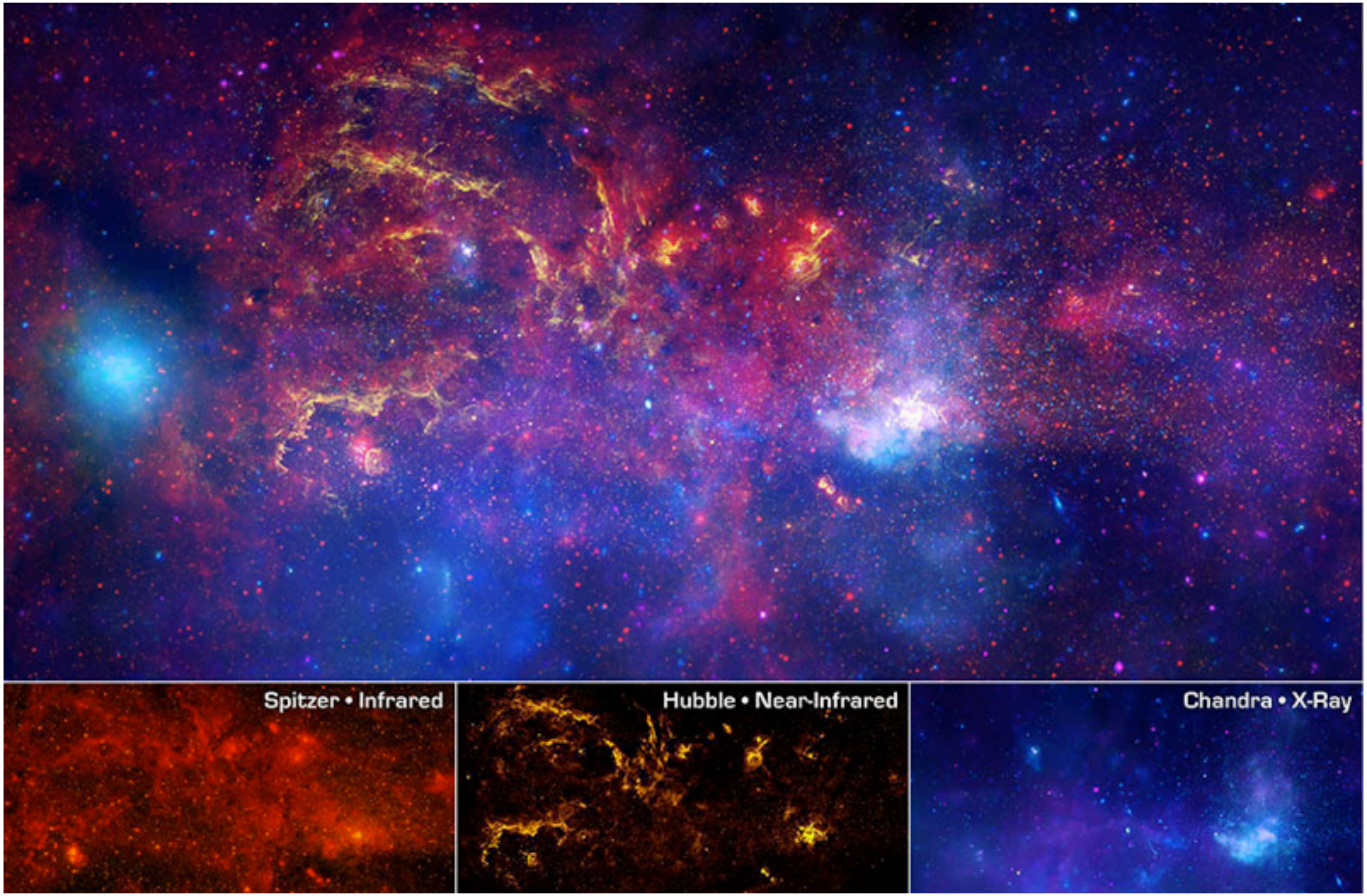
Theoretical Aspects in The Search for New Physics at the Galactic Center



Tim Linden
UC - Santa Cruz

Cosmic Frontiers Workshop SLAC March 6, 2013

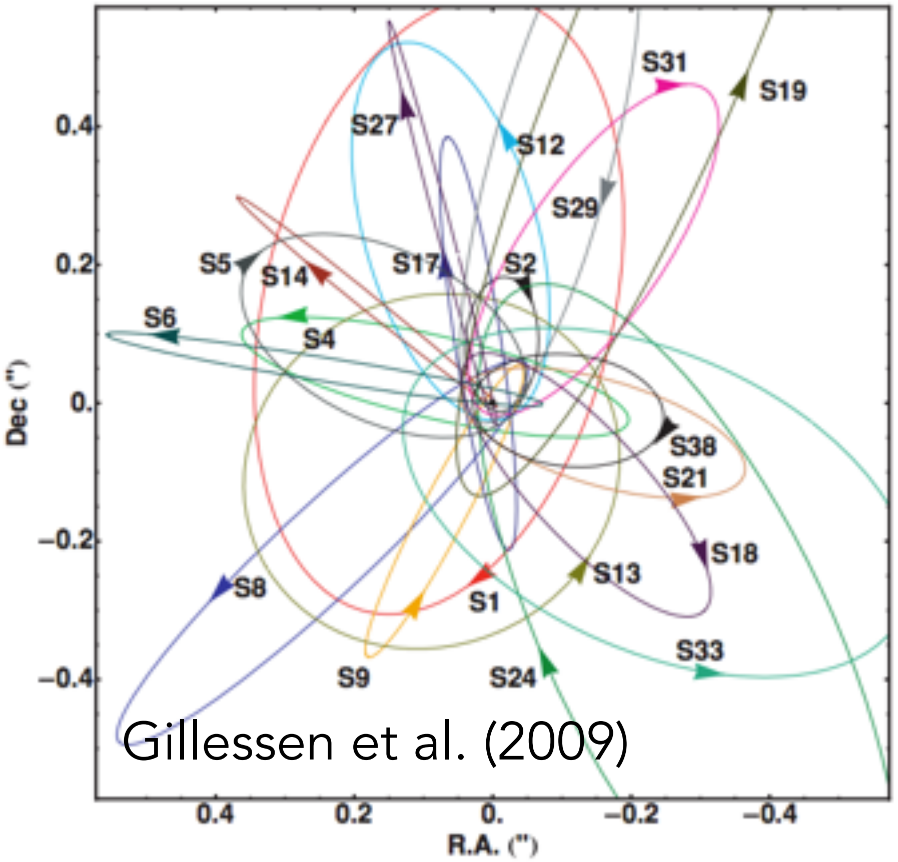
What can we observe at the galactic center?

What can we observe at the galactic center?

Basically - **everything**.

(For better or worse)

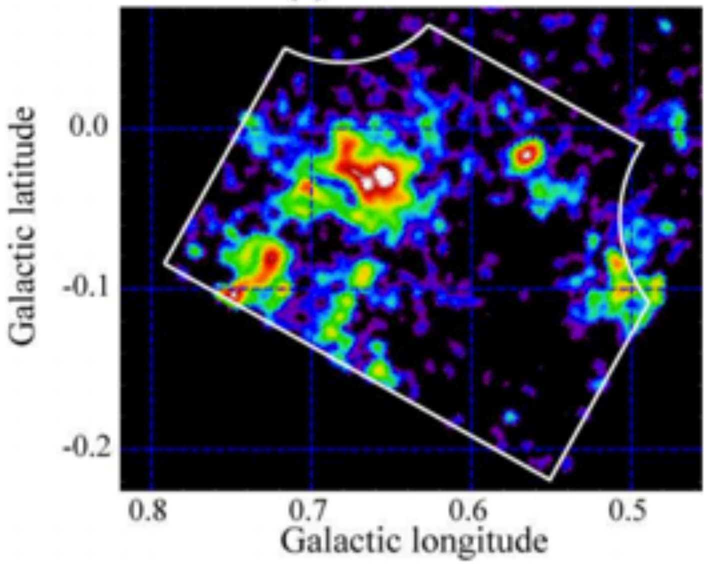
Supermassive Black Hole



Gillessen et al. (2009)

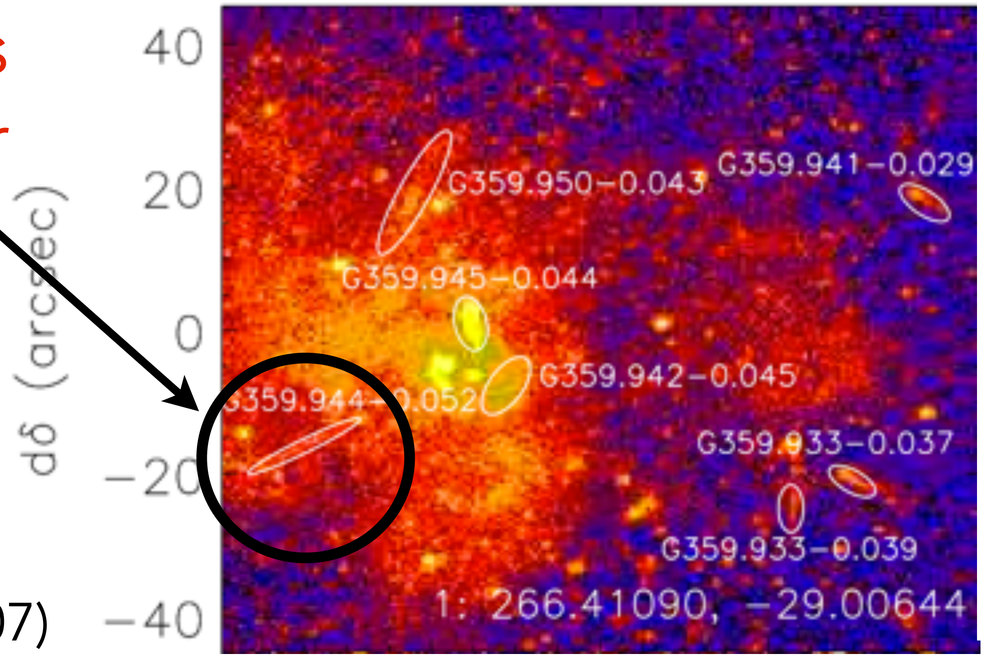
- Observations support a black hole mass of about 4 x 10^6 M_o
- Accretion from Black Hole is highly sub-Eddington (7 x 10^{35} erg s^{-1} is 10^{-9} Eddington)

(a) Chandra 2000



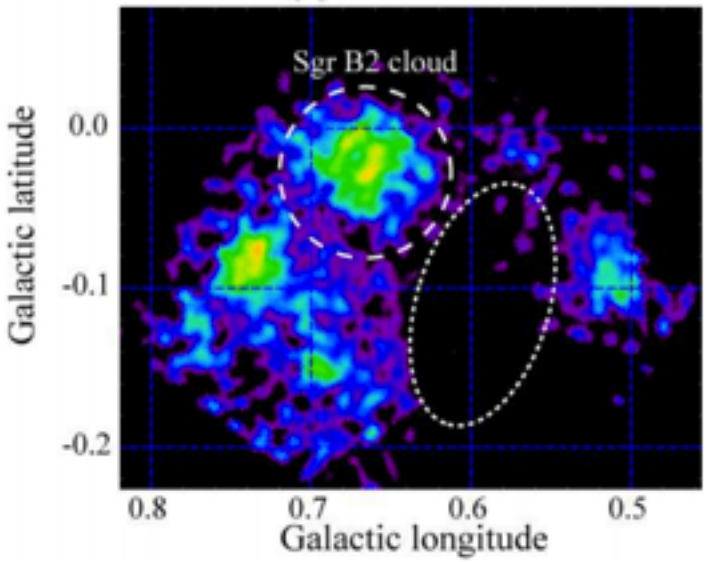
- There is evidence of an outburst ~300 years ago

- Possible evidence of jets from the Galactic Center



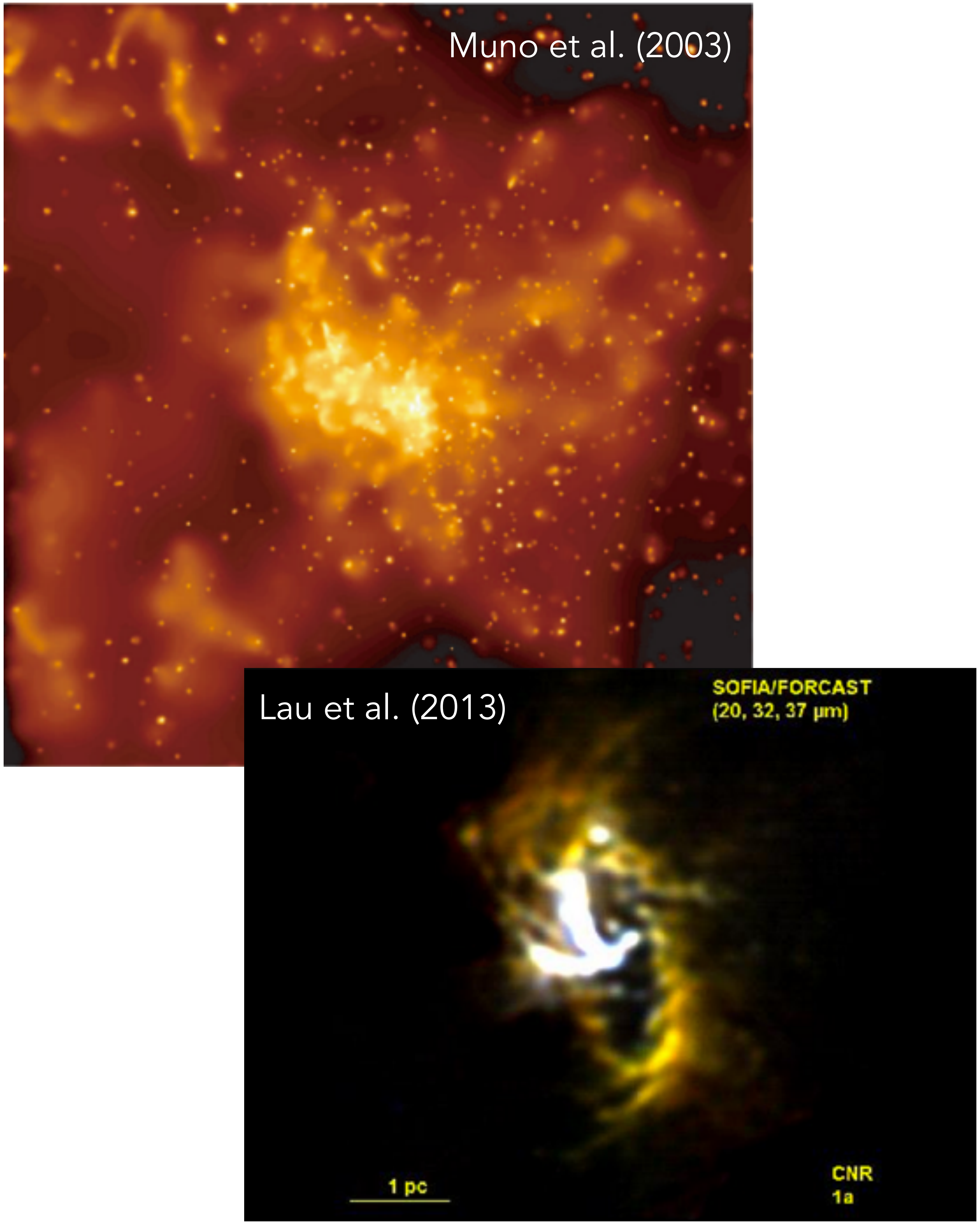
Muno et al. (2007)

(b) Suzaku 2005



Koyama et al. (2008)

Extremely Dense Star Formation Region



Muno et al. (2003)

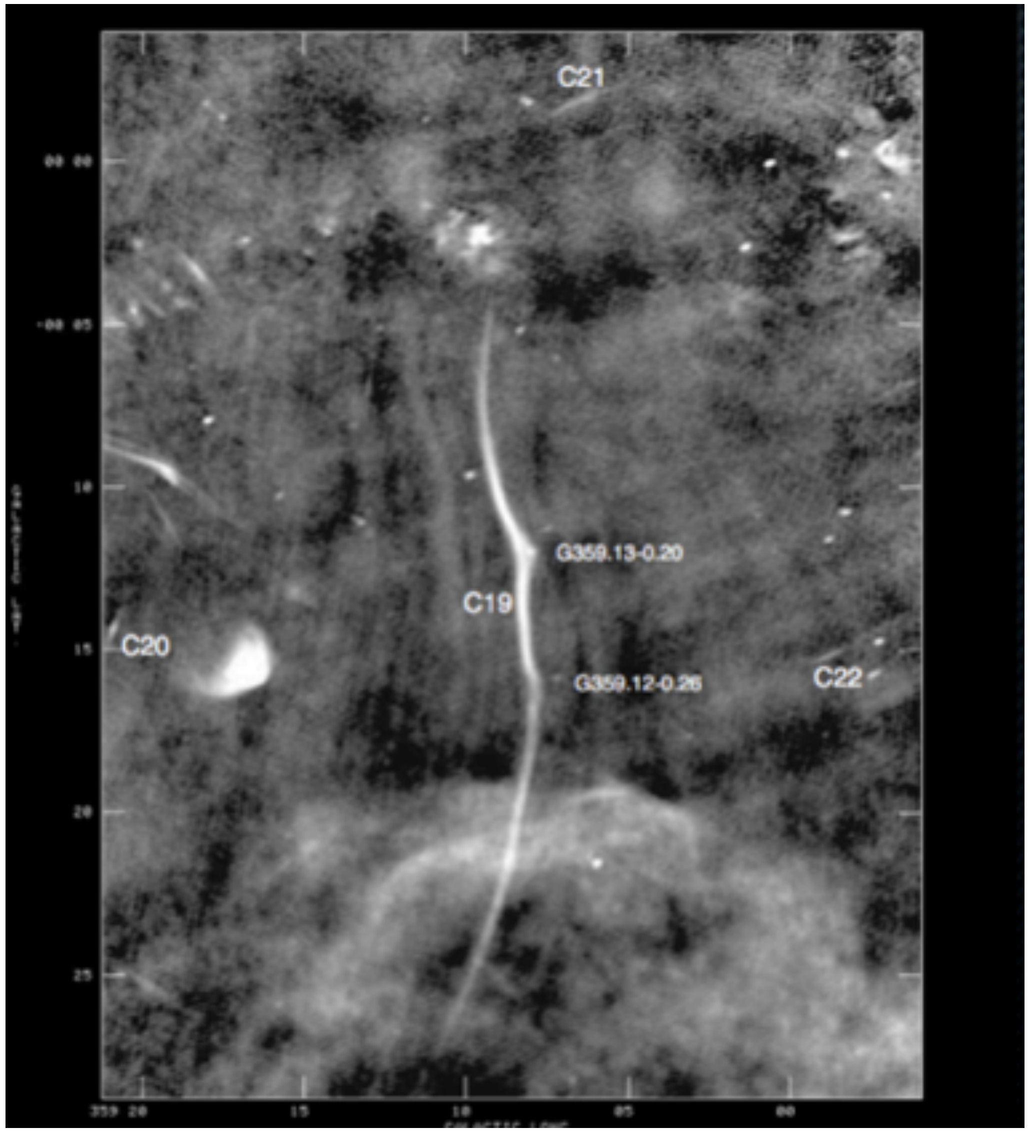
Lau et al. (2013)

- Chandra observed 2357 point sources within 20 pc of Sgr A*
- Majority of sources likely to be stellar remnants (CVs, HMXBs, LMXBs, pulsars, SNRs)
- Densest known Gas Cloud in the Milky Way (Circumnuclear Ring)
- Numerous Unsolved Theoretical Problems - “Paradox of Youth” and the “Conundrum of Old Age”

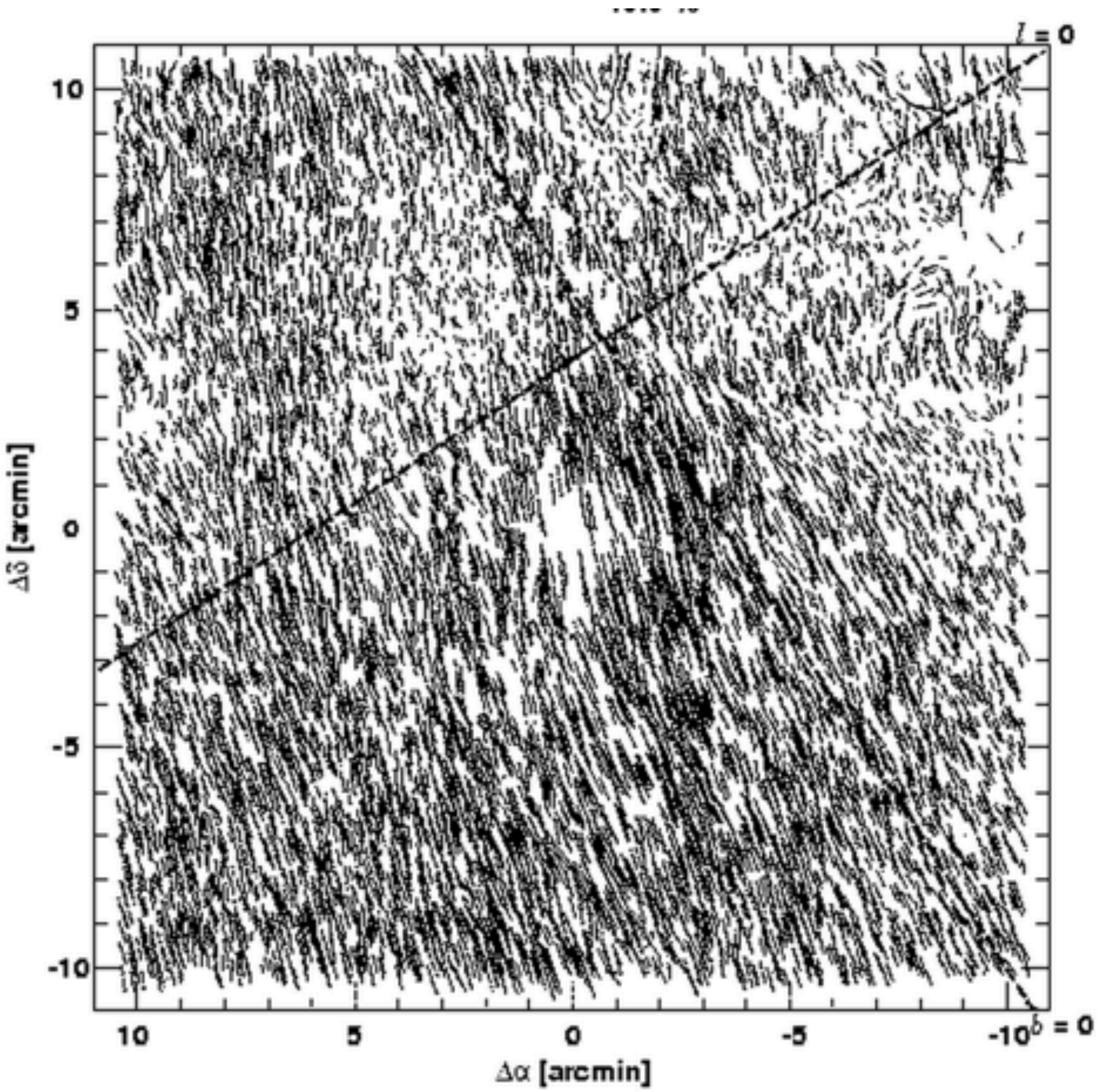
Tangled Magnetic Fields and Anisotropic Diffusion

- The magnetic fields of the galactic center are poloidal and very non-homogenous

- Peculiar regions, such as the filamentary arcs



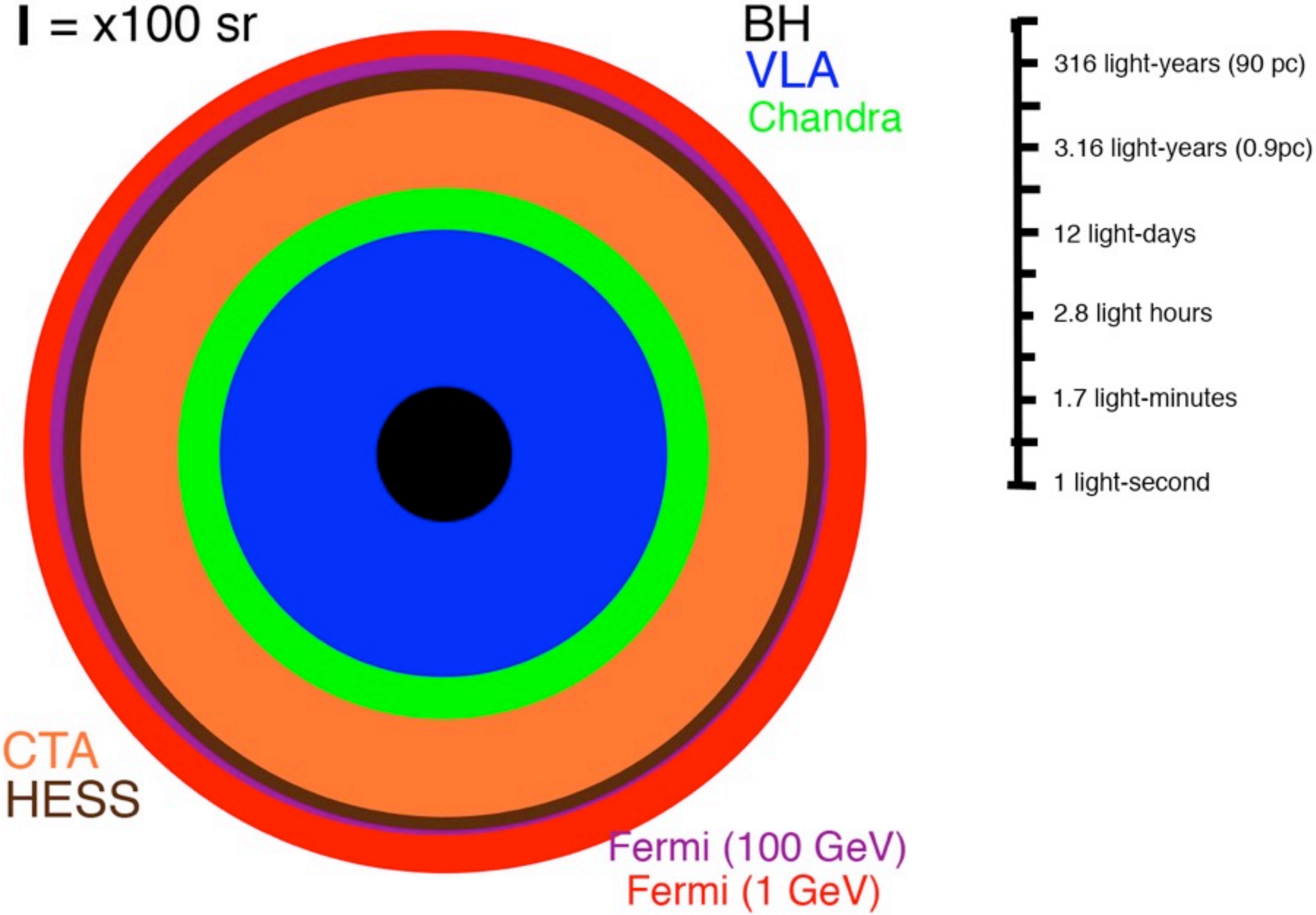
Yusef-Zadeh et al. (2004)



Nishiyama et al. (2009)

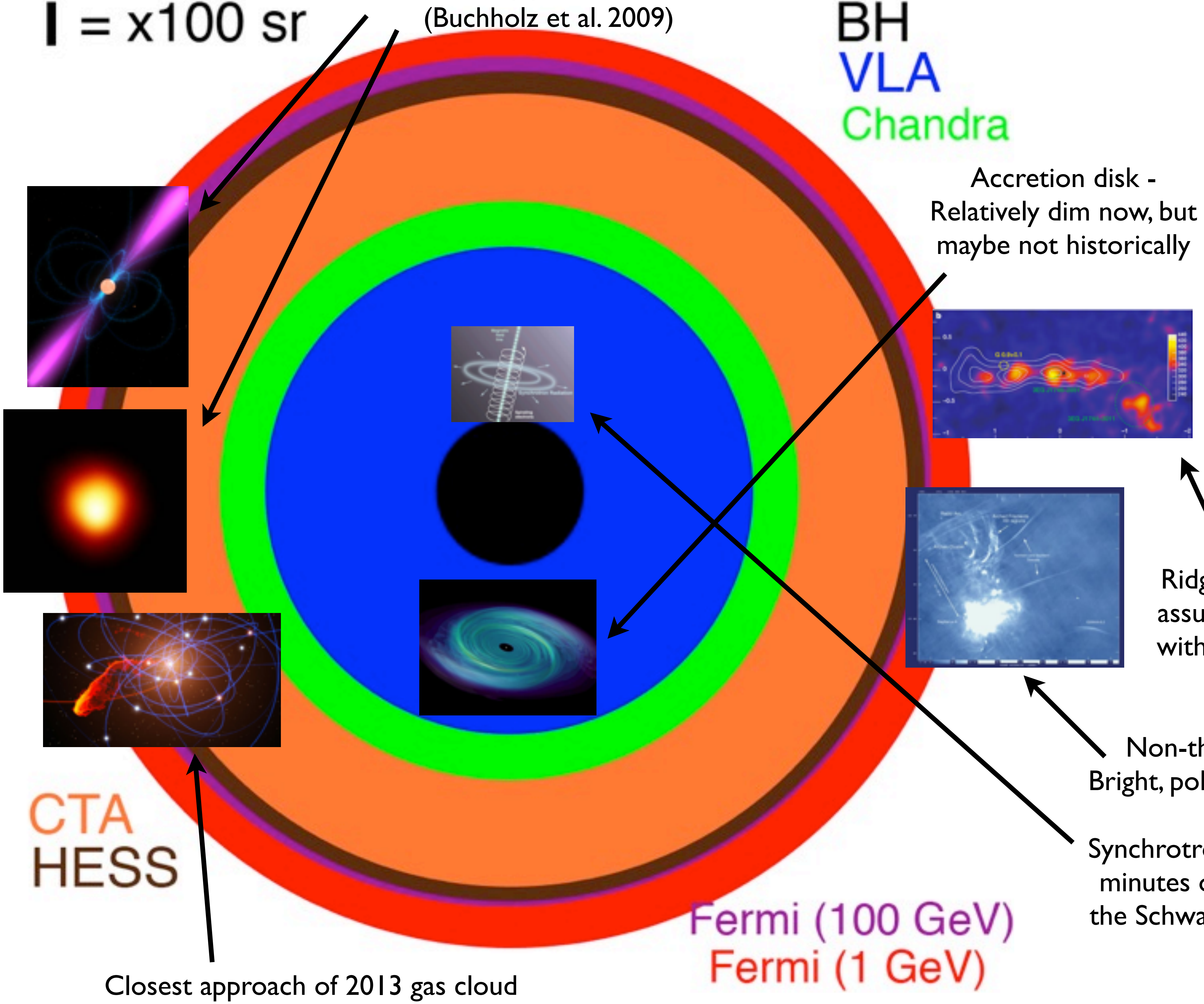
- Mechanism of filament creation and emission is unknown

Angular Scales of the Galactic Center



The Galactic Center "Zoo"

O-star/Pulsar density peaks at 0.5 pc, and falls sharply for smaller radii (Buchholz et al. 2009)



Accretion disk - Relatively dim now, but maybe not historically

Ridge of TeV gamma-ray emission assumed to be from p-p collisions with gas in the galactic disk (up to 200 pc)

Non-thermal Radio Filaments - Bright, polarized synchrotron sources

Synchrotron Emission within 20 light-minutes of Sgr A*, assumed to be at the Schwarzchild Radius (Gillessen et al. 2005)

Closest approach of 2013 gas cloud to Sgr A* (0.004 pc)

What can we learn in the next decade?

What can we learn in the next decade?

1.) The nature of the GC point source

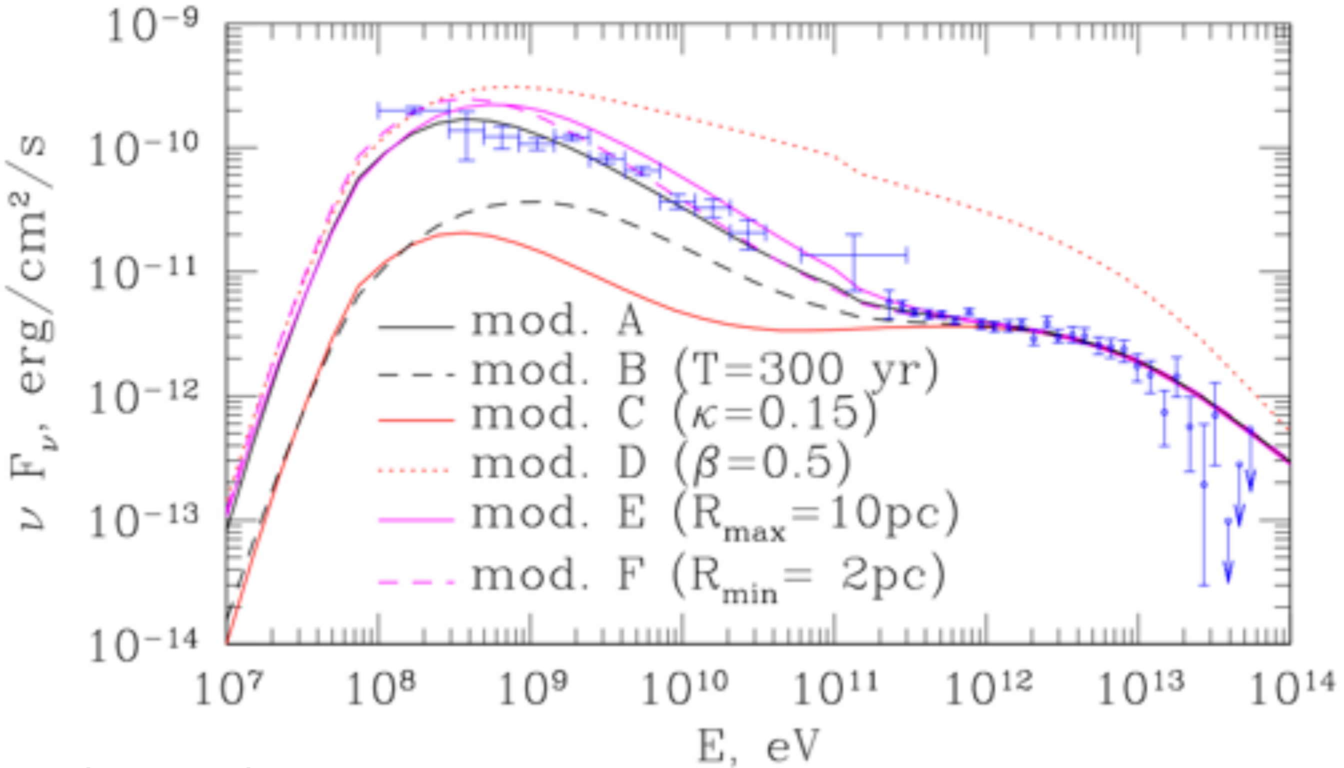
2.) The fate of the G2 gas cloud

3.) The origin of the Fermi bubbles

4.) The nature of Dark Matter

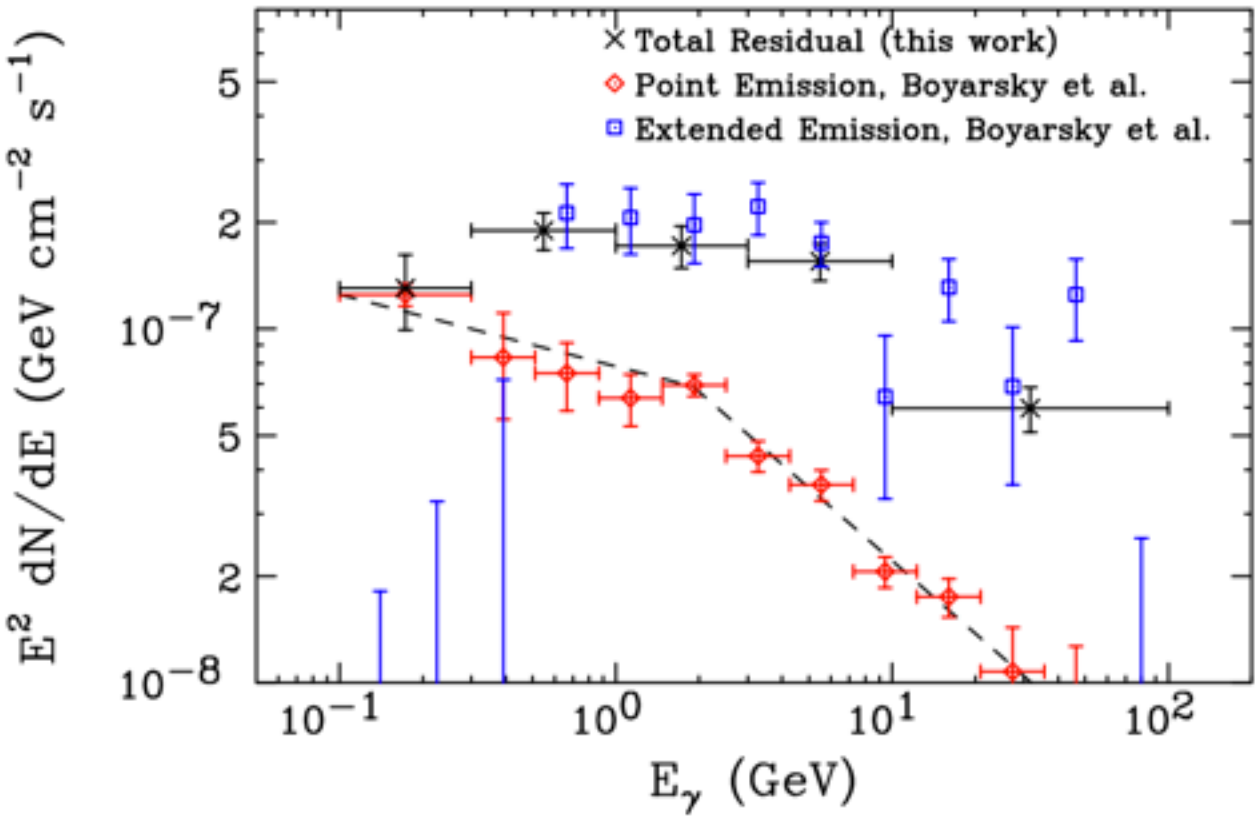
5.) Tests of General Relativity

Galactic Center Gamma-Ray Source

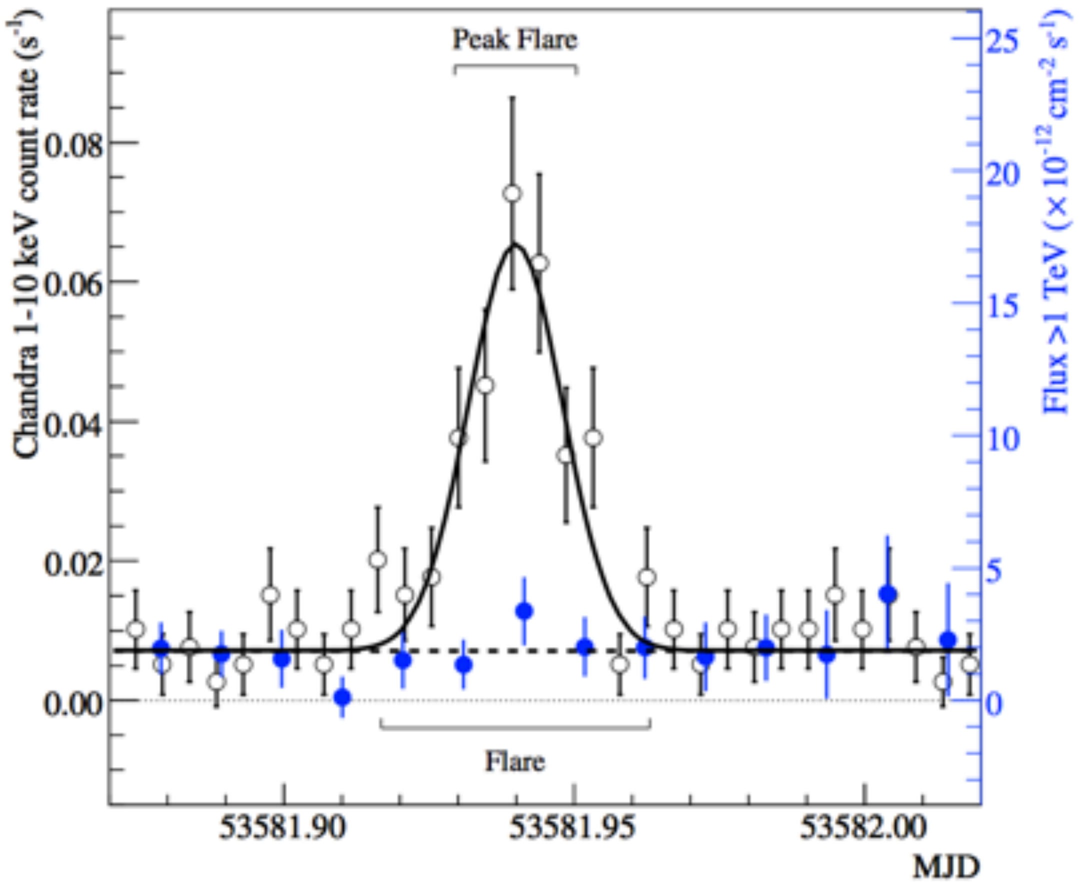


Chernyakova et al. (2011)

- HESS and Fermi both observe bright TeV sources coincident with the position of Sgr A*
- Sources are not time variable (unlike X-Ray and radio sources) -- Indicates cosmic-ray production?
- While HESS source is point-like, the Fermi source is extended

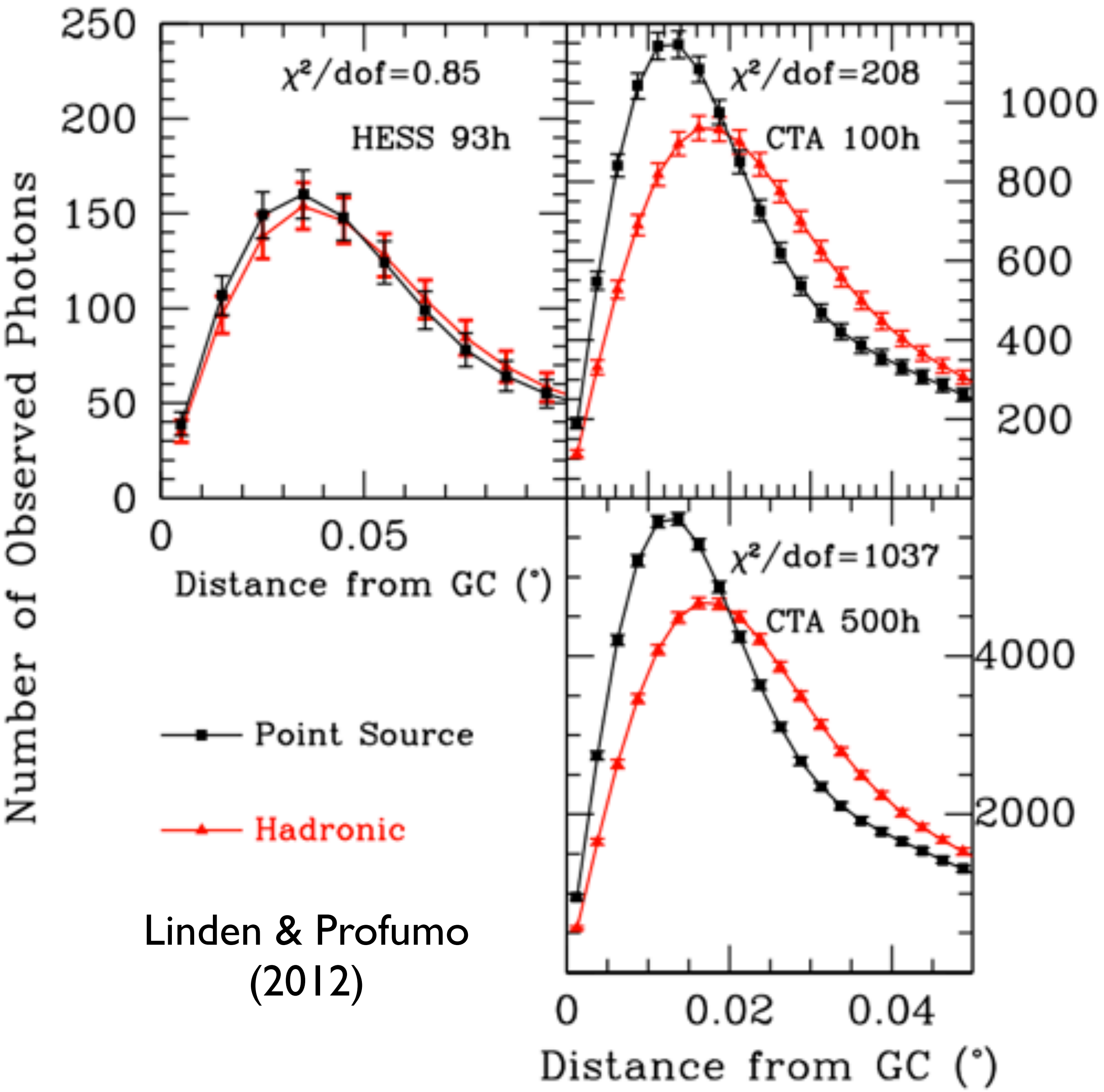


Hooper & Linden (2012)

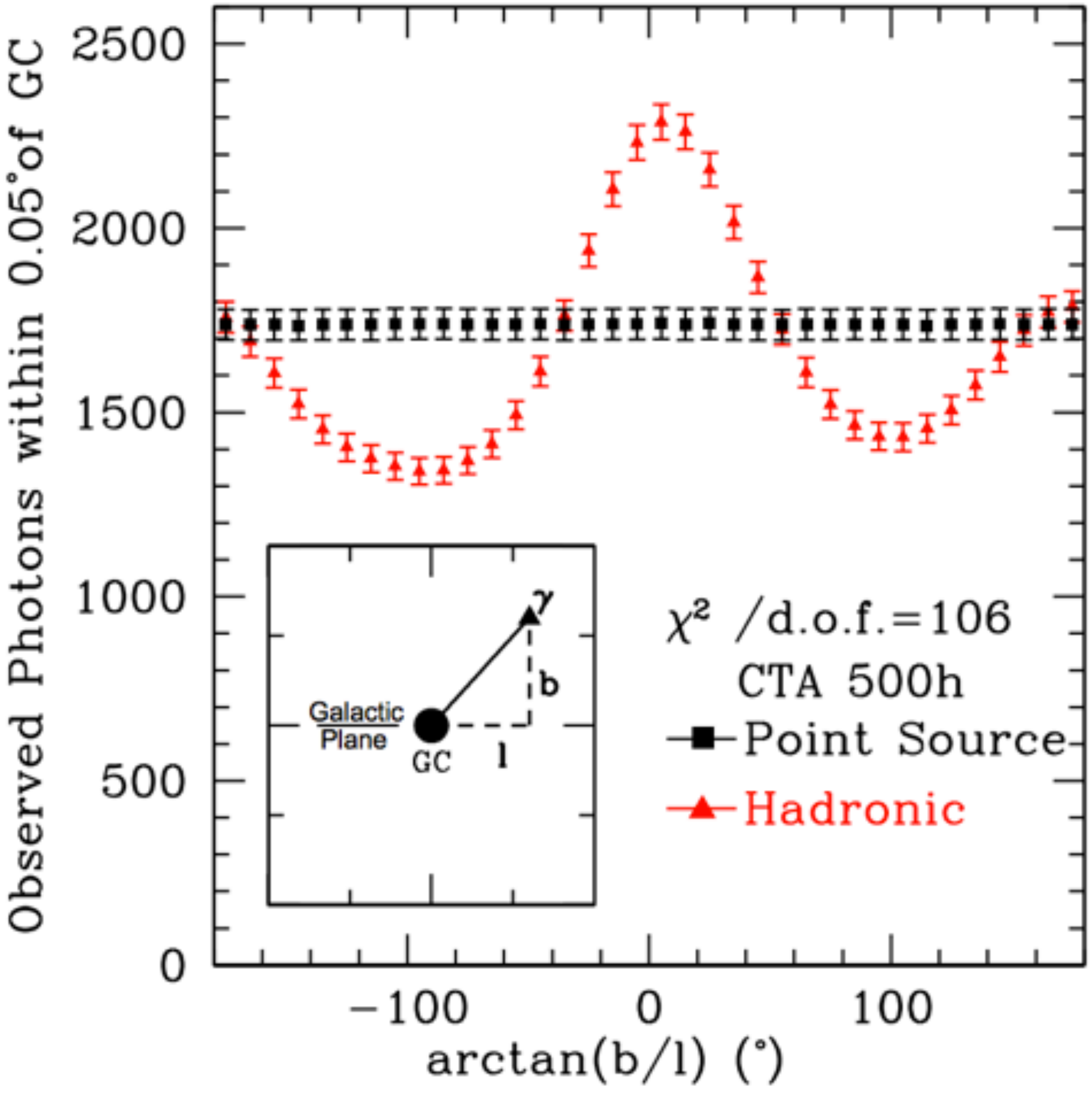


Aharonian et al. (2008)

CTA and the Galactic Center

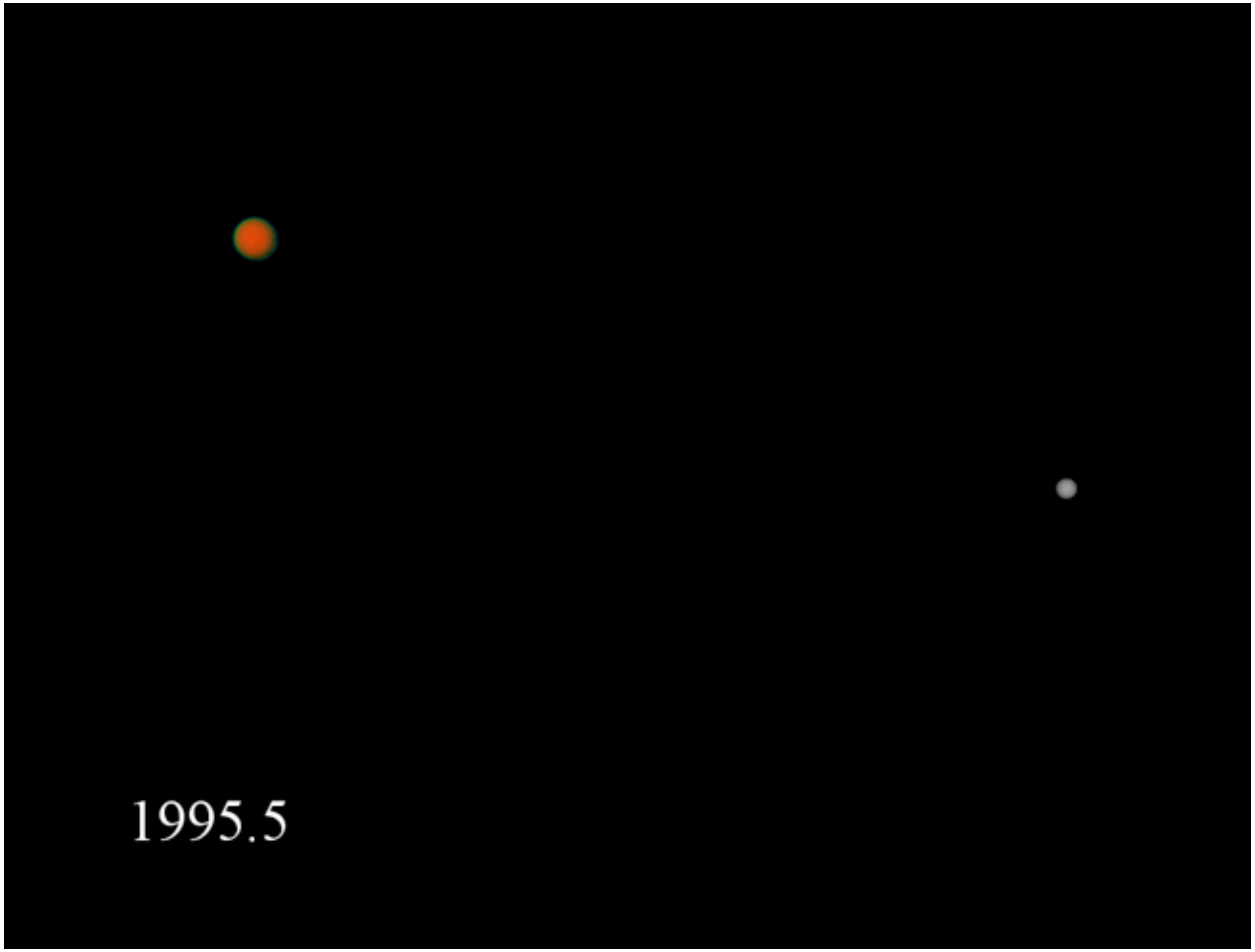


Linden & Profumo (2012)



G2 Cloud Colliding with the Galactic Center

- 3 Earth Mass Gas cloud
- Closest Approach is 2200 Schwarzchild Radii to Central Black Hole
- Beginning in 2013, average accretion rate is expected to be 5 - 19 x 10^{-8} $M_{\odot}$ yr^{-1}
- Luminosity boost can be 5% - order of magnitude



Colors show cloud density

Anninos et al. (2012)

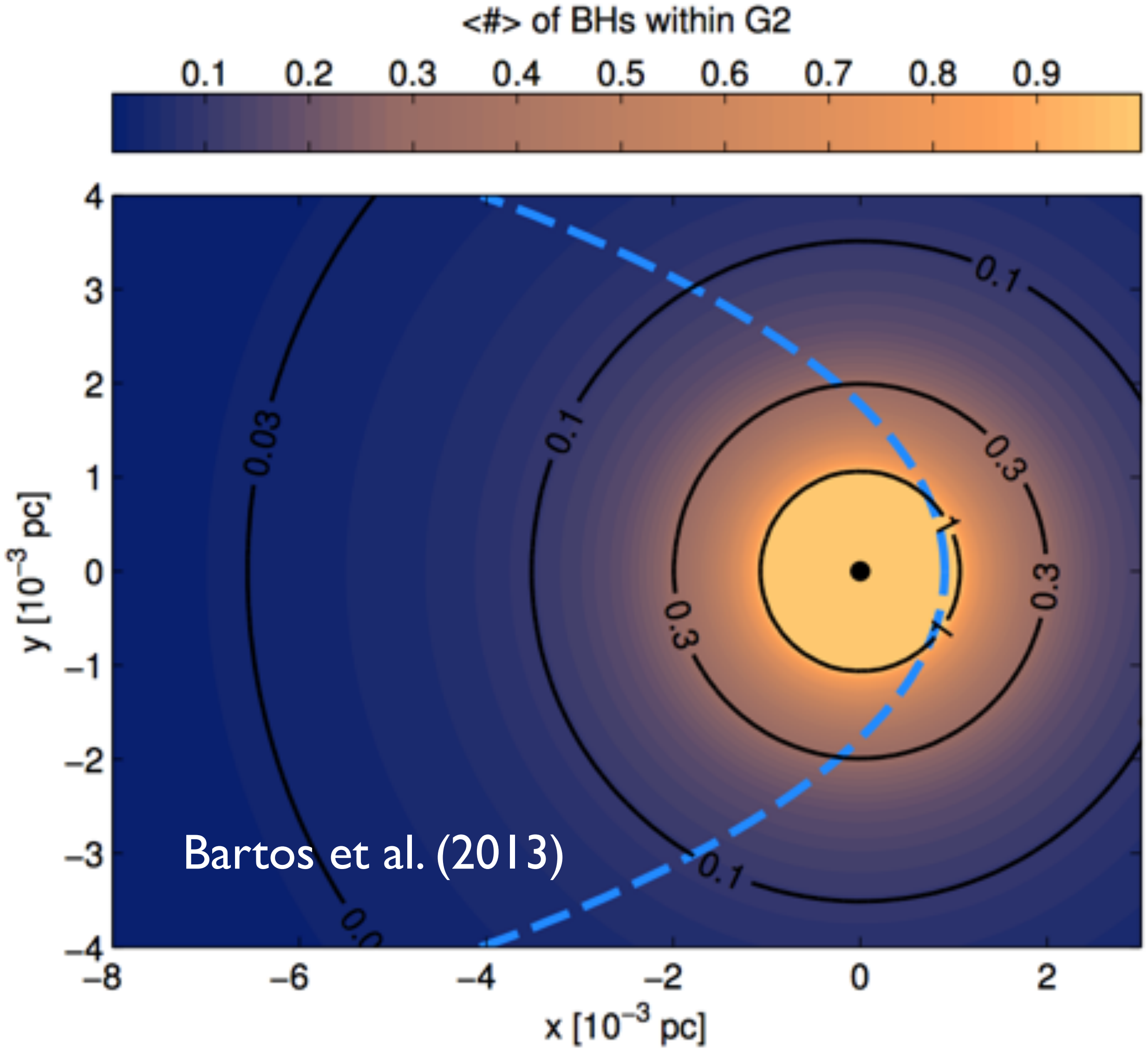
Gillessen et al. (2012)

G2 Cloud Colliding with the Galactic Center

Gillessen et al. (2012)

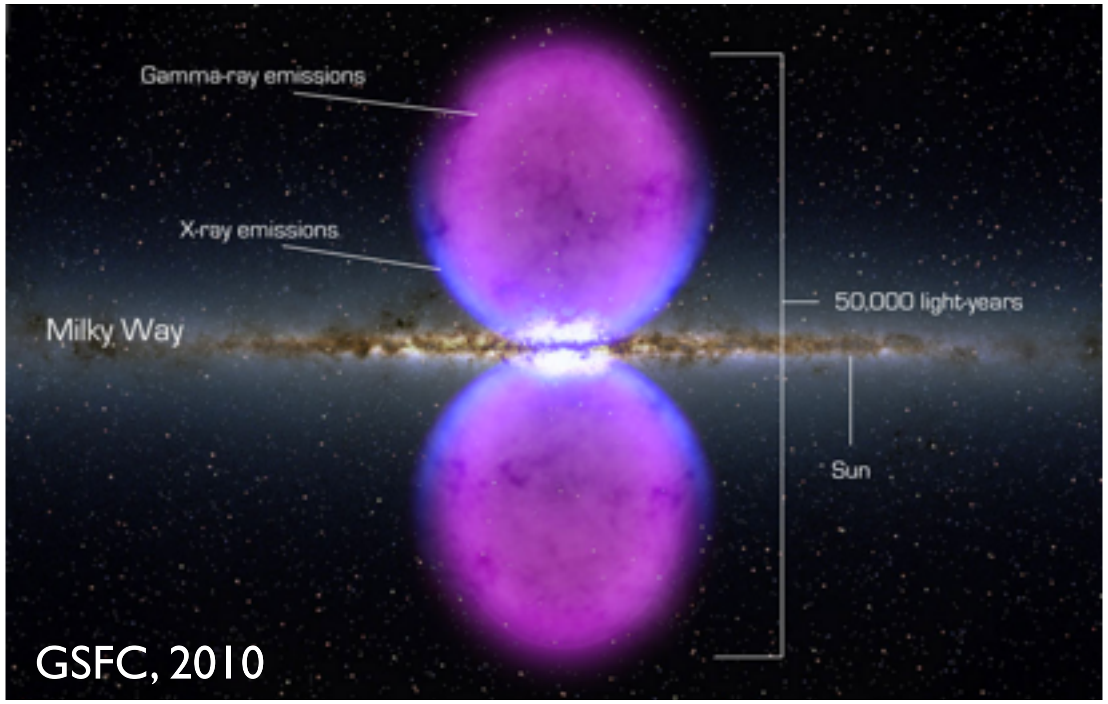
$$L_{cool}=\frac{M_c}{\mu}\frac{3}{2}kT_{pc}/t_{cool}=10^{35.6}\,f_V^{0.25}R_{15mas}^{0.5}\left(\frac{n_{c,postshock}}{10^6\,cm^{-3}}\right)\left(\frac{r}{3100\,R_S}\right)^{1.4}\quad(\mathrm{erg/s})$$

- Specifically, heating of the G2 cloud will significantly increase the X-Ray luminosity of the central source
- Accretion of G2 cloud could trigger “mini-AGN” activity, will act as vital probe of Sgr A* outbursts physics
- Outburst “Echos” will yield information about diffusion constant in galactic center
- Will probe BH population near Sgr A*



Bartos et al. (2013)

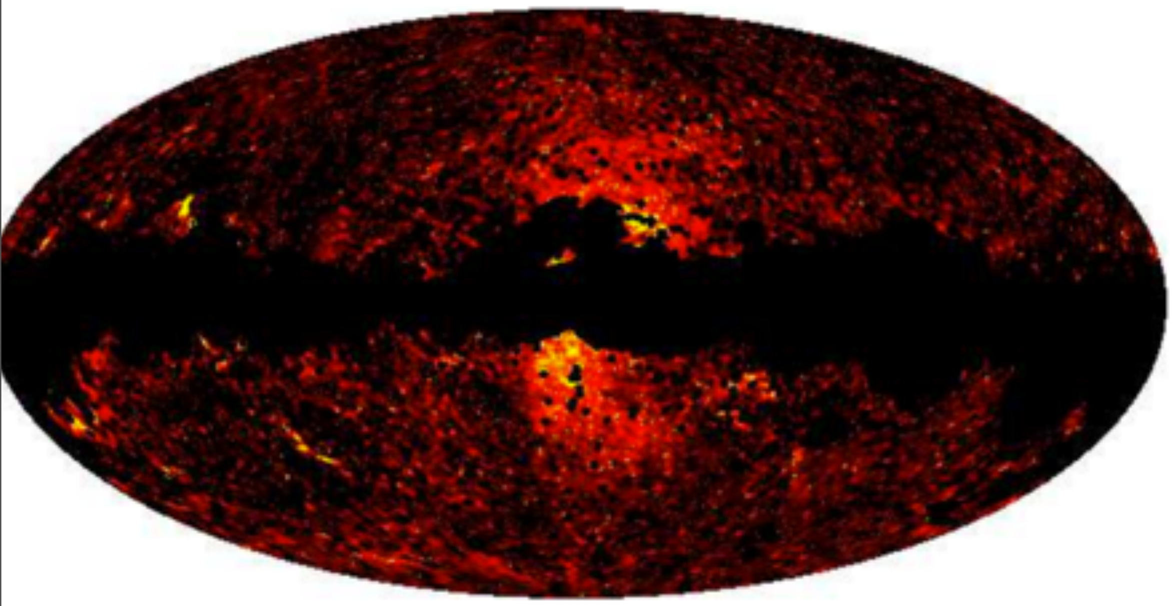
The Origin of the Fermi Bubbles?



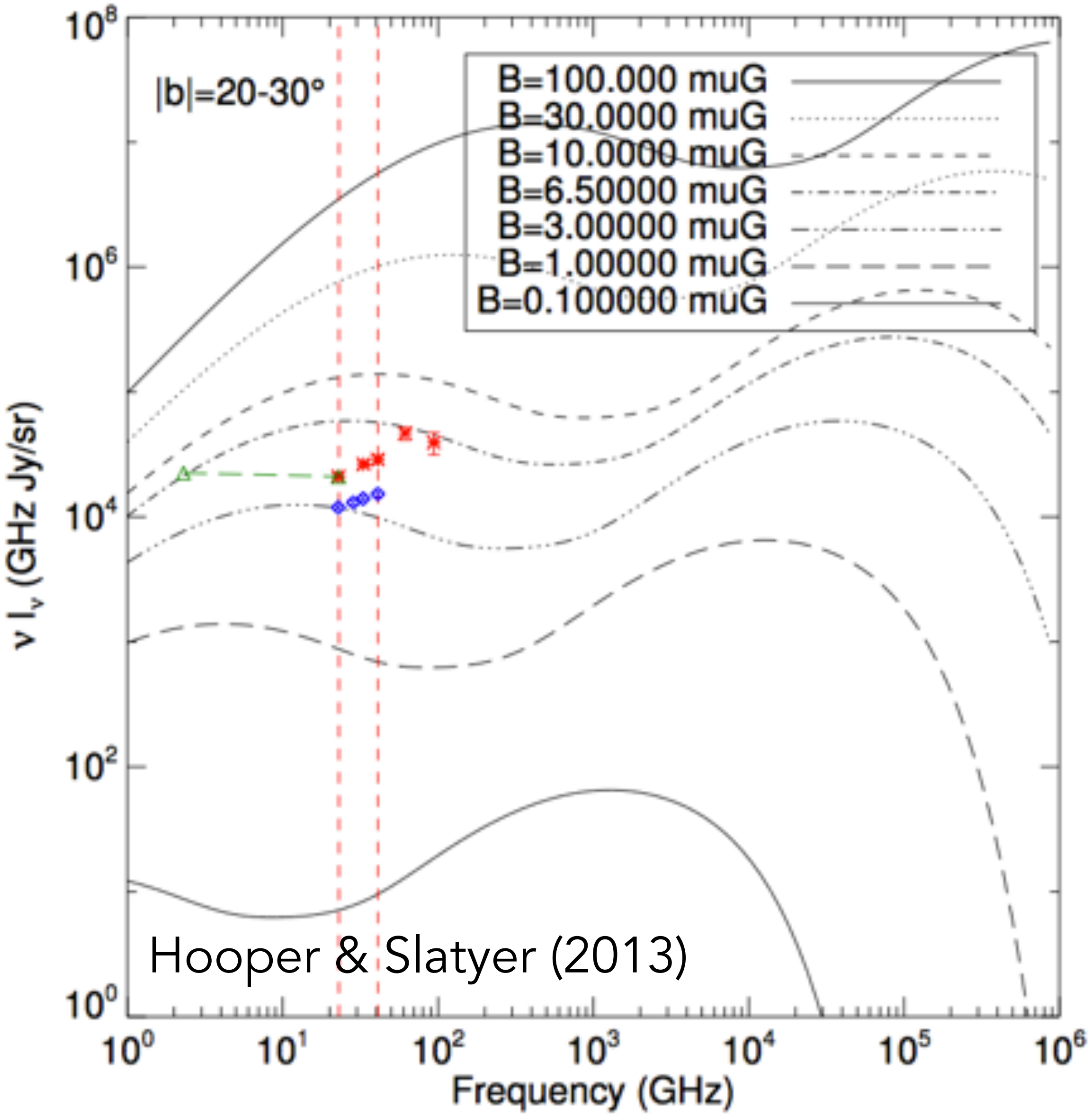
GSFC, 2010

- Bubbles are symmetric above and below the Galactic Center

- Observations from Fermi-LAT and Planck put strong limits on magnetic field above the galactic plane



PLANCK Collaboration (2012)



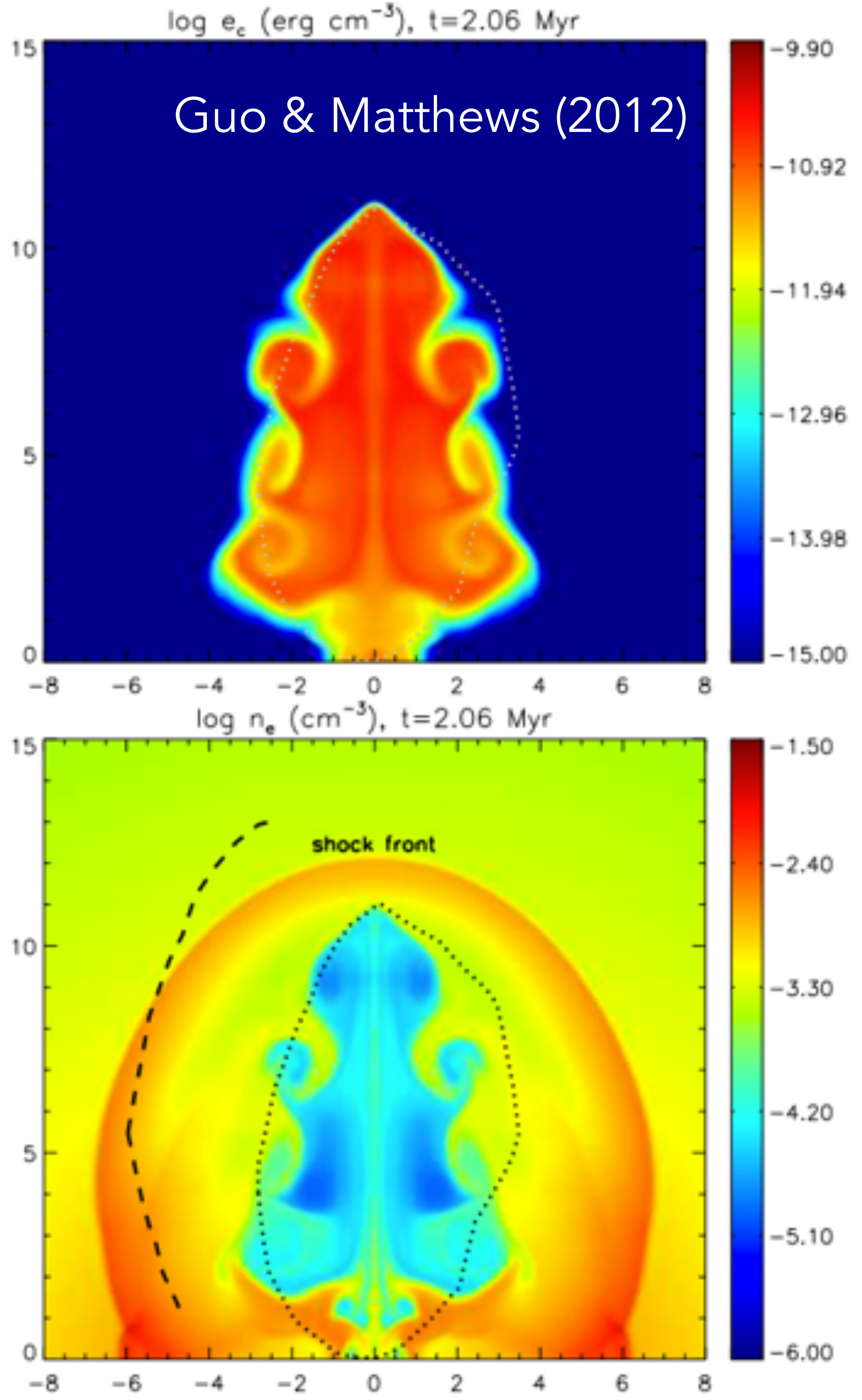
Hooper & Slatyer (2013)

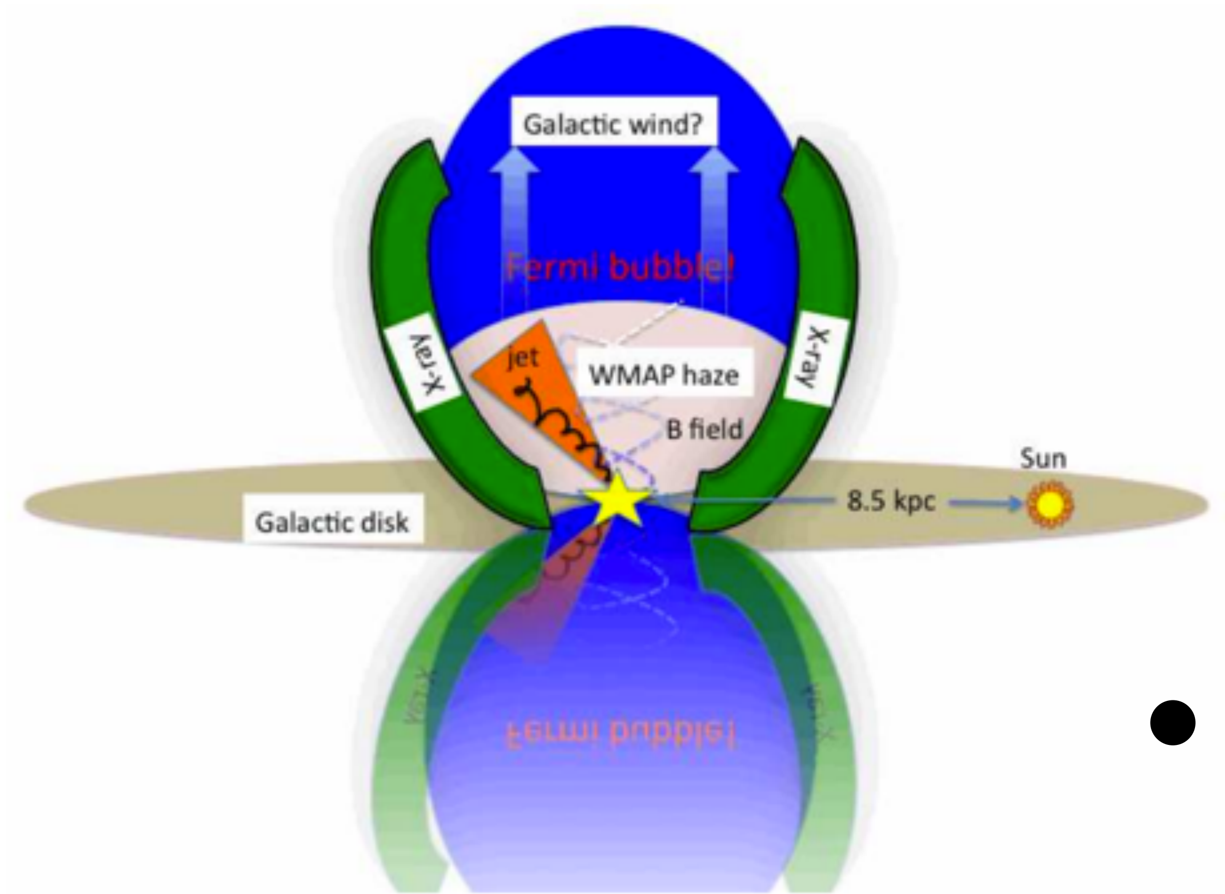
- Good example of Multiwavelength observations producing information inaccessible to either instrument

The Origin of the Fermi Bubbles?

- A compelling model for bubble creation is through prior AGN activity from the GC

- Another convincing model employs the large supernova rate in the GC, along with strong galactic winds, to propel high energy particles to high latitude


Guo & Matthews (2012)



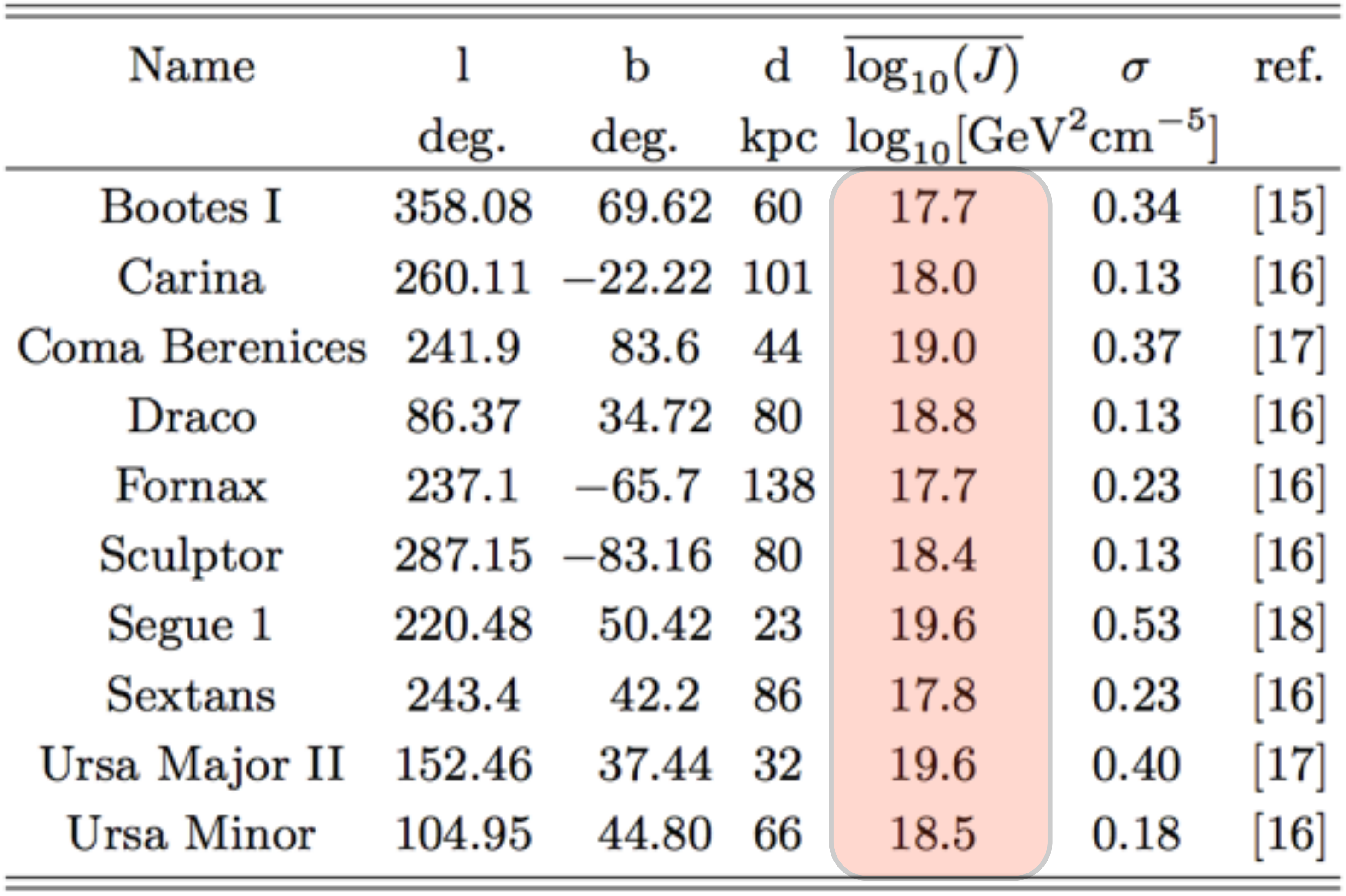
Su et al. (2010)

- G2 Cloud Observations will help to constrain or understand the AGN Model

Dark Matter at the Galactic Center

Ackermann et al. 2012

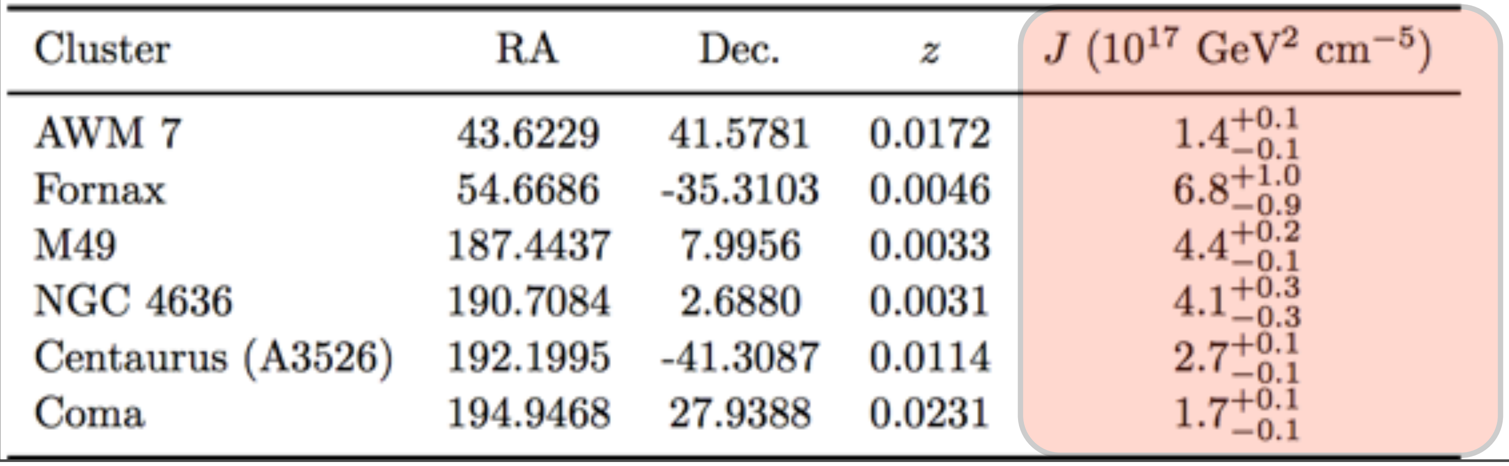
Dwarfs



Name	l deg.	b deg.	d kpc	$\overline{\log_{10}(J)}$ $\log_{10}[\mathrm{GeV}^2\mathrm{cm}^{-5}]$	σ	ref.
Bootes I	358.08	69.62	60	17.7	0.34	[15]
Carina	260.11	−22.22	101	18.0	0.13	[16]
Coma Berenices	241.9	83.6	44	19.0	0.37	[17]
Draco	86.37	34.72	80	18.8	0.13	[16]
Fornax	237.1	−65.7	138	17.7	0.23	[16]
Sculptor	287.15	−83.16	80	18.4	0.13	[16]
Segue 1	220.48	50.42	23	19.6	0.53	[18]
Sextans	243.4	42.2	86	17.8	0.23	[16]
Ursa Major II	152.46	37.44	32	19.6	0.40	[17]
Ursa Minor	104.95	44.80	66	18.5	0.18	[16]

Ackermann et al. 2010

Clusters



Cluster	RA	Dec.	z	J (10^{17} GeV^2 cm^{-5})
AWM 7	43.6229	41.5781	0.0172	$1.4^{+0.1}_{-0.1}$
Fornax	54.6686	-35.3103	0.0046	$6.8^{+1.0}_{-0.9}$
M49	187.4437	7.9956	0.0033	$4.4^{+0.2}_{-0.1}$
NGC 4636	190.7084	2.6880	0.0031	$4.1^{+0.3}_{-0.3}$
Centaurus (A3526)	192.1995	-41.3087	0.0114	$2.7^{+0.1}_{-0.1}$
Coma	194.9468	27.9388	0.0231	$1.7^{+0.1}_{-0.1}$

- Corresponds to the relative annihilation rate of the region compared to other astrophysical sources

$$\Phi_\gamma \propto J = \frac{1}{\Delta\Omega}\int \mathrm{d}\Omega \int_{\mathrm{l.o.s.}} \rho^2(l)\mathrm{d}l(\psi)$$

- The J-factor of the galactic center is approximately:

$\log_{10}(J) = 21.0$

for a region within 1° of the Galactic center and an NFW profile

Why is the Galactic Center Interesting?

Back of the Envelope Calculation

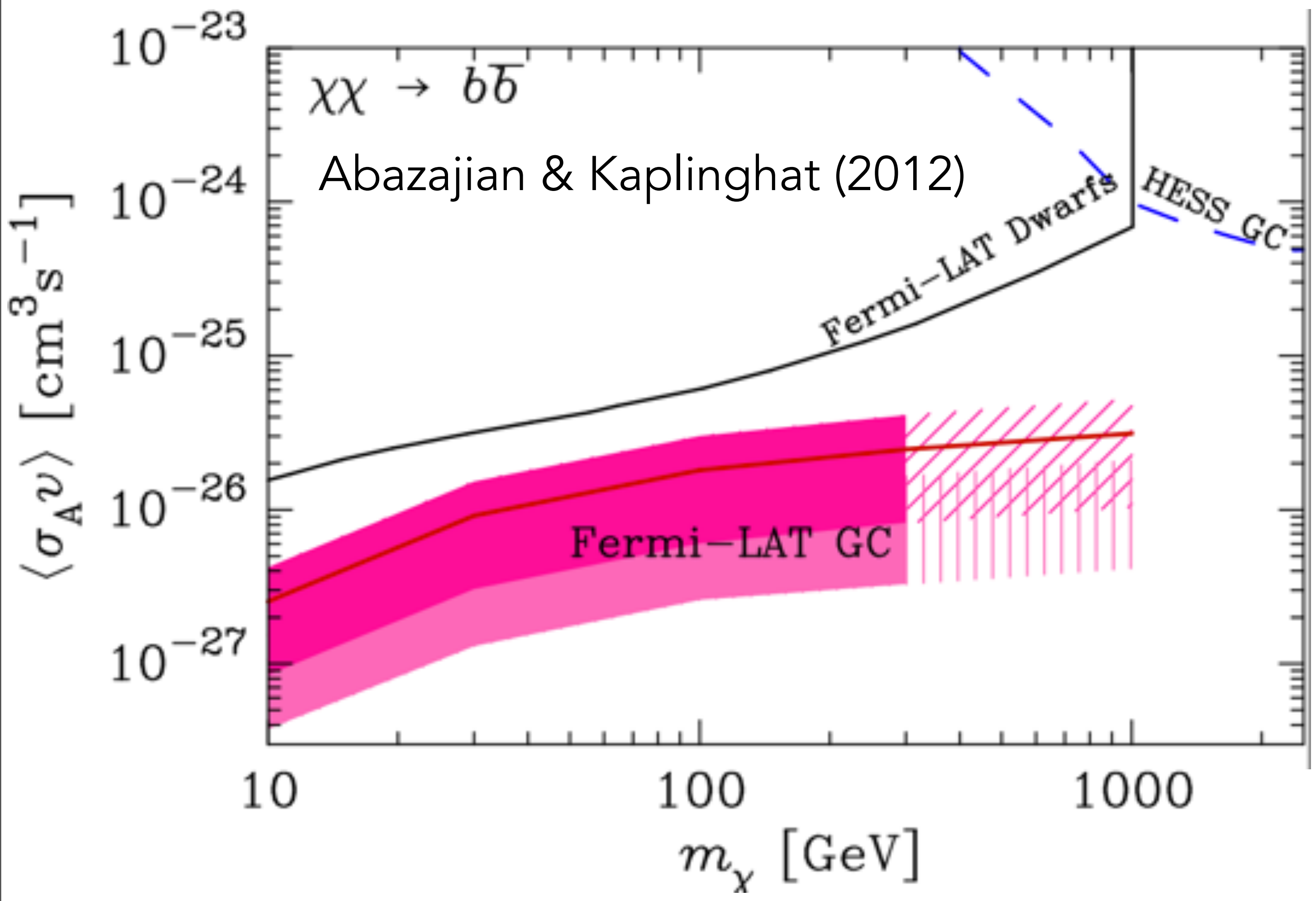
- Total Gamma-Ray Flux from 1-3 GeV within 1° of Galactic Center is

$$\sim 1 \times 10^{-7}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

- This is equivalent to the number of photons expected in this energy bin from a "vanilla" 100 GeV dark matter candidate annihilating to bb with a cross-section **$\langle\sigma v\rangle = 1.6 \times 10^{-25}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$**

- There's no reason this needs to be true -- the total gamma-ray emission from the Galactic center happens to fall within an order of magnitude of the **most naive** prediction from dark matter simulations

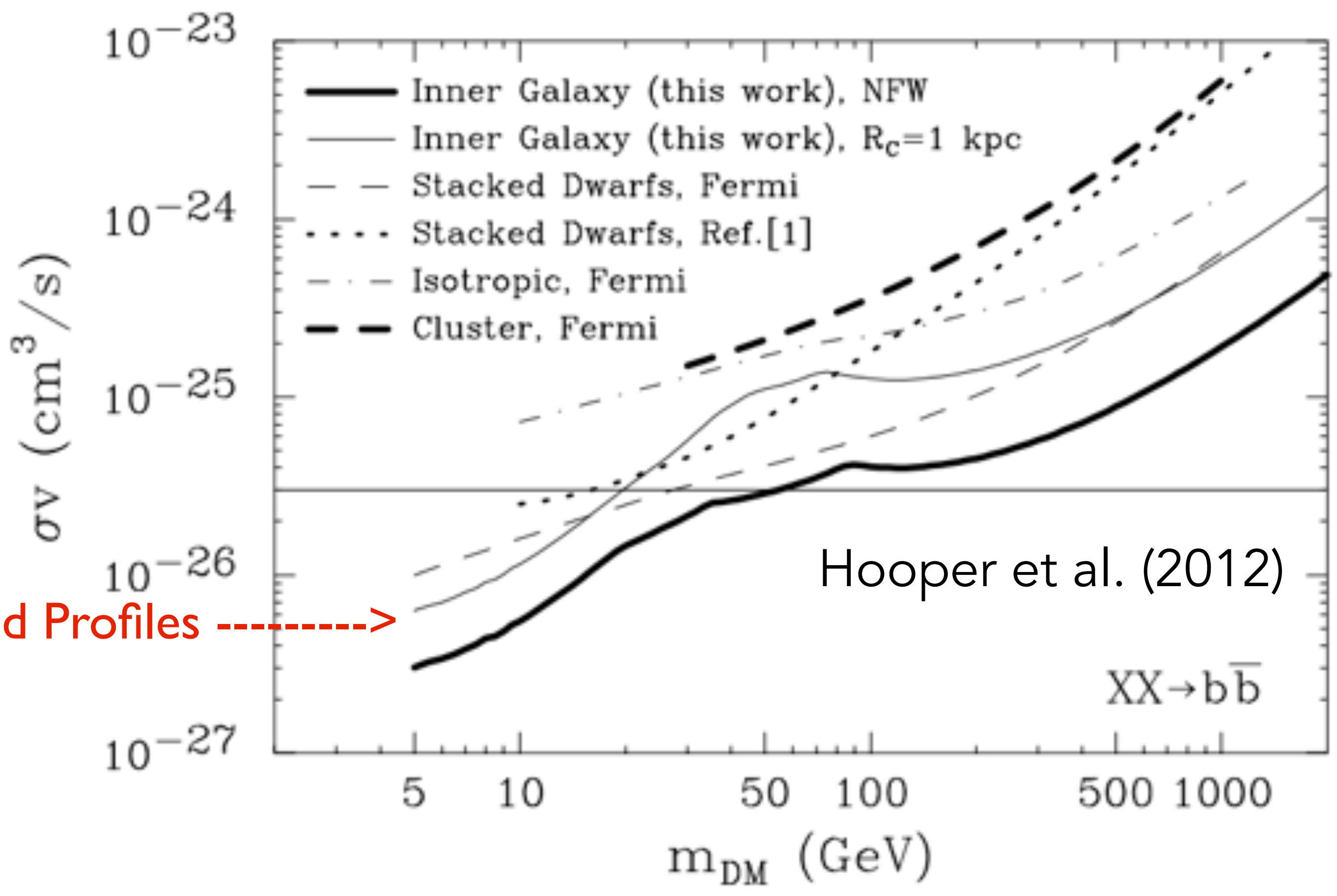
Dark Matter at the Galactic Center



Abazajian & Kaplinghat (2012)

- Thus, the constraints on dark matter annihilation from Fermi-LAT observations are extremely strong

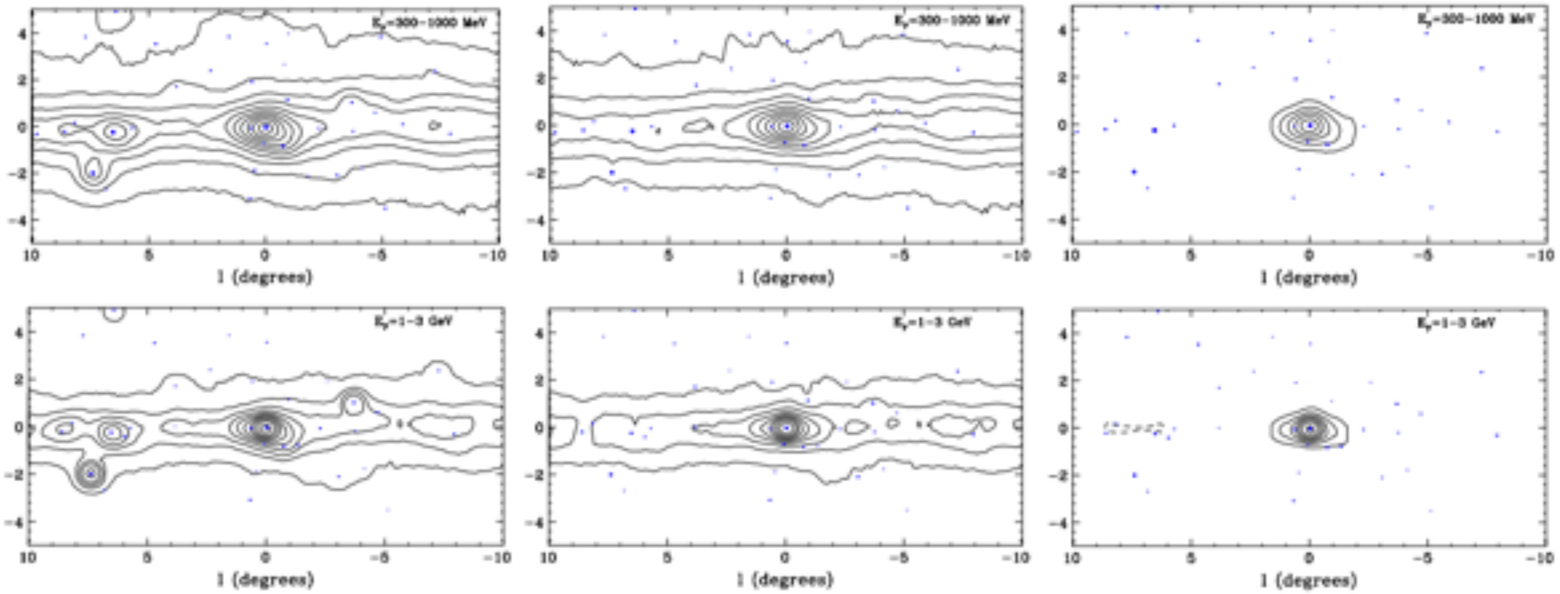
- **In spite** of very bright emission!



Hooper et al. (2012)

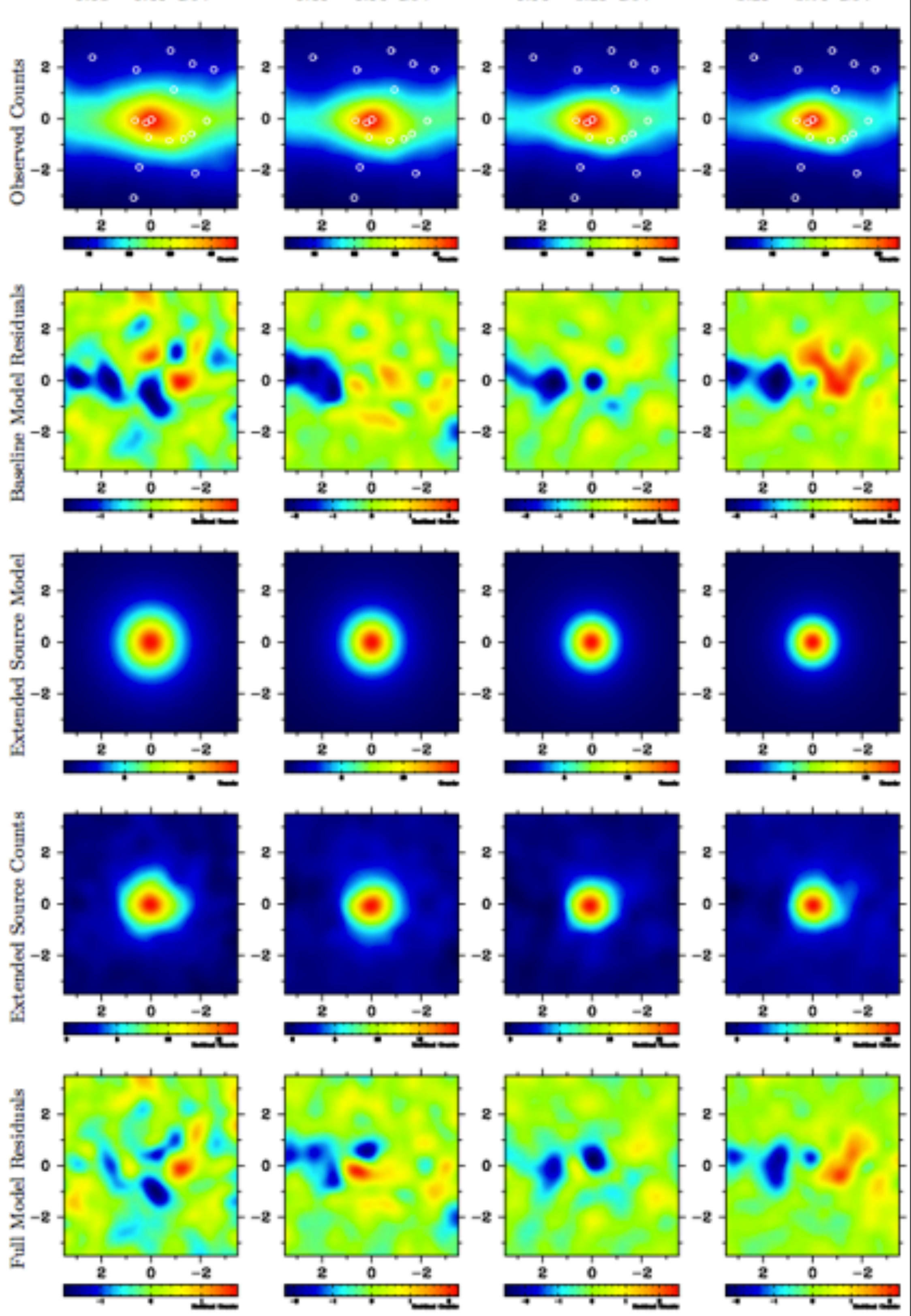
Cored Profiles --------->

Have we observed a signal?



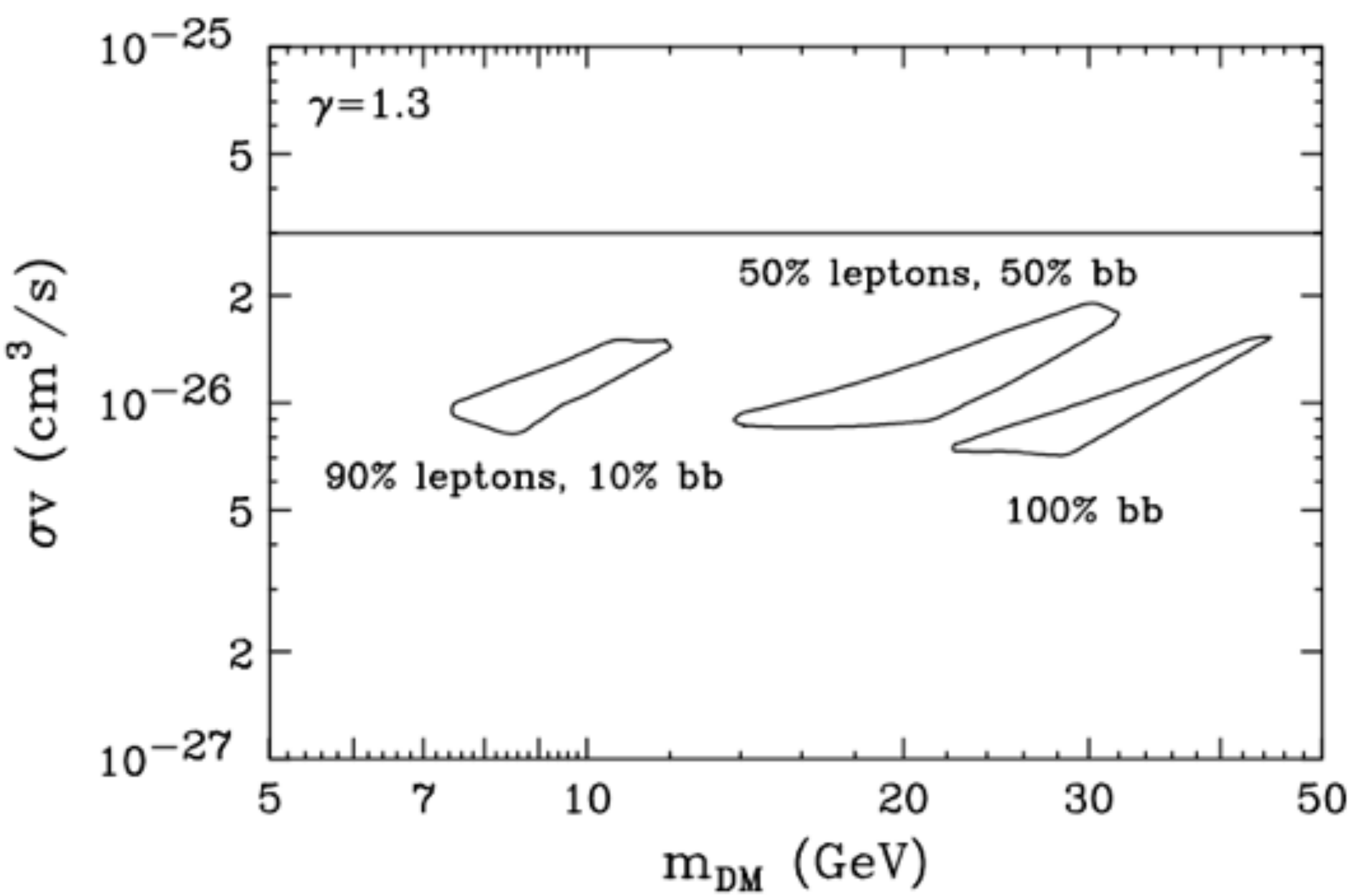
Hooper & Linden (2011)

- Two different models yield strong statistical preferences for a spherically symmetric, extended source at the Galactic center



Abazajian & Kaplinghat (2012)

Have we observed a signal?



statistical preferences for a spherically symmetric, extended source at the Galactic center

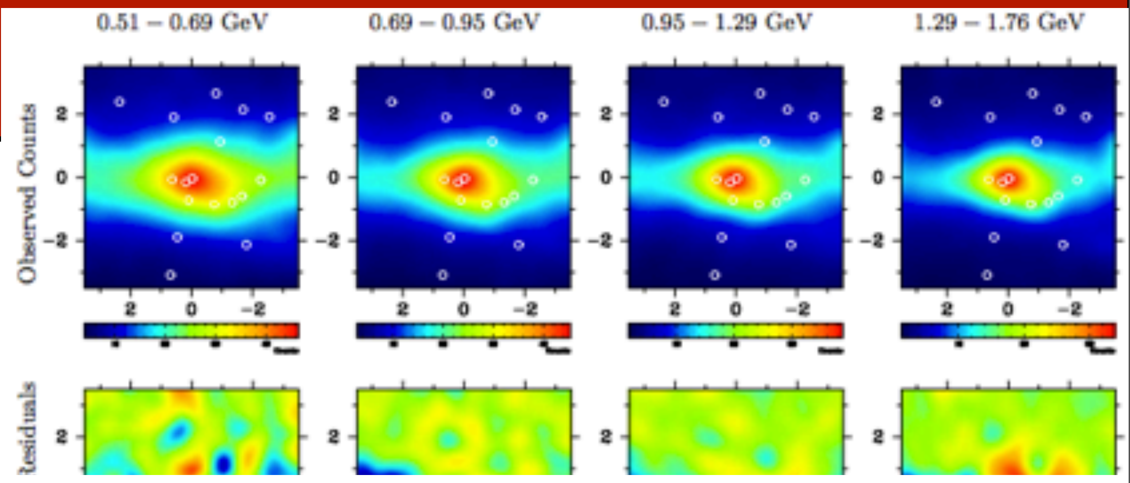
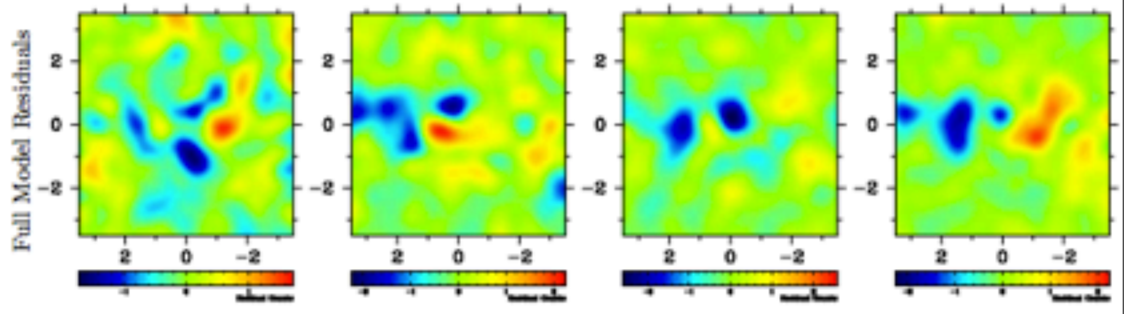


TABLE II. The best-fit TS, negative log likelihoods, and $\Delta\mathcal{L}$ from the baseline, for specific dark matter channel models, using the $\alpha\beta\gamma$ profile (Eq. 2.1) with $\alpha = 1, \beta = 3, \gamma = 1.2$.

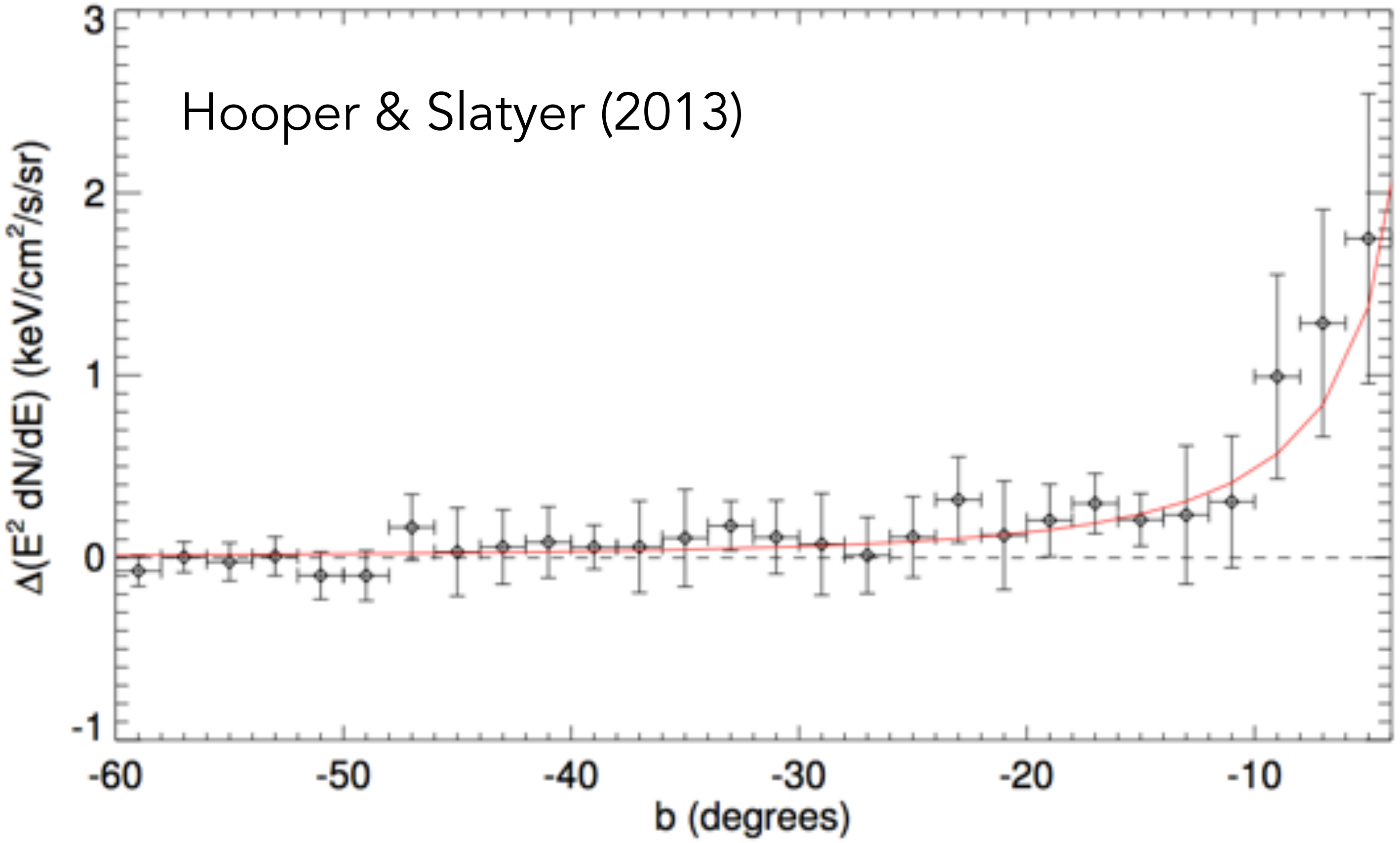
channel, m_χ	TS	$-\ln\mathcal{L}$	$\Delta\ln\mathcal{L}$
$b\bar{b}$, 10 GeV	2385.7	139913.6	156.5
$b\bar{b}$, 30 GeV	3460.3	139658.3	411.8
$b\bar{b}$, 100 GeV	1303.1	139881.1	189.0
$b\bar{b}$, 300 GeV	229.4	140056.6	13.5
$b\bar{b}$, 1 TeV	25.5	140108.2	−38.0
$b\bar{b}$, 2.5 TeV	7.6	140114.2	−44.0
$\tau^+\tau^-$, 10 GeV	1628.7	139787.7	282.5
$\tau^+\tau^-$, 30 GeV	232.7	140055.9	14.2
$\tau^+\tau^-$, 100 GeV	4.10	140113.4	−43.3



Abazajian & Kaplinghat (2012)

Have we observed a signal?

- New evidence shows this signal may extend to high latitudes

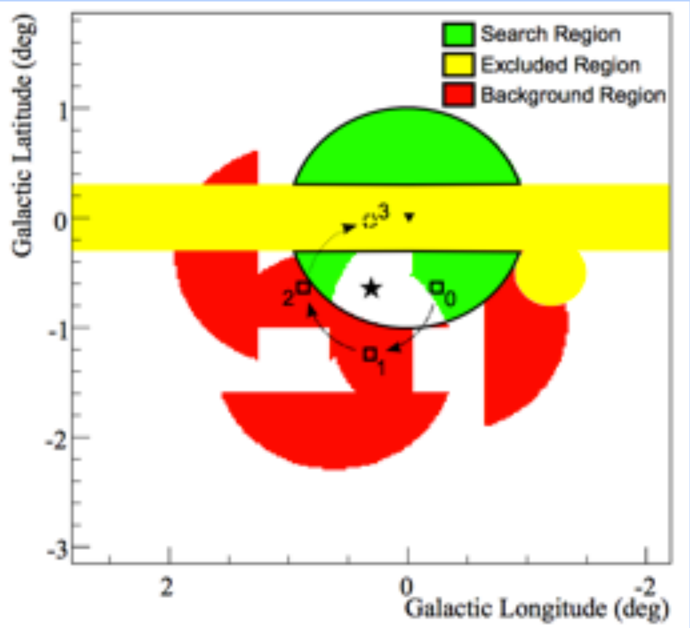


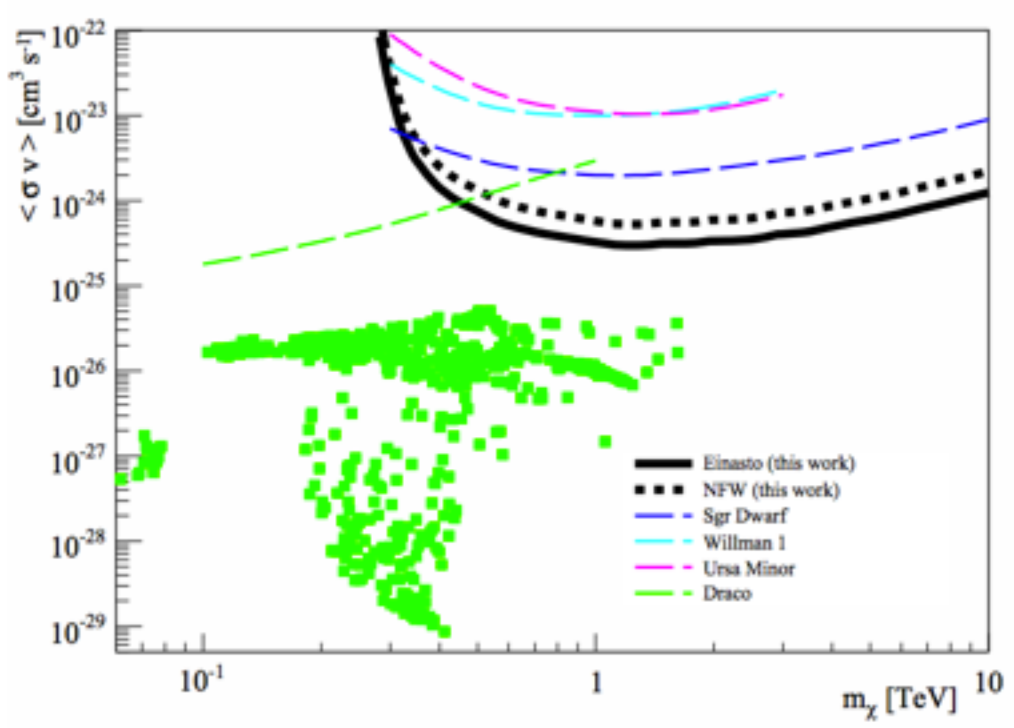
Stay Tuned!

HESS Limits on TeV Dark Matter

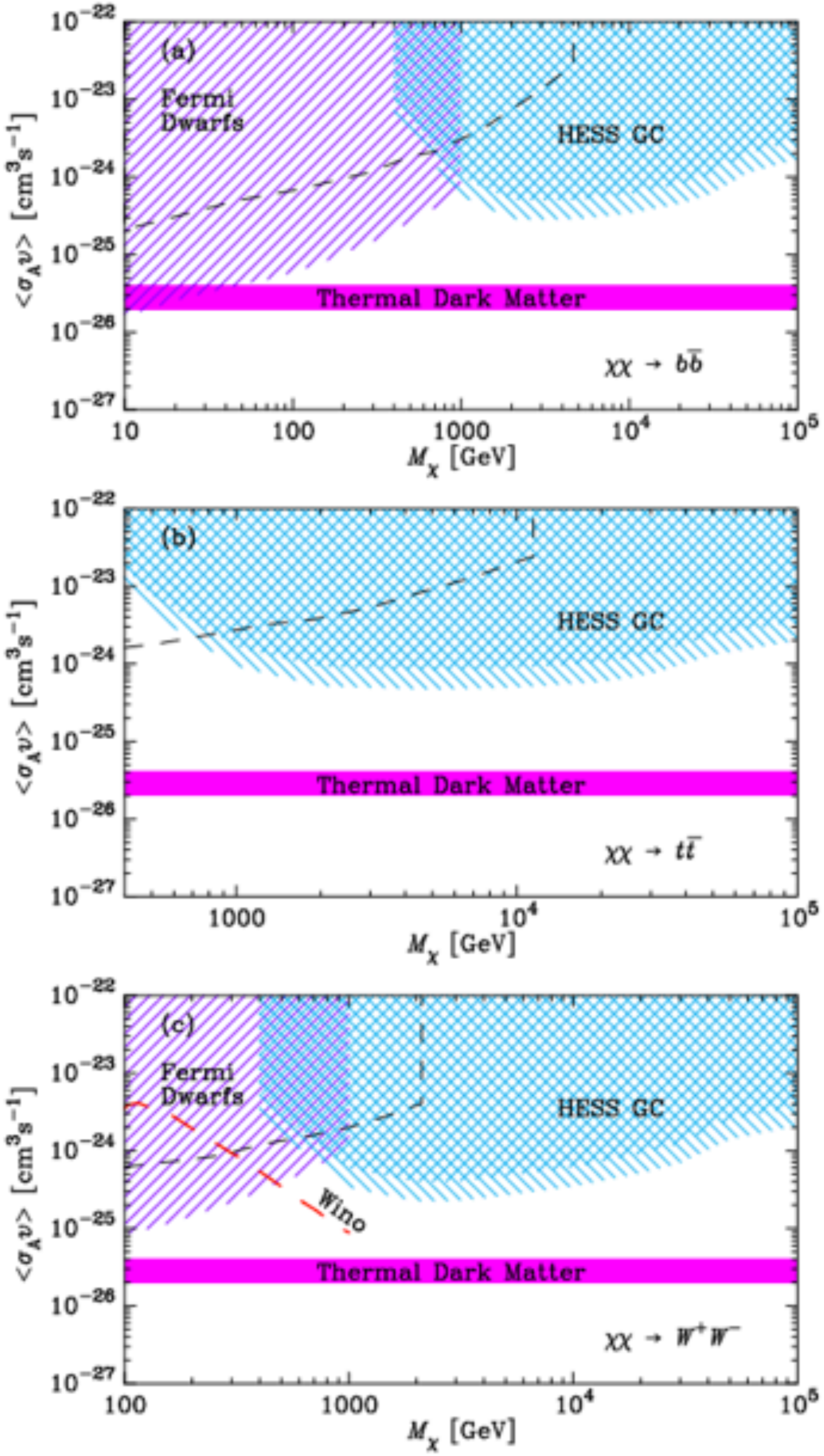
- HESS observations of the Galactic center, and Galactic Halo provide the strongest indirect limits on TeV dark matter

- Limits are strongly profile dependent -- background subtraction weakens bounds on isothermal dark matter models as well





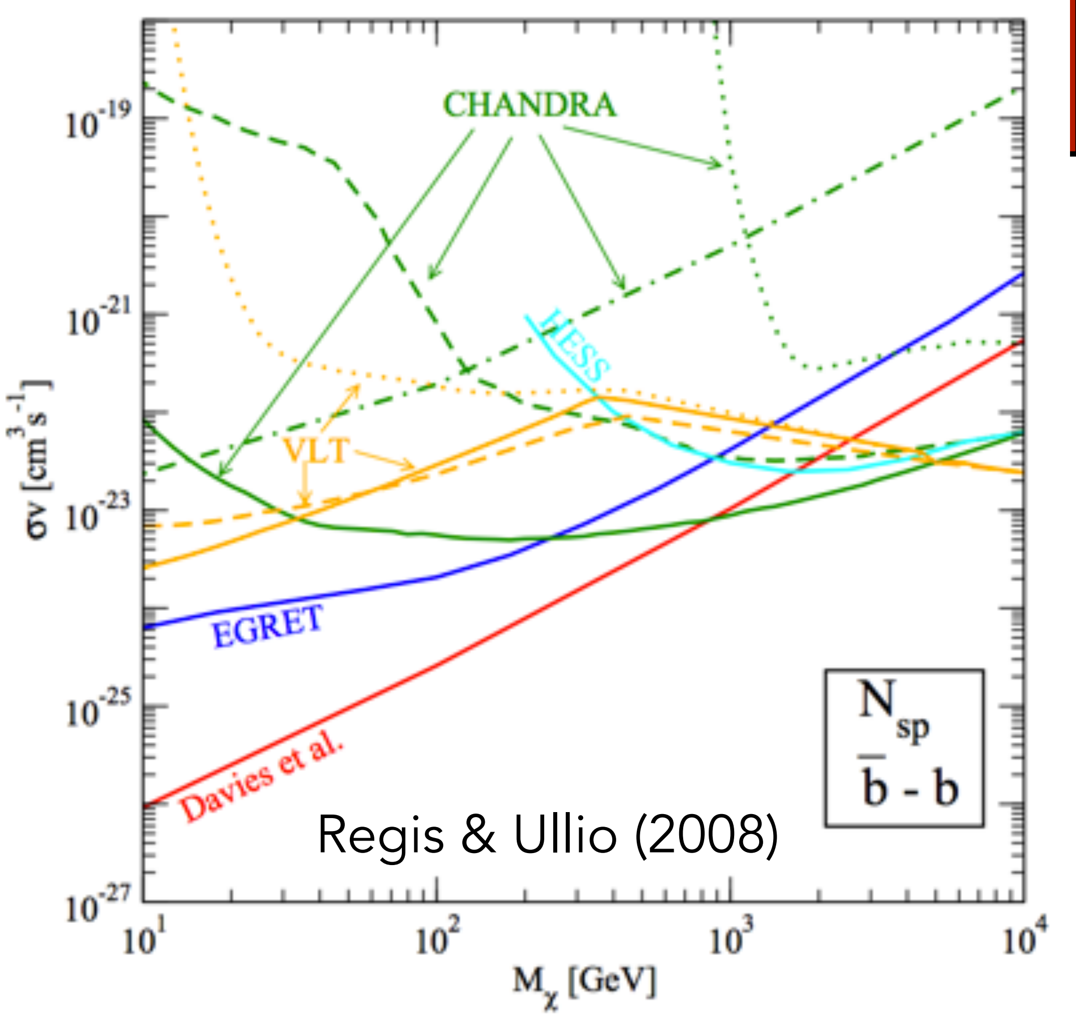
Abramowski et al. (2011)



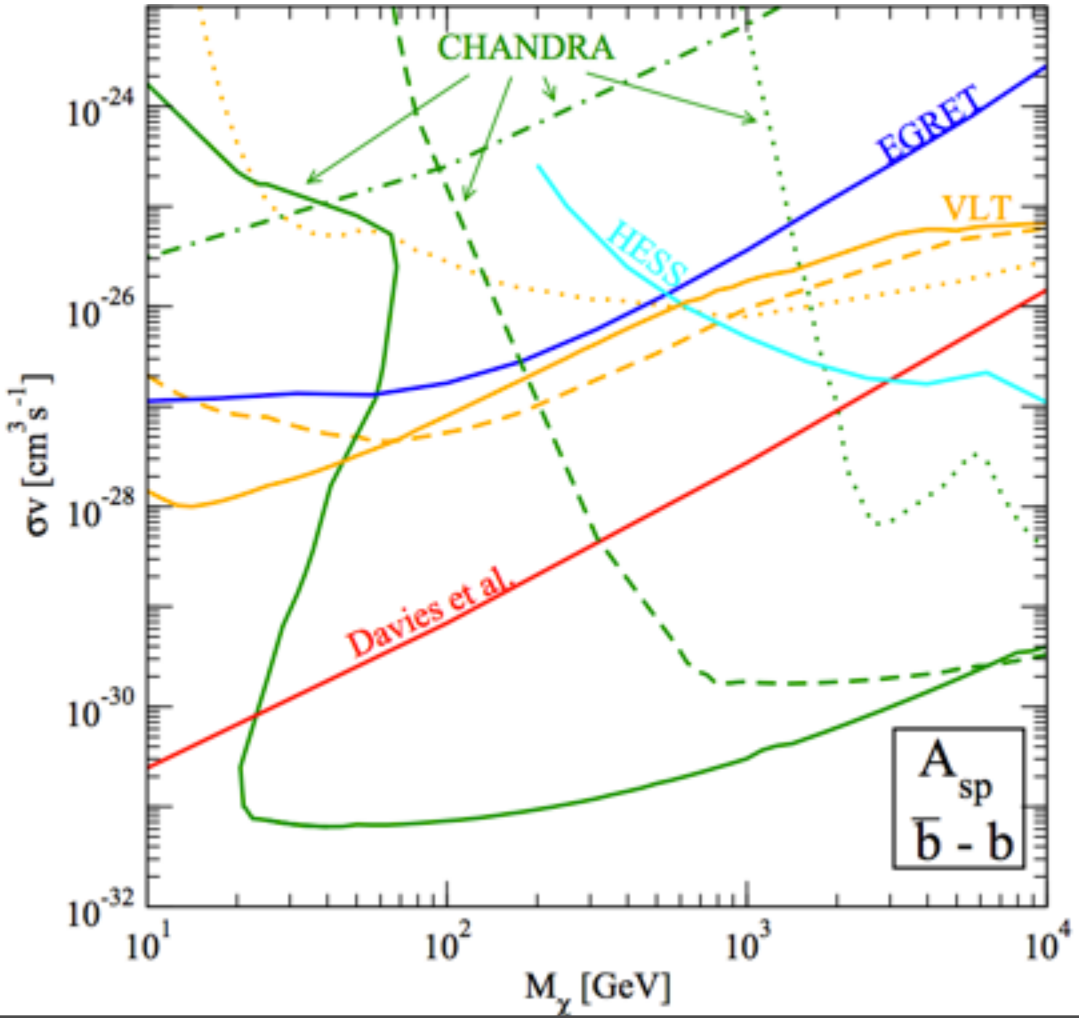
Abazajian & Harding (2011)

Radio and X-Ray Observations

- Very strong constraints can be placed on dark matter annihilation through radio and X-Ray observations
- Current techniques have focused on regions **very** close to the central black hole, utilizing the high density of dark matter expected there
- Two issues:
  - Dependent on diffusion parameters
  - High Resolution requires extrapolation of dark matter density profiles

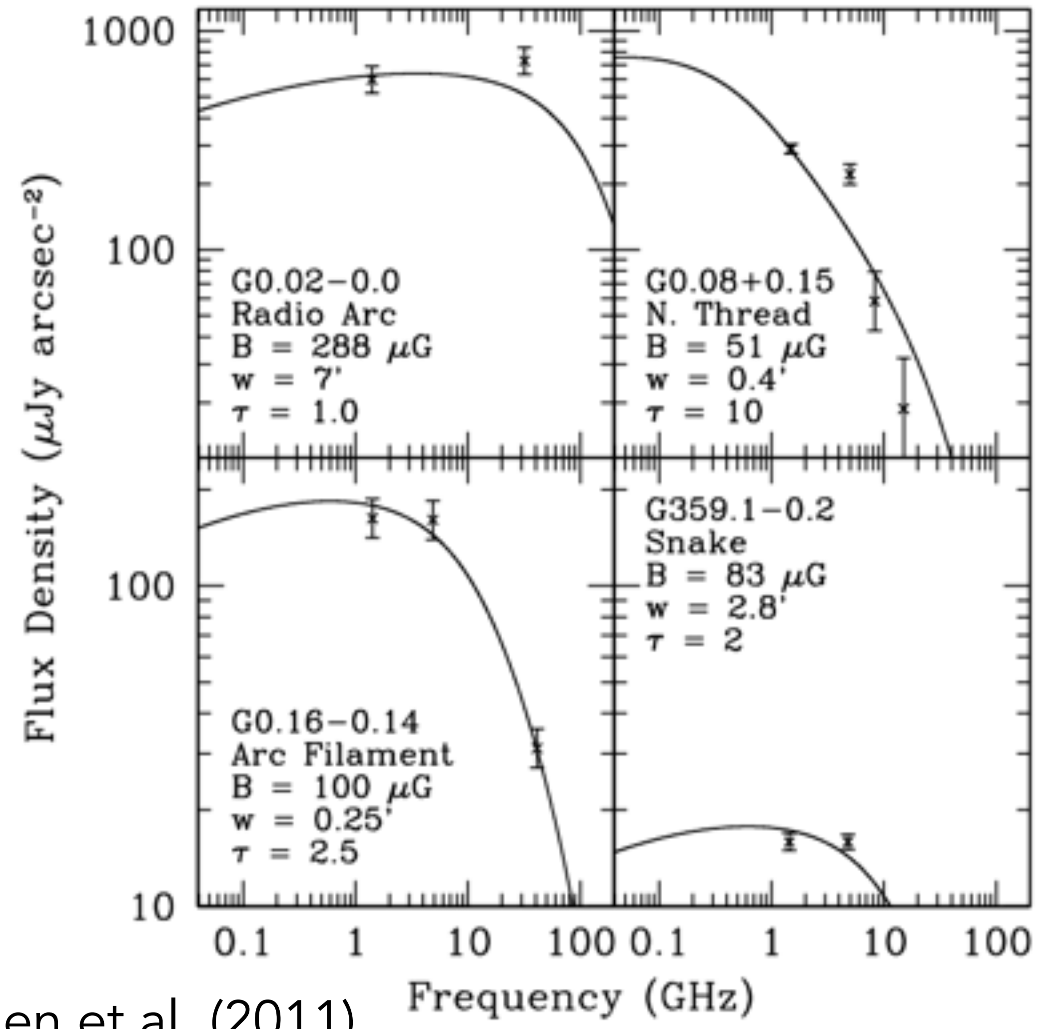


Regis & Ullio (2008)

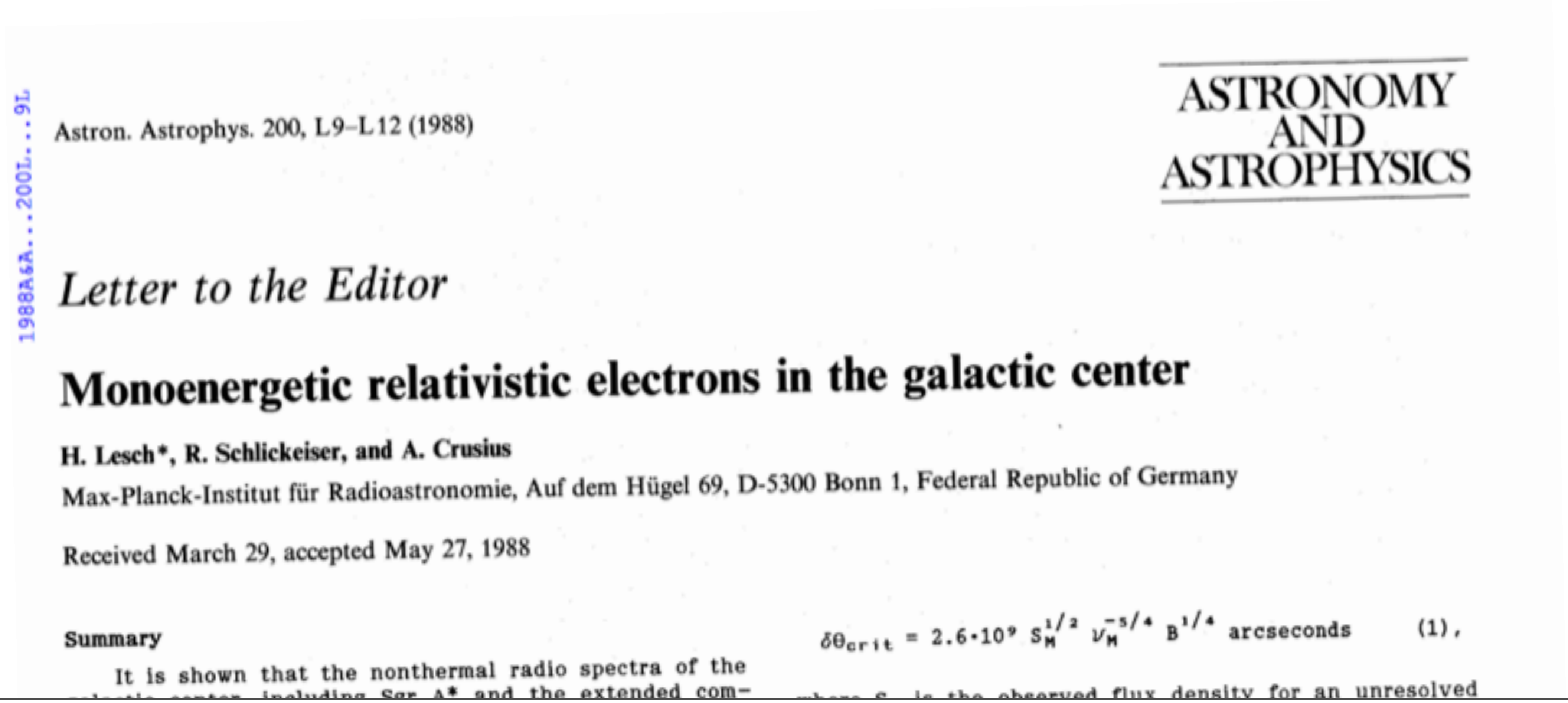


Radio and X-Ray Observations

- Can also place constraints (or find signals) in certain regions of space where you think you understand the magnetic fields better (e.g. the filamentary arcs)



Linden et al. (2011)



Astron. Astrophys. 200, L9–L12 (1988)

ASTRONOMY
AND
ASTROPHYSICS

Letter to the Editor

Monoenergetic relativistic electrons in the galactic center

H. Lesch*, R. Schlickeiser, and A. Crusius
Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-5300 Bonn 1, Federal Republic of Germany

Received March 29, accepted May 27, 1988

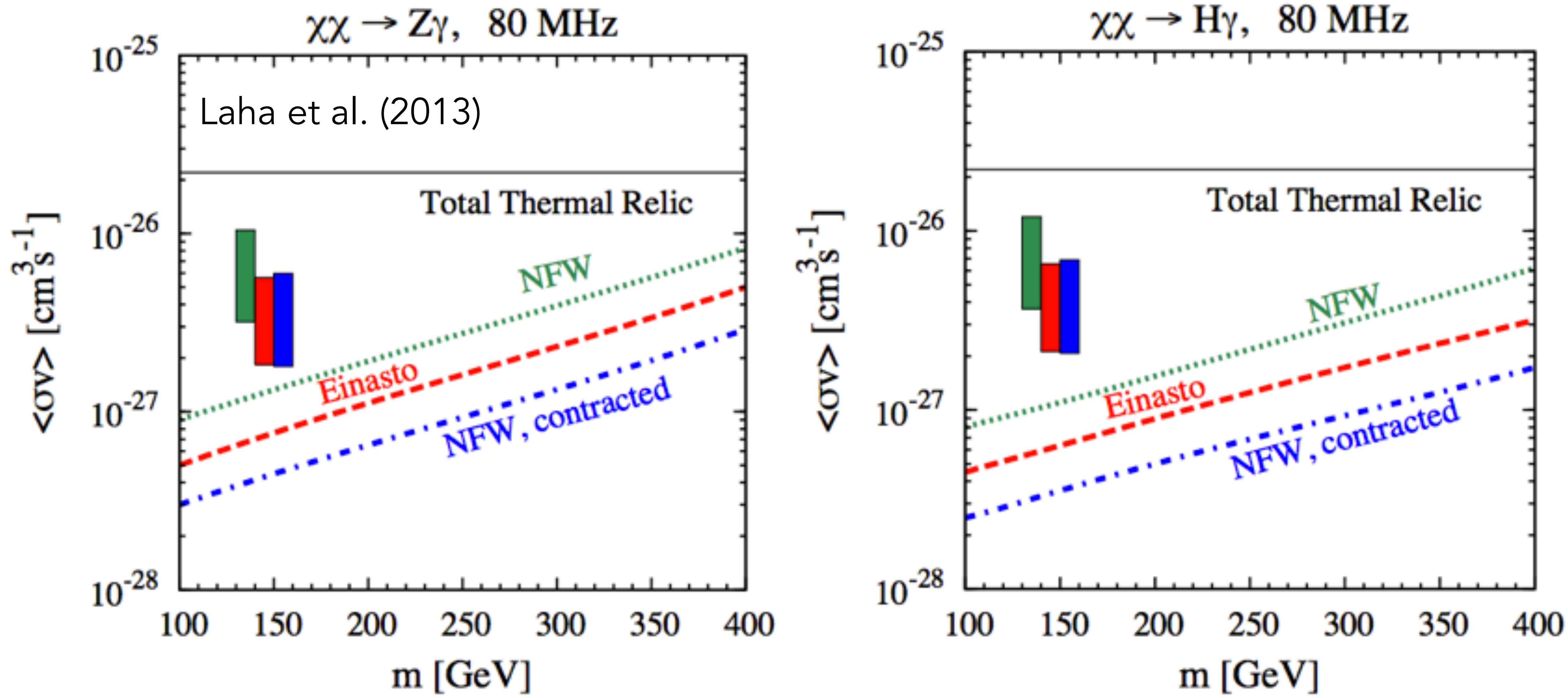
Summary

It is shown that the nonthermal radio spectra of the
including Sgr A* and the extended com-

$$\delta\theta_{crit} = 2.6\cdot10^9\ S_M^{1/2}\ \nu_M^{-5/4}\ B^{1/4}\ \text{arcseconds} \quad (1),$$

is the observed flux density for an unresolved

Future Radio and X-Ray Observations



Laha et al. (2013)

- Can also put constraints on certain gamma-ray models (like the 130 GeV line)

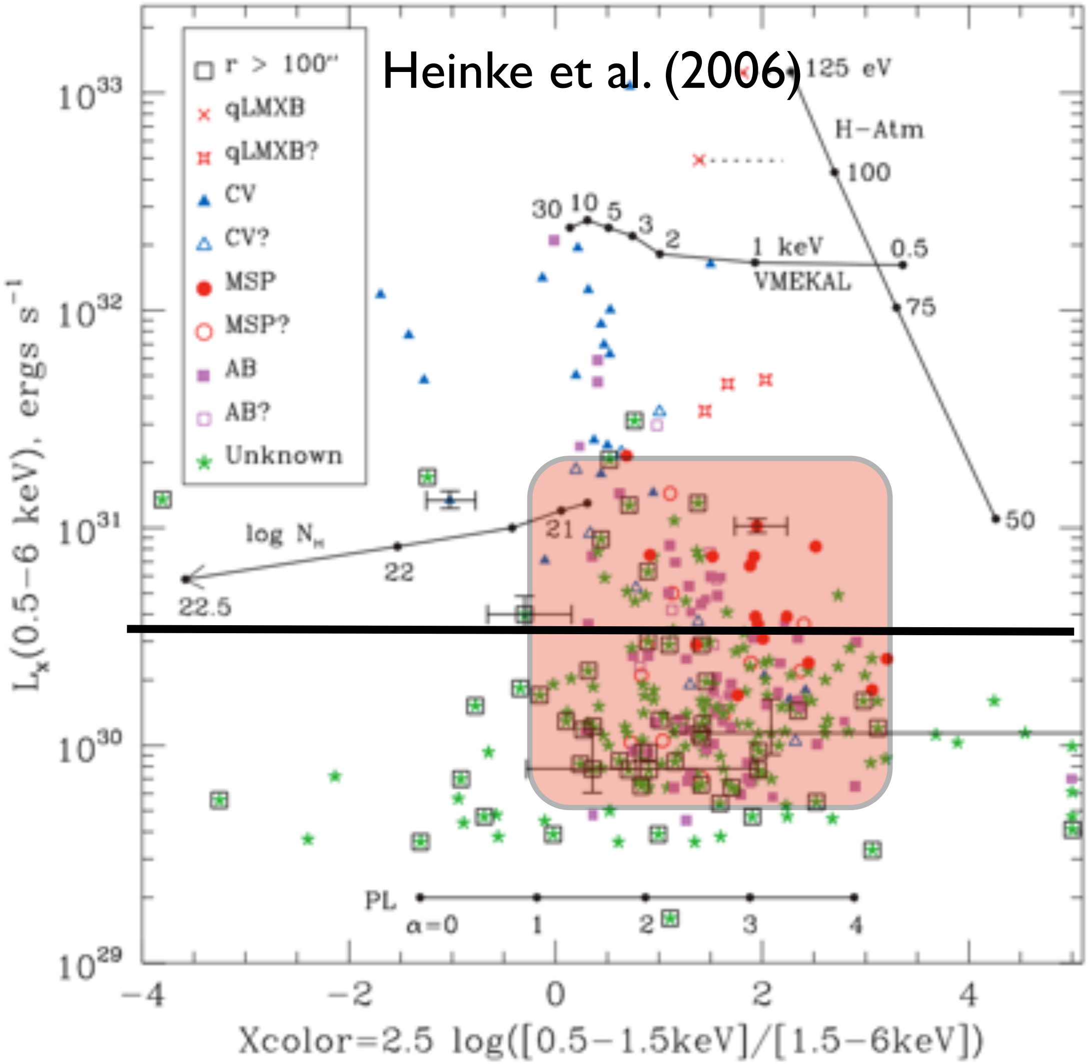
Future Radio and X-Ray Observations

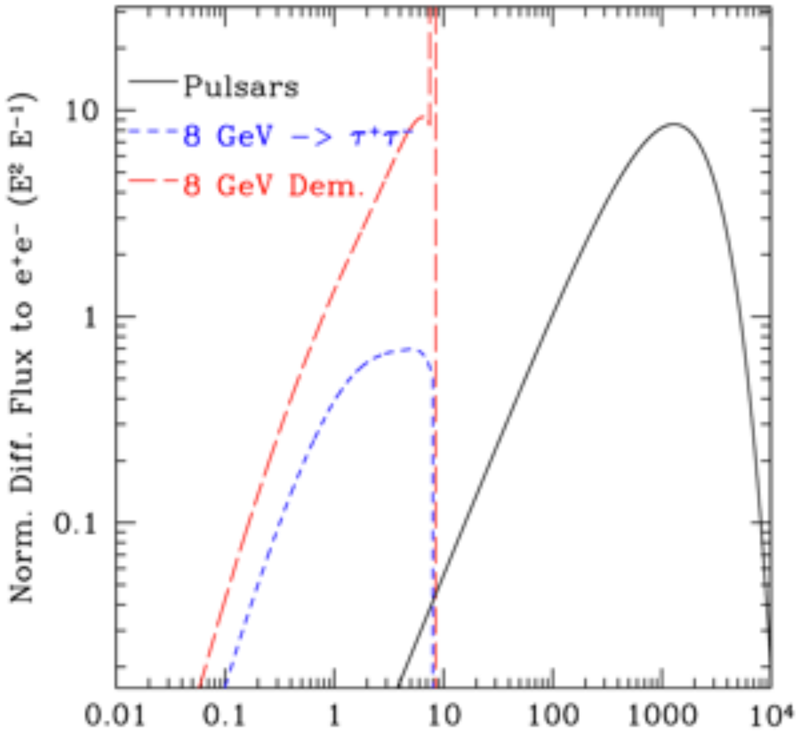
- The Gamma-Ray Signal at the galactic center can also be fit by MSPs

- Gamma-ray Observations will have a difficult time distinguishing these scenarios

- X-Ray point source observations may determine the spatial distribution of MSPs

- Radio observations can determine lepton population in GC

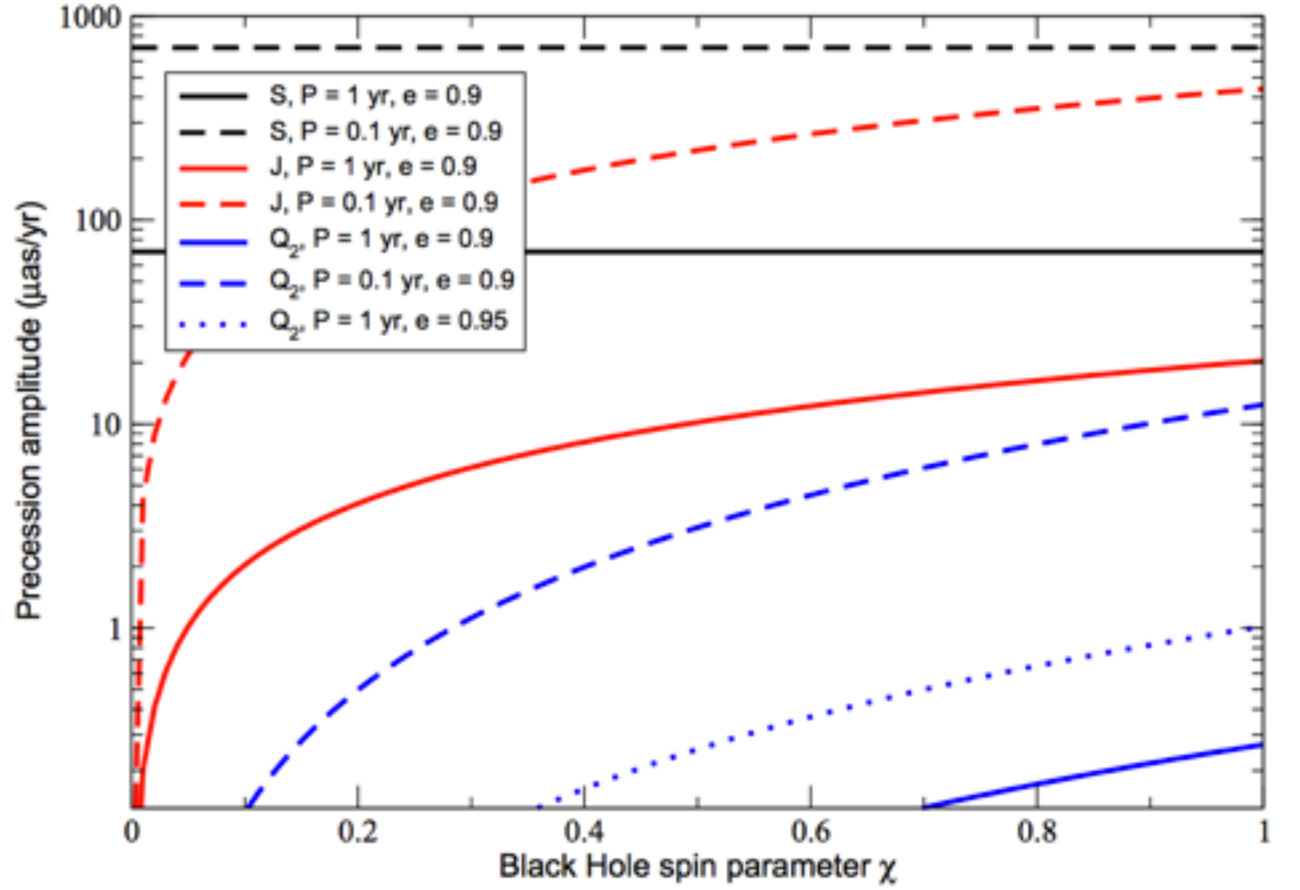

Heinke et al. (2006)



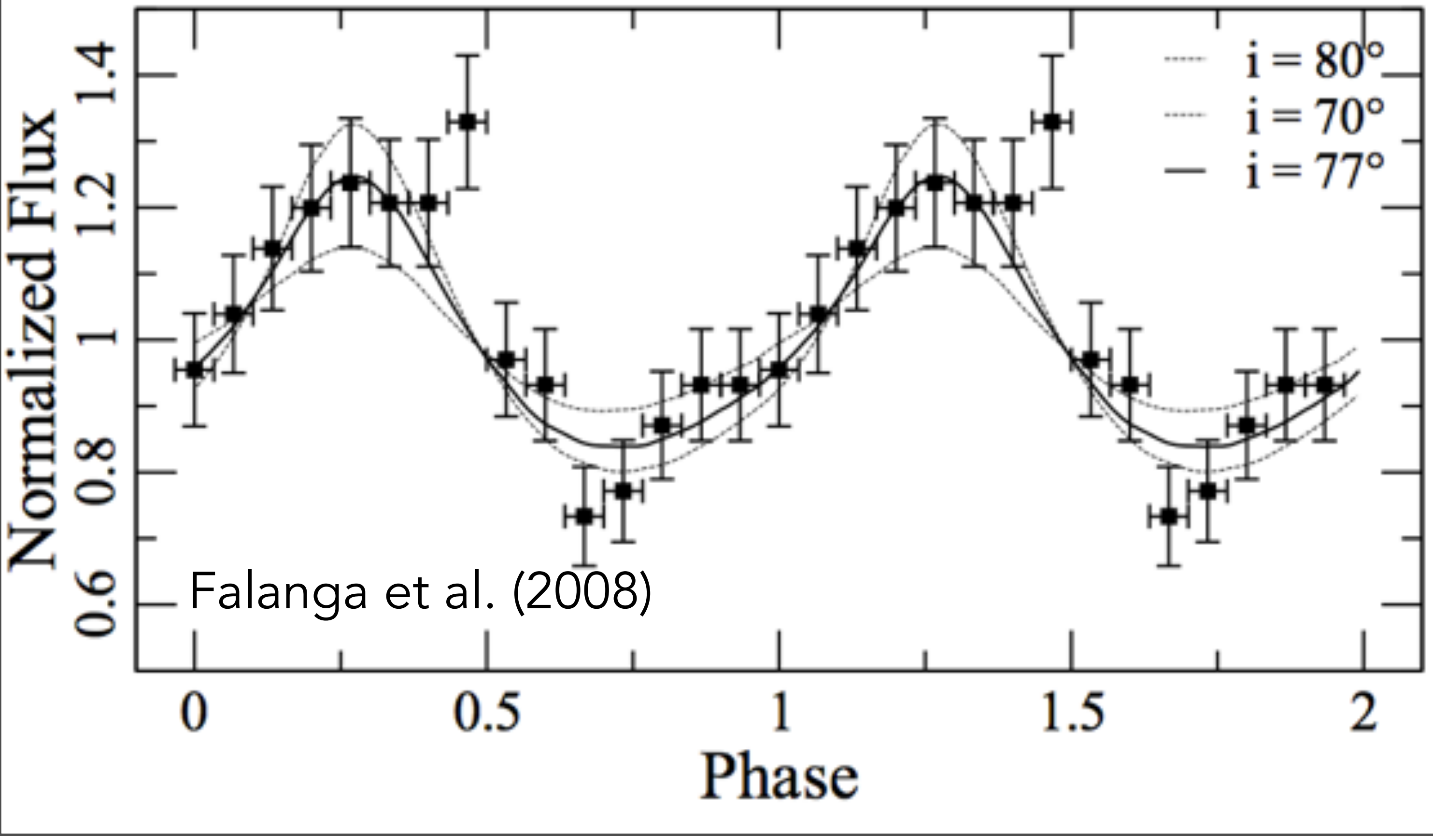
Fundamental Tests of General Relativity

- Two stars within an orbital period ~0.1 yr and an eccentricity e > 0.9 will provide novel tests of the relativistic no-hair theorem

$$Q_2 = \mathbf{J}^2 / M$$



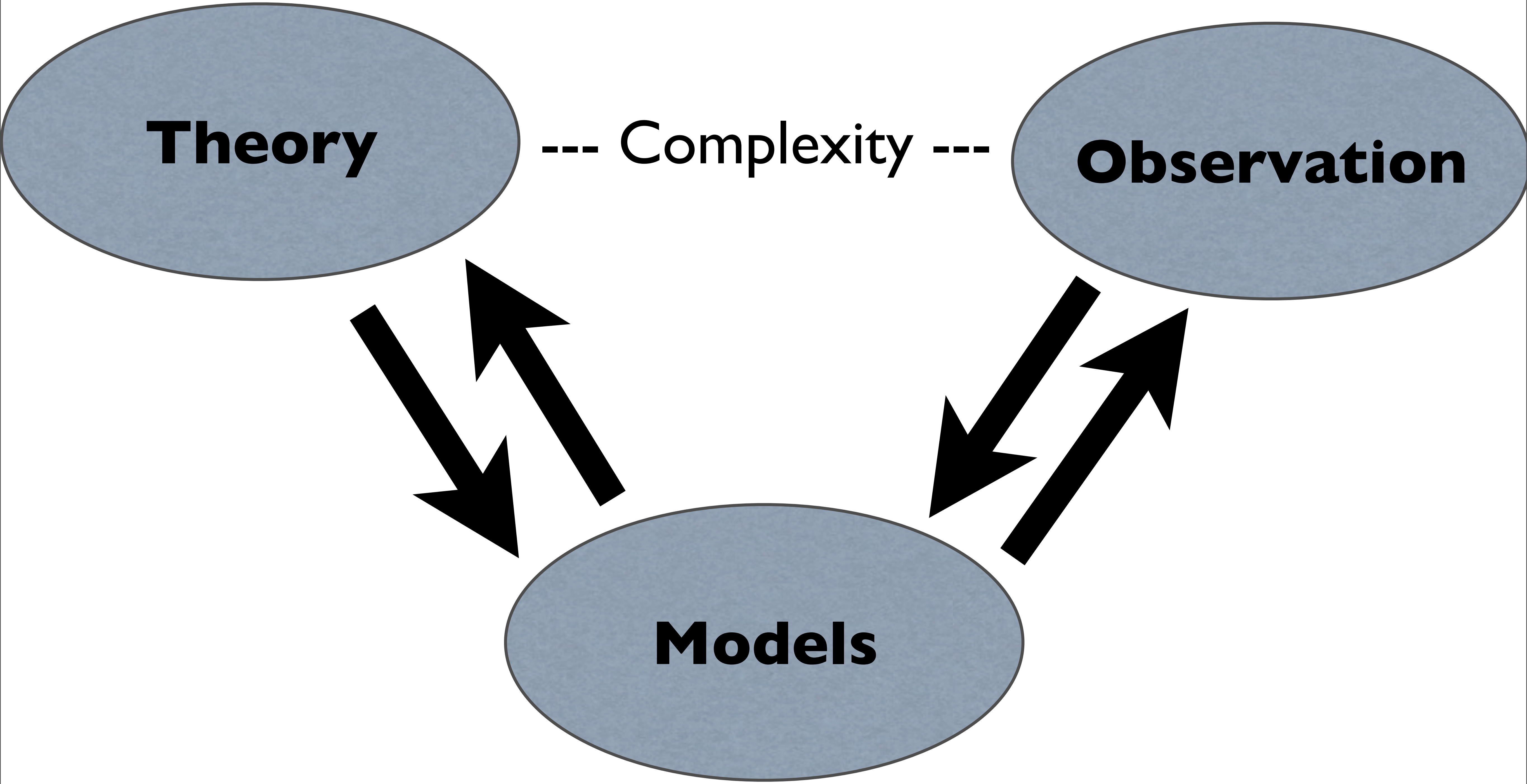
Will (2008)



Falanga et al. (2008)

- Improved measurements of the 22 minute amplitude modulation also depend on inhomogenities of an accretion disk at the ISCO

How Can We Learn About the Galactic Center?



Theory

--- Complexity ---

Observation

Models

Necessary Observational Advances

- Observational capabilities over the next decade are relatively set.

- **Angular Resolution** is the key to understanding the Galactic Center
  - Long Wavelength Array (<100 MHz) - 8″
  - ALMA (84-720 GHz) - 0.1″
  - JWST (0.04 - 2 eV) - < 0.1″
  - NuSTAR (5 - 80 keV) - 18″
  - Gamma400 (100 MeV - 3 TeV) - 0.01° (> 100 GeV)
  - CTA (>20 GeV) - 0.03° (> 1 TeV)

- We have great observational advantages in the Galactic Center - telescopes at every wavelength spend a significant portion of their time staring at it.

Necessary Theoretical Advances

- Understanding the Nature of Particle Dark Matter
  - If other observations (e.g. direct detection) hint at a specific dark matter model, indirect detection experiments become highly constraining

- Understanding the formation of magnetohydrodynamic instabilities

Necessary Modeling Advances

The biggest hurdle to understanding the Galactic Center

Necessary Modeling Advances

- New Models are Required
    - Current State of the Art: Galprop
    - Galprop is good for Galactic simulations, but lacks features like anisotropic diffusion, mesh-gridding, and time variable cosmic-ray injection necessary for understanding the Galactic center
- Algorithms must incorporate multi-wavelength observations seamlessly
    - This is something which (in the speaker's opinion) has been lacking in most novel work on the Galactic Center region
- Also, line emission, polarization, and moving sources must be taken into account to produce the best constraints

Necessary Modeling Advances

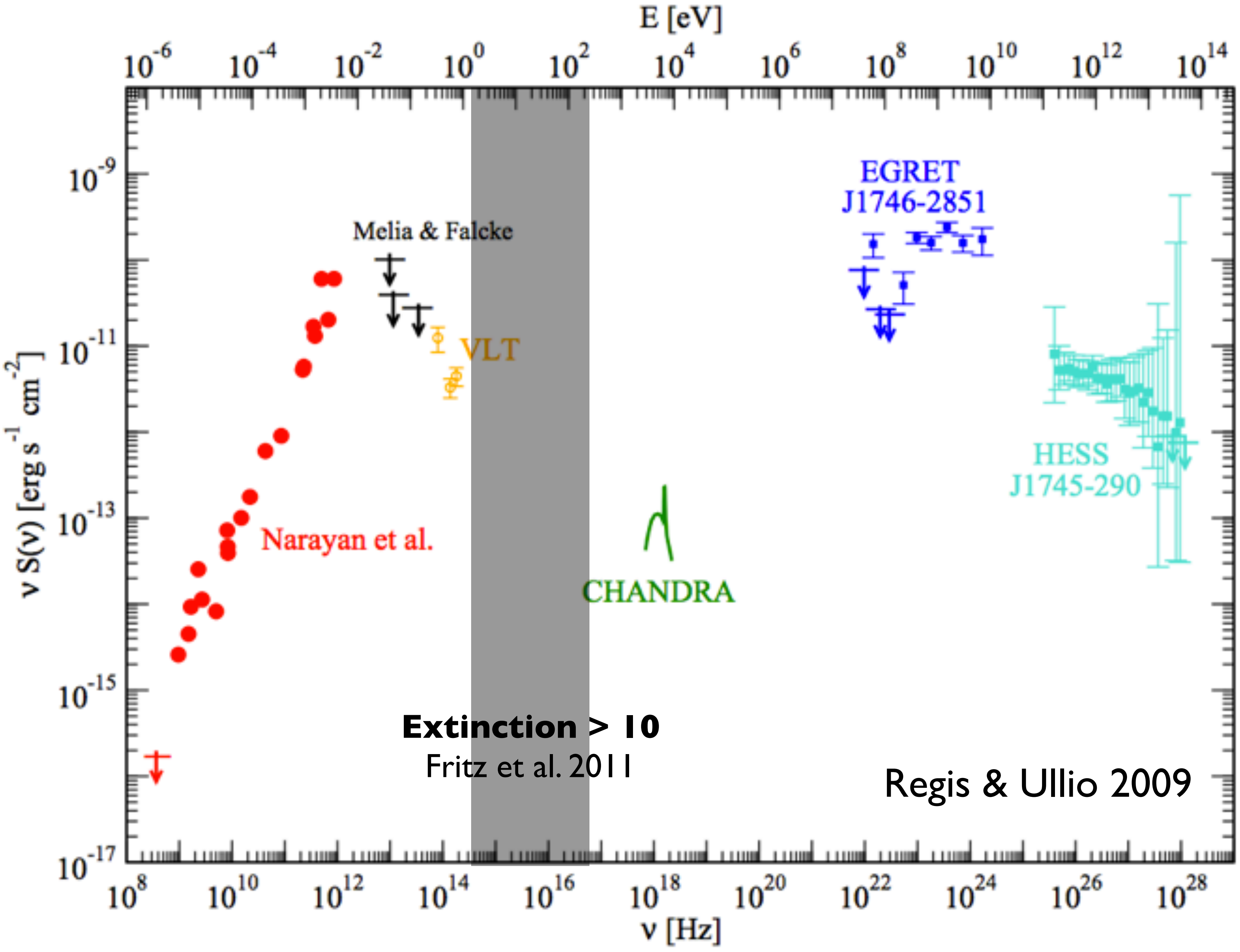
- Dozens of “free-parameters” require restraint from multiple observations and large parameter space explorations.
- Big Data Age of Galactic Center Observations - can we make sophisticated models to ensure that this data is used adequately?

Conclusions

- Galactic Center is filled with opportunities (and puzzles) for advances in fundamental physics
- Upcoming instruments will greatly advance our ability to differentiate source classes at the Galactic Center
- Large advances in modeling are necessary to take advantage of the datasets we will be given in the next decade

Extra Slides

The Multi-wavelength Galactic Center

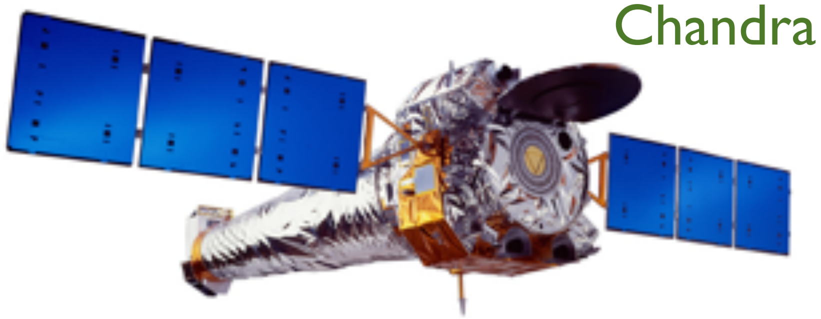


Extinction > 10
Fritz et al. 2011

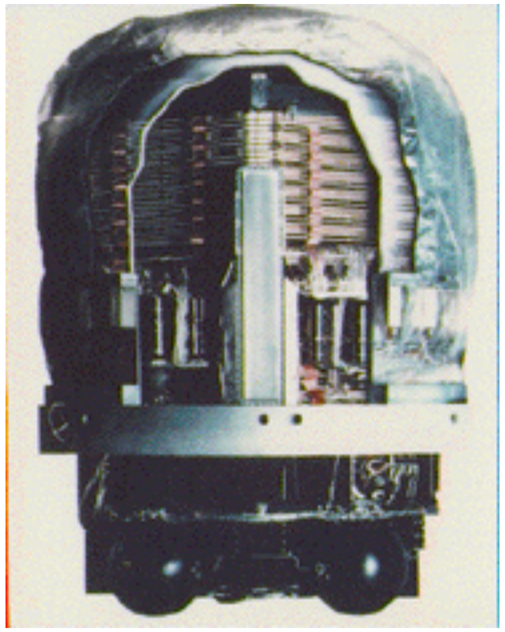
Regis & Ullio 2009

VLA

Chandra



EGRET



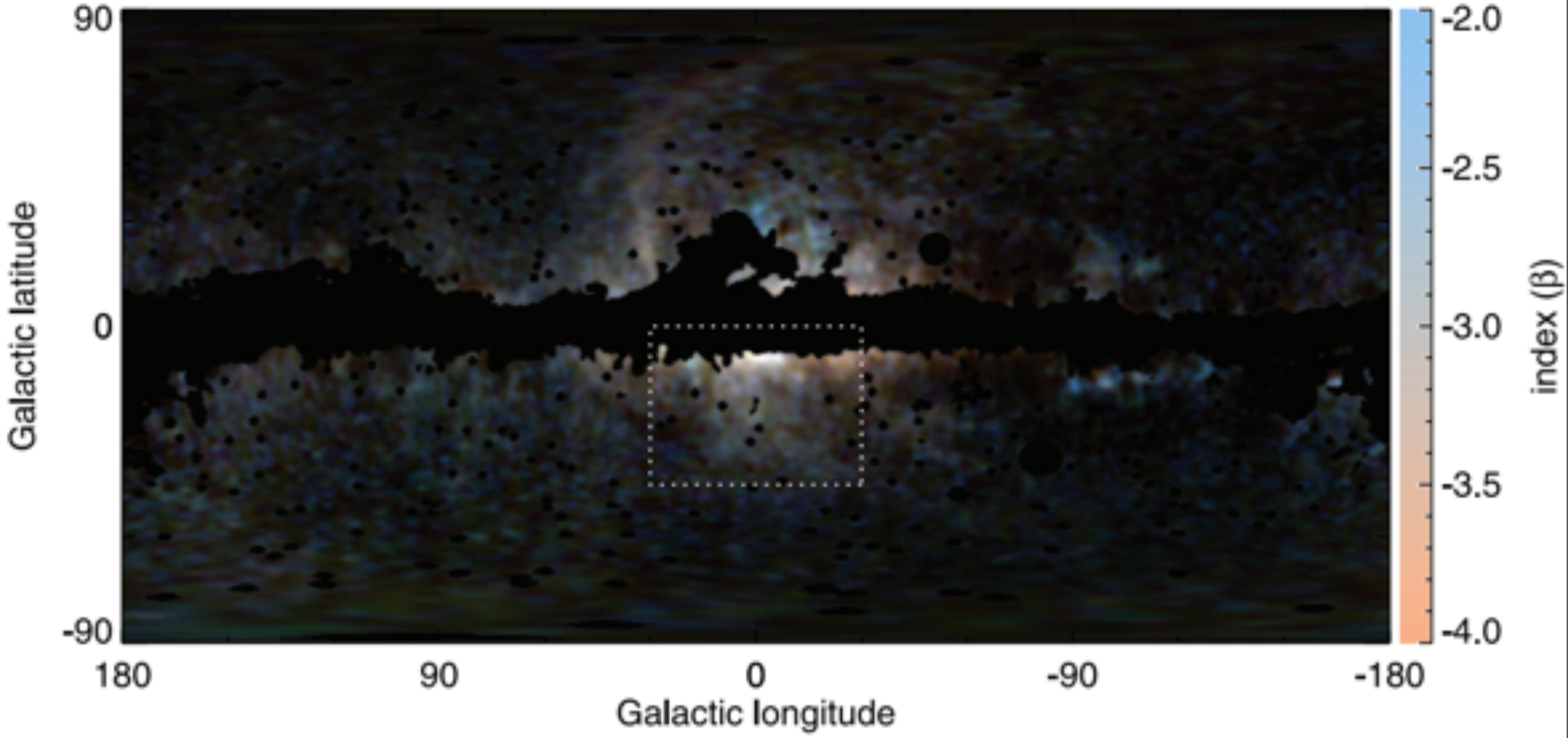
HESS

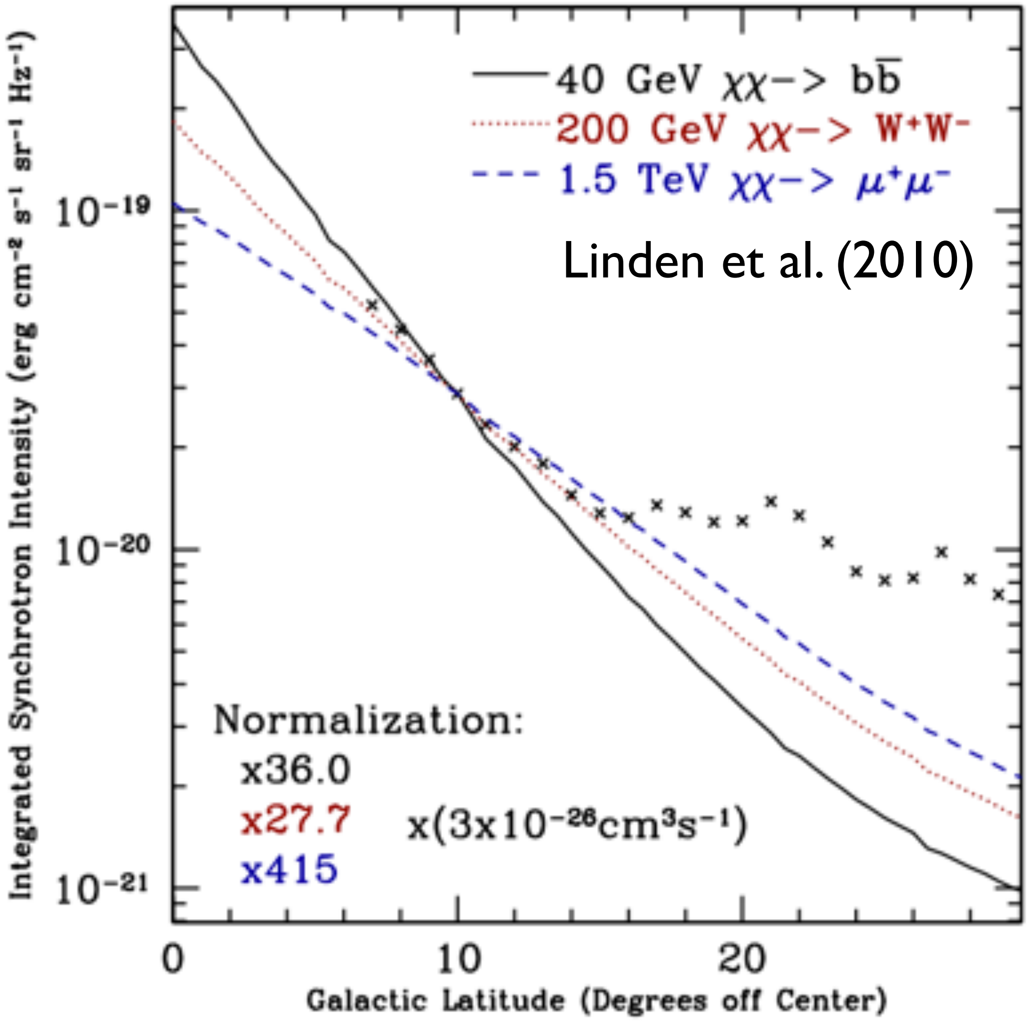
Fermi-LAT

What is the WMAP Haze?

- Discovered by Doug Finkbeiner in 2004
- Synchrotron origin determined by subsequent observations
- Hard spectrum difficult to fit with lepton injection spectra typical of astrophysical phenomena
- Well fit by dark matter models with typical annihilation cross-sections and spectra
- However, modifications are needed to magnetic fields in galactic halo

Dobler et al. (2008)

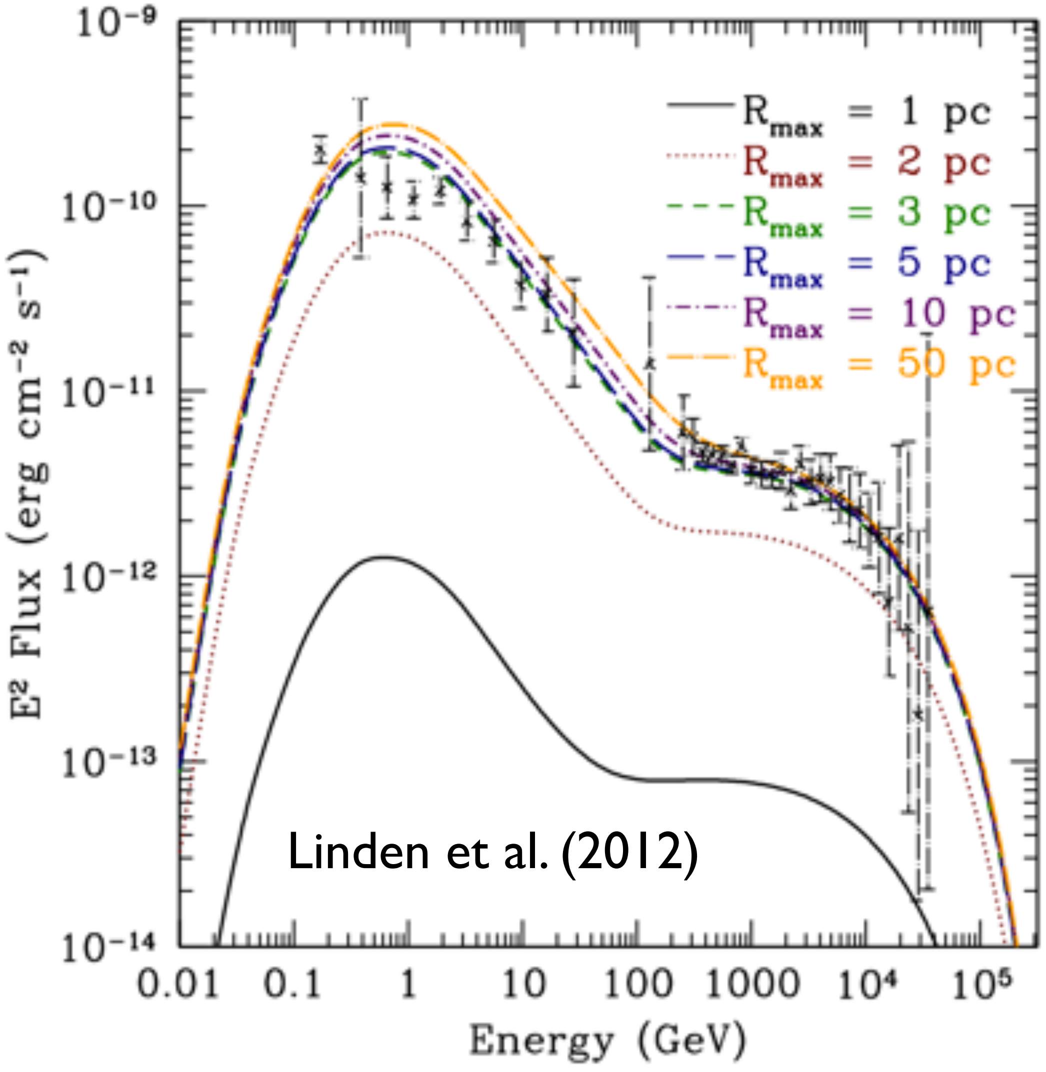



Linden et al. (2010)

Modeling Benefits of the Hadronic Scenario!

- Under the assumption that the proton source has a power-law spectrum and is in steady-state, then the slope of gamma-ray emission strongly constrains the diffusion constant in the galactic center region:

$$D_0 = 1.2 \times 10^{26} \, (E/1 \, \text{GeV})^{0.91}$$

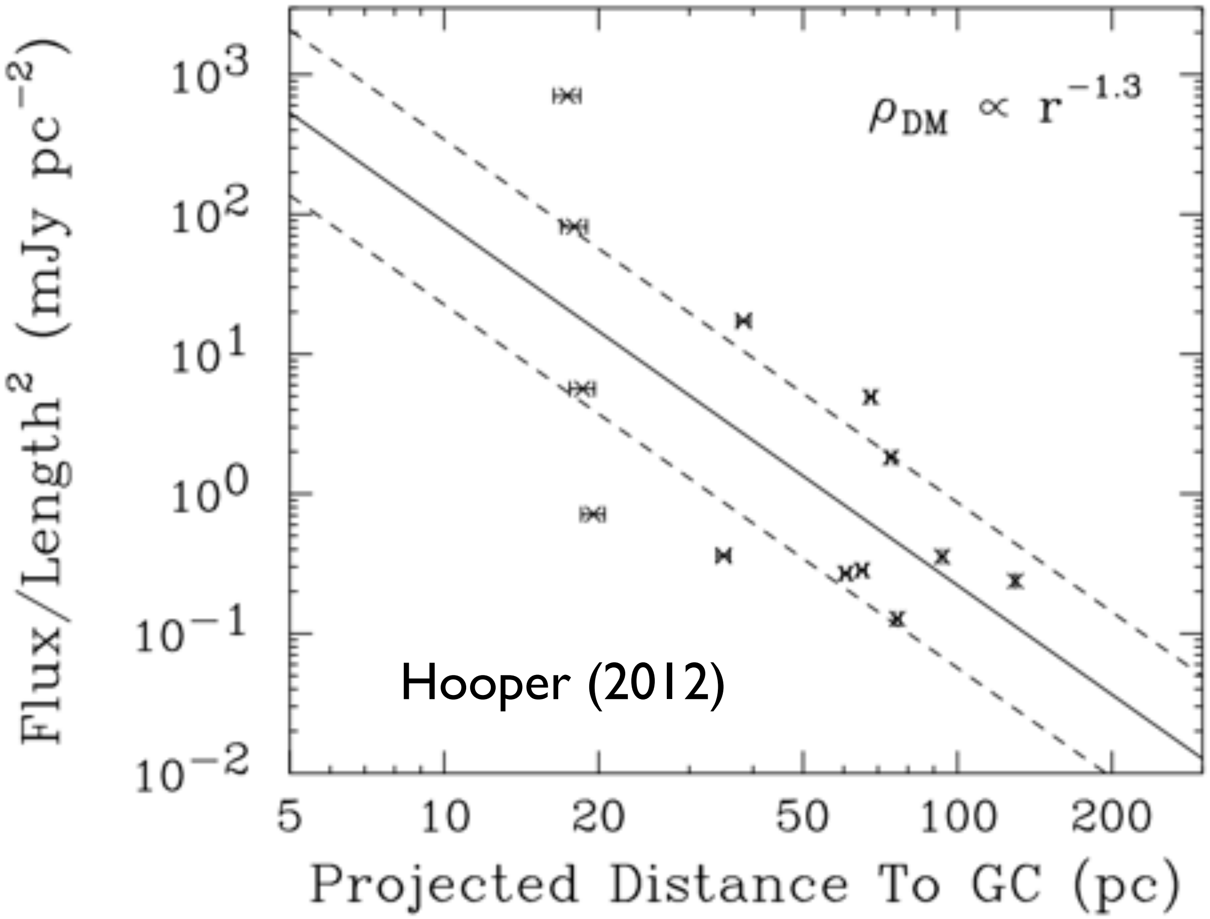


Linden et al. (2012)

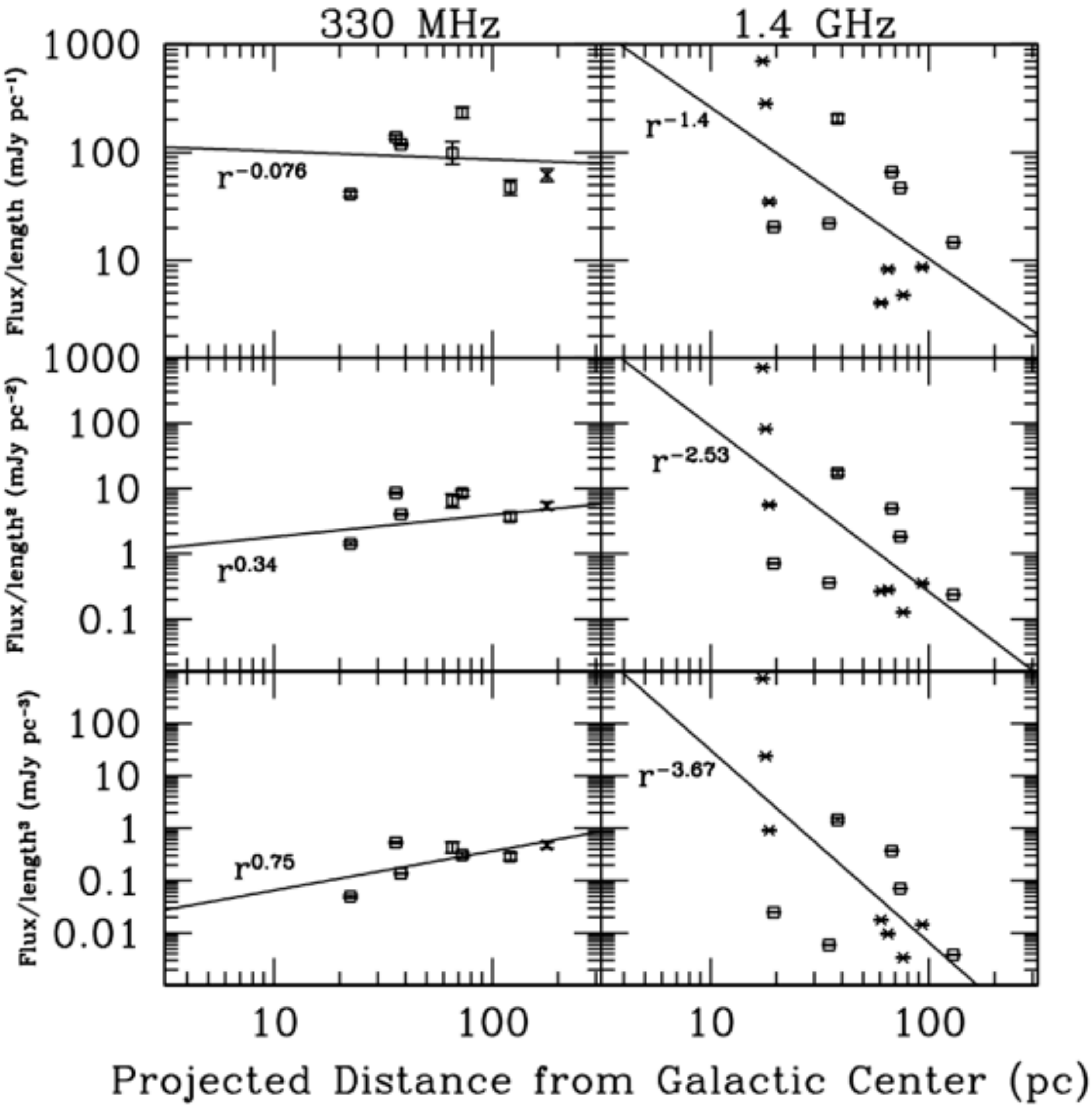
- This adds additional constraints to the an understanding of lepton diffusion and propagation in the galactic center region

The Radial Dependence of the Filamentary Arcs

- The intensity of multiple filamentary arcs show a strong dependence on their distance from the galactic center
- This is expected in dark matter models, but not in most astrophysical interpretations of the filaments



Hooper (2012)



Linden et al. (2011)