The Galactic Center

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MPE Garching

with slides from R. Genzel, S. Gillessen, G. Ponti, and the MPE GC group mpe.mpg.de/ir/GC

ESO/Y. Beletsky

The Galactic Center

1. Evidence for a massive black hole (14.11)
2. A paradox of youth (today)
3. Sgr A* and the faintest black holes (21.11)
4. Outbursts from Sgr A* and the high energy GC (23.11)

Seminar: strong gravity around Sgr A* (23.11)

About the lectures

- Selected topics: central parsec, highly biased
- Please ask questions!

- ~1 interactive Q / lecture:
  ~10 mins to think/calculate, discuss, share

- Further reading: Genzel+2010, Morris+2012, Falcke & Markoff 2013

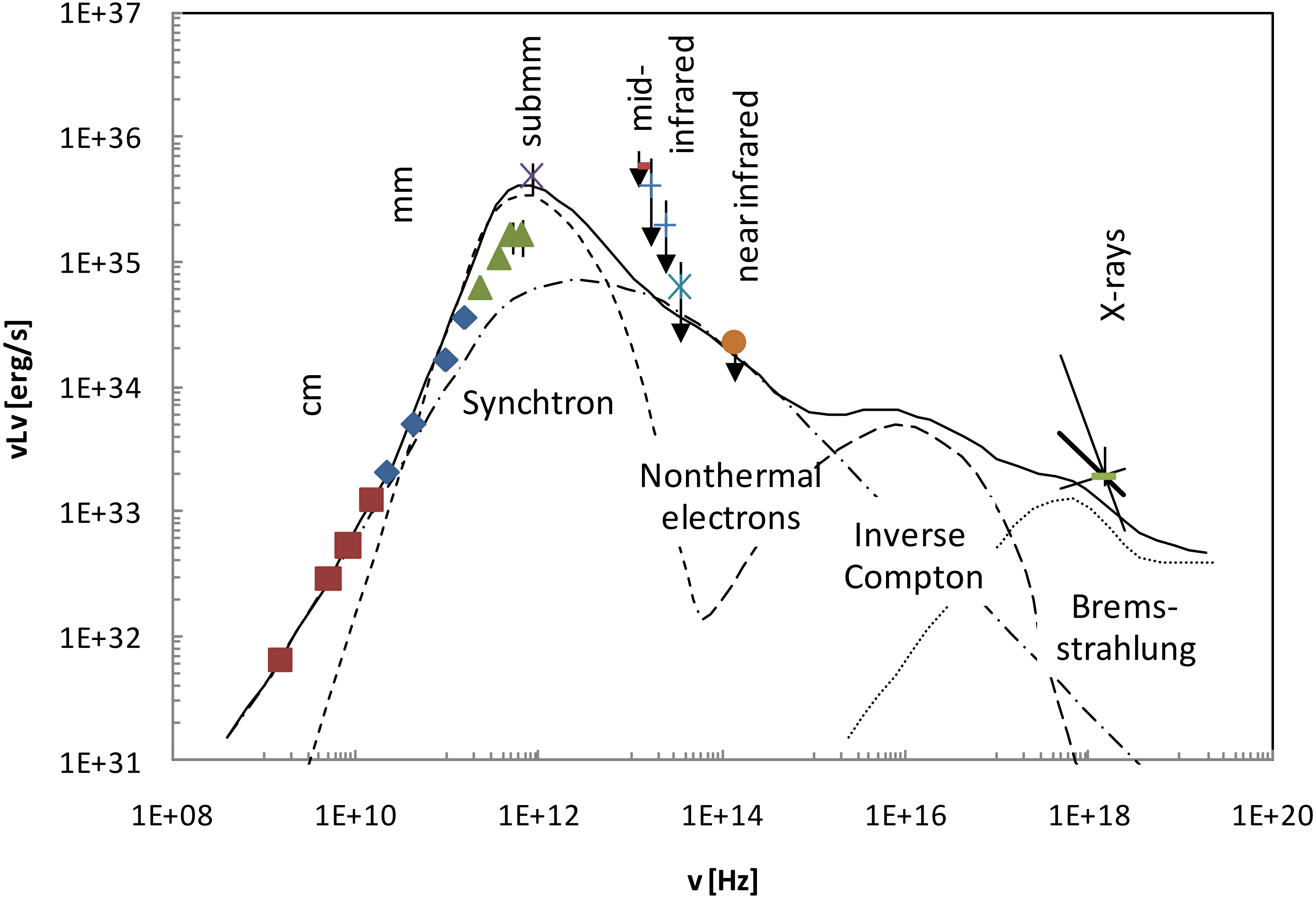
About the lectures

- pdf of slides online: mpe.mpg.de/~jdexter/gcslides.html
- Requests for topics: now or e-mail jdexter@mpe.mpg.de
- Any other Q’s: around after

3. The Galactic Center:
Sgr A* and the faintest black holes

Recap

Sgr A* quiescent spectrum



Sgr A* and normal black holes

- $L/L_{edd} \sim 10^{-8}$ compared to ~1 for AGN

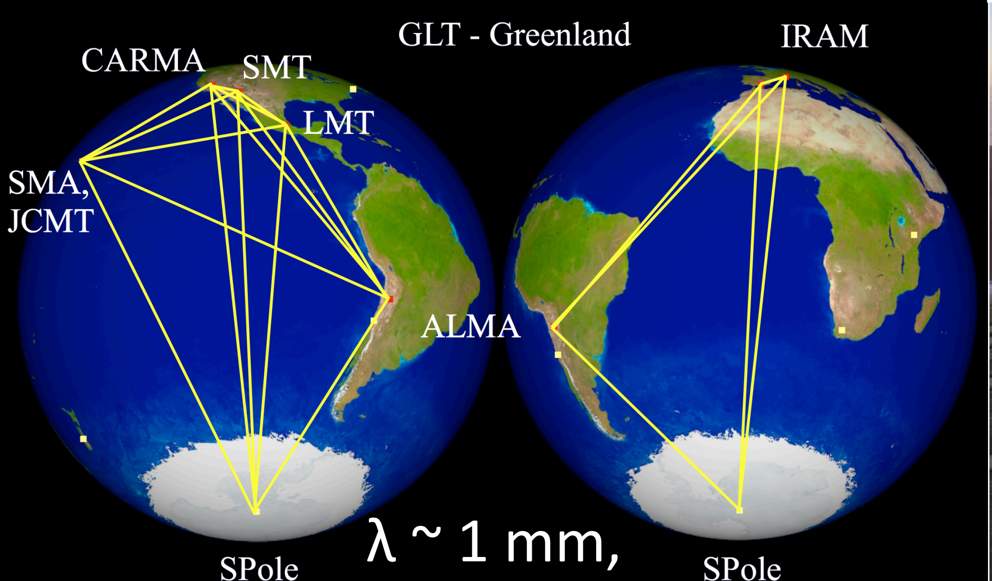
- Why?
  - Gas supply from stellar winds → ADAF/RIAF
  - > 99% of the gas does not reach the black hole!
  - Gas is hot, opt. thin: inefficient radiator

- Most black holes, most the time

Resolving an event horizon

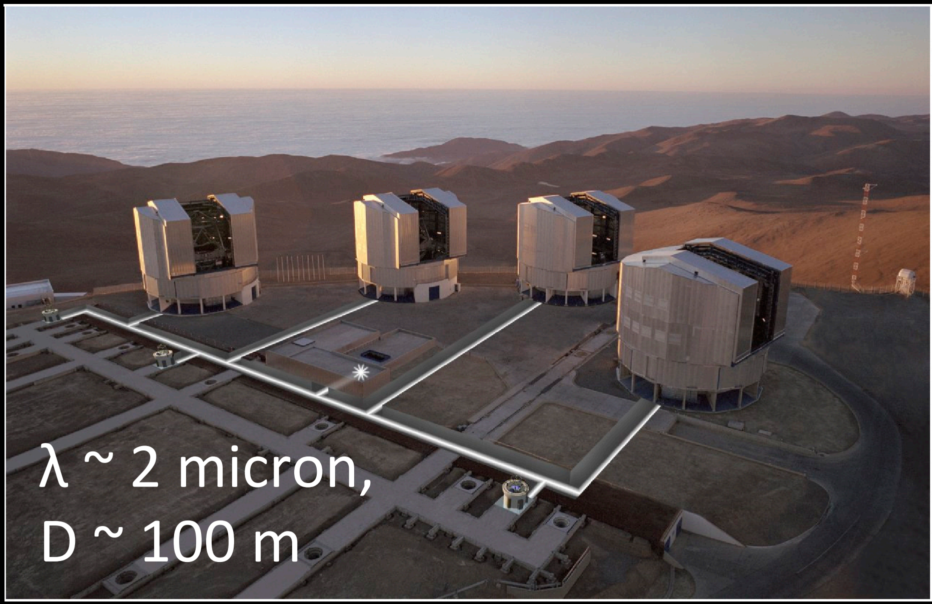
- Two new experiments to resolve gas near Sgr A*
- Resolution: 10-100 μas

Event Horizon Telescope



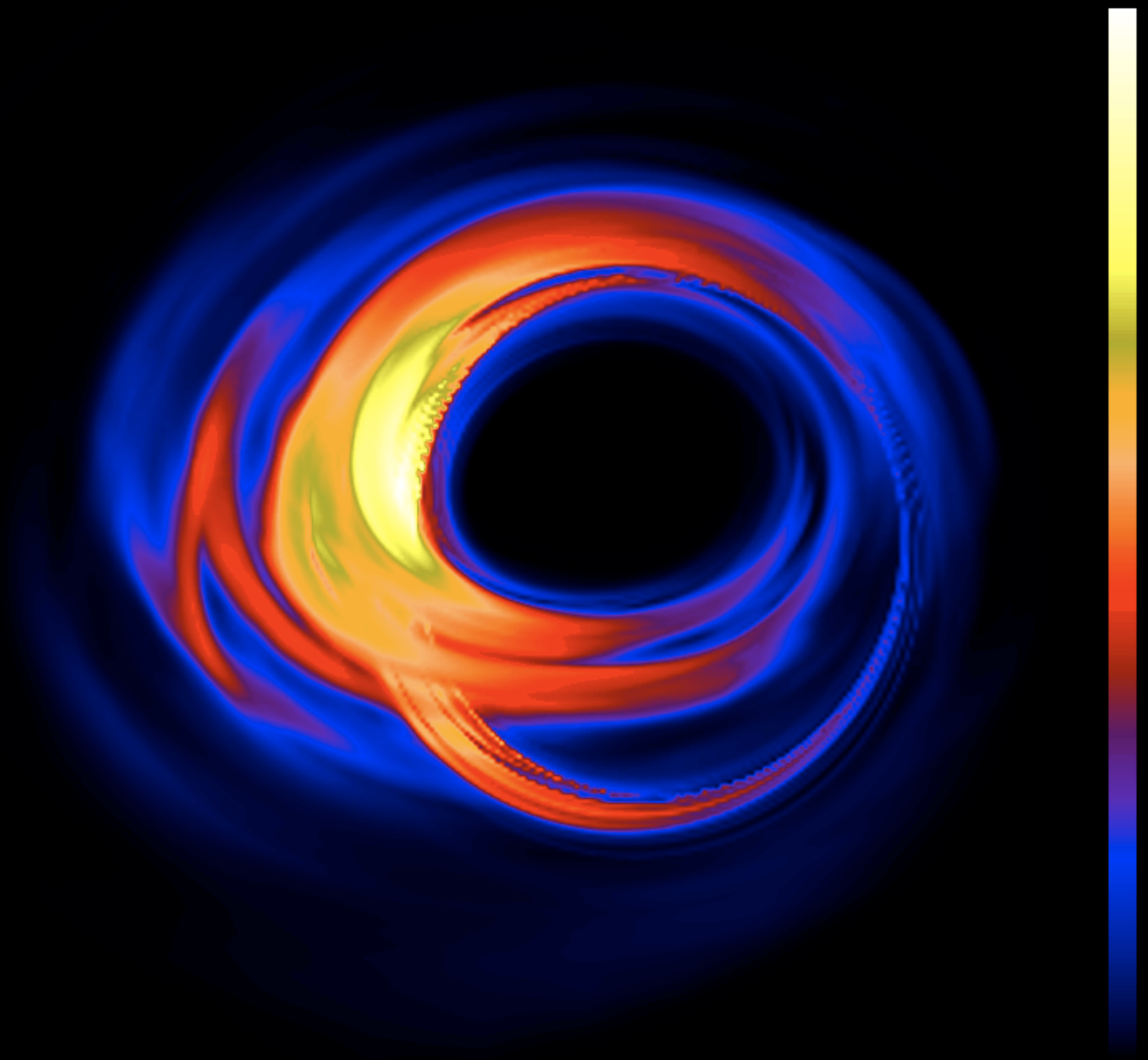
λ ~ 1 mm,
D ~ 5000 km

VLTI GRAVITY



λ ~ 2 micron,
D ~ 100 m

A black hole image

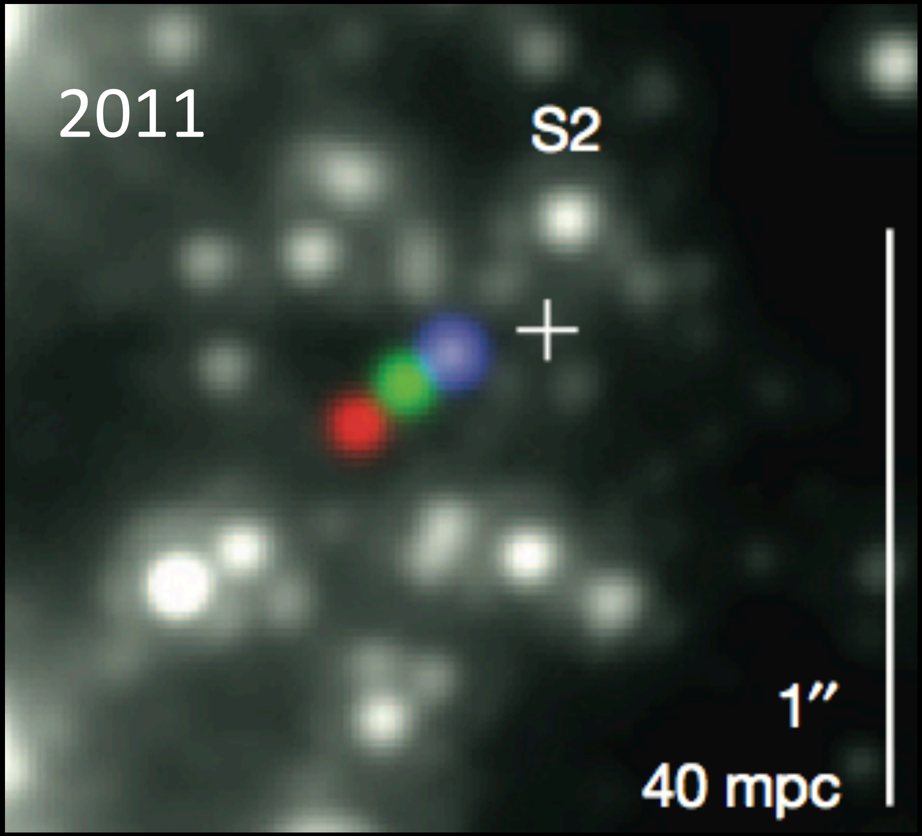


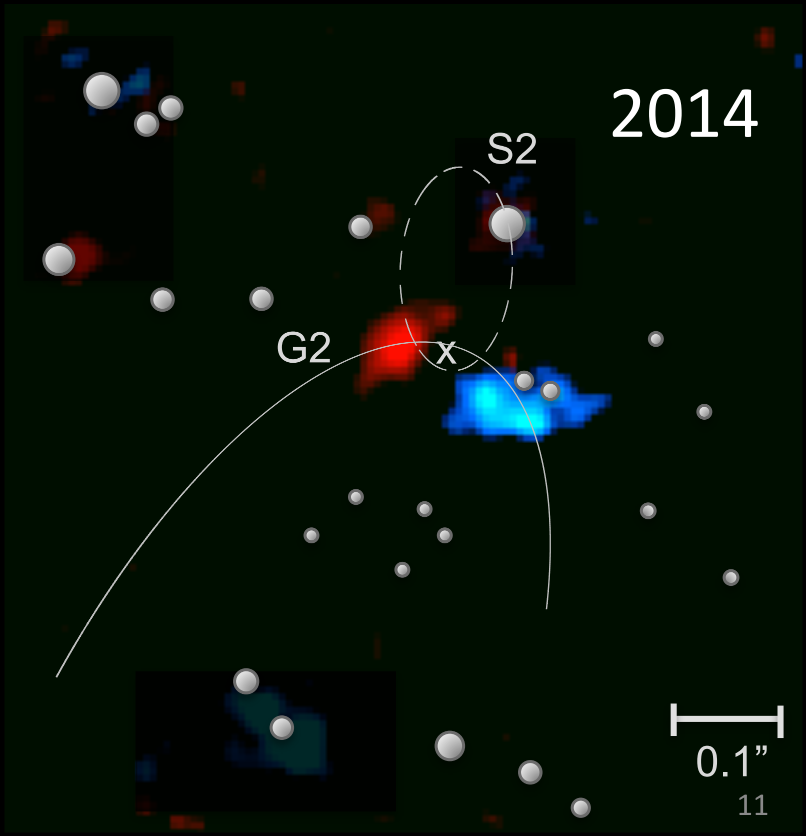
4. The Galactic Center

Outbursts from Sgr A* and the high energy GC

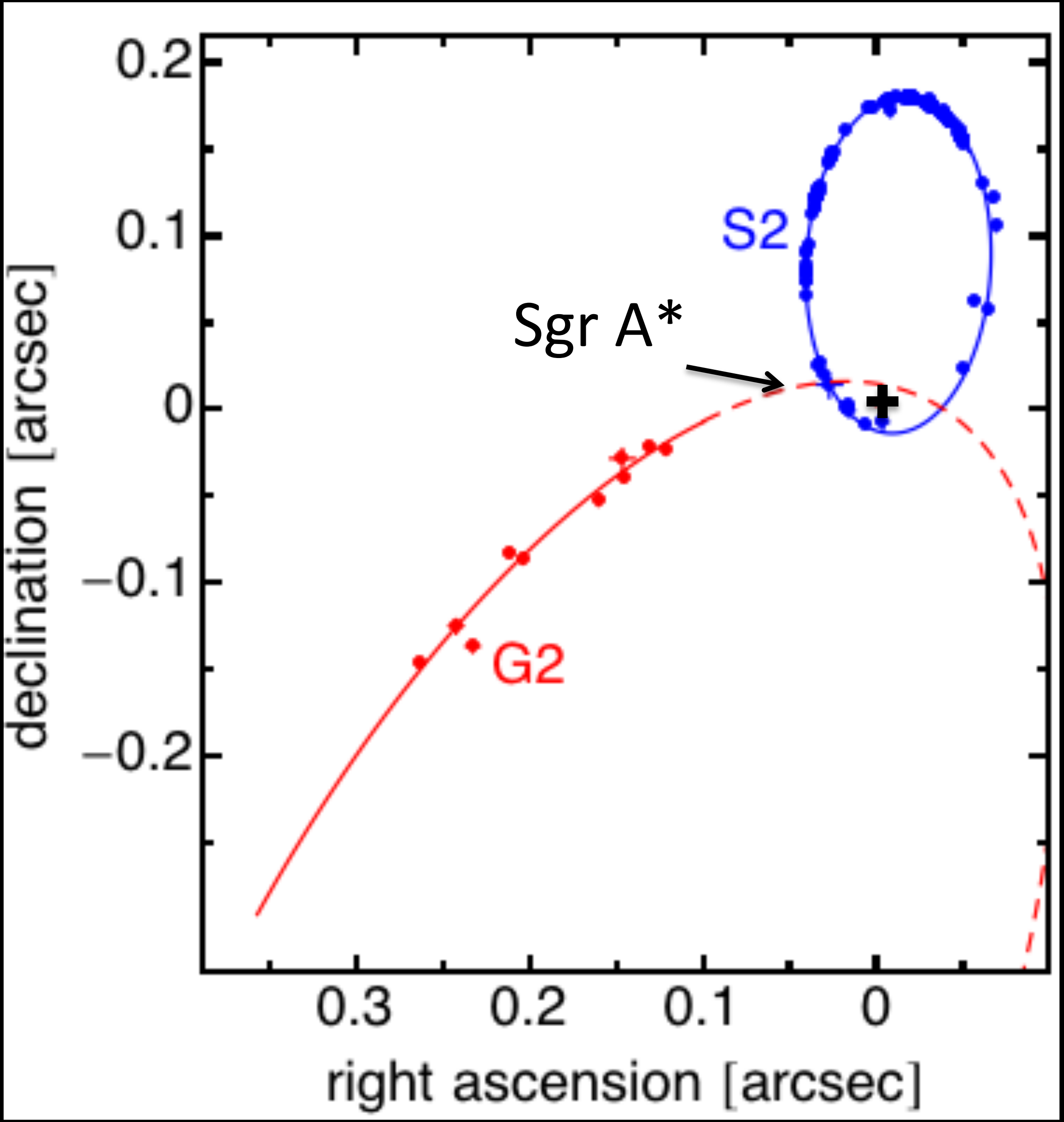
G2: real time accretion experiment

- A gas cloud on its way to (and past) Sgr A*
  (Gillessen+ 2011, 2013, Pfuhl+ 2015)

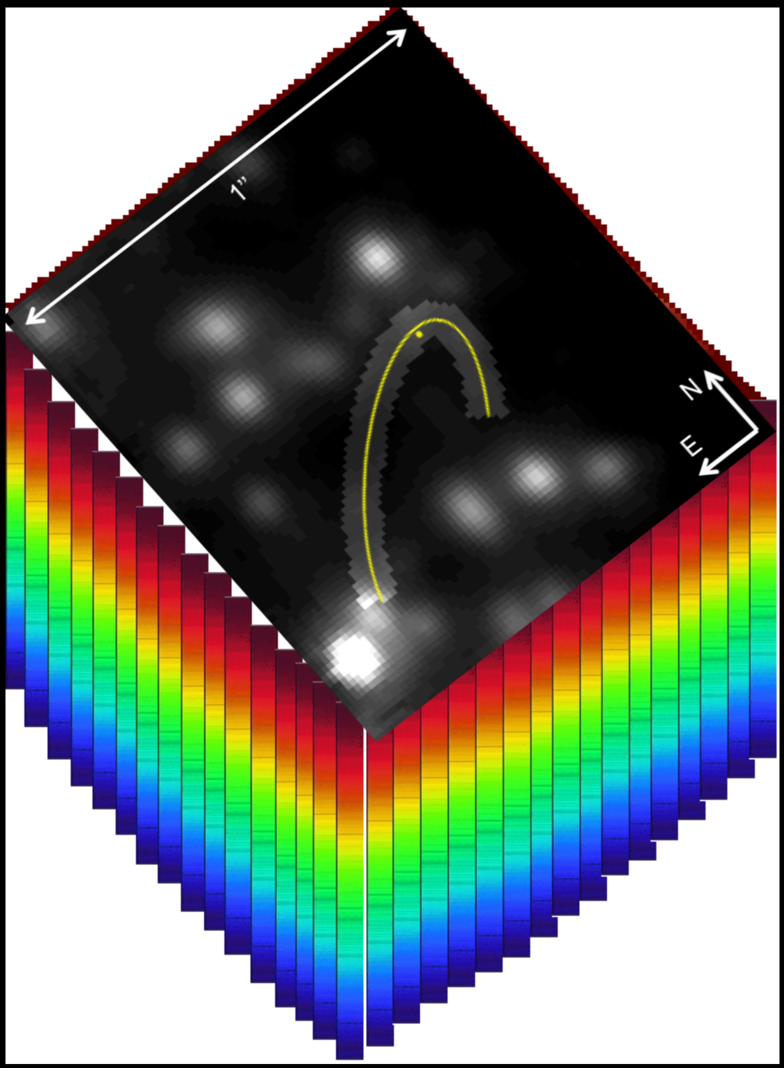


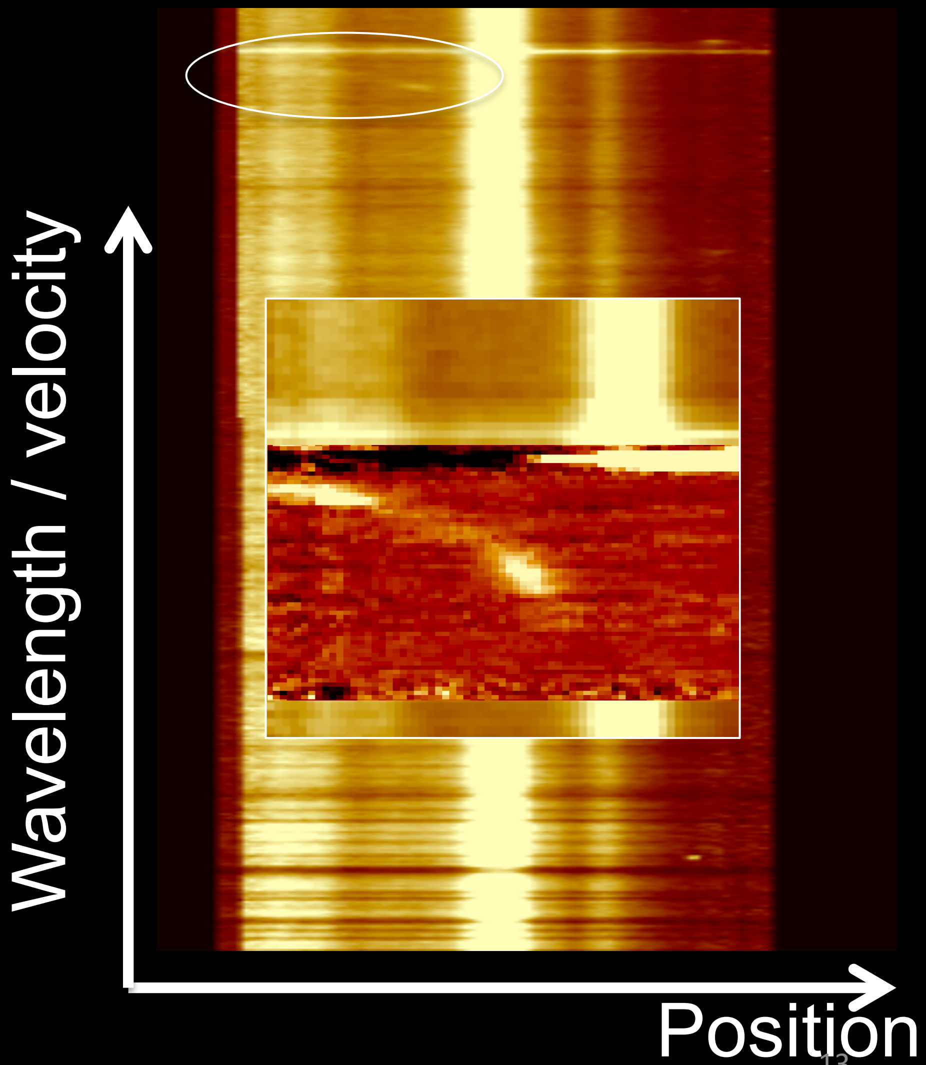


The radial orbit of G2



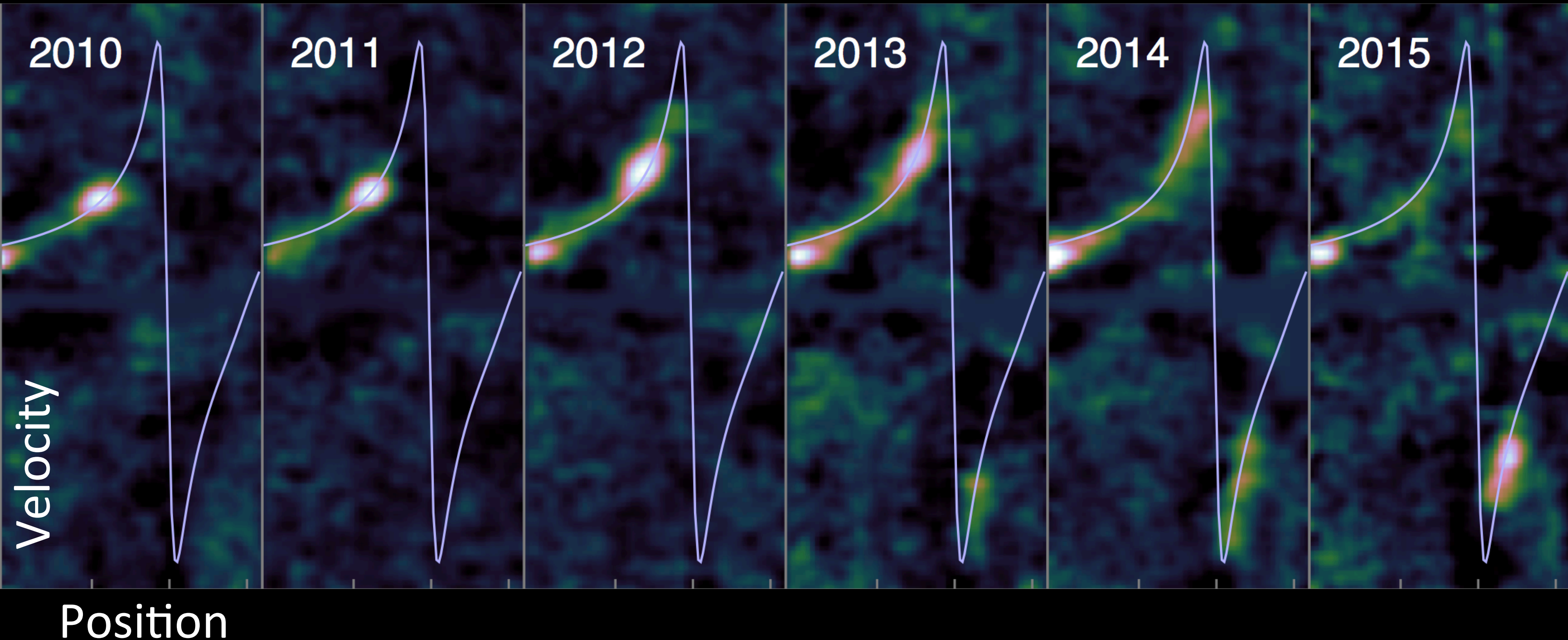
Position – velocity diagrams





The tidal disruption of G2

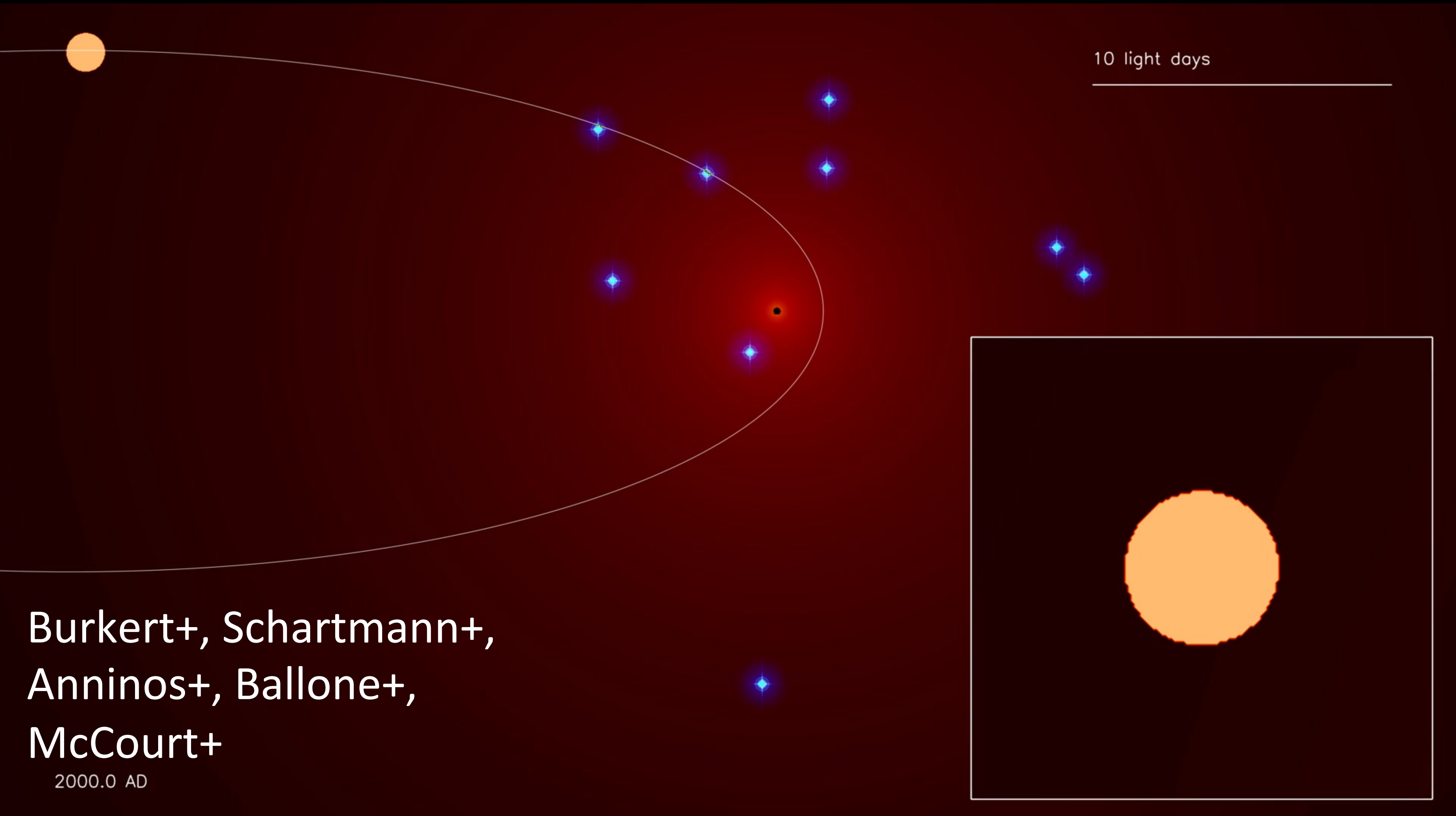
- A gas cloud on its way to (and past) Sgr A*
  (Gillessen+2011, 2013, Pfuhl+2015)



A gas stream or star+wind?

stellar wind debris	**disrupting disk**	**windy star**	**collisional debris**	**dust-enshrouded star / binary**
Gillessen et al. 2012/3ab	Murray-Clay & Loeb 2012	Scoville & Burkert 2013	Miralda-Escude 2012	Eckart et al. 2013
Pfuhl et al. 2015		Ballone et al. 2014	Guillochon et al. 2014	Valencia-S. et al. 2015
Schartmann et al. 2012		De Colle et al. 2014		Witzel et al. 2014
Burkert et al. 2012	**nova**			Prodan et al. 2014
Shcherbakov 2013	Meyer & Meyer-H. 2012			

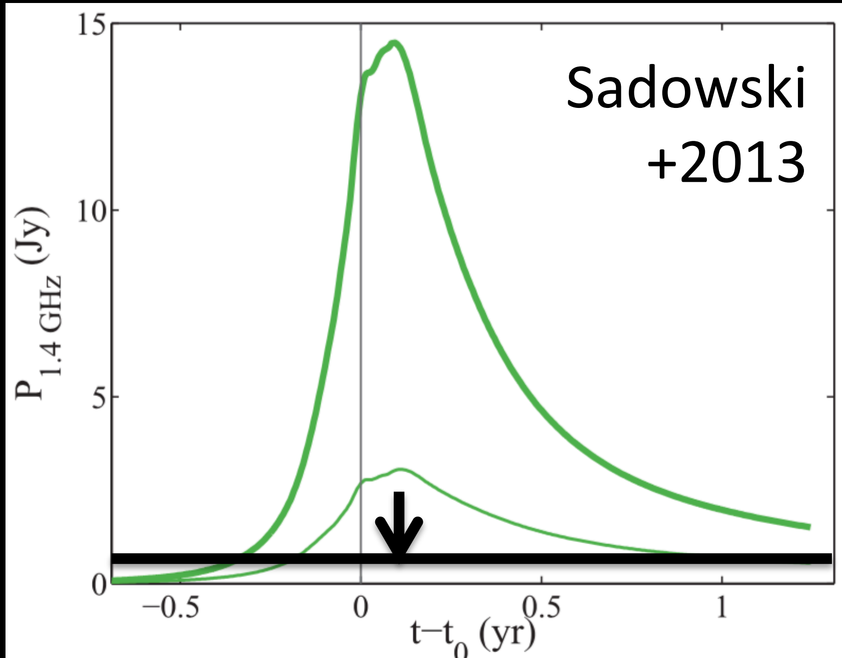
Missing: G2 interaction with the accretion flow

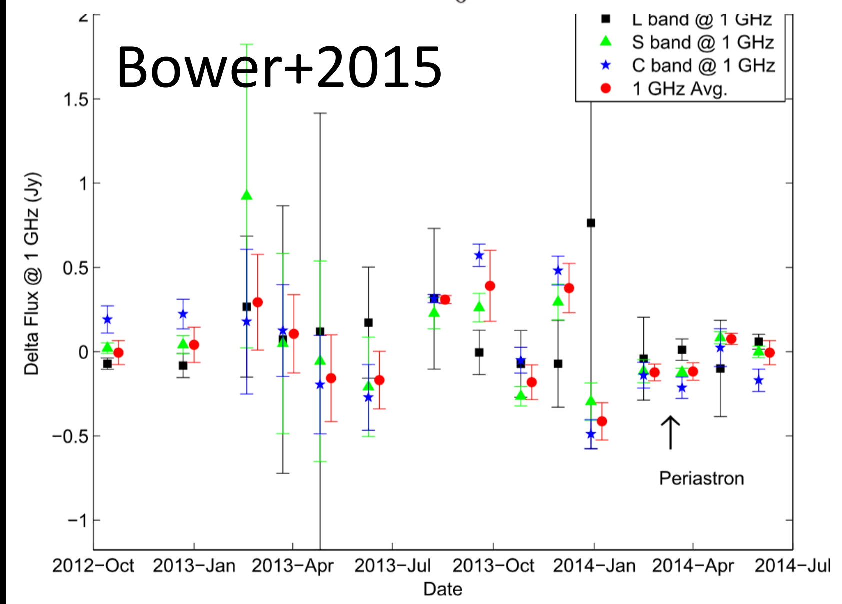


Burkert+, Schartmann+, Anninos+, Ballone+, McCourt+

G2 as probe of accretion flow

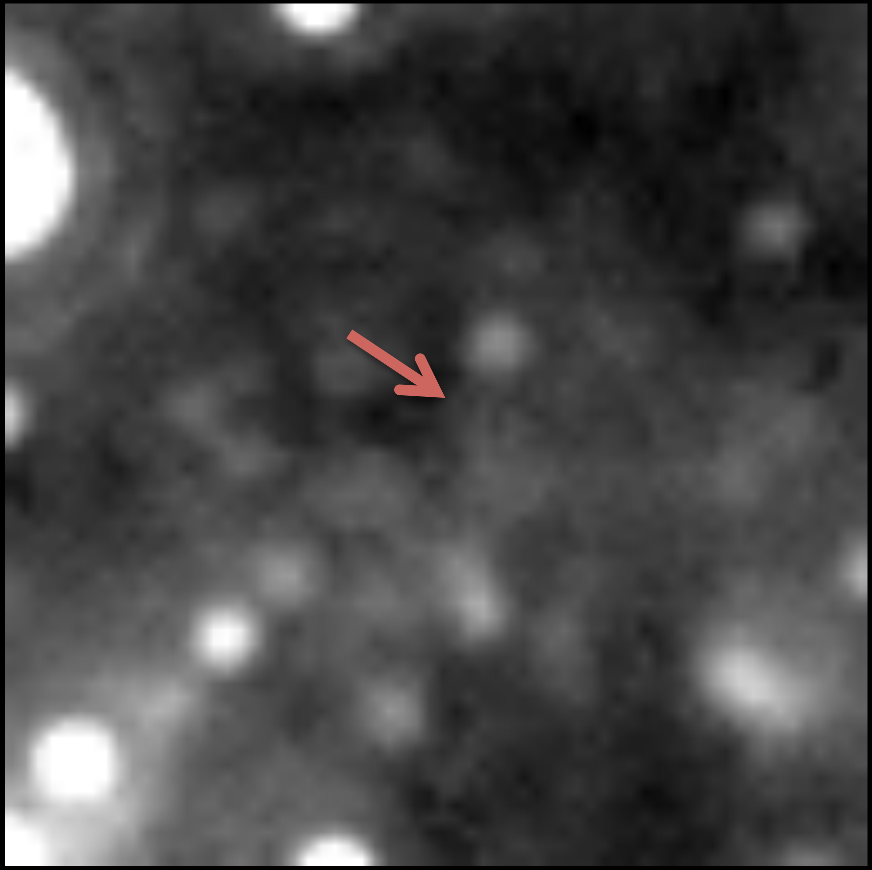
- No radio emission from bow shock
- No "drag" on G2 (Plewa+ in prep)
- $n < 10^3$ cm^{-3} at $R \sim 1000\ R_s$
- Mass lost at large radius?

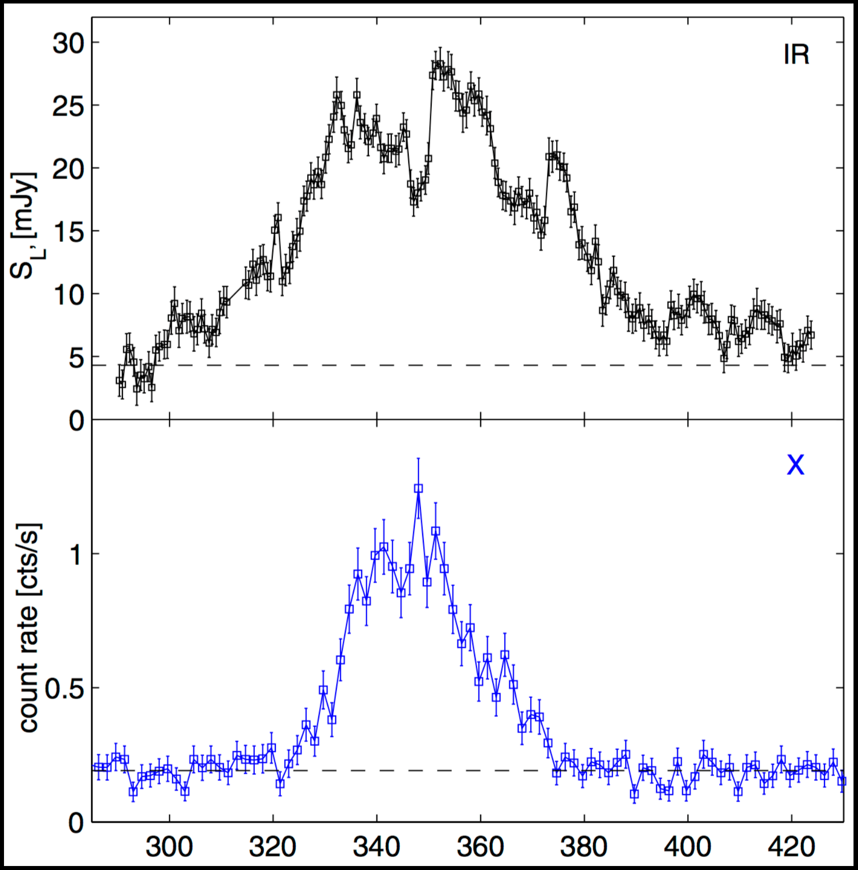




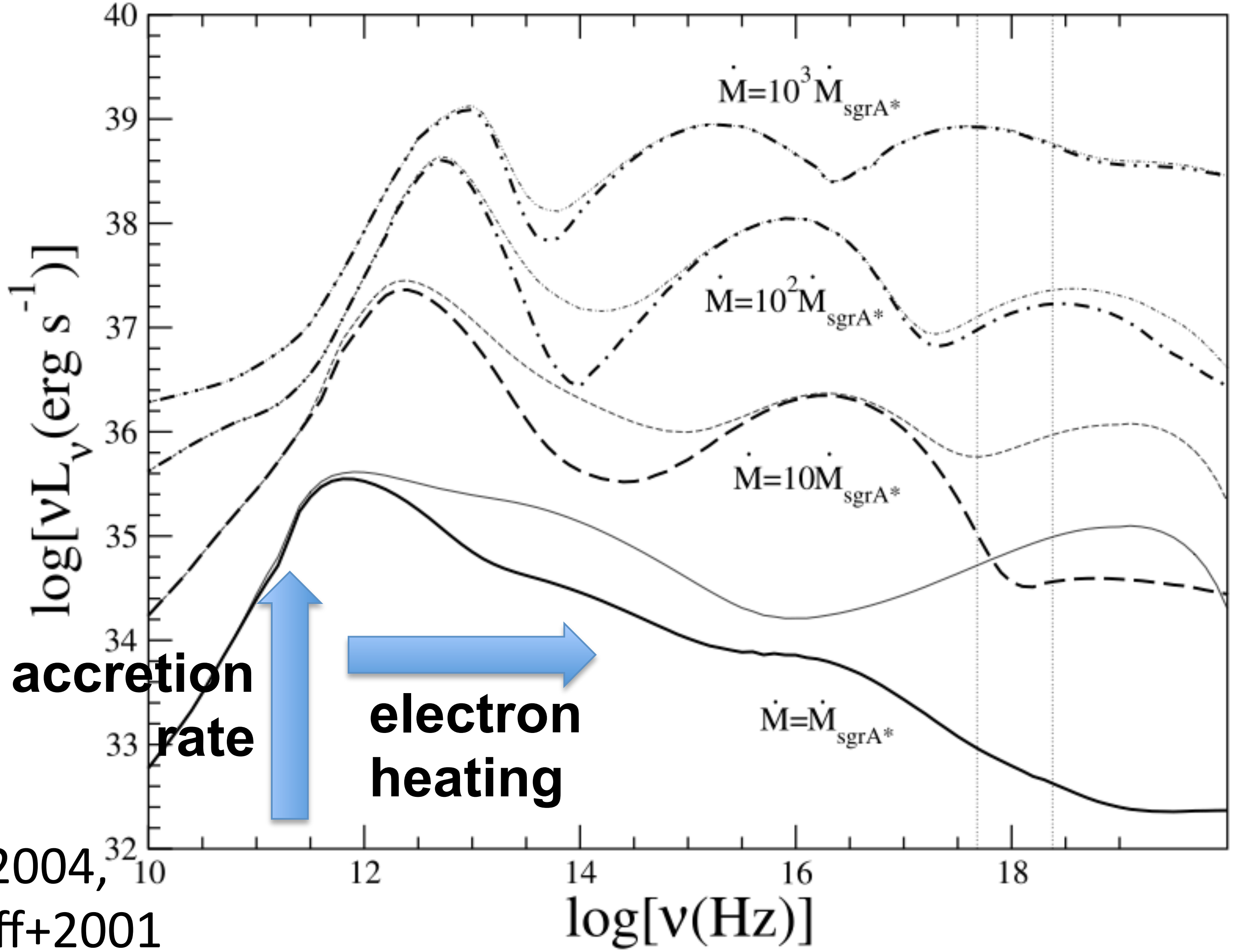
Infrared/X-ray flares from Sgr A*

- Sgr A*: rapidly variable IR/X-ray emission
  (Baganoff+2001, Genzel+2003, Ghez+2004)





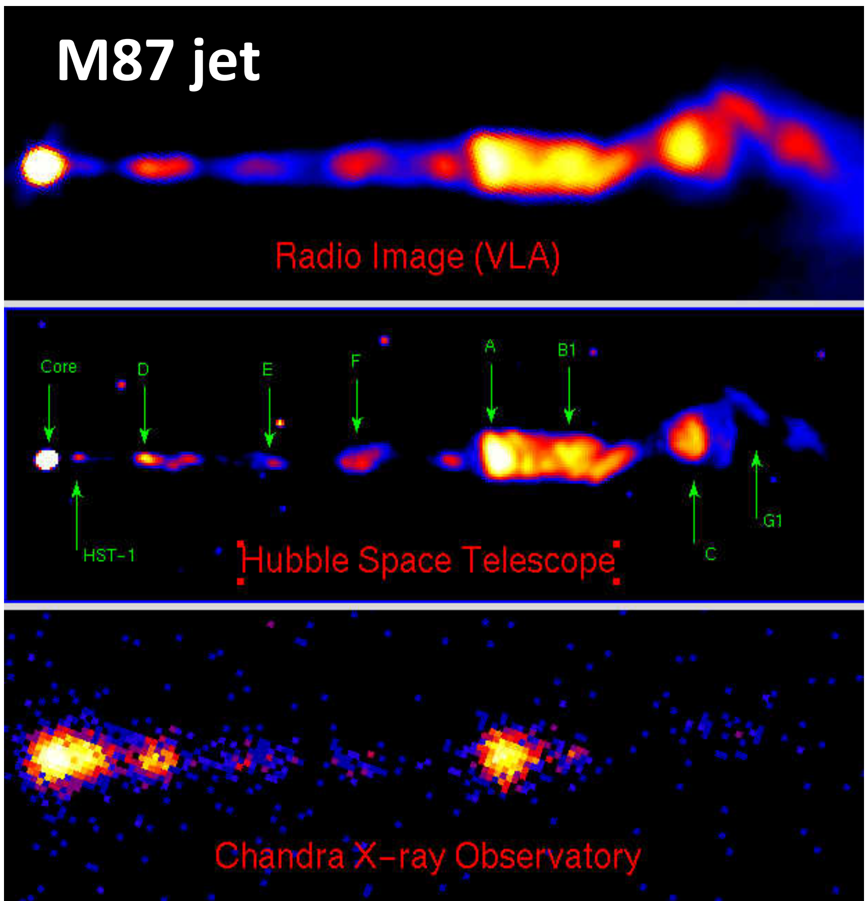
Flares: particle heating vs. G2: accretion

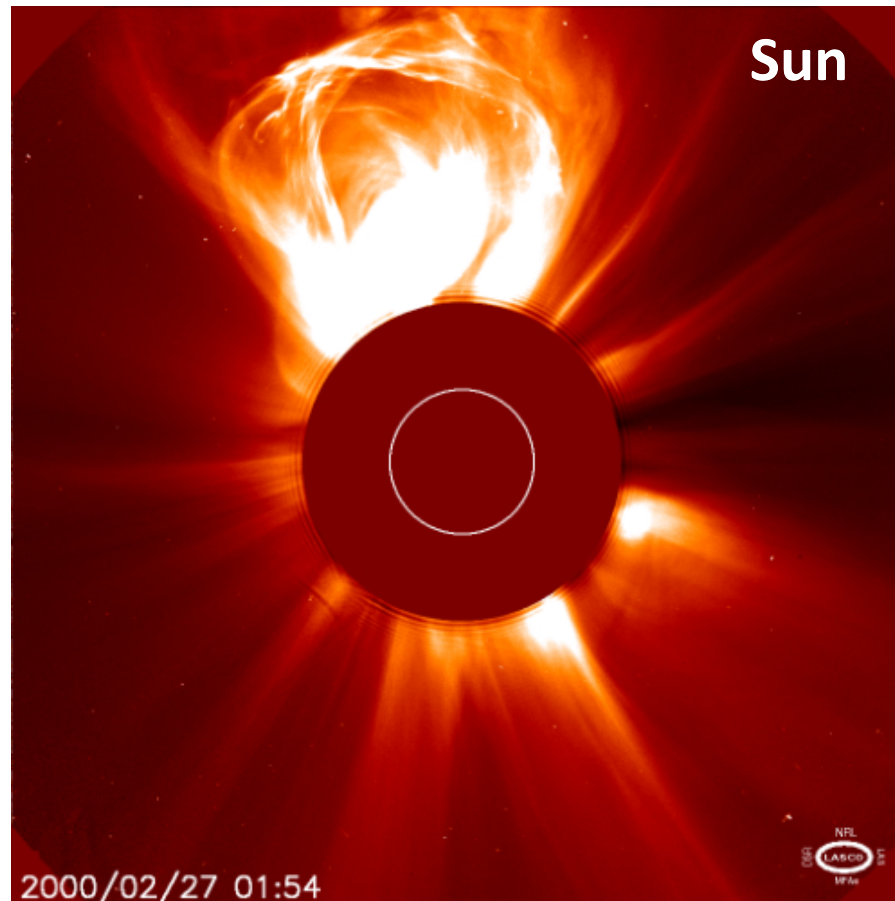


Yuan+2004,
Markoff+2001

Electron heating near black holes

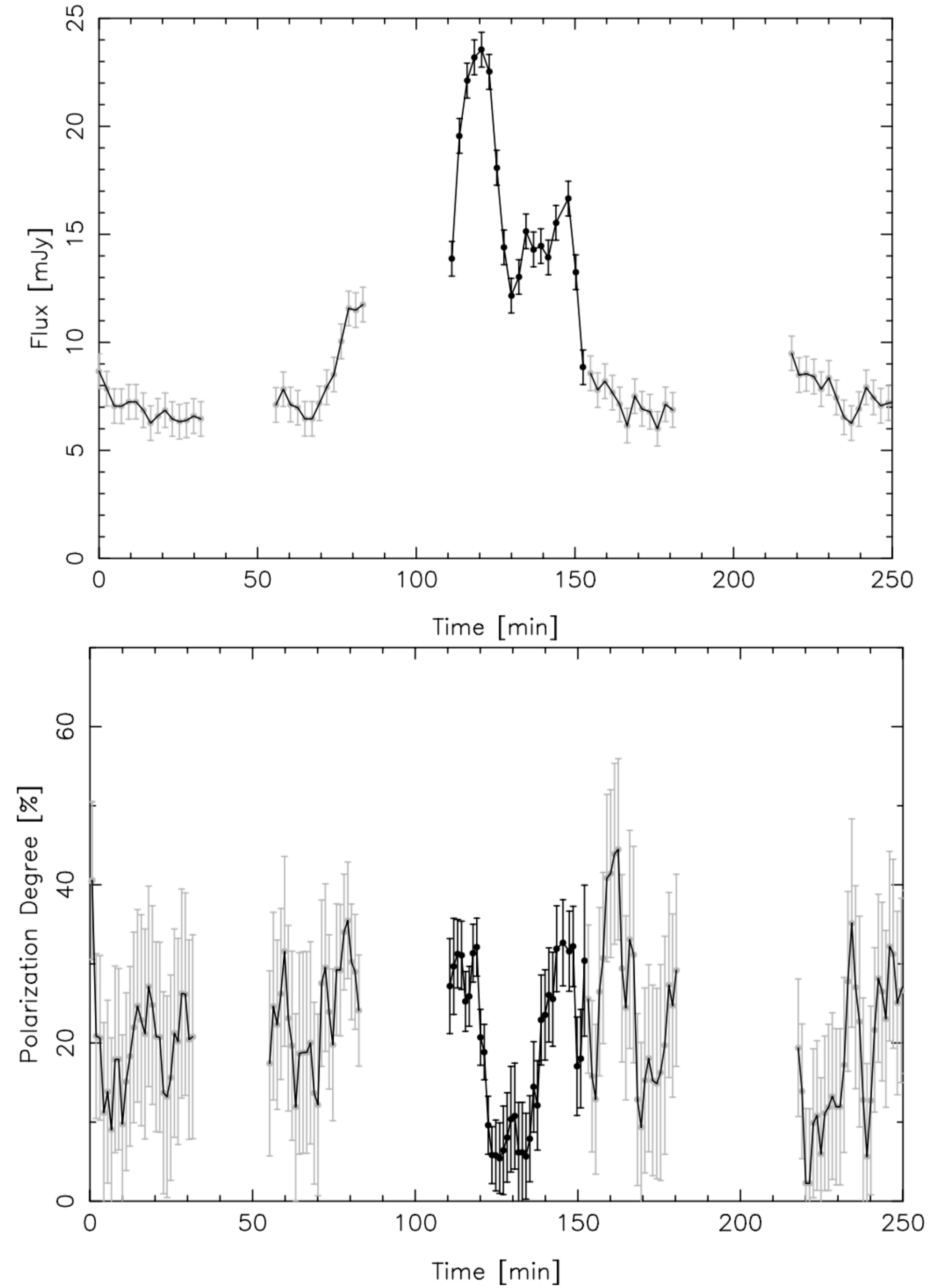
- Shock acceleration (jet? tilted disk?) or magnetic reconnection (corona?)



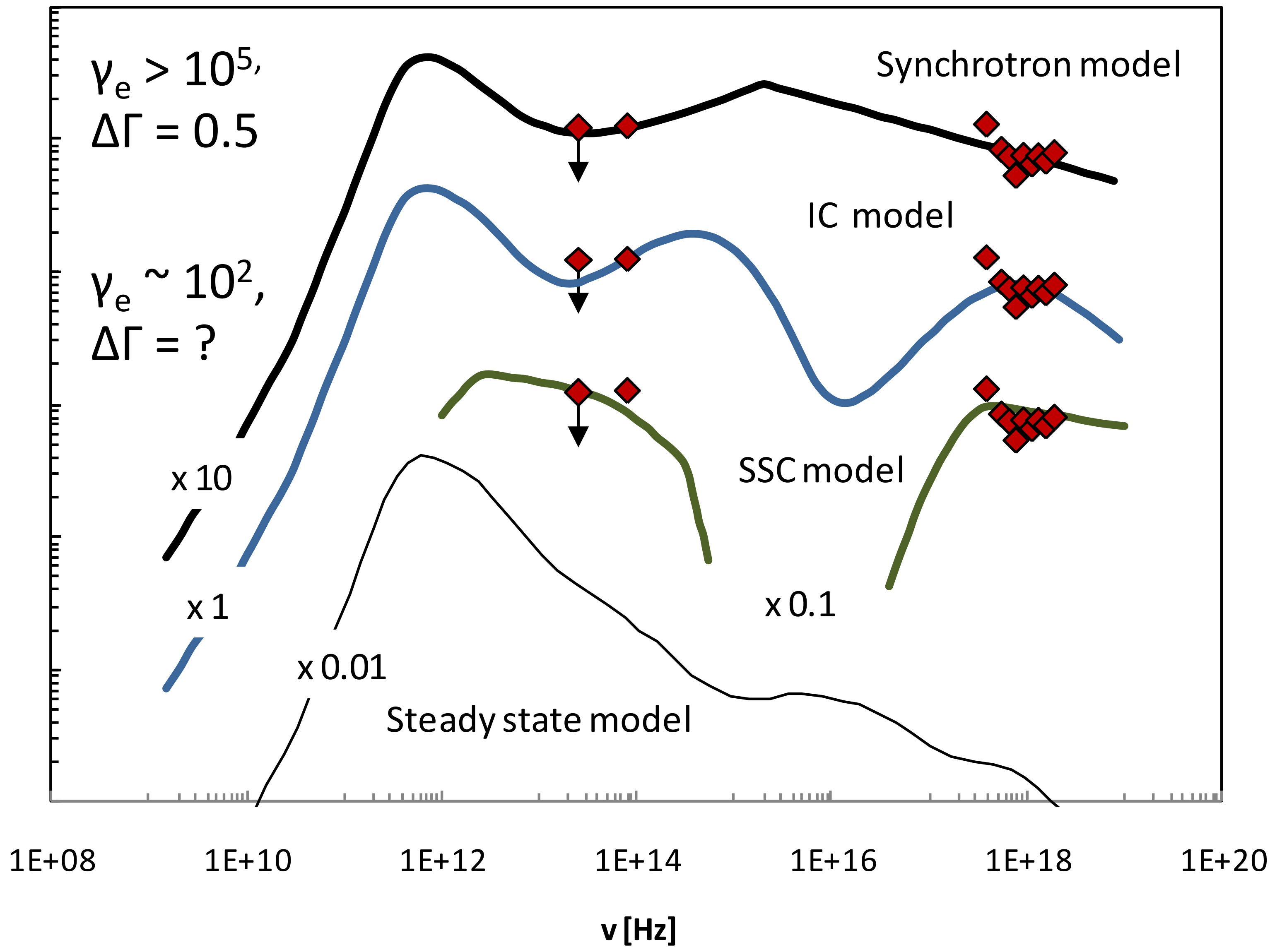


IR flares are synchrotron radiation

Eckart+2006, 2008



X-ray flare radiation mechanisms



Particle heating and cooling

- Why would synchrotron X-rays have a break?
- Synchrotron radiation:
  - $n(\gamma) \sim \gamma^{-p}$, $F_\nu \sim \nu^{-(p-1)/2}$
  - Electron energy evolution (Blumenthal & Gould 1970):

$$\frac{\partial \mathbf{n}(\gamma, \mathbf{t})}{\partial \mathbf{t}} = \mathbf{Q} - \frac{\partial(\dot{\gamma}\mathbf{n})}{\partial \gamma} - \frac{\mathbf{n}}{\mathbf{t}_{\mathrm{esc}}}$$

heating cooling escape

Cooling: $\dot{\gamma} = -\gamma/\mathbf{t}_{\mathrm{cool}} \sim -\gamma^{\mathbf{2}}$

$$\mathbf{t}_{\mathrm{cool}} \sim \gamma^{-\mathbf{1}}\mathbf{B}^{-\mathbf{2}}$$

Cooling fast at X-rays, ~slow in IR!

Particle acceleration and cooling

– Electron energy evolution
(Blumenthal & Gould 1970):

$$\frac{\partial \mathbf{n}(\gamma, \mathbf{t})}{\partial \mathbf{t}} = \mathbf{Q} - \frac{\partial(\dot{\gamma}\mathbf{n})}{\partial \gamma} - \frac{\mathbf{n}}{\mathbf{t}_{\mathrm{esc}}}$$

Steady state, no cooling:

$n(\gamma) = Q\, t_{esc}$

– Particles heat until they escape;
input e- spectrum → output IR spectrum

Particle acceleration and cooling

– Electron energy evolution (Blumenthal & Gould 1970):

$$\frac{\partial \mathbf{n}(\gamma, \mathbf{t})}{\partial \mathbf{t}} = \mathbf{Q} - \frac{\partial(\dot{\gamma}\mathbf{n})}{\partial \gamma} - \frac{\mathbf{n}}{\mathbf{t}_{\mathrm{esc}}}$$

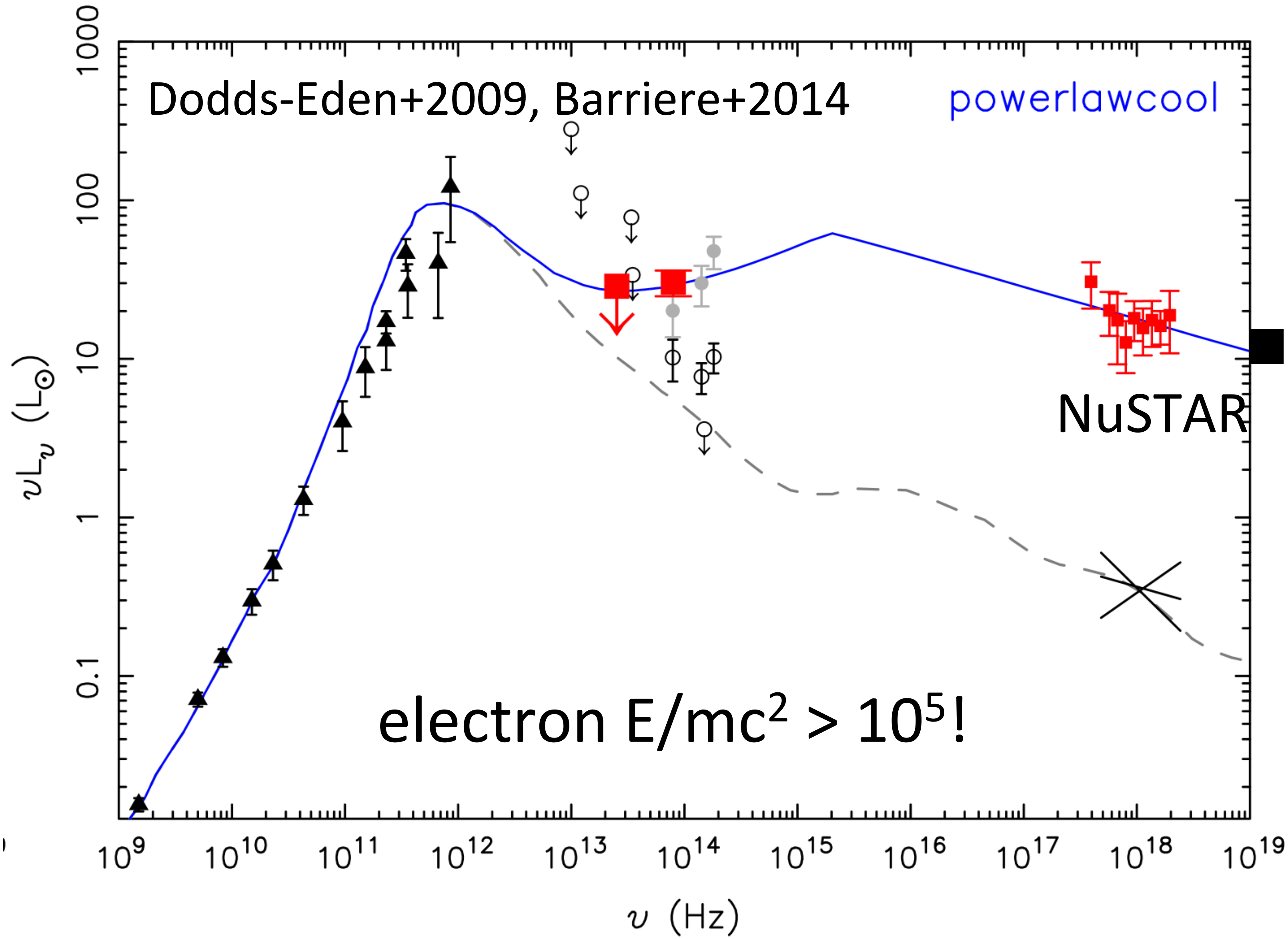
Steady state, rapid cooling:

look for solution n ~ γ^{-s}:

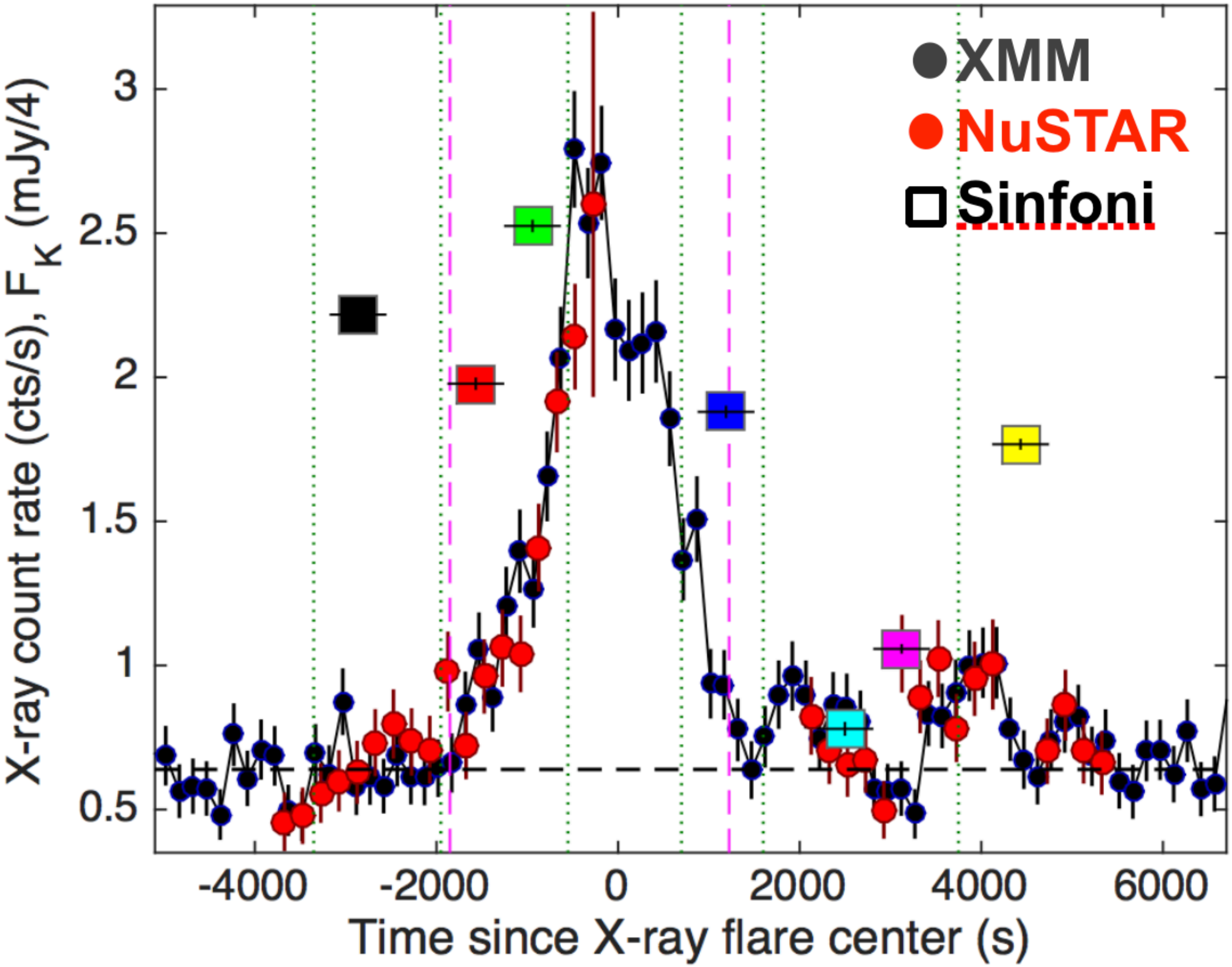
$$\mathbf{Q} \sim \frac{\dot{\gamma}\mathbf{n}}{\gamma} \quad \text{OR} \quad \mathbf{n}(\gamma) \sim \mathbf{Q}/\gamma$$

→ "Cooling break" in spectrum between IR, X-rays

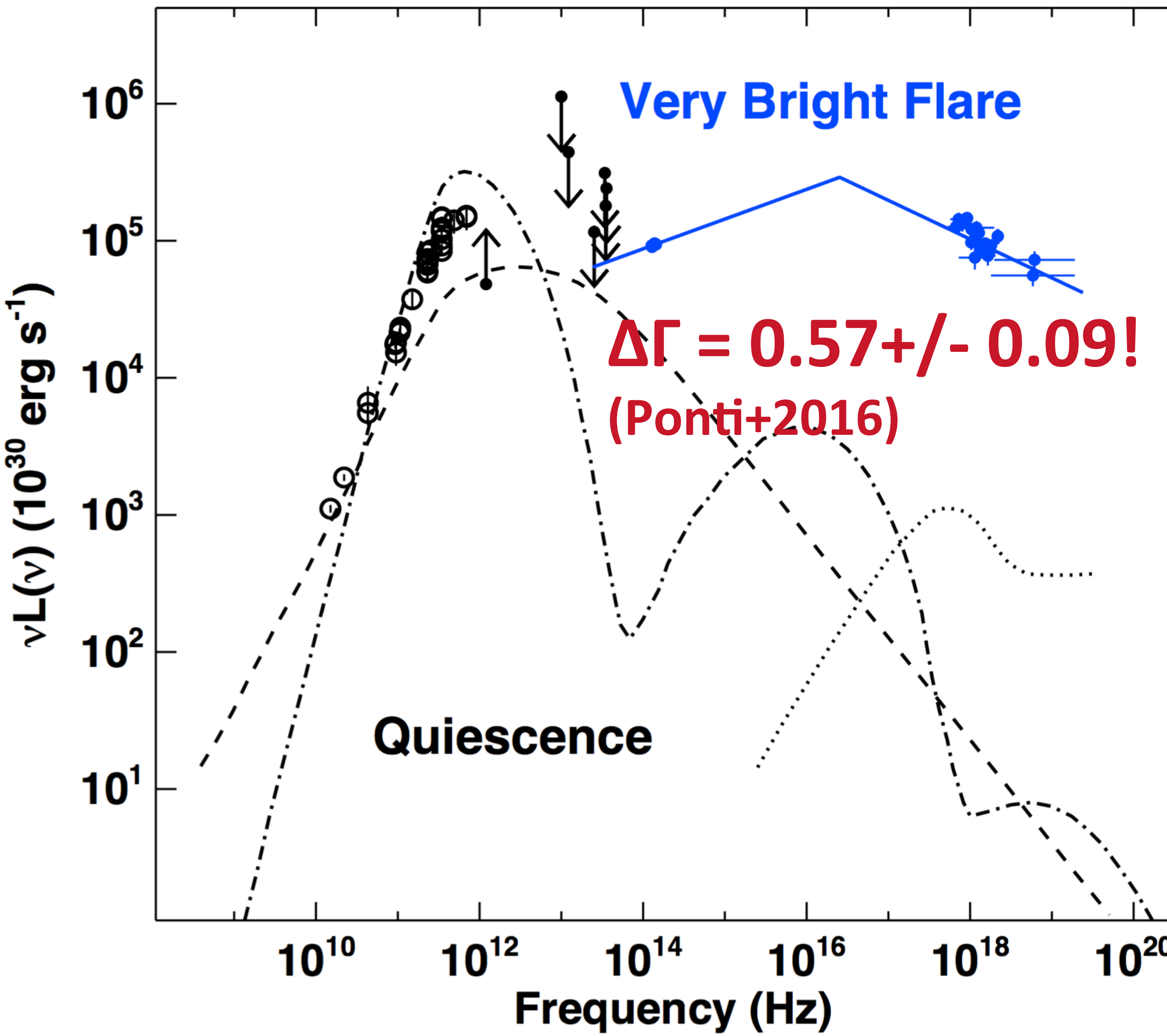
Evidence for synchrotron X-rays



Simultaneous IR/X-ray spectra



Even stronger evidence!

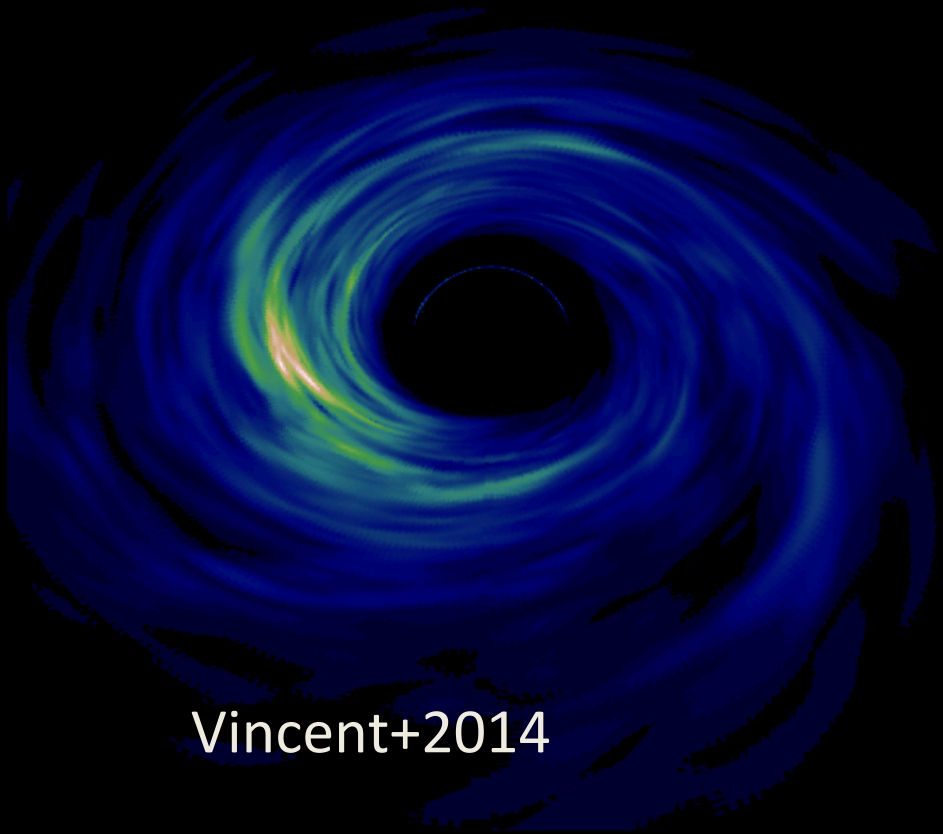


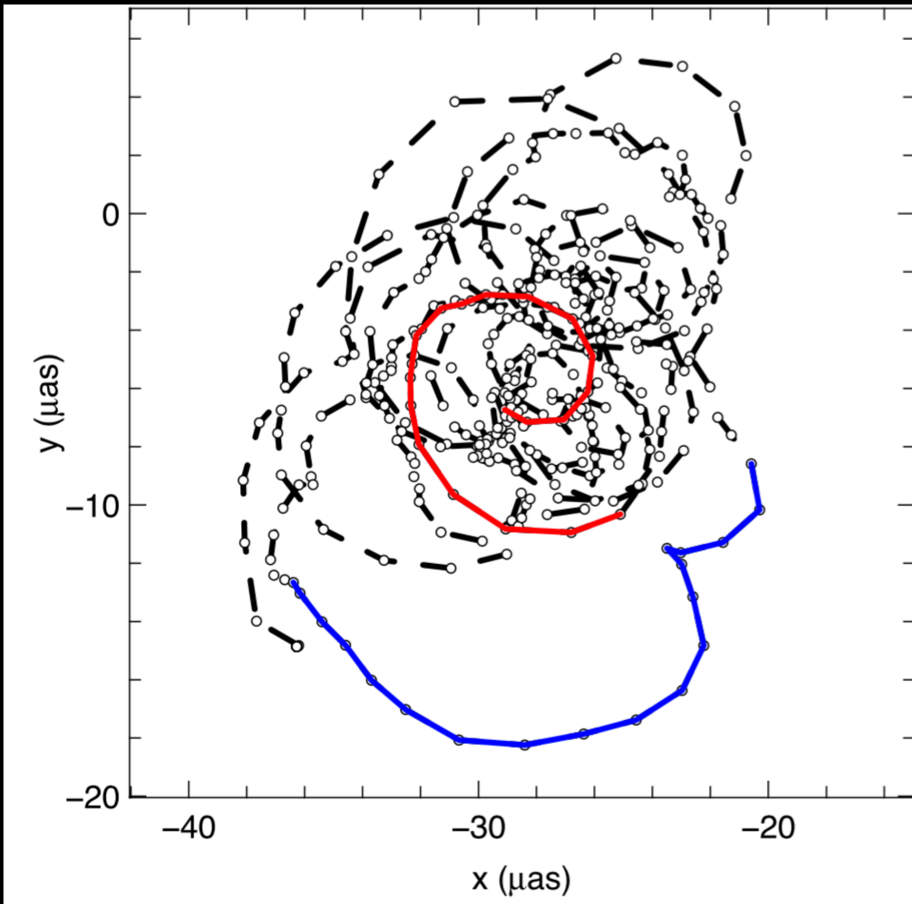
What do flare motions look like?

Hotspot (Hamaus+2009)

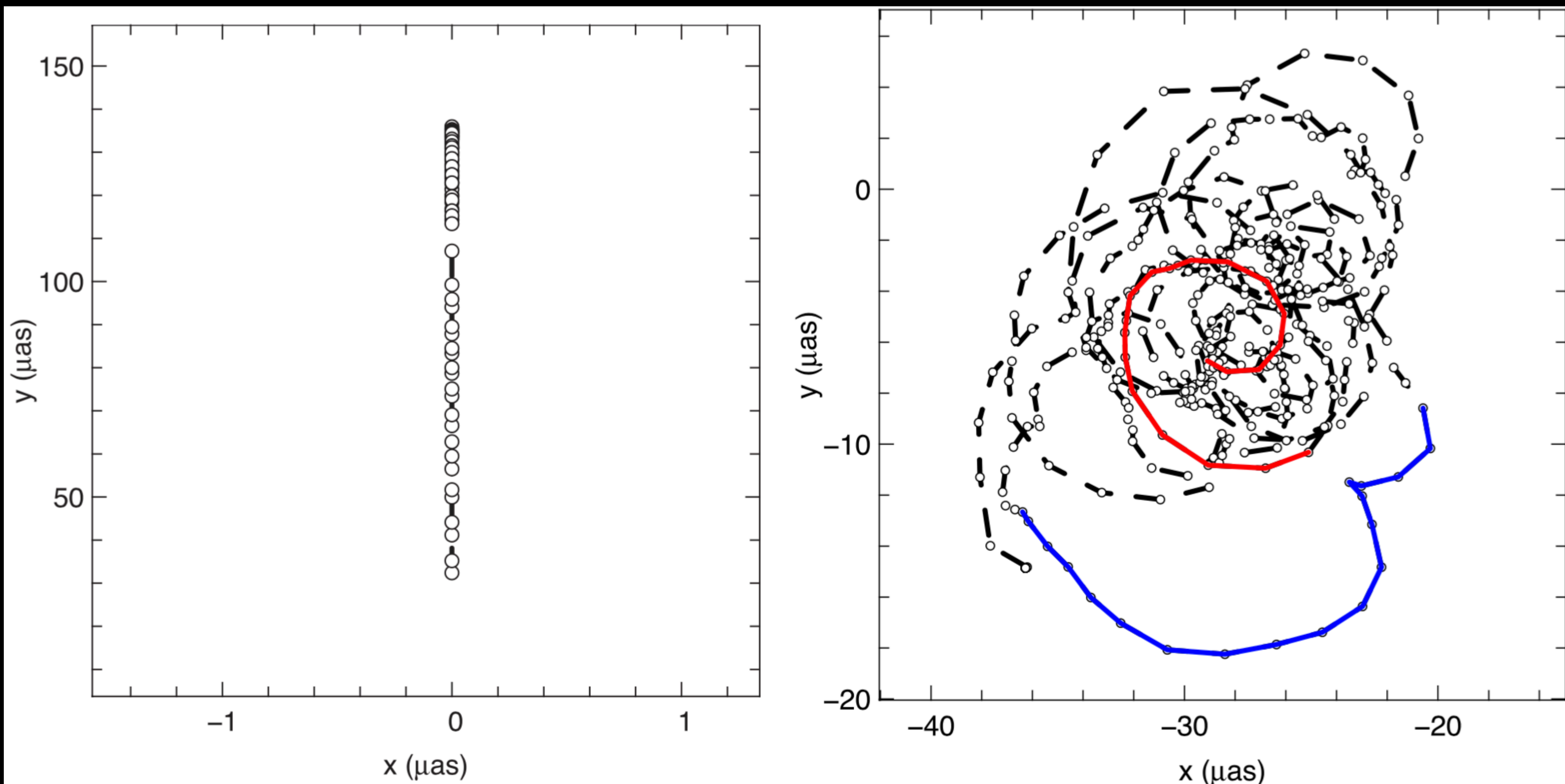
Shock (Dexter & Fragile 2013)

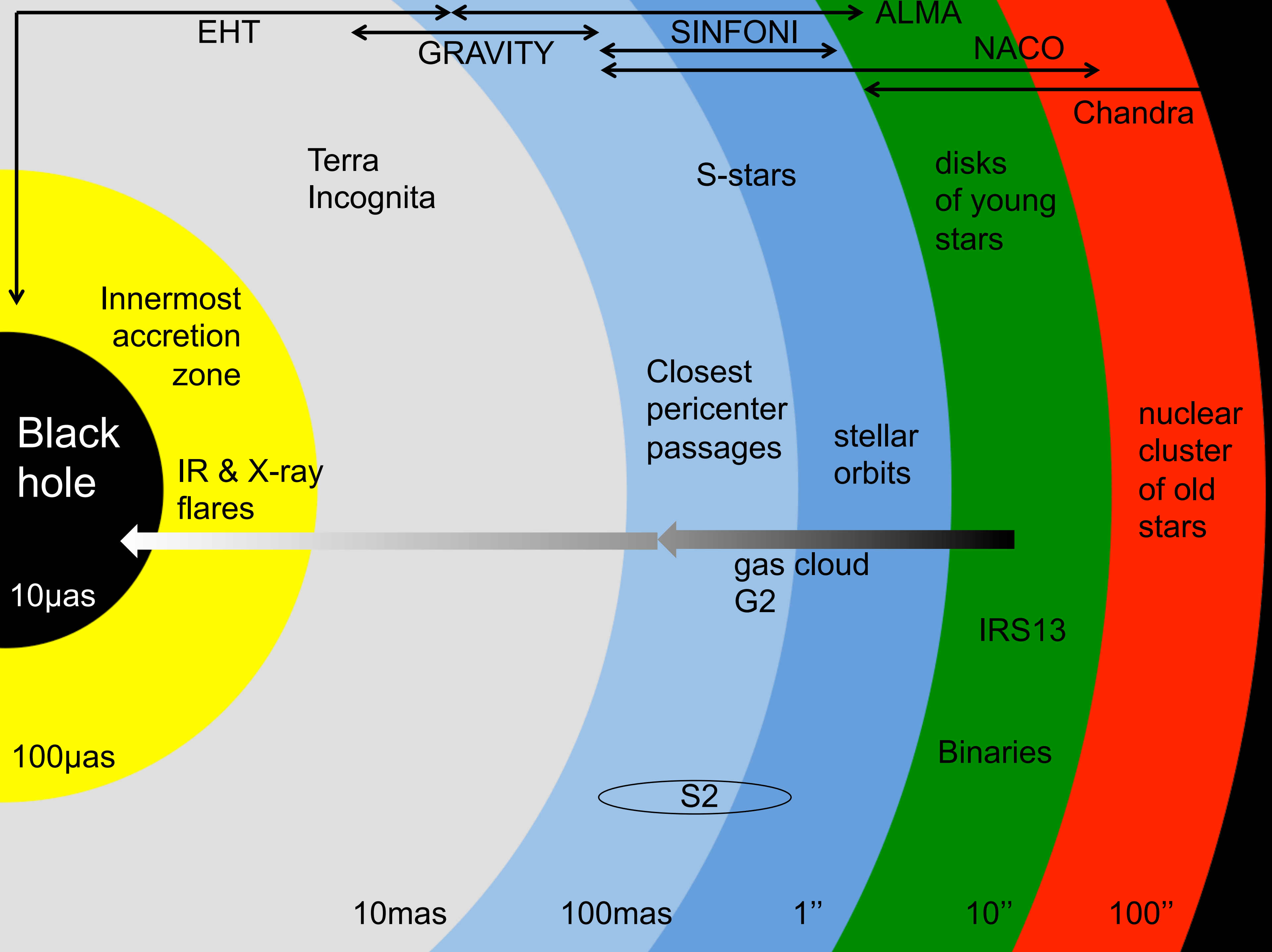
What do flare motions look like?



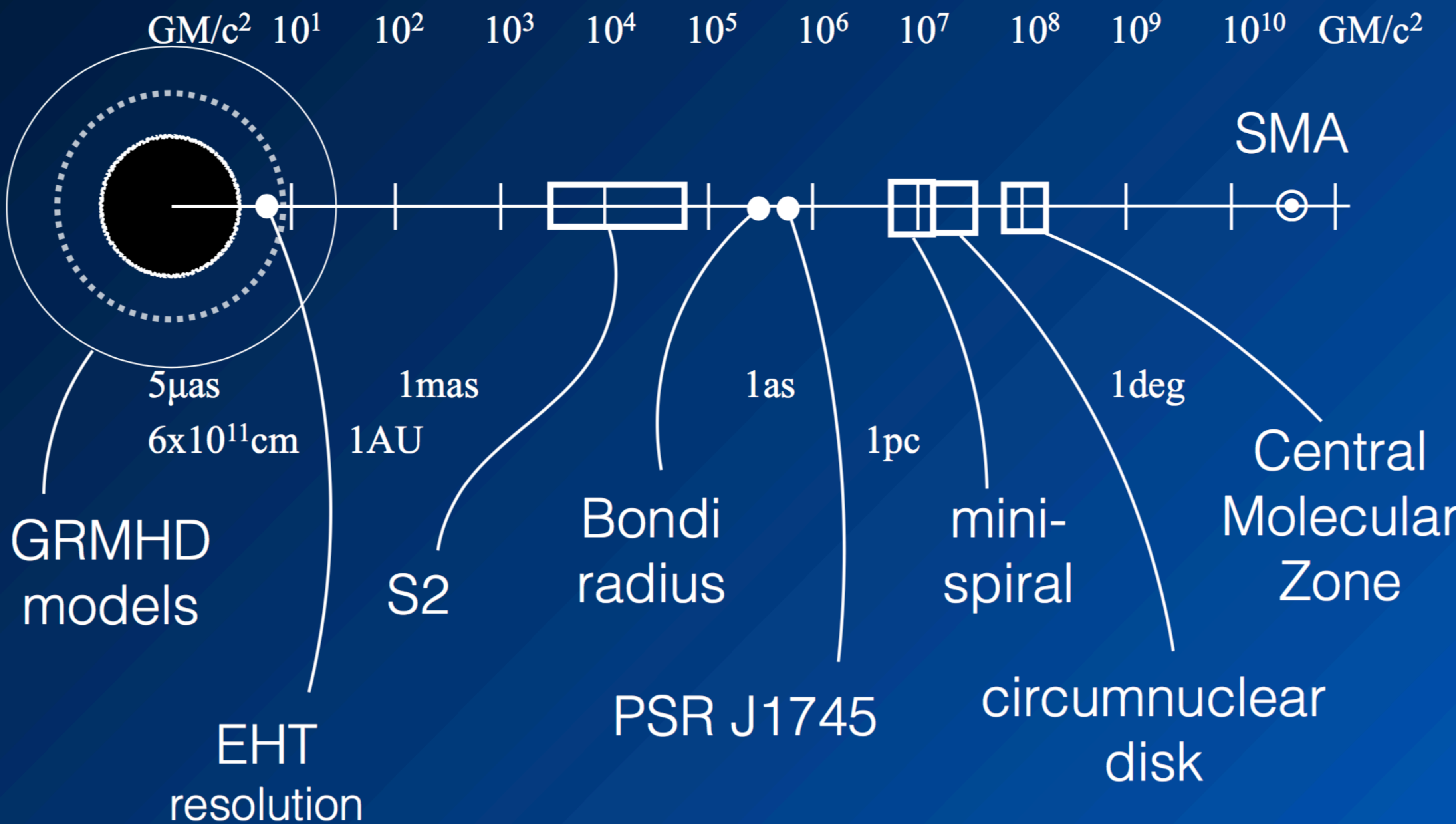


What will GRAVITY see?



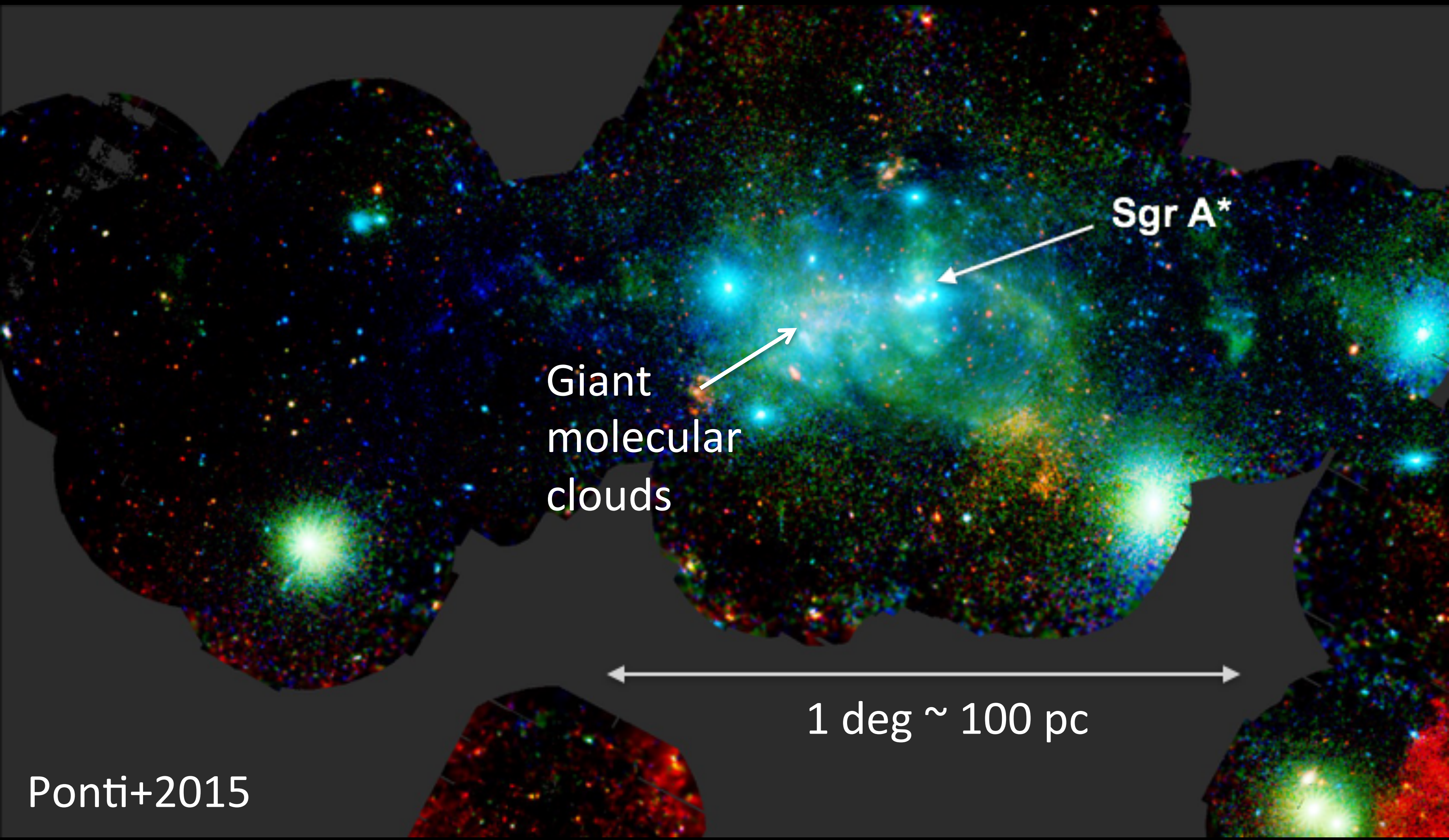

EHT
GRAVITY
SINFONI
ALMA
NACO
Chandra
Terra Incognita
S-stars
disks of young stars
Innermost accretion zone
Black hole
IR & X-ray flares
Closest pericenter passages
stellar orbits
nuclear cluster of old stars
gas cloud G2
10µas
IRS13
100µas
Binaries
S2
10mas
100mas
1''
10''
100''

Galactic Center Overview



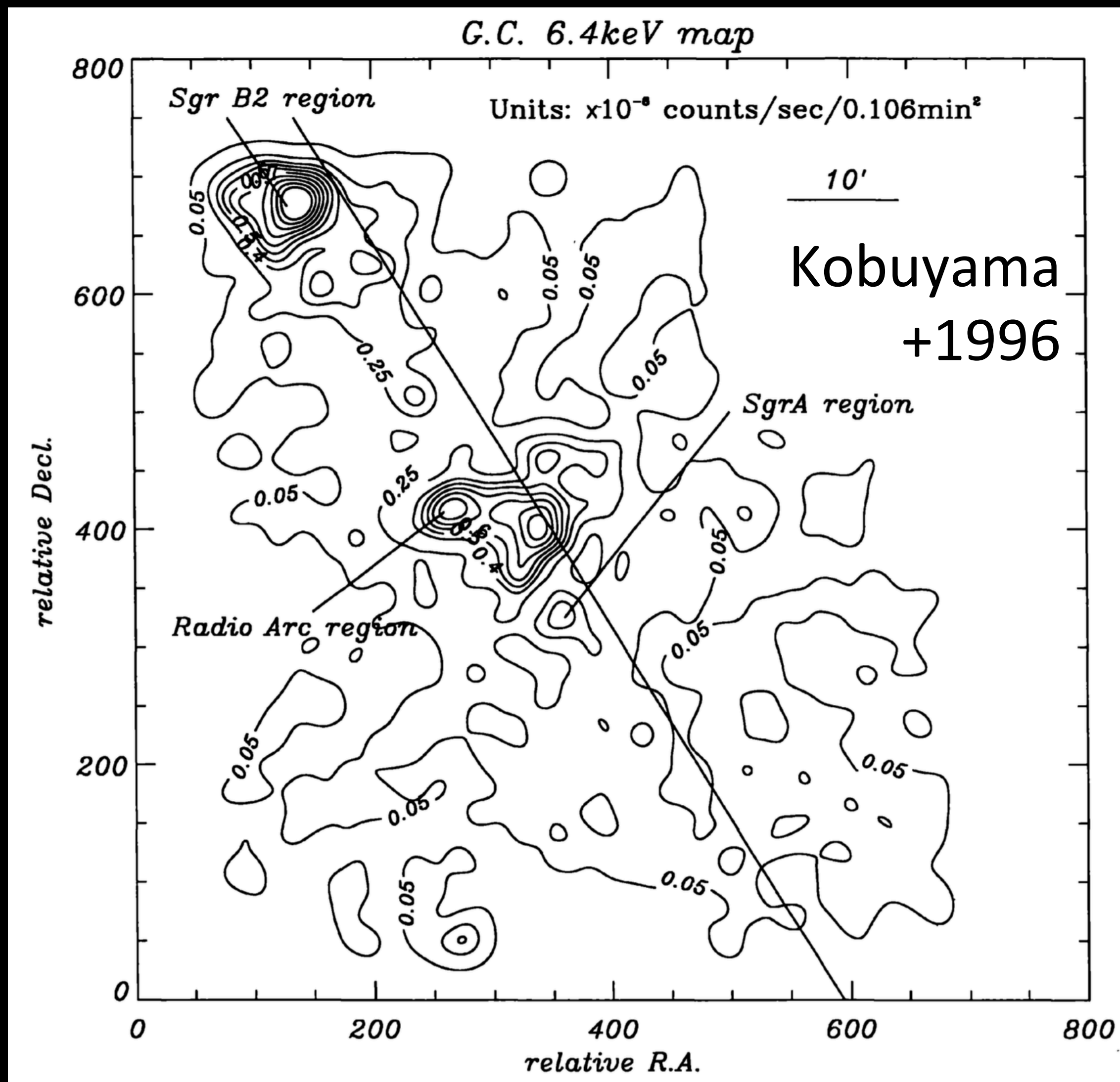
slide: C. Gammie

XMM-Newton view of the GC



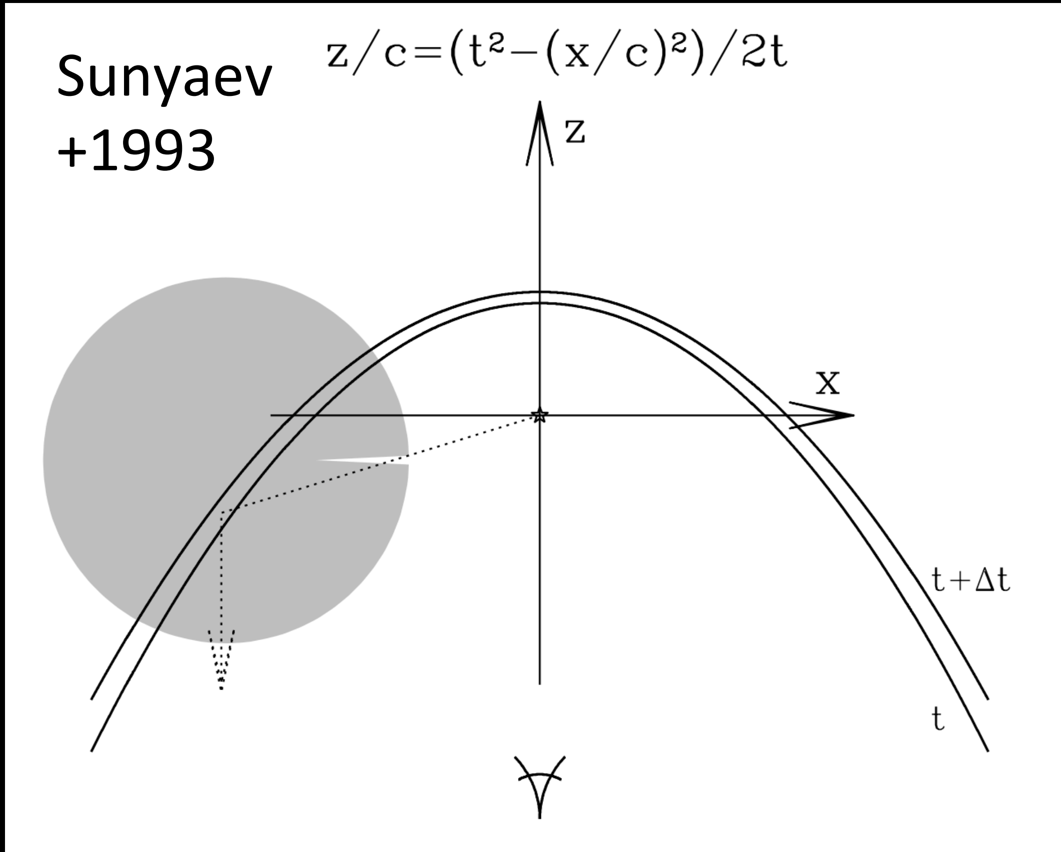
Ponti+2015

Hard X-rays from giant molecular clouds

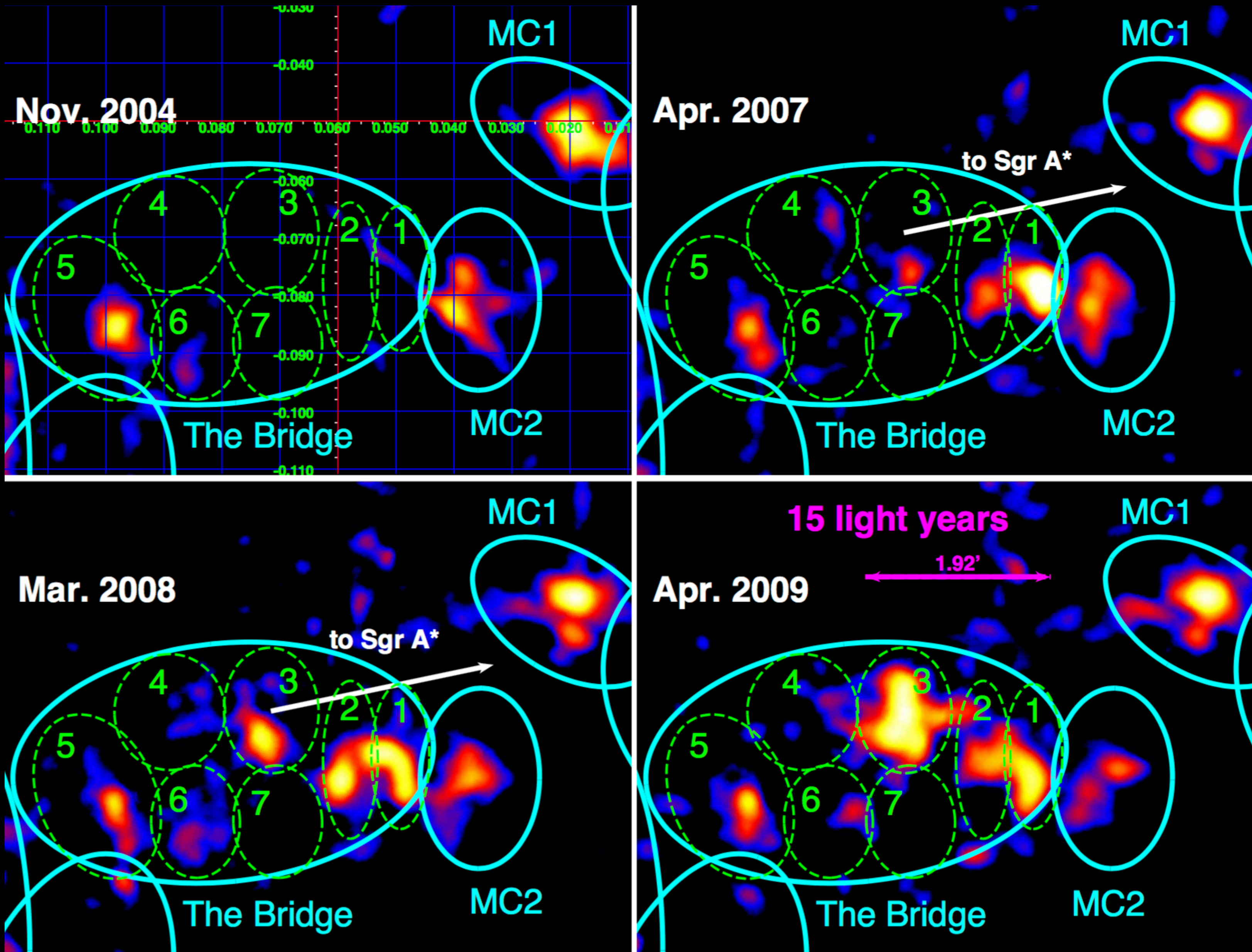


Possible origins?

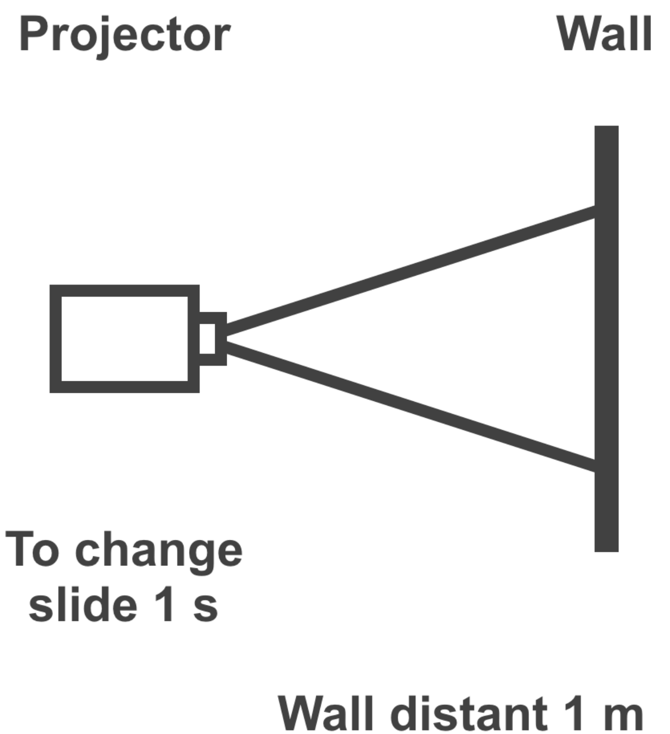
- Clouds are cold, Fe Kα is excited by X-ray irradiation
  $L_X \sim 10^{39}$ ergs / s $\sim 10^3 L_{Sgr\ A*} \sim L_{edd}$ for 10 M_{sun}



Signal is time variable!



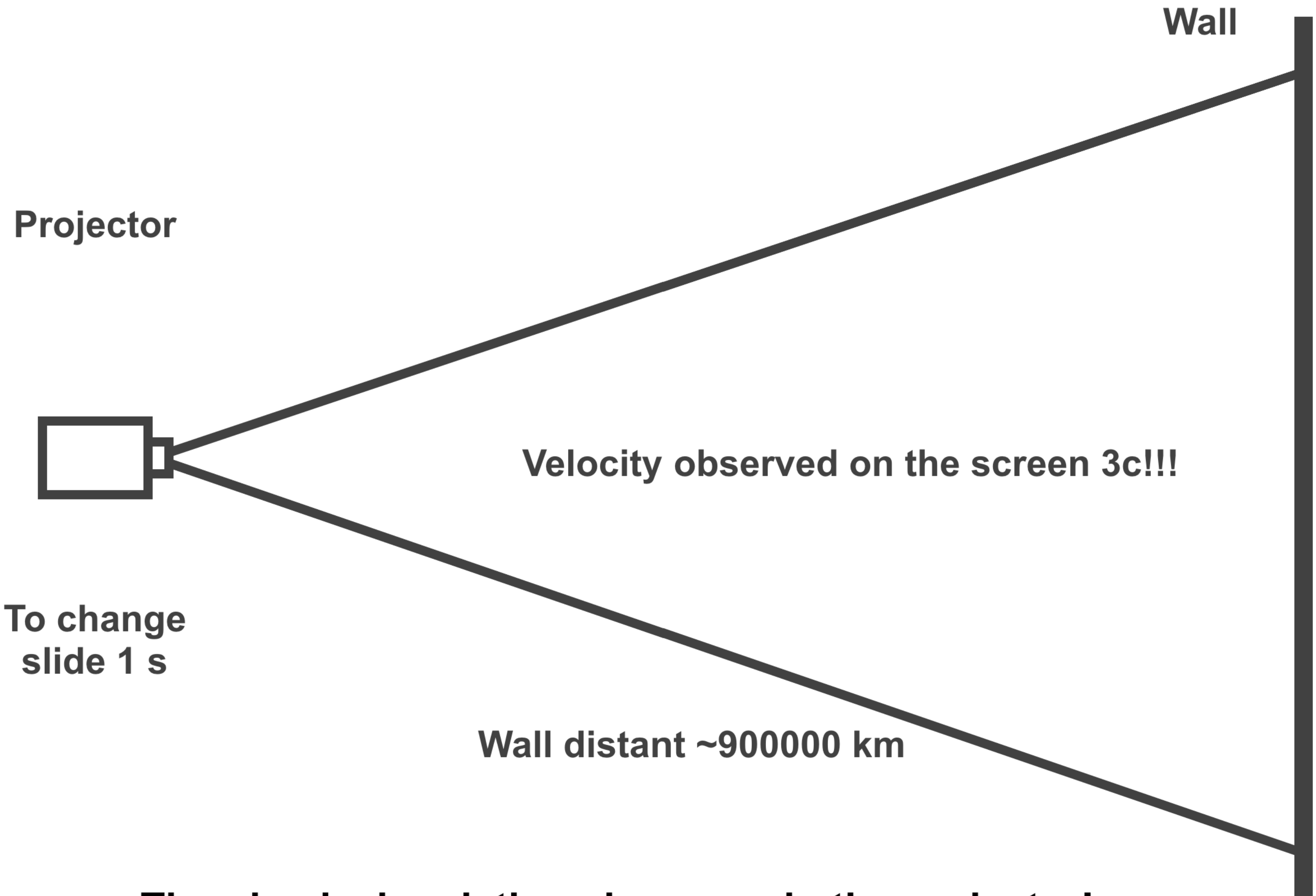
How can a super-luminal echo happen?



Velocity observed on the screen 1m/1s

e.g. Ponti +10;+13

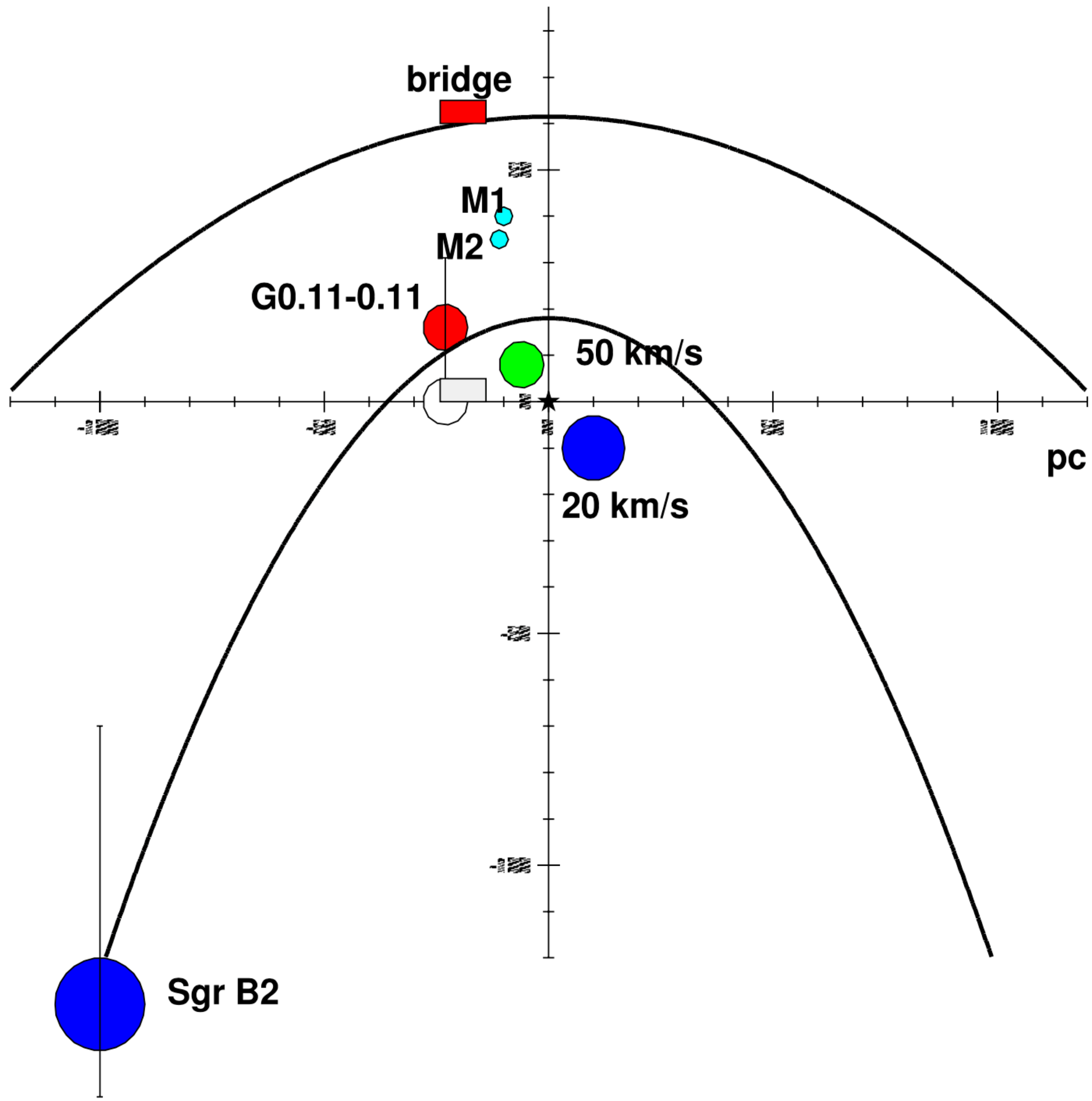
How can a super-luminal echo happen?



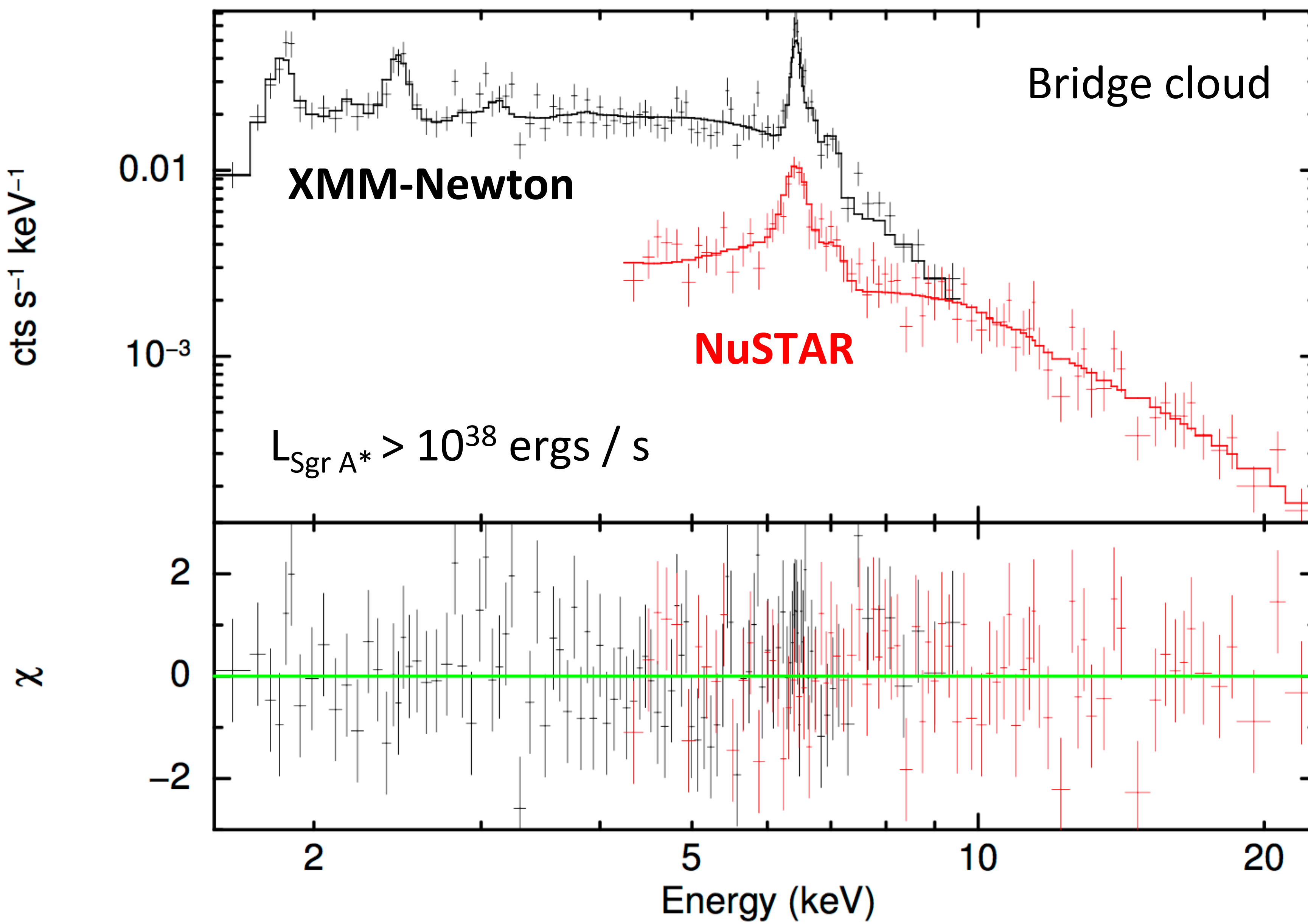
The physical variations happens in the projector!

e.g. Ponti +10;+13

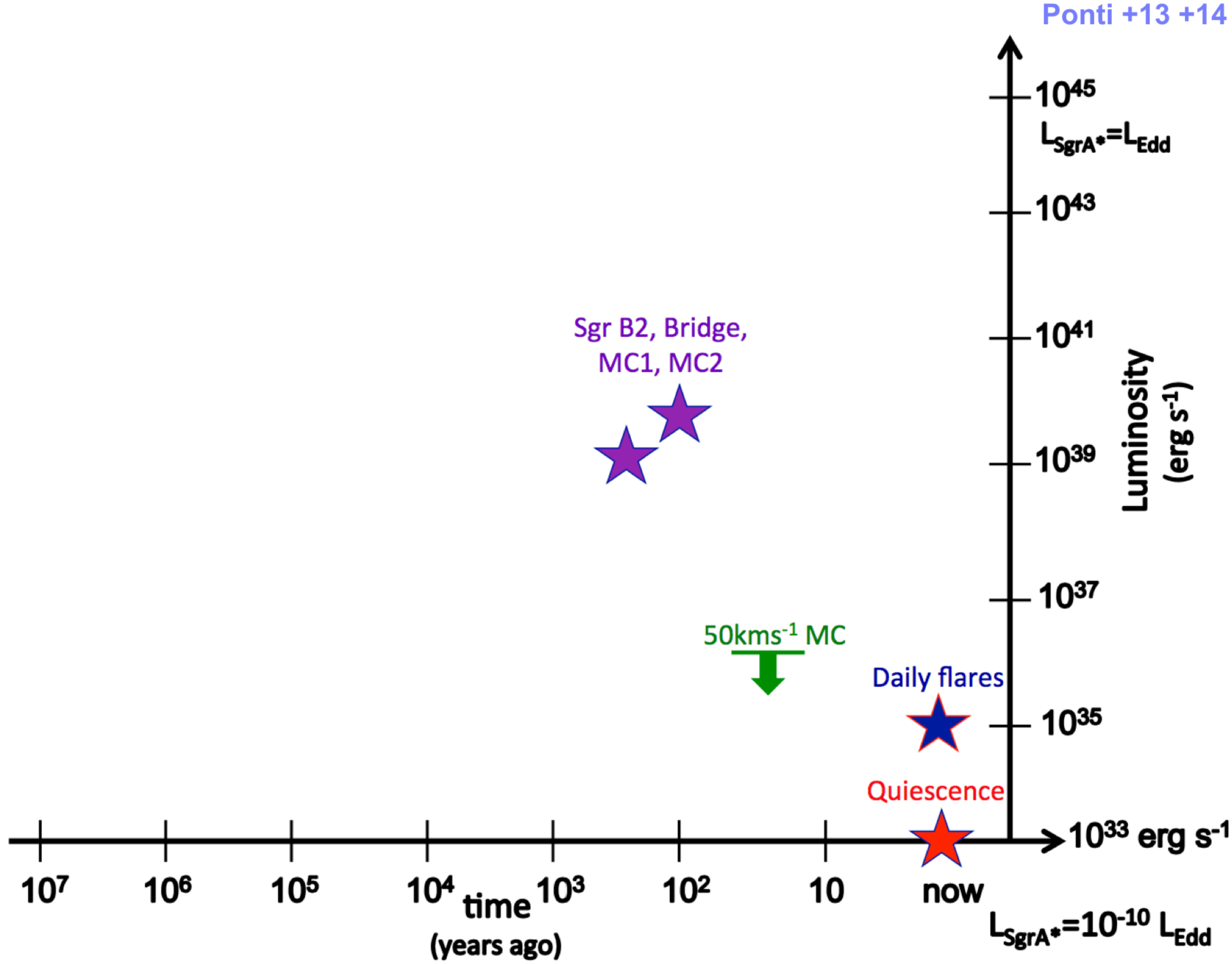
Past Sgr A* activity?



NuSTAR spectrum supports reflection



Sgr A's recent activity*

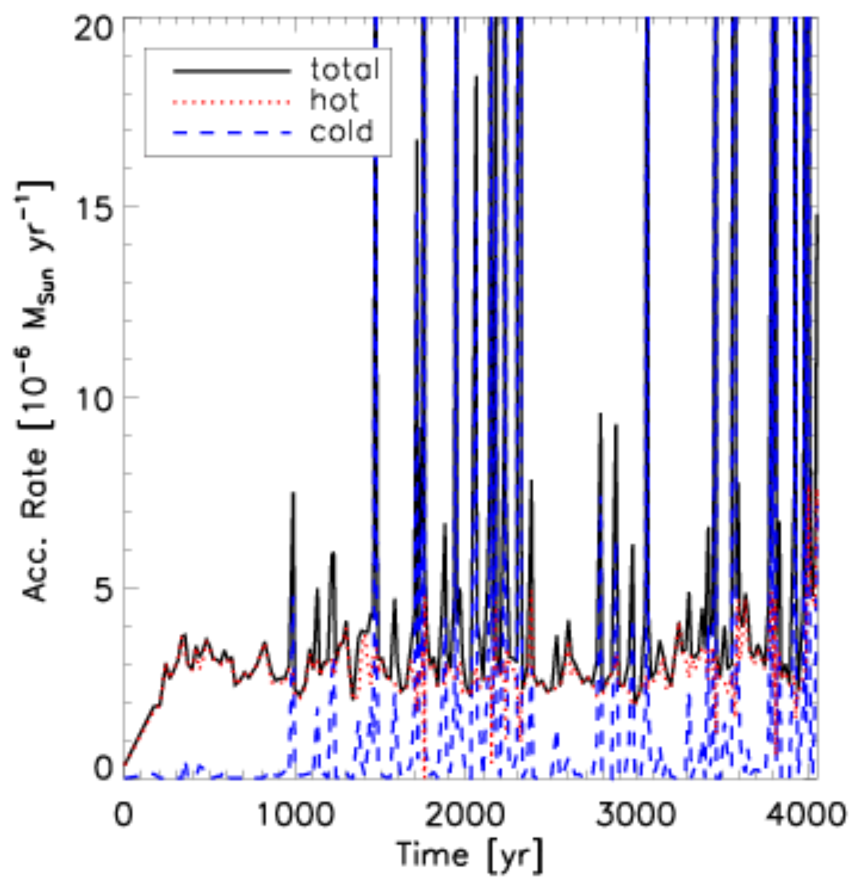


$L_{Sgr\ A*}$ ~ 10^{39} erg s^{-1} ~ 1-3×10^2 years ago

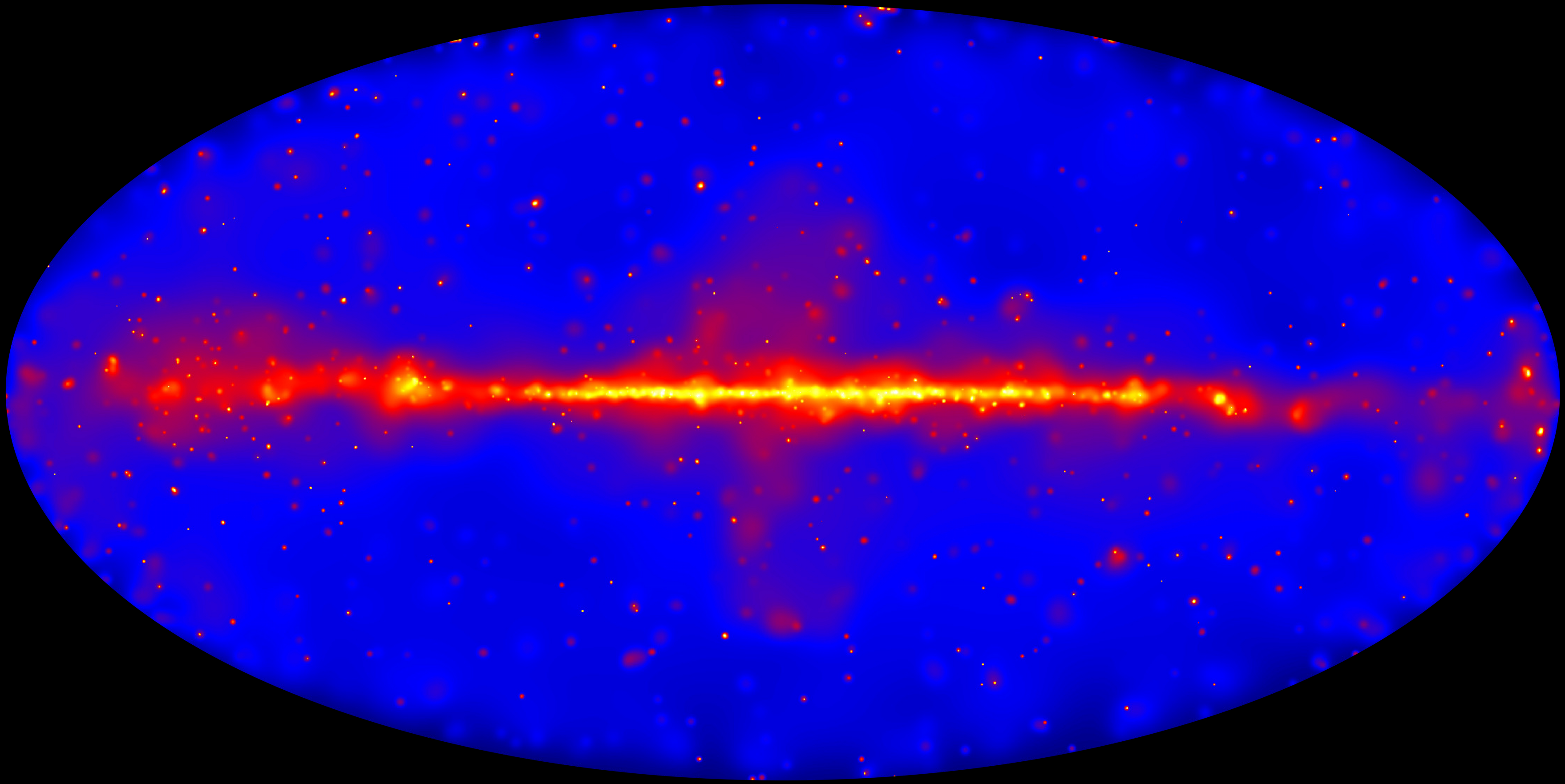
Why would Sgr A* be so much brighter?

- Spike of high Mdot (cold clump)
- Tidal disruption (every ~10^3-10^4 years)
- Giant flare?

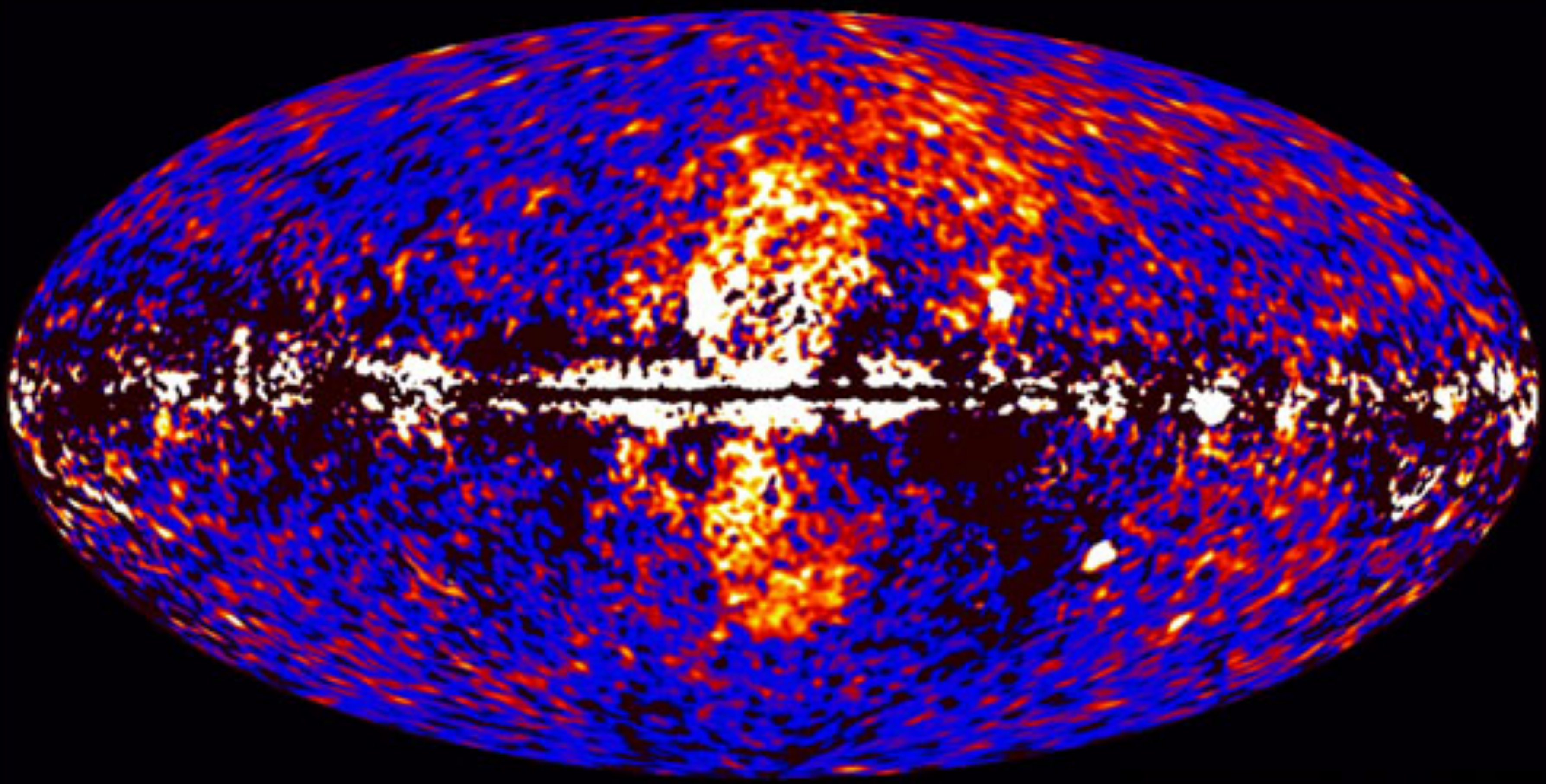
Cuadra+2008



The Fermi Sky



The Fermi Bubbles



Su+2010

Q: The Fermi Bubbles

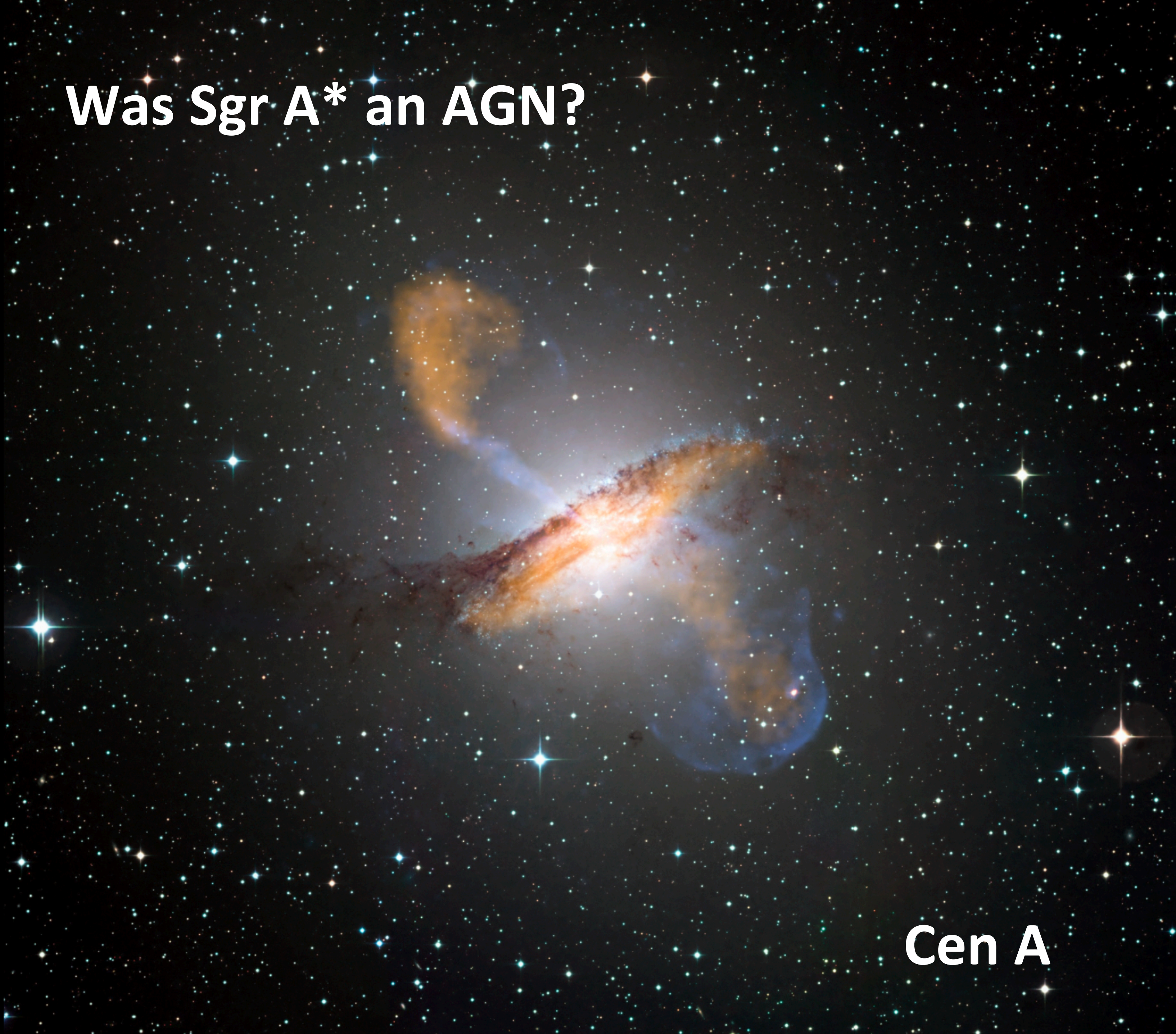
- X-ray gas: $T \sim 4 \times 10^7$ K; what is thermal speed? ($k \sim 1.38 \times 10^{-16}$ erg / K, $m_p \sim 1.67 \times 10^{-24}$ g)
- Height ~ 10 kpc; what is age? (kpc $\sim 3.1 \times 10^{21}$ cm)
- Total $E \sim 10^{55}$ erg; what is minimum luminosity to power the bubbles?

Q: The Fermi Bubbles:

- $v \sim (3kT / m_p)^{1/2} \sim 1000$ km / s
- $T \sim H/v \sim 10$ Myr
- $L_{inj} \sim E/T \sim 10^{40} – 10^{43}$ ergs / s $\sim 10^{3\text{-}6}\ L_{Sgr\ A*}$

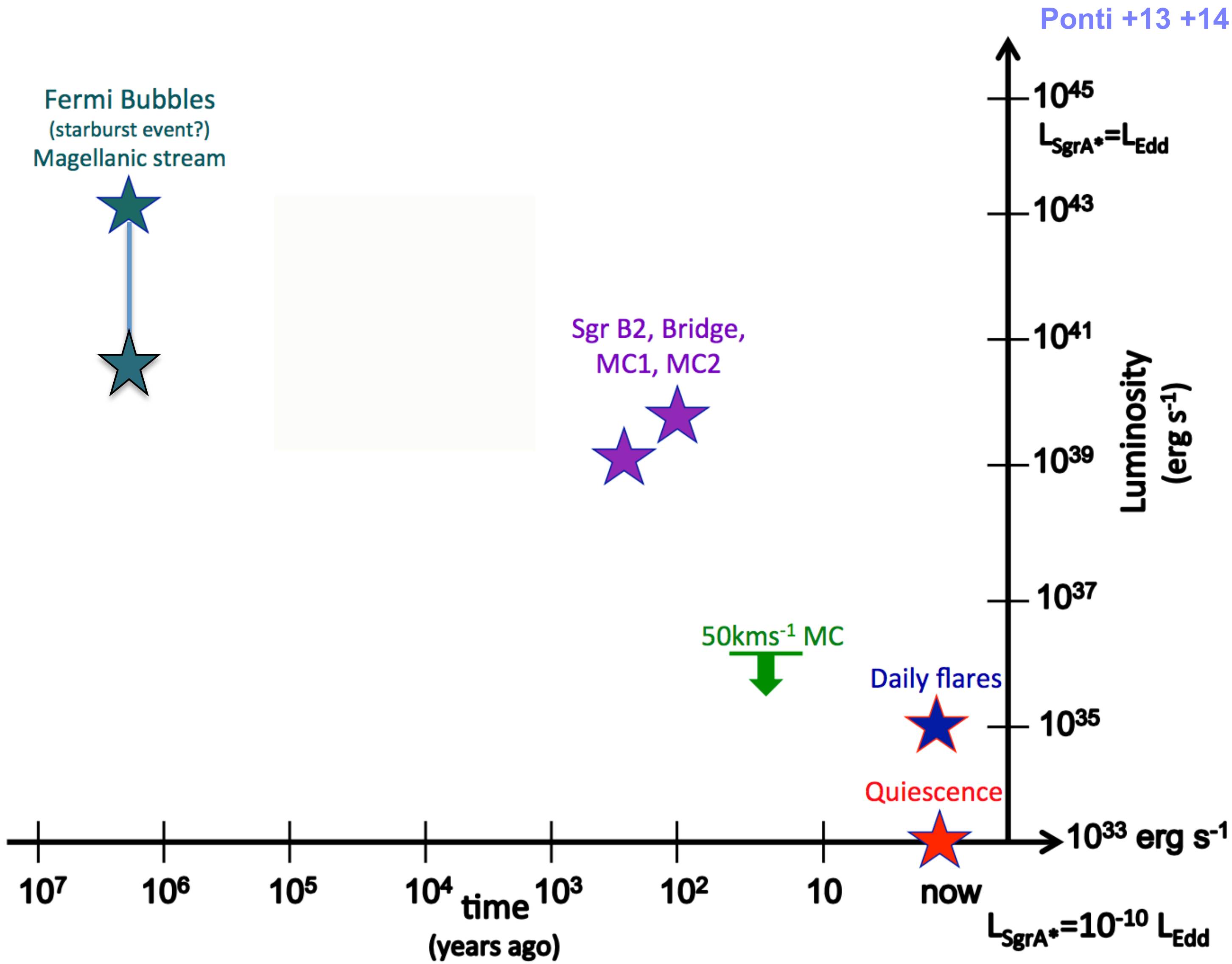
- Requires SFR ~ 0.1-1 M_{sun} / yr
(GC total ~ 0.05 M_{sun} / yr) or
Sgr A* outflow Mdot $c^2 \sim 10^{-5} – 10^{-2}\ L_{edd}$

Was Sgr A* an AGN?



Or was the Milky Way a starburst?

Sgr A's recent activity*



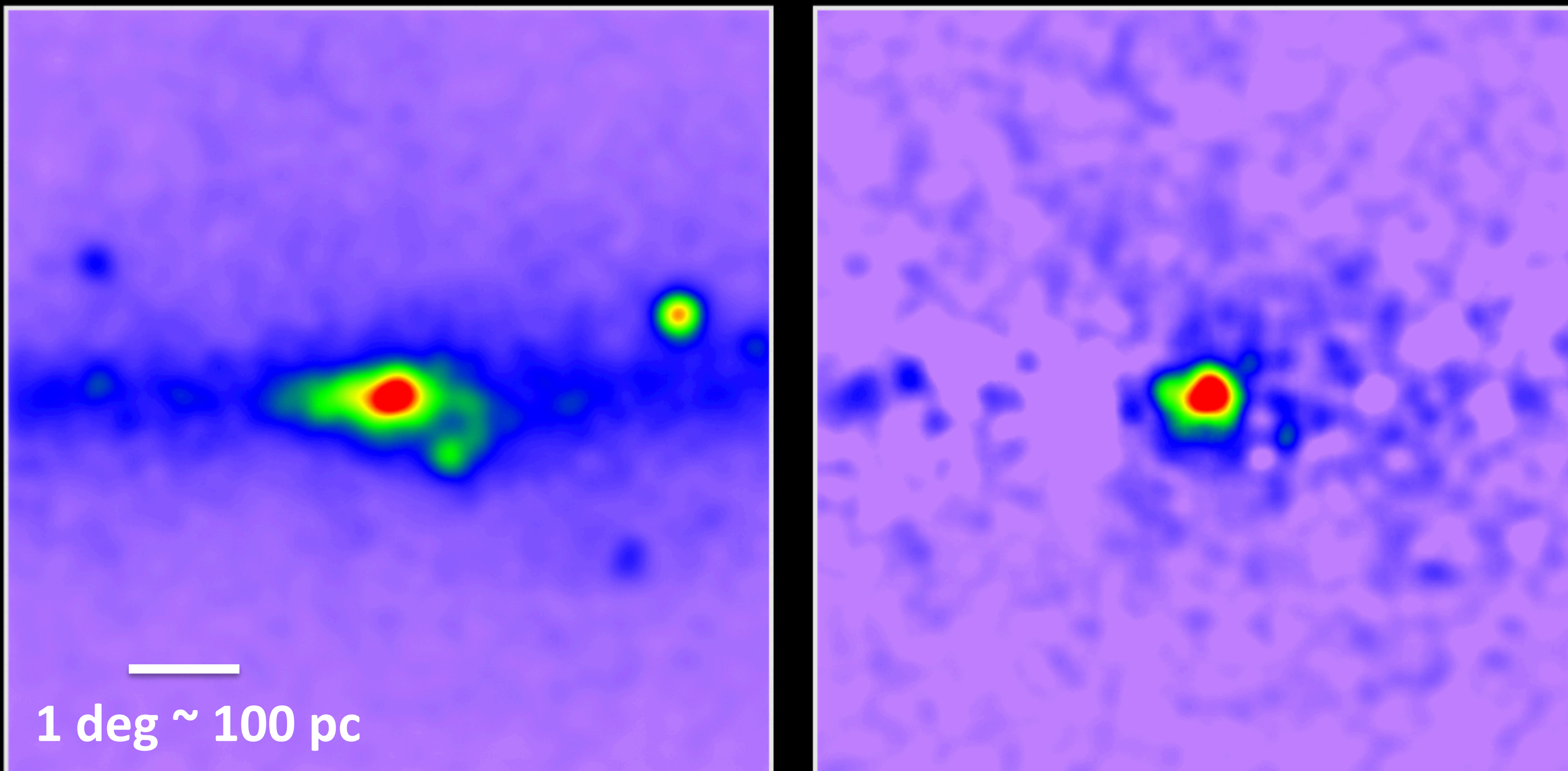
$L_{Sgr\ A^*}$ ~ 10^{39} erg s^{-1} ~ 1-3×10^2 years ago

Seyfert activity ~ 10^6 years ago?

The Fermi GeV excess

Hooper & Linden 2011, Boyarsky+, Chernyakova+

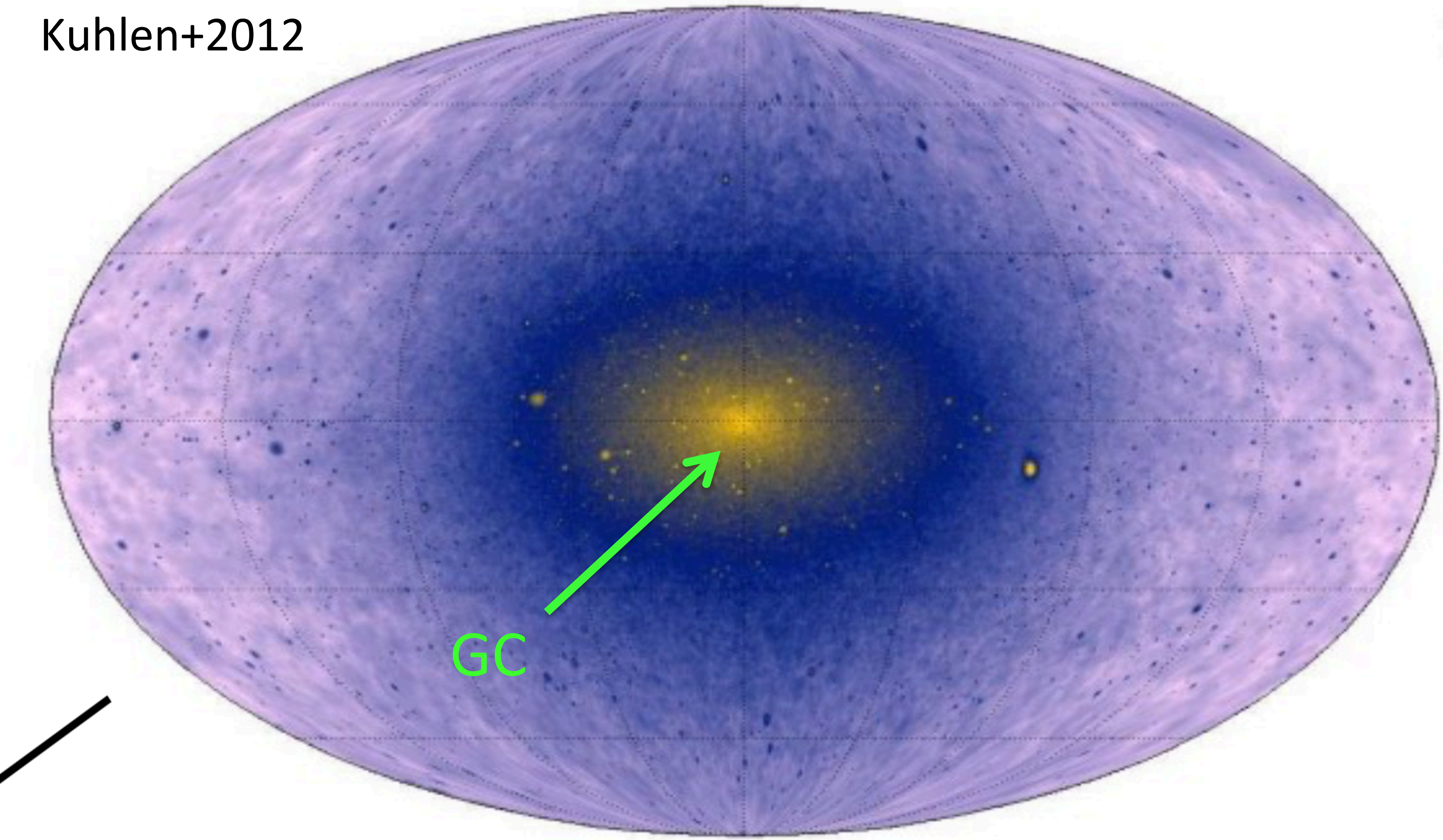
Uncovering a gamma-ray excess at the galactic center



Unprocessed map of 1.0 to 3.16 GeV gamma rays | **Known sources removed**

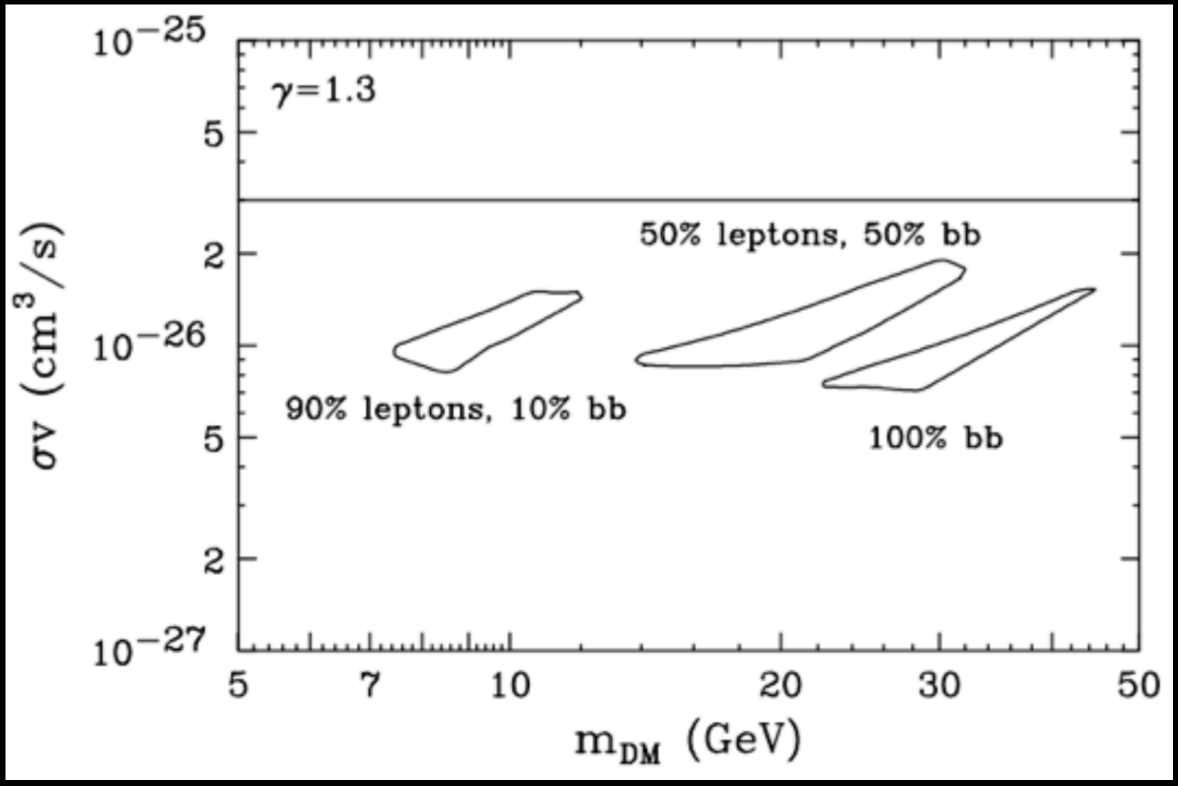
Dark matter signal from GC?

Kuhlen+2012

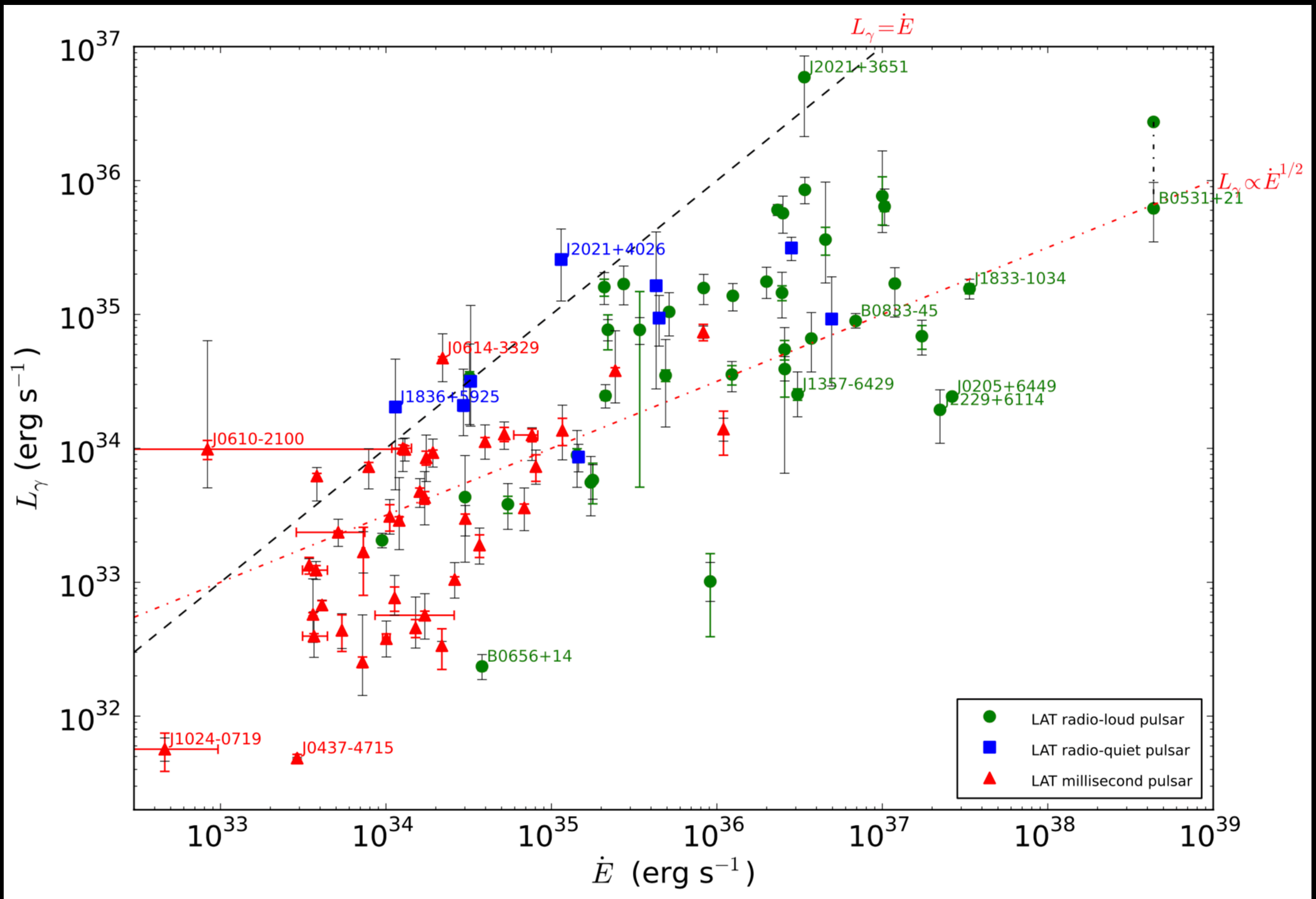


Dark matter can explain the excess

- From NFW profile ~$3x10^7$ M_{sun}
- "naive" cross section matches luminosity and morphology



Pulsars produce GeV gamma rays



Pulsars can also explain the excess

- Millisecond pulsars: faint, blur into "diffuse" emission, ~2000 to explain excess (Weniger+)
  - Galactic bulge from disrupted globular clusters? (Koscis+)
- Young pulsars (O'Leary+2015,2016): Need ~100, still faint and diffuse emission