

High-Energy Neutrinos and Photons from NGC 1068

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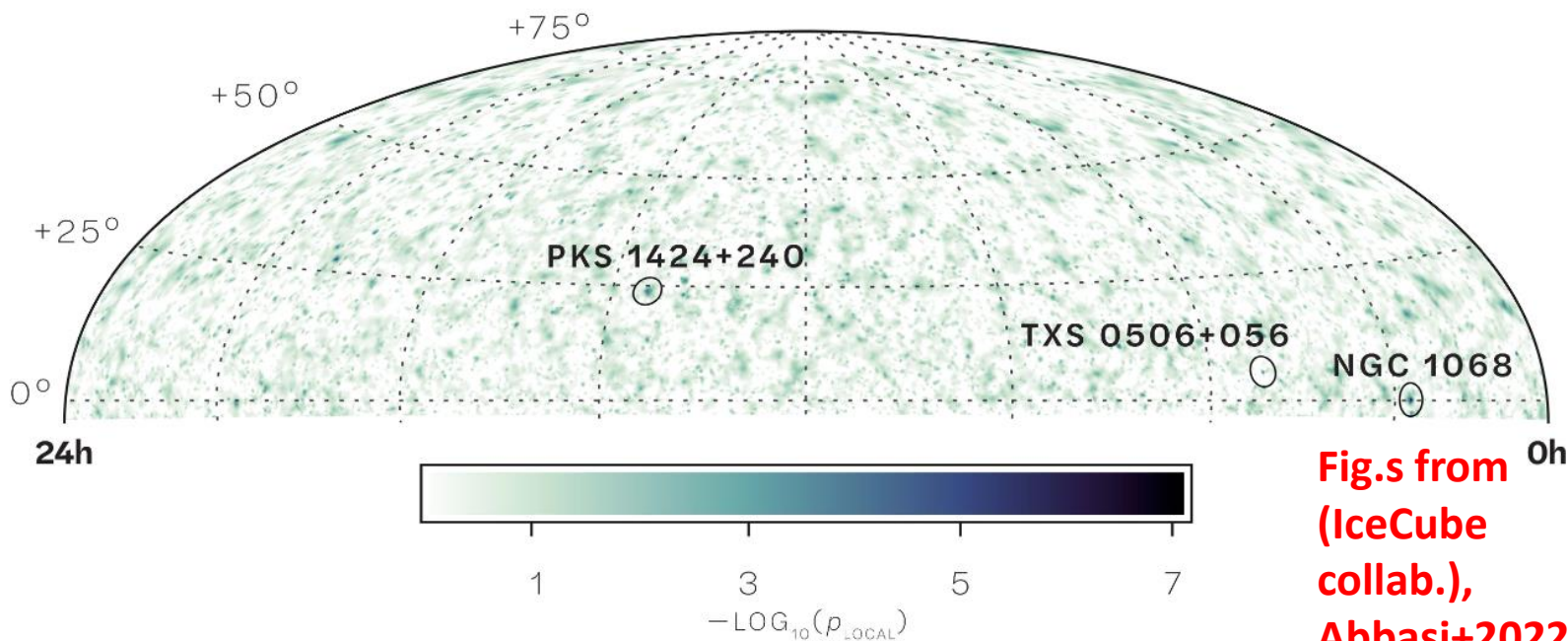
17th Marcel Grossmann Meeting



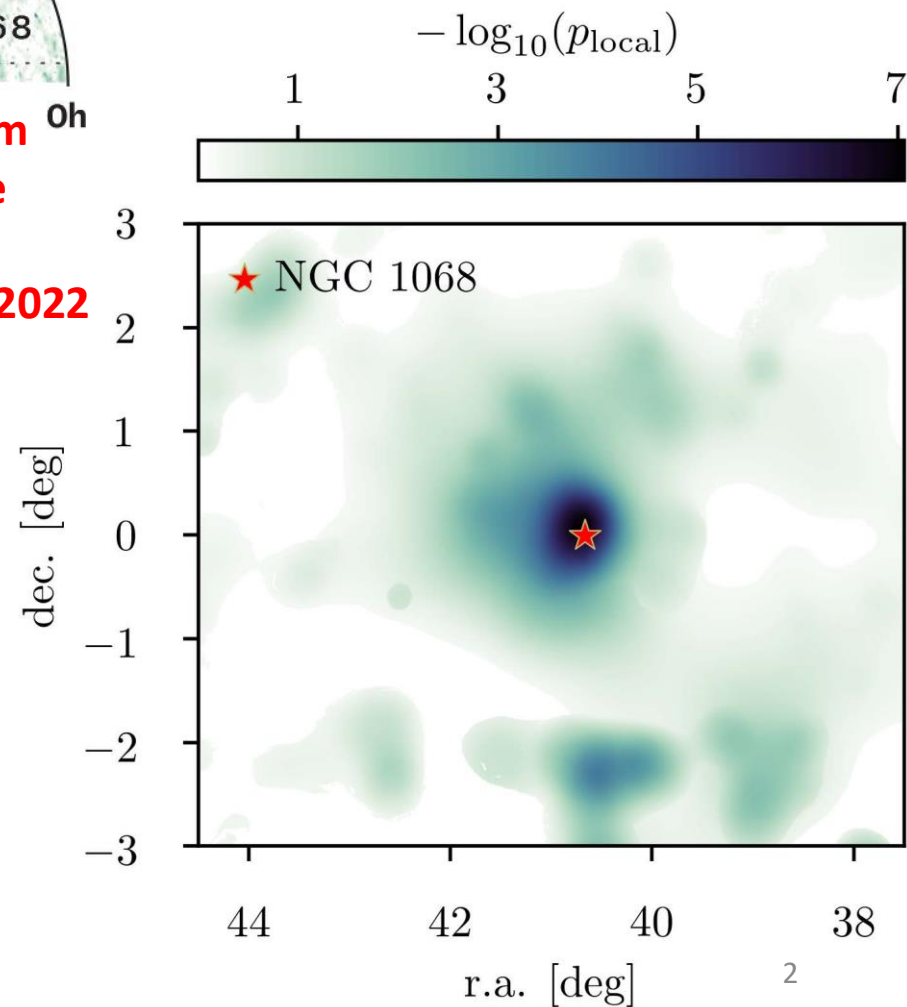
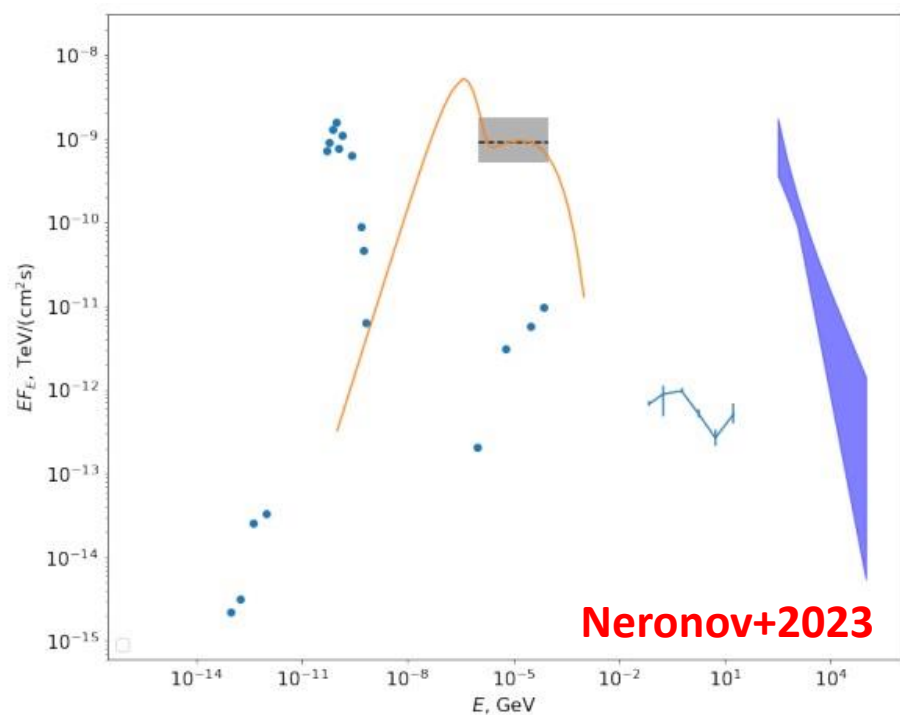
Université
Paris Cité



NGC 1068 is the brightest hotspot of IceCube



**Fig.s from
(IceCube
collab.),
Abbasi+2022**



Is NGC1068 unique (for ν)?

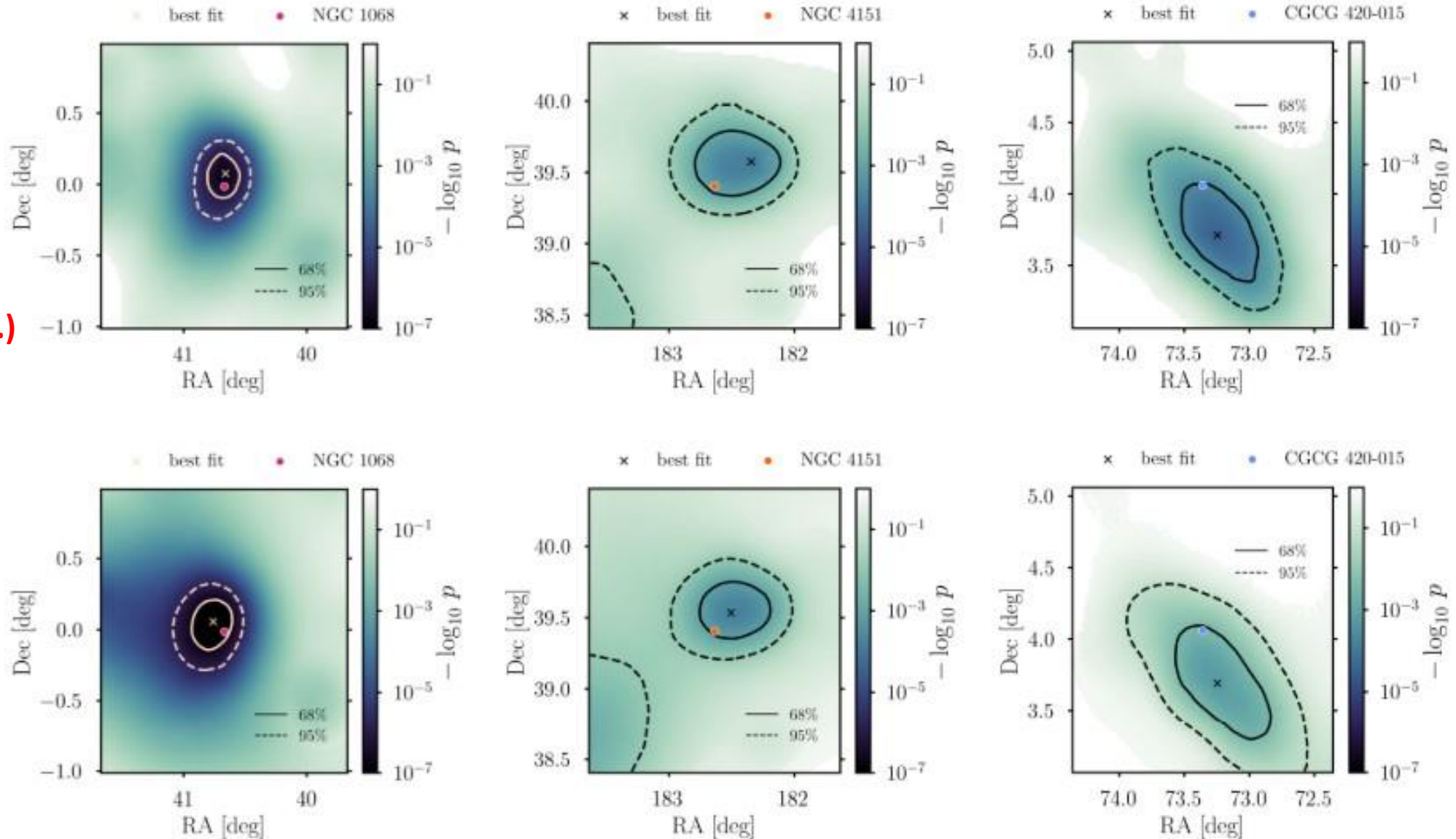




Fig. from
(IceCube collab.)
Abbasi+2024

(See also
Neronov+2023)



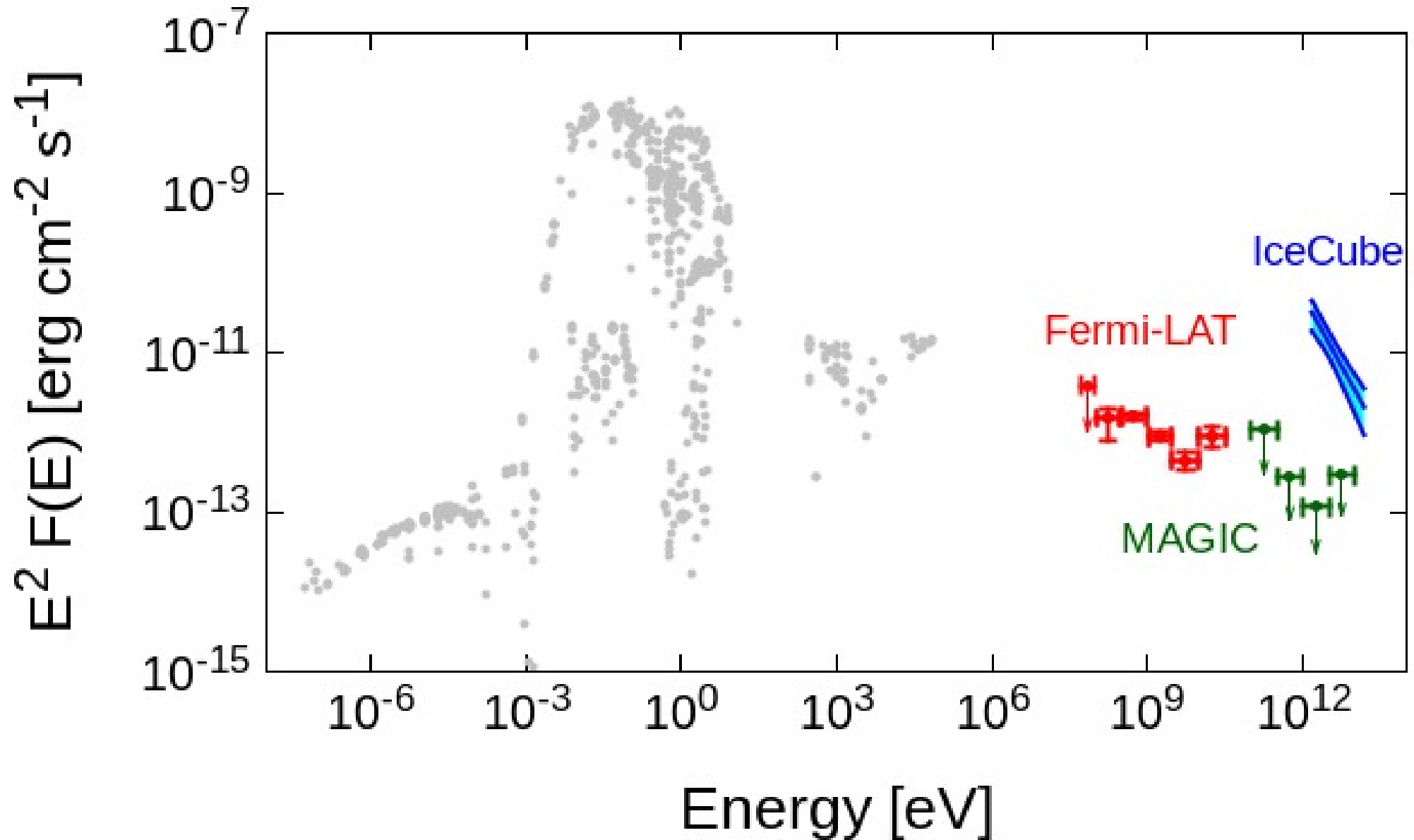
Credit: NASA, ESA & A. van der Hoeve

Seyfert II galaxy with several non-thermal sources

- 
- A detailed view of a Seyfert II galaxy, characterized by its bright central region and a prominent starburst ring. The galaxy's structure is complex, with a central AGN and various non-thermal sources. The image shows a bright, yellowish-white central core surrounded by a dense, multi-colored ring of star formation. The surrounding spiral arms are dark and dusty, with scattered red and blue spots indicating non-thermal emission.
- 1) Highly obscured AGN
 - 2) 500 pc-scale «weak» jet ($v < 0.05 c$)
 - 4) 50-400 pc scale AGN-driven wind (molecular)
 - 4) 2 kpc diameter starburst ring
 - 5) Star forming disk

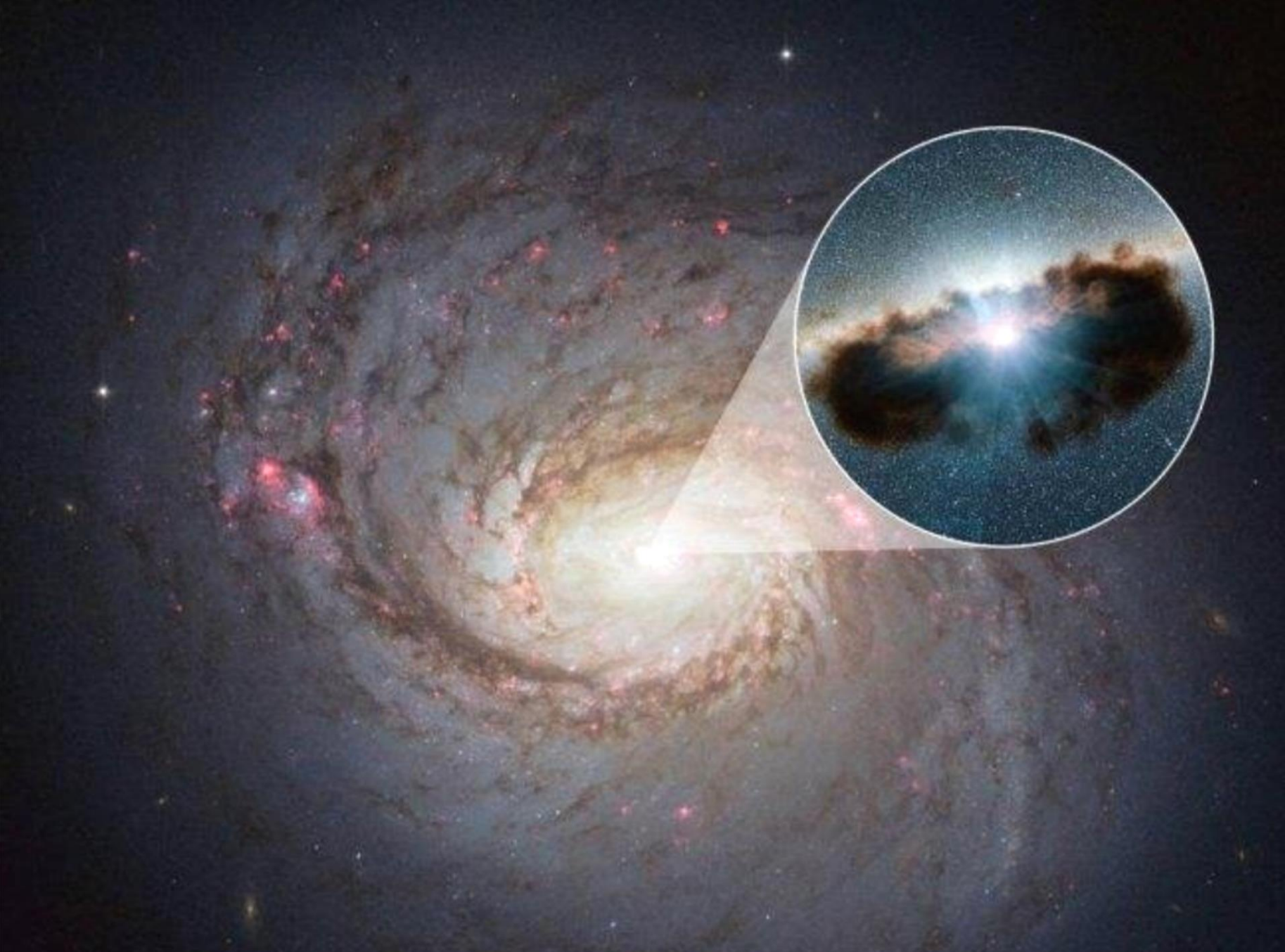
Credit: NASA, ESA & A. van der Hoeve

Multi-messenger spectrum

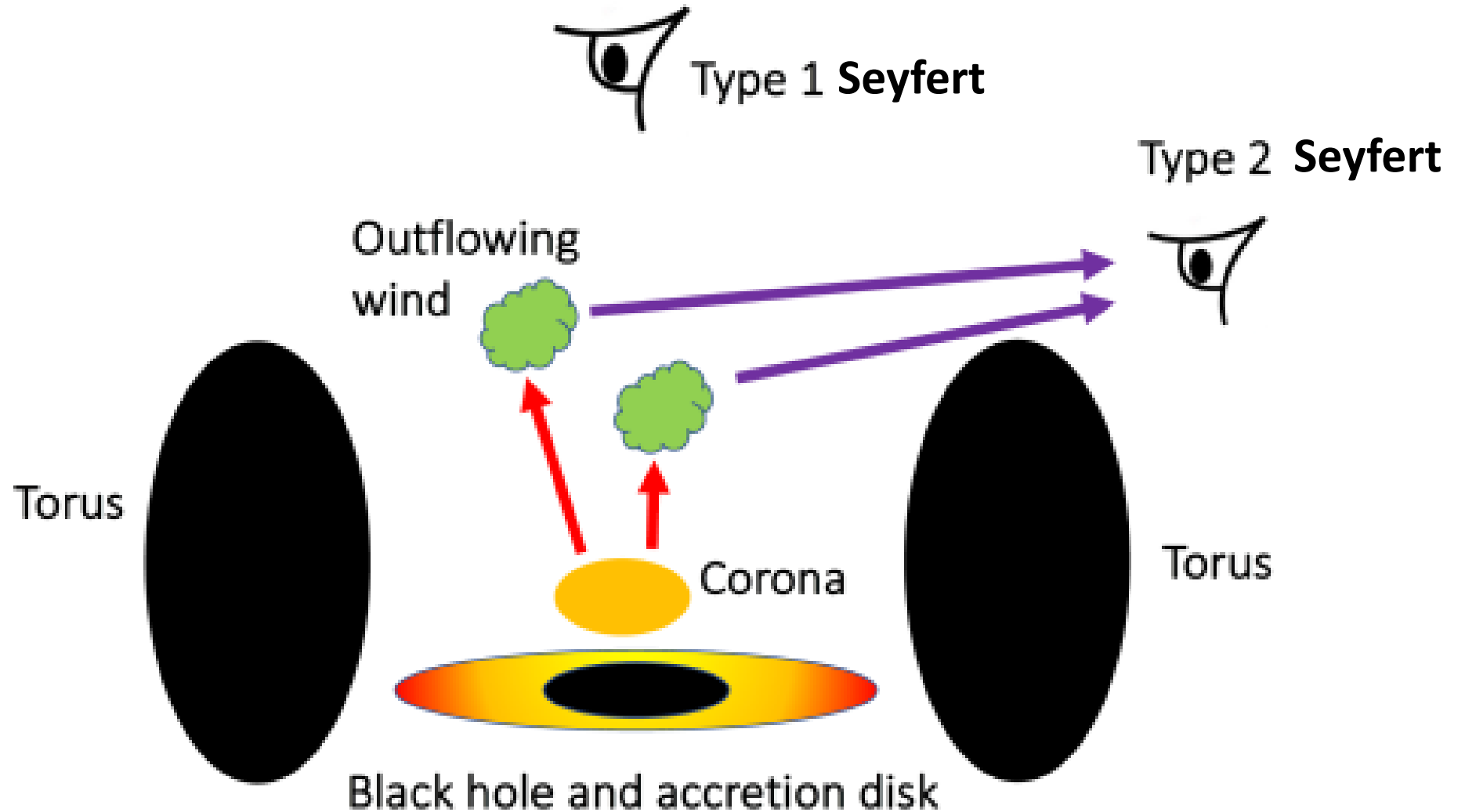


Deciphering the emission regions of NGC 1068

Credit: NASA, ESA & A. van der Hoeve



The AGN

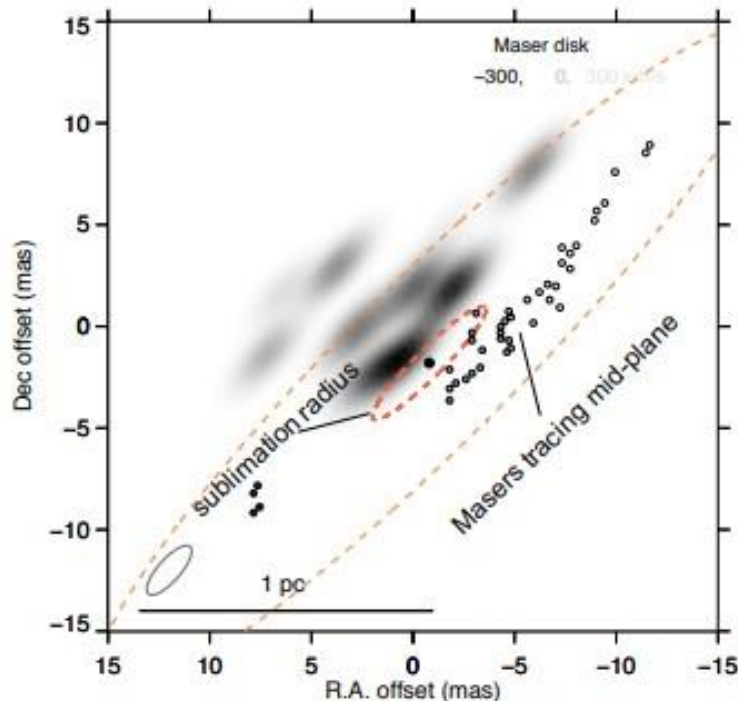


The AGN

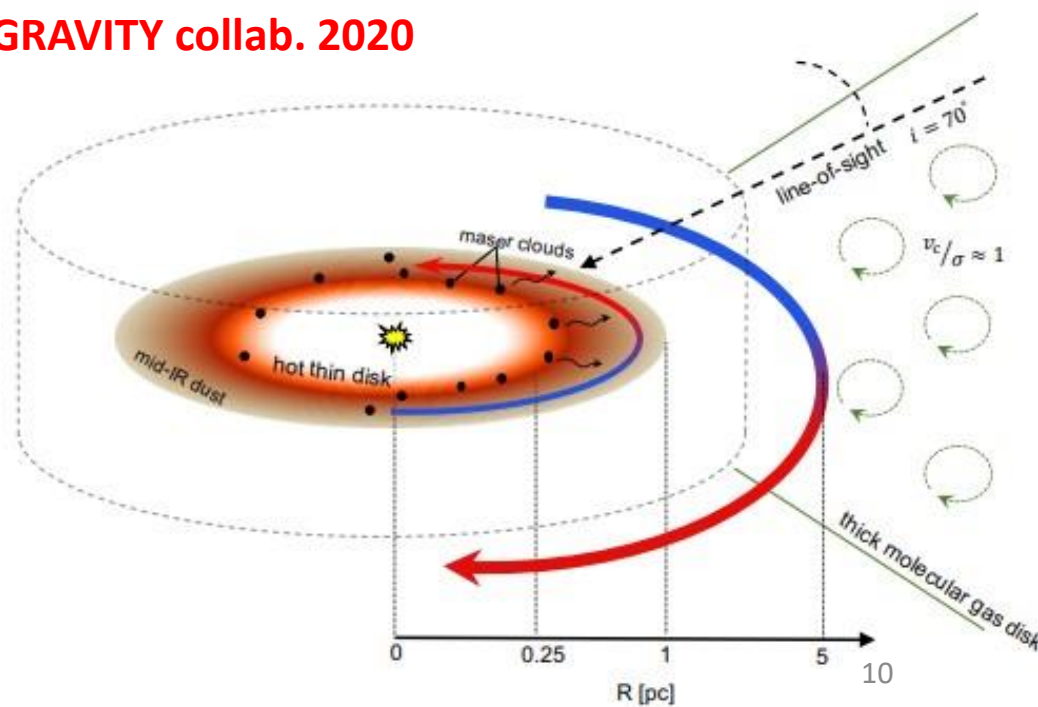
AGN Corona \rightarrow region of very hot ($T \approx 10^9 K$) electrons which inverse Compton scatter the UV photons from the disc and produce X-rays

$$L_{2-10keV} \approx 3 \cdot 10^{43} \text{ erg/s} \rightarrow L_{bol} \approx 10^{44.7} \text{ erg/s}$$

Torus \rightarrow Observed in the NIR band – resolved ring-like structure



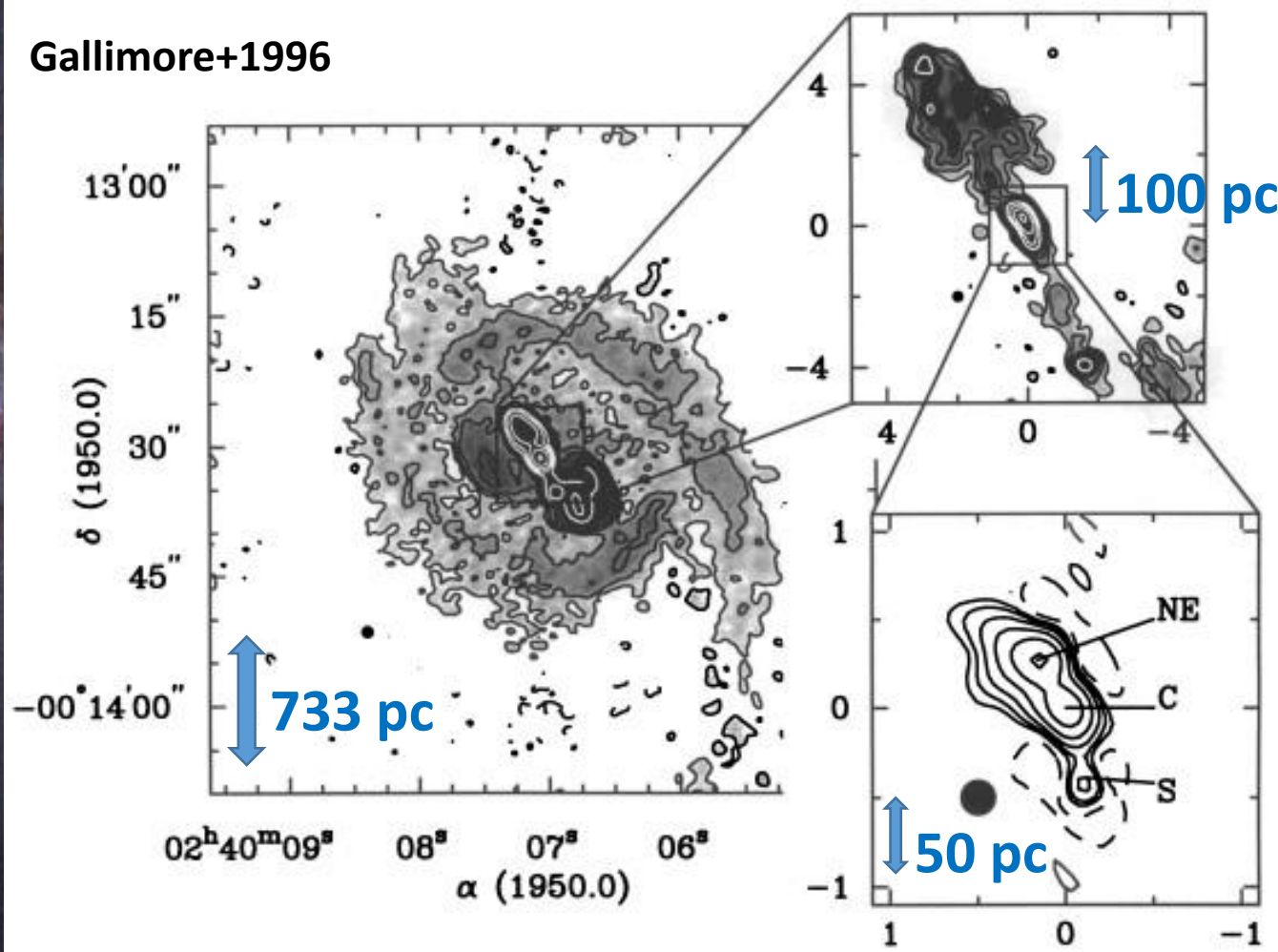
GRAVITY collab. 2020



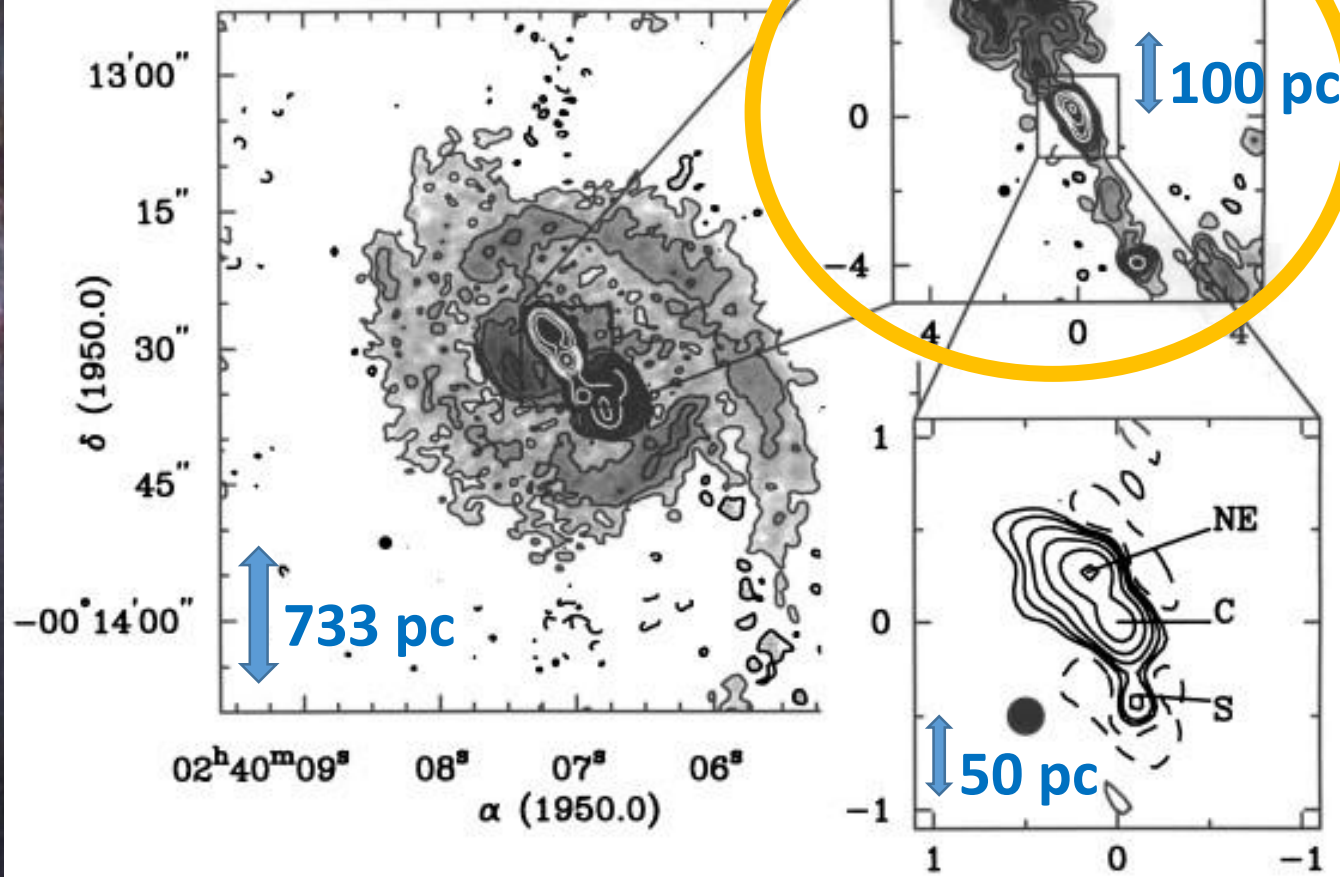


Credit: NASA, ESA & A. van der Hoeve

Gallimore+1996



Gallimore+1996



The jet

The measured radio power is

$$L_{1.4 \text{ GHz}} \approx 10^{38.9} \text{ erg/s}$$

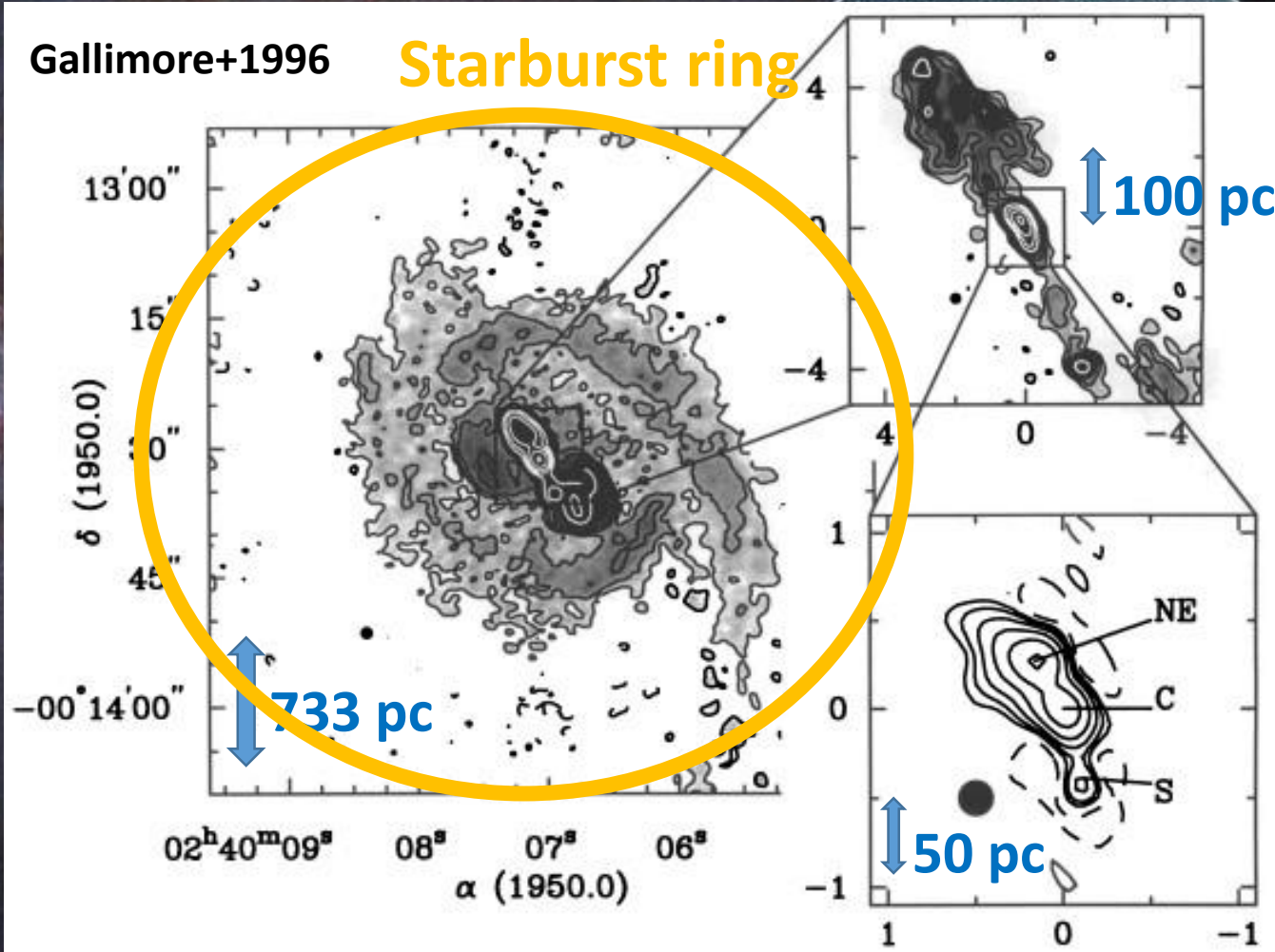
The origin of the radio photons is uncertain and could be possibly be associated only to the starburst activity.

However, if they were dominated by the jet contribution, the associated jet power would be

$$L_{jet} \approx 10^{42.2} \text{ erg/s}$$

Gallimore+1996

Starburst ring



The starburst

Starburst environments are promising cosmic-ray factories



Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

The starburst

Starburst environment:

cosmic-ray

Young stars and
supernovae

Particle
acceleration **2X**

High star
formation rate

High target density
& strong fields

Starburst-driven
wind

The starburst

Starburst environment:

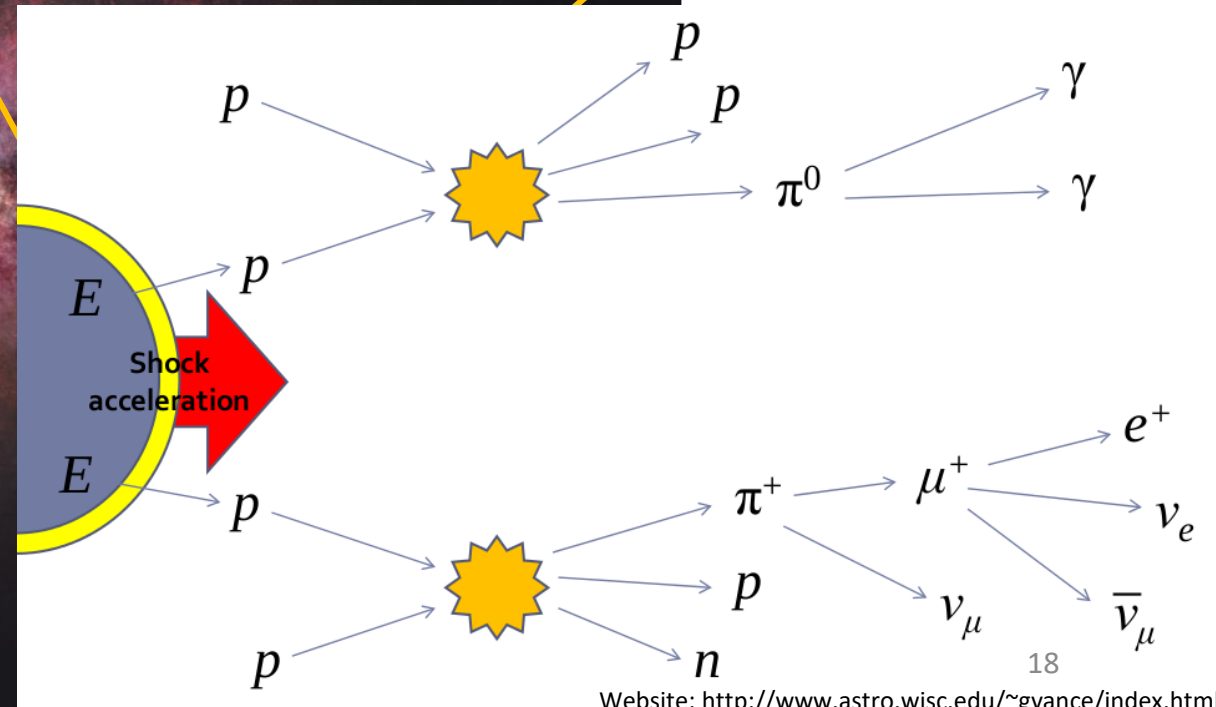
cosmic-ray

Young stars and supernovae

Particle acceleration **2X**

High star formation rate

High target density & strong fields



The starburst of NGC1068

The far infrared luminosity of NGC 1068 suggests a star formation rate of about $20 M_{\odot} yr^{-1}$

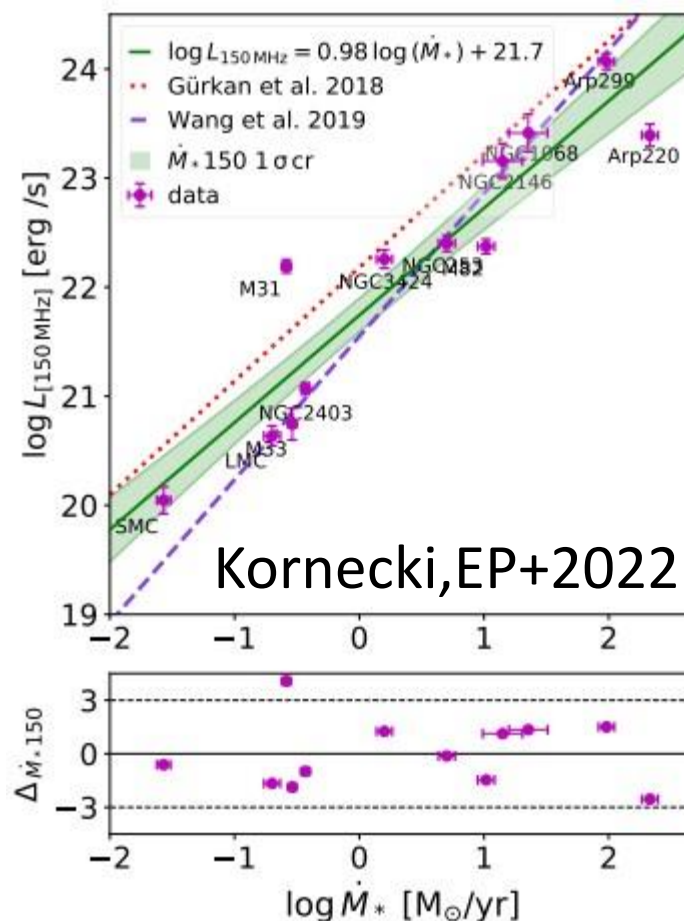
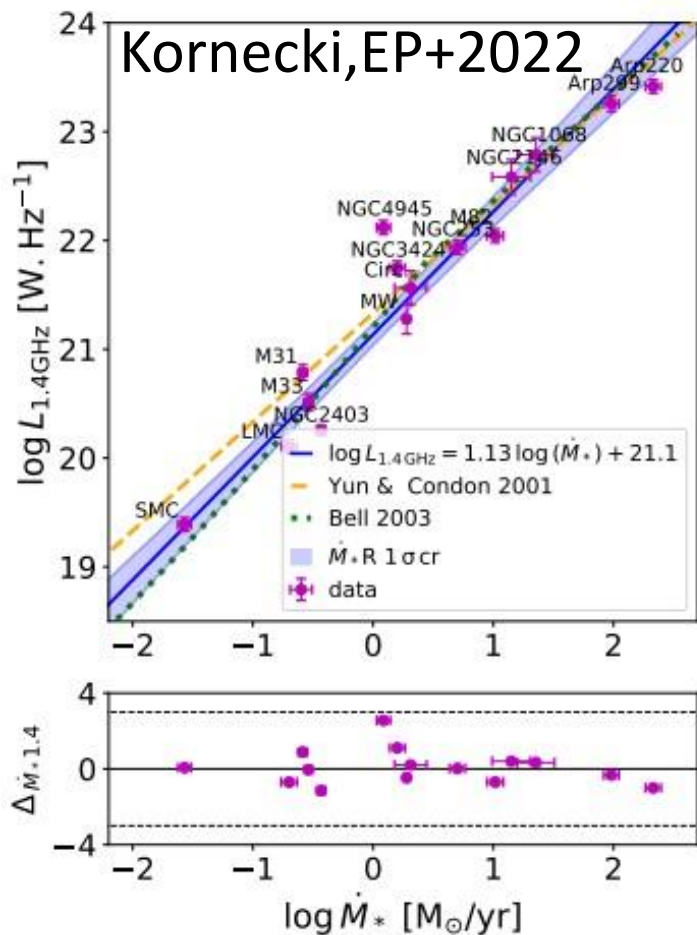
$$L_{FIR} \approx 10^{44.6} \text{ erg/s},$$

The associate power in supernova remnant is:

$$L_{SNe} \approx 10^{42.8} \text{ erg/s}$$

Radio emission from NGC 1068

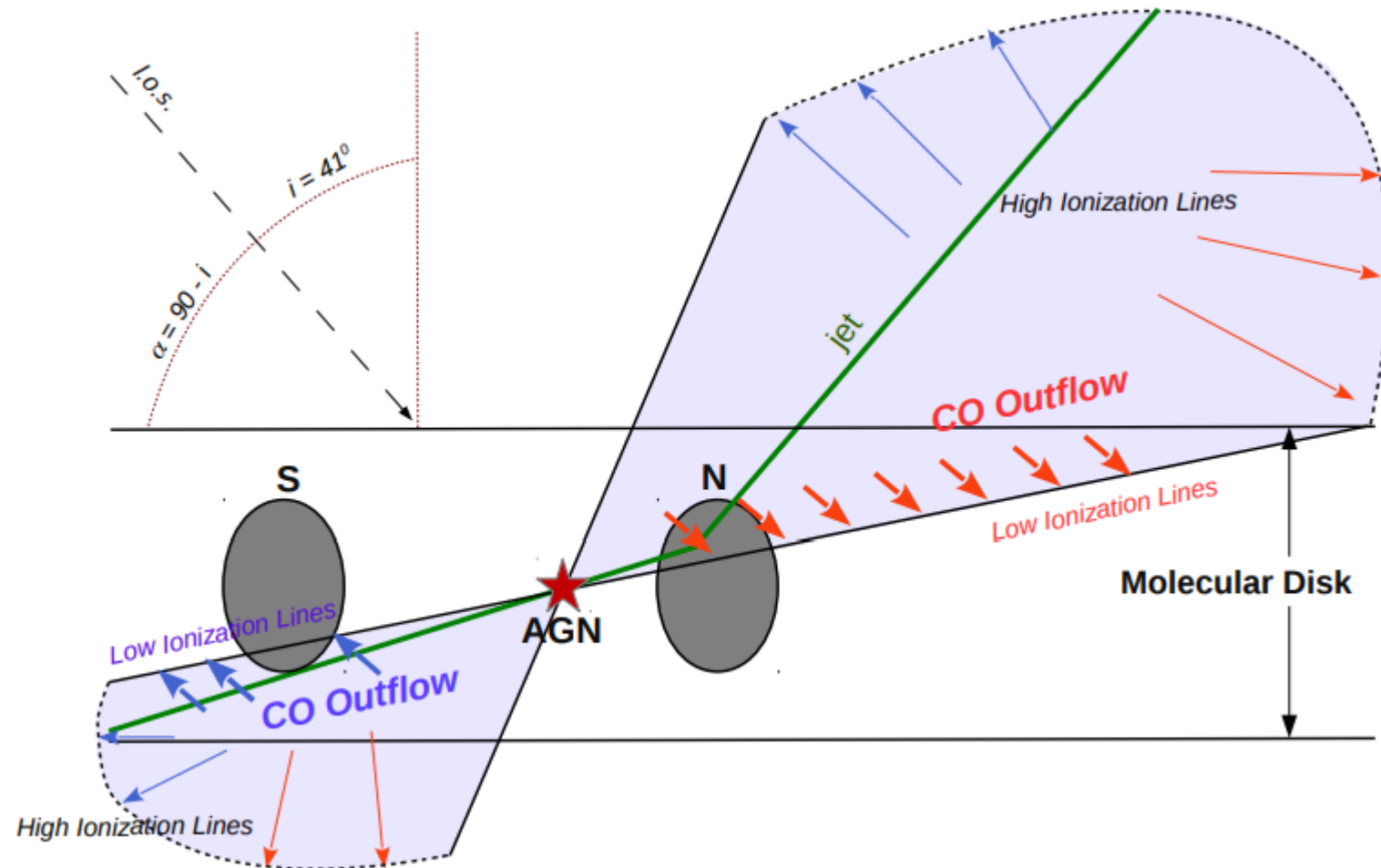
The radio luminosity is in agreement with the radio – SFR correlation \rightarrow the starburst hypothesis is well motivated

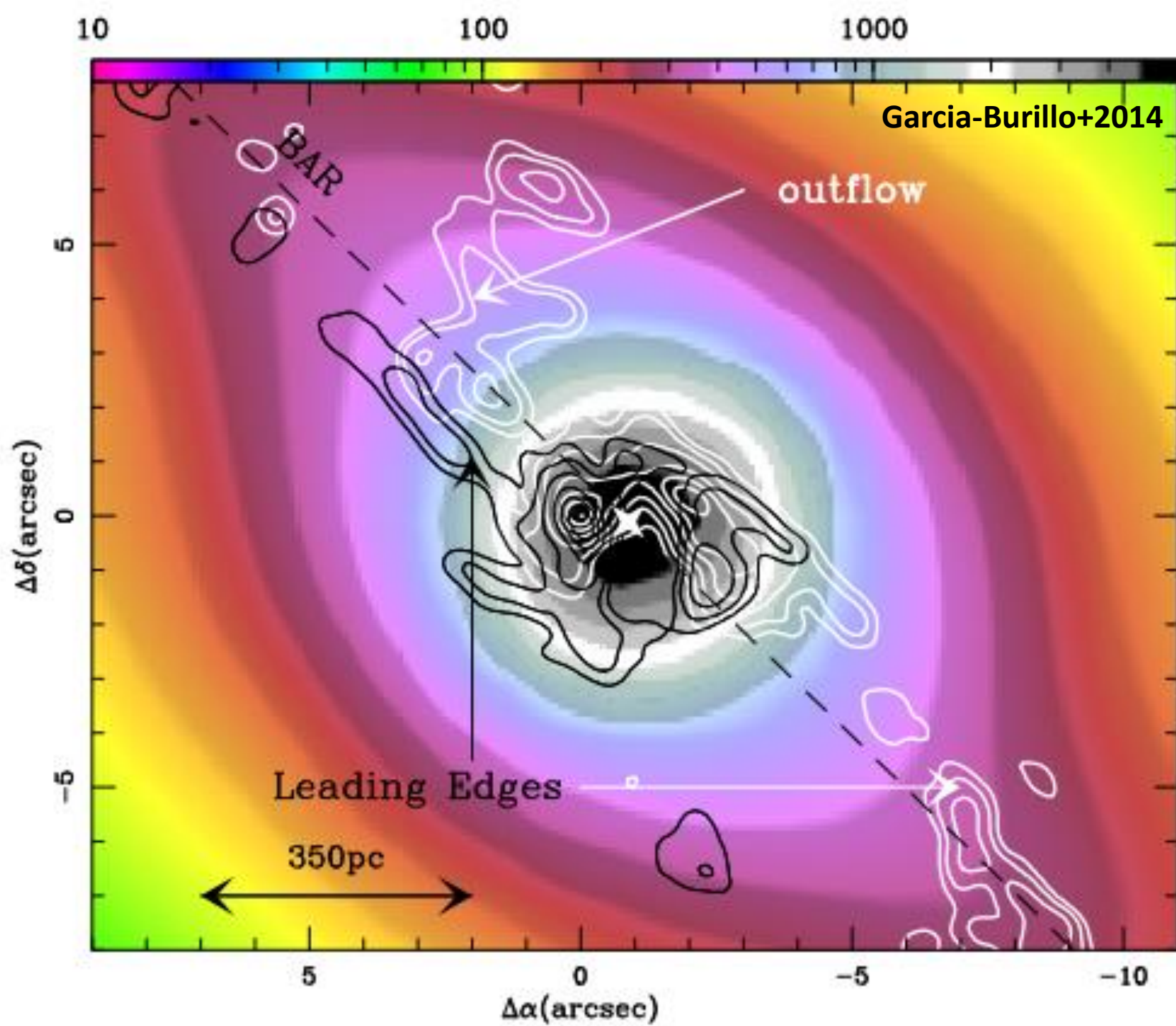


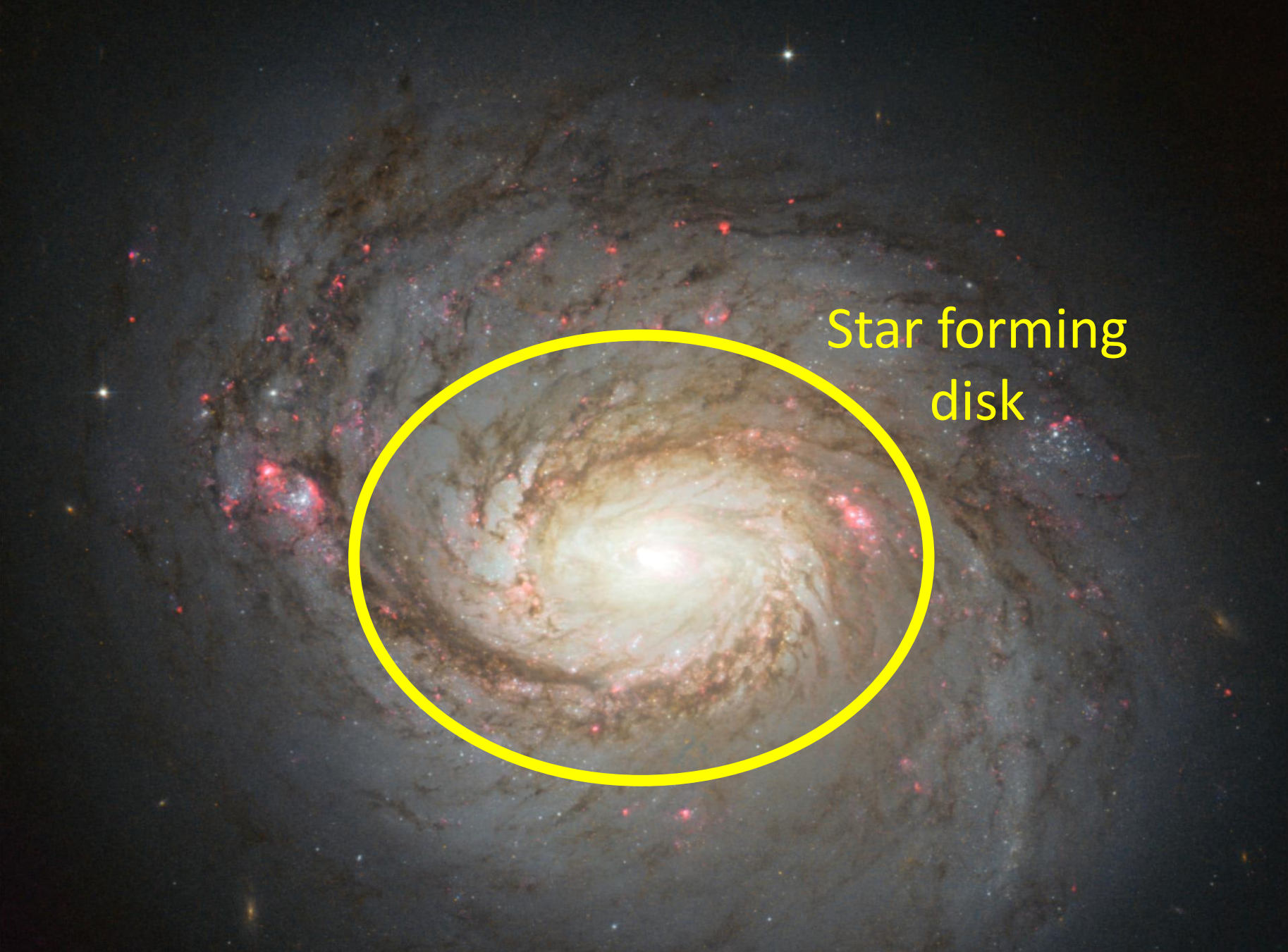
The molecular outflow

Observed by ALMA in the mm band through the emission of CO and HCN over a scale < 300 pc

$$L_{out} \approx \frac{M_{out} v_{out}^3}{R_{out}} \approx 10^{41.6} \text{ erg/s}$$







Star forming
disk

Luminosity and Power of NGC 1068

$$L_{bol} \approx 10^{44.7} \text{ erg/s}$$

$$L_{FIR} \approx 10^{44.6} \text{ erg/s}$$

$$L_X \approx 10^{43.5} \text{ erg/s}$$

$$L_{radio} \approx 10^{38.9} \text{ erg/s}$$

$$L_\gamma \approx 10^{40.9} \text{ erg/s}$$

$$L_\nu \approx 10^{42.1} \text{ erg/s}$$

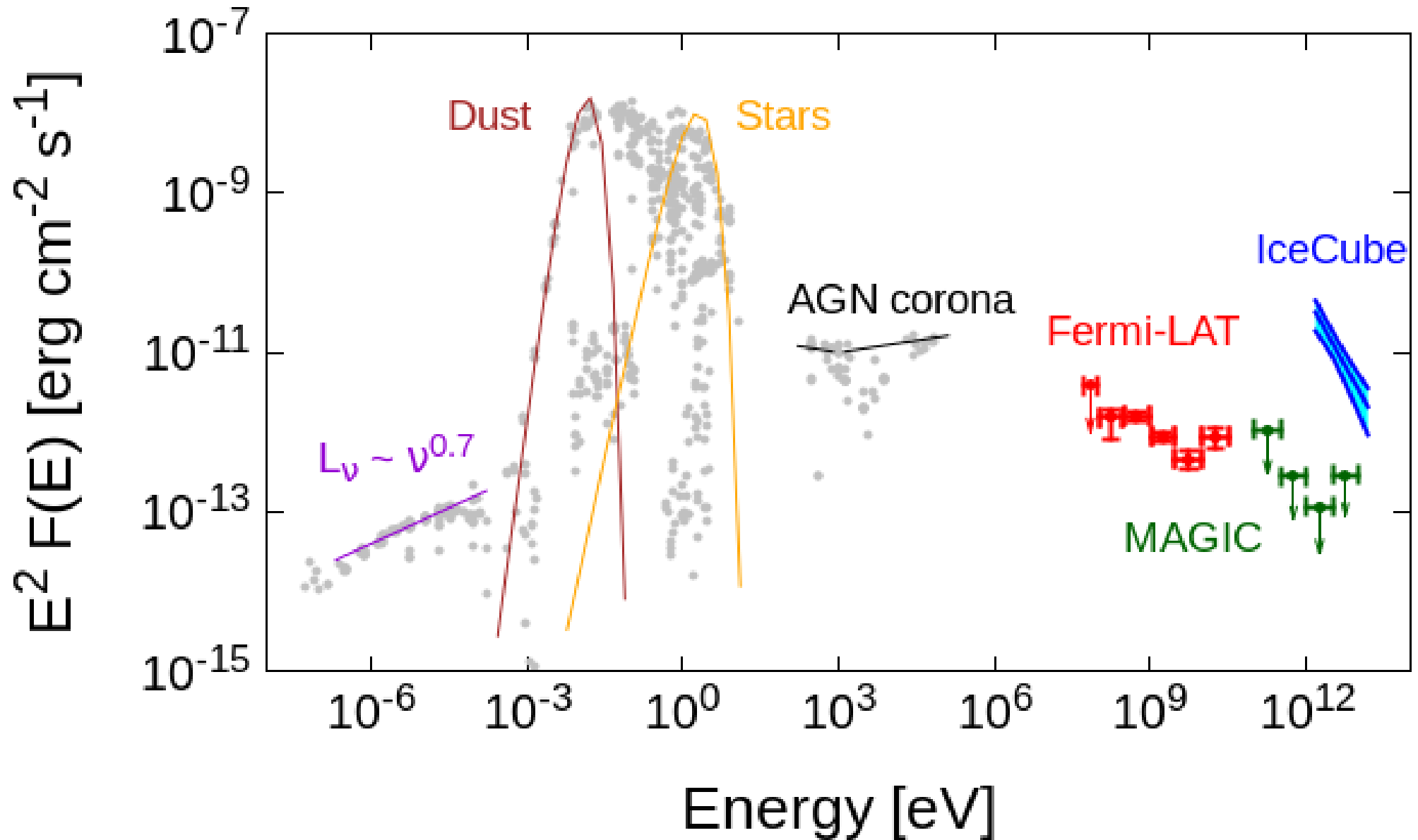
$$L_{SNe} \approx 10^{42.8} \text{ erg/s}$$

$$L_{out} \approx 10^{41.6} \text{ erg/s}$$

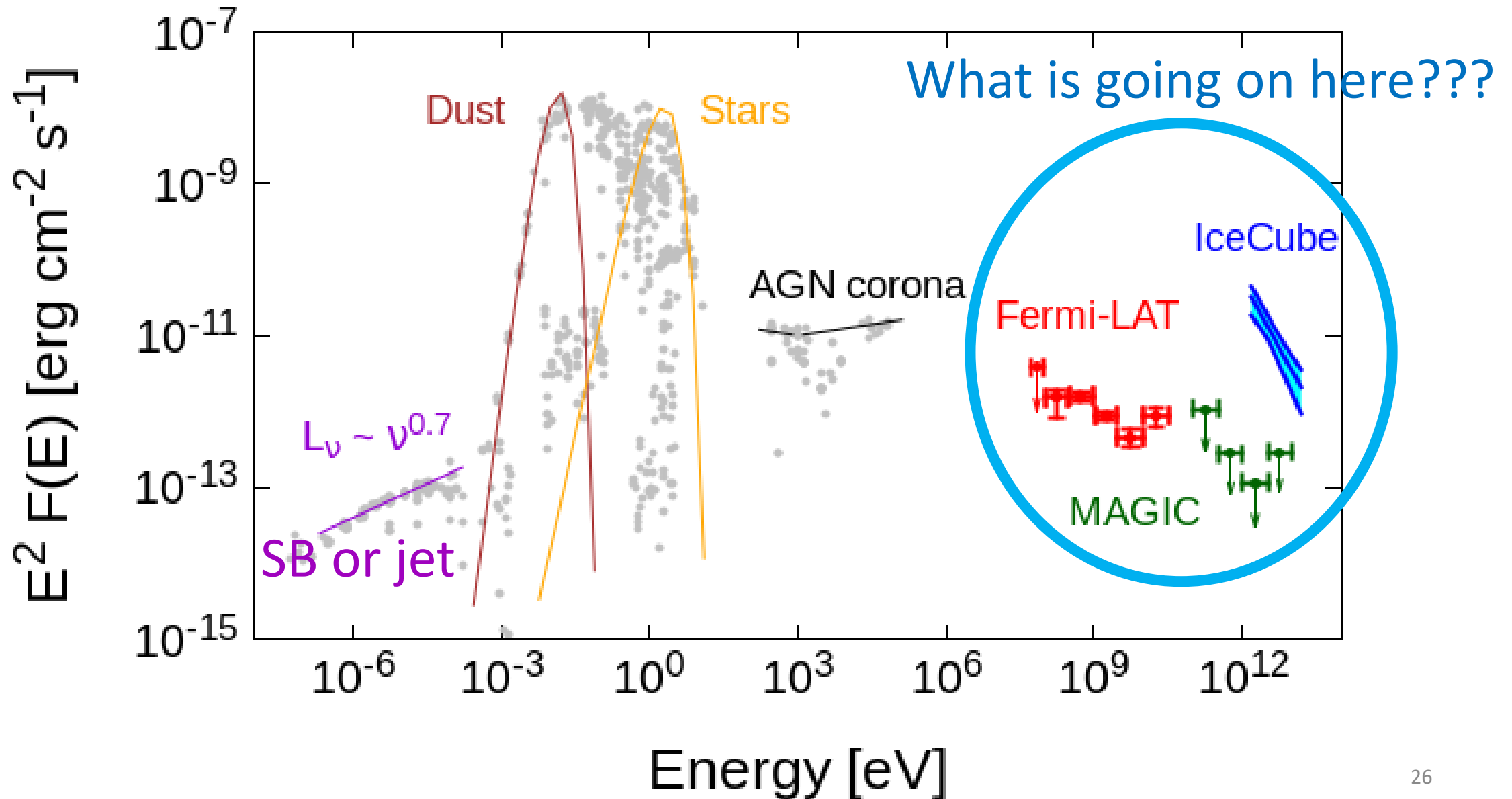
$$L_{jet} \approx 10^{42.2} \text{ erg/s (?)}$$

$$L_{corona} = \eta L_X$$

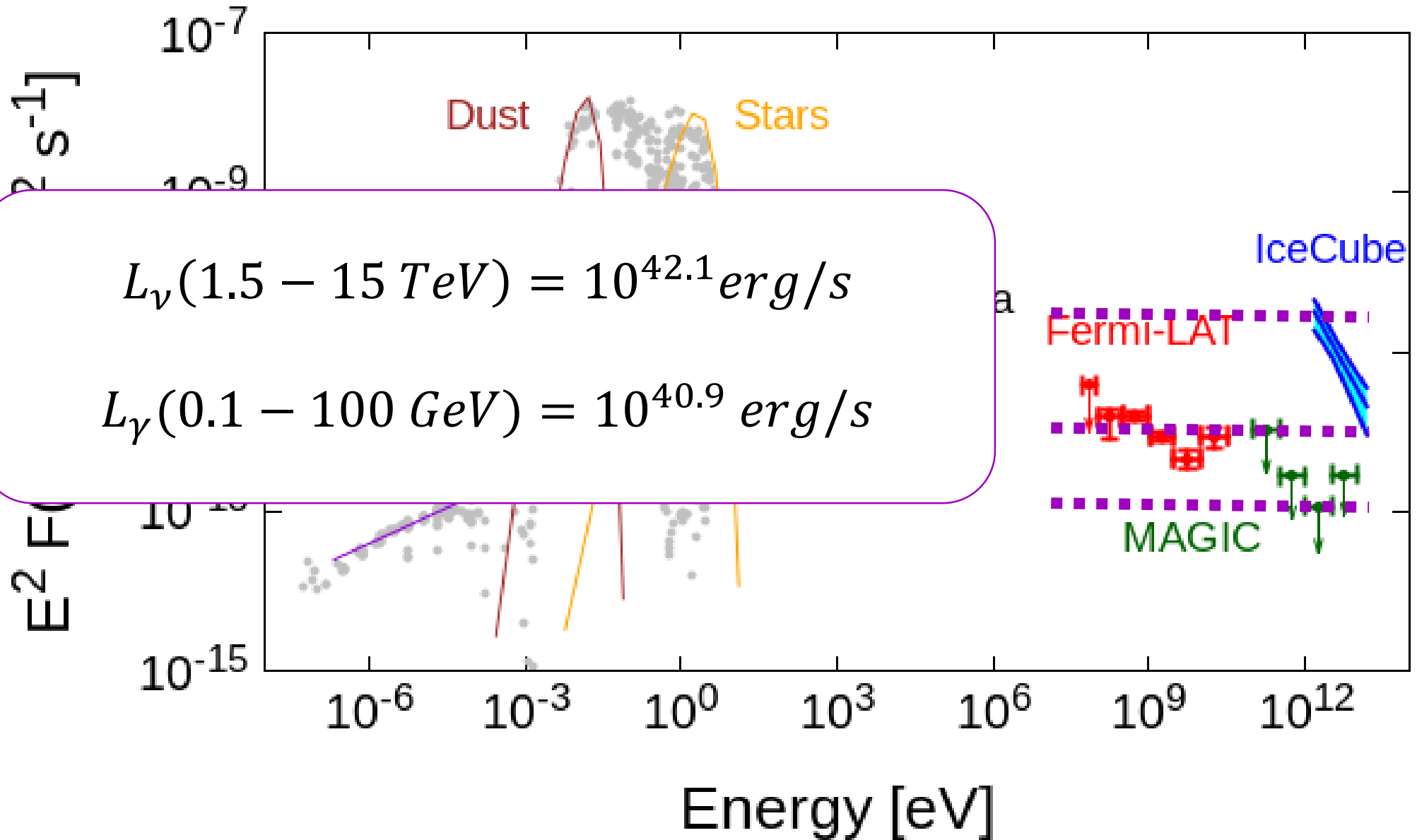
NGC 1068 is a complex object



Deciphering NGC 1068 at HE



The problem of NGC 1068



Hidden sources

Silberberg & Shapiro 1979

§9. Hidden sources

NEUTRINOS AS A PROBE FOR THE NATURE OF
AND PROCESSES IN ACTIVE GALACTIC NUCLEI

R. Silberberg and M. M. Shapiro
Laboratory for Cosmic Ray Physics
Naval Research Laboratory
Washington, D. C. 20375, U.S.A.

Eichler 1979

HIGH-ENERGY NEUTRINO ASTRONOMY: A PROBE OF GALACTIC NUCLEI?

DAVID EICHLER

Enrico Fermi Institute, University of Chicago
Received 1978 April 24; accepted 1979 February 13

ABSTRACT

The powerful infrared emission from active galactic nuclei may be driven, directly or indirectly, by nonthermal processes, in which case the power of high-energy particle production may be as high as the IR luminosity. The nuclei of active galaxies contain, on various scales, enough matter to stop high-energy protons before they diffuse out of the nuclear region via pion-producing collisions. Thus, the luminosity of the nucleus in high-energy neutrinos ($E_\nu \gtrsim 10^{12}$ eV) (the primary decay product of charged pions) may in turn be comparable to the total power radiated by the nucleus.

If such a hypothesis is true, then many active galactic nuclei may be detectable as point sources in high-energy neutrinos with the neutrino "telescopes" that are being discussed. The overall cosmic neutrino background due to active galaxies may be orders of magnitude above the detection threshold.

EXTRATERRESTRIAL NEUTRINO SOURCES AND HIGH ENERGY NEUTRINO ASTROPHYSICS

V.S. Berezinsky

Institute for Nuclear Research of the USSR Academy of Sciences

Berezinsky 1977

In the example of a massive black hole in a cocoon we encountered a model of a hidden source: an object which contains particles accelerated to high energies, but is not seen in high-energy electromagnetic radiation (X-ray and (or) gamma-ray radiation).

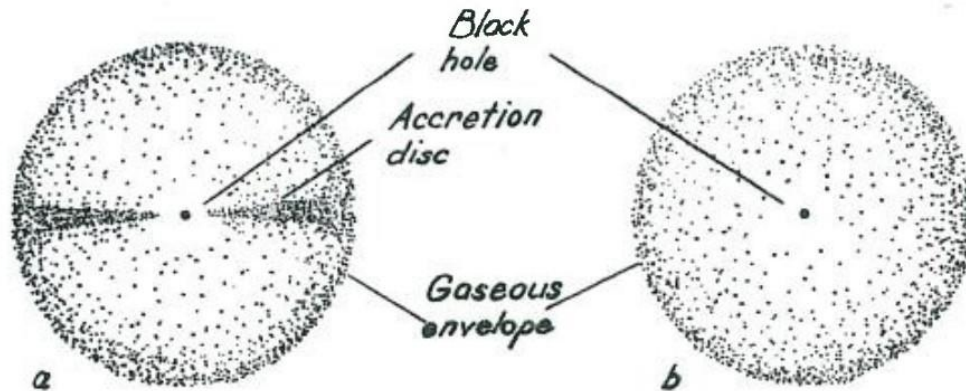
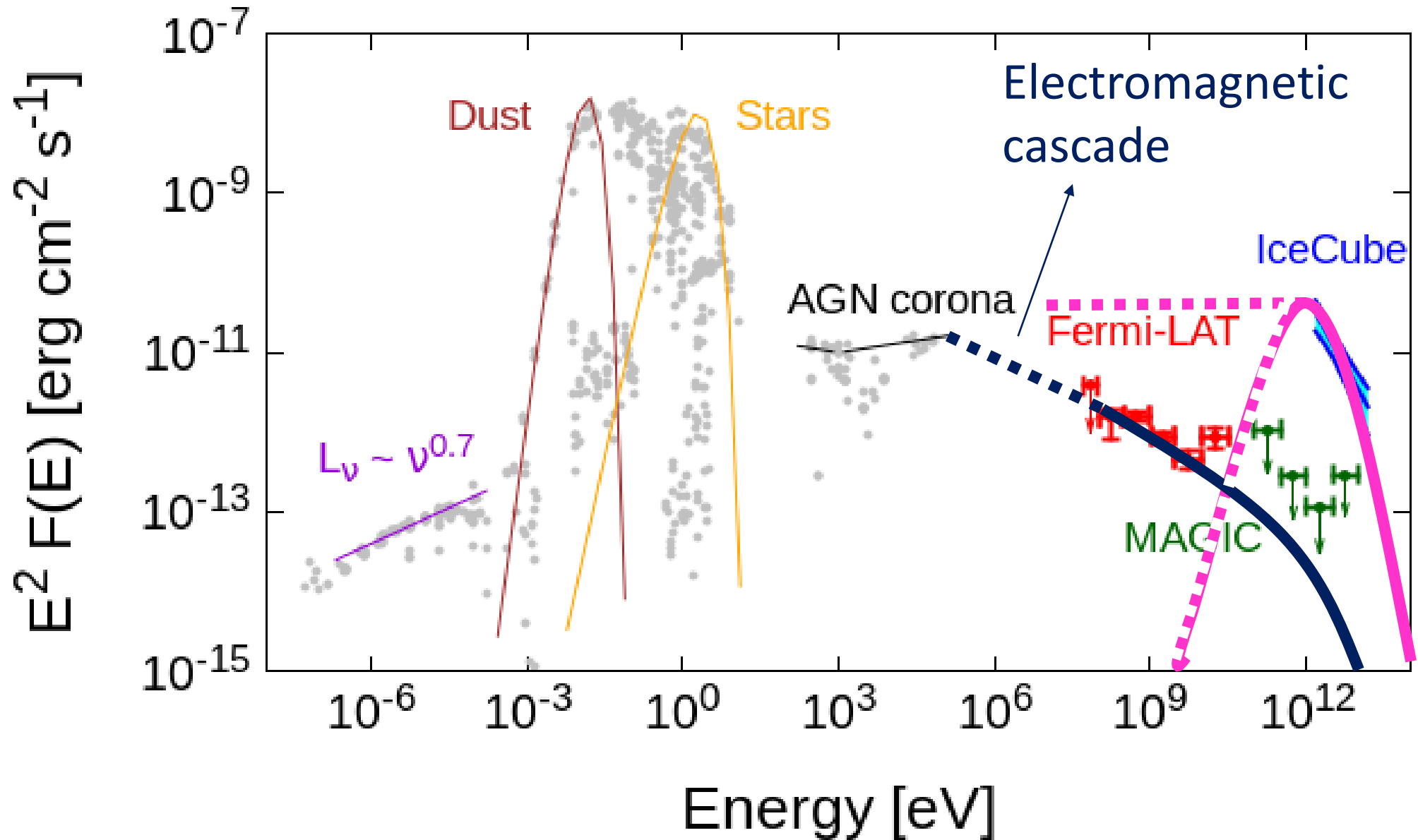


Fig. 8.3. Black hole in a cocoon: (a) disc accretion, (b) quasispherical accretion. The acceleration takes place in the vacuum cavity.

Astrophysics of Cosmic rays, Berezhinskii et al. 1990 (textbook)

Berezinsky & Ginzburg 1981

Hidden multi-messenger source



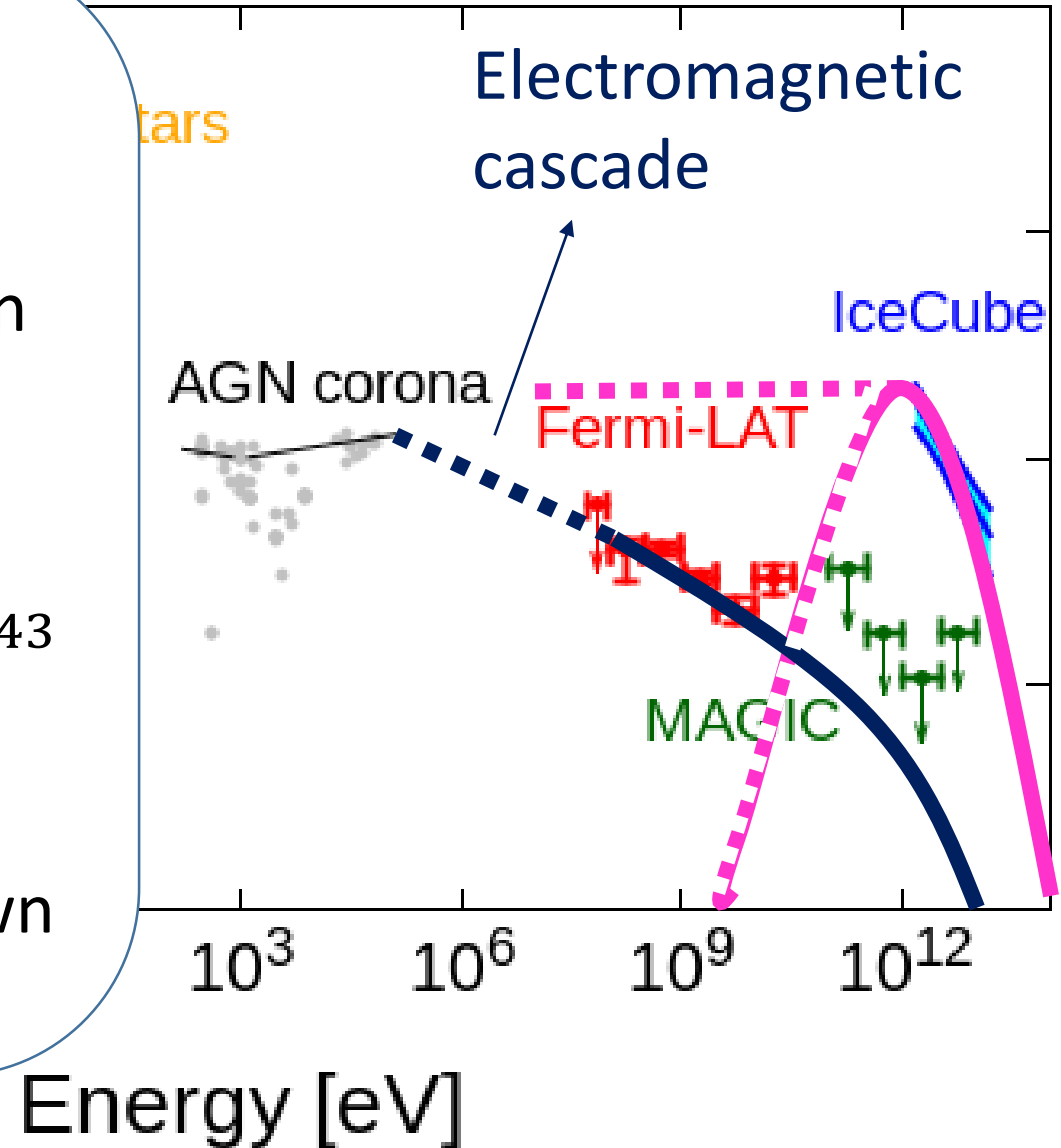
Hidden multi-messenger source

$$L_p = \xi_{CR} L_{bol} = \eta_{eq} L_X$$

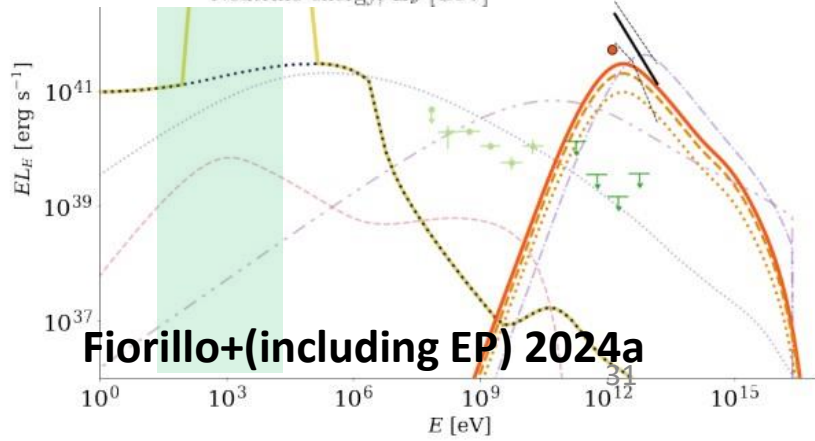
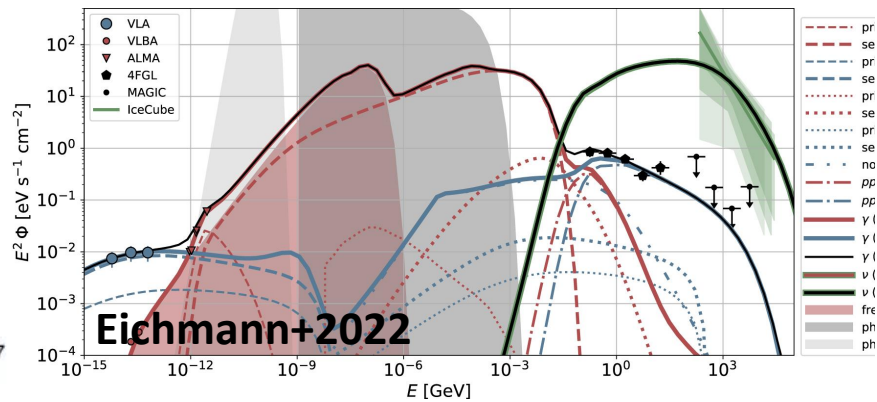
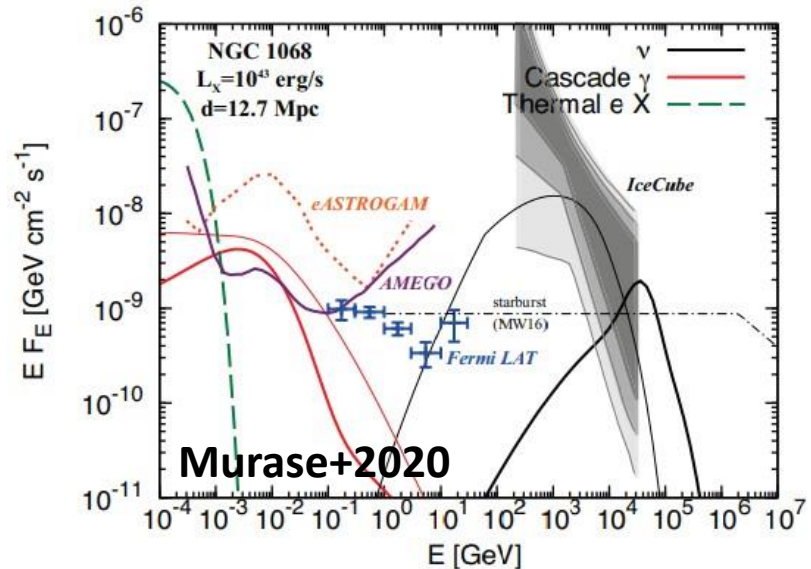
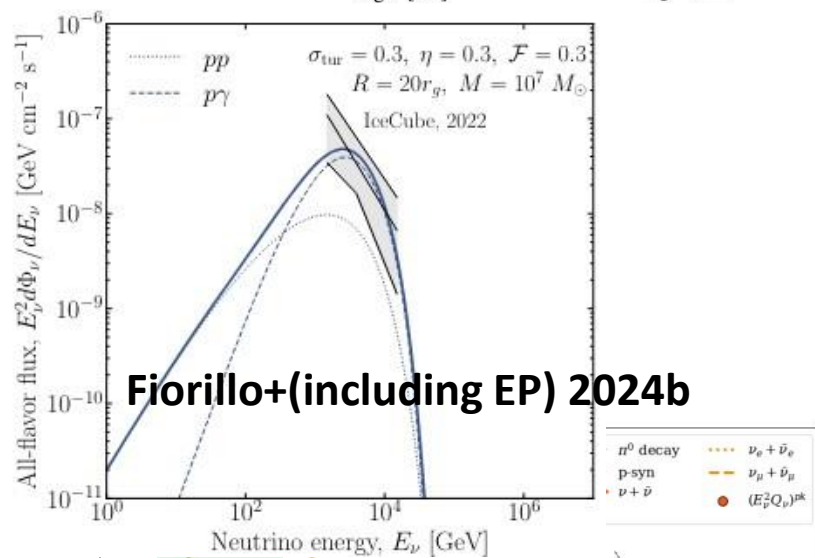
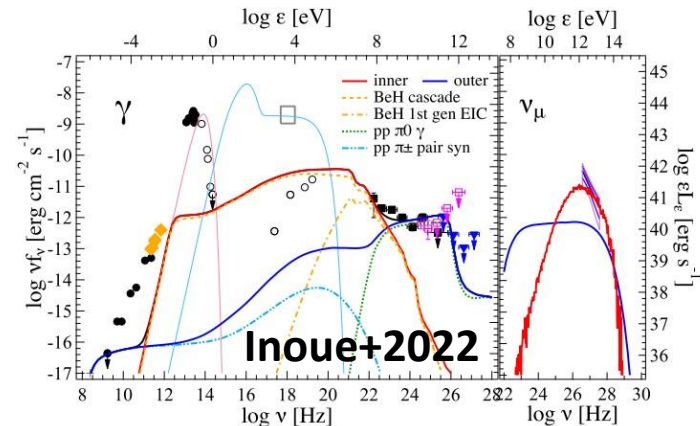
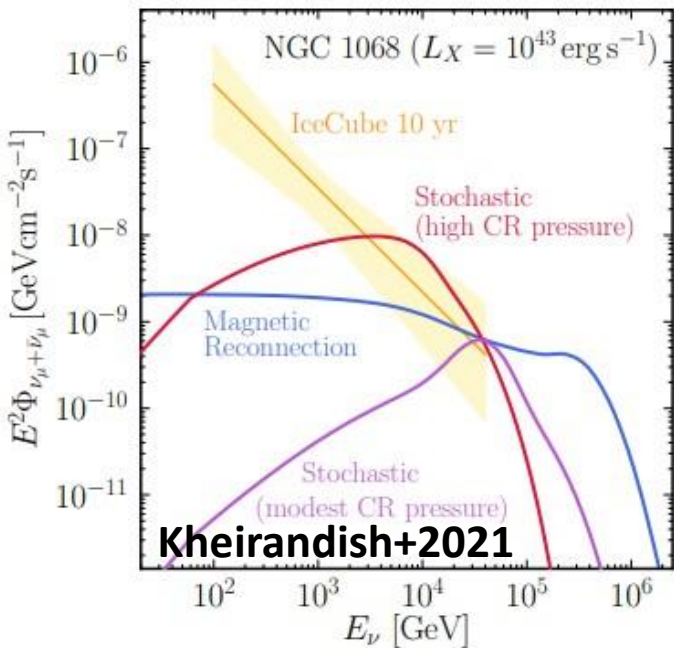
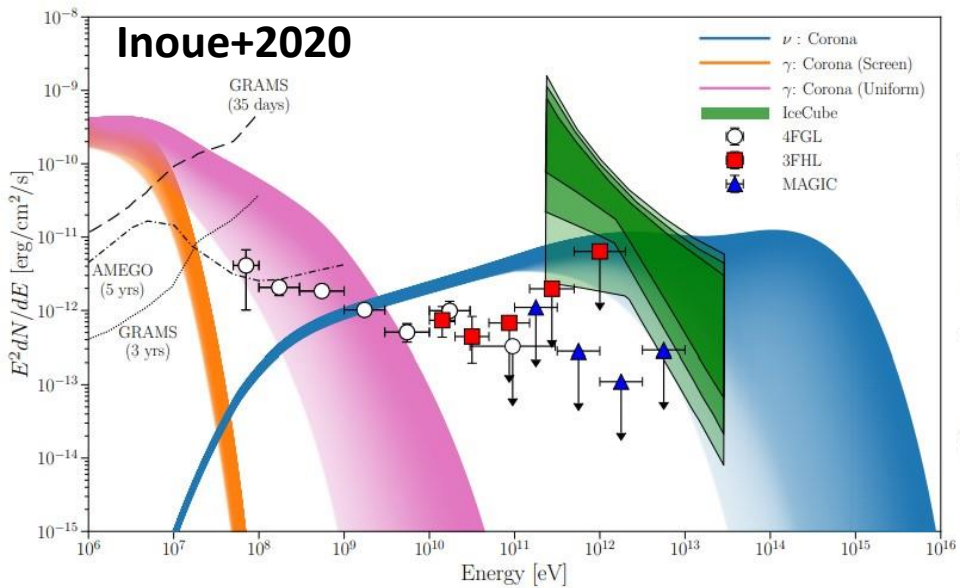
Cosmic rays might be in quasi-equipartition with the X-ray photon field in the coronal region

$$E^2 F_\nu(E = TeV) \approx 10^{-11} \frac{erg}{cm^2 s} L_{p,43}$$

The AGN photon field makes the corona neighbourhood opaque down to the GeV range for $\gamma\gamma \rightarrow e^+e^-$

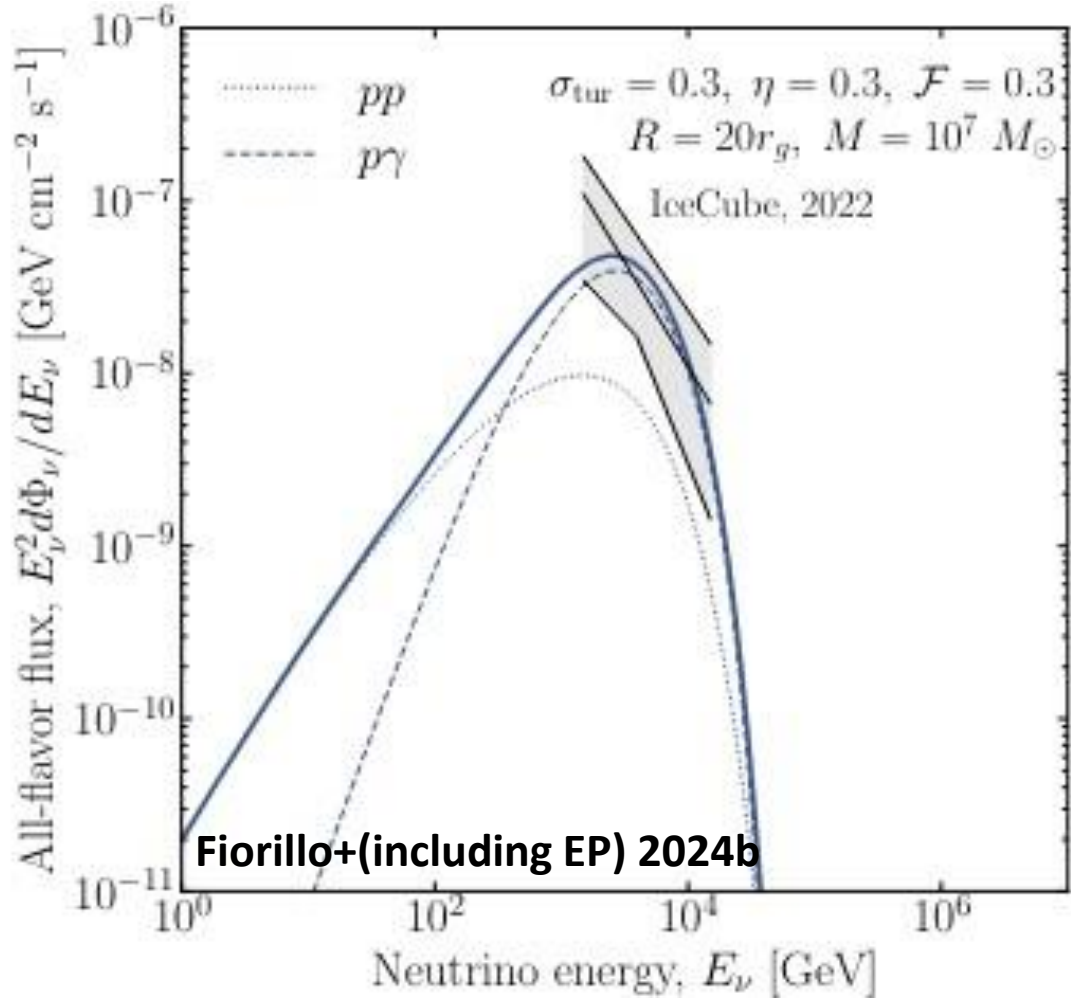


Recent models

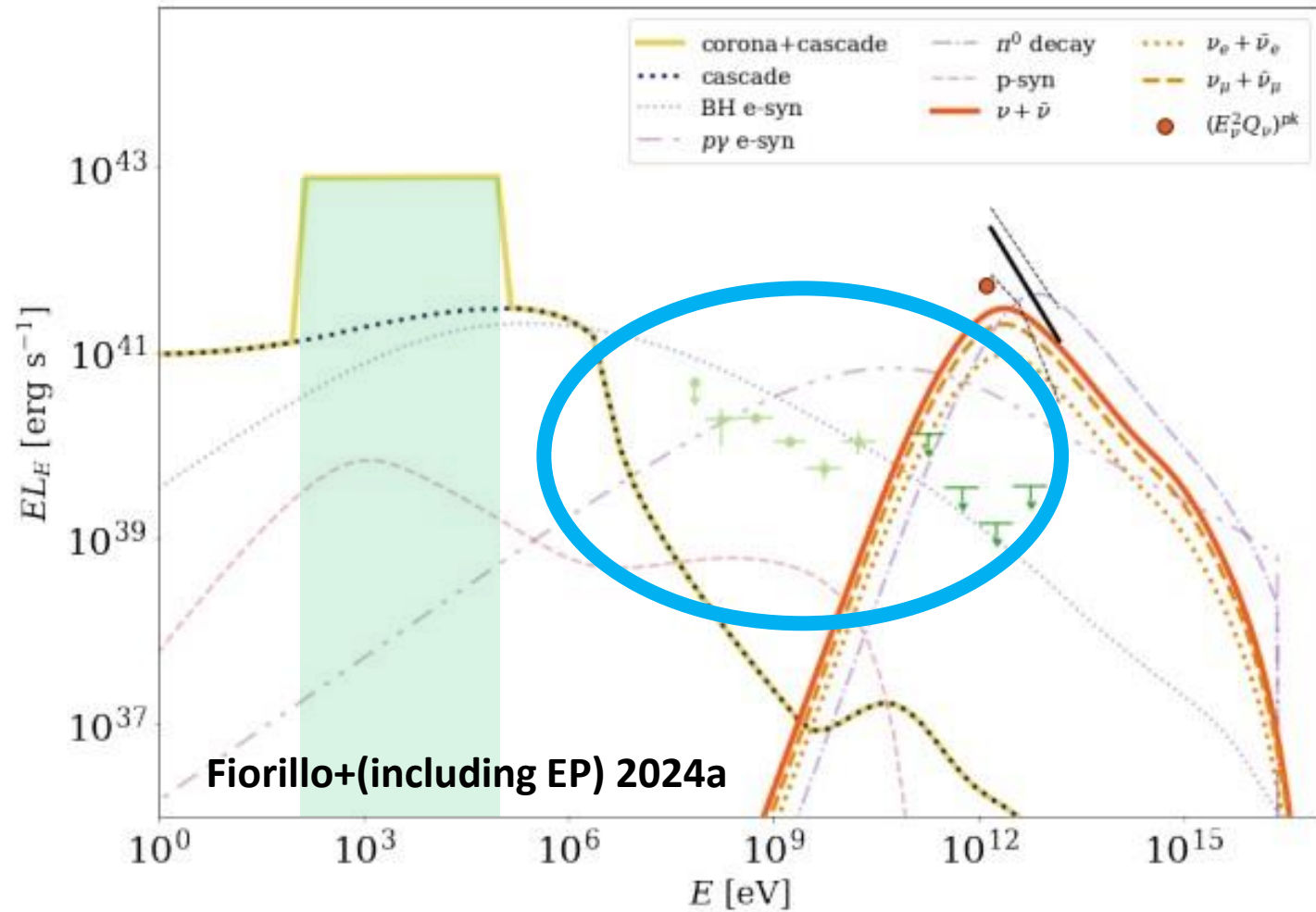


Recent models

Turbulence scenario



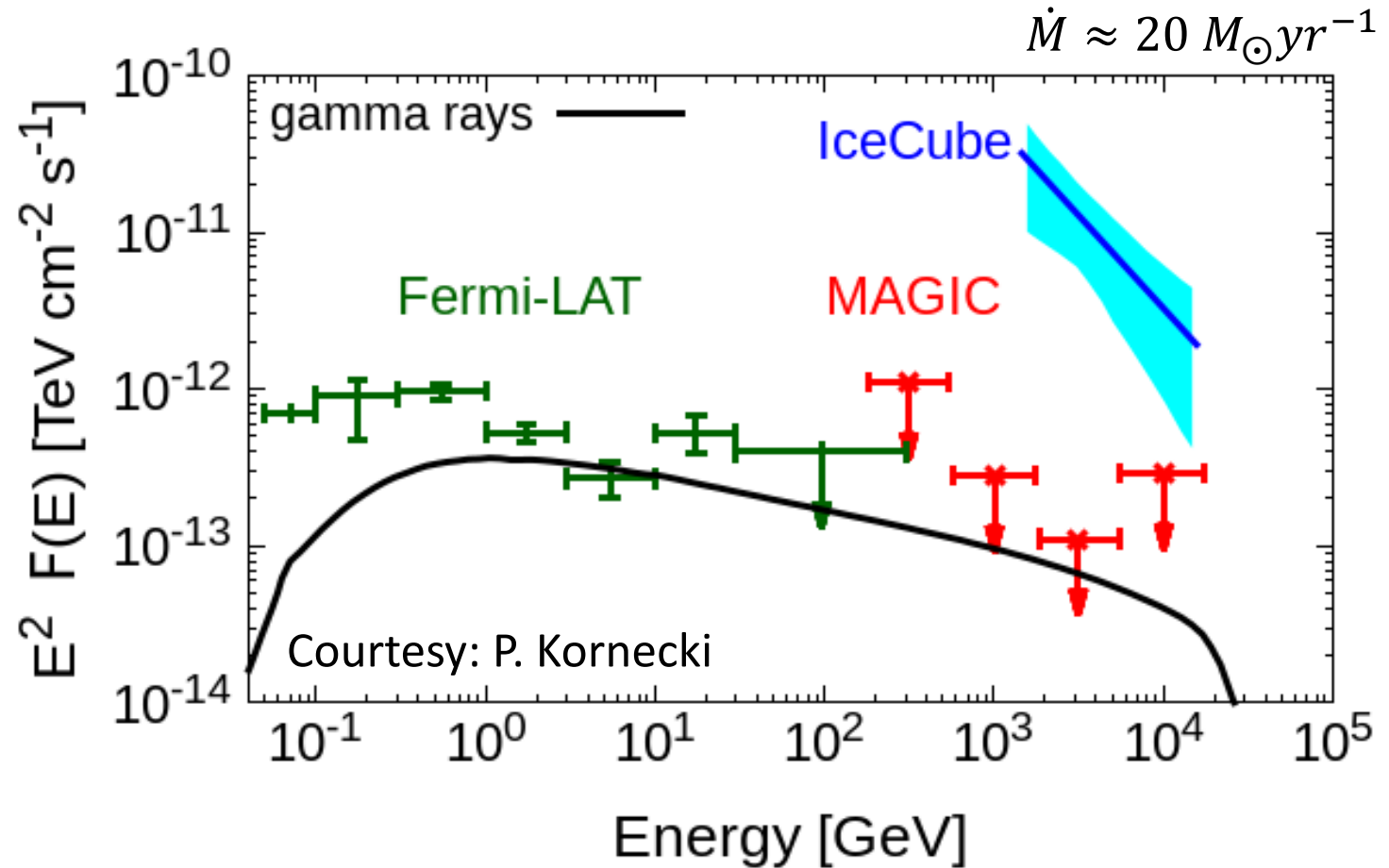
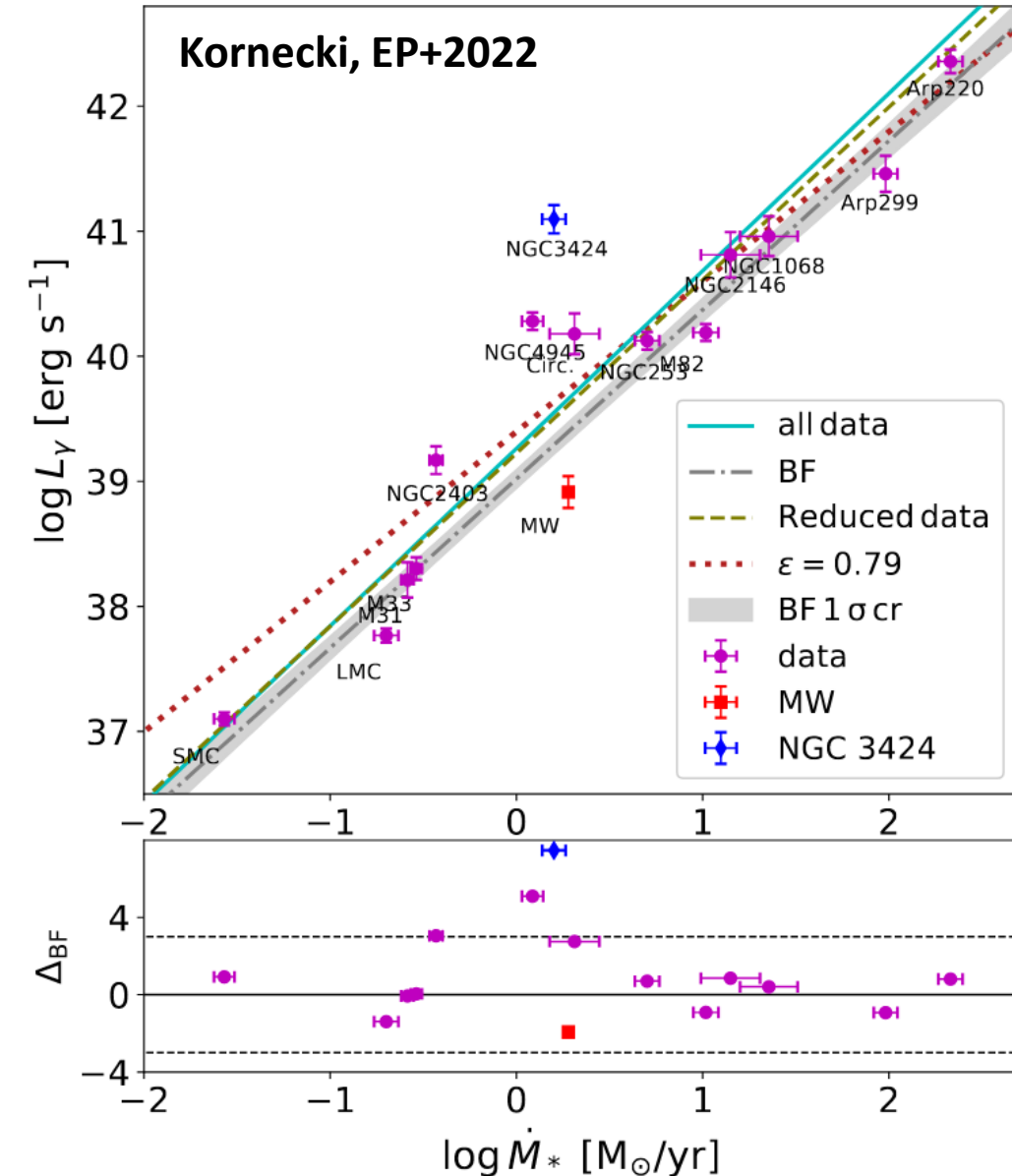
Magnetic reconnection scenario



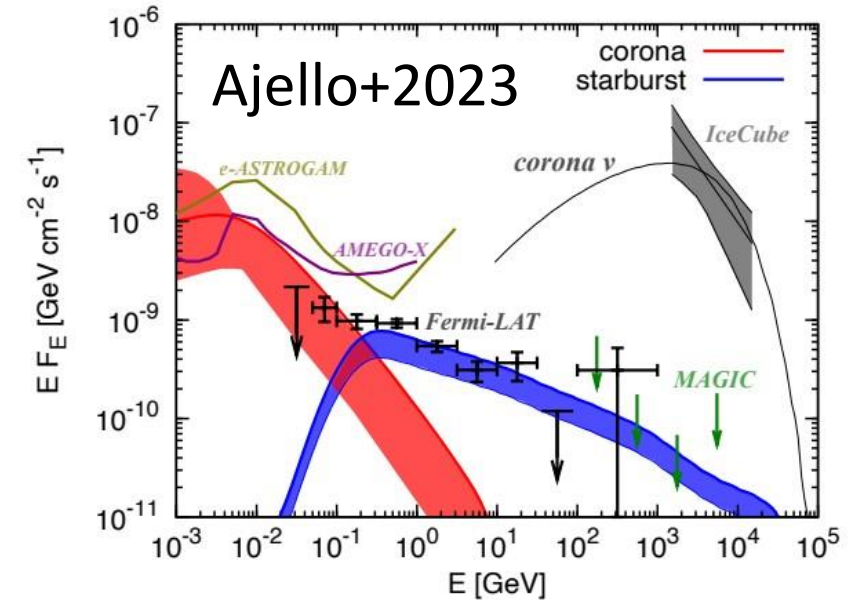
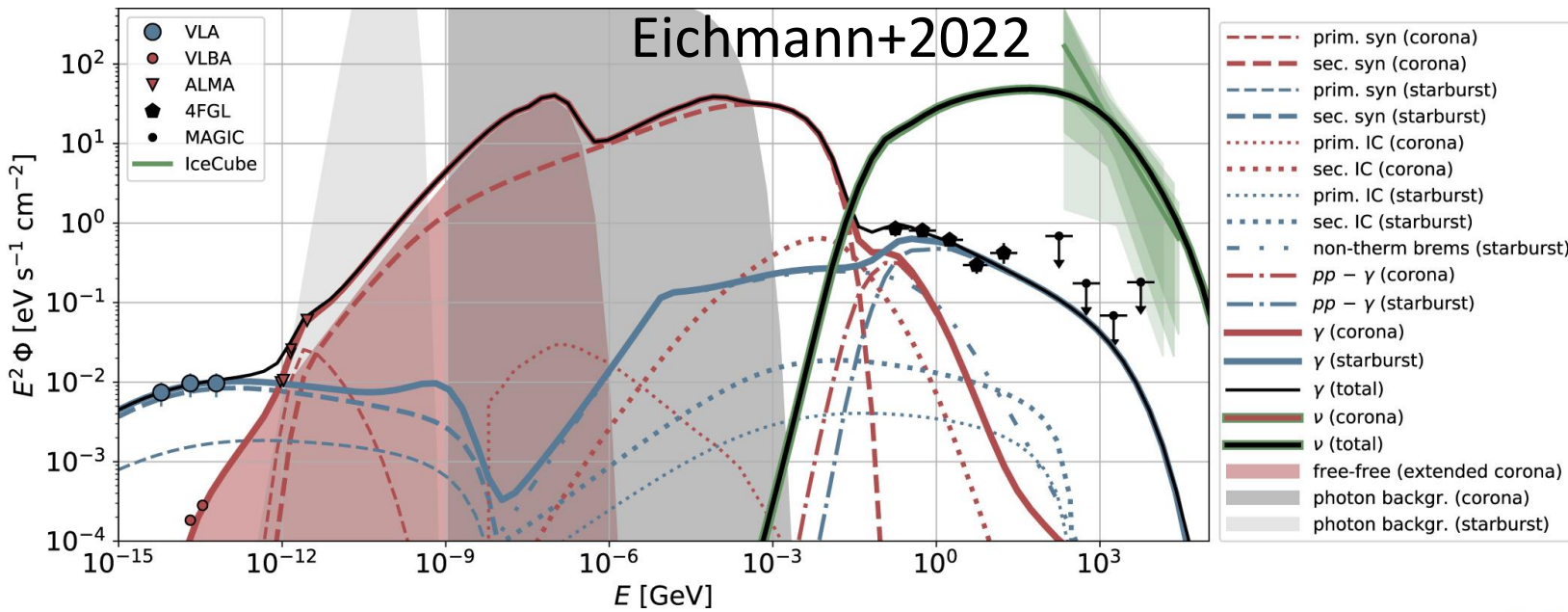
What about gamma rays?

- The corona neighbourhood reprocesses the HE radiation from the GeV-TeV range down to the MeV range.
- The observed gamma rays must have a different production region with respect to the neutrinos.
- This is a strong indication in support of a 2-zone-model!

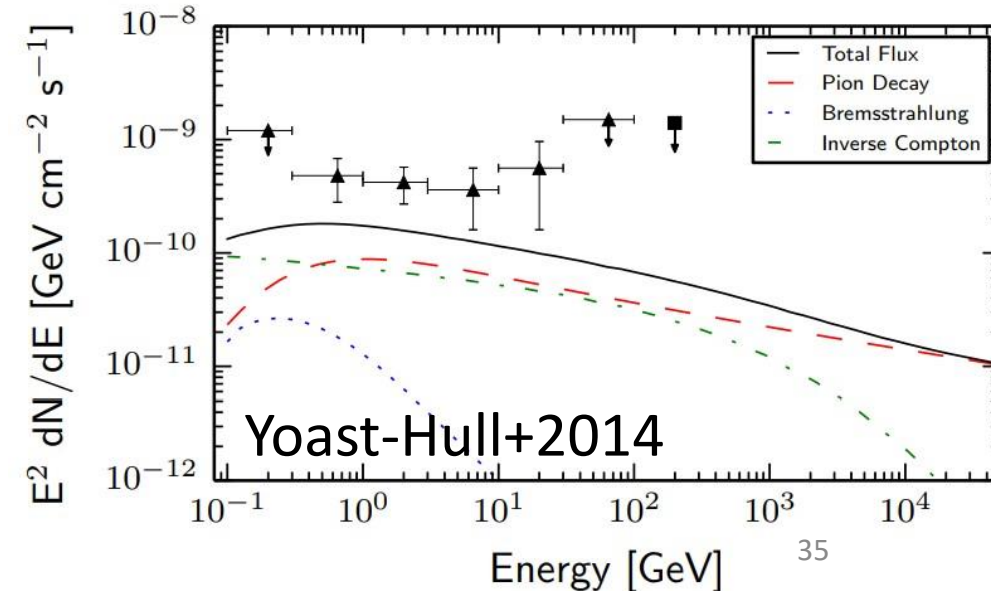
Gamma rays from the starburst of NGC 1068



Gamma rays from the starburst of NGC 1068



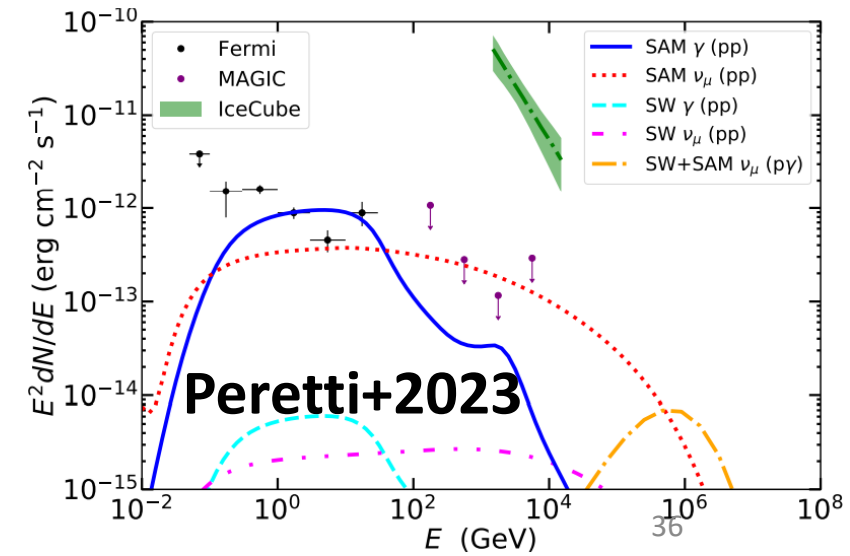
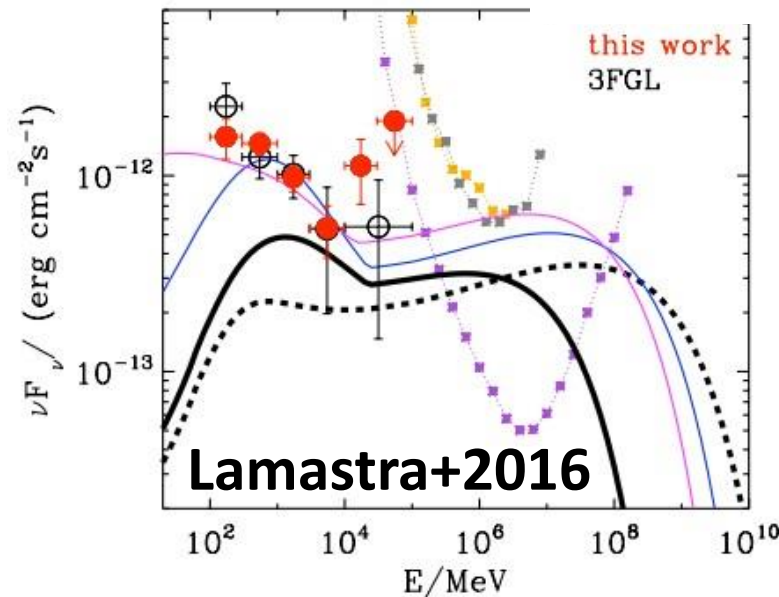
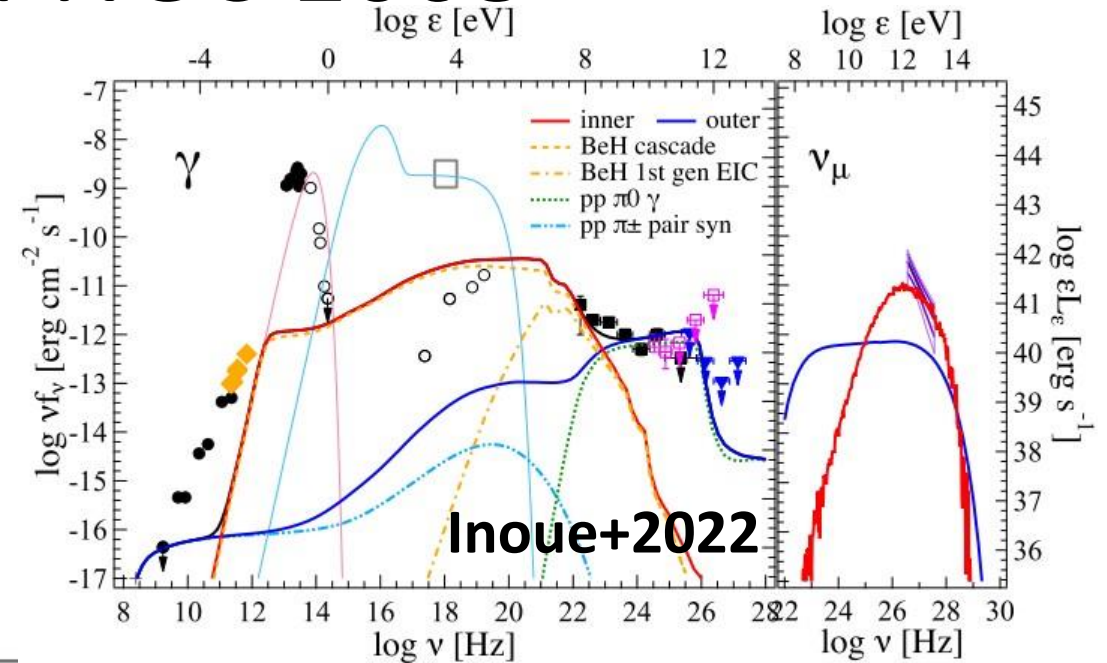
The starburst appears as the most plausible region for the production of gamma rays. However, it is not clear whether only the starburst is the only efficient gamma-ray emitter.



The AGN wind of NGC 1068

The AGN-driven wind could contribute to the gamma-ray luminosity of NGC 1068.

Diffusive shock acceleration in the molecular outflow as well as in inner wind - such as Ultra-Fast Outflows - can reach the required power.



The jet of NGC 1068

On the possible jet contribution to the γ -ray luminosity in NGC 1068

S. Salvatore^{1,2}, B. Eichmann^{1,2}, X. Rodrigues^{2,3,4}, R.-J. Dettmar^{2,4}, and J. Becker Tjus^{1,2,5}

- ¹ Ruhr-Universität Bochum, Fakultät für Physik und Astronomie, Theoretische Physik IV, 44780 Bochum, Germany
- ² Ruhr Astroparticle and Plasma Physics Center (RAPP Center), 44780 Bochum, Germany
- ³ European Southern Observatory, Karl-Schwarzschild-Straße 2, 85748 Garching bei München, Germany
- ⁴ Ruhr-Universität Bochum, Fakultät für Physik und Astronomie, Astronomisches Institut (AIRUB), 44780 Bochum, Germany
- ⁵ Department of Space Earth and Environment, Chalmers University of Technology, 412 96 Gothenburg, Sweden

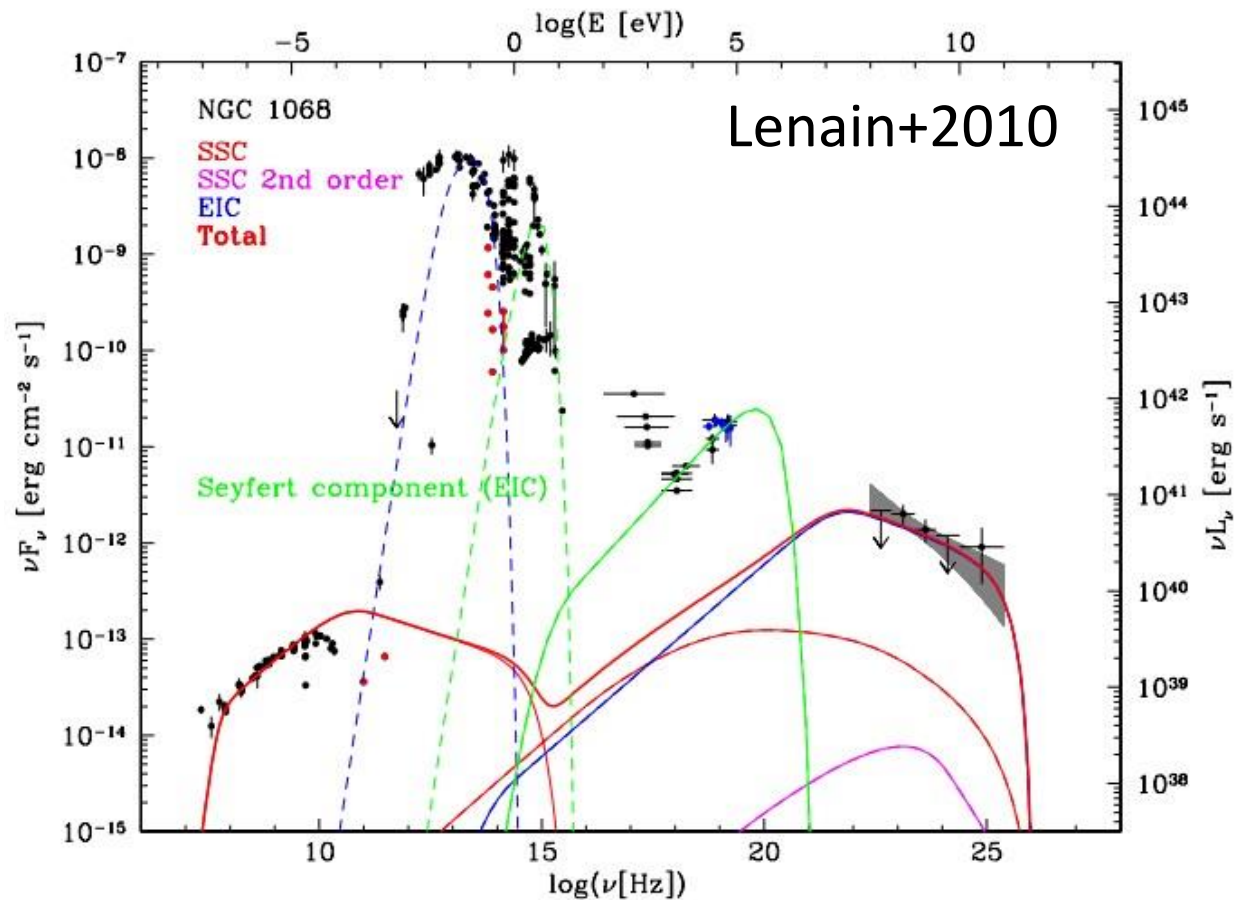
November 1, 2023

ABSTRACT

NGC 1068 is a nearby widely studied Seyfert II galaxy presenting radio, infrared, X- and γ -ray emission as well as strong evidence for high-energy neutrino emission. Recently, the evidence for neutrino emission could be explained in a multimessenger model in which the neutrinos originate from the corona of the active galactic nucleus (AGN). In this environment γ -rays are strongly absorbed, so that an additional contribution from e.g. the circumnuclear starburst ring is necessary. In this work, we discuss whether the radio jet can be an alternative source of the γ -rays between about 0.1 and 100 GeV as observed by Fermi-LAT. In particular, we include both leptonic and hadronic processes, i.e. accounting for inverse Compton emission and signatures from pp as well as $p\gamma$ interactions. In order to constrain our calculations, we use VLBA and ALMA observations of the radio knot structures, which are spatially resolved at different distances from the supermassive black hole. Our results show that the best leptonic scenario for the prediction of the Fermi-LAT data is provided by the radio knot closest to the central engine. For that a magnetic field strength ~ 1 mG is needed as well as a strong spectral softening of the relativistic electron distribution at $(1 - 10)$ GeV. However, we show that neither such a weak magnetic field strength nor such a strong softening is expected for that knot. A possible explanation for the ~ 10 GeV γ rays can be provided by hadronic pion production in case of a gas density $\geq 10^4 \text{ cm}^{-3}$. Nonetheless, this process cannot contribute significantly to the low energy end of the Fermi-LAT range. We conclude that the emission sites in the jet are not able to explain the γ -rays in the whole Fermi-LAT energy band.

Key words. galaxies: active – galaxies: Seyfert – gamma rays: galaxies

Salvatore+2023



Conclusions

- NGC 1068 is complex and our current understanding limited
- The corona (or its nearest surrounding) is probably the production site of the observed neutrinos
- The star forming region is the most plausible responsible for the gamma rays although an AGN wind cannot be excluded
- The radio emission is likely also associated to the star forming region but AGN jet and wind could contaminate

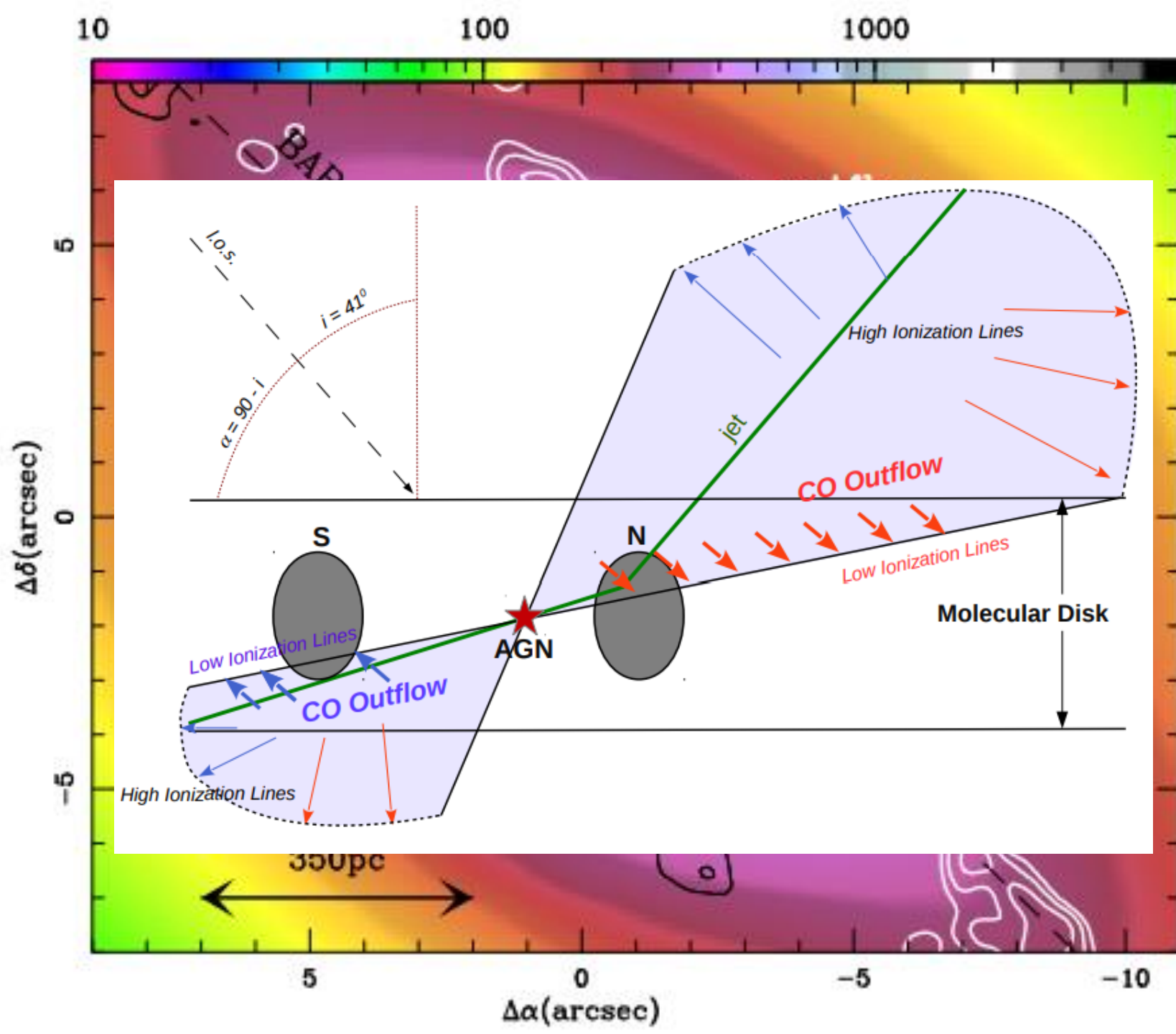
Conclusions

- NGC 1068 is complex and our current understanding limited.

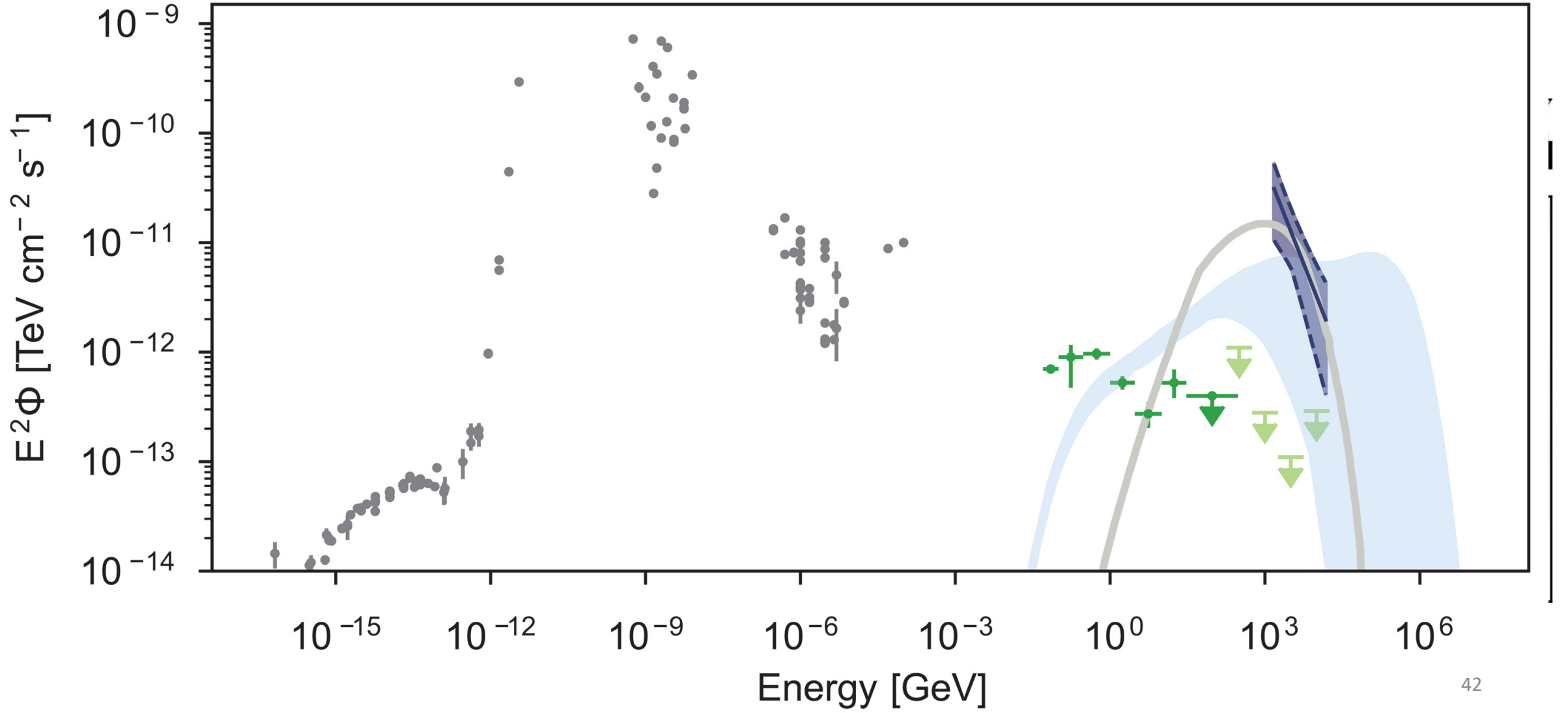
We need to observe
NGC 1068 at MeV!

- The radio emission is likely also associated to the star forming region but AGN jet and wind could contaminate.

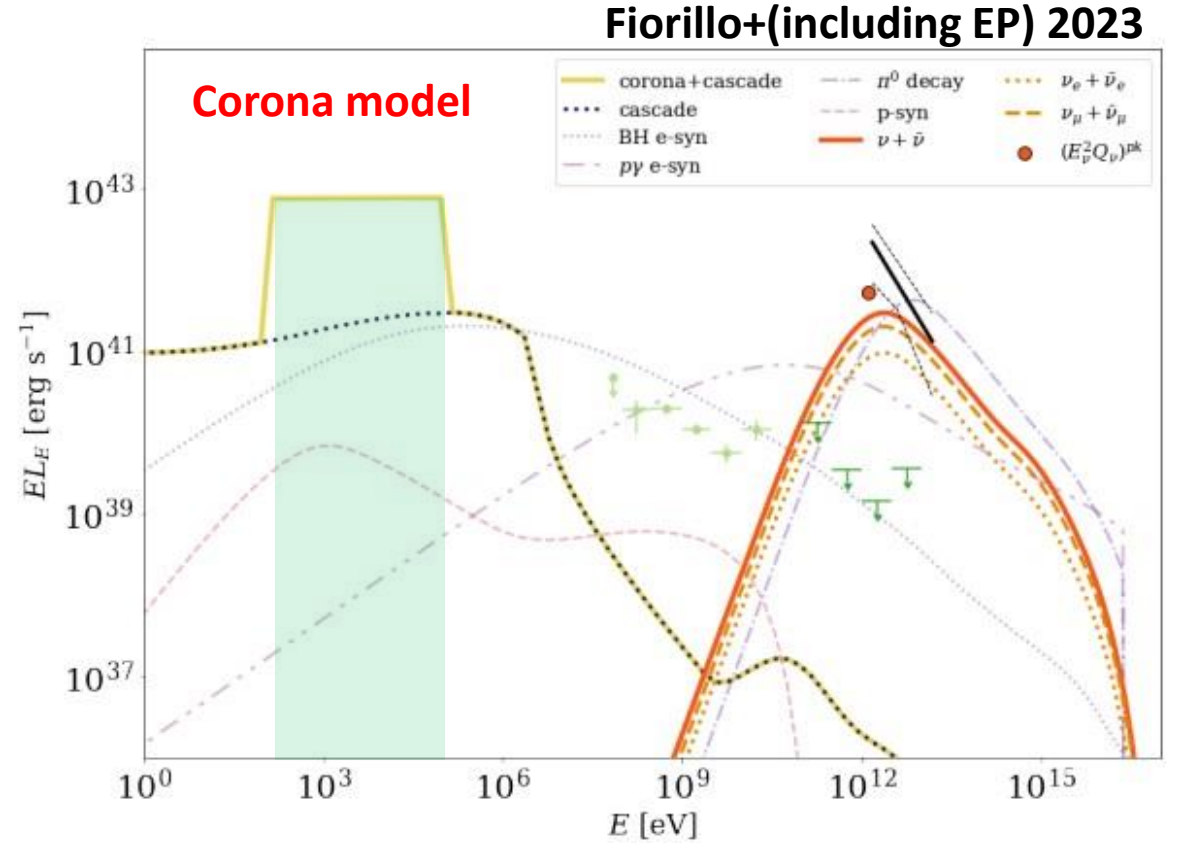
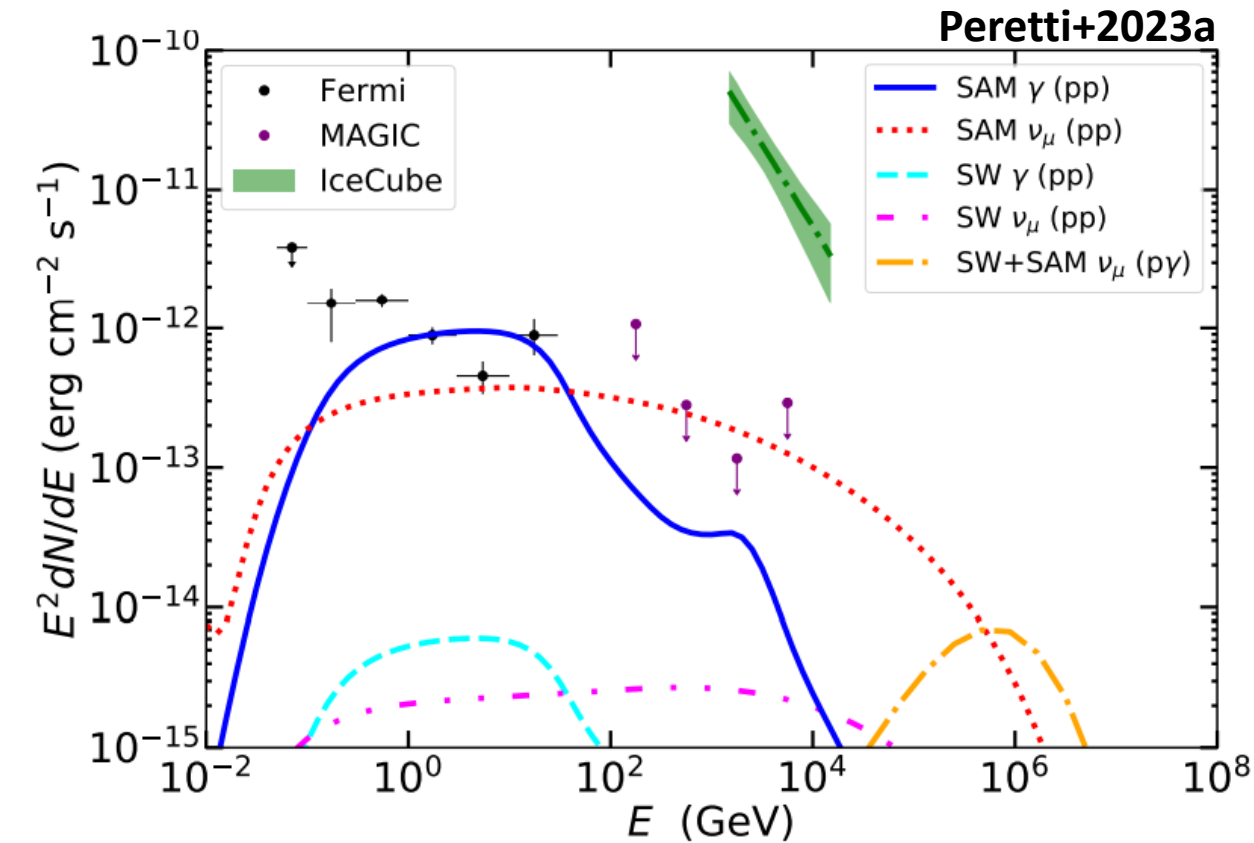
THANKS FOR YOUR ATTENTION!



- IceCube (this work)
- Theoretical ν model (52,55)
- Theoretical ν model (53)
- Electromagnetic observations (26)
- 0.1 to 100 GeV gamma-rays (40,41)
- > 200 GeV gamma-rays (42)

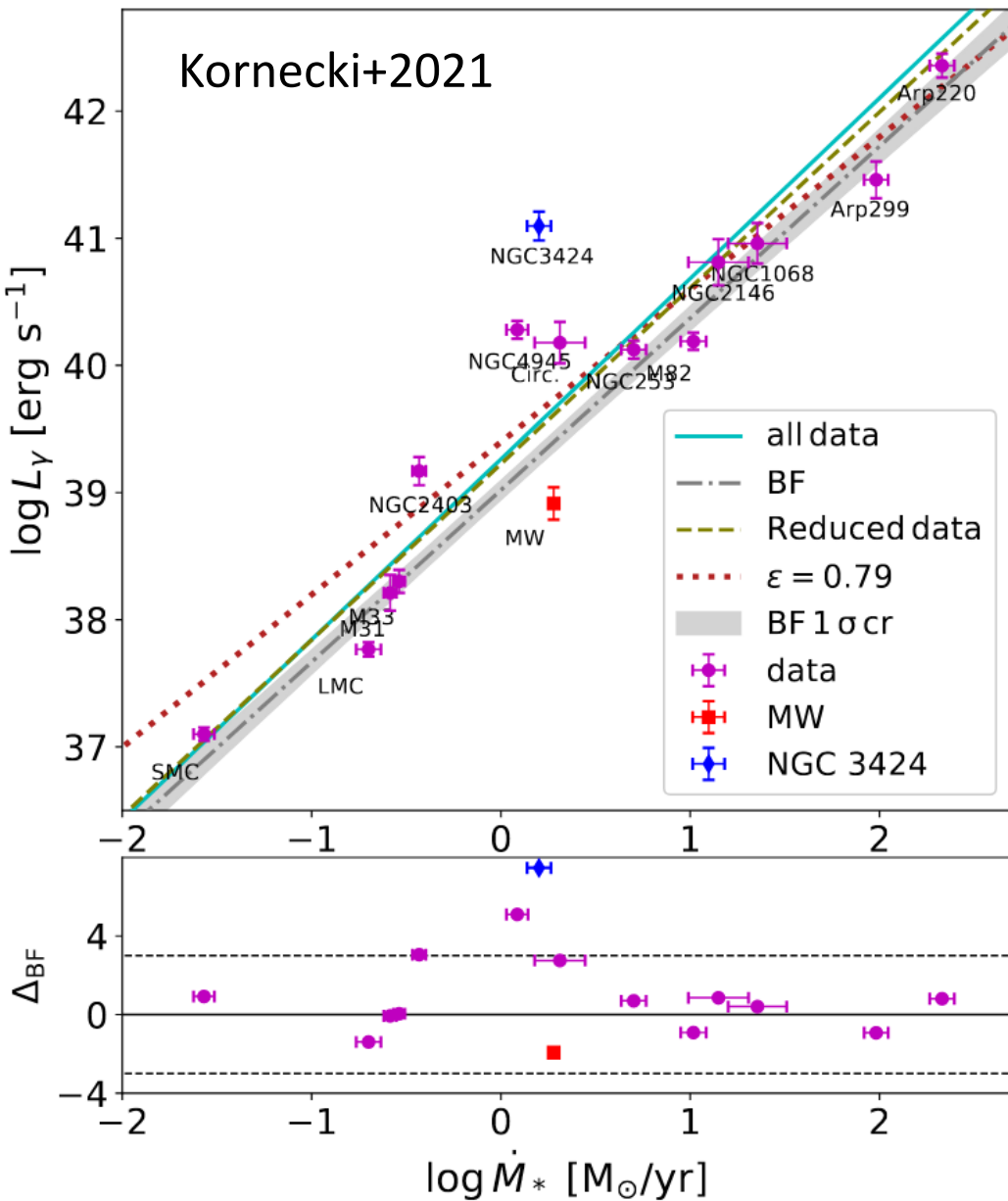


Multi-zone perspective for NGC 1068



- For similar 2 zone model studies see also: **Inoue S. et al. 2022** (failed wind/corona + successful wind/torus) and **Eichmann et al. 2022** (corona + starburst ring);
- For possible gamma-ray emission models see: **Lenain 2010** (jet and starburst), **Yoast-Hull+2014** (starburst) and **Lamastra+2016** (AGN wind forward shock model);
- For corona models see also: **Murase+2020** (stochastic acc.), **Inoue Y.+2020** (DSA), **Keirandish+2021** & **Mbarek+2023** (Reconn.)

The starburst of NGC 1068

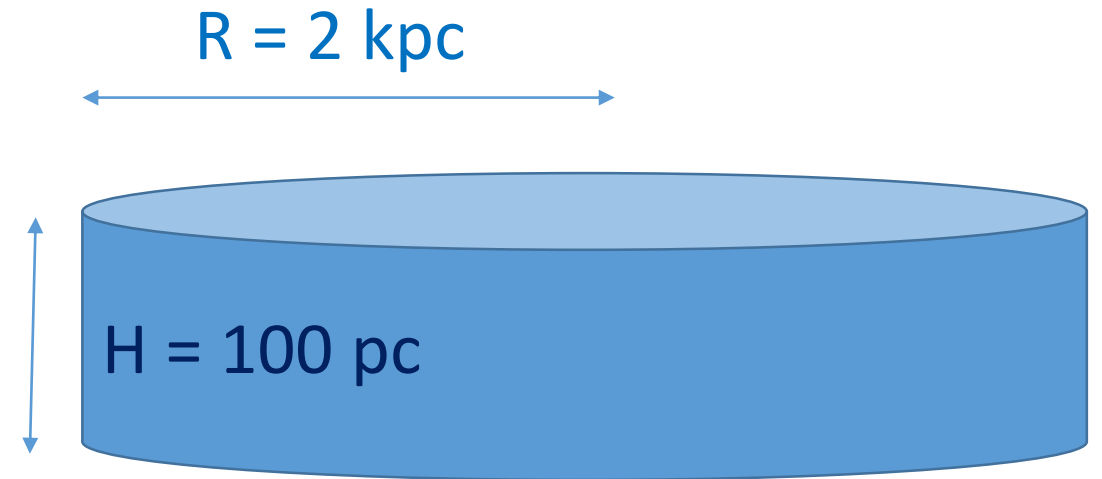


The starburst of NGC 1068

$$\tau_{pp}(GeV) \approx 5 \cdot 10^5 \left(\frac{n}{10^2 cm^{-3}} \right)^{-1} yr$$

$$\tau_{diff}(GeV) \approx 10^5 \left(\frac{H}{10^2 pc} \right)^2 \left(\frac{D}{10^{28} cm^2/s} \right)^{-1} yr$$

$$\tau_{adv}(GeV) \approx 10^6 \left(\frac{H}{10^2 pc} \right) \left(\frac{u}{10^2 km/s} \right)^{-1} yr$$



Calorimetry is possible but not trivial