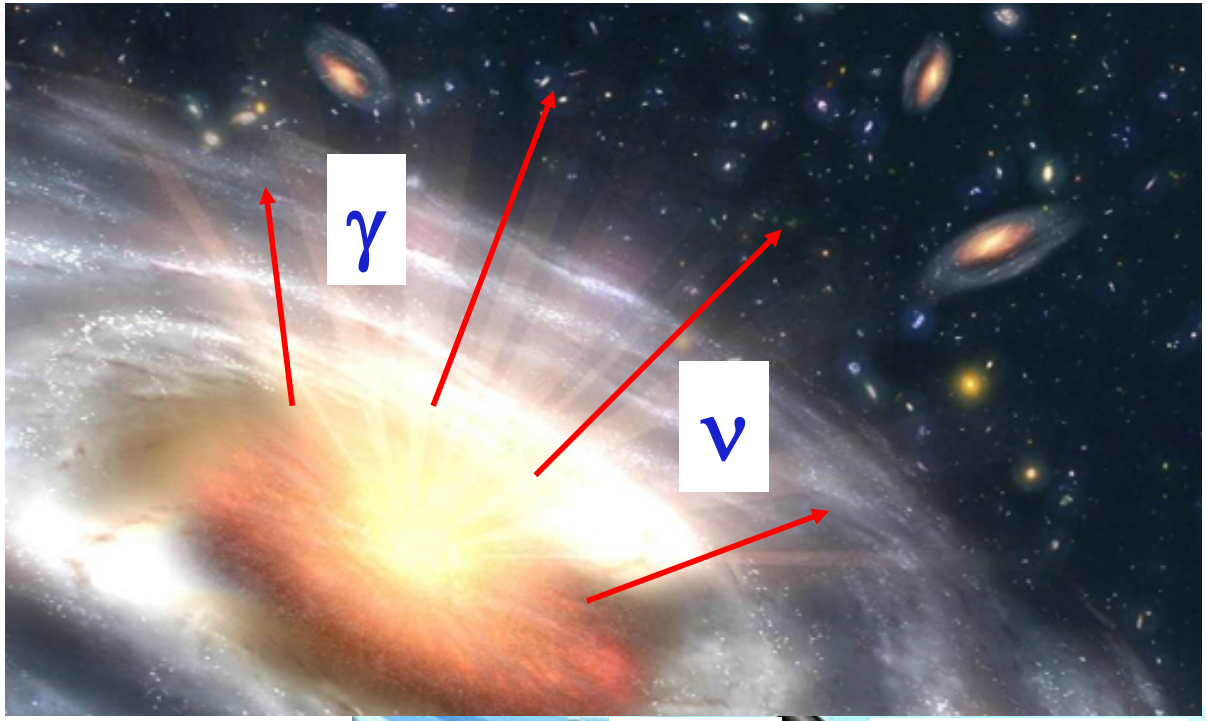
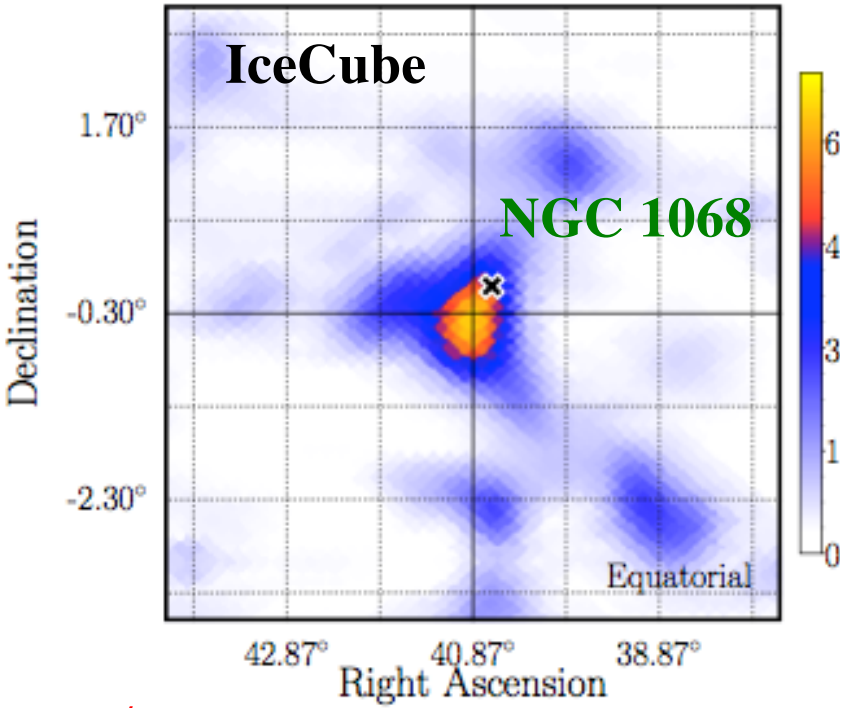
Multi-messenger (electroweak) emission from AGN: wind, torus, NGC 1068

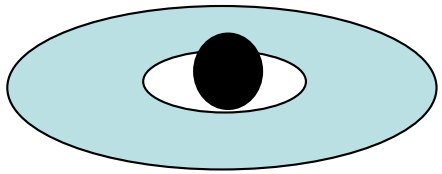
Susumu Inoue (Bunkyo U./RIKEN), Matteo Cerruti (APC)
Kohta Murase (PSU/YITP), Ruo-Yu Liu (Nanjing U)





active galactic nuclei (AGN)

supermassive black hole +accretion disk



relativistic jet

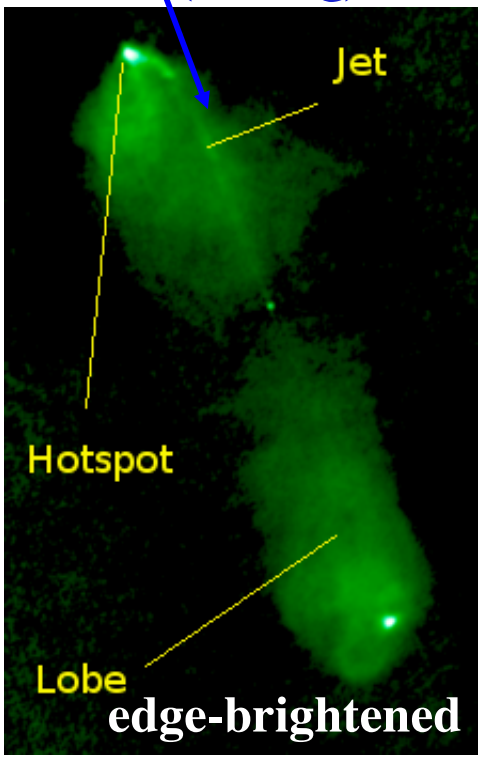
radio-loud

high-power

~<1%

FR 2 radio galaxy

GeV blazar (FSRQ)

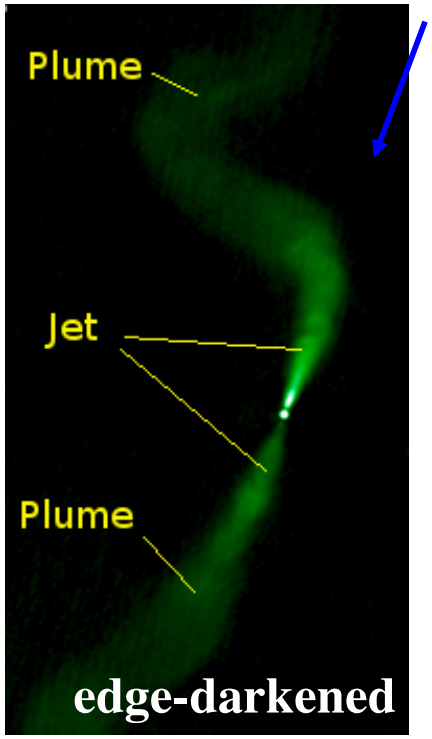


low-power

~9%

TeV blazar (BL Lac)

FR 1 radio galaxy



no/weak jet

~90%

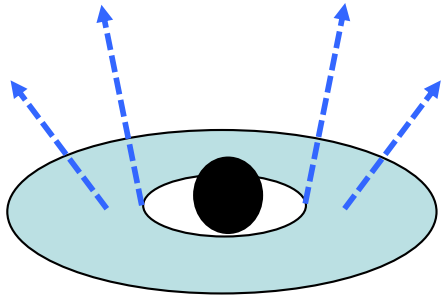
radio-quiet

Seyfert galaxy
radio-quiet quasar

nonthermal emission =particle acceleration

active galactic nuclei (AGN)

supermassive black hole +accretion disk(+wind)



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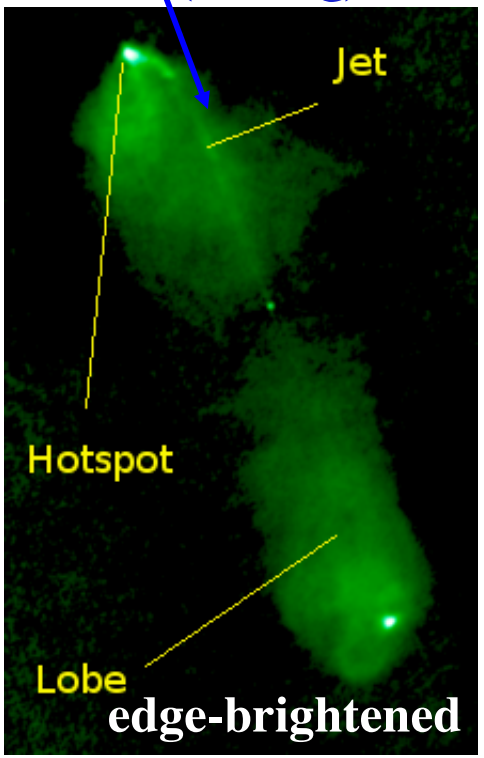

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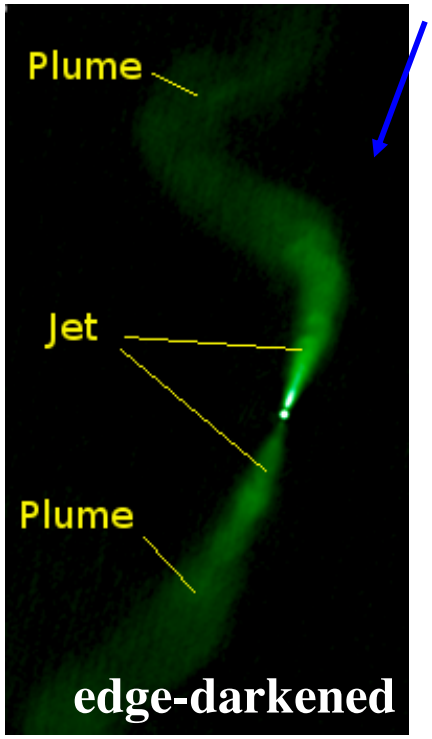

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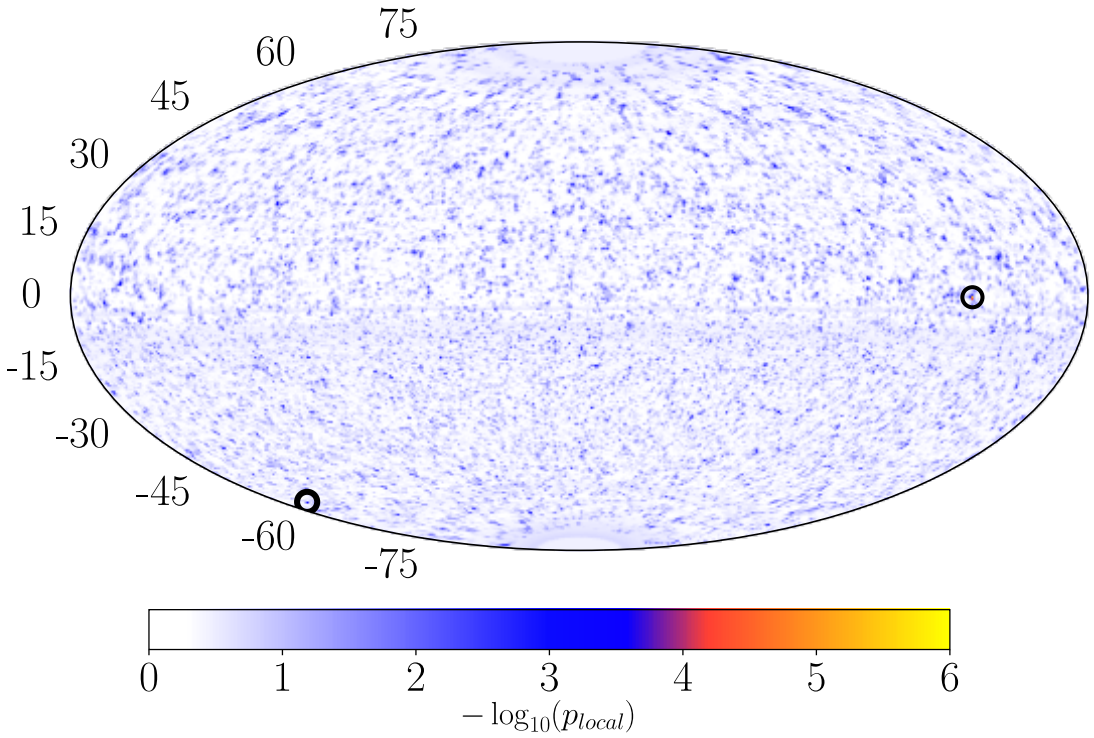
radio-quiet

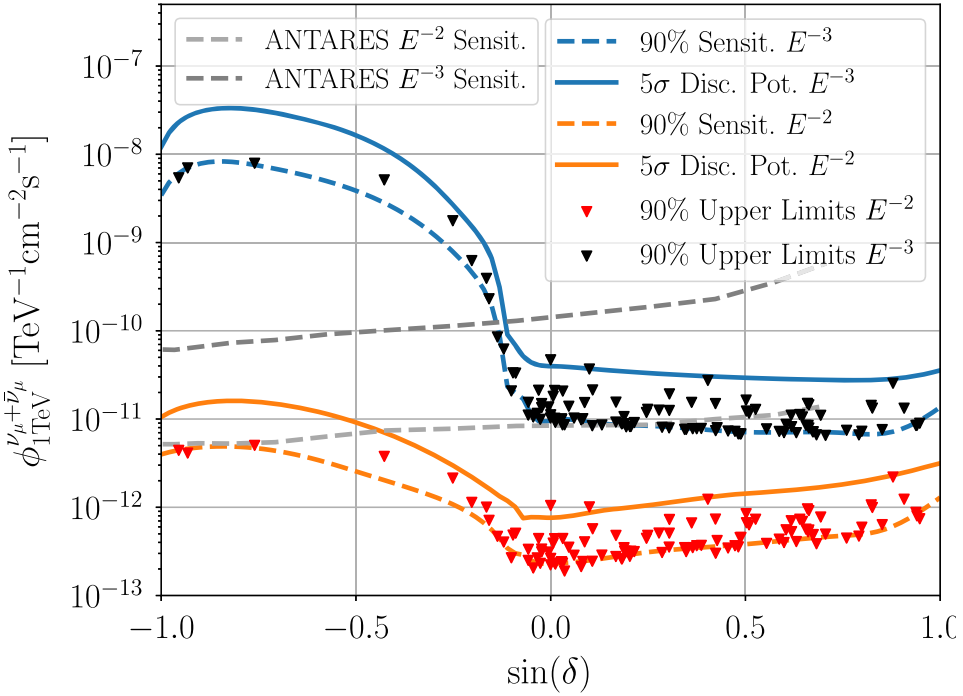
Seyfert galaxy
radio-quiet quasar

nonthermal emission =particle acceleration

high-energy neutrinos: point source search

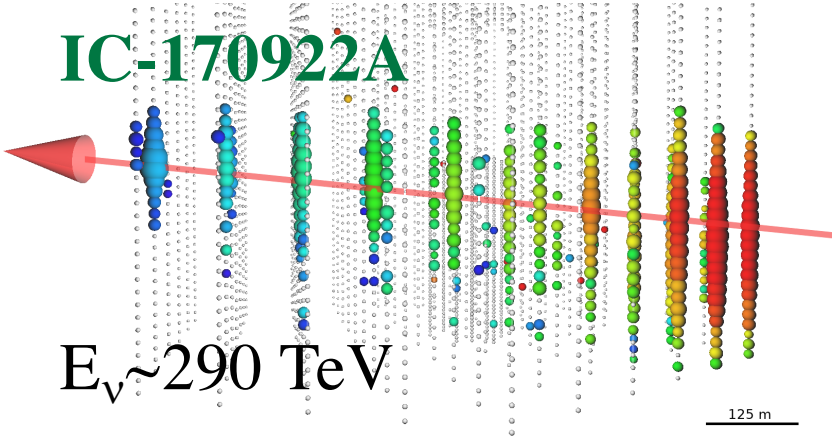
IceCube 10-yr time-integrated source search 1910.08488

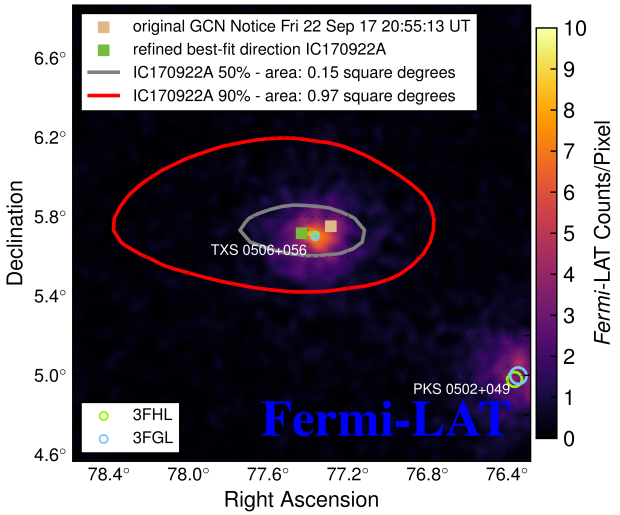




- most significant point in North from full-sky scan coincident with NGC 1068 (Seyfert II)
- 2.9σ excess at position of NGC 1068 in source catalog search
- cumulative excess at 3.3σ due to NGC 1068, TXS 0506+056, PKS 1424+240, GB6 J1542+6129 (blazars)

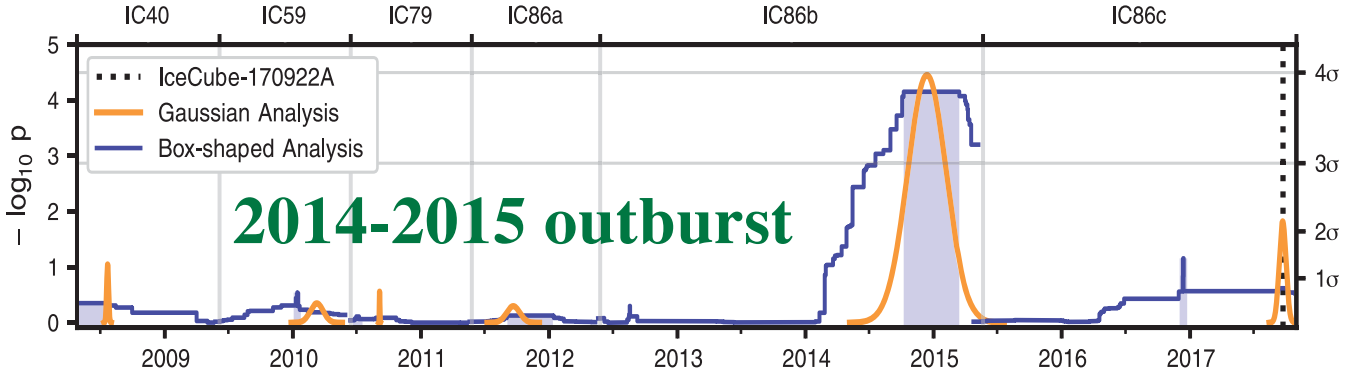
high-energy neutrinos from TXS 0506+056?





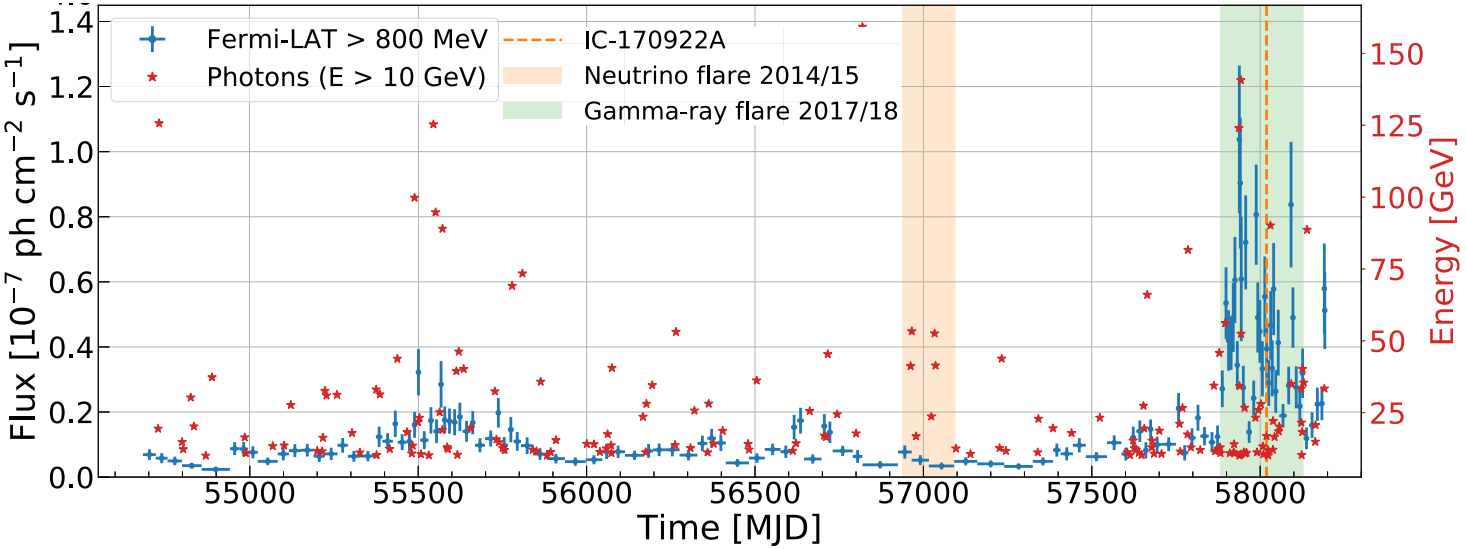
significance of association ~3σ

IceCube, Fermi, MAGIC+, 2018
Science 361, eaat1378



3.5σ excess in archival analysis

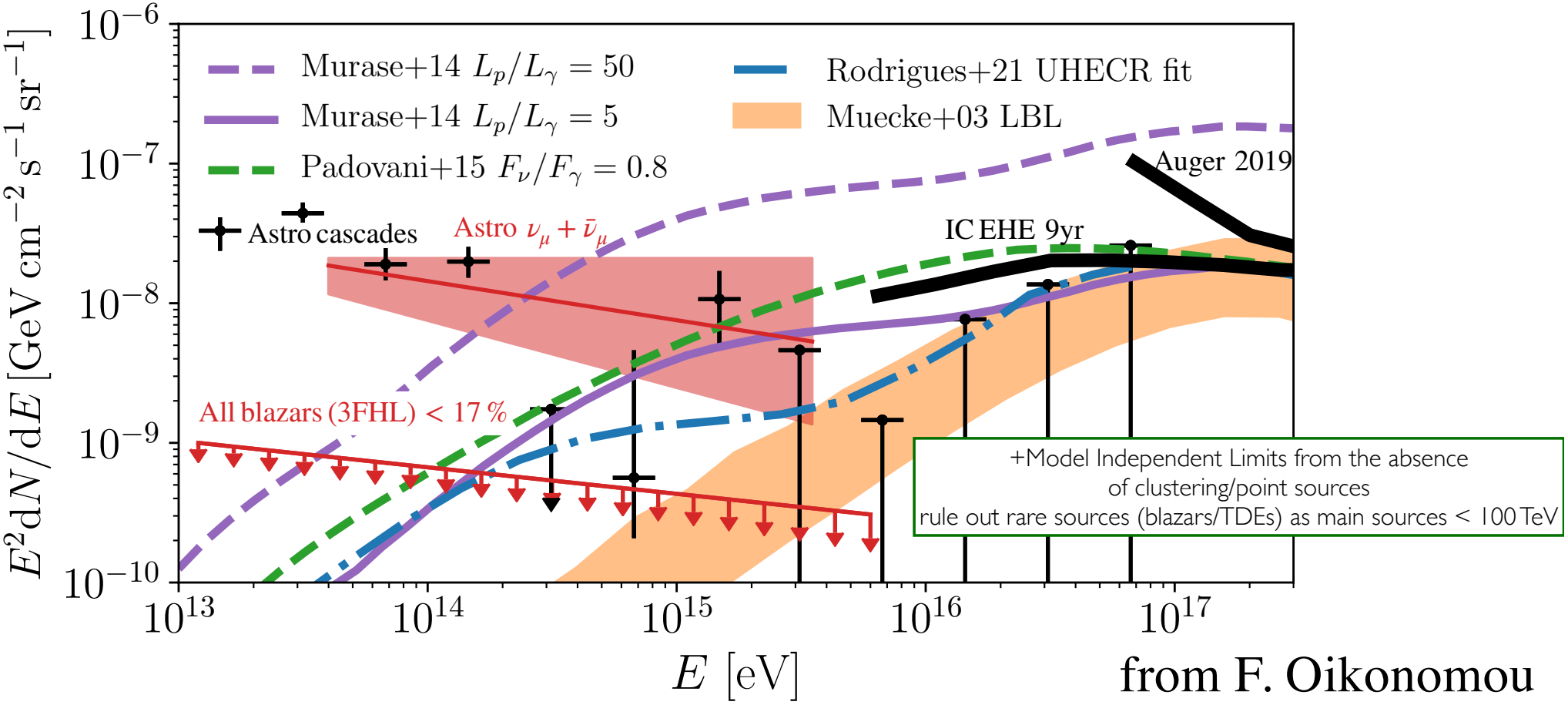
IceCube, 2018
Science 361, 147



faint in GeV γ, contrary to 2017

Garappa+ 19

diffuse high-energy neutrinos: limits on contribution from γ-ray bright blazars



from F. Oikonomou ICRC 2021

γ-ray blazars strongly constrained as main sources of diffuse HE ν

importance of AGN winds

thermal, baryonic plasma; weakly collimated <-> rel. jets

1. Observed to exist, widespread (radio-quiet or radio-loud)

~<pc – blueshifted ion abs. (X-ray UFOs; UV BAL outflows)

v>~0.1c, L_{kin}~<L_{Edd}, $\dot{M}$~<M_{edd}

~<kpc – ion abs. (X-ray WAs; UV NAL), ion emi. (UV-IR)

v>~1000km/s

>~kpc – molecular emi. (CO, OH, etc.)

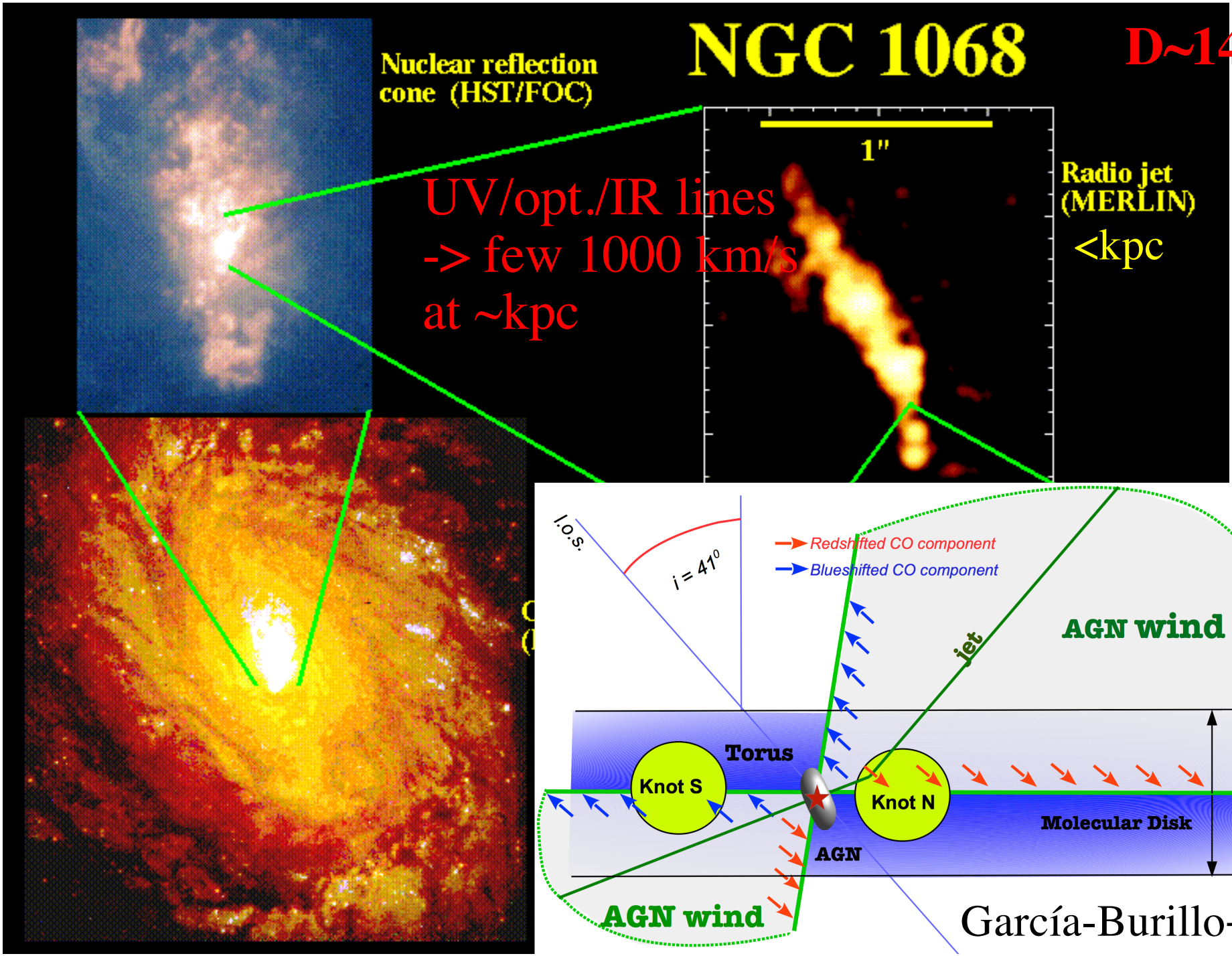
v~<1000 km/s, $\dot{M}$~<100 M_{Θ}/yr, L_{kin}~<L_{bol}

2. Plausibly expected from accretion disks via various mechanisms (unlike jets): thermal, radiative, magnetic…

3. May provide mechanical/thermal feedback onto host gas -> observed BH scaling relations, star formation quenching

4. May be particle accelerators + nonthermal emitters weakly beamed, quasi-isotropic

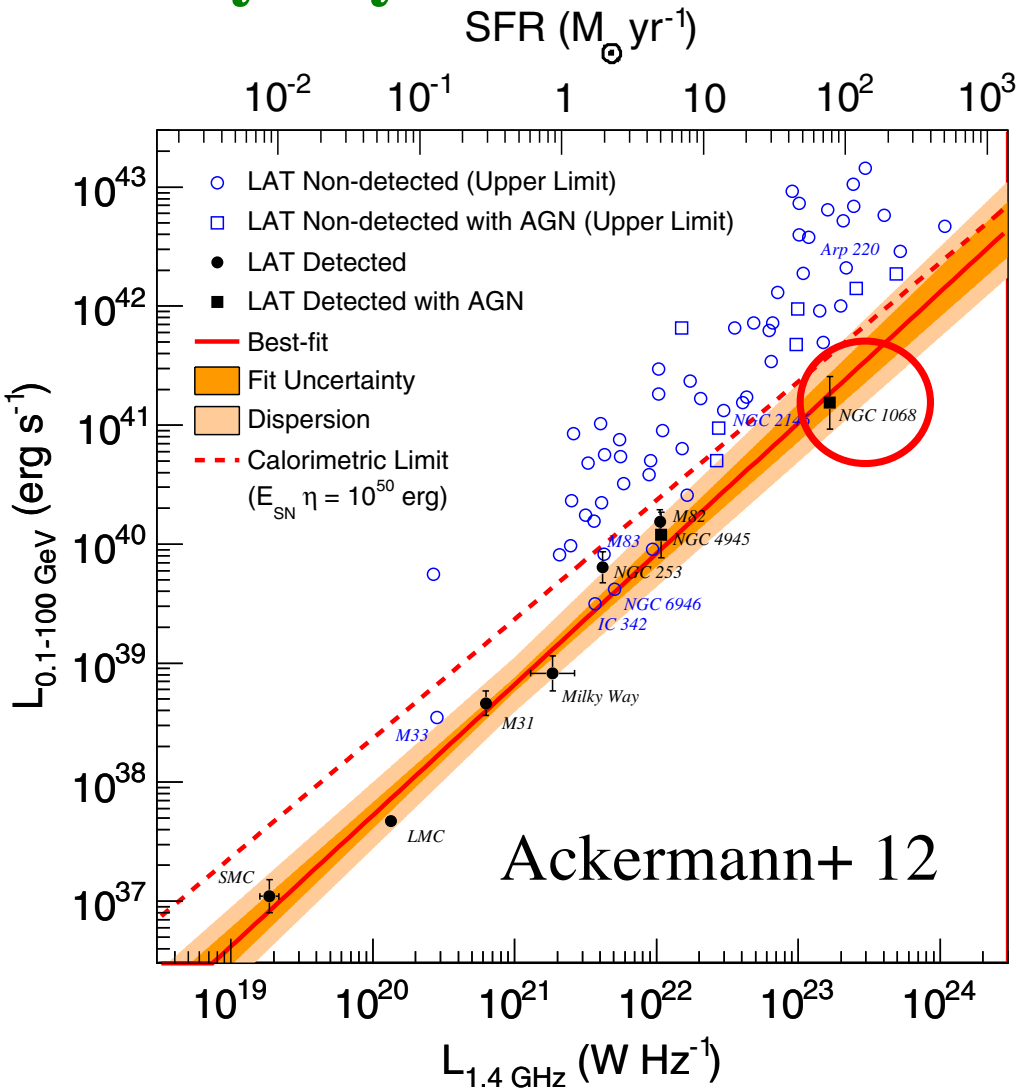
NGC 1068: Seyfert II with fast wind + obscuring torus



García-Burillo+ 19

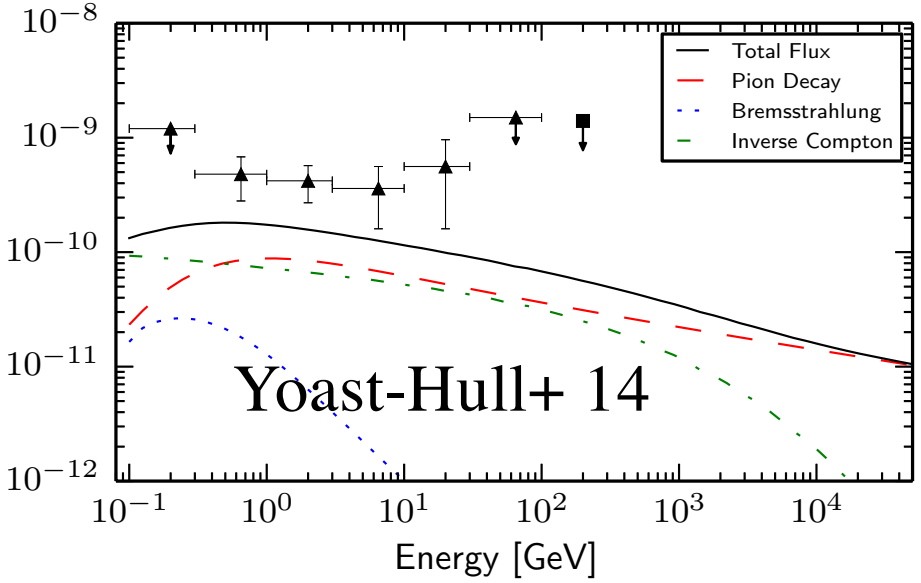
GeV gamma rays from NGC 1068: starburst?

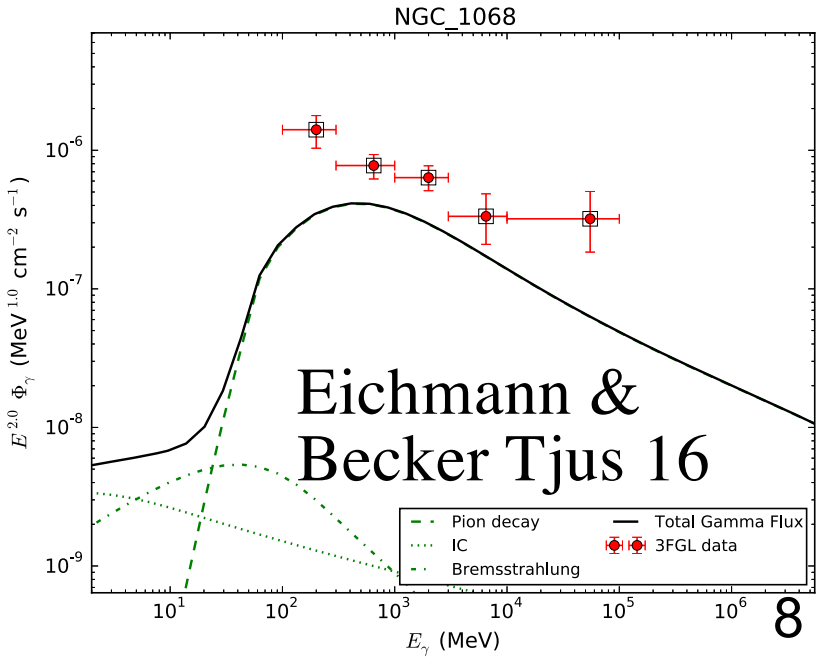
consistency with L_γ-SFR relation
-> **maybe yes**



Fermi-LAT sample of
"starburst"+normal galaxies

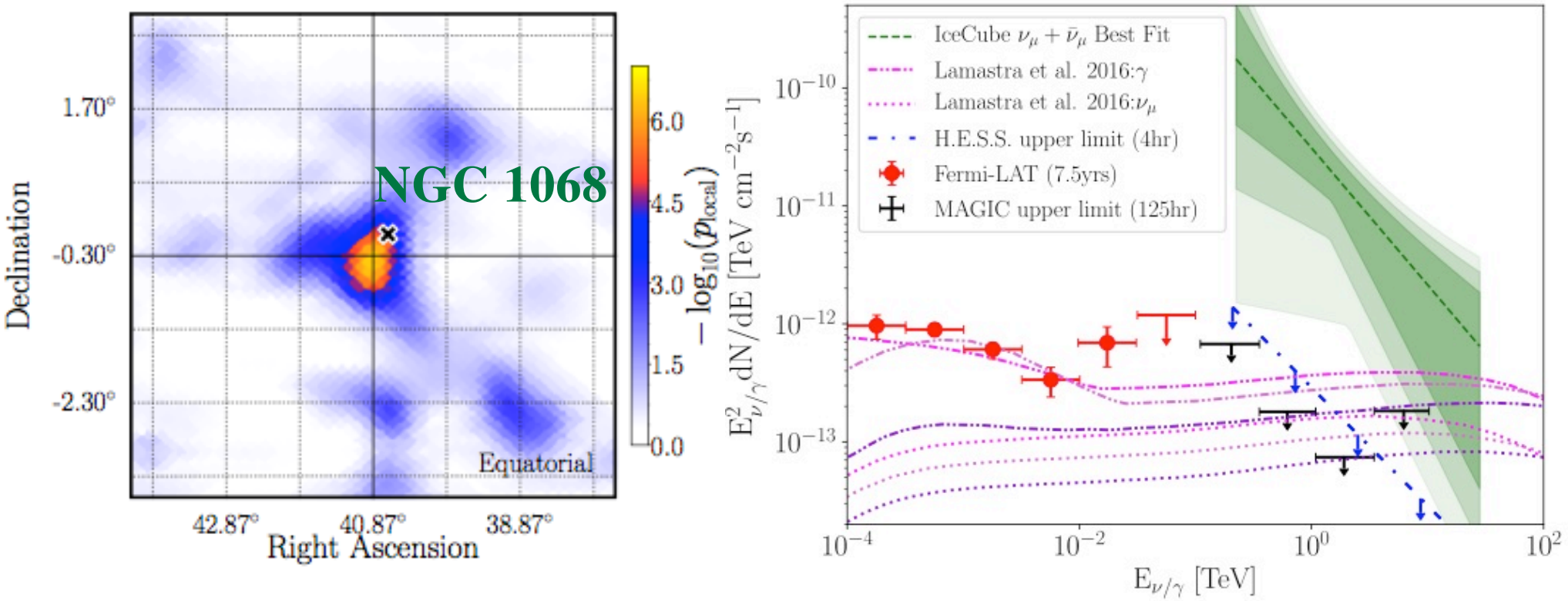
modeling of detailed
MWL data -> **NO**





high-energy neutrinos from NGC 1068?

IceCube 10-yr time-integrated source search 1910.08488



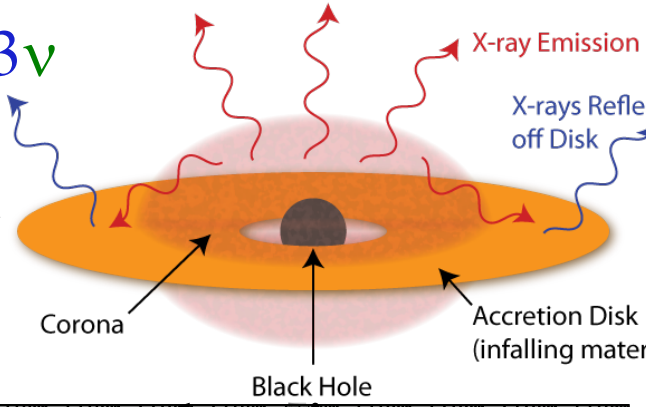
- most significant point in North from full-sky scan coincident with NGC 1068
- 2.9σ excess at position of NGC 1068 in source catalog search
- soft, TeV-range spectrum inferred
- some indications in time-dependent search 2109.05818

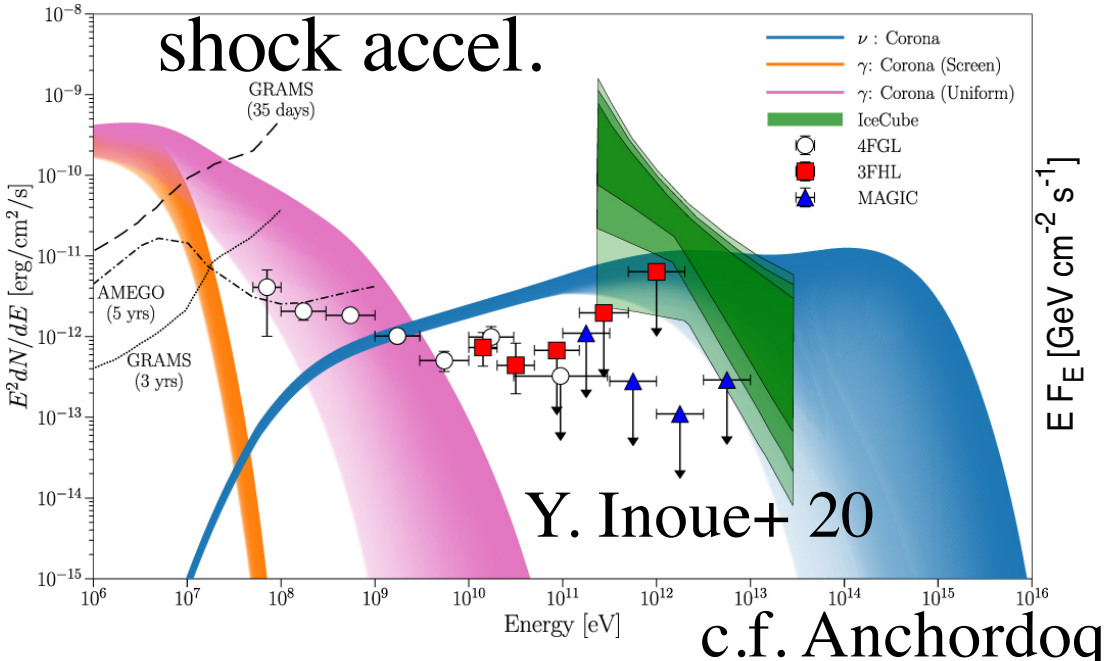
neutrino + gamma from NGC 1068: AGN origin?

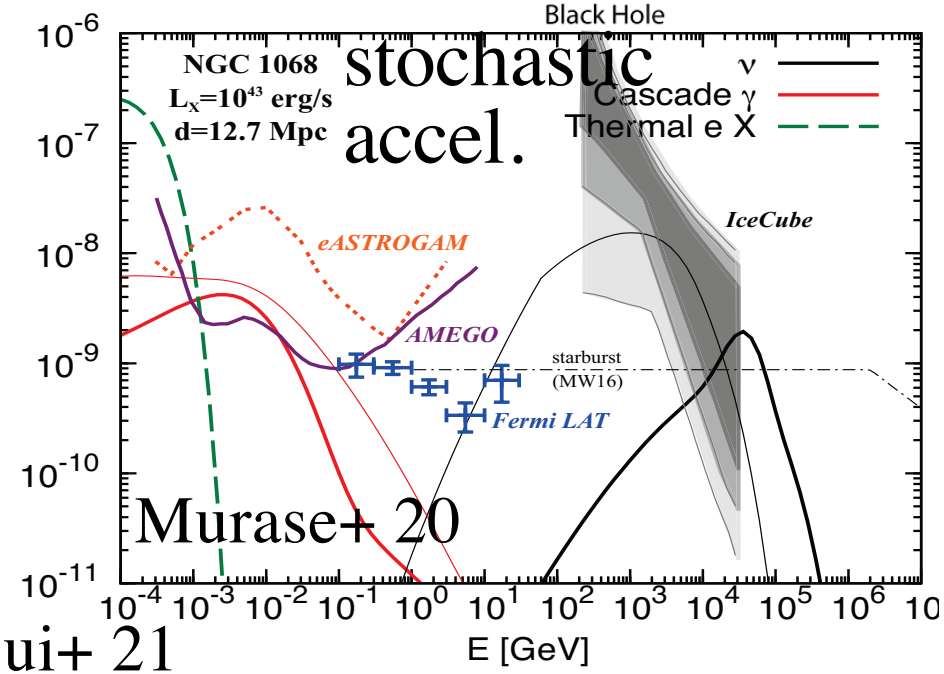
AGN wind external shock models e.g. Lamastra+ 16
(generally pp models optically thin to γγ)
strongly constrained by MAGIC TeV upper limits

$p_{CR}+p_{gas} \rightarrow N + \pi^0, \pi^{\pm}$ $\pi^0 \rightarrow 2\gamma$ $\pi^{\pm} \rightarrow \mu^{\pm}\nu \rightarrow e^{\pm}+3\nu$

pp(+pγ) in compact regions optically thick to γγ, e.g. accretion disk coronae?







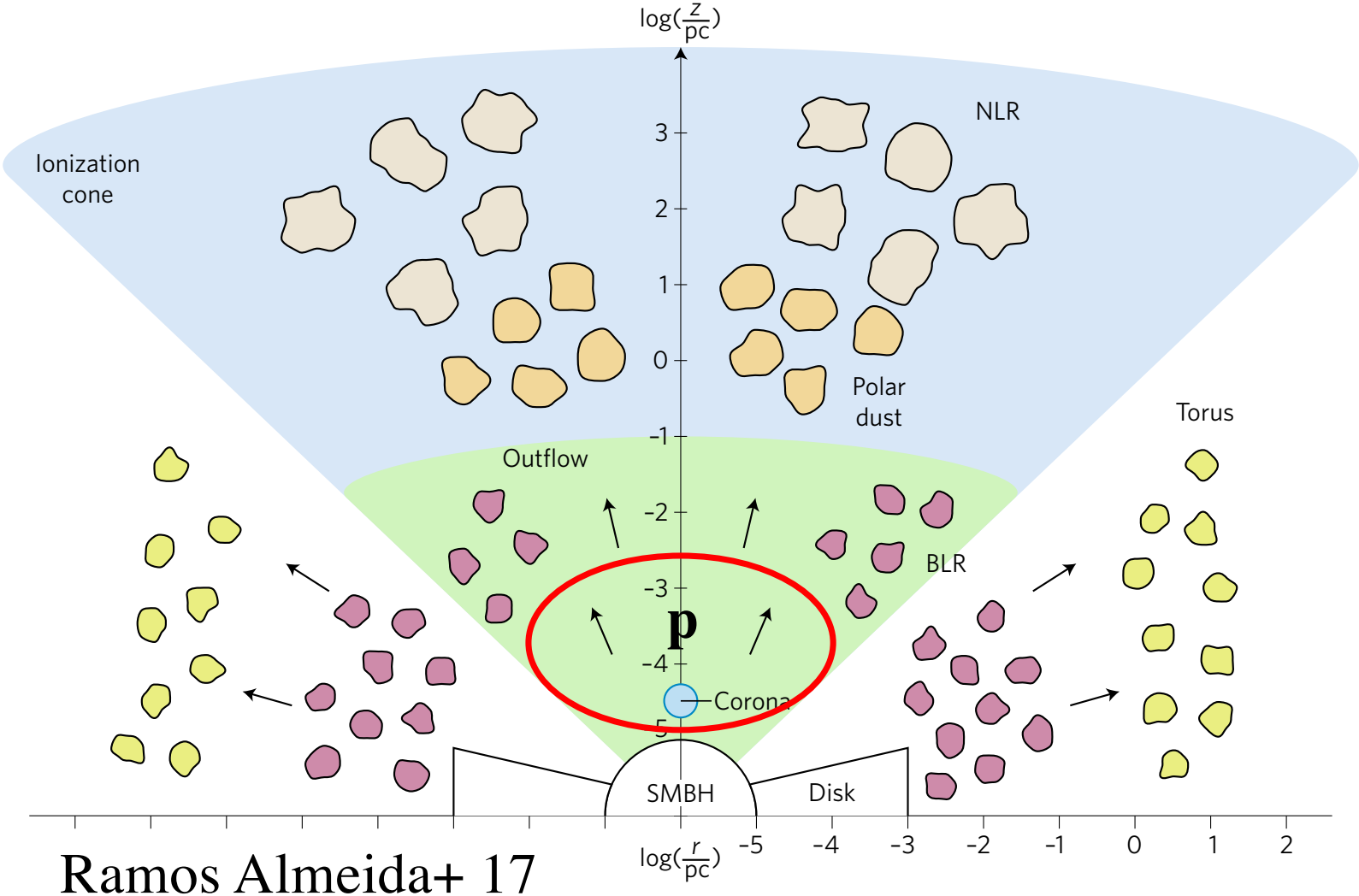
c.f. Anchordoqui+ 21

robustness of particle acceleration? GeV γ rays?

pγ ν+γ from inner regions of AGN winds

potential particle acceleration via:

- internal shocks caused by highly variable wind ejection (observational evidence + theoretical support)
- "interaction" shocks with external or internal clouds/stars



obs.

Ramos Almeida+ 17

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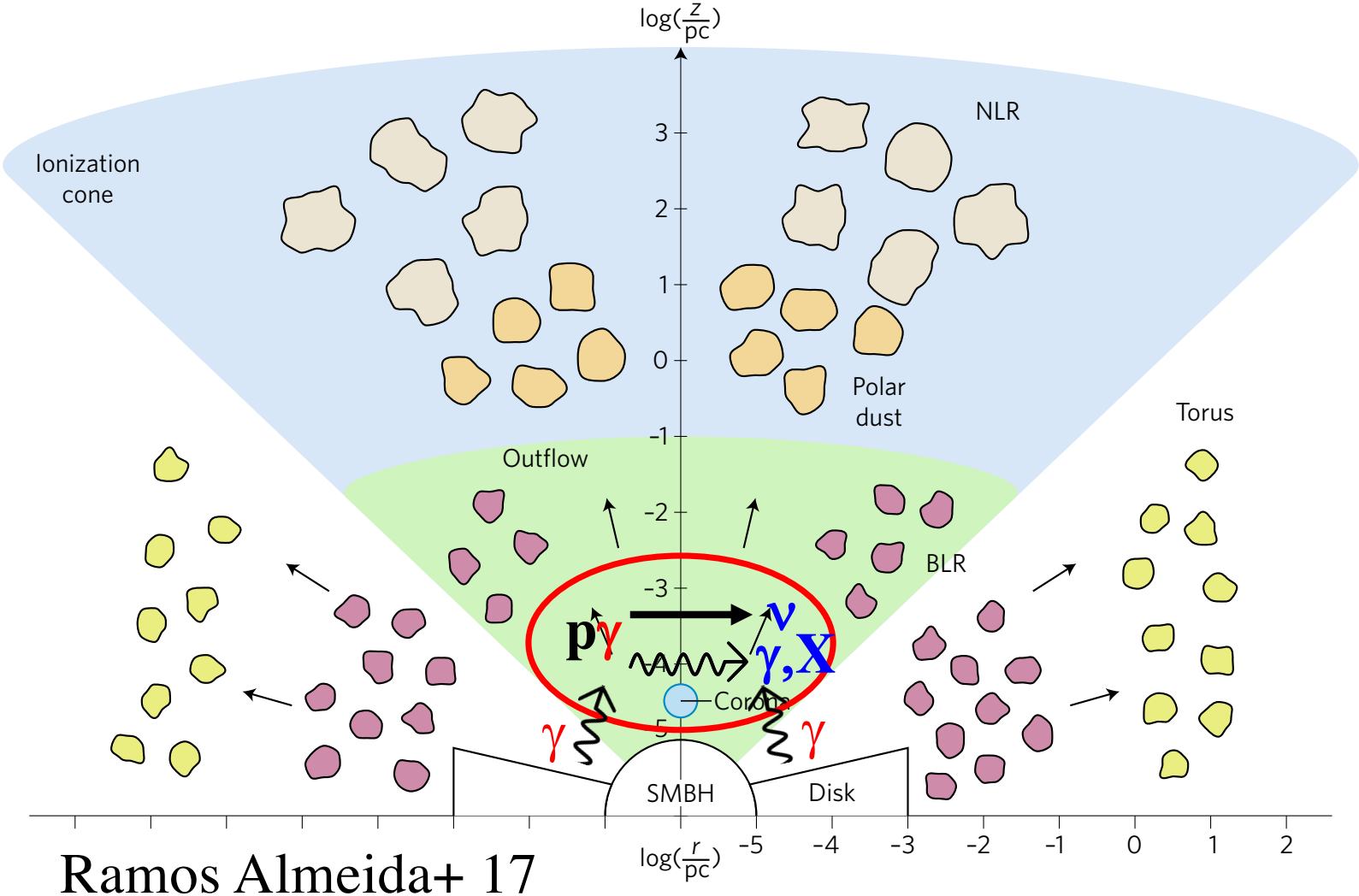

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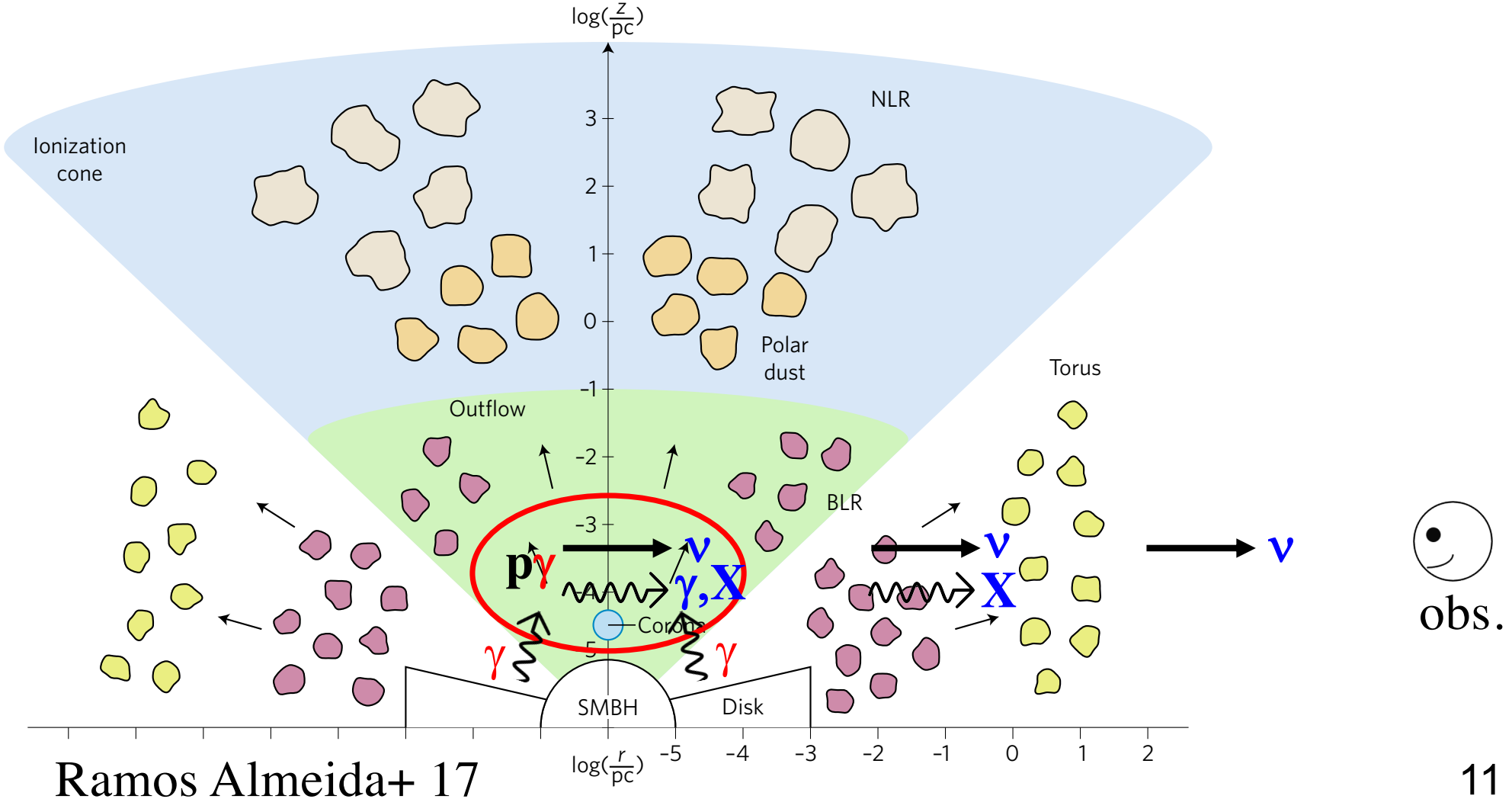

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pγ interactions with nuclear radiation
- neutrinos ~<TeV-PeV
- cascade ~<MeV-GeV

$p+\gamma \rightarrow N+ \pi^0, \pi^{\pm}$

$\pi^0 \rightarrow 2\gamma$ $\pi^{\pm} \rightarrow \mu^{\pm} \nu \rightarrow e^{\pm}+3\nu$

$\mu^{\pm}+B \rightarrow \mu^{\pm}+\gamma$ muon synchrotron

$\gamma+\gamma \rightarrow e^+e^-$ electron-positron

$e^+e^-+B/\gamma \rightarrow e^+e^-+\gamma$ sync./IC cascade

$p+\gamma \rightarrow p+e^+e^-$ Bethe-Heitler pair production

$p+B \rightarrow p+\gamma$ proton synchrotron

pγ ν+γ from inner regions of AGN winds

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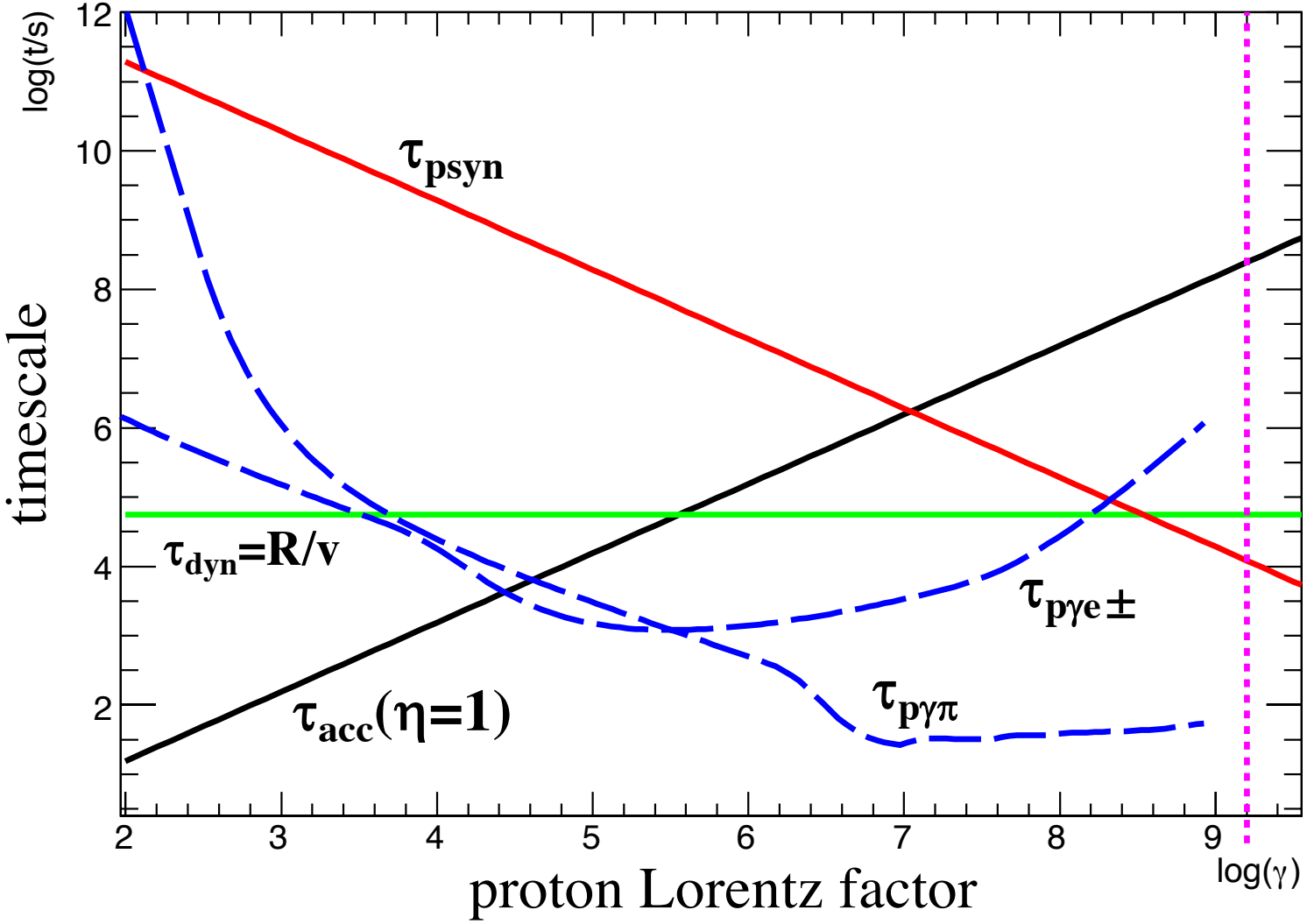
NB: photoelectric abs. + extinction in torus -> mid IR - soft X significantly attenuated

pγ in inner regions of AGN winds: timescales

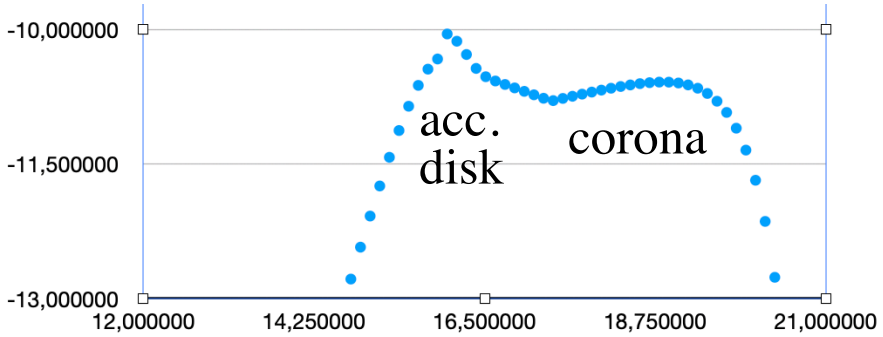


R=10^{13} cm ($3R_s$)
z=10^{14} cm ($30R_s$)
B=500 G
(c.f. ε_B~0.08 for
$L_{kin}=10^{44}$ erg/s)

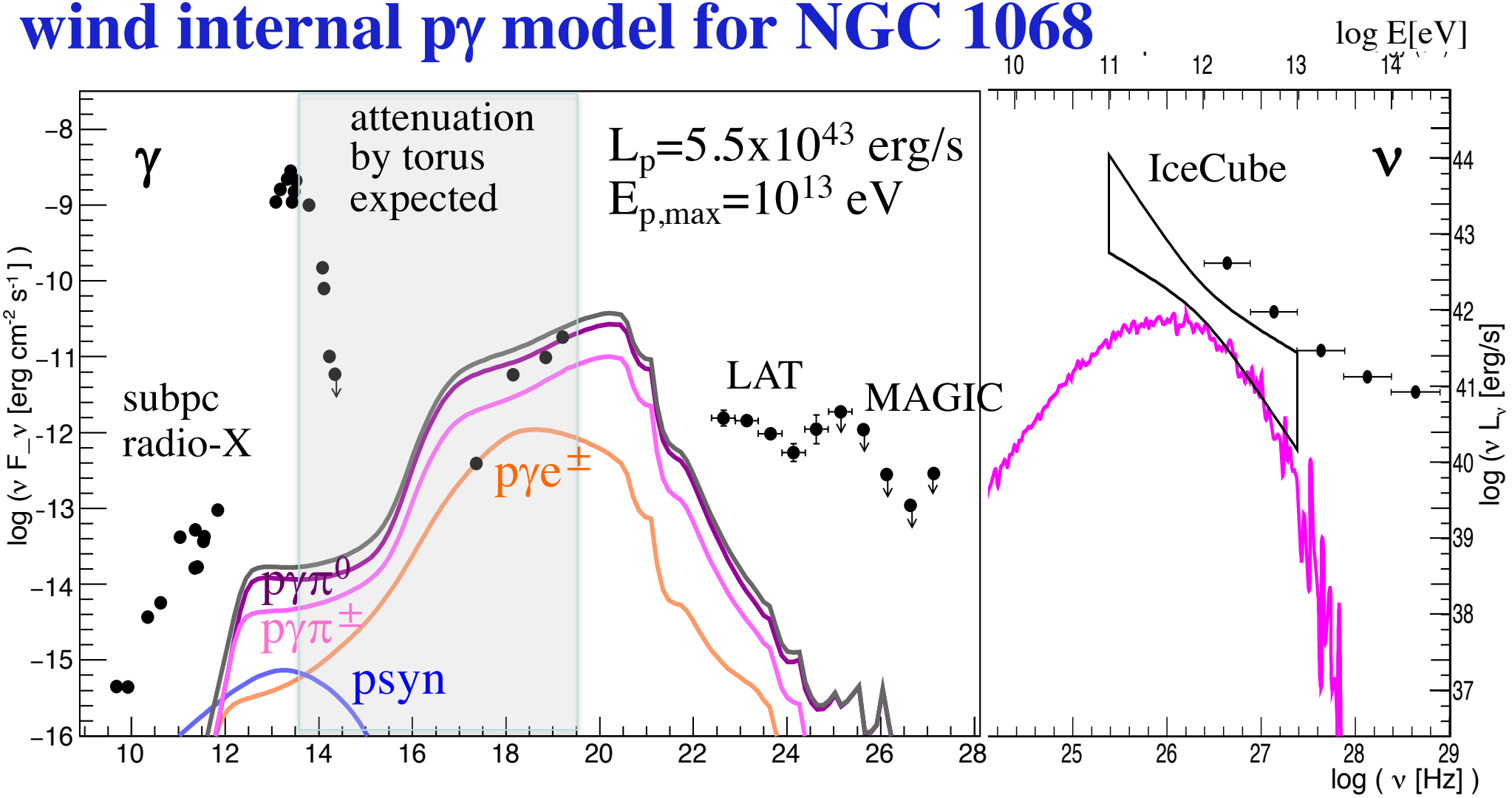
v=1000 km/s
-> $E_{p,max}$~10 TeV
-> $t_{p\gamma\pi}(X)/t_{dyn}$~<1

NB v<< ~0.1c
"generic" velocity

$M_{BH}=10^7\,M_\odot$
$L_{disk}=10^{45}$ erg/s
$L_{cor}=0.1\,L_{disk}$



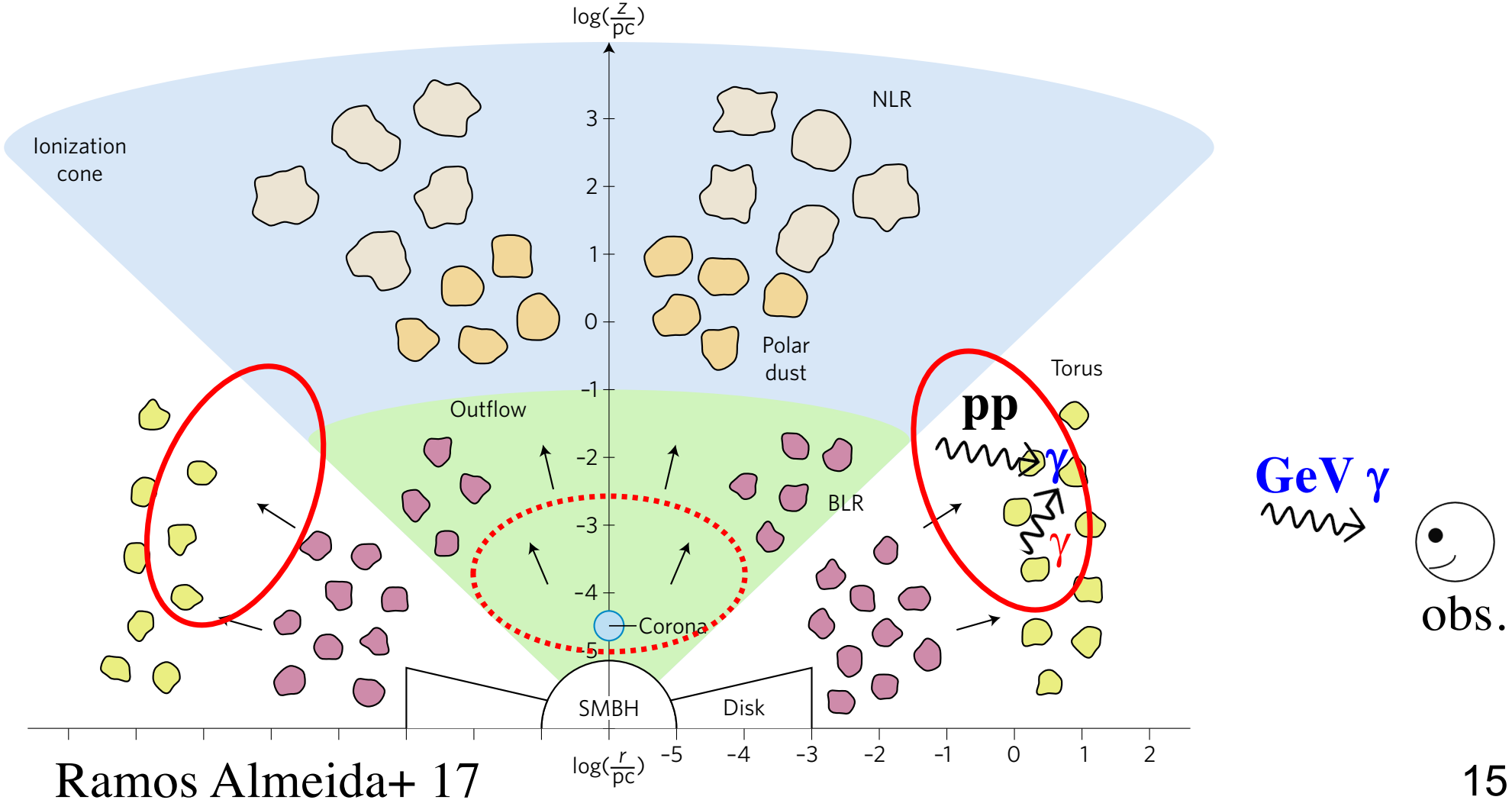
wind internal pγ model for NGC 1068



- neutrinos: flux and spectrum reasonable wrt IceCube
- photons: hadronic cascade consistent wrt available MWL
  γγ attenuated at GeV-TeV by disk UV-X
  prominent at (keV-)MeV -> interesting for future instruments

pp γ(+ν) from AGN wind+torus interaction

wind + torus interaction (inevitable)
-> external shock formation -> proton acceleration
-> pp interactions with torus gas
-> GeV escape, TeV γγ attenuated with torus IR



GeV γ

obs.

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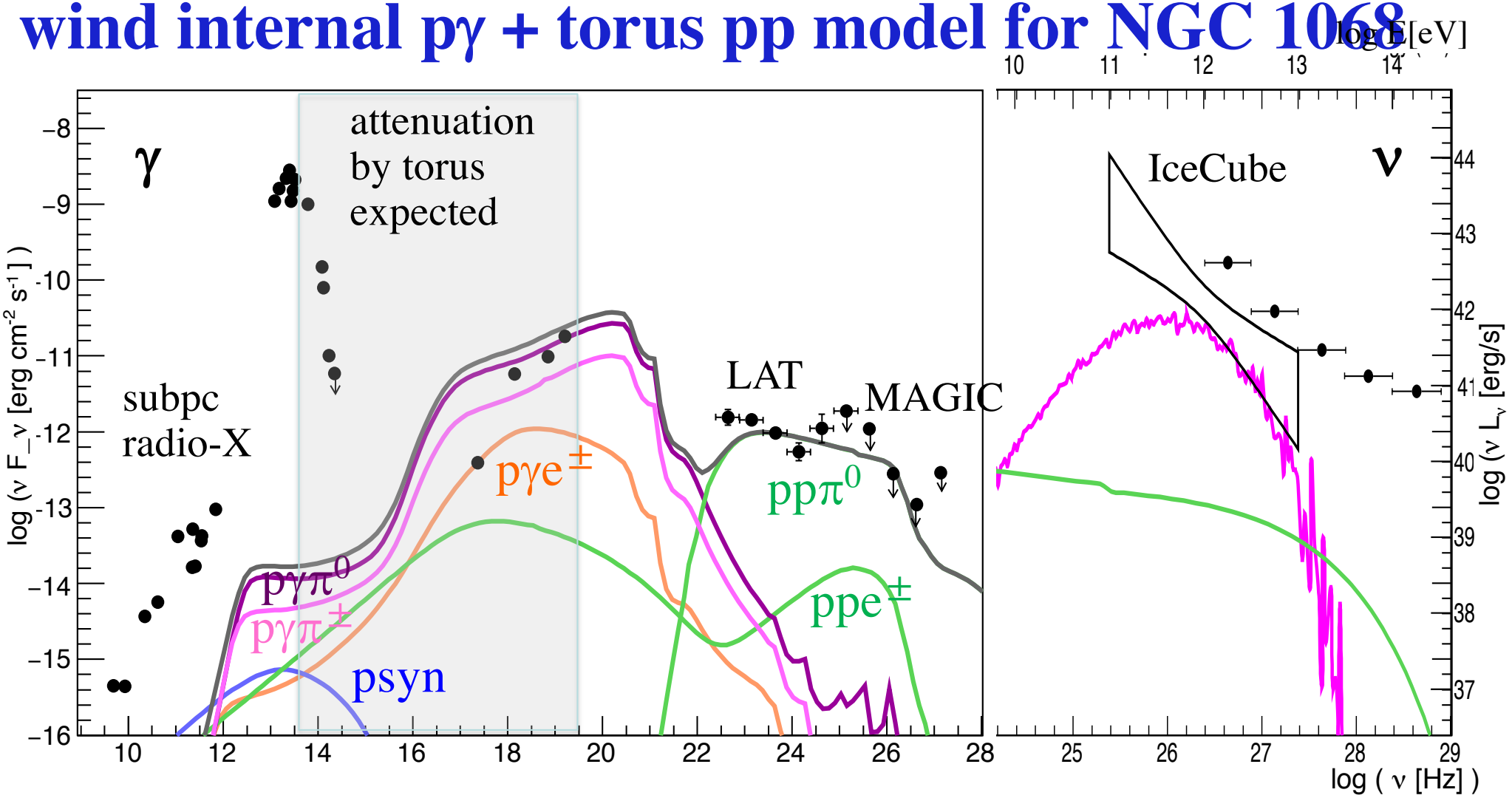
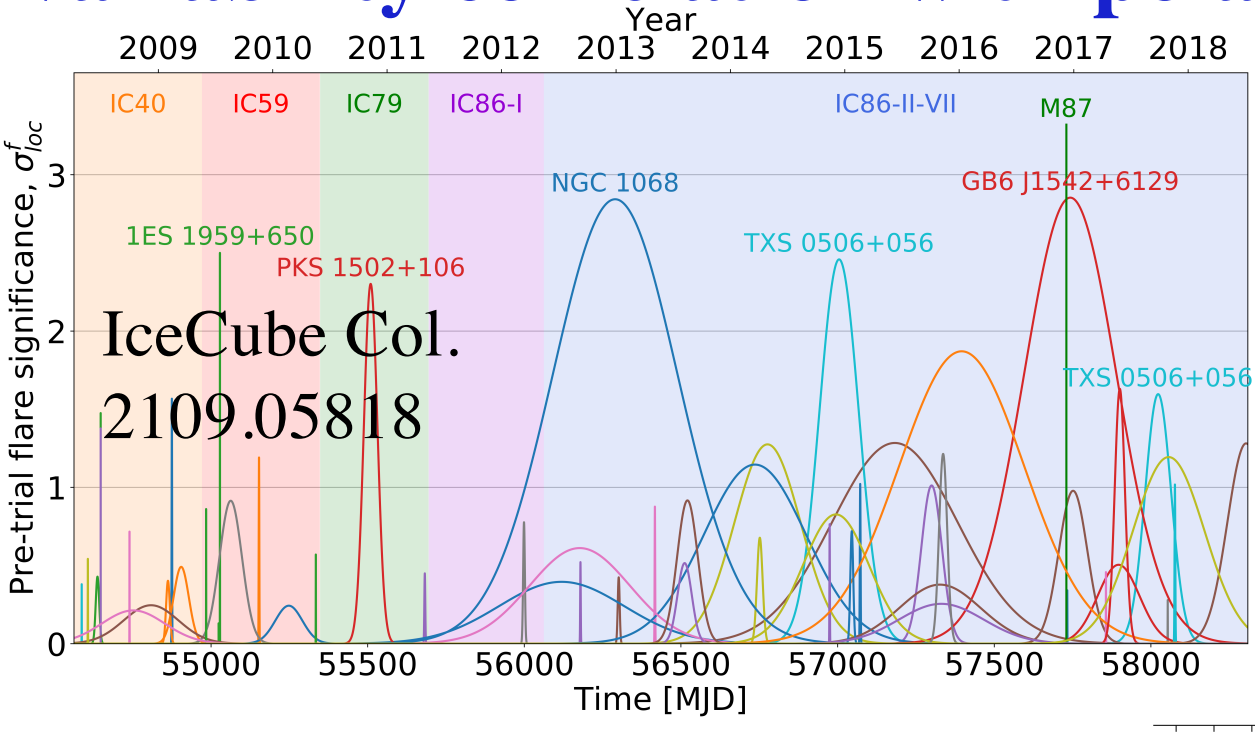
wind internal pγ + torus pp model for NGC 1068



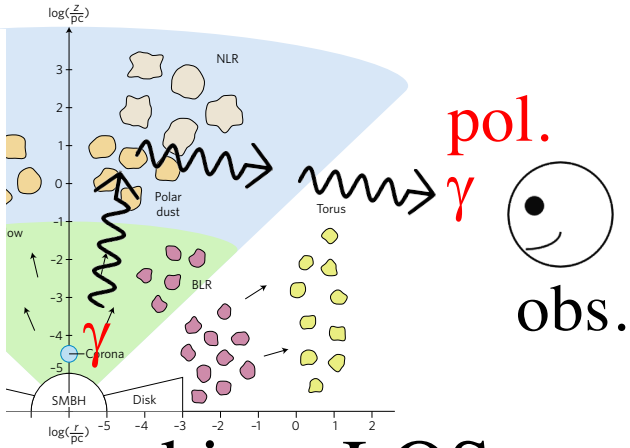
- GeV: pp γ-rays from wind-torus interaction shock
  TeV: γγ attenuated by torus IR

$R_{tor}=10^{17}$ cm, $n_{tor}=10^{7}$ cm^{-3}, $B_{tor}=0.1$ G
v=1000 km/s
$L_p=2.3\times10^{41}$ erg/s, $E_{p,max}=2.5\times10^{14}$ eV

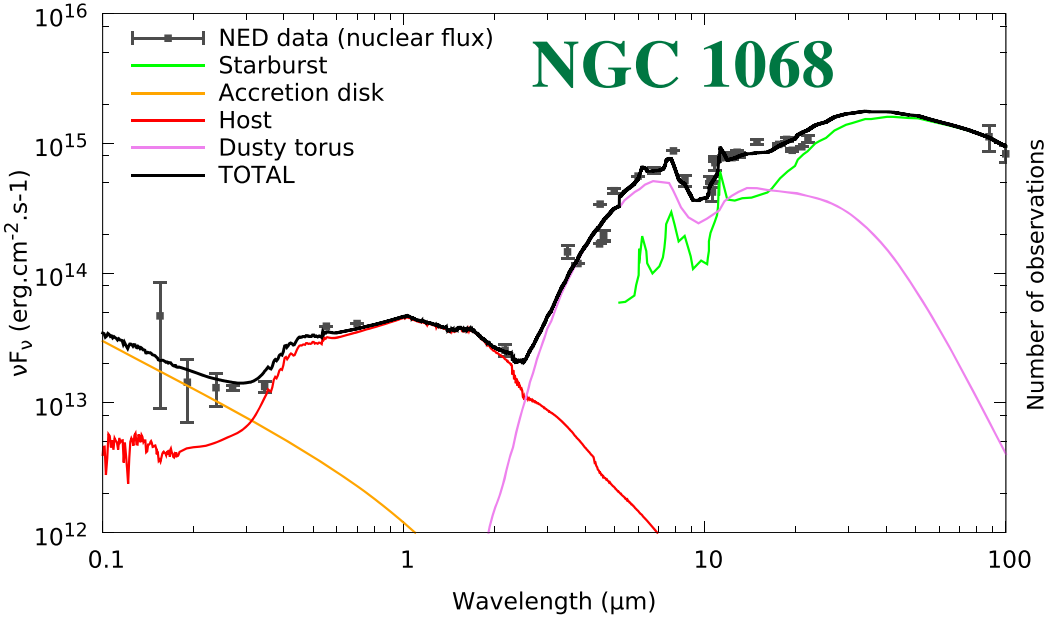
variability correlation with polarized opt.-NIR?

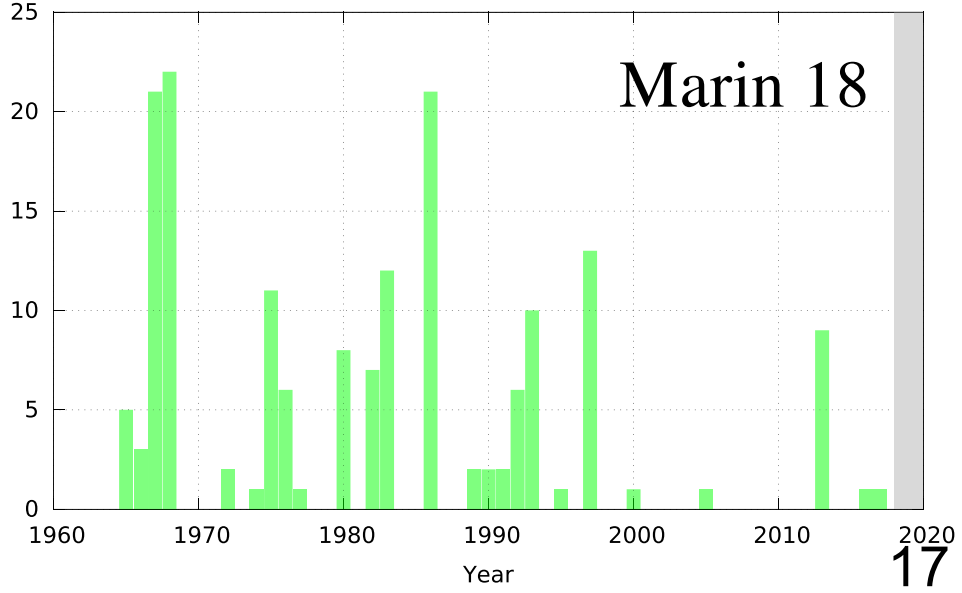


yr-timescale variability?
-> if real, likely due to accretion rate variations

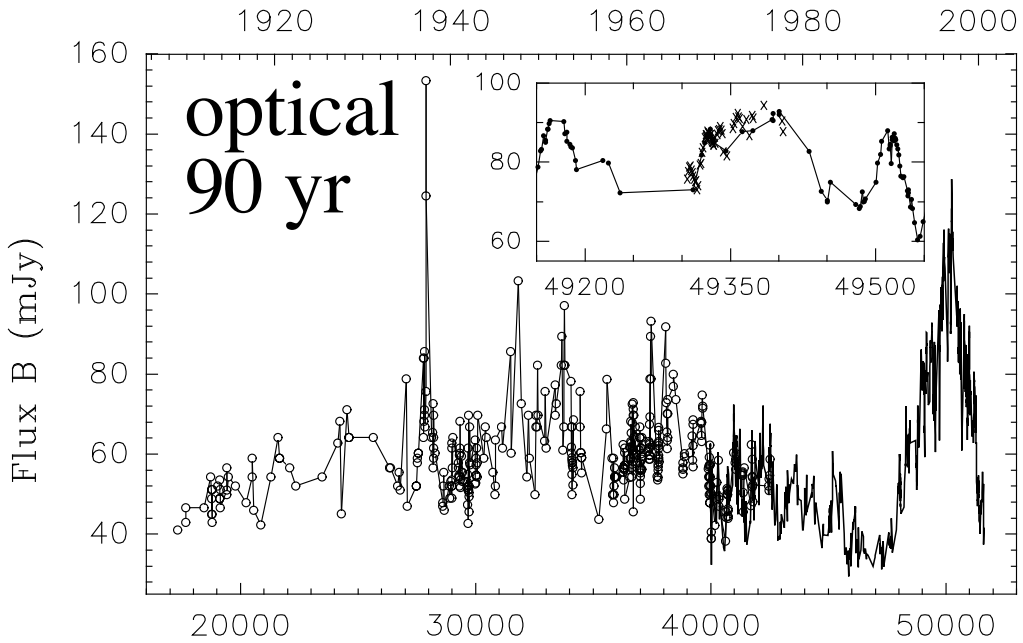


polarized optical-NIR: nuclear emission scattered into LOS



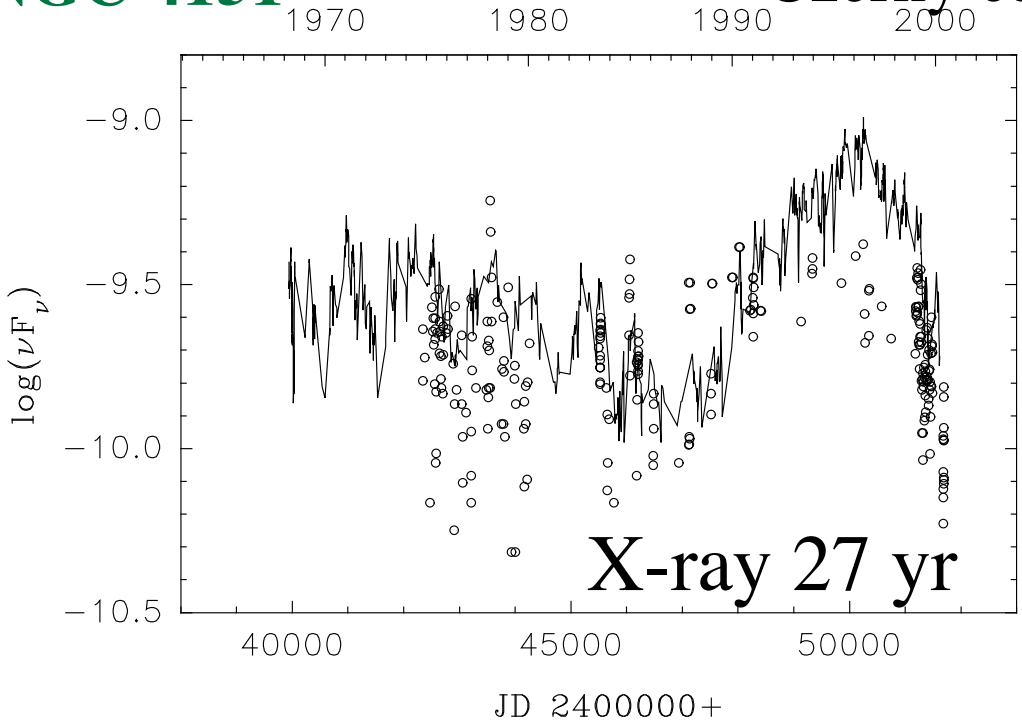


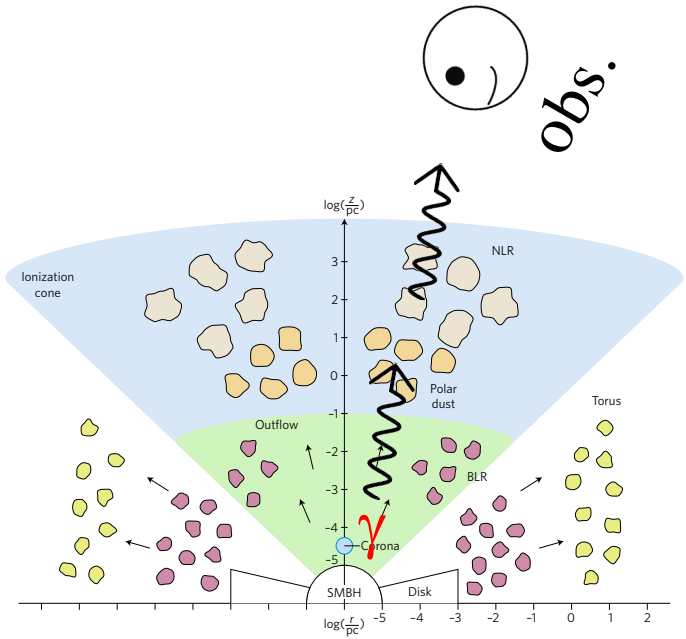
variability in unobscured Seyfert I with wind



NGC 4151

Czerny 03





summary

fact: AGN winds - fast, powerful, widespread, inc. NGC 1068

interpretation of electroweak emission from NGC 1068
- p accel. in inner regions near nucleus
- assuming v~1000 km/s, pγ neutrinos with soft TeV spectrum
- cascade photons γγ attenuated at GeV-TeV, prominent at MeV
- p accel. in wind-torus interaction shock, pp γ-rays at GeV

future tests and prospects
- cascade MeV, variability correlation w. polarized optical-NIR
- other nearby Seyferts with winds by IceCube-Gen2, CTA, etc
- contribution to diffuse ν background
- unique info on AGN winds (B field, etc)

Paper to be submitted soon
please stay tuned!