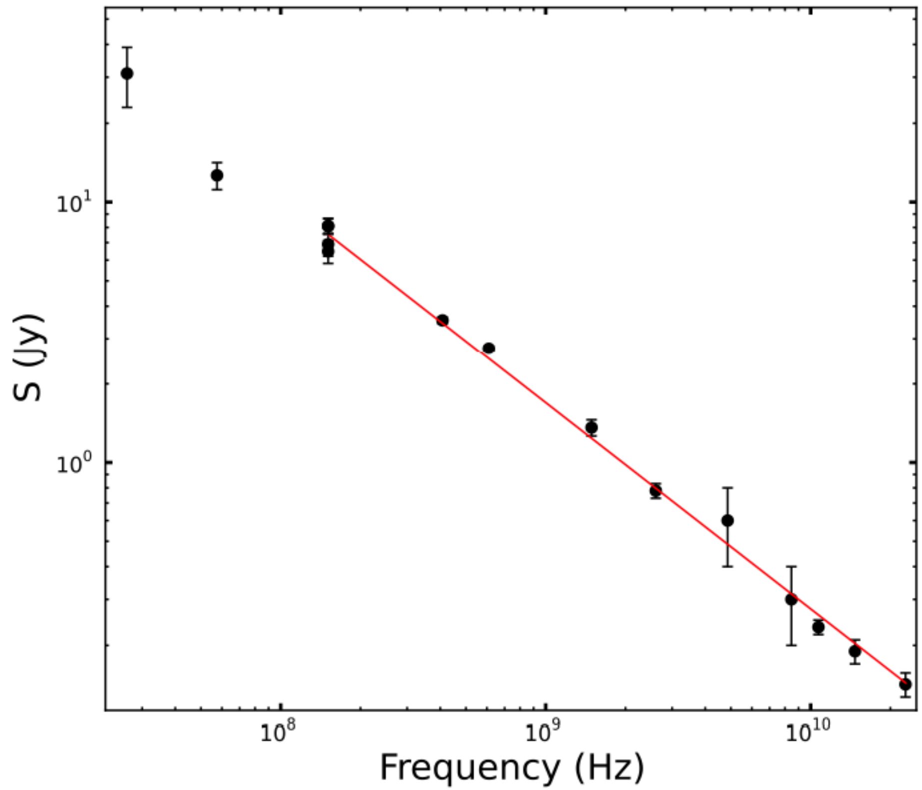
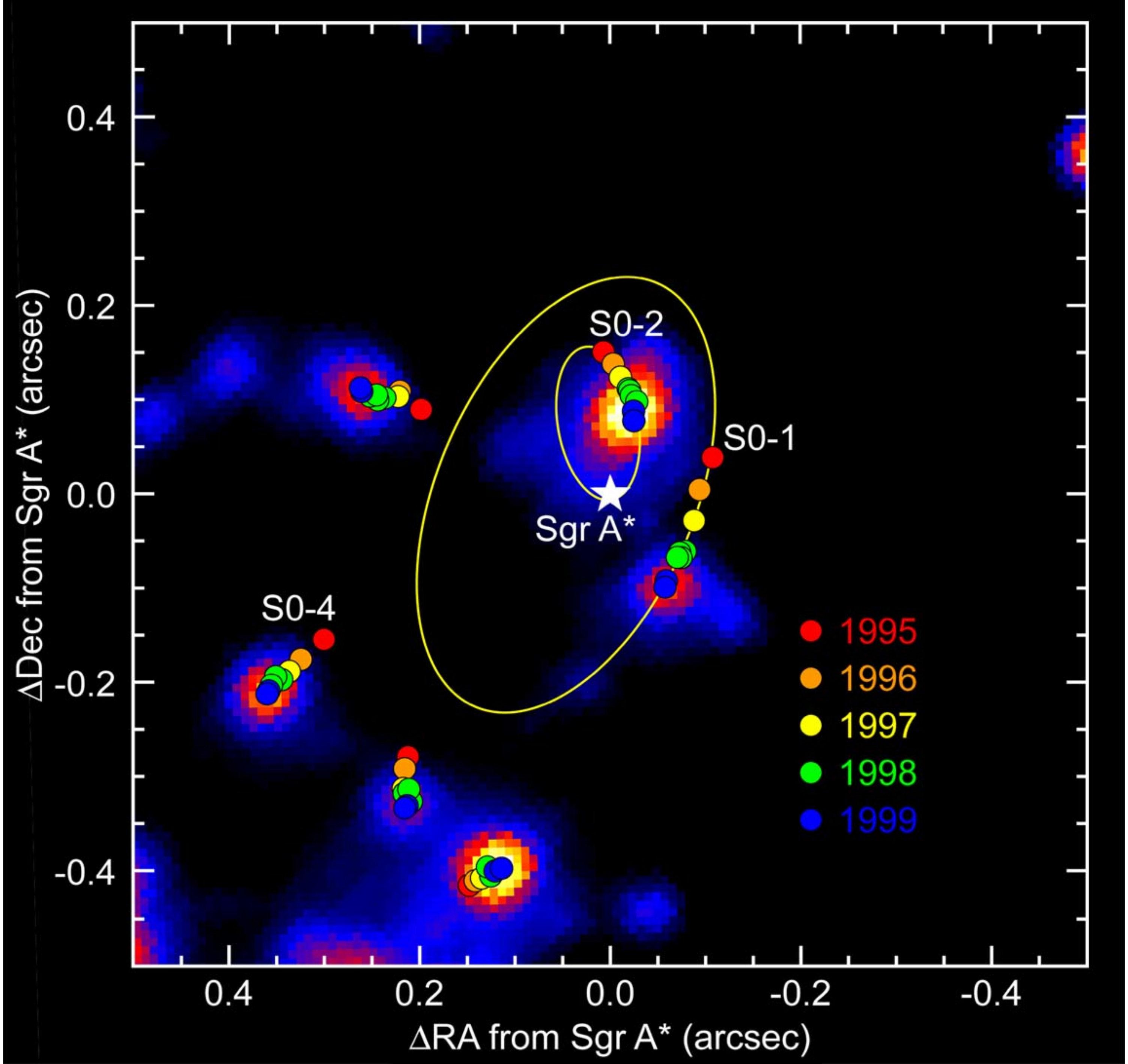


Fig. 4. The integrated flux density of M51 with a power law fit of slope α = -0.79 ± 0.02. The integrated flux values of 11 ± 1.5 Jy from Israel & Mahoney (1990) at 57.5 MHz **and 31 ± 8 Jy at 26.3 MHz (Viner & Erickson 1975) are** also plotted


S0-2
S0-1
S0-4
Sgr A*
1995
1996
1997
1998
1999
0.4
0.2
0.0
-0.2
-0.4
ΔDec from Sgr A* (arcsec)
ΔRA from Sgr A* (arcsec)

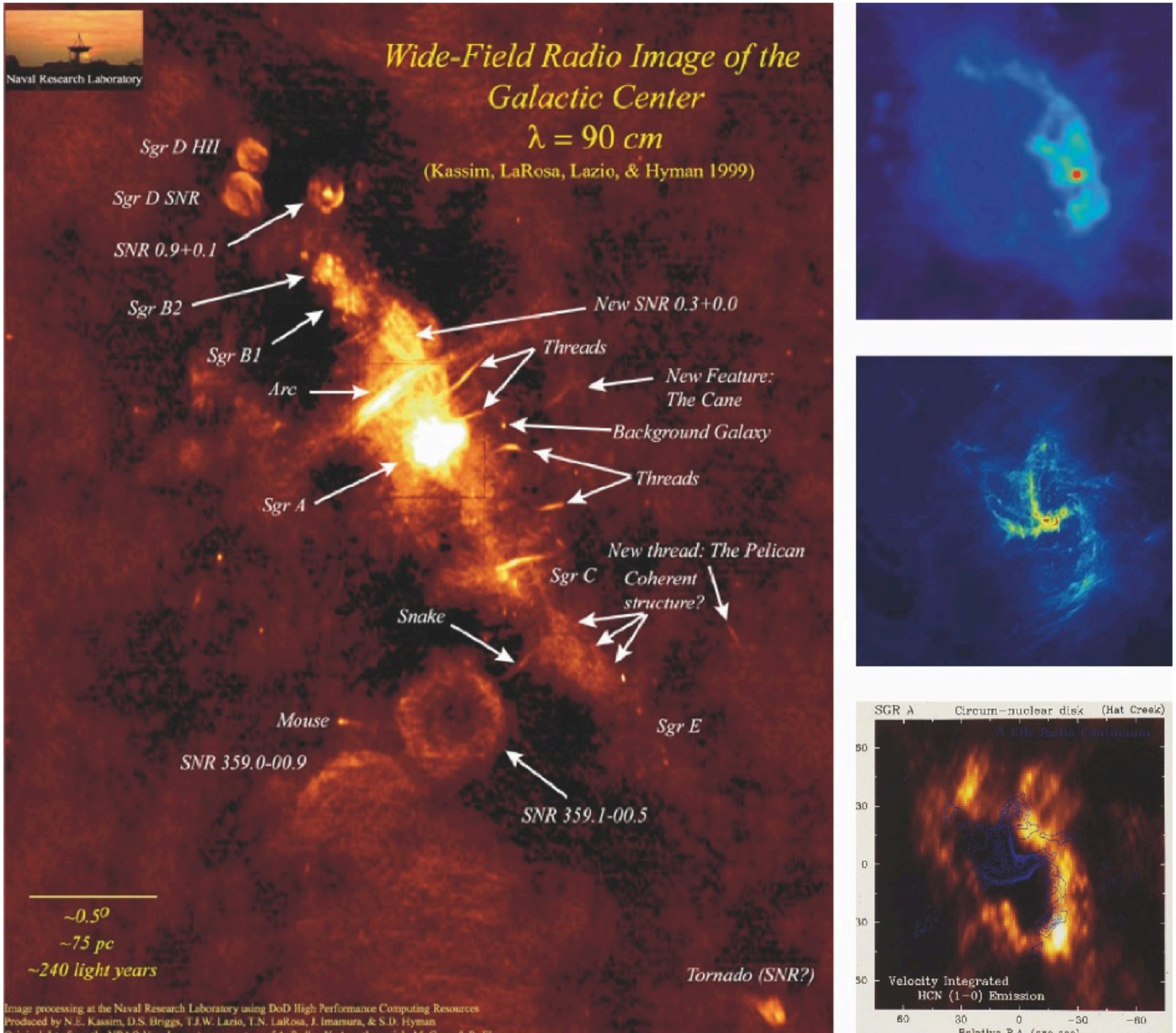


Fig. 2.34. Left: A VLA wide-field image of the region around the Galactic center, with a large number of sources identified. Upper right: a 20 cm continuum VLA image of Sgr A East, where the red dot marks Sgr A*. Center right: Sgr A West, as seen in a 6-cm continuum VLA image. Lower right: the circumnuclear ring in HCN line emission

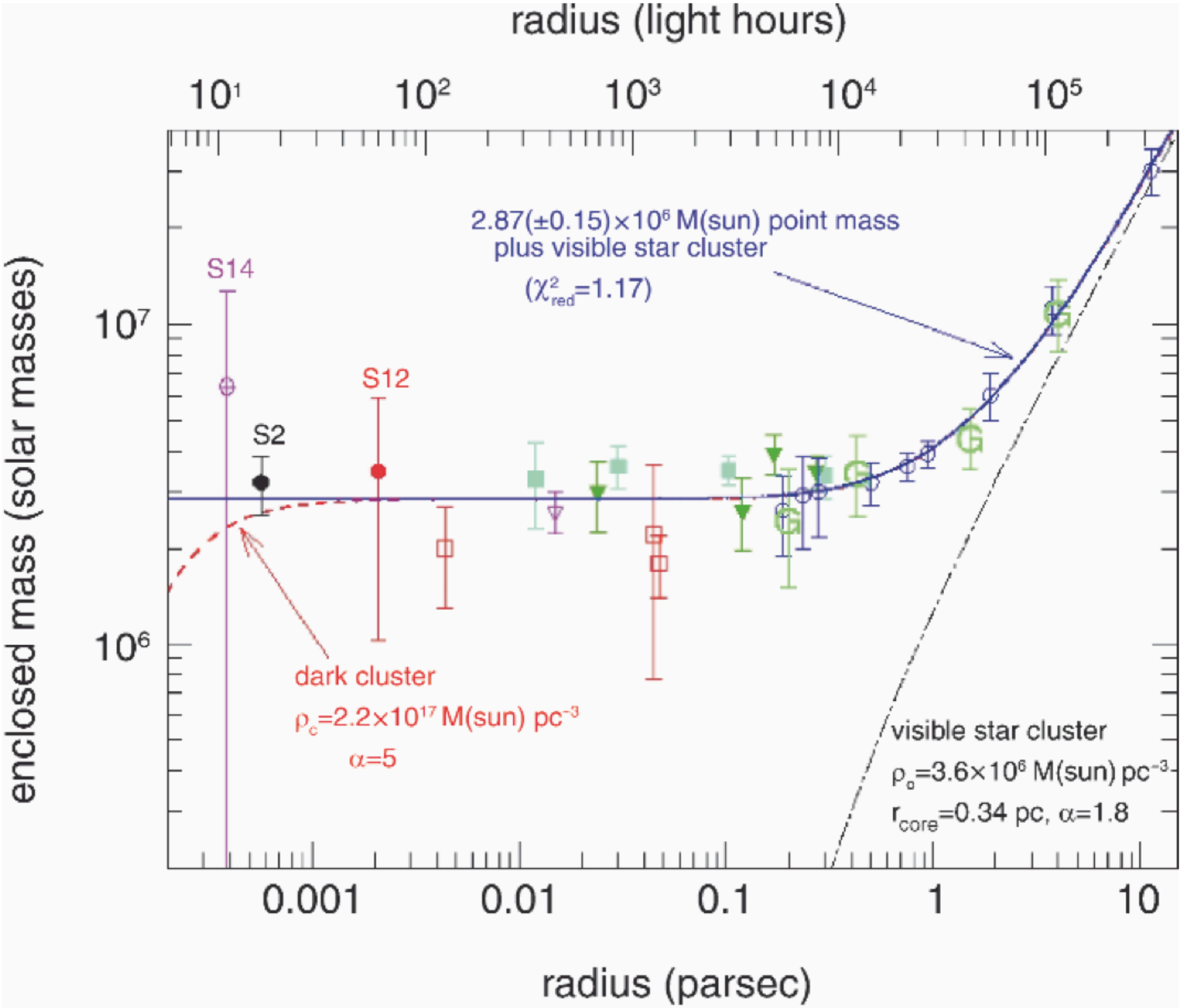
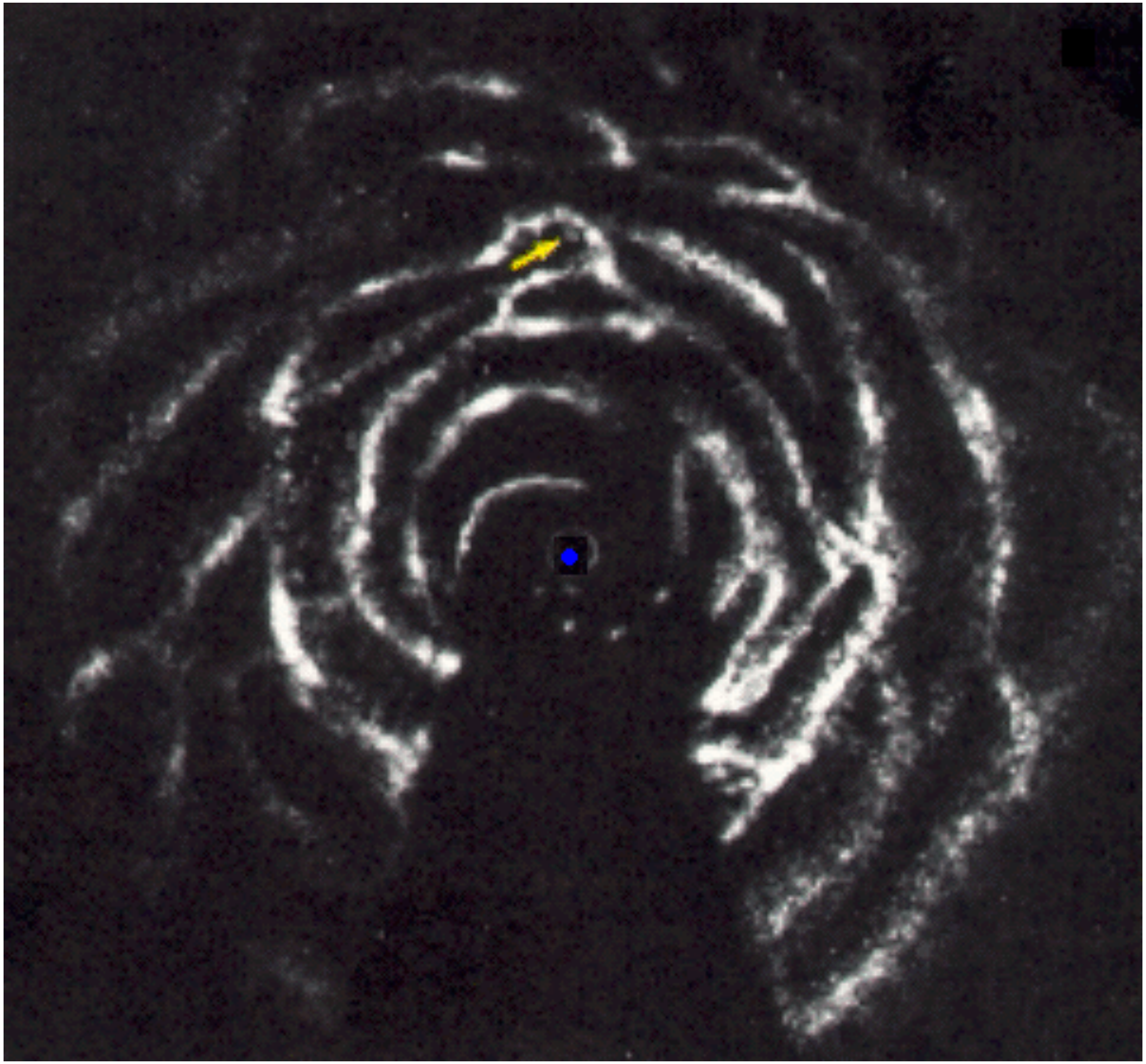
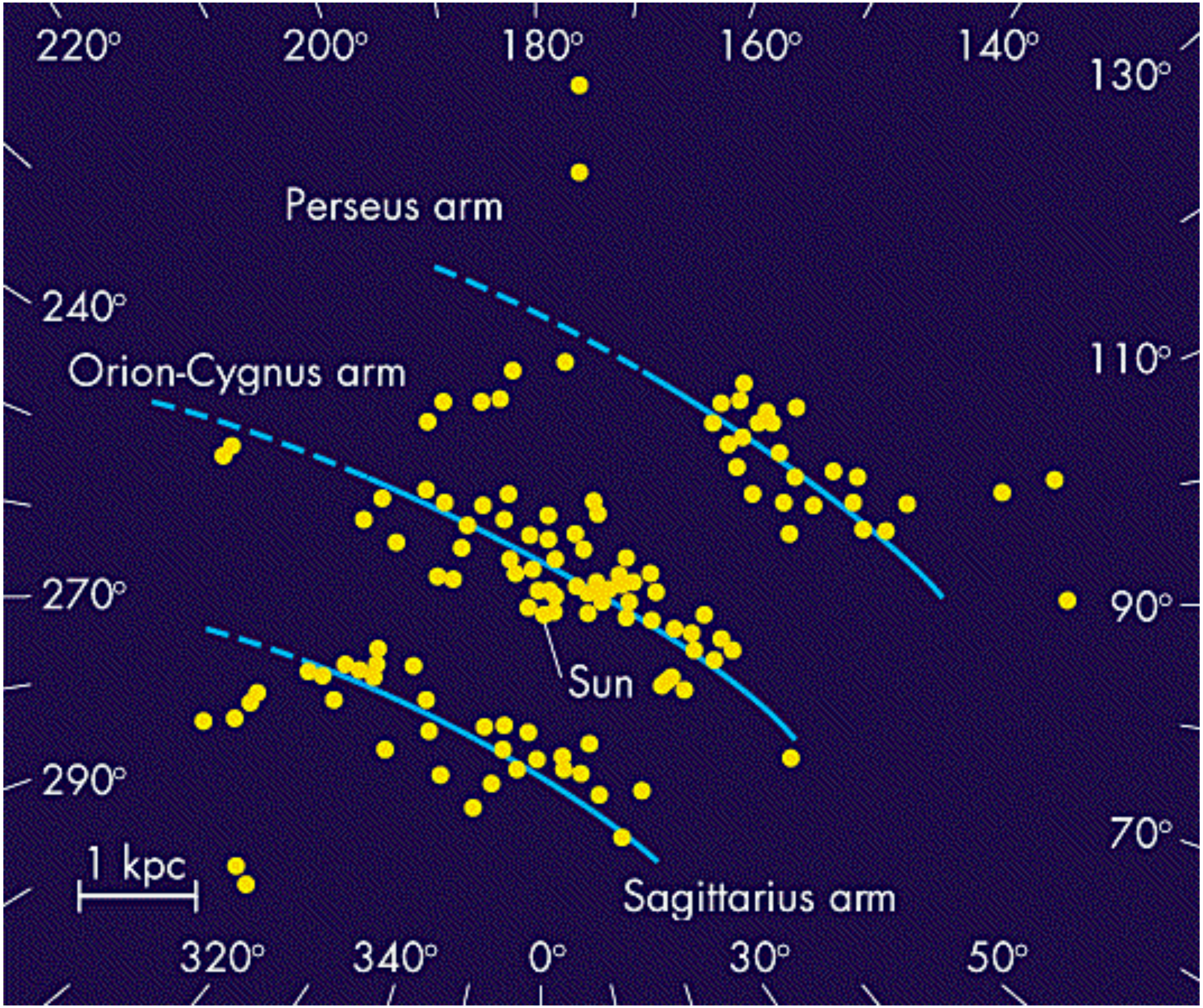


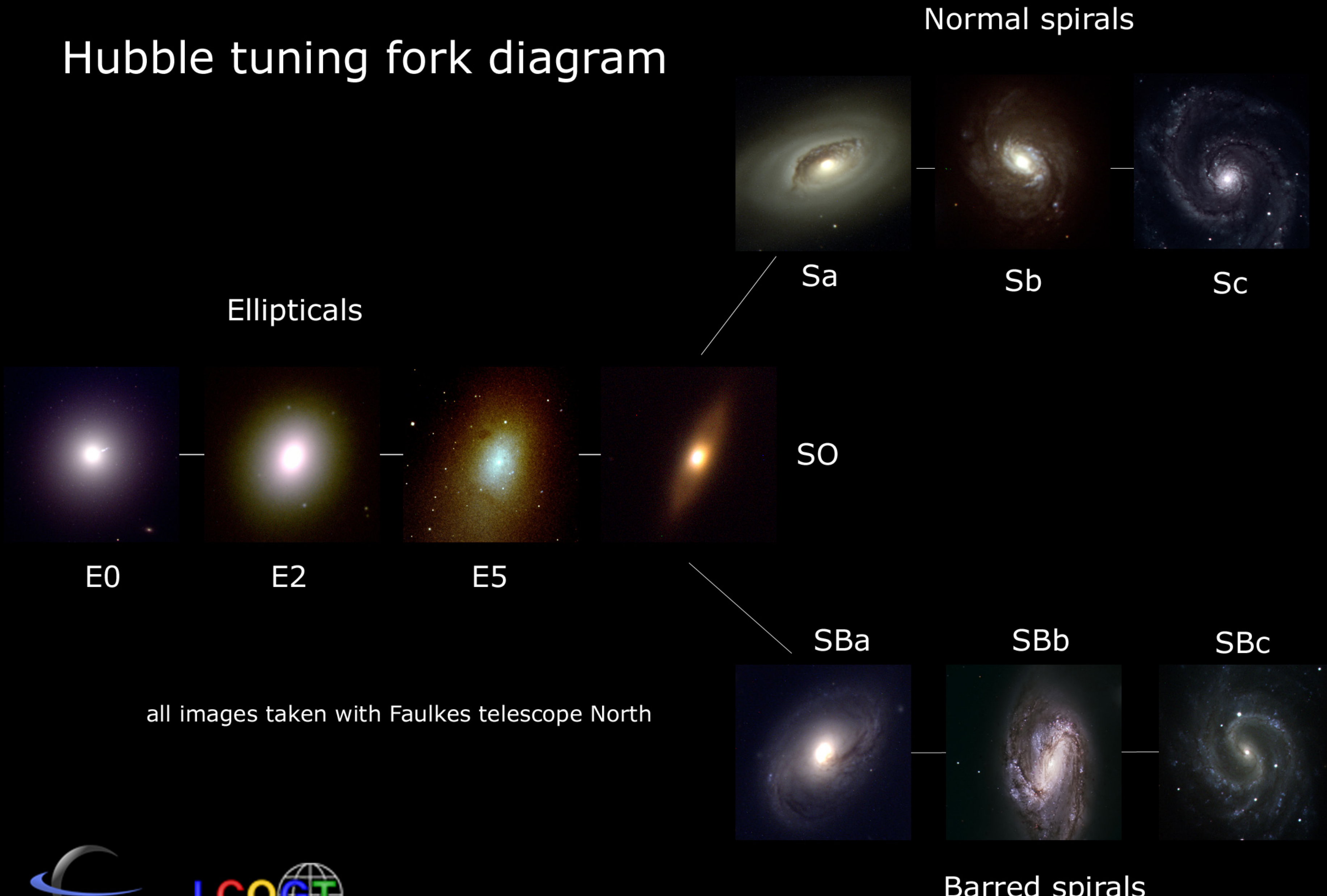
Fig. 2.38. Determination of the mass $M(r)$ within a radius r from Sgr A*, as measured by the radial velocities and proper motions of stars in the central cluster. Mass estimates obtained from individual stars (S14, S2, S12) are given by the points with error bars for small r. The other data points were derived from the kinematic analysis of the observed proper motions of the stars, where different methods have been applied. As can be seen, these methods produce results that are mutually compatible, so that the mass profile plotted here can be regarded to be robust. The solid curve is the best-fit model, representing a point mass of $2.9 \times 10^6 M_\odot$ plus a star cluster with a central density of $3.6 \times 10^6 M_\odot/\mathrm{pc}^3$ (the mass profile of this star cluster is indicated by the dash-dotted curve). The dashed curve shows the mass profile of a hypothetical cluster with a very steep profile, $n \propto r^{-5}$, and a central density of $2.2 \times 10^{17} M_\odot\,\mathrm{pc}^{-3}$





220°
200°
180°
160°
140°
130°
Perseus arm
240°
110°
Orion-Cygnus arm
270°
90°
Sun
290°
70°
1 kpc
Sagittarius arm
320°
340°
0°
30°
50°

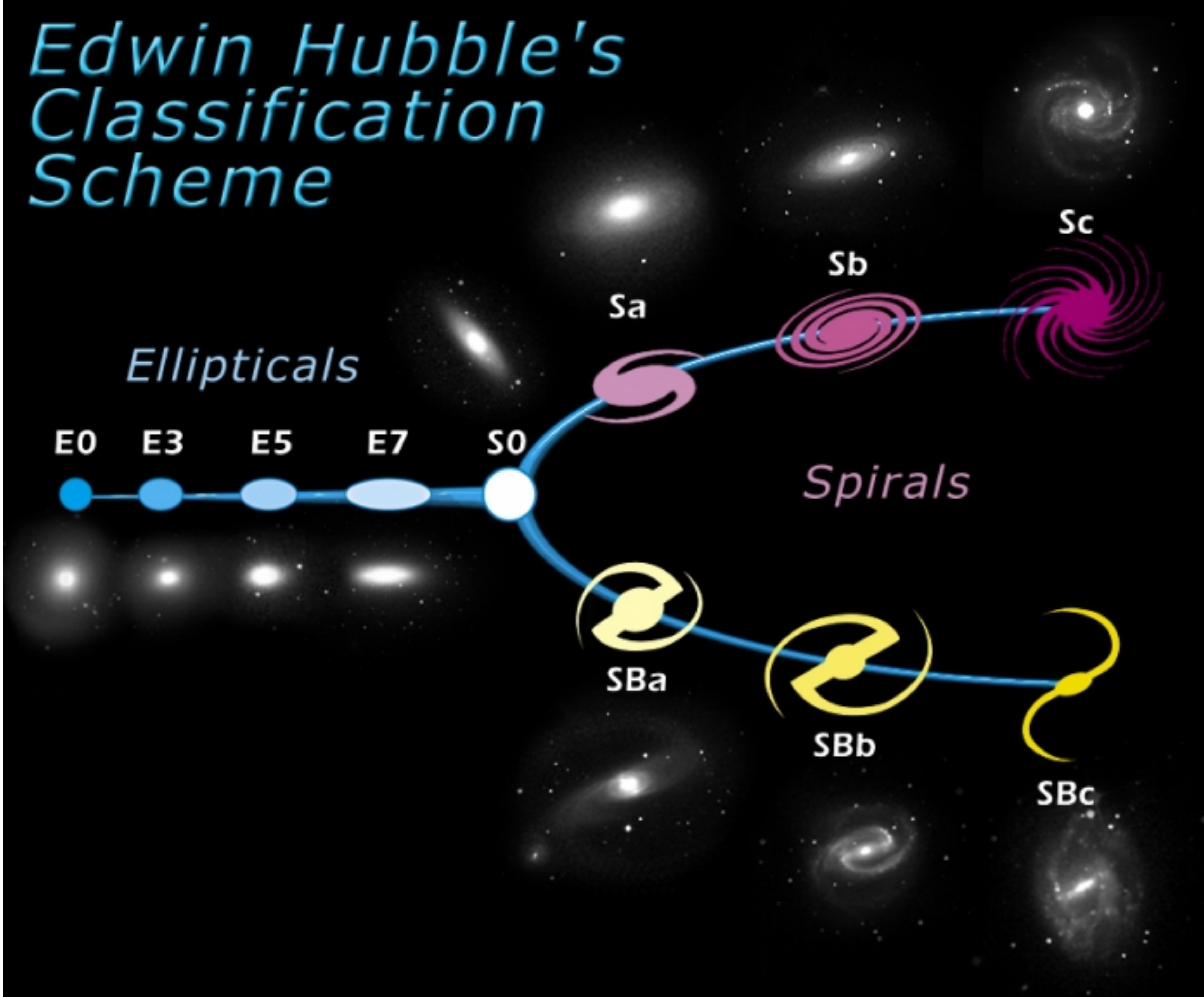
Hubble tuning fork diagram



all images taken with Faulkes telescope North

FAULKES TELESCOPE

LCOGT.net

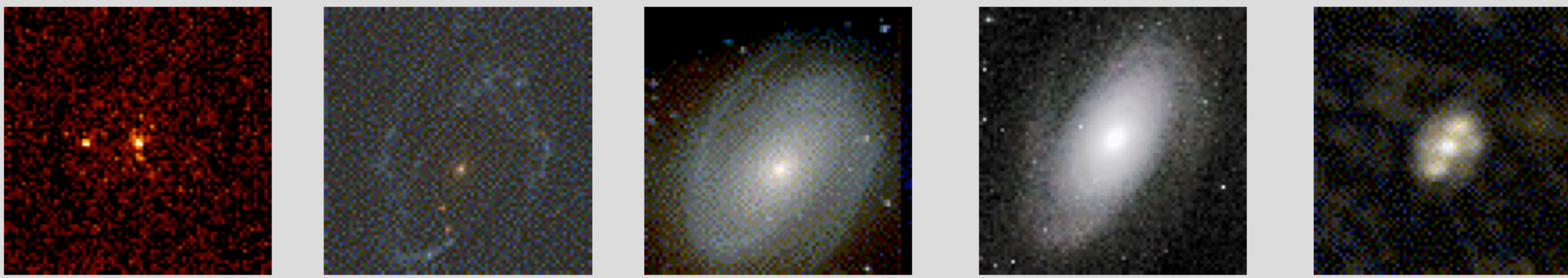


Edwin Hubble's Classification Scheme
Ellipticals
E0
E3
E5
E7
S0
Sa
Sb
Sc
Spirals
SBa
SBb
SBc

Problems with traditional galaxy classification

Appearance of galaxies is strongly dependent on **which wavelength** the observations are made in.

e.g. the nearby galaxy M81



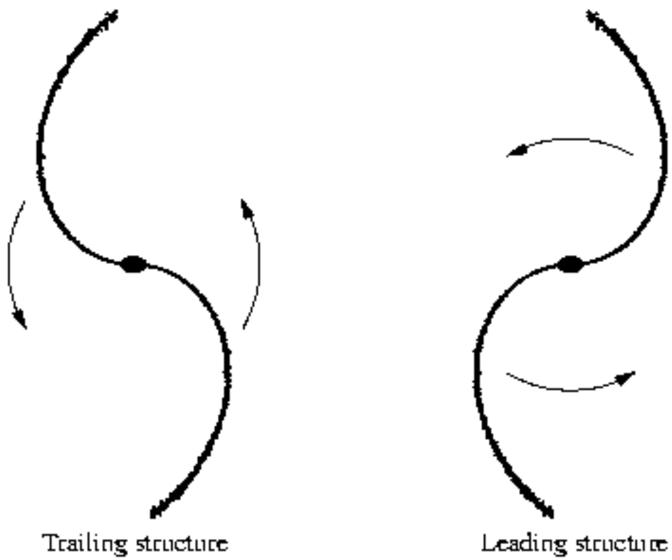
X-ray UV Visible Near-IR Far-IR

Note: large change in appearance between the UV and the near infrared images.

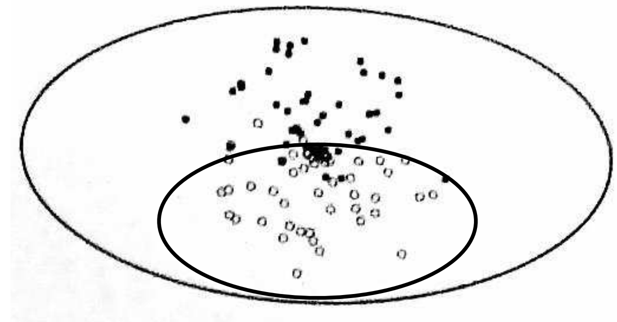
Galaxies look `clumpier' in the UV, and increasingly smooth as we go to the visible and longer wavelengths.

How do the arms in spiral galaxies evolve with time?

Most spiral arms are found to be trailing.

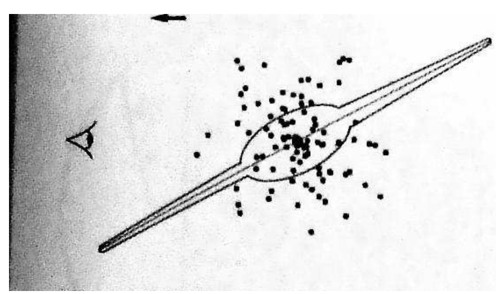


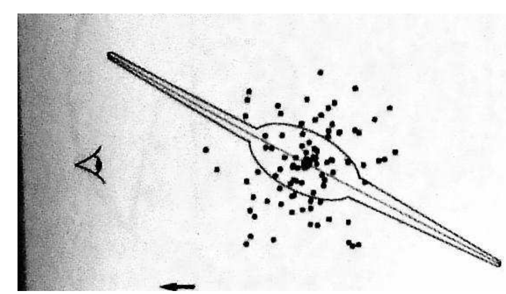
This could be determined by looking at reddening in globular clusters / novae



globular clusters seen around disk galaxy. amount of reddening indicated by whether circles are solid or open

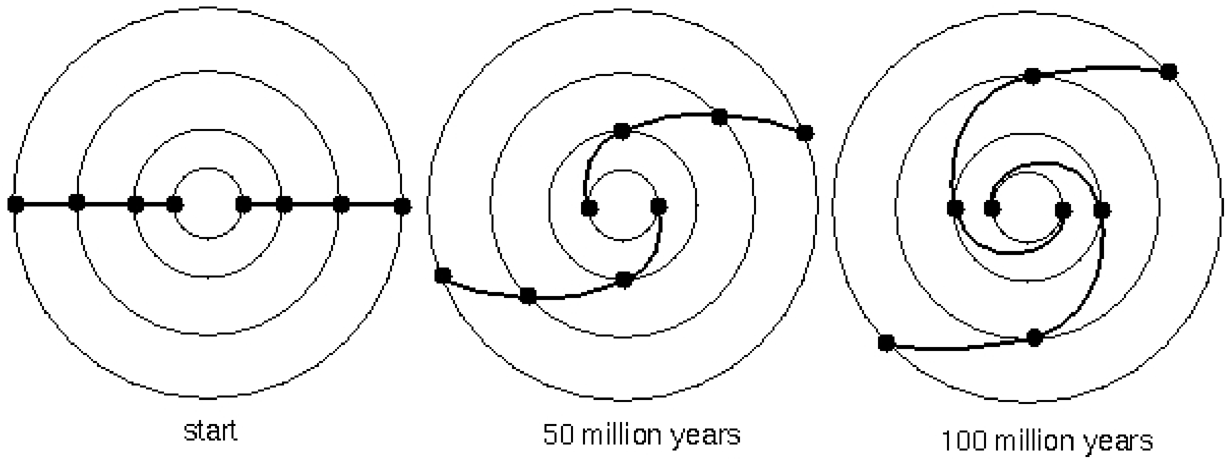
allows us to determine which way a spiral galaxy is tilted.



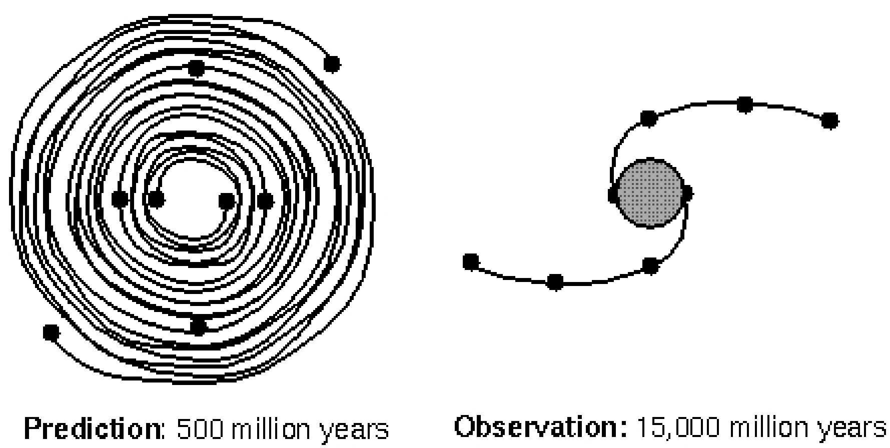


What is nature of the arms in spiral arms?

Do the spiral arms travel at the same speed as the stars? If spiral arms did,one would predict that the spiral arms in a galaxy would wind up very quickly.



Differential rotation: stars near the center take less time to orbit the center than those farther from the center. Differential rotation can create a spiral pattern in the disk in a short time.

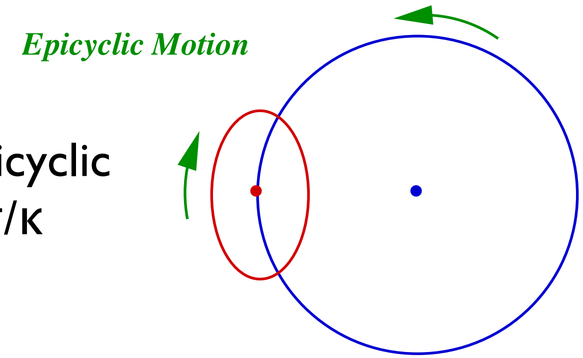


The predicted outcome is in contrast to what is observed!

Stars in Spiral Galaxies are on Epicyclic orbits

The motion can be approximately described as the combination of orbital motion around a disk galaxy and an epicyclic motion in radius:

Frequency of epicyclic motion = 2π/κ



Orbital Frequency around Disk Galaxy = 2π/Ω

The orbital frequency of a star Ω(R) can be written as follows

$$\Omega^2(R) = \frac{1}{R}\left(\frac{\partial\Phi}{\partial R}\right)_{(R,0)} = \frac{L_z^2}{R^4},$$

Meanwhile, the frequency of epicyclic motion κ(R) can be written as follows:

$$\kappa^2(R_g) = \left(R\frac{d\Omega^2}{dR} + 4\Omega^2\right)_{R_g}.$$

The frequency of epicycle motion is very similar to the orbital frequency:

In general, $\Omega < \kappa < 2\,\Omega$

Near the solar system, the epicycle frequency $\kappa \sim 1.3\,\Omega$

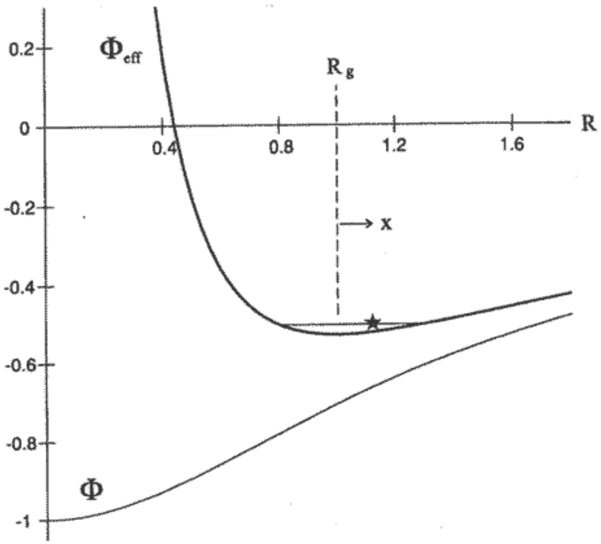


Figure 3.7 Effective potential $\Phi_{\rm eff}$ (upper curve) for a star with angular momentum $L_z = 0.595$, orbiting in a Plummer potential Φ_P (lower curve). The scale length $a_P = 1$; L_z is in units of $\sqrt{G\mathcal{M}a_P}$; units for Φ and $\Phi_{\rm eff}$ are $G\mathcal{M}/a_P$. The vertical dashed line marks the guiding center R_g; the star oscillates about R_g between inner and outer limiting radii.

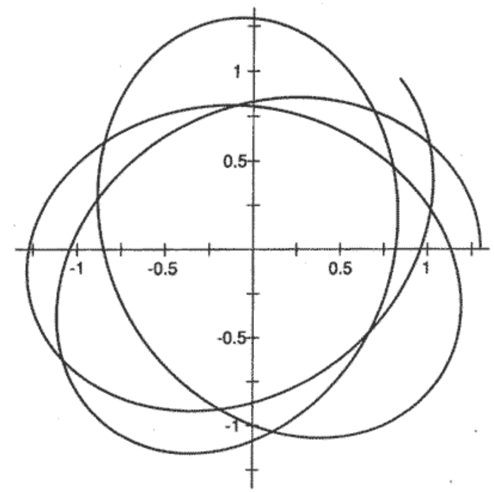
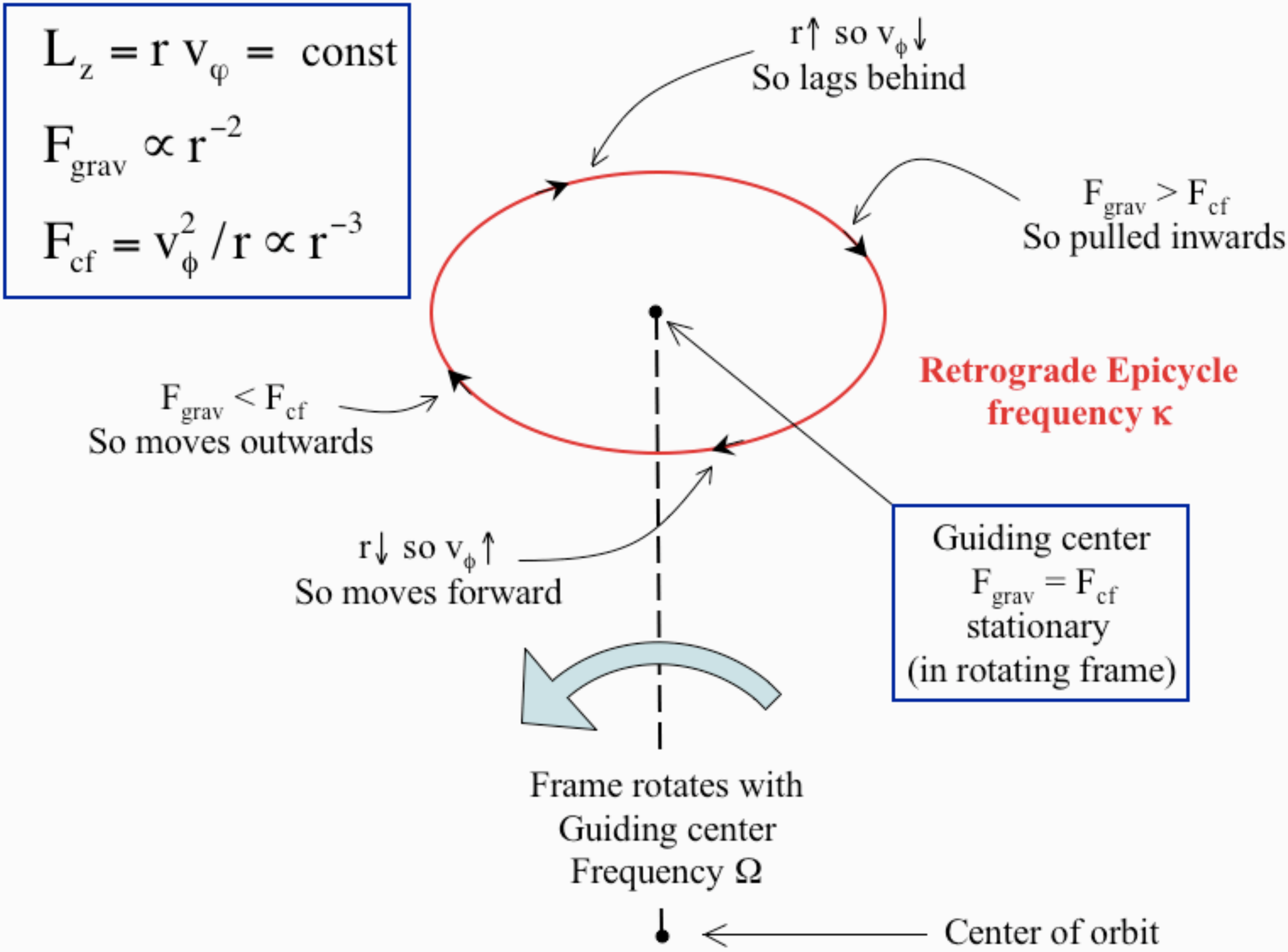


Figure 3.9 Path of the star of Figure 3.7, viewed from above the Galactic plane; the orbit started with ($R = 1.3$, $\phi = 0$) and ($\dot{R} = 0$, $R\dot{\phi} = 0.4574$).



$L_z = r\,v_\varphi = \text{const}$
$F_{grav} \propto r^{-2}$
$F_{cf} = v_\phi^2 / r \propto r^{-3}$
r↑ so v_ϕ↓
So lags behind
$F_{grav} > F_{cf}$
So pulled inwards
Retrograde Epicycle
frequency κ
$F_{grav} < F_{cf}$
So moves outwards
r↓ so v_ϕ↑
So moves forward
Guiding center
$F_{grav} = F_{cf}$
stationary
(in rotating frame)
Frame rotates with
Guiding center
Frequency Ω
Center of orbit

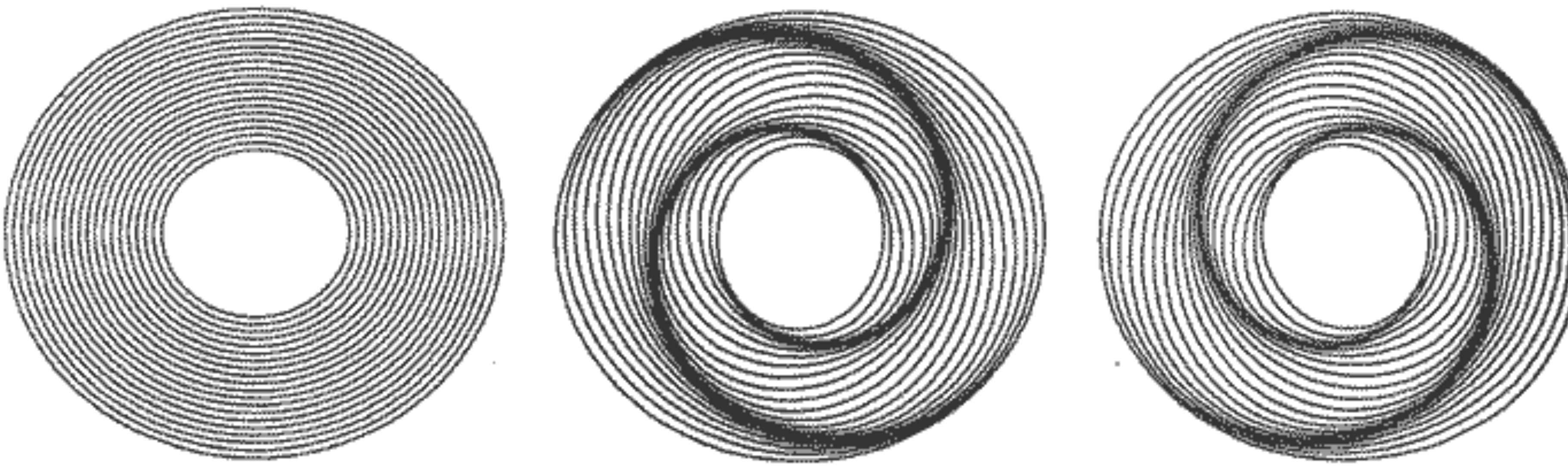
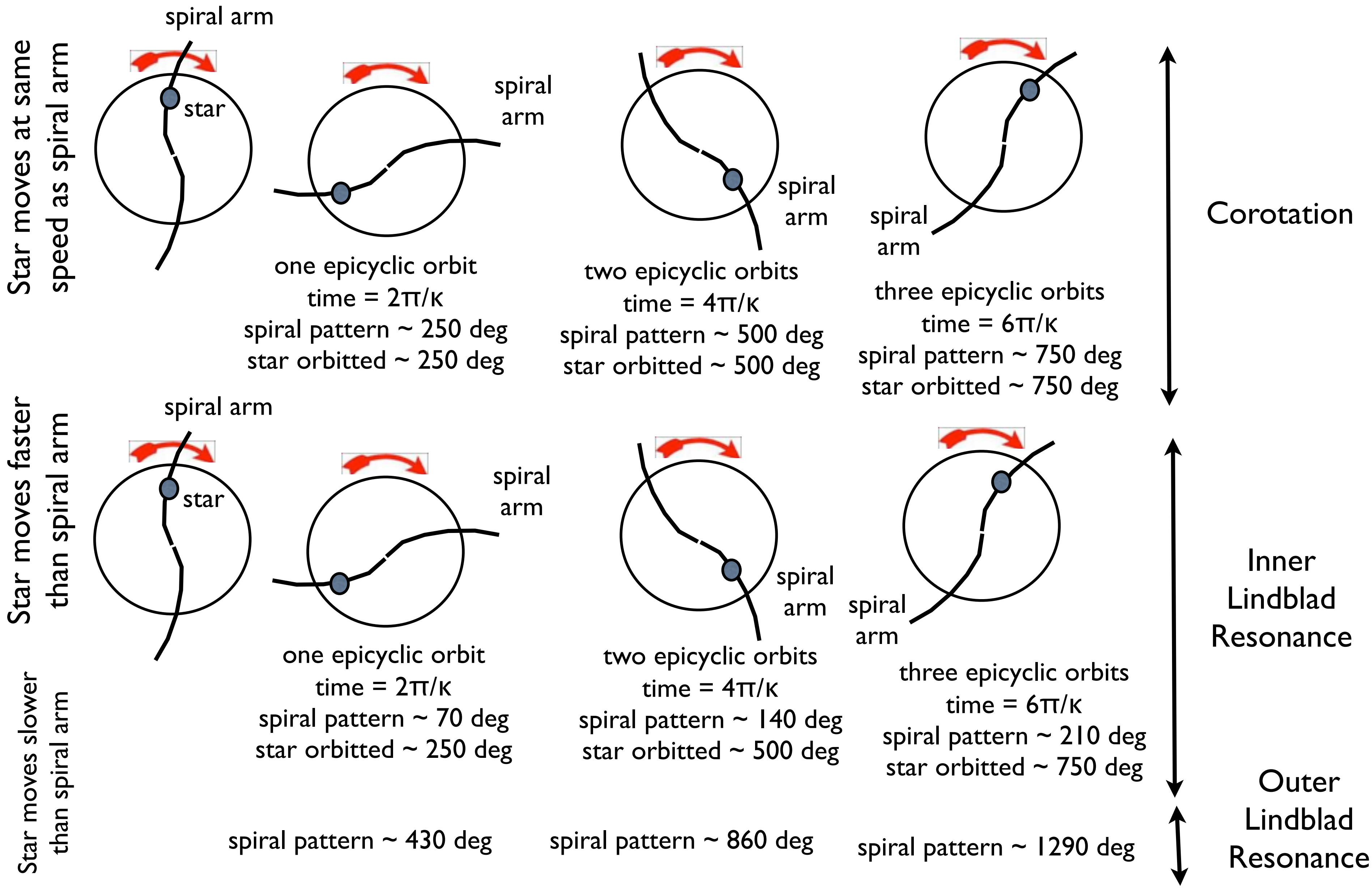


Figure 6-11. Arrangement of closed orbits in a galaxy with $\Omega - \frac{1}{2}\kappa$ independent of radius, to create bars and spiral patterns (after Kalnajs 1973).

Let’s consider snapshots in time where the star completes an entire epicyclic orbit. Typically a star must complete 70% of a revolution around a galaxy before this happens.



Resonances can occur to reinforce structure in spiral arms of galaxies, if the epicyclic frequency of a stellar orbit is similar to the frequency at which a star orbitting around the galaxy encounters a spiral arm.

some integer

$$n\kappa = m\overbrace{(\Omega_p - \Omega)}^{\text{frequency at which orbiting stars encounter spiral arms}}$$

Epicyclic Frequency

# of Spiral Arms

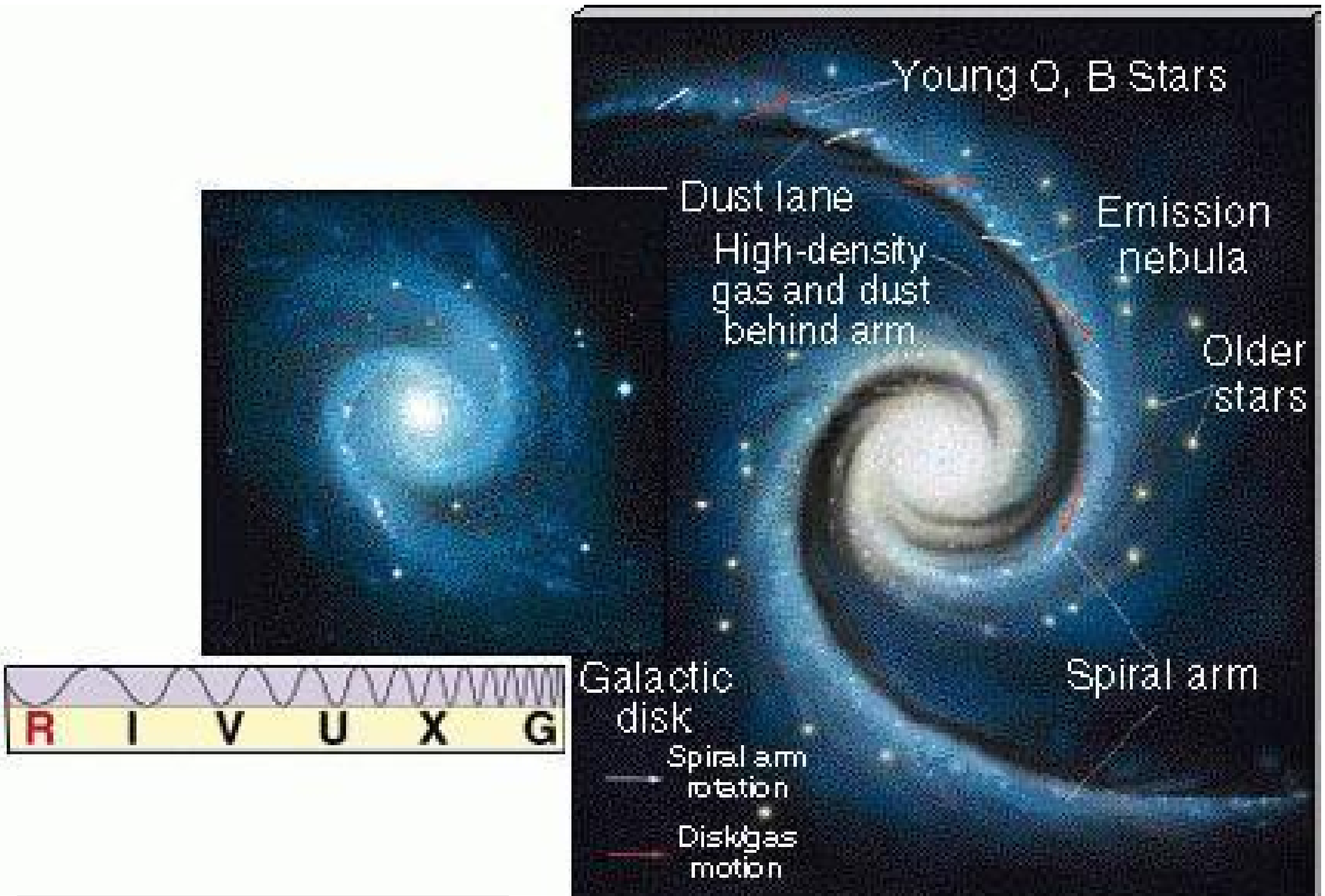
Orbital Frequency of Spiral Arms

Orbital Frequency of Stars on Circular Orbits

The only integers n for this relation that are interesting are 0, +1, -1.

Density Wave Theory

What astrophysical processes occur in these spiral density waves as they rotate around a spiral disk?



Credit: van der Kruit

the hot stars are somewhat ahead of the gas/ dust lane, since there is some time lag between when gravitational collapse begins and when the stars finally form (i.e., are on the main sequence)

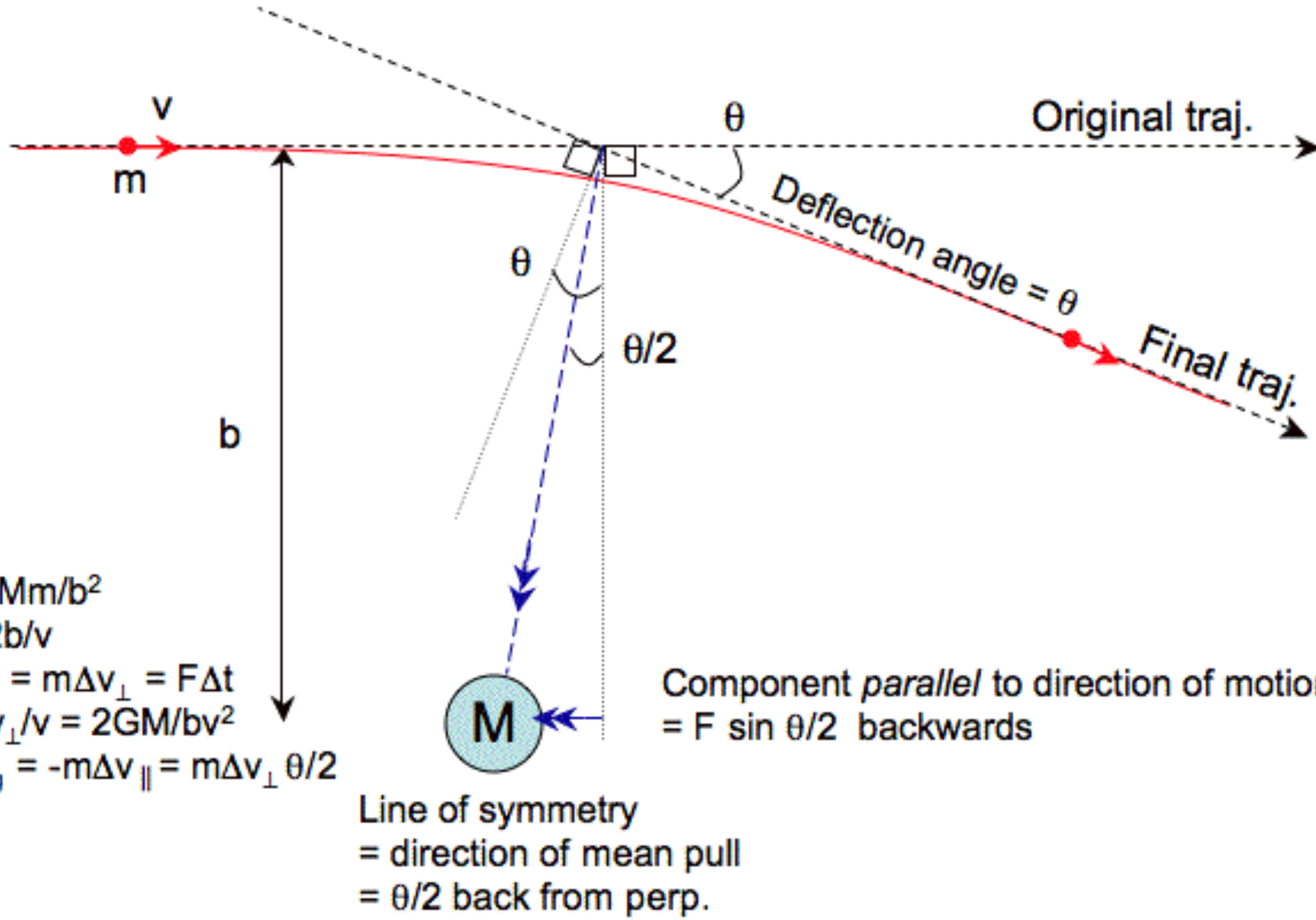
at inner radii in spiral galaxies, stars travel faster than the spiral density wave.

gas and dust lanes (formed from the metal output of the supernovae explosions) indicate the position of the high density spiral density wave

hot (massive) stars do not travel much beyond the spiral density wave in which they are formed

it is only the old (low mass) stars that can travel far enough to get ahead of the spiral wave

Dynamical Friction II



$F = GMm/b^2$

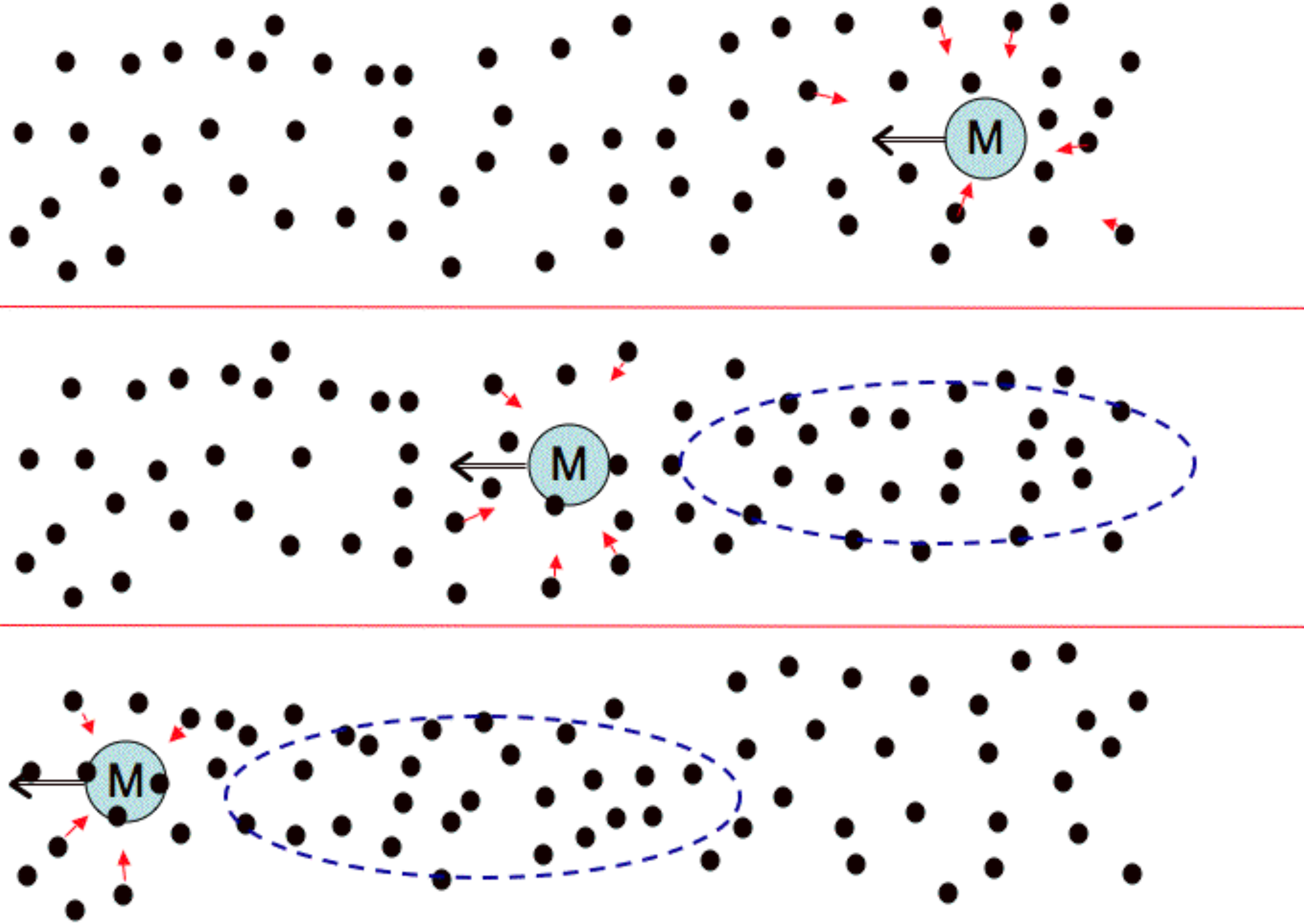
$\Delta t = 2b/v$

$M\Delta V_\perp = m\Delta v_\perp = F\Delta t$

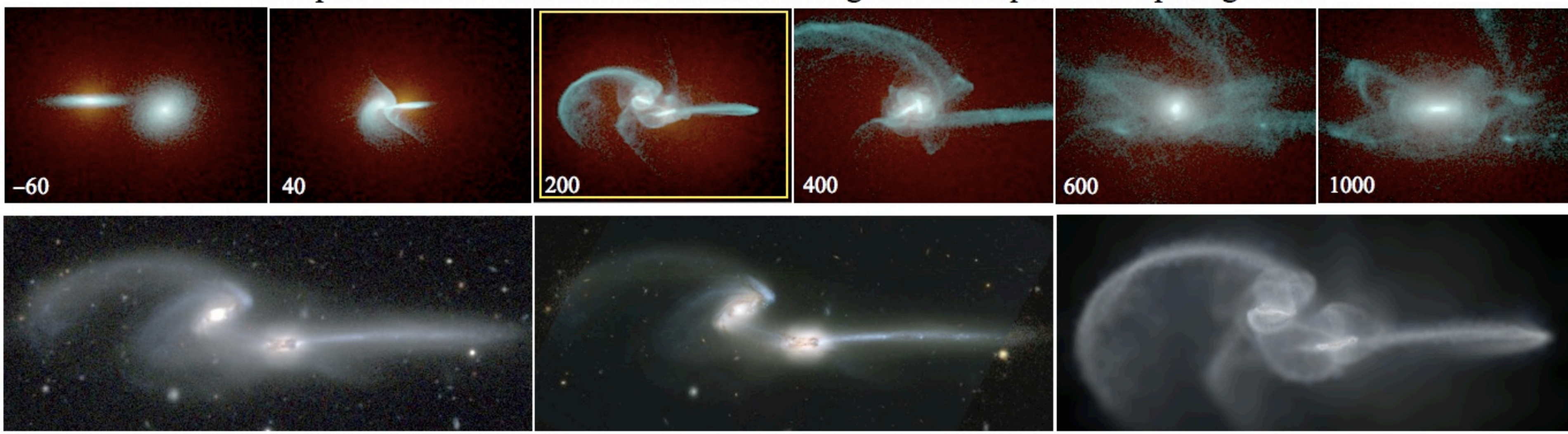
$\theta = \Delta v_\perp / v = 2GM/bv^2$

$\Delta F_{drag} = -m\Delta v_{\|} = m\Delta v_\perp \, \theta/2$

Dynamical Friction I



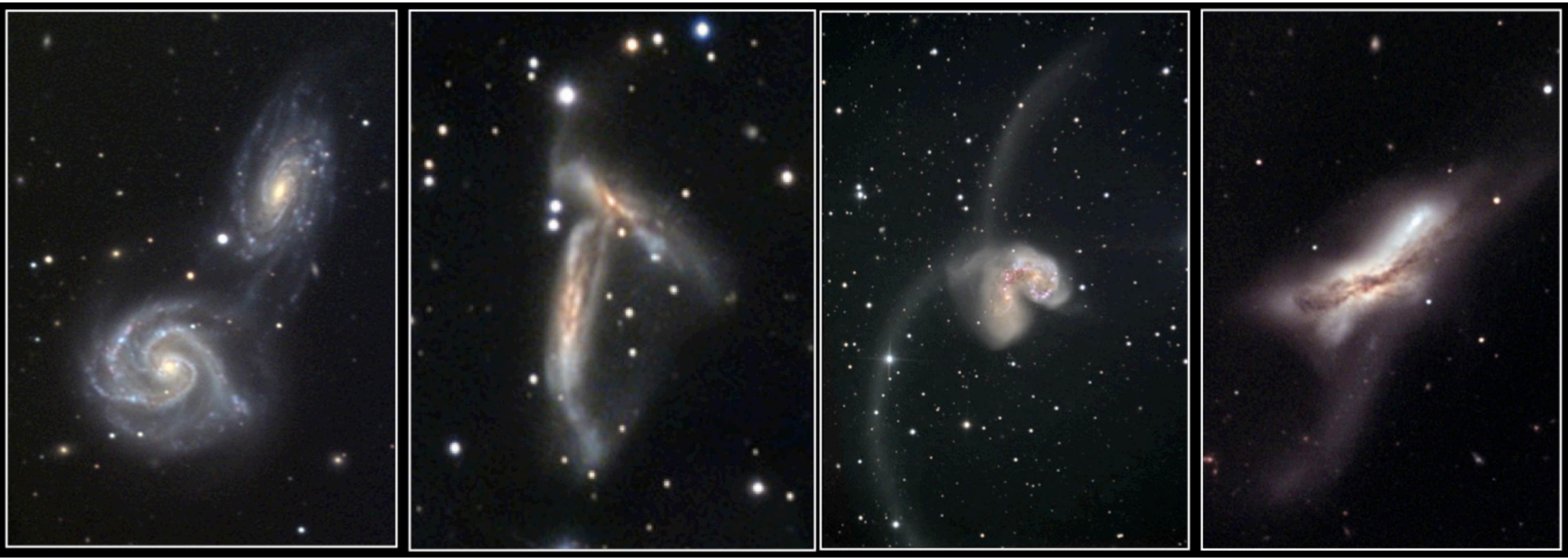
Computer calculation of the collision and merger of two equal-sized spiral galaxies

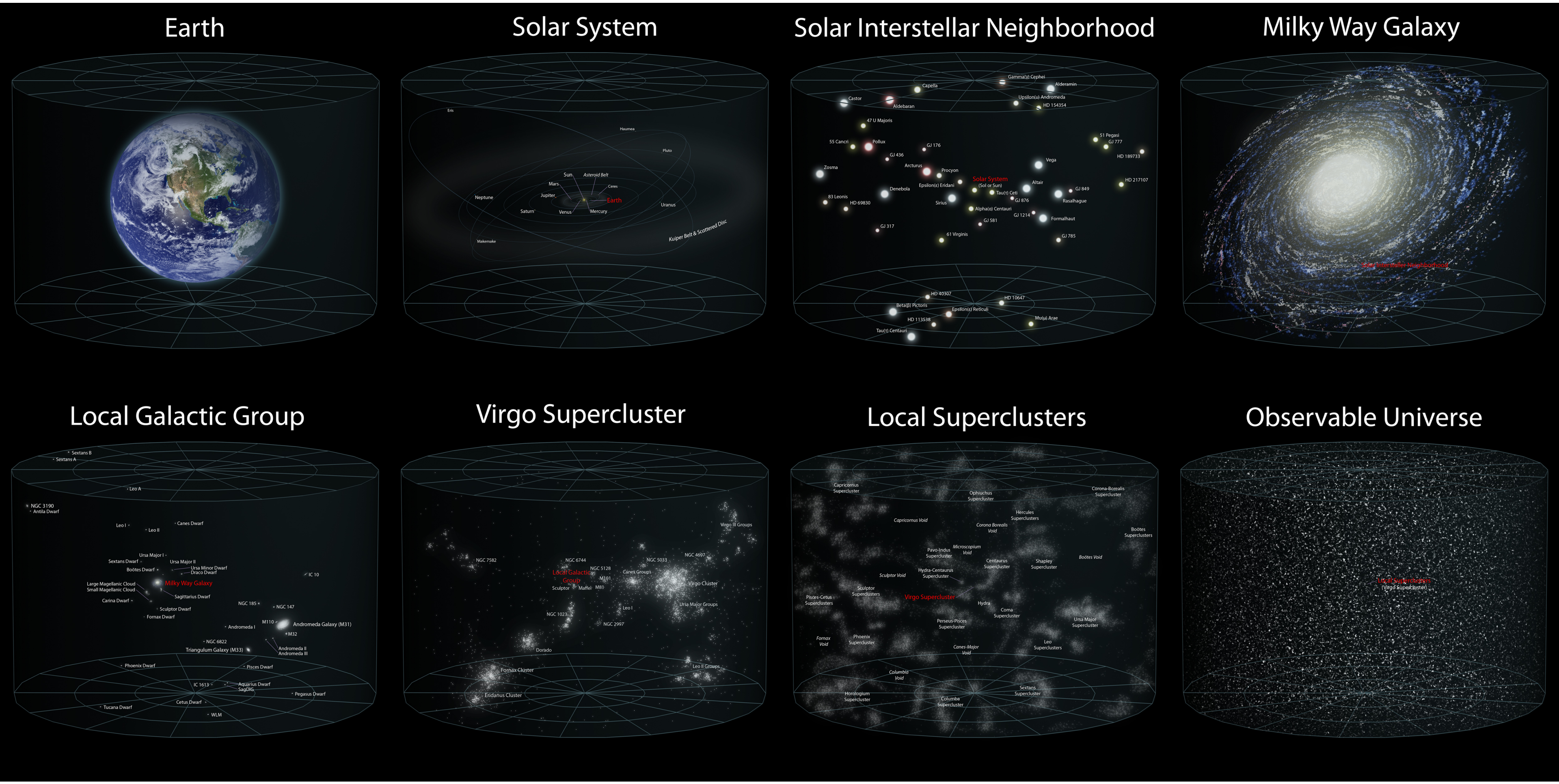


The Mice: ground-based image

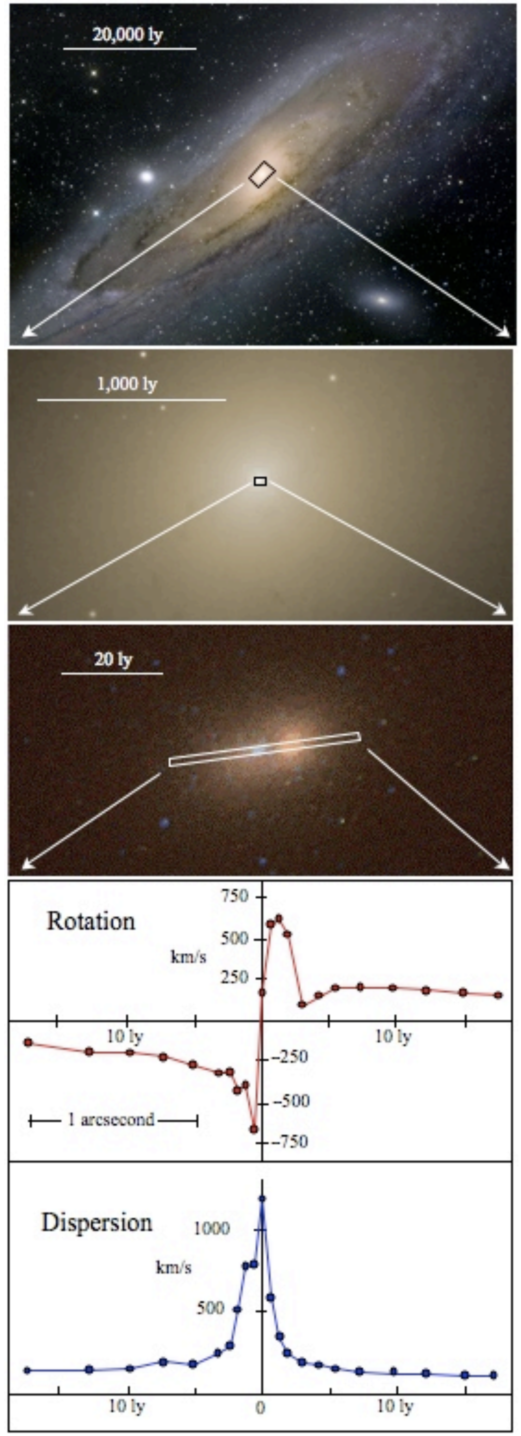
The Mice: Hubble Space Telescope

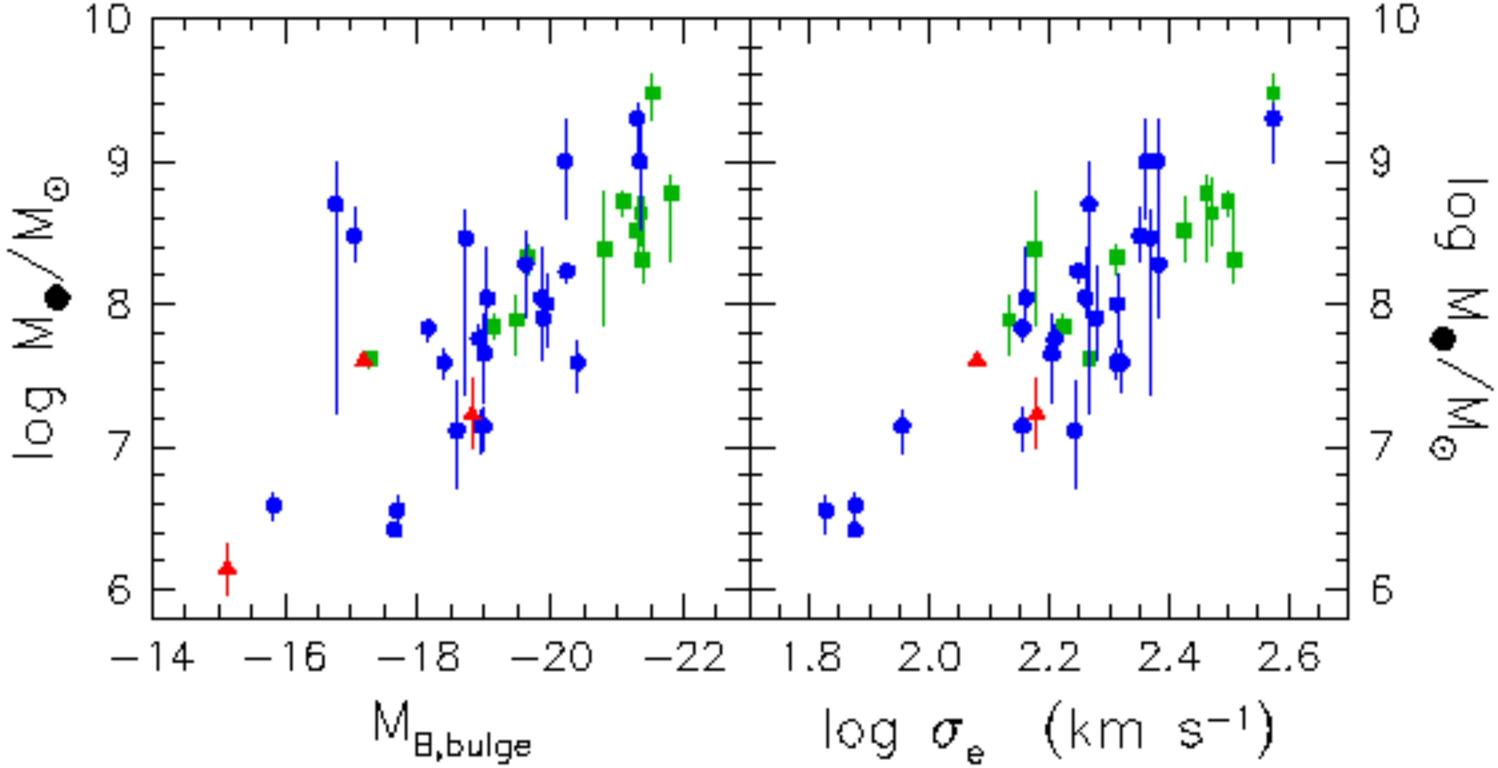
More sophisticated calculation




Earth
Solar System
Solar Interstellar Neighborhood
Milky Way Galaxy
Local Galactic Group
Virgo Supercluster
Local Superclusters
Observable Universe
Kuiper Belt & Scattered Disc
Milky Way Galaxy
Andromeda Galaxy (M31)
Triangulum Galaxy (M33)
Virgo Cluster
Fornax Cluster
Eridanus Cluster
Virgo Supercluster

M31
Andromeda





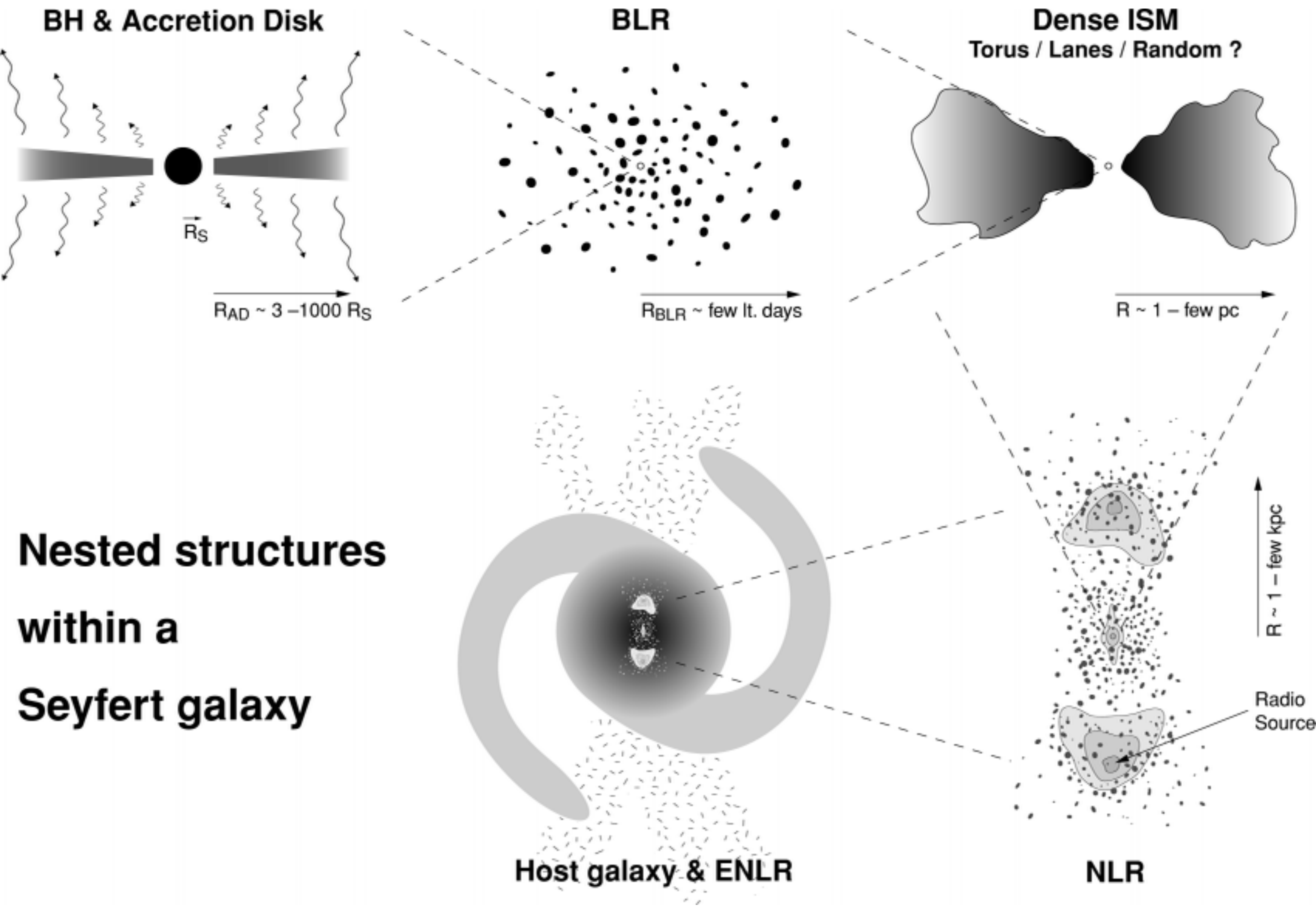
log $M_\bullet/M_\odot$
$M_{B,\mathrm{bulge}}$
log σ_e (km s^{-1})
log $M_\bullet/M_\odot$

Classes of AGN

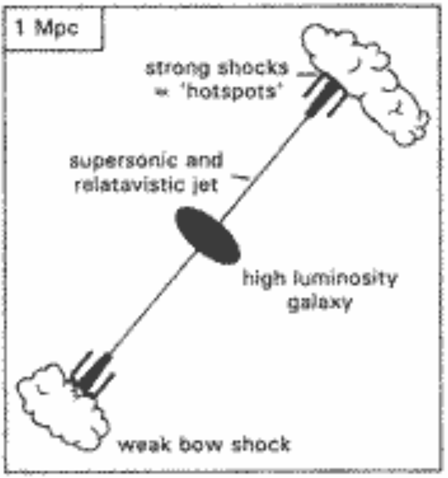
Radio Luminosity	Emission Lines	$L_N \gtrsim L_{gal}$	$L_N \lesssim L_{gal}$	$L_N << L_{gal}$
Radio Quiet $L_R \lesssim 10^{-4} L_{opt}$	Broad + Narrow	RQ QSO	Seyfert 1	LINER 1.9 LINER/ Seyfert 2
			1.5	
	Narrow Only	[NLQSO]	Seyfert 2	
	None	------	------	
Radio Loud $L_R \gtrsim 10^{-2} L_{opt}$	Broad + Narrow	RL QSO [QSR]	BLRG	PRG Weak lines LINERs
	Narrow Only	------	NLRG	
	None	Blazar [BL Lac] (OVV, HPQ)	------	

RQ-AGN host galaxies are usually: Early type Spirals (often disturbed)

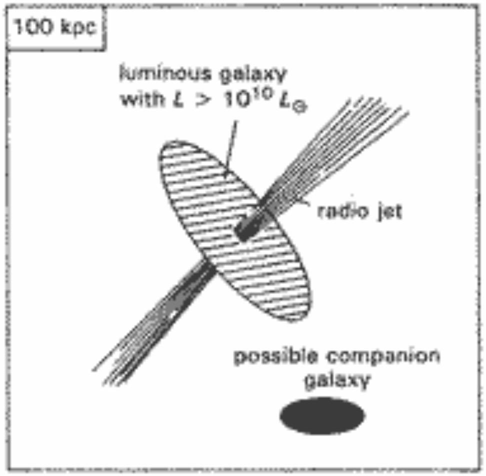
RL-AGN host galaxies are usually: S0 or Ellipticals (often with nuclear dust lanes)



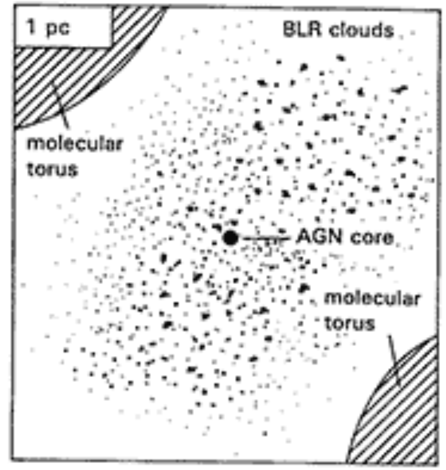
BH & Accretion Disk
$\vec{R}_S$
R_{AD} ~ 3 –1000 R_S
BLR
R_{BLR} ~ few lt. days
Dense ISM
Torus / Lanes / Random ?
R ~ 1 – few pc
Nested structures
within a
Seyfert galaxy
R ~ 1 – few kpc
Radio
Source
Host galaxy & ENLR
NLR



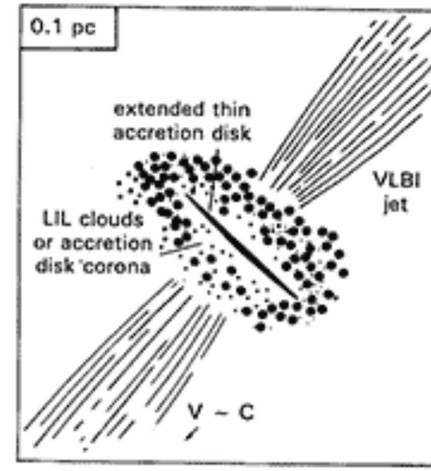
Extended radio sources — shown is an FRII source with an edge-brightened structure. The FRIs have lower jet velocities and fade-out to the ends.



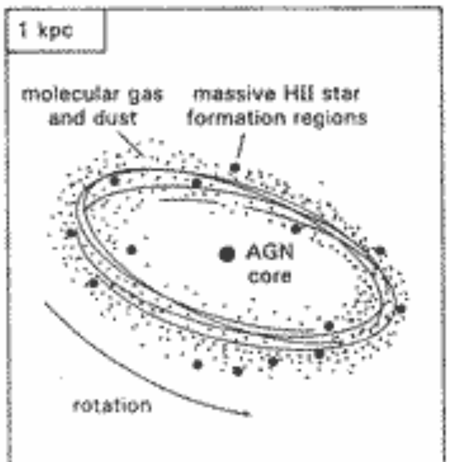
The host galaxy. Although shown as an early type galaxy with a smooth profile, it could also be highly irregular with multiple nuclei as a result of merging.



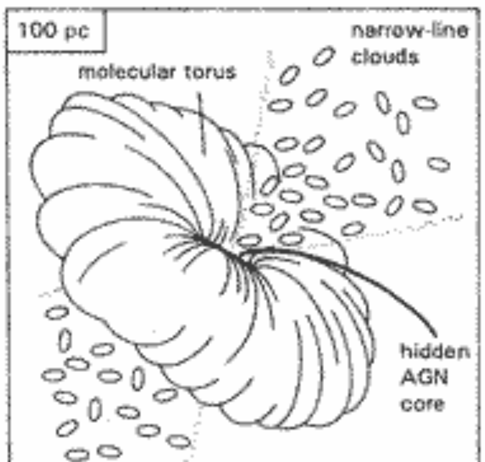
The outer extent of the broad-line region and the deep-walled molecular torus which can provide an effective shield of the central AGN, depending on the relative orientation of the observer.



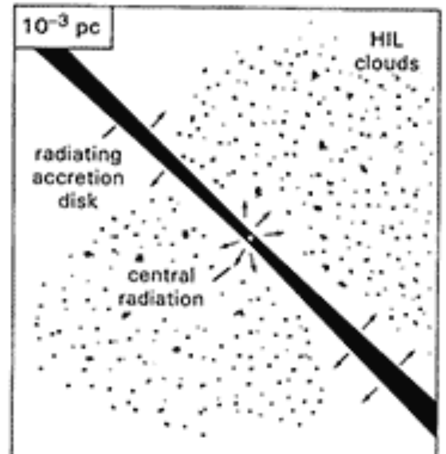
Inside the molecular torus — the VLBI jet becomes self-absorbed closer in, and the low ionization lines of the BLR, which might be the corona of the accretion disk.



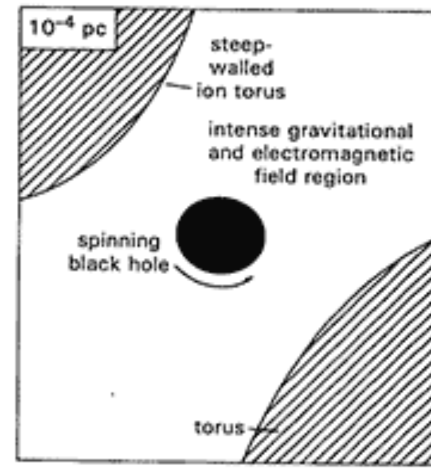
The central kpc star formation disk. This strong far infrared emitting zone might be fed by a bar structure, as seems to be the case for NGC1068.



The narrow-line region comprising small but numerous clouds of the interstellar medium ionized by the central AGN core.



The accretion disk which radiates strongly at UV and optical wavelengths. The high ionization clouds of the BLR are excited by the central continuum radiation field.



The black hole. The Schwarzschild radius for a 10^8 $M_\odot$ black hole is 2 AU (10^{-5} pc). The spin will introduce twisted magnetic field lines and particle acceleration.

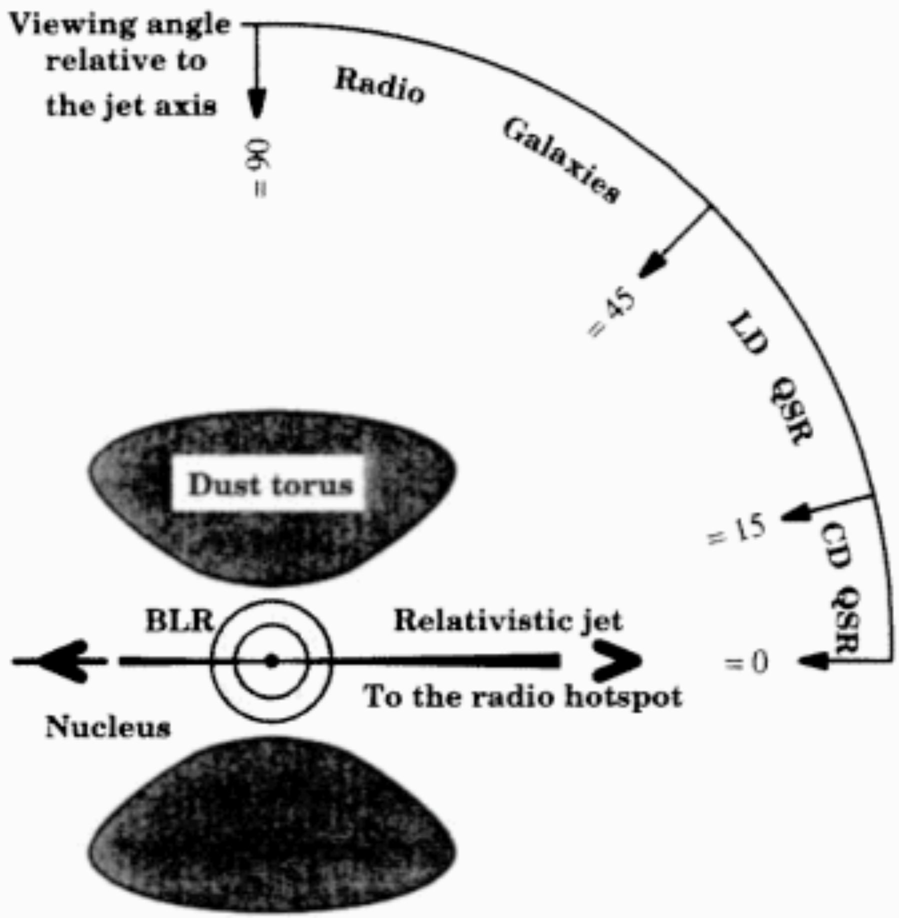


Fig. 12.4. Schematic representation of the unified model for radio galaxies and quasars. BLR: broad line region. CD: core-dominated quasars. LD: lobe-dominated quasars. Figure kindly provided by R. Athreya.