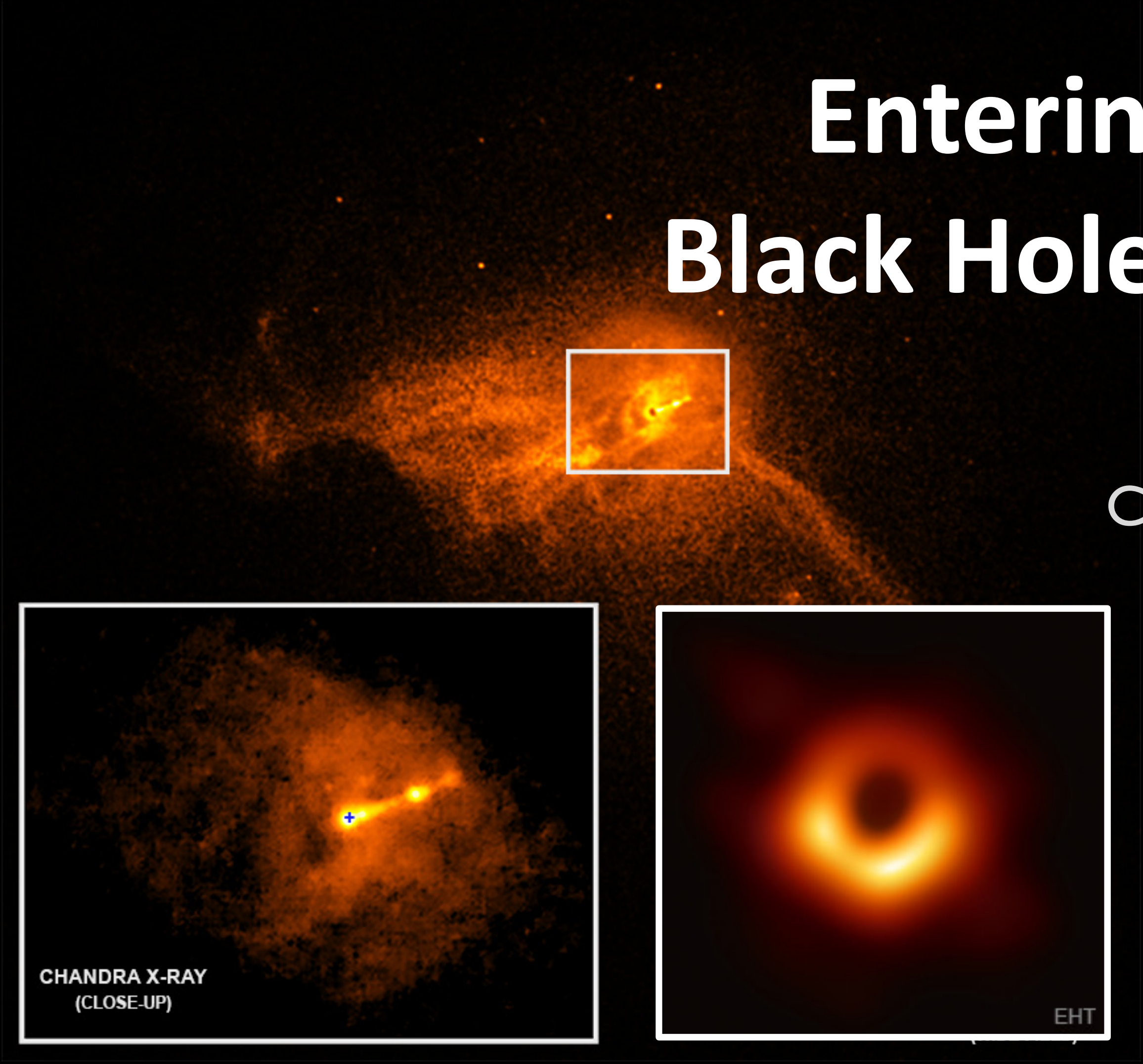
Entering an Era of Black Hole Discovery

Daryl Haggard
McGill University
Canada Research Chair



Institut Spatial de McGill
McGill Space Institute

MEGA McGill Extreme Gravity & Accretion Group

PI Daryl Haggard

Dr. Kristen Dage

Hope Boyce

Soud Al Kharusi**

Nicholas Vieira*

Anan Lu

Nicole Ford*

Samuel Gagnon-Hartman*

Nayyer Raza

Event Horizon Telescope

- **Event Horizon Telescope Collaboration & Multi-wavelength Science Working Group** (Co-coords: K. Hada, D. Haggard, S. Markoff)

Post-bac Researchers:

- Thomas Abbott
- Eitan Buffaz
- Emma Barbisan

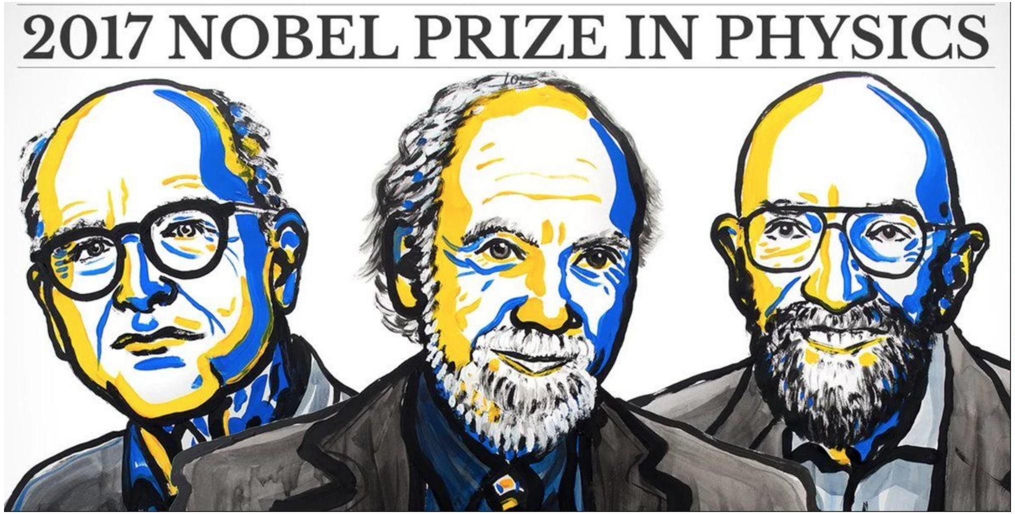
* co-supervised w/ Prof J. Ruan (Bishops)

** co-supervied w/ Prof T. Brunner (McGill)

Undergrad Honours Theses

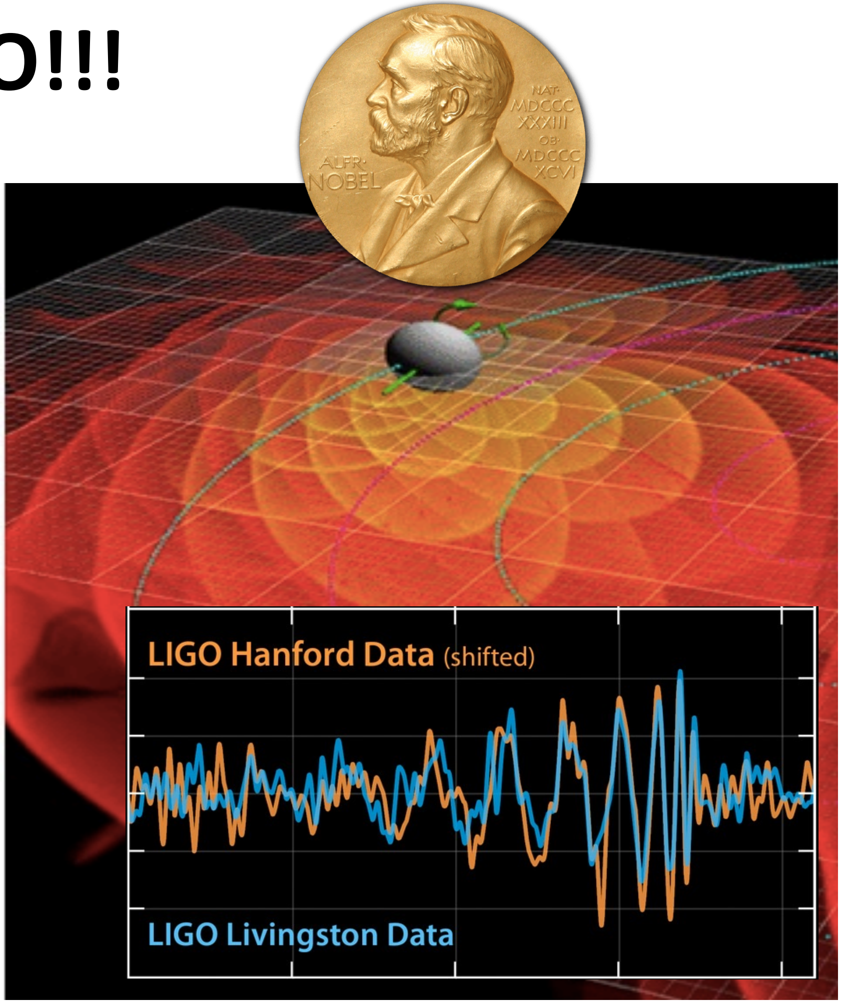
- Alex Bojanich*
- Jasmine Zhang
- Maude Larivíere
- Jeff Huang
- Yifan Sun
- Sneha Nair

Nobel Prize in Physics: LIGO!!!



Rainer Weiss, Barry Barish, Kip Thorne

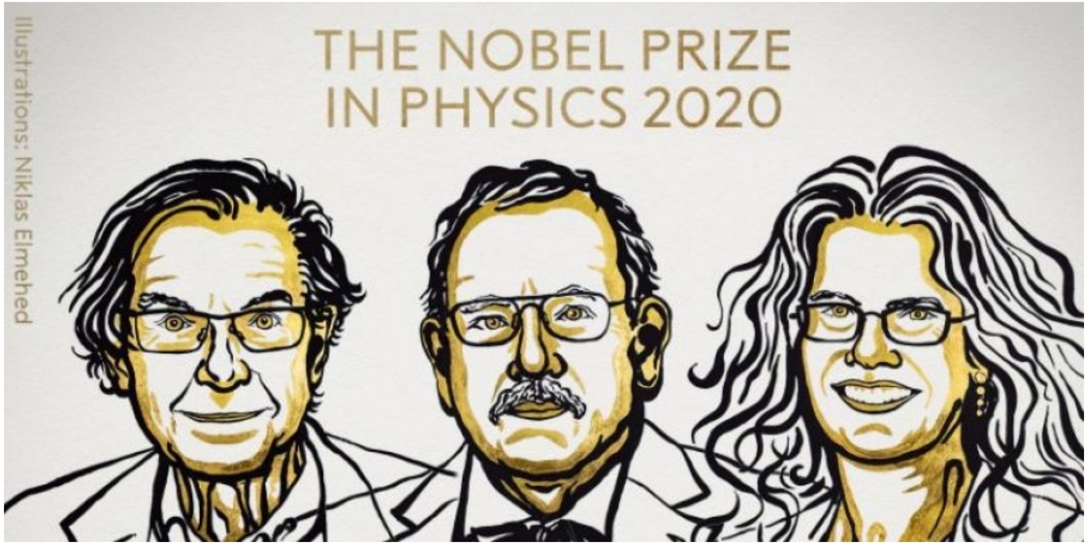
“Every day is an interesting day.” – ***Rai Weiss***

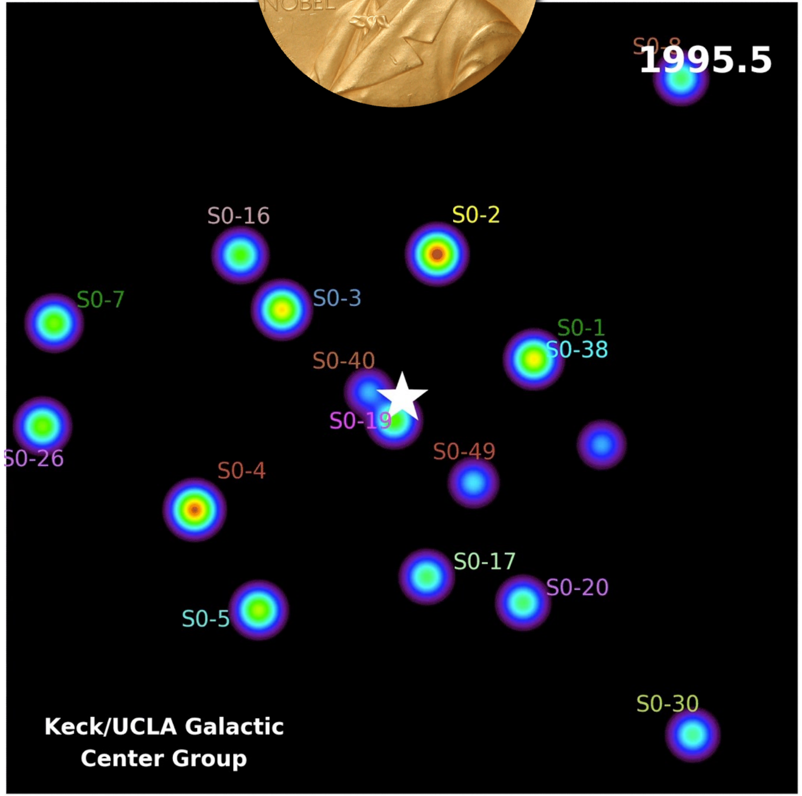



Science
AAAS
2017
BREAKTHROUGH
of the YEAR


Science
AAAS
2019
BREAKTHROUGH
of the YEAR

Nobel Prize in Physics: Sgr A*!!!





Roger Penrose, Reinhard Genzel, Andrea Ghez

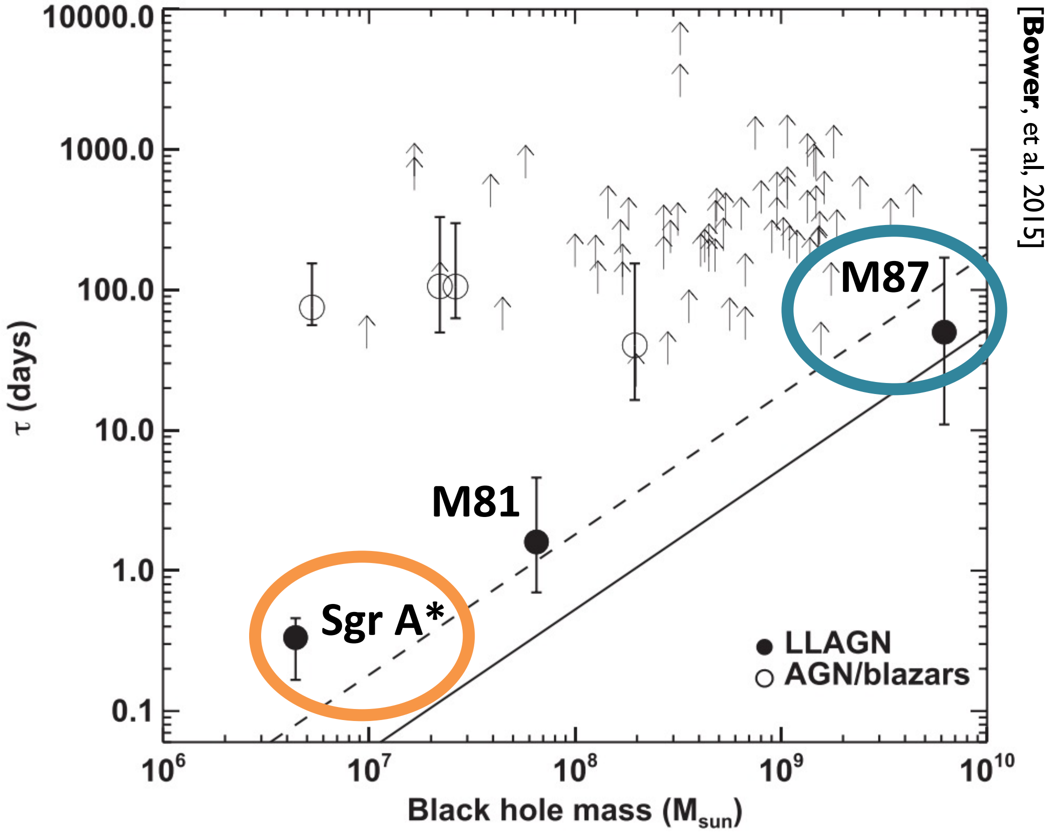
*"I hope I can inspire other young women into the field. It's a field that has so many pleasures, and if you are passionate about the science, there's so much that can be done." - **Andrea Ghez***


SMBH Variability
& Spectral Energy
Distributions

Zoom Chat Blast #1: Which of the following do you consider definitive evidence for black holes?

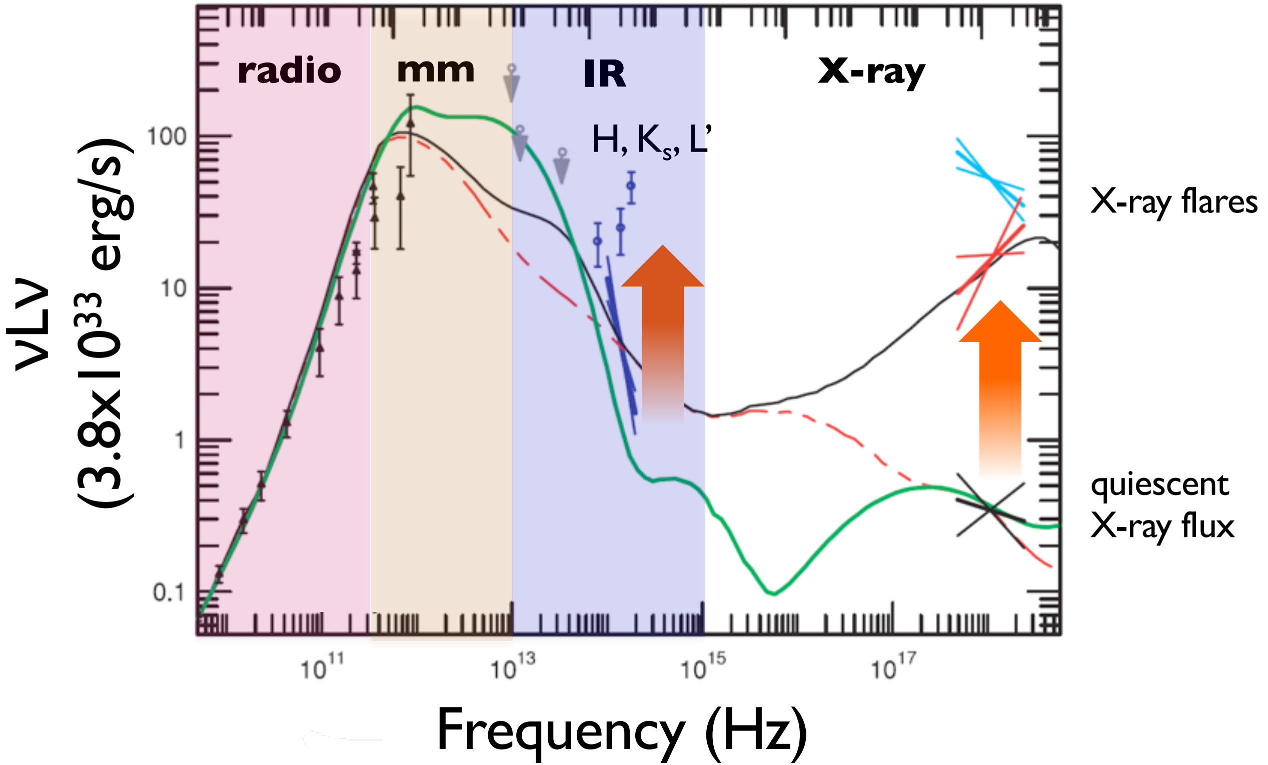
a) Radio detections of quasars and AGN
b) X-ray detections of black hole accretion flows
c) S-star orbits around Sgr A*
d) LIGO-Virgo detection of GW from BH mergers
e) EHT image of M87's BH shadow
f) All of the above
g) None of the above

SMBH Variability Timescales



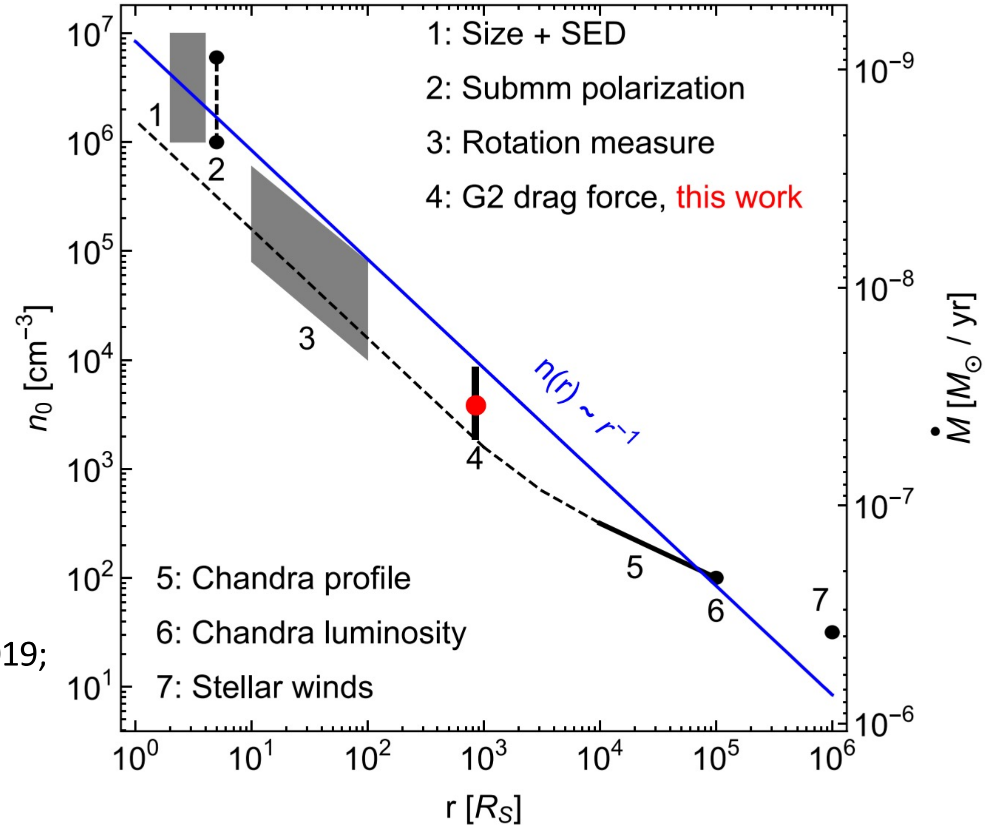
Sgr A*: Highly Variable Spectral Energy Distribution

[**Genzel**, et al. 2003; **Yuan** et al. 2004]



Sgr A*: Bondi to the Event Horizon

Mdot ~ n v R^2 ~ $R^{3/2-a}$ for n ~ R^{-a}, v ~ $R^{-1/2}$



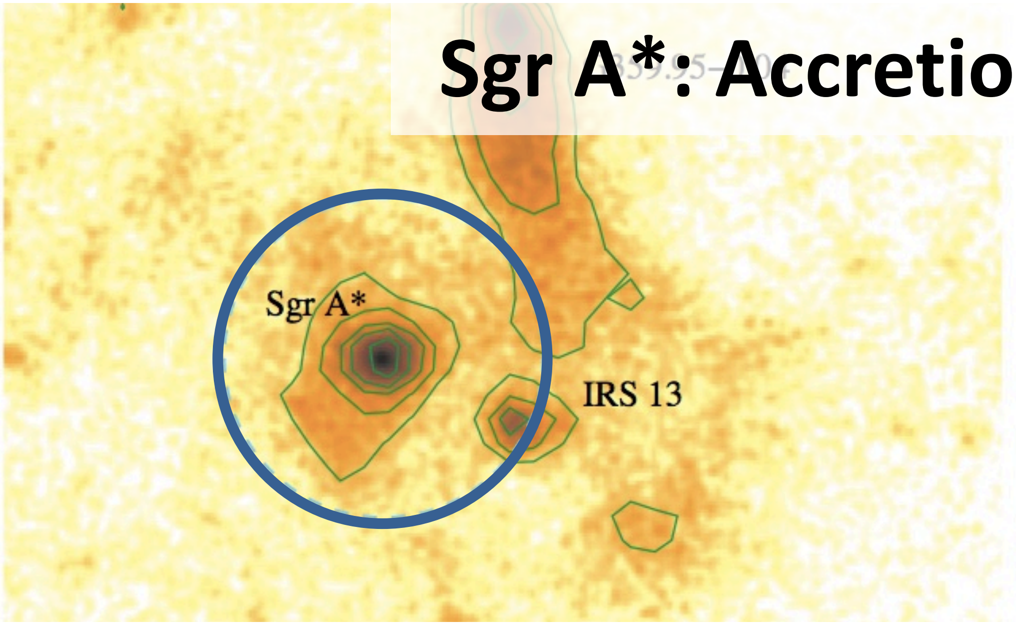
Gillessen+2019;
Pfuhl+2015,
Plewa+2017

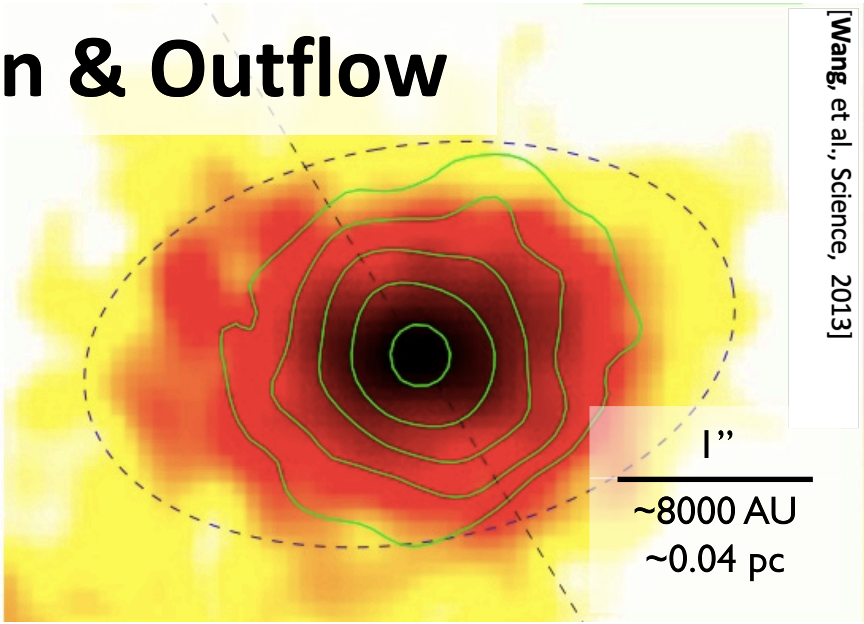

X-ray


IR
SPITZER
SPACE TELESCOPE

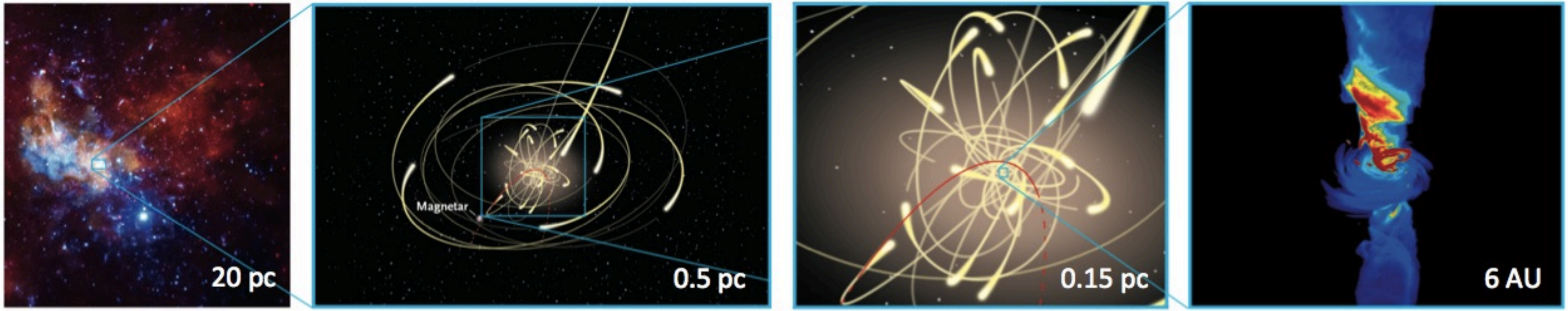

Sub-mm

Sgr A*: Accretion & Outflow

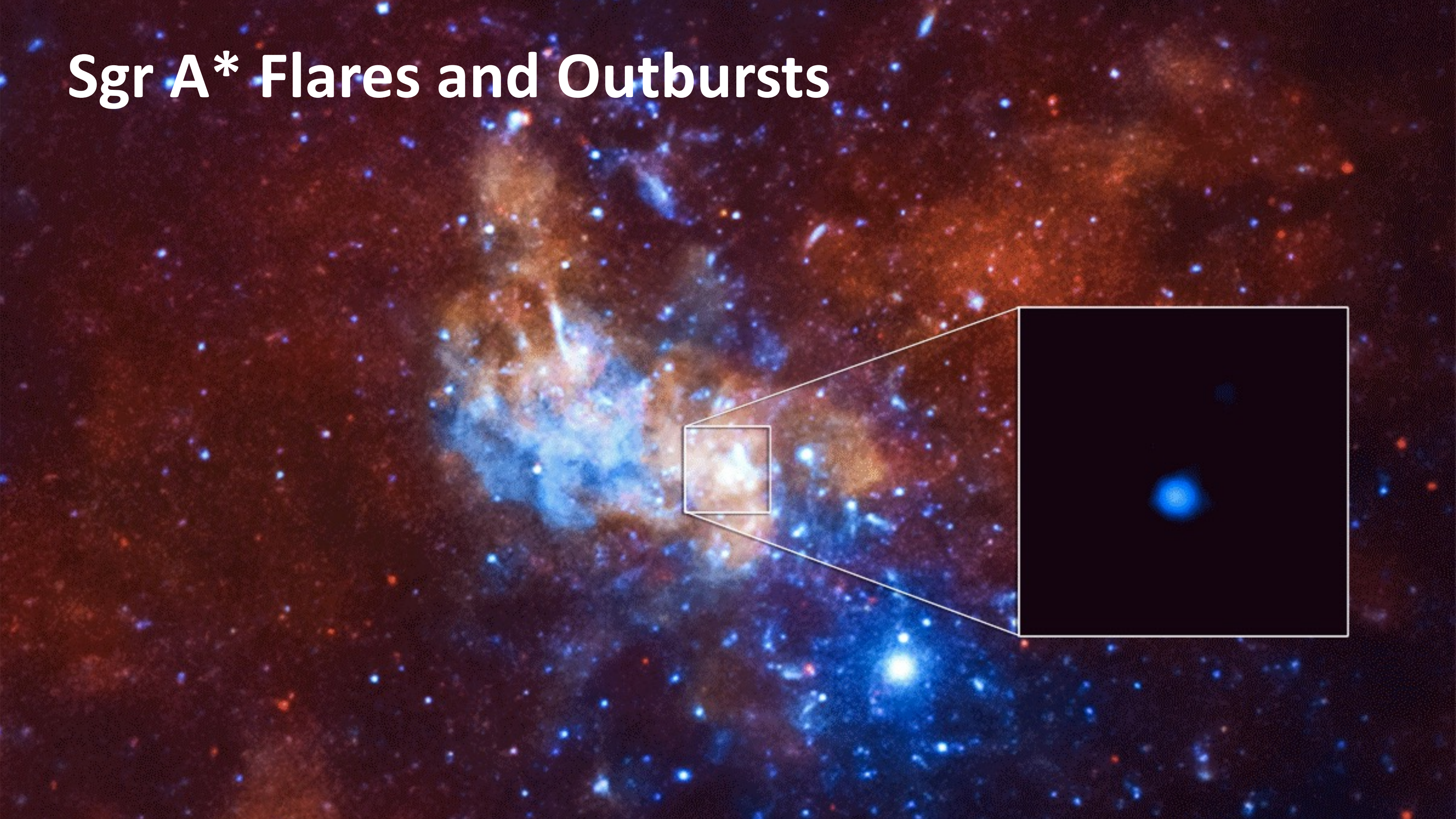




[**DH** & **Bower**, Sky & Tel, 2016]



Sgr A* Flares and Outbursts



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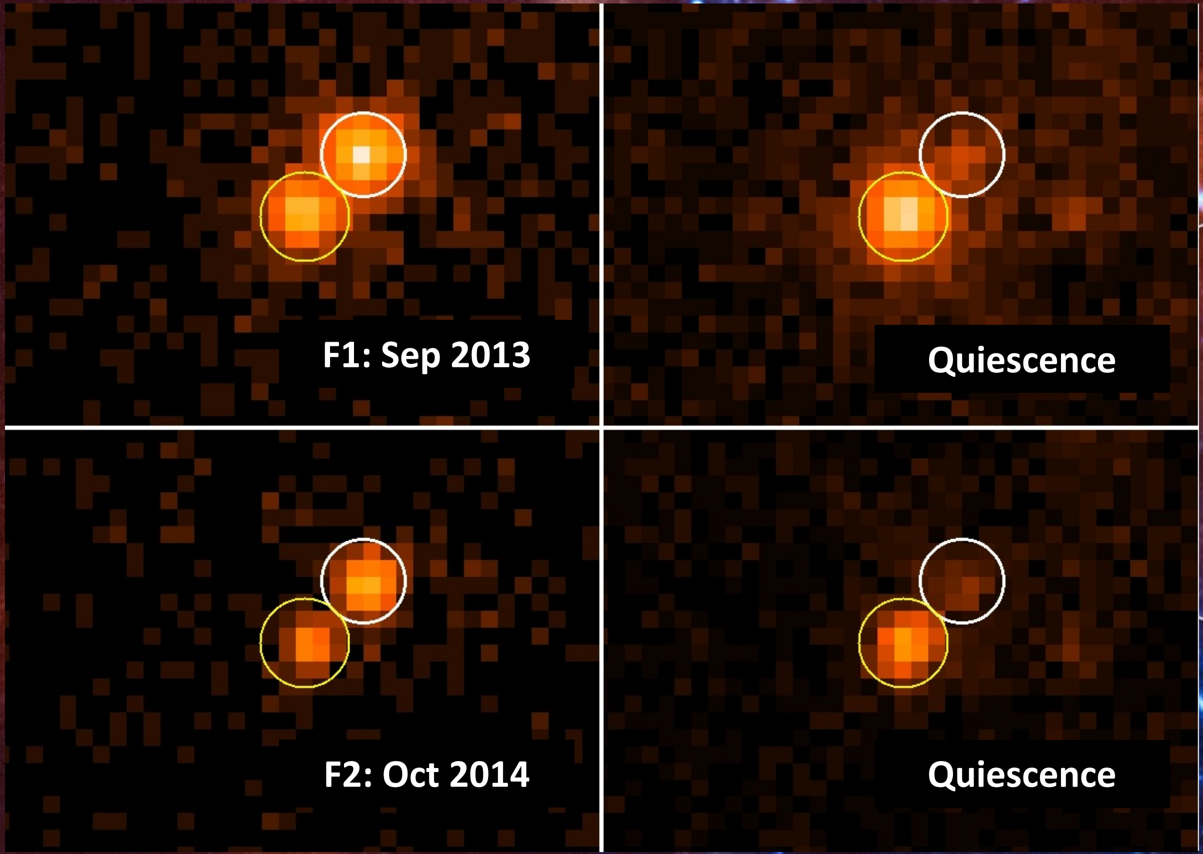
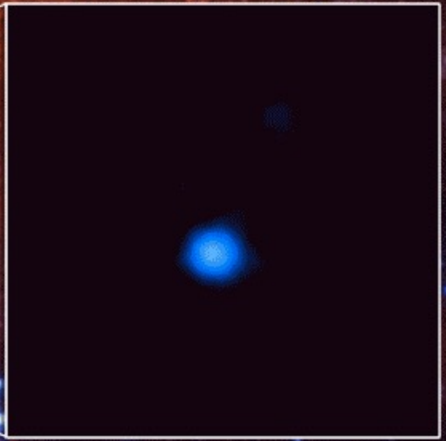
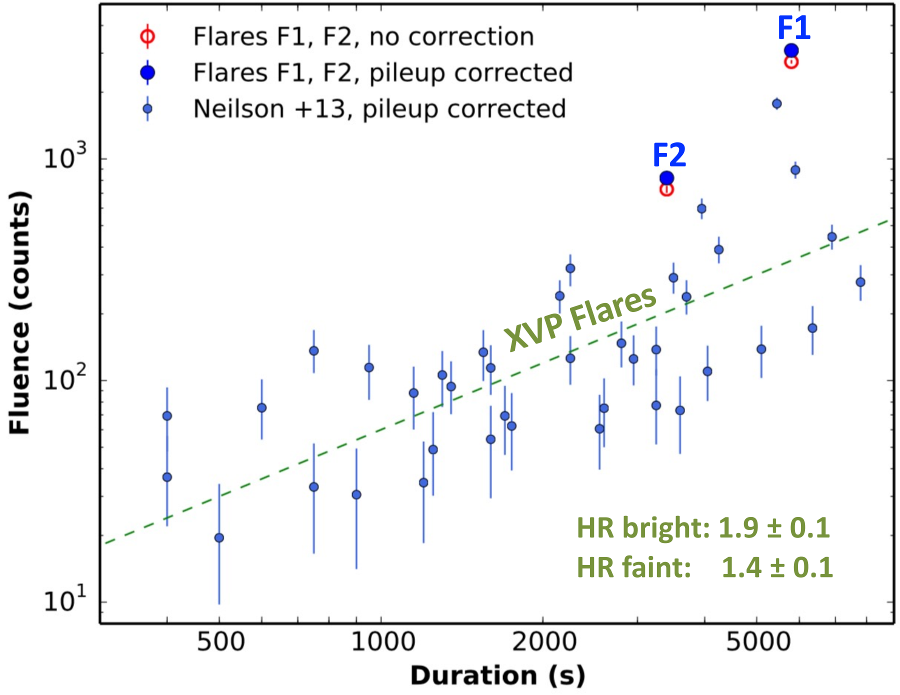
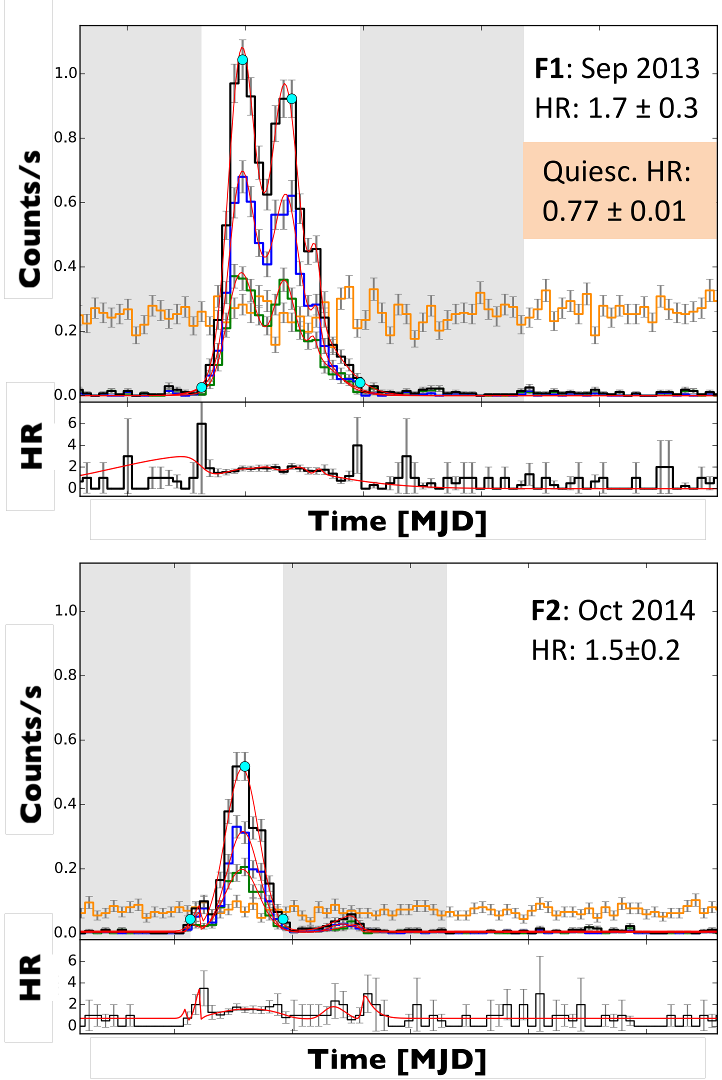




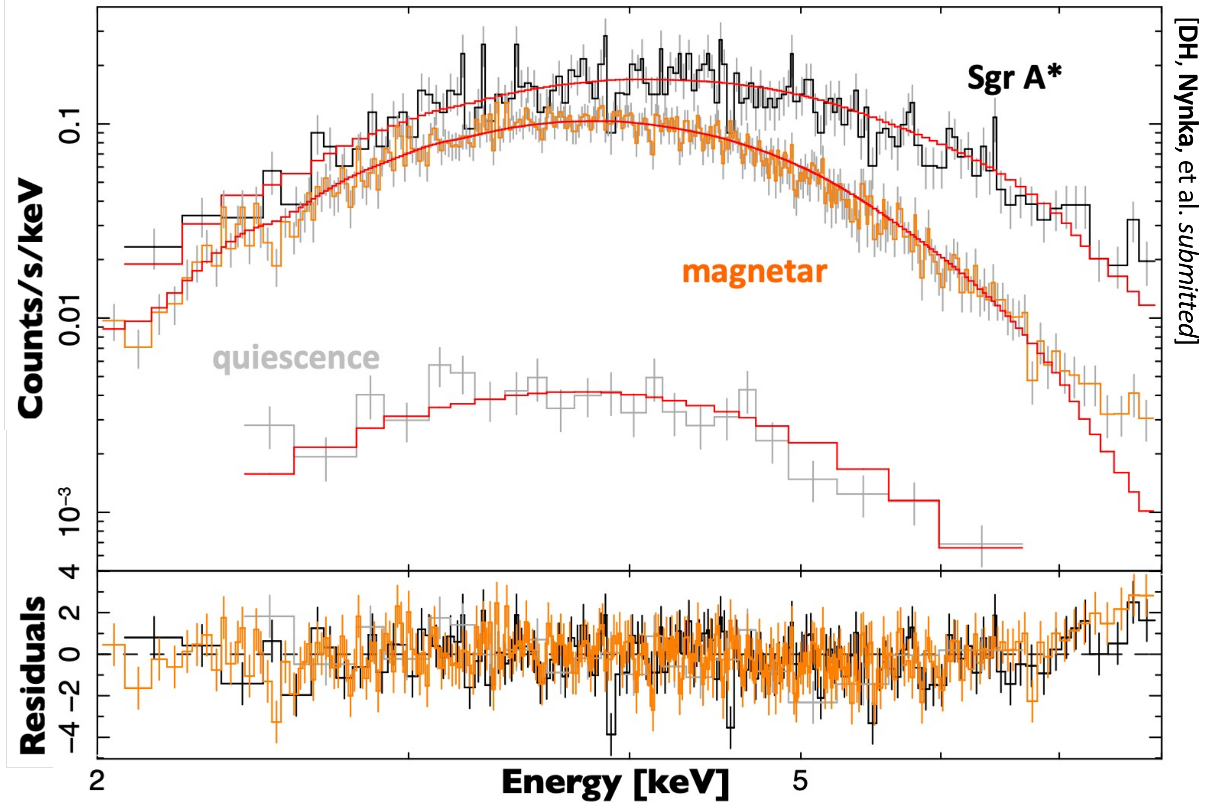
Sgr A* Bright *Chandra* Flares





[DH, Nynka, et al. 2019]

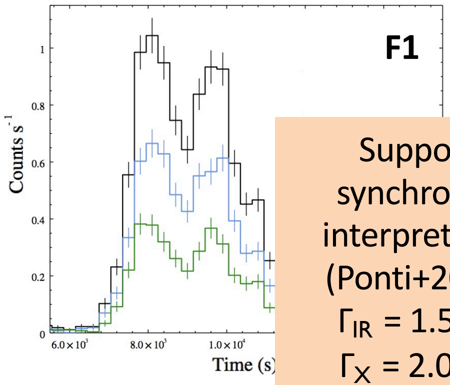
F1 *Chandra* X-ray Spectrum

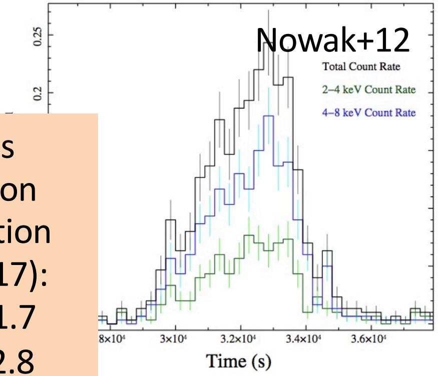


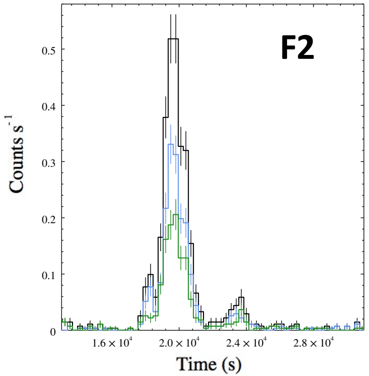
F1, quiescent, and 3% magnetar joint fit: Γ_{flare} = **2.03±0.14**

F1 – non-flare (quiescent + magnetar) fit: Γ_{flare} = **1.89 ± 0.14**

Bright X-ray Flare Spectroscopy





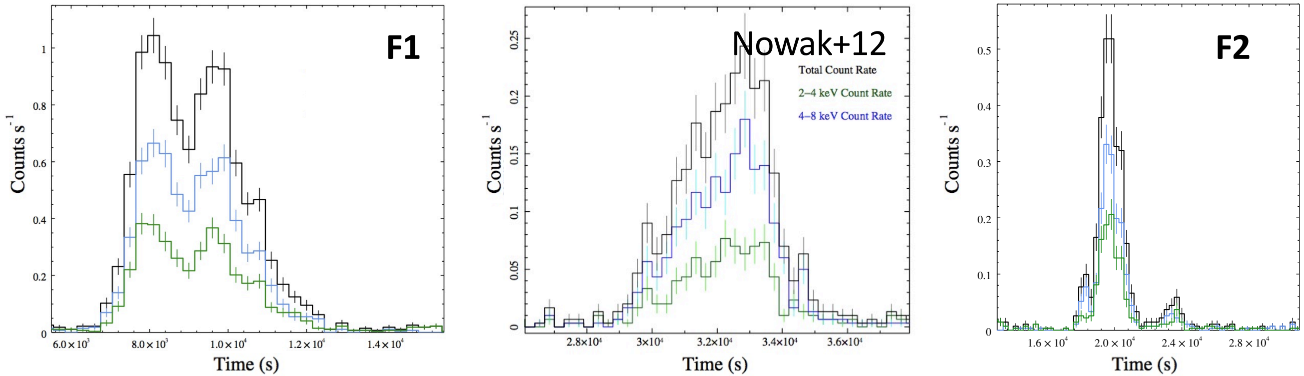


[DH, Nynka, et al. 2019]

Supports synchrotron interpretation (Ponti+2017):
Γ_{IR} = 1.5-1.7
Γ_X = 2.0-2.8

Flare	**NH [10^{23} cm^{-2}]**	**Γ**	**fx (2-8 keV, abs) [erg/cm^2/s]**	**Duration [ks]**	**Fluence [erg/cm^{-2}]**	**Energy (2-10keV) [erg]**
F1	$1.63_{-0.9}^{+0.4}$	2.1±0.1	$28.5_{-1.6}^{+1.7}$ x 10^{-12}	5.7	1.6±0.1 x 10^{-7}	3.3 x 10^{39}
Nowak+12	$1.43_{-3.6}^{+4.4}$	$2.0_{-0.6}^{+0.7}$	8.5±0.9 x 10^{-12}	5.6	4.7±0.5 x 10^{-8}	1.0 x 10^{39}
F2	$1.63_{-0.9}^{+0.4}$	2.0±0.3	10.8±0.9x 10^{-12}	3.4	3.6±0.2 x 10^{-8}	7.4 x 10^{38}
Ponti+17	1.6±0.3	2.3±0.3	$7.6_{-3.4}^{+7.1}$x 10^{-12}	3.4	2.6±2.4 x 10^{-8}	5.3 x 10^{38}
Porquet+03 (Nowak+12)	$1.61_{-2.2}^{+1.9}$	2.3±0.3	7.7±0.3 x 10^{-12}	2.8	2.2±0.1 x 10^{-8}	5.3 x 10^{38}
Porquet+08 (Nowak+12)	$1.63_{-2.6}^{+3.0}$	$2.4_{-0.3}^{+0.4}$	$4.8_{-0.3}^{+0.2}$ x 10^{-12}	2.9	1.4±0.1 x 10^{-8}	3.5 x 10^{38}

Bright X-ray Flare Spectroscopy



[DH, Nynka, et al. 2019]

Flare	NH $[10^{23}$					Energy (2-10keV) [erg]
F1	1.63_{-0}					3.3×10^{39}
Nowak+12	1.43_{-3}					1.0×10^{39}
F2	1.63_{-0}					7.4×10^{38}
Ponti+17	1.6±0					5.3×10^{38}
Porquet+03 (Nowak+12)	1.61_{-2}					5.3×10^{38}
Porquet+08 (Nowak+12)	$1.63_{-2.6}^{+3.0}$	$2.4_{-0.3}^{+0.4}$	$4.8_{-0.3}^{+0.2} \times 10^{-12}$	2.9	$1.4 \pm 0.1 \times 10^{-8}$	3.5×10^{38}

Volume containing this magnetic energy:

$$E_B = u_B V = (B^2/8\pi)(4/3\,\pi R^3) = E_X$$

$$R \sim 2\,(B/30\text{ G})^{-2/3}\,(E_X/3 \times 10^{39}\text{ erg/s})^{1/3}\,R_S$$

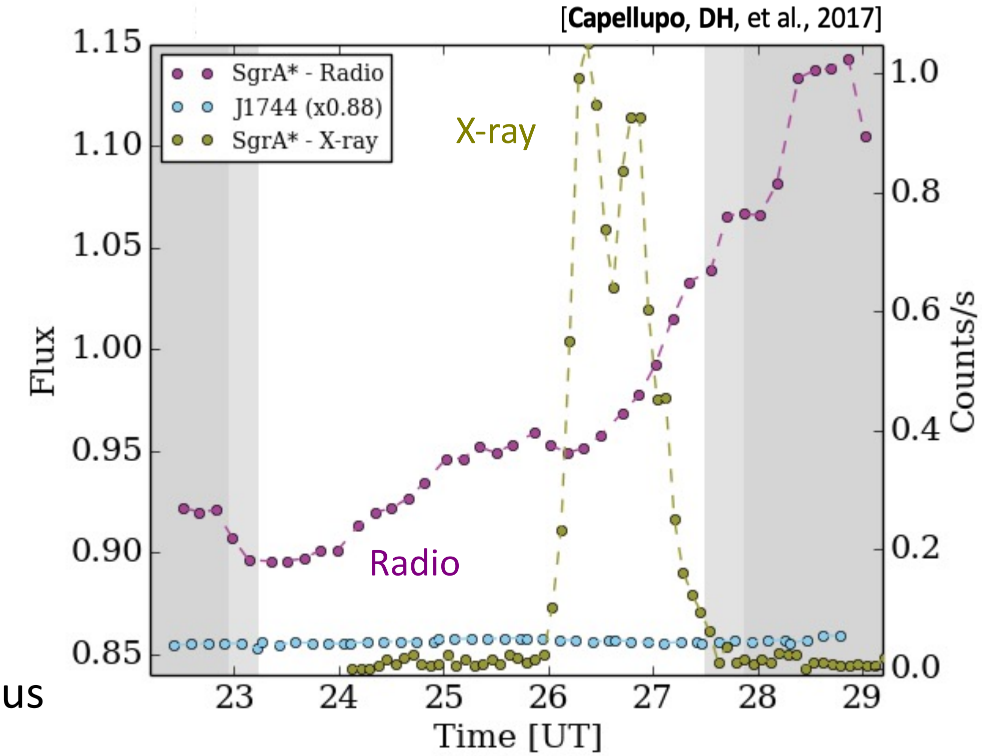
$$\sim 3 - 5\,R_S \sim 6 - 10\,R_g$$

GRAVITY polarization periods

➔ $R \sim 6 - 10\,r_g$

Simultaneous *Chandra*/VLA Obs

- Simultaneous *Chandra* + VLA data
- Radio flux increase of 25% (3.6 cm; 8-10 GHz)
- Anti-correlation at X-ray rise? (e.g., Dodds-Eden+2009)
- Cross correlation peak ~125 min
- Consistent with previous time delay estimates



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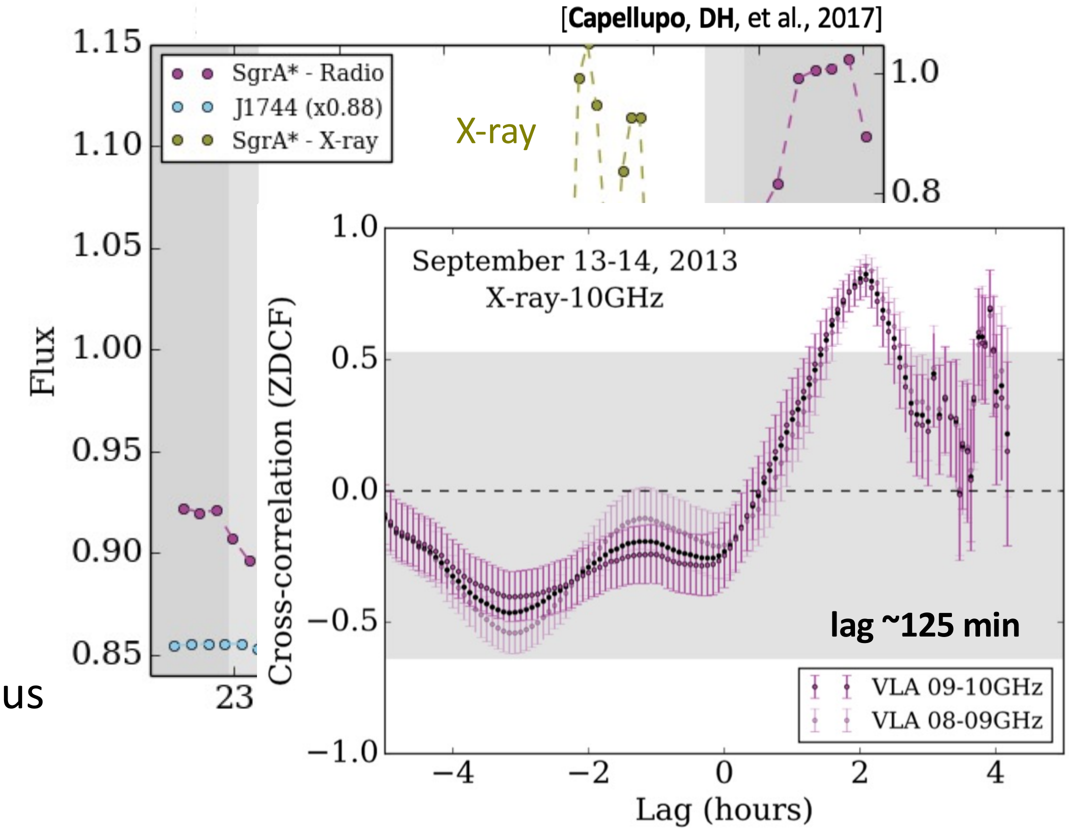
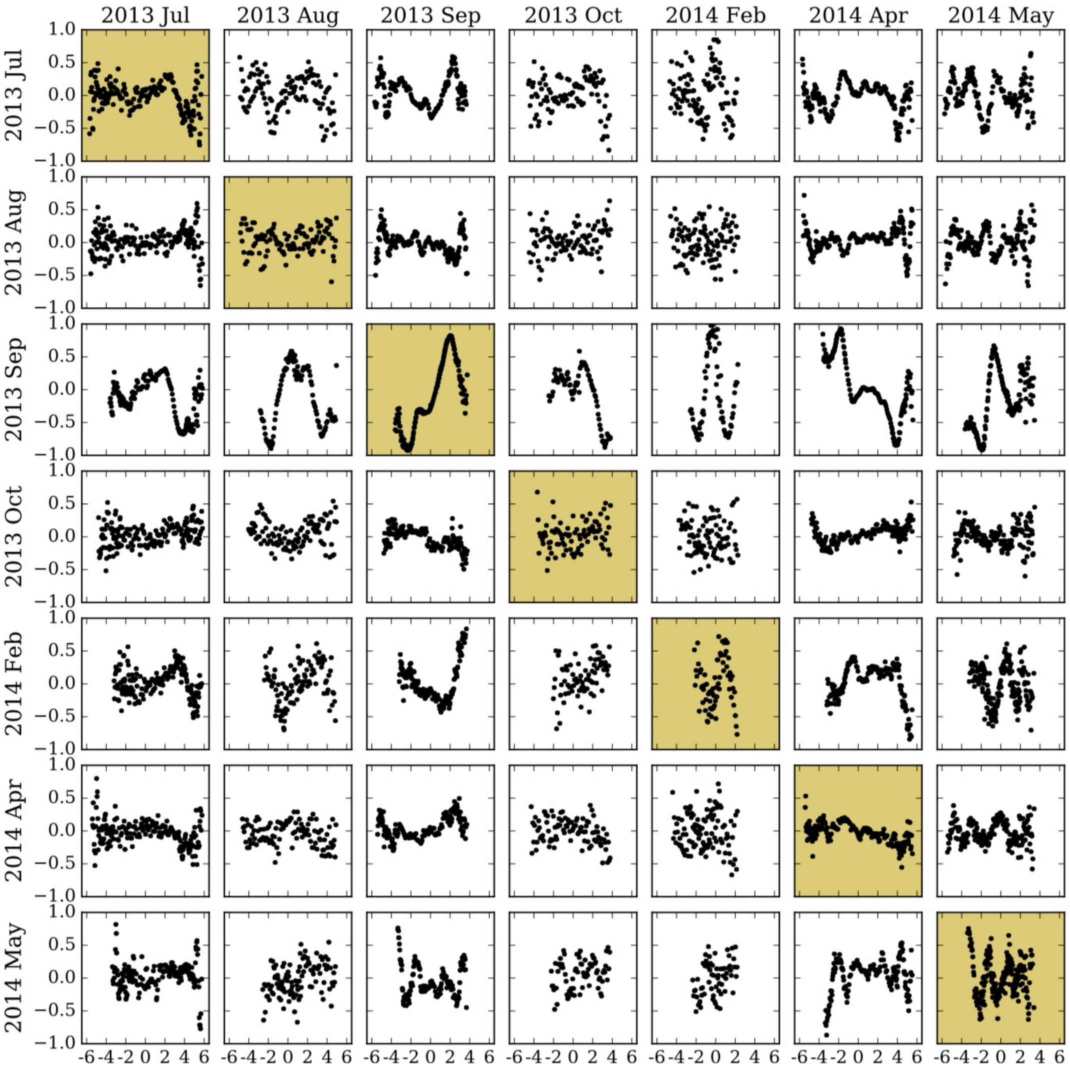
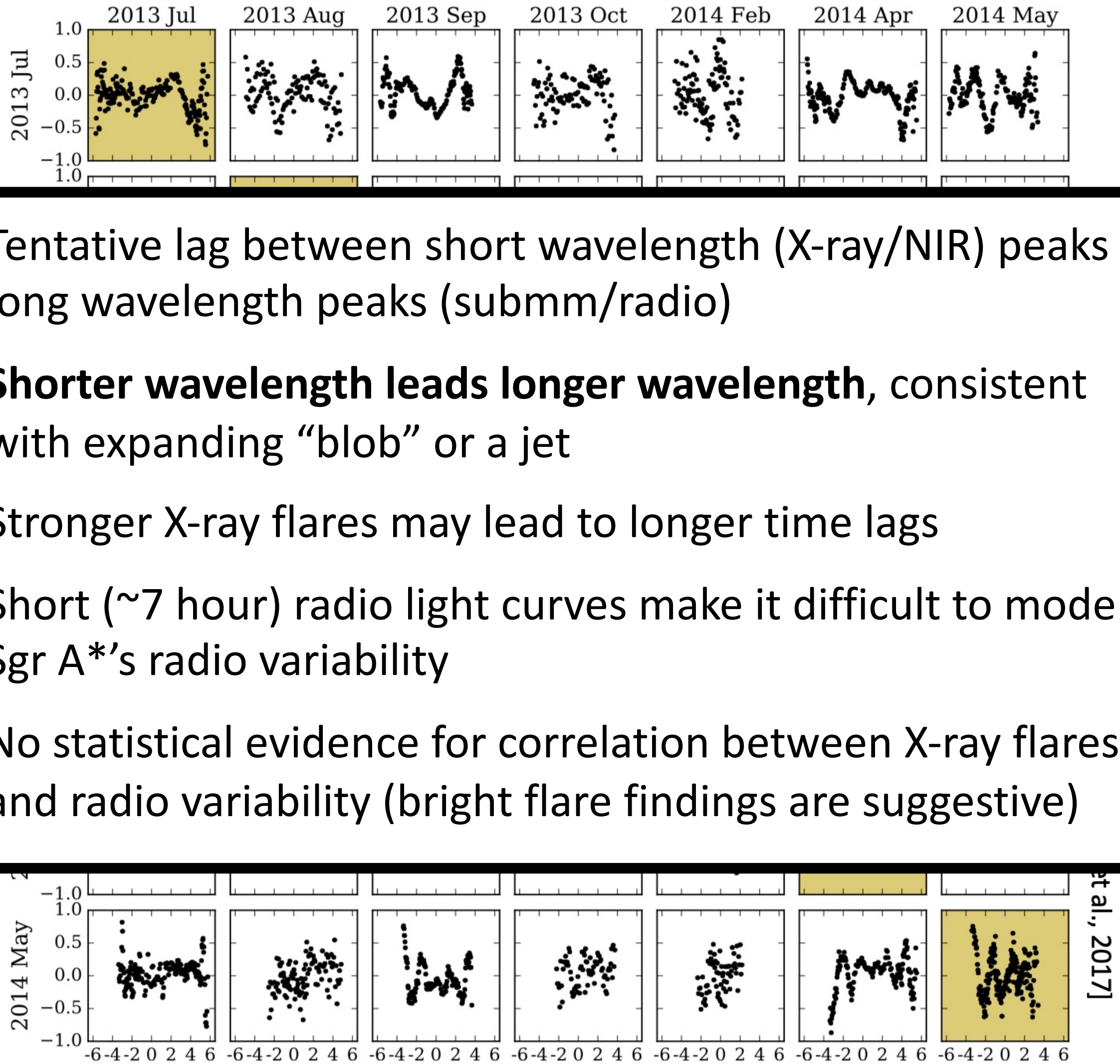


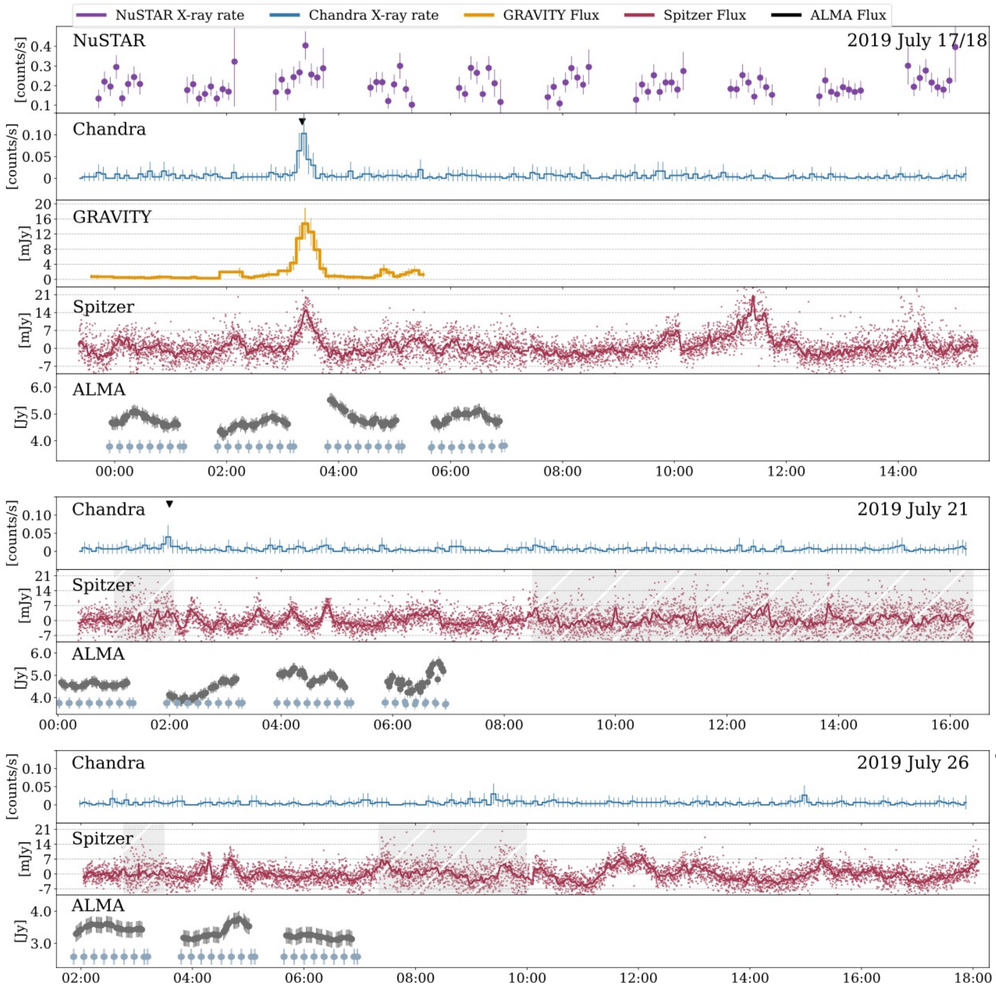


[Capellupo, DH, et al., 2017]



- Tentative lag between short wavelength (X-ray/NIR) peaks & long wavelength peaks (submm/radio)
- **Shorter wavelength leads longer wavelength**, consistent with expanding “blob” or a jet
- Stronger X-ray flares may lead to longer time lags
- Short (~7 hour) radio light curves make it difficult to model Sgr A*’s radio variability
- No statistical evidence for correlation between X-ray flares and radio variability (bright flare findings are suggestive)

Simultaneous Chandra-Spitzer Observations (2019)

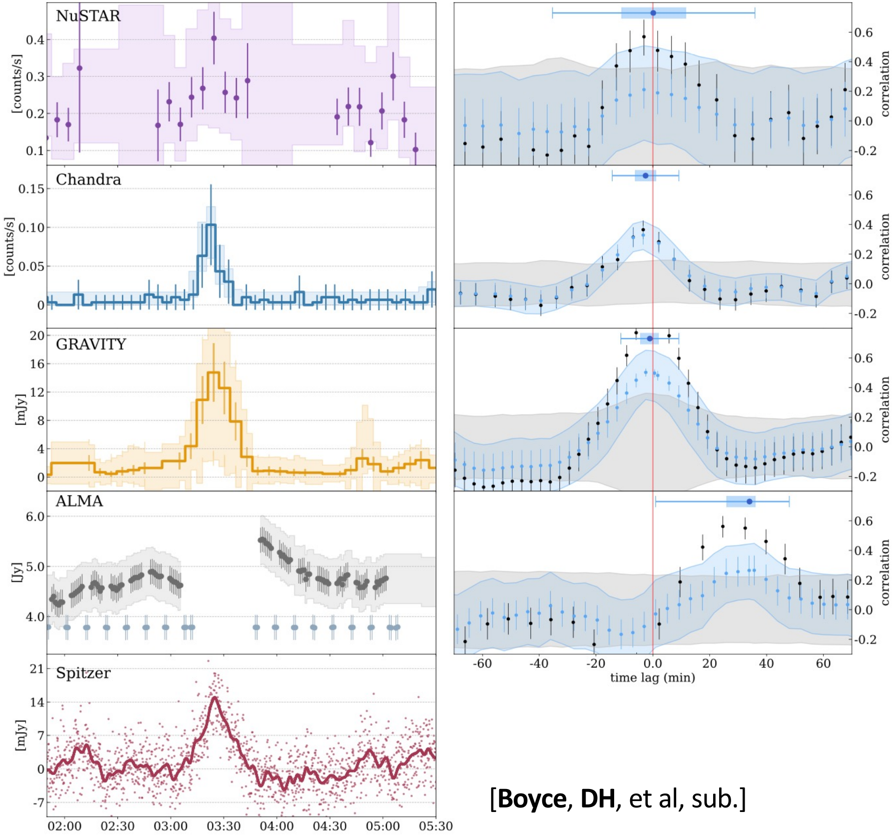


[Witzel et al 2018; Boyce, DH, et al, sub.]

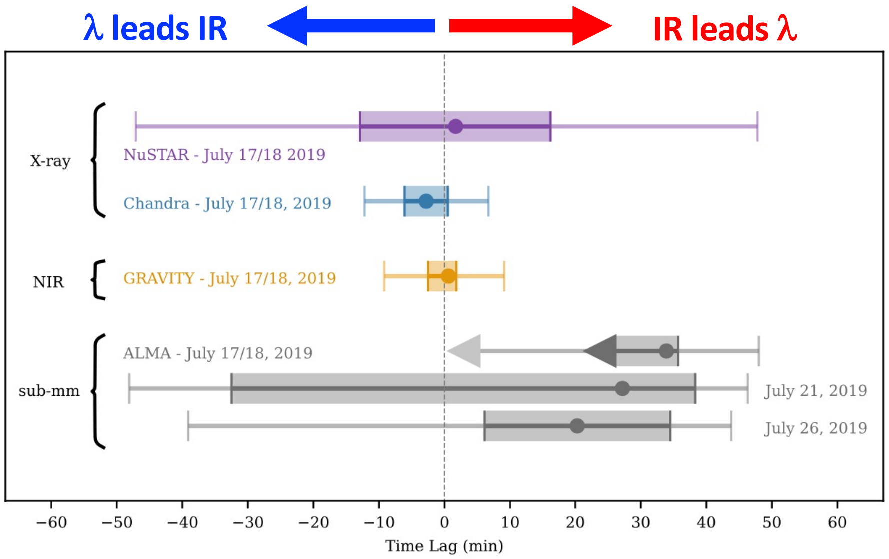
- Spitzer IRAC observed Sgr A* at 4.5 µm for eight ~24-hour-long stretches between 2013 and 2017 (Hora et al. 2017; Witzel et al. 2018)
- Six obs had simultaneous monitoring from the Chandra (Boyce et al. 2019)
- In 2019 three additional epochs of simultaneous monitoring totalling ~48-hours were observed
- Total dataset contains ~155 hours of simultaneous X-ray and IR data, with additional coordinated coverage from NuSTAR, GRAVITY, and ALMA (Boyce et al. submitted)

Multi-wavelength Cross Correlations (ZDCF)

- Time lags between multi-λ observations and Spitzer 4.5μm July 2019 light curves
- 68% (shaded boxes) & 99.7% (thin error bars) conf. intervals shown
- Sub-mm lag on July 18 is an upper limit



[Boyce, DH, et al, sub.]



Multi-wavelength Cross Correlations (ZDCF)

Table 2. Time delays with respect to 4.5 μm (Spitzer) for X-ray (NuSTAR, Chandra), $\sim$2 μm (GRAVITY), and 340 GHz (ALMA) variability.

Instrument	time lag (min)	68% interval	99.7% interval
July 18 2019:			
NuSTAR	$+2^{+15}_{-15}$	(−13,+16)	(−47, 48)
Chandra	-3^{+3}_{-3}	(−6,+0)	(−12, +7)
GRAVITY	$+0^{+1}_{-3}$	(−3,+1)	(−9, +9)
ALMA	$+34^{+2}_{-8}$	(+26,+36)	(+1, +48)
July 21 2019:			
ALMA	$+27^{+12}_{-60}$	(−33,+39)	(−48, +46)
July 26 2019:			
ALMA	$+20^{+14}_{-14}$	(+6,+35)	(−39, +44)

Note: Positive values mean flares lag Spitzer flares. Uncertainties on the time lag in the first column span the 68% confidence interval on the 10,000 MC runs. The second column displays the boundaries of this 68% confidence interval, while the third column contains the 99.7% confidence interval.

[**Boyce**, **DH**, et al, sub.]

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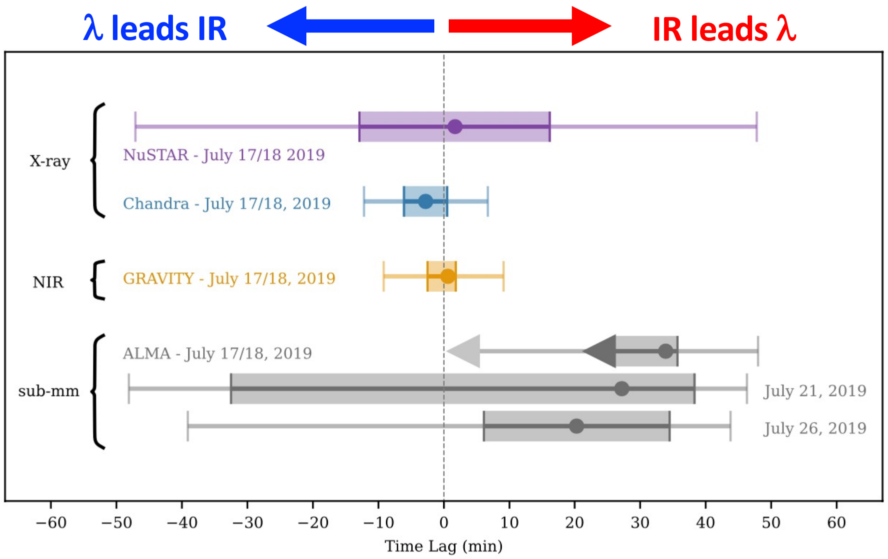
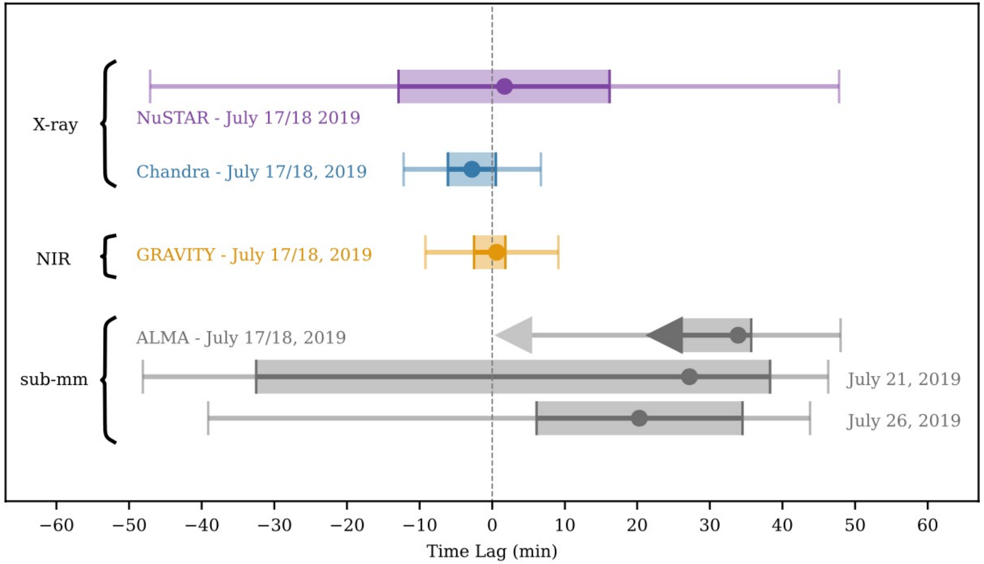
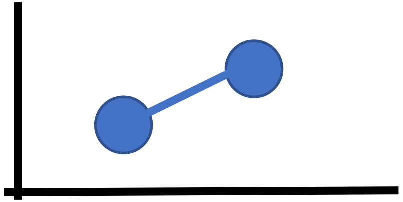


Want to Explain both *Timing* and *SED*

Timing

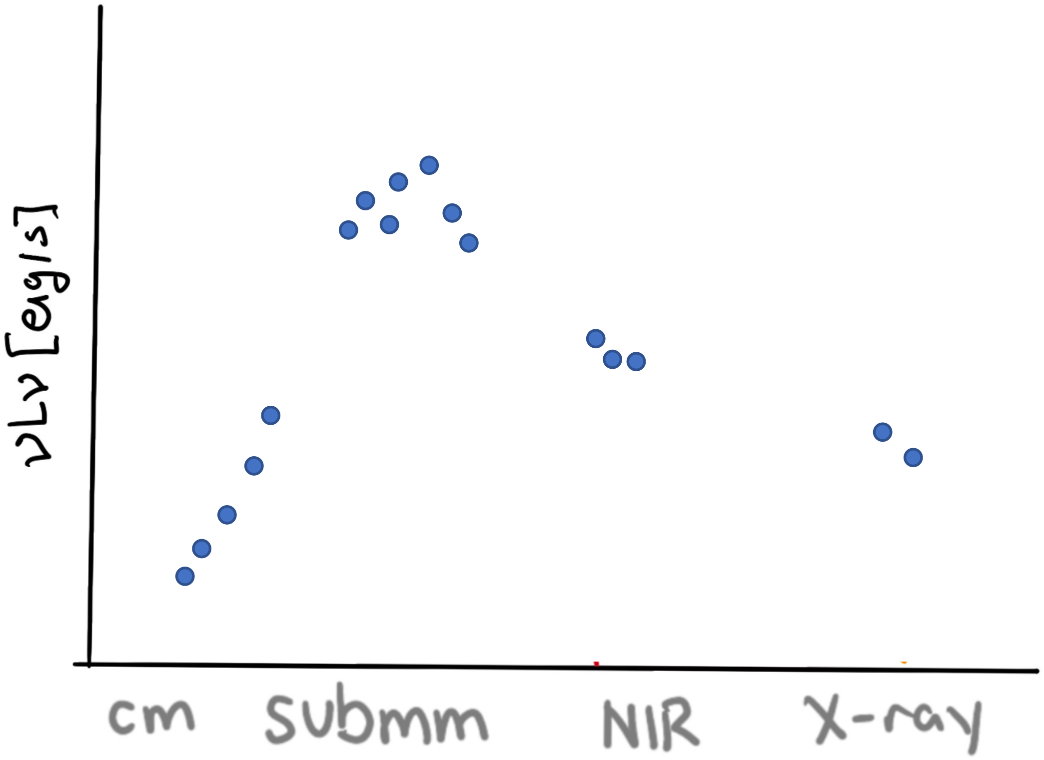


NIR spectral index



Slide credit: **Hope Boyce**

Understanding Sgr A*'s Spectral Energy Distribution



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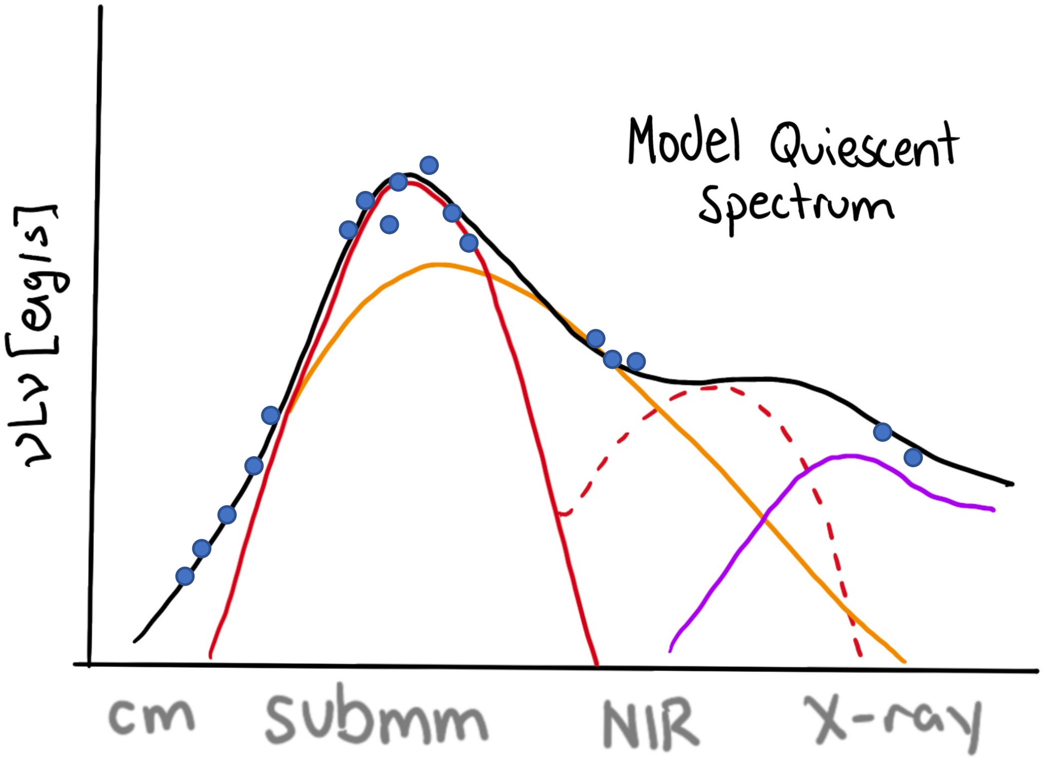

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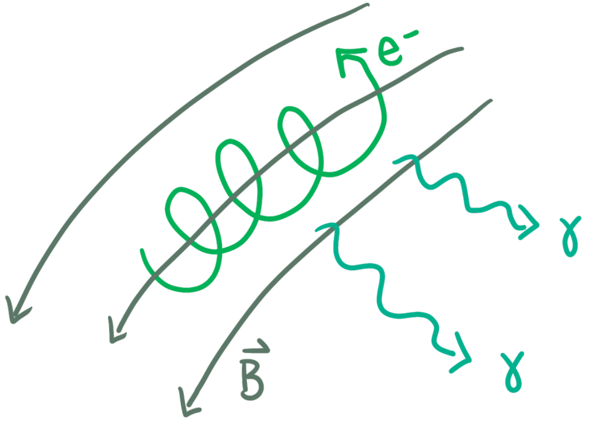
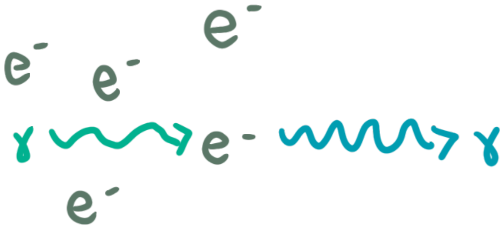
Understanding Sgr A*'s Spectral Energy Distribution

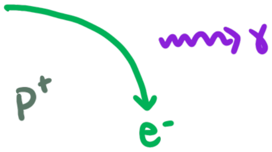
Synchrotron





Inverse-Compton

Bremsstrahlung



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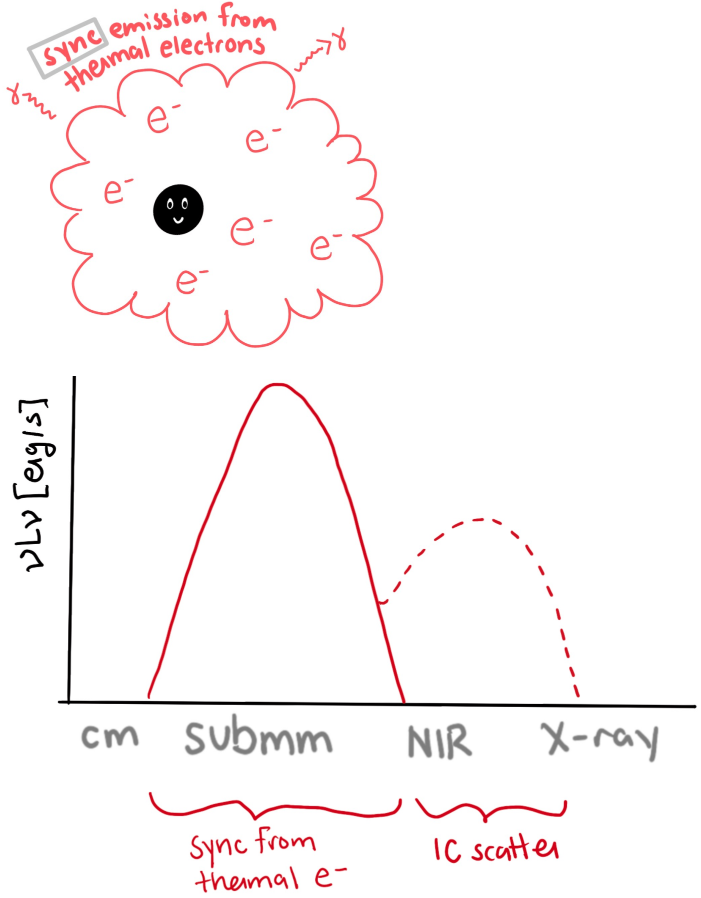

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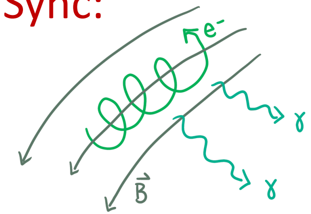

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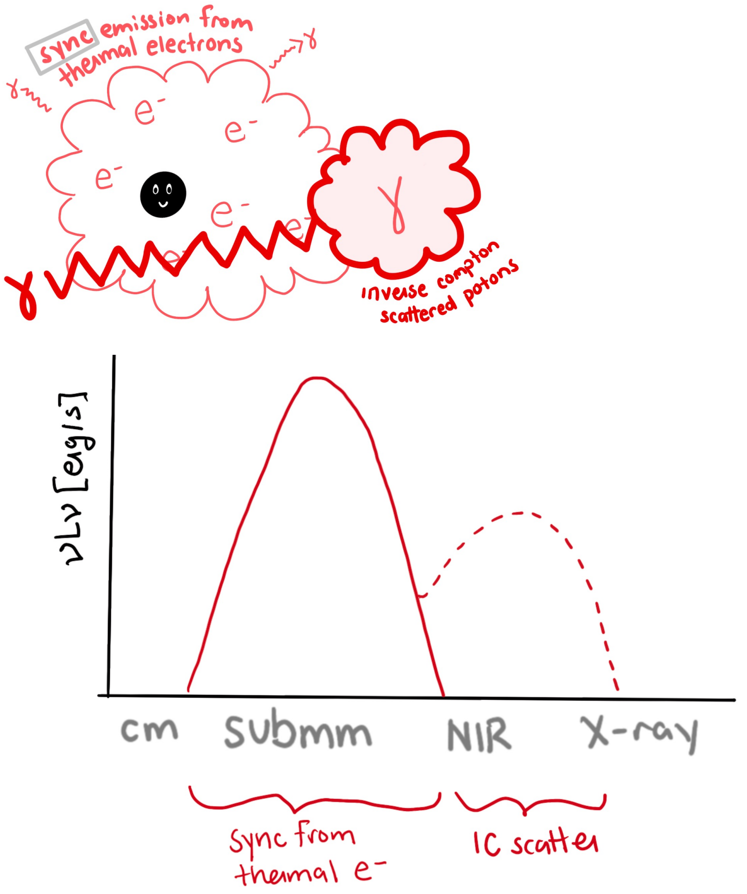

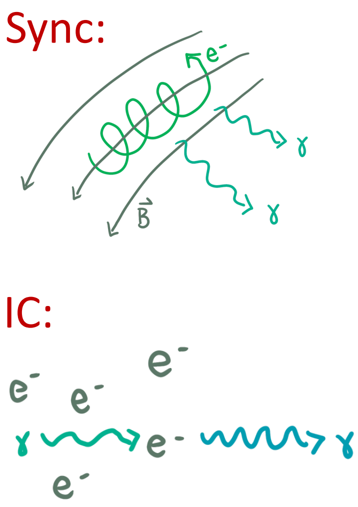

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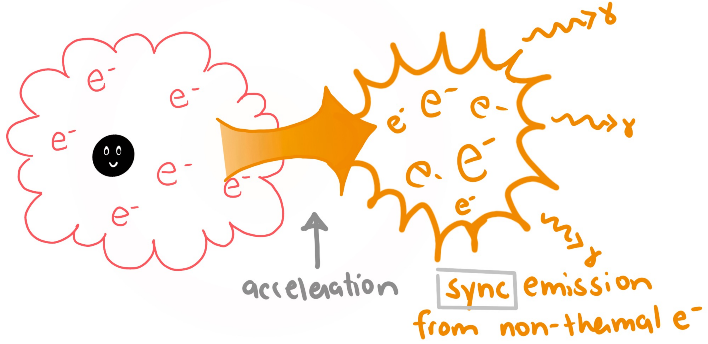

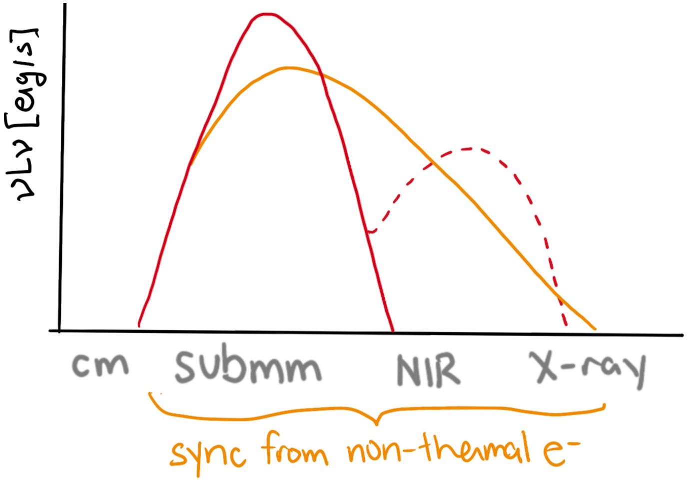

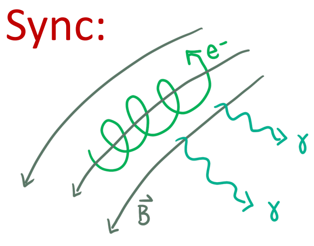

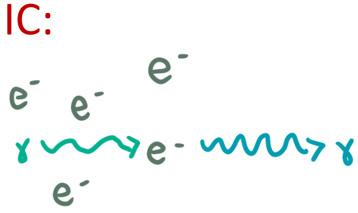

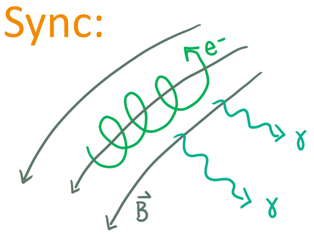

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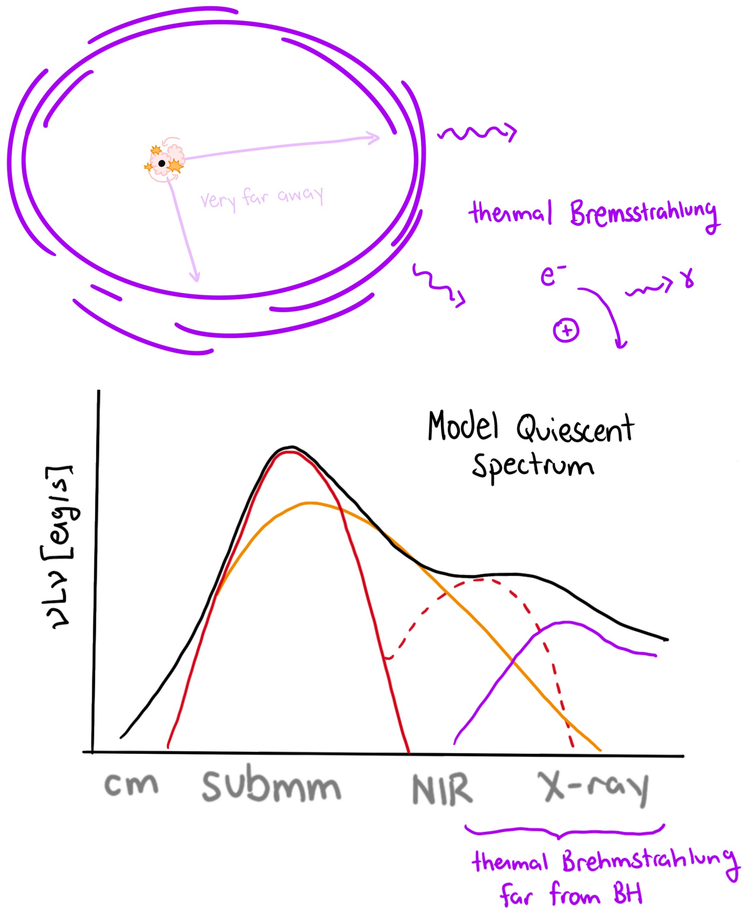
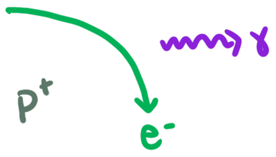


Bremss:



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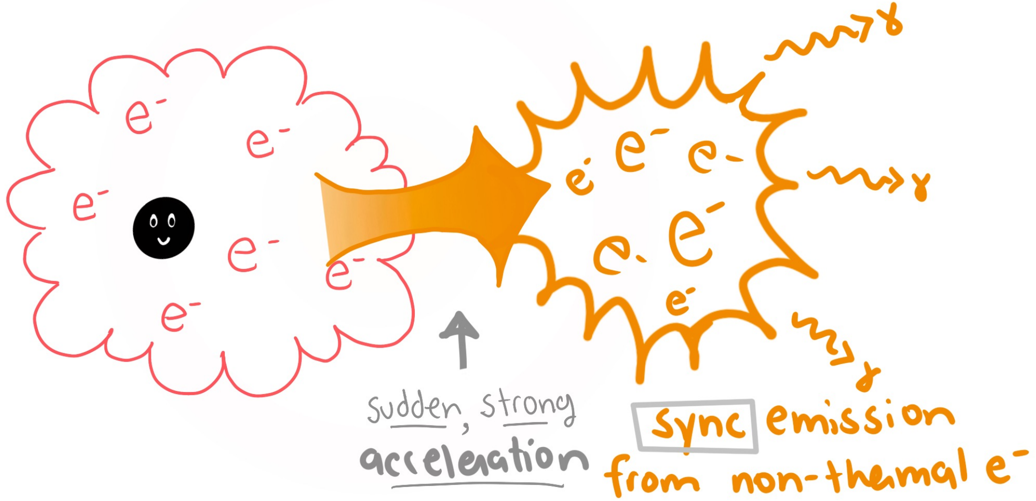
Flaring Model: Synchrotron Only



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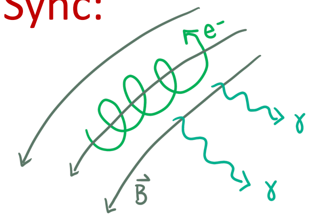
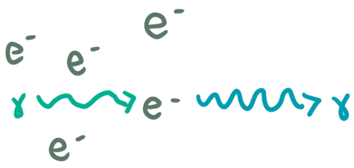


IC:



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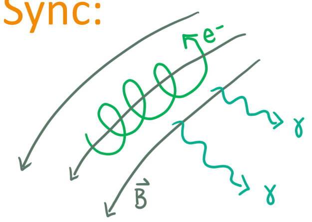
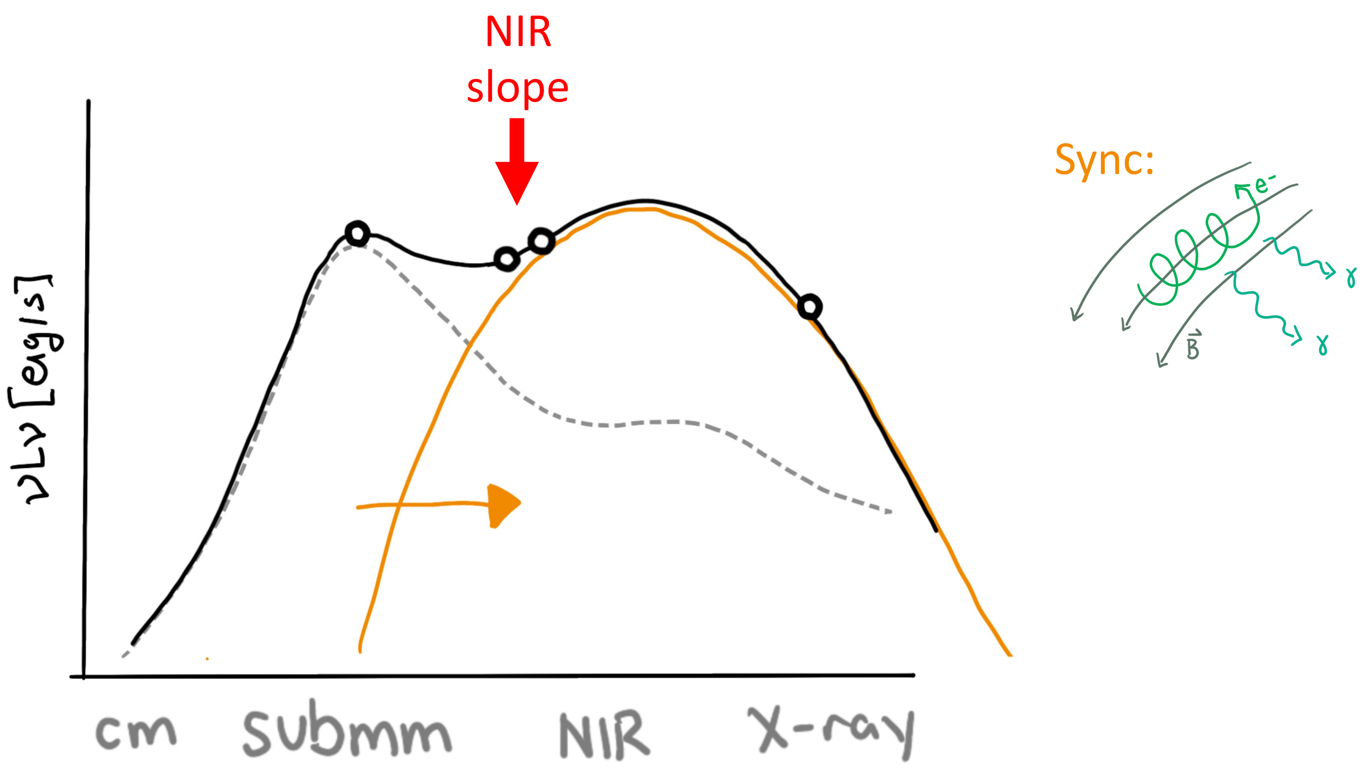


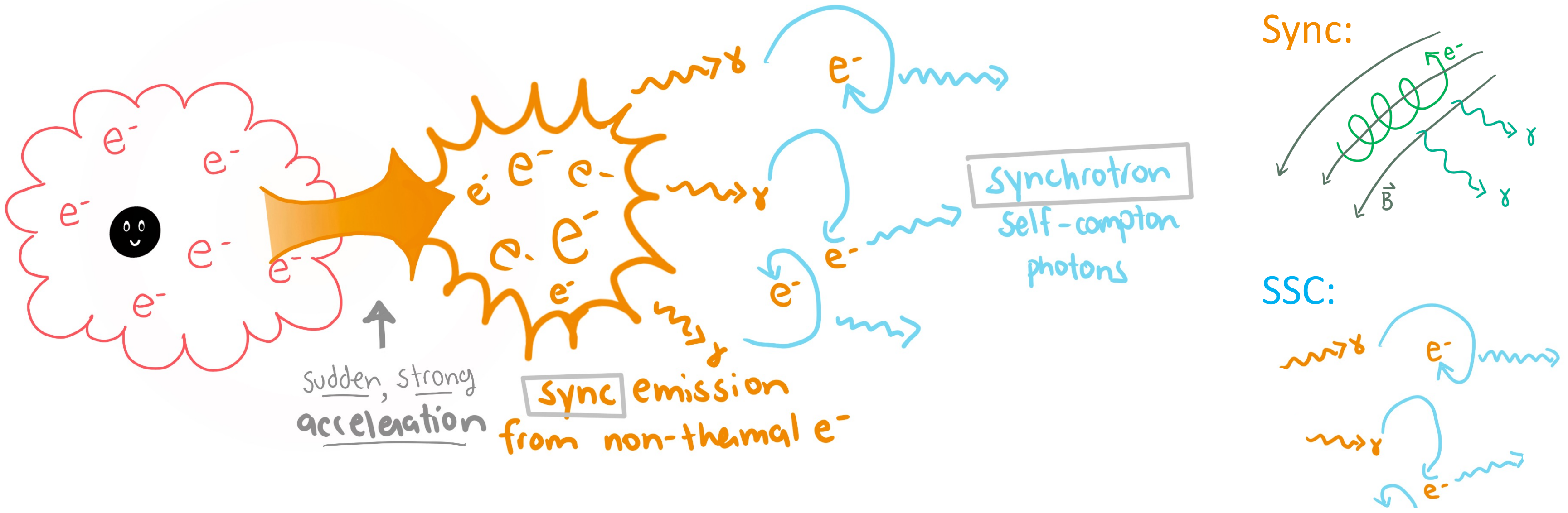
Slide credit: **Hope Boyce**

Flaring Model: Synchrotron Only



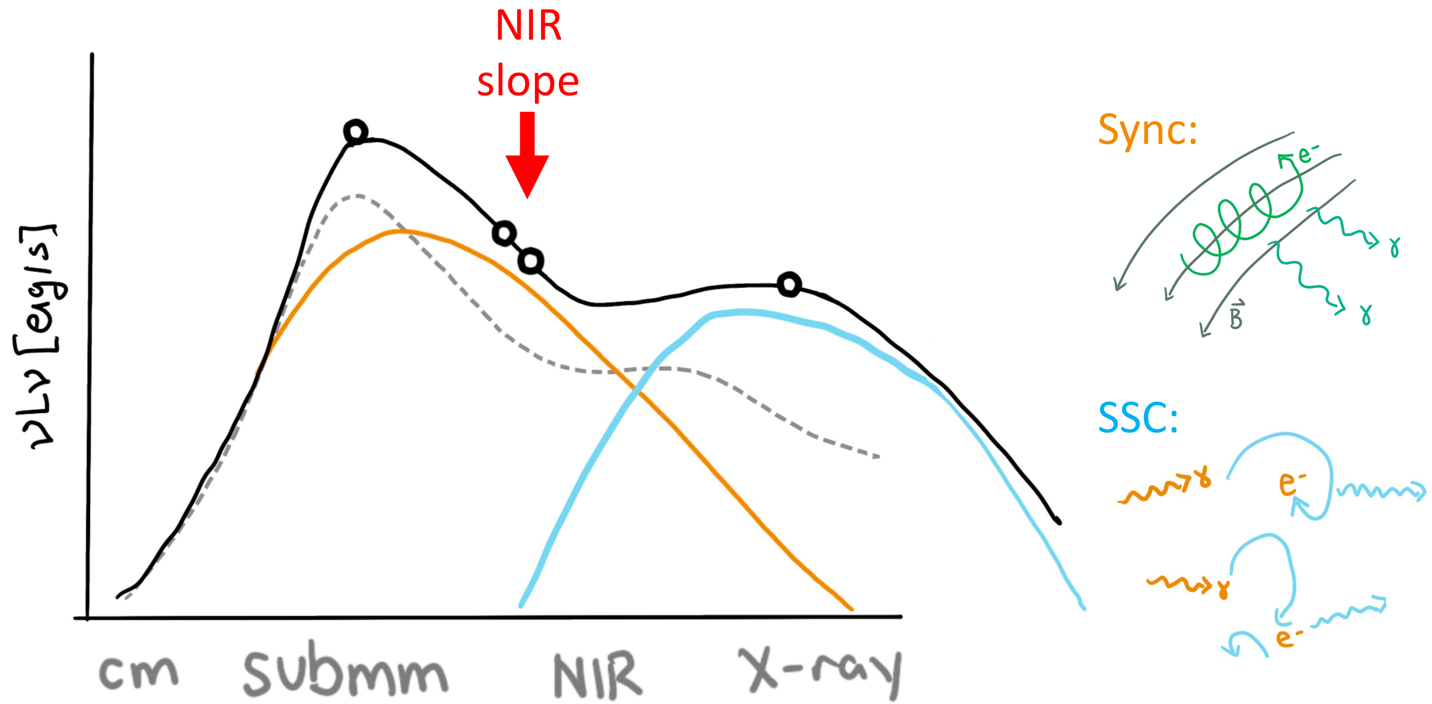
Slide credit: **Hope Boyce**

Flaring Model: Synchrotron Self-Compton (SSC)



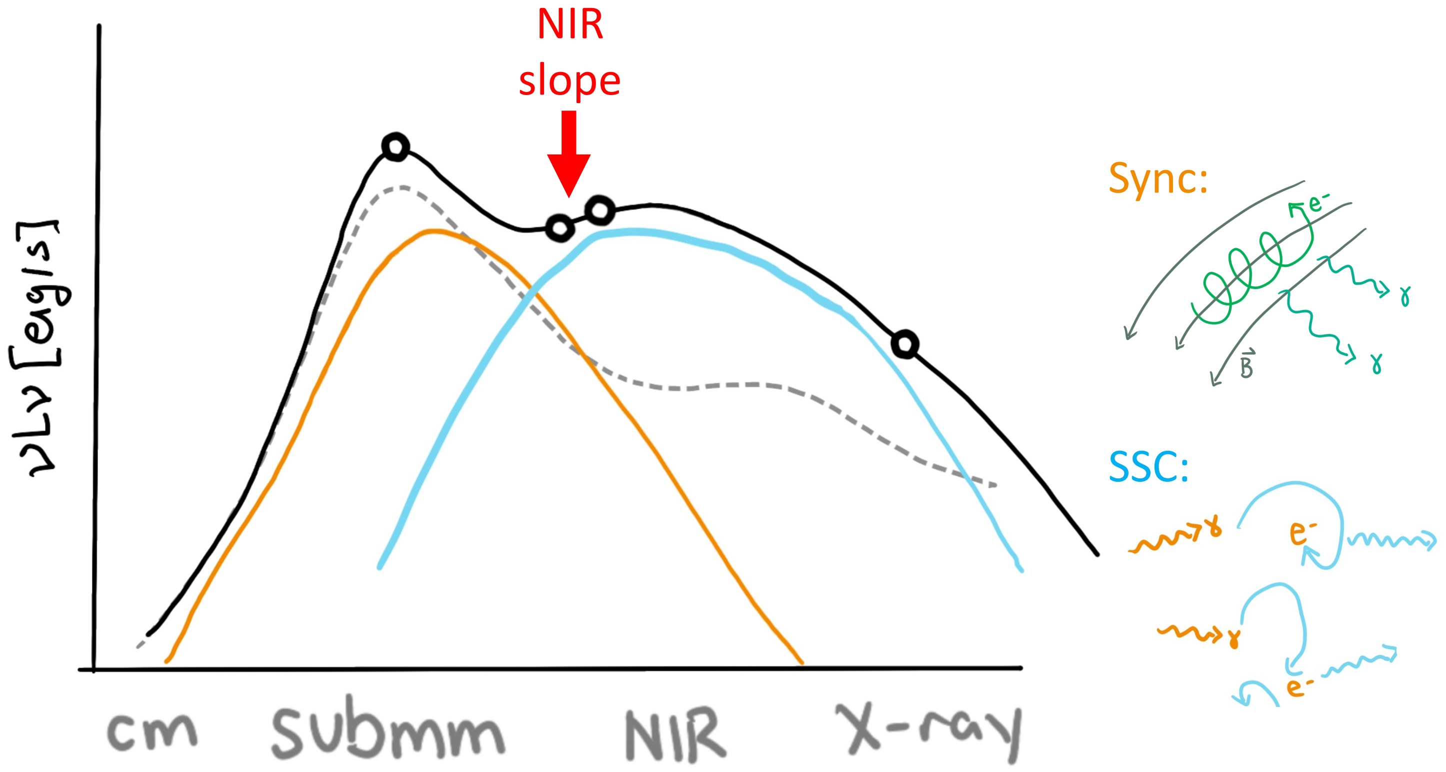
Slide credit: **Hope Boyce**

Flaring Model: Synchrotron Self-Compton (SSC)



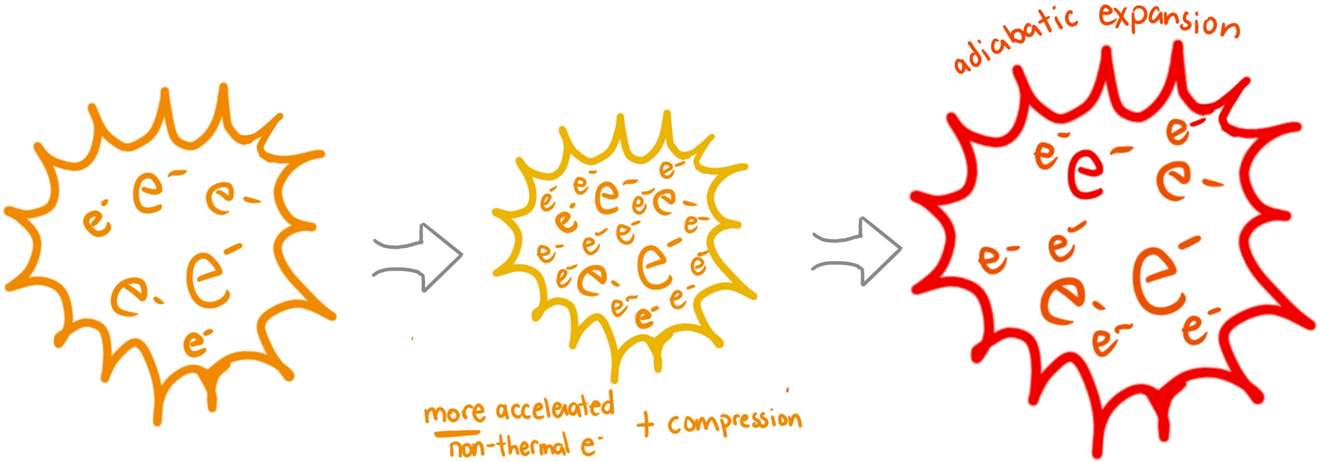
Slide credit: **Hope Boyce**

Flaring Model: SSC + higher electron density



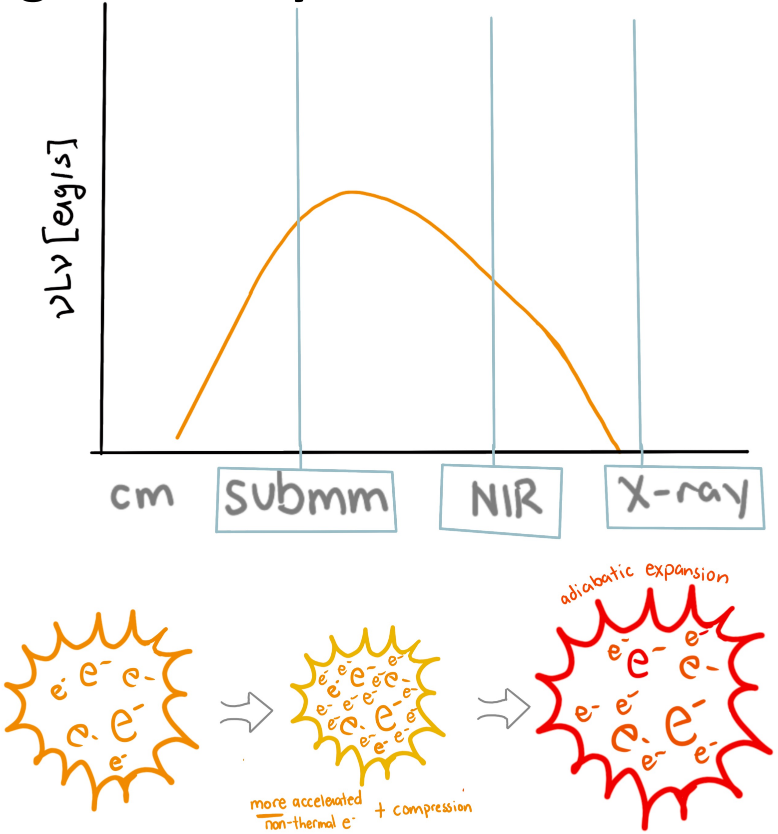
Slide credit: **Hope Boyce**

Flaring Model: Synchrotron source evolving



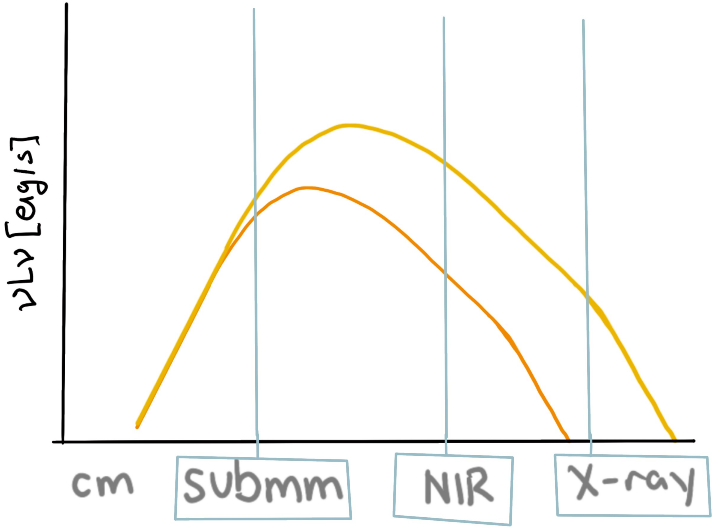
Slide credit: **Hope Boyce**

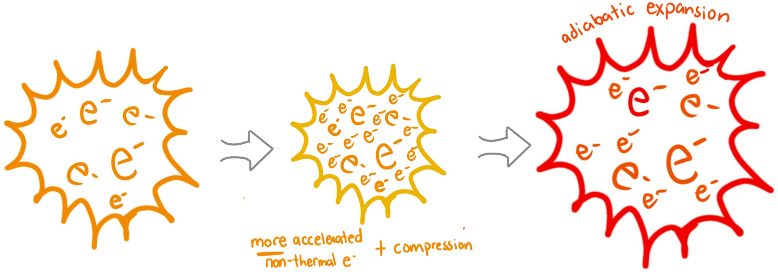
Flaring Model: Synchrotron source evolving



Slide credit: **Hope Boyce**

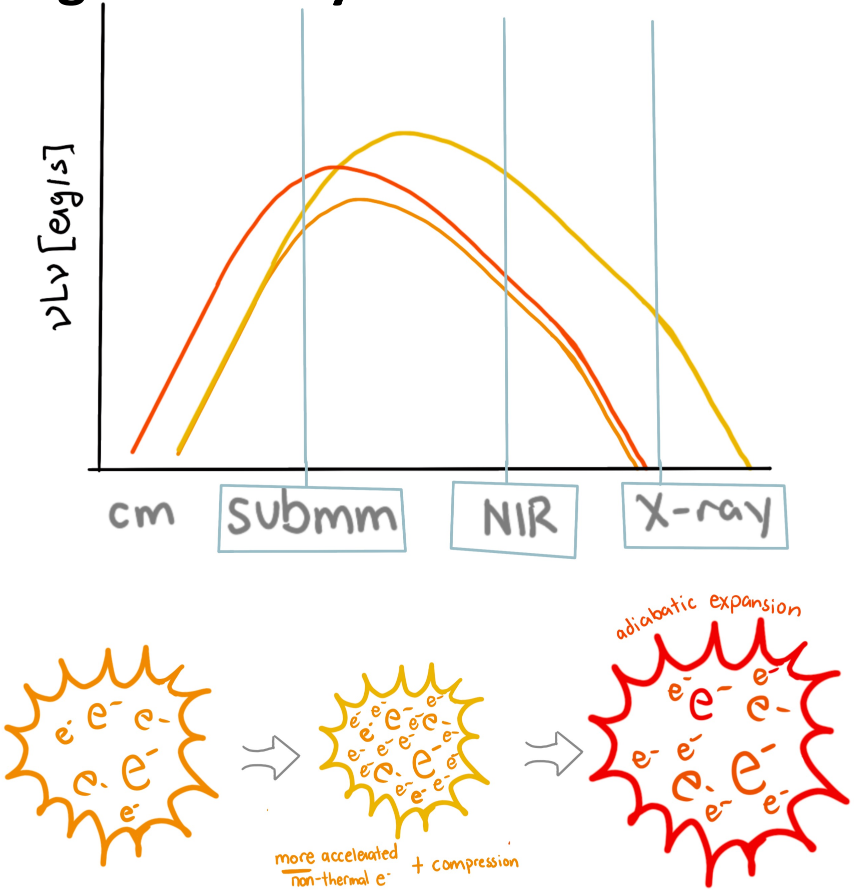
Flaring Model: Synchrotron source evolving





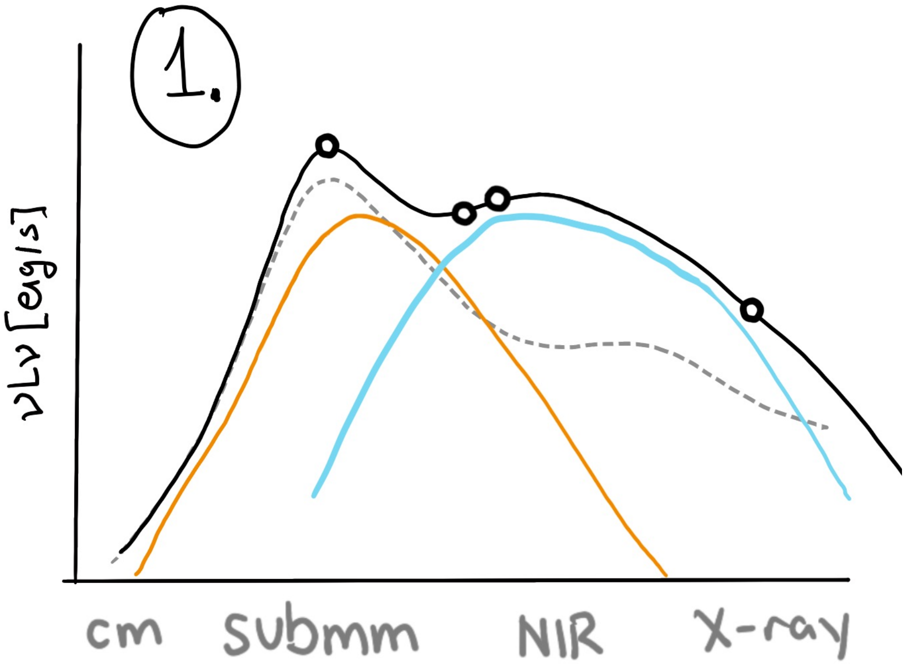
Slide credit: **Hope Boyce**

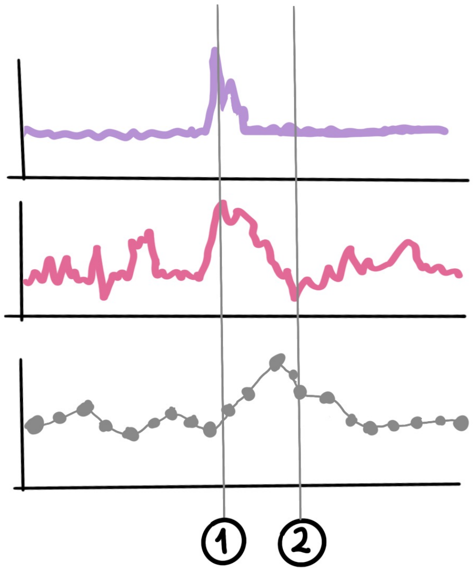
Flaring Model: Synchrotron source evolving



Slide credit: **Hope Boyce**

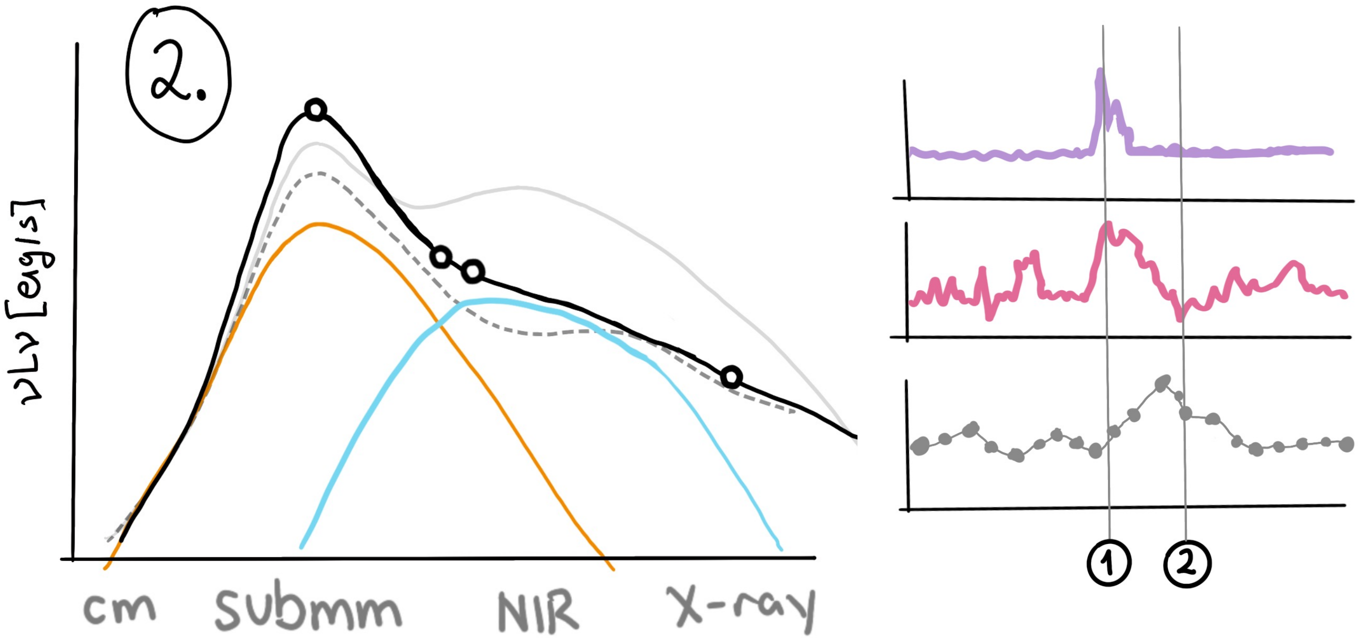
Flaring Model: Synchrotron source evolving





Slide credit: **Hope Boyce**

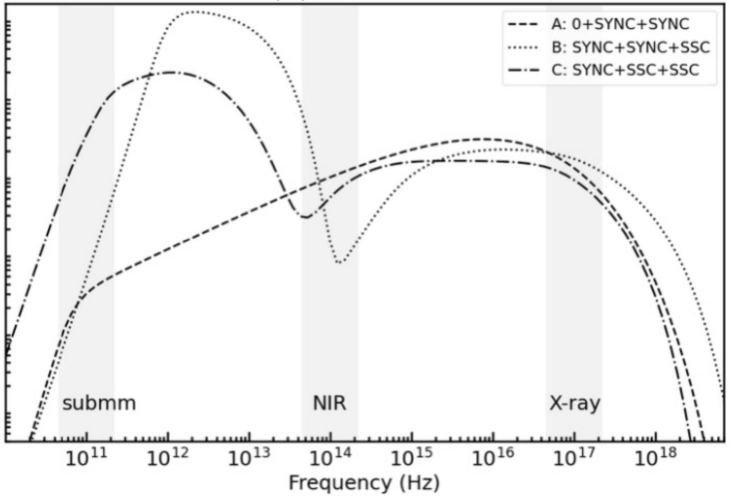
Flaring Model: Synchrotron source evolving



Slide credit: **Hope Boyce**

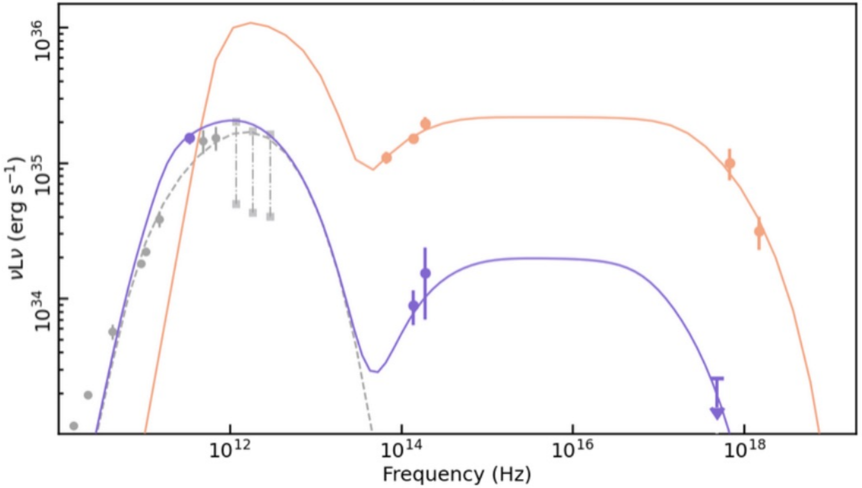
SED Modelling

SEDs at NIR/X-ray peak:



[**Boyce, DH**, et al, sub; Dallilar et al, in prep]

Time Evolution of Model (C):



[**Boyce, DH**, et al, sub; Dallilar et al, in prep]

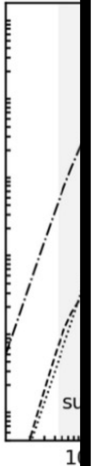
A. NIR and X-ray described by a SYNC source that contributes negligibly to the submm
B. Optically thick cut-off of non-thermal SYNC contributes to submm; varying optically thin cut-off of same SYNC component contributes to NIR, and X-ray variability is produced through SSC
C. Submm flux explained through optically thick SYNC, NIR and X-ray flux dominated by SSC

Model (C) SYNC-SSC-SSC under adiabatic expansion:

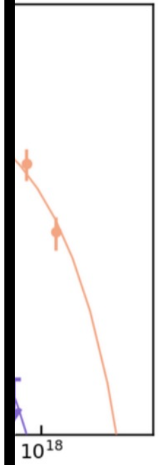
- Orange pts: measured at peak of the NIR and X-ray flare
- Purple pts: measured at presumed "peak" of 340 GHz flux ~35 min later
- Light grey: historic quiescent SED in radio/submm w/ thermal synch. component fit to these data (dashed line)
- Solid lines: best-fit models with the thermal component

SED Modelling

SEDs



- Flux & timing of 2019 July 17–18 flare w/ 3 scenarios: (A) both NIR and X-ray due to SYNC, (B) NIR/X-ray from SSC, (C) NIR from SYNC/X-ray from SSC
- Sub-mm anomalously high (~5.5 Jy) – radiative processes may be non-typical compared to conditions for historic variability
- Peak of 340 GHz sub-mm flare not captured—only measure upper limit on time-lag between sub-mm & NIR
- Model (C) delayed sub-mm flux w/ SYNC source cooled via adiabatic expansion to see if it can self-consistently describe submm increase & NIR/X-ray flux at peak
- Adiabatic expansion producing SSC NIR and X-ray emission works if very high submm/THz peak occurs at the time of the NIR/X-ray peak ***and*** e^- density reaches log(ne)~10
- Also consider a SYNC source fitted to the NIR/X-ray but it could not evolve (cool) and explain the submm flux increase, BUT does not require extraordinarily large electron densities (GRAVITY/Abuter et al. 2021)
- Need simultaneous, multi-wavelength observations of more Sgr A* flares to differentiate between these radiation mechanisms!!



[**Boyce, DH**, et al, sub; Dallilar et al, in prep]

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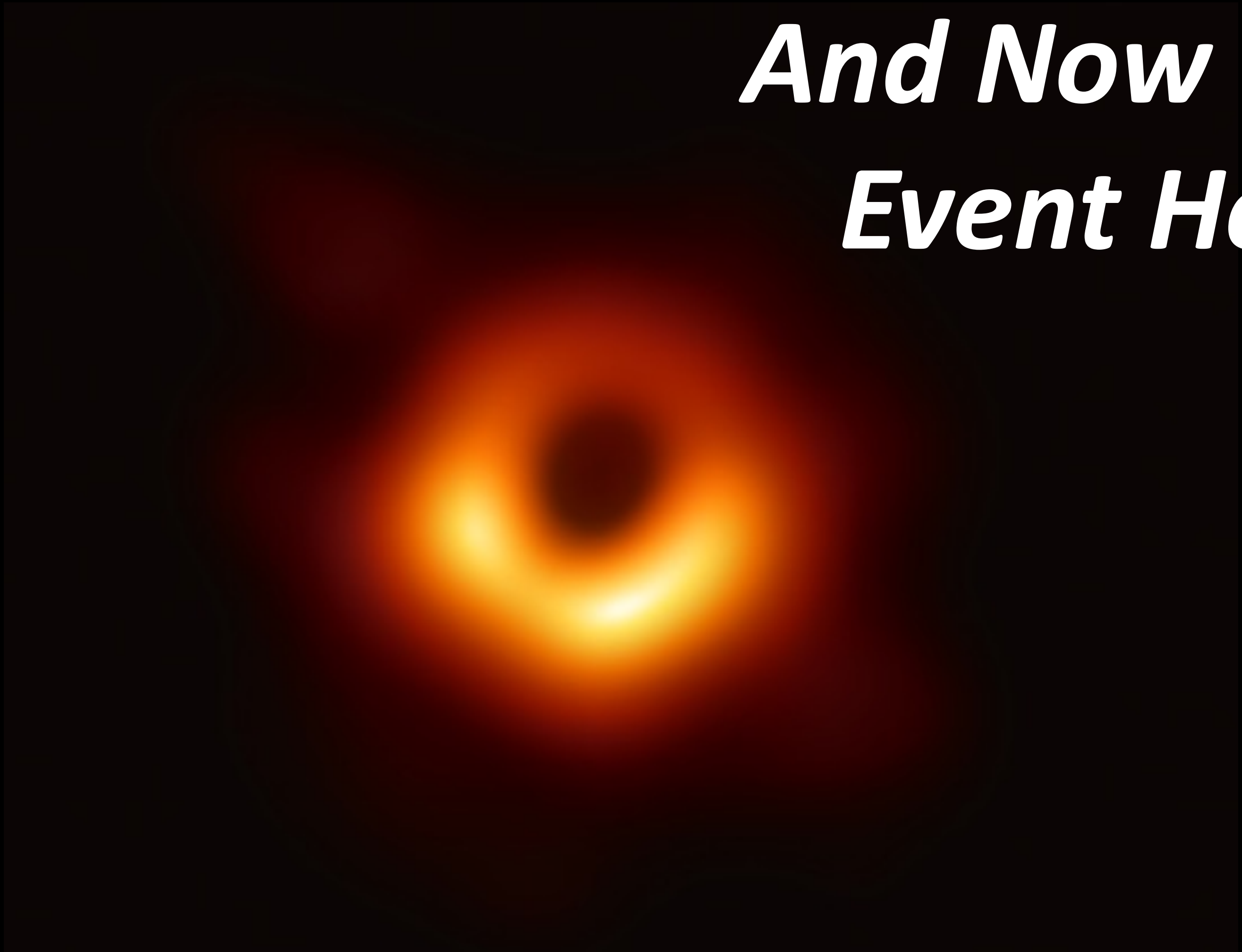
And Now to the Event Horizon



Zoom Chat Blast #2: Which of the following do you think offers a legitimate test of general relativity?

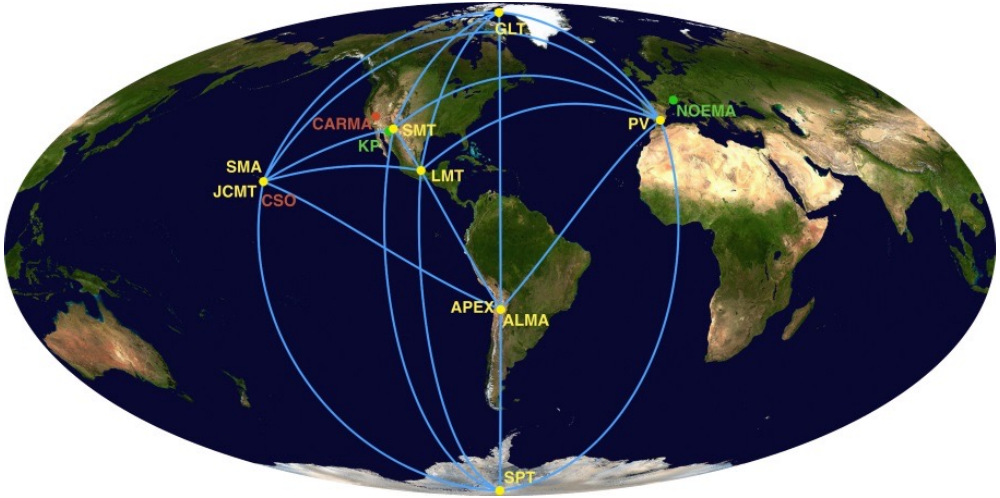
a) Precession of Mercury's orbit around the Sun
b) Gravitational lensing
c) S-star orbits around Sgr A*
d) LIGO-Virgo detection of GW from BH mergers
e) EHT image of M87's BH shadow
f) All of the above
g) None of the above

Approaching the Event Horizon

- Known Mass & Distance: BH shadow ~ 50 microarcseconds
- High S/N on timescales ~ r_g/c (20 sec)

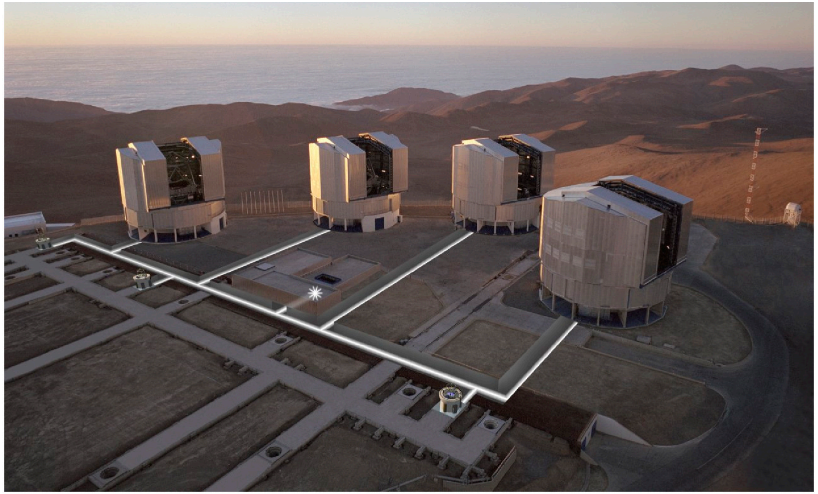
Slide credit:
J. Dexter

Event Horizon Telescope

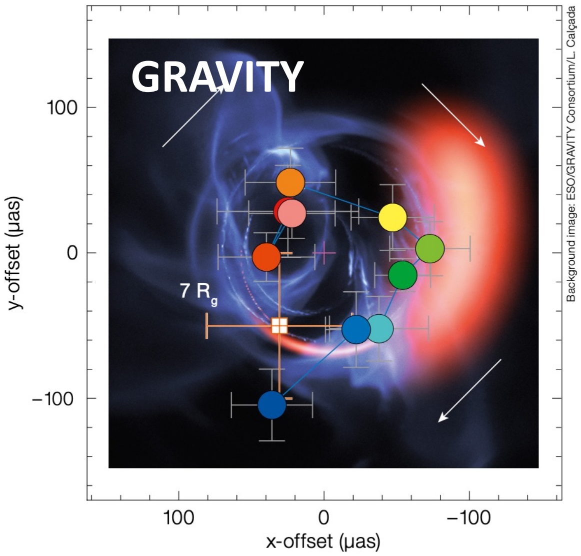


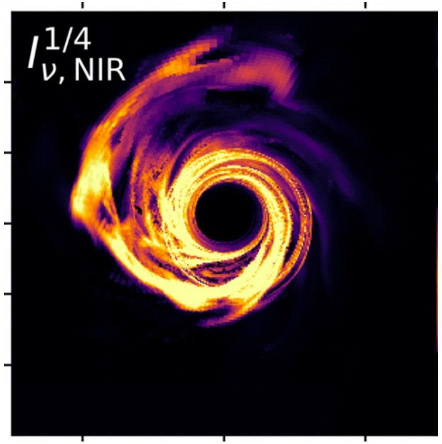
λ ~ 1 mm, B ~ 10000 km
θ ~ 20 μas

VLTI GRAVITY



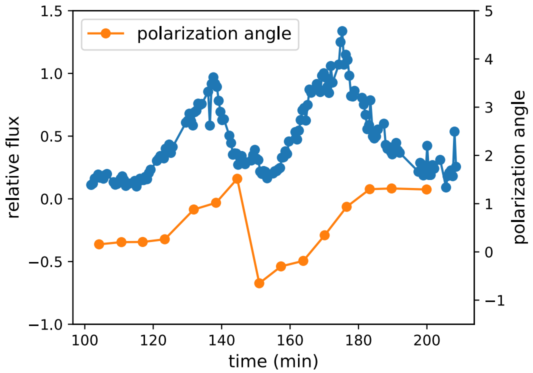
λ ~ 2 micron, B ~ 100 m
θ ~ 4 mas

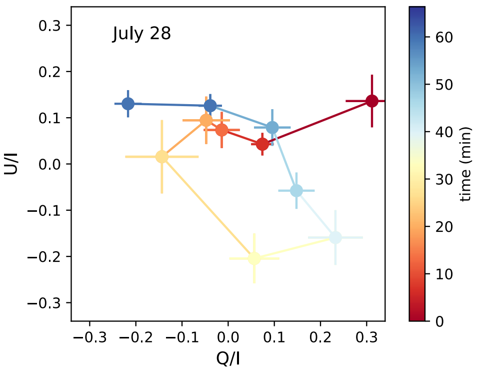


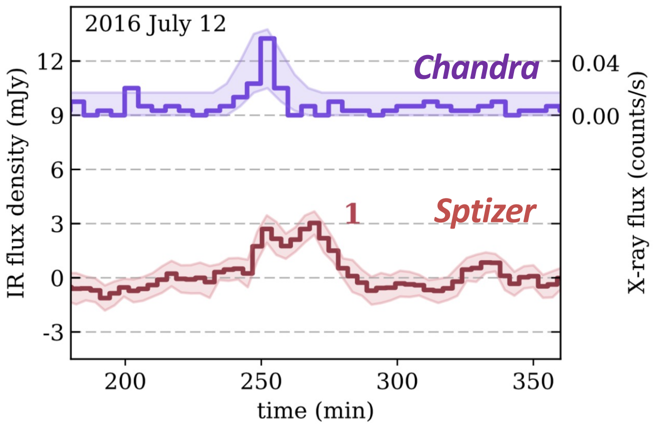


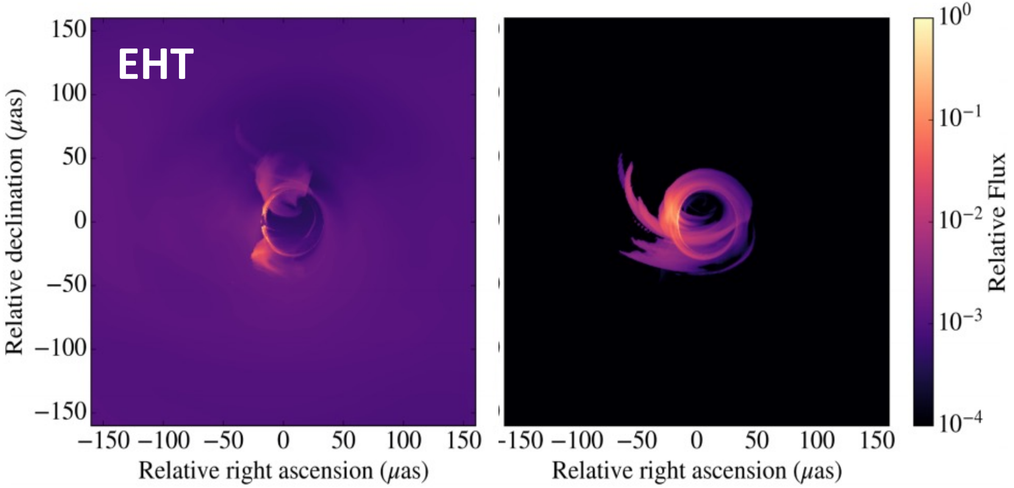
- **EHT** & multi-wavelength coordination with **NuSTAR**, **Chandra**, **Spitzer**, **VLA** and **GRAVITY**
- Changes in radiative output ←→ changes in structure **at the event horizon**

[**GRAVITY Collab** 2018; Dexter et al. 2020; **Boyce** et al. 2018]



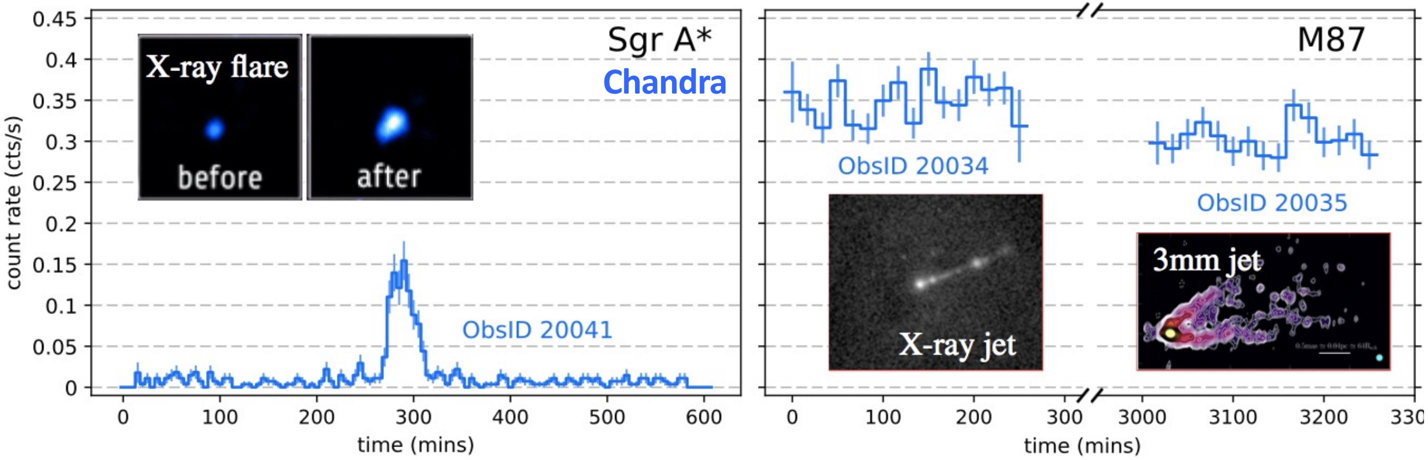


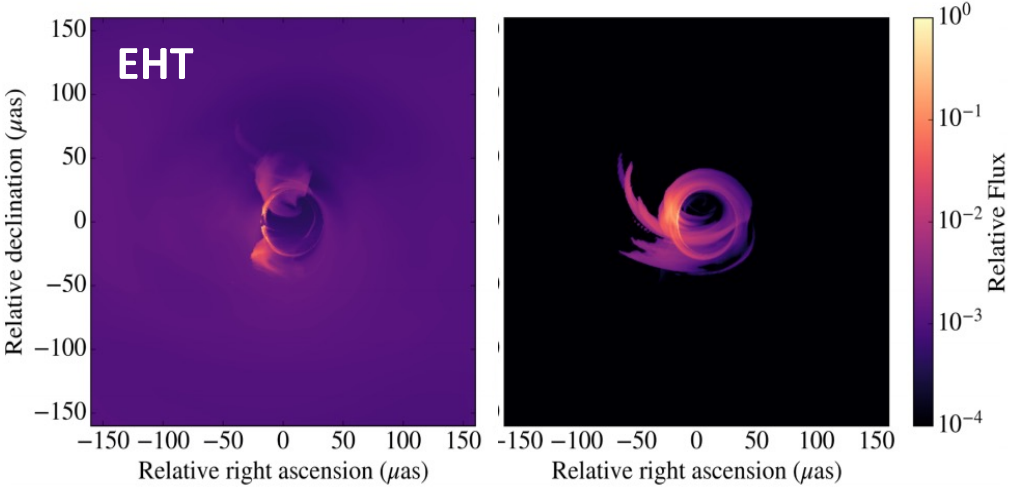




- Multiwavelength Coord. w/ **EHT**, **Chandra**, **NuSTAR**, **VLT**,++ in 2017,2018, 2021?
- Campaigns are ongoing:
  - Chandra, NuSTAR, GRAVITY Apr 2019, 2020
  - Chandra, Spitzer 2019
  - Joint w/ EHT Mar 2021

[**Ball**, et al. 2016; **Boyce** et al. 2018; **M. Johnson** for **EHT MWL WG (Markoff & Hada)** 2018]





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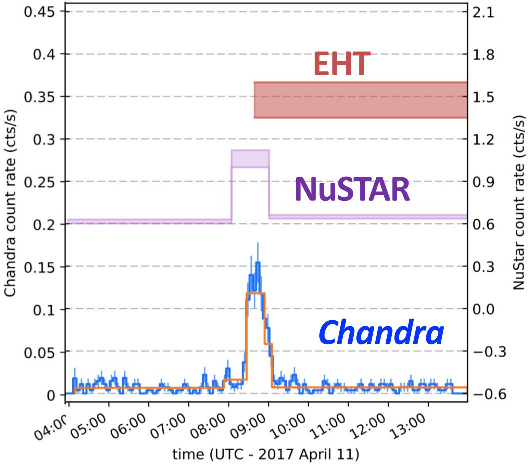
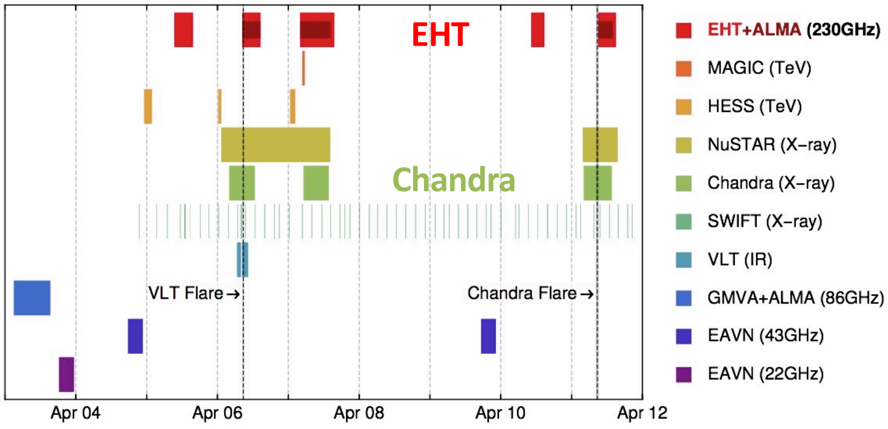




Sgr A*Variability & Multi-λ Summary

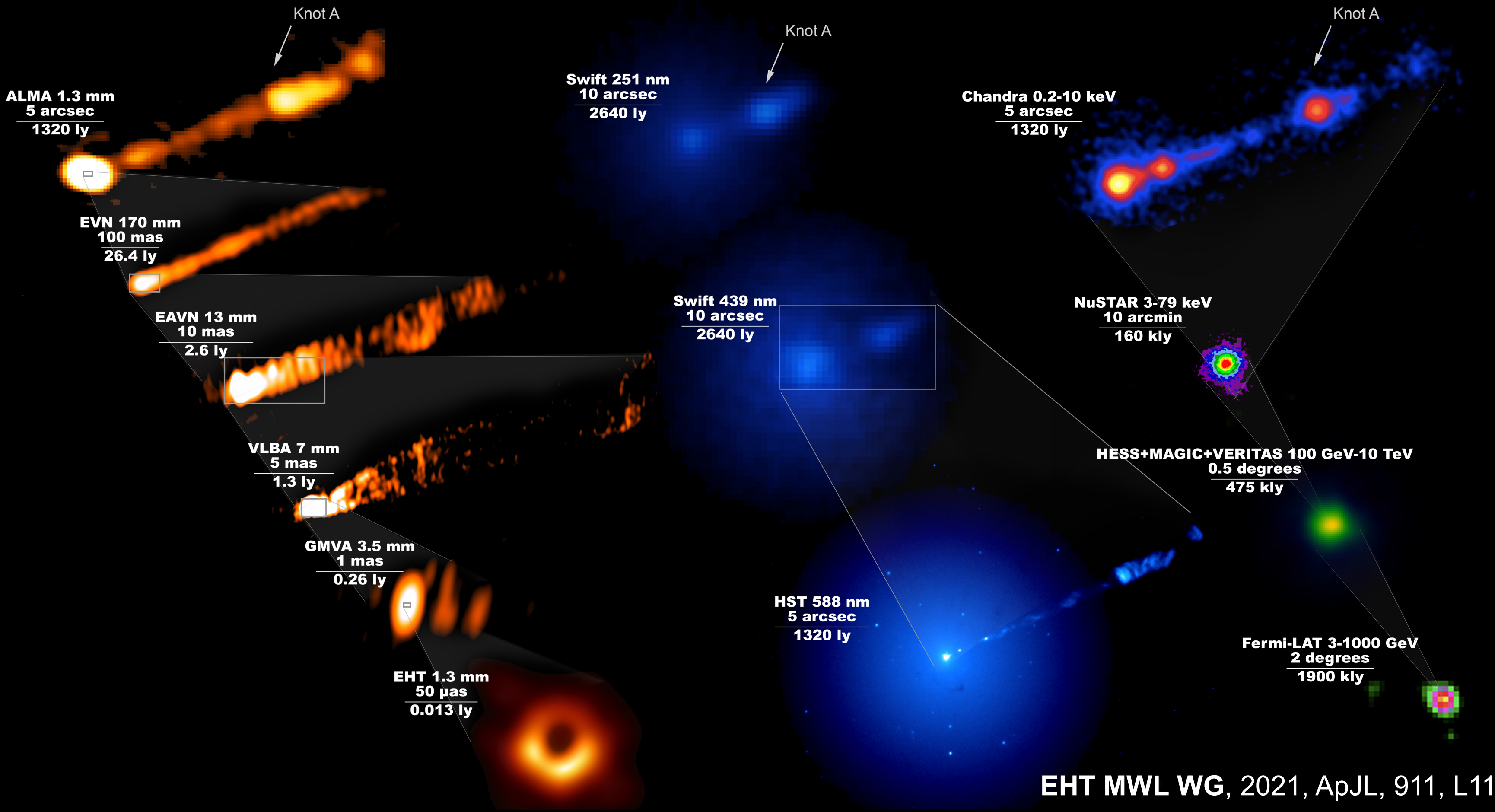
- Sgr A* bright X-ray and multi-wavelength flares
  - Similar X-ray HR & spectra: $\Gamma \sim 2$, $L_X \sim 10^{35}$ erg/s, $E_X > 10^{39}$ erg
  - ”Long” timescales probe scales of ~10 R_g
  - Marginal evidence for “short” timescale variability (no QPOs)
  - X-ray flares lead IR peaks, and possibly radio
  - Flare mechanism/microphysics still debated
- Chandra+EHT & MWL, Chandra+Spitzer, Chandra+GRAVITY & MWL 2021++
- Probe accretion, outflow, plasma physics
- Variability tied to particle acceleration and may be traced to structural changes near the BH event horizon

EHT+ALMA (230GHz)
MAGIC (TeV)
HESS (TeV)
NuSTAR (X–ray)
Chandra (X–ray)
SWIFT (X–ray)
VLT (IR)
GMVA+ALMA (86GHz)
EAVN (43GHz)
EAVN (22GHz)
XMM (X-ray)

The Spectacular M87

EHTC, 2021, ApJL, 910, L12 & ApJL 910, L13

The Spectacular M87



EHT MWL WG, 2021, ApJL, 911, L11

Cen A's Extraordinary Jet

Janssen & EHTC, 2021, Nature Astronomy, 5, 1017

Your feedback here!

https://bit.ly/BlackHoleDiscovery