High-energy neutrinos and gamma rays from winds and tori in active galactic nuclei

Role of failed winds, wind-torus interaction

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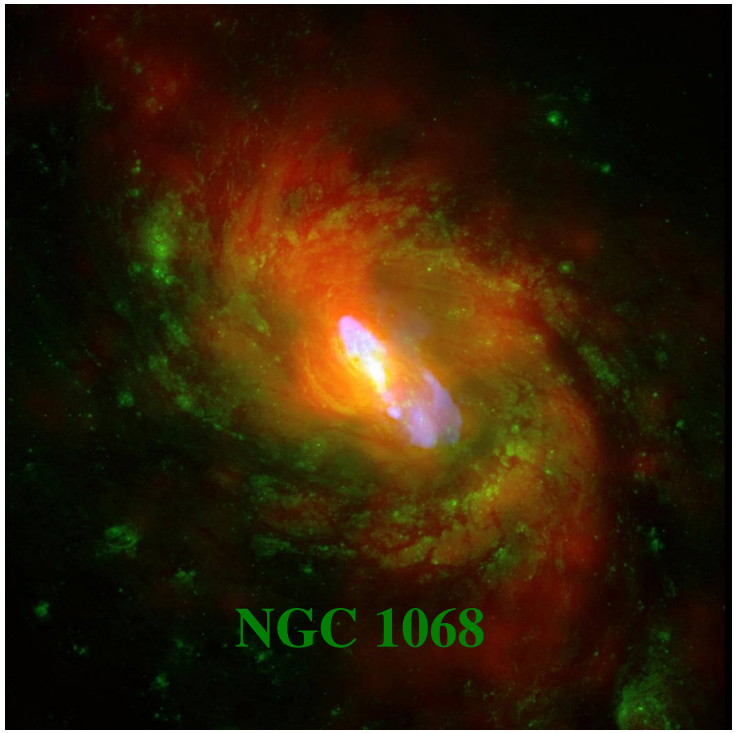
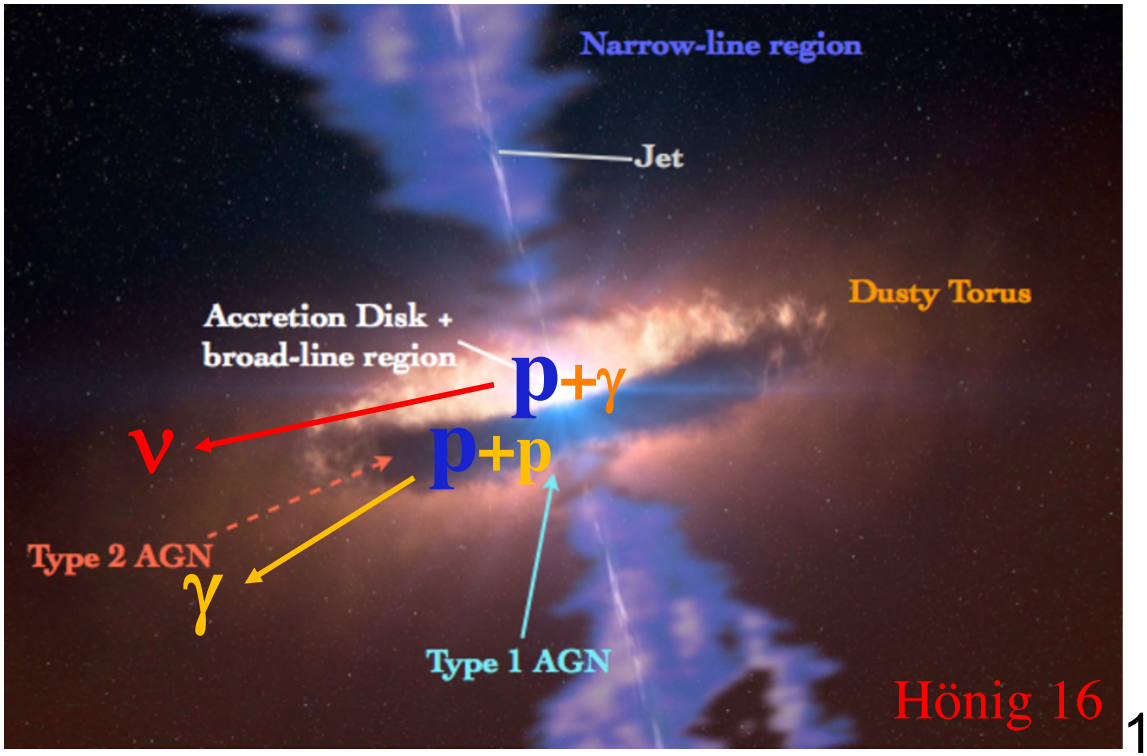
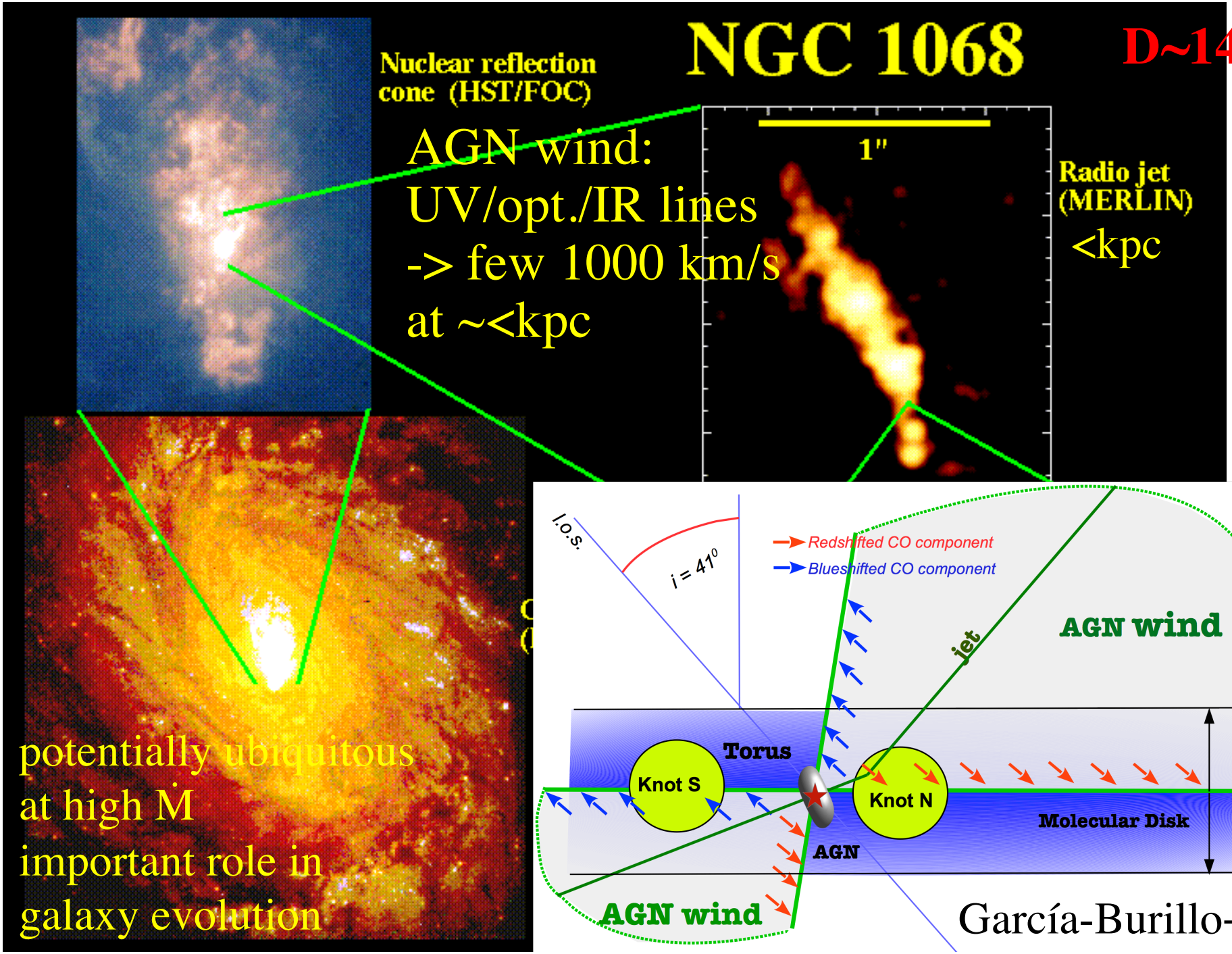
Matteo Cerruti (APC), Kohta Murase (PSU/YITP),
Ruo-Yu Liu (Nanjing U)

arXiv: **2207.02097**, submission to PRL imminent



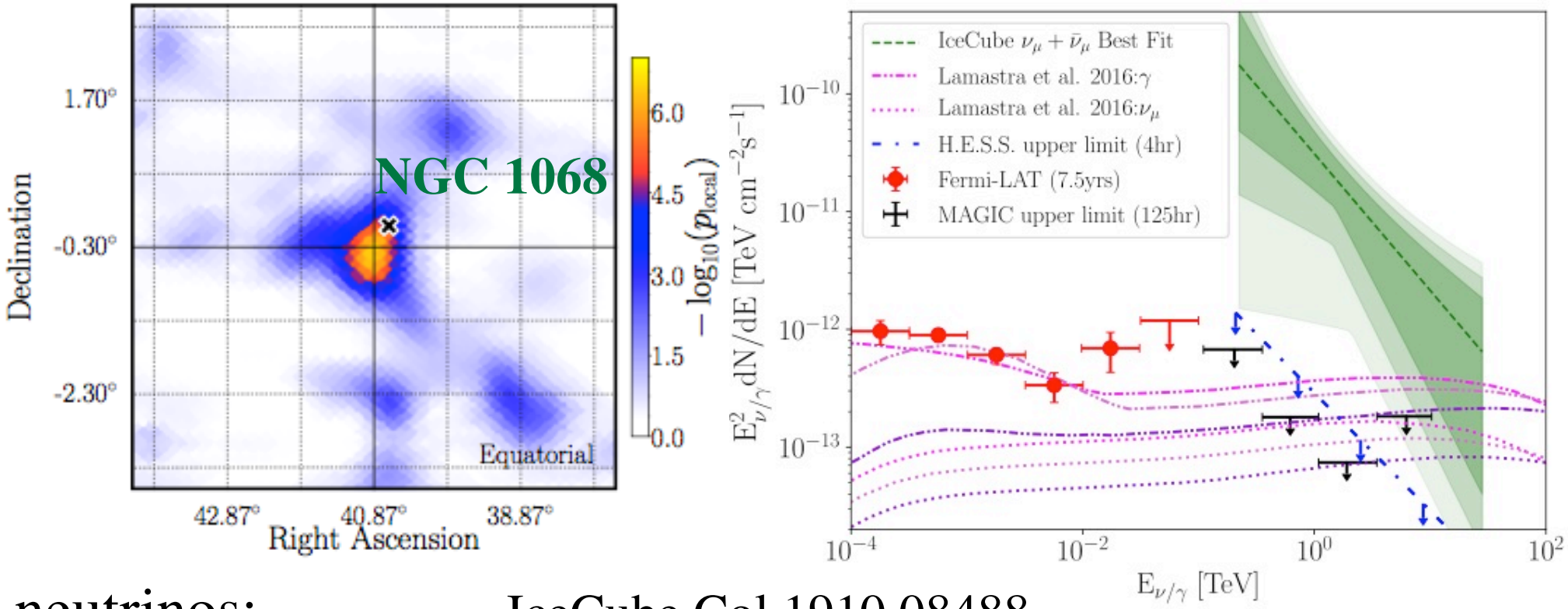


NGC 1068: Seyfert 2 with wind + obscuring torus



García-Burillo+ 19

neutrinos and gamma rays from NGC 1068



neutrinos: IceCube Col.1910.08488

- ~3σ excess from 2 independent methods, more results coming
- soft, TeV-range spectrum, $\nu L_\nu \sim 10^{42}$ erg/s $(\varepsilon_\nu/1\ \mathrm{TeV})^{-3.2}$

GeV γ: exceeds starburst expectation -> AGN origin?

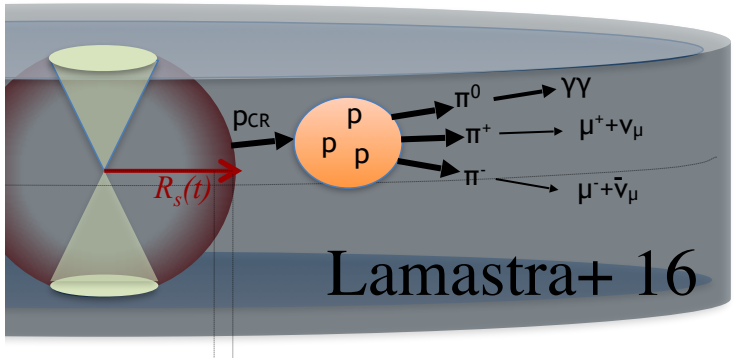
Yoast-Hull+ 14, Eichmann & Becker Tjus 16

TeV γ: upper limits rule out low $\tau_{\gamma\gamma}$ environments

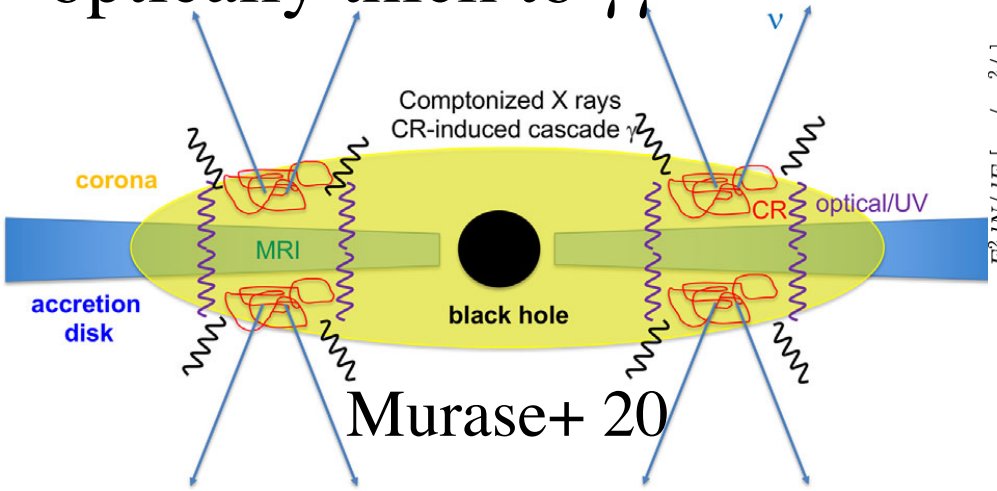
MAGIC Col. 19

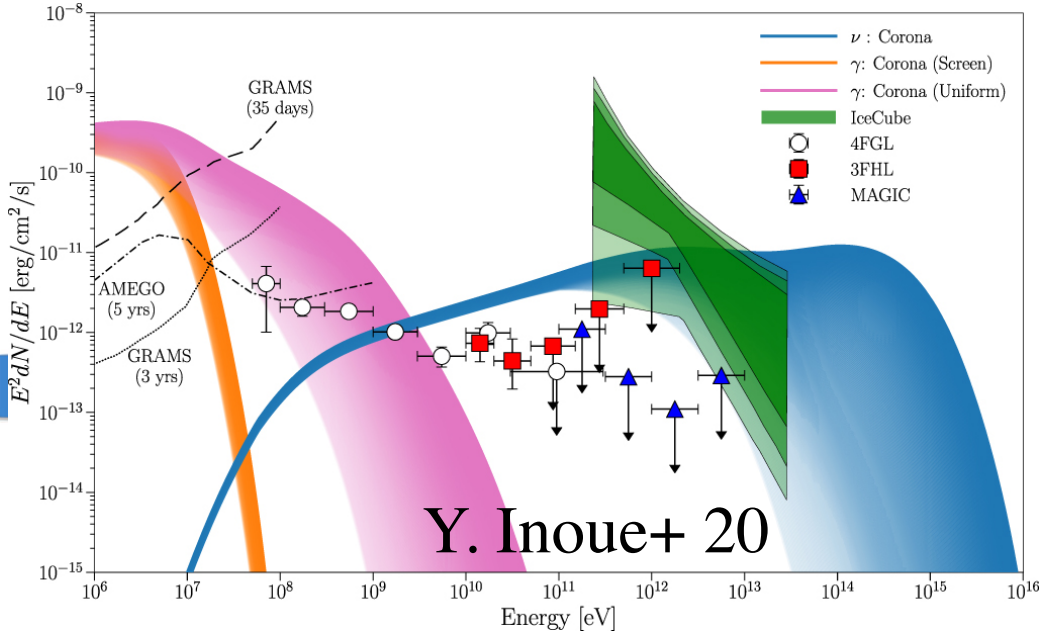
neutrino + gamma from NGC 1068: AGN origin?

AGN wind kpc-scale ext. shock?
-> ruled out by TeV upper limits



hot coronal regions of accretion disks?
pp+pγ in compact regions
optically thick to γγ





issues:
- acceleration in corona robust?
- origin of GeV γ rays?
- cascade at <<MeV?

neutrino + gamma from NGC 1068: AGN origin?

AGN wind kpc-scale ext. shock?
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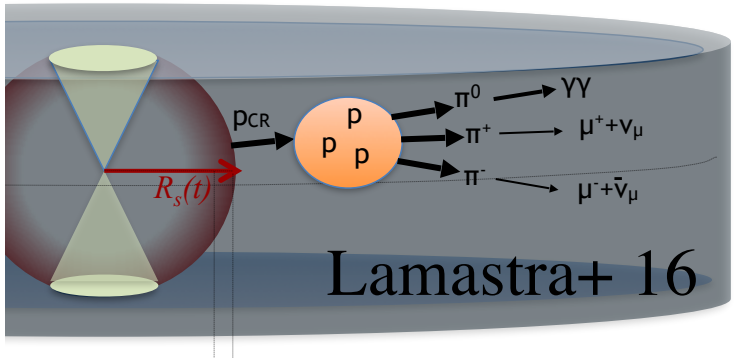

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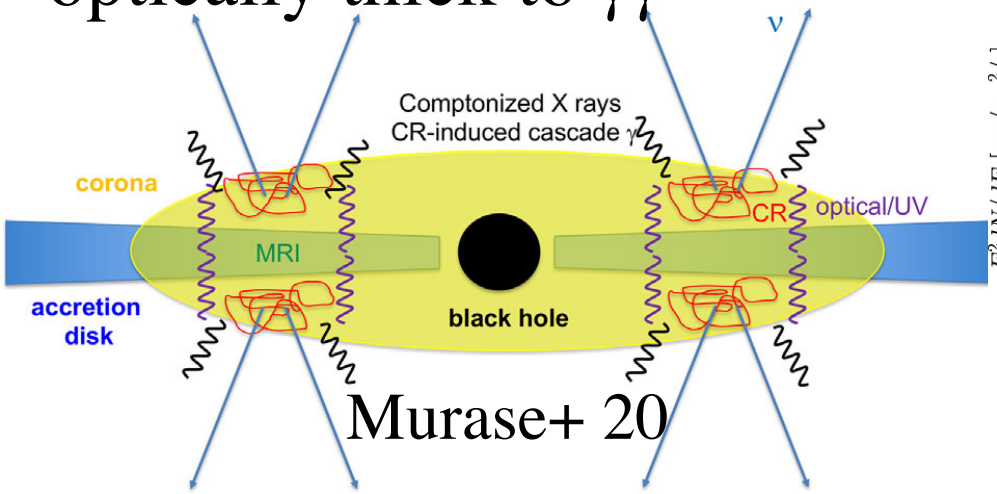
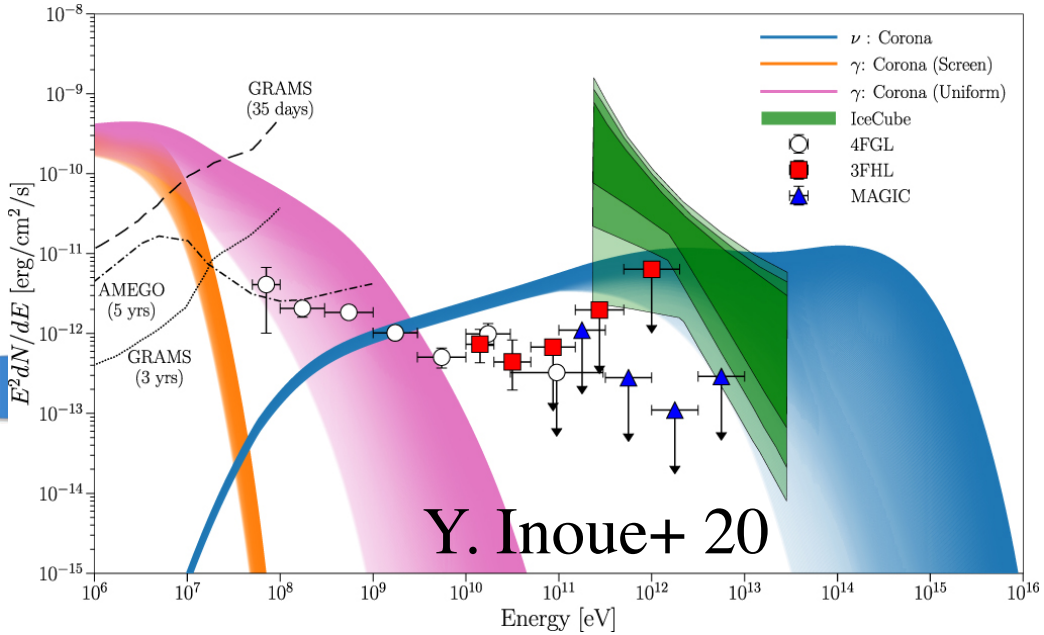


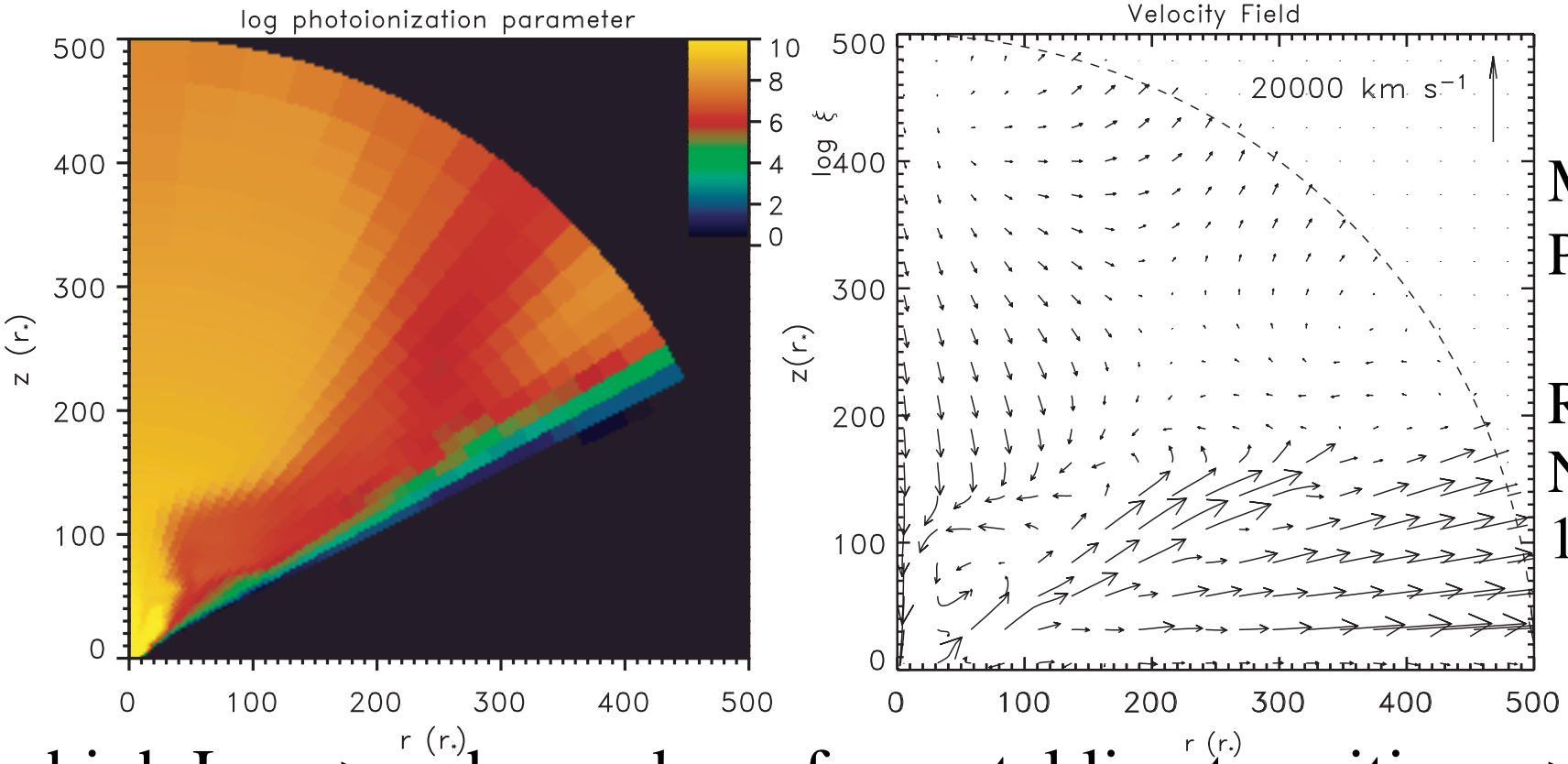


issues:
- acceleration in corona robust?
- origin of GeV γ rays?
- cascade at <<MeV?

-> this study:
- shock accel. in winds
- inner pγ + outer pp
- evaluate down to radio

line-driven winds: successful vs failed

c.f. CAK75



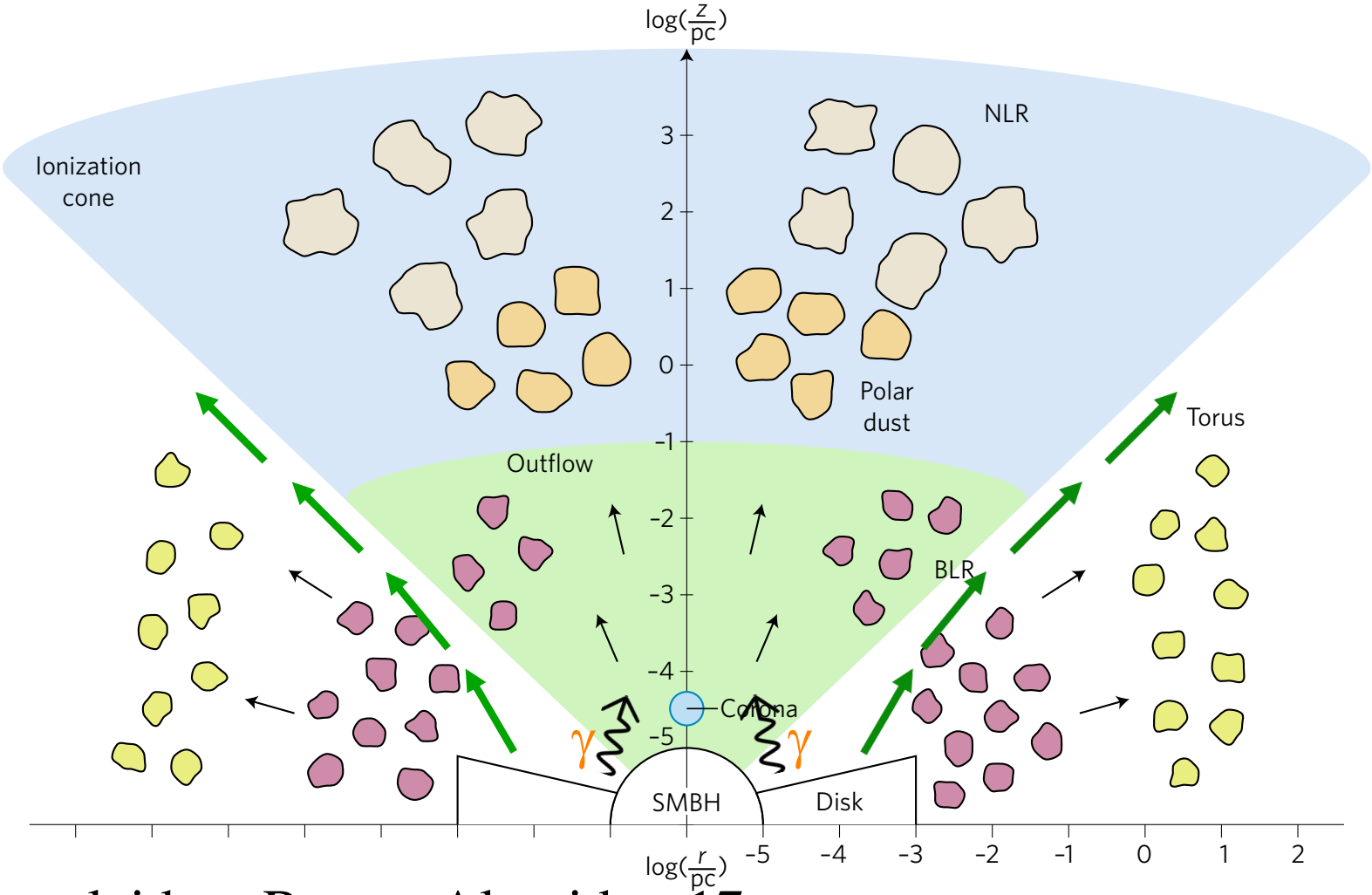
Murray+ 95
Proga+ 00
04
Risaliti+ 10
Nomura+
16, 17, 20

- high L_{UV} -> enhanced p_{rad} for metal line transitions -> outflow
- high L_X ->

inner R: overionization, p_{rad} loss -> failed wind ($v<v_{esc}$, fallback)
outer R: shielding -> successful wind ($v>v_{esc}$, mainly equatorial)

- failed winds expected for moderate/high $\dot{M}$, inc. NGC 1068 ->
  X-ray obscurers, BLR, soft X excess? Giustini & Proga 19
- outflow + fallback -> shock formation? high P? Sim+ 10

pγ ν+γ from inner regions of AGN winds

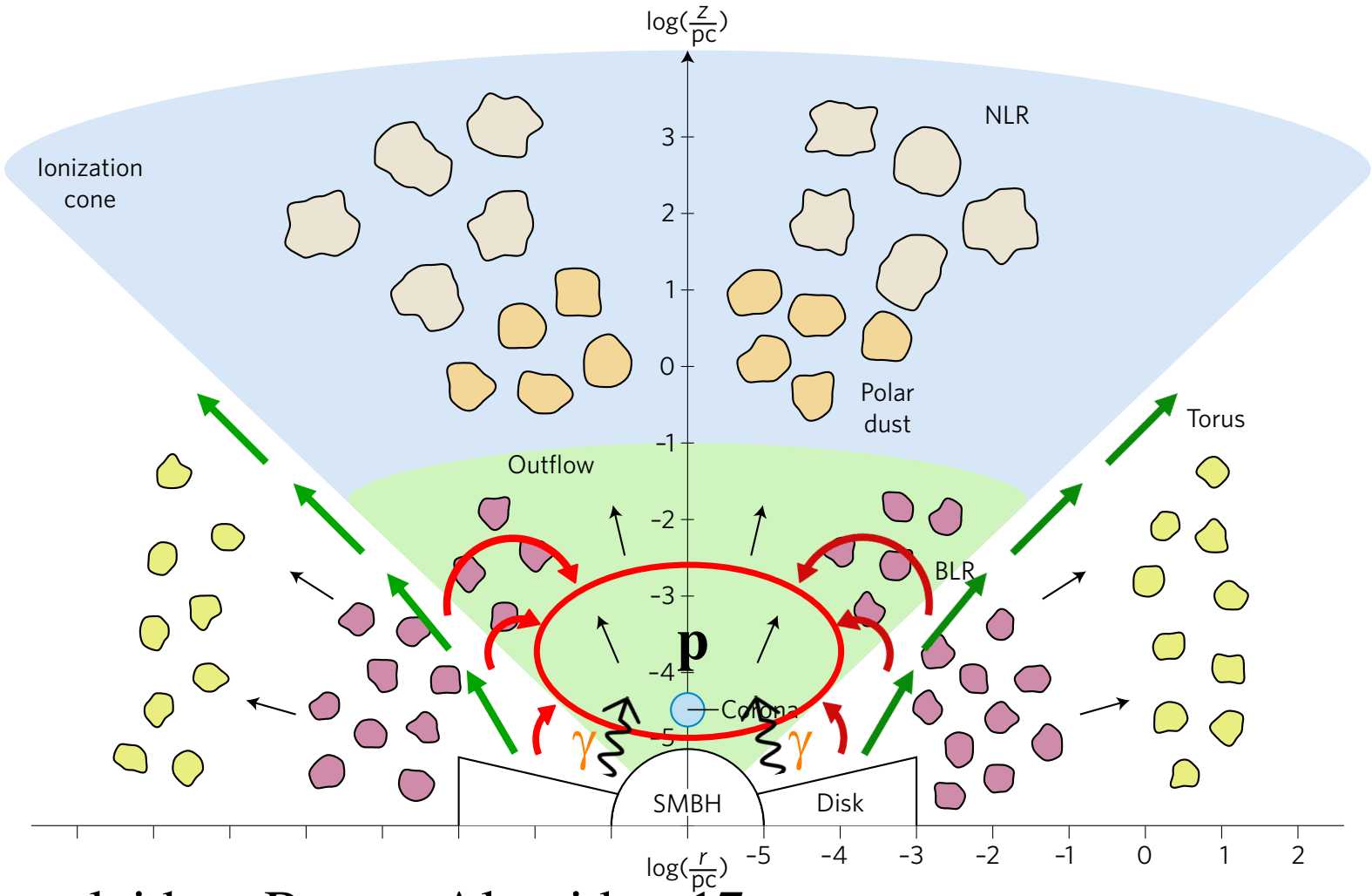


obs.

overlaid on Ramos Almeida+ 17

pγ ν+γ from inner regions of AGN winds

inner failed winds -> “internal” shocks -> proton acceleration



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pγ ν+γ from inner regions of AGN winds

inner failed winds -> "internal" shocks -> proton acceleration

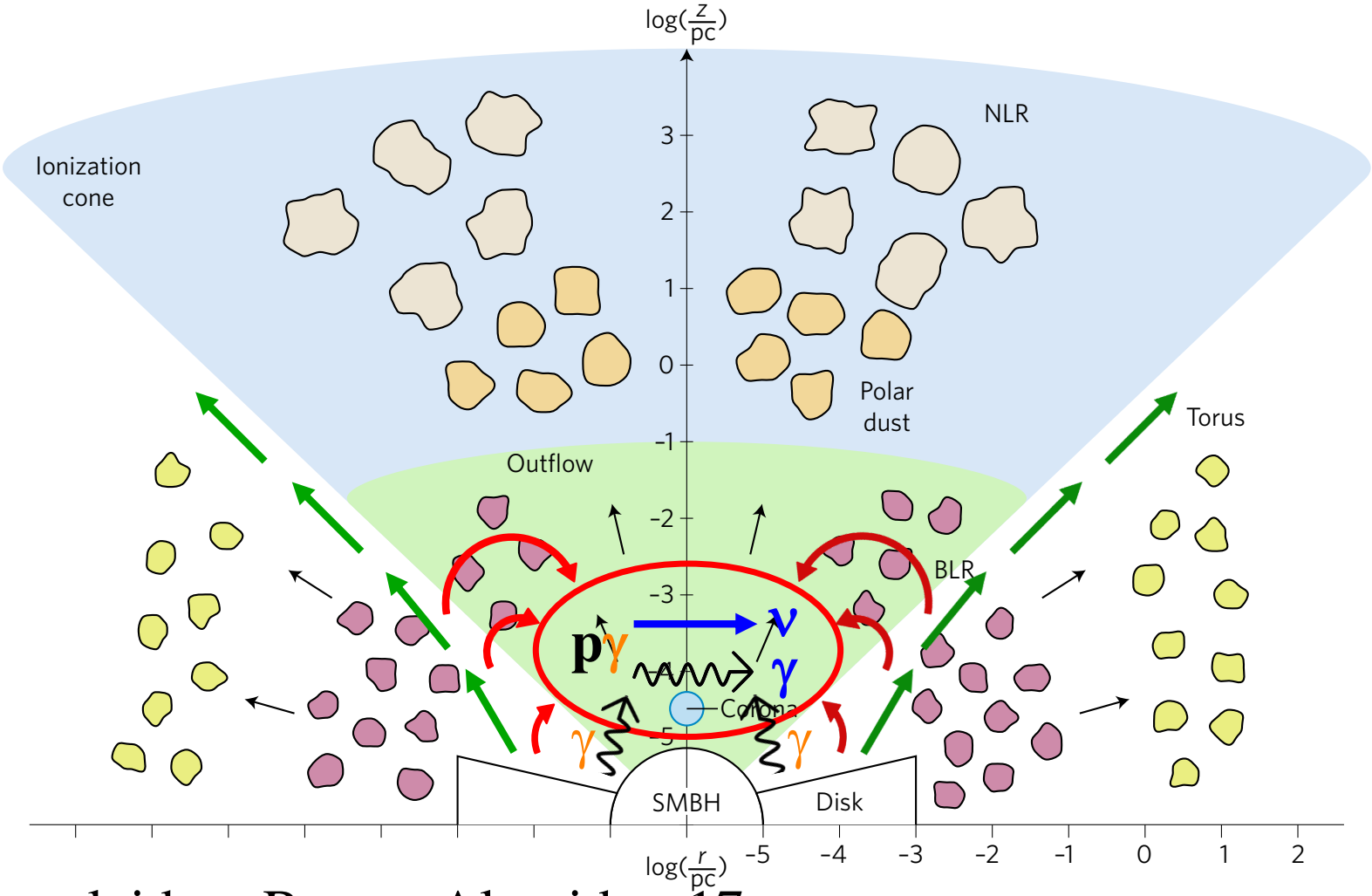
$p+\gamma \rightarrow N+ \pi^0, \pi^{\pm}$

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

$E_p \varepsilon_\gamma \sim 10^{17}$ eV^2

$E_\nu \sim 0.05\ E_{p,CR}$

$E_\nu \sim 1$ TeV:
$E_p \sim 20$ TeV
$+\ \varepsilon_\gamma \sim 7$ keV



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

$e^+e^-+B/\gamma \rightarrow e^+e^-+\gamma$

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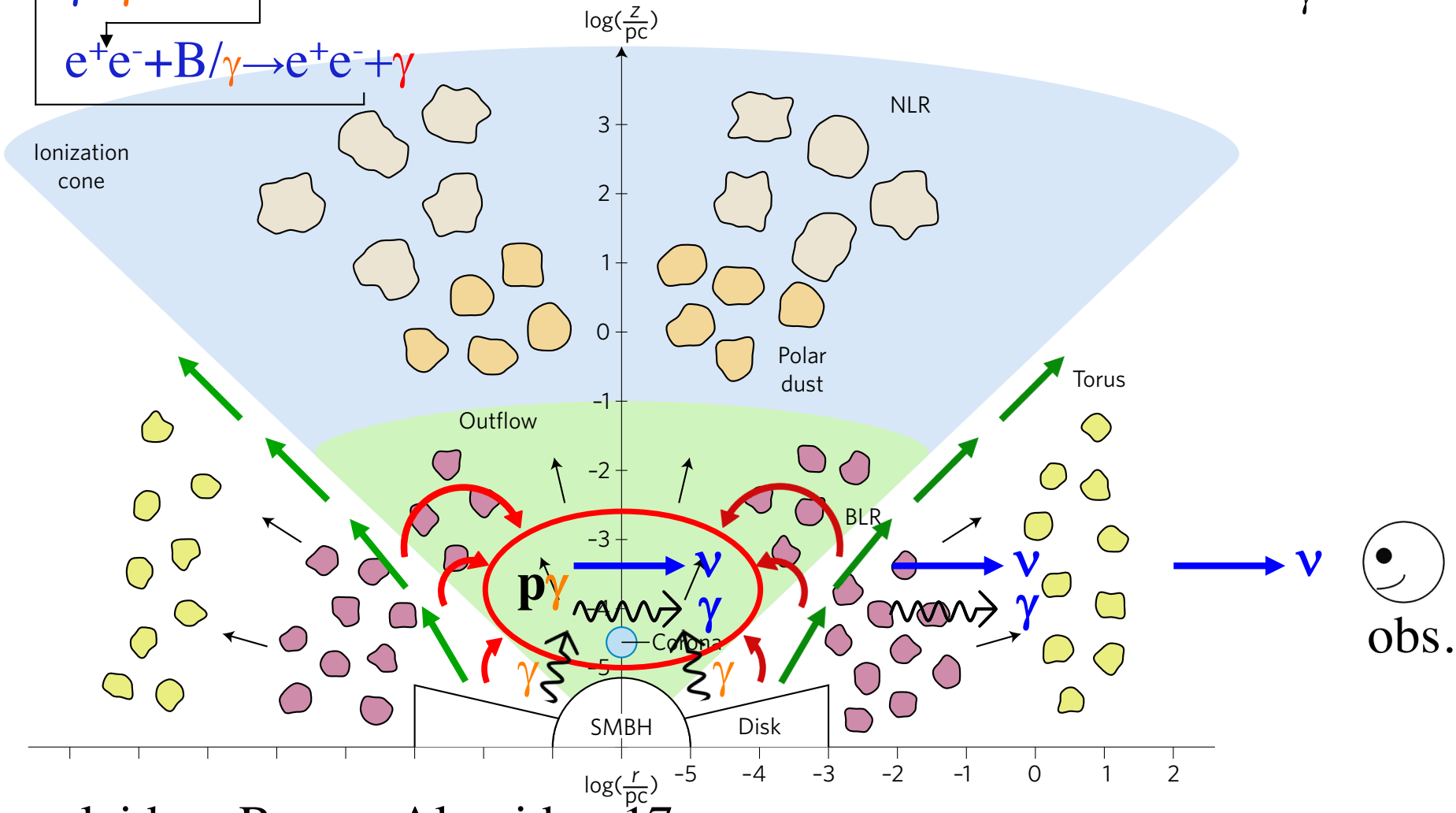

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$E_\nu \sim 1$ TeV:
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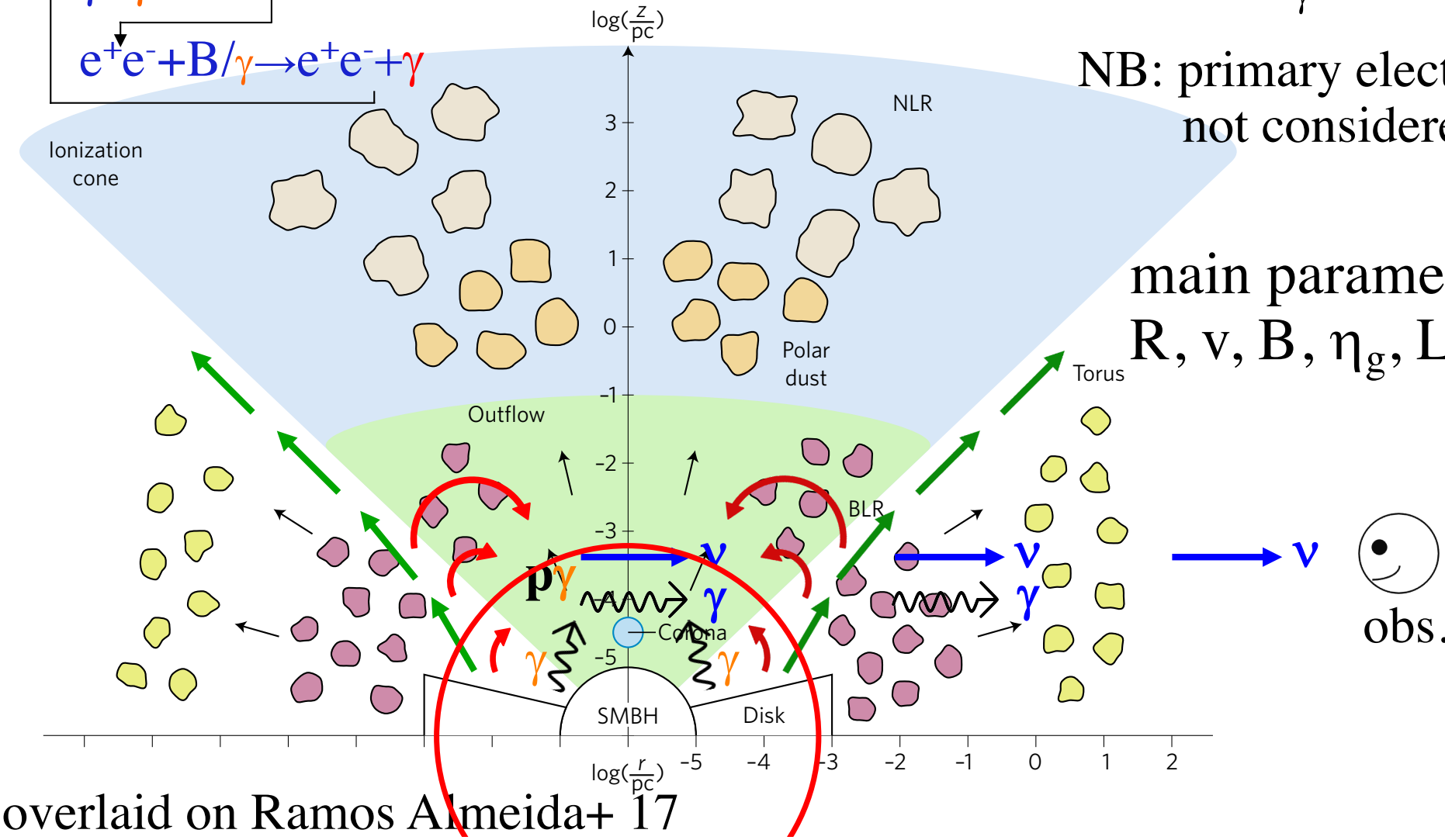
NB: primary electrons not considered

main parameters:
R, v, B, η_g, L_p



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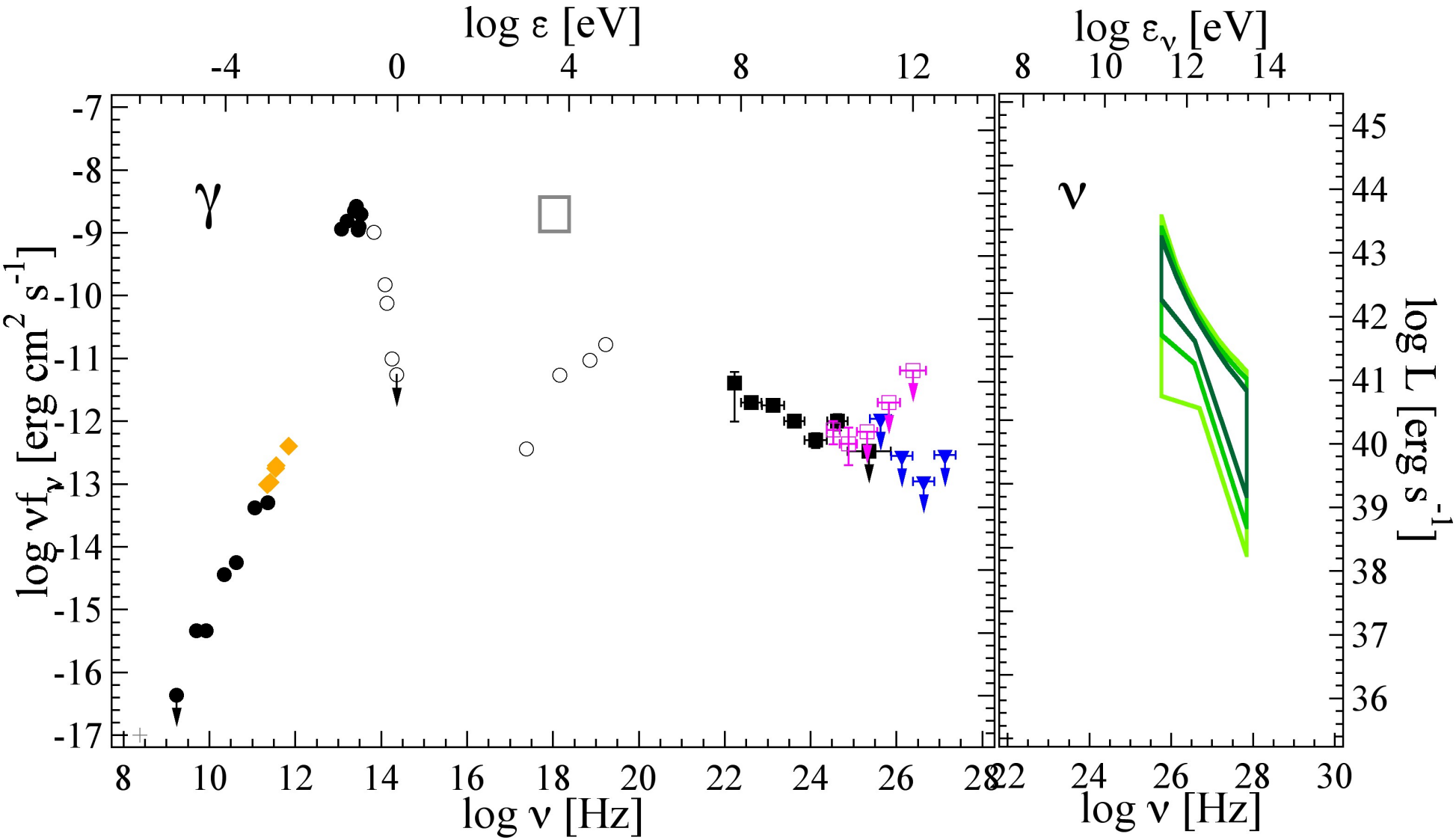
MM SED: NGC 1068



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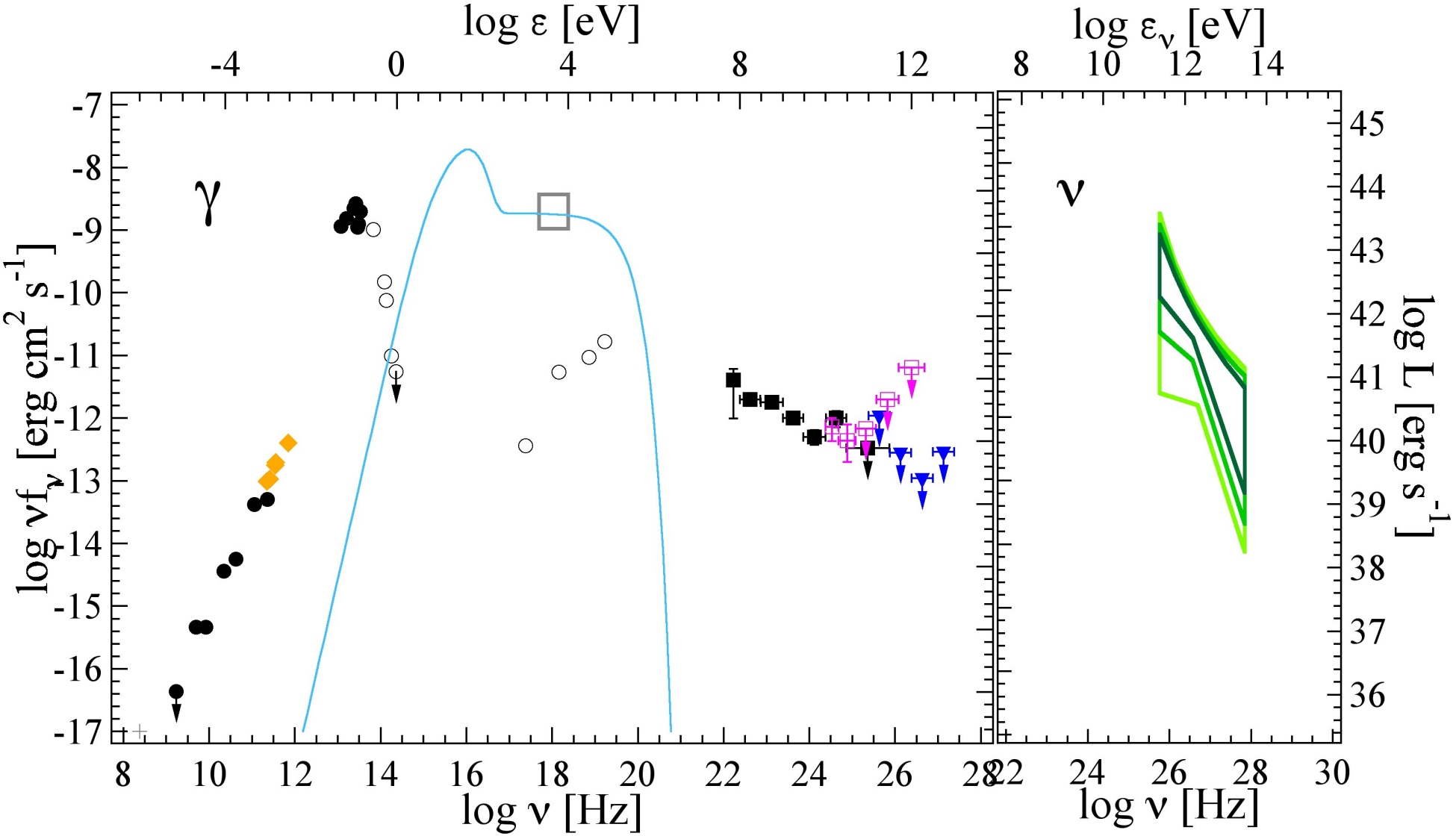
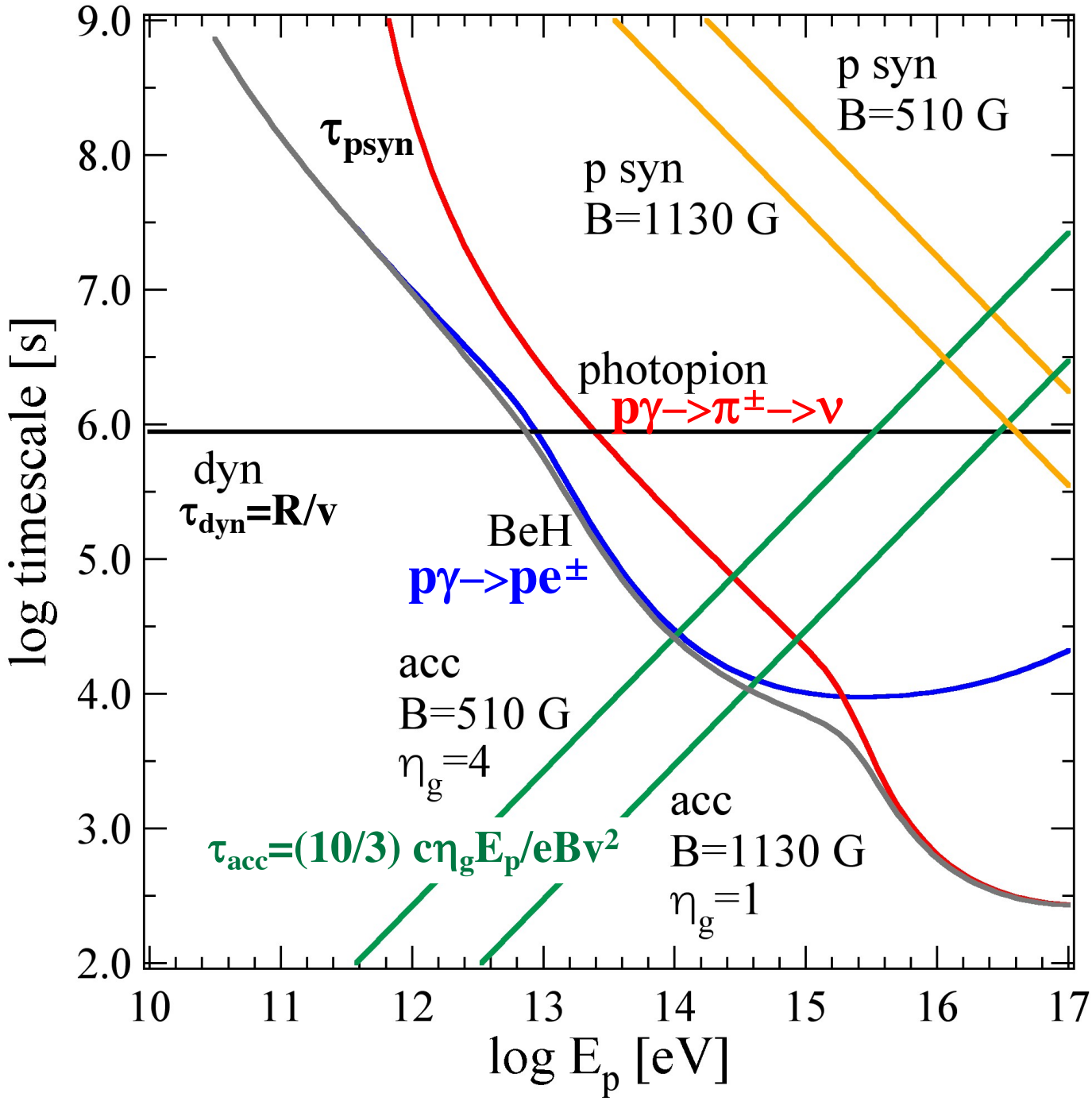


D=14 Mpc, $M_{BH}=3\times10^7\,M_\odot$
$L_{disk}=10^{45}$ erg/s, $\varepsilon_{disk}=32$ eV
$L_{cor,2\text{-}10}=7\times10^{43}$ erg/s, $\Gamma_{cor}=2$, $\varepsilon_{cor}=128$ keV

Greenhill+ 96, Gallimore+ 96
Woo & Urry 02
Bauer+ 15, Marinucci+ 16

inner region (failed wind): timescales

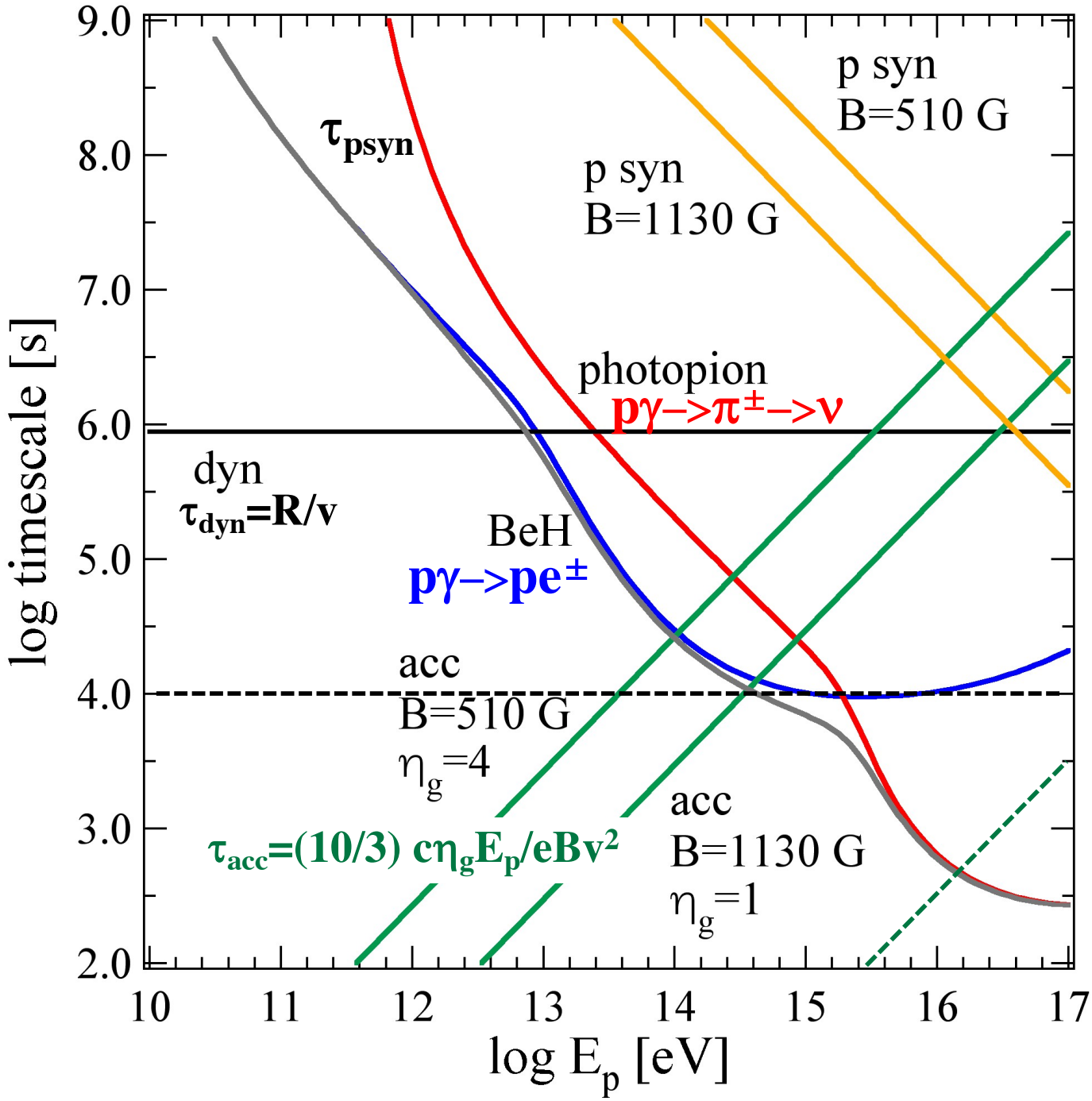


$R=10R_s=0.9\times10^{14}$ cm
B=510 G
($\varepsilon_B=0.1$ for
$L_{fw}=3\times10^{44}$ erg/s)

v=1000 km/s ->
$E_{p,br} \propto Rv \sim 20$ TeV
$E_{p,max} \propto B^{1/2}R^{1/2}v$
~ 100 TeV

NB $v << v_{esc} \sim 0.3c$
<-> failed wind

inner region (failed wind): timescales



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~ 100 TeV

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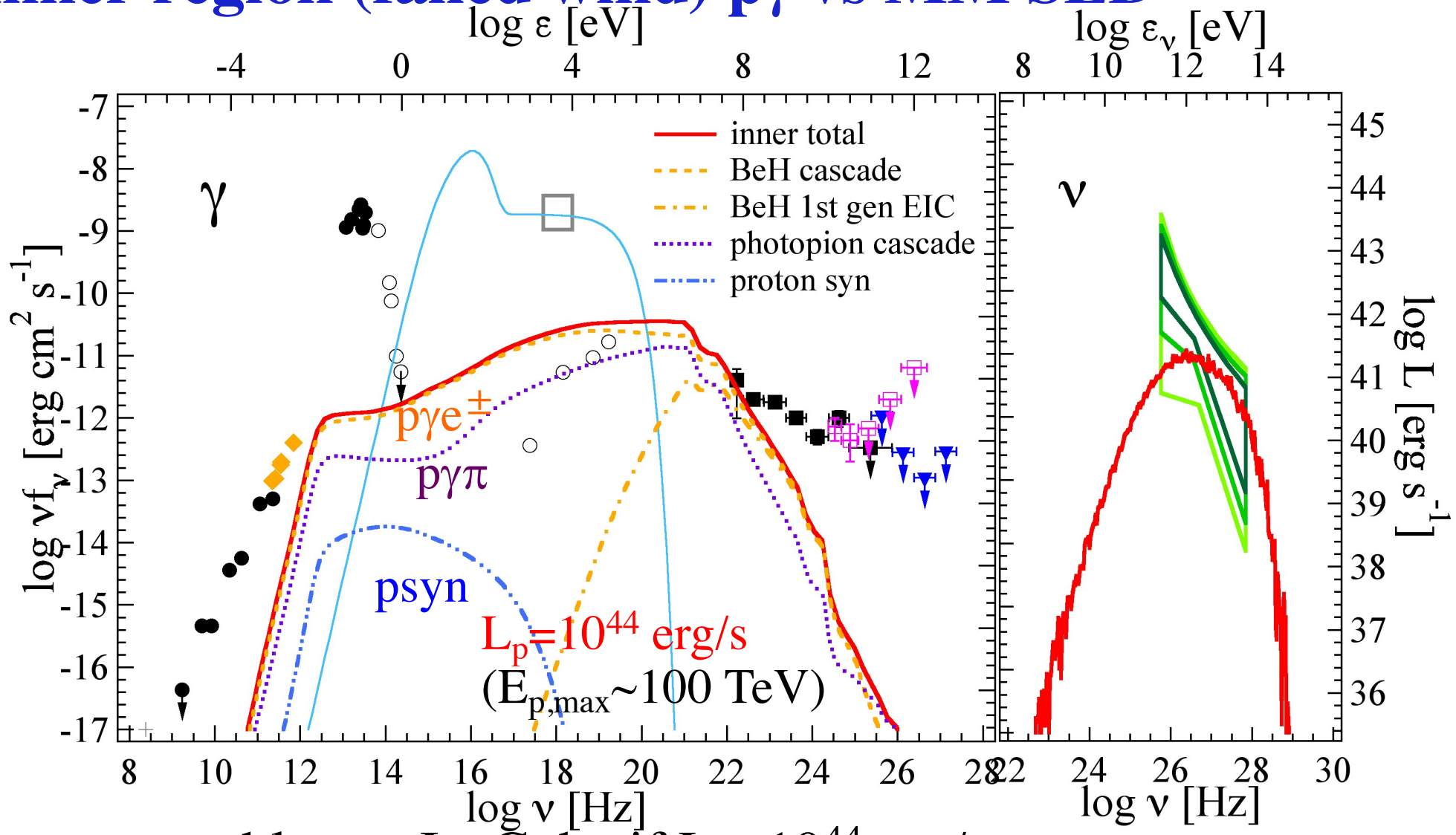
$v\sim v_{esc}\sim0.3c$
-> $E_{p,br}\sim400$ TeV
$E_{p,max}\sim10$ PeV

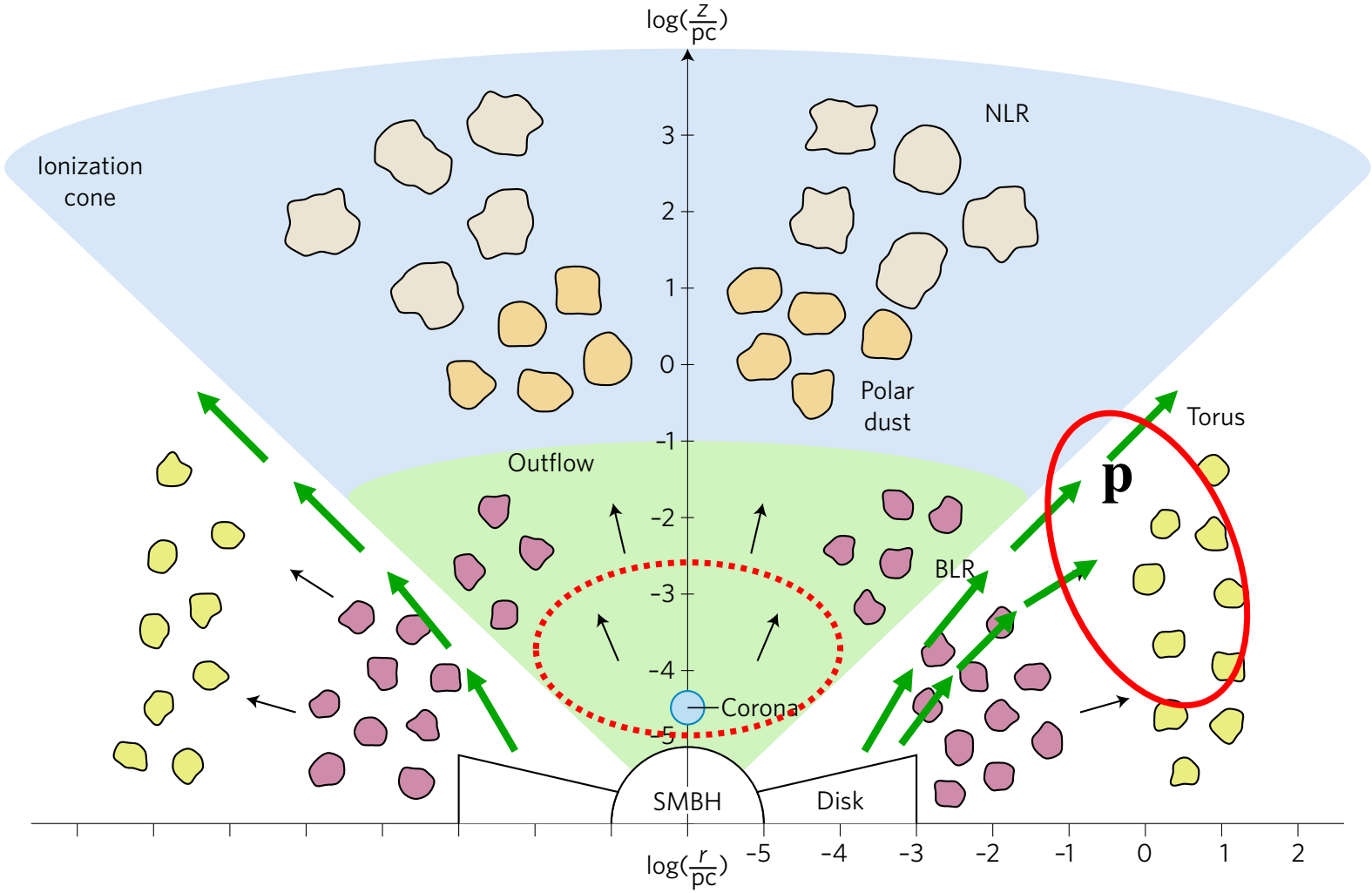
inner region (failed wind) pγ vs MM SED



- ν: reasonable wrt IceCube if L_p~10^{44} erg/s
- γ: EM cascade (mostly pγe$^{\pm}$) consistent wrt available MWL
  γγ attenuated by disk UV-X >~MeV but non-negligible ~<GeV
  prominent at (keV-)MeV -> for future instruments

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

outer successful wind + torus impact c.f. García-Burillo+ 19
-> external shock -> proton acceleration



obs.

overlaid on Ramos Almeida+ 17

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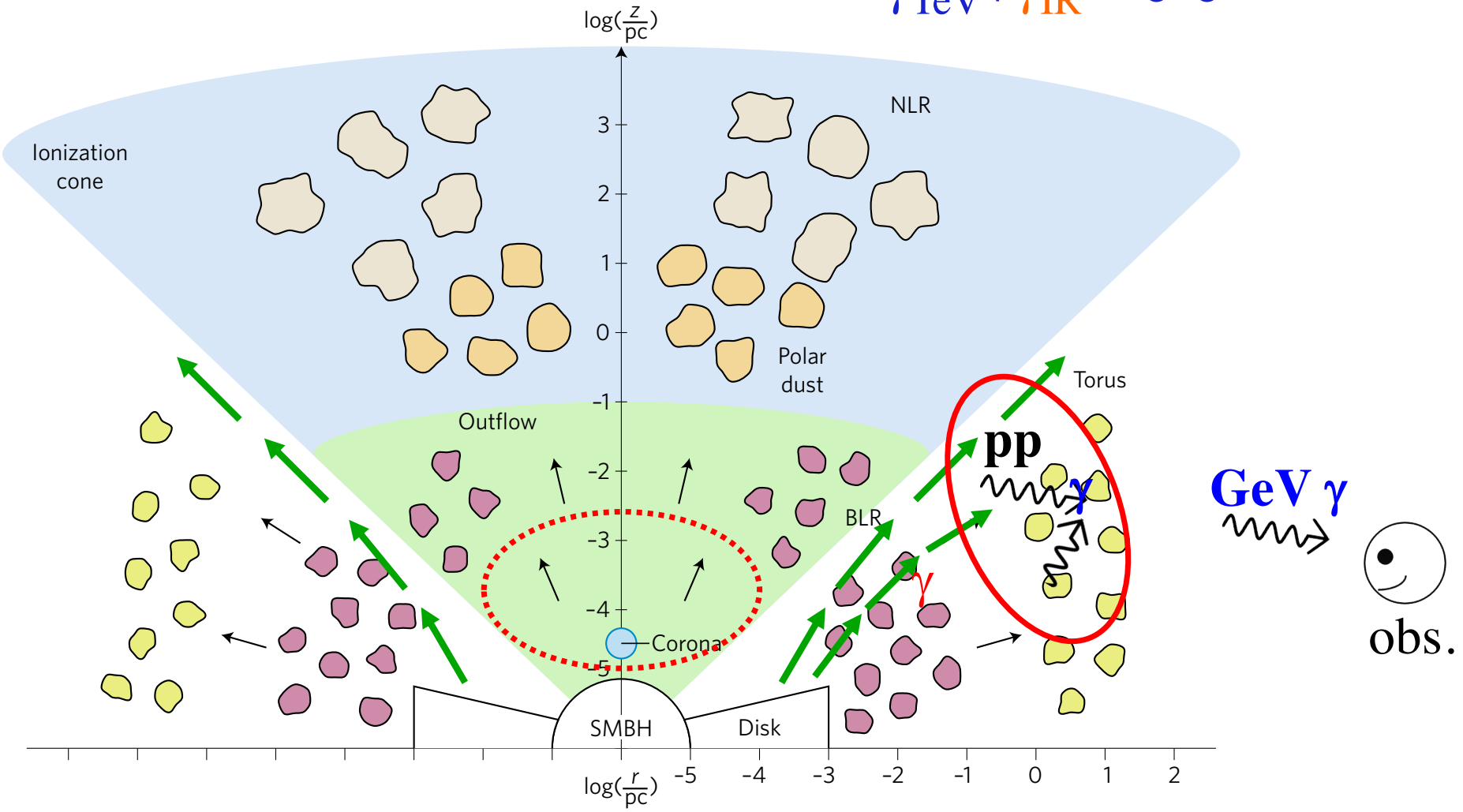
$p_{CR}+p_{gas}\rightarrow N+ \pi^0, \pi^{\pm}$ $\pi^0\rightarrow 2\gamma$

$\gamma_{TeV}+\gamma_{IR}\rightarrow e^+e^-$



GeV γ

obs.

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c.f. García-Burillo+ 19

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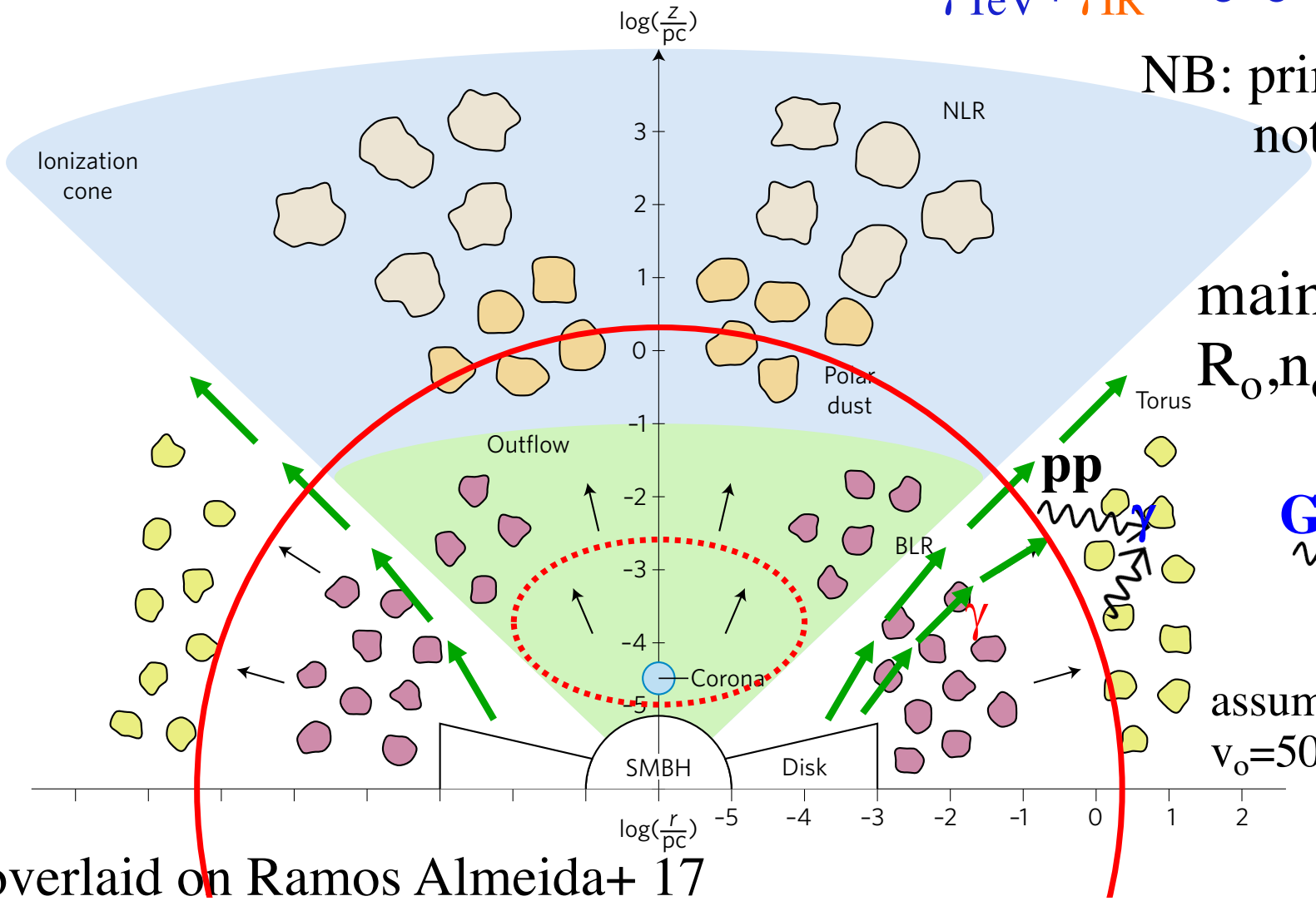


NB: primary electrons not considered

main parameters:
$R_o, n_o, B_o, L_{p,o}$

pp γ

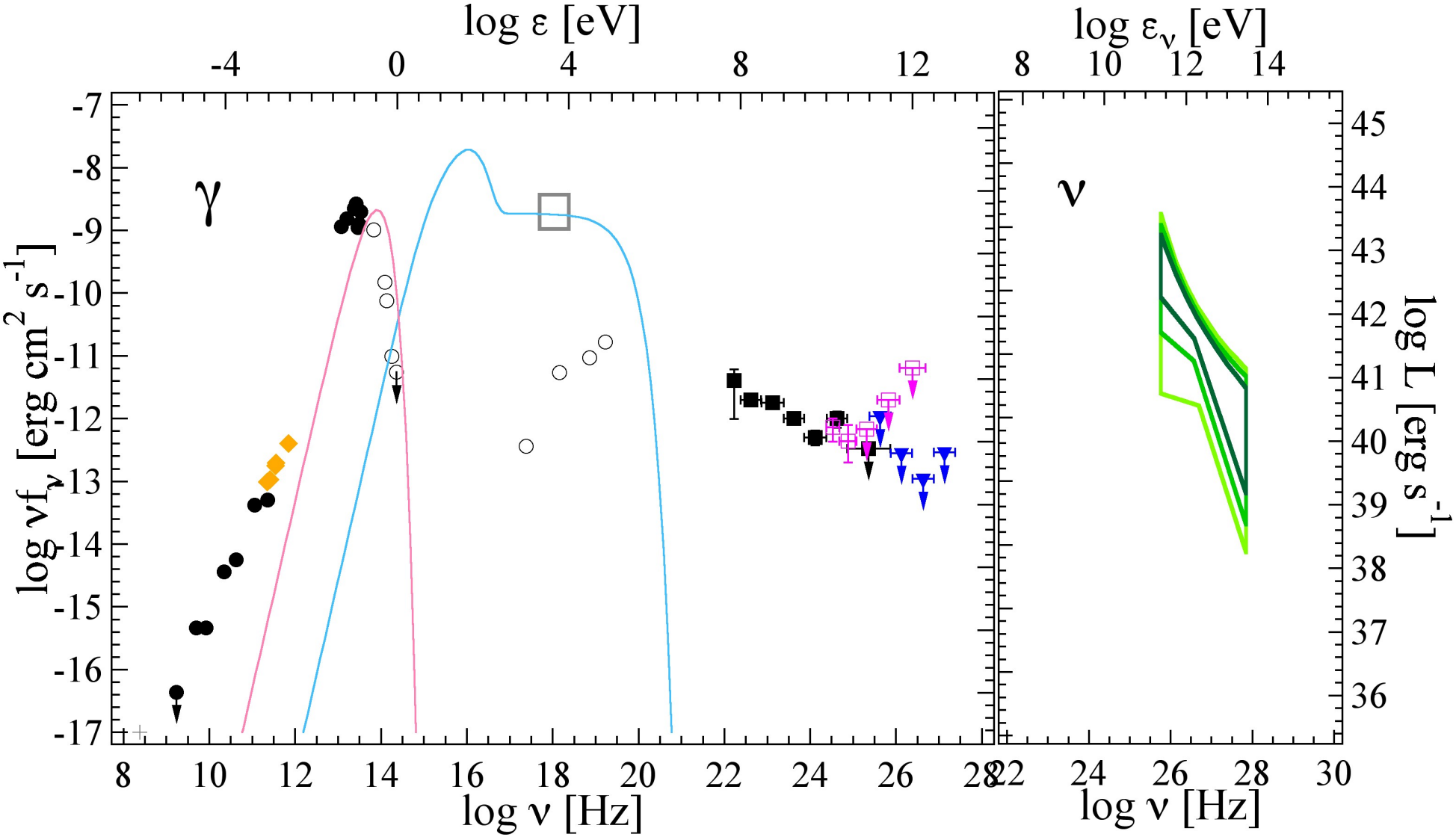
GeV γ

obs.

assume
v_o=5000 km/s, $\eta_{g,o}$=10

overlaid on Ramos Almeida+ 17

MM SED: NGC 1068



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$R_{tor}=0.1$ pc, $T_{tor}=1000$ K

Greenhill+ 96, Gallimore+ 96
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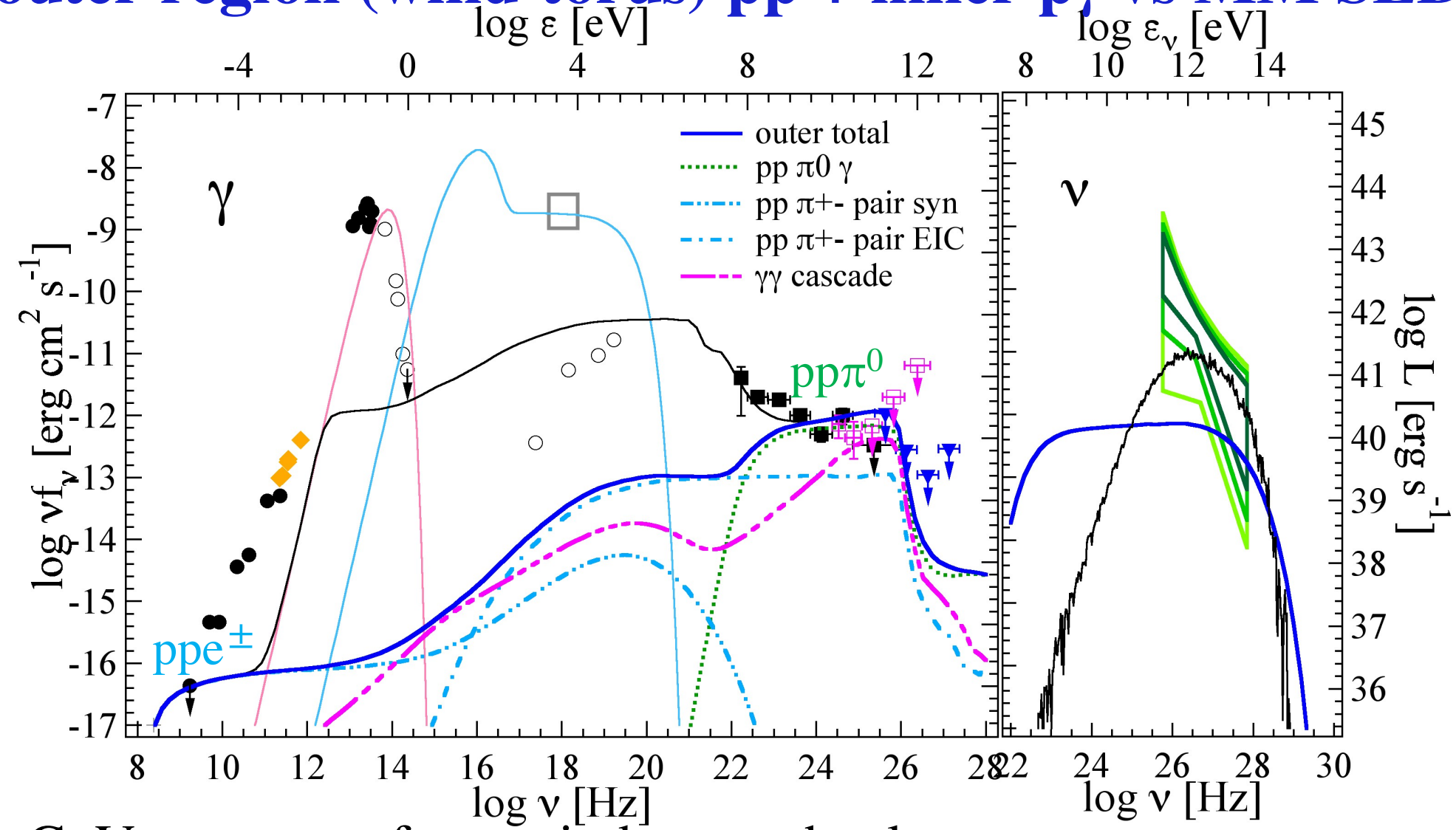
Gamez Rosas+ 22

outer region (wind-torus) pp + inner pγ vs MM SED

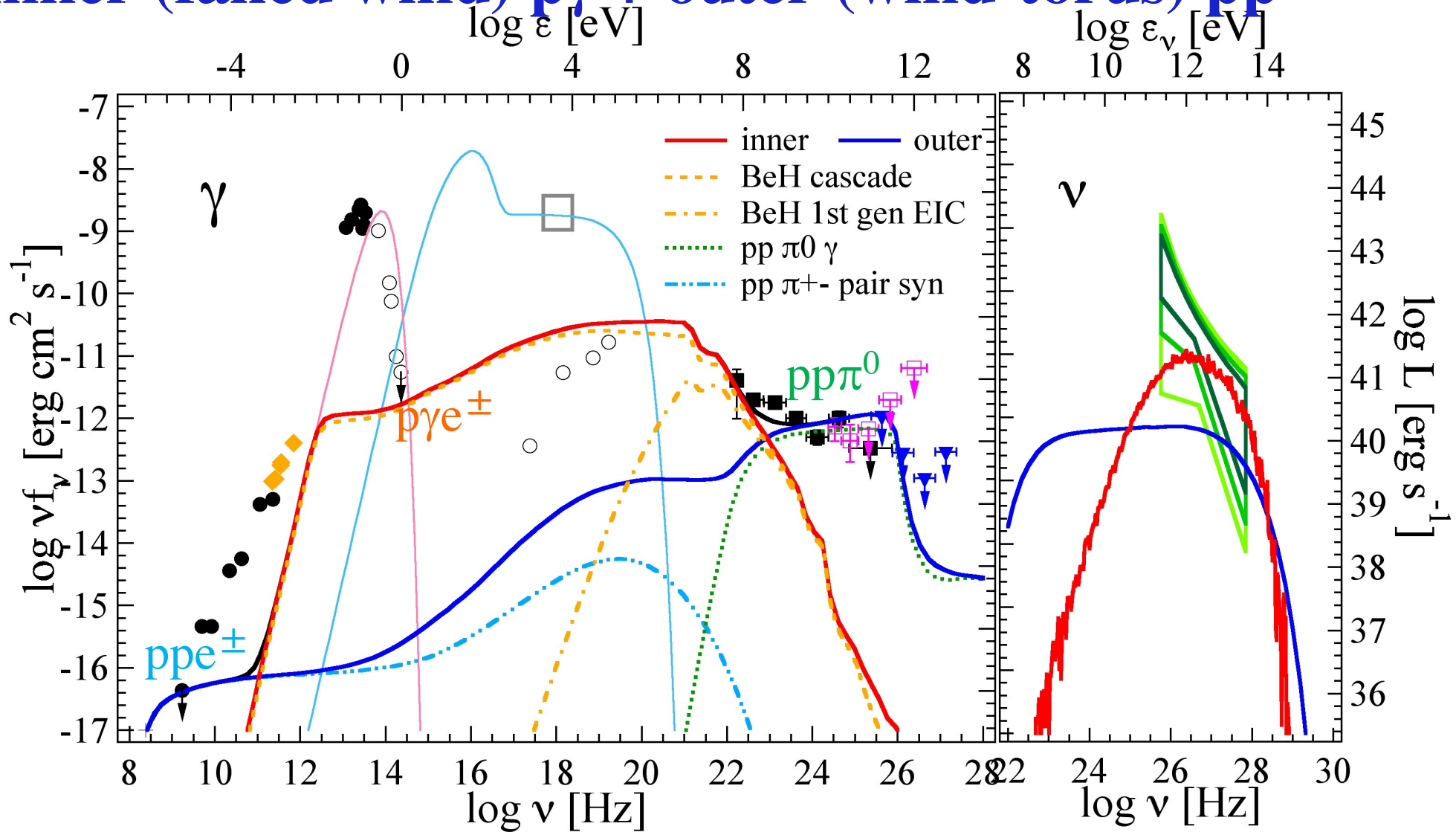


- GeV: pp γ-rays from wind-torus shock
- TeV: γγ attenuated by torus IR
- potential contribution to radio

also e.g. Circinus
Fermi UFO sample?

R_{tor}=0.1 pc, n_{tor}=10^6 cm^{-3}, B_{tor}=7 mG, L_p=2.6x10^{42} erg/s

inner (failed wind) pγ + outer (wind-torus) pp



- inner region (failed wind) pγ: TeV ν, <GeV cascade
- outer region (wind-torus) pp: >GeV γ, GHz radio

summary

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

interpretation of ν+γ emission from NGC 1068

- p accel. in inner regions near BH <- failed line-driven wind
- assuming $v \ll v_{esc}$, pγ neutrinos with soft TeV spectrum
- EM cascade γγ attenuated >MeV but non-negligible <GeV
- p accel. in wind-torus interaction shock, pp at GeV γ, potentially radio -> to be explored

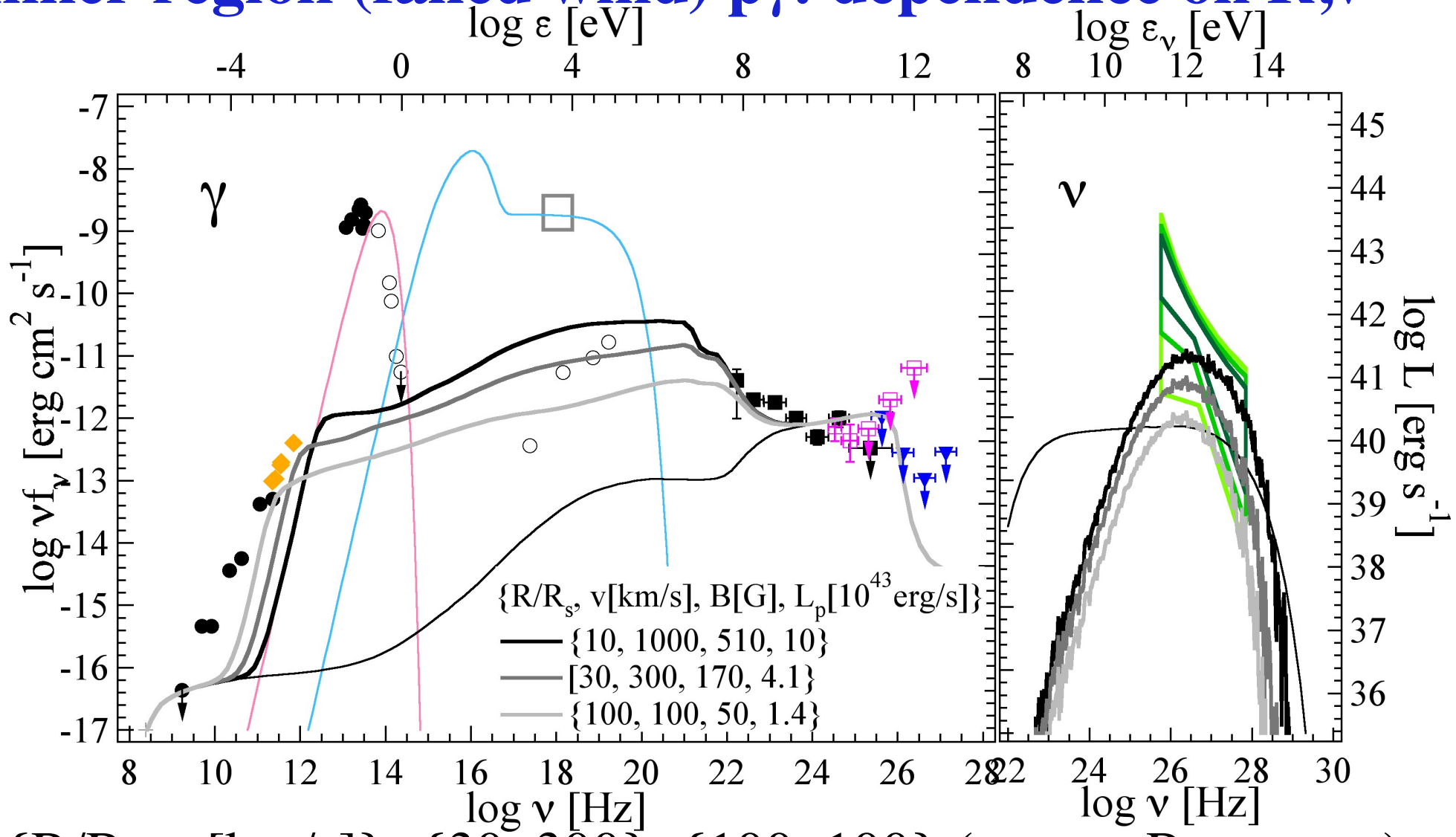
future tests and prospects

- cascade MeV, MM variability: ν, <GeV γ vs polarized opt/NIR
- other AGN (esp. unobscured) by IceCube-Gen2, CTA, etc
- contribution to diffuse ν background
- unique info on AGN wind formation, esp. obscured objects

arXiv: **2207.02097**
for submission to PRL

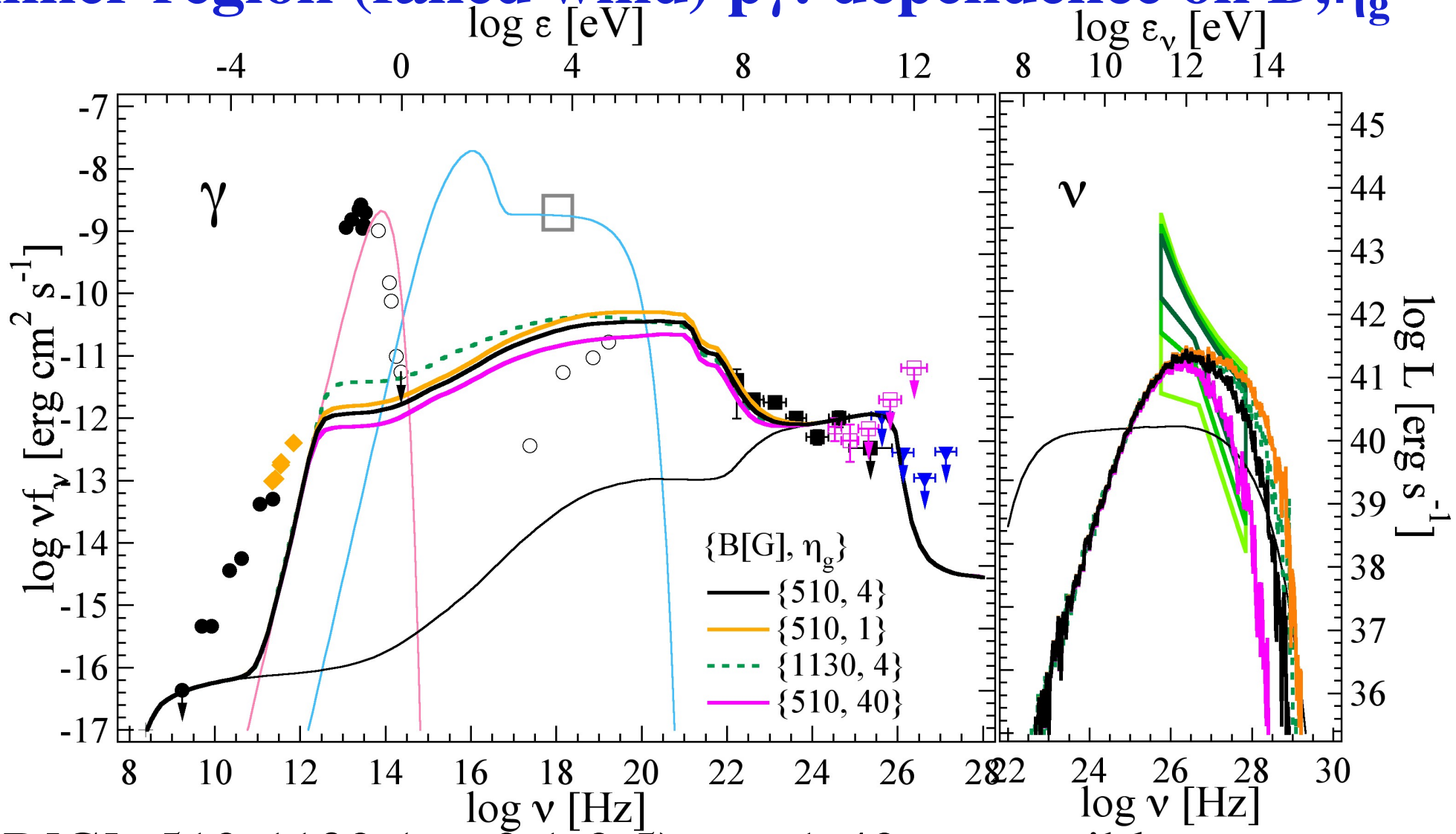
backup slides

inner region (failed wind) pγ: dependence on R,v



- {R/Rs, v[km/s]}={30, 300}, {100, 100} ($\varepsilon_{\nu,max} \propto Rv \sim$const.)
- γγ abs., SSA ↓ when R↑ -> L_p↓ for consistency with EM data
  -> disfavored due to f_ν↓

inner region (failed wind) pγ: dependence on B,η_g



- B[G]~510-1130 (ε_B~0.1-0.5), η_g~1-40 compatible with IceCube data

importance of AGN winds

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

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

~<pc – blueshifted atomic absorption

X-ray UFOs / UV BAL: v>~0.1c, L_{kin}~<L_{Edd}, $\dot{M}$~<M_{edd}

X-ray WAs / UV NAL: v>~1000km/s

~<kpc – narrow emission line region (UV-IR): v>~1000km/s

>~kpc – molecular emission (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…

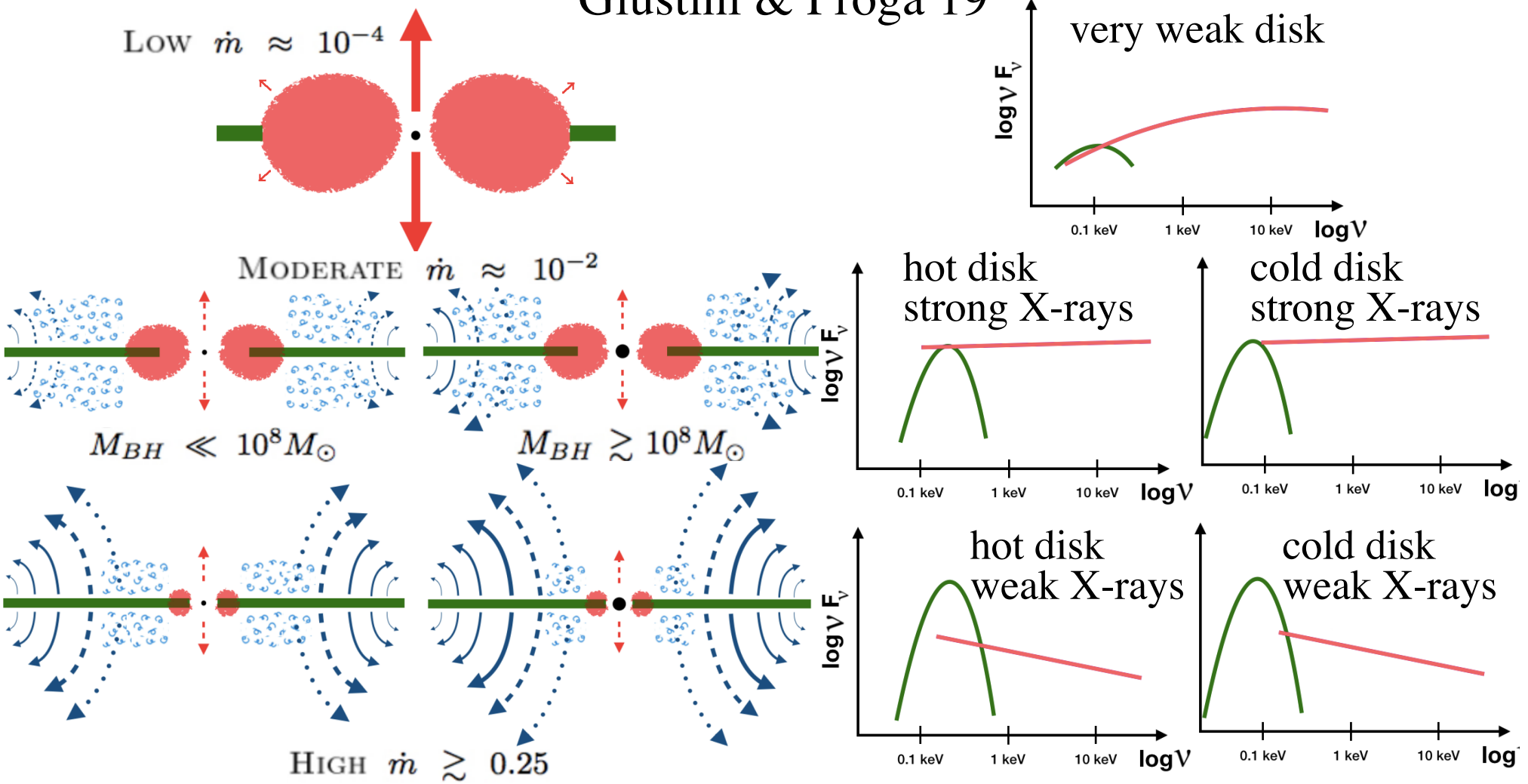
3. Likely important for collimating jets in radio-loud objects

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

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

successful/failed winds vs accretion rate, BH mass

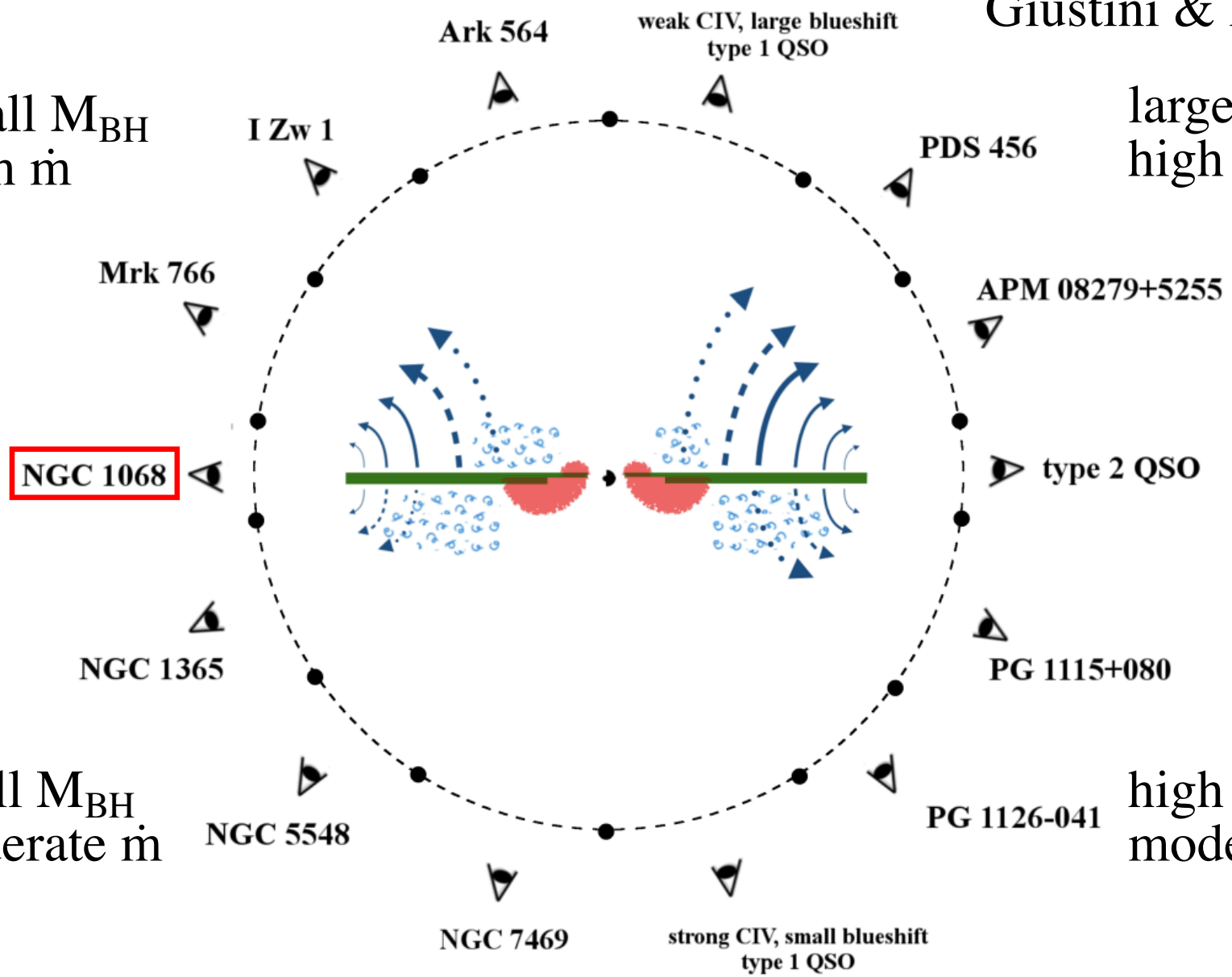
Giustini & Proga 19



- qualitative scenario assuming ṁ scaling of thin disk+corona
- consistent with observed AGN SEDs, wind signatures
- robust failed winds at inner R for moderate to high ṁ:
  origin of BLR, X-ray obscurers (e.g. NGC 5548)?

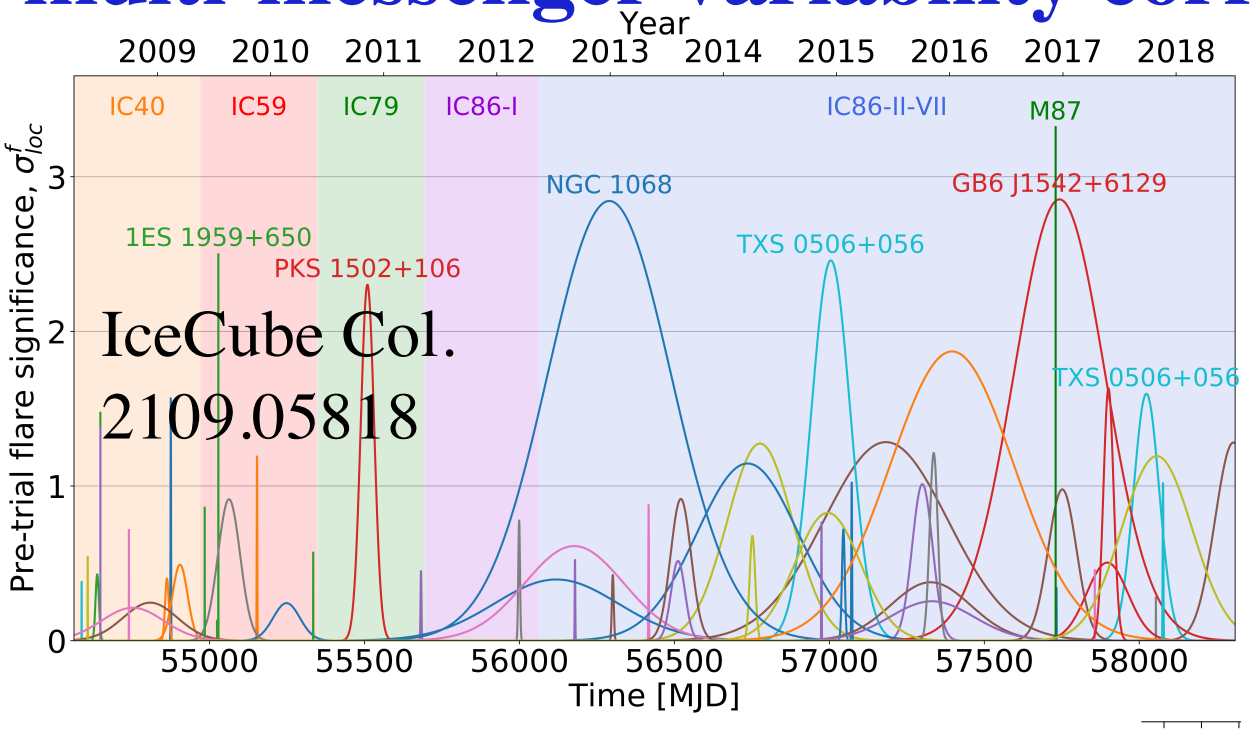
failed winds in inner regions of NGC 1068?

Giustini & Proga 19

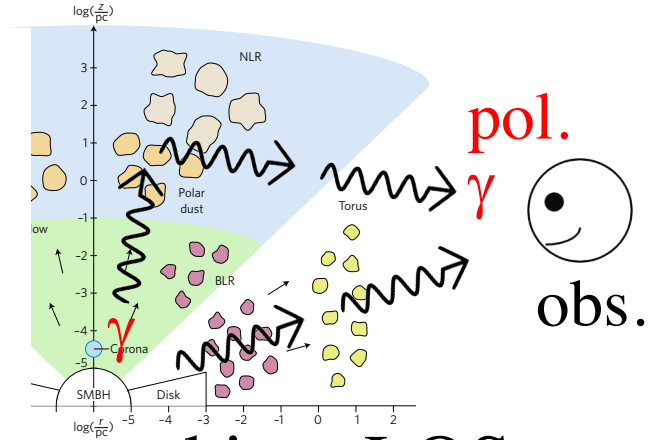


- NGC 1068: log $M_{BH}/M_{\odot}$~7.2, $\dot{m}$~0.5
  -> failed winds in inner regions expected

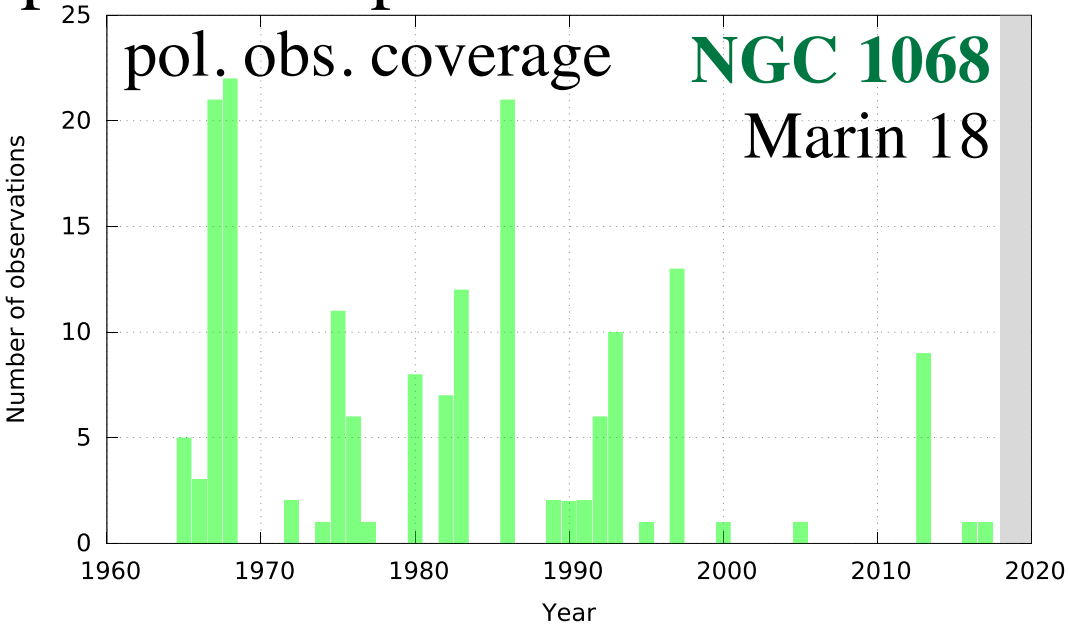
multi-messenger variability correlation



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



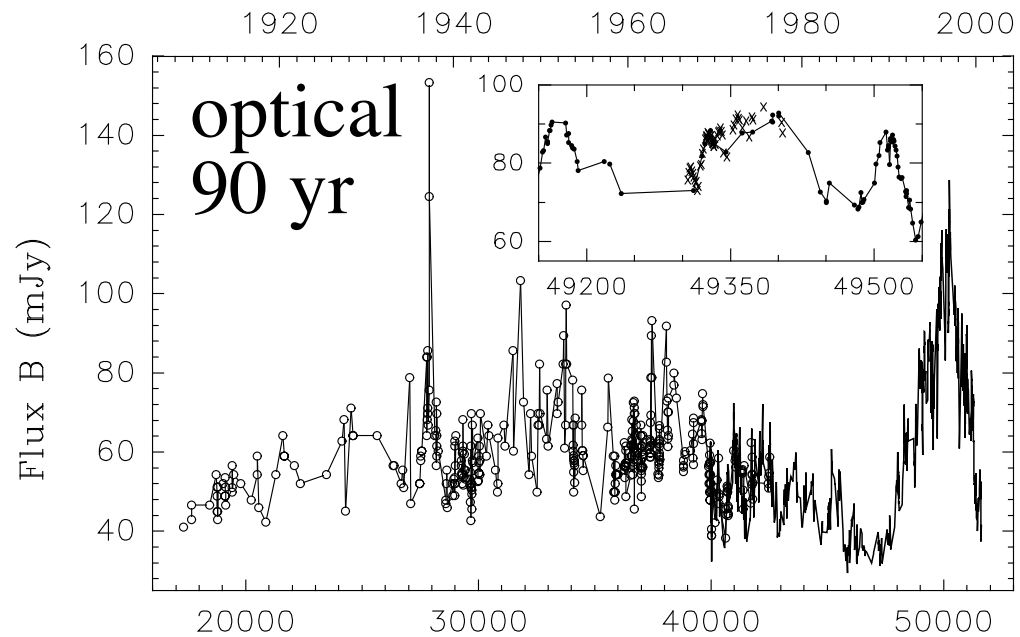
polarized optical-NIR: nuclear emission scattered into LOS



also escaping hard X-rays

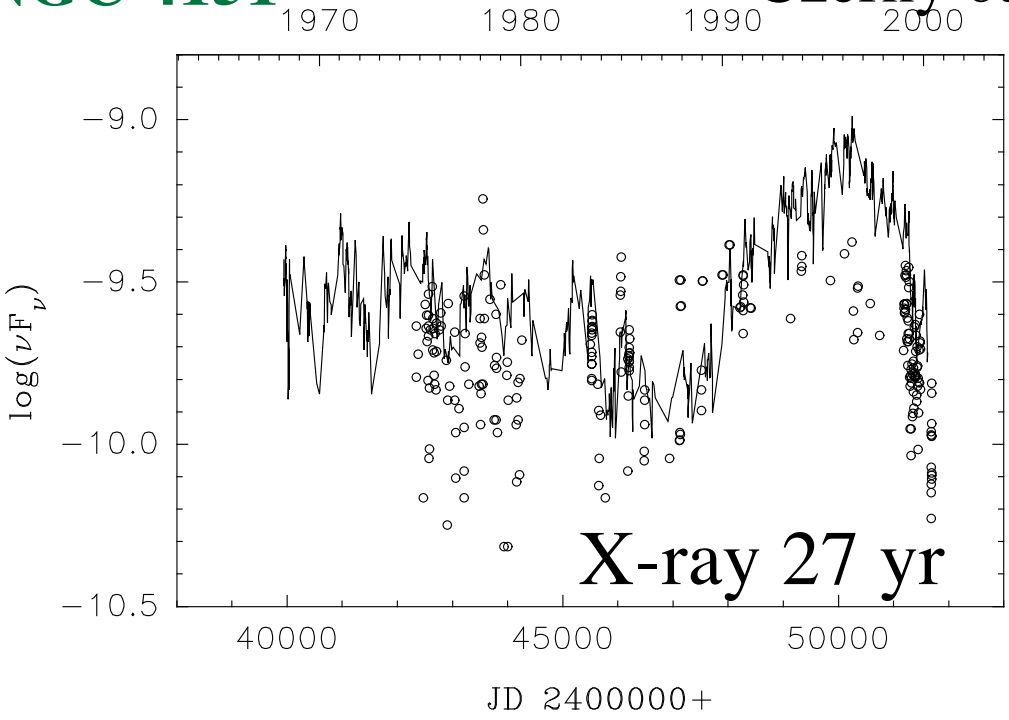
even better:
unobscured Seyfert 1

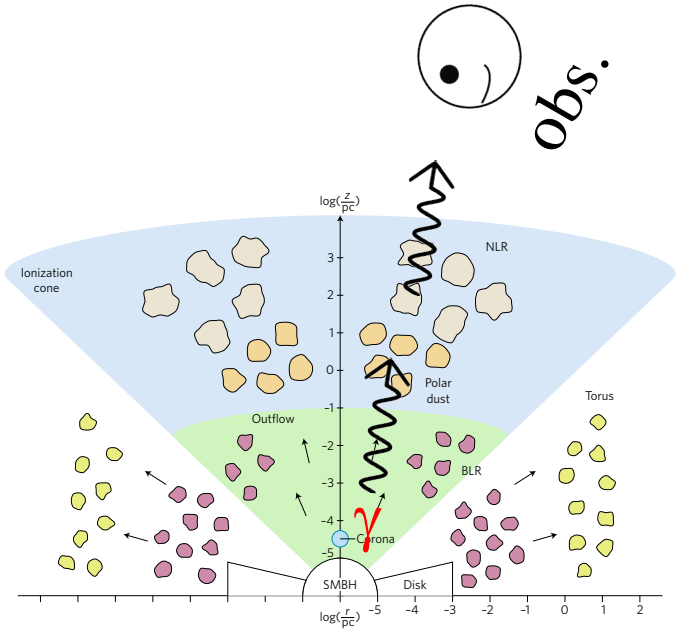
variability in unobscured Seyfert I with wind



NGC 4151

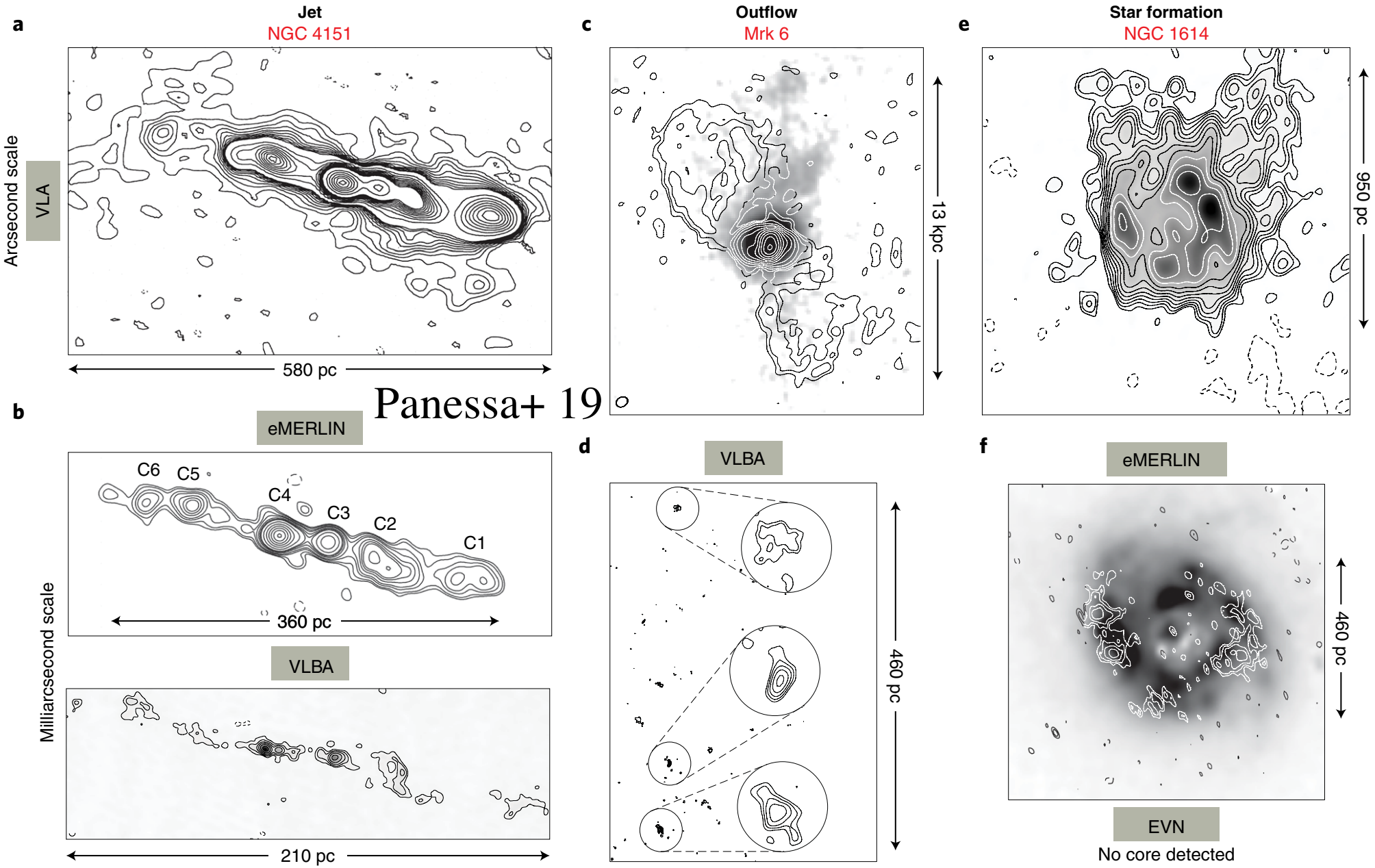
Czerny 03



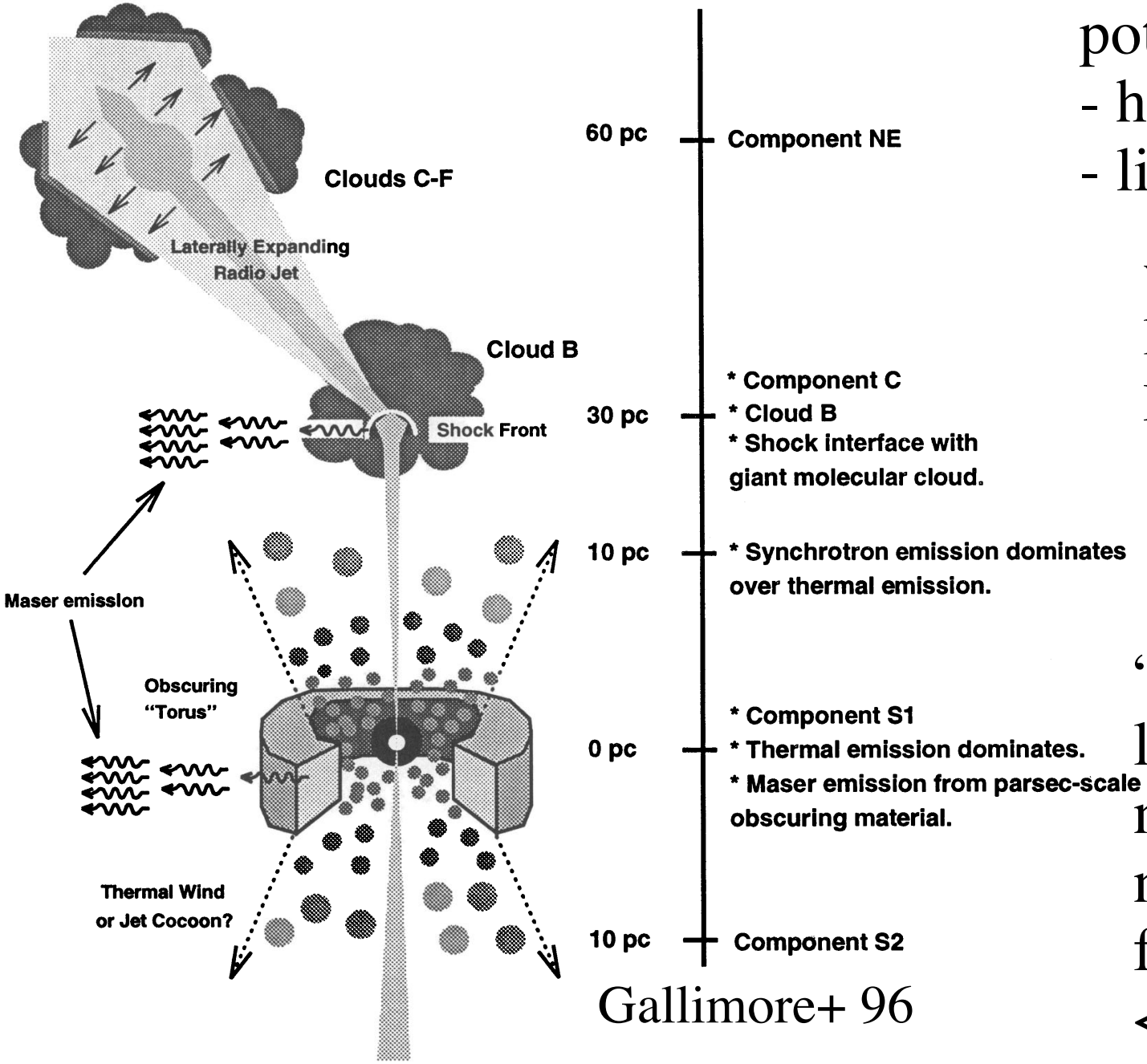


radio emission of radio-quiet AGN

origin? star formation, winds, “jets”, disk coronae...



kpc-scale ("mini"-)jet in NGC 1068



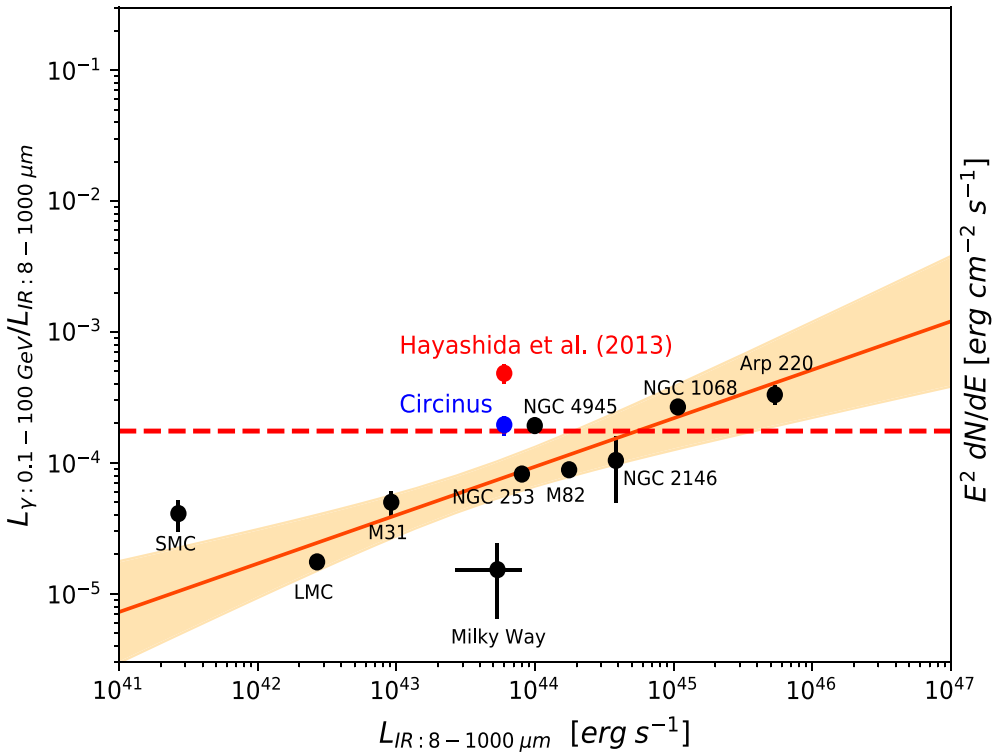
Gallimore+ 96

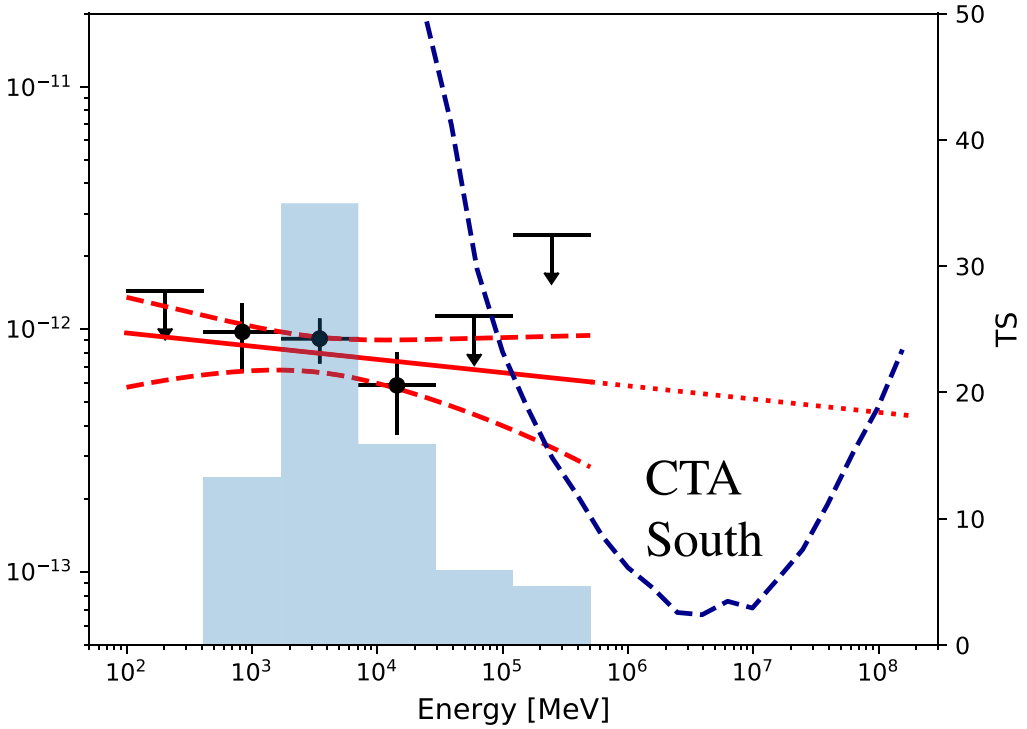
jet origin of protons?
potential challenges:
- high velocity
- limited power

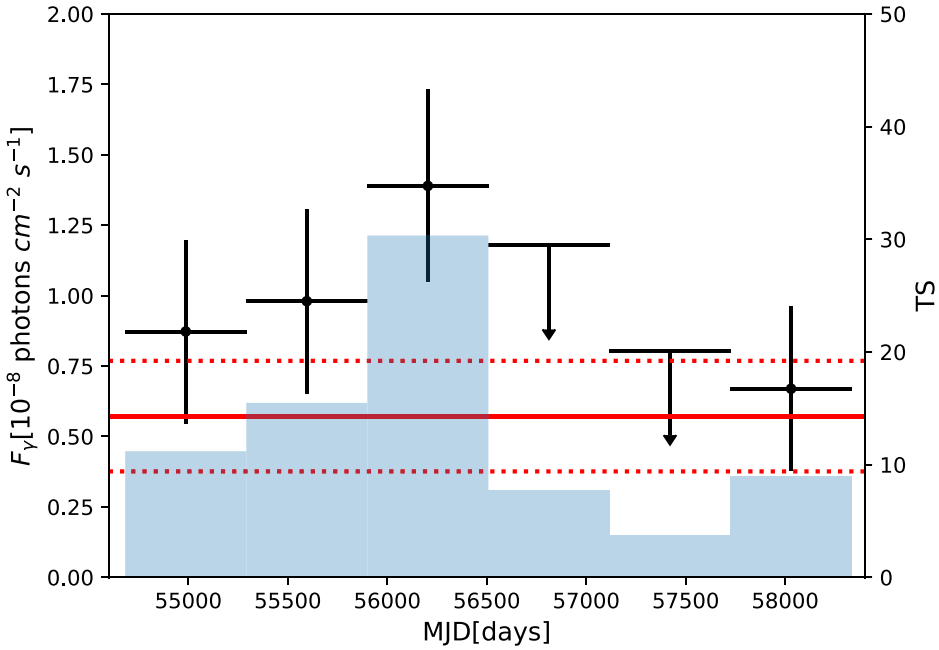
v_{jet}~0.06c at ~60 pc
likely higher at base
Bicknell+ 08

"failed jet" with
lower v, higher P
near BH?:
no support so far
from theory or obs.
<-> failed wind

Circinus galaxy: next candidate?







Guo+ 19 c.f. Ackermann+ 12
Hayashida+ 13

- GeV γ excess over starburst expectation
- marginal evidence for variability