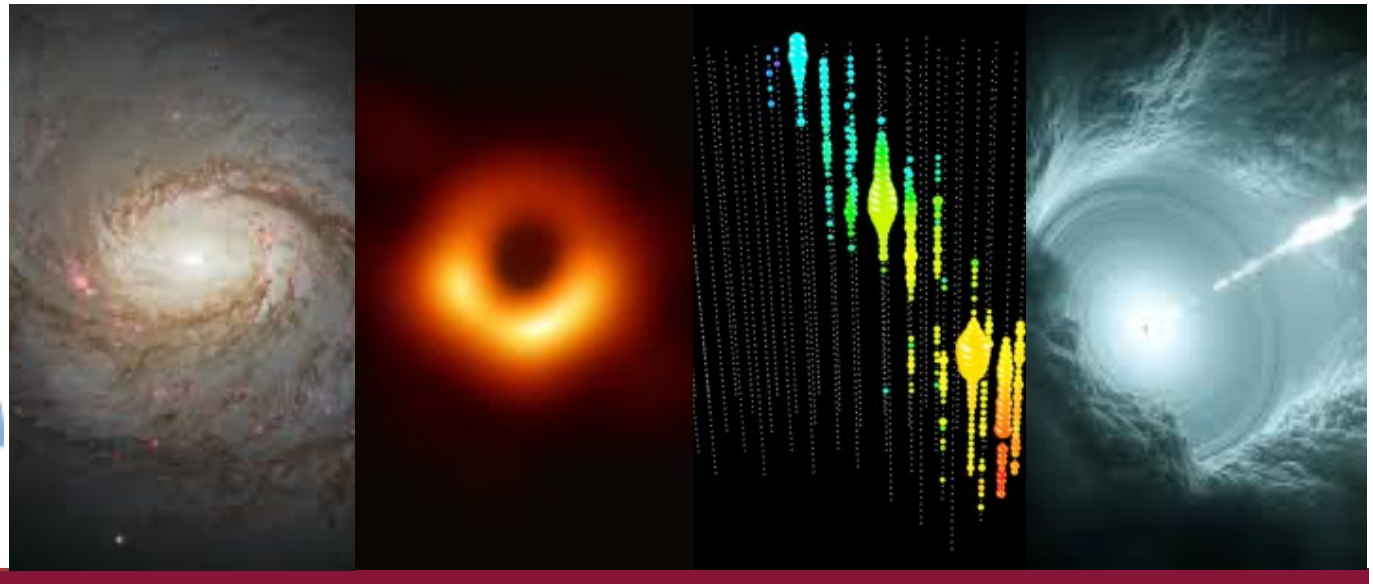


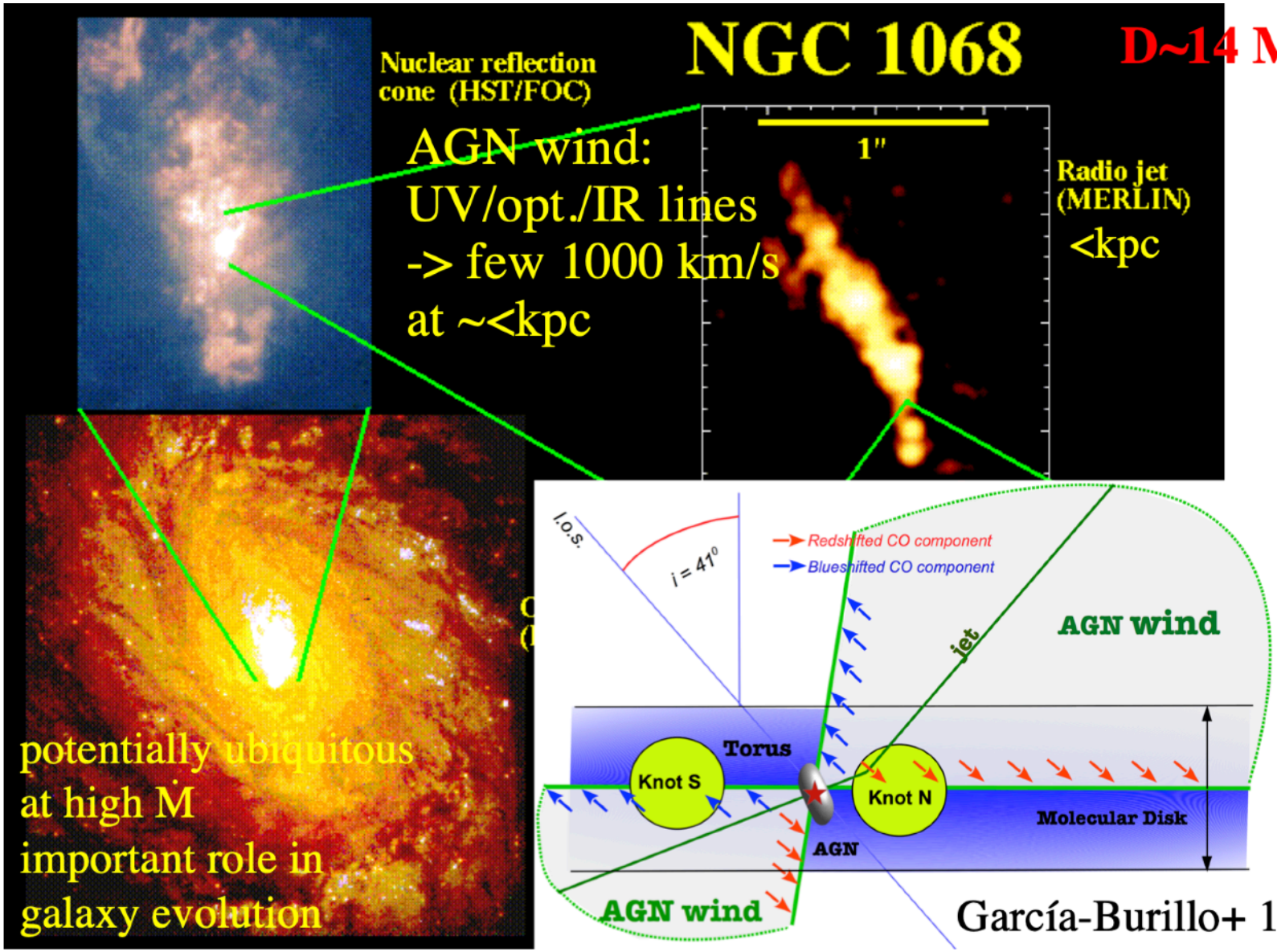
High-energy ν and γ from winds and tori in active galactic nuclei

Susumu Inoue
Matteo Cerruti
Kohta Murase
Ruo-Yu Liu

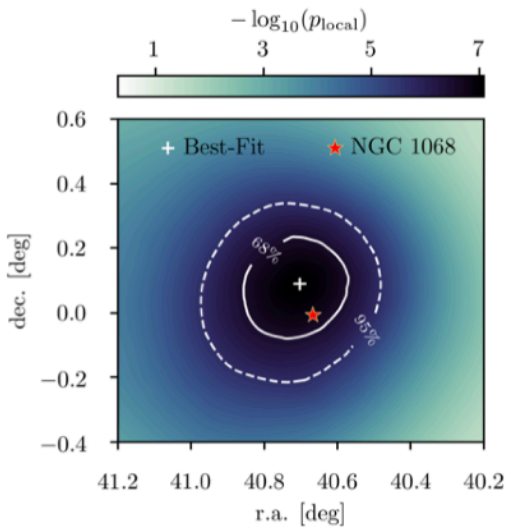
arXiv:2207.02097 , under review
Slides by Susumu Inoue @ Gamma22

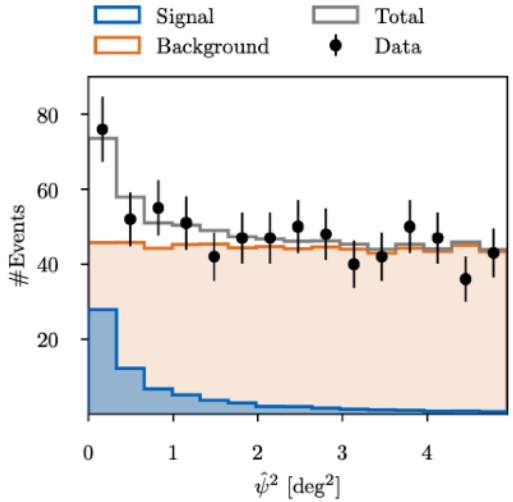
Astrophysics Workshop on Numerical Multimessenger Modeling
Bohum
February 27, 2023

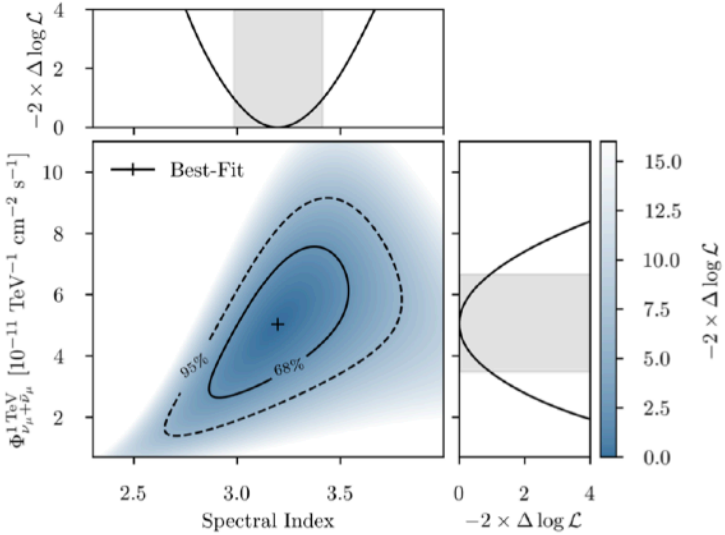
NGC 1068


NGC 1068
D~14 Mpc
Nuclear reflection cone (HST/FOC)
AGN wind:
UV/opt./IR lines
-> few 1000 km/s
at ~<kpc
1"
Radio jet (MERLIN)
<kpc
potentially ubiquitous
at high Ṁ
important role in
galaxy evolution
l.o.s.
i = 41°
Redshifted CO component
Blueshifted CO component
AGN wind
jet
Torus
Knot S
Knot N
Molecular Disk
AGN
AGN wind
García-Burillo+ 19

ν AND γ FROM NGC 1068







GeV γ: exceeds starburst expectation -> AGN origin?

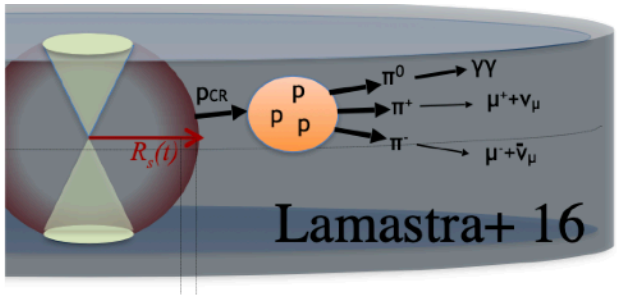
Yoast-Hull+ 14, Eichmann & Becker Tjus 16

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

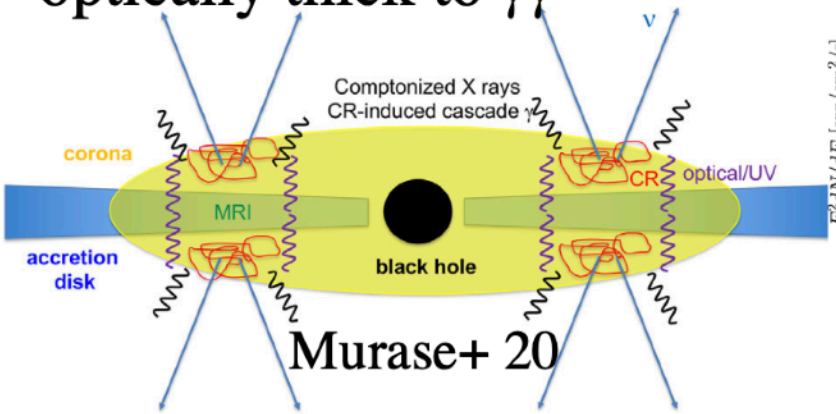
MAGIC Col. 19

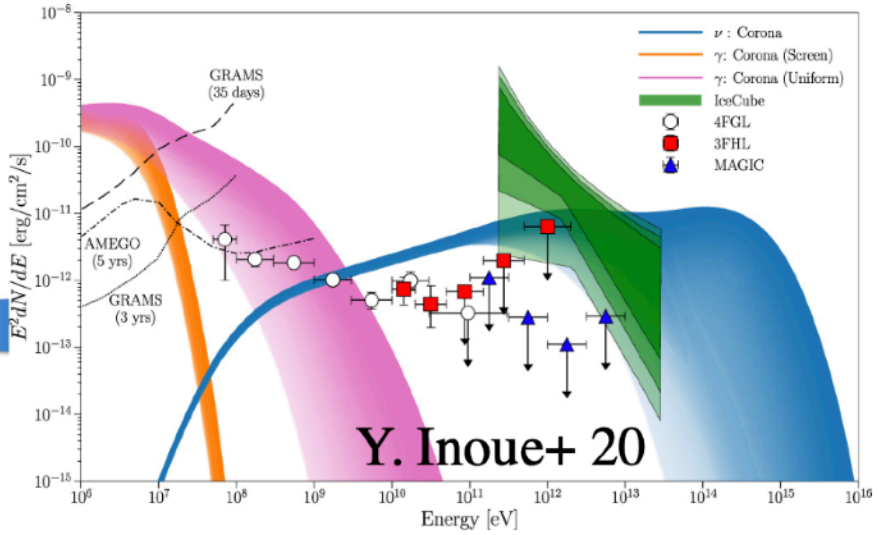
ν AND γ FROM NGC 1068

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

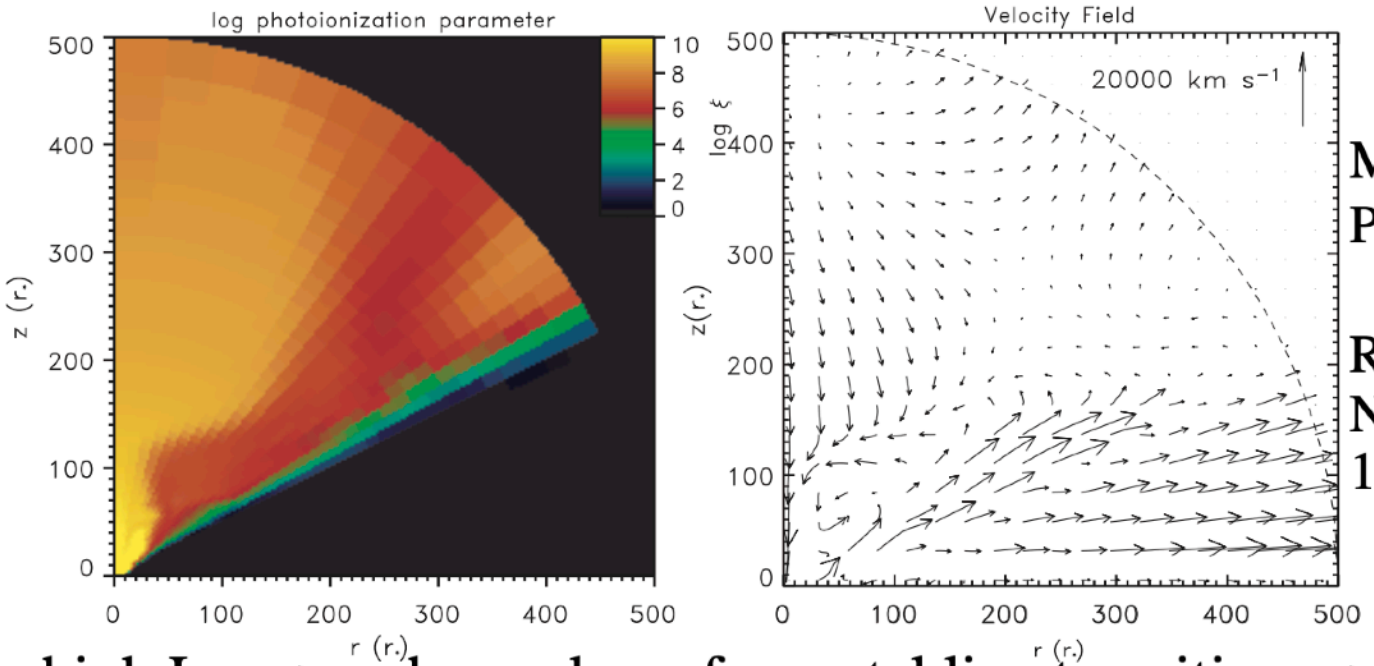




issues:
- acceleration in corona robust?
- origin of GeV γ rays?
- cascade at <<MeV?

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

LINE DRIVEN WINDS: SUCCESSFUL vs FAILED



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

p-γ ν AND γ FROM INNER REGION

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

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

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

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

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

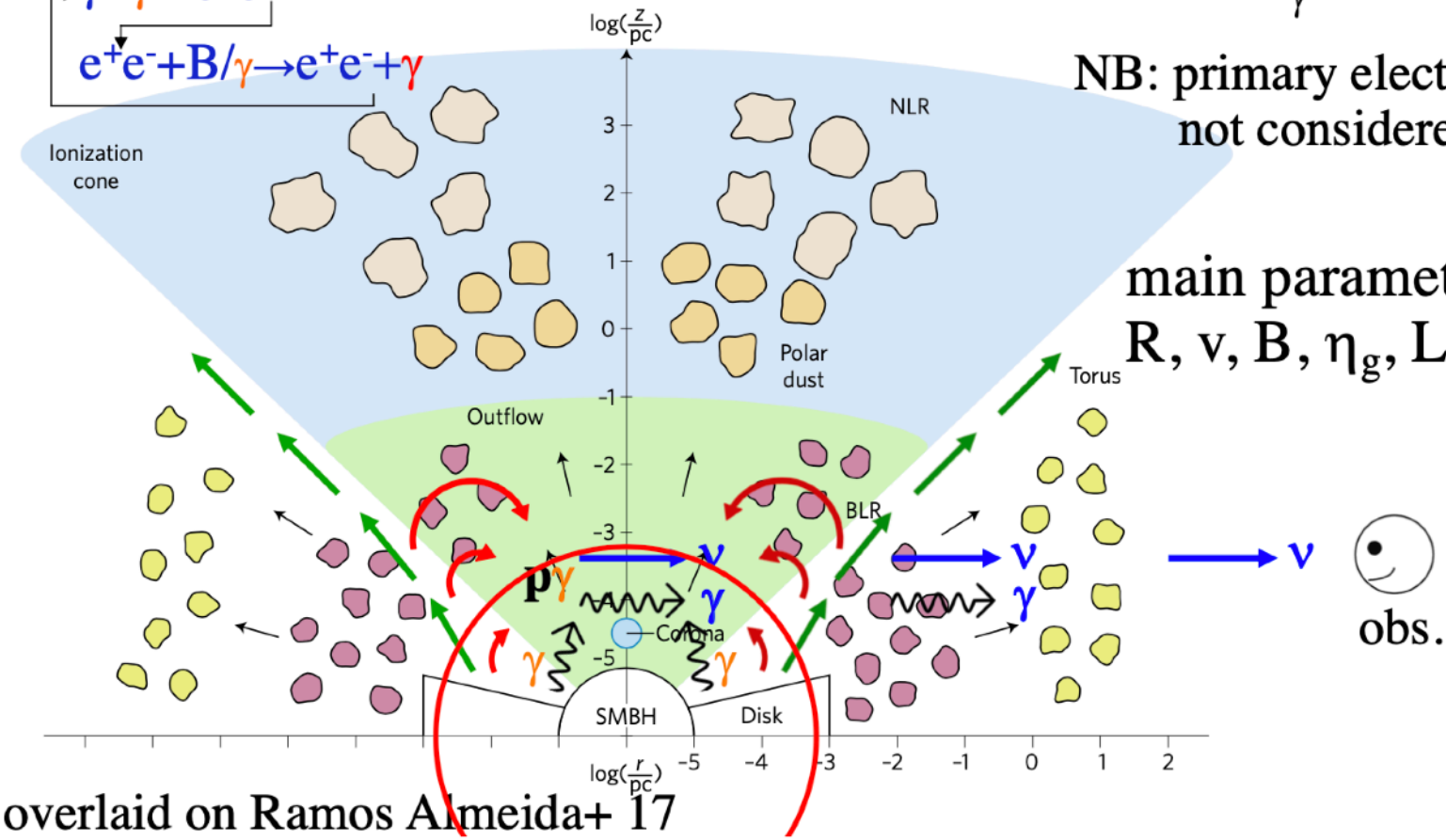
$E_p\varepsilon_\gamma \sim 10^{17}$ eV^2

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

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

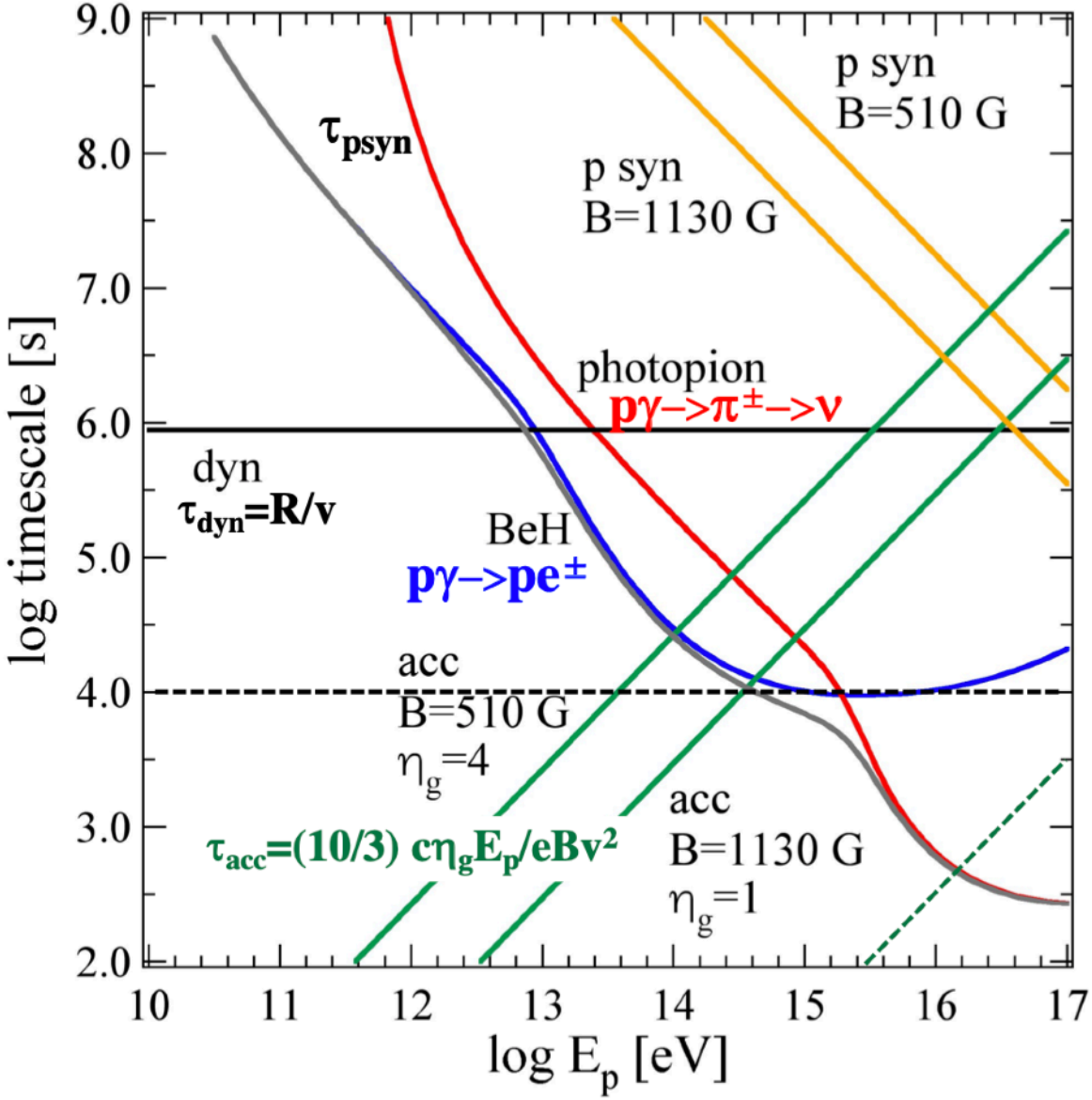
NB: primary electrons not considered

main parameters:
R, v, B, η_g, L_p



overlaid on Ramos Almeida+ 17

INNER REGION 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

$v \sim v_{esc} \sim 0.3c$
-> $E_{p,br} \sim 400$ TeV
$E_{p,max} \sim 10$ PeV

ON LeHa

Radiative lepto-hadronic code to model *blazar* SEDs

Photo-meson interactions computed running SOPHIA on the fly

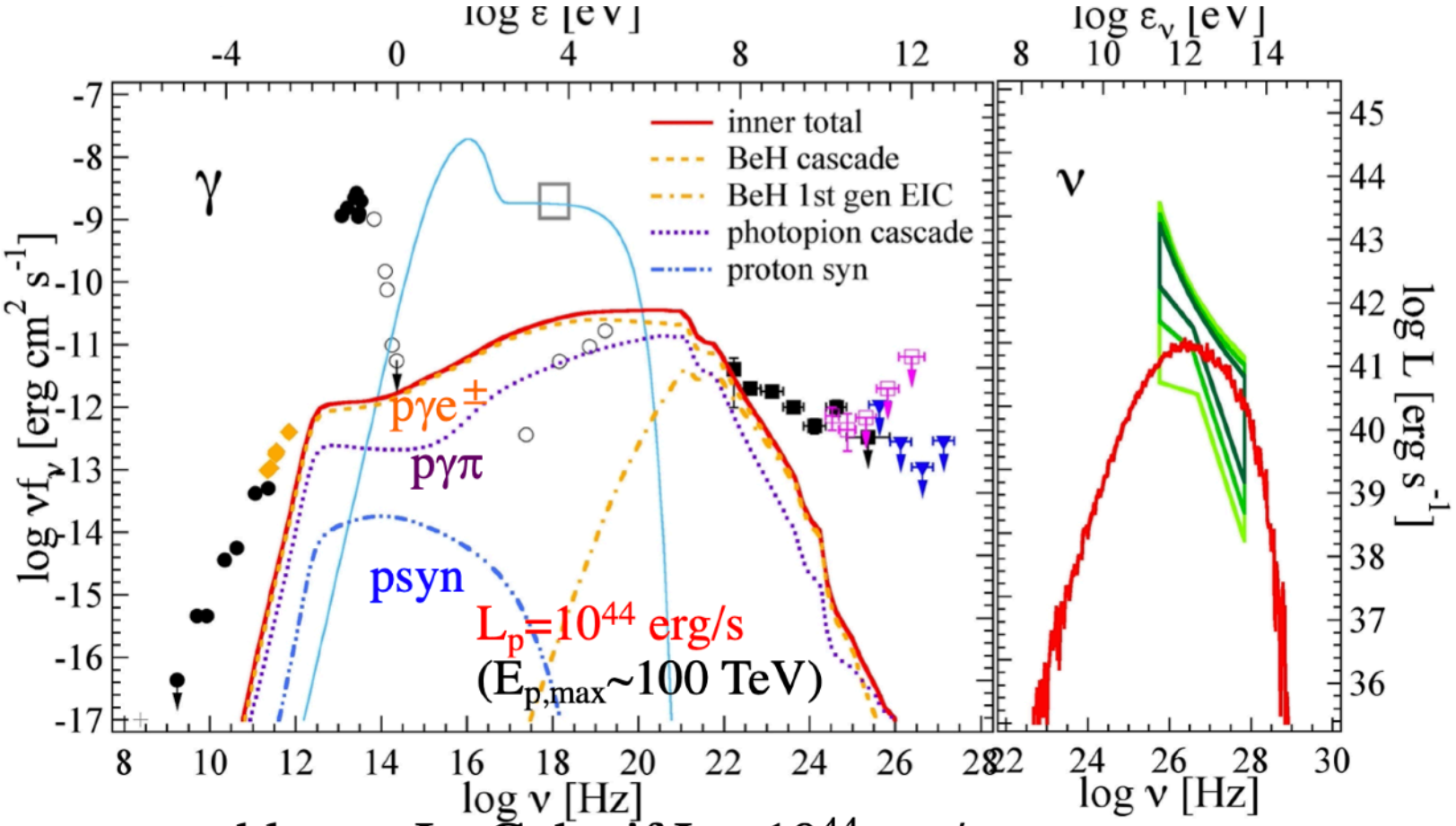
Code description with application to extreme blazars in 2015

Recently extended to work with *any* arbitrary external field

For this work, added p-p following Kelner&Aharonian

-> Two spherical emitting regions, slowly moving.
Proton distribution self-consistently computed from cooling time-scales (in practice, run LeHa twice).

INNER REGION EMISSION



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

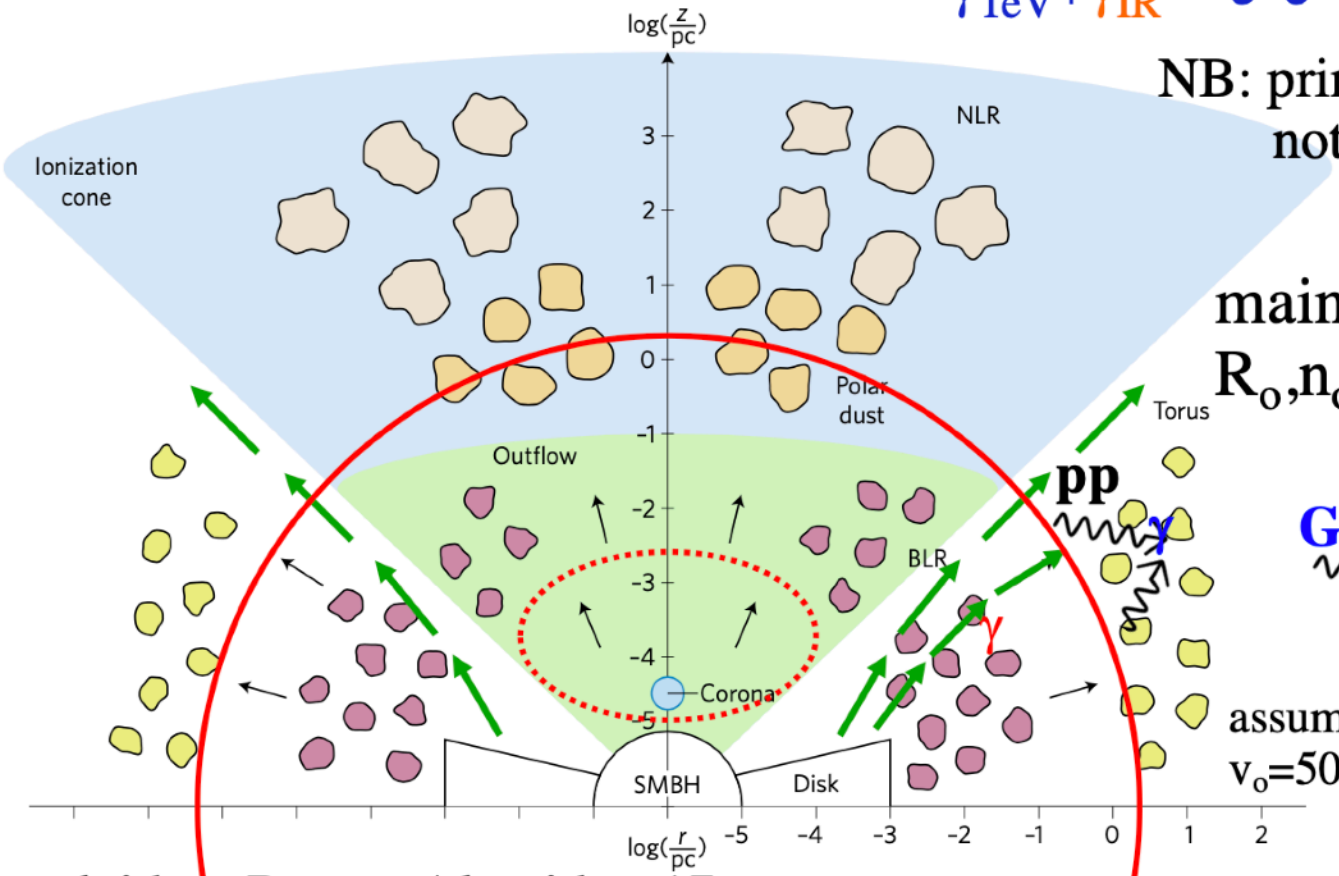
p-p ν AND γ FROM OUTER REGION

outer successful wind + torus impact
-> external shock -> proton acceleration

c.f. García-Burillo+ 19

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

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



NB: primary electrons not considered

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

pp γ

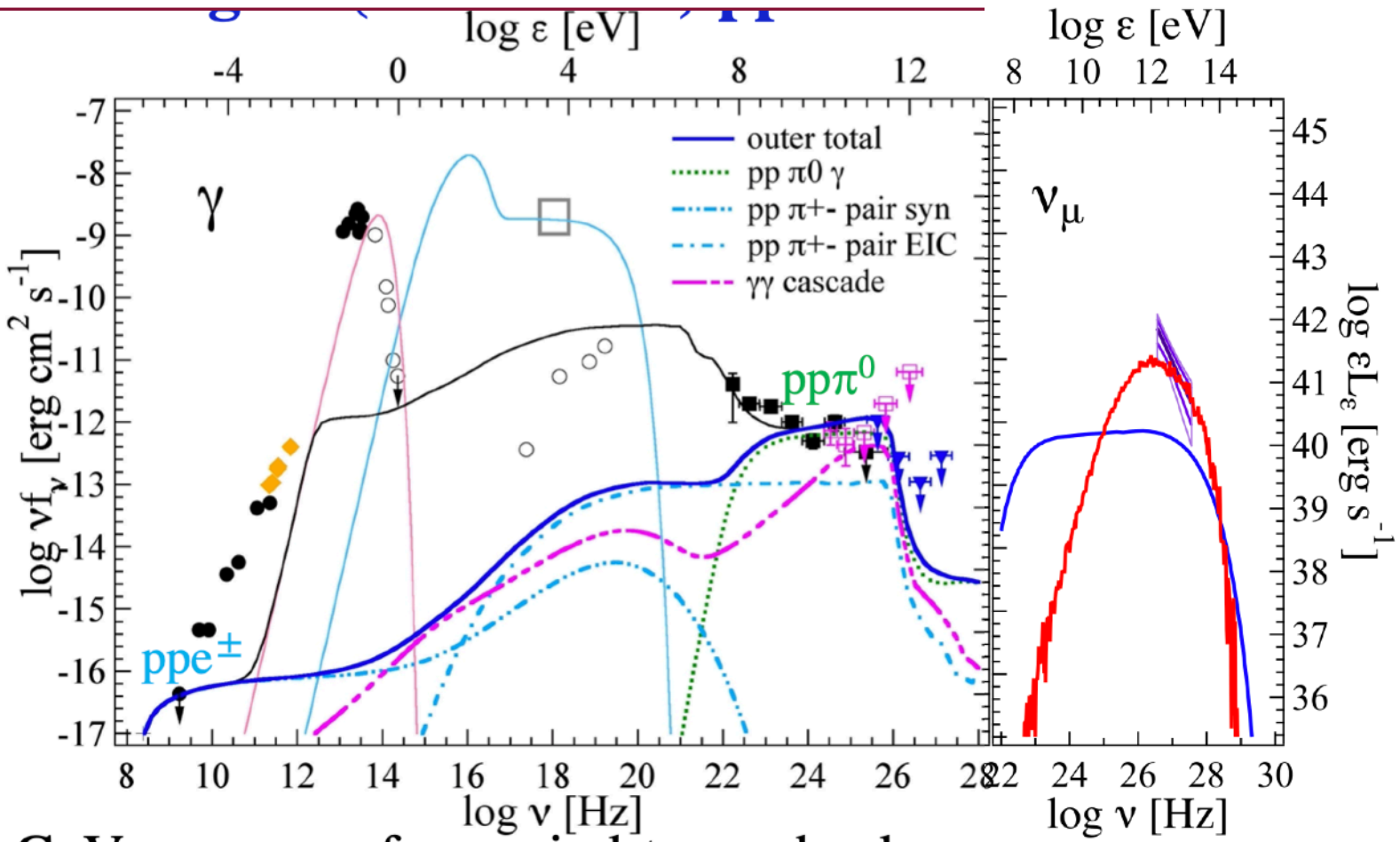
GeV γ

obs.

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

overlaid on Ramos Almeida+ 17

OUTER REGION EMISSION

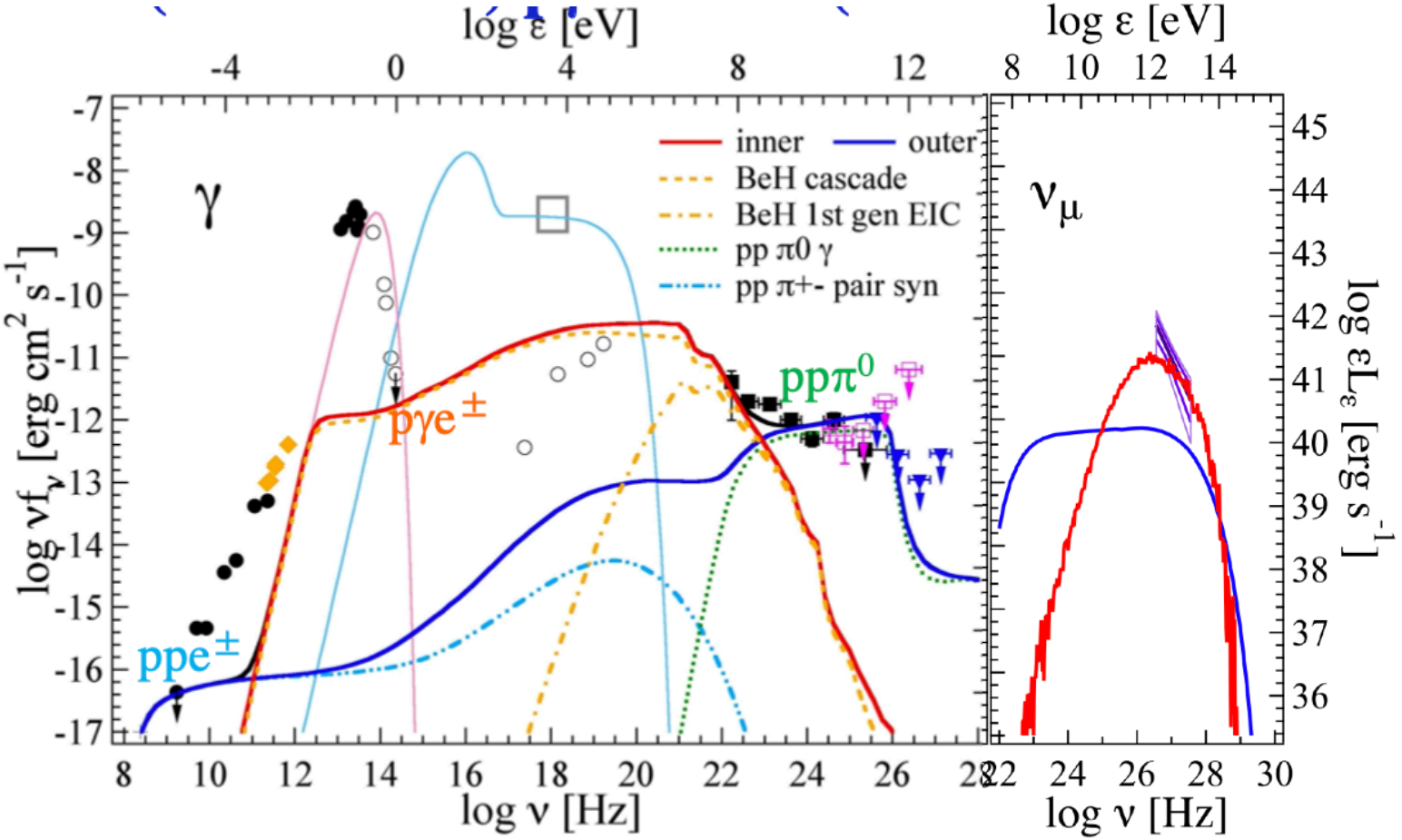


- GeV: pp γ-rays from wind-torus shock
- TeV: γγ attenuated by torus IR
- potential contribution to radio

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

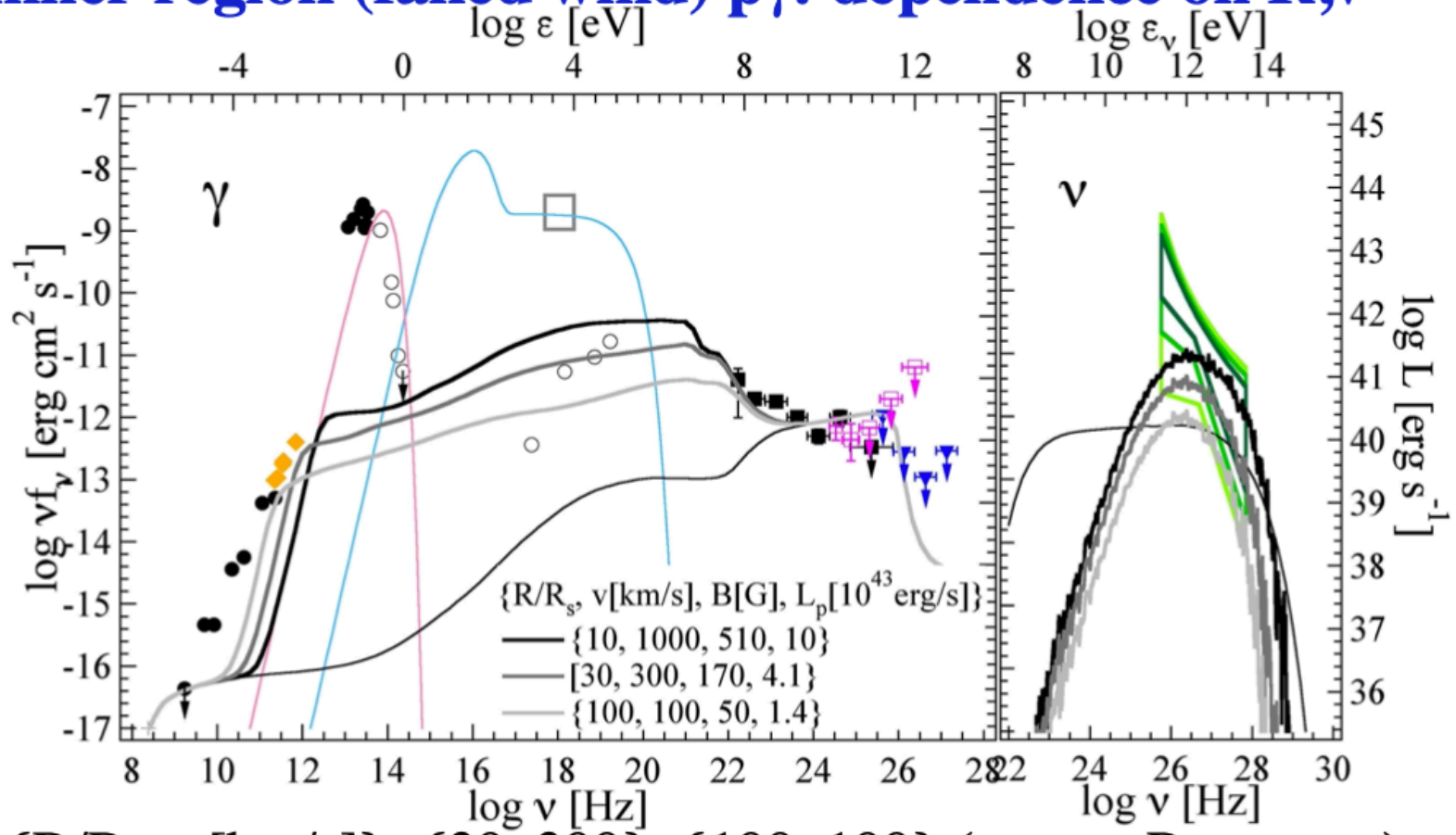
OVERALL EMISSION



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

EFFECT OF MODEL PARAMETERS

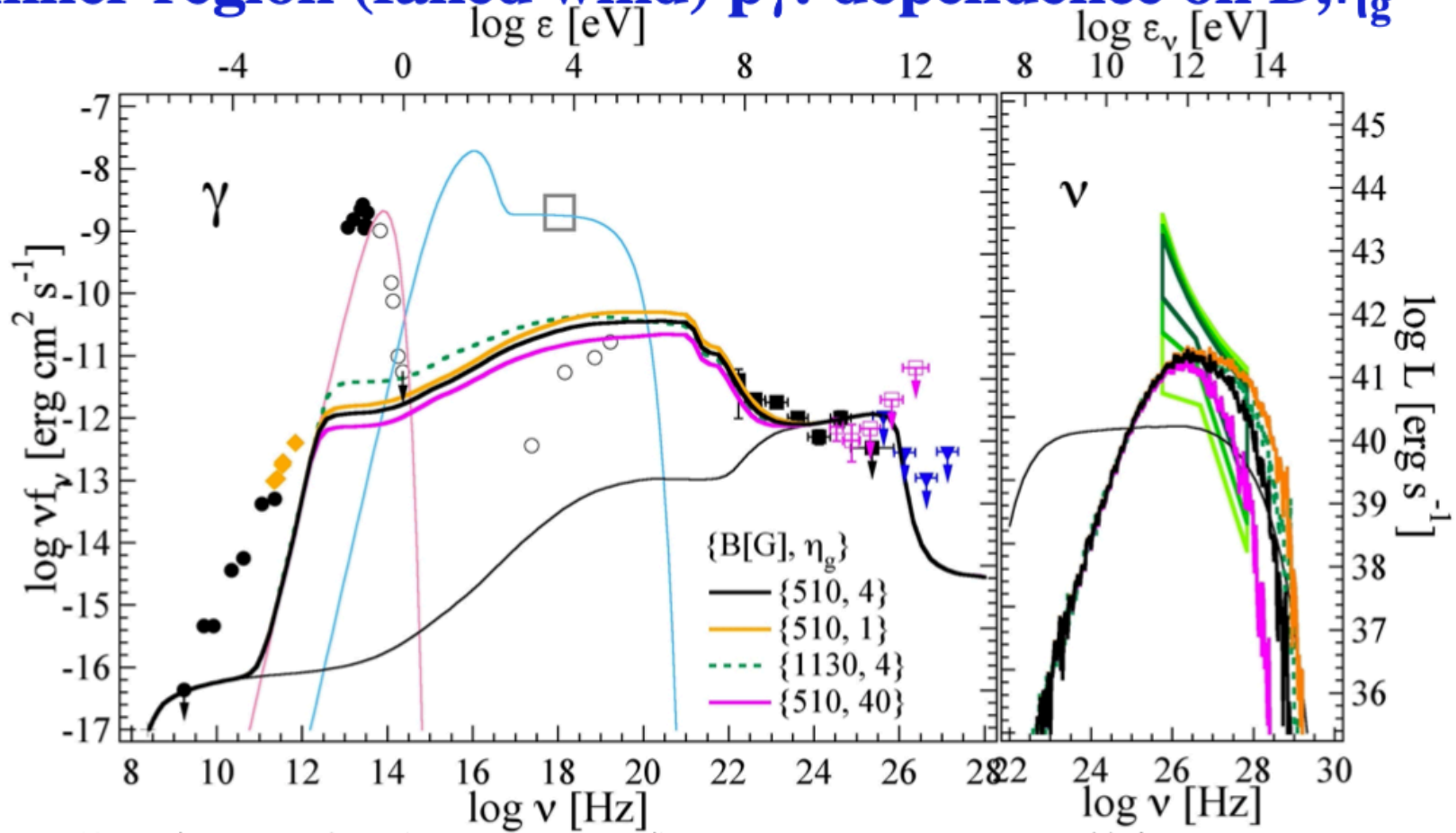
inner region (failed wind) pγ: dependence on R,v



- {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↓

EFFECT OF MODEL PARAMETERS

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

CONCLUSIONS

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 $v << v_{esc}$, 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/NIF
- other AGN (esp. unobscured) by IceCube-Gen2, CTA, etc
- contribution to diffuse ν background
- unique info on AGN wind formation, esp. obscured objects