Photons and Neutrinos from NGC 1068

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Workshop on Numerical Multi-messenger Modeling

NGC 1068 is the brightest hotspot of IceCube

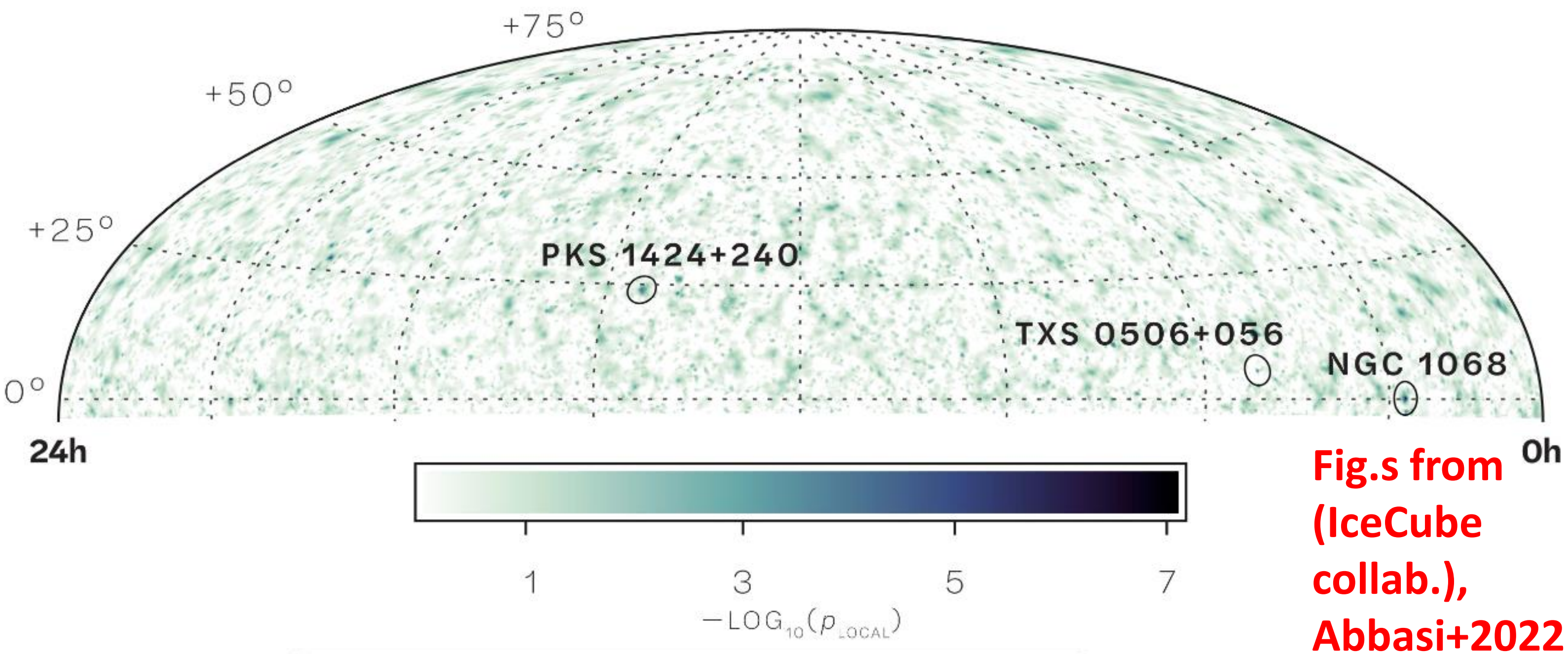
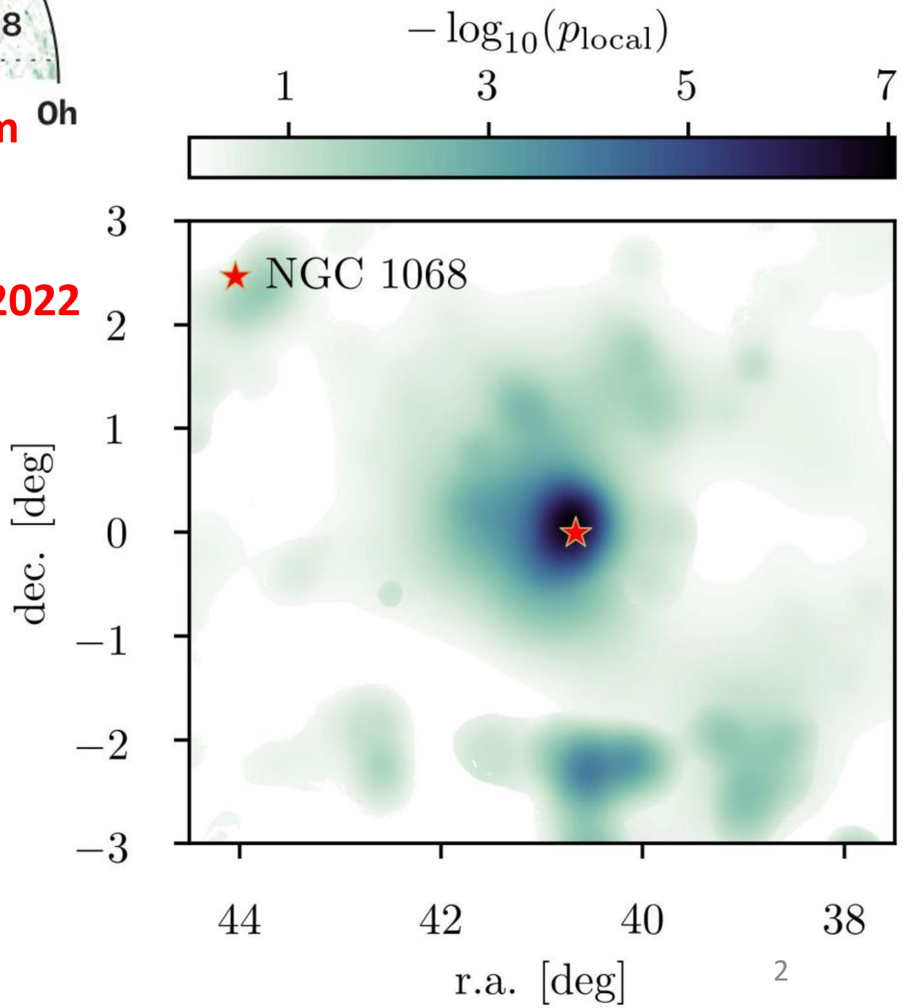
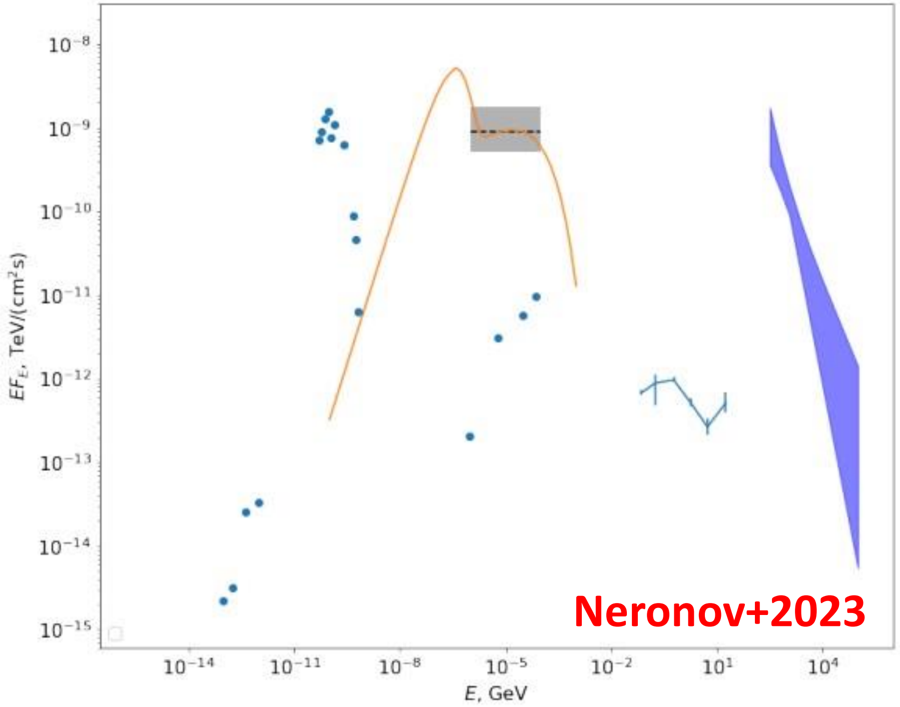


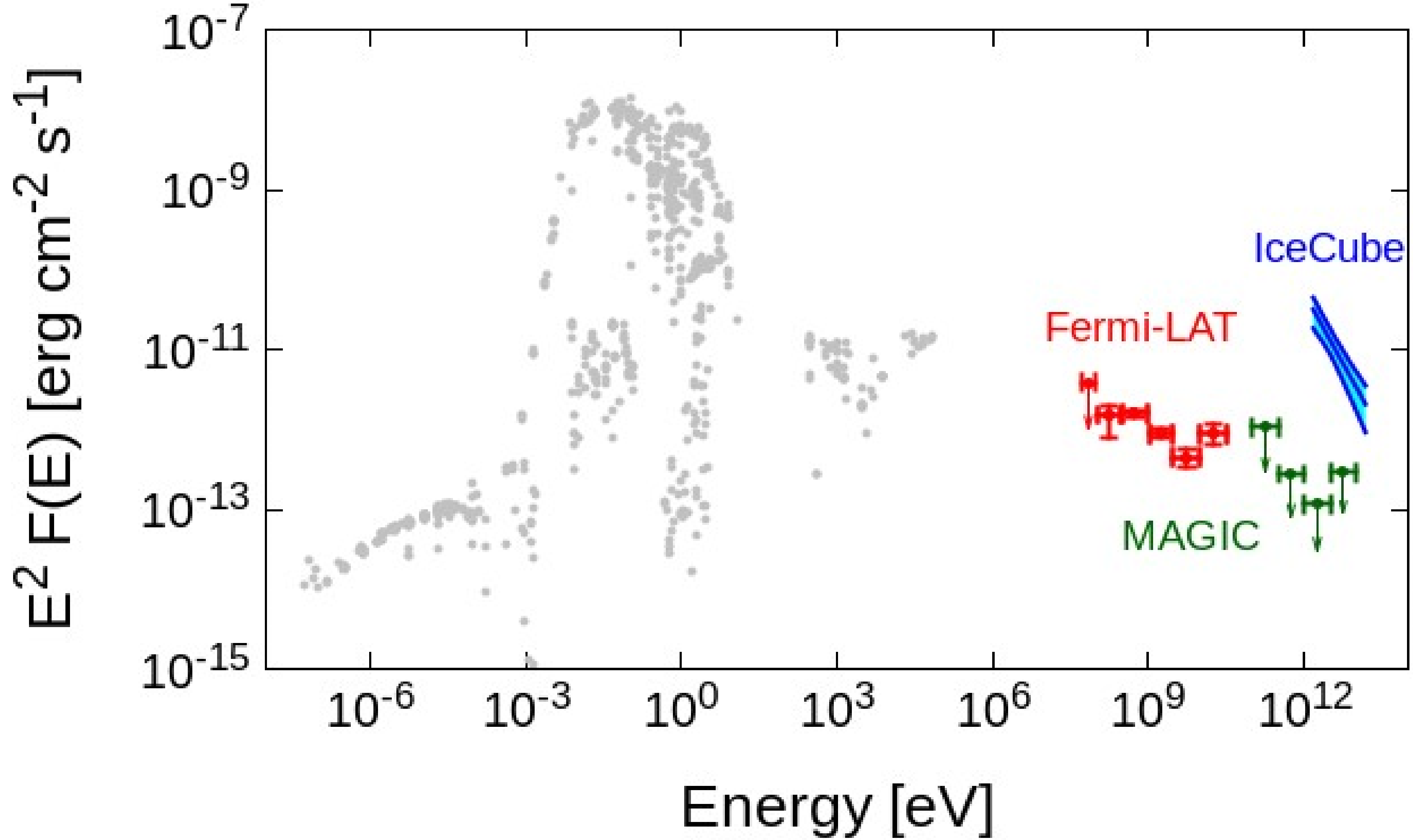
Fig.s from (IceCube collab.), Abbasi+2022





Neronov+2023

Multi-messenger spectrum




Credit: NASA, ESA & A. van der Hoeve

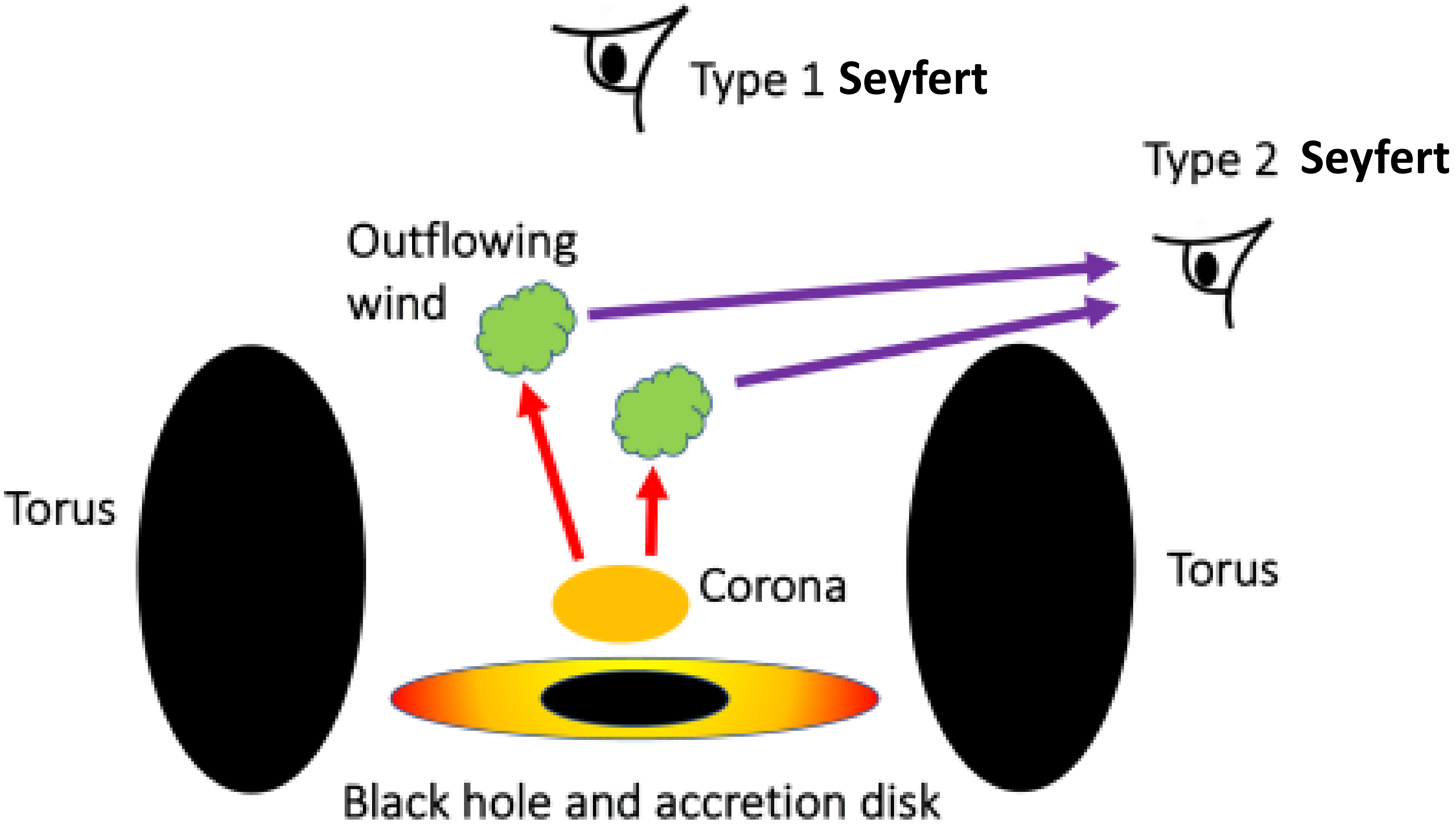
Seyfert II galaxy with at least two star forming regions:

1) Highly obscured AGN
2) 500 pc-scale mild 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

Credit: NASA, ESA & A. van der Hoeve

The AGN

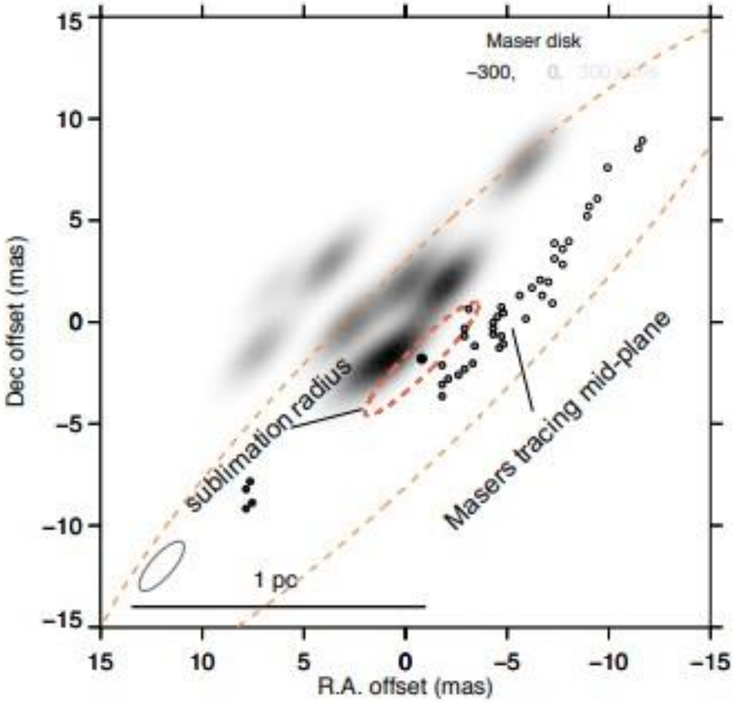

Type 1 Seyfert
Type 2 Seyfert
Outflowing
wind
Torus
Corona
Torus
Black hole and accretion disk

The AGN

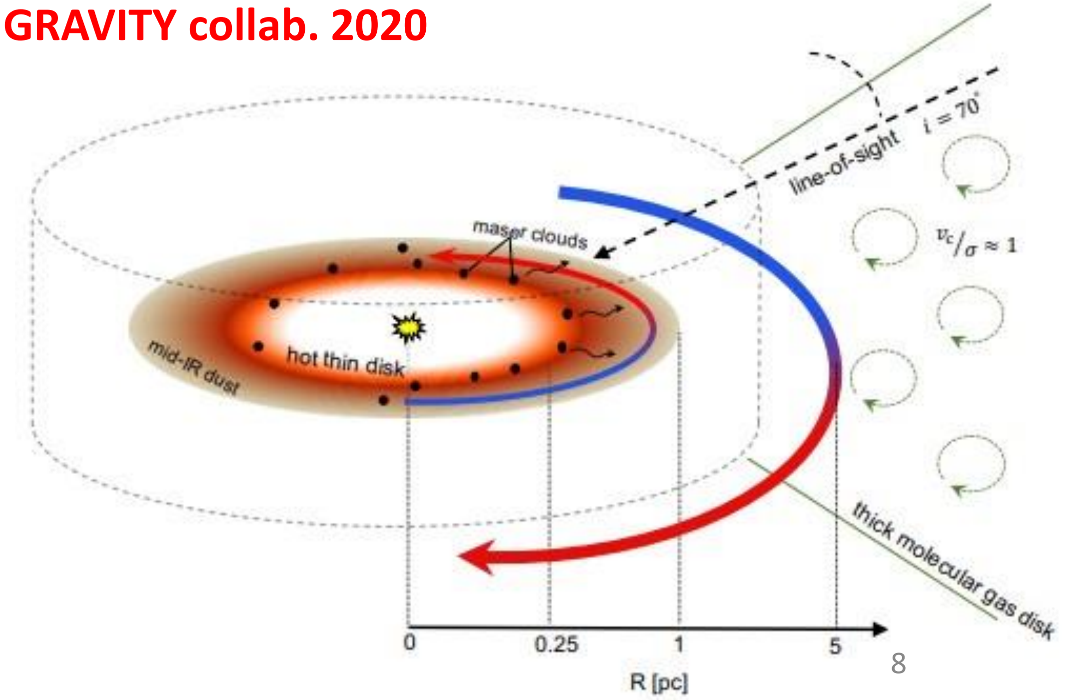
AGN Corona → region of very hot ($T \approx 10^9 K$) electrons which inverse Compton scatter the UV photons from the disc and produce X-rays

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

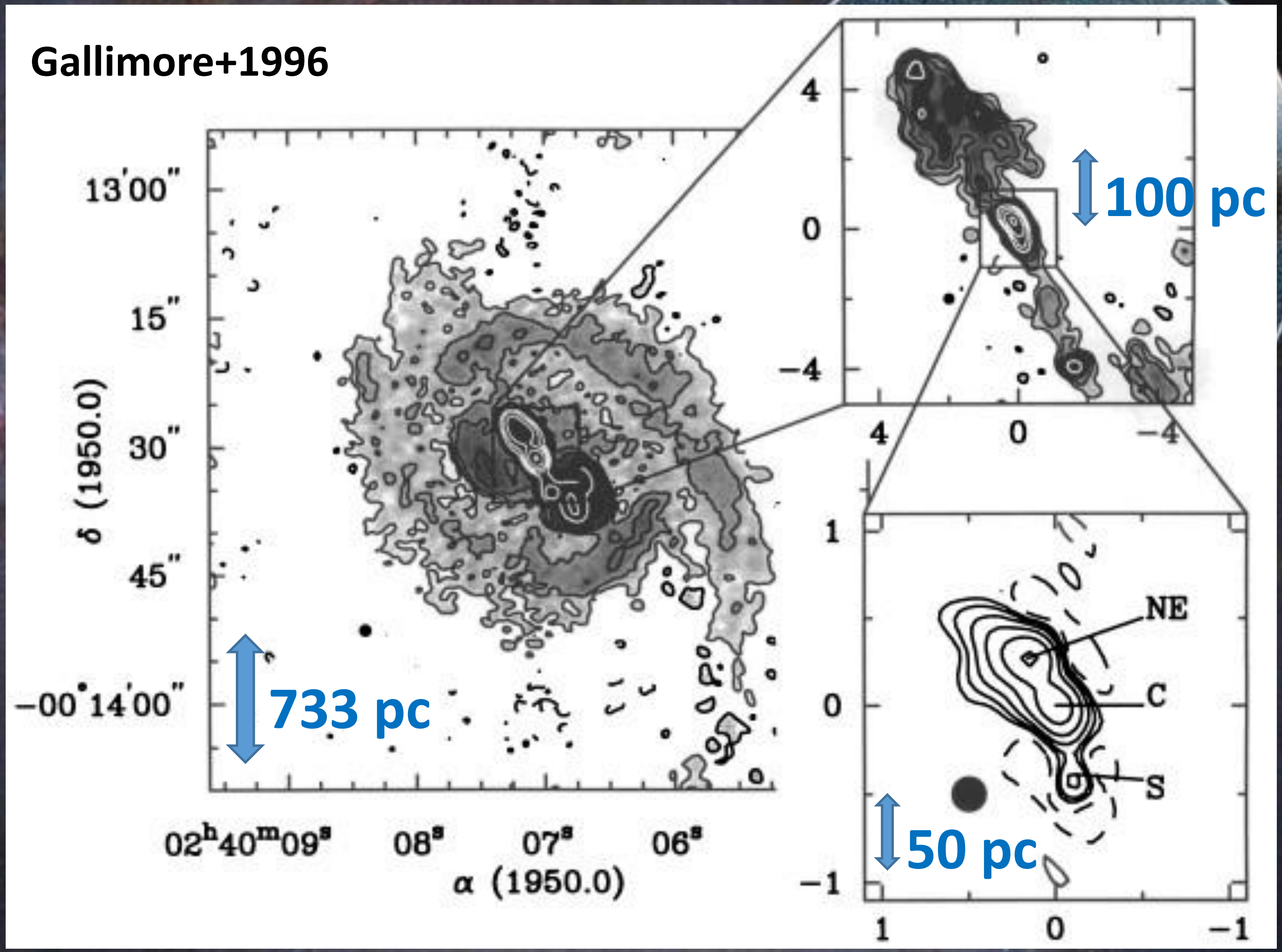
Torus→ Observed in the NIR band – resolved ring-like structure



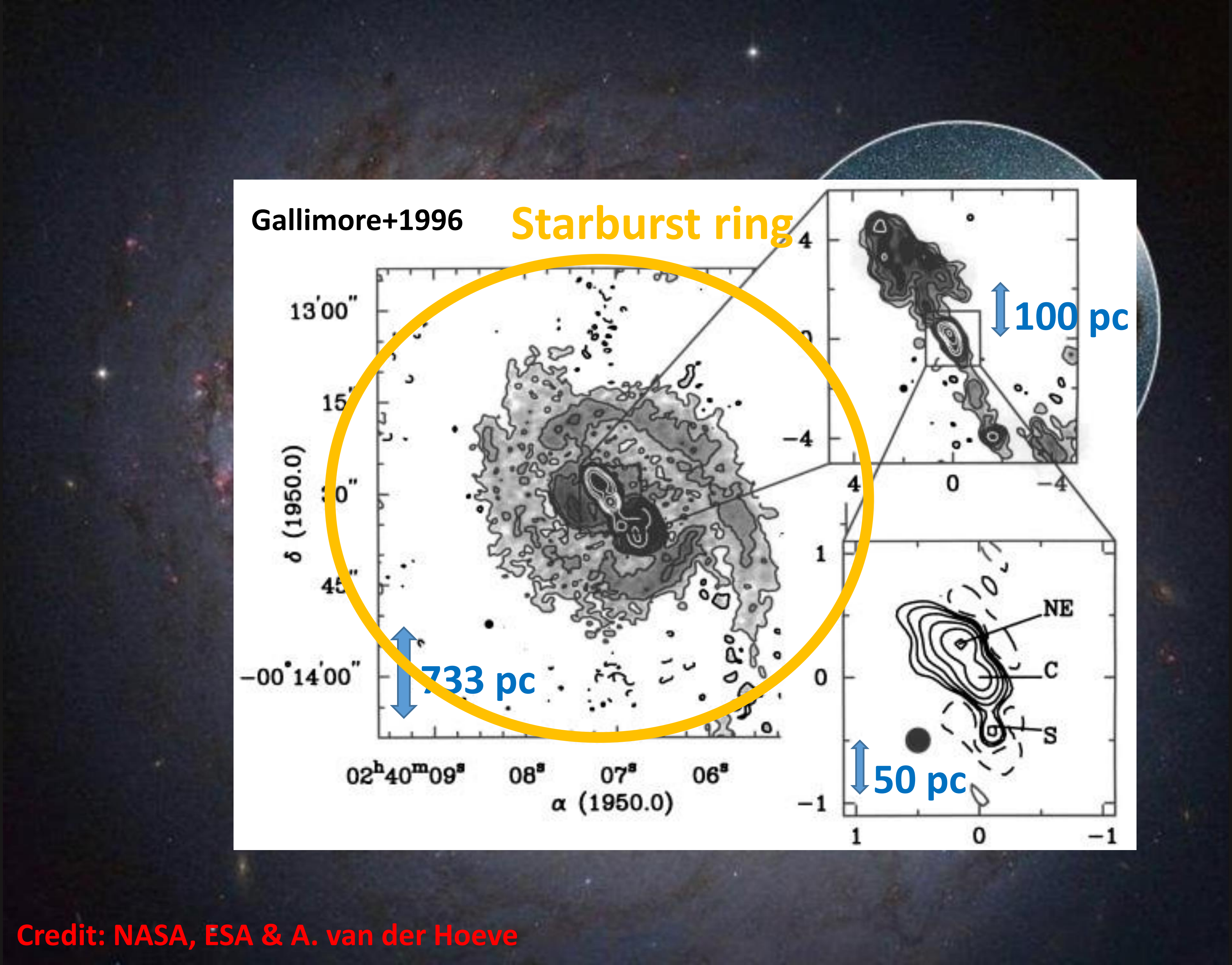
GRAVITY collab. 2020



Credit: NASA, ESA & A. van der Hoeve



Credit: NASA, ESA & A. van der Hoeve


Gallimore+1996
Starburst ring
13′00″
15″
30″
45″
−00°14′00″
δ (1950.0)
733 pc
02h40m09s
08s
07s
06s
α (1950.0)
4
0
−4
100 pc
1
0
−1
NE
C
S
50 pc
Credit: NASA, ESA & A. van der Hoeve

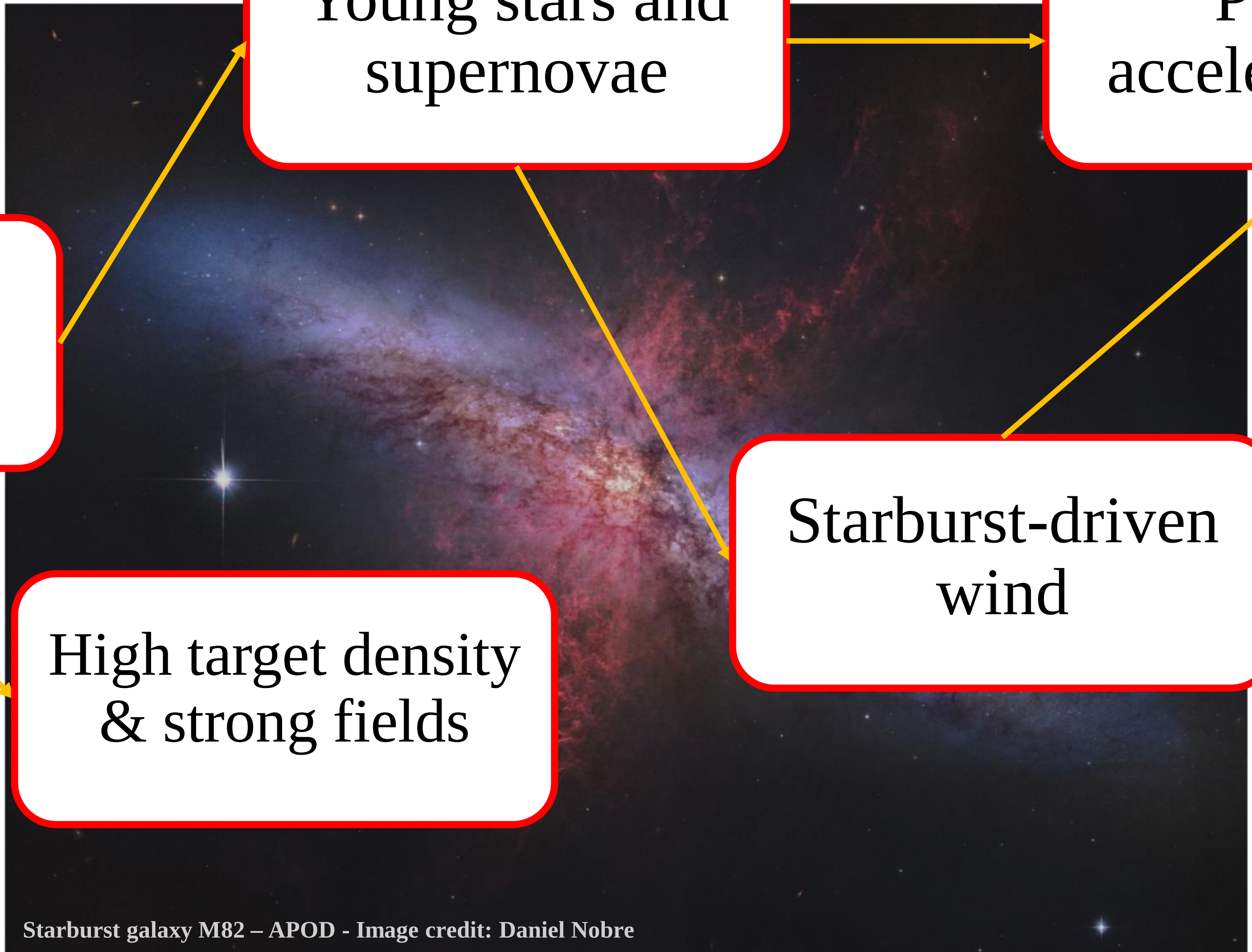
The starburst

Starburst environments are promising cosmic-ray factories

Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

The starburst

Starburst environments … smic-ray



Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

The starburst

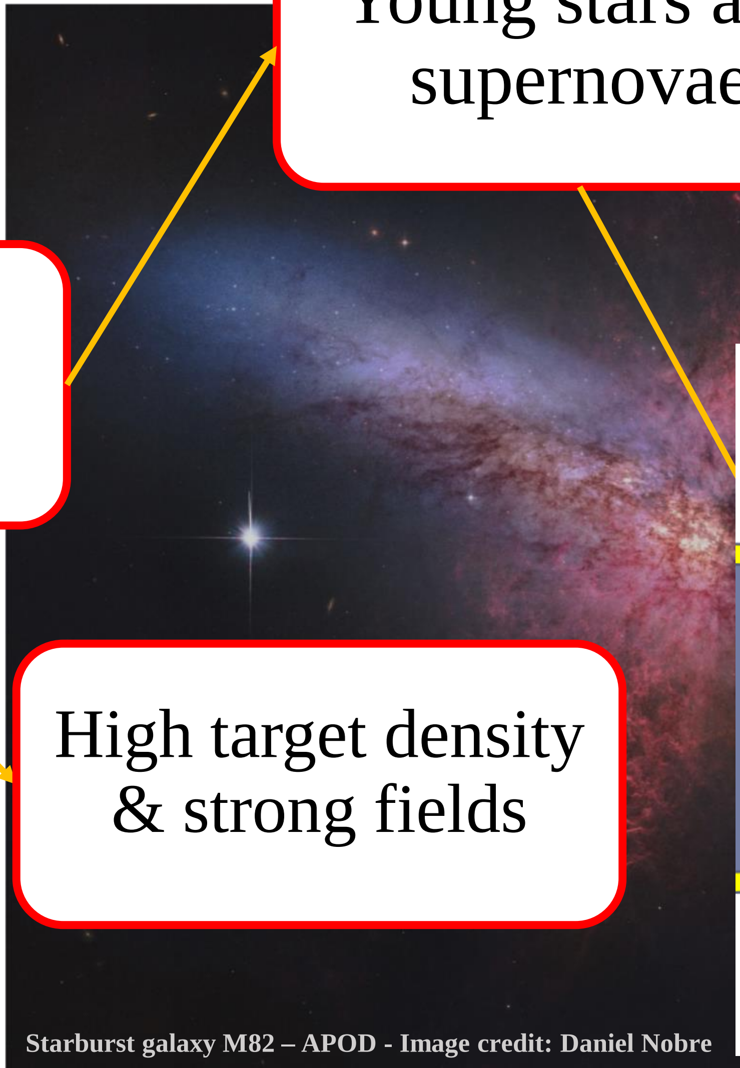
Starburst environments ... smic-ray

Young stars and supernovae

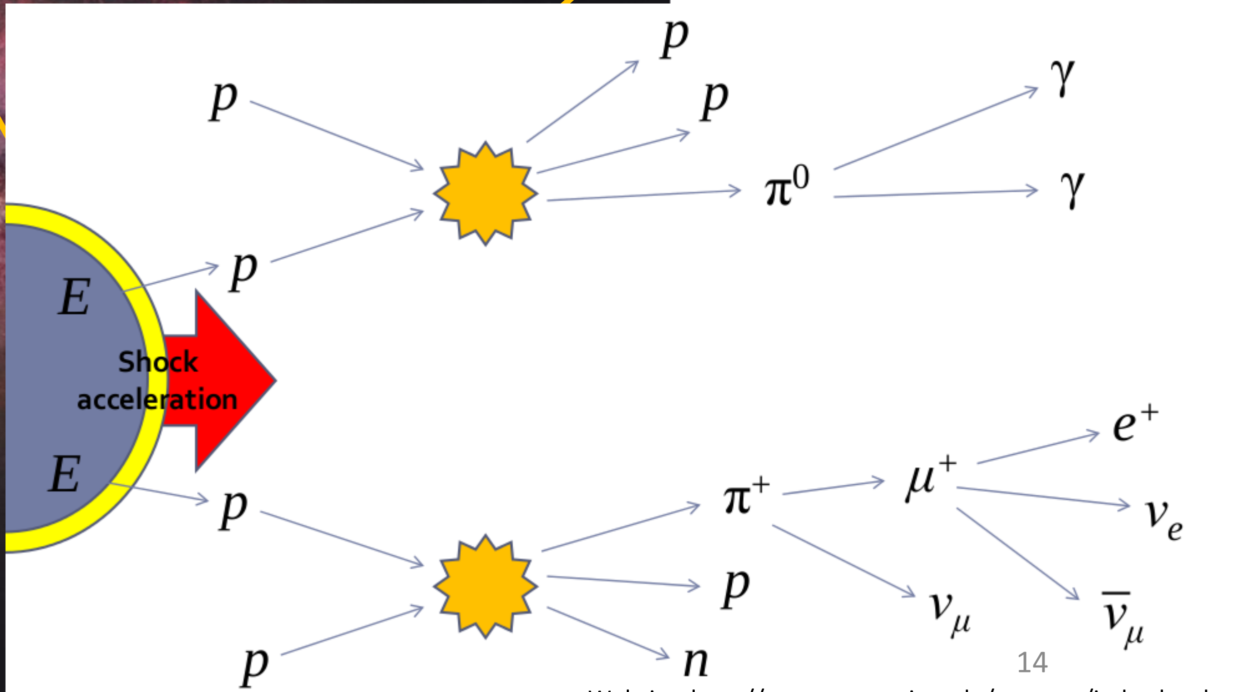
Particle acceleration 2X

High star formation rate

High target density & strong fields



Starburst galaxy M82 – APOD - Image credit: Daniel Nobre



Website: http://www.astro.wisc.edu/~gvance/index.html

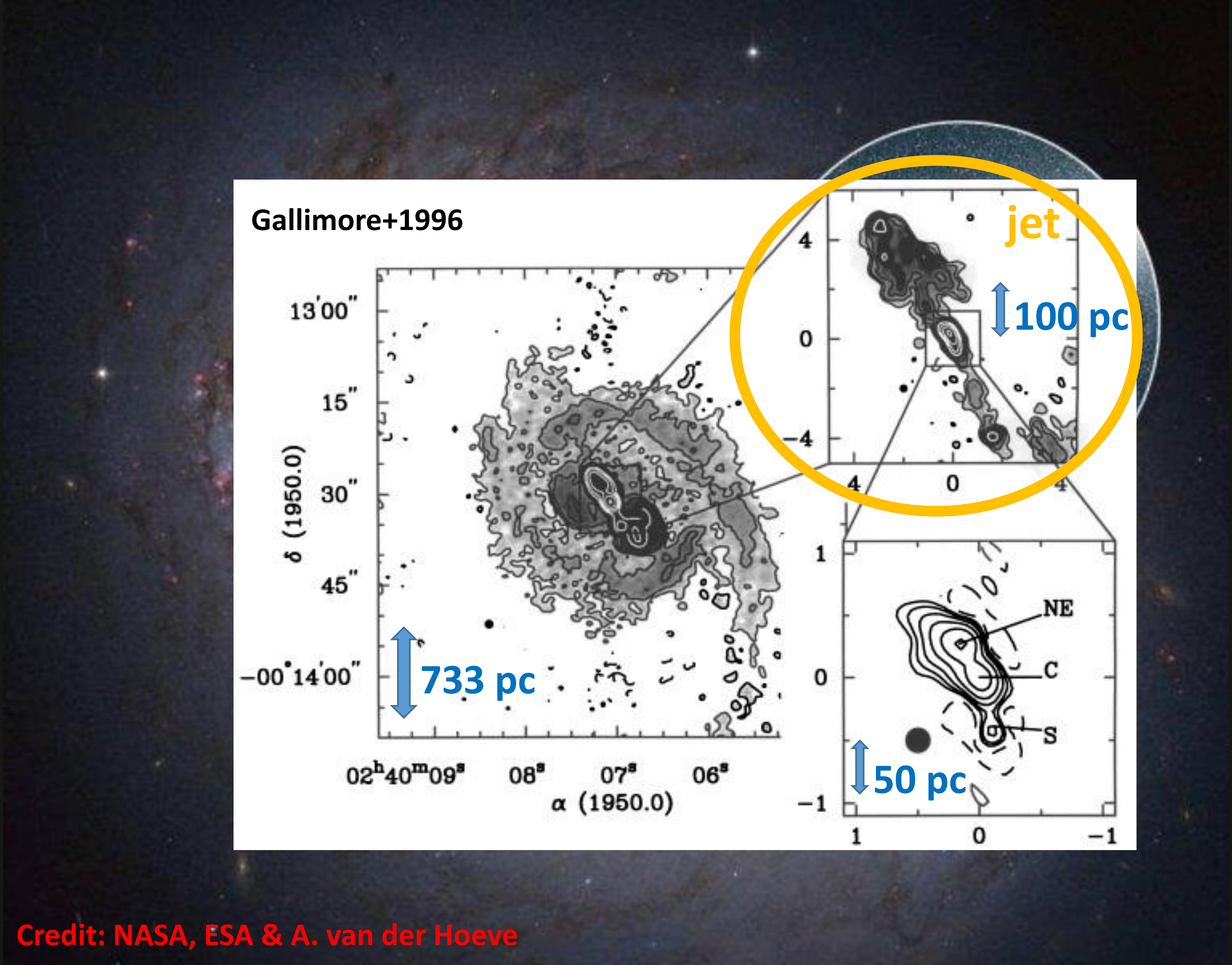
The starburst

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

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

The associate power in supernova remnant is:

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



Credit: NASA, ESA & A. van der Hoeve

The jet

The measured radio power is

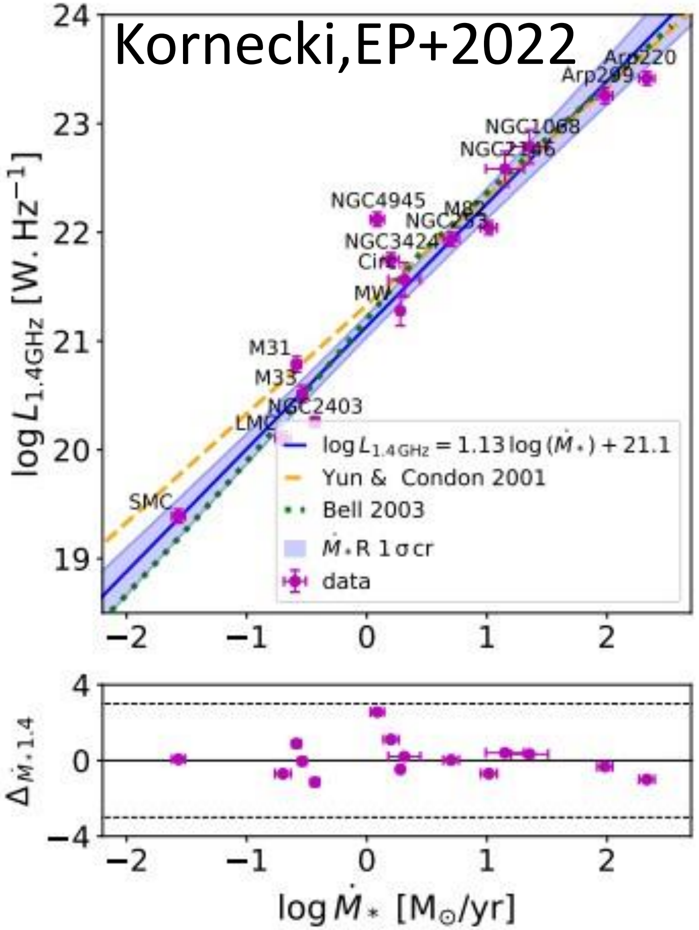
$$L_{1.4\ GHz} \approx 10^{38.9}\ erg/s$$

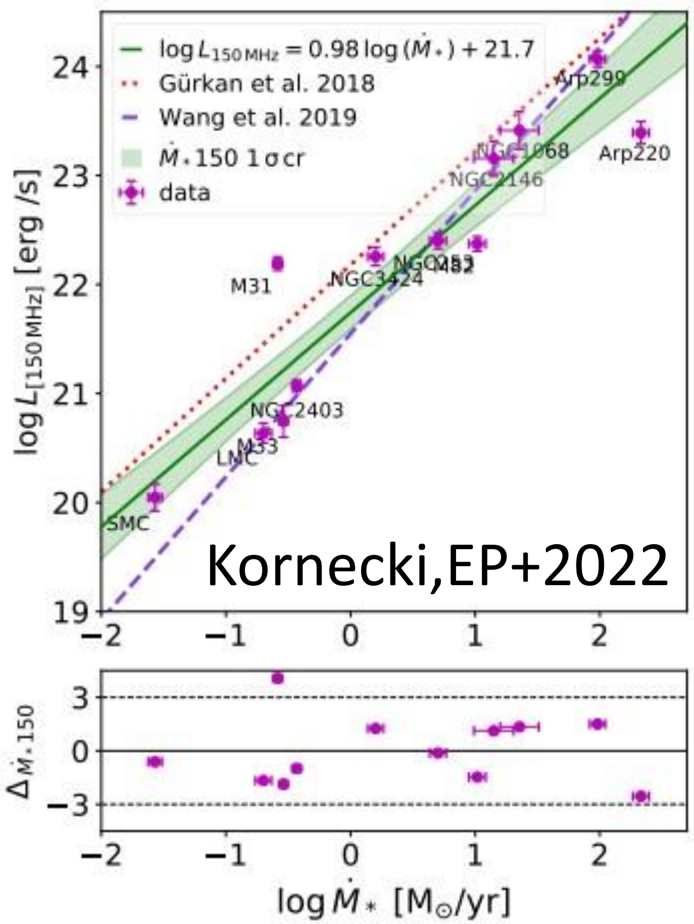
The origin of the radio photons is uncertain and could be possibly be associated only to the starburst activity.
However, if they were dominated by the jet contribution, the associated jet power would be

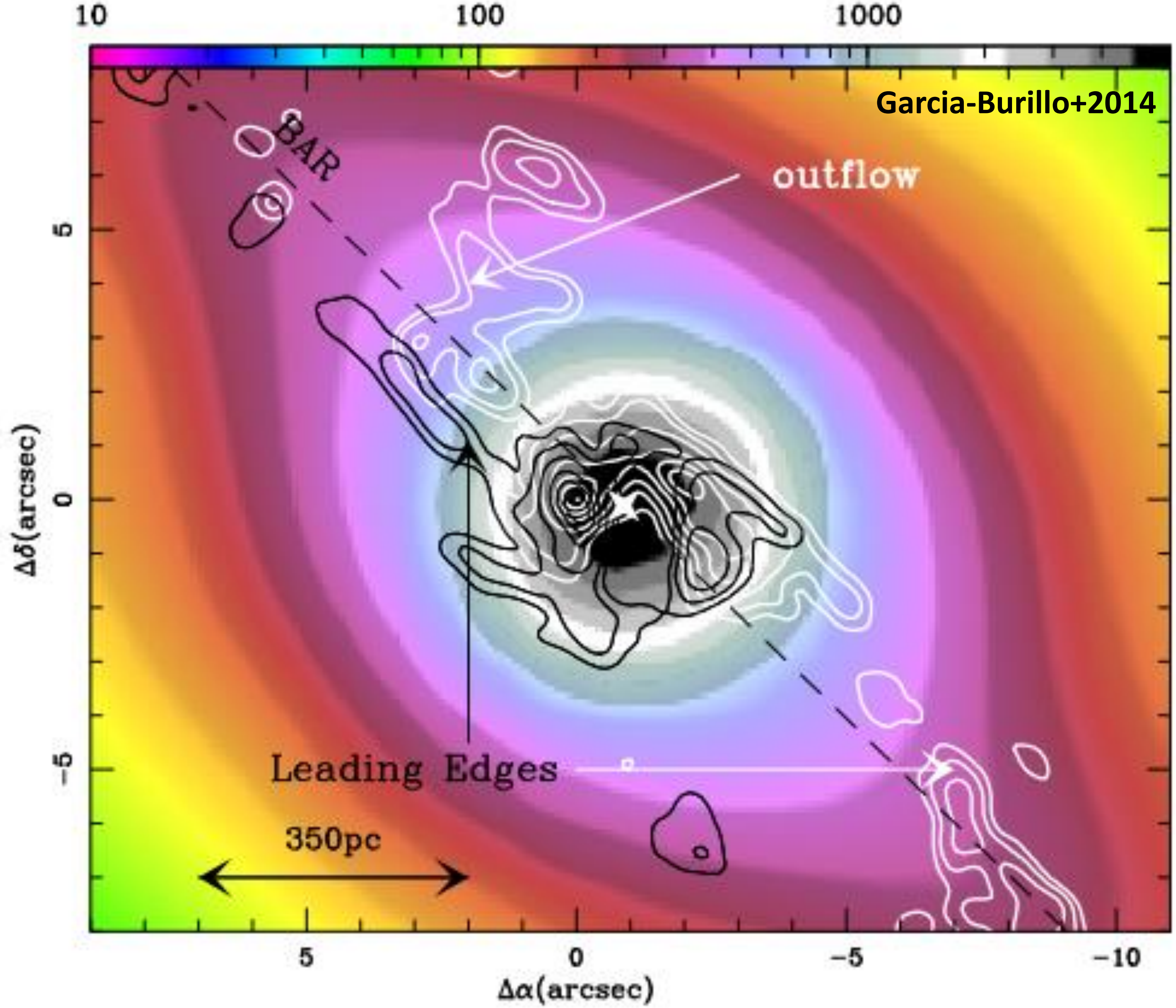
$$L_{jet} \approx 10^{42.2}\ erg/s$$

Radio emission from NGC 1068

The radio luminosity is in agreement with the radio – SFR correlation → the starburst hypotesys is well motivated





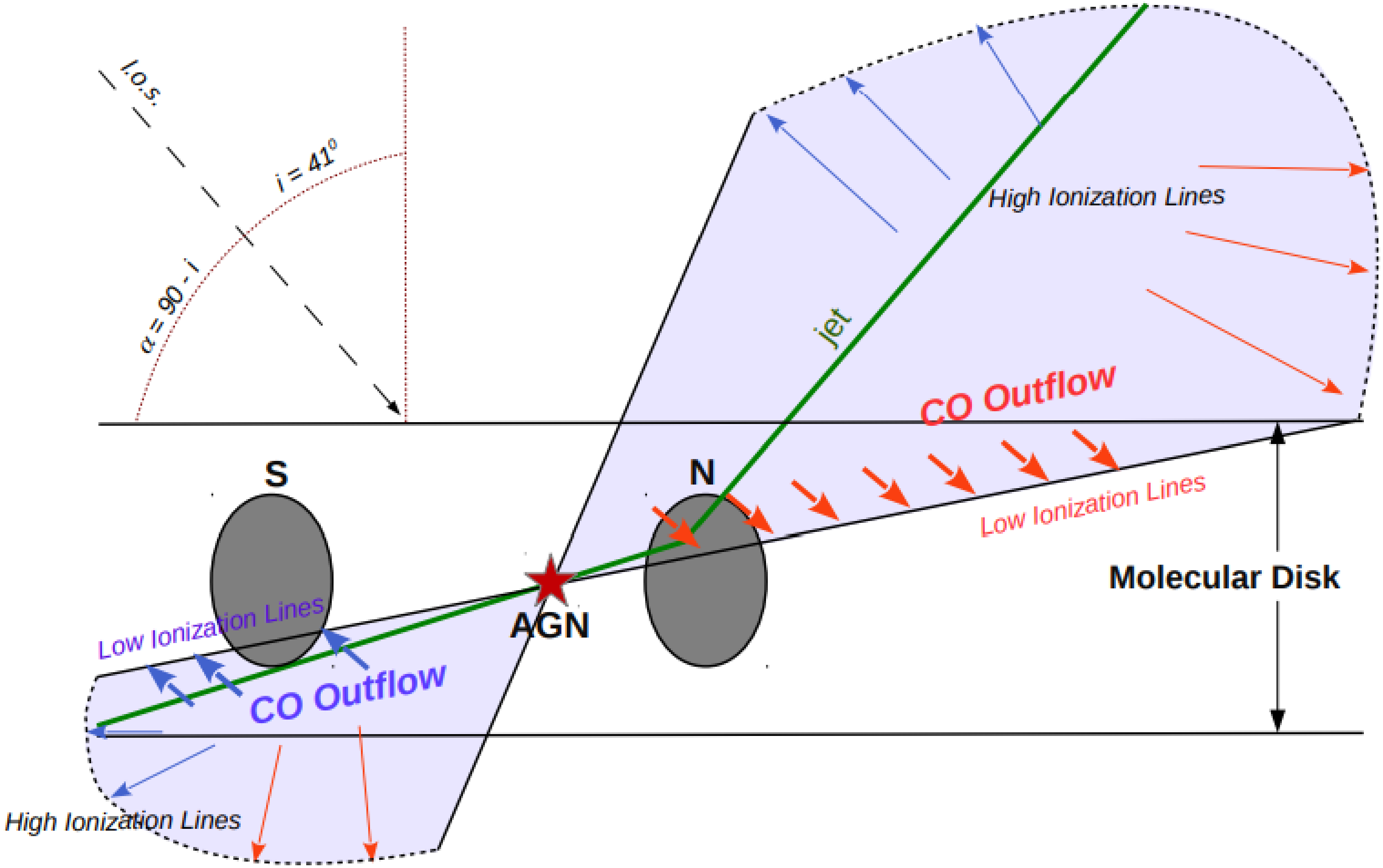

10
100
1000
Garcia-Burillo+2014
BAR
outflow
Leading Edges
350pc
5
0
−5
−10
Δδ(arcsec)
Δα(arcsec)

The molecular outflow

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

$$L_{out} \approx \frac{M_{out} v_{out}^3}{R_{out}}$$

$$\approx 10^{41.6} \ erg/s$$




Star forming
disk
Credit: NASA, ESA & A. van der Hoeve

Luminosity and Power of NGC 1068

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

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

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

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

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

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

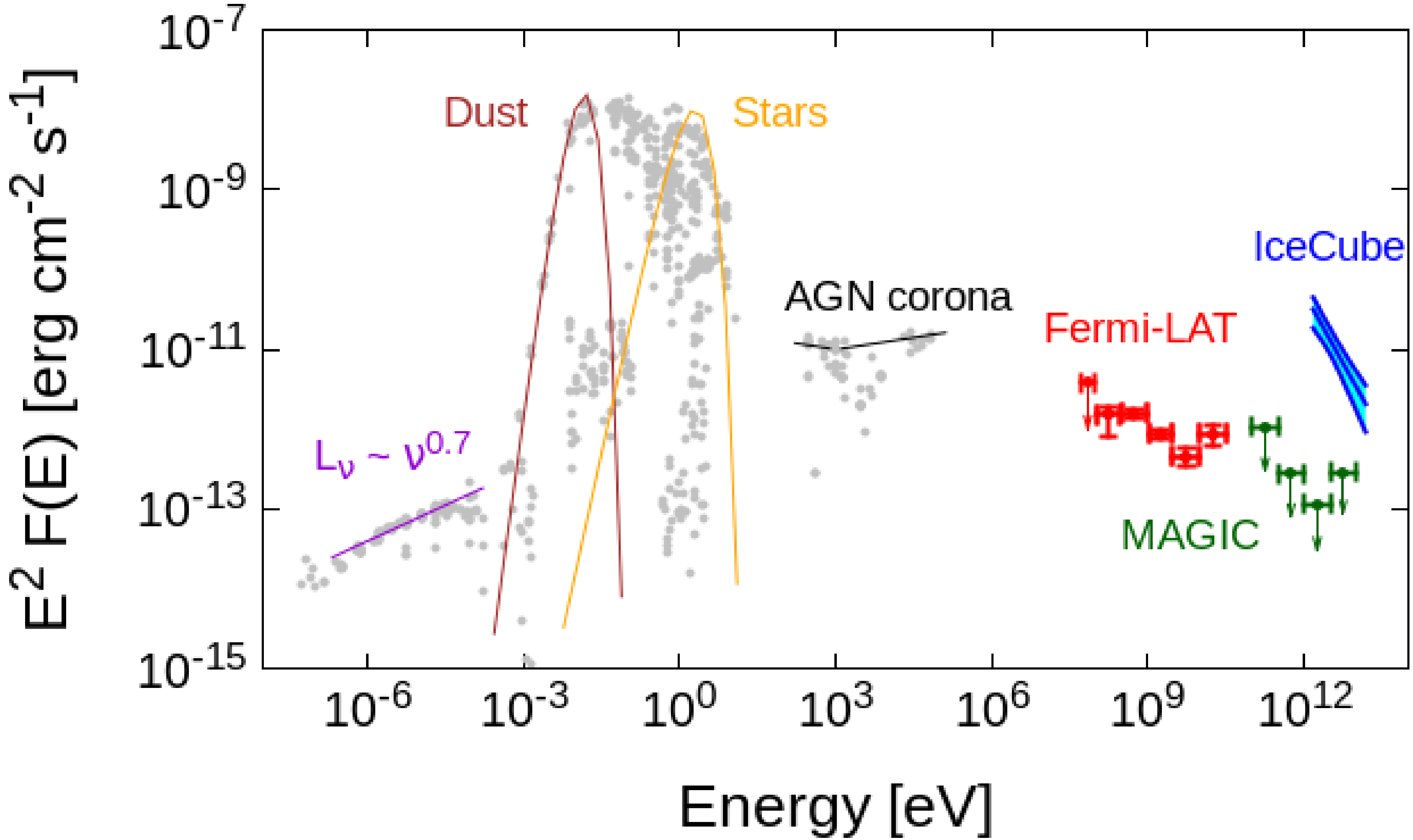
$L_{SNe} \approx 10^{42.8}\ erg/s$

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

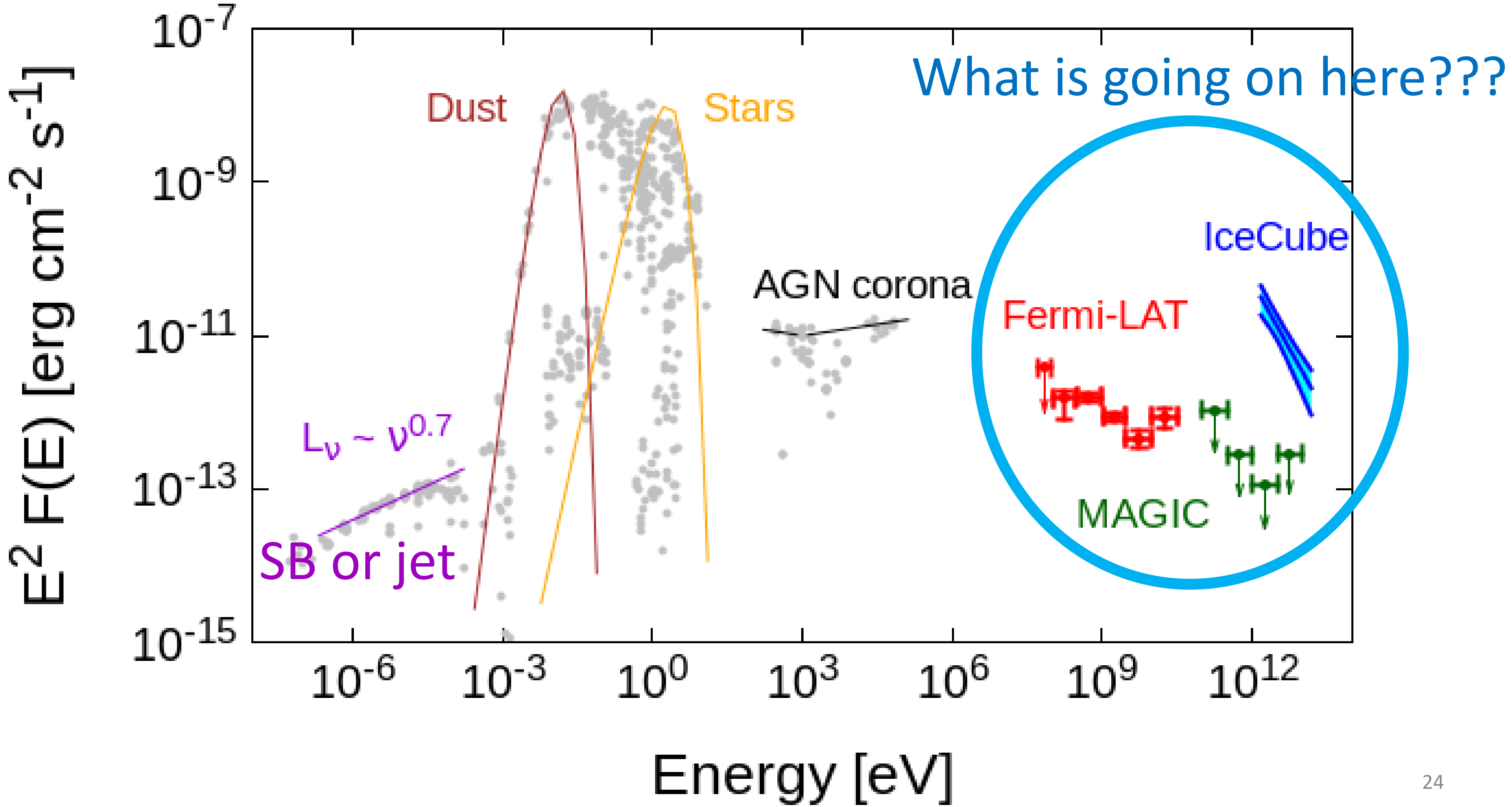
$L_{jet} \approx 10^{42.2}\ erg/s$ (?)

$L_{corona} = \eta\ L_X$

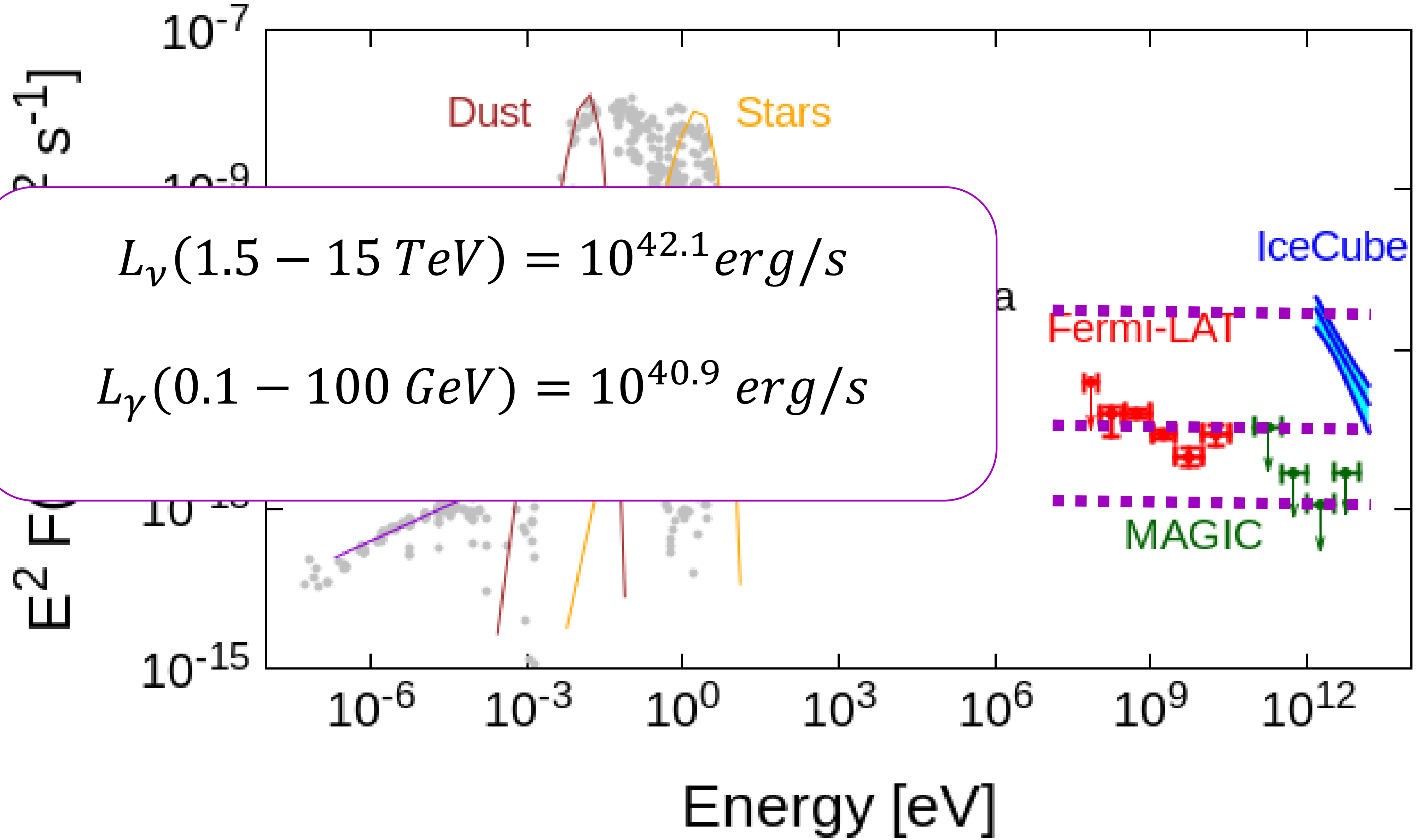
NGC 1068 is a complex object



Deciphering NGC 1068 at HE



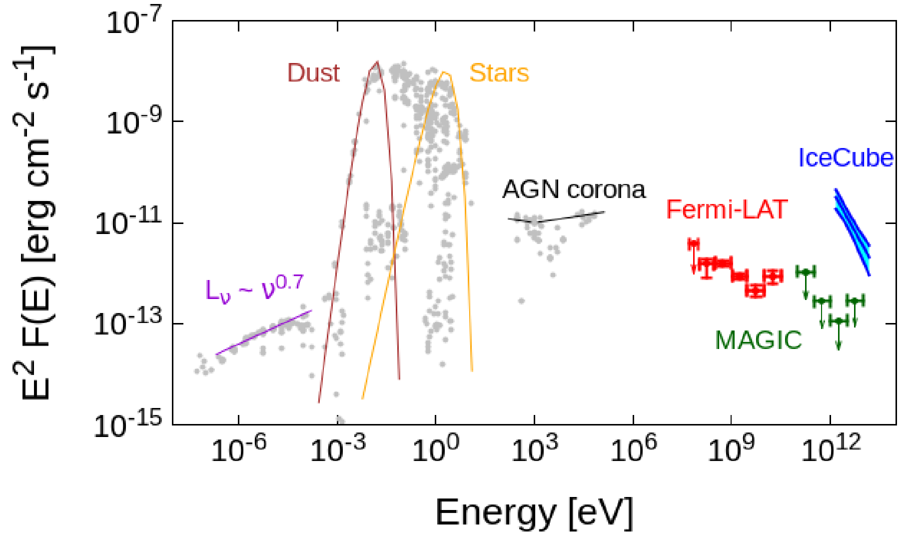
The problem of NGC 1068



$$L_\nu(1.5 - 15\,TeV) = 10^{42.1} erg/s$$

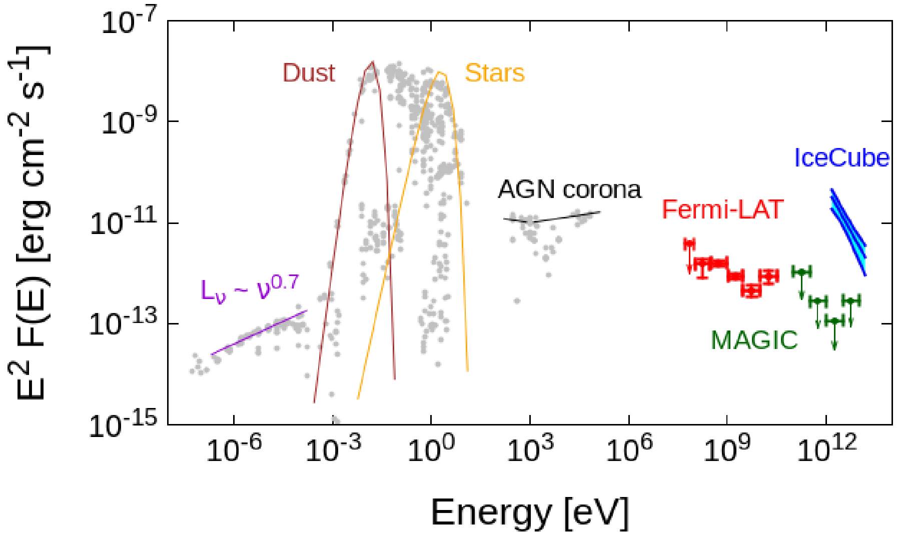
$$L_\gamma(0.1 - 100\,GeV) = 10^{40.9}\, erg/s$$

NGC 1068 the puzzle of the HE multi-messenger spectrum



$$L_\nu \gg L_\gamma$$
$$p + p/\gamma \rightarrow X + n\,\pi^0 + n\,\pi^{\mp}$$
$$\pi^0 \rightarrow \gamma\gamma$$
$$\pi^{\mp} \rightarrow \mu^{\mp}\nu_\mu \rightarrow e^{\mp}\nu_e\nu_\mu\nu_\mu$$

NGC 1068 the puzzle of the HE multi-messenger spectrum



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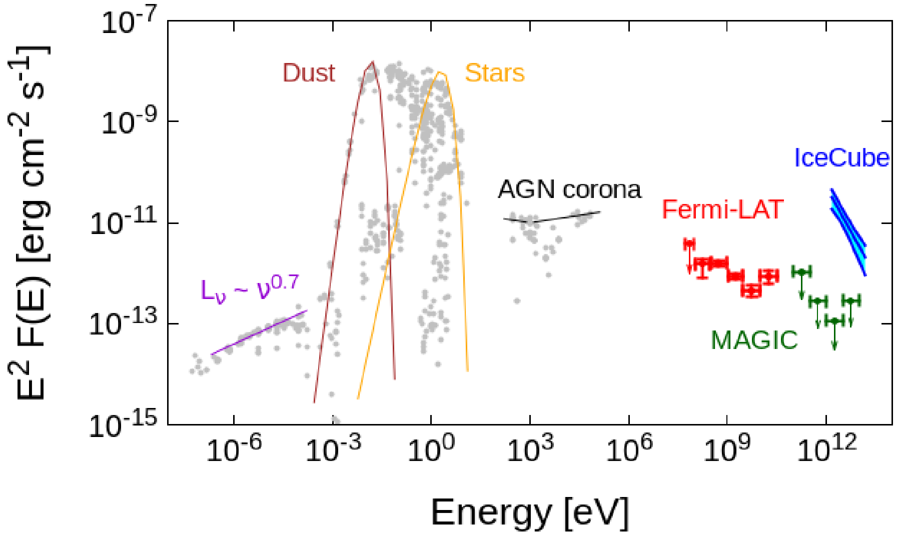
TeV gamma rays must be absorbed efficiently.
We need a strong eV ph field.

NGC 1068 the puzzle of the HE multi-messenger spectrum



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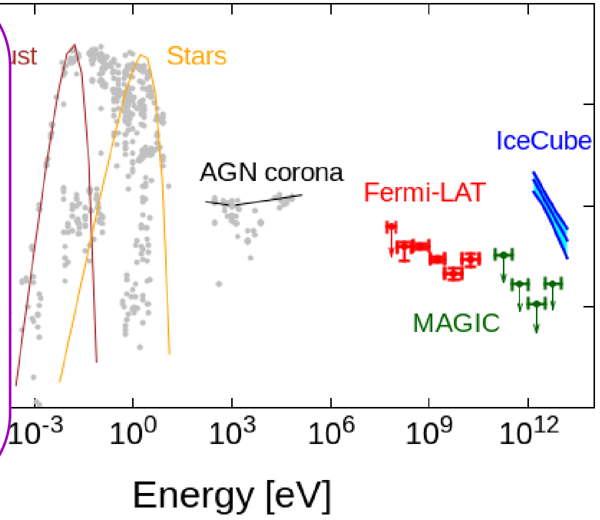
NGC 1068 the puzzle of the HE multi-messenger spectrum

The starburst can only absorb >10 TeV photons. We must be close to the accretion disk of the AGN.



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TeV gamma rays must be absorbed efficiently.
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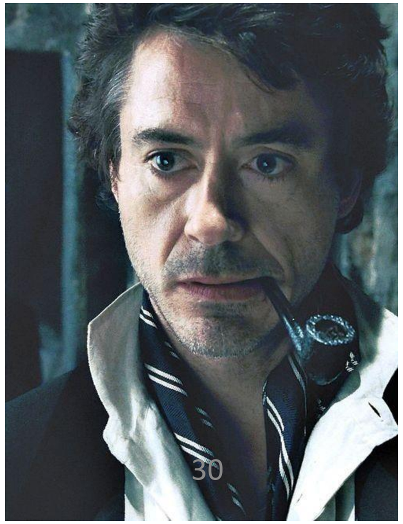
NGC 1068 the puzzle of the HE multi-messenger spectrum

The starburst can only absorb >10 TeV photons. We must be close to the accretion disk of the AGN.

Given the discrepancy in the GeV gamma-ray flux and the TeV neutrino flux we must be close to the AGN corona and/or have very hard proton spectra.



Hidden sources

Silberberg & Shapiro 1979

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.

§9. Hidden sources

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).

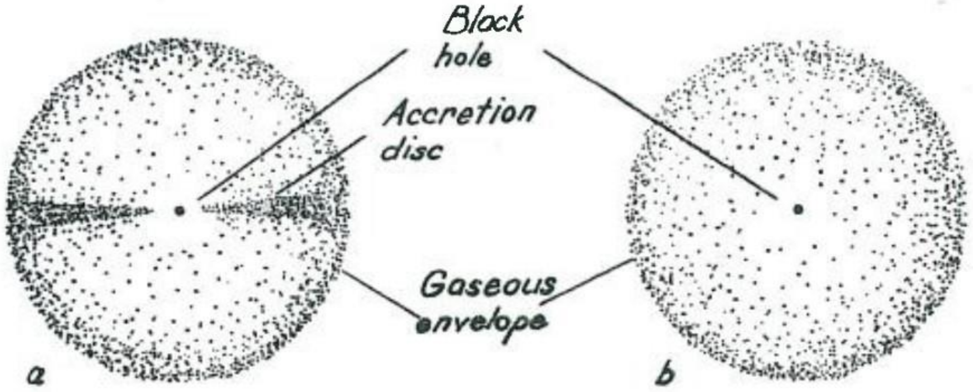


Fig. 8.3. Black hole in a cocoon: (a) disc accretion, (b) quasispherical accretion. The acceleratio takes place in the vacuum cavity.

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

Berezinsky & Ginzburg 1981

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.

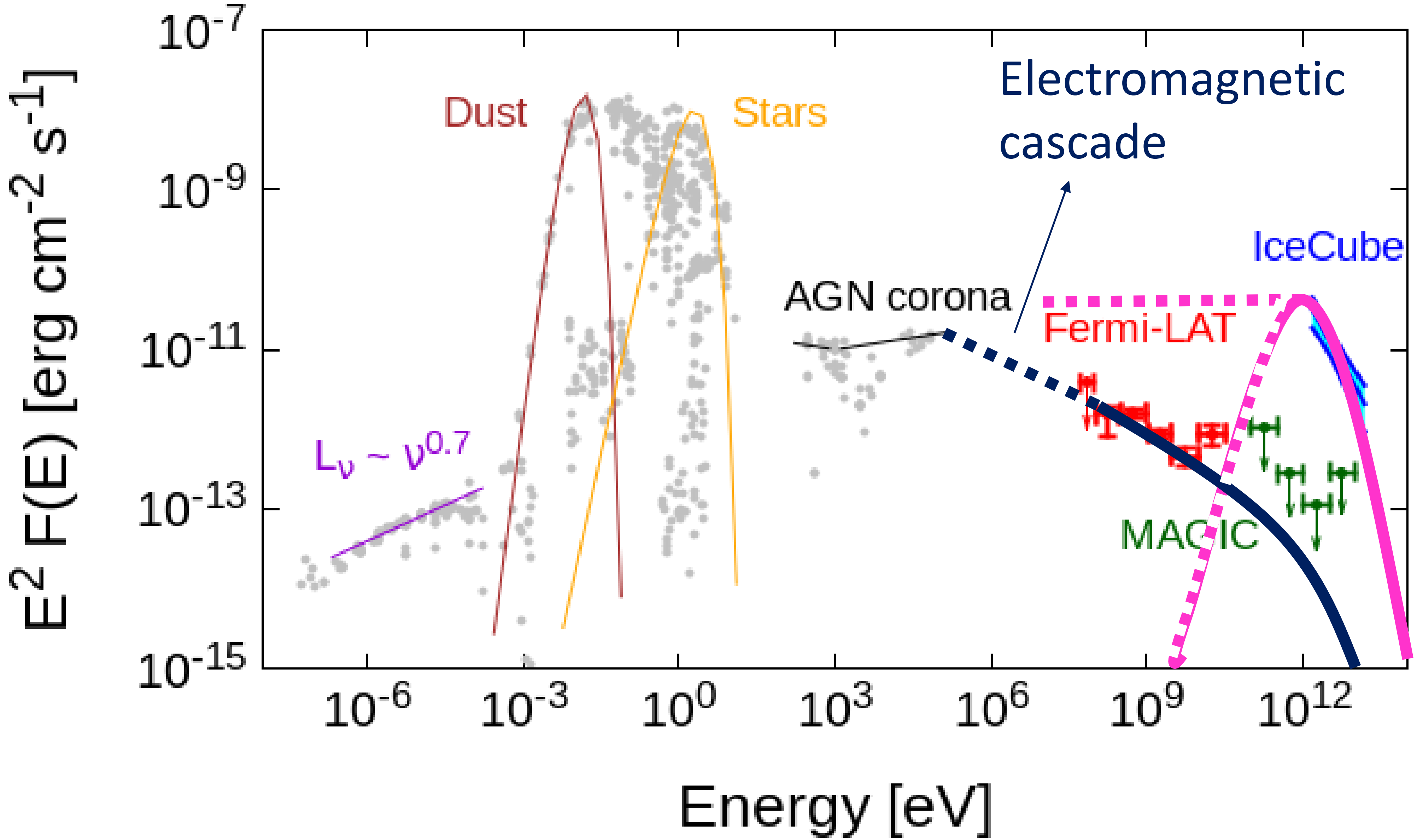
If such a hypothesis is true, then many active galactic nuclei may be detectable as point sources in high-energy neutrinos with the neutrino "telescopes" that are being discussed. The overall cosmic neutrino background due to active galaxies may be orders of magnitude above the detection threshold.

EXTRATERRESTRIAL NEUTRINO SOURCES AND HIGH ENERGY NEUTRINO ASTROPHYSICS

V.S.Berezinsky
Institute for Nuclear Research of the USSR Academy of Sciences

Berezinsky 1977

Hidden multi-messenger source



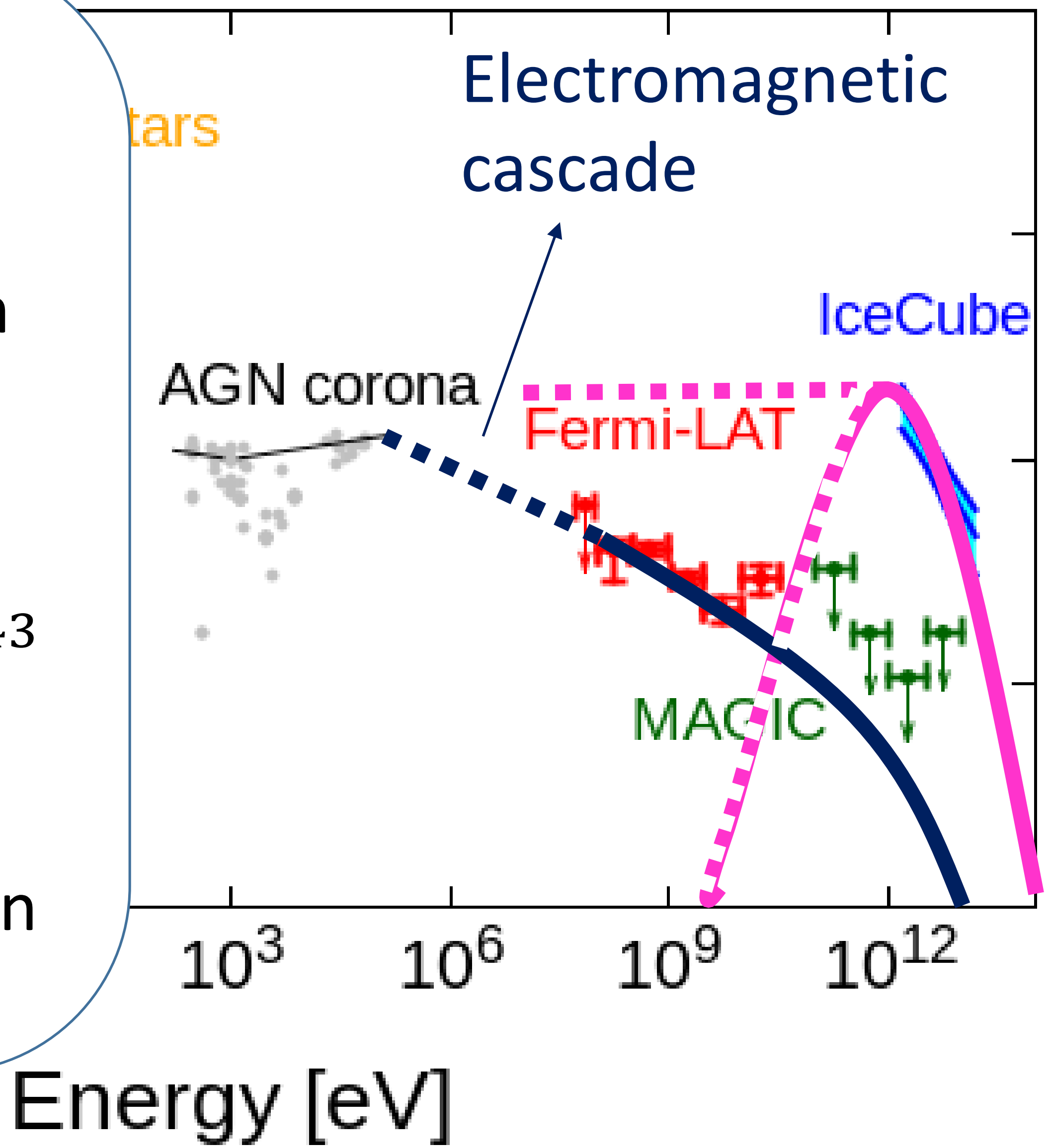
Hidden multi-messenger source

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

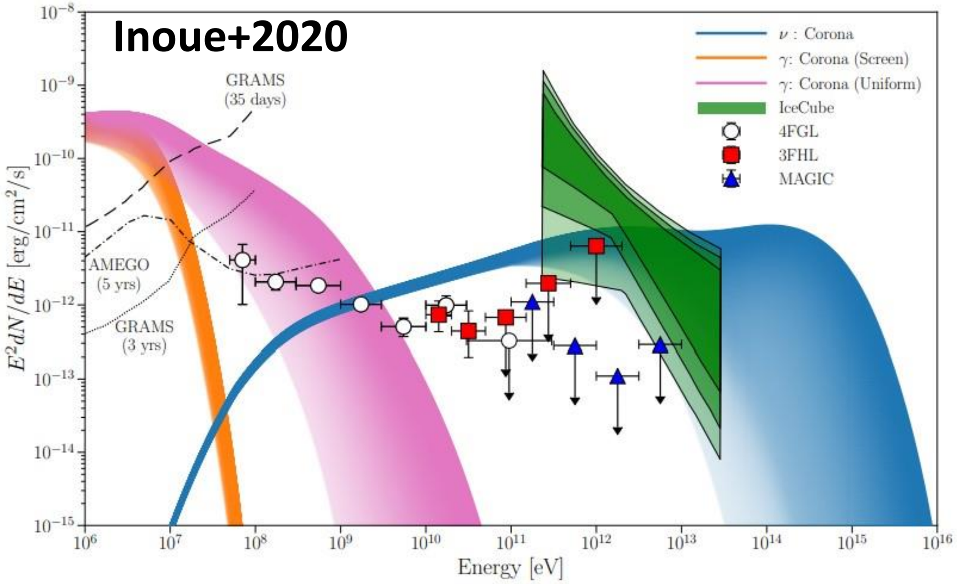
Cosmic rays might be in quasi-equipartition with the X-ray photon field in the coronal region

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

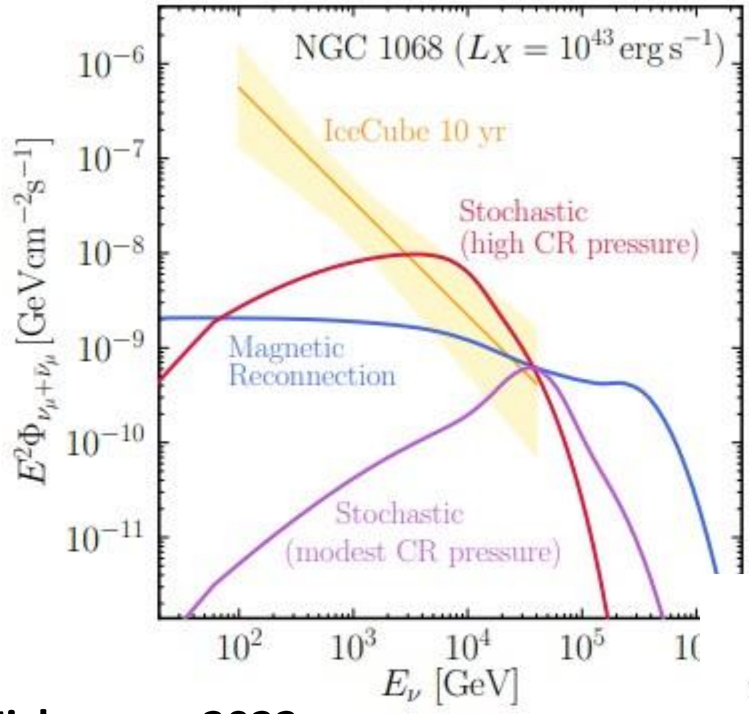
The X-ray photon field makes the corona neighbourhood opaque down to the GeV range for $\gamma\gamma \rightarrow e^+ e^-$

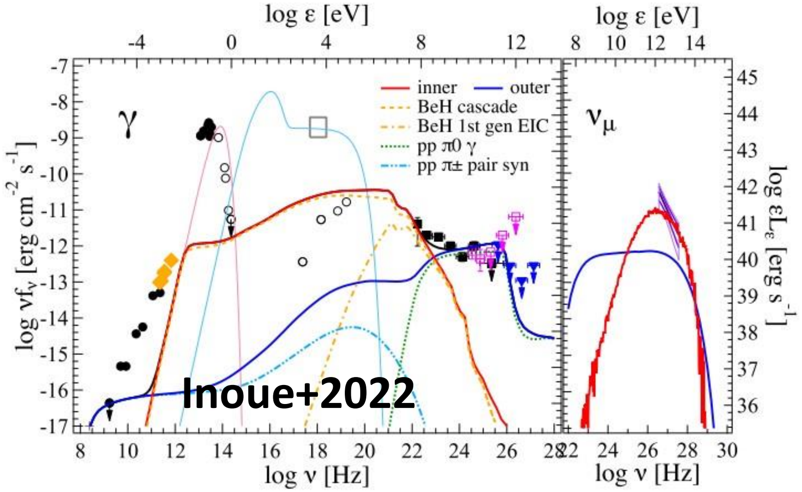


Recent models

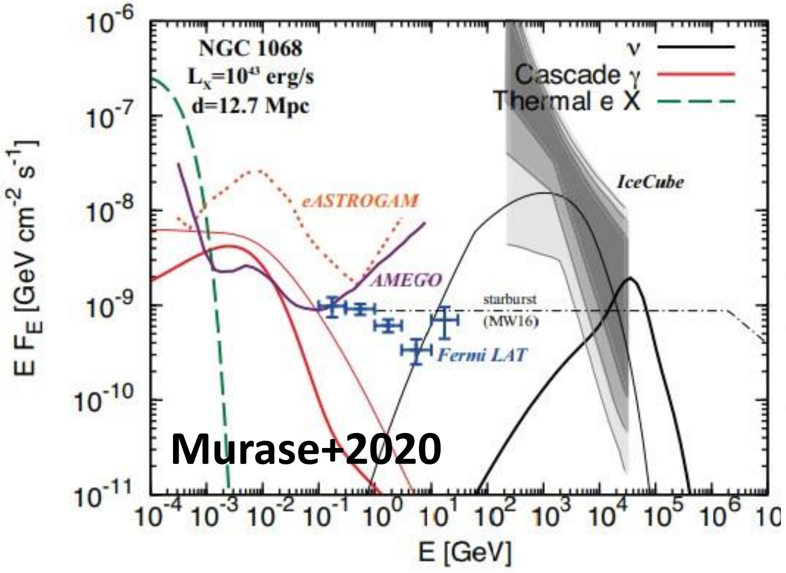


Kheirandish+2021

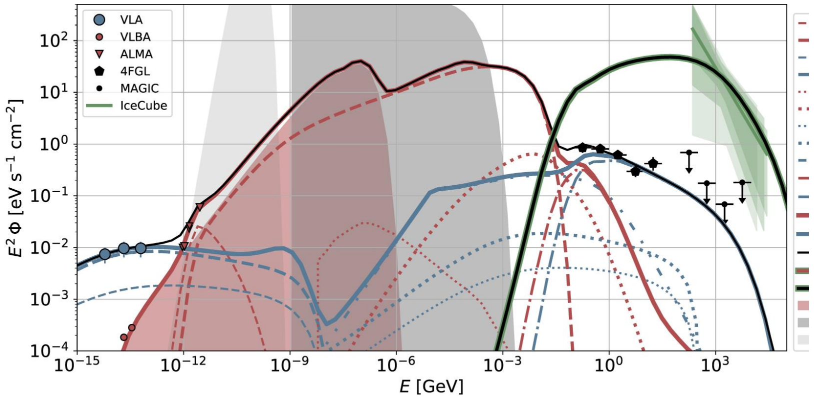


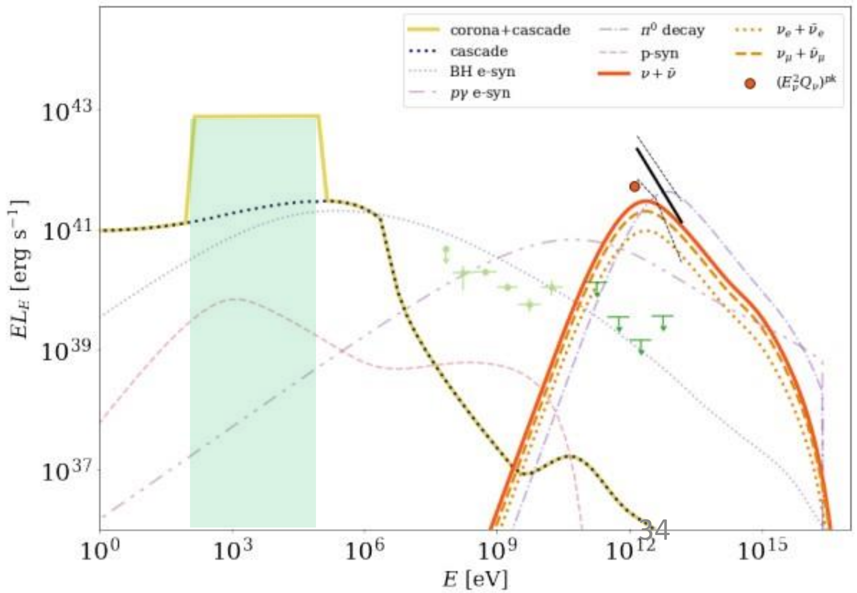


Fiorillo+(including EP) 2024

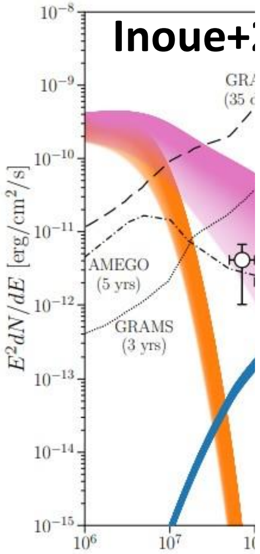


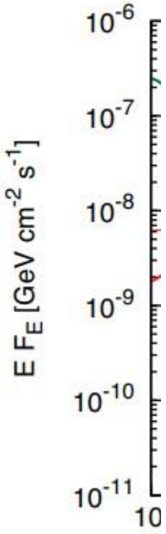
Eichmann+2022

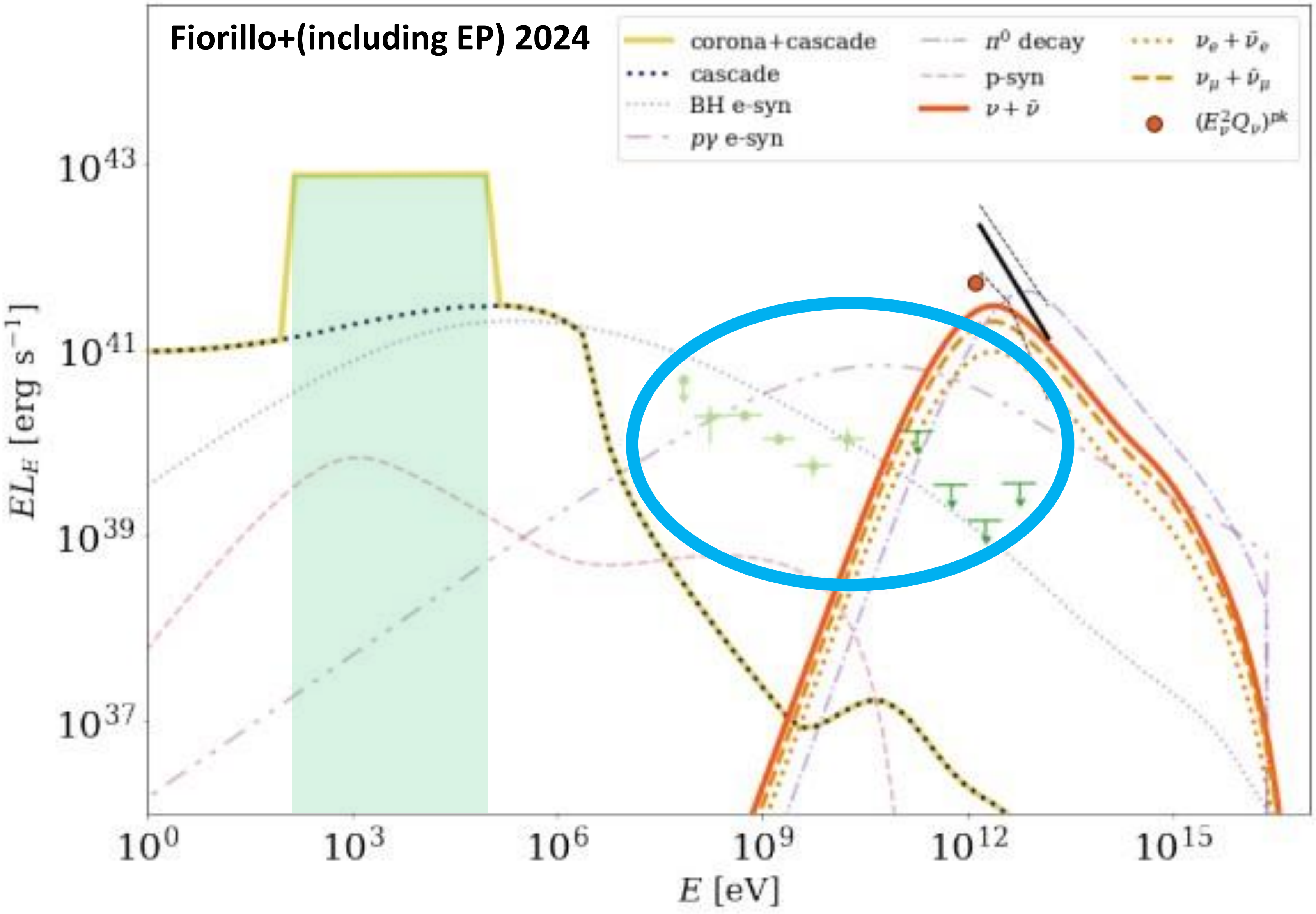


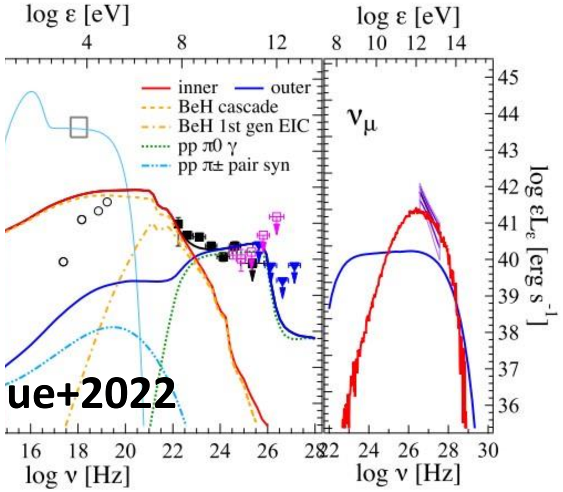


Recent models

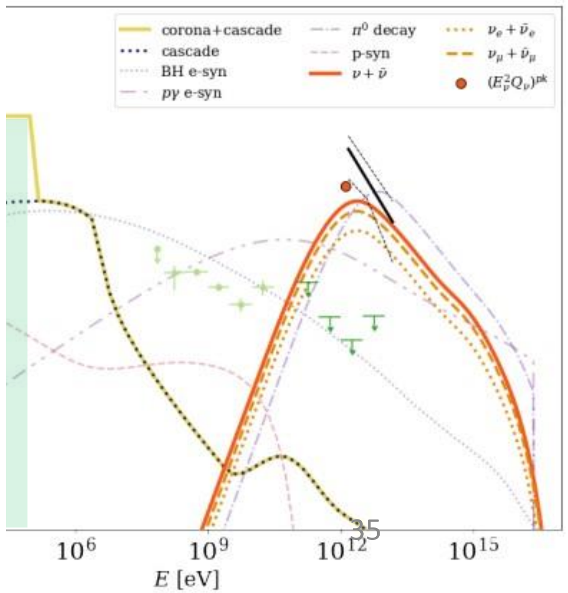








Fiorillo+(including EP) 2024



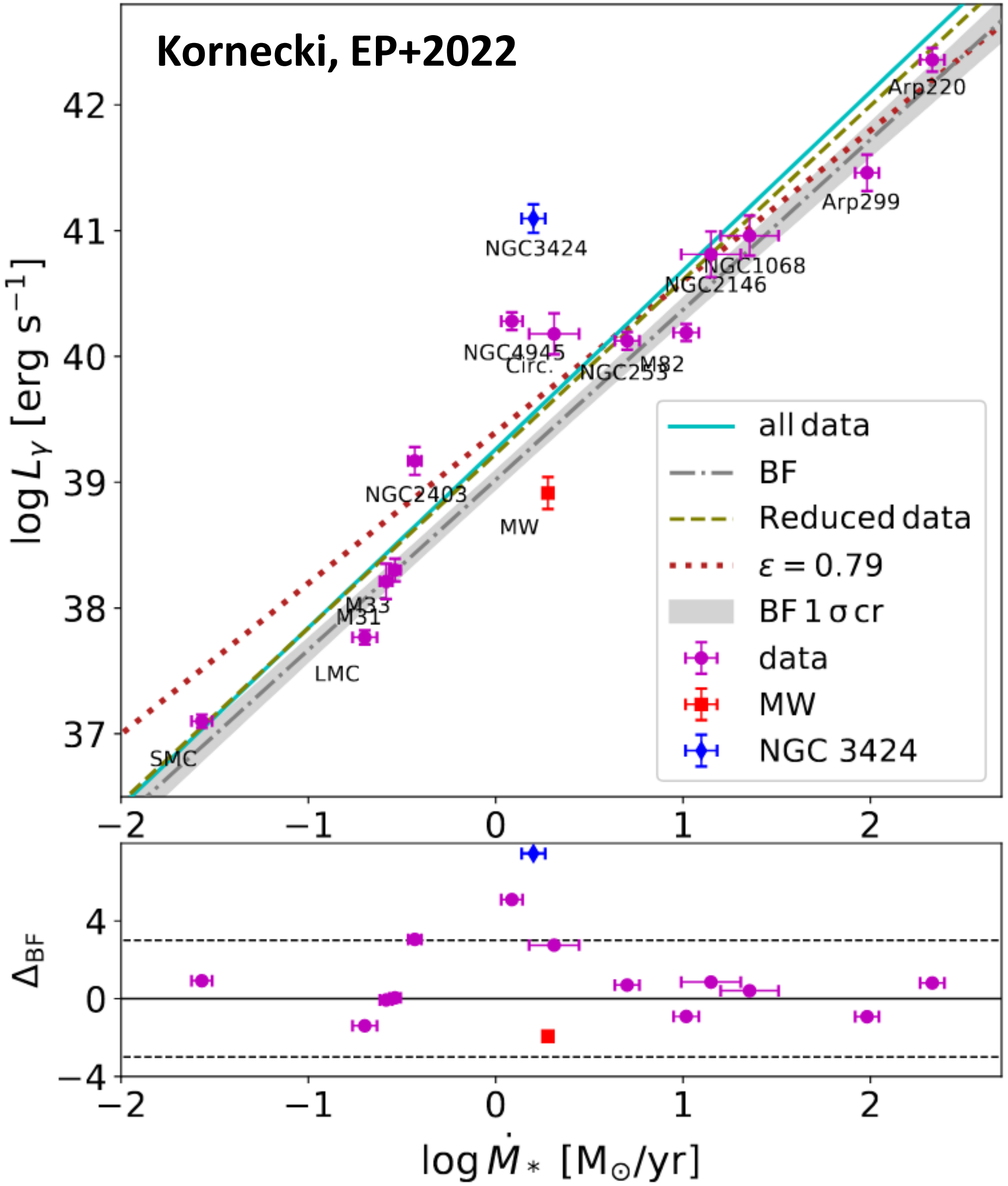
What abot gamma rays?

- 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.

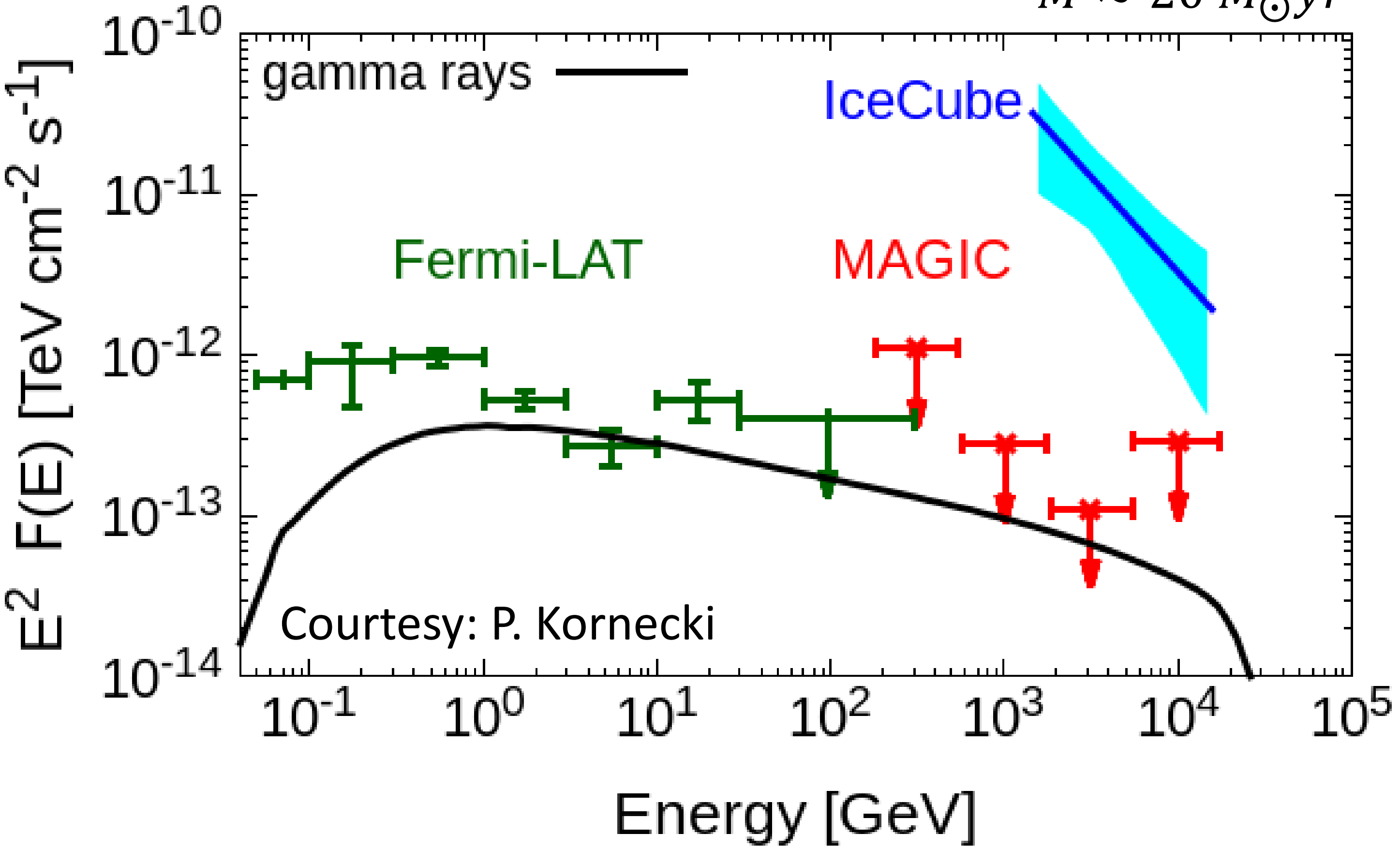
- This is a strong indication in support of a 2-zone-model!

The starburst of NGC 1068

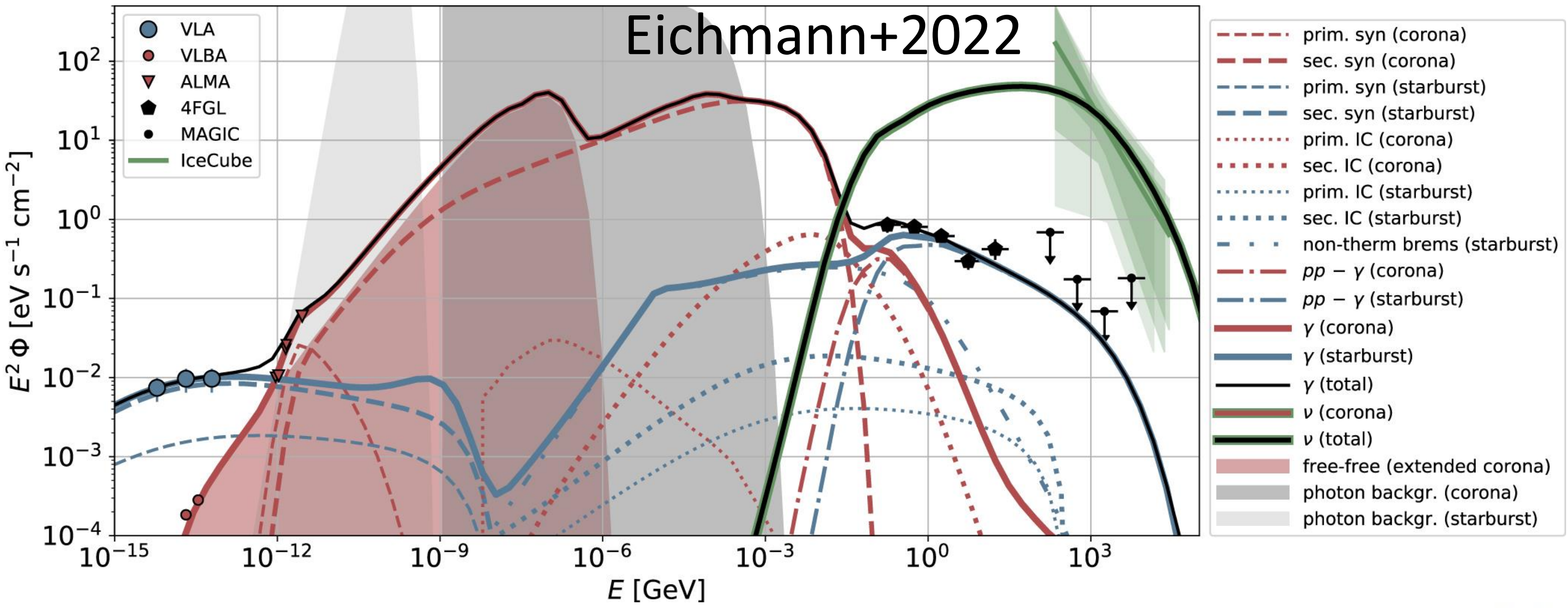


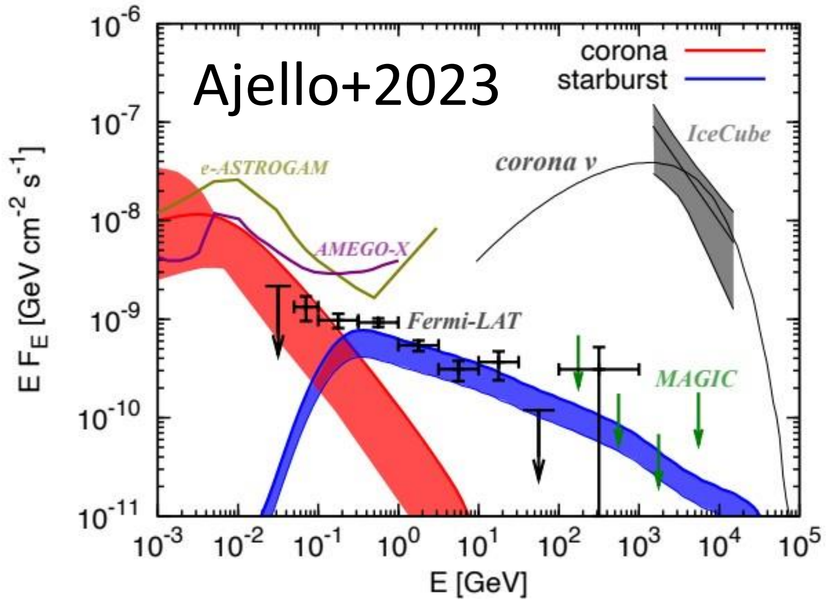
$D = 14.4\ Mpc$

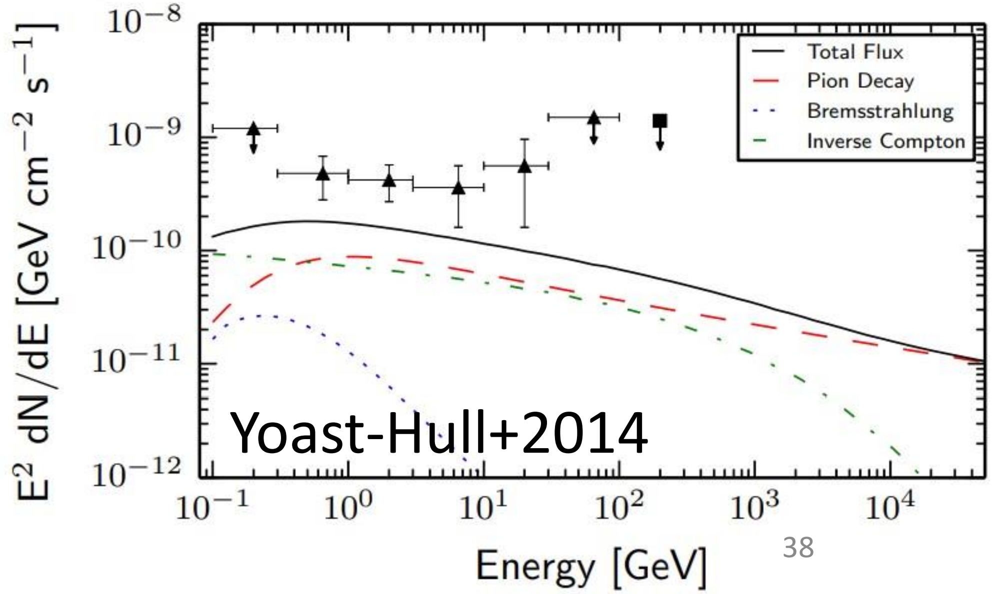
$\dot{M} \approx 20\ M_\odot yr^{-1}$



The starburst of NGC 1068





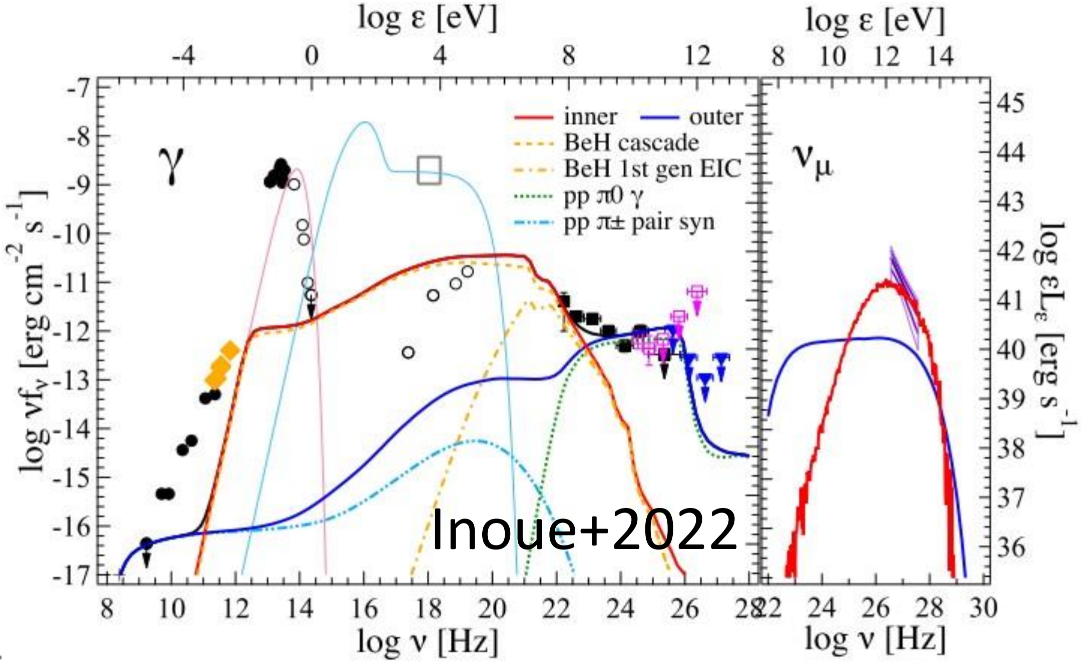


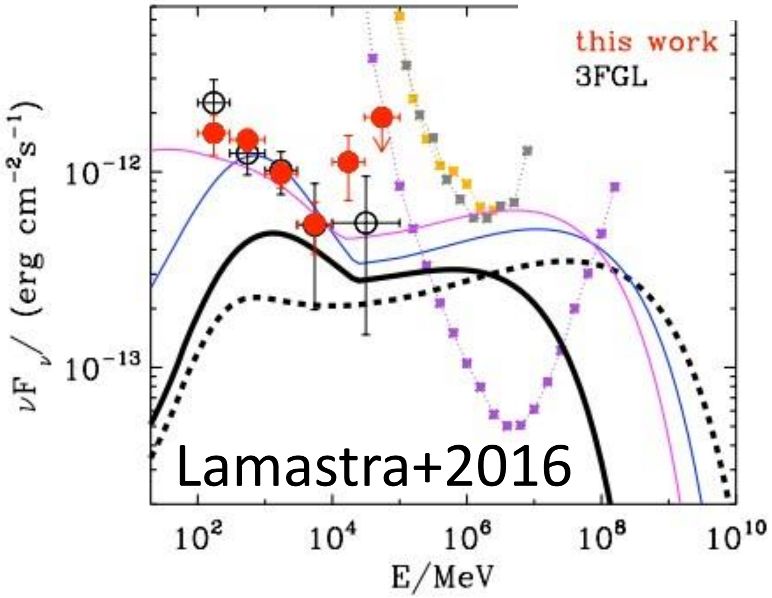
The starburst appears as the most plausible region for the production of gamma rays. However, it is not clear whether only the starburst is the only efficient gamma-ray emitter.

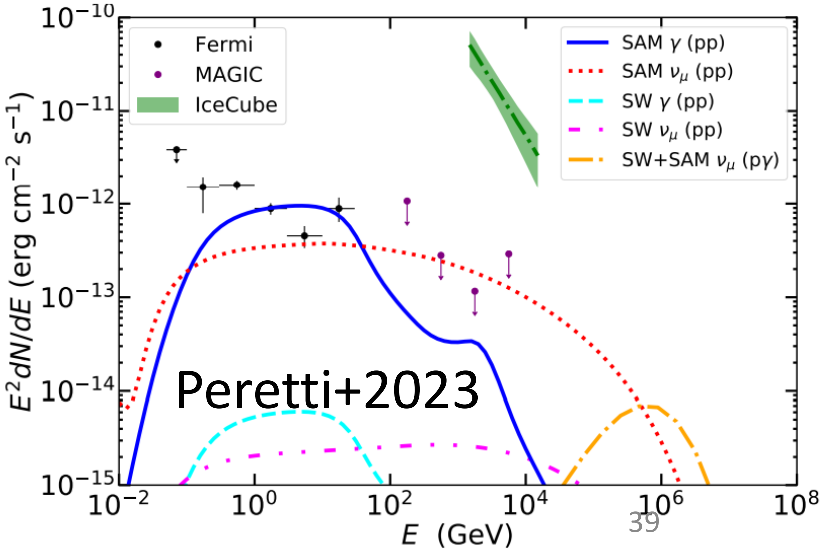
The AGN wind of NGC 1068

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

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[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

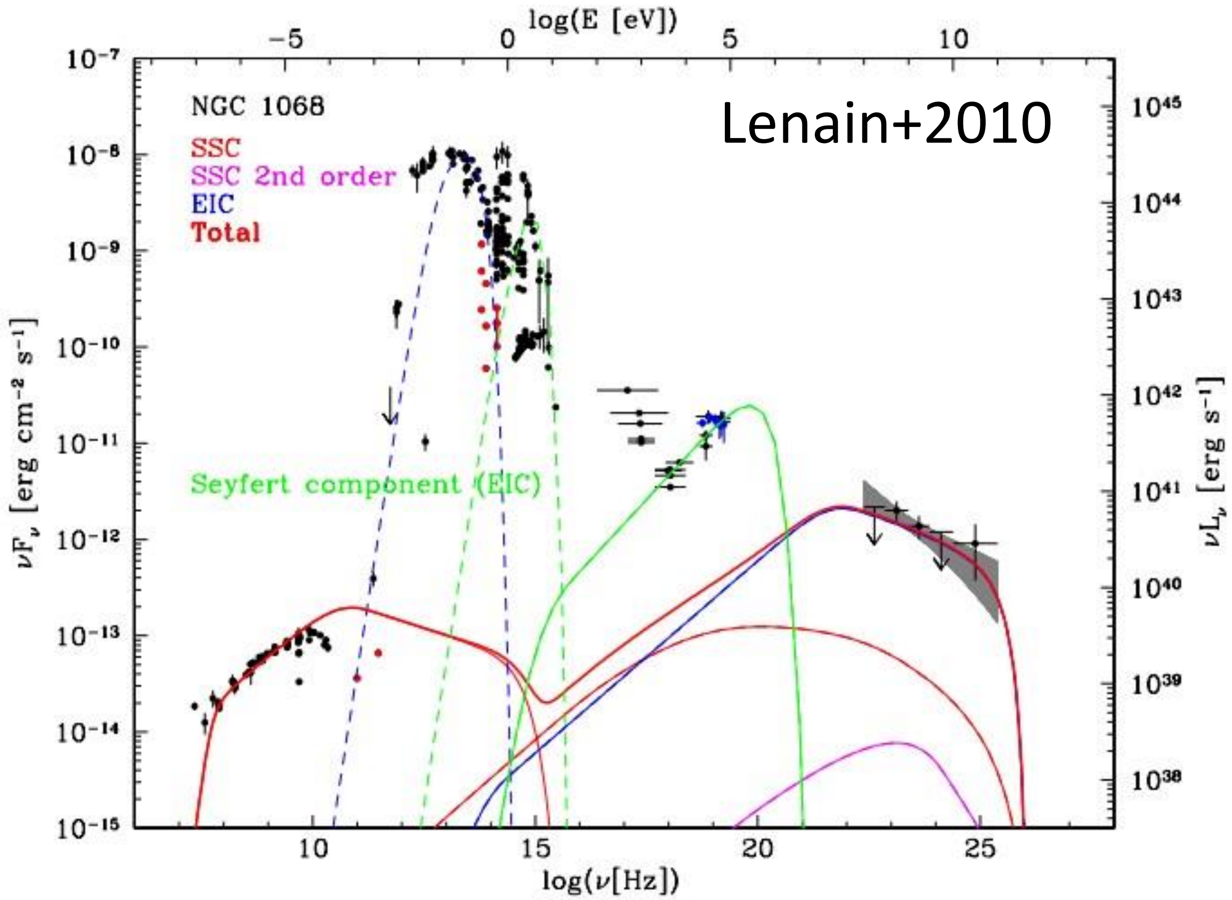
November 1, 2023

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 $\sim$ 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 $\sim$ 10 GeV γ rays can be provided by hadronic pion production in case of a gas density $\gtrsim 10^4$ 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 altough 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.

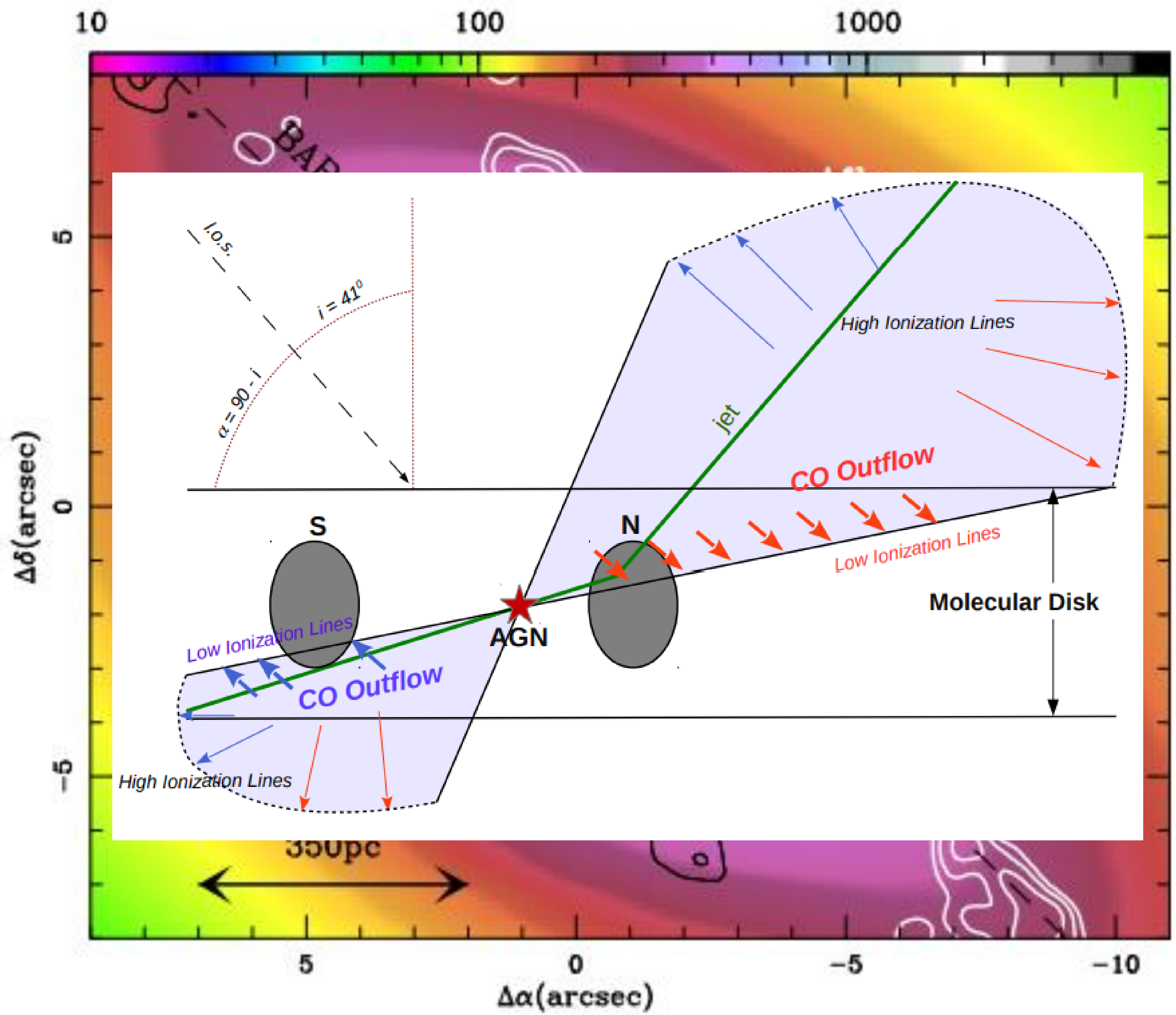
Conclusions

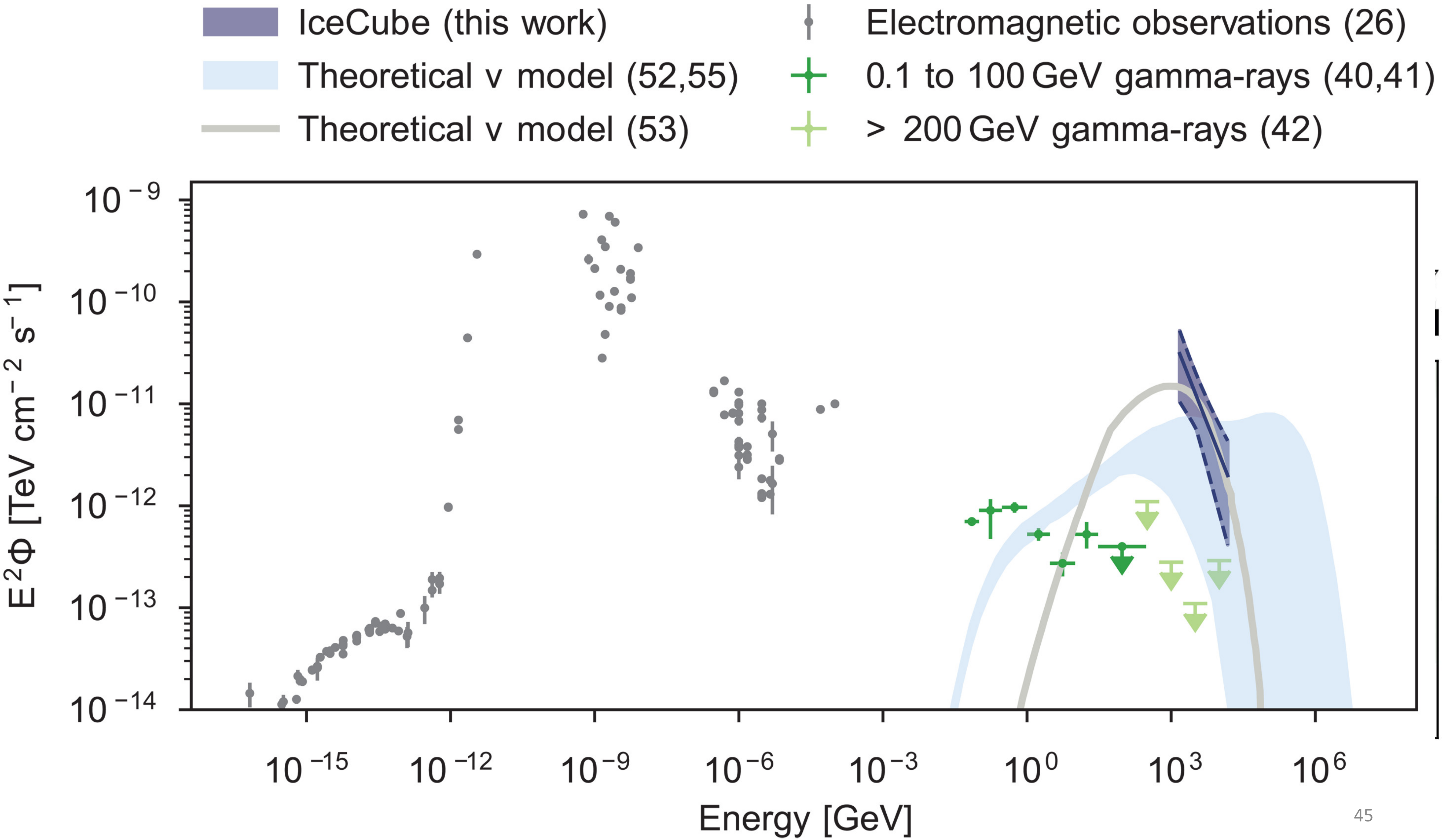
- NGC 1068 is complex and our current understanding limited.

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.

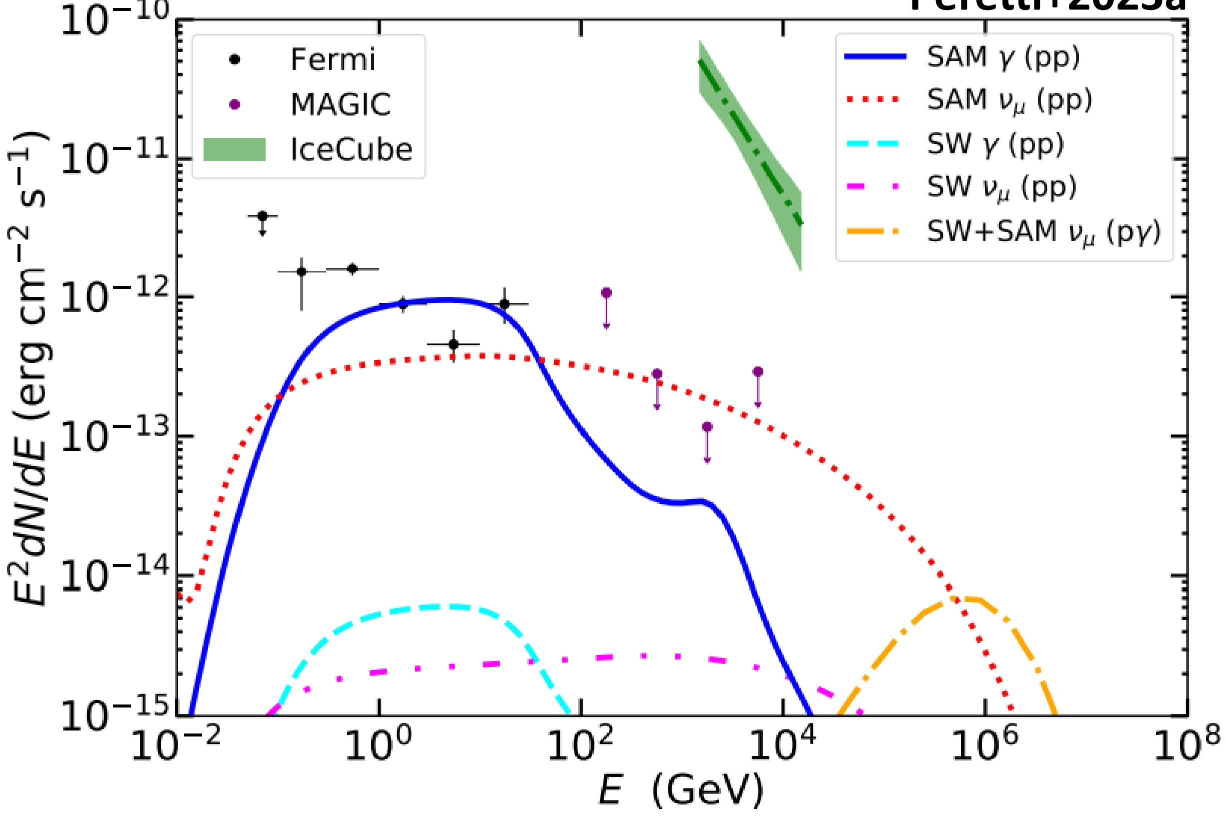
Thanks for your attention!


10
100
1000
l.o.s.
i = 41°
α = 90 - i
jet
High Ionization Lines
CO Outflow
Low Ionization Lines
S
N
AGN
Molecular Disk
Low Ionization Lines
CO Outflow
High Ionization Lines
350pc
5
0
−5
−10
Δα(arcsec)
Δδ(arcsec)

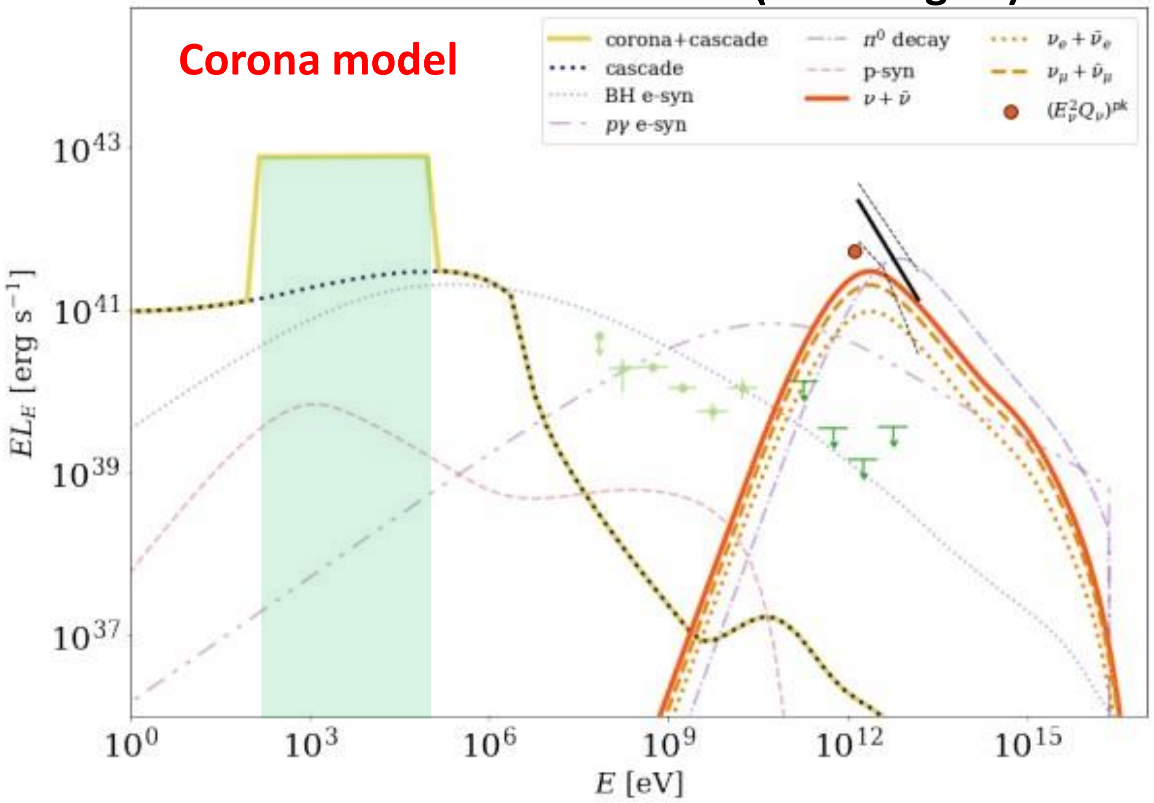

IceCube (this work)
Theoretical ν model (52,55)
Theoretical ν model (53)
Electromagnetic observations (26)
0.1 to 100 GeV gamma-rays (40,41)
> 200 GeV gamma-rays (42)
$E^2\Phi$ [TeV cm^{-2} s^{-1}]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
Energy [GeV]

Multi-zone perspective for NGC 1068

Peretti+2023a

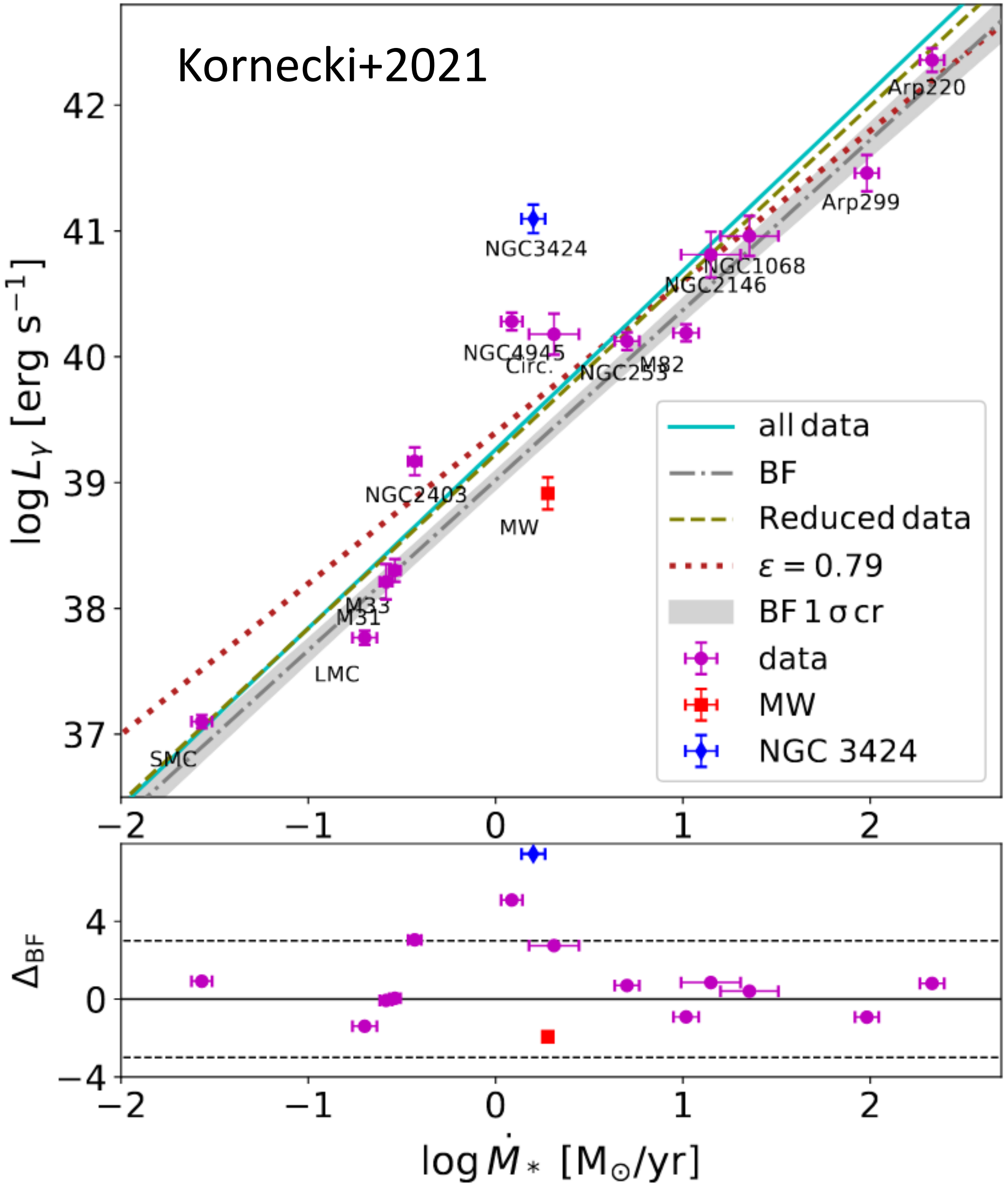


Fiorillo+(including EP) 2023



- 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

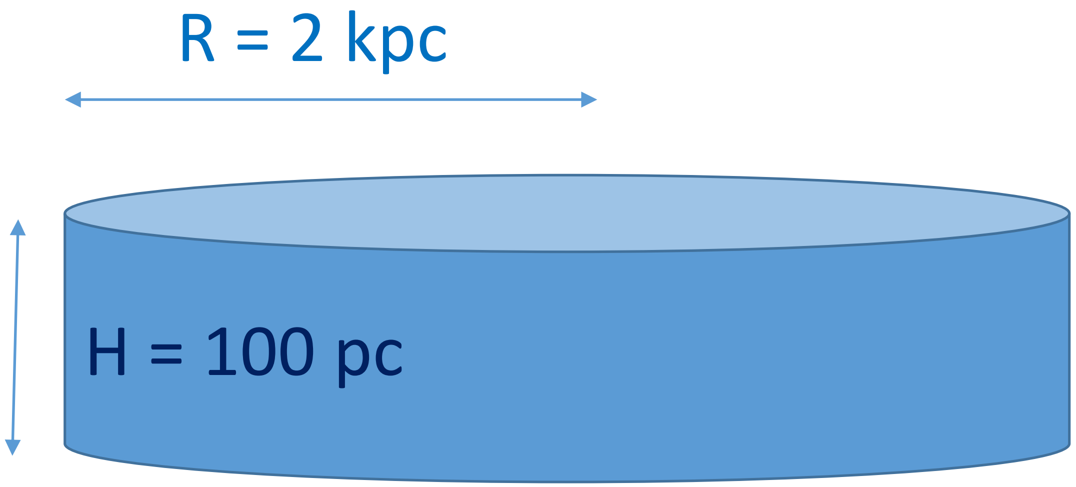


The starburst of NGC 1068

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

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

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



Calorimetry is possible but not trivial