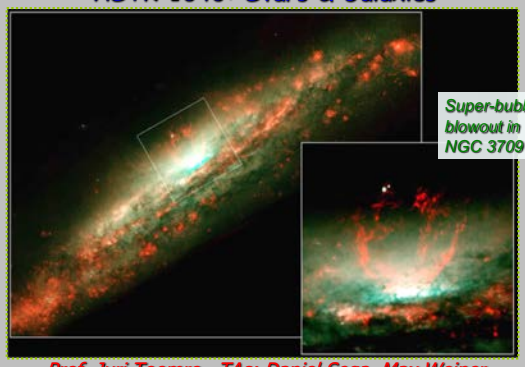
ASTR 1040: Stars & Galaxies



Prof. Juri Toomre TAs: Daniel Sega, Max Weiner
Lecture 22 Thur 2 Apr 2020
zeus.colorado.edu/astr1040-toomre

Surprises with Our Milky Way Galaxy

- Revisit *spiral pattern making in galaxy disk*
- Consider *rotation curve* of our galaxy, and the unseen mass *(dark matter)* that it implies
- Examine how *21-cm radio emission* works: can map our galaxy (and its spiral structure)
- *Super-massive black hole* at center of MW
- Edwin Hubble using `Cepheid variables' showed *Andromeda* is a distinct *"island universe" – another Galaxy !*

Our Schedule

- *Homework #10* due today (submit to Canvas "Assignments", new *HW #11* available (from "Modules")
- Overview read *Chap 20 "Galaxies and Foundations of Modern Cosmology"*
- *Then read with care 20.2 `Measuring Cosmic Distances' and 20.3 `Hubble's Law'*

We are Zoom-Interactive

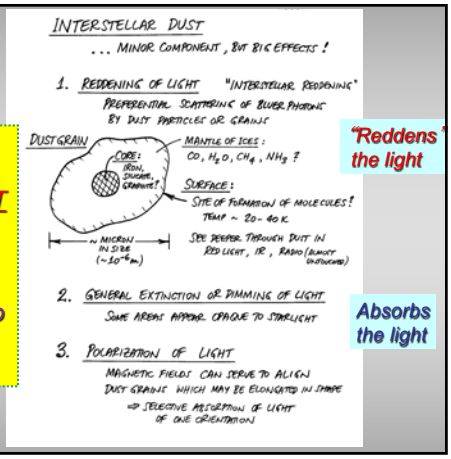
- "*Raise Hand*" *(Max monitors "Participants")*
- *"Send Chat" Message (Max will act)*
- Juri will get to your question or comment within at most a few minutes
- *If pressing, Unmute your mike and ask question*
- *We are happy to adjust "how to interact", with your advice and experience*

REVISIT

ISM:

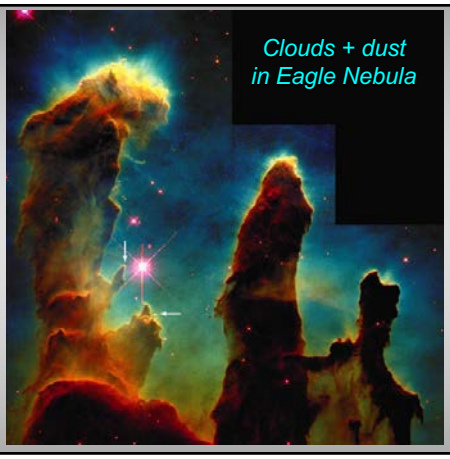
A little DUST goes a long way!

Confusing to distance & color



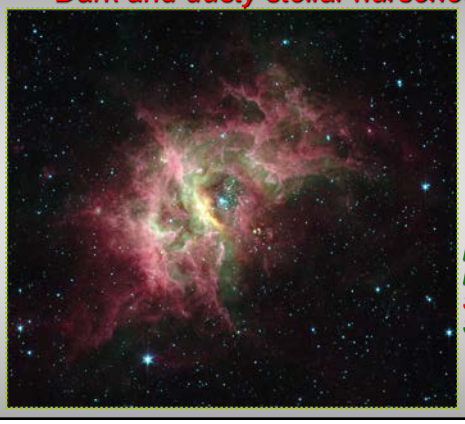
"Reddens" the light

Absorbs the light



Rosetta Nebula
O & B star carving + dust filaments

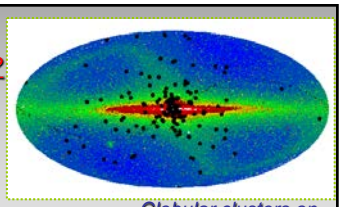
Dark and dusty stellar nurseries



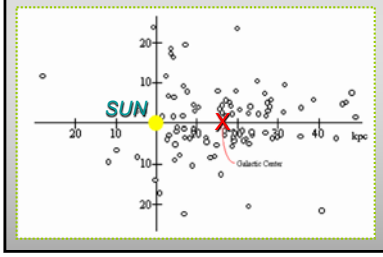
Nebula RCW 49
Stellar jewels
Spitzer IR

WHERE are we in MW?

Dust makes it hard to estimate distances (stars dimmed)



Globular clusters on COBE IR sky image



Shapley's (1920) distances to globular clusters: Sun at 18 kpc from center (twice too far!)

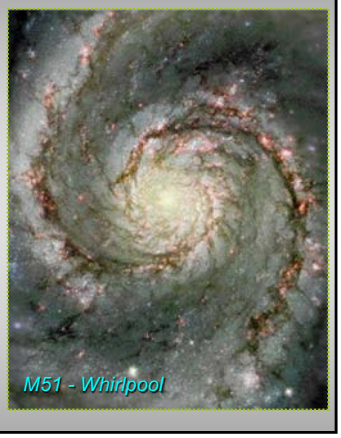
REVISIT

Why spiral arms?

"Density waves" – stars move in and out of denser regions

More like ripples in a pond than arms of a pinwheel

In dense regions, star formation is more intense, so "arms" are brighter

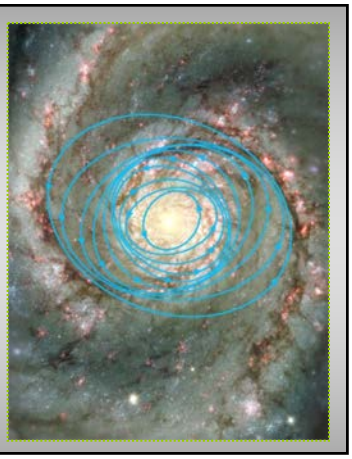


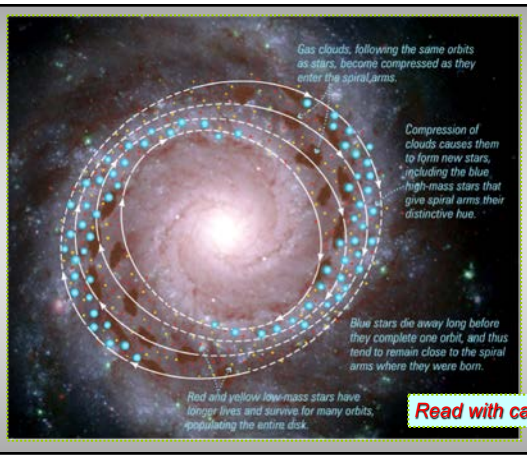
M51 - Whirlpool

Push and pull of gravity in disk

Gas/stars are pulled a little forward or backward toward the high density regions

Such clumping helps create a spiral pattern "traffic jam"





Read with care

"Density wave" story – how spiral structure is built

Gravitational instability of disks (gentle)

THEORY OF SPIRAL STRUCTURE ...

DENSITY – WAVE THEORY

1. "SPIRAL ARMS ARE STELLAR TRAFFIC JAMS"
2. STARS SLOW DOWN (DUE TO GRAVITY), THEREFORE BUNCH UP
3. SLOWDOWN PATTERN HAS SPIRAL SHAPE, PERPETUATES ITSELF (ROTATES LIKE A PINWHEEL)
4. EFFECT ON GAS IN DISK IS MOST PRONOUNCED, SINCE STRONG COMPRESSION AND SHOCKS ⇒ STAR FORMATION
5. SPIRAL TRACERS : YOUNG MASSIVE STARS (O & B) BRIGHT EMISSION NEBULAE COLD GAS CLOUDS
6. STARS AND GAS CLOUDS CAN OVERTAKE SPIRAL ARMS AND PASS THROUGH THEM (ELLIPTIC KINEMATIC WAVES)

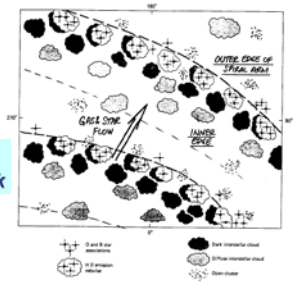
Stars and gas move through spiral wave

Star birth strongly enhanced by shock

DENSITY WAVES AND SPIRAL ARMS

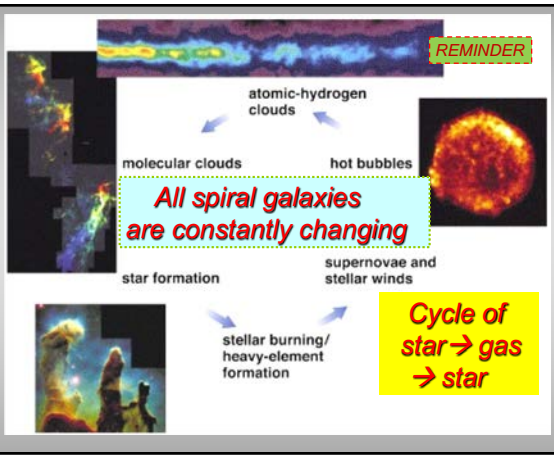
FASTER MOVING GAS AND STARS OVERTAKE A DENSITY WAVE (COMPRESSION SHOCK WAVE)

STRONGLY ENHANCED STAR FORMATION AFTER SHOCK



SPIRAL DENSITY WAVE IS A ROTATING (FIXED) PATTERN WITH STARS & GAS MOVING THROUGH IT

REMINDER



All spiral galaxies are constantly changing

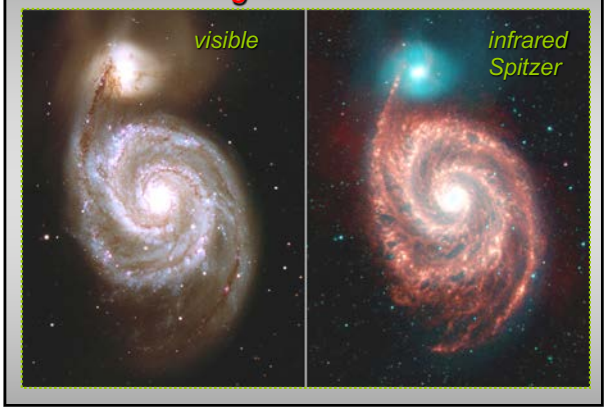
Cycle of star → gas → star

Crash/bang of star birth and recycling: rotating through the spiral arms in the disk

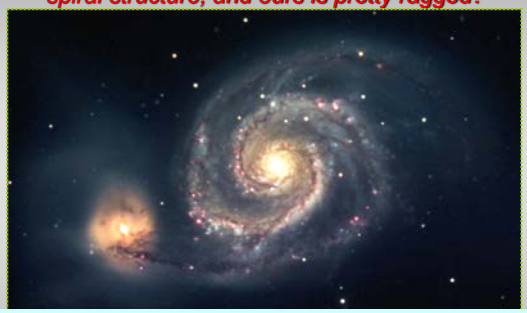
Bright O & B stars mark the spiral pattern

M51 Whirlpool Galaxy HST

Outlining starbirth in M51



Q: Why does "M51 – Whirlpool" have open spiral structure, and ours is pretty ragged?



A: Collision with companion galaxy enhanced its spiral wave

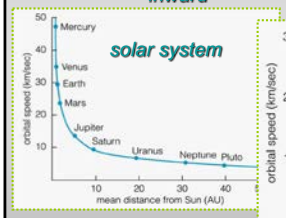
Questions or Comments

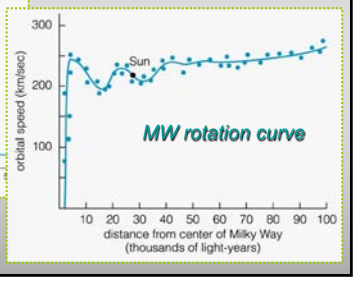
Break-Out Room: Meet & Greet

Stars moving in circles: orbital velocity law

$$M_R = R \times V^2 / G$$

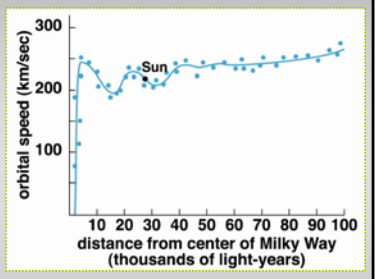
mass inward | radius | orbital velocity | …faster orbit, more mass





Reality for the Milky Way

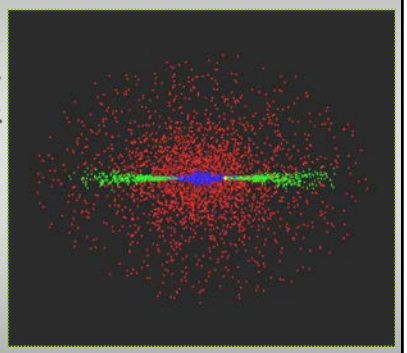
- Rotation curve is flat or even rising!
- Most of the mass of the galaxy must be outside the solar circle!
- But few stars, little gas there…



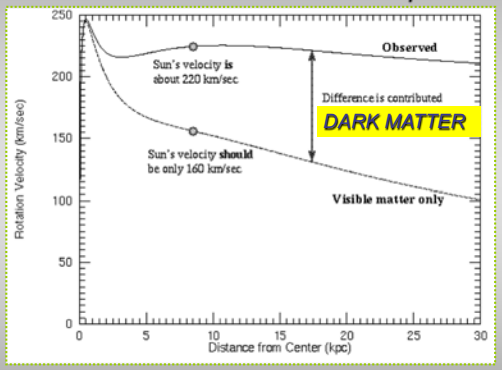
DARK MATTER ! probably in large halo -- outweights stars+gas by factor of about 10 !

Massive dark matter halo for MW

- Stars and gas are embedded in a much larger dark matter halo
- Don't know what dark matter is … probably not baryonic (usual protons, neutrons, electrons)

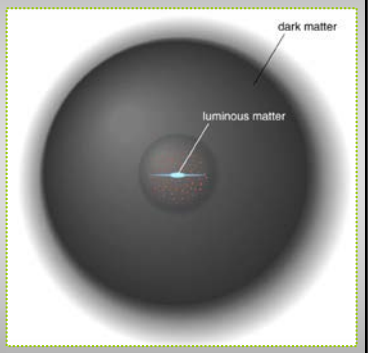


Role of dark matter on rotation profile



Dark matter halos for all galaxies

- Presence revealed by rotation curves (motions of stars in galaxy)
- Dark matter extends beyond visible part of the galaxy -- mass is ~10x stars and gas !
- Most likely subatomic particles, as yet unidentified (weakly interacting massive particles – WIMPs ?)



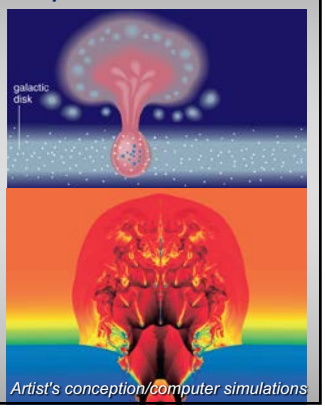
Poll 1 Why Halo stars poor in metals

- Why are stars in the halo poor in the common elements carbon, nitrogen and oxygen?

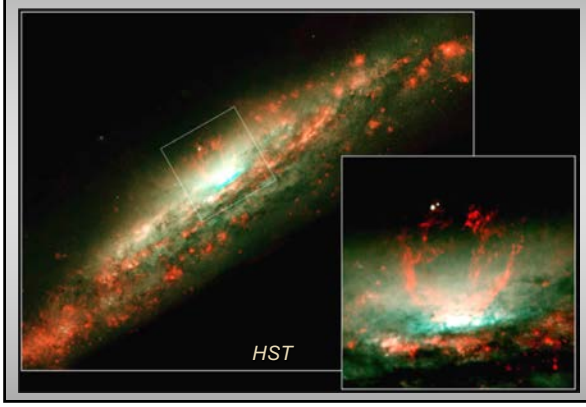
- A. Those elements have been used up in halo stars
- B. C, N and O are biological elements, and there is no life out there to make them
- C. The halo stars formed before these elements were made in abundance
- D. Making C, N and O requires massive stars, and these have been absent in the halo

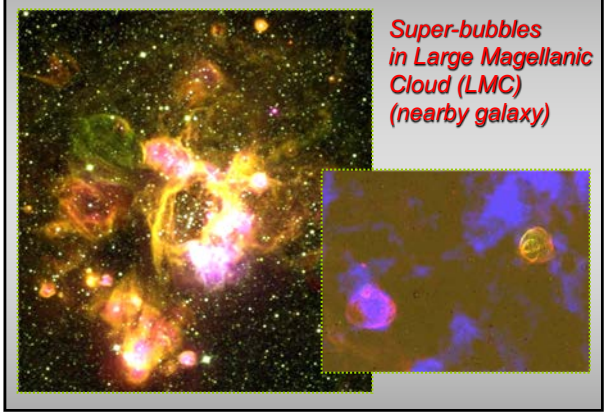
Multiple SN: Super-bubbles

- When multiple bubbles join (from a cluster) they can create superbubbles.
- If the superbubbles reaches the edge of the disk, it can blast hot gas out of the Galaxy!
  - Some will rain back down and mix into the galaxy



Super-bubbles in spiral galaxy NGC 3079

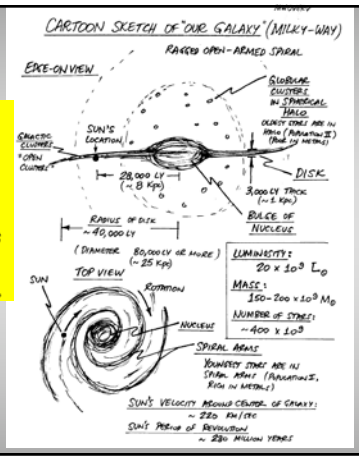




Super-bubbles in Large Magellanic Cloud (LMC) (nearby galaxy)

Q: Just HOW do we know that MW has spiral structure?

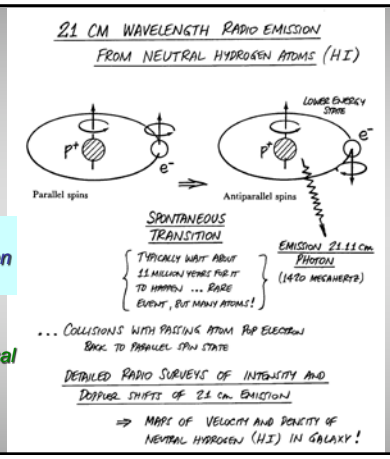
A: Radio astronomers could map it with 21-cm line of hydrogen



21 cm emission (radio)

Sampling neutral hydrogen atoms (cold)

also how MRI does it in medical imaging!



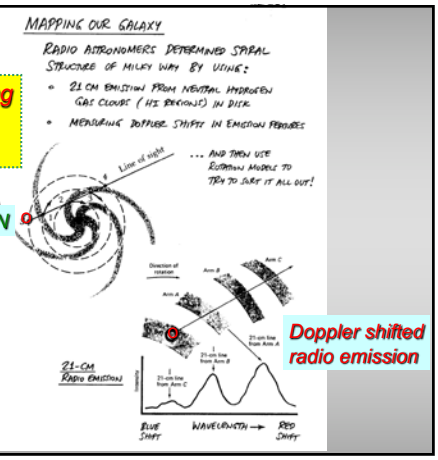
Green Bank 100 m Radio Telescope VA

VLBA Radio Telescope Owens Valley

Very Large Array (VLA) Socorro NM

Radio mapping cool H clouds in MW disk

SUN

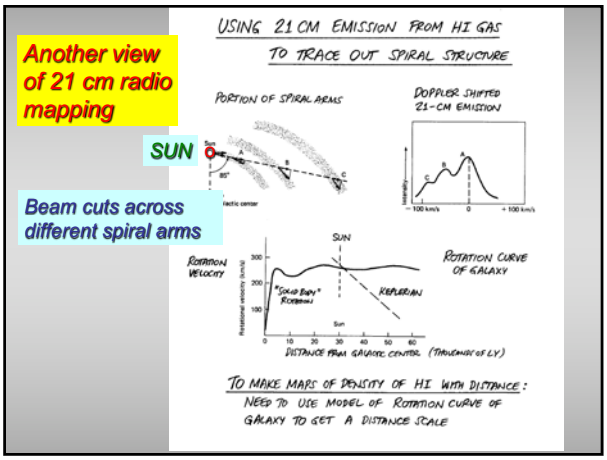


Doppler shifted radio emission

Another view of 21 cm radio mapping

SUN

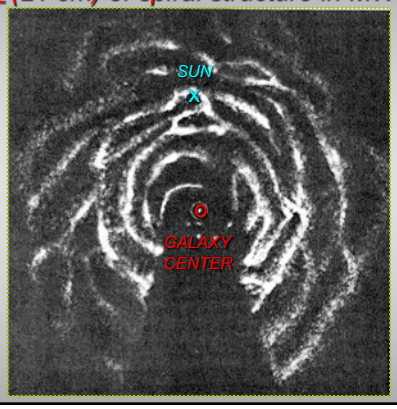
Beam cuts across different spiral arms



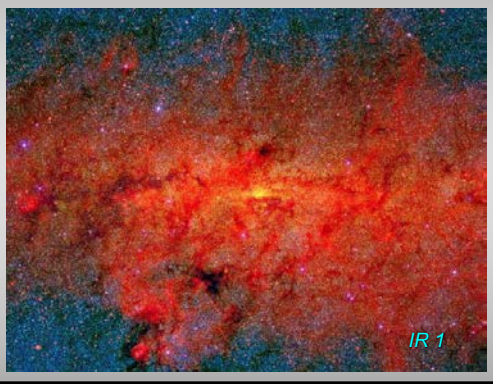
Radio map (21 cm) of spiral structure in MW

Ragged spiral structure revealed

Emitted radio waves can penetrate through gas and dust



Galactic center in direction of Sagittarius: IR reveals a dense star cluster



Unusual activity at galaxy center

THE GALACTIC CENTER

TOTALLY OBSCURED IN VISIBLE LIGHT

VISIBLE IN: RADIO, IR, X-RAY, γ-RAY, MILLIMETER

EVIDENCE FOR UNUSUAL ACTIVITY AT CENTER:

1. HIGH SPEED GAS – STREAMERS
2. DENSE CLUSTERS OF STARS
3. COMPACT X-RAY, γ-RAY SOURCES

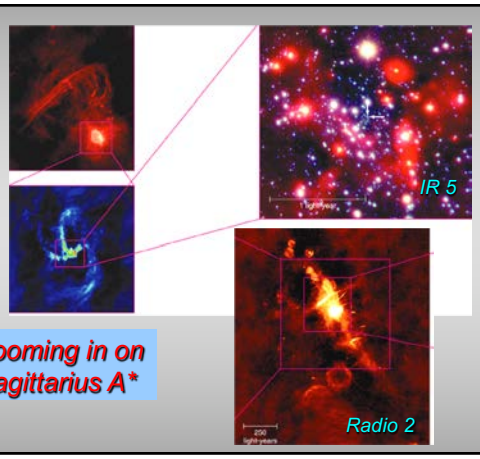
APPEARS AS IF $> 10^6 M_\odot$ IN INNER FEW PARSECS !

⇒ MASSIVE BLACK HOLE ?

.... BUT COULD BE STARS

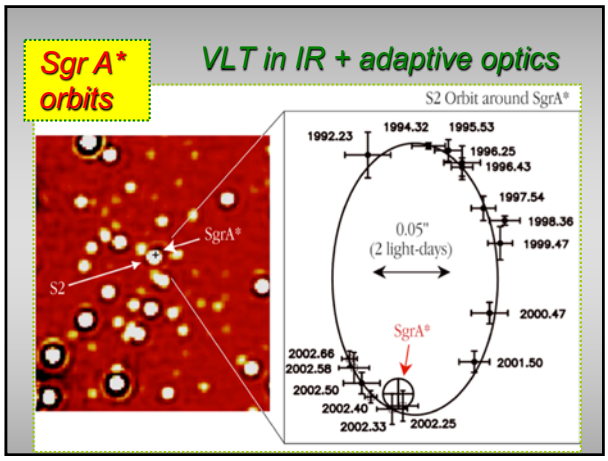
Radio mapping of galactic center

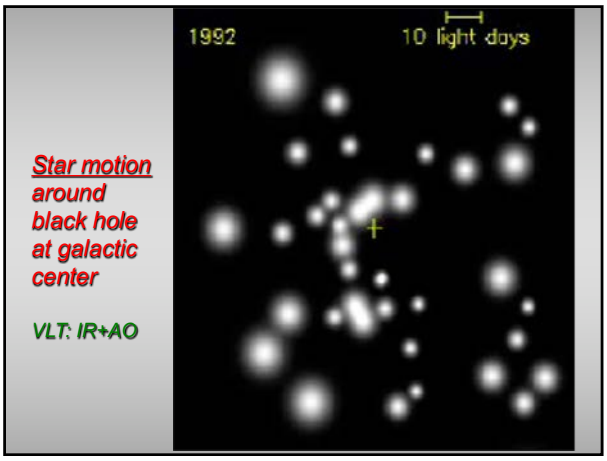
Zooming in on Sagittarius A*

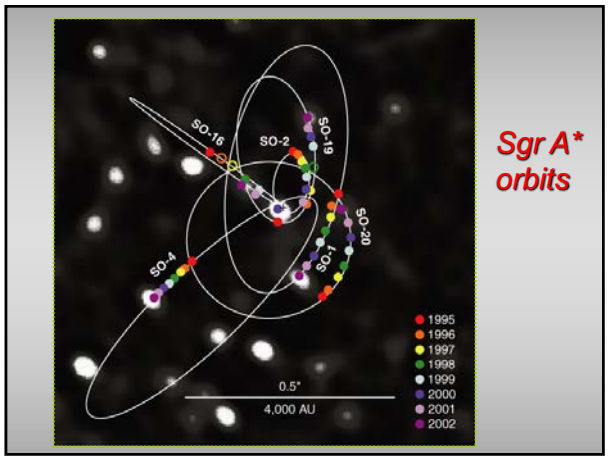


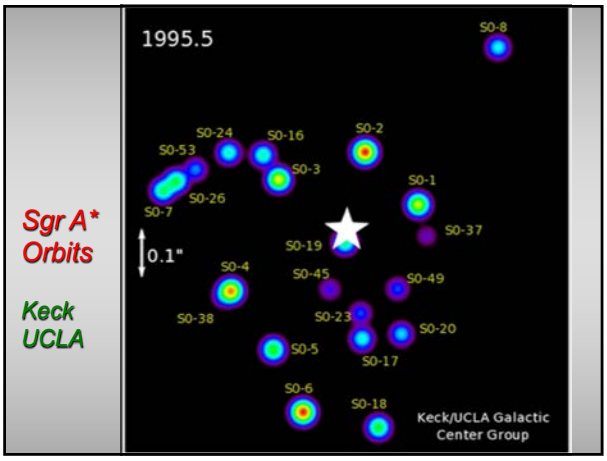
Sgr A*

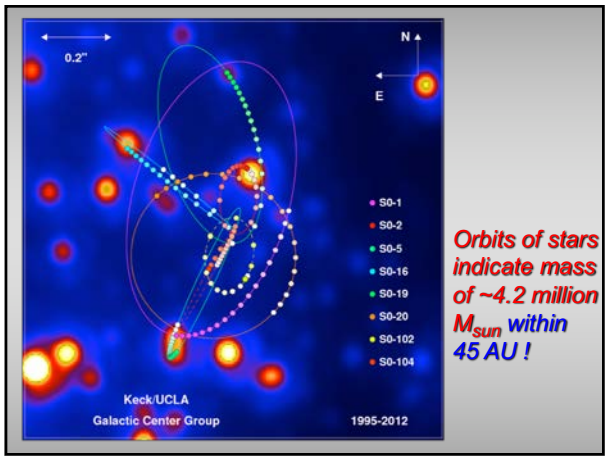
VLT IR+AO

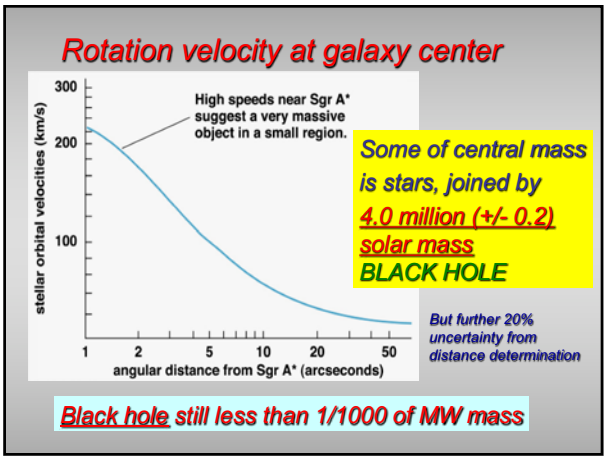

Sgr A* orbits
VLT in IR + adaptive optics
S2 Orbit around SgrA*
SgrA*
S2
0.05"
(2 light-days)
1992.23
1994.32
1995.53
1996.25
1996.43
1997.54
1998.36
1999.47
2000.47
2001.50
2002.25
2002.33
2002.40
2002.50
2002.58
2002.66

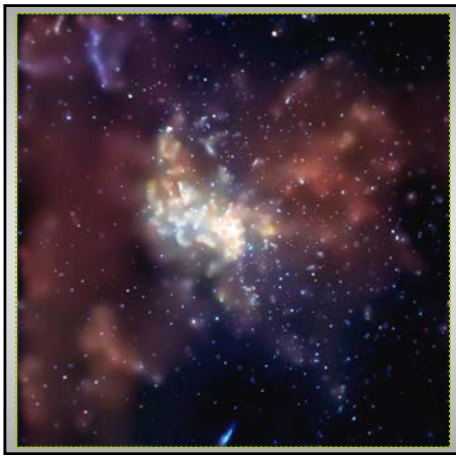

Star motion around black hole at galactic center
VLT: IR+AO
1992
10 light days


Sgr A* orbits
S0-16
S0-2
S0-19
S0-20
S0-4
S0-1
0.5"
4,000 AU
1995
1996
1997
1998
1999
2000
2001
2002


Sgr A* Orbits
Keck UCLA
1995.5
S0-8
S0-24
S0-16
S0-2
S0-53
S0-3
S0-1
S0-26
S0-7
S0-37
0.1"
S0-19
S0-4
S0-45
S0-49
S0-38
S0-23
S0-20
S0-5
S0-17
S0-6
S0-18
Keck/UCLA Galactic Center Group


0.2"
N
E
S0-1
S0-2
S0-5
S0-16
S0-19
S0-20
S0-102
S0-104
Keck/UCLA
Galactic Center Group
1995-2012
Orbits of stars indicate mass of ~4.2 million M_{sun} within 45 AU !


Rotation velocity at galaxy center
High speeds near Sgr A* suggest a very massive object in a small region.
stellar orbital velocities (km/s)
300
200
100
1
2
5
10
20
50
angular distance from Sgr A* (arcseconds)
Some of central mass is stars, joined by 4.0 million (+/- 0.2) solar mass BLACK HOLE
But further 20% uncertainty from distance determination
Black hole still less than 1/1000 of MW mass



Sag A* *in Chandra X-ray view*

Exhibits outbursts, but starved of fuel ?

Question: *Why no powerful jet and accretion disk near MW's supermassive black hole?*

- *Modest emission in X-rays…though other signs of activity*
- **Answer**: *maybe it has eaten all it can – at least for now ?*

Questions or Comments

HOW DID IT ALL BEGIN?

Measuring galactic distances

Edwin Hubble *made breakthrough using Cepheid variables to measure distance*

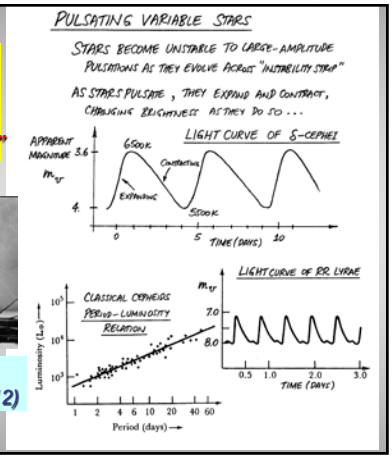
Found Andromeda far outside Milky Way

Huge step forward in thinking about universe

NGC 4414

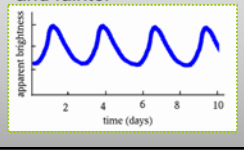
Cepheid variable stars *as distance indicators: "standard candle"*

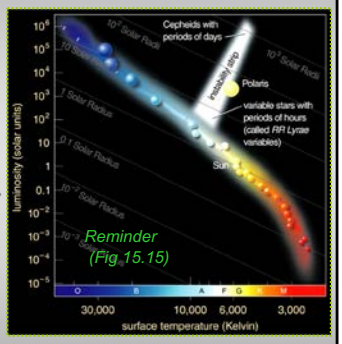
Vital discovery by Henrietta Leavitt (1912)



Cepheid stars in H-R diagram

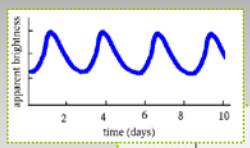
- **"Instability strip"** -- *region in H-R diagram with large, bright stars*
- *Outer regions of star are unstable and tend to pulsate*
- **Star expands and contracts**, *getting brighter and fainter*

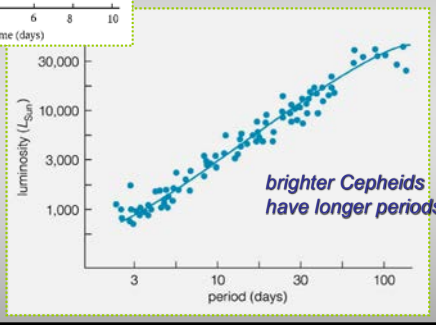




Reminder (Fig.15.15)

Cepheid variable stars





Period - Luminosity relation

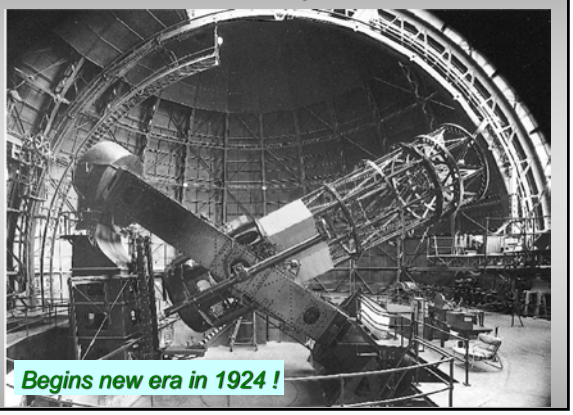
brighter Cepheids have longer periods

Andromeda found to be far outside Milky Way – another "island universe": galaxy!

- Edwin Hubble in 1924 identified Cepheids in Andromeda (M31) → showed they were far outside of Milky Way!
- Now known distance: 2.54 million ly (778 kp)
- His first big discovery (more to come) …

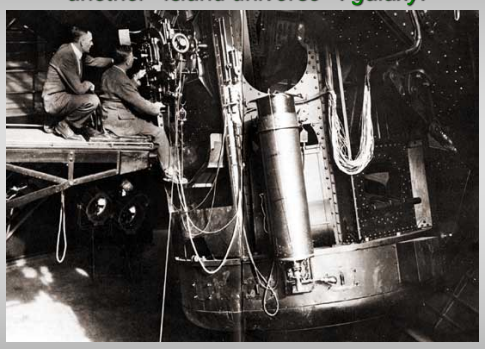
Hubble using new 100" Hooker telescope at Mt. Wilson (above LA)

100" Hooker telescope at Mt Wilson



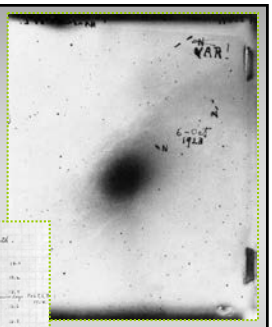
Begins new era in 1924 !

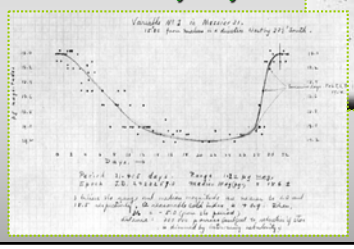
Andromeda found to be far outside Milky Way – another "island universe": galaxy!



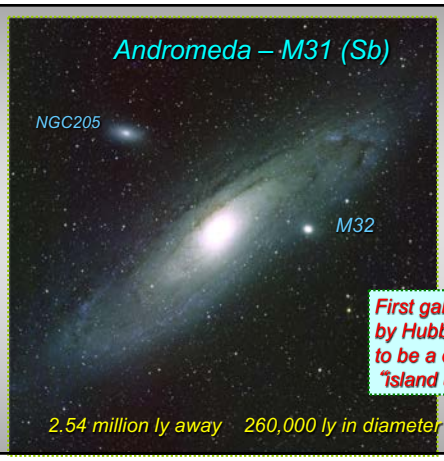
Hubble (and Jeans) at new 100" Hooker telescope on Mt. Wilson

Edwin Hubble in 1924 identified Cepheids in Andromeda (M31) → showed they were far outside of Milky Way!





Andromeda – M31 (Sb)



First galaxy shown by Hubble (1924) to be a distinct "island universe"

2.54 million ly away 260,000 ly in diameter

LATEST IR IMAGING

M31 from WISE + M32 (below) + M110 (NGC 205)

Hubble's scheme to label galaxies

HUBBLE'S "TUNING FORK"

"MORPHOLOGICAL" CLASSIFICATION OF GALAXIES ... BASED ON STRUCTURE (SHAPE)

spirals S

ellipticals E

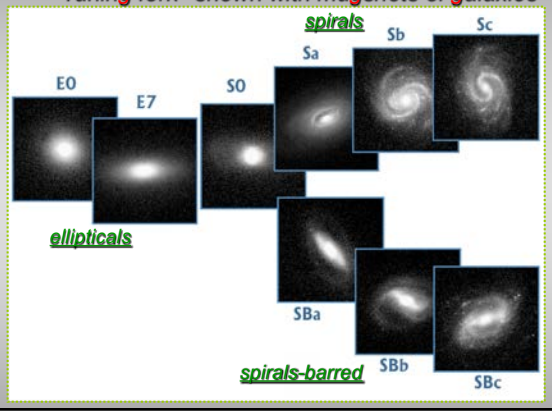
lenticular

barred spirals SB

+ some "irregulars"

NOT AN EVOLUTIONARY SEQUENCE!

"Tuning fork" shown with mugshots of galaxies



Spirals

~80% of galaxies

- Disks (with spiral arms) +
- Spheroids (bulges+halos)

M100 center