Class 18 : Our Galactic Center

ASTR350 Black Holes (Spring 2022)

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RECAP

- So far in our discussion of supermassive BHs…
  - Discovery of quasars...
    - First realization that there are accreting supermassive BHs
  - Jets and radio-loud AGN
    - Powerful directed outflows from AGN
    - Relativistic (one sided; superluminal motion)
  - Optical properties of AGN
    - Accretion disk thermal emissions
  - X-ray properties of AGN
    - Evidence for strong gravity

This class

- What about our own Galaxy?
- Today…
  - Evidence for a 4 million solar mass BH at the center of the Milky Way
  - The incredible quiescence of our SMBH
  - Evidence for past activity

I : How do we search for a massive black hole in nearby galaxies?

- How do you find a supermassive black hole when it's **very dim** not accreting very much?
- Look for the influence of its gravitational field on nearby stars and gas using Newtonian physics (up to a point)
- Suppose **stars/gas** are in circular orbit about black hole (but some distance from it)… then

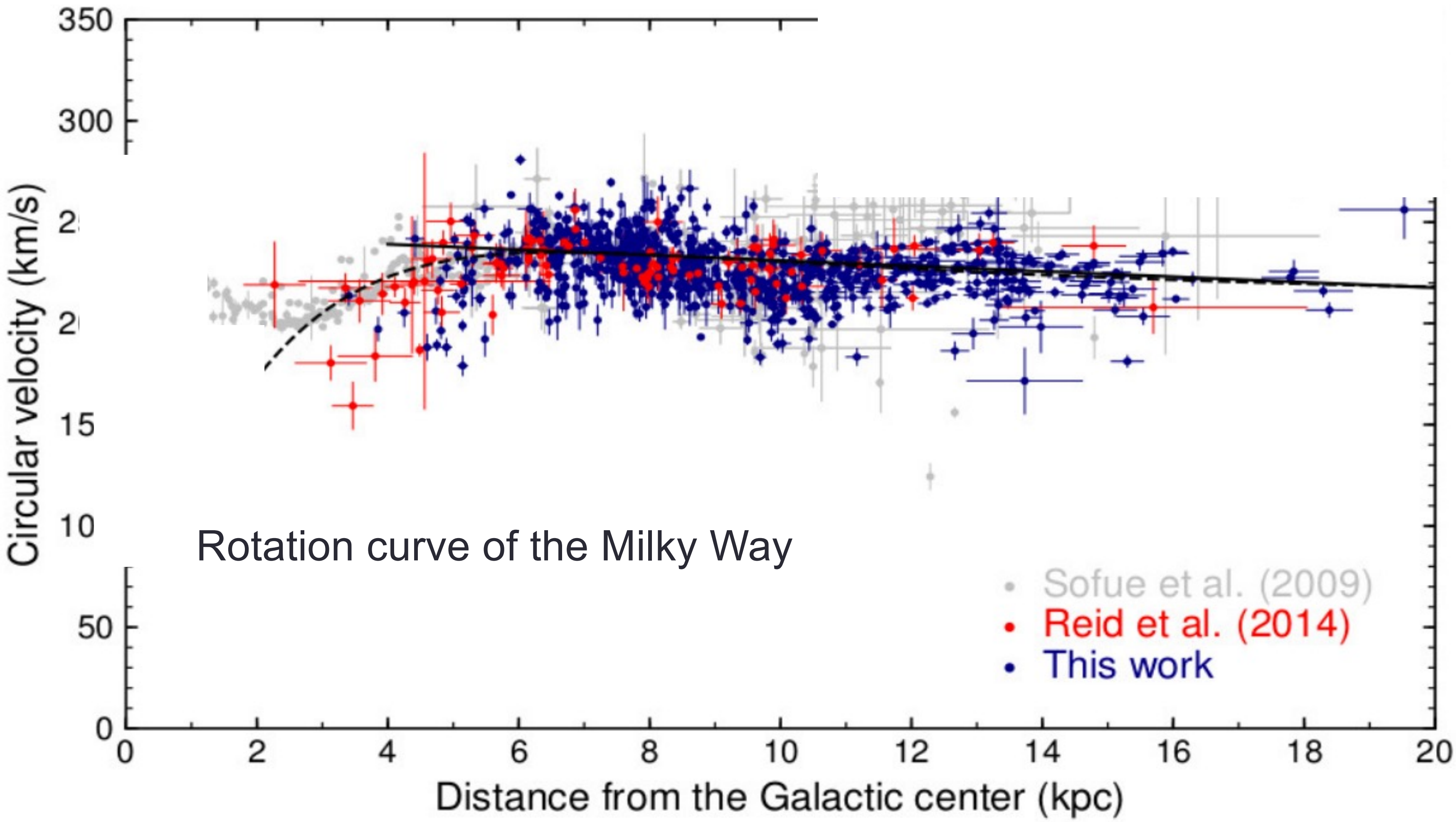
$$\frac{V^2}{R} = \frac{GM}{R^2} \Rightarrow V = \sqrt{\frac{GM}{R}}$$

So need data close to the BH (R small) and look for velocities (V) higher than 'expected' based on our understanding of galaxies*
What sort of values do you expect for the velocities if there is a BH and at what scale do you think GR is needed?

What Do We Know About Galaxies

- We can use the velocities and positions of stars and gas to infer the distribution of mass (just like we use the positions and velocities of planets to determine their mass and the mass of the sun)- this data is called a 'rotation curve'
- We can then construct a model which predicts the velocities as a function of position in the galaxy (model is the distribution of mass)
- This allows us to predict what the velocity should be even close to the center of the galaxy IF there were NOT a BH there.

What Do We Know About Galaxies



Rotation curve of the Milky Way

Why Study the MW Galactic Center?

- The nucleus of our own Galaxy is~ 100 times closer than the nearest large galaxy, M31 (the Andromeda galaxy) and more than a thousand times closer than the nearest active galactic nuclei.
- We can observe it in every energy band from long wavelength radio to very high energy gamma-rays (18 orders of magnitude in energy)
- We can therefore study physical processes happening in our own Galactic center at a level of detail that will never be reached in the more distant, but more spectacular systems

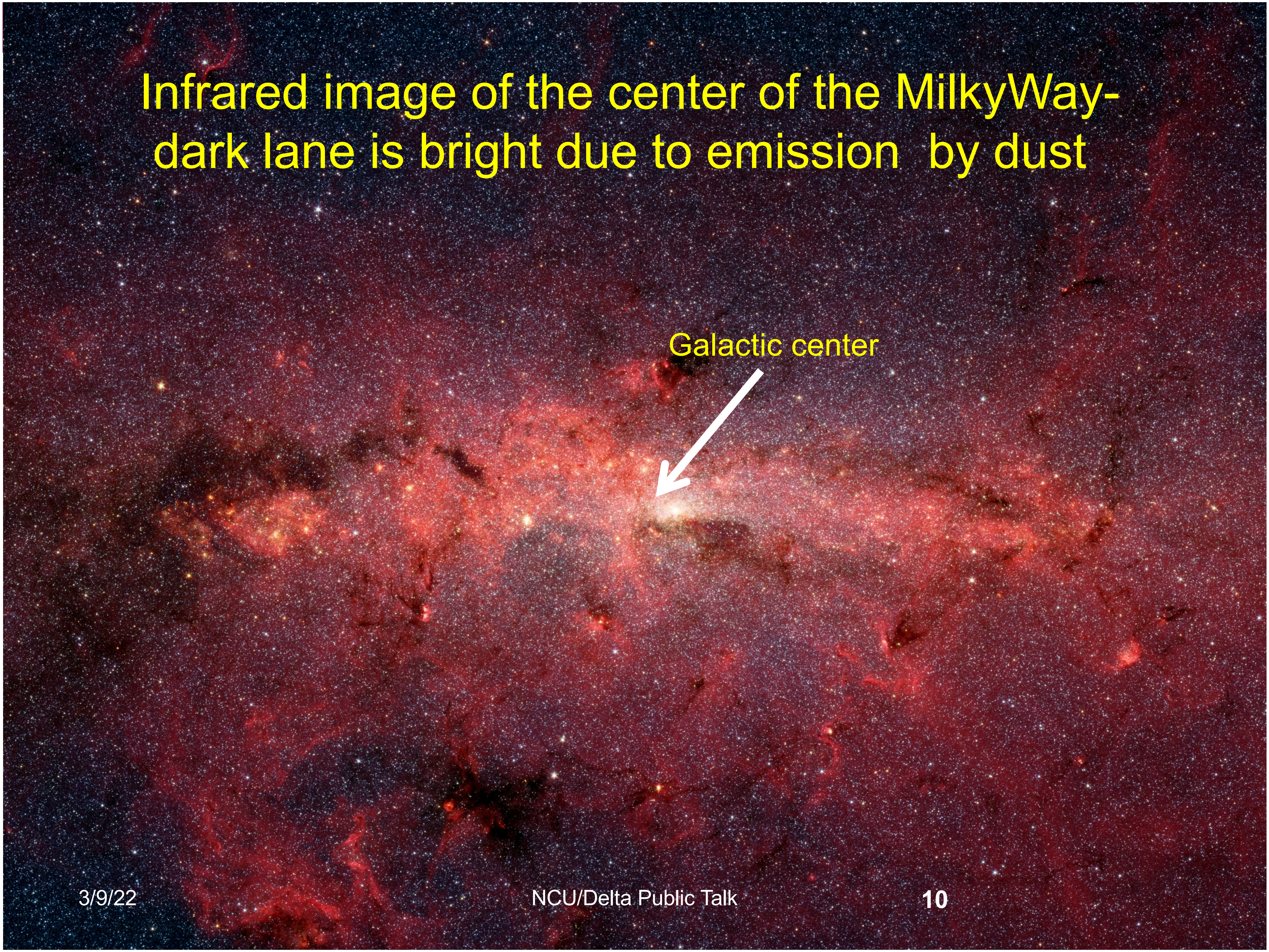
II : Our Galactic Center (GC)

Cannot see center of our galaxy in optical light because of large amount of dust and gas in the galactic plane between us and the GC

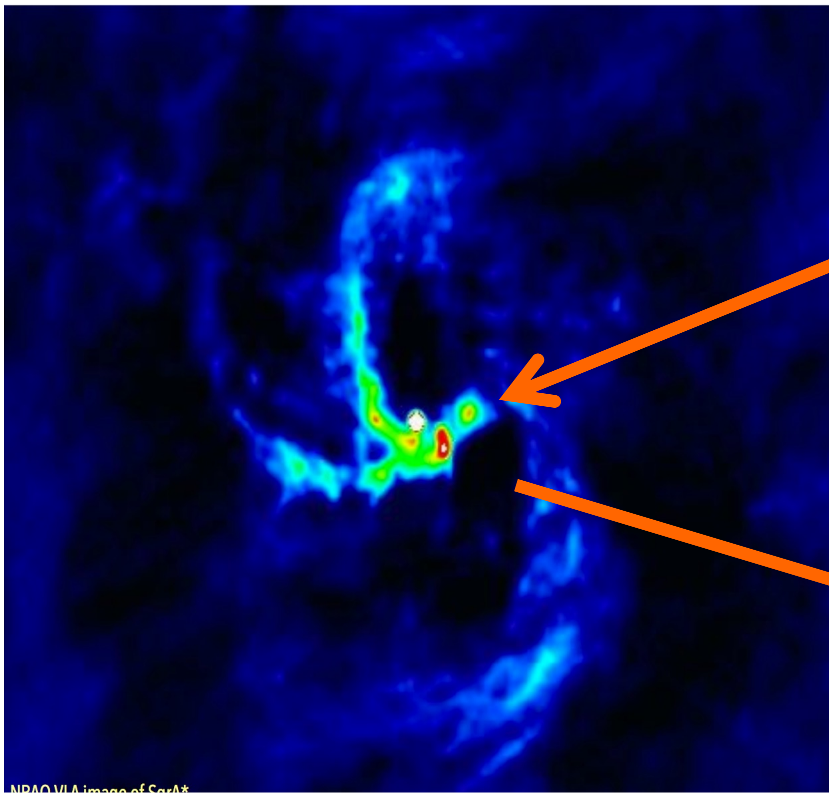
- The dust and gas absorbs optical and UV light giving over 20 magnitudes of extinction (factor of 10^{12} !)
- Need to look in bands which have less absorption: radio, IR or X-ray

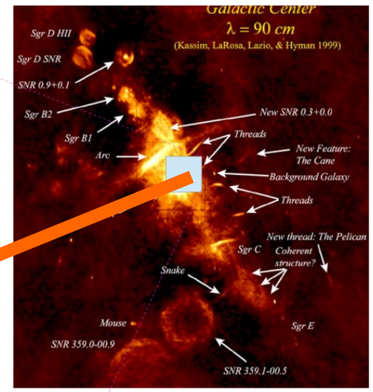
Optical image of the center of the MilkyWay-
lots of absorption by dust!

Infrared image of the center of the MilkyWay- dark lane is bright due to emission by dust



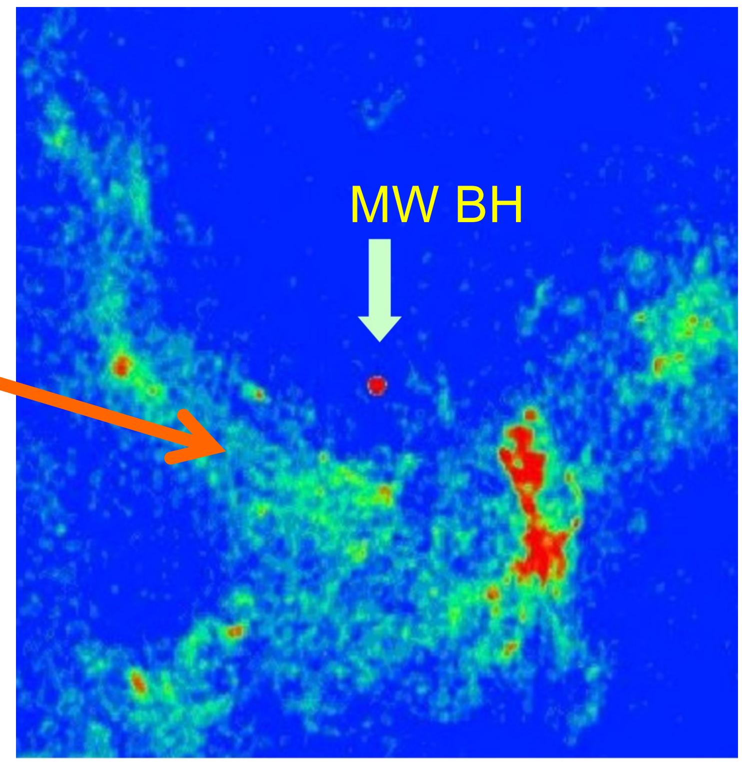
Radio and IR Images of center of MW





The center of the MW is the location of a very small radio source called SgrA*

box is 0.4pc on a side



lor (left) of the radio wave emission covers the inner 10″ (0.4 pc) of the M

Mini-spiral of ionized gas observed in radio

II : Our Galactic Center (GC)

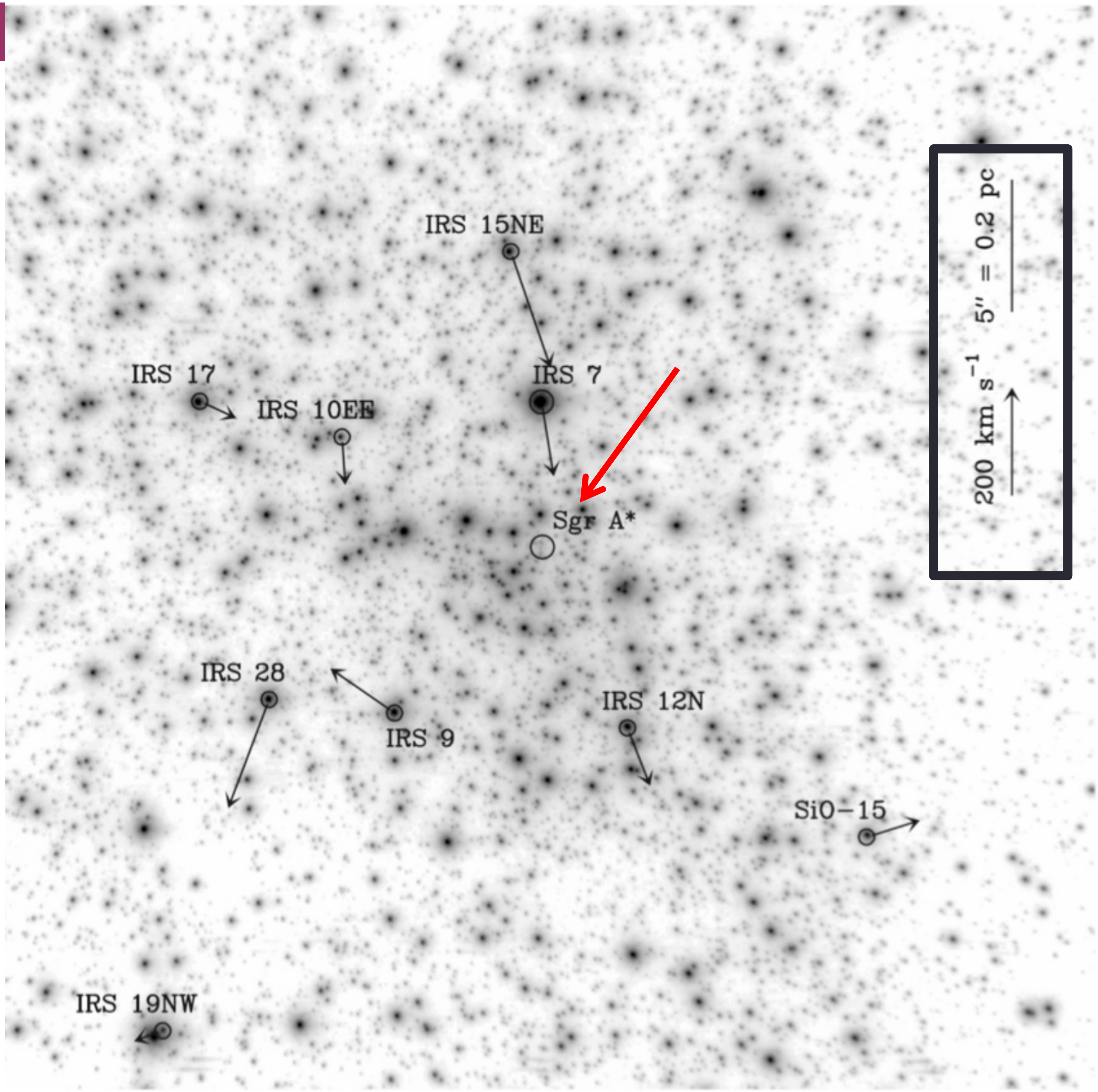
- Infra-red and x-ray observations have shown that
  - The density of stars is approximately 10^7 times as large as in the solar vicinity. The motions of the stars in the central region are due to gravitational forces
  - There is also lots of gas moving fast
  - The observed motions of gas and stars shows that something very massive lurks at the center of our galaxy.
  - The first dynamical evidence came from the motions of the ionized gas streamers of the mini-spiral orbiting Sgr A*.

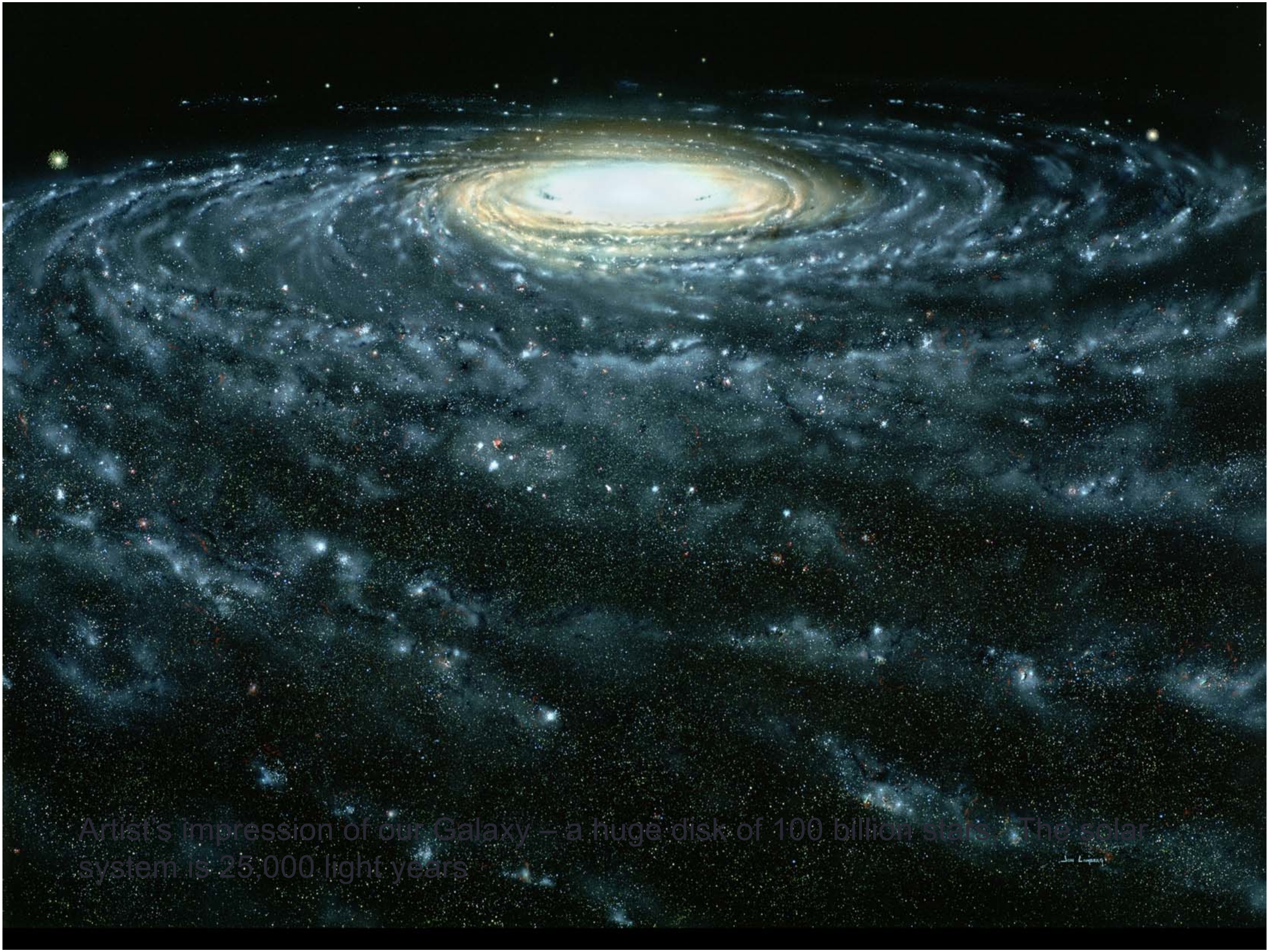
II : Our Galactic Center in infrared light

Notice the huge number of stars and the weakness of SgrA*

The arrows show the motion in the plane of the sky with scale on the right

The bar on right gives angular scale

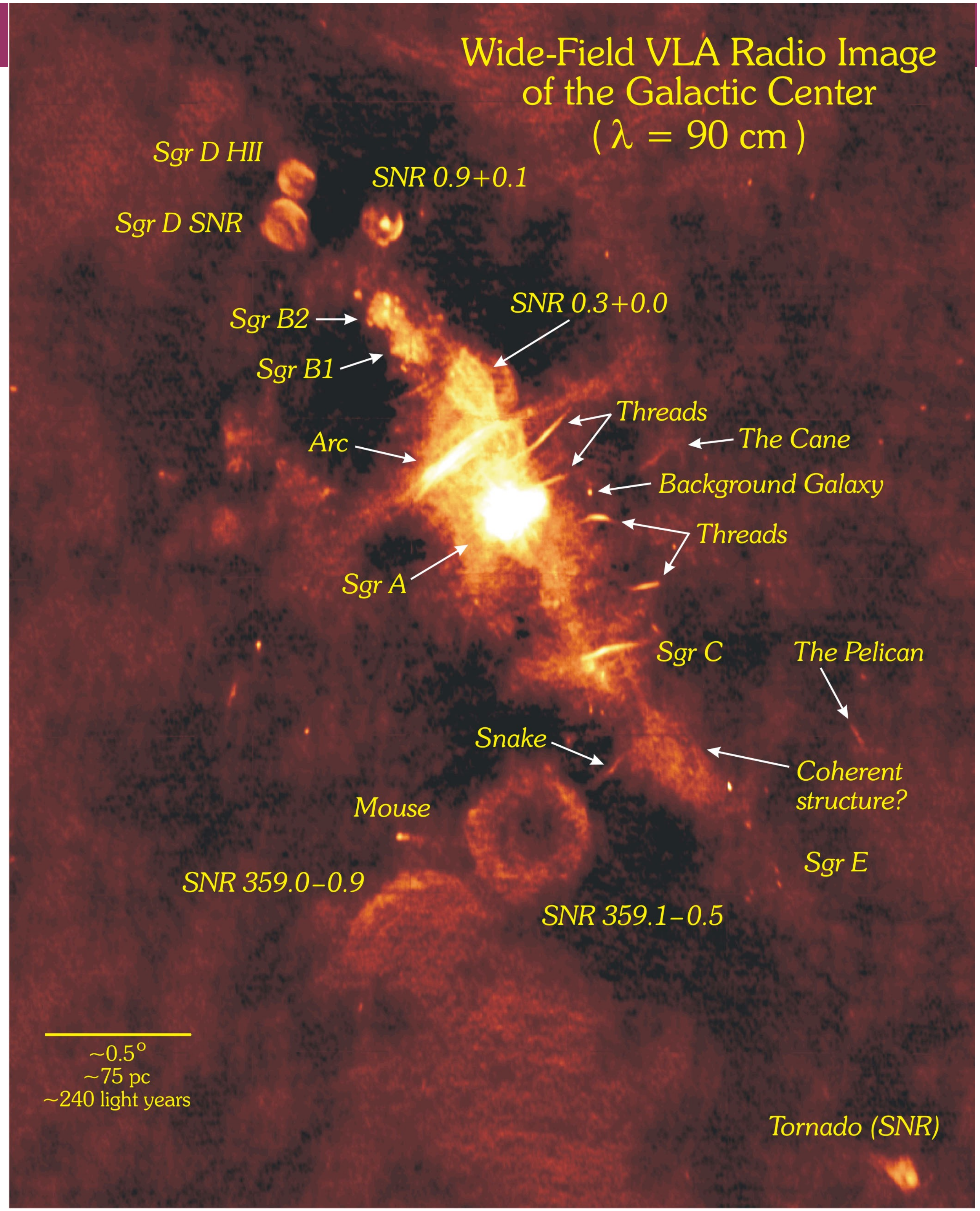




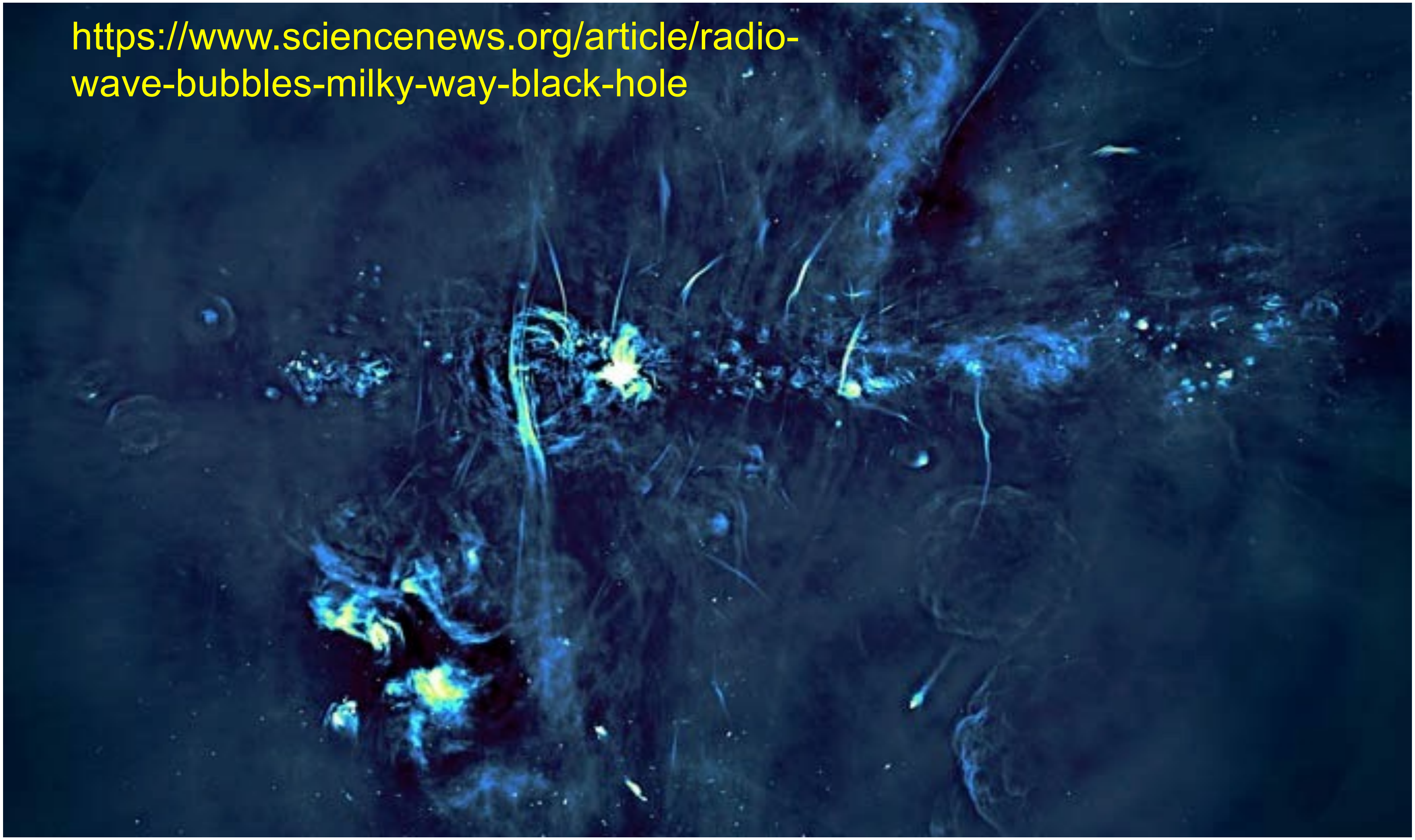
Artist's impression of our Galaxy – a huge disk of 100 billion stars. The solar system is 25,000 light years

II : Our Galactic Center (GC)

- In radio and X-ray, there is a unique compact source at precise the center of Galaxy… long suspected that this was black hole



Something is Going On!
Radio Image of MW GC

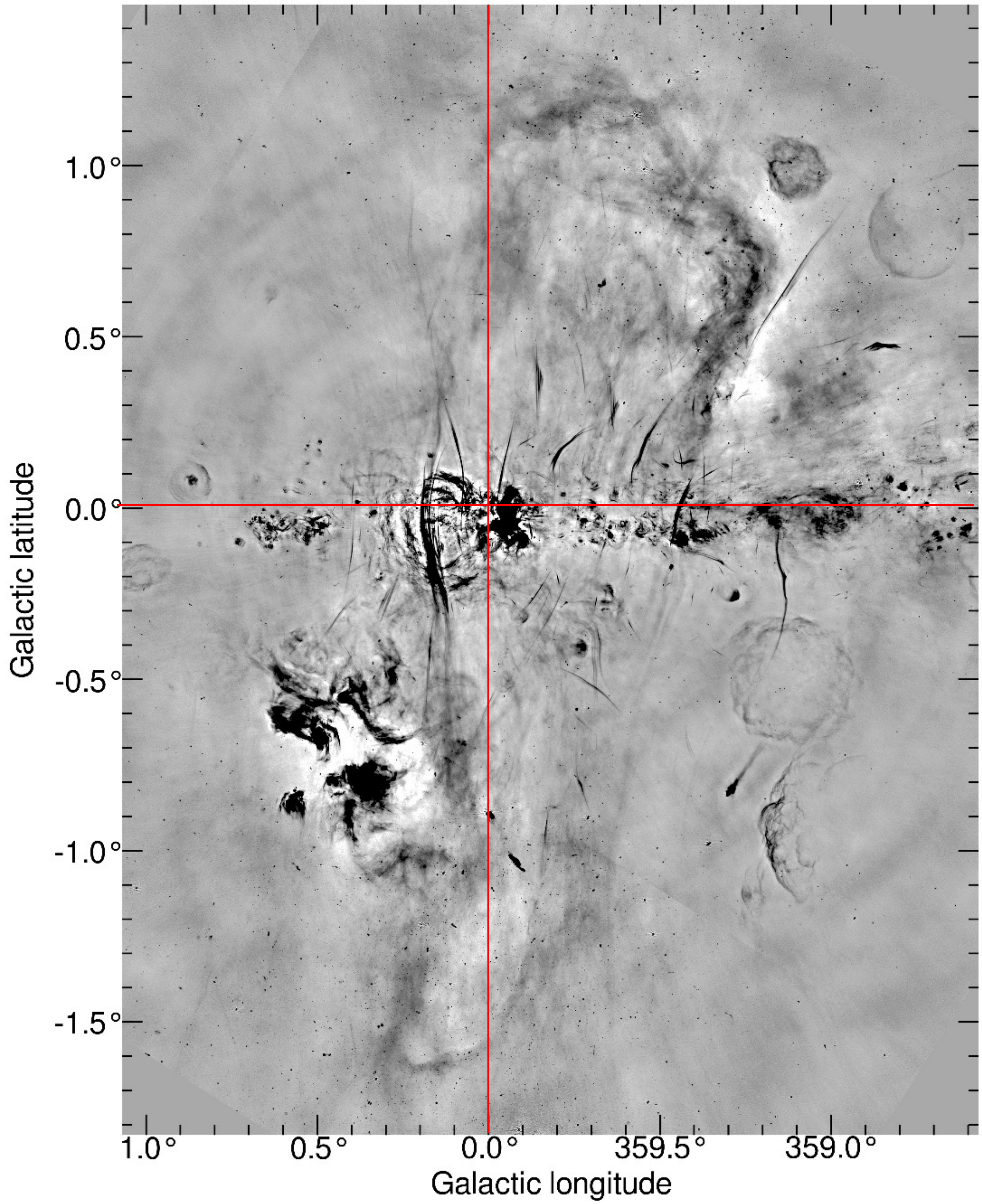


II : Our Galactic Center (GC)

- In radio and X-ray, there is a compact source of energy at precise center of Galaxy… long suspected that this is a black hole

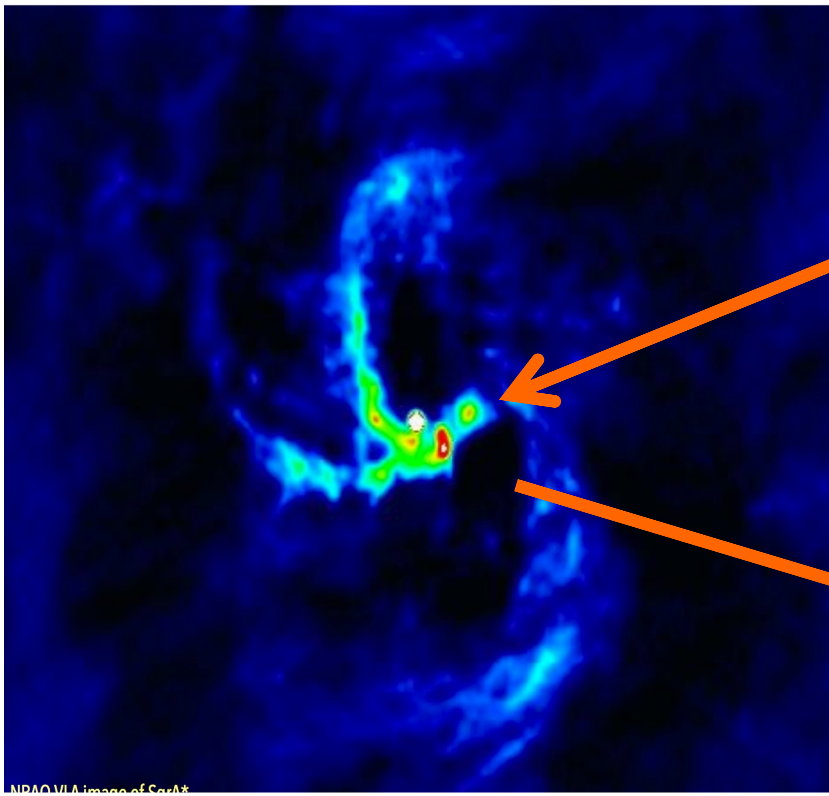
- Dramatic evidence came from IR observations
  - In IR band, see dense cluster of young stars within central light year of Galaxy
  - Can see these stars move on orbits about an unseen mass at the Galactic center
  - **Infer that there must be 4 million solar masses contained within a radius of 40AU…**
  - A black hole is the only viable option (unless there is something seriously wrong with our understanding of physics)

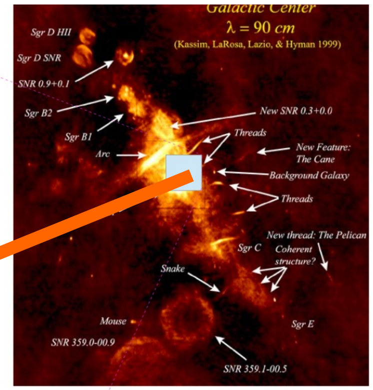
Angular scale of 1 degree=140pc

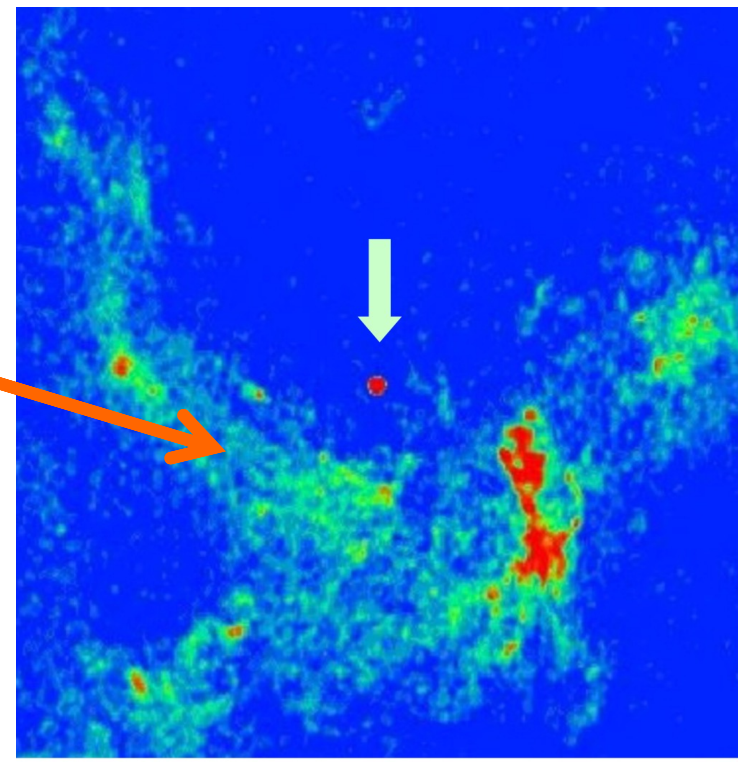


Radio Image of Center of MW

Radio emission is transparent





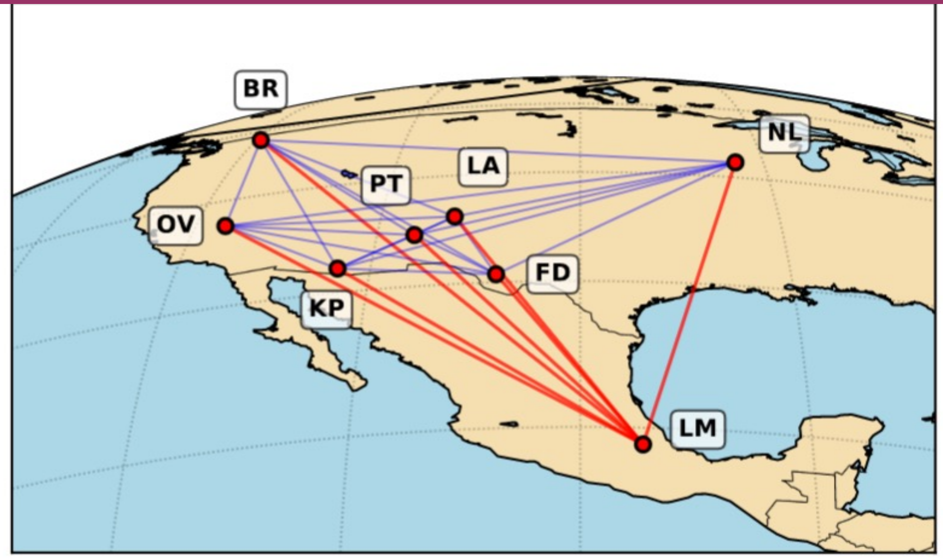


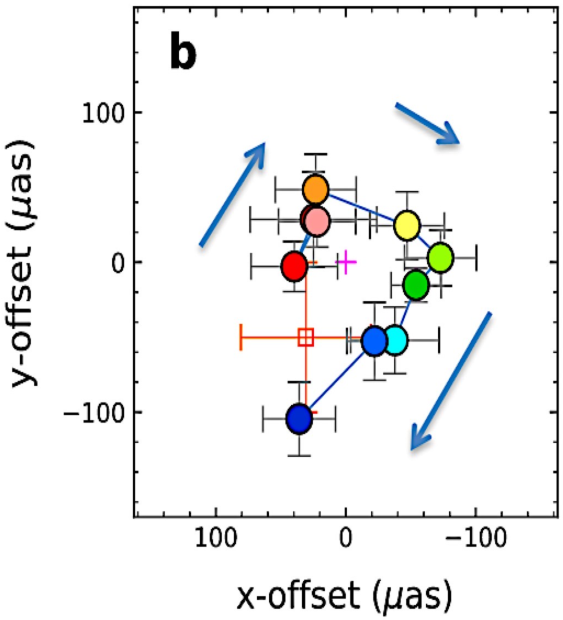
lor (left) of the radio wave emission covers the inner 10″ (0.4 pc) of the M

Best Image of SgrA*

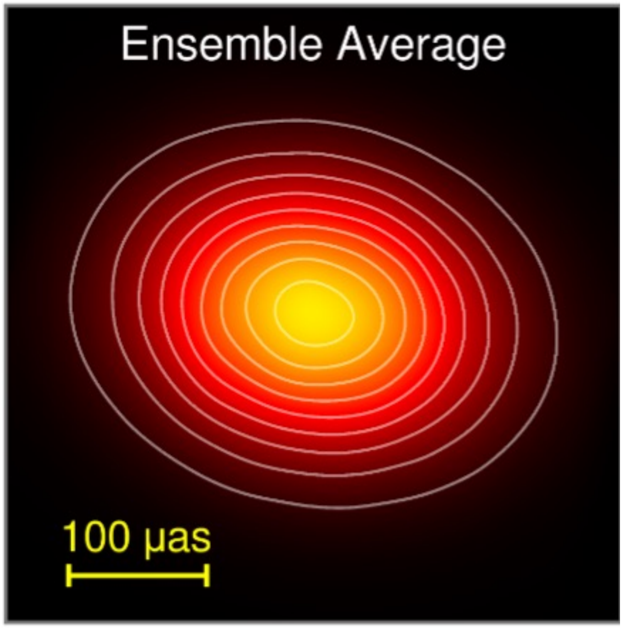
- (147±7μas) × (120±12μas), at position angle 88°±7° (Ortiz-Léon 2016)
  100μas=~10^{13}cm
- This corresponds ~ 6.5 R_S for a $4x10^6$ $M_\odot$ black hole.
- Detection of orbital motions near the last stable circular orbit of the massive black hole SgrA* -we are seeing SgrA* "face on"
- GRAVITY Collaboration 2018

arxiv.org/pdf/1810.12641.pdf





Radio image of SgrA*



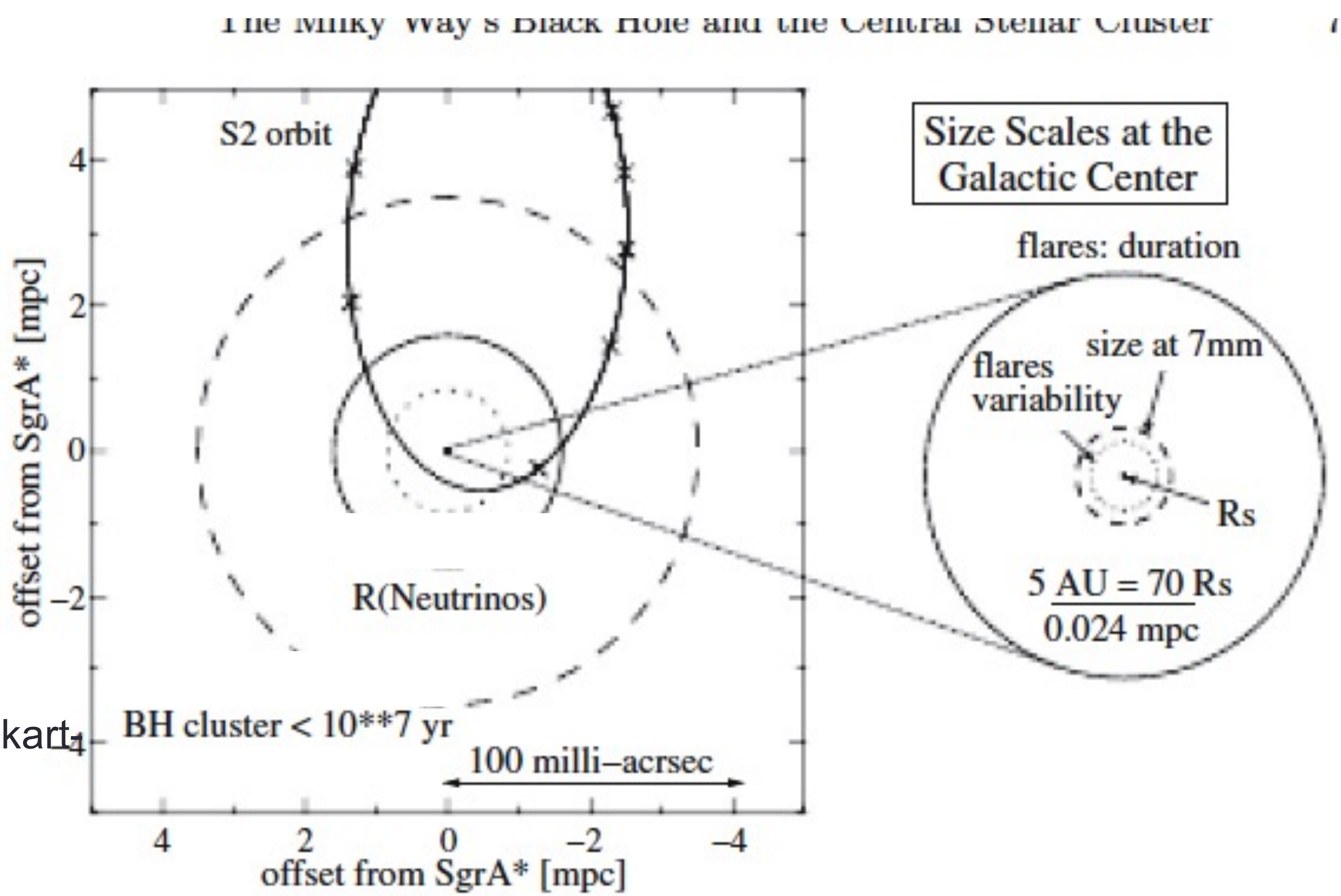
II : Our Galactic Center (GC)

- Using the velocities of the gas estimated from the Doppler shift of spectral lines, it was estimated that a mass of $6x10^6 M_\odot$ must lie within 10 arcseconds of Sgr A* (0.4 pc)

  - This did not explicitly prove the existence of a black hole since there is a lot of normal matter as seen by a high density of stars in the GC
  - BUT inside 2 arc sec more measurements required an additional, 'dark' mass component of ~ $4 x10^6 M_{sun}$

  - Also a black hole candidate exhibiting time-variable, hard X-ray/gamma-ray/IR emission and a complex radio source was detected.
    - However its luminosity is VERY low and its nature was not clear.

Size Scales at GC

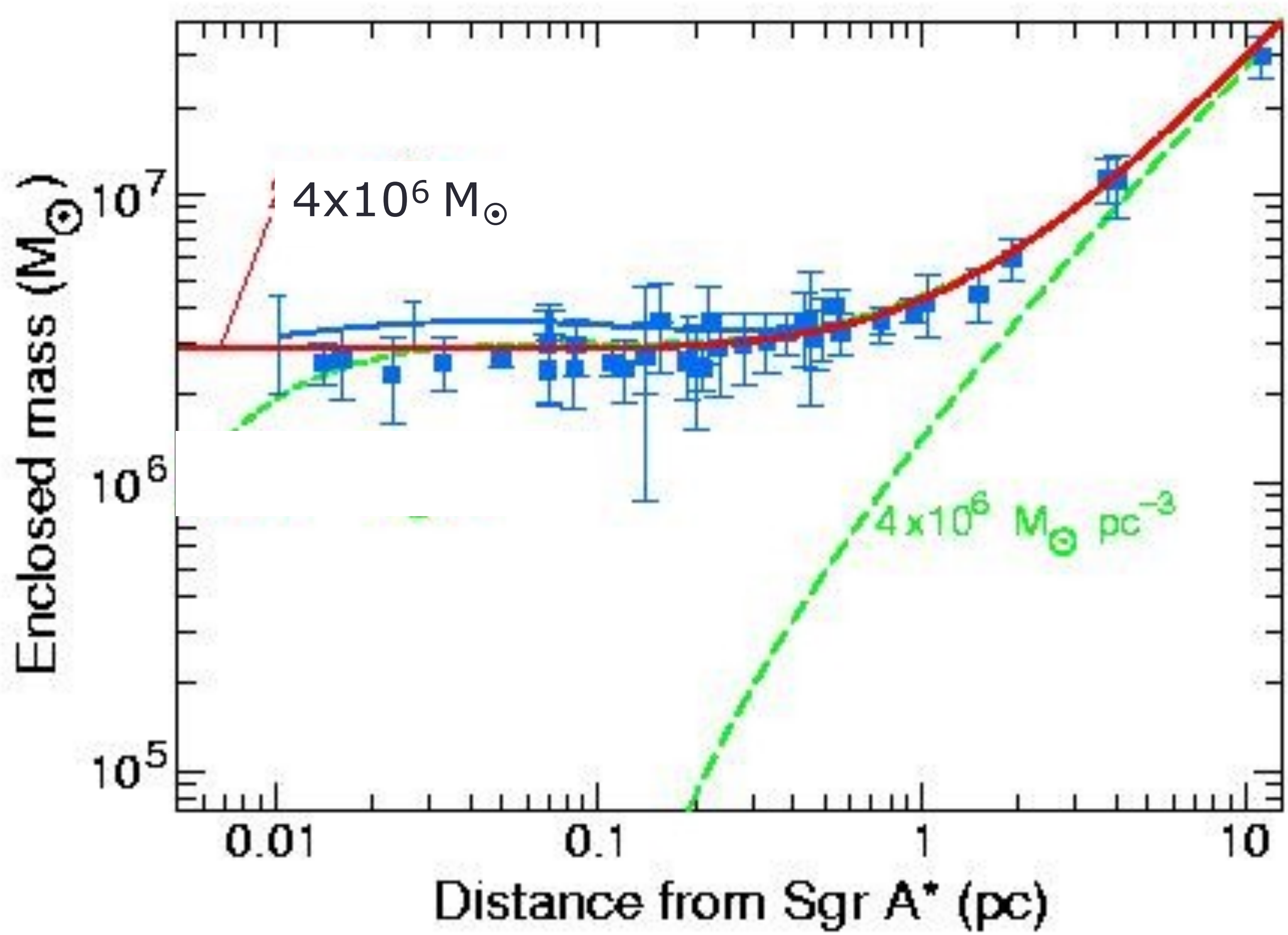


Eckart

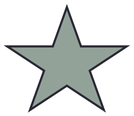
Fit of the motion and position of the stars to a model of the Milky Way

The green line is the mass due to normal stars and the red line is due to a BH of mass ~$4x10^6 M_{sun}$

Blue are the data points

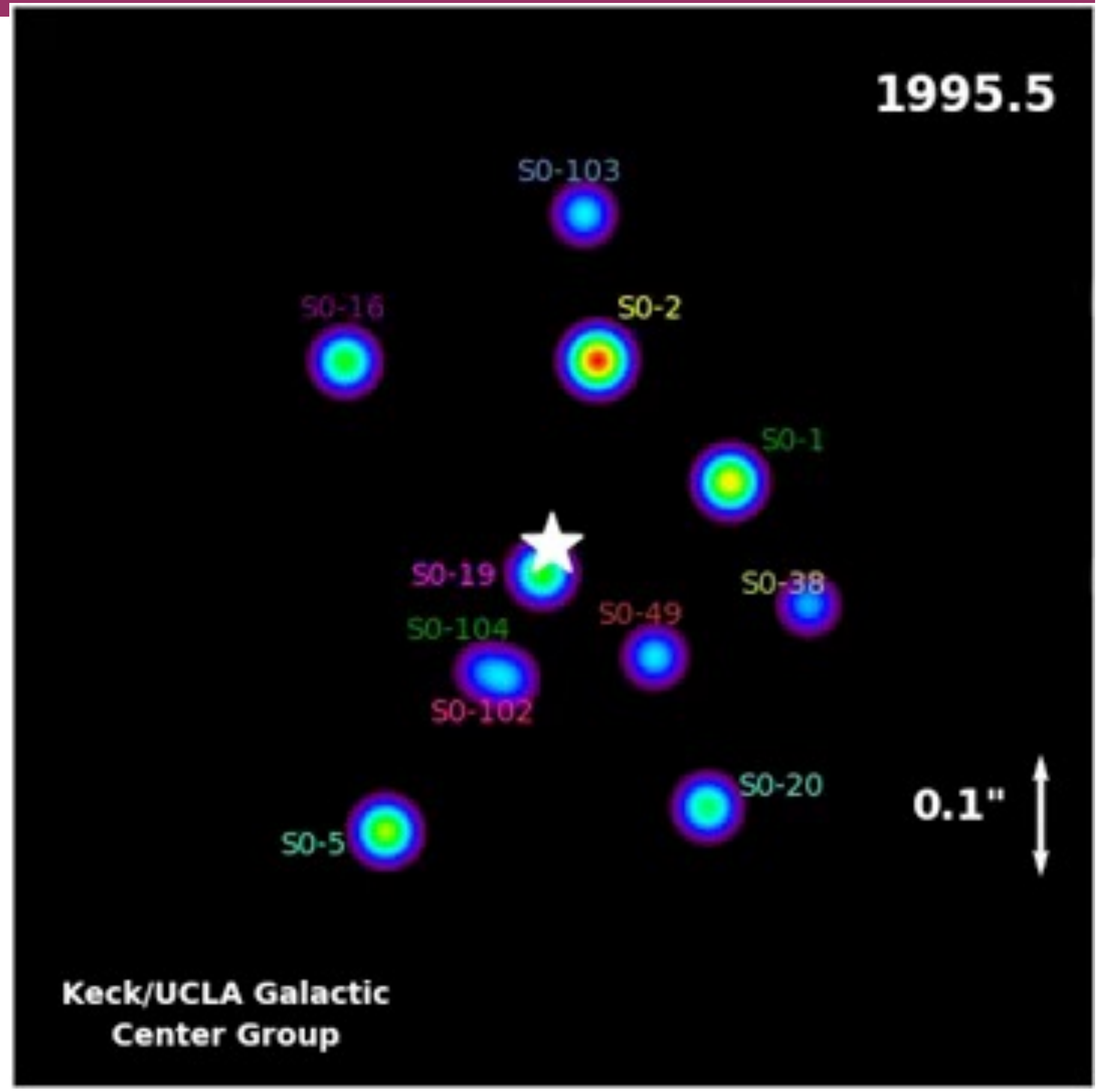


Motion of stars in the galactic center over ~20 years

The  is the GC and the motion of the stars is mostly controlled by the mass of the MWs supermassive black hole

Use Newton's Laws to determine mass and position of the BH

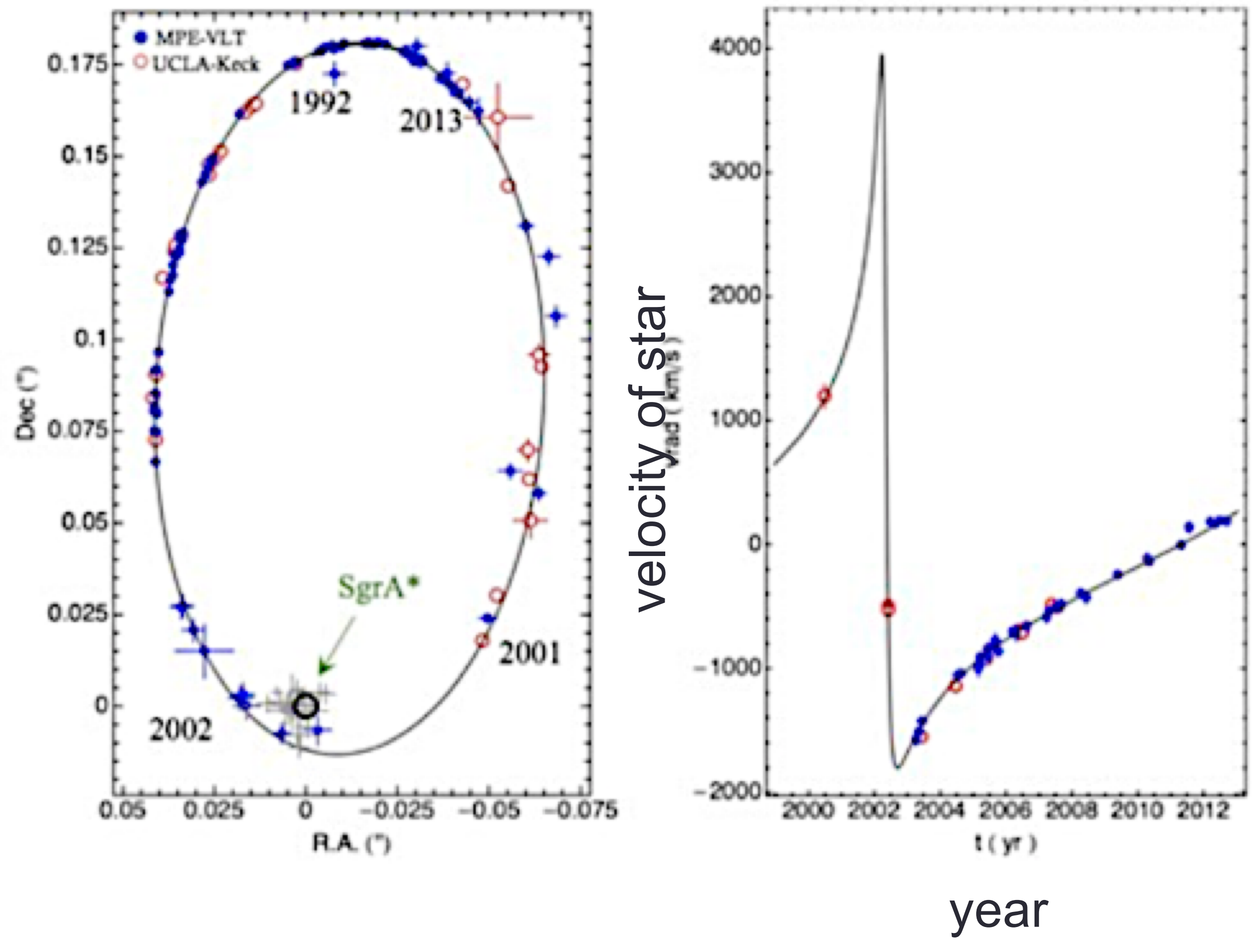
Several of these stars approach SgrA* to within tens of light hours, moving there with a speed of several 10^3 km/s



Fit of the Orbit of Stars

S2 is orbiting Sgr A* every 16 years in a Keplerian ellipse- notice the very large velocity ~3000 km/sec

The orbit of S2 (1992-2013)



The orbit of the stars orbiting around our GC is very sensitive to the mass of the BH
The solid lines are the solution for a mass of 4×10^6M and the dots are the data (showing the position of the star in RA and Dec vs time and its velocity) using Newton's Laws for one of many stars.

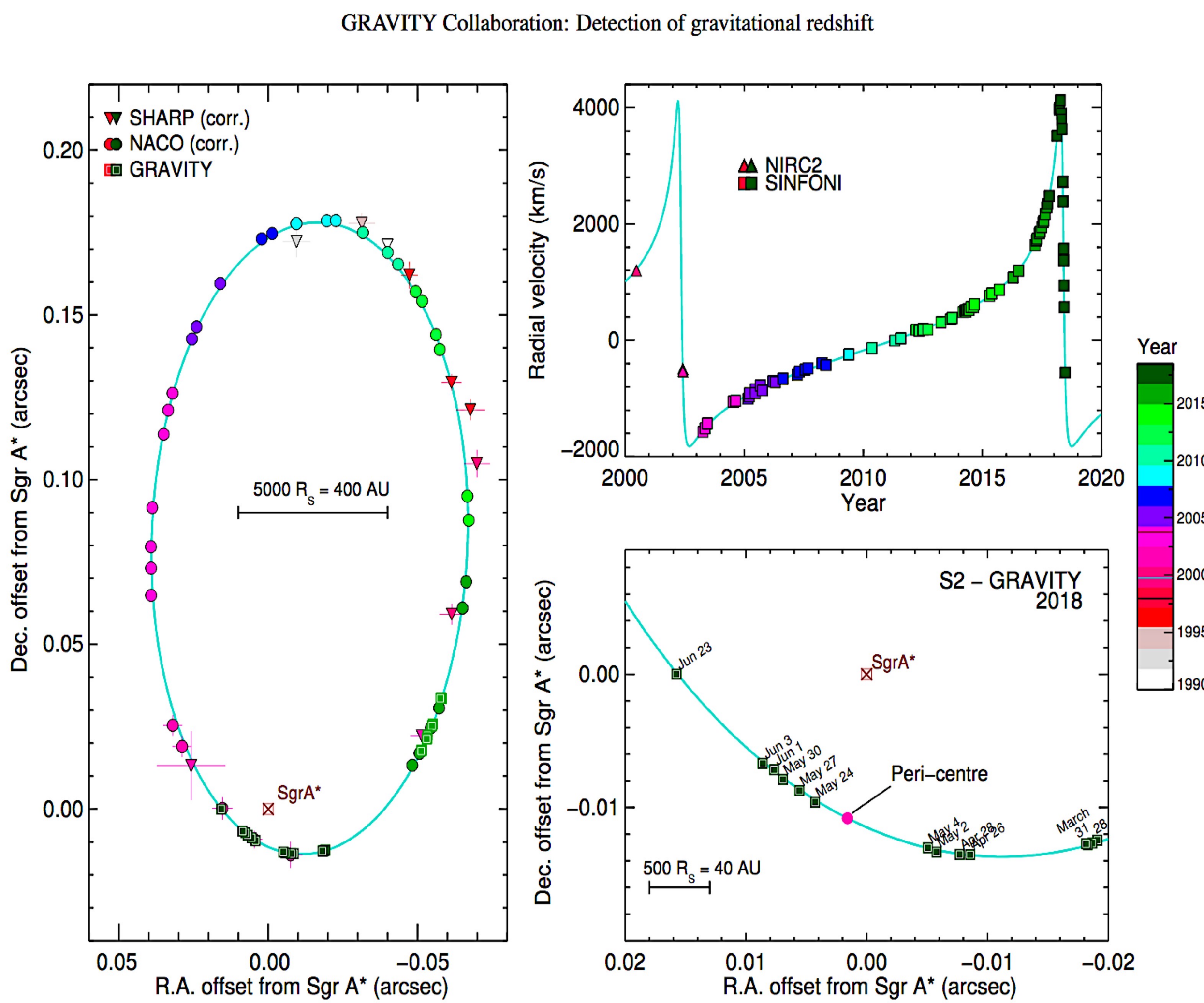
Simple Estimate of MW BH Mass

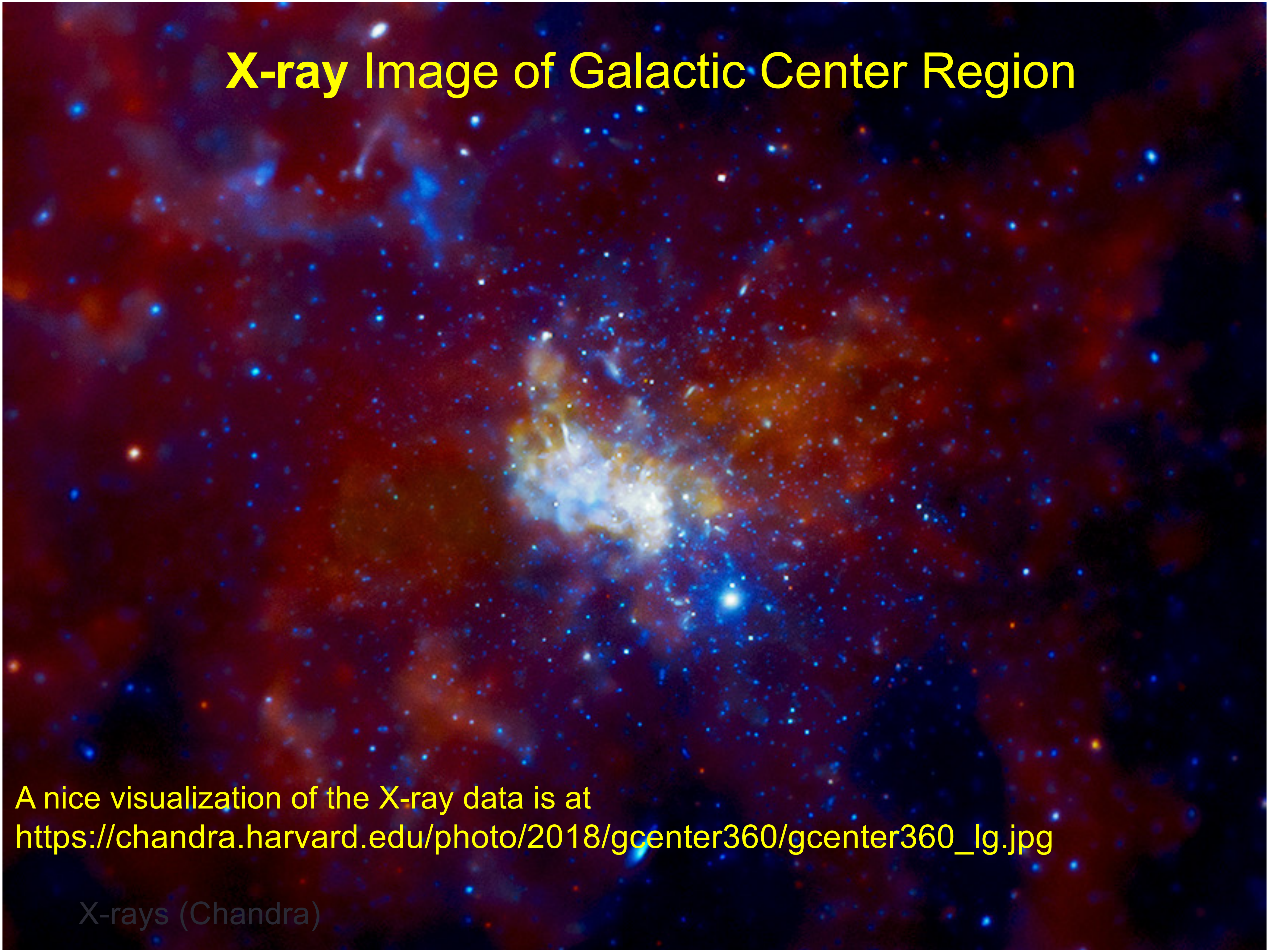
The equation is $M=v^2R/G$ (circular orbit, and know inclination); putting v=3000km/sec,
$R=.1''=4\times10^{-3}$pc one gets $8\times10^{6}\ M_{\odot}$- pretty close to the true value of $4\times10^{6}\ M_{\odot}$

The full analysis is a little more complex, need to know the actual orbit

Enormous Improvements

- **Detection of the gravitational redshift in the orbit of the star S2 near the Galactic center massive black hole[*]**
  GRAVITY Collaboration
  A&A V615, July 2018 L15
- "Near pericentre at 120 AU ≈ 1400 Schwarzschild radii, the star has an orbital speed of ≈7650 km s^{-1} (V/c~.025), such that the first-order effects of Special and General Relativity have now become detectable"



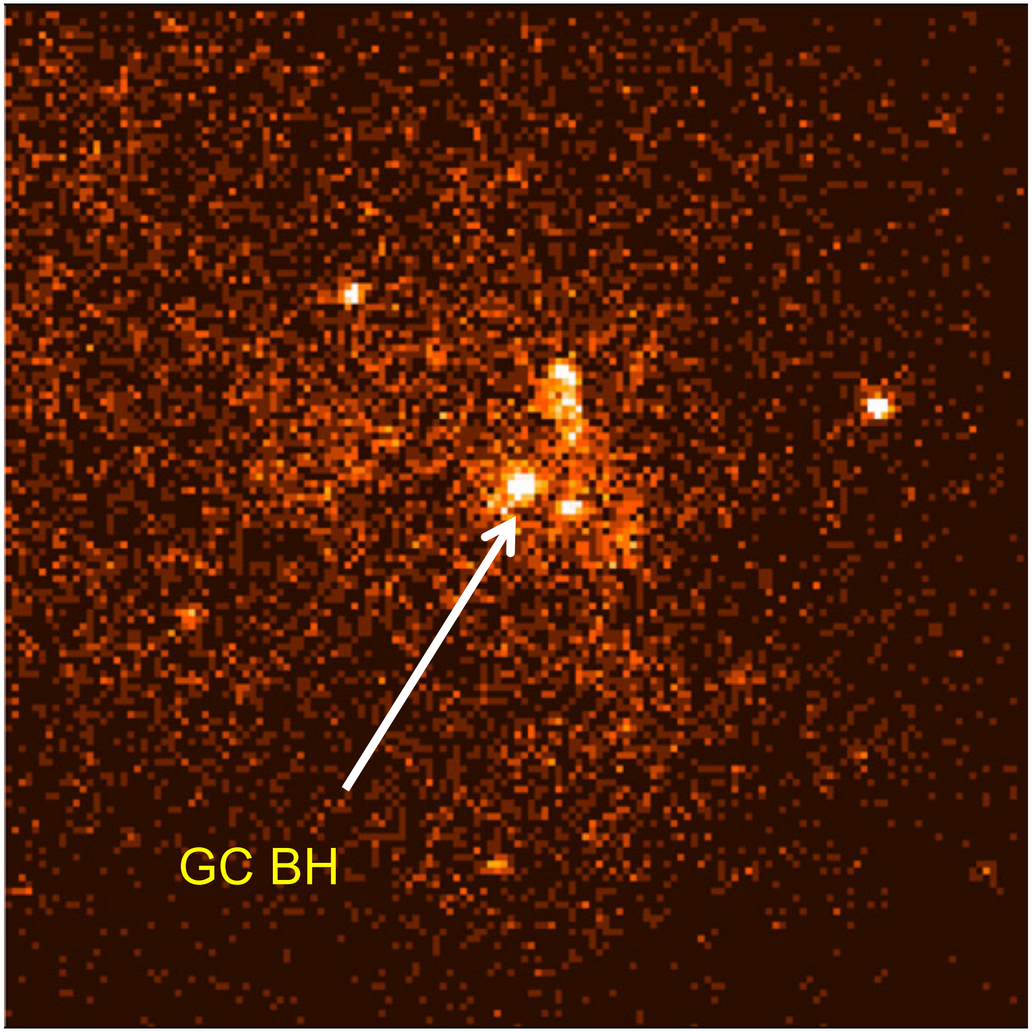

X-ray Image of Galactic Center Region
A nice visualization of the X-ray data is at
https://chandra.harvard.edu/photo/2018/gcenter360/gcenter360_lg.jpg
X-rays (Chandra)

X-ray Image of GC

- Surprisingly the X-ray image of the BH shows that it is NOT the brightest X-ray source in the central 100pc

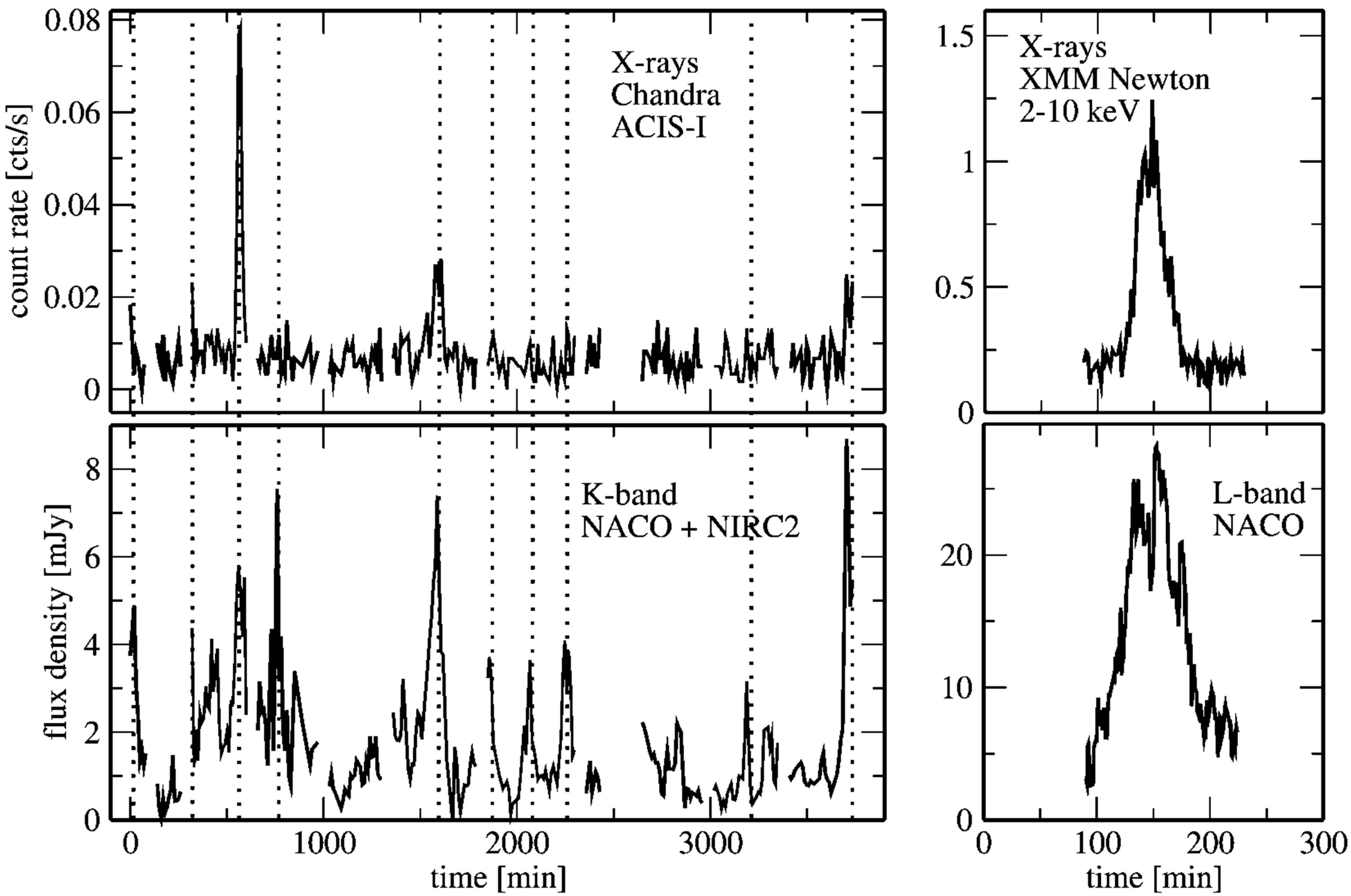
Its 'normal' X-ray luminosity of 2×10^{33} ergs/sec is less than many NS x-ray binaries

Its total luminosity is **10^{-9}** of the Eddington limit for a $4 \times 10^{6} M_{\odot}$ BH!



III : Activity from the Galactic Center

- While the total luminosity from SgrA* is very low it varies a lot (IR and x-ray data)- 'flares'- major changes on time scale of minutes
-



X-ray

Infrared

IV : Past activity of Sgr A*

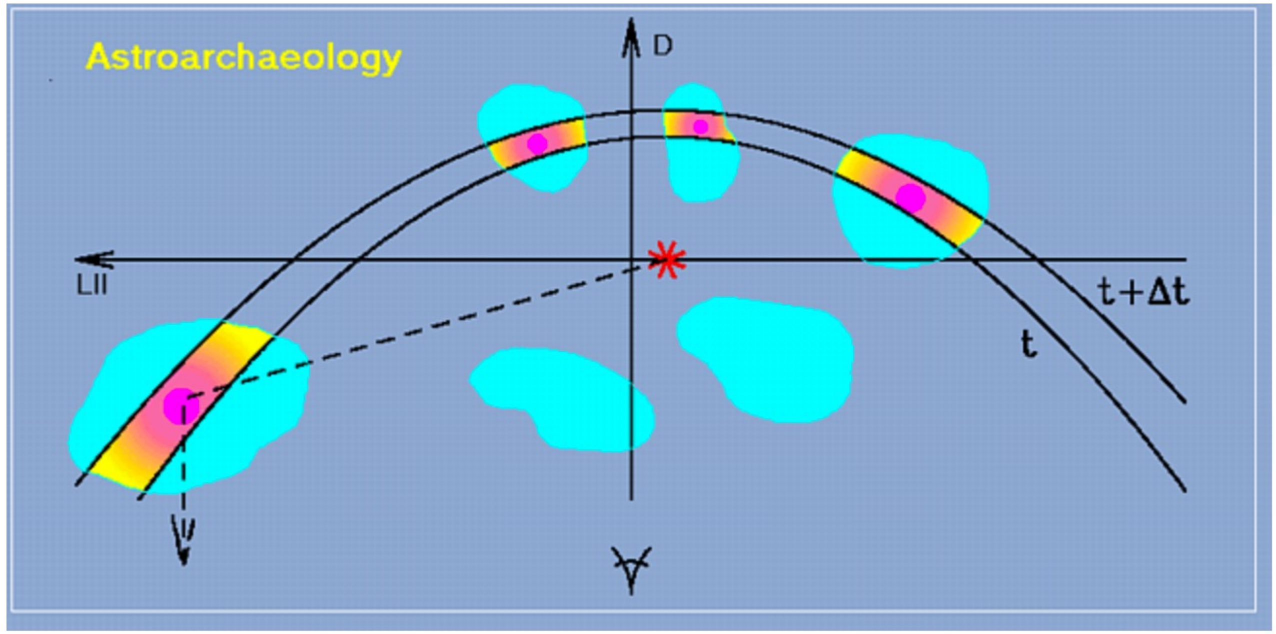
- X-ray light echoes
  - Can see echoes of an outburst in the X-ray band from gas clouds in the Galactic Center region
  - Suggests that the Sgr A* was a million times brighter (in X-rays) a few hundred years ago
  - So… the Milky Way flared up to be a low-power AGN a few hundred years ago
  - Maybe the disruption of a passing gas cloud…

Light Echo

Basic idea:
x-ray flare from SgrA* hits a molecular cloud

The cloud reprocess and re-emits x-rays

But the distance from



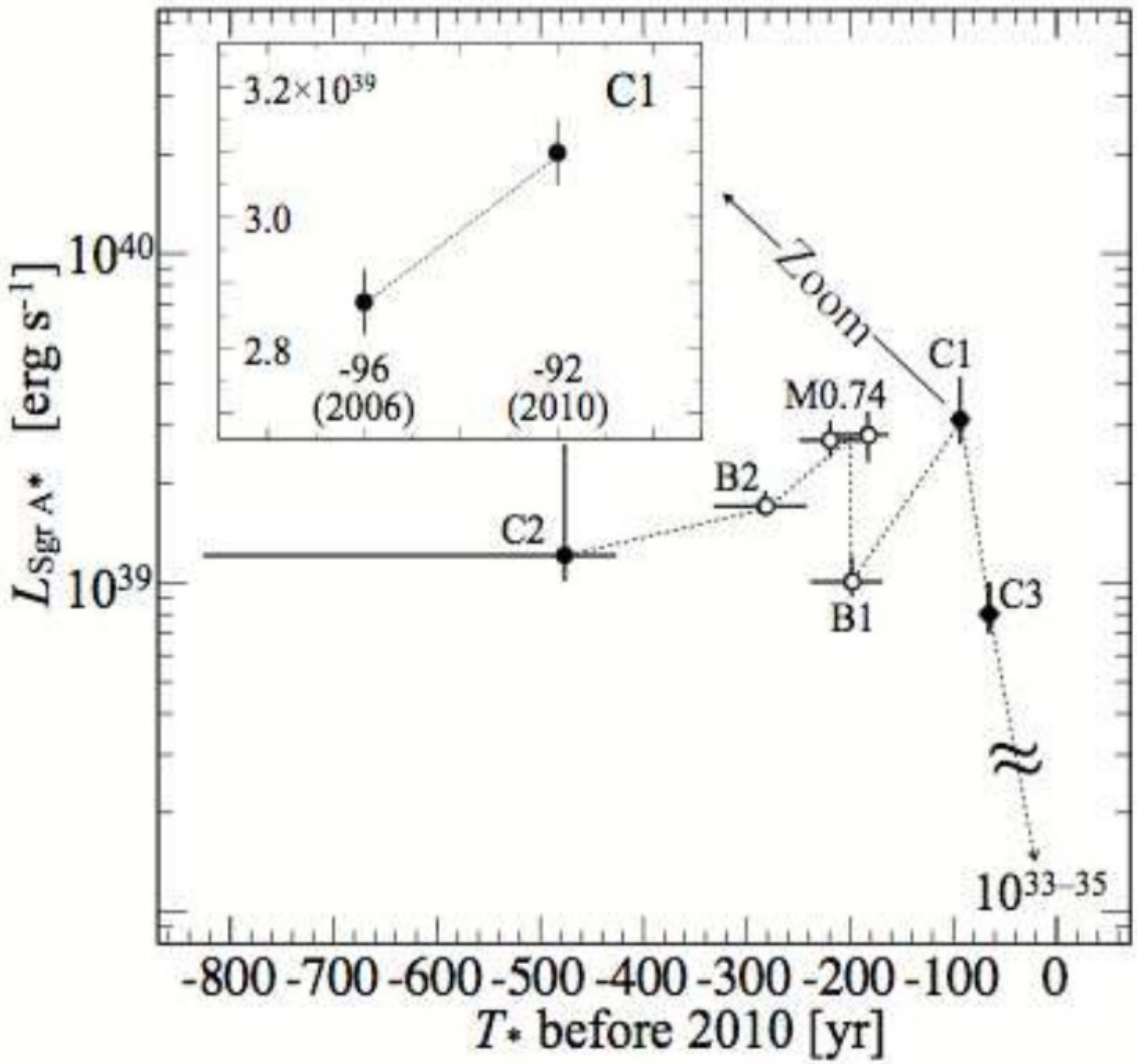
the cloud to us is different from that of SgrA* so the signal arrives at a different time (light travel time is different) if the cloud is further away we are looking at what happened in the past

In this figure points of equal light travel time lie on the parabola

Light Echo

This is the inferred past history of SgrA* in X-rays (Ryu et al 2018)

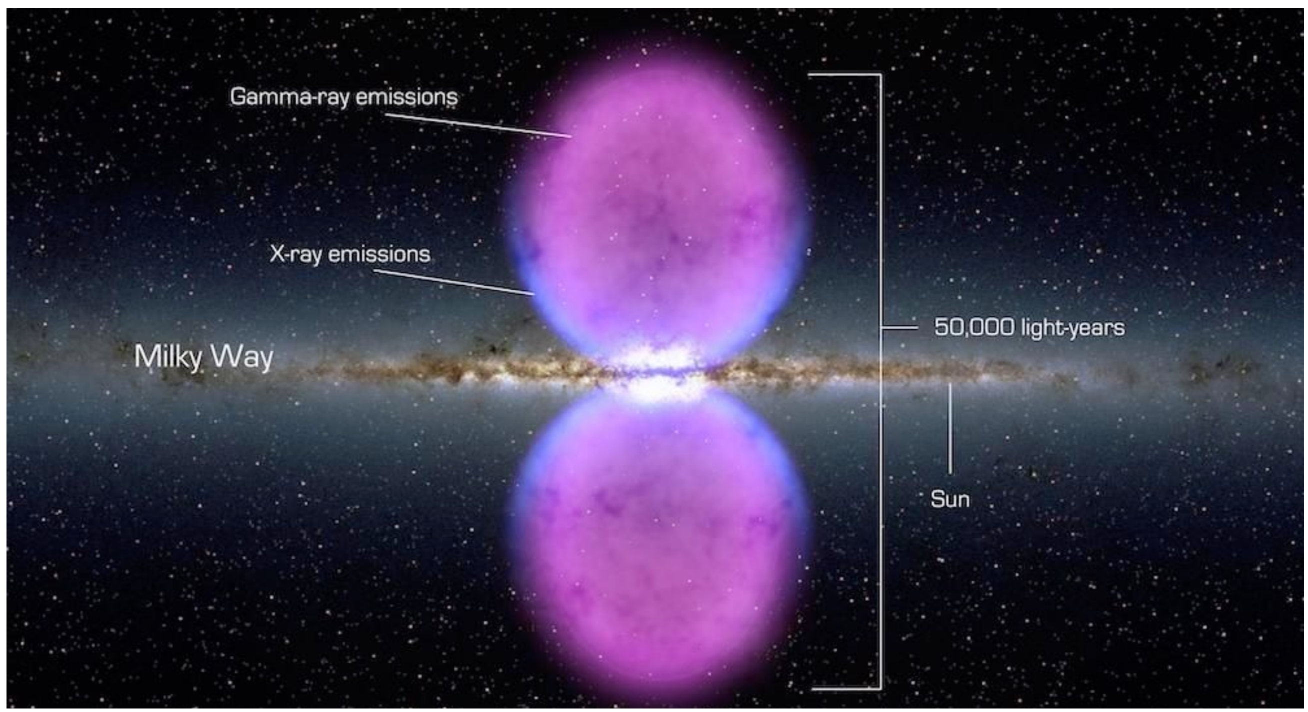
Notice the enormously higher luminosity just 200 years ago!



IV : Past activity of Sgr A*

- The Fermi Bubbles
  - The Fermi gamma-ray telescope discovered giant bubbles above and below the Milky Way- also seen by WMAP in high freq radio
  - Preferred model : Sgr A* was a jetted AGN ~5 million years ago. The jets blew these bubbles.
  - Fits with other evidence for activity during this era.

Our BH was much more luminous about 5 million years ago



Some Problems with Sgr A*

- There is lots of gas for accretion in the galactic center from the ISM and stellar winds
- Yet the observed luminosity is very low ($L/L_{Edd} \sim 10^{-9}$)
- What happens to the accretion energy- where does the mass and energy go

- Sgr A* is similar to >95% of all massive galaxies- they have big black holes, but low luminosities