Insights into the the Galactic Center environment

from

VHE gamma-ray observations with ground-based facilities

16th Marcel Grossmann Meeting – Rome 2021

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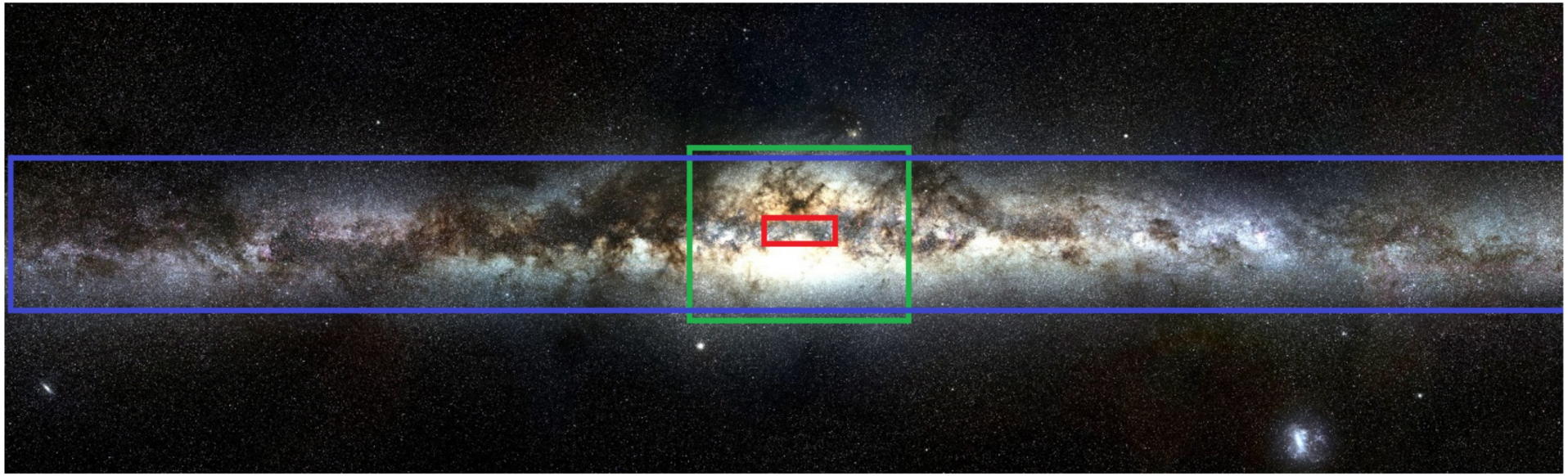
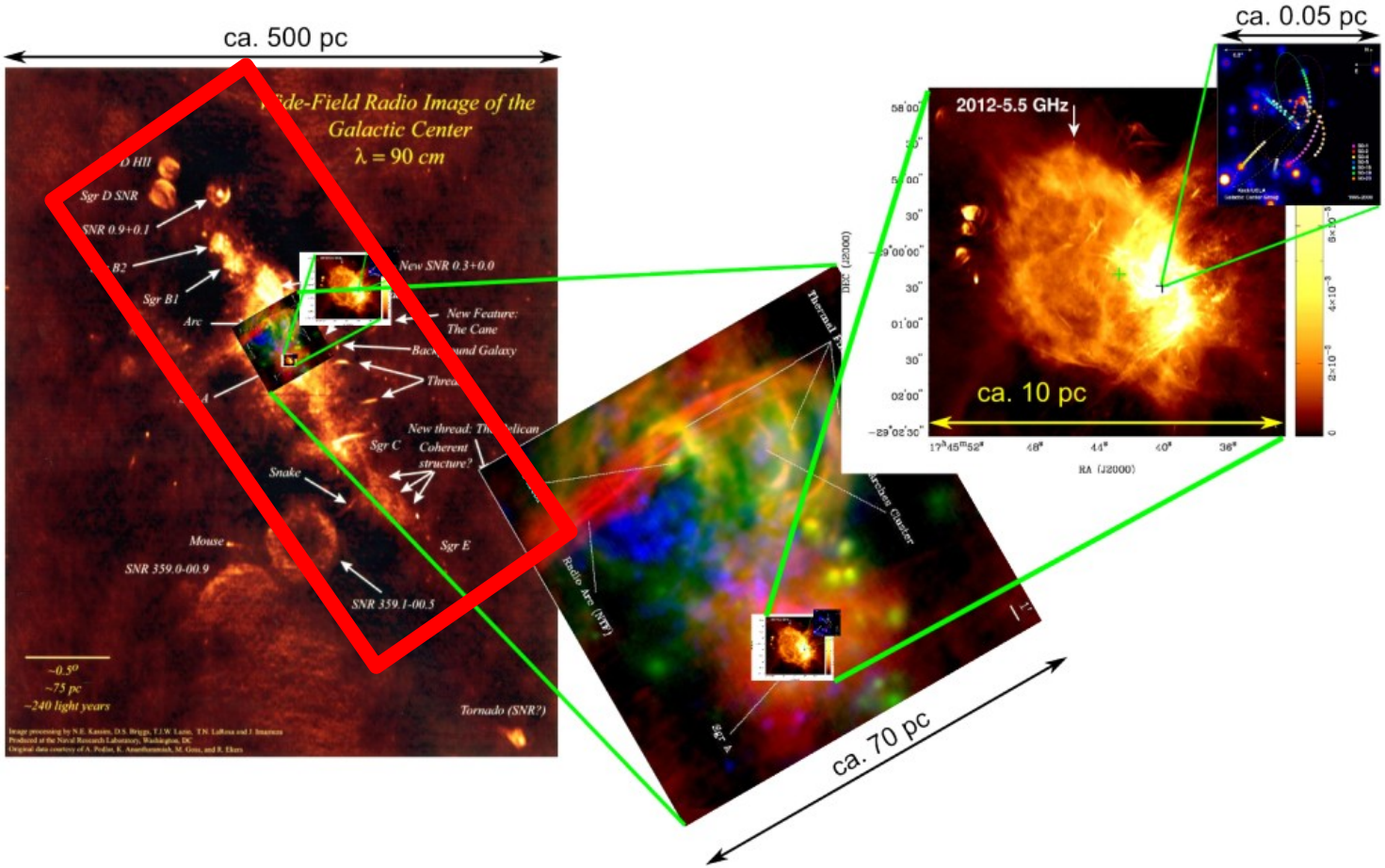
Galactic Center Astrophysics – Scales 1



- disk (30 kpc x 0.3 kpc): young stars, gas, molecular clouds, dust
- bar (4.5 kpc) and bulge (1.5 kpc): old stars low star formation
- Central Molecular Zone (CMZ, 250 pc): dense molecular clouds high star formation rate

image source: https://apod.nasa.gov

Galactic Center Astrophysics – Scales 2



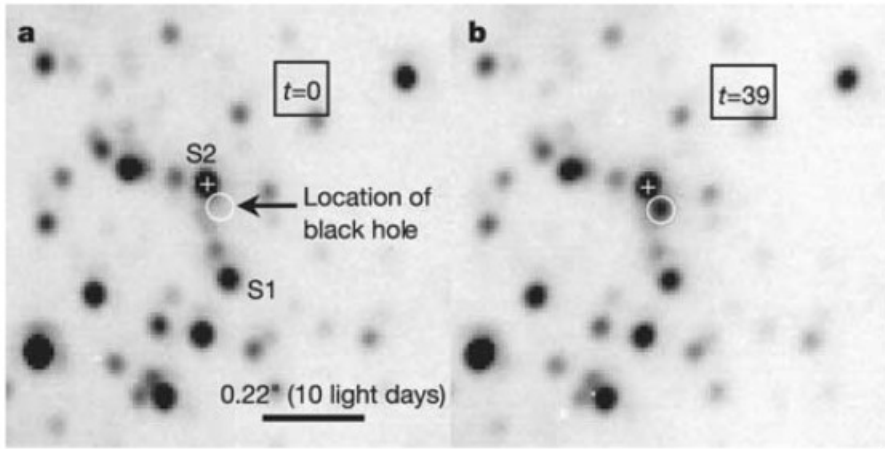
- few 10 OB stars confined inside the central arc-sec around SgrA*
- star S2 periastron: 120 AU, period: 15.6 y

refer to for example: Ghez, A. M., et al. The Astrophysical Journal 509.2 (1998): 678.

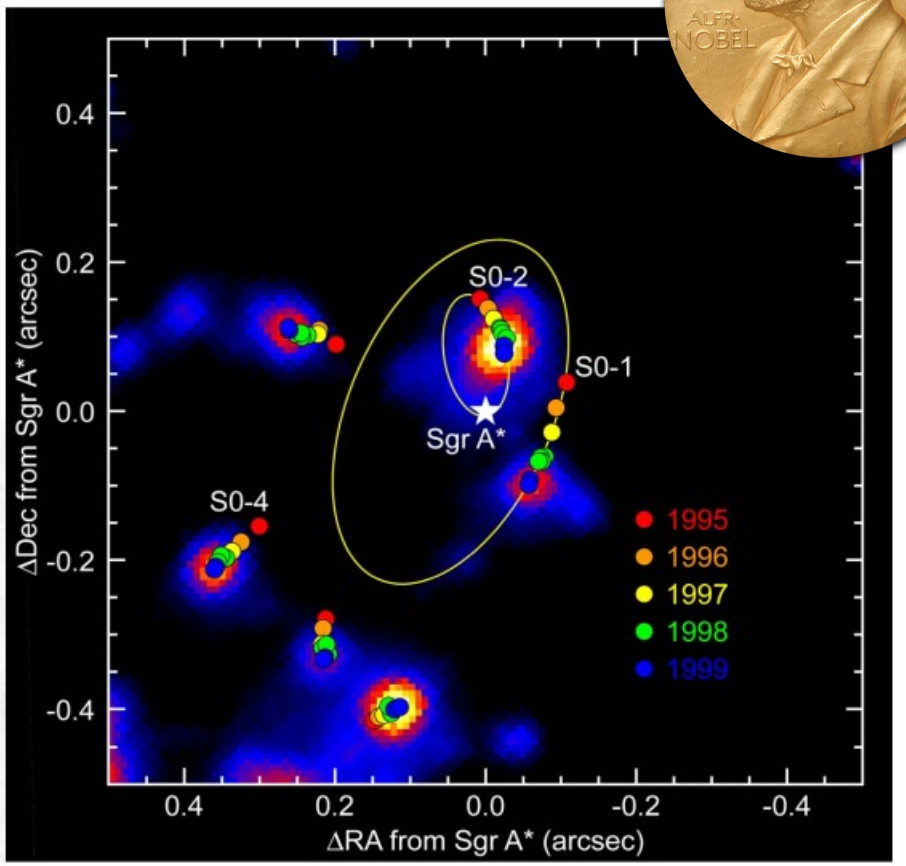
- IR image with S-stars/orbits highlighted (right)
- SgrA* is highly variable in the IR

Gravitational radius:
$r_s = \frac{2GM}{c^2} = 1.2 \cdot 10^{12}\,\mathrm{cm} = 4 \cdot 10^{-7}\,\mathrm{pc} = 10\,\mu\,\mathrm{arc\,sec}$

- Expected to be resolved in the mm/sub-mm radio with VLBI (EHT)



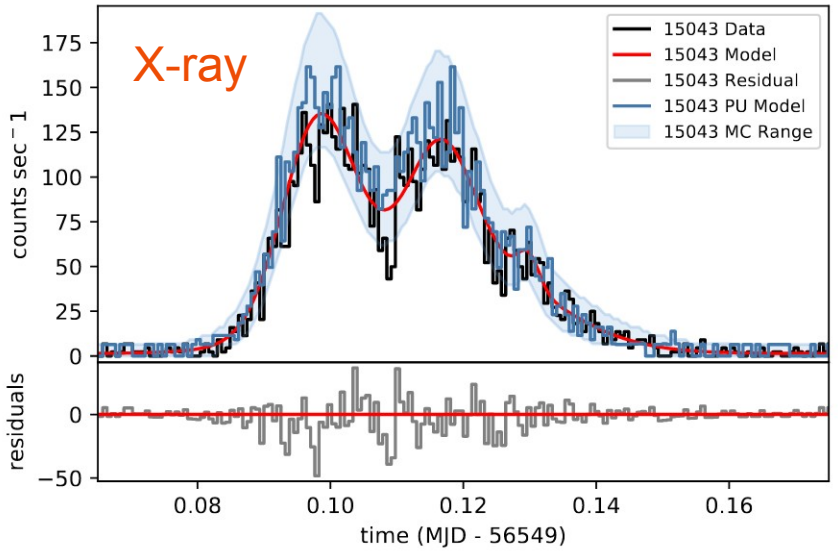
Genzel et al. 2003



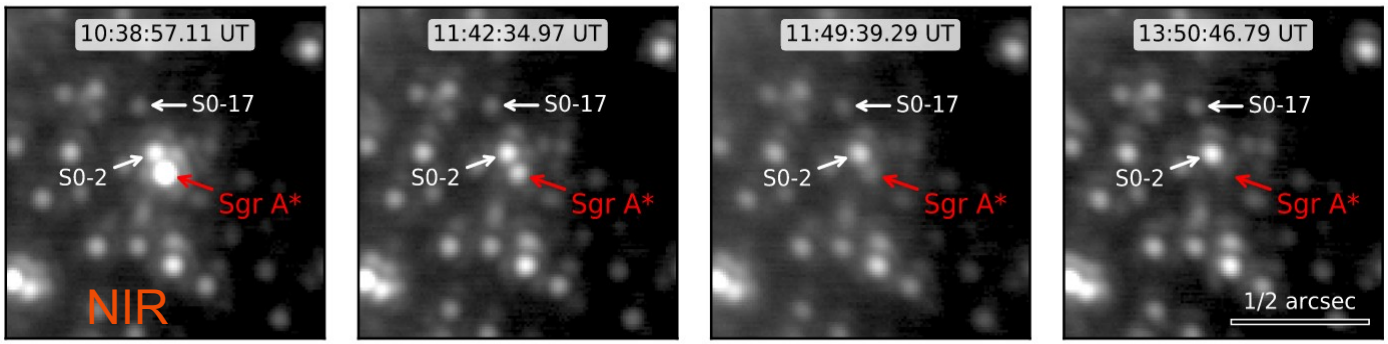
A. M. Ghez et al. 2000

Short time-scale variability:

- Minute-day-scale variability
- X-ray, IR and Radio
- Changes by orders of magnitude
- From direct vicinity of the BH
- No direct link to specific events (G2 pericenter passage, etc.)



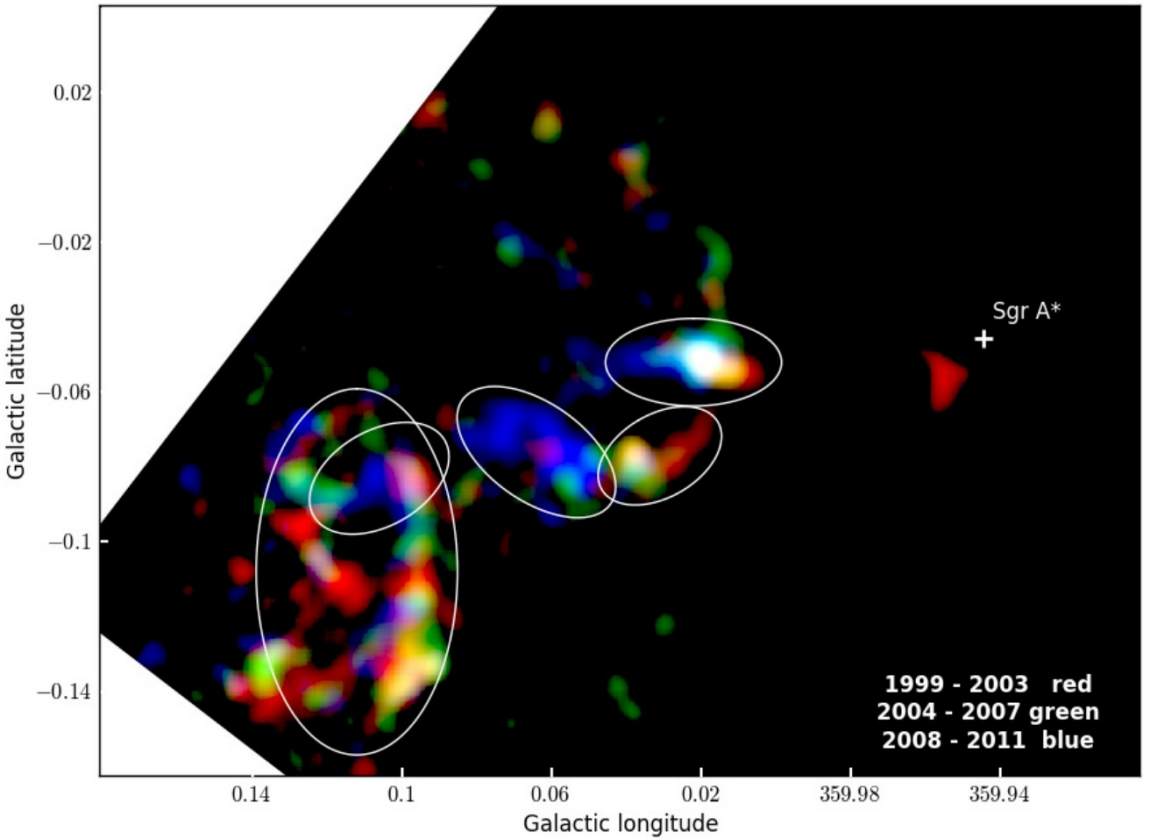
Daryl Haggard et al 2019 ApJ 886 96



Tuan Do et al 2019 ApJL 882 L27

Intermediate time-scale variability:

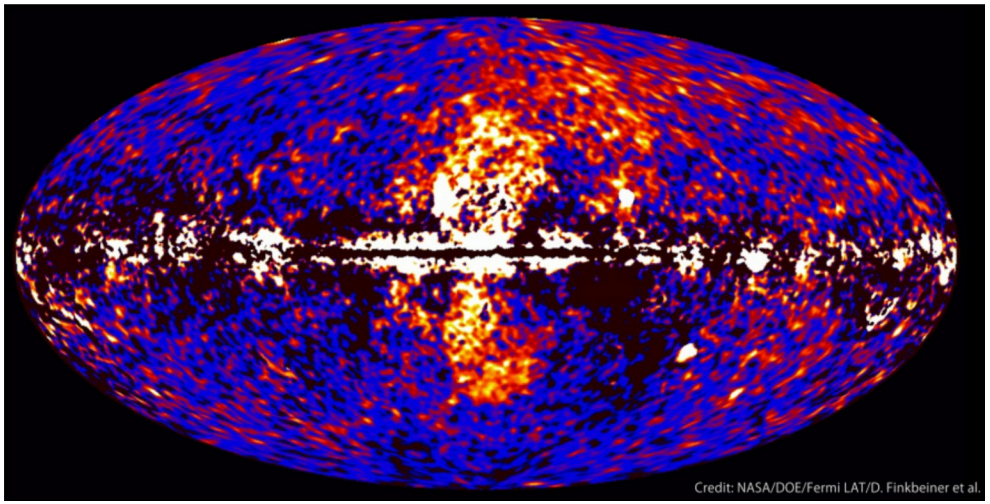
- Indirect evidence from X-ray echos
- Probably linked to past very bright flares
- Echo can be seen propagating
- time-sale of years
- Causes not precisely known

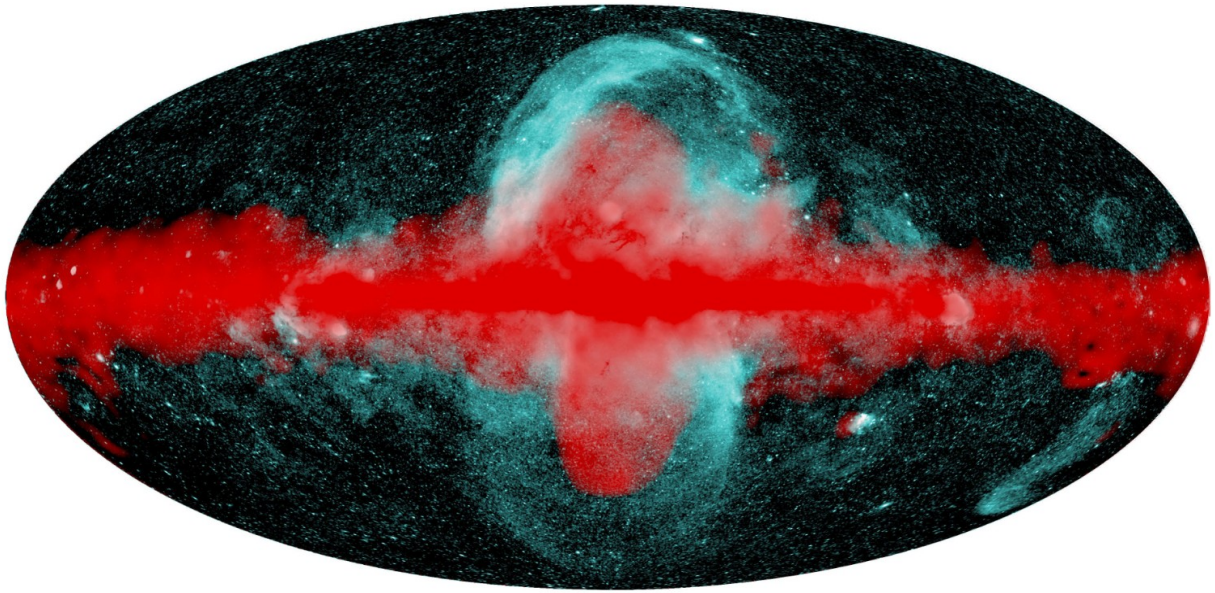


A&A 558, A32 (2013)

Long time-scale variability(?):

- Galaxy-scale structures in X-rays and gamma rays
- Fermi bubbles (2010), ~GeV
- EROSITA bubbles (2020), ~keV
- Could be linked to past activity of SgrA*
- Remnant of possible jet-like structure (timescale of ~My)
- Different explanations possible (Epochs of intense star formation, etc.)

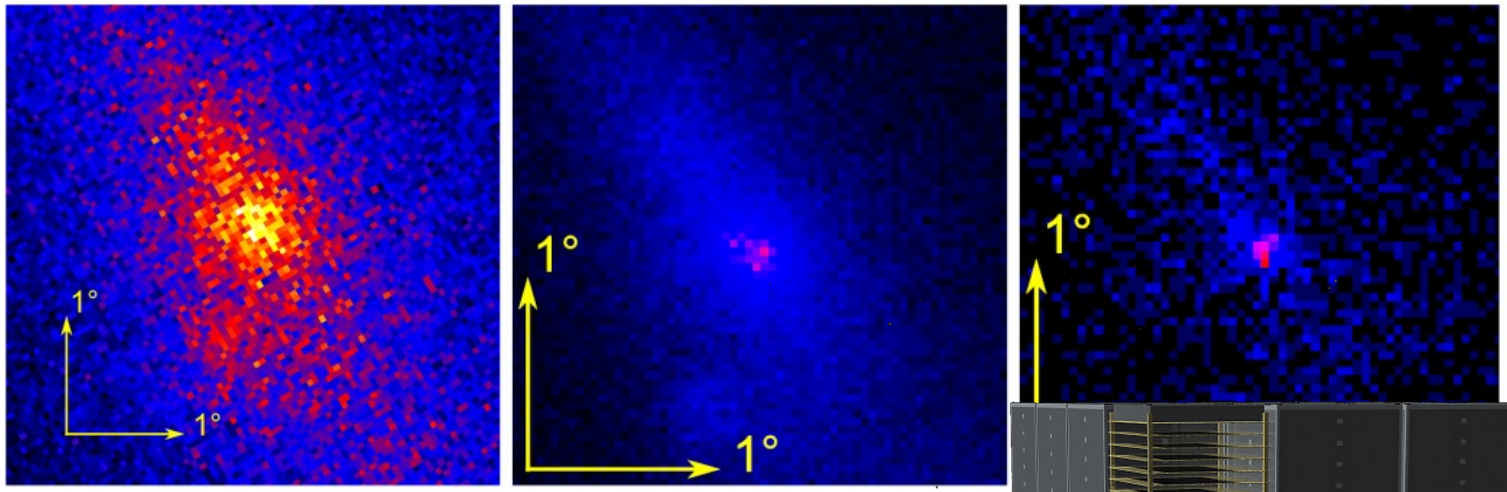




Nature volume 588, pages 227–231 (2020)

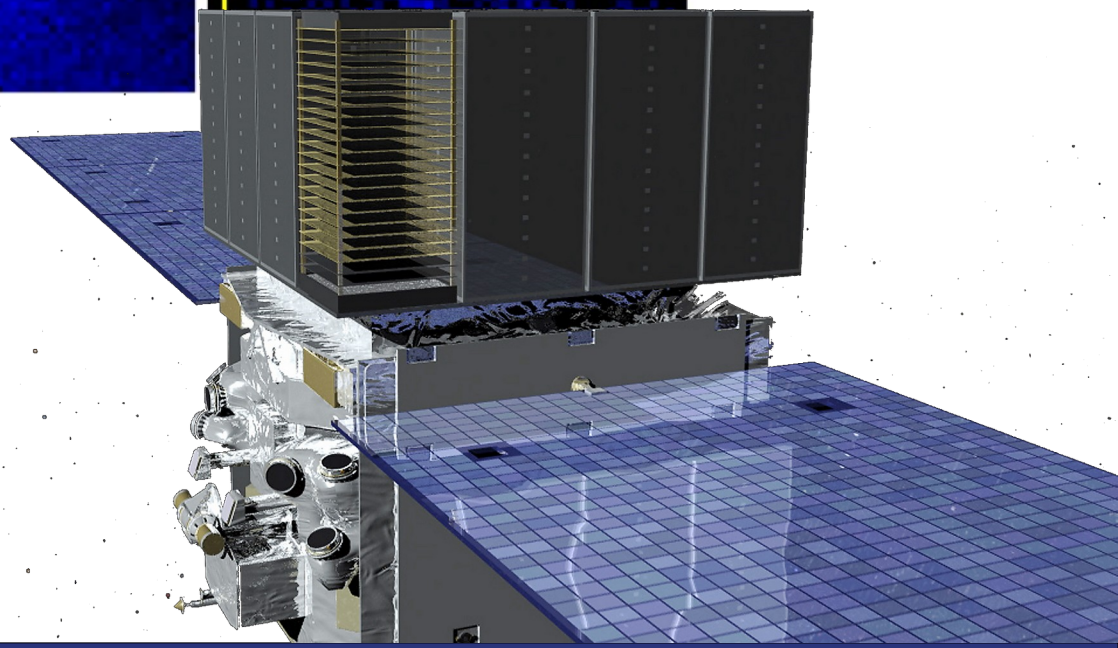
The Galactic Center viewed by Fermi

Count maps ($E > 100\,\mathrm{MeV}$, $E > 1\,\mathrm{GeV}$, $E > 10\,\mathrm{GeV}$):



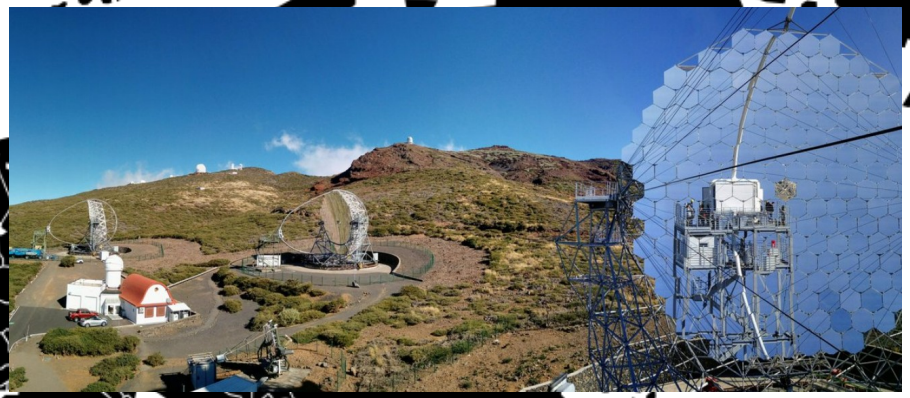
- limited resolution
- crowded FoV

$\Rightarrow$ source association difficult

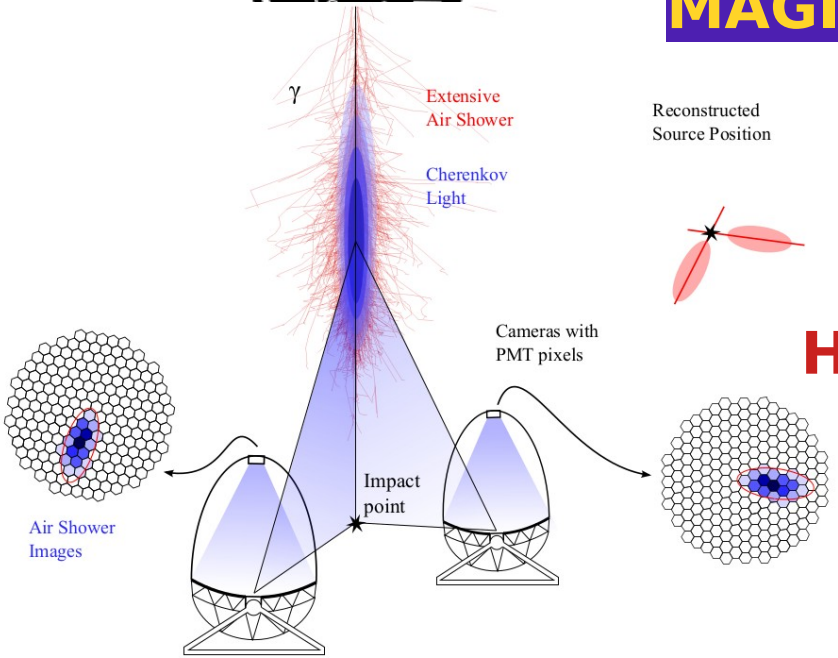


VHE gamma-ray telescopes – IACTs

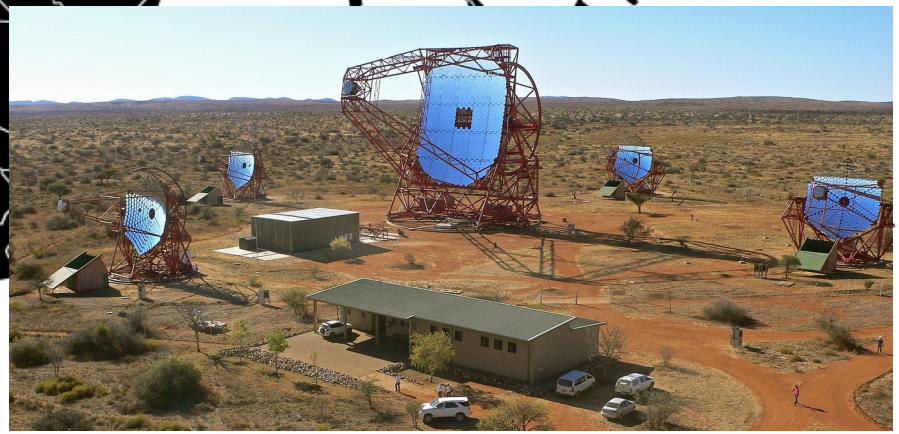
VERITAS



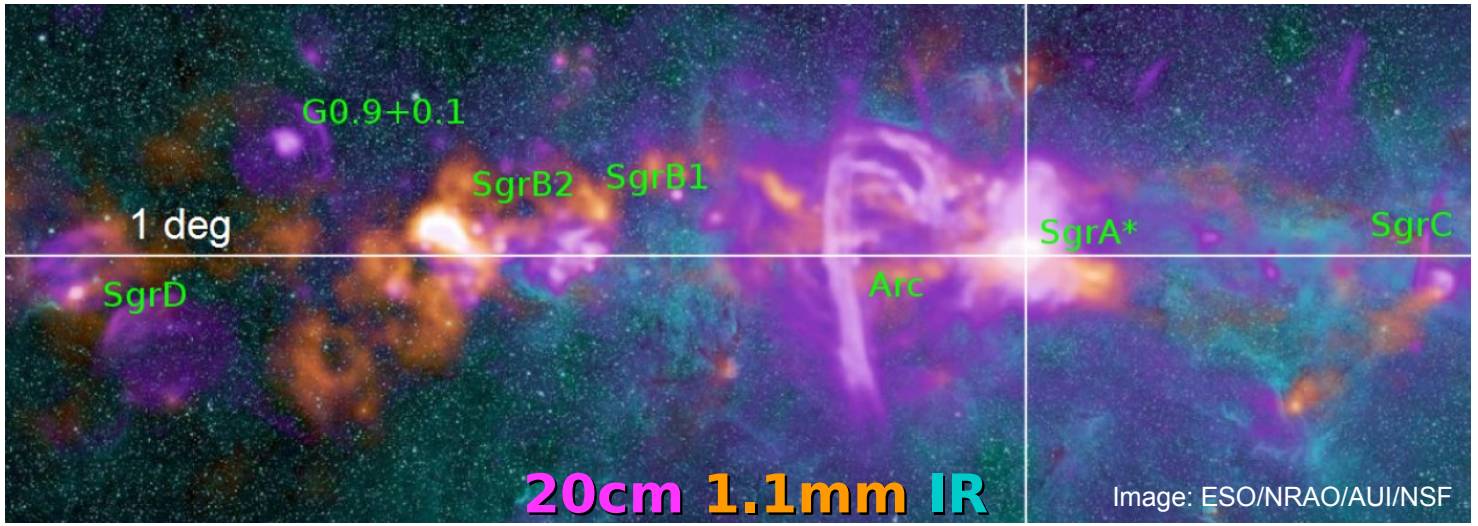
MAGIC



H.E.S.S.



The Galactic Center in the scope of IACTs



The Central Molecular Zone (CMZ):

- Extends ~200 pc in positive and ~100 pc in negative gal. longitude
- Very rich astrophysical environment: high star forming rate, many SNRs, dense gas, dust and super-massive MCs
- Bright throughout the EM spectrum up to VHE gamma-rays
- high risk of source confusion

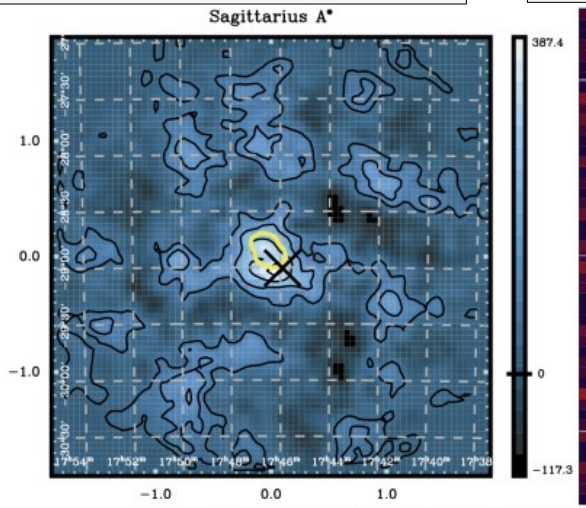
Radio source SgrA* and the SMBH:

- SgrA* is a point-like radio source that is highly variable in X-ray
- Associated with 4 $M_{\odot}$ SMBH
- Source candidate for gamma-ray emission
- Role as CR-accelerator speculated upon (PeVatron)
- Variable in VHE?

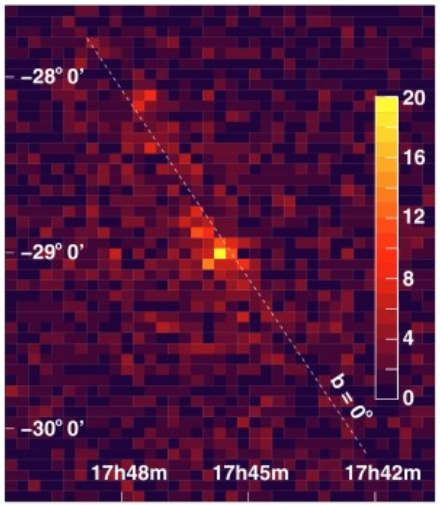
First detections:

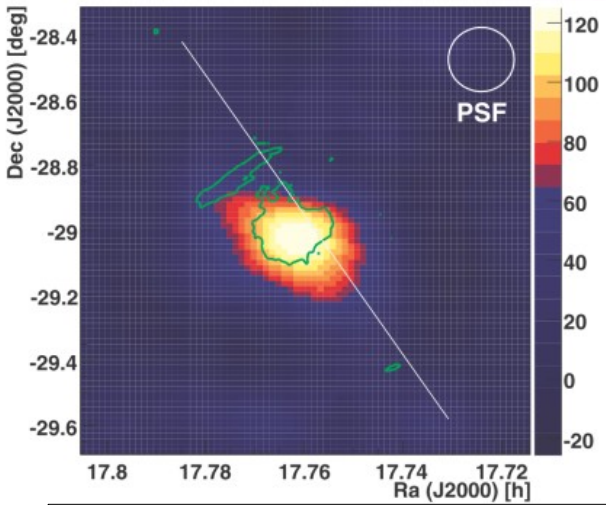
- CANGAROO II
  (K. Tsuchiya et al. 2004)
- Whipple
  (Kosack et al. 2004)
- HESS J1745-290
  (Aharonian et al. 2004)
- MAGIC
  (Albert et al. 2006)

K. Kosack et al 2004 ApJ 608 L97



A&A 425, L13-L17 (2004)

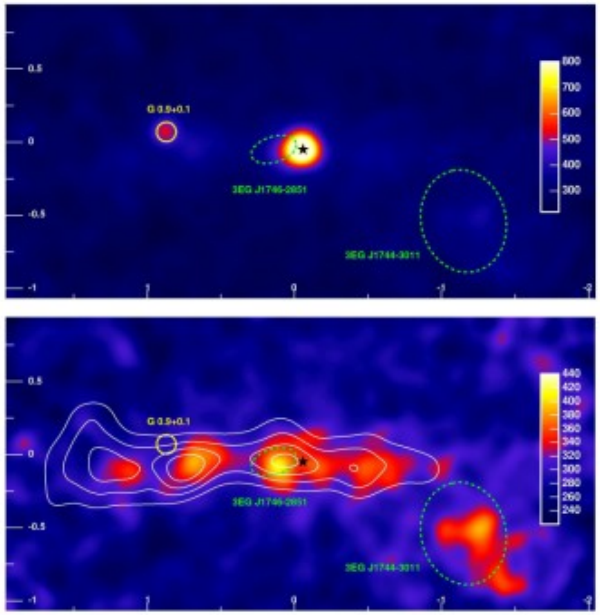




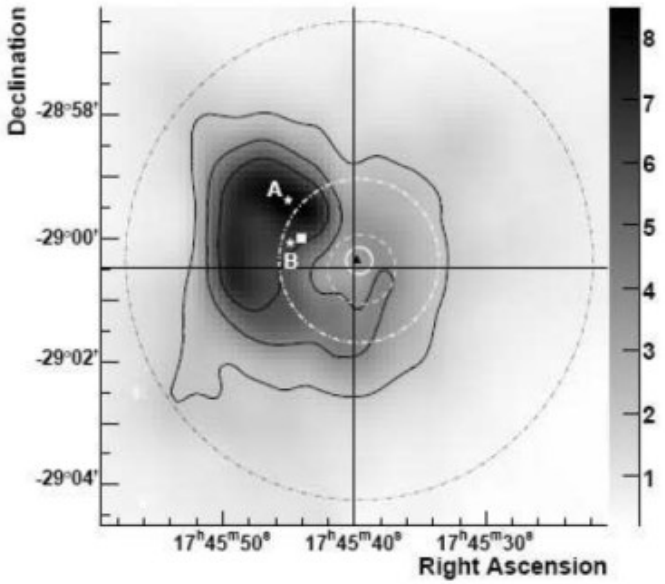
J. Albert et al 2006 ApJ 638 L101

Detailed studies by H.E.S.S. in 2006-2010:

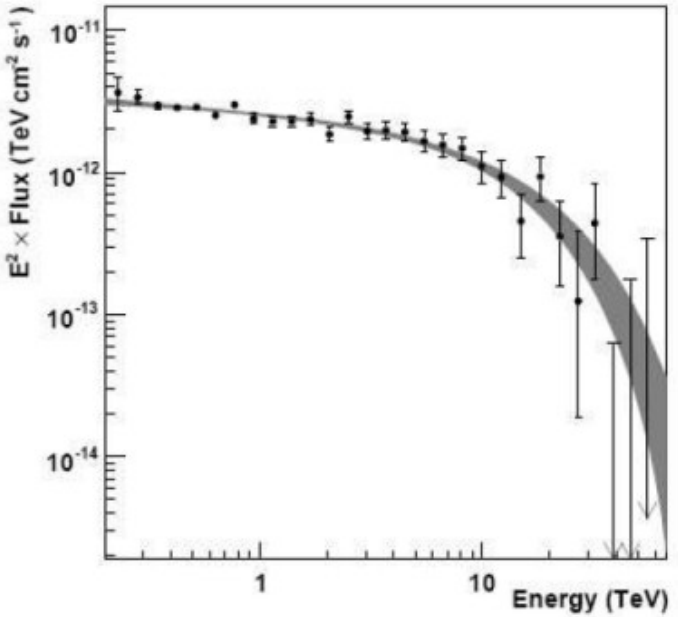
- Extended VHE emission from “Galactic Ridge“ (Aharonian et al. 2006)
- SED of HESS J1745-290 with clear cut-off at ~10 TeV (Aharonian et al. 2009)
- Precise localization of HESS J1745-290 (Acero et al. 2010), excluding SNR SgrA East as source of TeV emission



Nature volume 439, pages 695–698 (2006)



MNRAS, Vol. 402, Issue 3, Mar. 2010, p. 1877–1882



A&A, 503 3 (2009) 817-825

MAGIC observation campaign during G2 fly-by

The G2 object event:

- Gas cloud of 3m$_\oplus$ detected on its way towards SgrA* (S. Gillessen et al. 2012)
- Pericentre passage 2013-2014, at ~2000 r$_g$ (S. Gillessen et al. 2013)
- Possible interaction with the SMBH
- Monitoring campaigns triggered in nearly all wavelengths (radio to gamma-rays)
- Observations by MAGIC from 2012 on
- No variability detected in integral flux above 1 TeV and above 10 TeV

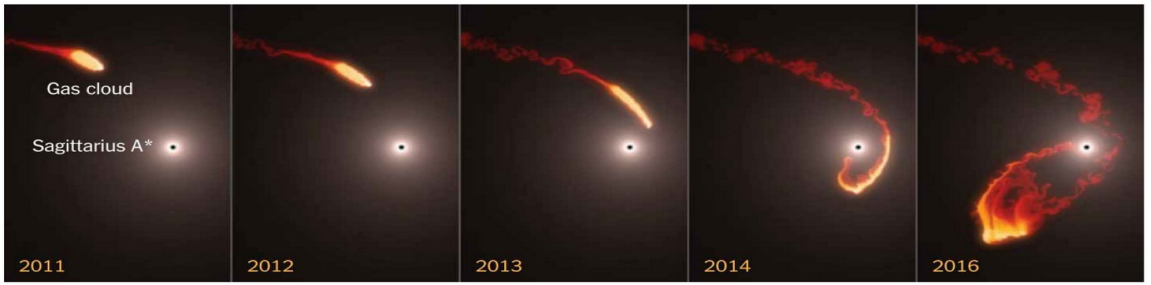
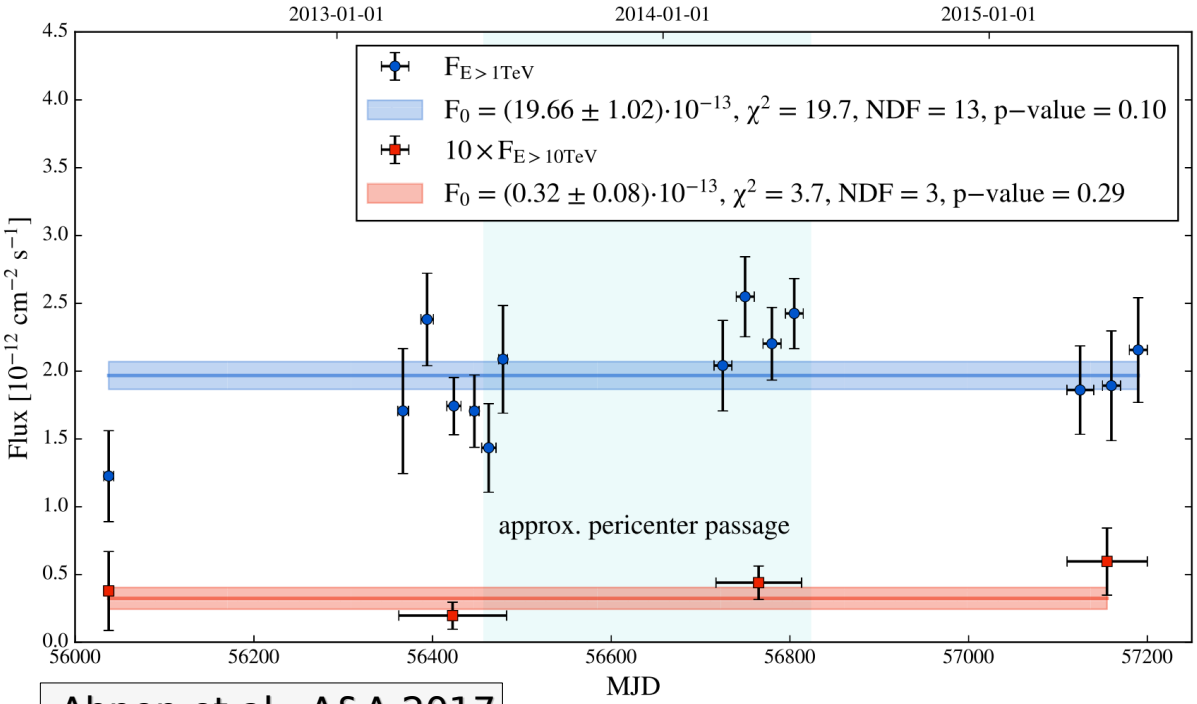


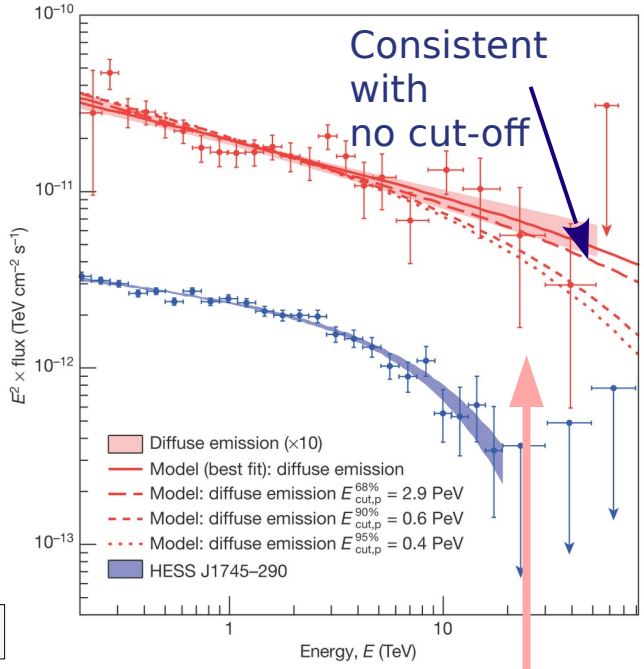
Image source: ESO

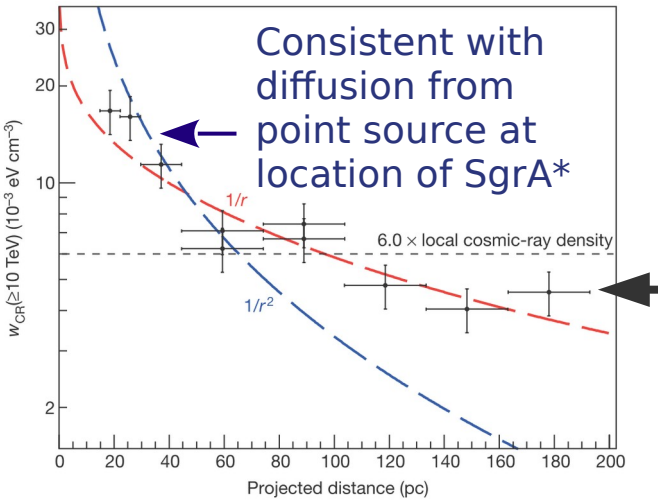


Ahnen et al., A&A 2017

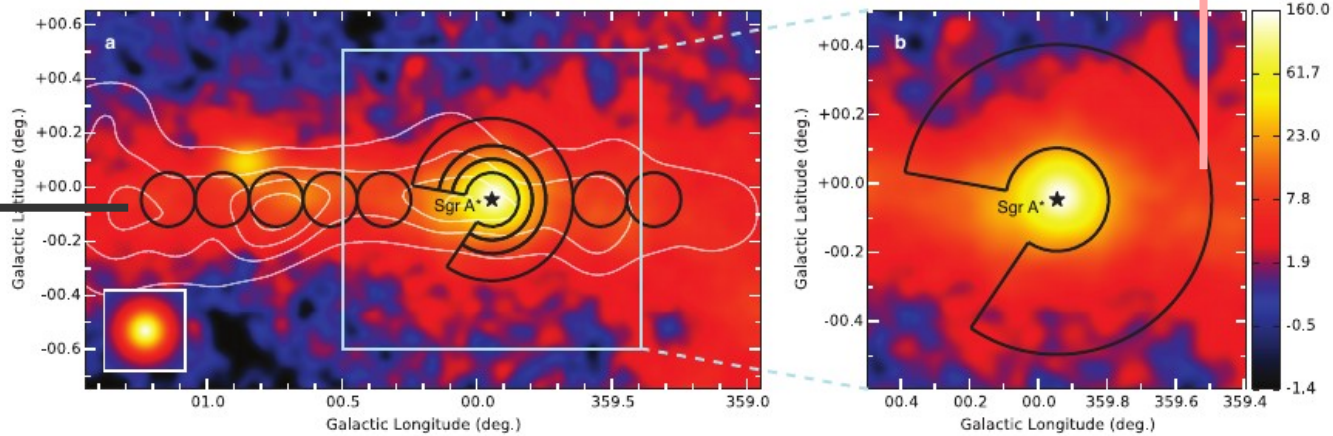
H.E.S.S. Abramowski et al., Nature 2016:

- Spectrum of GC diffuse emission measured up to 40 TeV
- No cut-off below ~100 TeV
- CR density profile shows increasing flux towards SgrA*
- GC SMBH as potential PeVatron?





H.E.S.S. Abramowski et al., Nature 2016

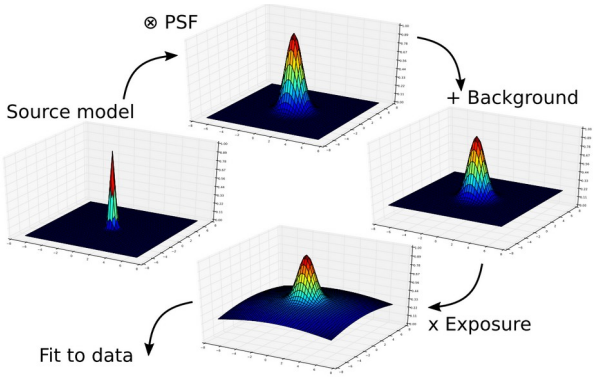


Extended emission study by MAGIC

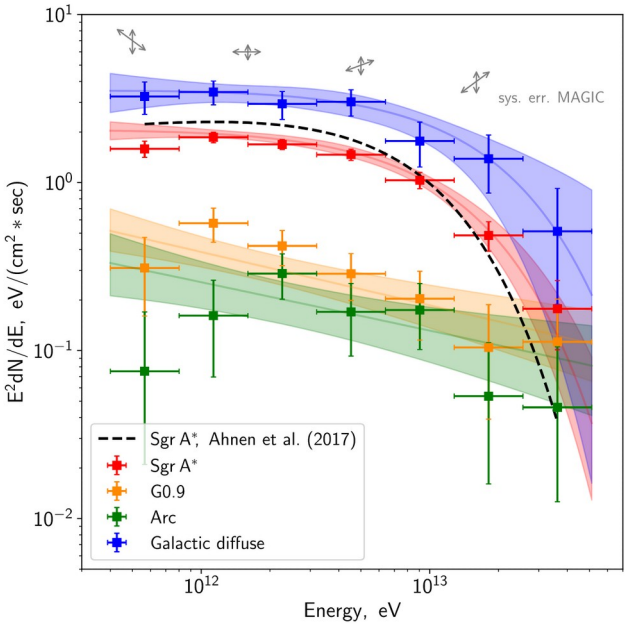
New MAGIC analysis:

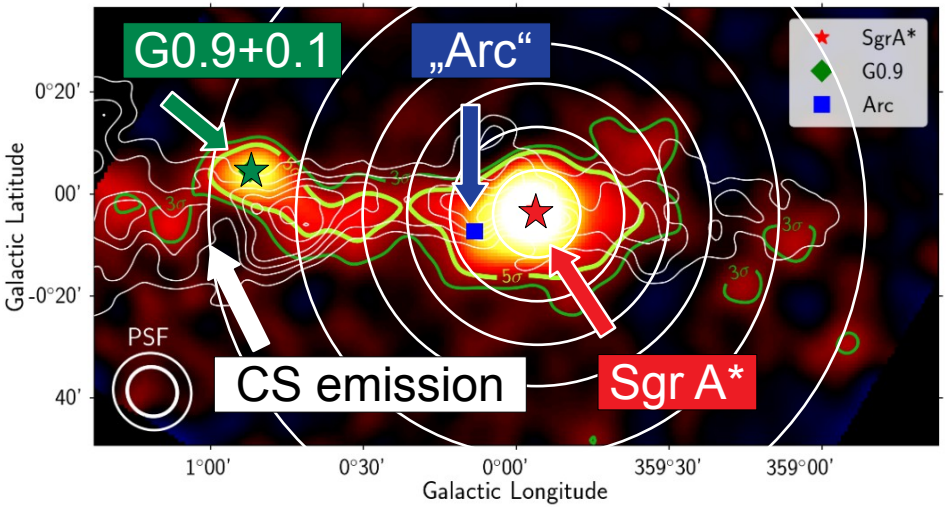
- MAGIC sky map E ≥ 1 TeV
- Sky map smeared with PSF-sized kernel
- Developed new likelihood code: SkyPrism (A&A 619, A7 (2018))
- 2D fit of arbitrary source shapes
- Contours indicate CS emission (Tsuboi+ '99)
- Indiv. sources (SgrA*, G0.9, 'Arc') + Gal. Ridge

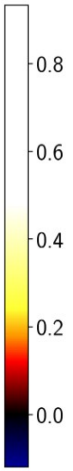
SkyPrism:



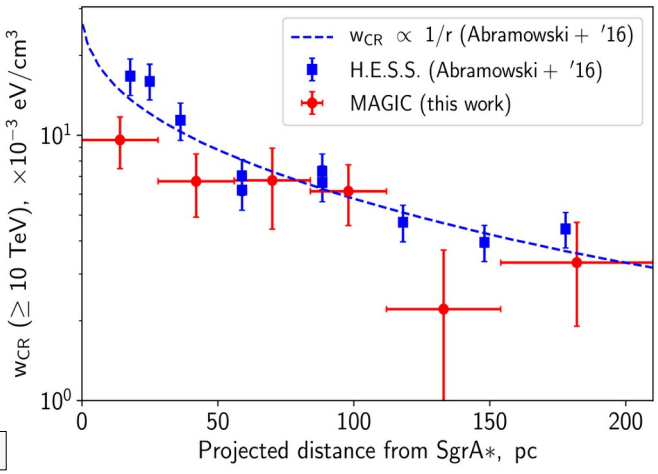
Vovk et al., A&A 2018





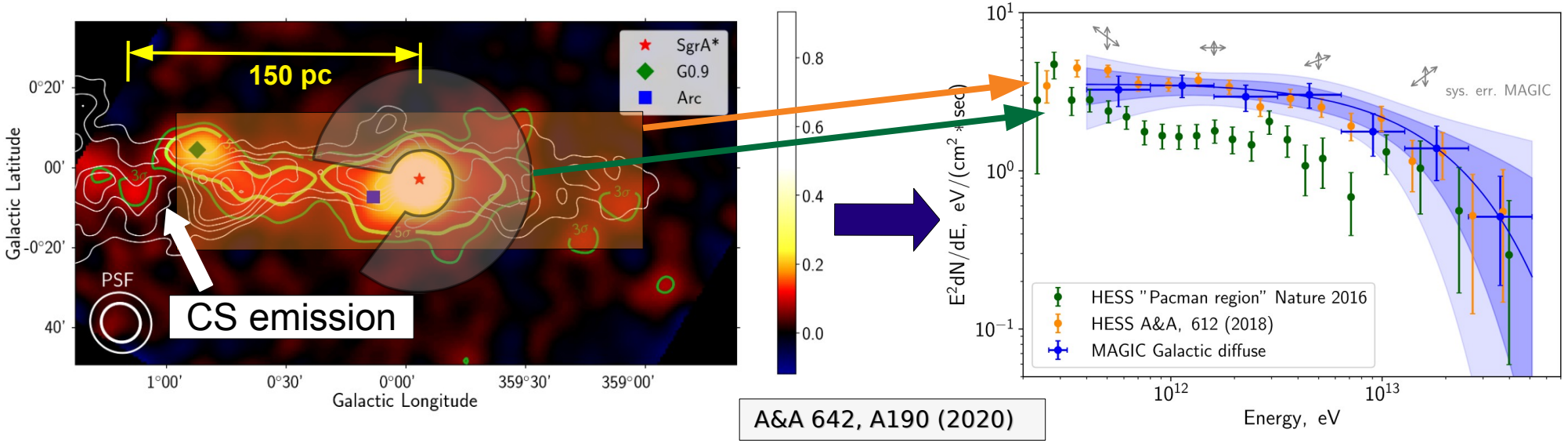


Cutting Gal. Ridge into rings and fit separately



A&A 642, A190 (2020)

Diffuse emission SED by MAGIC (2020)



A&A 642, A190 (2020)

Regions and methods:

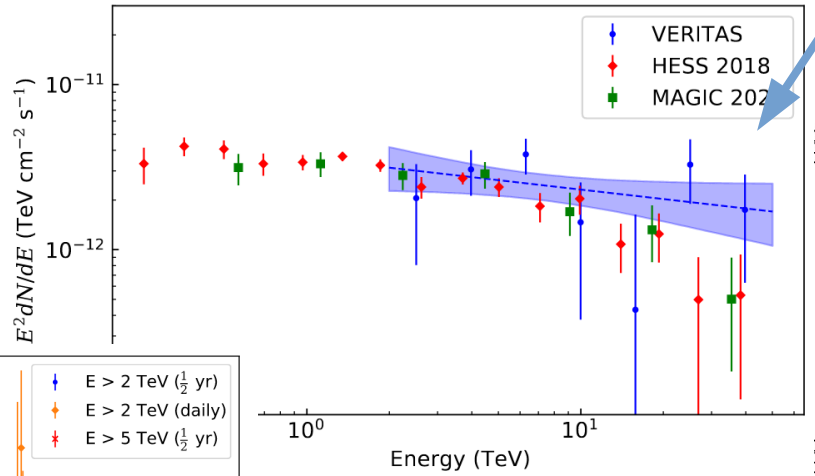
- H.E.S.S. (Nature 2016) spectrum extracted from 'pacman' (open annulus) region
- H.E.S.S. (A&A 2018) used rectangular bins covering ~orange box
- MAGIC spectrum is result of 2D likelihood fit containing also SgrA*, Arc and G0.9

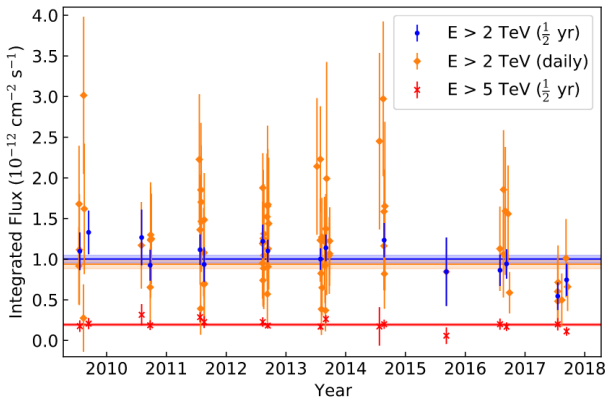
Results:

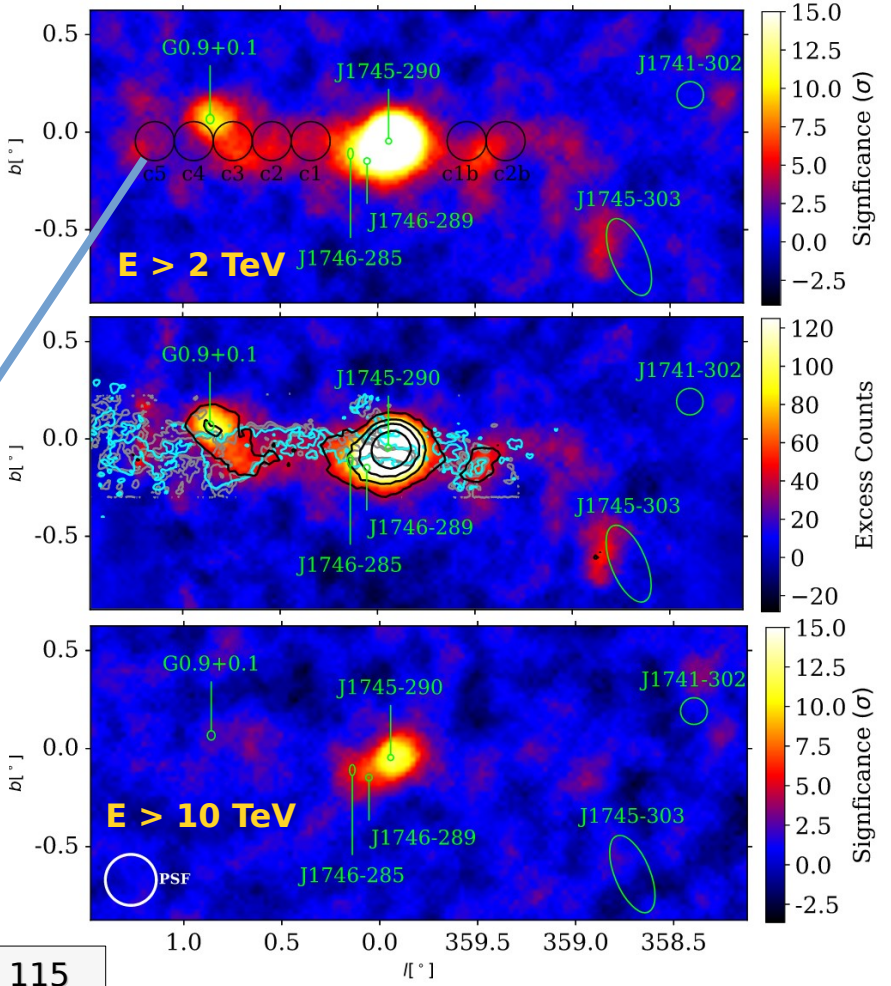
- The 68% and 95% error bands result from a cross-bin MCMC sampling of the parameter space including energy forward folding
- SEDs are very similar within errors (MAGIC vs. H.E.S.S. A&A 2018)
- MAGIC SED shows 2 σ hint for cut-off at ~20TeV

VERITAS study of GC region:

- Same circular regions used like HESS (2016)
- No hint for cut-off in VERITAS diffuse emission SED but also not excluded below 100 TeV
- SEDs for G0.9+0.1 and J1746/Arc, largely consistent with H.E.S.S./MAGIC
- No hint for long term variability after 8y







C. B. Adams et al 2021 ApJ 913 115

Summary:

- The Galactic Center has been studied extensively in VHE gamma rays during the past ~2 decades using IACTs.
- A central point-like source is spacially coincident with SgrA* that is associated with a ~4 M solar-mass black hole.
- No variability could be detected for any of the VHE sources at the GC.
- Degree-scale extended gamma-ray emission is spatially consistent with massive molecular clouds
- The energy spectrum reaches several 10s of TeV, without clear indication for a cut-off, hinting at CR acceleration reaching ~PeV energies
- The morphology of the diffuse source hints at a CR source close to SgrA* and a diffusion scenario (1/r CR flux density).
- Exciting results are to be expected from water Cherenkov arrays like HAWC/LHAASO!

Thanks for your attention!