Revelations in our own backyard: Chandra's unique Galactic Center Discoveries

Sera Markoff
(University of Amsterdam)

Thanks to my many GC collaborators & colleagues

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Rainer Schödel
Daniel Wang

Feng Yuan
Farhad Yusef-Zadeh
******

GCNEWsletter team
Chandra Schedulers!
ACIS/HETGS Teams
CXC PR: Peter & Megan
Claude Canizares
Harvey Tannanbaum

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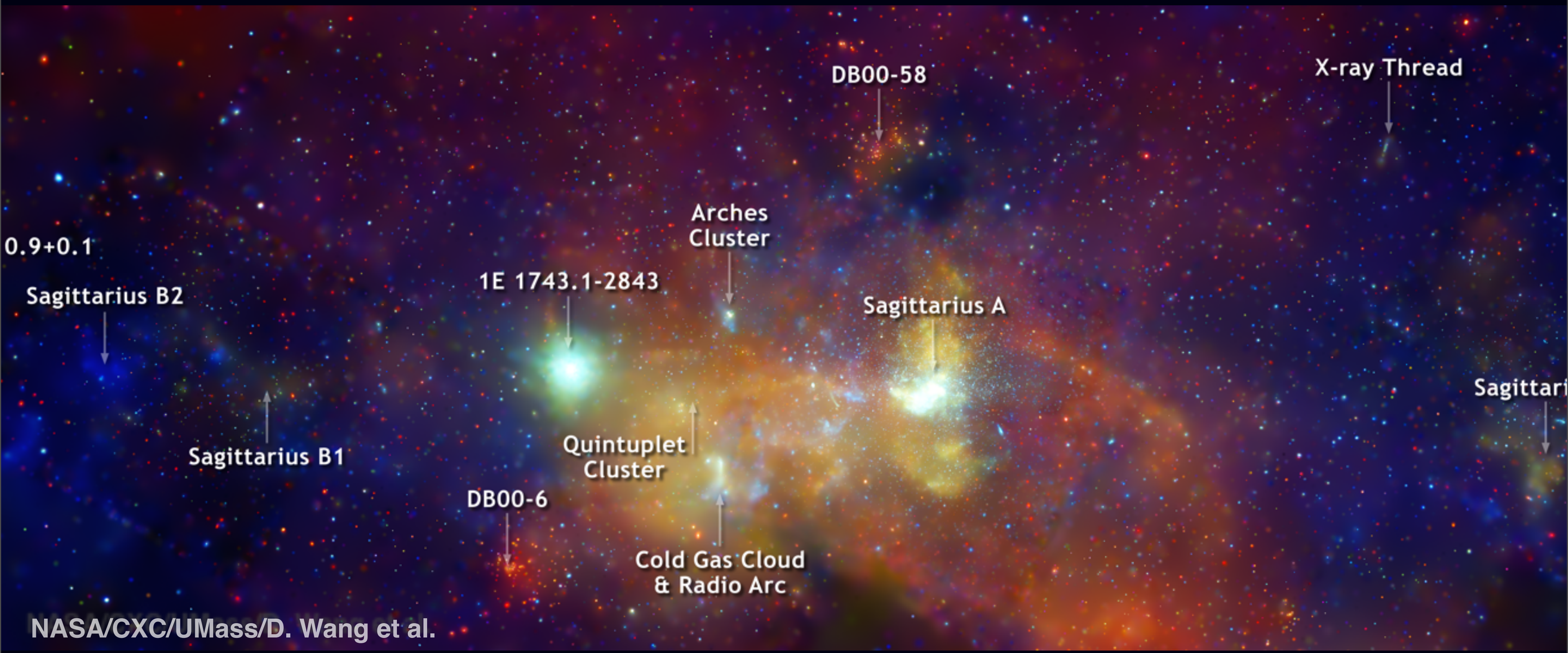

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Zooming in on the Galactic center

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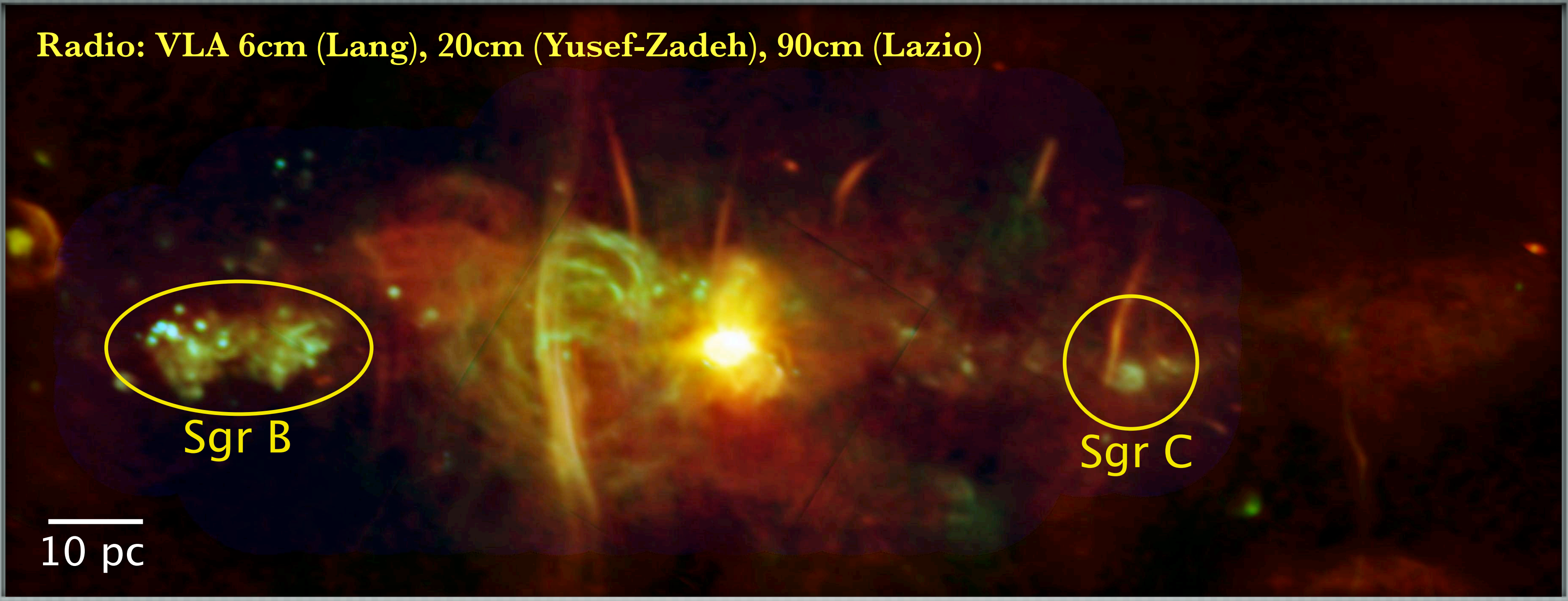

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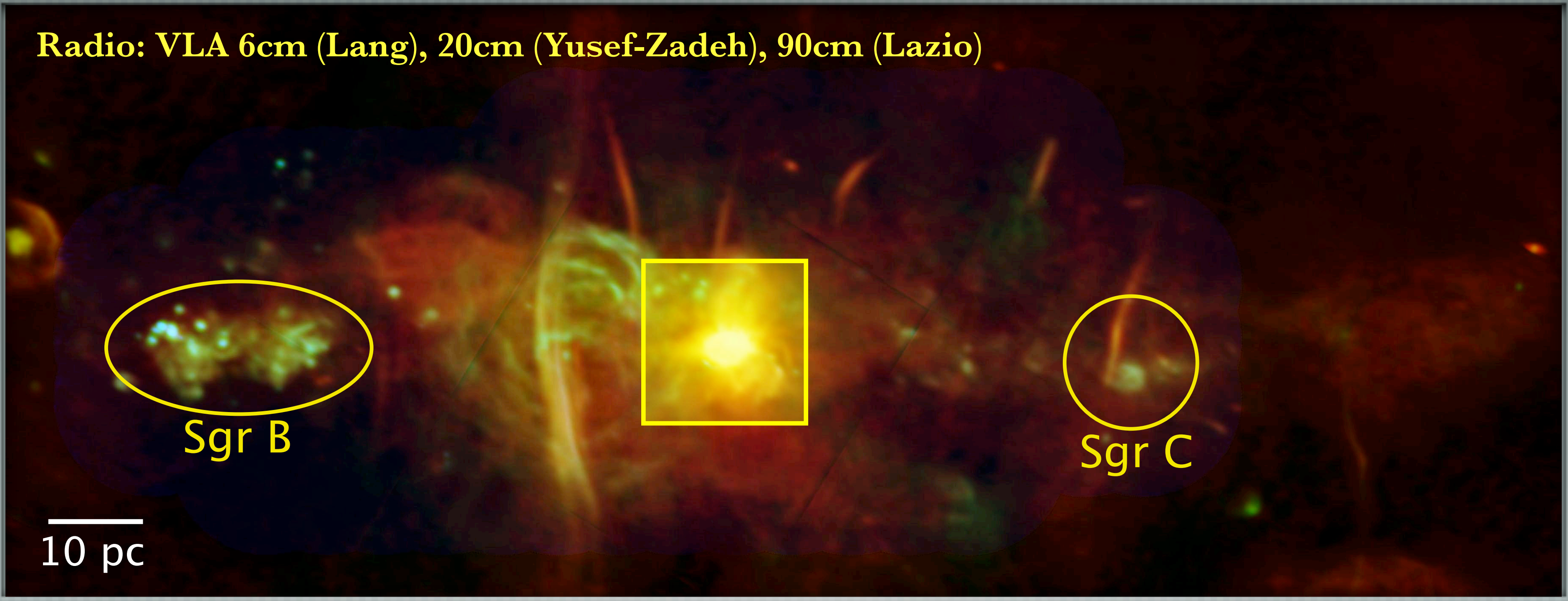

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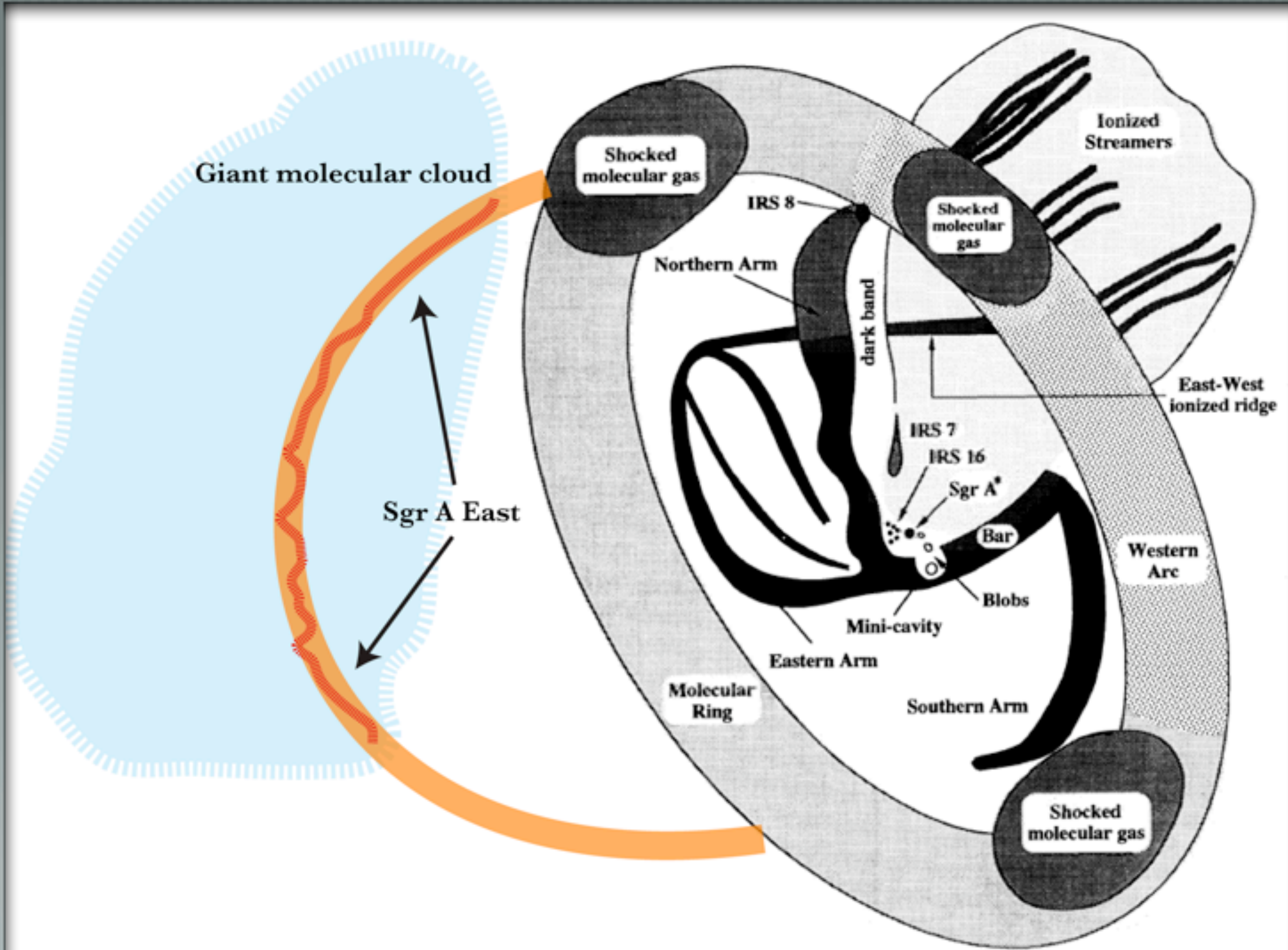

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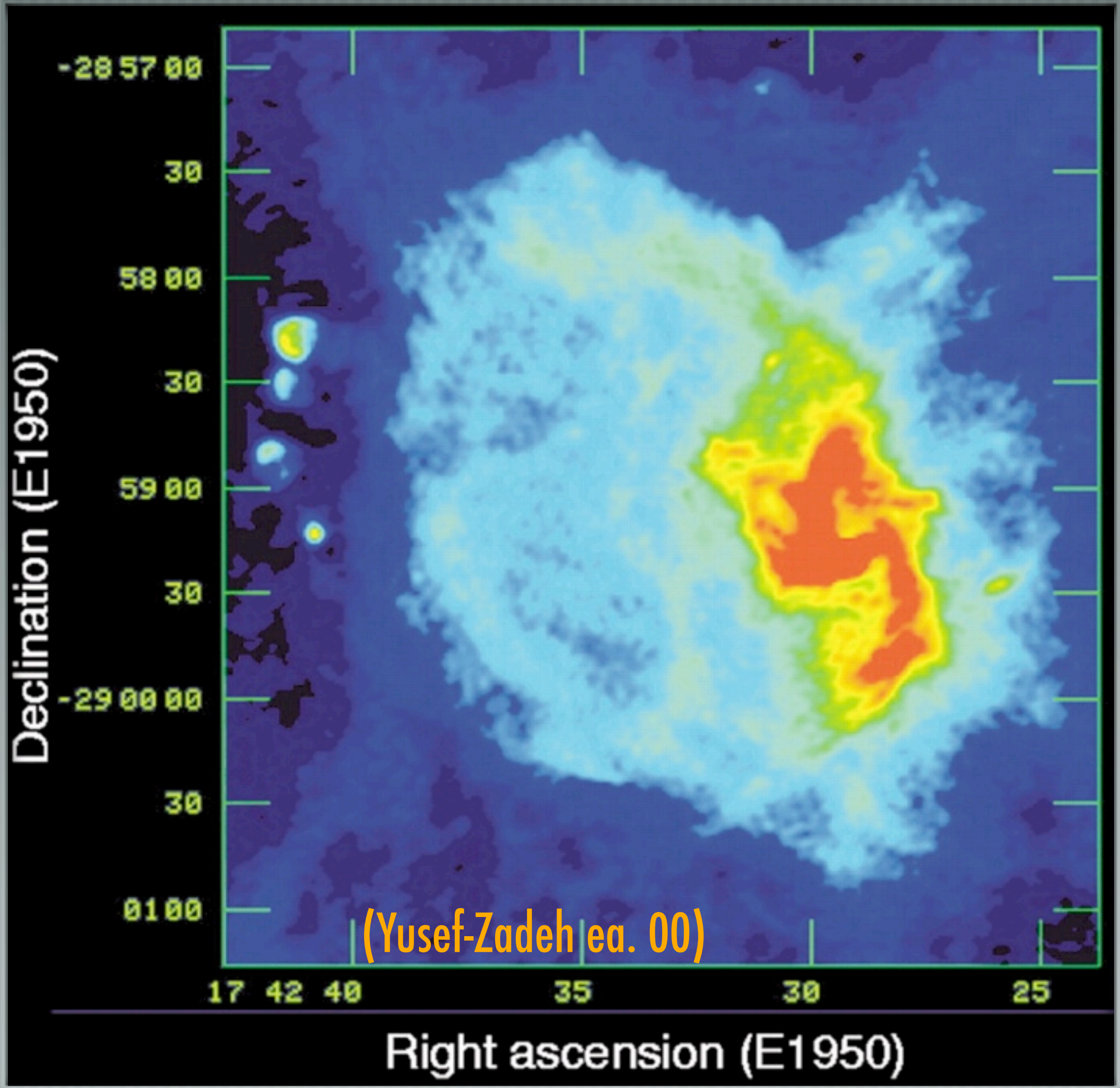

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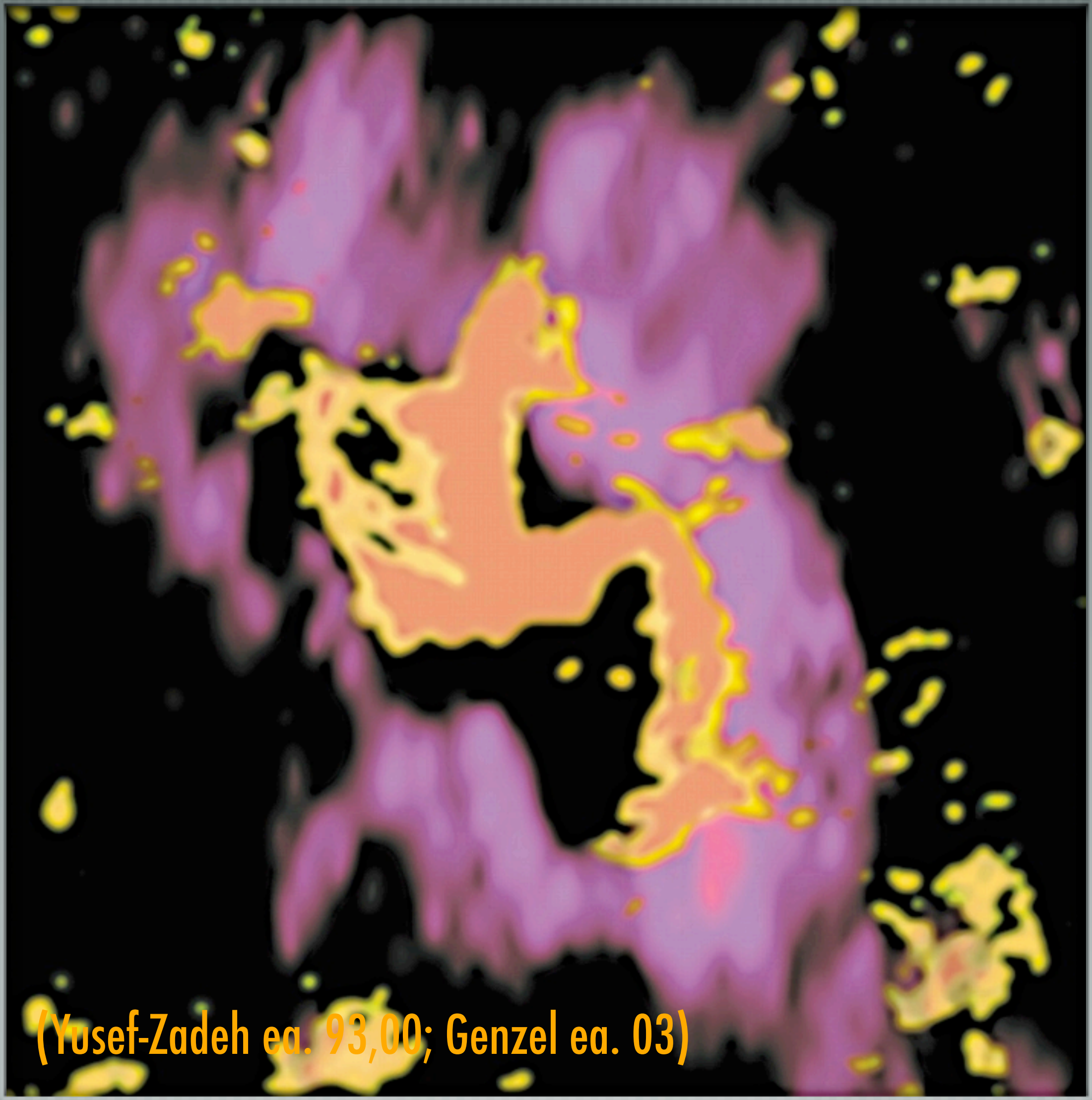

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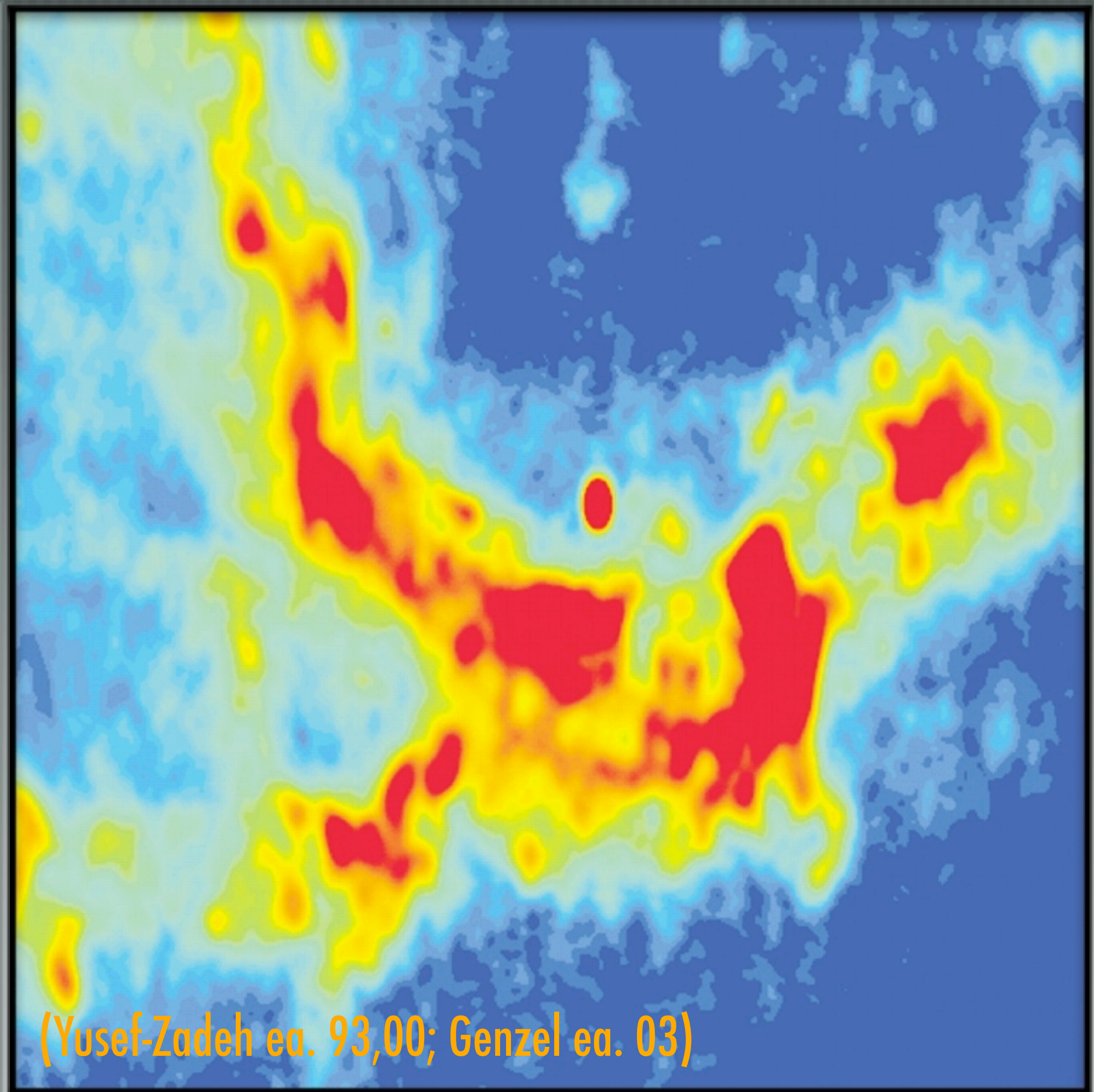

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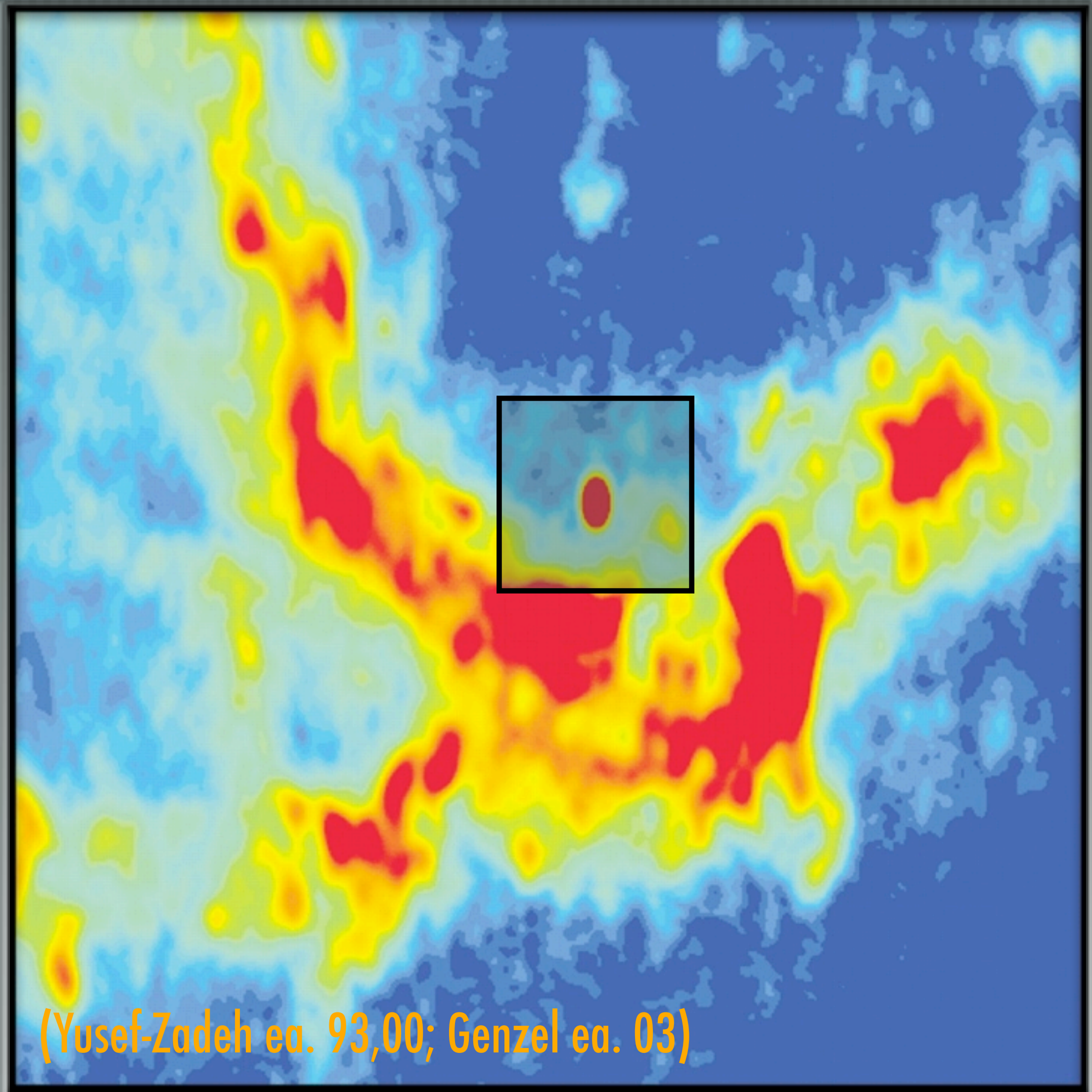

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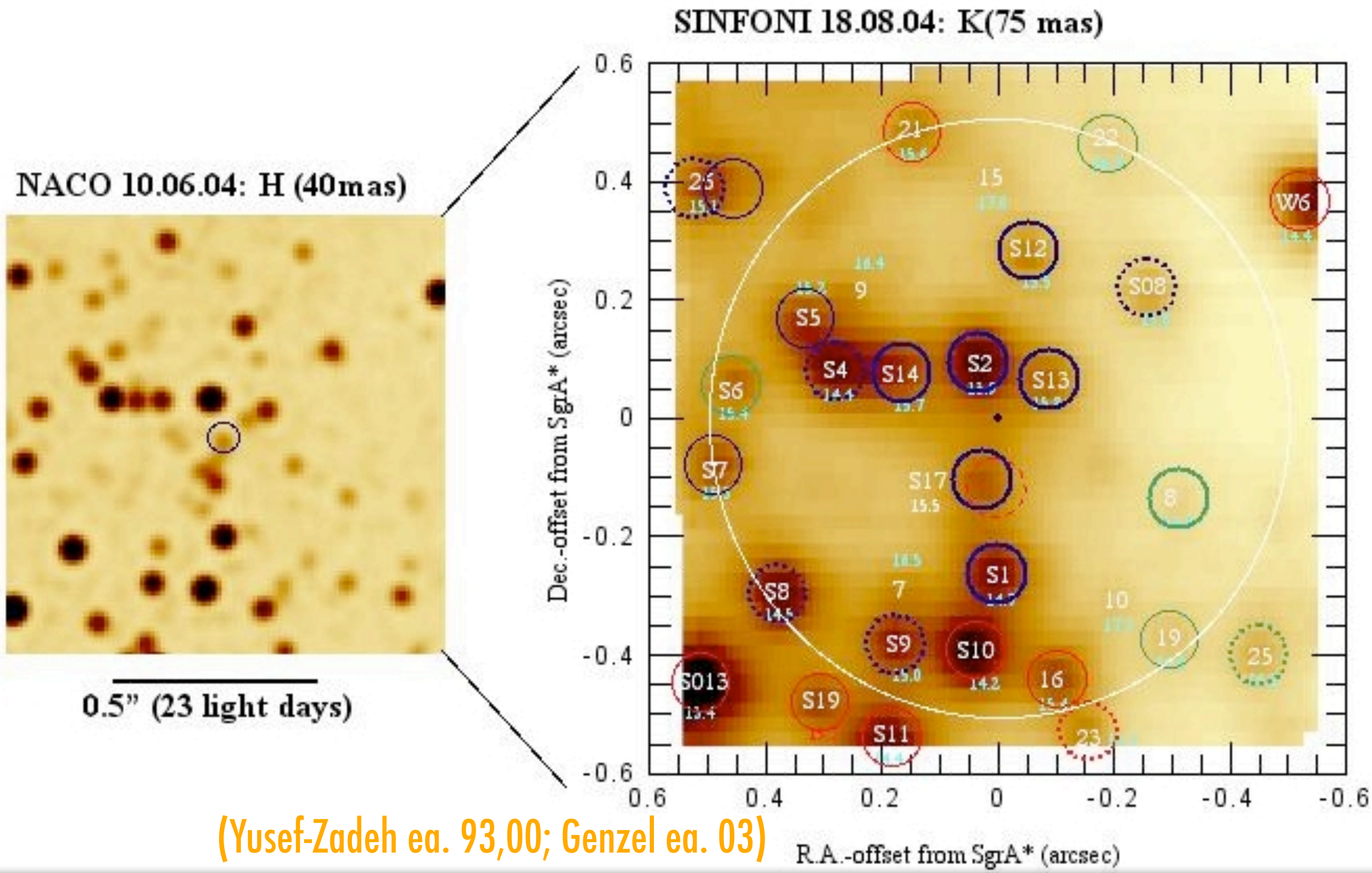
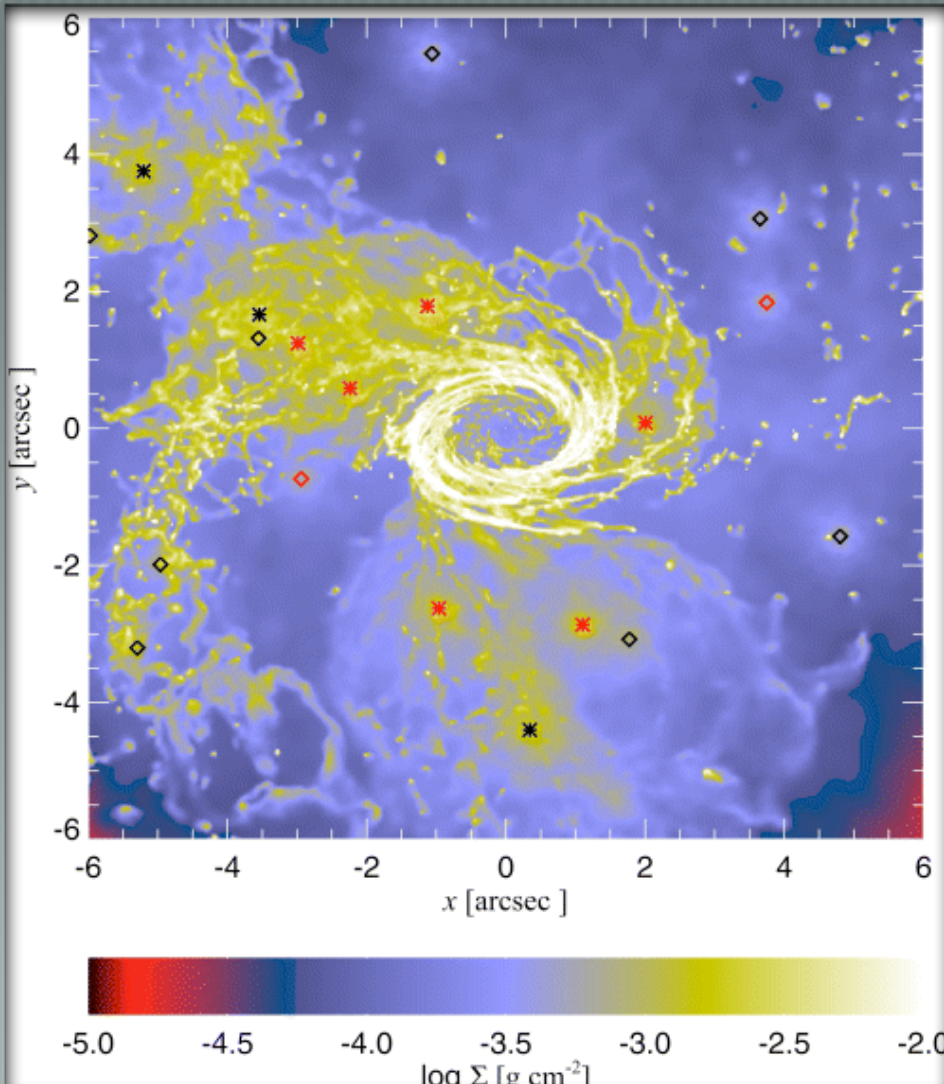


(Yusef-Zadeh ea. 93,00; Genzel ea. 03)

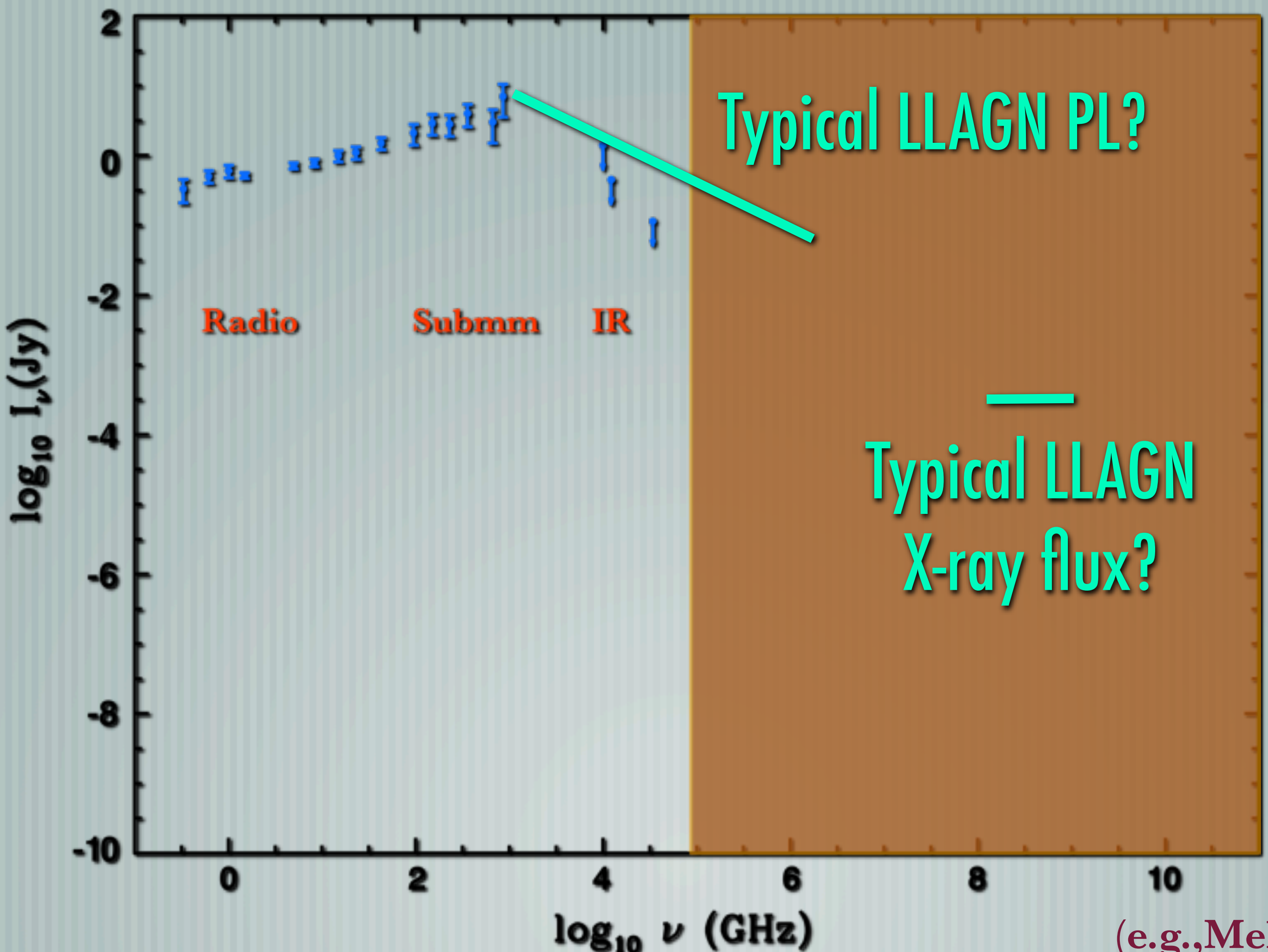
Stellar orbits and types measured – Can estimate available "fuel" for SMBH



- Estimates based on stellar winds and simulations thereof: $10^{-5} – 10^{-3}$ M⊙/yr
- At 10% efficiency would expect $L_{Bol} \sim 10^{-4 – -2} L_{Edd}$

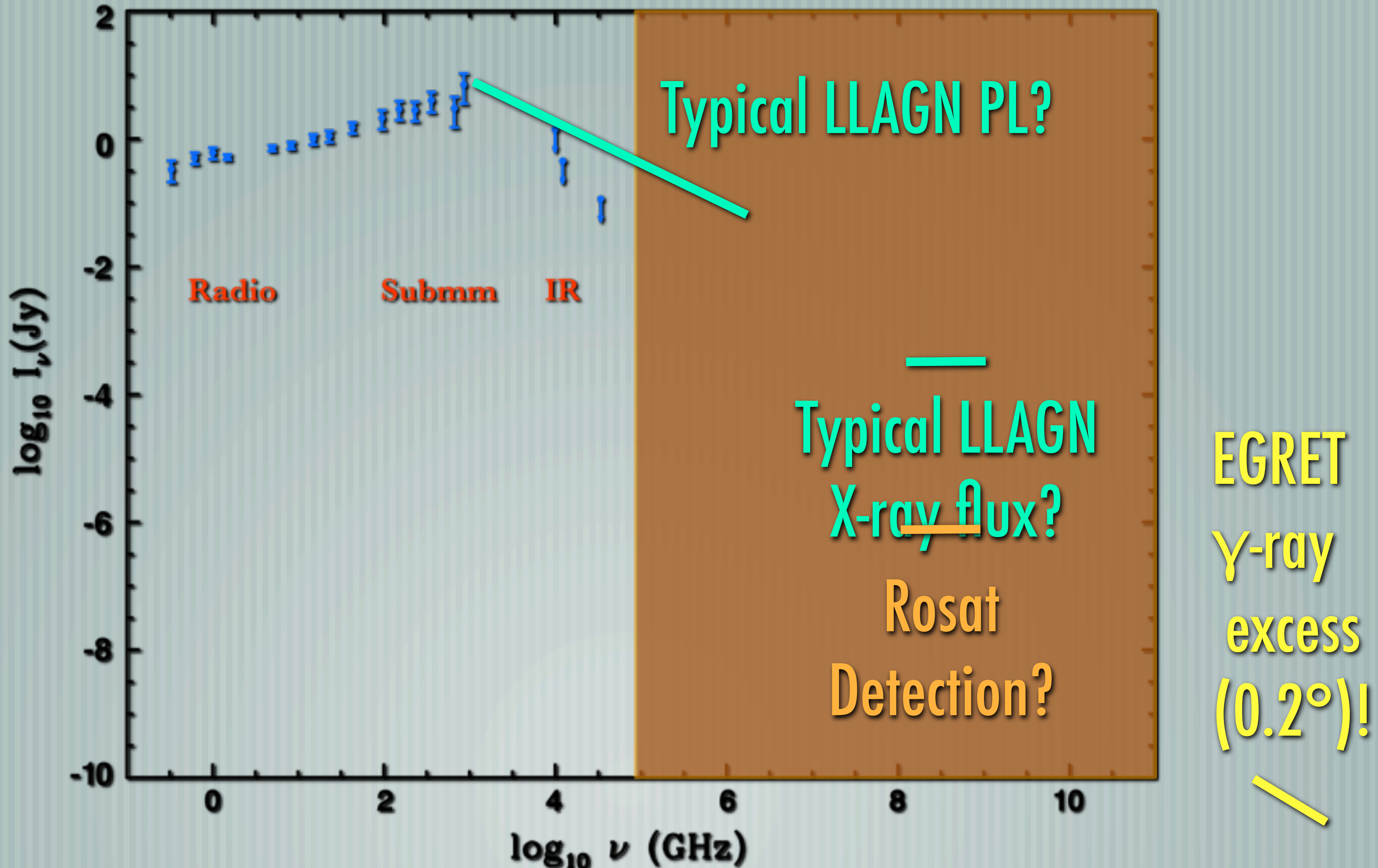
(Coker & Melia 97, 00, Cuadra ea. 05)

Before Chandra's launch we only had radio limits for Sgr A*, upper limits in IR

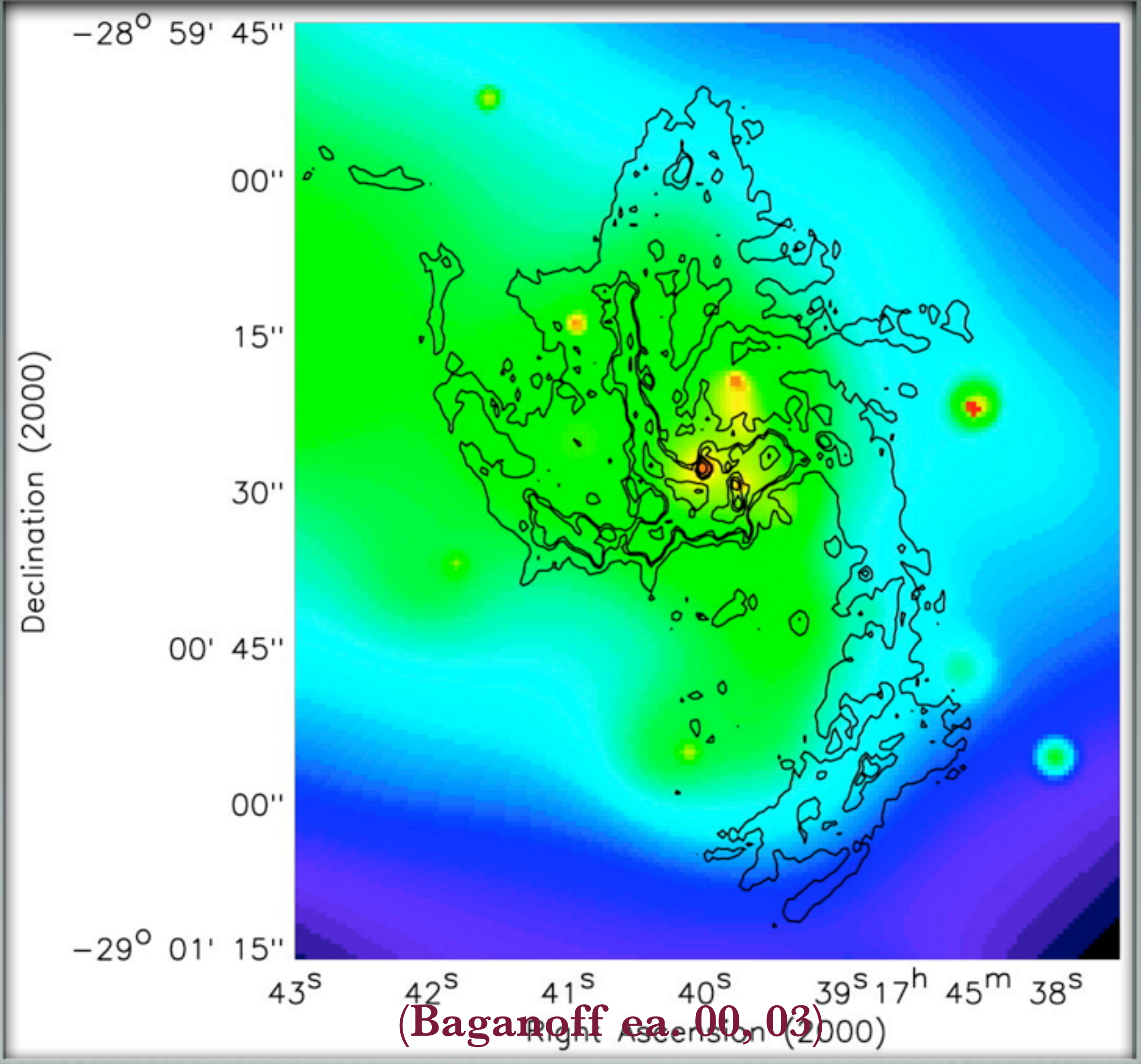


(e.g.,Melia & Falcke 0

Nor did we have a good sense from the earlier X-ray/gamma-ray missions



Finally, Chandra discovers X-rays conclusively from Sgr A*!



(Baganoff ea. 00, 03)

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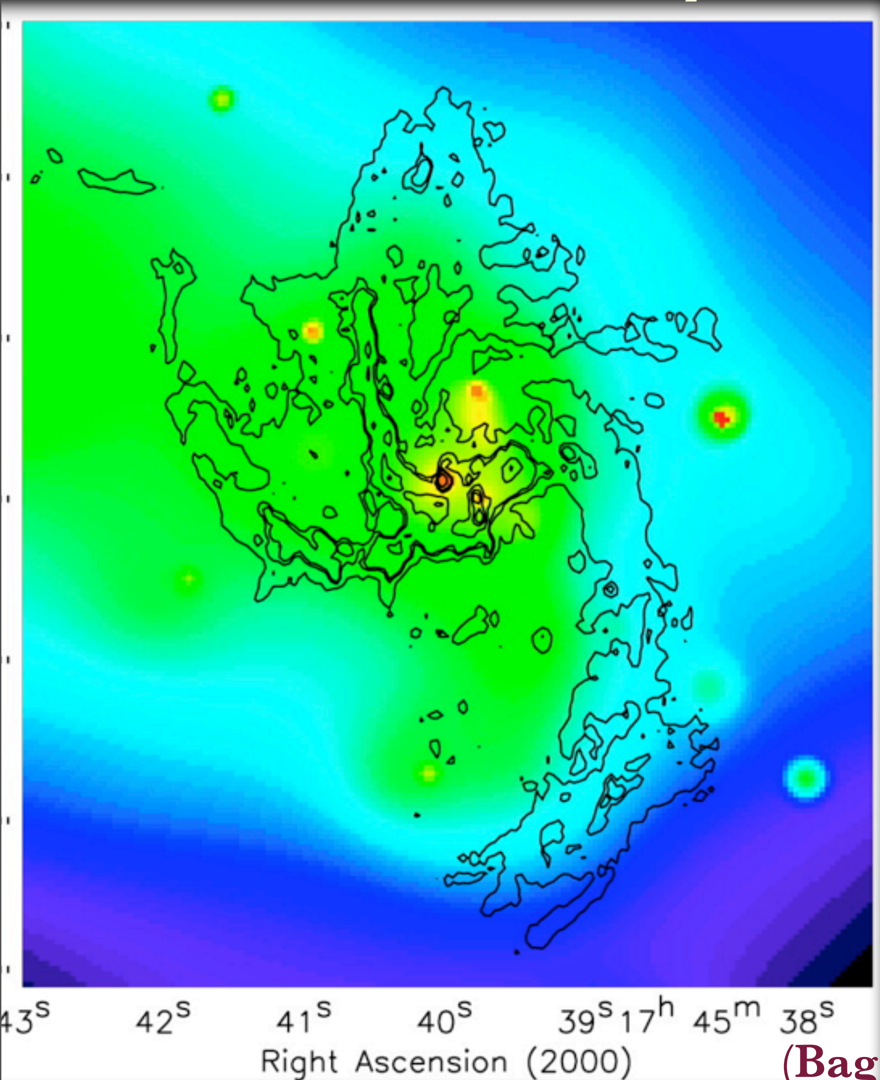

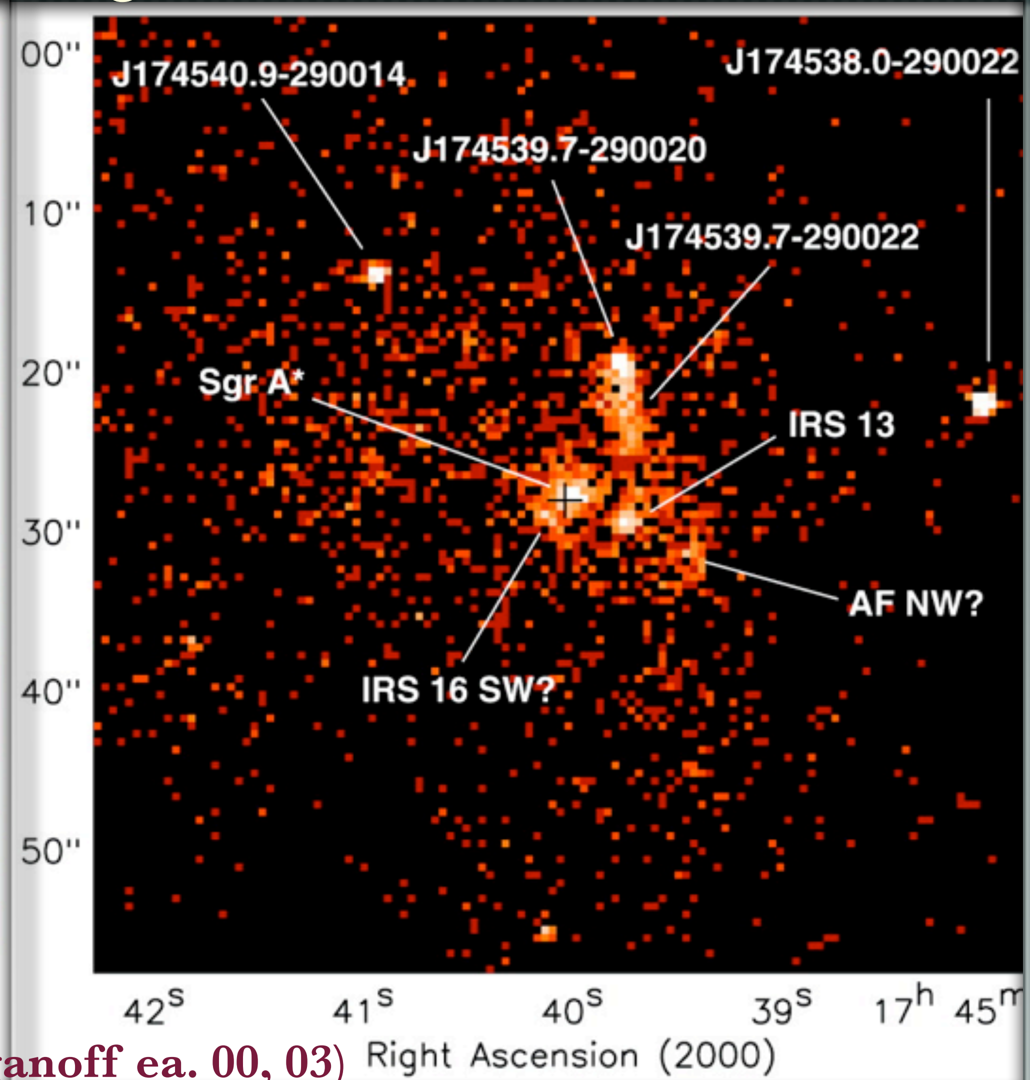

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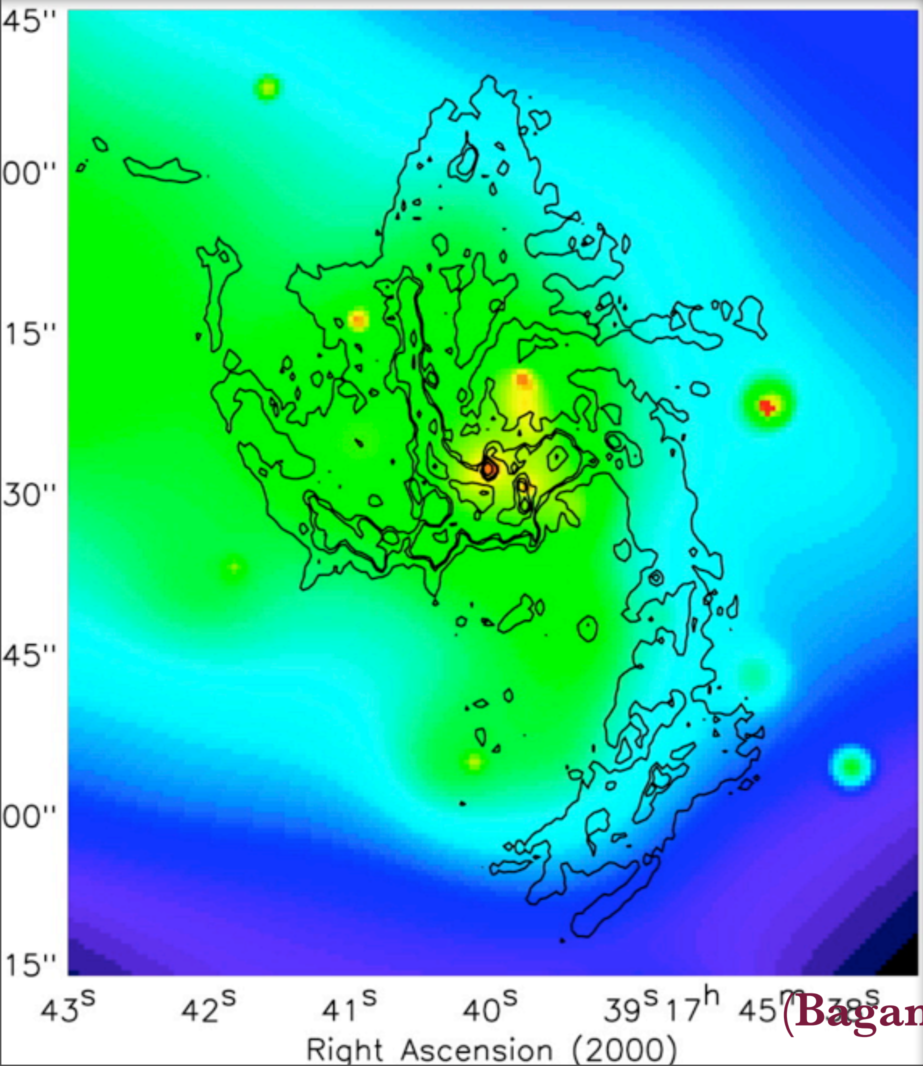
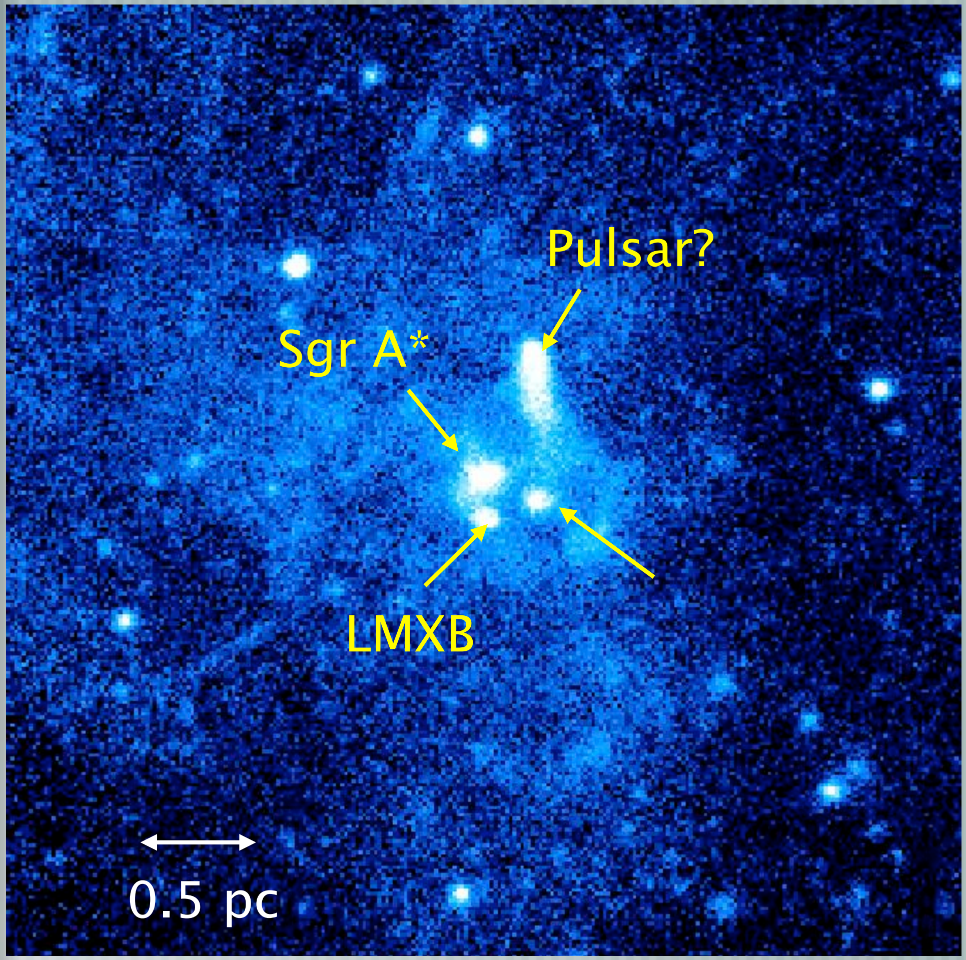
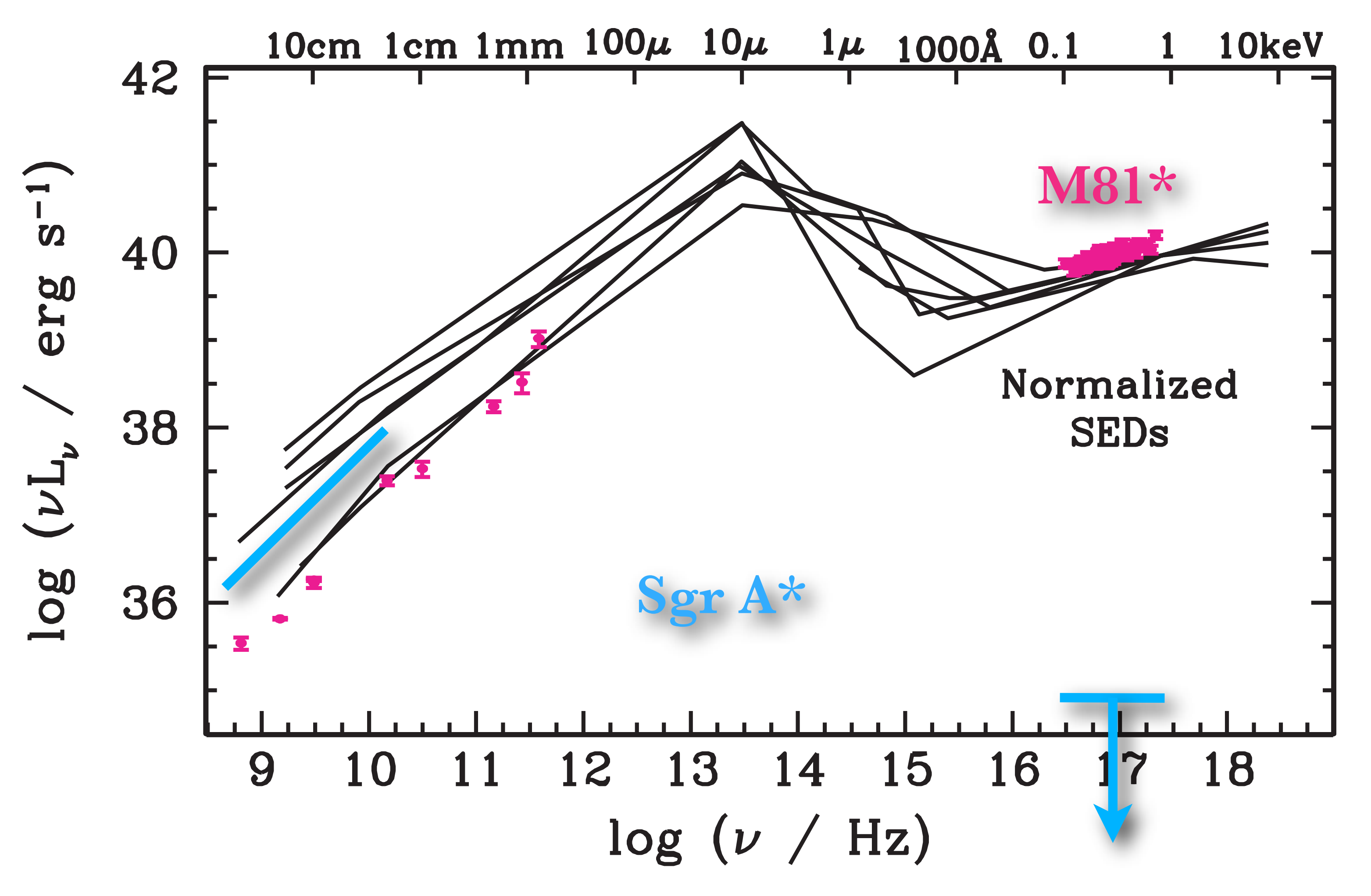




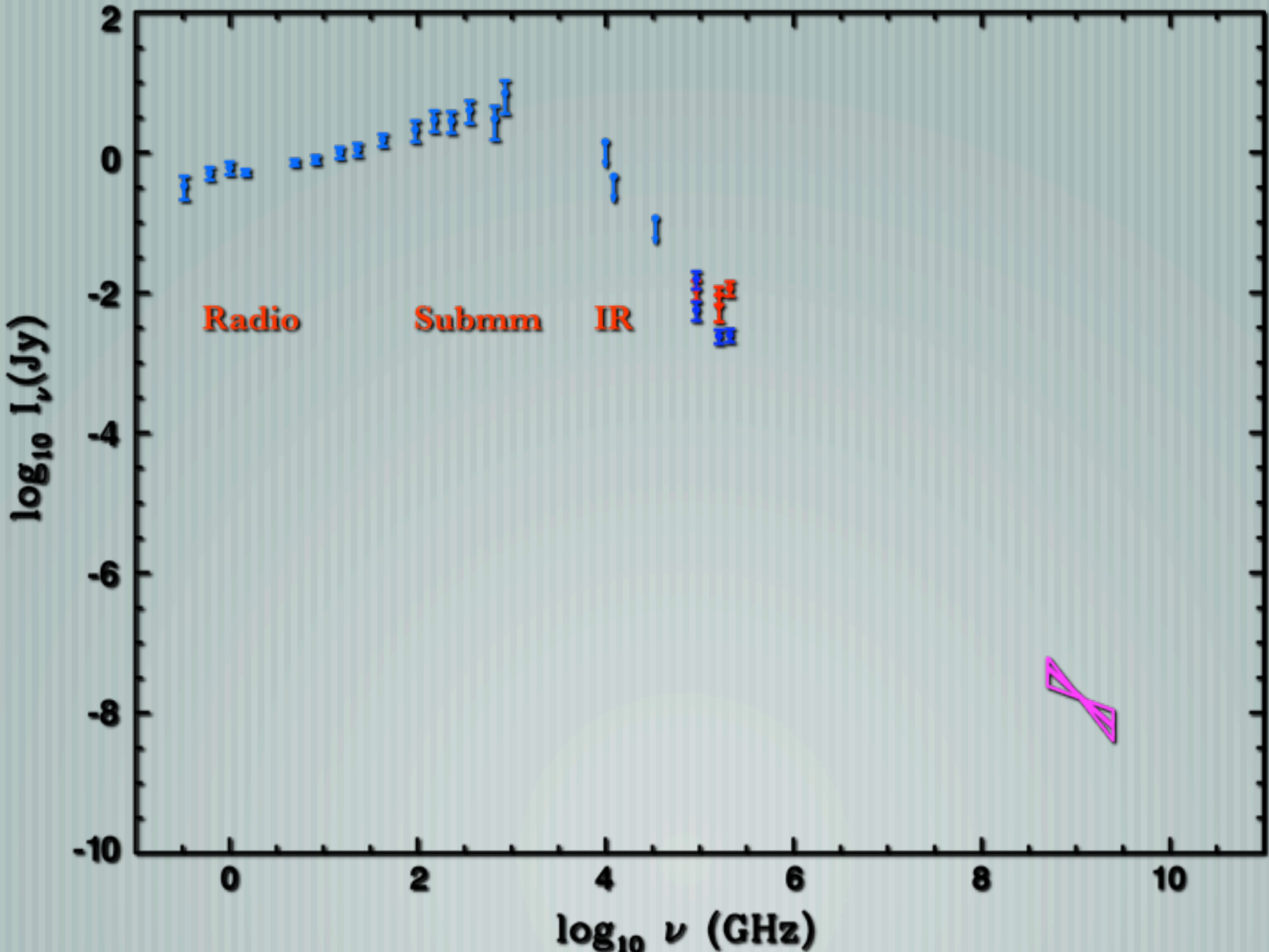
(Baganoff ea. 00, 03)

Comparison with nearby LLAGN



(Ho ea. 99, SM ea 08)

Sgr A* quiescent spectrum – Very weak!



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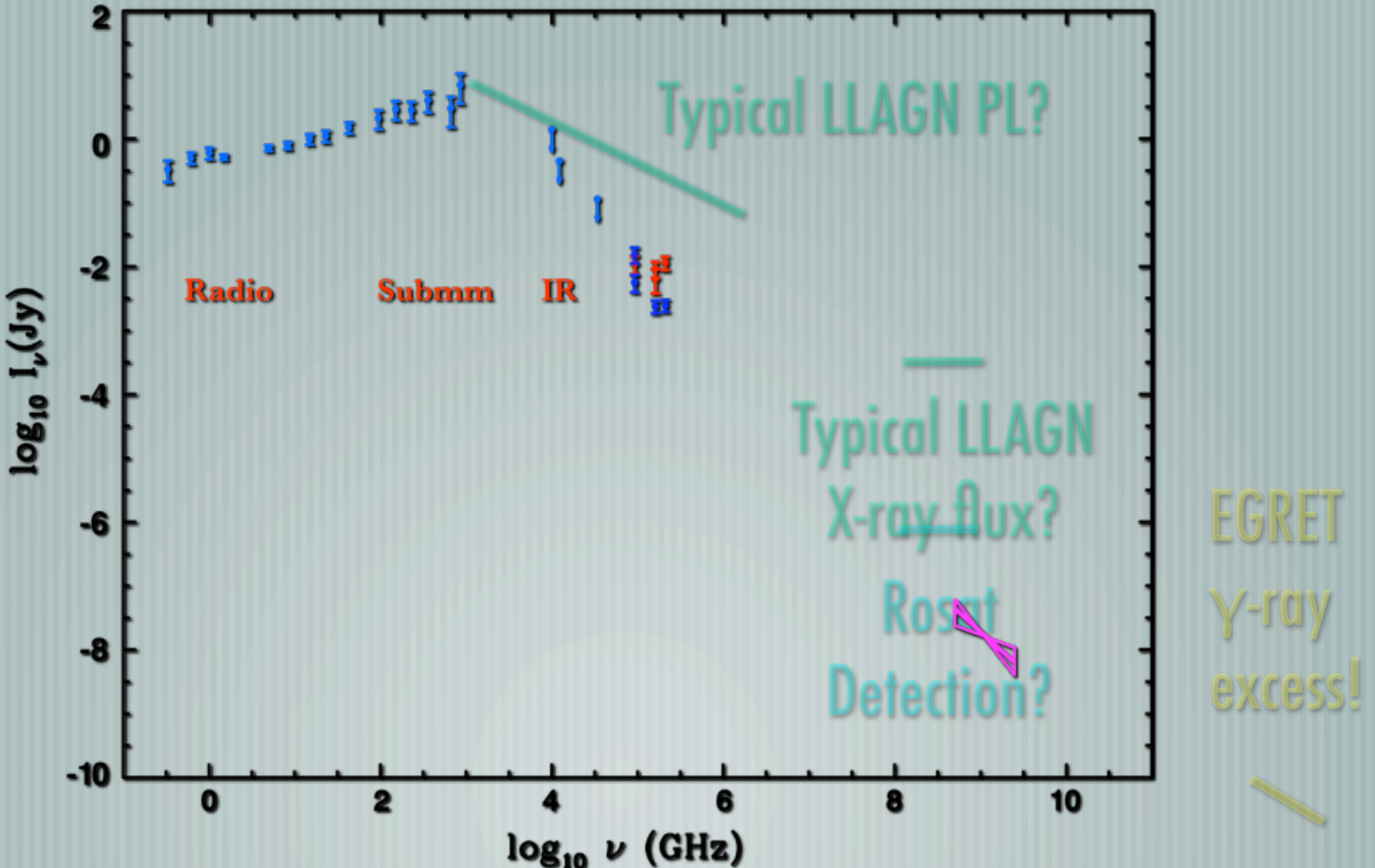

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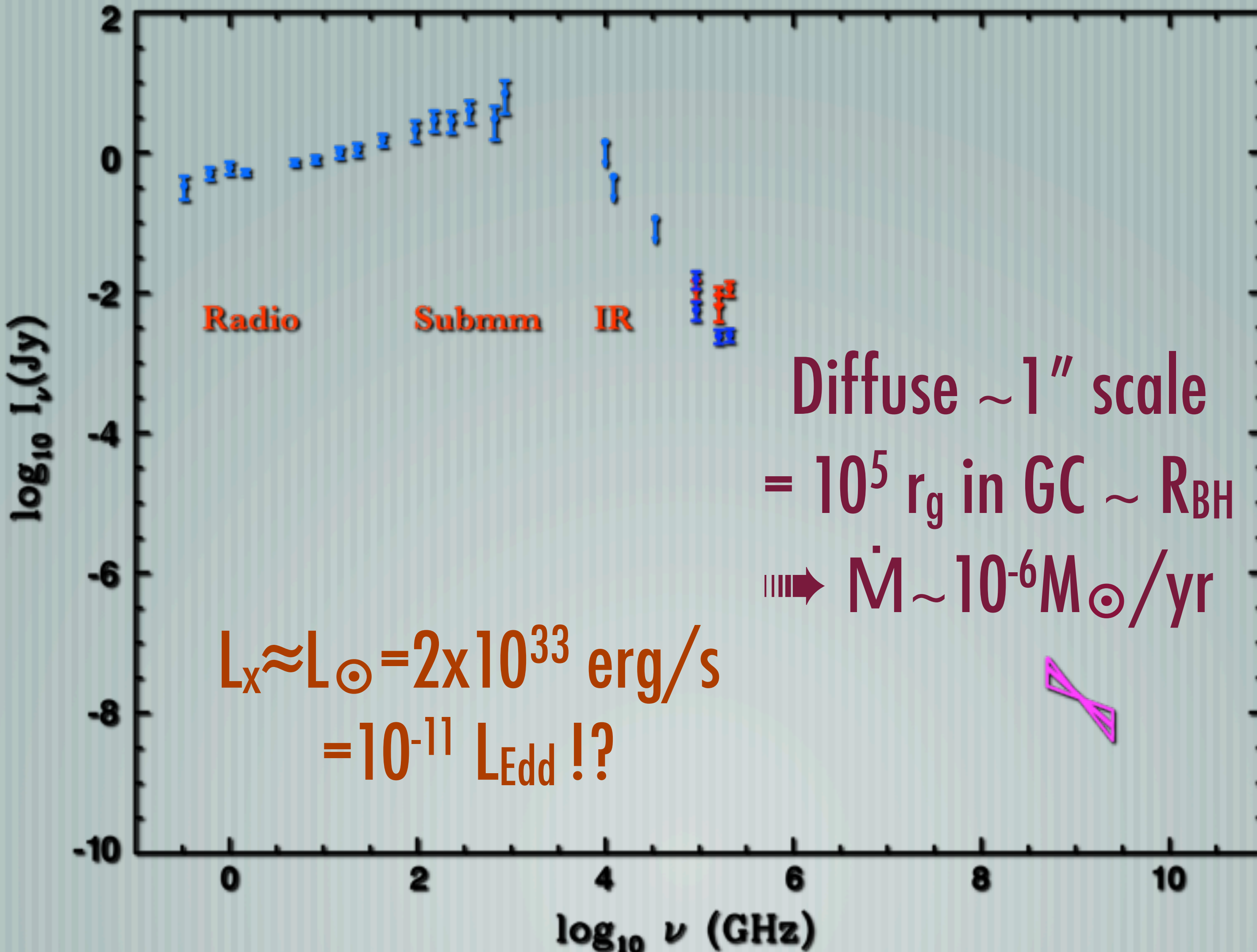


This was quite a shocker for theorists!

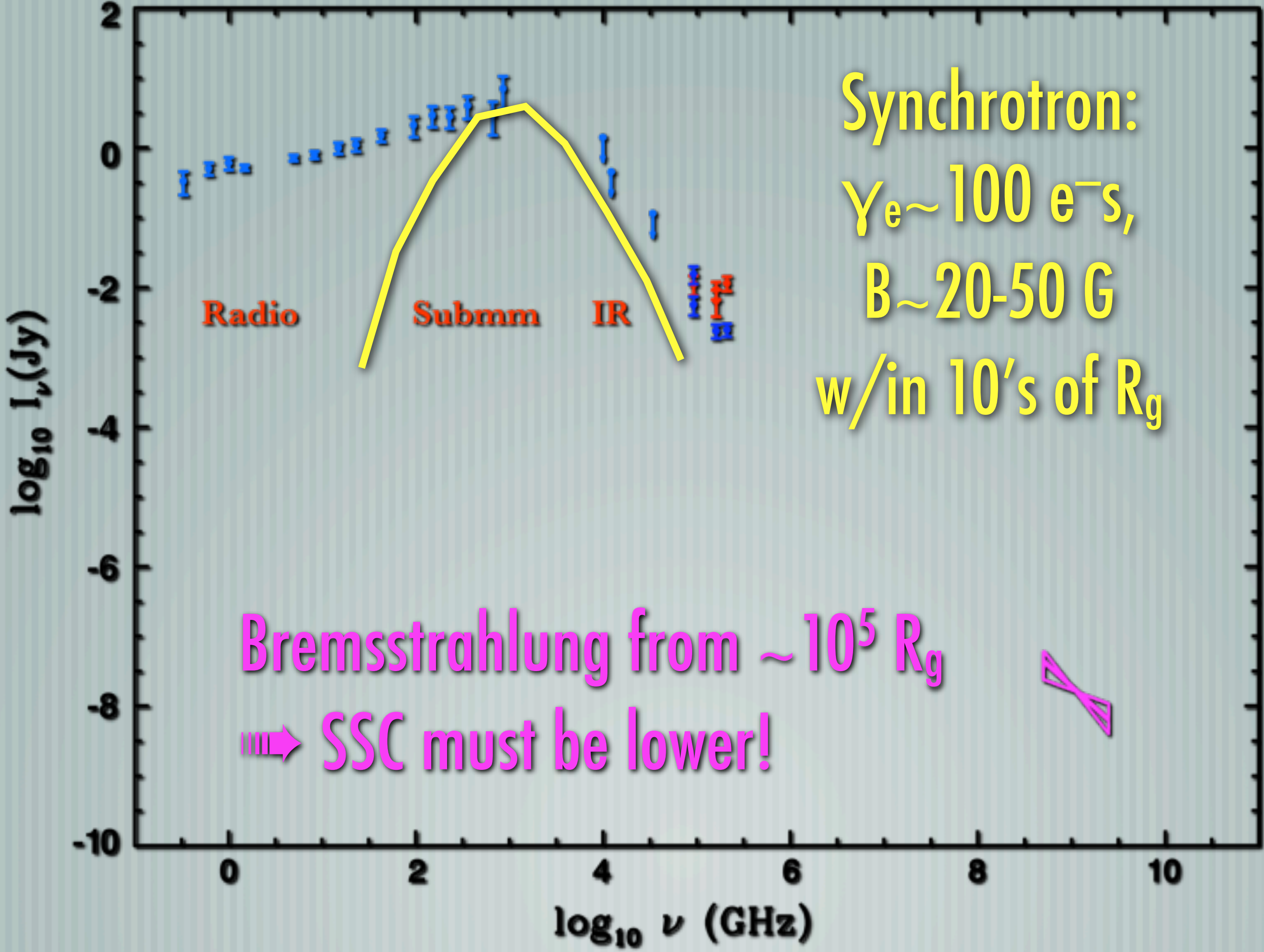
What happened to all that matter from stars?

- Reliance on some form of radiative inefficiency:

  ADAFs ~ Ichimaru '77, Rees ea. '82, Narayan ea. 95,98; Jets ~ Falcke & SM '00

- Very soft spectrum + pathetically low L_x leaves three possibilities:
  - $\dot{M} \ll \dot{M}_{BH}$, radiative inefficiency not needed?
  - $\dot{M} \leq \dot{M}_{BH}$ ➡ radiative inefficiency + reworking
  - $\dot{M} \leq \dot{M}_{BH}$ ➡ outflows/jets (+ radiative ineffic.?)

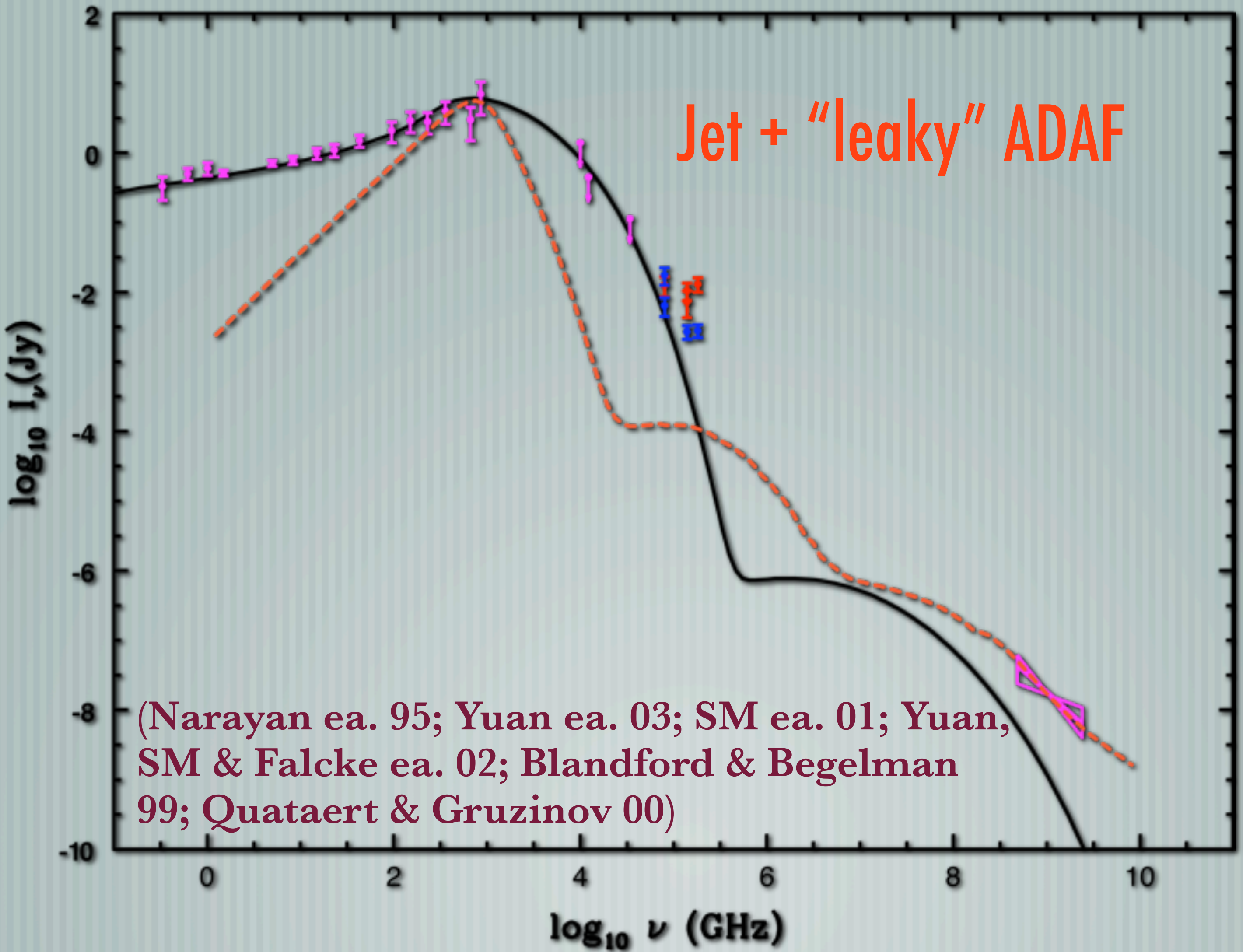
Sgr A* in quiescence– physical processes



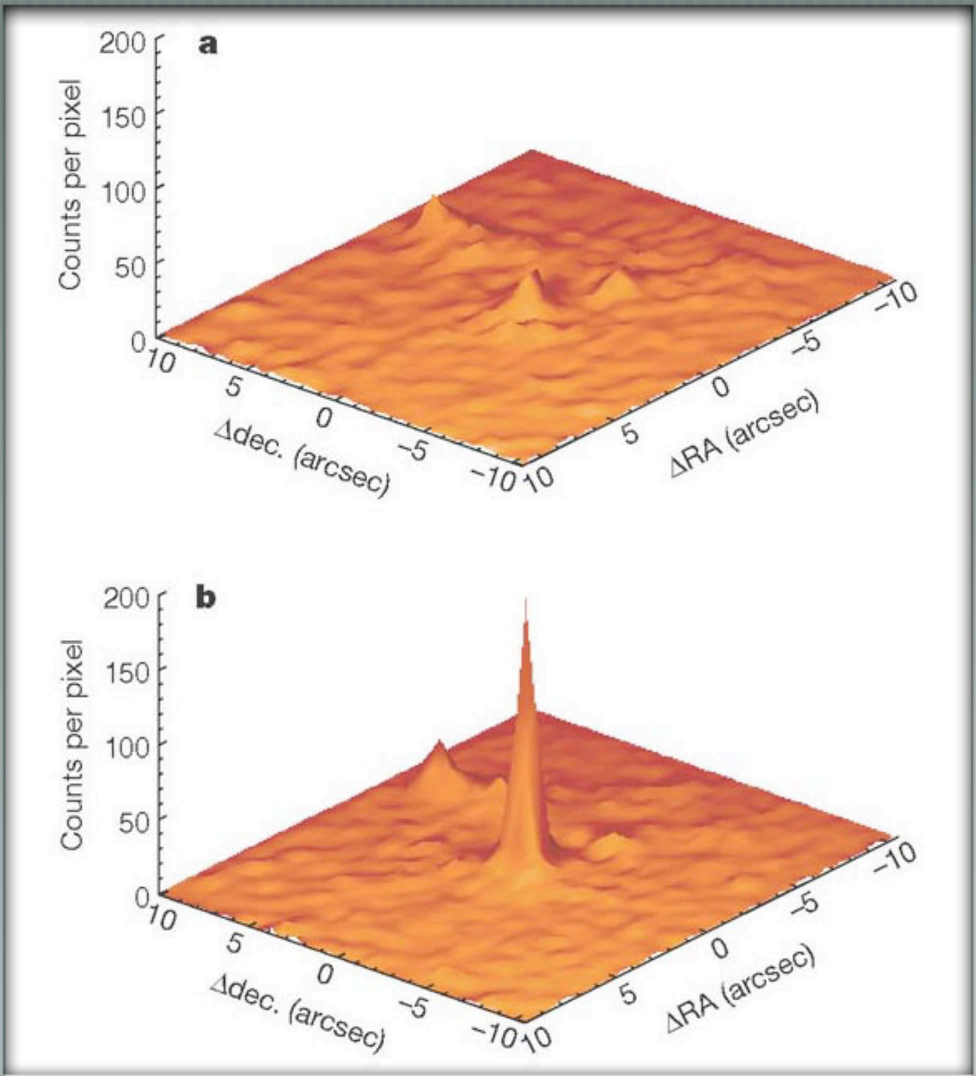
Synchrotron:
$\gamma_e \sim 100$ e^-s,
B~20-50 G
w/in 10's of R_g

Bremsstrahlung from ~10^5 R_g
➡ SSC must be lower!

Sgr A* in quiescence– models



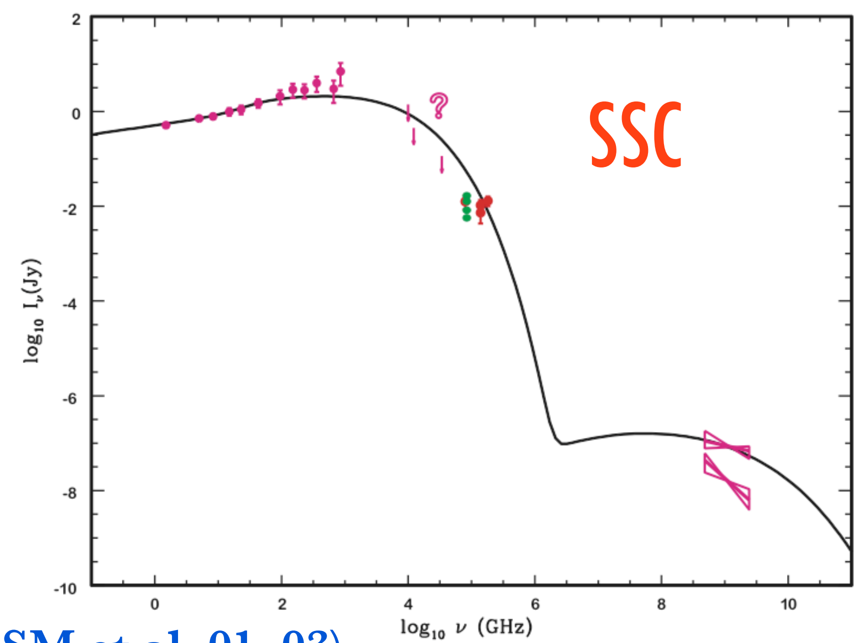
But wait, there's more! – X-ray flares



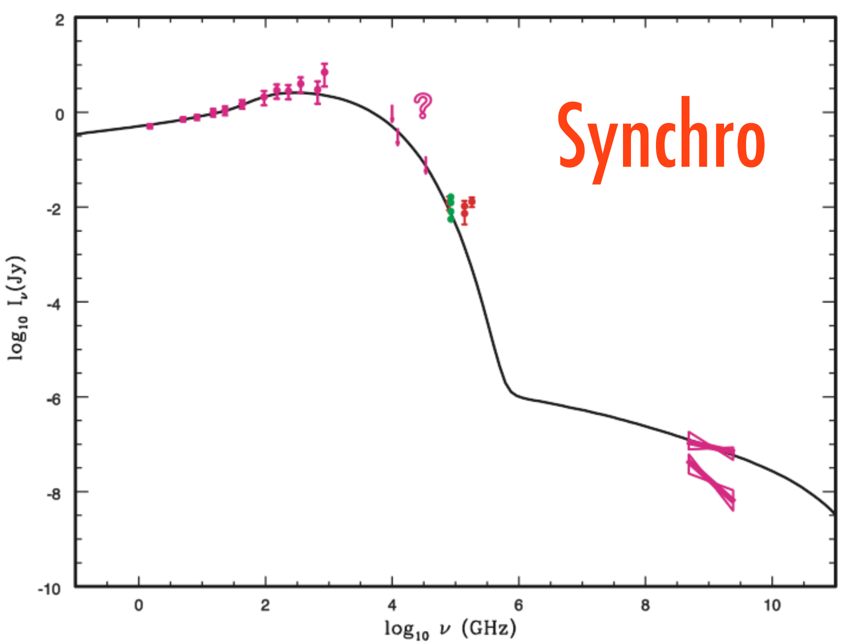
- **Sgr A* underwent an hour flare, ~100x brighter**
- **Spectrum hardened from Γ ~ 2.2 → 1.2**
- **Nonthermal: 10 min. timescale, implying origin w/in 10's of R_g of black hole!**

(**Baganoff ea. 2001, Nature**)

Sgr A* flaring – magnetic processes



SM et al. 01, 03)



Many more flares detected with Chandra (& XMM). Average flare ~ daily with 5-10x, but larger flares show "hiccups" (Porquet et al. 2008) like aftershocks! All models focus on SSC/synchrotron processes (Liu & Melia; Yuan, Quatert & Narayan; Yusef-Zadeh ea.; Dodds-Eden ea.)

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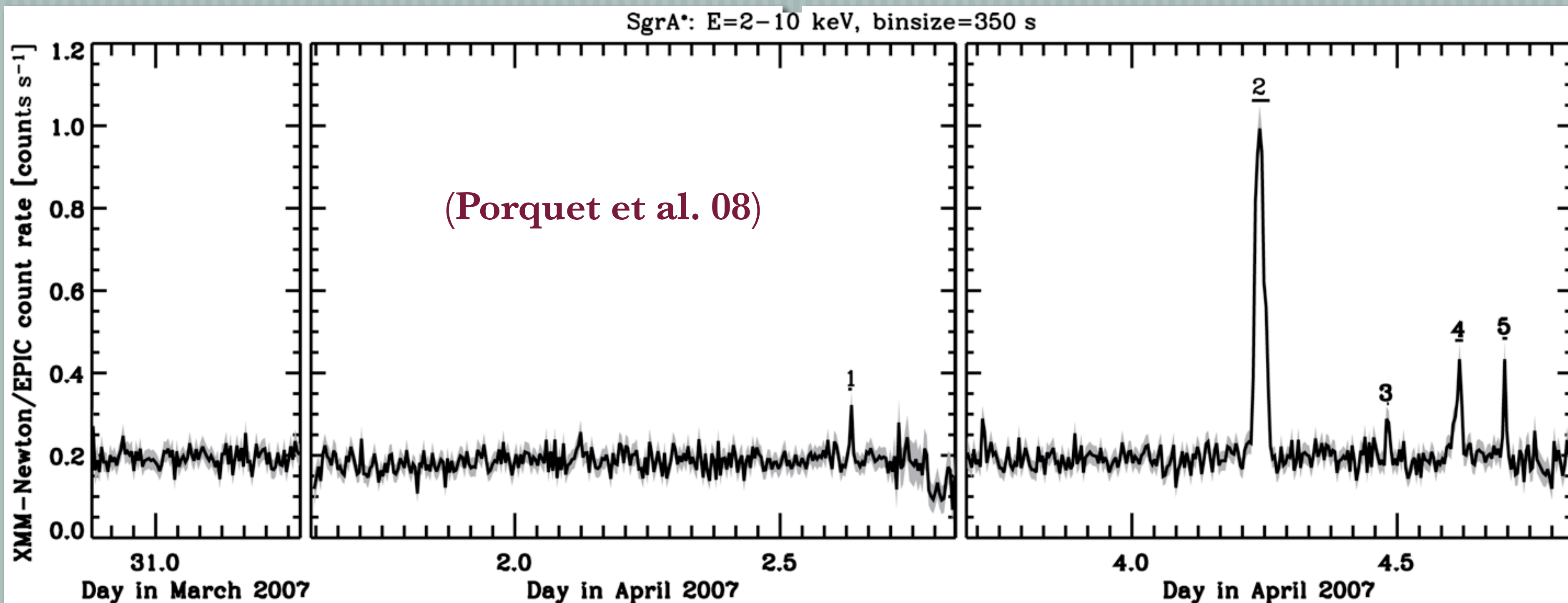

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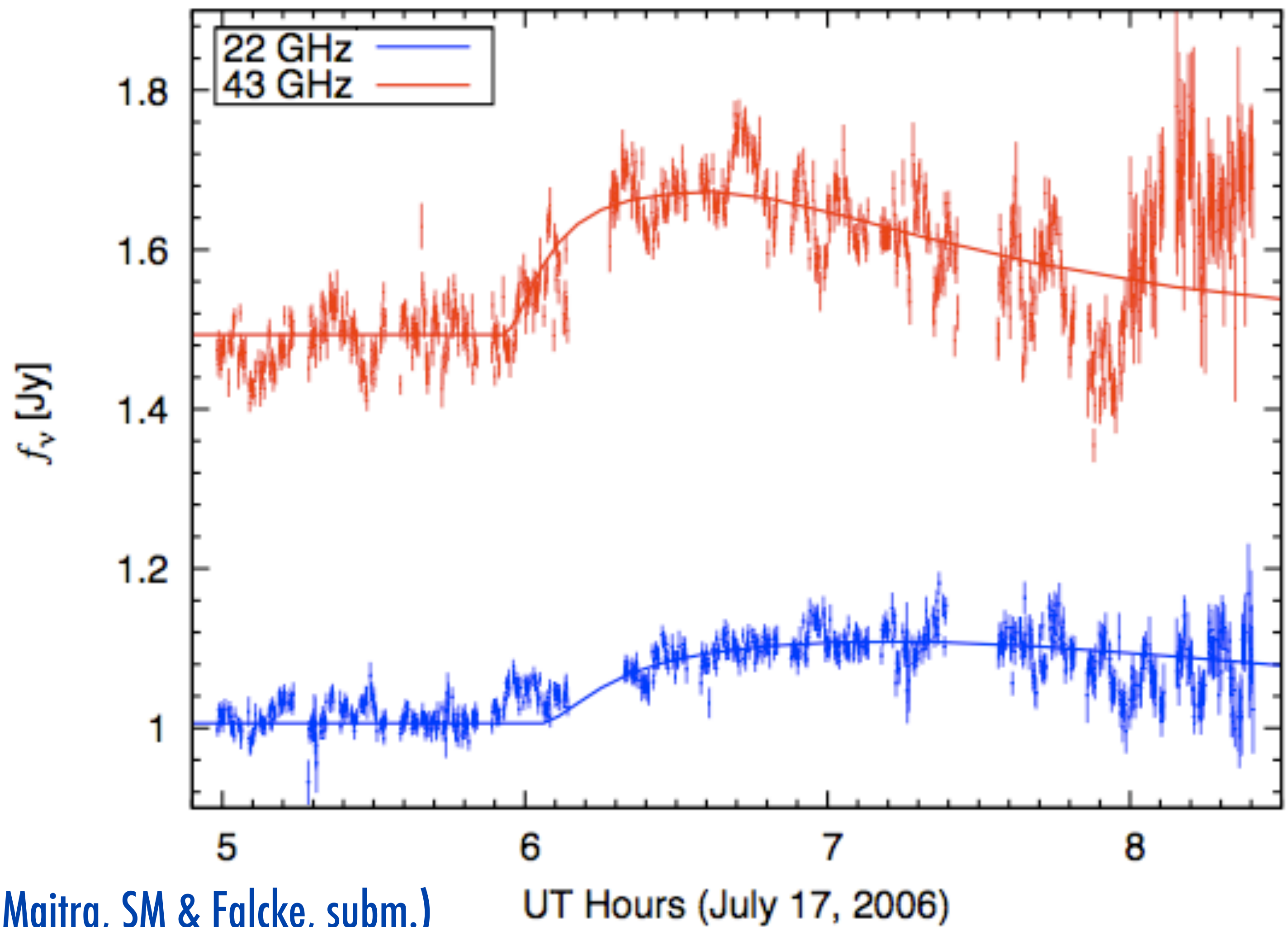

(Maitra, SM & Falcke, subm.)

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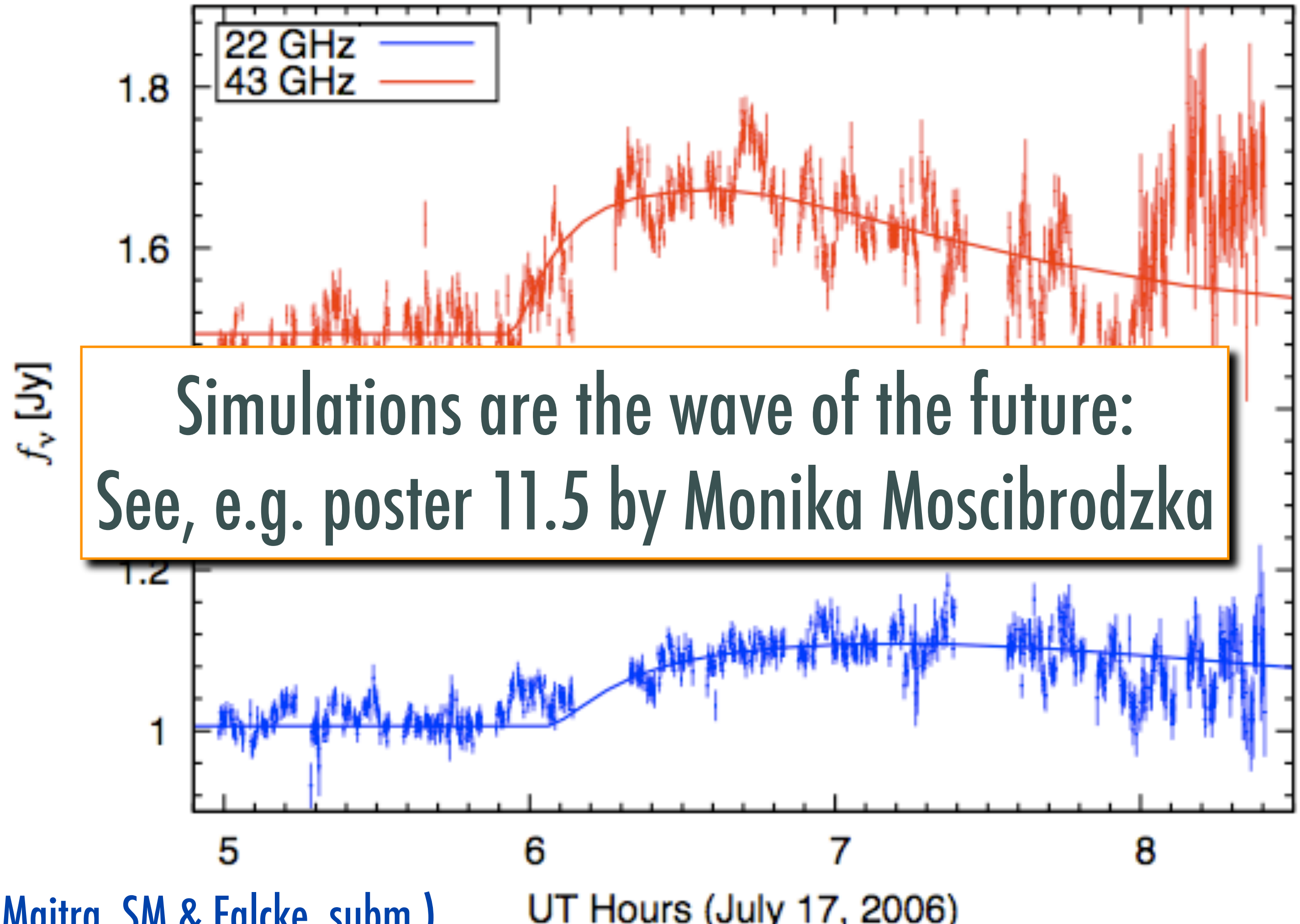
Sgr A* flaring – magnetic processes



Simulations are the wave of the future:
See, e.g. poster 11.5 by Monika Moscibrodzka

(Maitra, SM & Falcke, subm.)

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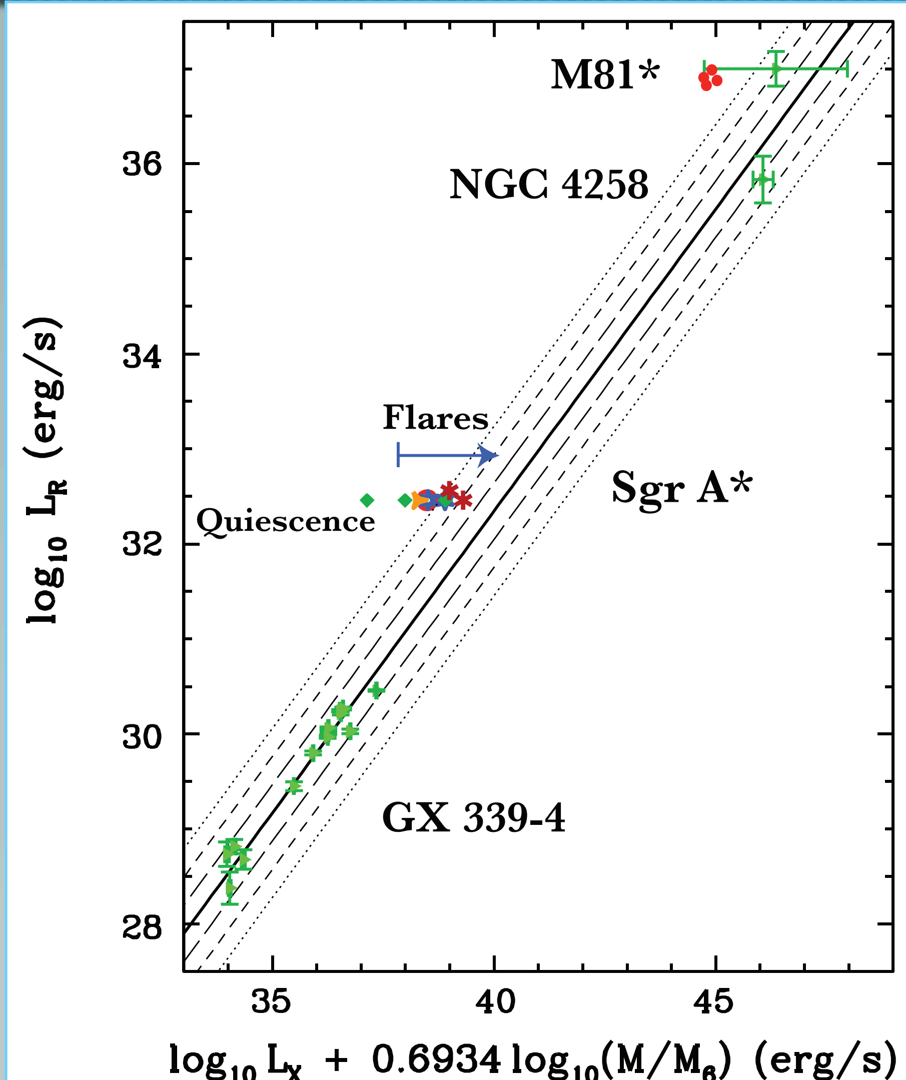
Sgr A* flaring – ramping up to active?



(SM 2005)

Always be careful with statistics – QPOs?

After flare discovery, claims of ~20 minute periodicities abounded in several X-ray and IR papers

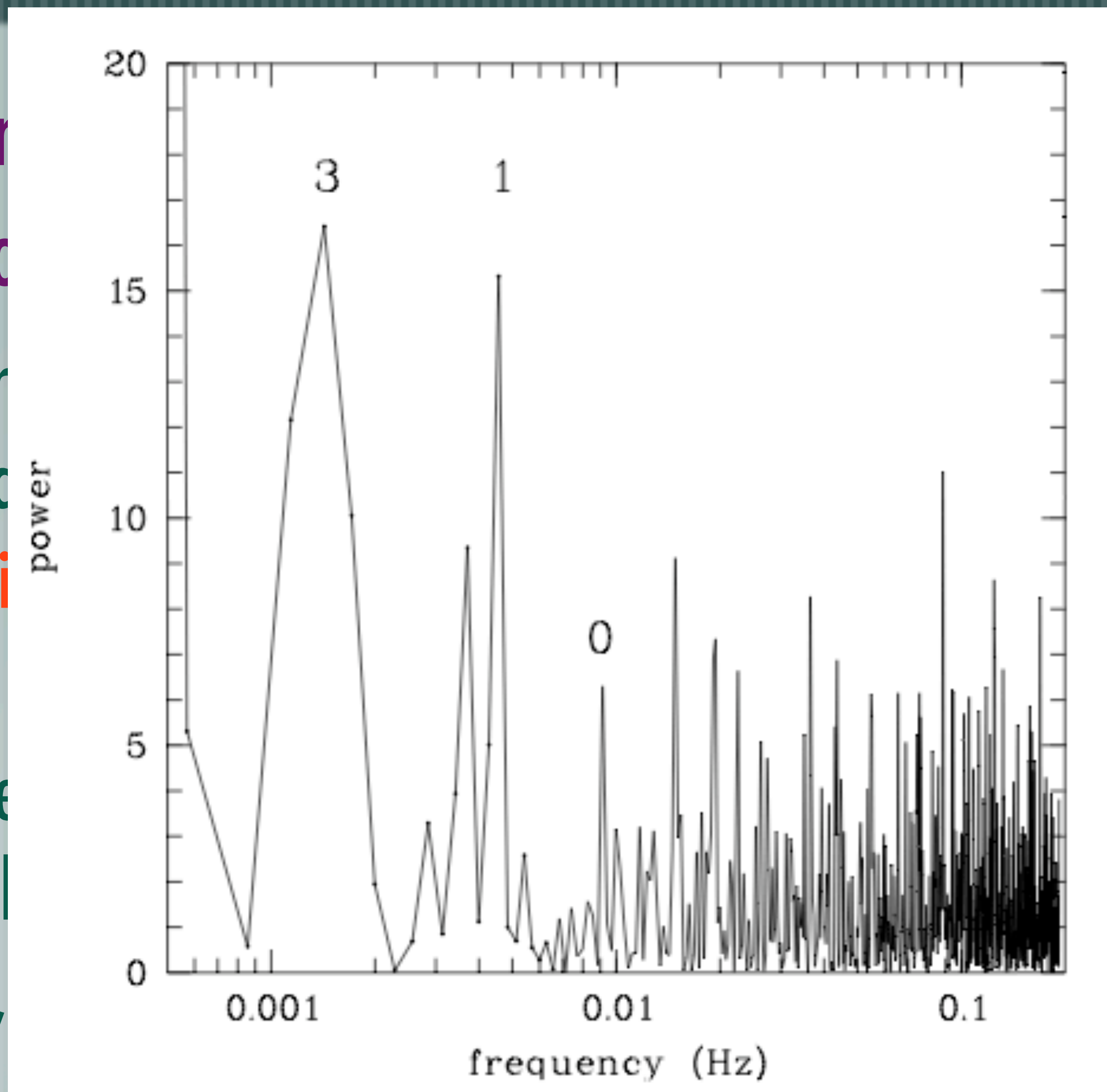
- Current status: claimed in VLT & XMM, not in Chandra and Keck, never seen with HST. Periodicity now deemed insignificant after Monte Carlo simulation tests (Meyer ea. 08, Do ea. 09, Belanger ea. in prep.)
- Interestingly, break timescale in *IR* PSD may be consistent with timing studies based on X-rays of other AGN (Meyer ea. 09, McHardy ea. 06)

Always be careful with statistics – QPOs?

After

peric … IR papers

- Cur … andra and Kec … ned insi … Meyer ea. 08, Do
- Inte … be consistent witl … N (Meyer ea. 09,



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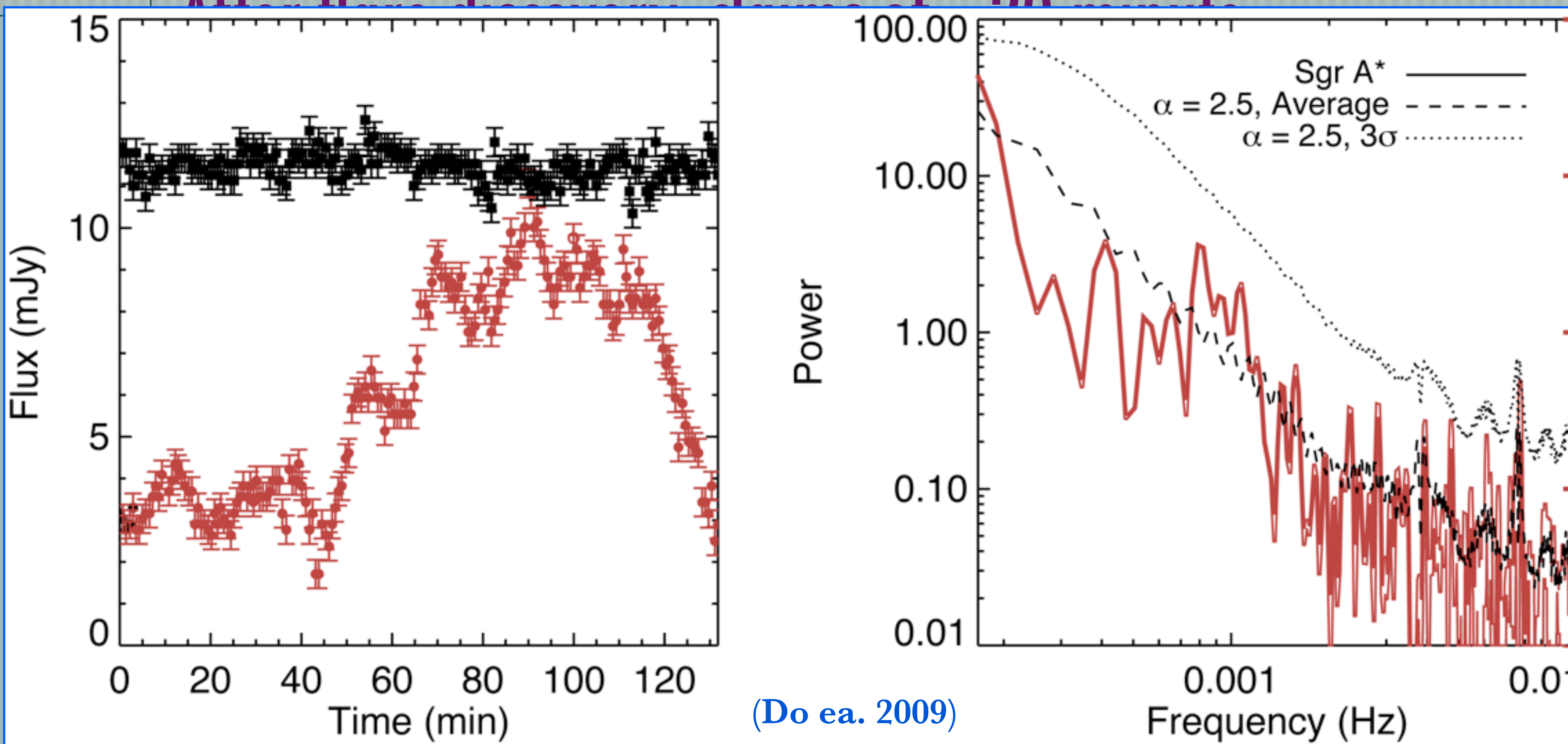
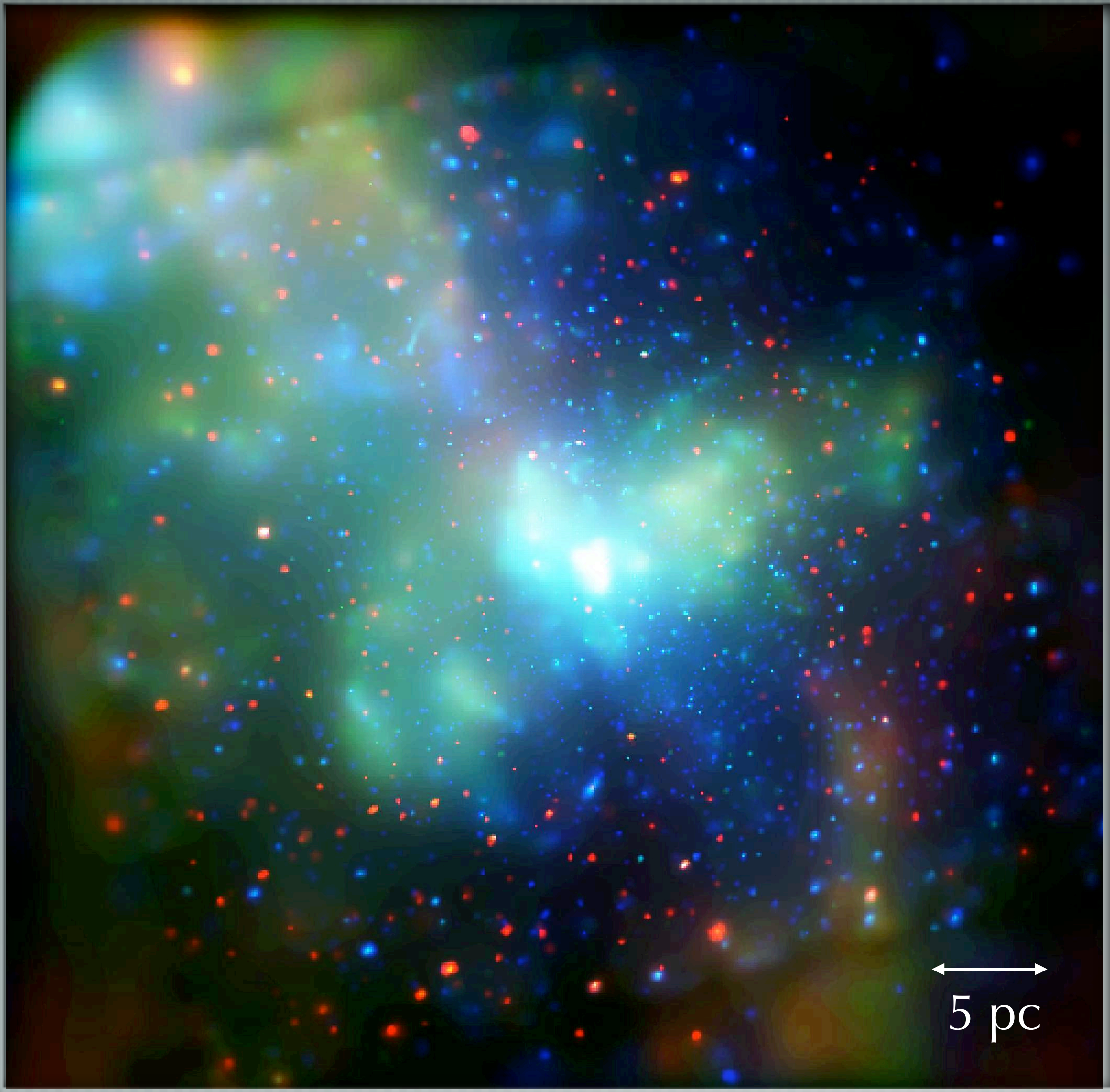


(Do ea. 2009)

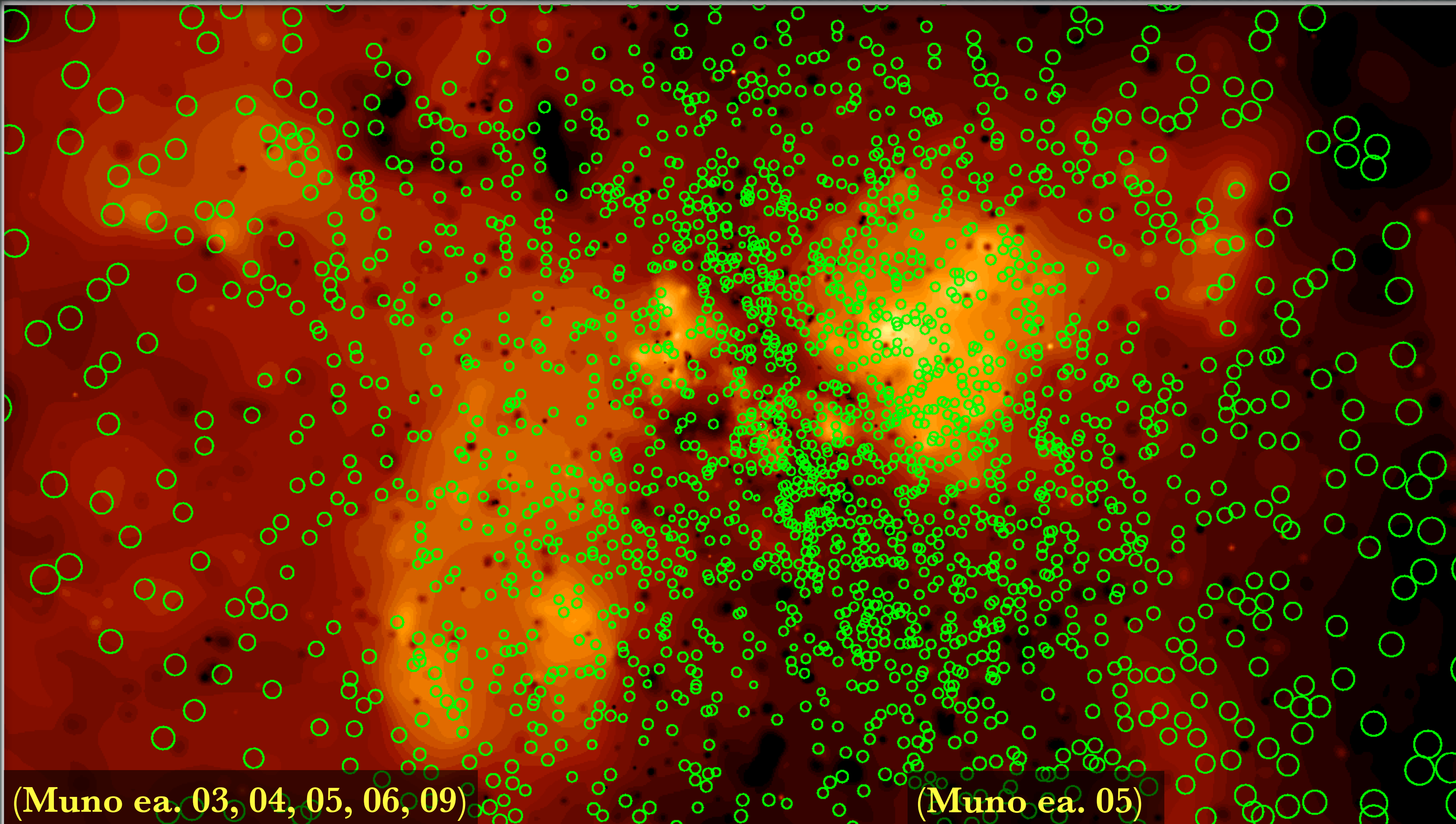
Why is Sgr A* so weak?



- 1 Msec (12 days) with Chandra ACIS over 7 yrs
- Reveals 4000+ pt. sources, diffuse gas, lobes, jet-like extrusion
- Hints about fate of infalling gas (and why it does not seem to reach Sgr A*)

(Baganoff ea. 03; Muno ea. 03, 04; Park ea. 04; Muno ea. 05)

Majority of inflowing molecular gas probably goes to star formation



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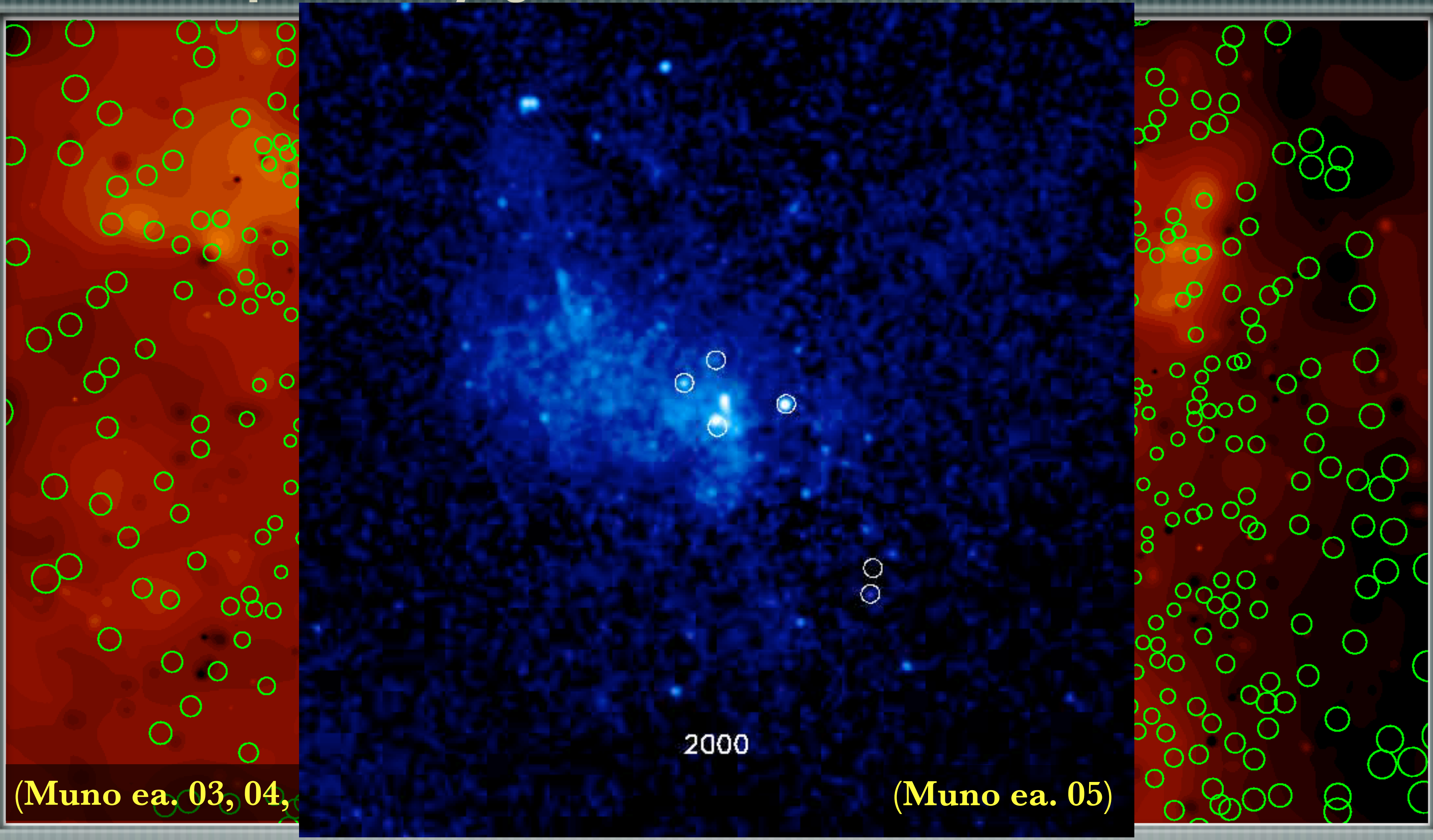
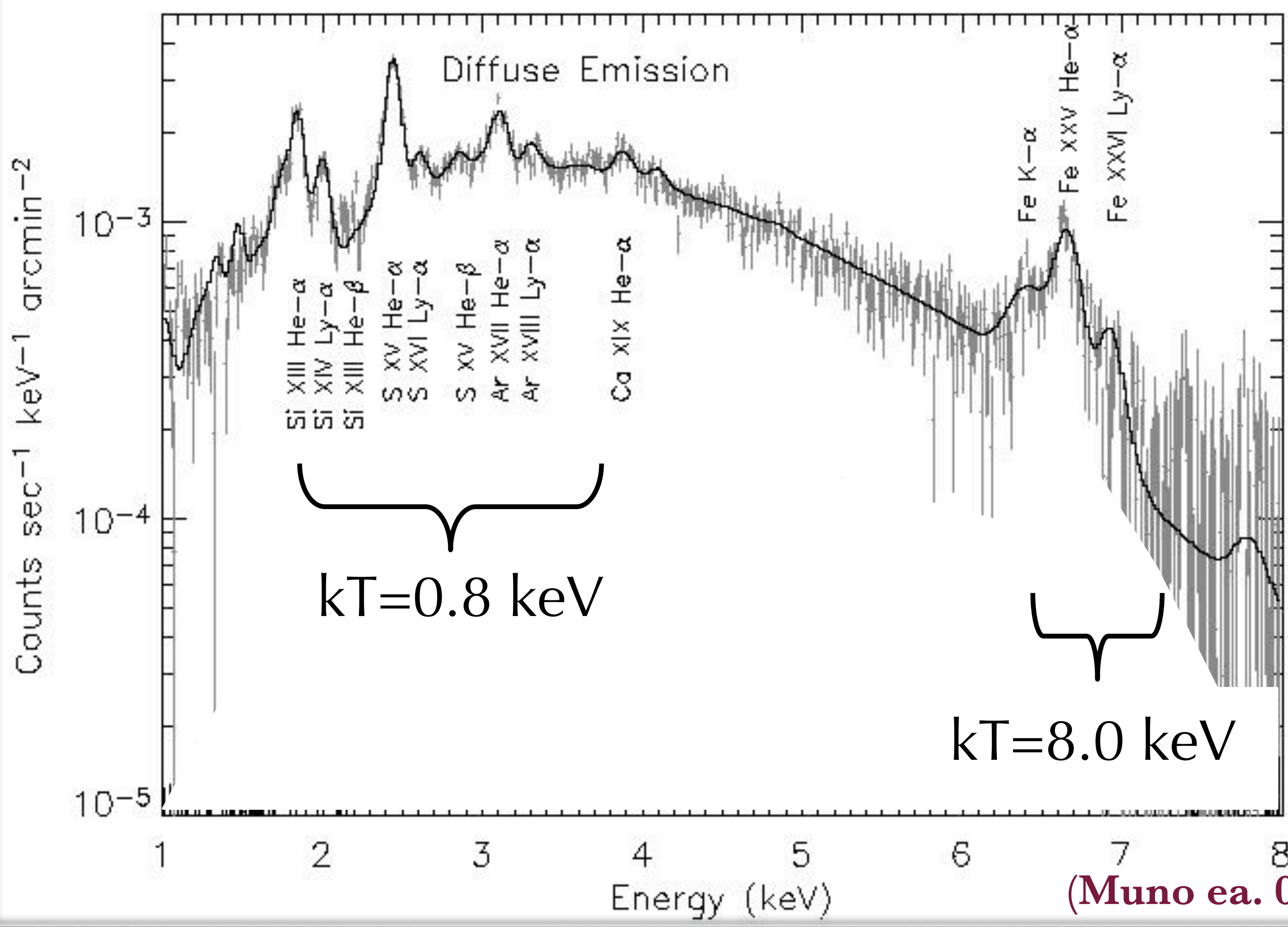


Two phases of diffuse gas in GC



(Muno ea. 04)

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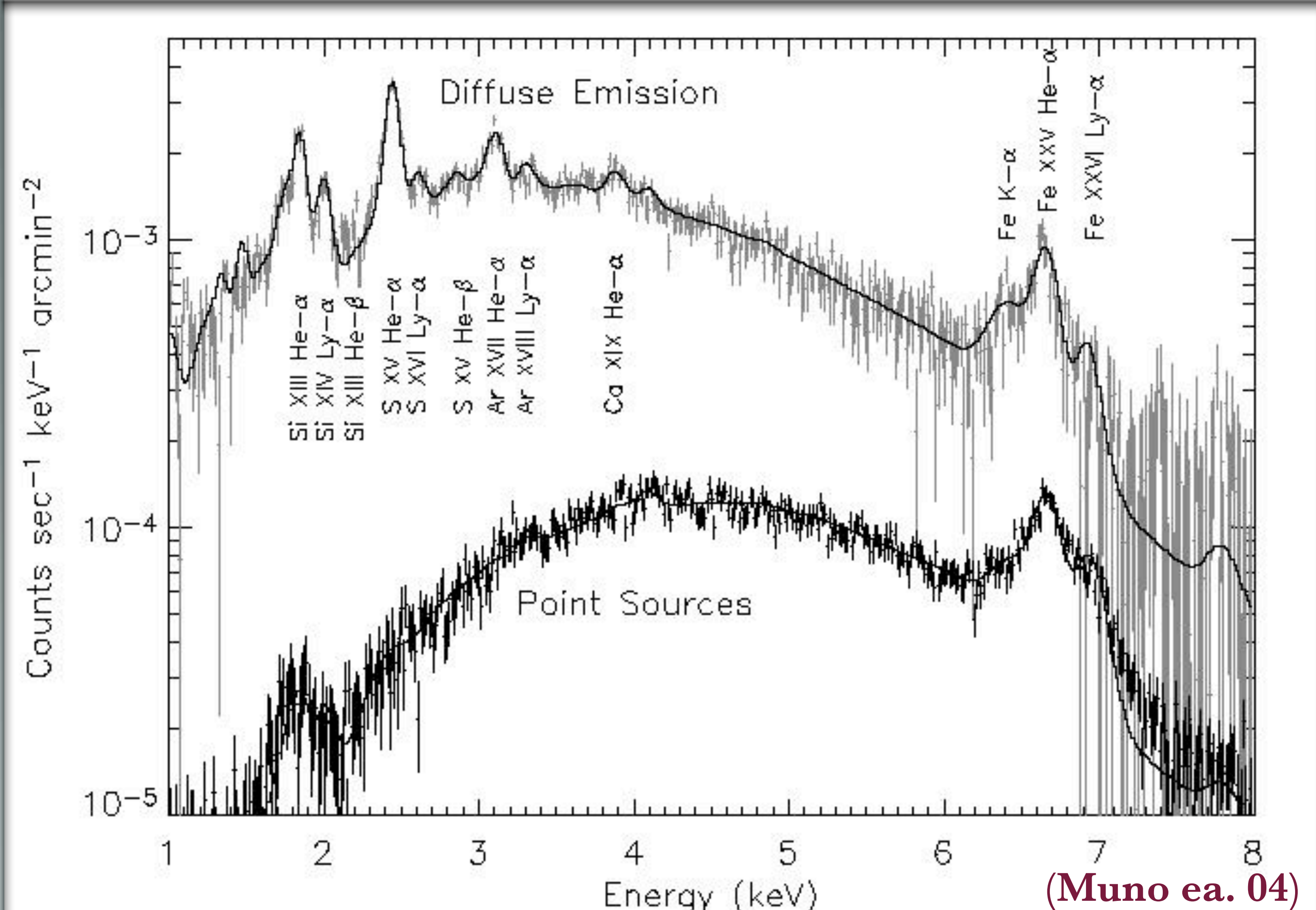
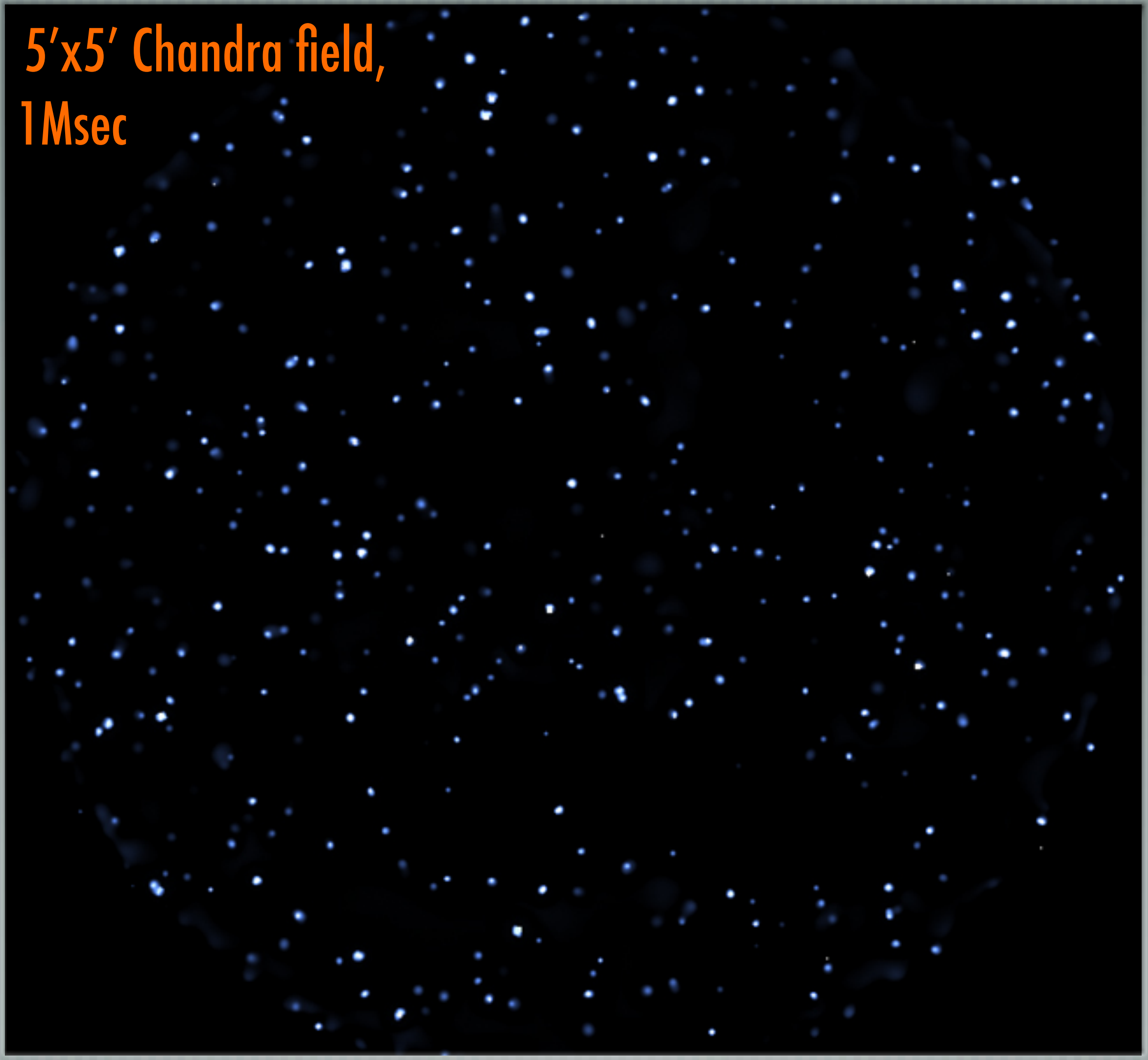


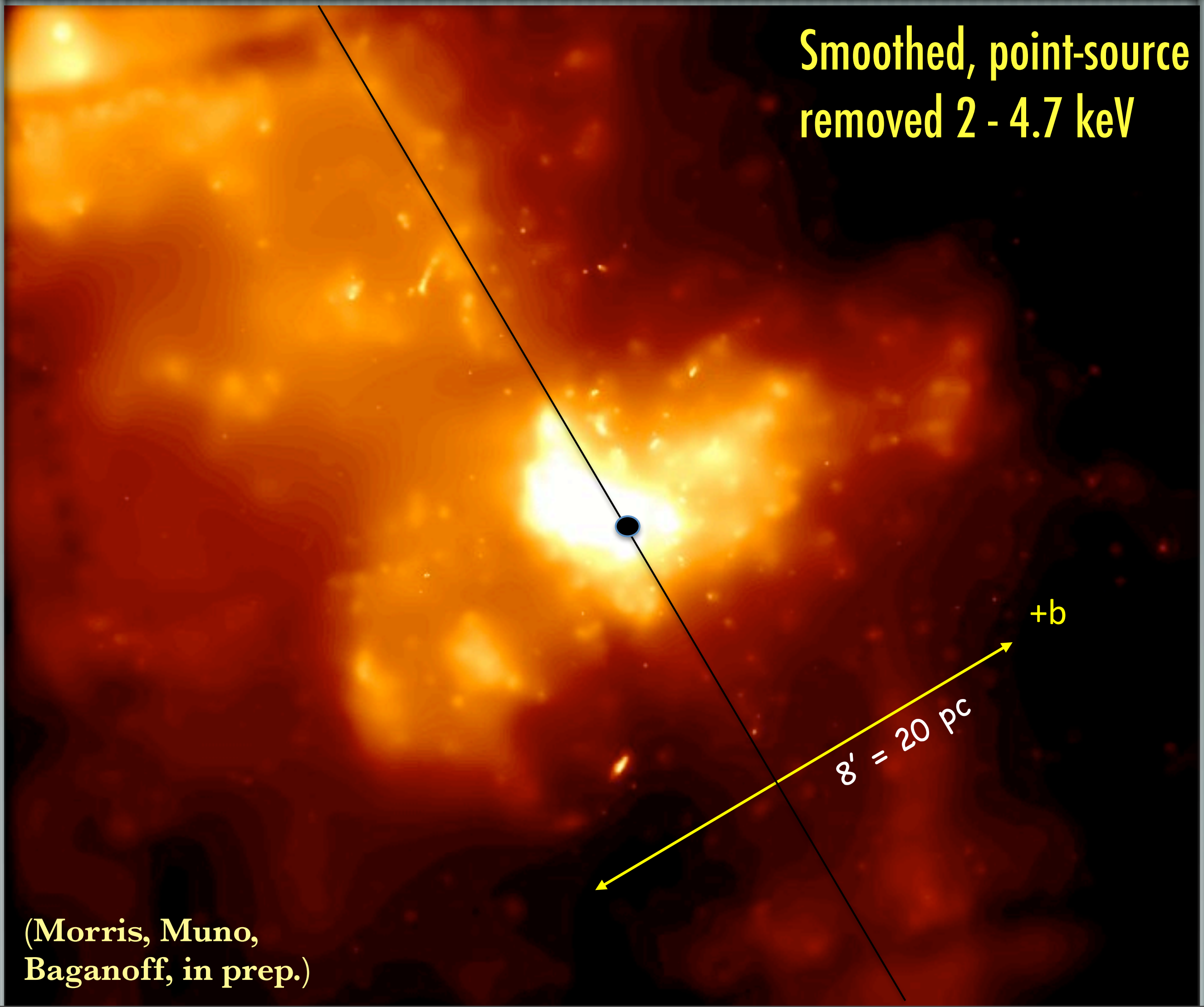
(Muno ea. 04)

Hot (8 keV) plasma = 80% resolved?

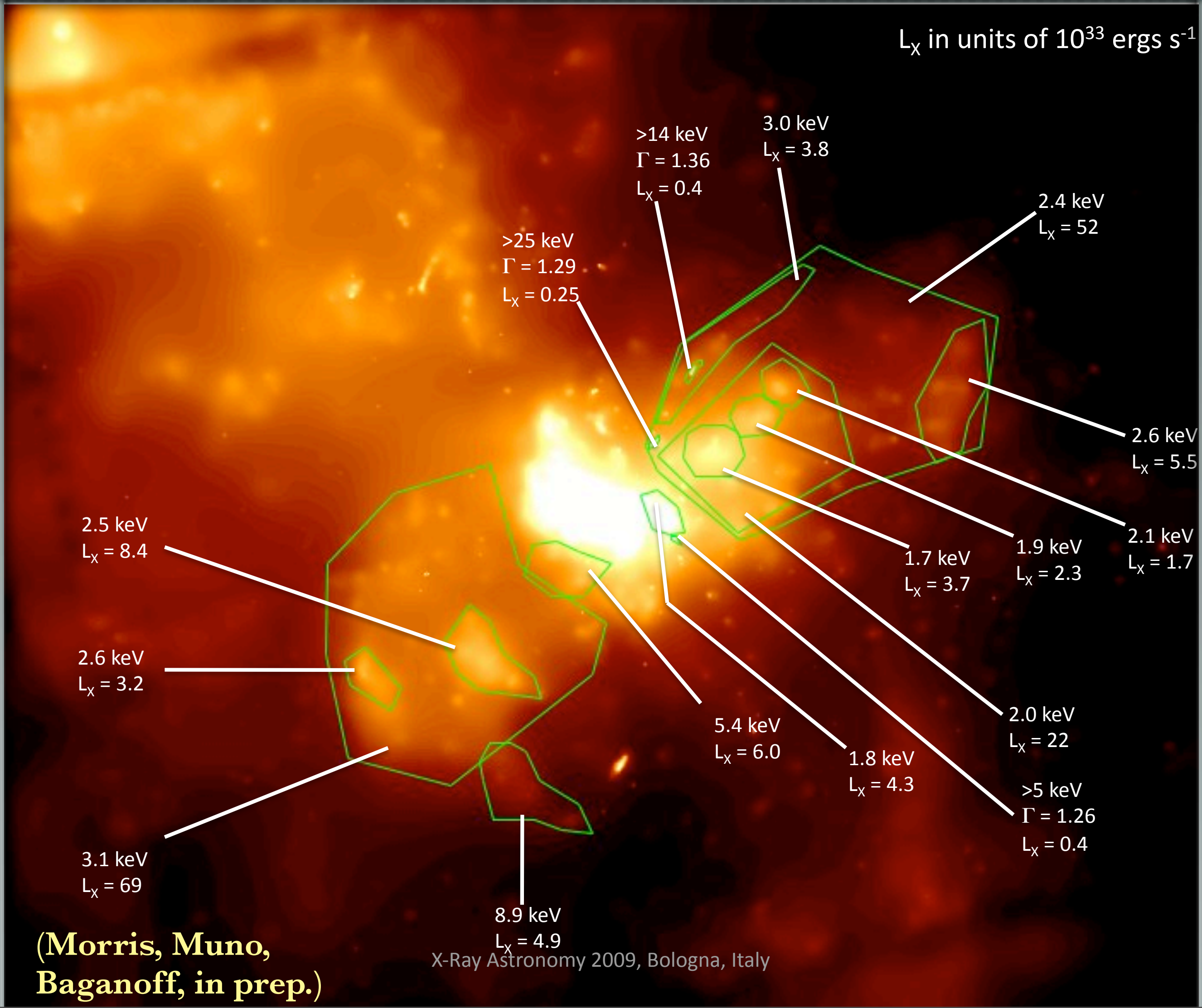


(Revnivtsev ea. 09, Nature)

Soft plasma – bipolar lobes



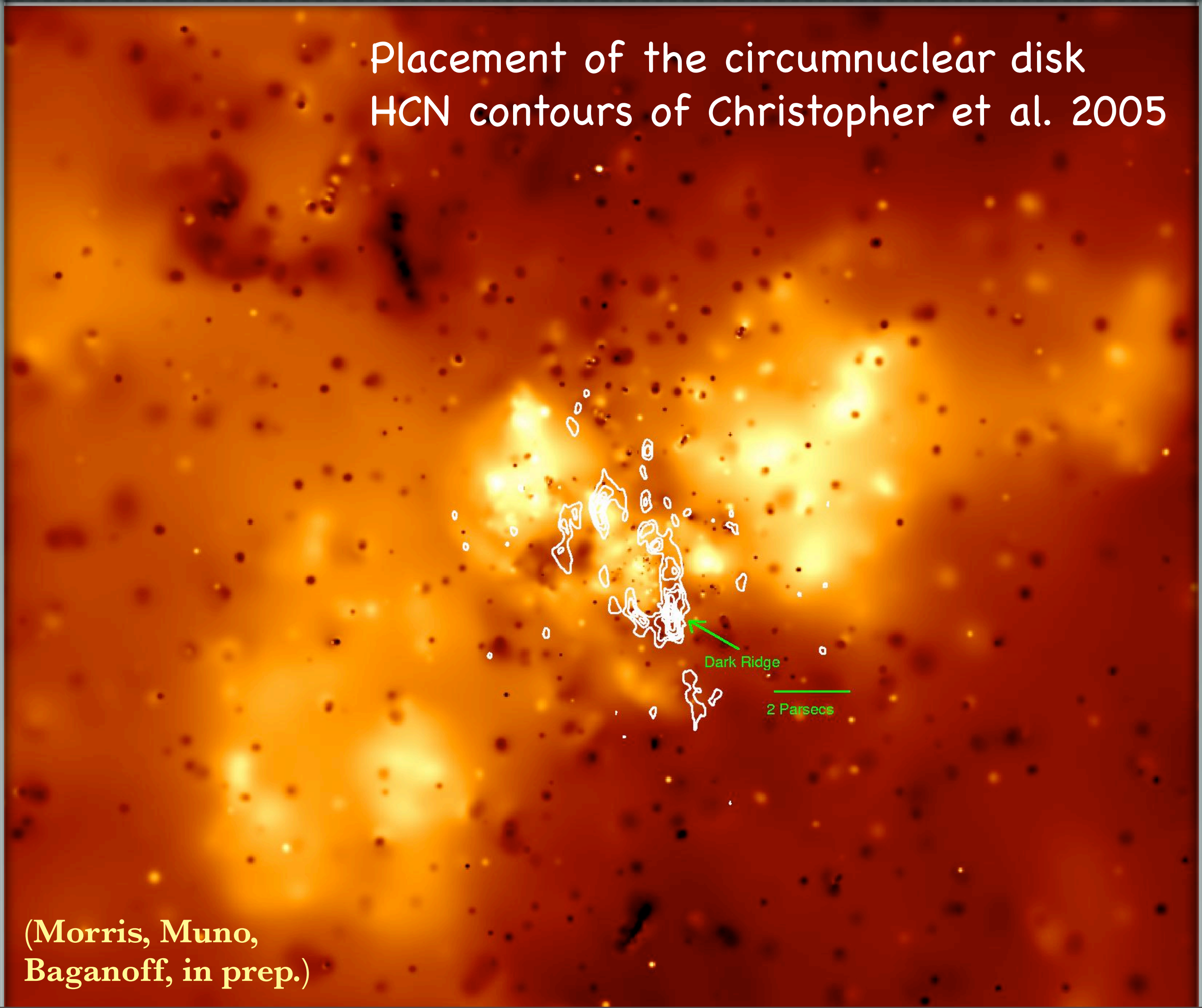
Soft plasma – episodic bursts?



(Morris, Muno, Baganoff, in prep.)

(Revnivtsev 09, Nature)

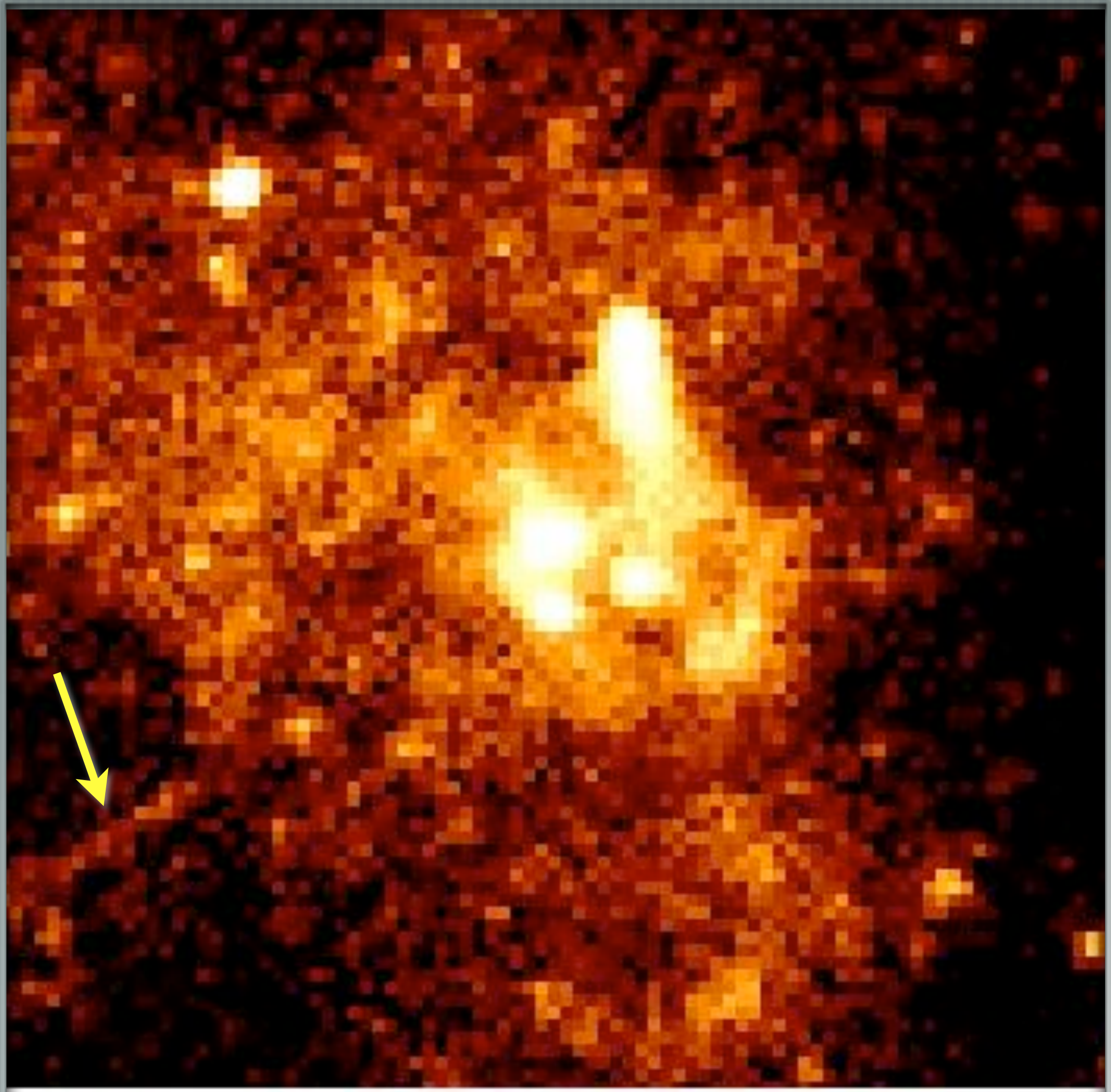
Bipolar lobes – Collimated thermal wind?



(Morris, Muno, Baganoff, in prep.)

(Revnivtsev 09, Nature)

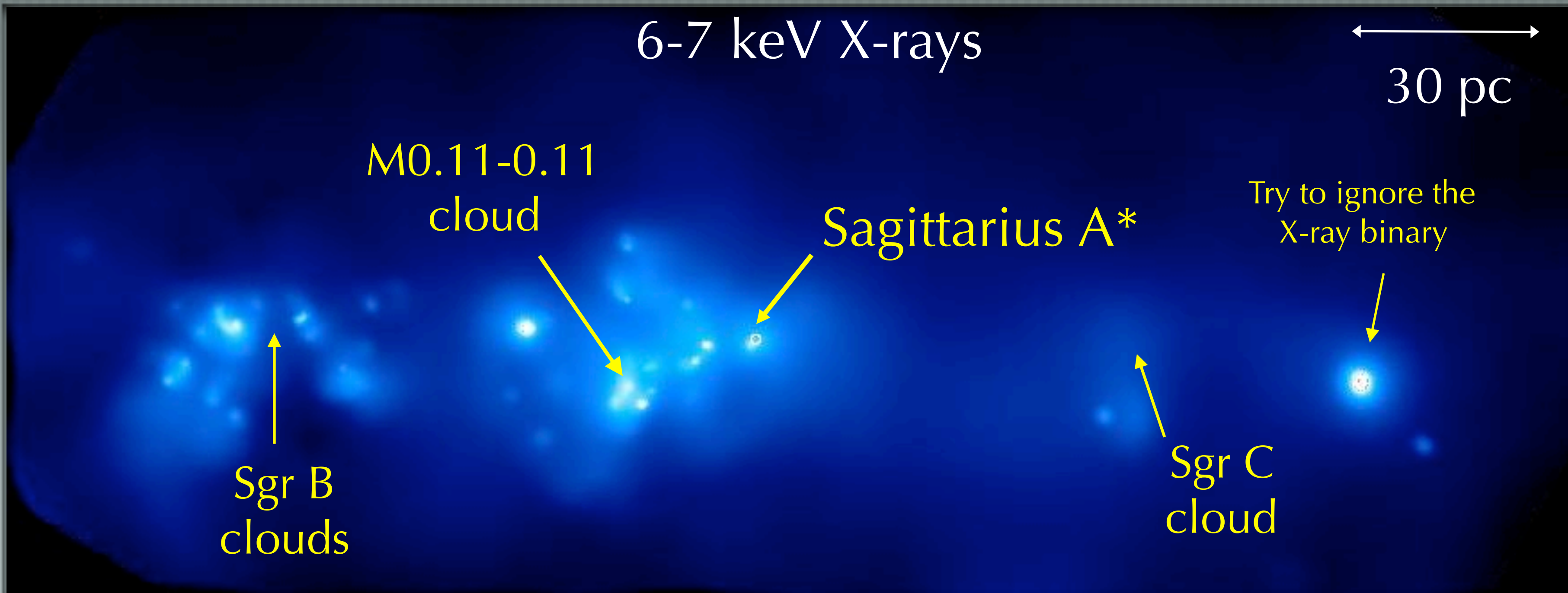
...or jet/episodic bursts from Sgr A*?



- Jet-like feature on same axis as lobes
- 3-4 pc separation of blobs ➠ 5000 yrs at thermal velocity
- Same timescale as predicted for tidal disruption of stars (T. Alexander)?
- Could be embedded in thermal wind

(Morris, Muno, Baganoff in prep.)

Was Sgr A* more active in the past?

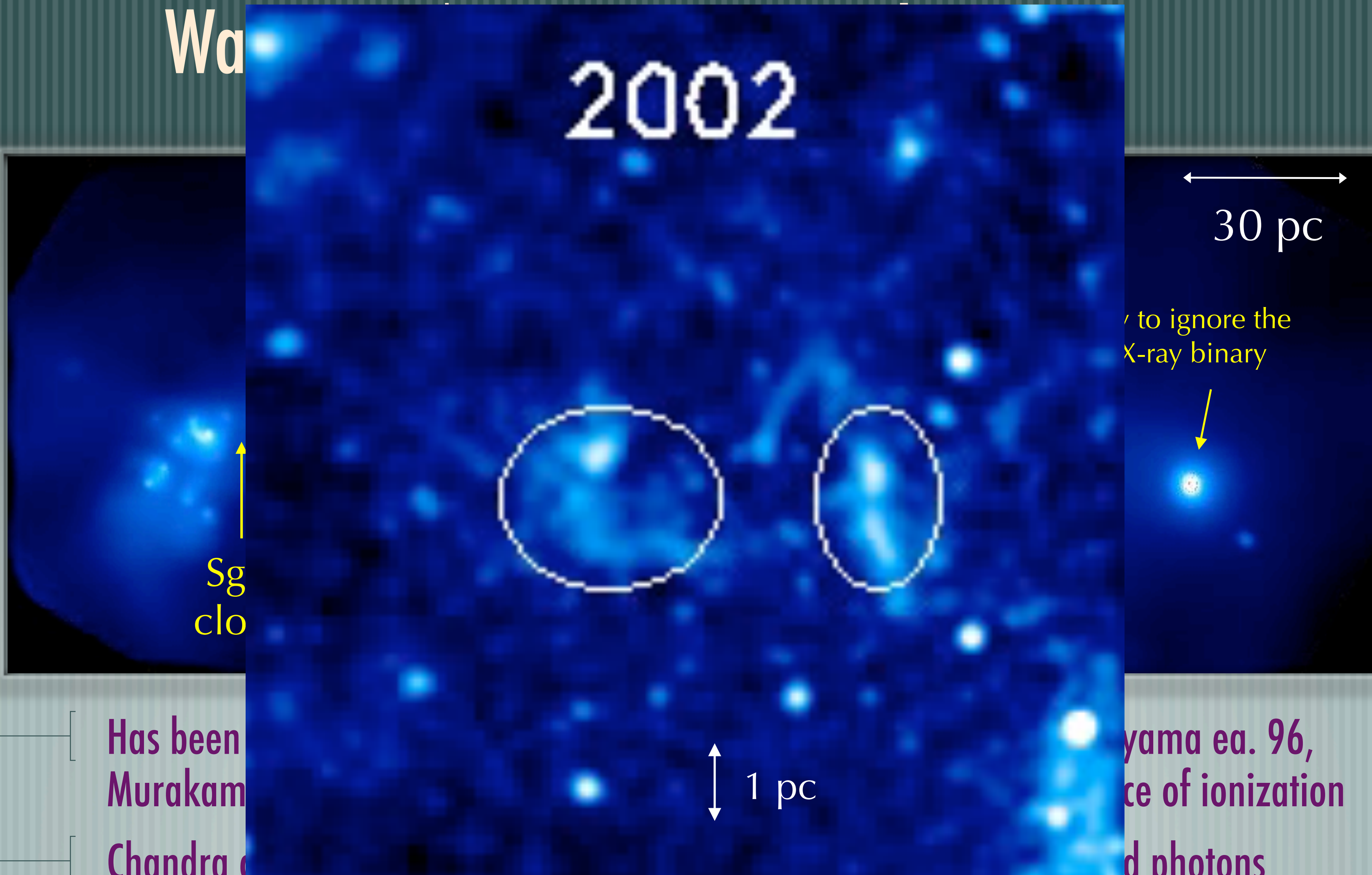


Muno et al.)

- Has been suggested that the best source is prior activity of Sgr A* (Koyama ea. 96, Murakami ea 00, Revnivtsev ea. 04) but some controversy about source of ionization
- Chandra can actually resolve the "wave" of fluorescence, must be hard photons
- Implies L≤10^{38} erg/s outburst lasting 3 yrs, about 60 & 300 years ago!

1 pc

Wa



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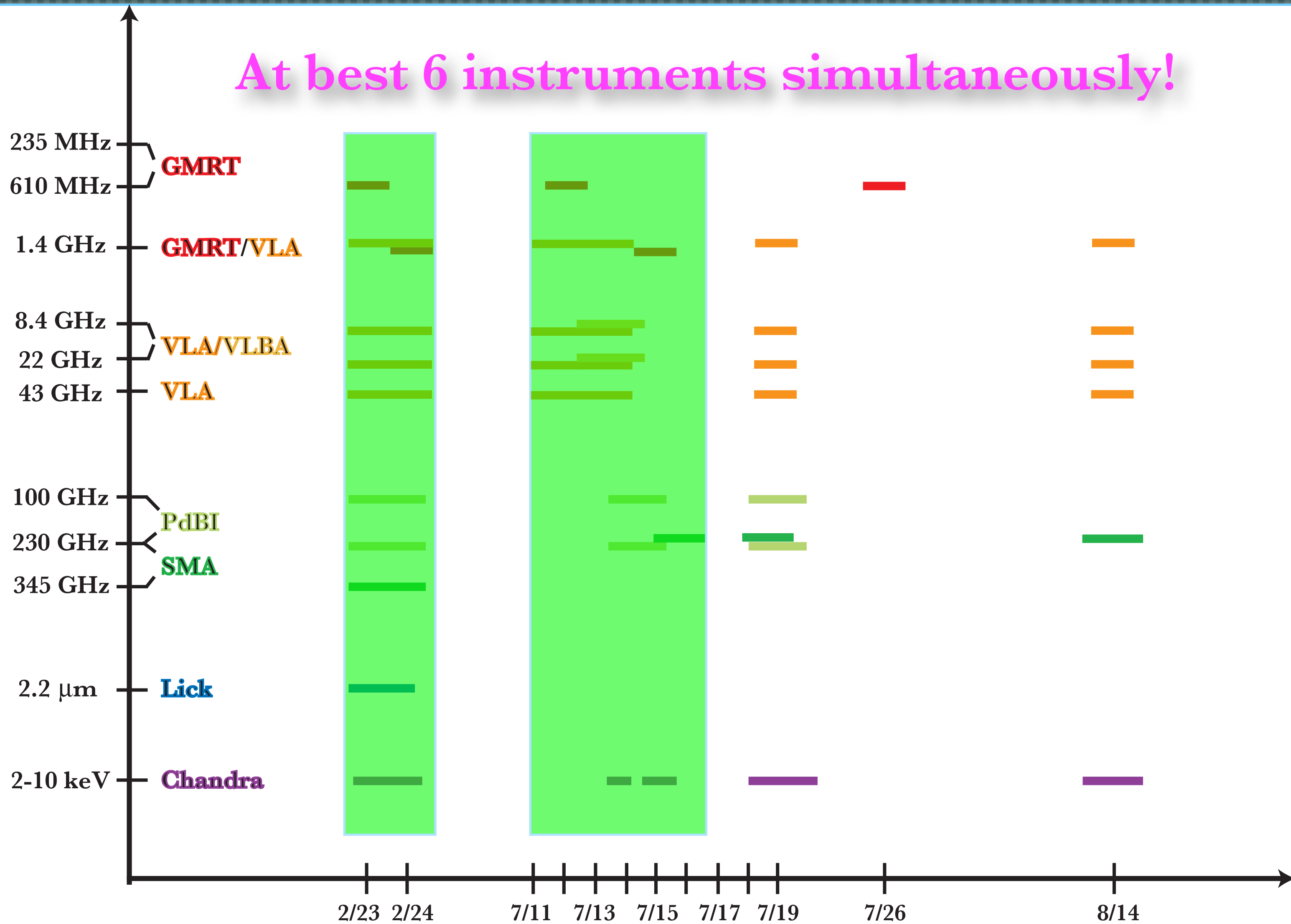
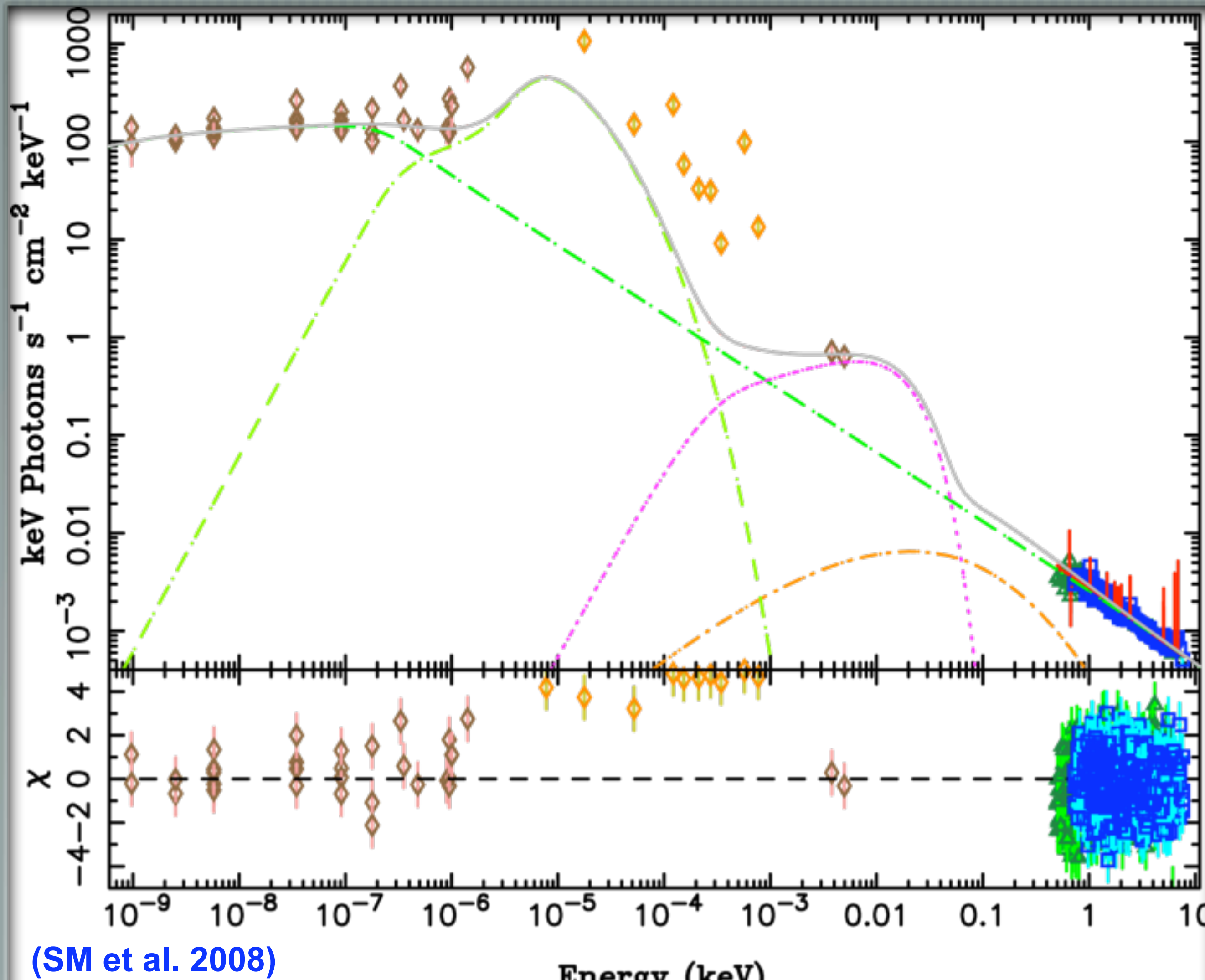
Best bridge from Sgr A* to LLAGN: M81*



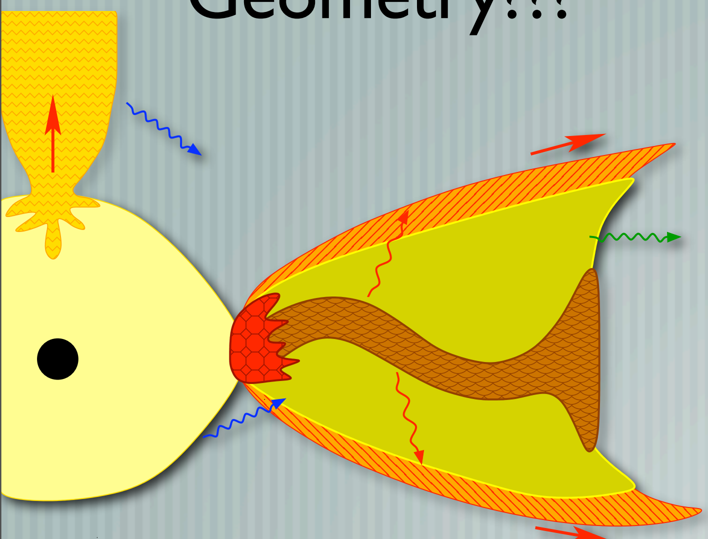
(SM, Nowak, Young ea. 08)

M81: Hard state equivalent (LLAGN)?

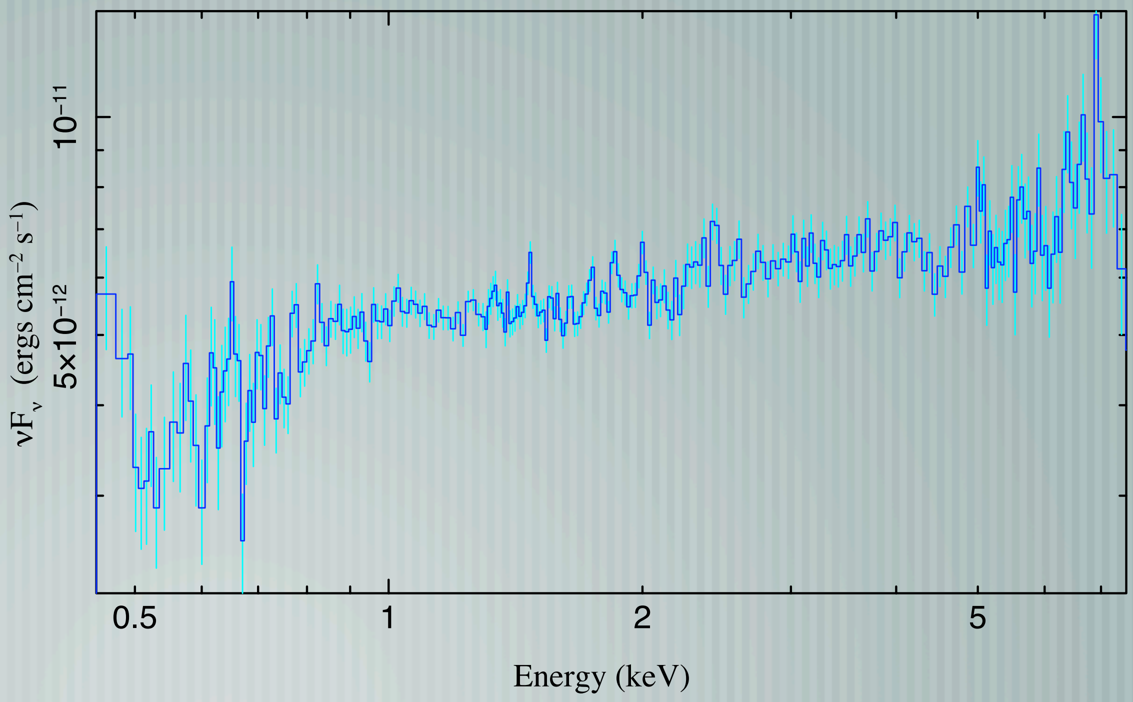


M81*: 450 ks with HETGS (GTO + GO)

First evidence for ADAF-Type multi-T Geometry???



300 ksec Chandra-HETG



(Young, Nowak, SM ea. 07; SM, Nowak, Young ea. 08)

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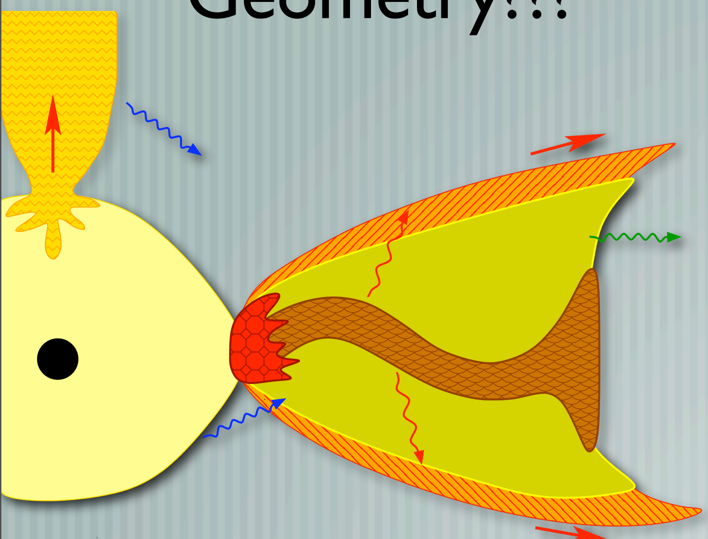

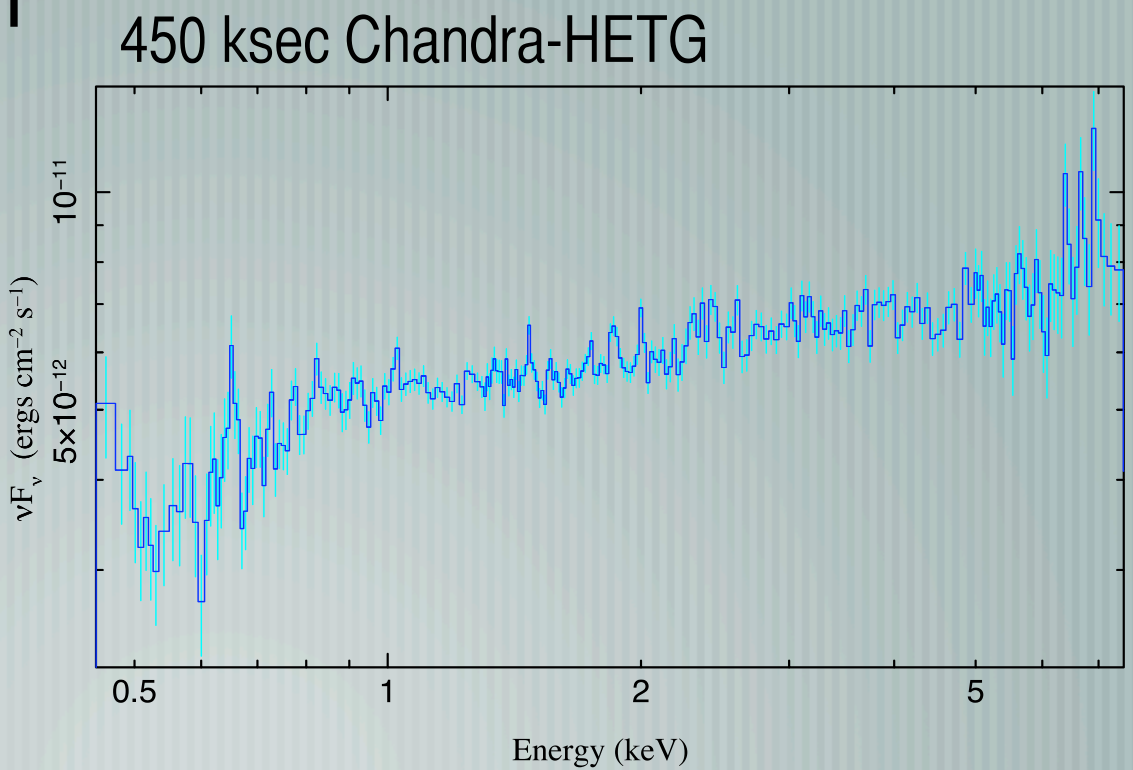

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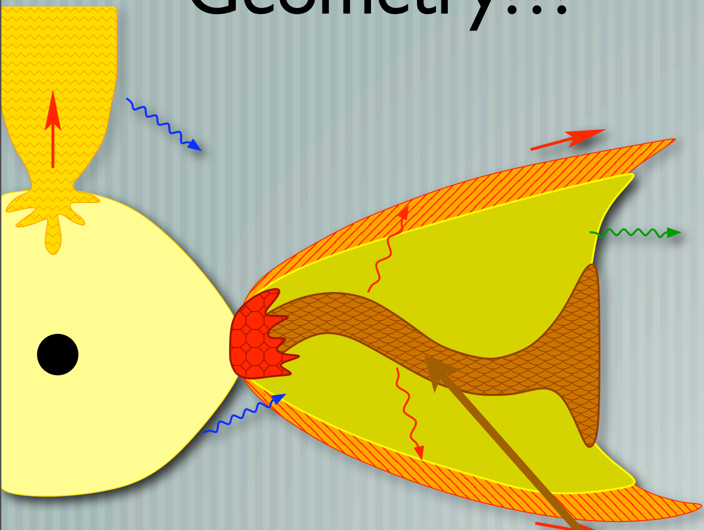

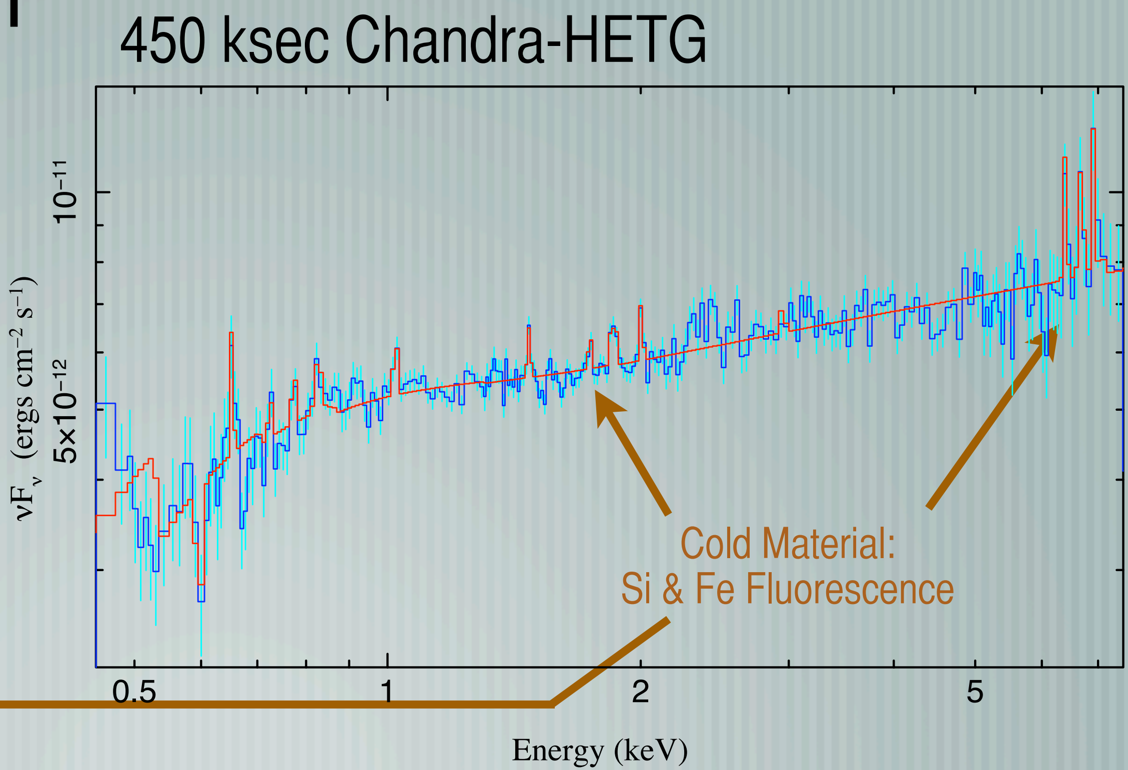

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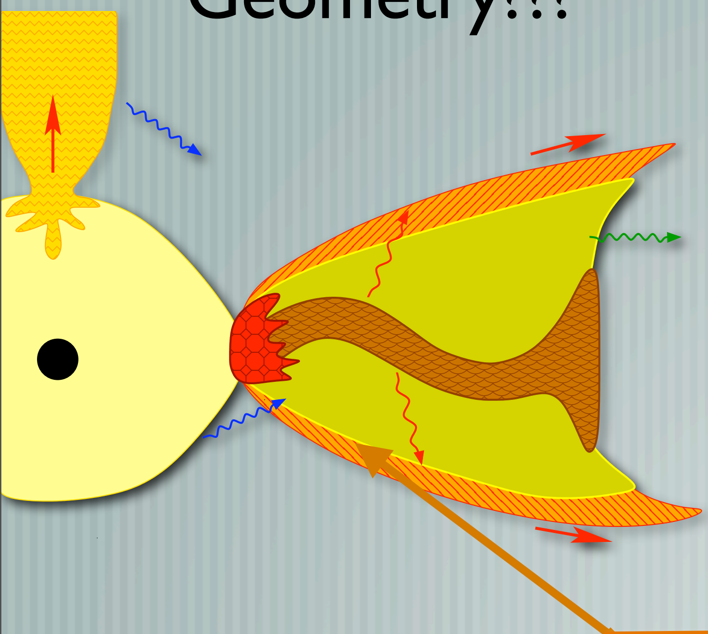

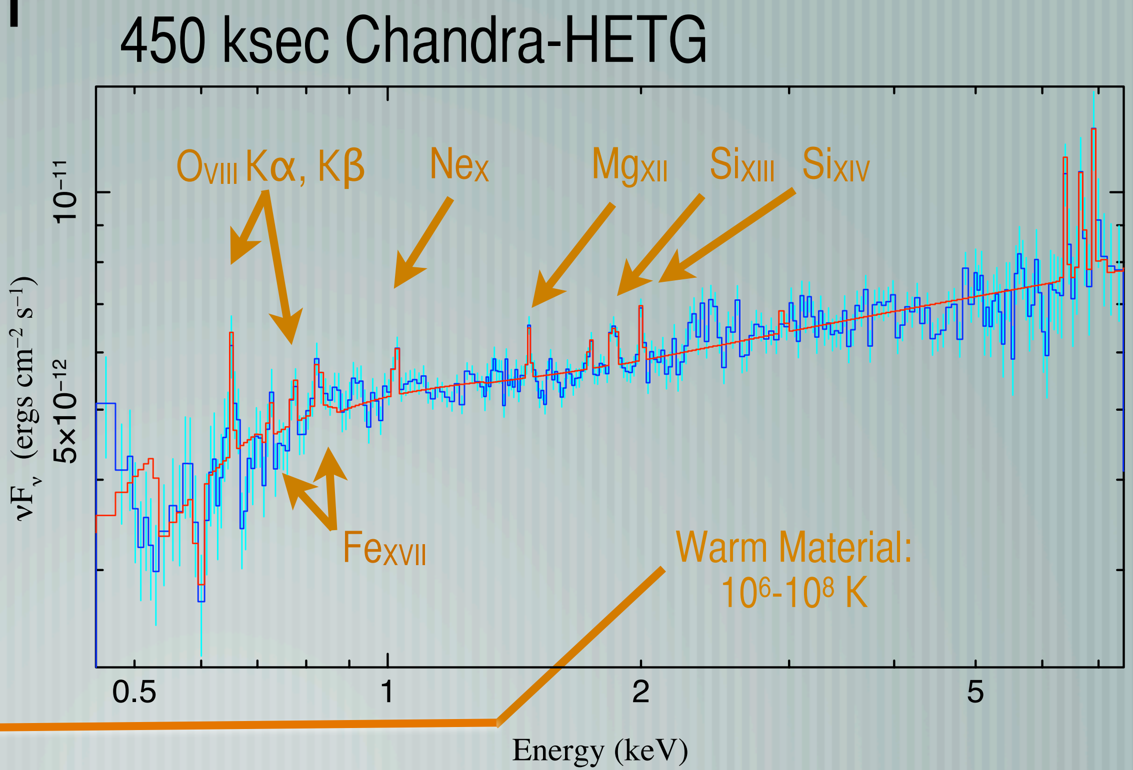

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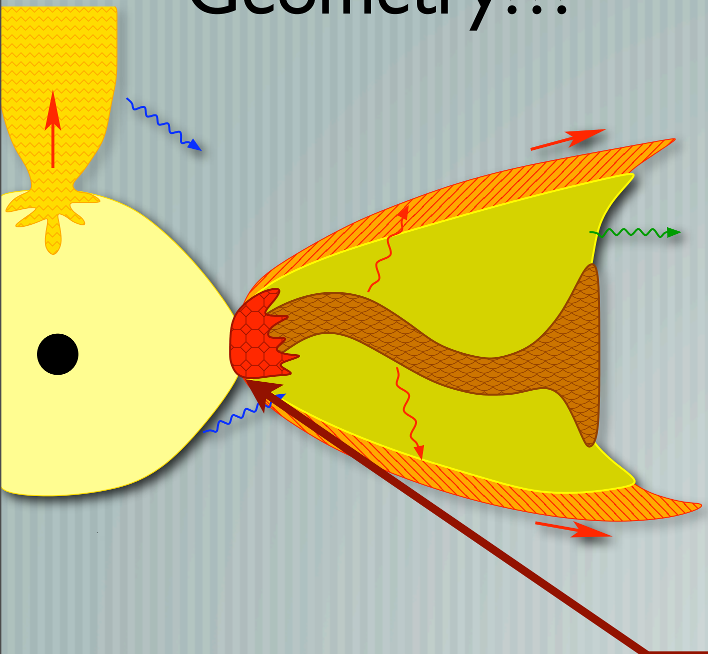
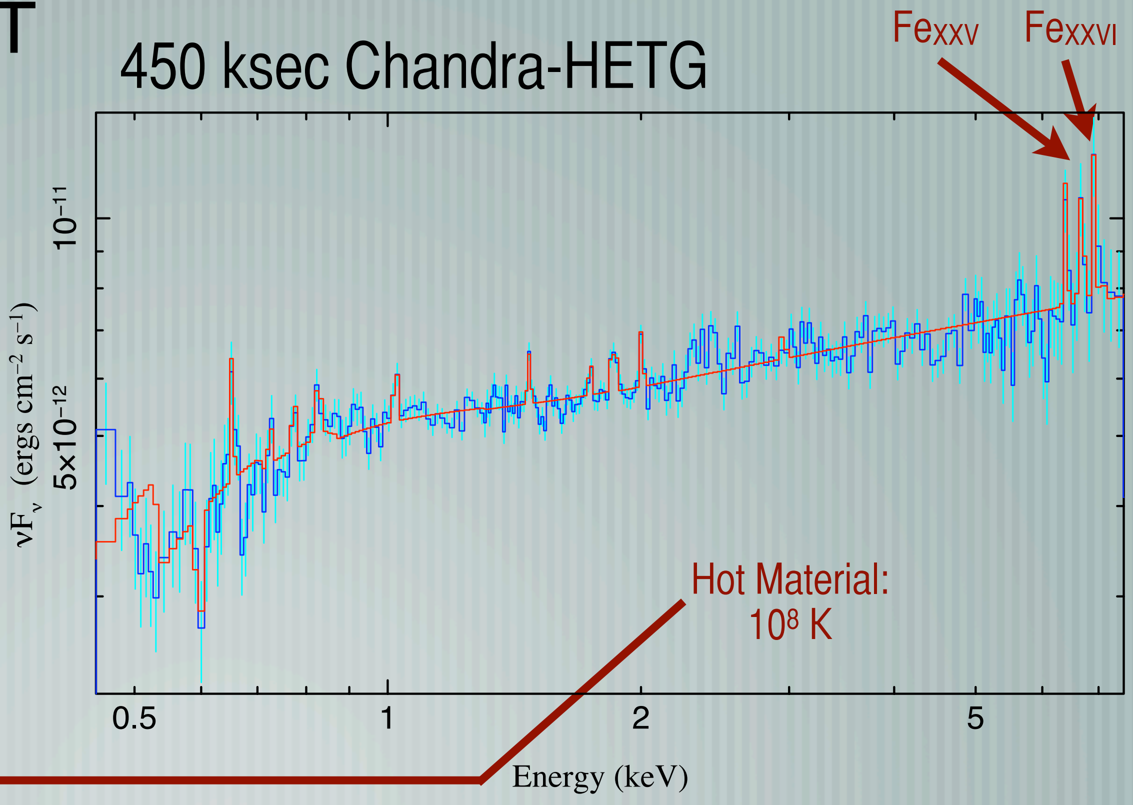
First evidence for ADAF-Type multi-T Geometry???





(Young, Nowak, SM ea. 07; SM, Nowak, Young ea. 08)

Cool stuff I don’t have time to cover

With over 100 papers on Chandra’s GC observations, I obviously am missing several important studies, including:

- Sgr A East: Maeda ea. 2002
- Top-heavy mass function? Nayakshin & Sunyaev 2005
- IRS 13 cluster detection: IMBH or WR colliding winds? Arendt ea. 2008
- Arches cluster detection: Yusef-Zadeh ea. 2002
- Magnetic field-related features, wisps and filaments: Morris, Wang, Lang
- Relationship of Sgr A* to XRBs and other LLAGN: SM, Nowak,Falcke
- NGC4258 multiwavelength campaign a la Sgr A* and M81: SM, Nowak, Reynolds, Wilms, Greenhill

Summary/Outlook

Without Chandra's amazing spatial resolution, we would never have found Sgr A*, or resolved the ~10k GC X-ray sources

- Sgr A* is very weakly active, so weak that we needed to modify our understanding of accretion: radiative efficiency not enough!
- But it is probably very typical of a phase many galaxies undergo
- Diffuse gas shows bipolar features, hints of past activity
- Incredible resolution of Chandra has revealed entire populations of stellar remnants and young stars, providing clues about star formation and its relationship to the AGN phenomenon
- Future: as IR interferometry (PRIMA,GRAVITY) and submm VLBI develop, potential of MW combined with Chandra to solve outstanding problems is unprecedented: can image *every* piece of the puzzle!