THE SUPERMASSIVE BLACK HOLE AT OUR GALACTIC CENTER

Lecture 10, Introduction to Black Hole Astrophysics (PHYS480)

Hsiang-Yi Karen Yang, NTHU, 5/4/2021

ANNOUNCEMENTS

- Slides for each lecture will be posted on iLMS before the class. Feel free to download in advance and take notes!
- HW5 & HW4 solutions will be posted on iLMS today. HW5 due next Tuesday.
- Please search for black hole news for the oral presentation and paste the news link here:

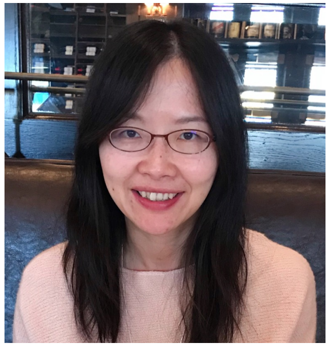
https://docs.google.com/spreadsheets/d/1_aYyMj1wf_uGheZ7zp_hvthmy4mdmPwIxFDdZOMG-nc/edit?usp=sharing

- For the oral presentations, I will compile the scores and comments from the audience and send to you after the presentation

FINAL TEAM REPORT (30%)

- ***By 5/11 (next Tuesday),*** please form a team of 3 people for the final report. Choose a team leader and enter your names on iLMS -> 小組專區. ***After 5/11, people who have not found a team will be assigned.***
- Each team will choose any black-hole-related topics, do research and gather information, study, discuss, brainstorm, and ***write a 3-5 page research proposal*** （中英皆可）
- The research proposal will include background introduction to the topic, what unknown question to be solved, and proposed methods used to answer the question
- The report will be ***due on 6/11 (Friday) at 5pm through iLMS***
- ***On Week 16 (6/15), the proposals will be evaluated by panels formed by other teams***
- Please start gathering ideas and discuss strategies with your team members.
- For ideas, please pay attention to the "***Open Questions***" part of the lectures
- Your team could also come to discuss with the instructor/TA during ***office hours***

OFFICE HOURS



- 授課教師：
  - 清華大學天文研究所 楊湘怡 助理教授
  - 綜二館 R504, hyang@phys.nthu.edu.tw
  - Office hour: 每週五11am-noon

- 課程助教：
  - 清華大學物理所碩士生 謝陸程
  - 綜二館 R529-8, ienjoy1218@gmail.com
  - Office hour: 每週一1-2pm

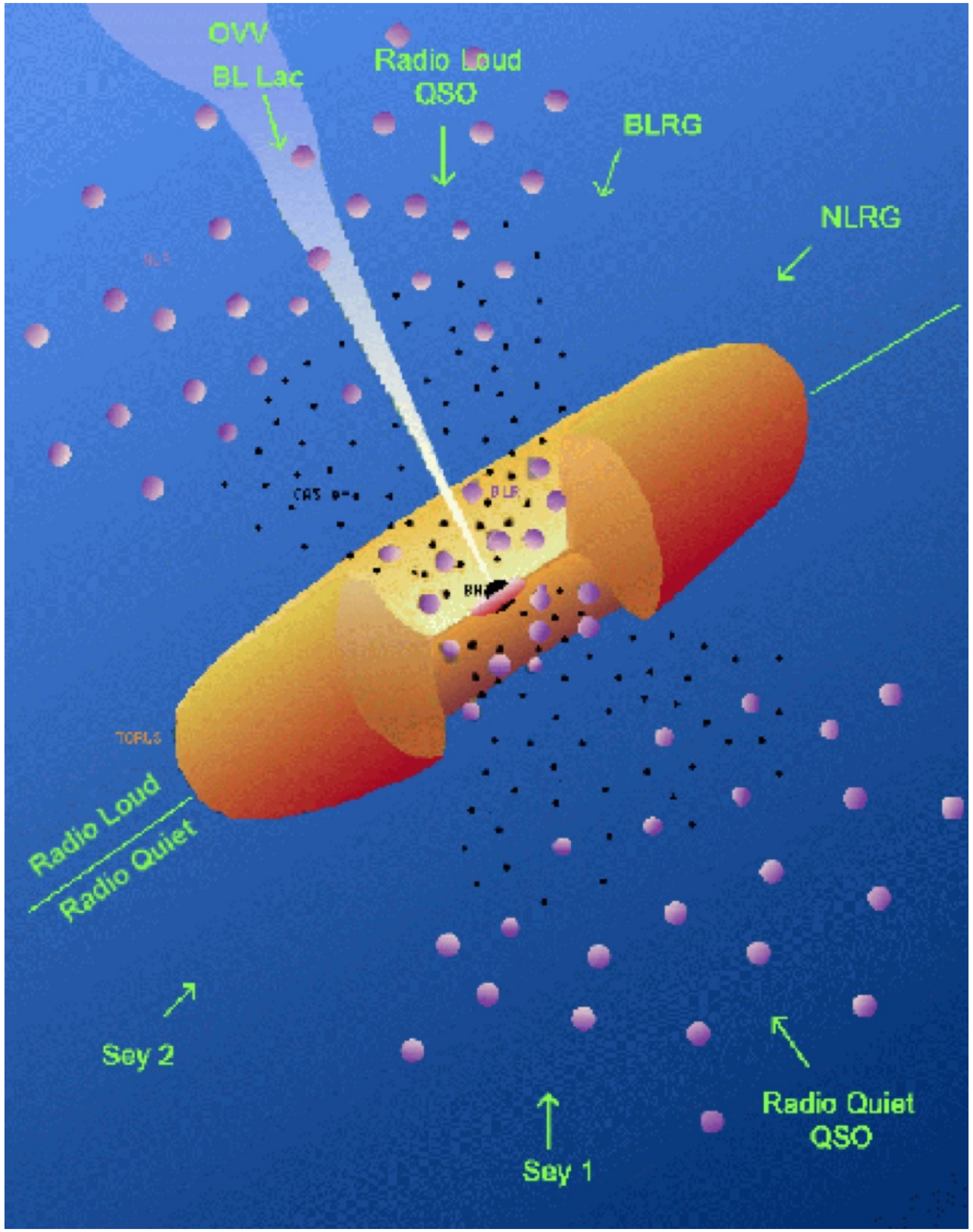
PLEASE PROVIDE YOUR FEEDBACK!

- Your feedback and comments would be valuable for improvements of this course!
- Link to the course evaluation form:

  https://qrgo.page.link/9f6cE
- Or scan the QR code here:

PREVIOUS LECTURE…

- ***Active galactic nuclei (AGN) = actively accreting SMBHs***
- Observationally they have many different faces – ***quasars, Seyfert galaxies, radio galaxies***, etc, are all different types of AGN
- Radiative processes: thermal & non-thermal (Compton, Bremsstrahlung, synchrotron)
- The spectrum of AGN at different wavelengths comes from different components
  - ***Jets*** – radio, optical, X-ray, gamma-rays
  - ***Accretion disk*** – UV/optical
  - ***Corona*** (hot gas with unknown origin) – soft and hard X-ray
  - ***Dusty torus*** – infrared
  - ***Gas clouds*** – broad and narrow emission lines
- AGN ***unification*** – we see different types of AGN due to the viewing angle
- Only ***~1-10%*** SMBHs are AGNs. While quasars are preferentially found in merging galaxies, most AGNs are triggered as long as there is abundant gas supply



AGN UNIFICATION

- The different types of AGN can be largely explained by our viewing angle relative to the ***orientation*** of the disk, rather than their intrinsic differences
- Radio-loud AGN
  - Blazars: looking along the jets
  - Radio-loud QSO/quasar: jets + disk + BLR + NLR
  - Broad-line radio galaxy (BLRG): jets + BLR + NLR
  - Narrow-line radio galaxy (NLRG): jets + NLR + dusty torus
- Radio-quiet AGN
  - Radio-quiet QSO/quasar: disk + BLR + NLR
  - Type-1 Seyfert galaxy: BLR + NLR
  - Type-2 Seyfert galaxy: NLR + dusty torus

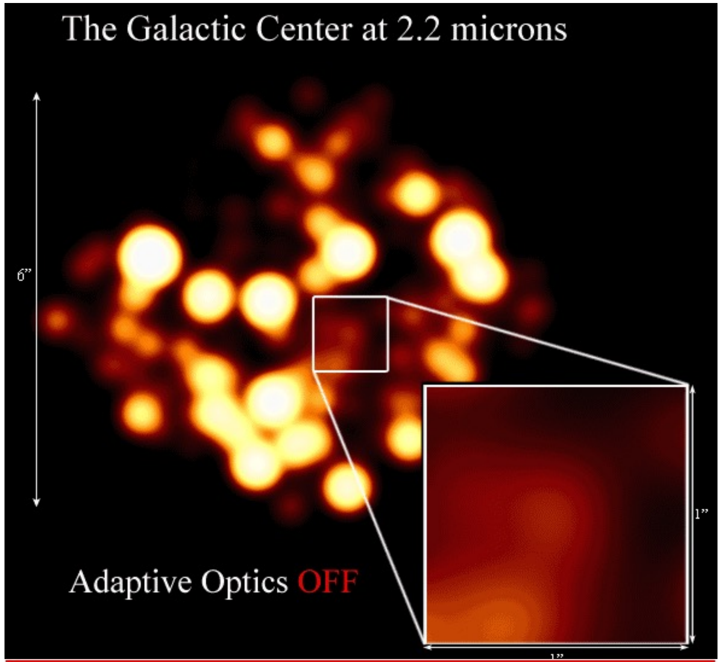
OPEN QUESTIONS REGARDING AGNS

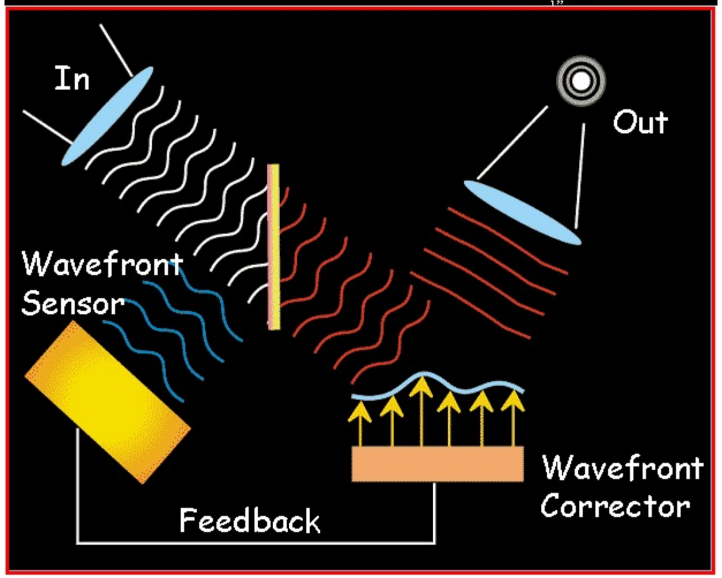
- Why does only a minor fraction of SMBHs appear as AGNs? What triggers the AGNs?
- What is the structure and origin of the corona and how it depends on mass accretion rates?
- What is the composition, geometry, and morphology of the obscuring dust? How is it formed?
- What are the connections among different types of AGN, e.g., are there any evolution sequences?
- Are AGNs scaled-up versions of X-ray binaries?
- Why do some AGN have jets and others do not? (Lecture 11)
- How do the radiation and jets of AGN influence galaxy formation? (Lecture 12)
- How do SMBHs form and grow? (Lecture 13)

THIS LECTURE

- Overview of the GCBH -- Sgr A*
- Observational properties of Sgr A*
- Tidal disruption events (TDEs)
- Evidences for past activity of Sgr A*
- GR effects close to Sgr A*
- Future prospects and open questions

GALACTIC CENTER SMBH





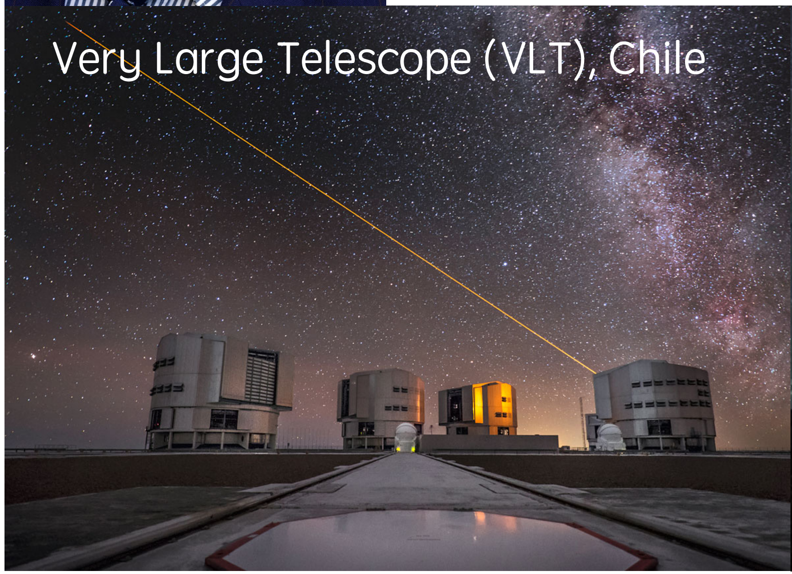
THE OBSERVATION IS NON-TRIVIAL!!

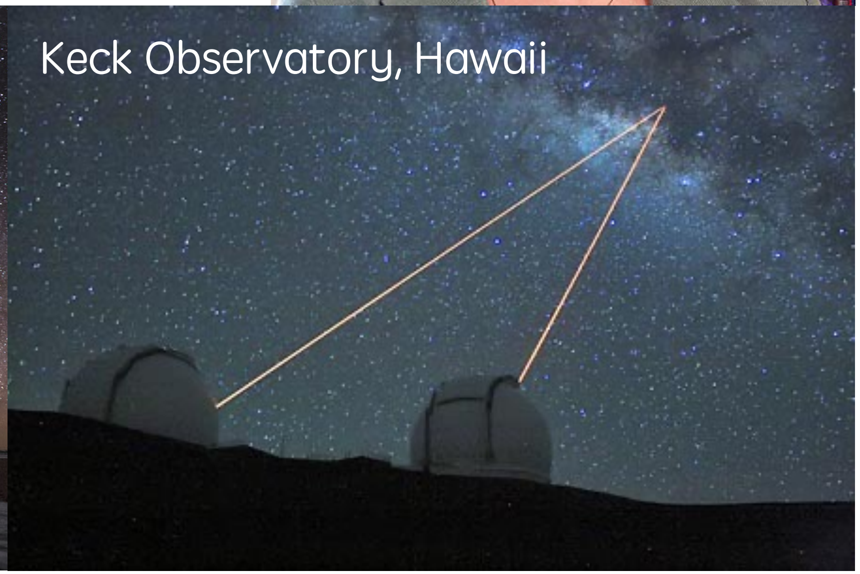
- This is only possible with the technology of ***adaptive optics (AO; 自適應光學)*** !!
- The images are blurred and distorted due to atmospheric turbulence
- Adaptive optics uses deformable mirrors to correct for turbulence in real time
- Without correction, Keck's resolution is ~ 1 arcsec
- With correction, resolution ~ 30-60 milliarcsec!!

TWO TEAMS OF BLACK HOLE HUNTERS

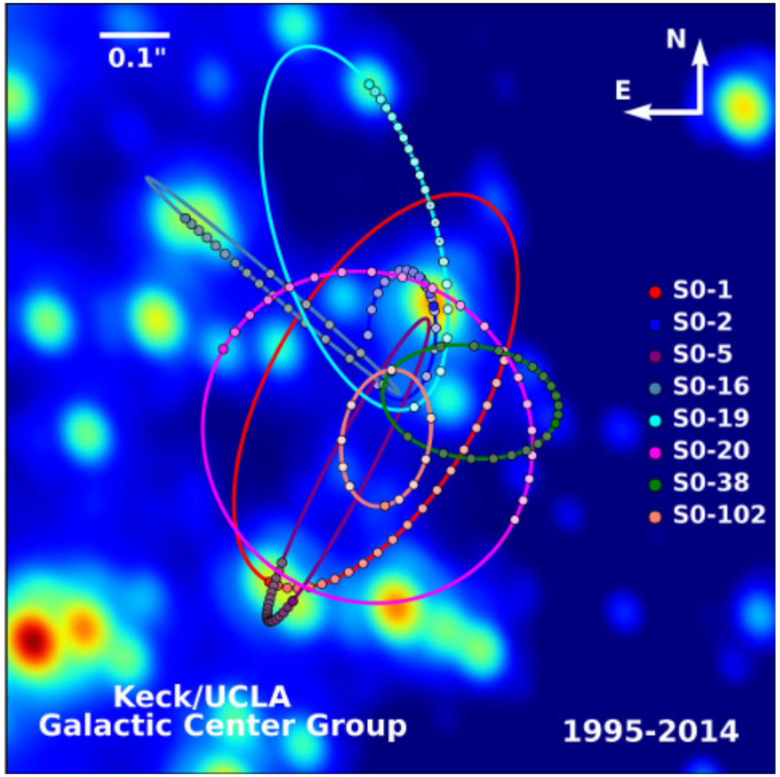
Reinhard Genzel (1952–)

Andrea Ghez (1965–)





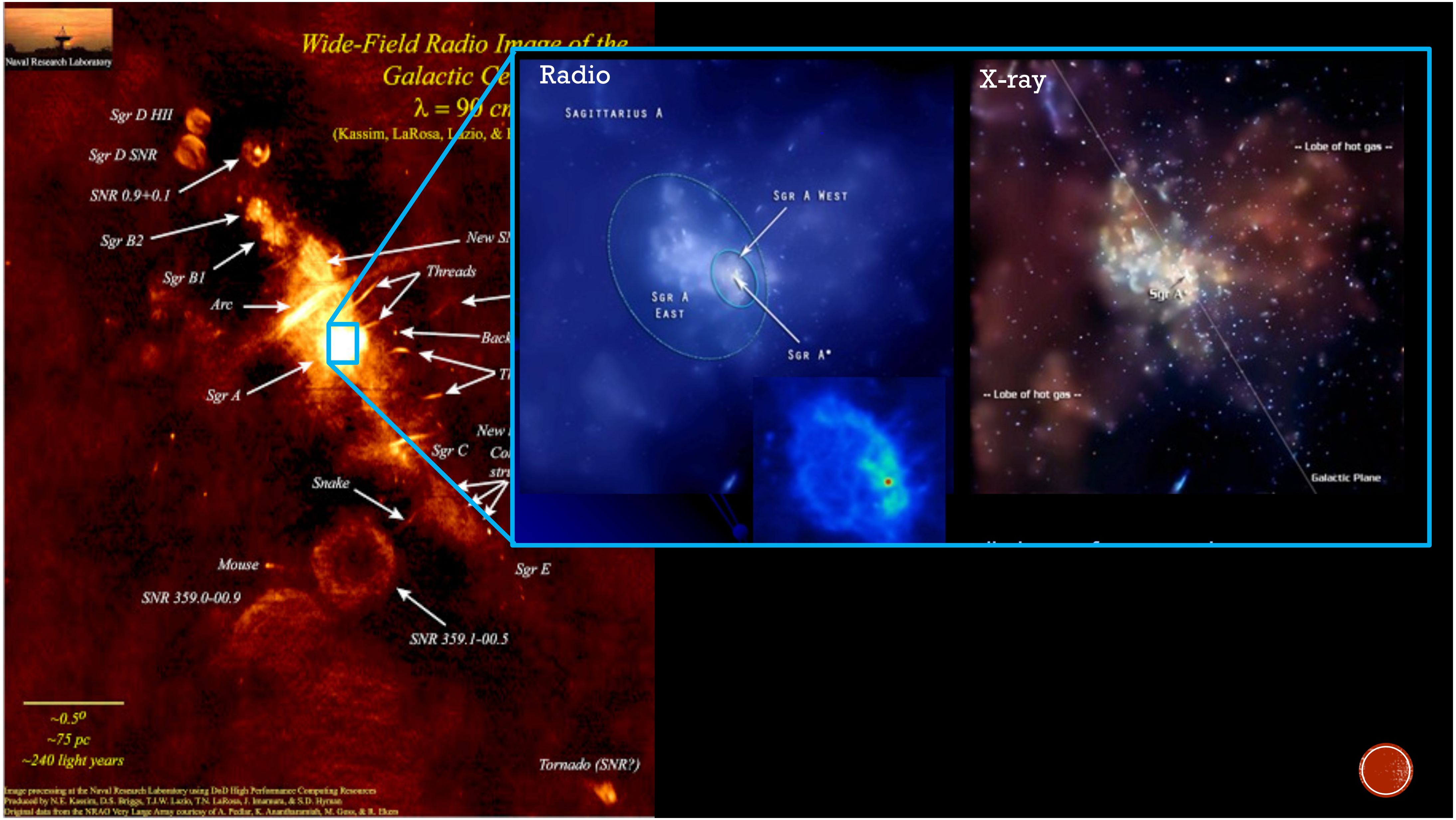
THE SMBH IN OUR BACKYARD



- ~20 years of IR observations of the star cluster at the GC
- ~25000 light-years away
- The first confirmed SMBH with precise mass measurement
- M_{BH} = 4.6 million M_{sun}
- Thanks to its proximity, we could learn a lot about SMBHs, e.g., emission mechanisms, feeding, GR effects, etc

PUT THE SCALES INTO PERSPECTIVE

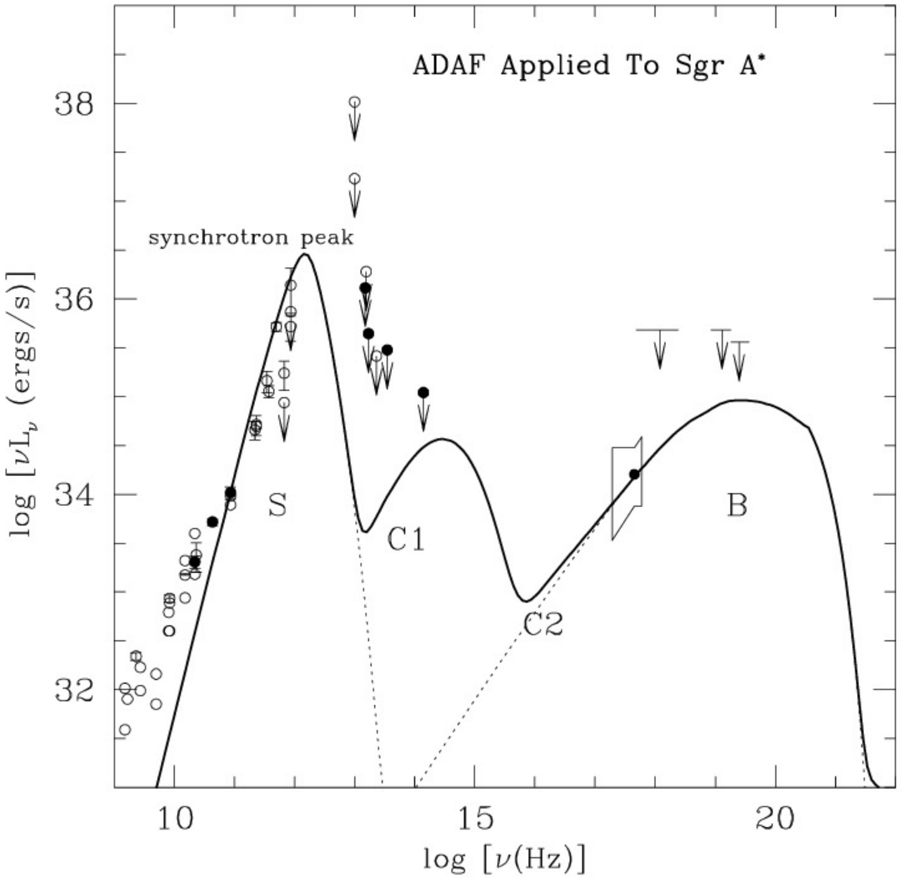
- For the GCBH, d=25000 lyr, 1 milliarcsec ~ 10^{14}cm ~ 1 light-hour ~ 100 R_s
- Implications:
  - Even with Keck's resolution with AO of ~ 30-60 milliarcsec, it is impossible to resolve the accretion flow close to the GCBH
  - Changes of accretion flow properties would cause variability on a timescale of < 1 hour
  - The current resolution of the Event Horizon Telescope (EHT) is ~ 25 microarcsec, thus possible to resolve down to the Horizon scale, but fast variability makes it difficult for data analysis



Naval Research Laboratory
Wide-Field Radio Image of the
Sgr D HII
Sgr D SNR
SNR 0.9+0.1
Sgr B2
Sgr B1
Arc
Threads
Sgr A
Sgr C
Snake
Mouse
SNR 359.0-00.9
SNR 359.1-00.5
Sgr E
Tornado (SNR?)
~0.5°
~75 pc
~240 light years
Image processing at the Naval Research Laboratory using DoD High Performance Computing Resources
Produced by N.E. Kassim, D.S. Briggs, T.J.W. Lazio, T.N. LaRosa, J. Imamura, & S.D. Hyman
Original data from the NRAO Very Large Array courtesy of A. Pedlar, K. Anantharamaiah, M. Goss, & R. Ekers
Radio
Sagittarius A
Sgr A West
Sgr A East
Sgr A*
X-ray
-- Lobe of hot gas --
-- Lobe of hot gas --
Sgr A*
Galactic Plane

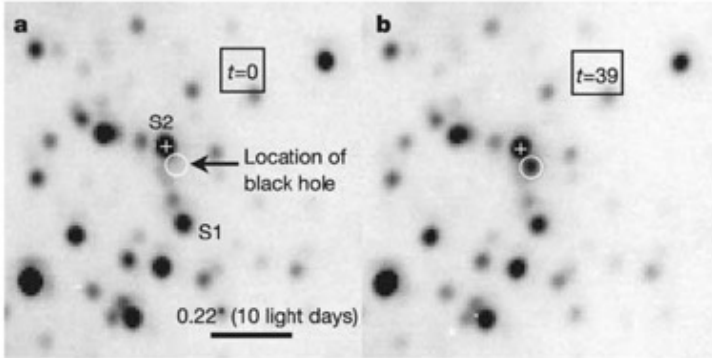
PROPERTIES OF SGR A*

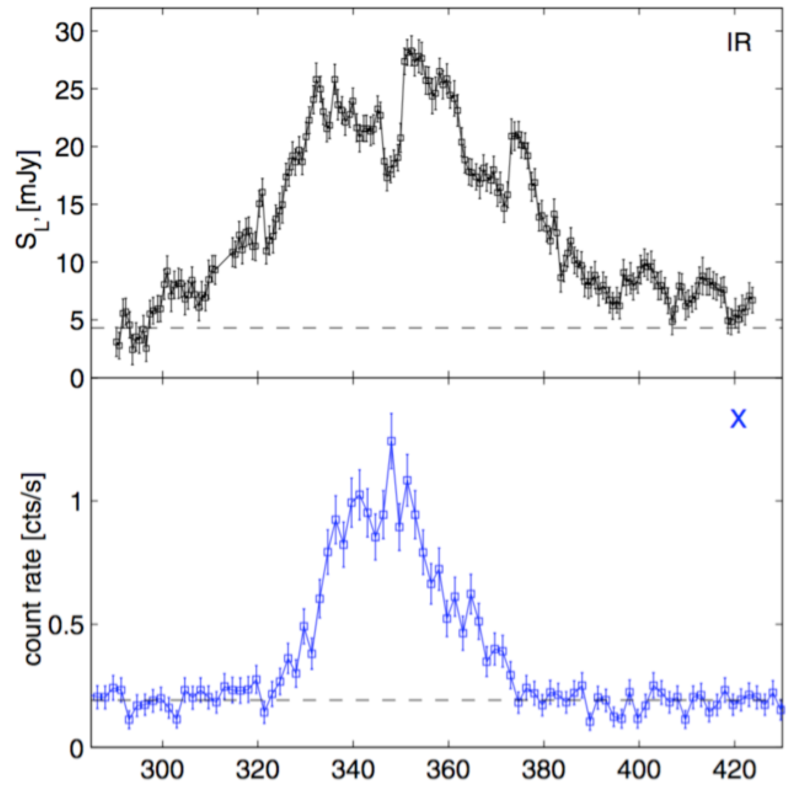
- $M_{BH} \sim 4.6x10^6\ M_{sun}$, $R_s \sim 1.4x10^{12}$cm
- $L_{edd} \sim 5x10^{37}$ W
- $L_{obs} \sim 10^{28}$ W ~ $10^{-9} \sim 10^{-10}\ L_{edd}$ -> ***not an AGN***
- Spectrum can be described by ***thick disks*** rather than thin disks
- Recall the thick disk model
  - Eddington ratio < 1%
  - Radiatively inefficient -> heat not radiated away but advected into the BH (jargon: advection-dominated accretion flow or ADAF)
  - Accretion flow is hot –> geometrically thick
  - Radiation from non-thermal emission by hot electrons (synchrotron, Compton, bremsstrahlung emission)

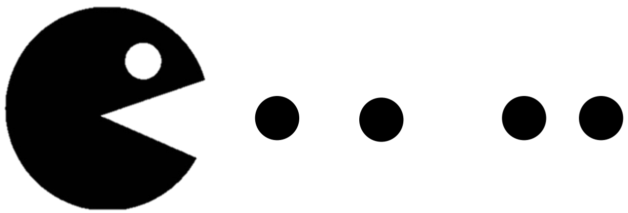


FLARES OF SGR A*

- ***Flares*** – occasional increase in fluxes by a factor up to 10-100
- Variability timescale ~ 30 mins -> size of emission ~ 50 R_s

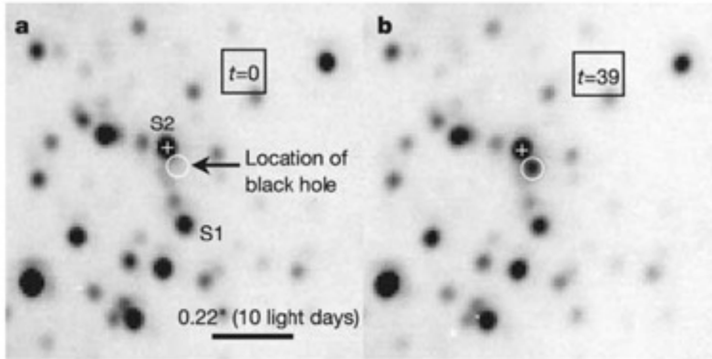


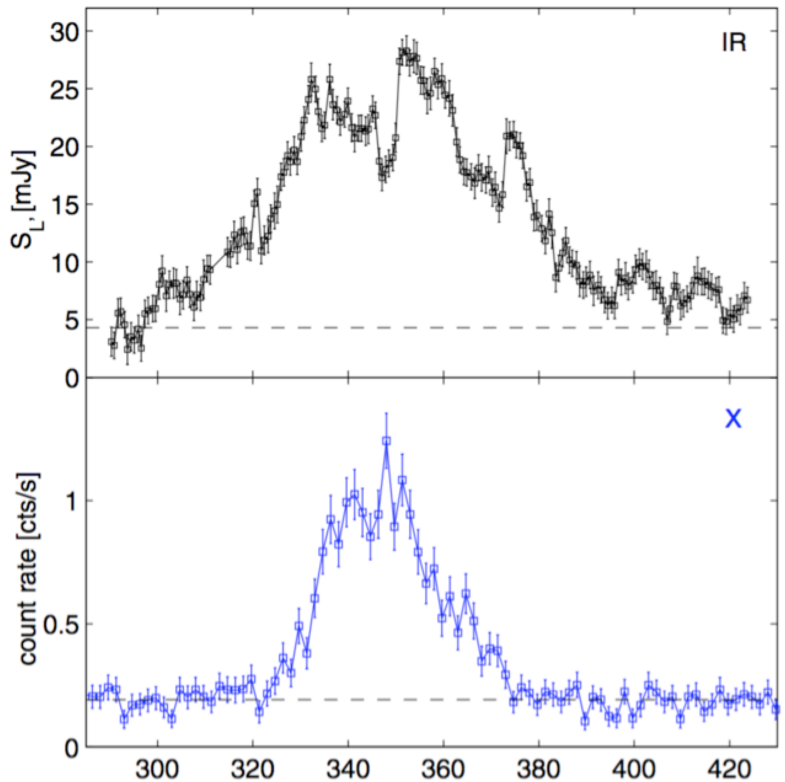


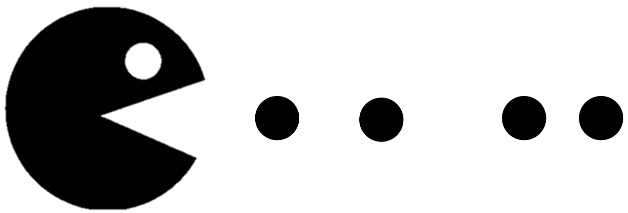


FLARES OF SGR A*

- Multi-wavelength observations of flares allow us to constrain the emission mechanism and probe changes in the accretion flow
- Example: Right figure shows a flare observed in 2014. Spectrum consistent with synchrotron. Measuring changes in spectral shape could constrain B field strength and infer the mechanism causing the flare

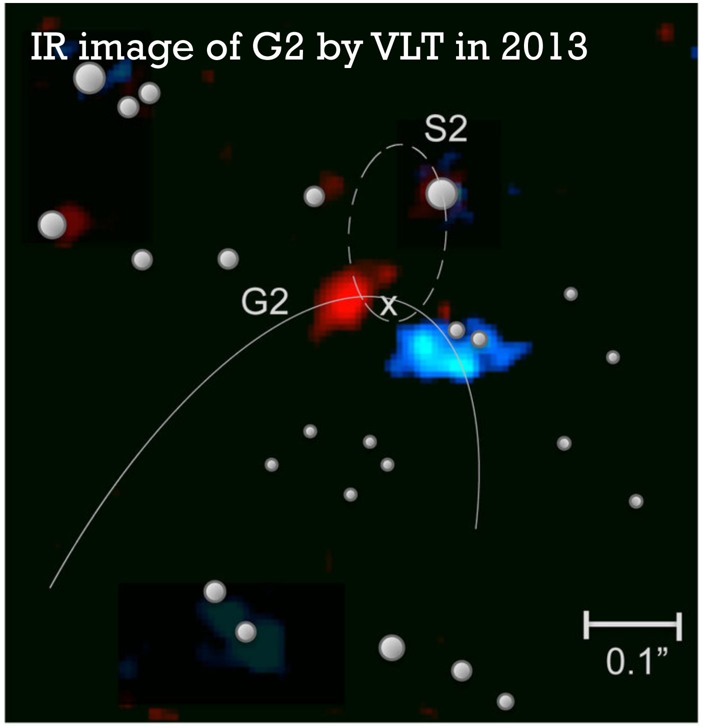


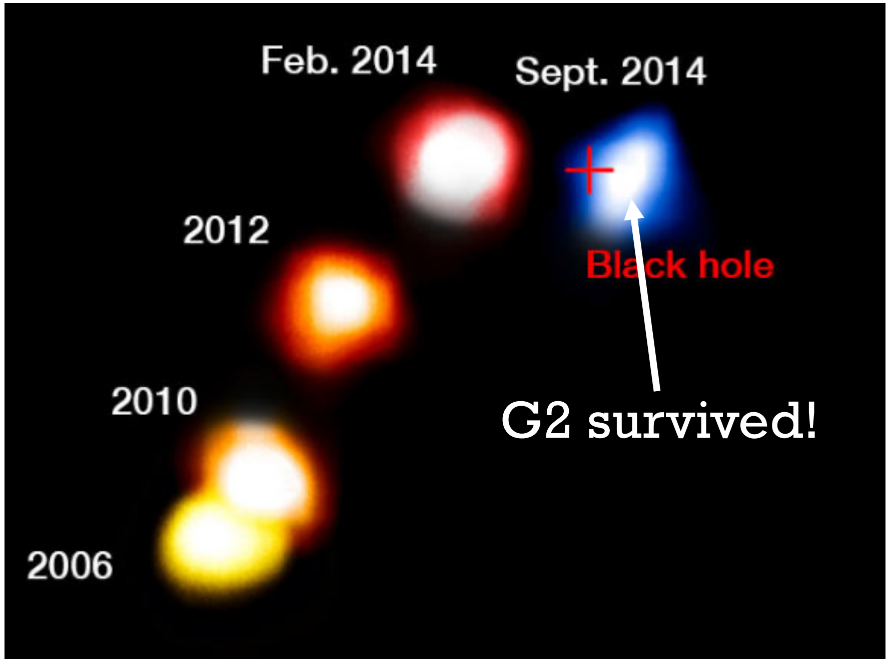




AN UNLUCKY CLOUD PASSING BY SGR A*?

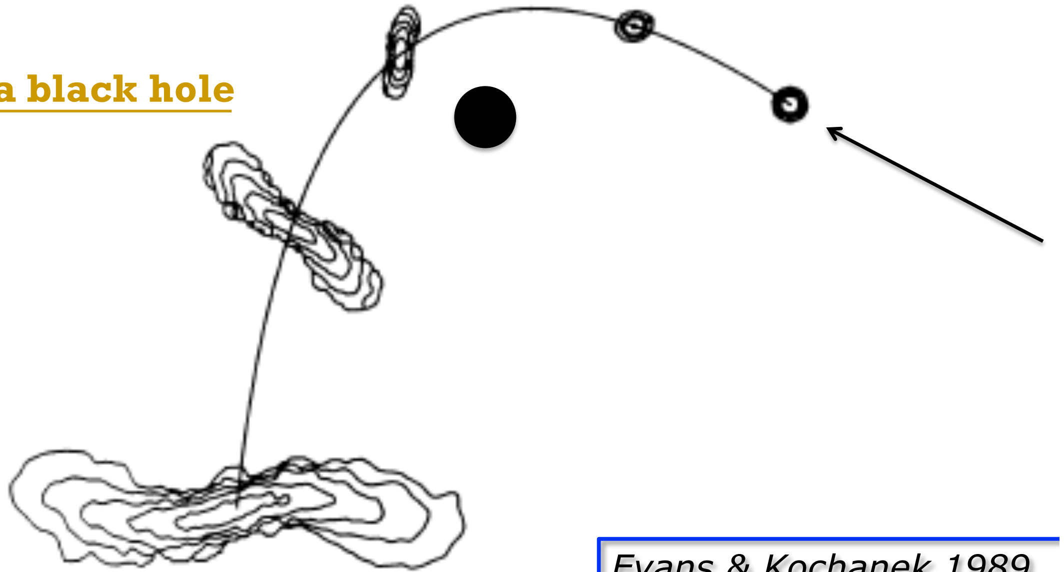
- In 2013, a cloud called G2 was predicted to pass by Sgr A*, disrupted, and create a firework show





COULD STARS BE EATEN?

- Yes if they get too close – a star would be ***spaghettified*** and disrupted by tidal forces due to the curved spacetime near the SMBH!
- This is called ***tidal disruption events (TDEs;*** **潮汐破壞事件)**
- Recent news:
  - **Astronomers see a star spaghettified by a black hole**
  - 恒星被黑洞吞噬產生的幽靈粒子



Evans & Kochanek 1989

TIDAL DISRUPTION EVENTS

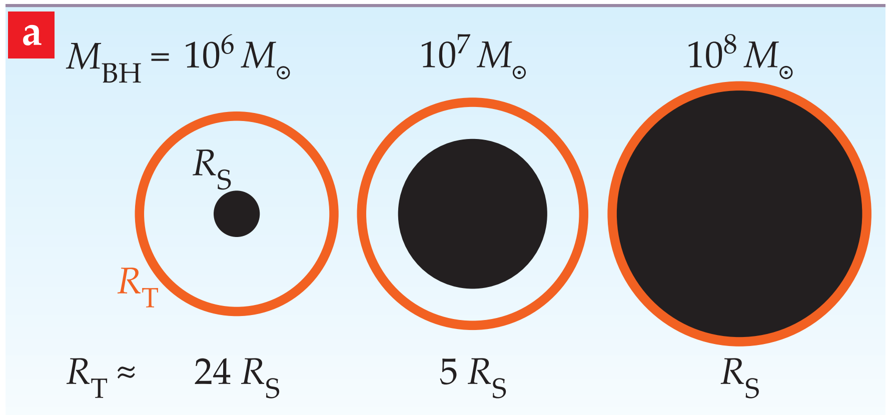
- A star would be ripped apart when tidal forces overcome the self gravity of the star:

$$\frac{GMR_*}{r^3} = \frac{Gm_*}{R_*^2}$$

- ***Tidal disruption radius R_T***:

$$R_T \approx R_*(M_{BH}/m_*)^{1/3}$$

- A sun-like star would be eaten by SMBHs >~ 10^8 M_{sun} without disruption!
- TDEs are more likely to occur for smaller SMBHs

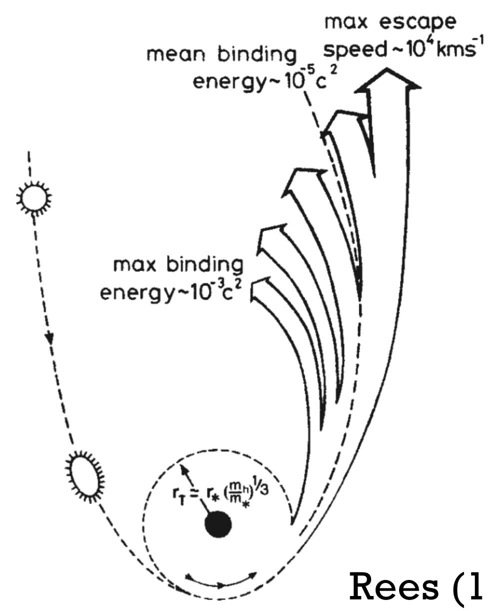


TIDAL DISRUPTION EVENTS

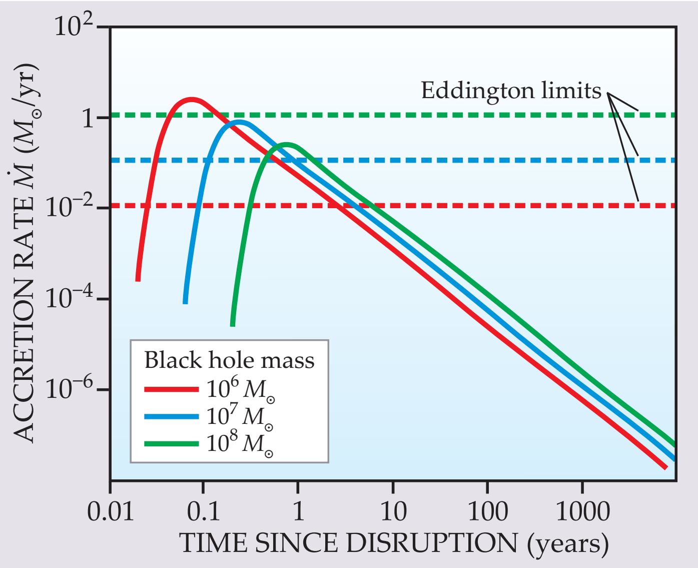
- In 1988, Martin Rees predicted tidal disruption of stars by SMBHs of <~ 10^8 M_{sun} in nearby galaxies
- Once a star passes within R_T, the star would be stretched and disrupted. Half of the mass would fall back while the other half escape
- The bound materials would form accretion disks and give out radiation lasting ***months***
- Assuming light curve follows the mass fallback rate:

$$L = \varepsilon \dot{M} c^2 \propto t^{-5/3}$$

- Peak accretion rate can be ***super-Eddington*** for smaller SMBHs!

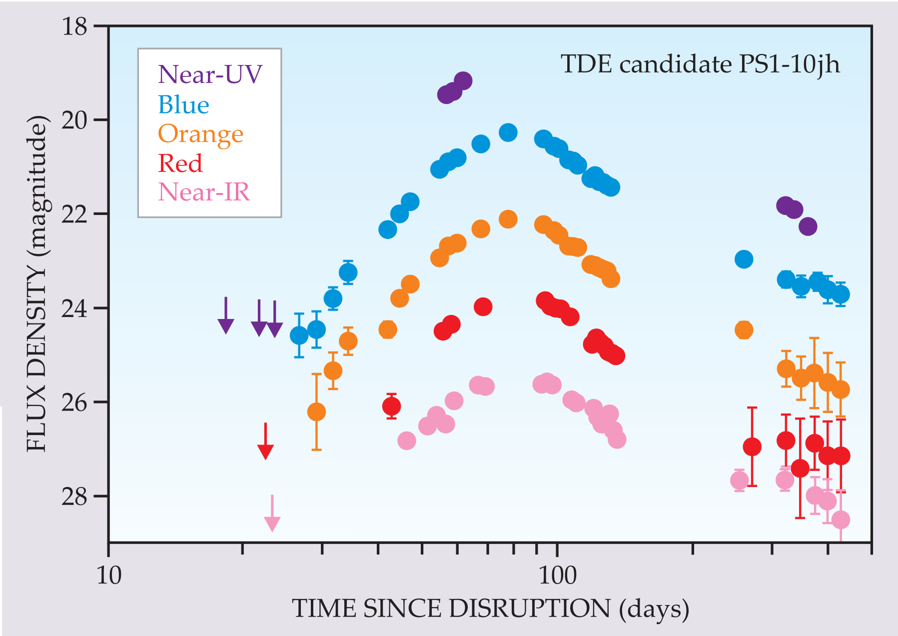


Rees (1988)



TIDAL DISRUPTION EVENTS

A TDE candidate observed in 2010

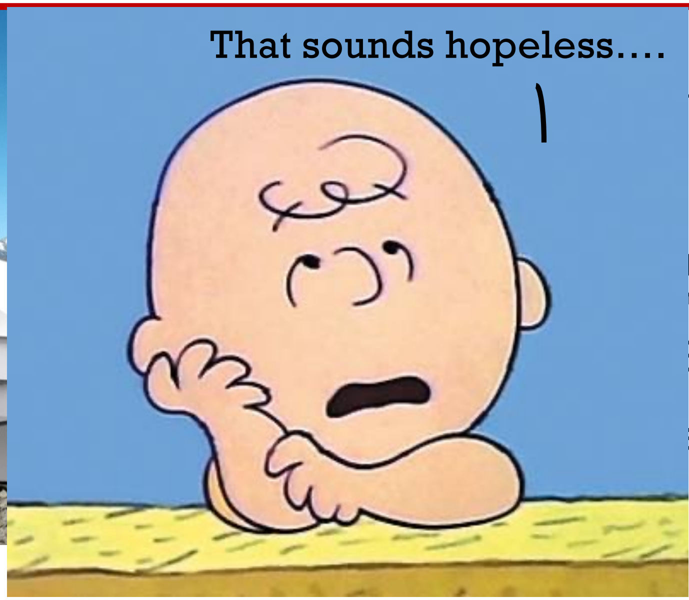


- So far 20-30 TDE candidates have been identified in the local universe
- Why study TDEs?
  - Super-Eddington accretion
  - Trace quiescent SMBHs (a unique chance to measure their spins!)
  - Search for low-mass SMBHs and understand how they grow

TIDAL DISRUPTION EVENTS

Vera R

For a galaxy with 10^6 M_{sun} BH, predicted TDE rate ~ 1 event every 10^4 years….



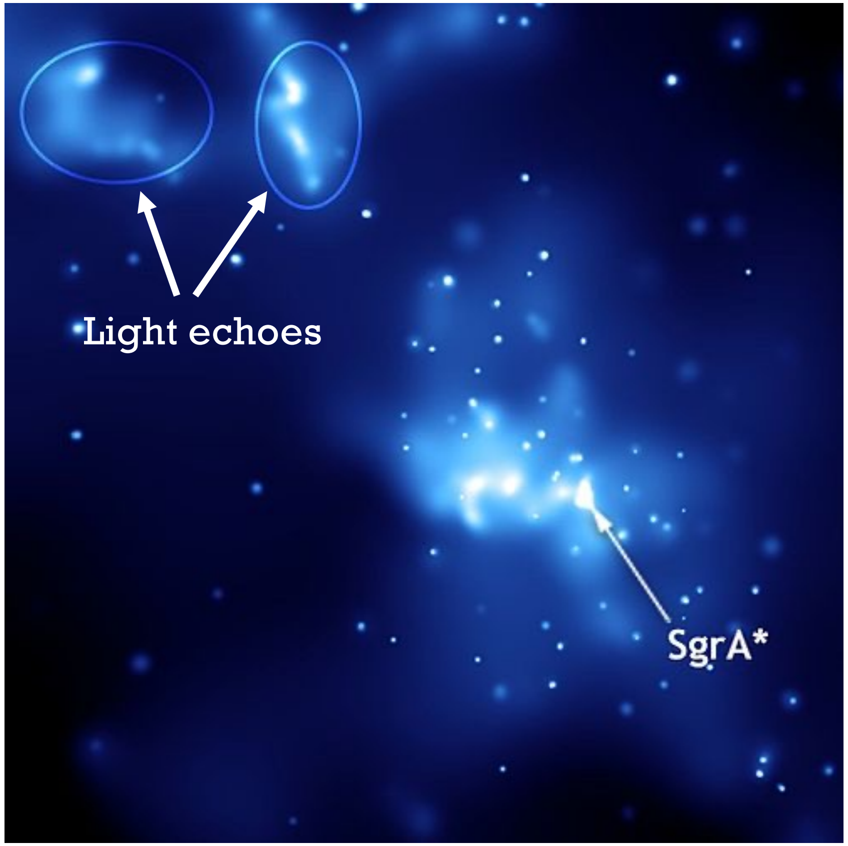
$$\ldots^{-1}\left(\frac{M}{10^6 M_\odot}\right)^{4/3}\left(\frac{\mathcal{N}_*}{10^5\,\mathrm{pc}^{-3}}\right)\left(\frac{\sigma_*}{100\,\mathrm{km\,s}^{-1}}\right)^{-1}$$

Observatory (previously
noptic Survey
') in Chile will soon find
Es!

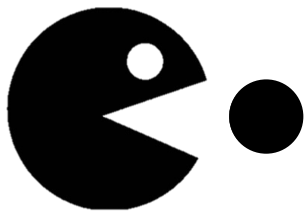
able to see TDEs by Sgr A*?

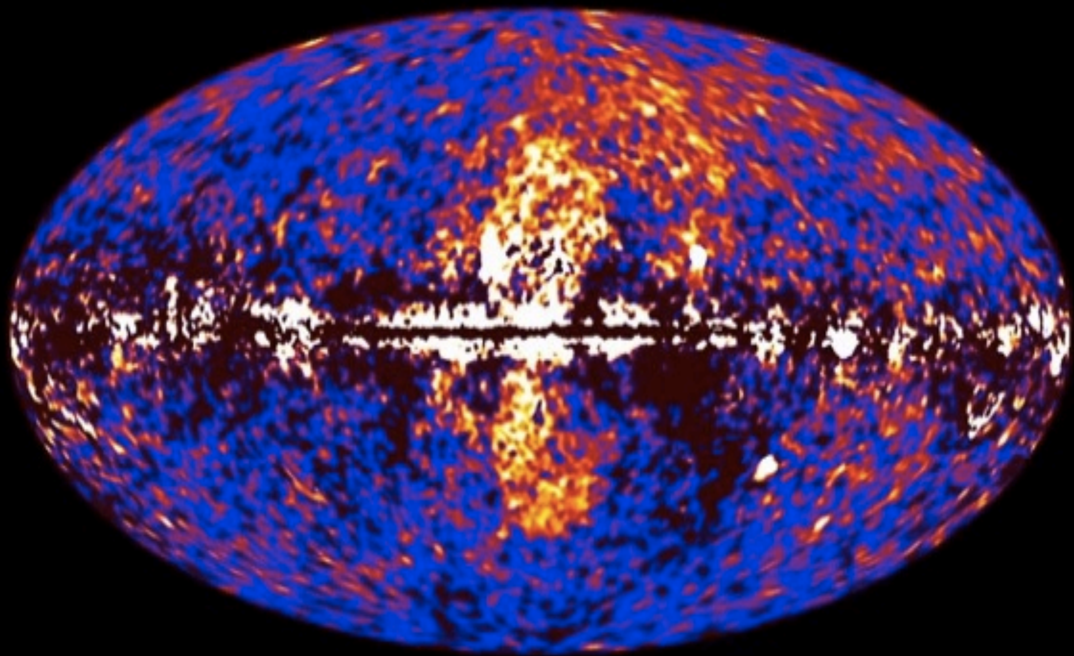
PAST ACTIVITY OF SGR A*

X-RAY LIGHT ECHOES



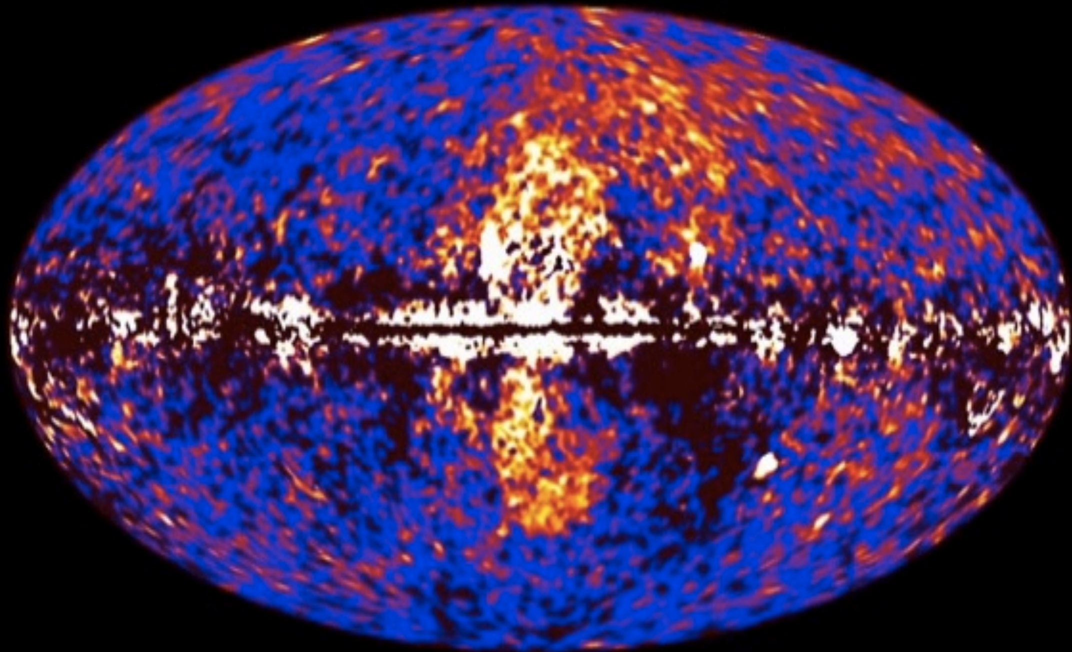
- Evidence of past activity inferred from ***X-ray light echoes / reflection nebulae***
  - Electrons in gas clouds excited by radiation from Sgr A* and emit in X-ray
  - Mechanism similar to BLR clouds in reverberation mapping
- In 2007, echoes of an outburst were observed in the X-ray band from gas clouds in the GC region
- Suggests that Sgr A* was ~10^5 times brighter in X-ray about 50 years ago
  - Distance between clouds and Sgr A* is 50 lyrs -> time delay effect
- Sgr A* may have eaten a Mercury-mass object





THE FERMI BUBBLES

- Giant gamma-ray bubbles revealed by Fermi Gamma-ray Space Telescope in 2010
- Extending ~50 degrees (i.e., 100 full moons!) above and below the GC
- Energy required to inflate the bubbles is enormous



Starburst winds (M82)

Black hole jets (Cen A)

THE FERMI BUBBLES

- Giant gamma-ray bubbles revealed by Fermi Gamma-ray Space Telescope in 2010
- Extending ~50 degrees (i.e., 100 full moons!) above and below the GC
- Energy required to inflate the bubbles is enormous
- The symmetry suggests they originate from ***past*** activity from the GC such as nuclear starburst or SMBH activity

Nov. 9, 2010
NASA's Fermi Telescope Finds Giant Structure in our Galaxy
View briefing materials related to this feature here.
Fermi discovers giant bubbles in Milky Way
Astronomy Now
Celebrating 25 years of the UK's best astronomy magazine
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Top Stories
Fermi finds giant bubbles in Milky Way
DR EMILY BALDWIN
ASTRONOMY NOW
Posted: 11 November 2010
SHARE
A previously unseen structure spanning across 50,000 light years and possibly millions of years old has been discovered in the heart of our Galaxy.
Gamma-ray emissions
X-ray emissions
Milky Way
50,000 light-years
Sun
The structure spans more than half the visible sky from the constellation of Virgo to Grus. Hints of the bubbles' edges were first observed in X-rays (blue) by ROSAT. The gamma rays mapped by Fermi (magenta) extend much farther from the Galaxy's plane. Image: NASA's Goddard Space Flight Center.
SPECIAL OFFER
Moon Disc Atlas + Night Sky Wallchart
The Planets
From tiny Mercury to distant Neptune and Pluto, The Planets profiles each
TONIGHT'S SKY
Waukesha, W
SUN & MOON
Sun
RISE 7:24 AM
SET 4:25 PM
Dec. 31: Jupiter is
Astronomy magazine
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Advanc
Alt Az - EQ Man
Modular Des
Home / Magazine / 50 Weirdest Objects in the Cosmos / Weird Object:
Like 3.5k Tweet G+1 2 Share
Weird Object: Fermi Bubbles
No. 1: Double Bubble, Toil and Trouble
HOME / NEWS & EVENTS / NEWS /
2014 Rossi prize awarded to Douglas Finkbeiner, Tracy Slatyer, and Meng Su
January 8, 2014

Fermi bubbles require

Starburst

--> 10 x current star formation rate!

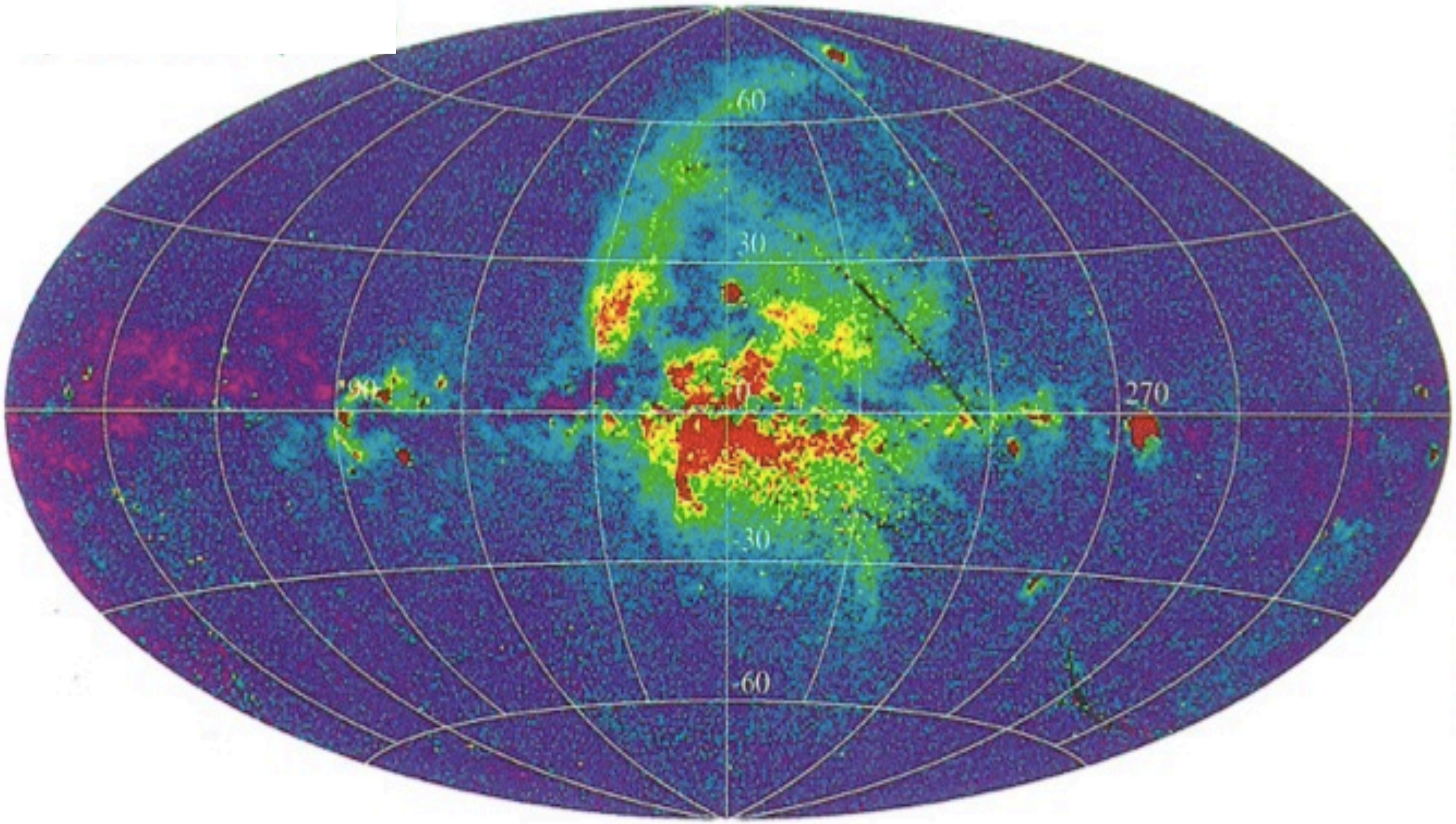
Black hole activity

--> 10000 x current black hole activity!!!

Our Milky Way

NOW	*PAST*
	

X-ray map by the ROSAT satellite (Snowden+ 1997)

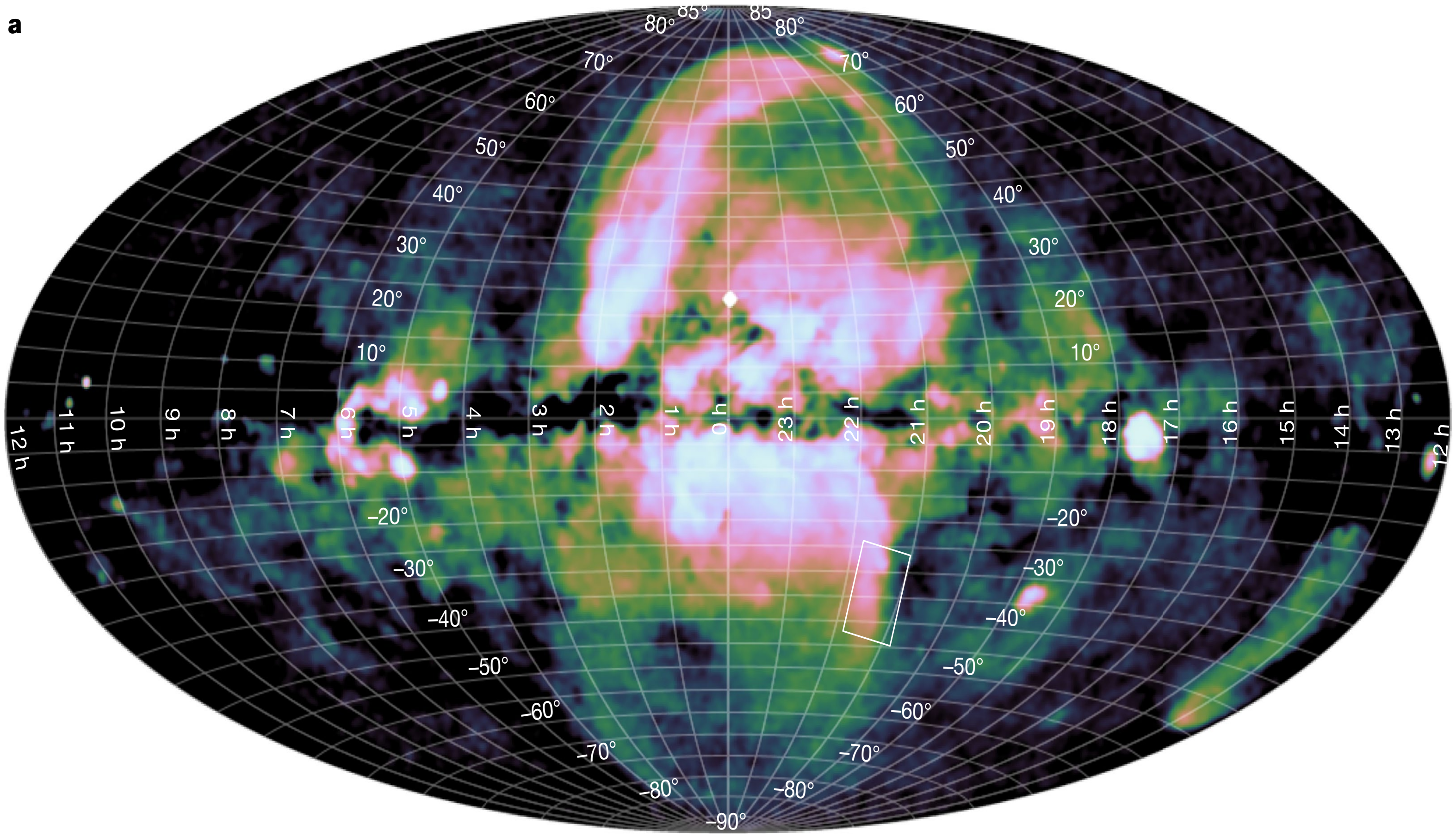


**X-ray emission is produced by gas within the Milky Way (bremsstrahlung emission by gas with T~10^6 K)

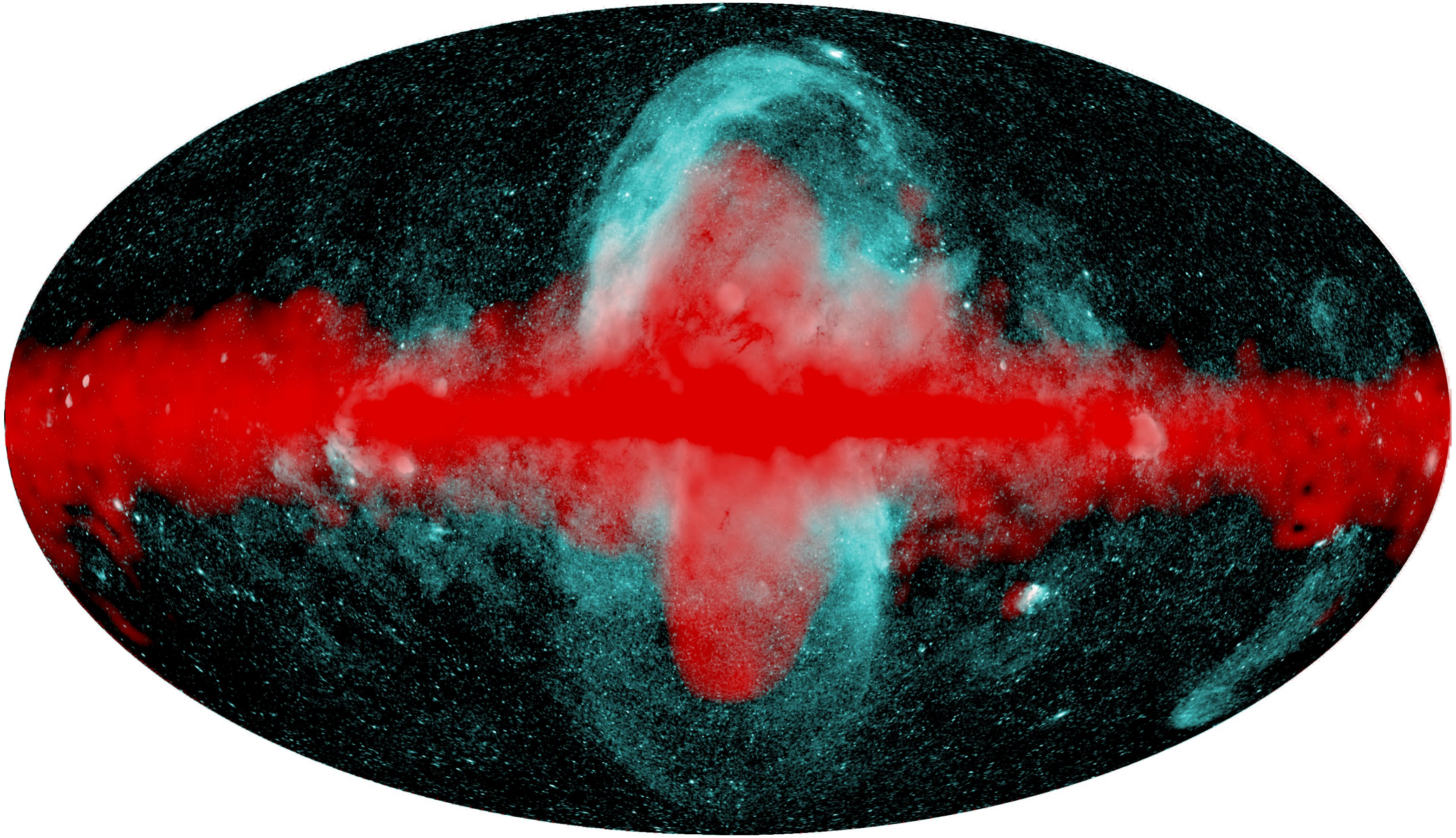
X-ray map by the eRosita satellite [click here for news link]

(Predehl et al., 2020, Nature, 588, 227)

a

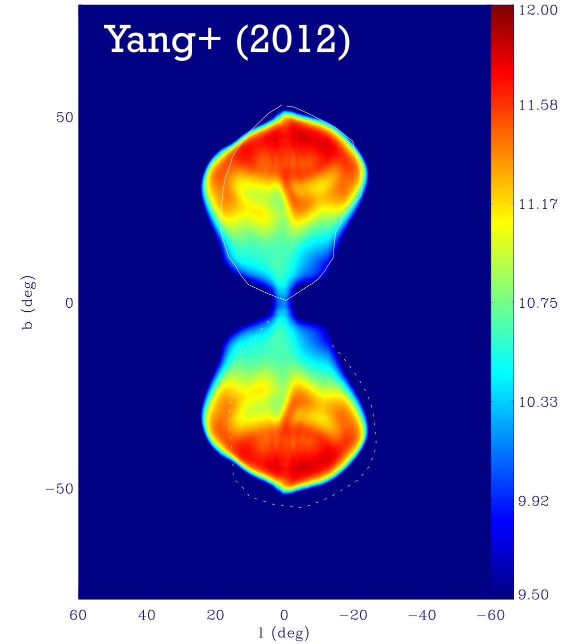


X-ray map by eRosita + Gamma-ray by Fermi

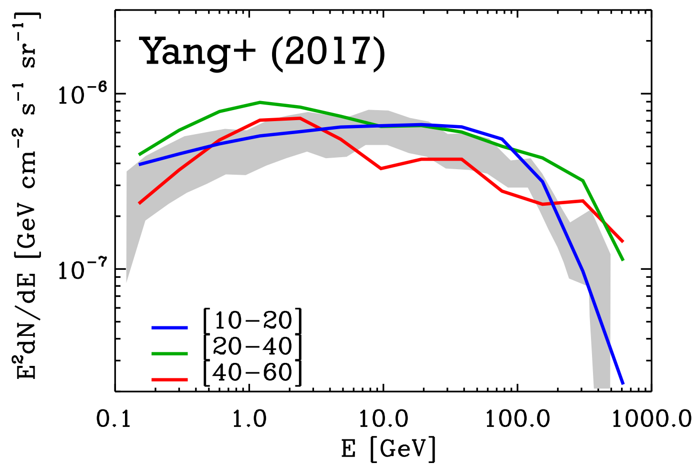


***Fermi bubbles**: cosmic rays injected from past activity at the Galactic center*
***eRosita bubbles**: gas being compressed by shocks due to the energetic outburst*

IF FERMI BUBBLES ARE INFLATED BY JETS FROM SGR A*



- Simulations have found that the SMBH jet model can successfully explain the morphology and multi-wavelength spectra of the observed bubbles
- Parameters constrained by the jet model:
  - Bubble age ~ a few Myr
  - Jets were active for ~0.3 Myr
  - Eddington ratio ~ 1-10% -> AGN!!
  - Mass accreted ~ 10^3 M_{sun}!



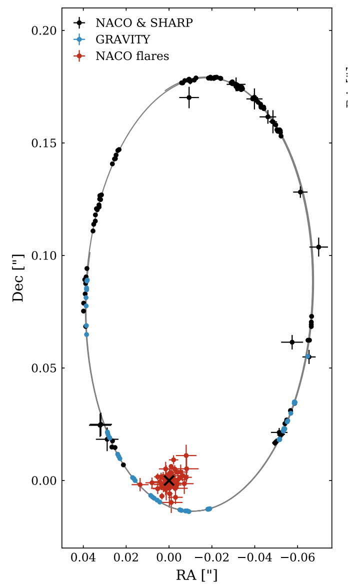
**Note that there are many different models proposed, and each of them could give different estimates

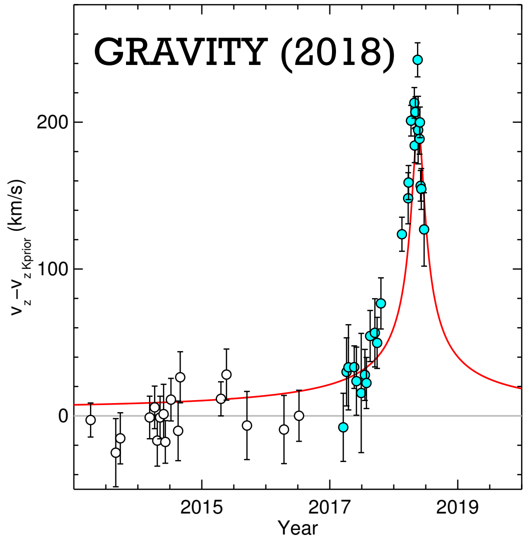
PROBING GR EFFECTS CLOSE TO SGR A*

PROBING GR EFFECTS NEAR SGR A*

- GRAVITY (2^{nd}-generation VLT) uses IR interferometry to precisely measure properties of the S2 star with resolution of 4 milliarcsec
- S2: pericenter ~ 120AU ~ 1400 R_s, max orbital speed ~ 7650 km/s
- By collecting data over the past 26-year, they have confirmed two important predictions of GR
- ***Gravitational redshift (bottom right)***: velocities measured from redshifts of lines close to pericenter is consistent with the GR prediction
- ***GR precession (upper right)***: objects would orbit not in closed ellipses but would precess. The precession of Mercury's orbit around the Sun was one of the first confirmation of GR. Precession angle of S2 is consistent with GR [see news here]

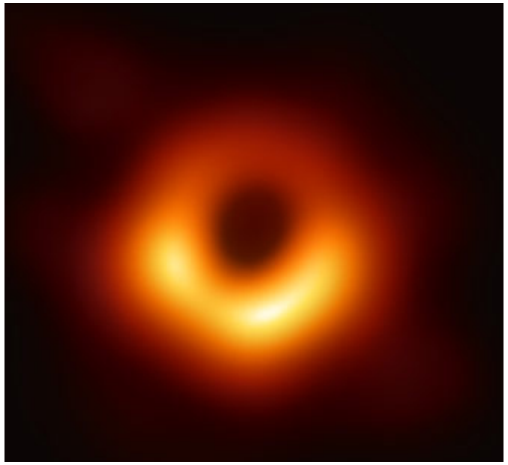
GRAVITY (2020)



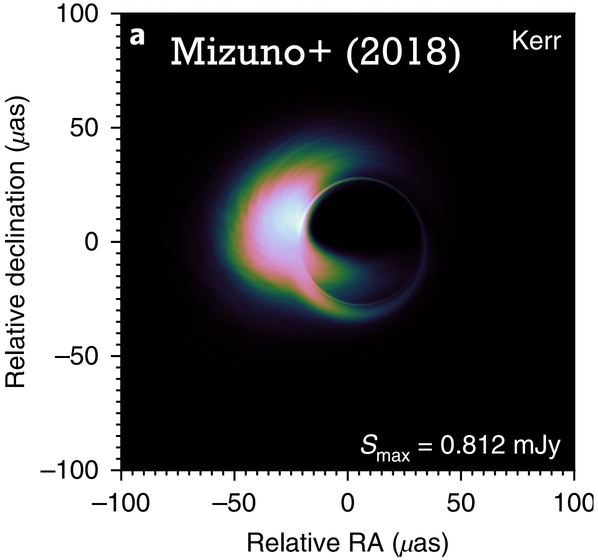


COMING SOON -- IMAGE OF SGR A*

EHT image of M87 SMBH



Simulated image of Sgr A*



- ***Event horizon telescope (EHT)*** combines radio telescopes around the globe to reach resolution of 25 microarcsec!
- Predicted shadow size of Sgr A* ~ 52 microarcsec
- M87 SMBH is 1500x more massive and 2000x more further away -> shadow size ~ 40 microarcsec
- These are the ***ONLY TWO*** BHs in the universe for which the shadow can be resolved with current resolution!!
- Why observation of Sgr A* has not been announced? -> Variability timescale < 1 hour!

SOME OPEN QUESTIONS

- What will we see and learn from the image of Sgr A* by EHT?
- Will we continue to validate GR or will we find new physics?
- What can we learn from the TDEs?
- What is the origin of the Fermi bubbles?
- What is the activity history of Sgr A* and what it tells us about the history of our Milky Way galaxy?

SUMMARY

- Advancement in technology (adaptive optics, interferometry with long baselines) has allowed us to study Sgr A* with unprecedented details and learn about SMBHs
- Currently, Sgr A* is a dormant SMBH with occasional flares
- We might see accretion events from gas clouds like G2, but unlikely to see tidal disruption of stars by Sgr A*
- Tidal disruption events (TDEs)
  - A star would be disrupted by tidal forces when it passes within the tidal disruption radius
  - About half of the materials would fall back, form accretion disks, and shine
  - Predicted lightcurve follows a $t^{-5/3}$ decay and can be super-Eddington
- Evidences (X-ray light echoes, Fermi bubbles) suggest elevated past activity of Sgr A*
- GR effects have been confirmed. EHT image of Sgr A* is coming soon!

Link to the video: https://www.youtube.com/watch?v=lDYjnjTy0wQ&t=2s

PRESENTATIONS 5/4

- Researchers find the origin and maximum mass of black holes observed by GWs by Hao-Sheng Wang 王皓陞

https://qrgo.page.link/Lku6u

- NICER probes the squeezeability of NSs by Ying-Chi Hu 胡英祈

https://qrgo.page.link/Pyyk3

- Primordial black holes and the search for dark matter from the multiverse by Jean Nelson 倪宇強

https://qrgo.page.link/ULxy2