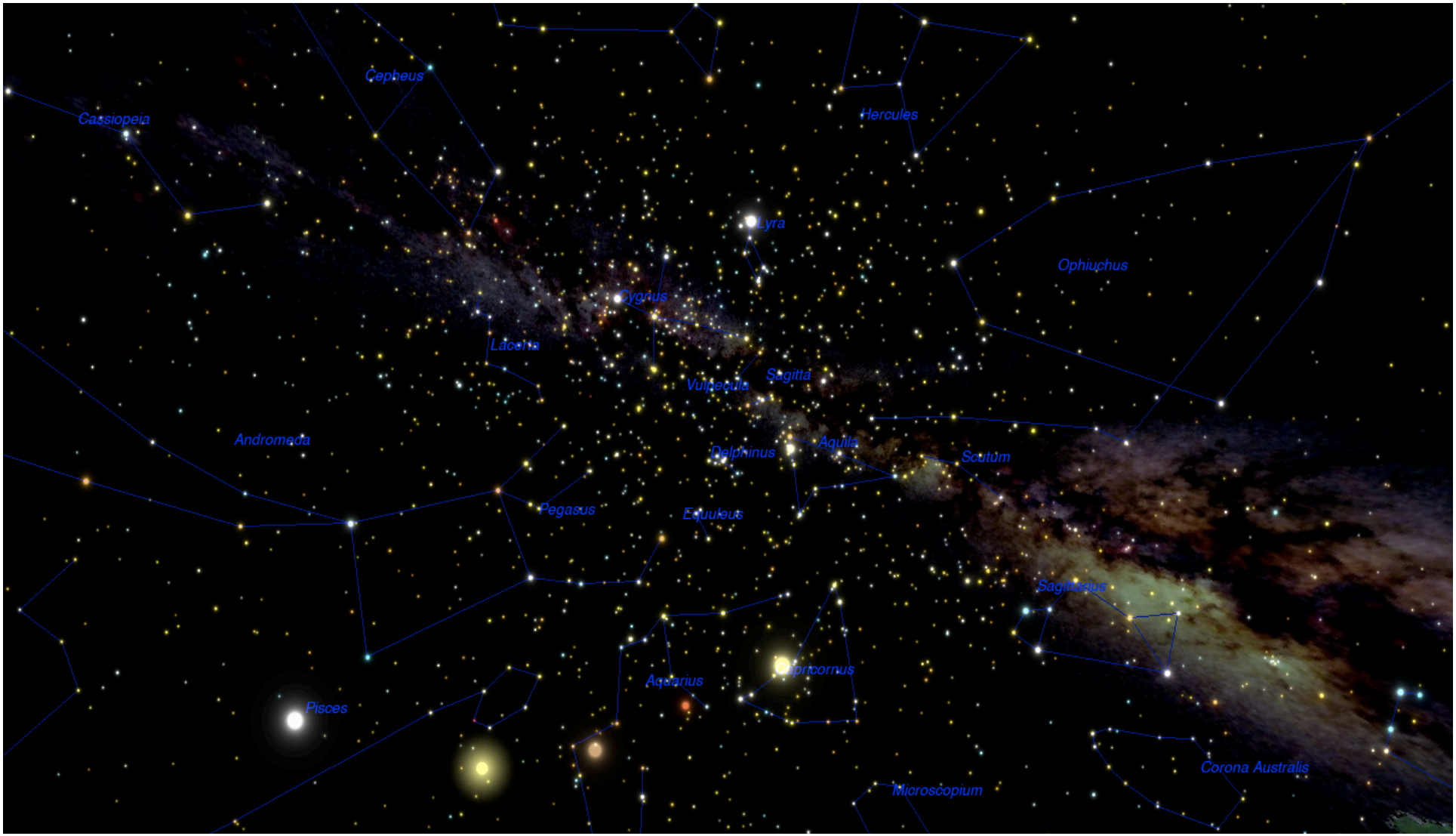
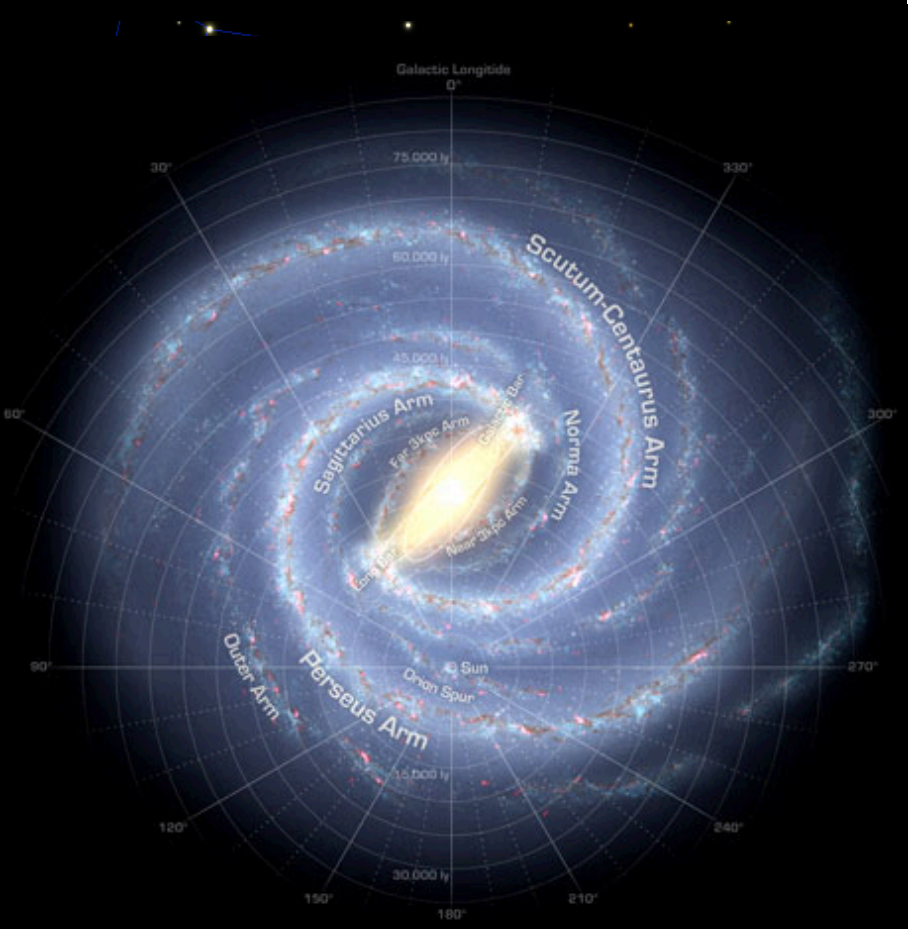
The Milky Way

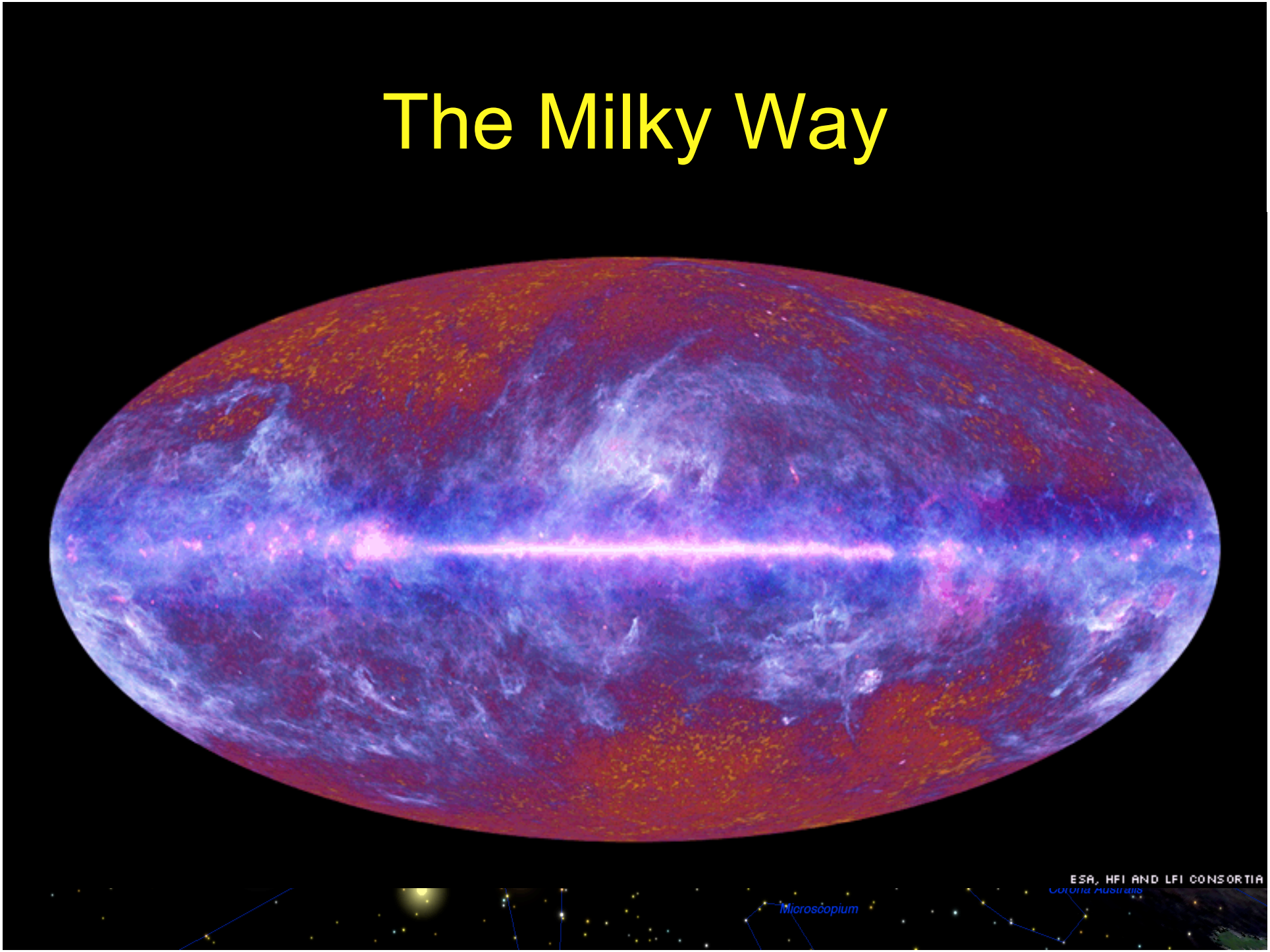


The Milky Way

- Ingredients
  - Stars
  - Star remnants: Dwarfs, pulsars, black holes
  - Interstellar gas and dust
  - Central black hole
  - Dark matter (WIMPs?)
- Structure
  - Central black hole
  - Central “bulge”; ”bars”?
  - Disk with spiral arms (thin and thick components)
  - Halo (old, metal poor stars, globular clusters, “MaCHOs”)



The Milky Way



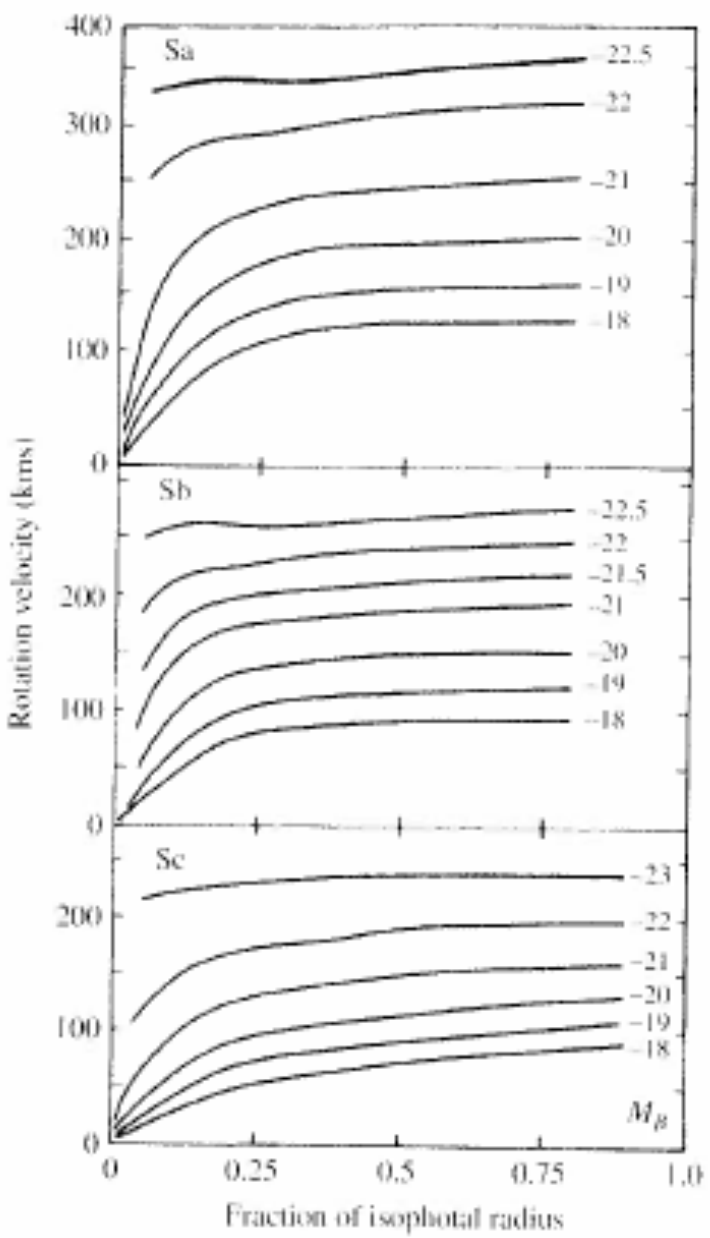
Distribution and Proper Motion of Stars in the Milky Way

- Use parallax to measure distance to “nearby” stars (up to 200 pc => 20% precision); further away: Use magnitude-temperature (main branch) or magnitude-variability correlation (Cepheids)
- Measure “sideways” motion by detecting angular displacement over time (after subtracting parallax)
- Measure radial motion using Doppler effect
- => get local distribution in space, relative velocities of 50 km/s average (exception: Kapteyn’s star - 300 km/s => Halo star)
- Grand picture: find our position and motion relative to far-away halo stars (clusters) (all very old; well known magnitude)
- Result: Sun is about 8 kpc away from center of Milky Way, moving with 220 km/s around that center
- Surprise! All other parts of the Milky way seem to ALSO have that same approximate velocity!

Consequences

- 220 km/s = 225 pc/Myr => ω = 0.028 rad/Myr
  => One revolution takes 224 Myr (20 times since sun came into being)
- $\omega^2 = GM/r^3$ => $M \approx 10^{11}\ M_{sun}$
- since ωr is roughly constant, M increases like r
- Little paradox: Why haven't the spiral arms been "wound tightly around the center"? My guess: They don't represent actual motion of stars, but rather compression "wave" of luminous gas where new stars are born (while older stars fall behind)
- BIG paradox: Lots more mass than visible stars; constant $v = \omega r$ extends much beyond "visible" edge *)

1 pc = $3 \cdot 10^{16}$ m *) Most of the visible mass lies within sun's radius ($2 \cdot 10^{10}\ L_{sun}$)

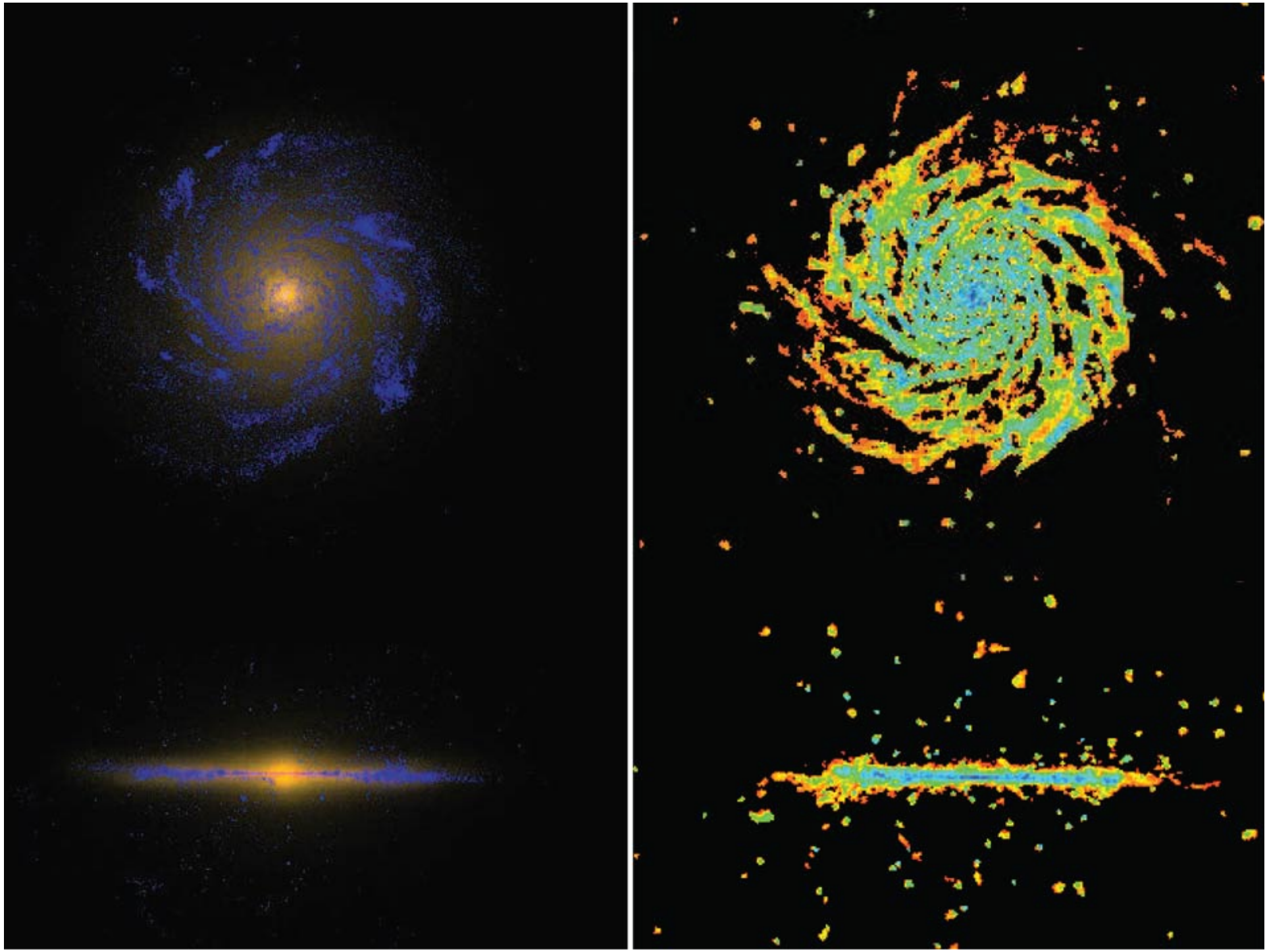


Another view of the Milky Way

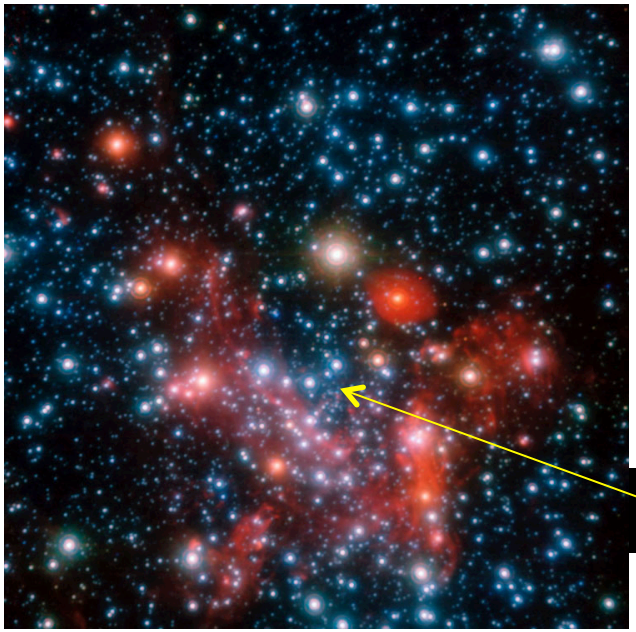
Rotation curves for different types of galaxies, as function of absolute magnitude

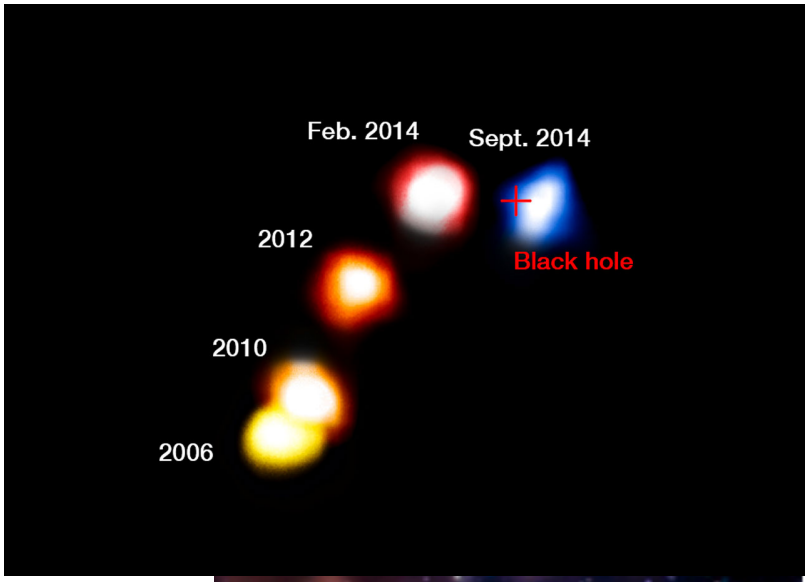
=> Dark Matter

- Candidates:
  - MaCHOs: Brown dwarfs, white dwarfs, black holes; Can be detected through gravitational lensing: Some are there, but probably not enough
  - Neutrinos: We know how many there must be, but they have too little mass
  - Dust etc.: Would be visible in IR or radio
  - WIMPs! (Weakly Interacting Massive Particles) = new type of matter, not yet discovered; probably more massive than a U atom but only interacting via weak force and gravity (neutral!); “Neutralinos” predicted by Supersymmetry => Wait for CERN’s LHC



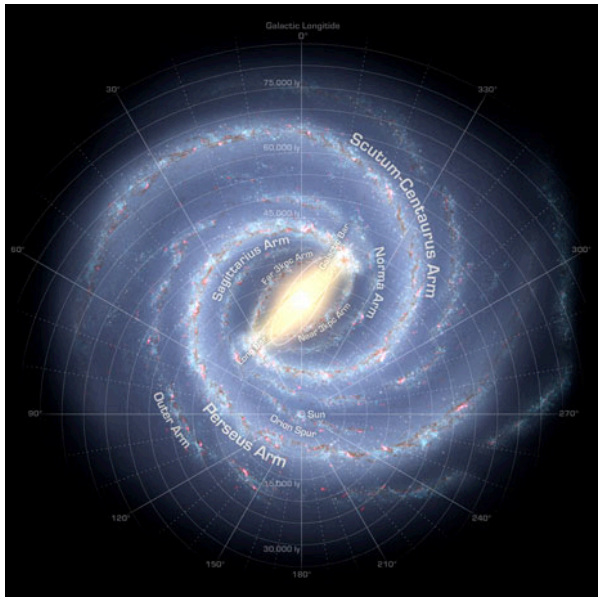
What about the Center?

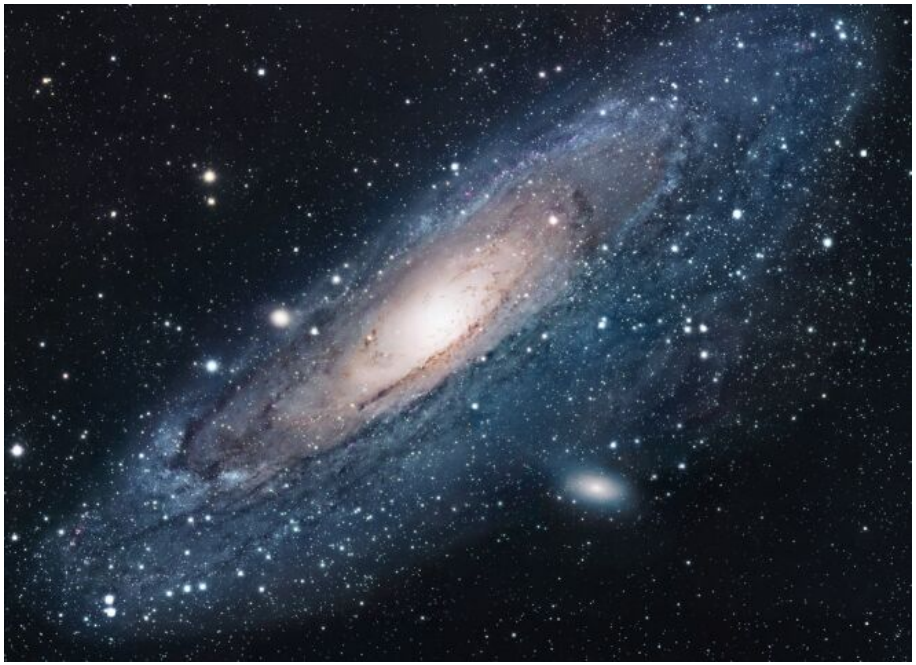


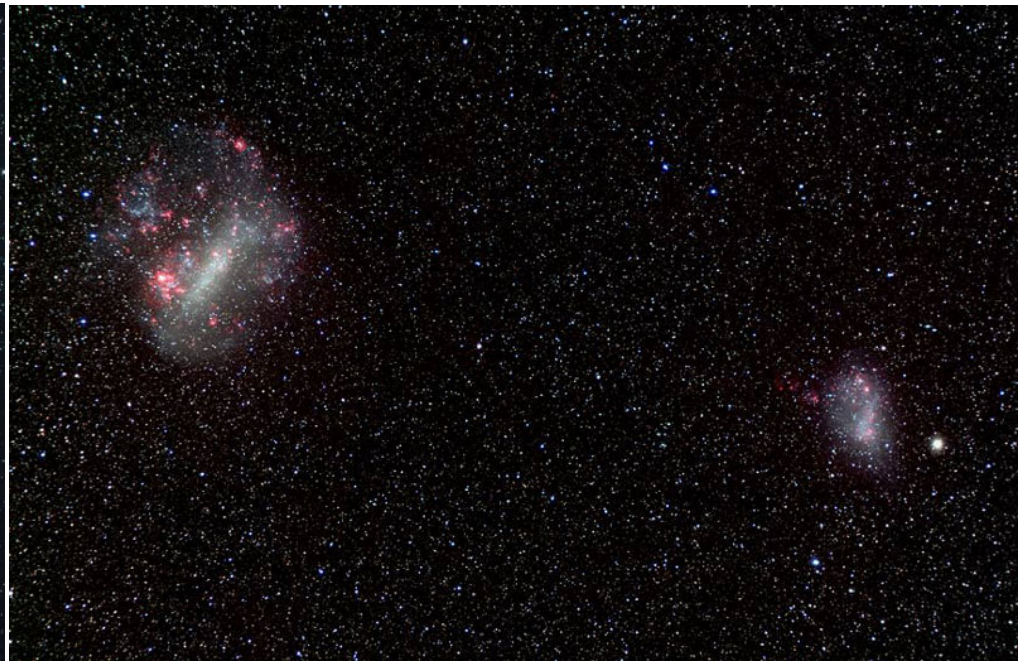


- invisible for light (too much dust in the way)
- visible in IR and radio waves (see image)
- Star density 10^8 times larger (collisions not negligible!)
- Highly compact radio source
- < 6 AU in size! (angular resolution in radio band, time resolution in X-rays)
- High luminosity (> 1000 suns)
- Motion of nearby stars + Kepler's Law => $M = 4 \cdot 10^6\ M_{sun}$
- Black hole!
- Schwarzschild radius = 0.07 AU
- Mass influx of order M_{sun}/3000yr

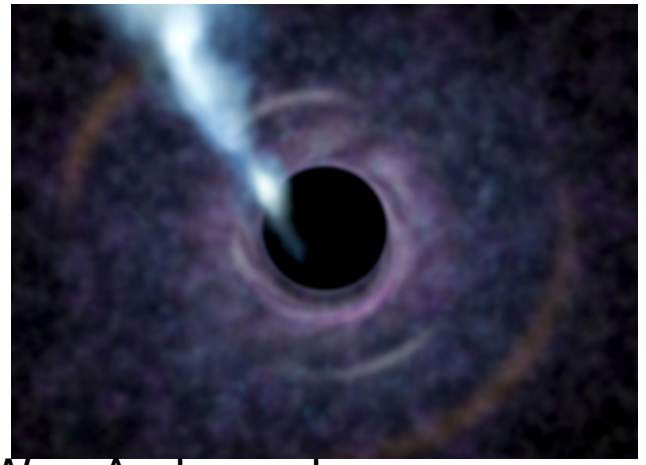
What about the other galaxies?



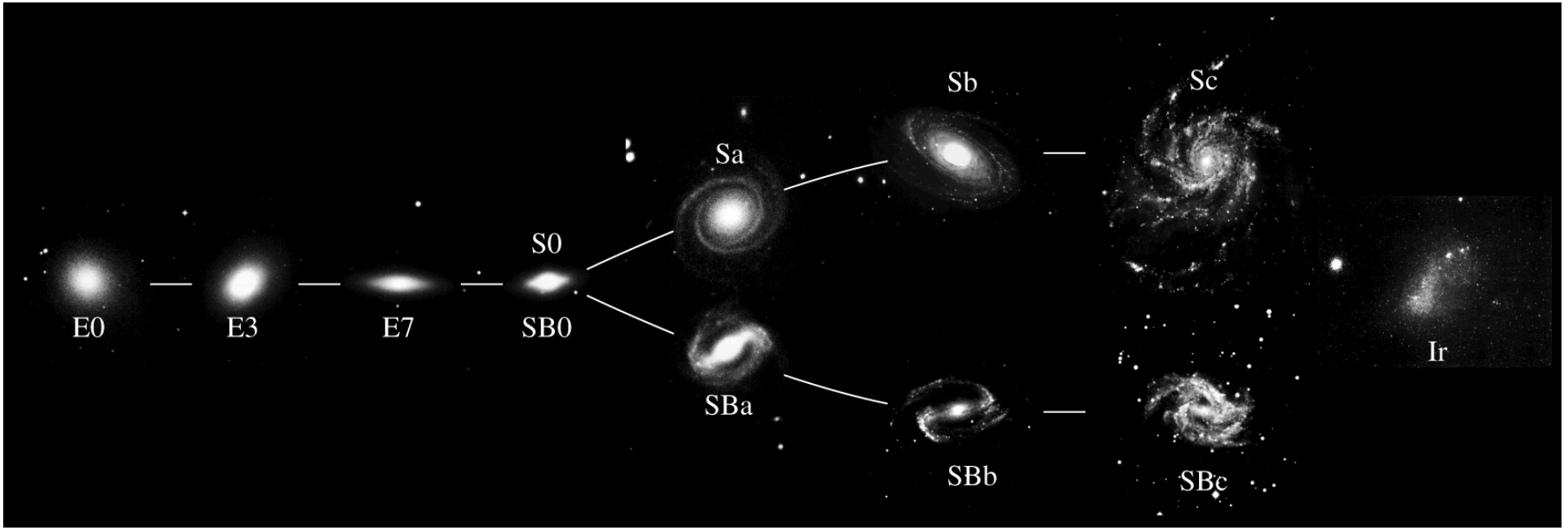


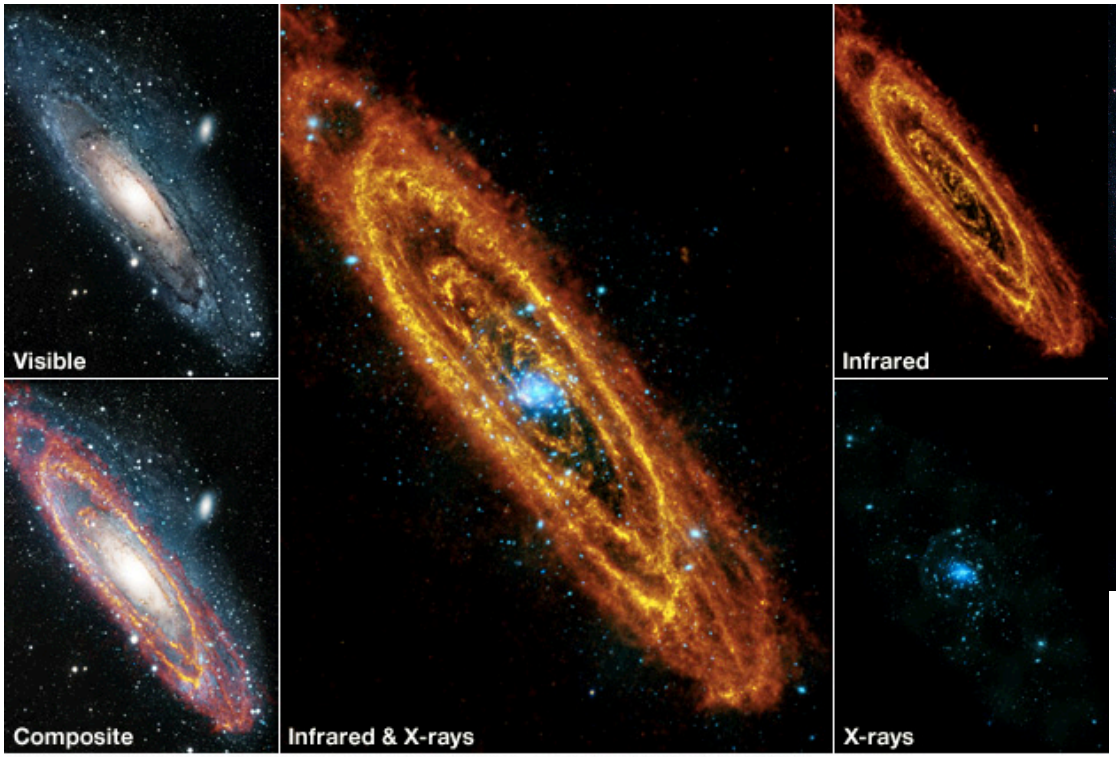


What about the other galaxies?



- 3 major types:
  - Spiral (with and without central “bar”) - Milky Way, Andromeda,…
    - mostly larger (10^9 - 10^{12} M_{sun}, 5 - 100 kpc)
  - Irregular (similar, but not much structure) - Large Magellanic Cloud…
  - Elliptical (see next slide)
  - Probably all have central black holes





Source: ESA/Herschel/PACS/SPIRE/J.Fritz,UGent/XMM-Newton/EPIC/OM/W.Pietsch/MPE

Messier 51, “Whirlpool galaxy”. Picture courtesy Josh Frechem ©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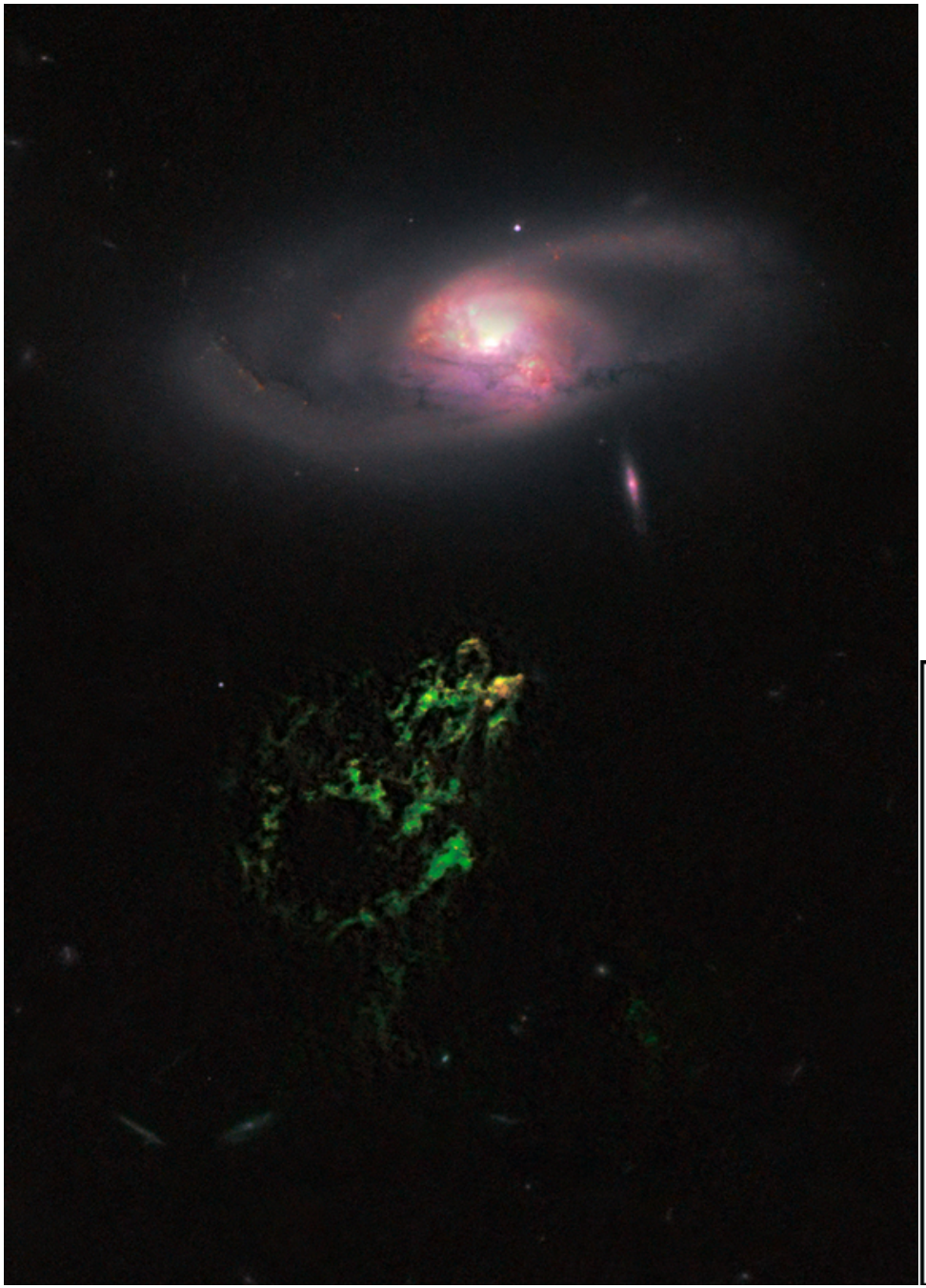


Hanny's Voorwerp

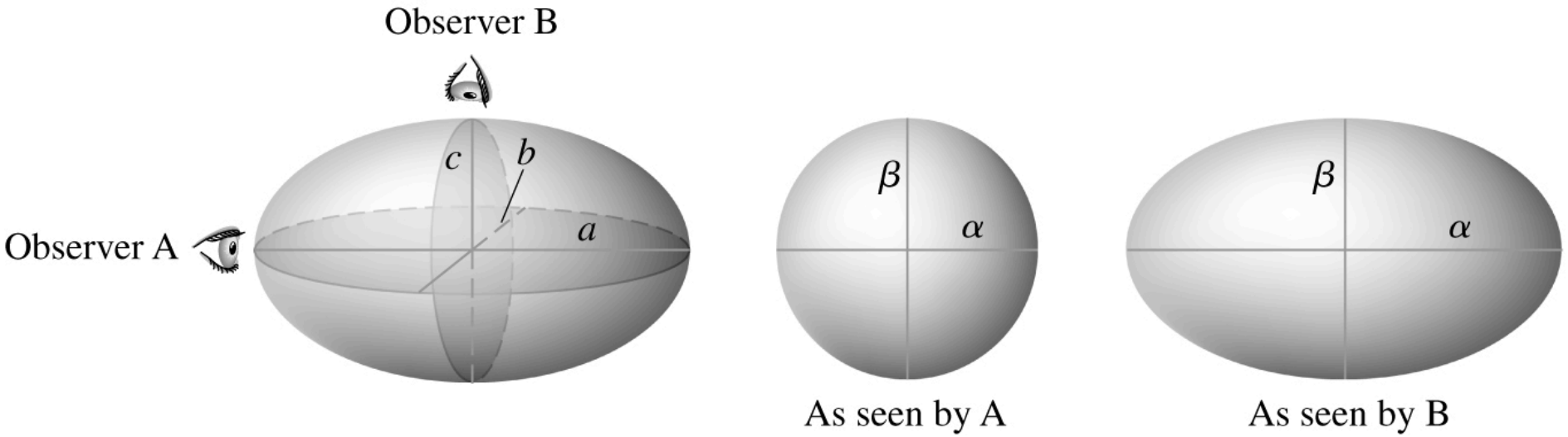
Arms without a galaxy?
(Giving birth to new stars)

Pinwheel galaxy

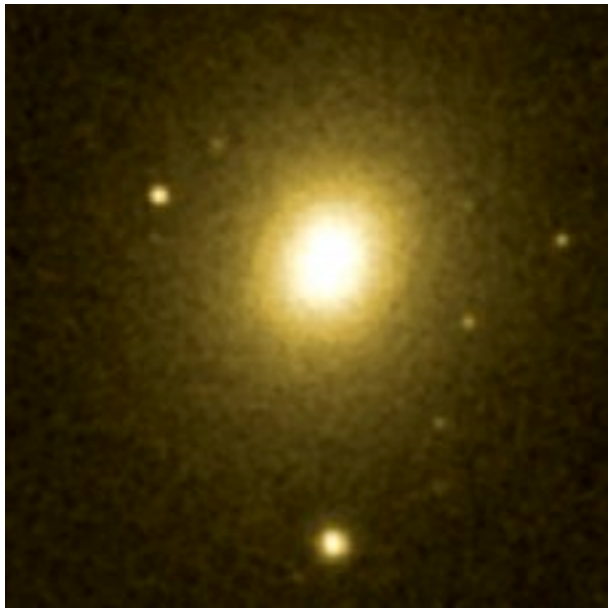
showing star formation in red arms (far from center)

Elliptical galaxies

- Mostly structure-less, range from humongous (100's of kpc, 10^{13} M_{sun}) to tiny (globular cluster size; those are the most frequent)
- Tend to contain "older stars" (and therefore may be older themselves)
- Some gas and dust, but less than spirals
- Star motion mostly random, little correlated rotation
- "True" eccentricity can't be established easily - the most eccentric **observed** has $\varepsilon = 0.7$ (but any given galaxy could be more eccentric then it appears)



Elliptical galaxies

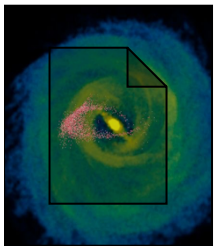


- Recent discovery: Elliptical galaxies may contain a lot more red dwarfs than previously thought (maybe 10x as many as the Milky Way)
  - Milky Way: 100 times more than sun-like stars
  - Possibly slightly less dark matter needed to explain total mass
  - …but **more** stars in the Universe overall!

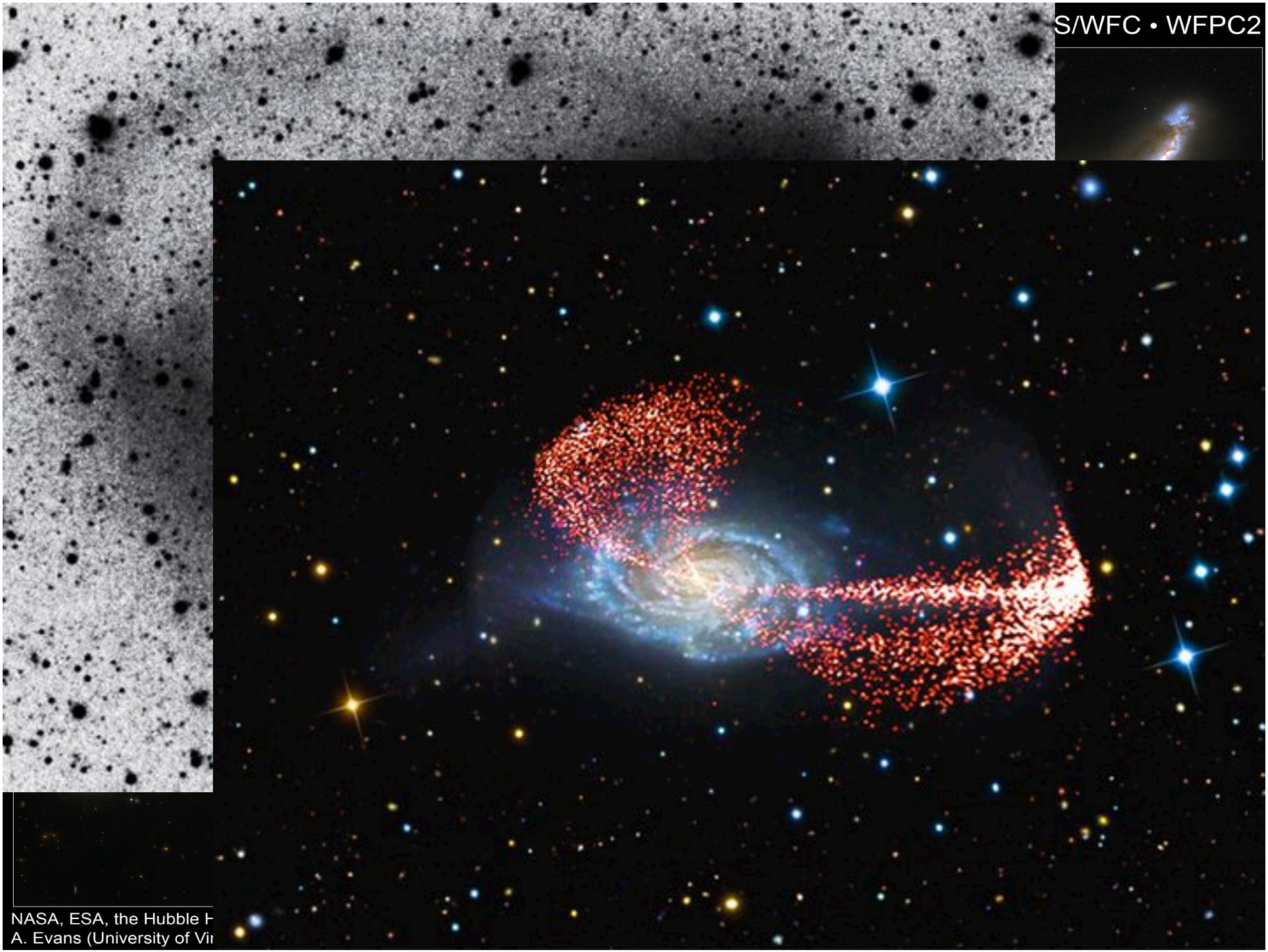
- Largest galaxies: cD ellipticals
  - up to 1 MPc across, 10^{13} - 10^{14} M_{sol}
  - Mostly in center of large, dense clusters

Galactic Encounters of the 3rd Kind

- Probability for collisions:
  - our sun with another star: 1 in 10 billion/4.6 Gyr
  - depends on star density x cross sectional area x relative speed; 1/80 Gyr in galactic center
  - 1/17 Gyr for galaxy in Coma cluster (10^4 galaxies)!
- => Galaxy collisions are rather likely, especially in dense clusters! (Andromeda and Milky Way are next *)
  - can merge into a single galaxy (2 black holes?)
    - possible source for elliptical galaxies - mergers where much more frequent in the past when the Universe was smaller!
  - or pass through each other (stars rarely collide)
  - even at glancing collision, deformation (tidal forces)
    - tails, rings (ripple “waves” after passage of one through other)



*) about 3-5 Gyr… don’t hold your breath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Monster black hole turned on by galaxy collision

And even more gigantic collisions…

Colliding galaxy clusters overlaid with lensing images of dark matter.