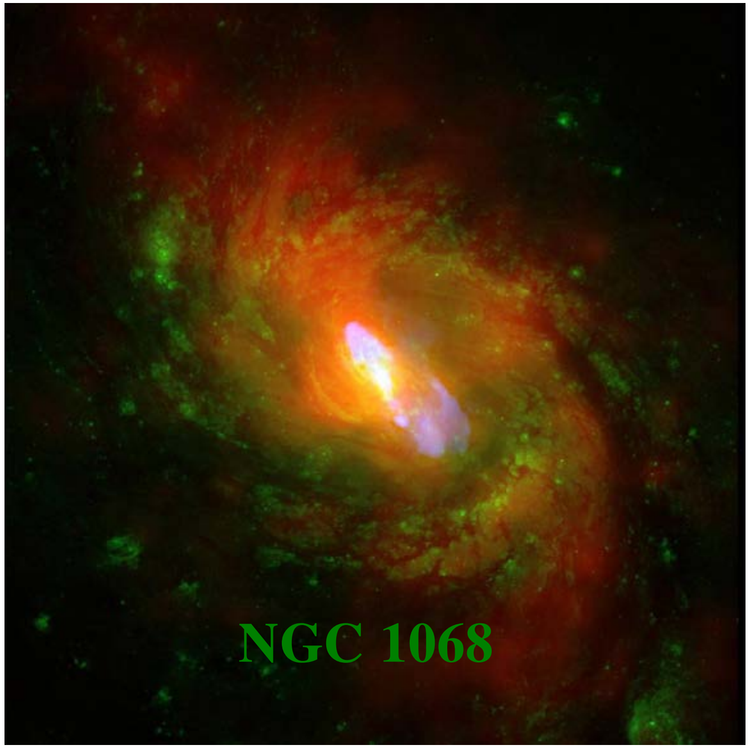
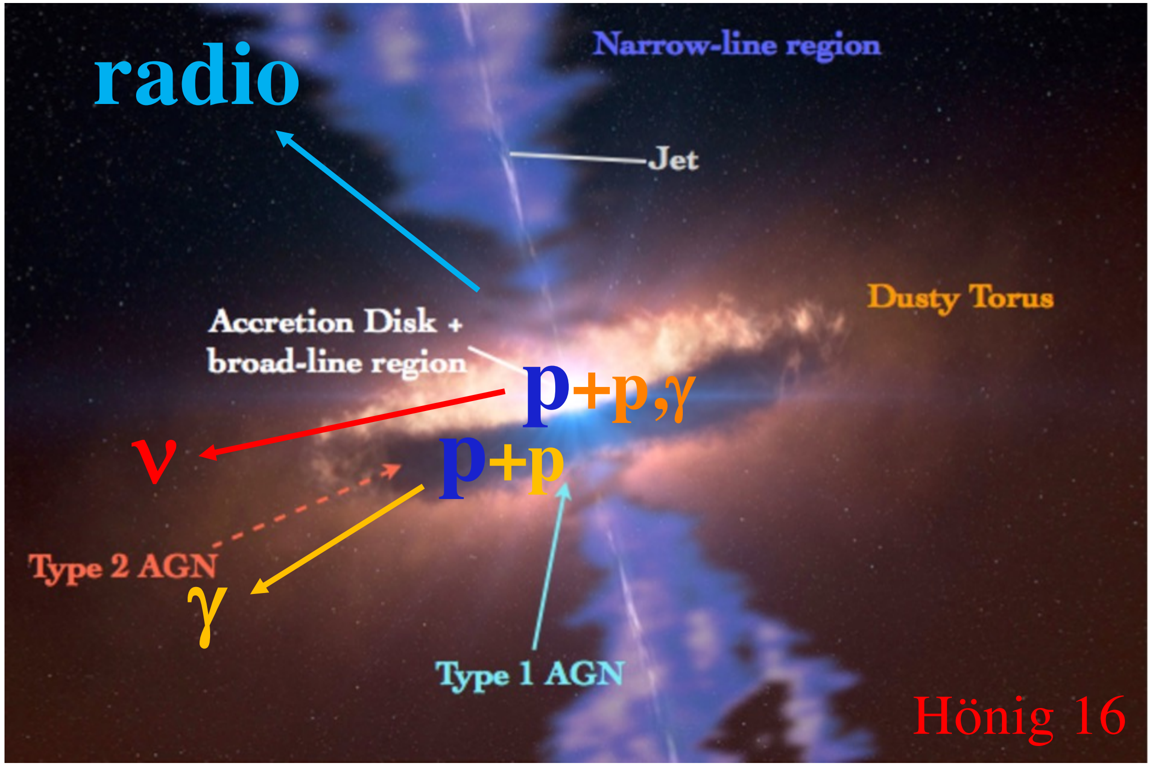
Multi-messenger emission from weak-jetted (radio-quiet) active galactic nuclei
neutrinos, gamma rays, radio

Susumu Inoue (Tokyo Metropolitan Univ.)

Thanks to:
Matteo Cerruti, Kohta Murase, Ruo-Yu Liu,
Yuki Kudoh, Keiichi Wada, and others



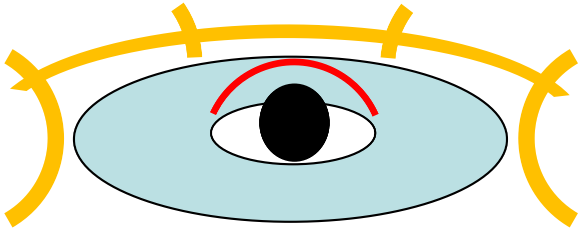


outline

1. AGN: disk coronae, strong vs weak jets, winds
2. weak-jetted (radio-quiet) AGN:
   observational evidence of non-thermal processes
3. multimessenger emission from NGC 1068:
   coronae vs winds
   SI, Cerruti, Murase, Liu, arXiv: 2207.02097
4. Future prospects

active galactic nuclei (AGN)

supermassive black hole
+accretion disk-corona +torus



relativistic jet

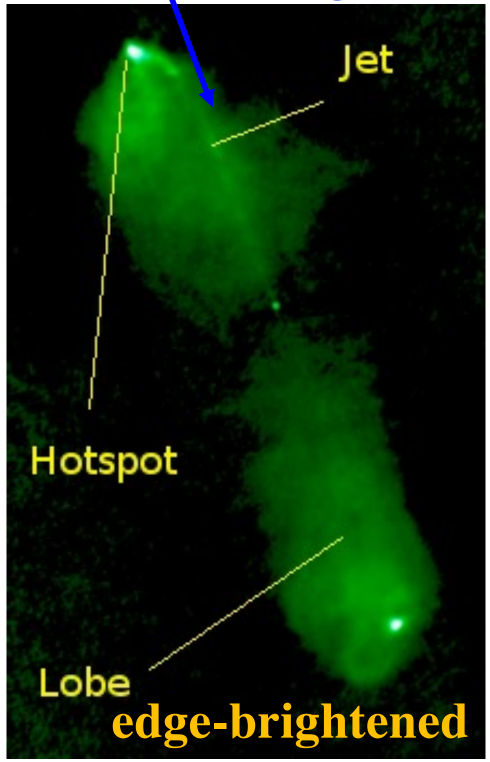
radio-loud

high-power

~<1%

FR 2 radio galaxy

GeV blazar (FSRQ)

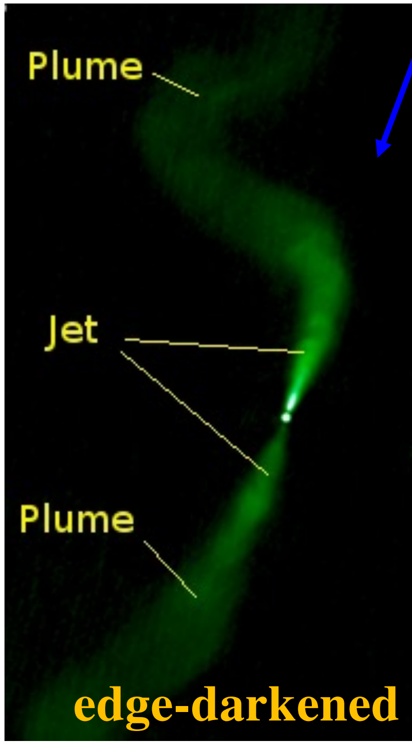


low-power

~10%

FR 1 radio galaxy

TeV blazar (BL Lac)



no/weak jet

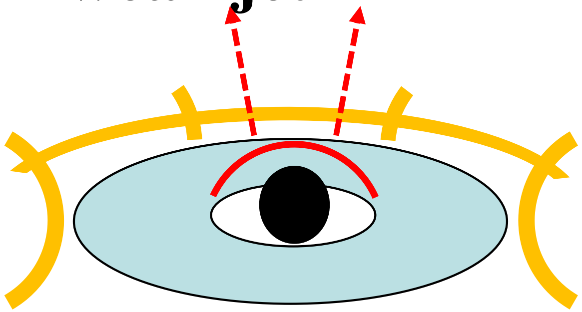
~90%

radio-quiet

Seyfert galaxy
radio-quiet quasar

active galactic nuclei (AGN)

supermassive black hole
+accretion disk-corona +torus
+weak jet



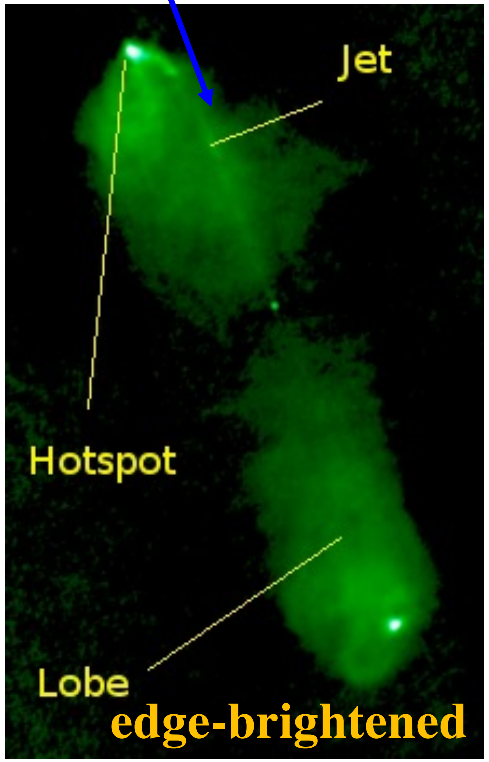
relativistic jet

radio-loud
strong-jetted

high-power
~<1%

FR 2 radio galaxy

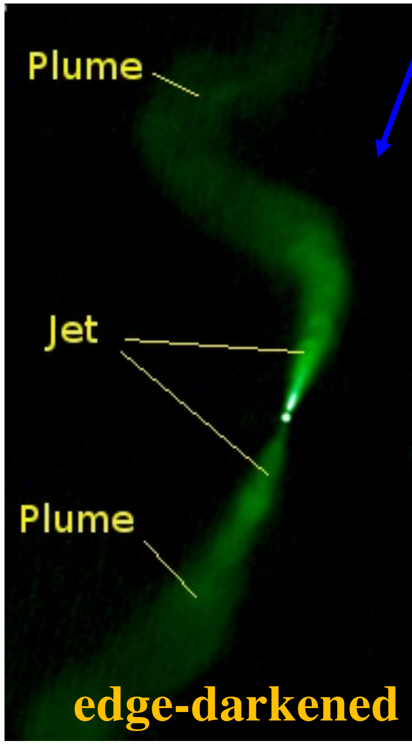
GeV blazar (FSRQ)



low-power
~10%

TeV blazar (BL Lac)

FR 1 radio galaxy



strong-jetted (rare)
blazars: overaligned (very rare)

weak-jetted (more common)

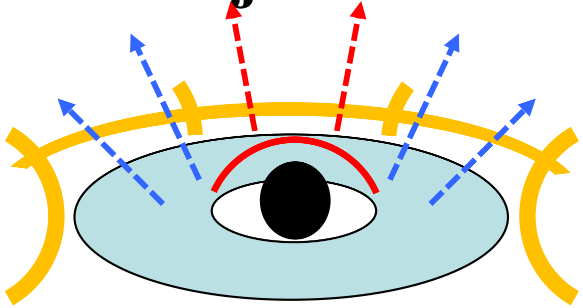
no/weak jet
~90%

radio-quiet
weak-jetted

Seyfert galaxy
radio-quiet quasar

active galactic nuclei (AGN)

supermassive black hole
+accretion disk-corona +torus
+weak jet +wind



relativistic jet

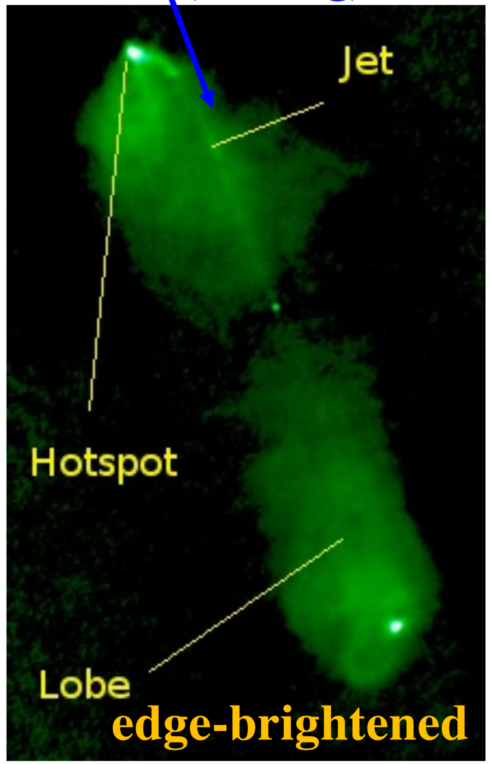
radio-loud
strong-jetted

high-
power

~<1%

FR 2
radio
galaxy

GeV blazar
(FSRQ)

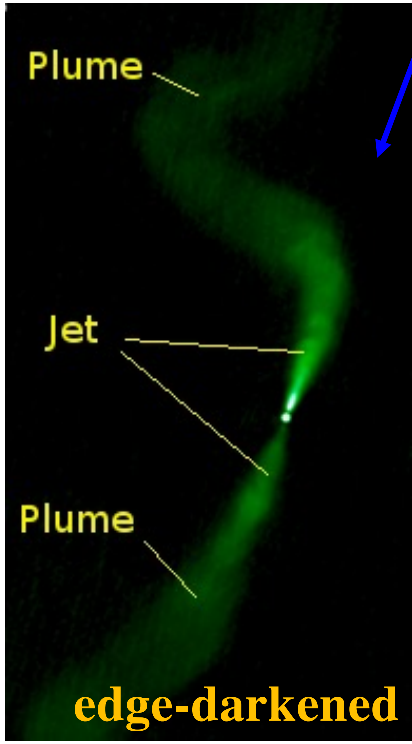


~10%

low-
power

TeV blazar
(BL Lac)

FR 1
radio
galaxy



no/weak
jet
~90%

radio-
quiet
weak-jetted

Seyfert galaxy
radio-quiet quasar

strong-jetted (rare)
blazars: overaligned
(very rare)

weak-jetted
(more common)
winds possibly ubiquitous

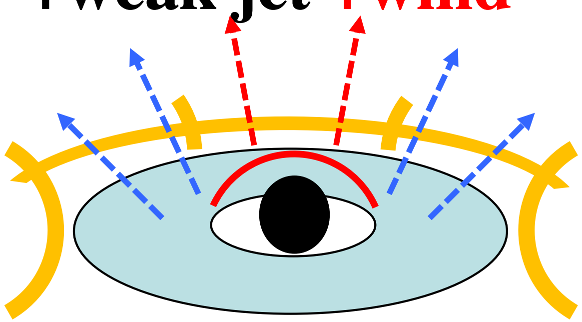
AGN winds: potential importance

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

1. Observed to exist: UV/X absorption, UV-IR/submm emission
   Widespread, potentially ubiquitous (radio-quiet or radio-loud)
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

active galactic nuclei (AGN)

supermassive black hole
+accretion disk-corona +torus
+weak jet +wind



relativistic jet

radio-loud
strong-jetted

high-
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~<1%

FR 2
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GeV blazar
(FSRQ)

~10%

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radio
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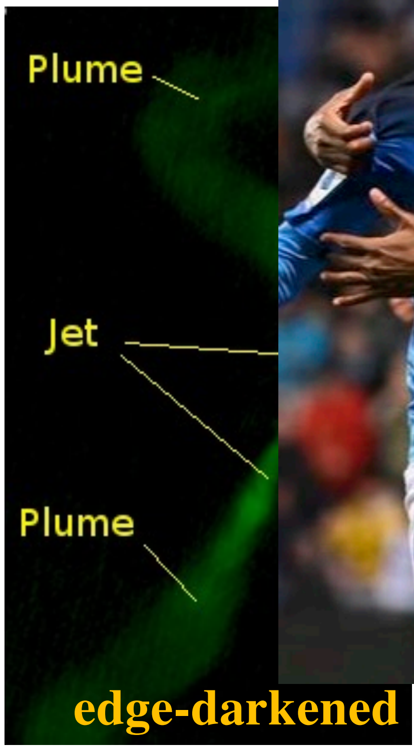
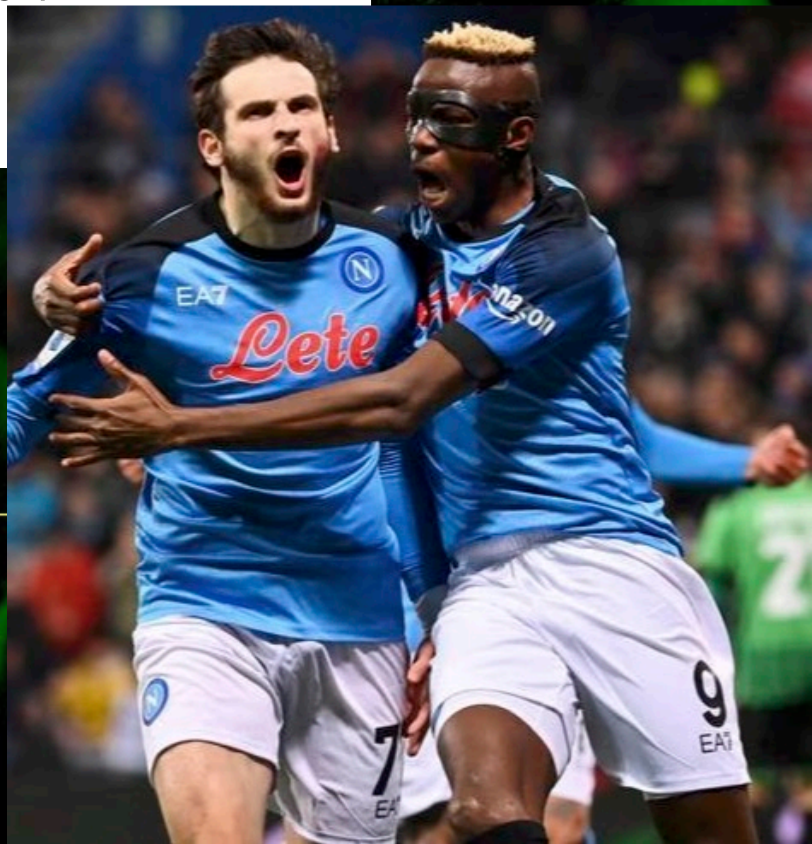
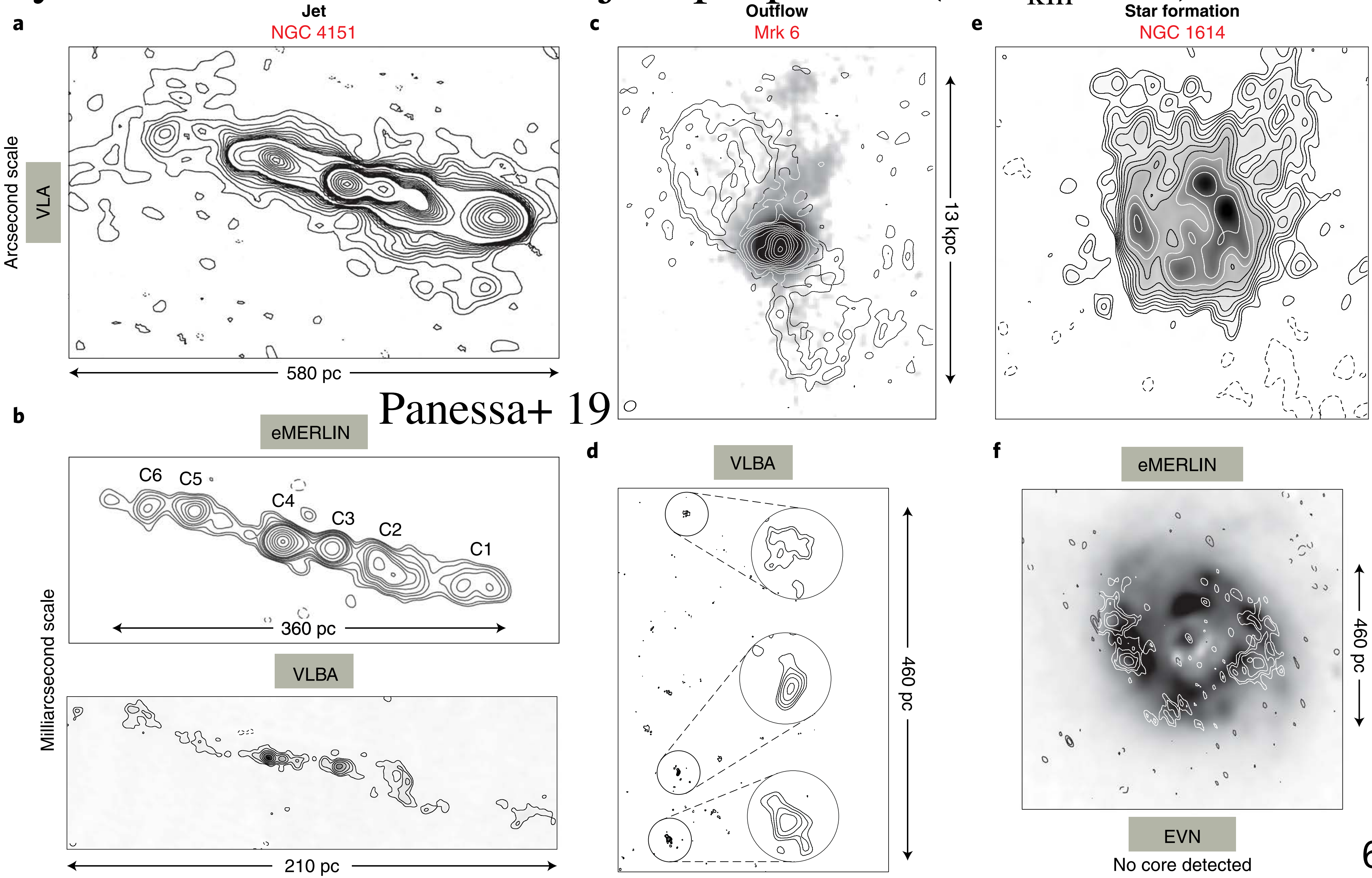




radio emission of radio-quiet AGN

star formation, weak "jets", winds, or disk coronae?

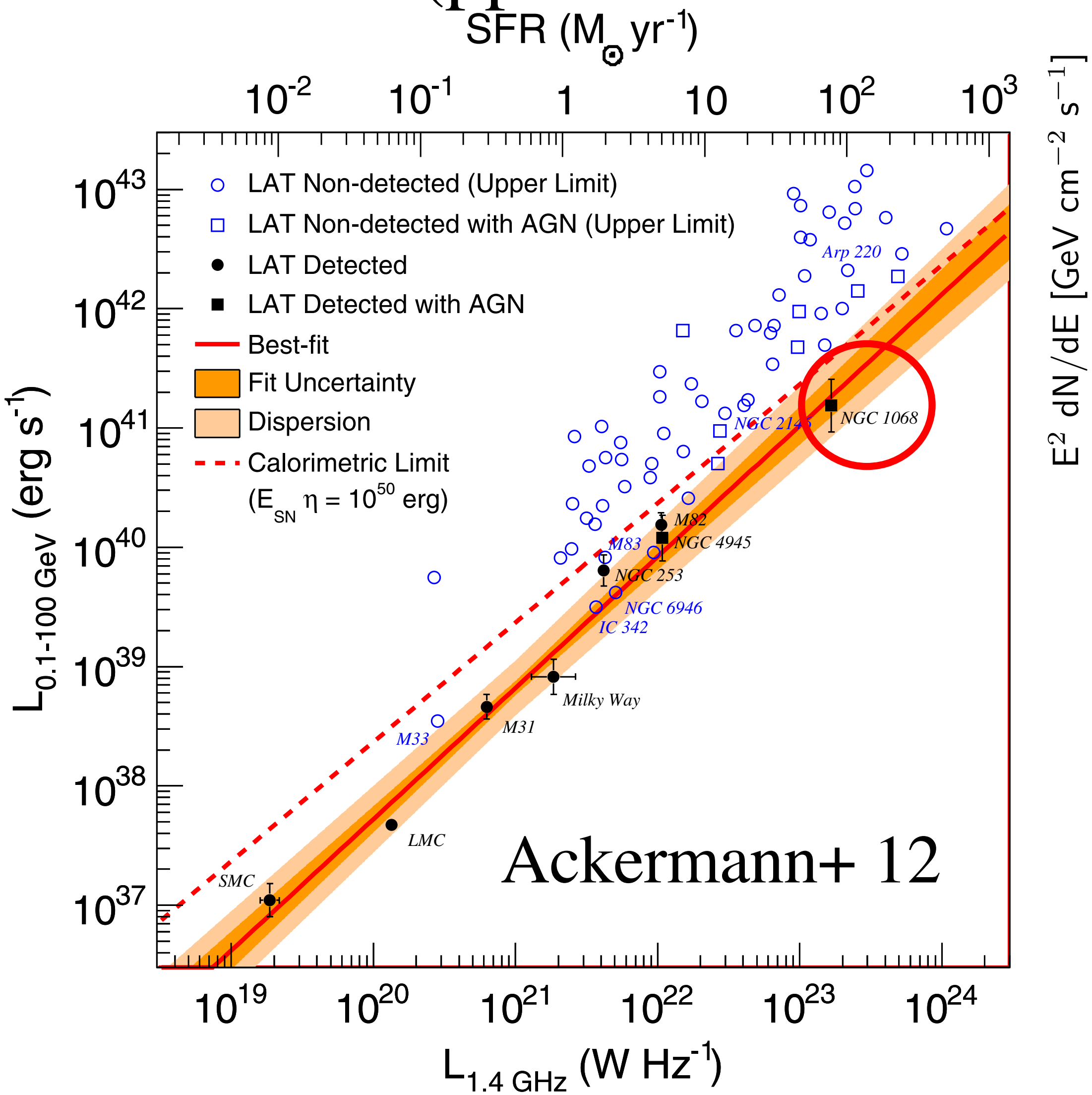
sync. or free-free? weak "jet" properties (v, L_{kin}, B...)?



Panessa+ 19

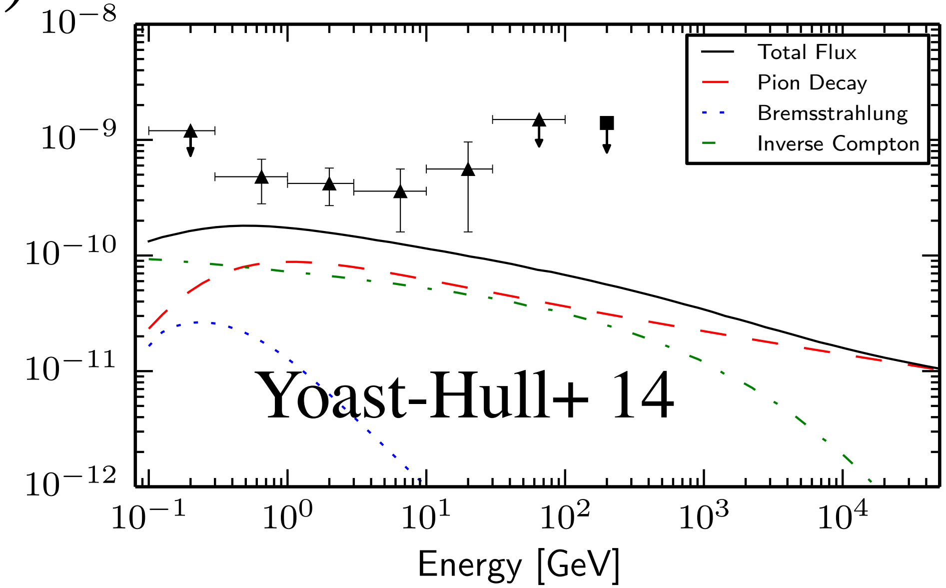
GeV gamma rays from NGC 1068

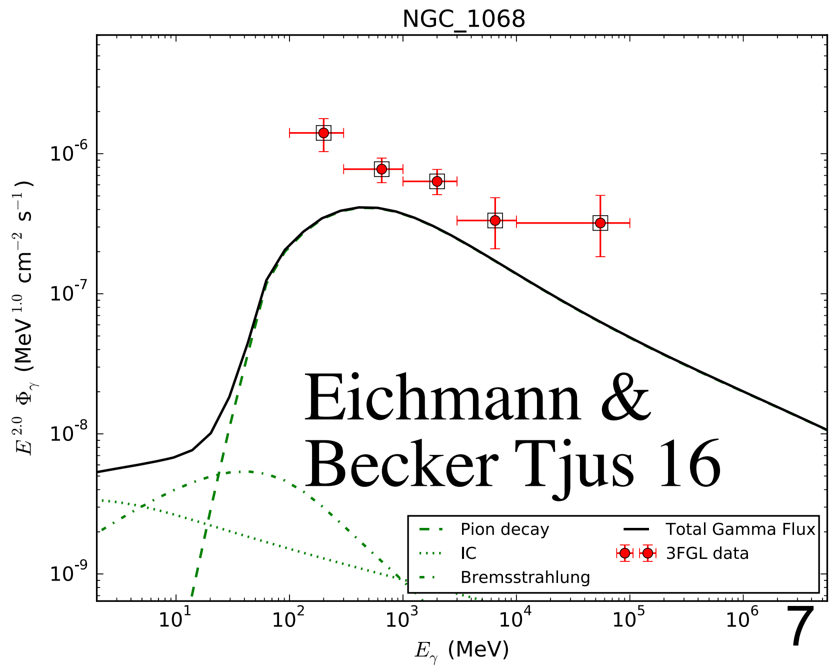
consistency with L_γ-SFR relation
-> starburst (pp π^0 from host ISM)?



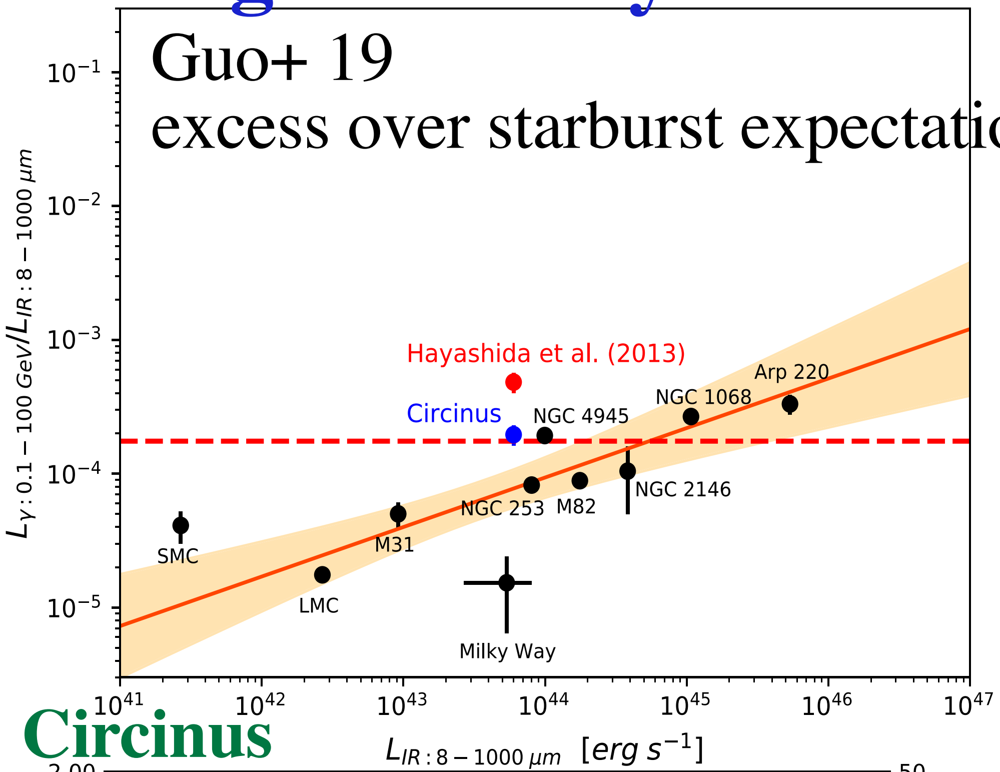
Fermi-LAT sample of
"starburst"+normal galaxies

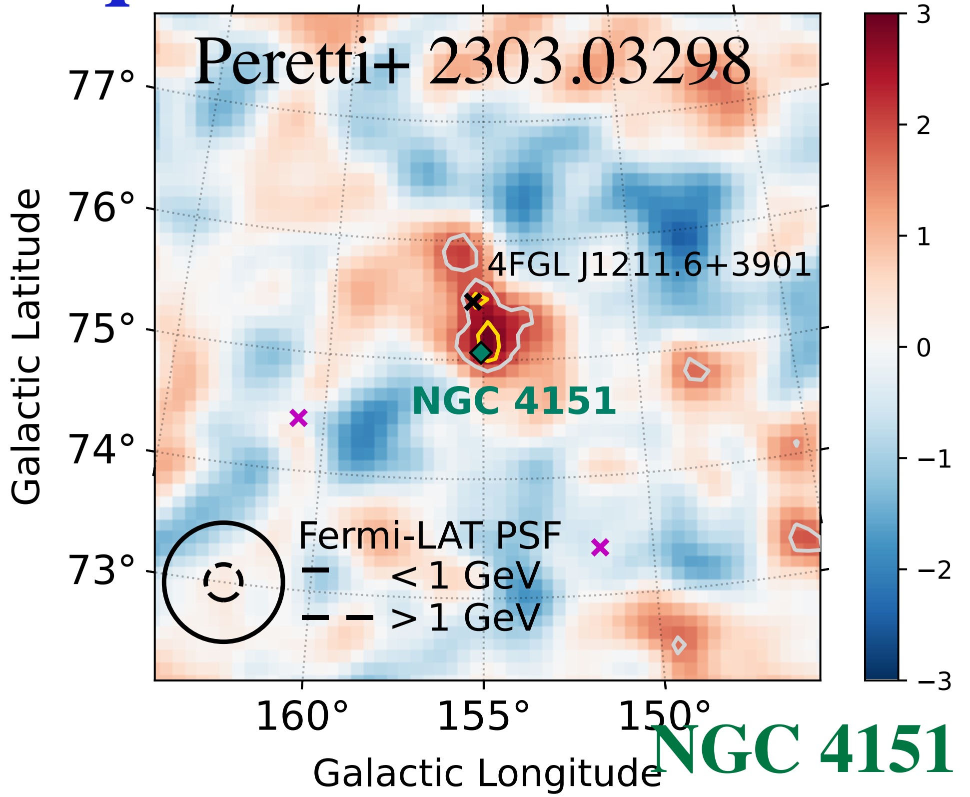
modeling of detailed
MWL data -> **NO**



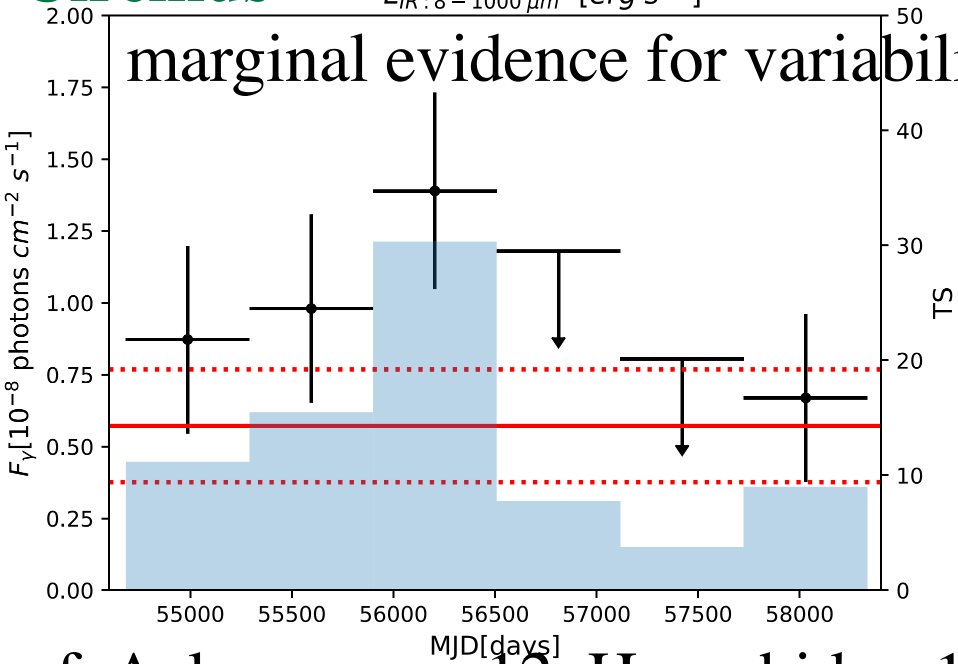


GeV gamma rays from radio-quiet AGN?

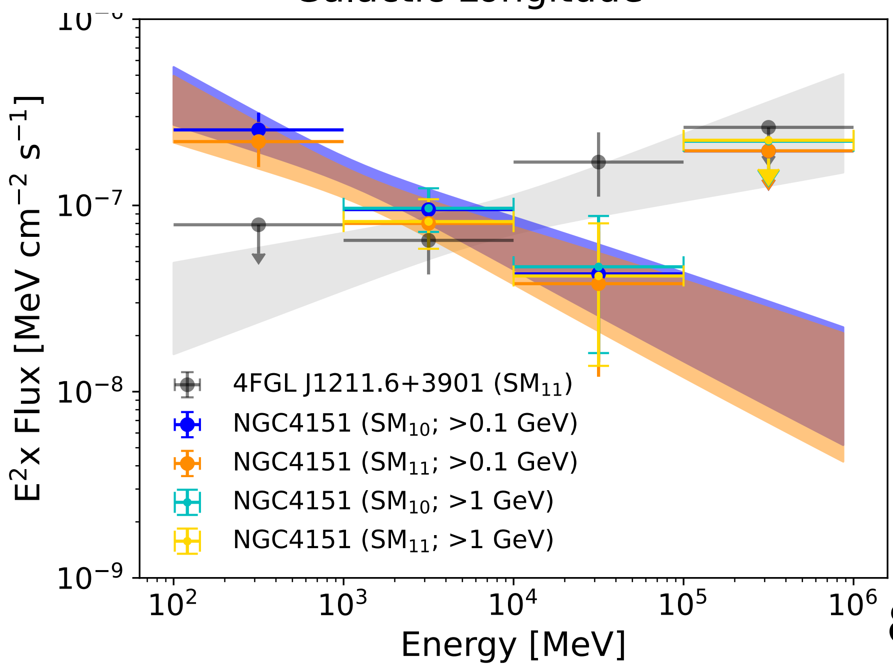




Circinus

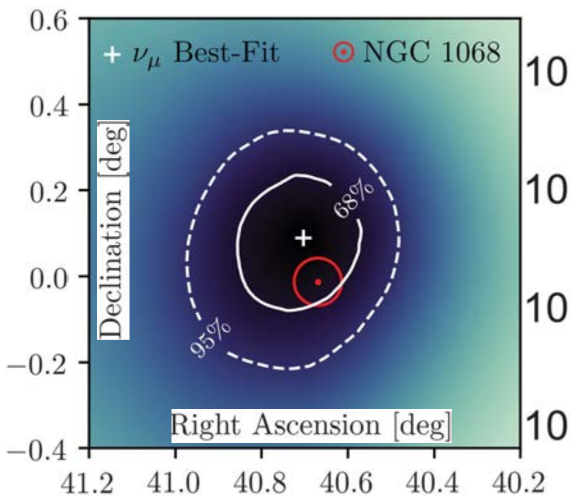


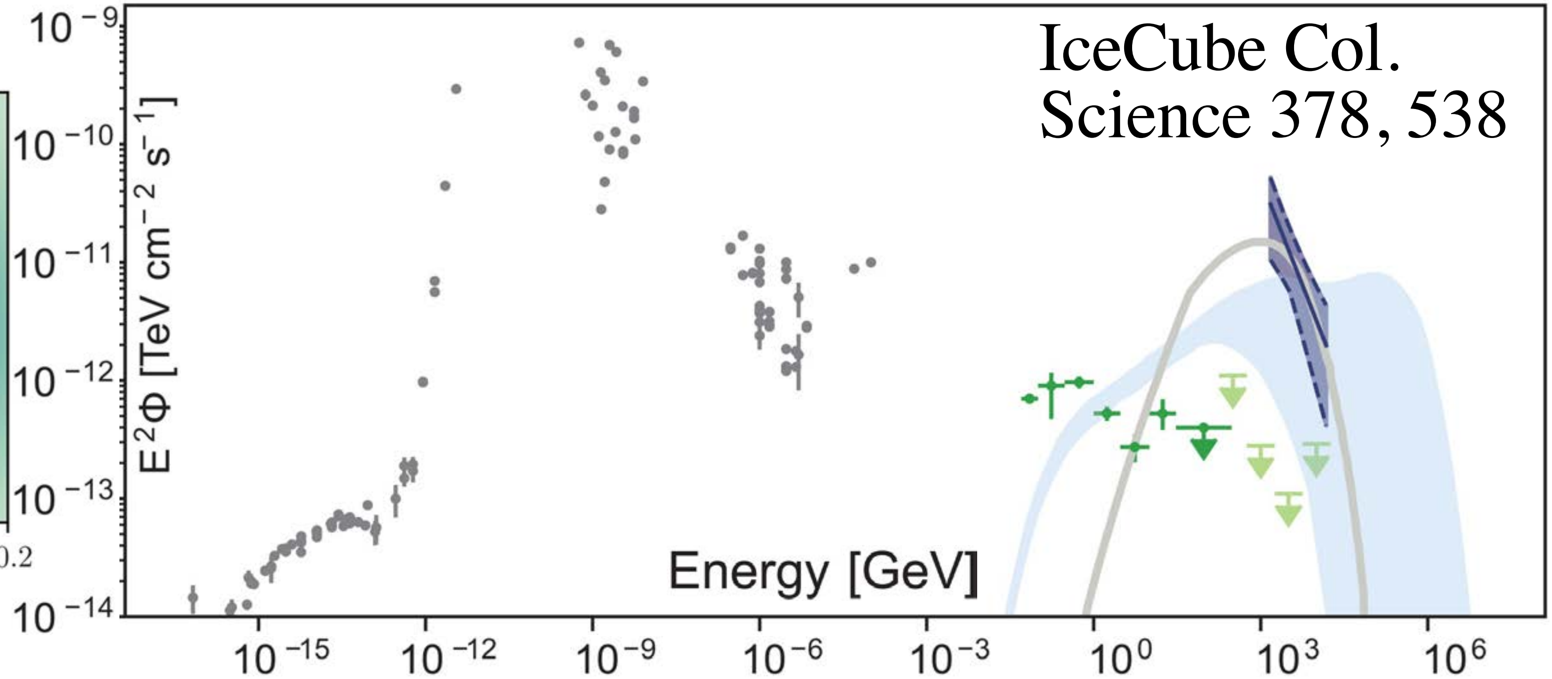
NGC 4151



c.f. Ackermann+ 12, Hayashida+ 13

neutrinos and gamma rays from NGC 1068





neutrinos:
- coincident w. highest excess (2.0σ) point in North sky scan
- 4.2σ excess at position in catalog search, ~80 events
- luminous, soft spectrum, $\nu L_\nu \sim 3\mathrm{x}10^{42}$ erg/s $(\varepsilon_\nu/1\ \mathrm{TeV})^{-3.2}$

  c.f. some excess also near NGC 4151? Neronov+, Semikoz talk

GeV γ: exceeds starburst expectation -> AGN origin?

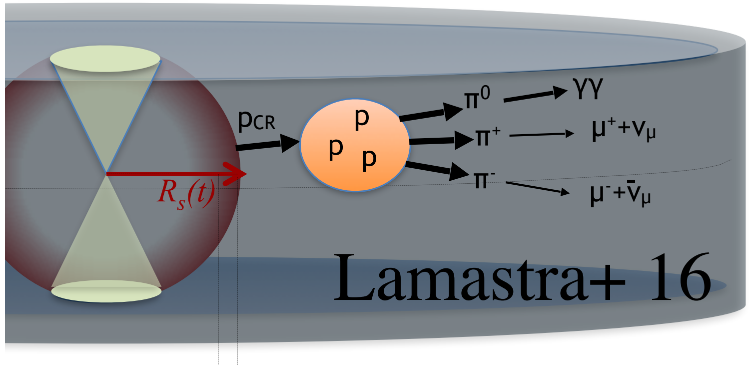
Yoast-Hull+ 14, Eichmann & Becker Tjus 16; see also Ajello+ 23, Ji+ 23

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

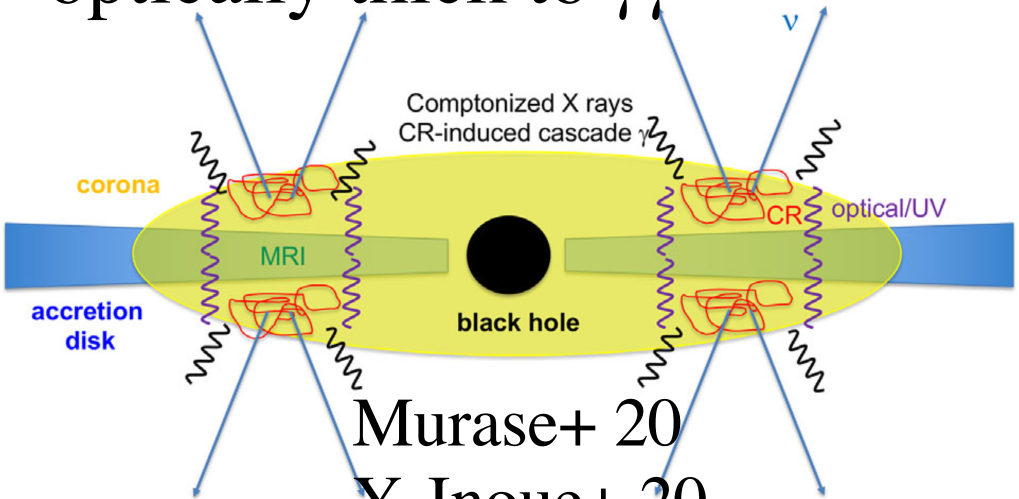
MAGIC Col. 19

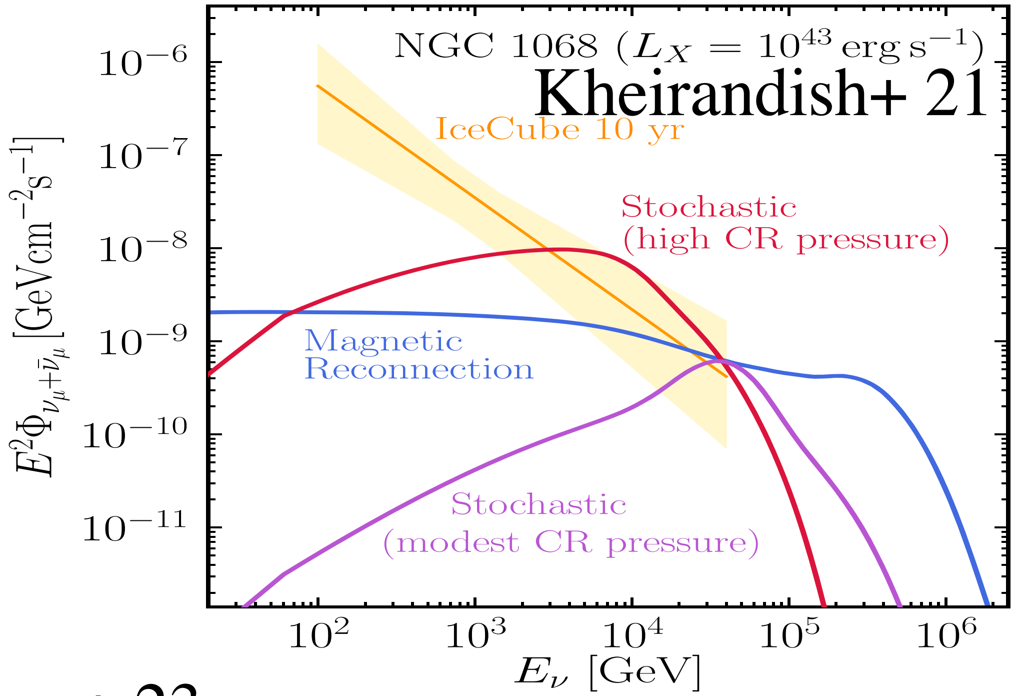
particle acceleration sites in radio-quiet AGN

AGN wind kpc-scale ext. shock?
-> disfavored for NGC 1068
by TeV upper limits



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

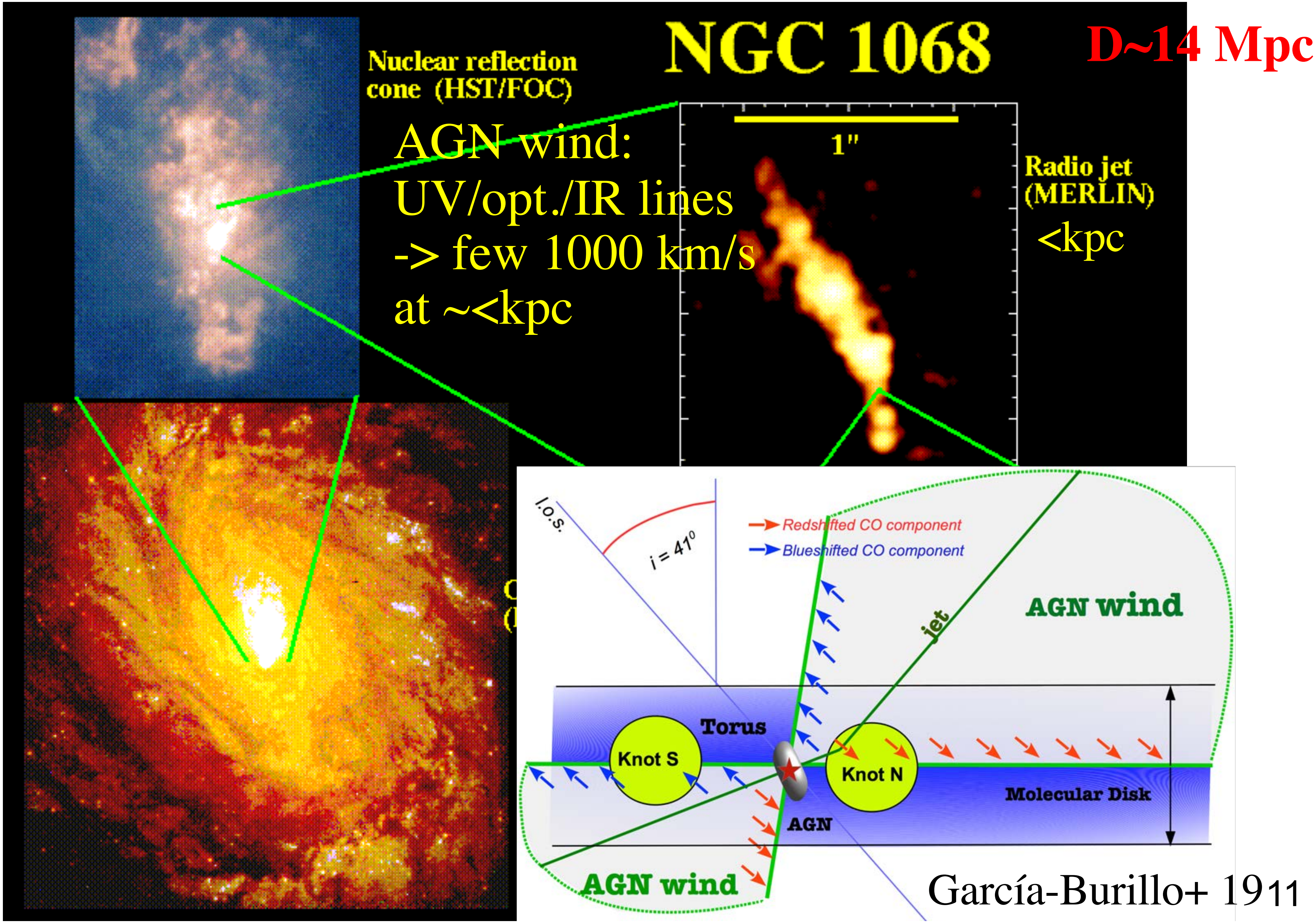




Murase+ 20
Y. Inoue+ 20
also Eichmann+ 22, Blanco+ 23

issues for coronae: physics uncertain for
- corona formation
- particle acceleration

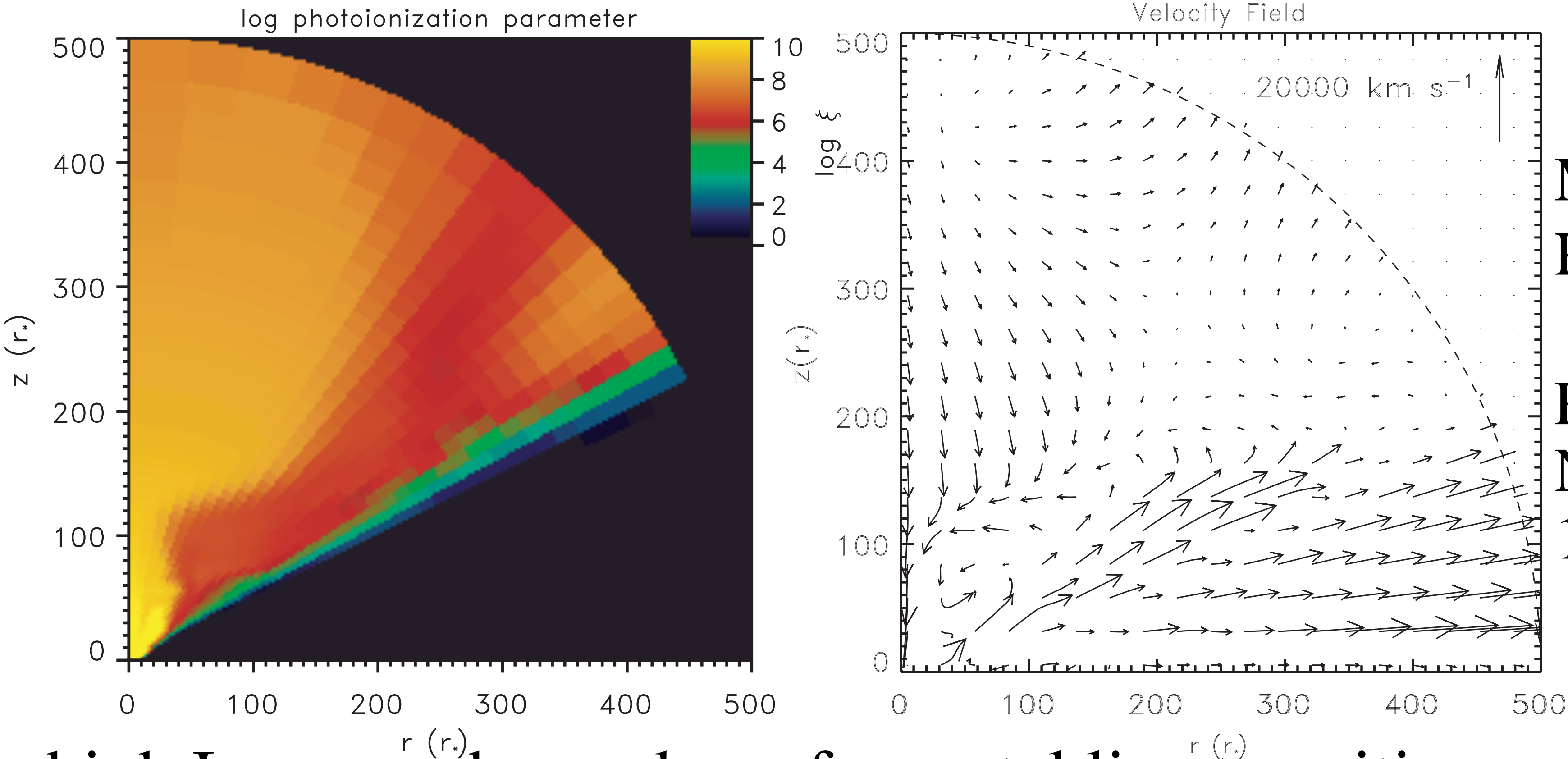
NGC 1068: Seyfert 2 with wind + obscuring torus



García-Burillo+ 19

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

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

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

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

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

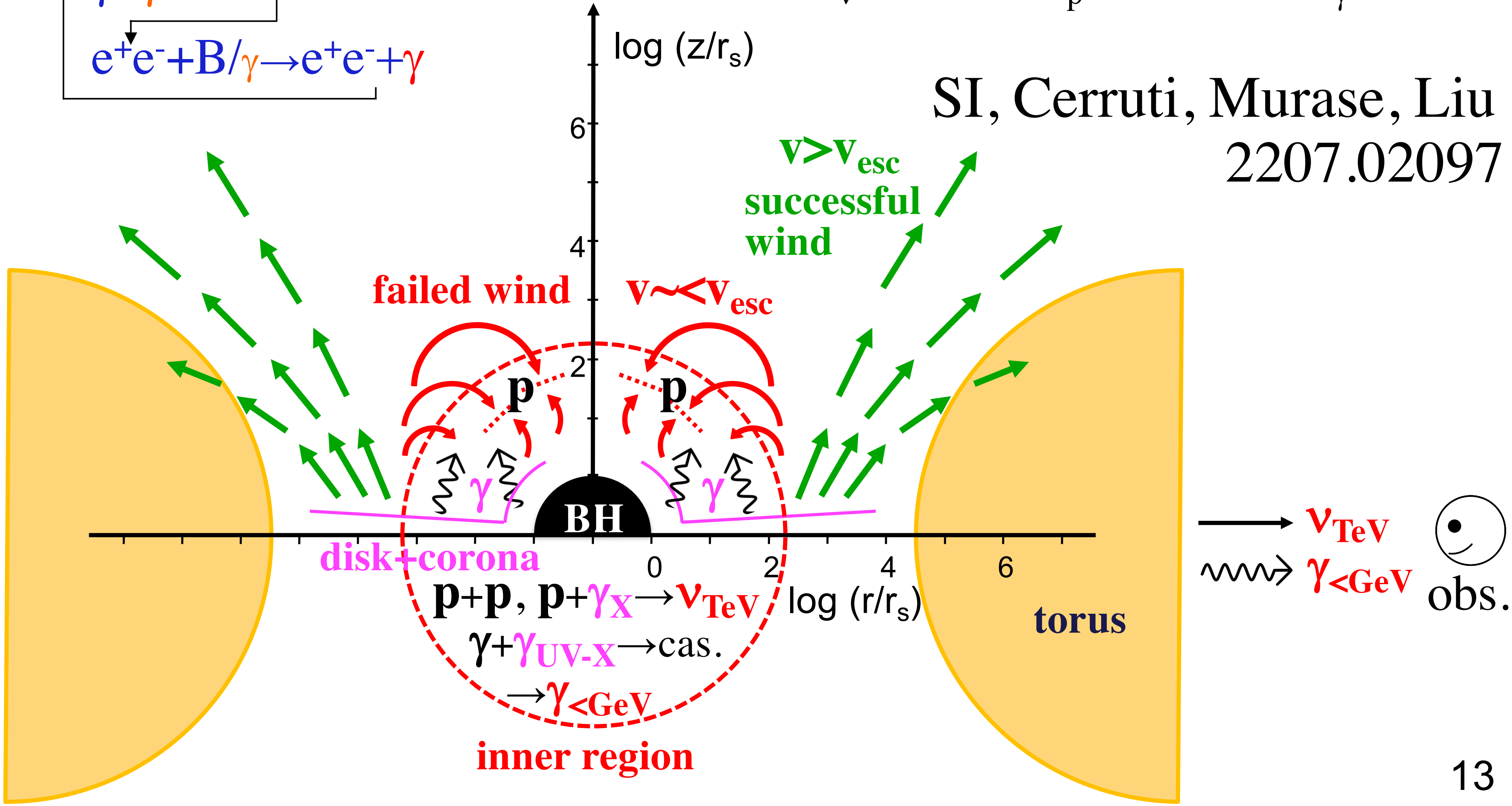
$e^+e^- + B/\gamma \rightarrow e^+e^- + \gamma$

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

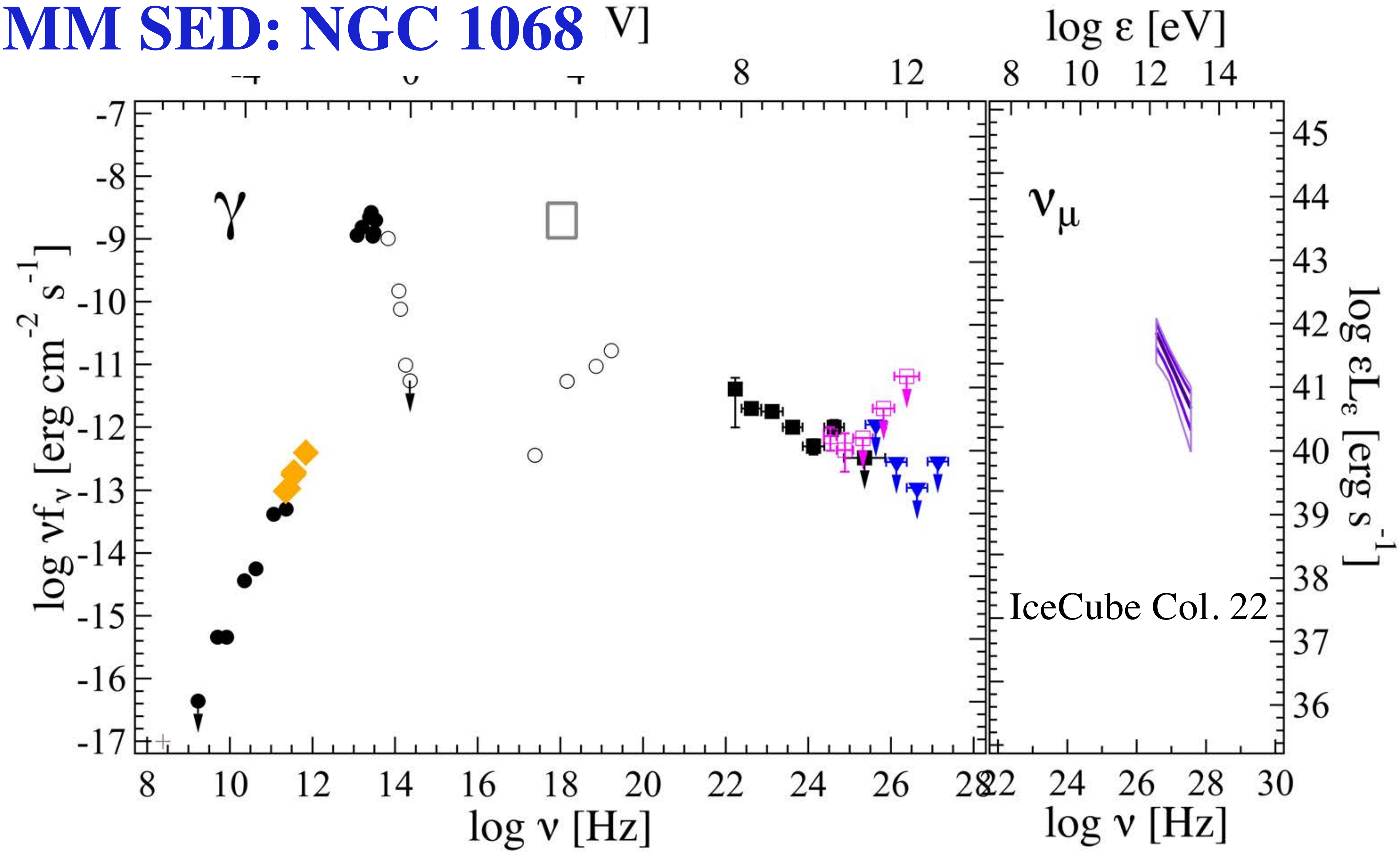
$E_p \varepsilon_\gamma \sim 10^{17}\ \mathrm{eV}^2$

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

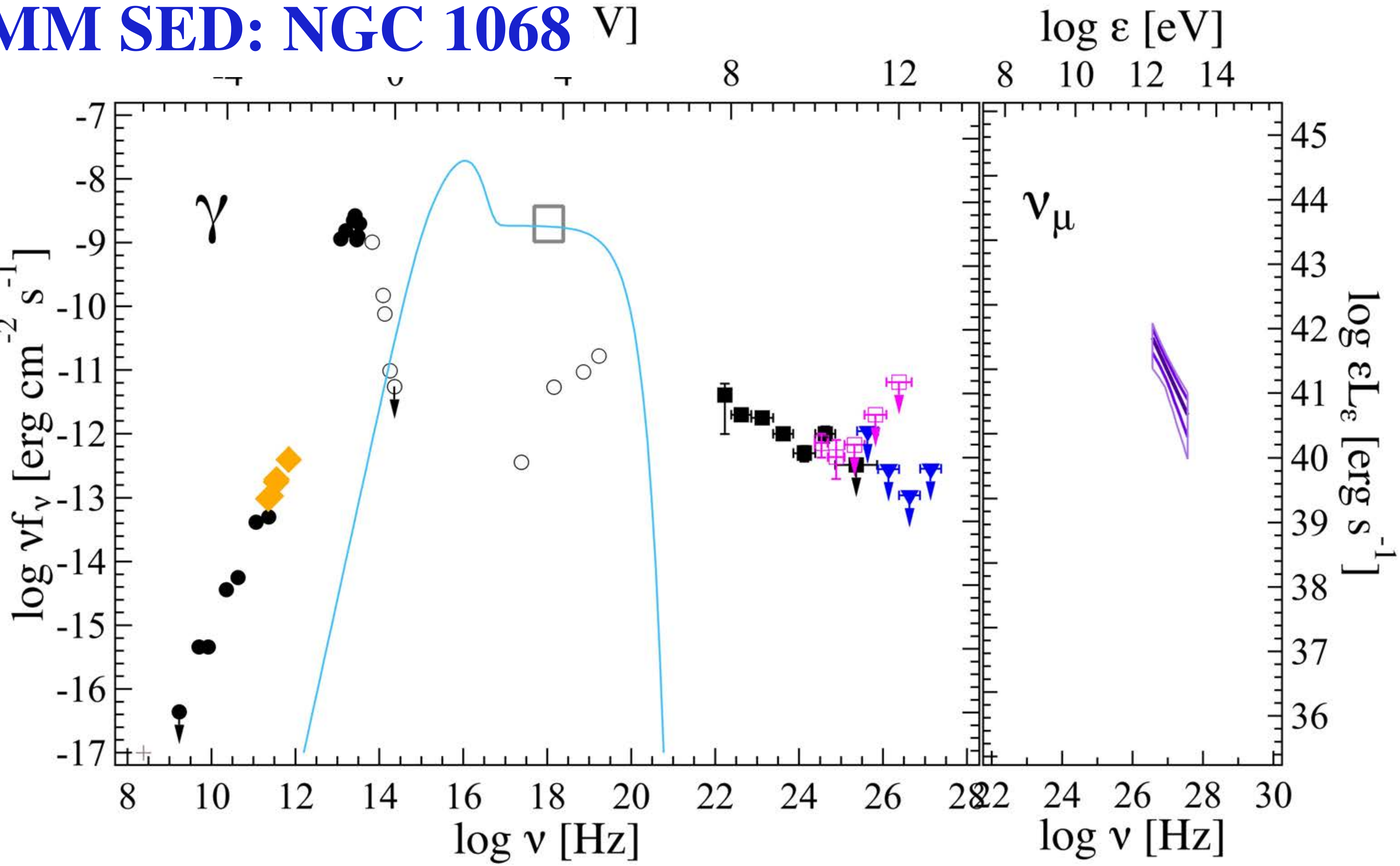
SI, Cerruti, Murase, Liu 2207.02097



MM SED: NGC 1068



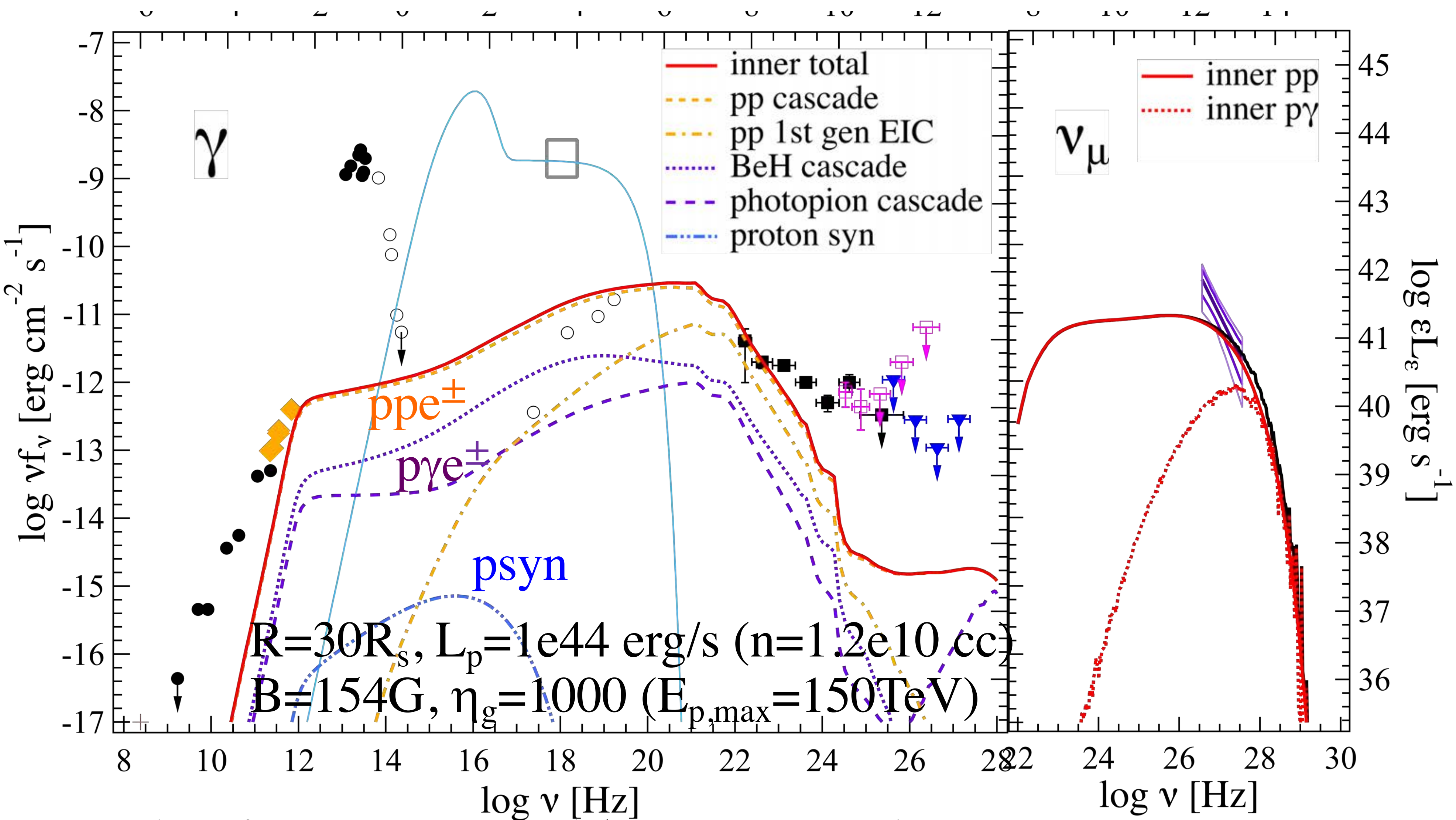
MM SED: NGC 1068



$D=14$ 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
intrinsically X-ray brightest AGN in whole sky

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

inner region (failed wind) pp+pγ vs MM SED

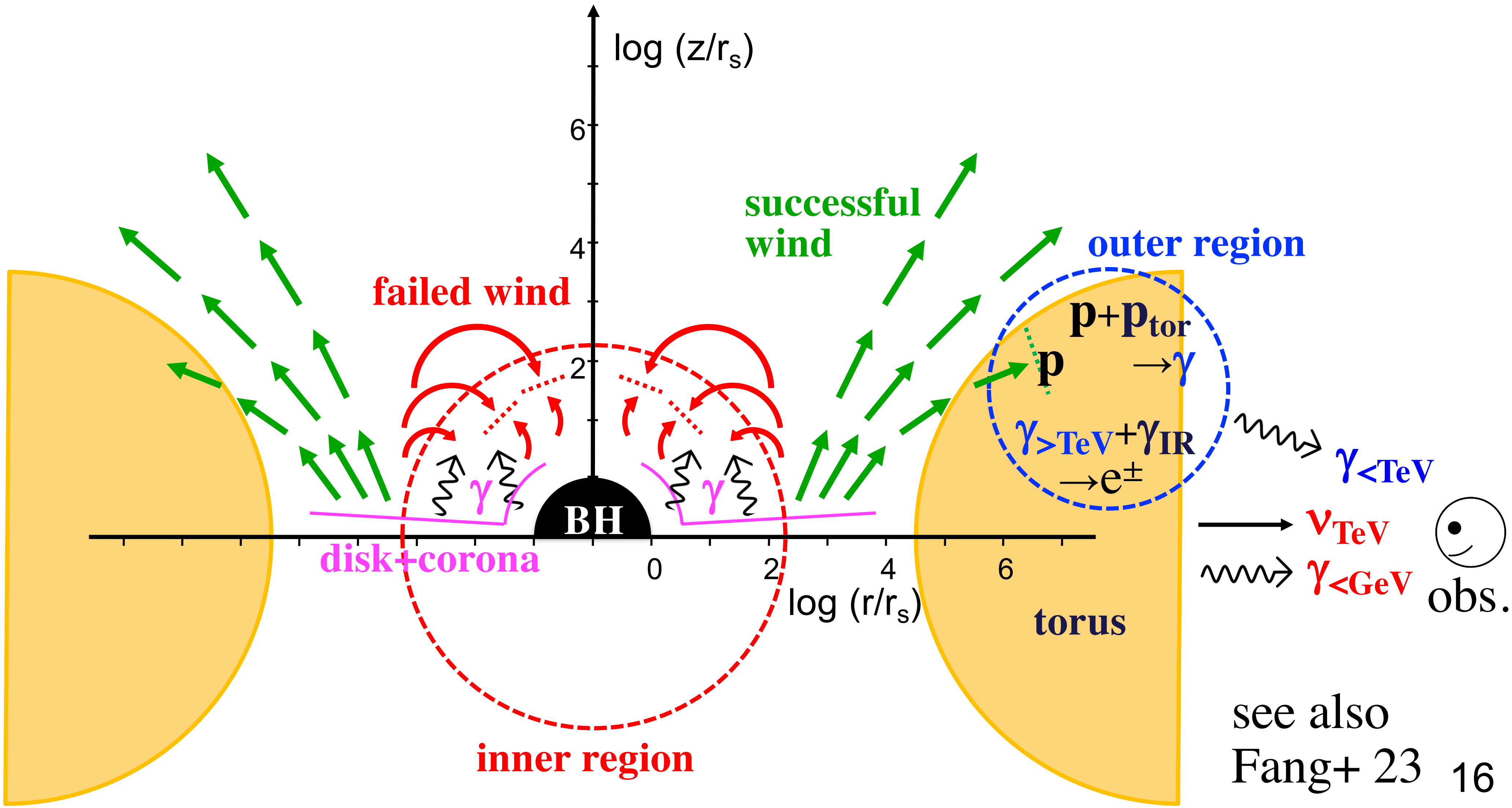


- ν: pp dominant, reasonable wrt IceCube
- γ: EM cascade (mostly ppe$^{\pm}$) consistent wrt available MWL
  γγ attenuated by disk UV-X: prominent at (keV-)MeV
  observationally relevant for ~<GeV, ~submm

pp $\gamma(+\nu)$ from AGN wind+torus interaction

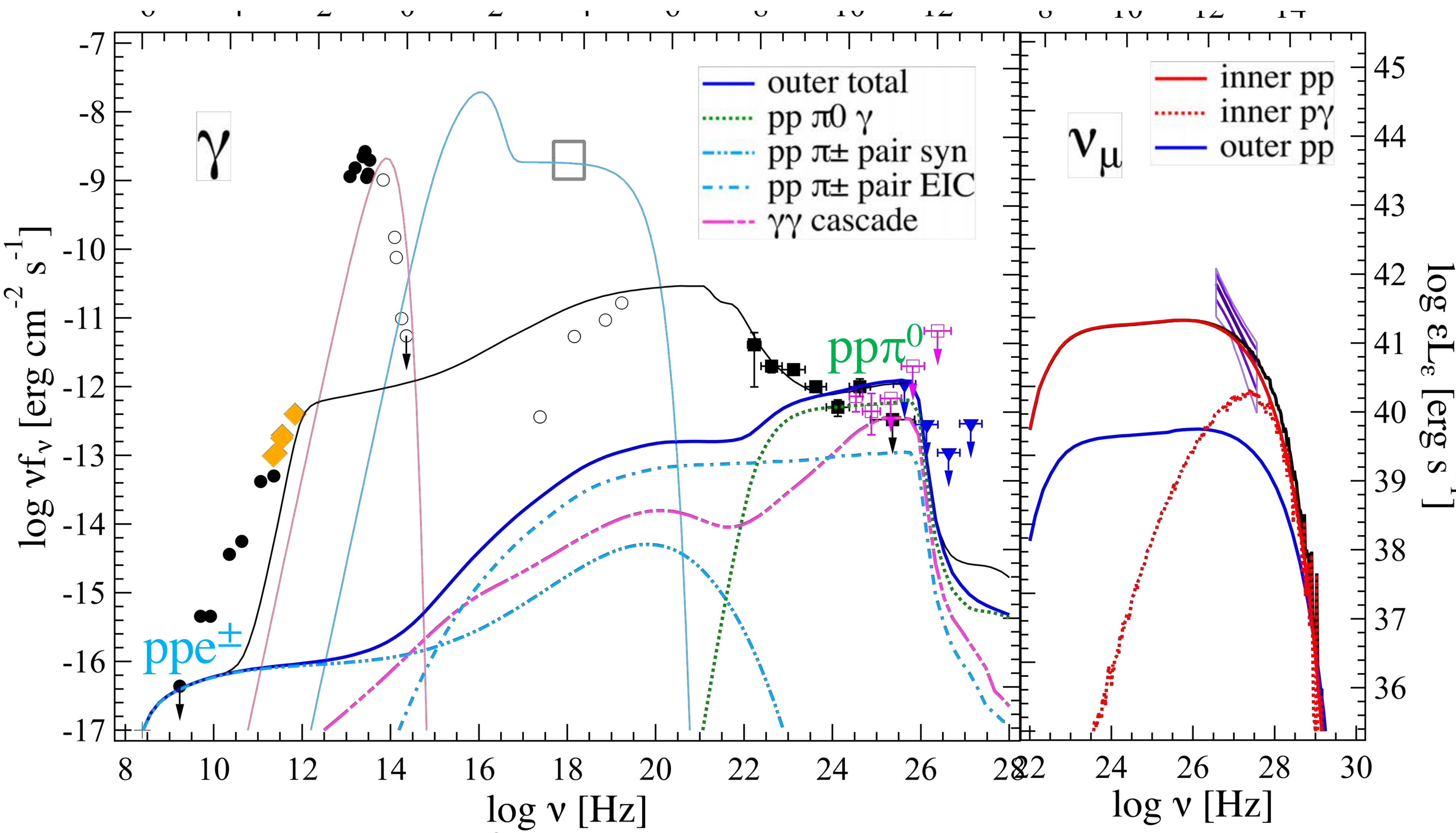
outer successful wind + torus impact
-> external shock -> proton acceleration

$p_{CR}+p_{gas} \rightarrow N+\pi^0, \pi^\pm$ $\quad \pi^0 \rightarrow 2\gamma$ $\quad \gamma_{TeV}+\gamma_{IR} \rightarrow e^+e^-$



see also
Fang+ 23

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

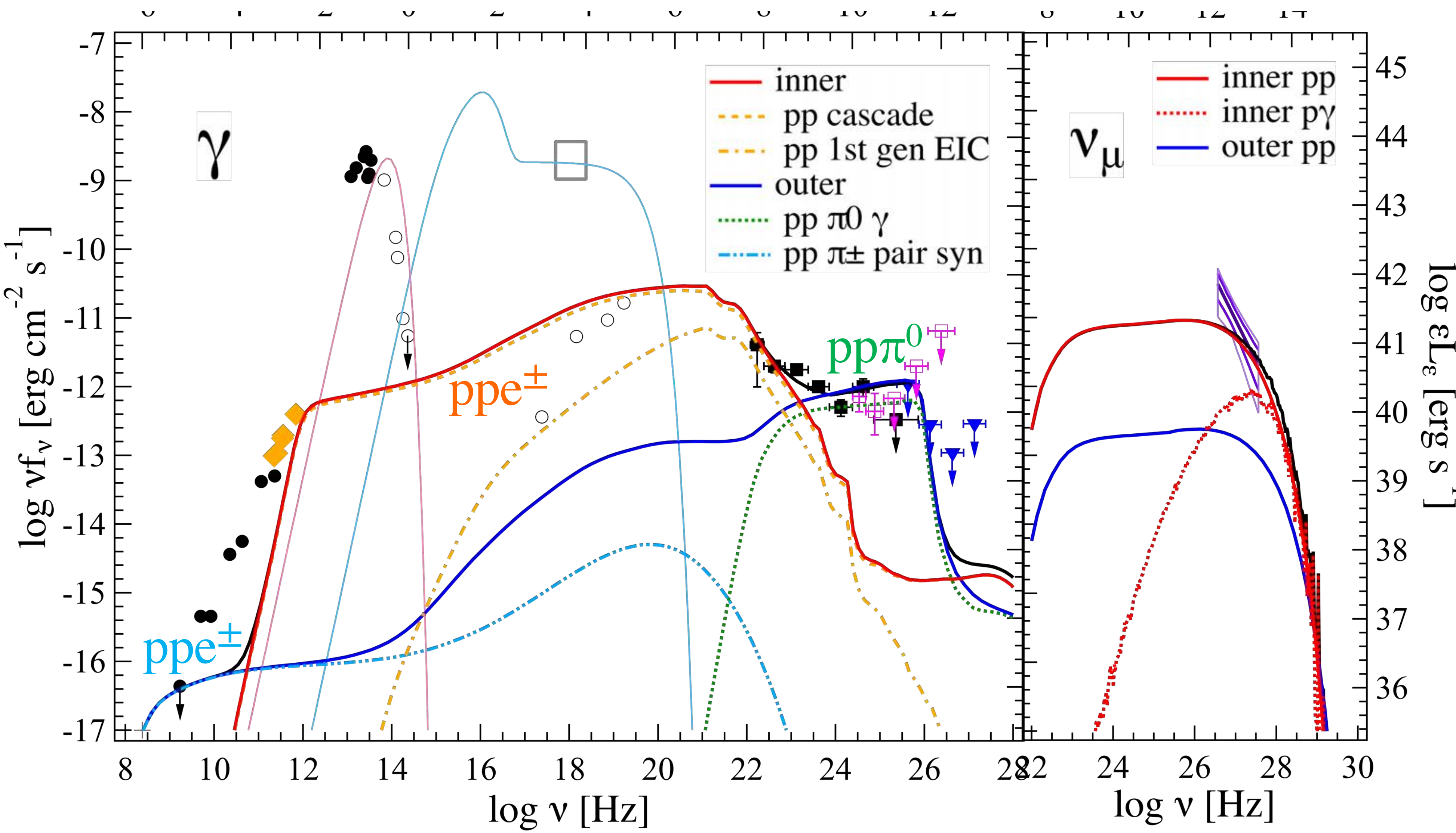


R_{tor}=0.1 pc, n_{tor}=1e6 cm^{-3}, B_{tor}=15 mG, L_p=2.6e42 erg/s

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

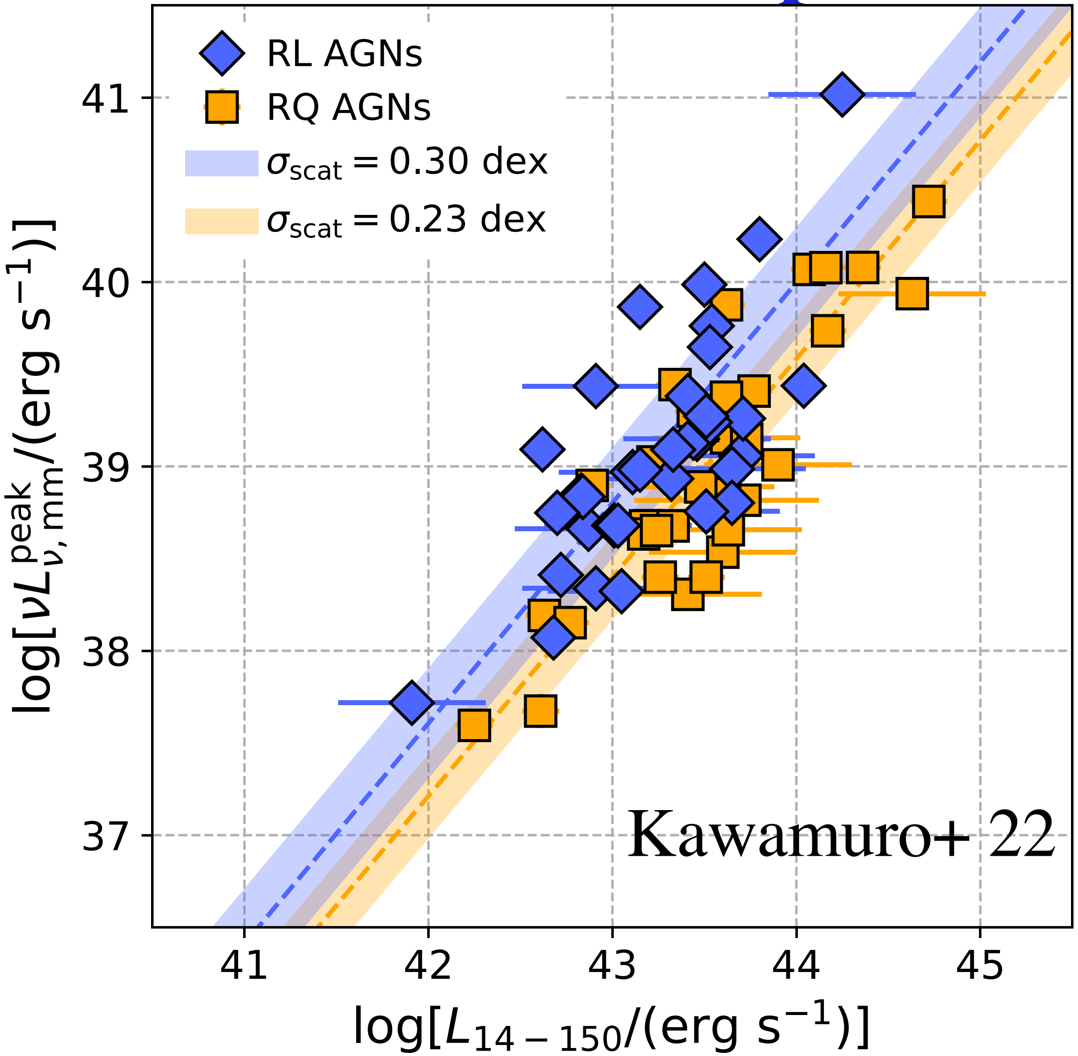
also e.g. Circinus
Fermi UFO sample?

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

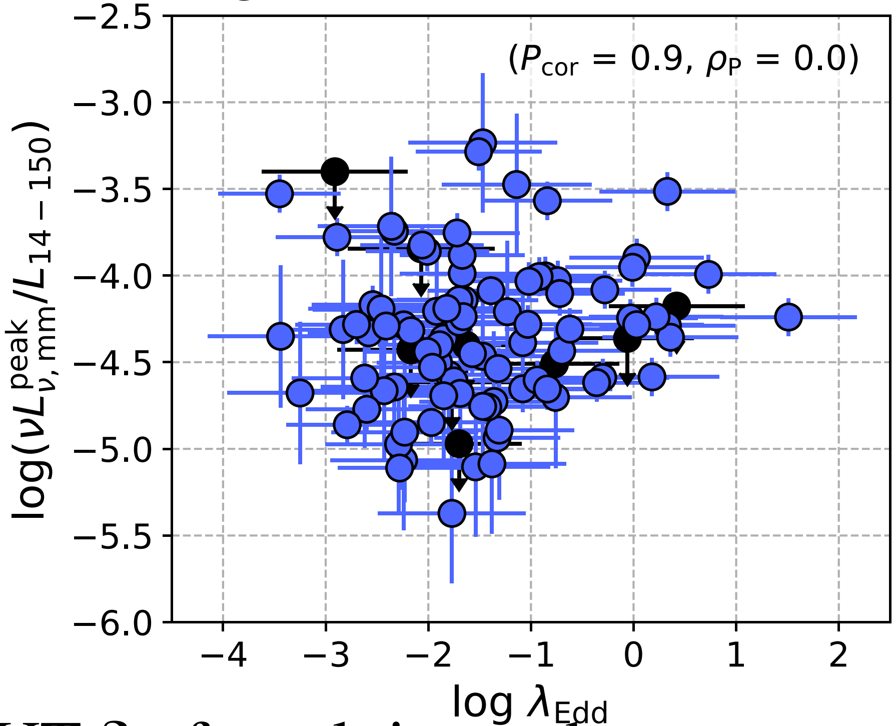


- inner region (failed wind) pp: TeV ν, <GeV, submm cascade
- outer region (wind-torus) pp: >GeV γ, GHz sec. sync.
- potentially unique info on AGN wind formation, especially in electromagnetically obscured objects

mm radio @~<100 pc vs X-rays of radio-quiet AGN



98 BAT-selected AGN
ALMA 211-275 GHz
~1-200 pc resolution
log $L_{14\text{-}150\ \mathrm{keV}}$~40-45 erg/s
log M_{BH}~5-10 M_{sun}
log λ_{Edd}~-4 - +2



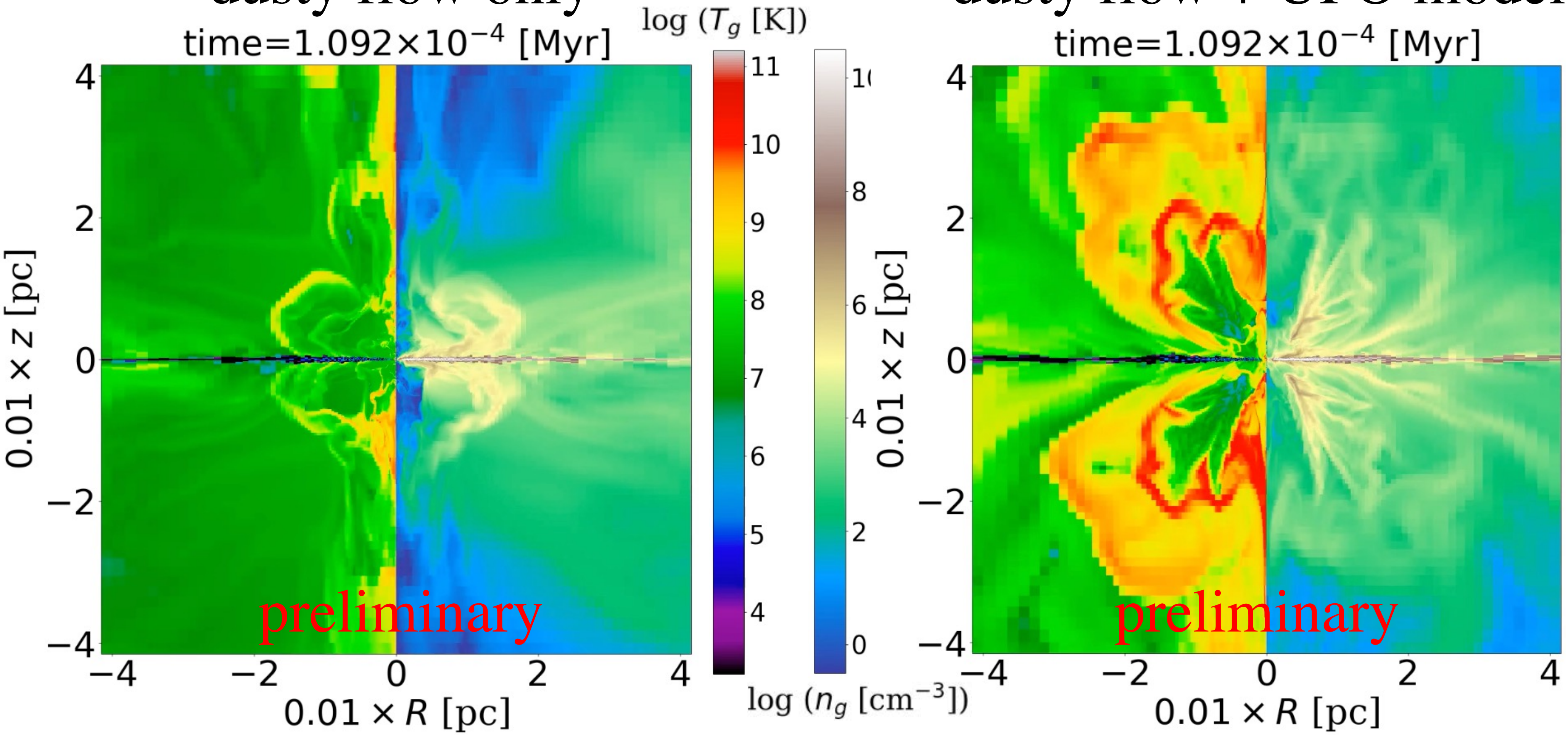
dust? most spectra too flat
jet? little dependence on inclination? BUT δ of weak jets unknown
wind? inconsistent with ISM interaction?
BUT dissipation+emission possible from <<kpc scale
corona? very weak B required (β>>1) see also Ricci+ 23, Ruffa+ 23

complex "inflow/outflow" shocks

Kudoh+ 23
Kudoh, Wada+
in prep.

extension of "ab-initio" simulations
down to regions ~<0.01 pc

dusty flow only — dusty flow + UFO model



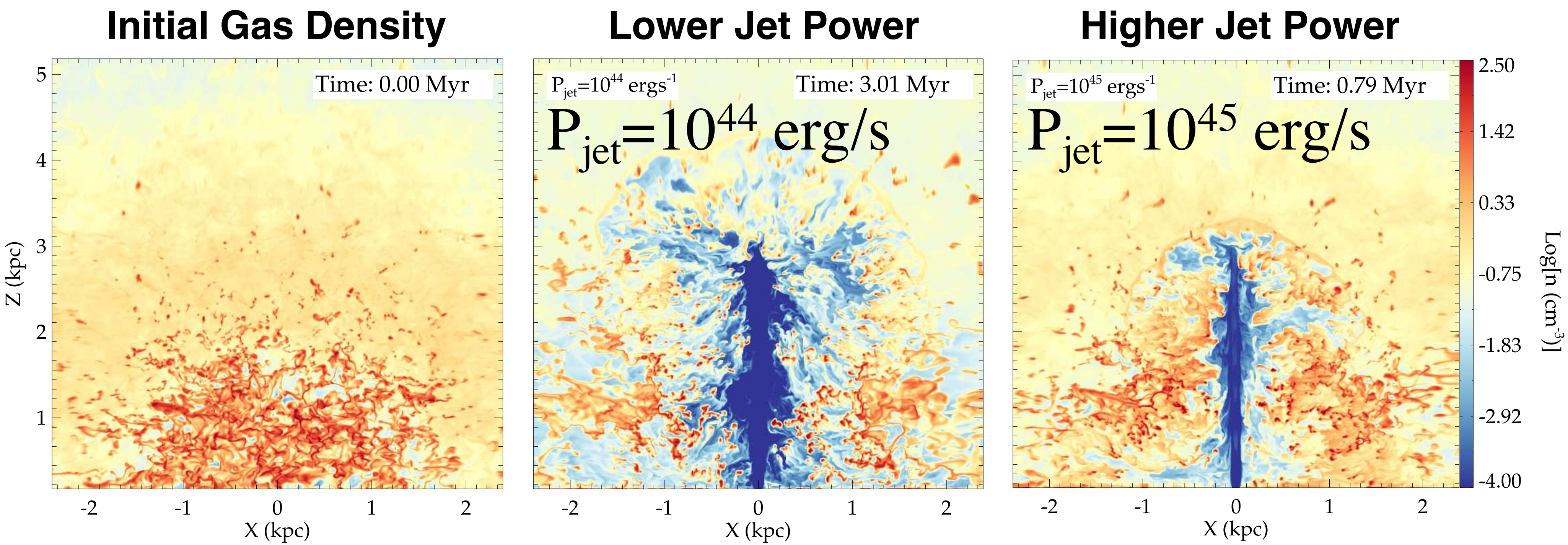
- much more complex and dynamic compared to simple view of disk+wind+BLR+torus

see Peretti+ 2301.13698

- shocks ubiquitous due to variable inflows/outflows

low-power jets: impact on host ISM Nylund+ 18

NB still radio-loud range Mukherjee+ 16, 17



weaker jets for radio-quiet AGN?

- origin of radio-loud/quiet dichotomy: BH spin? B fields?
- feedback effects on host ISM?
- CR acceleration+non-thermal emission?

c.f. talks by Marinelli+, Salvatore

summary

AGN: radio-quiet AGN possess weak jets + winds

AGN winds: potentially crucial for feedback, jet collimation,
CR acceleration+nonthermal emission

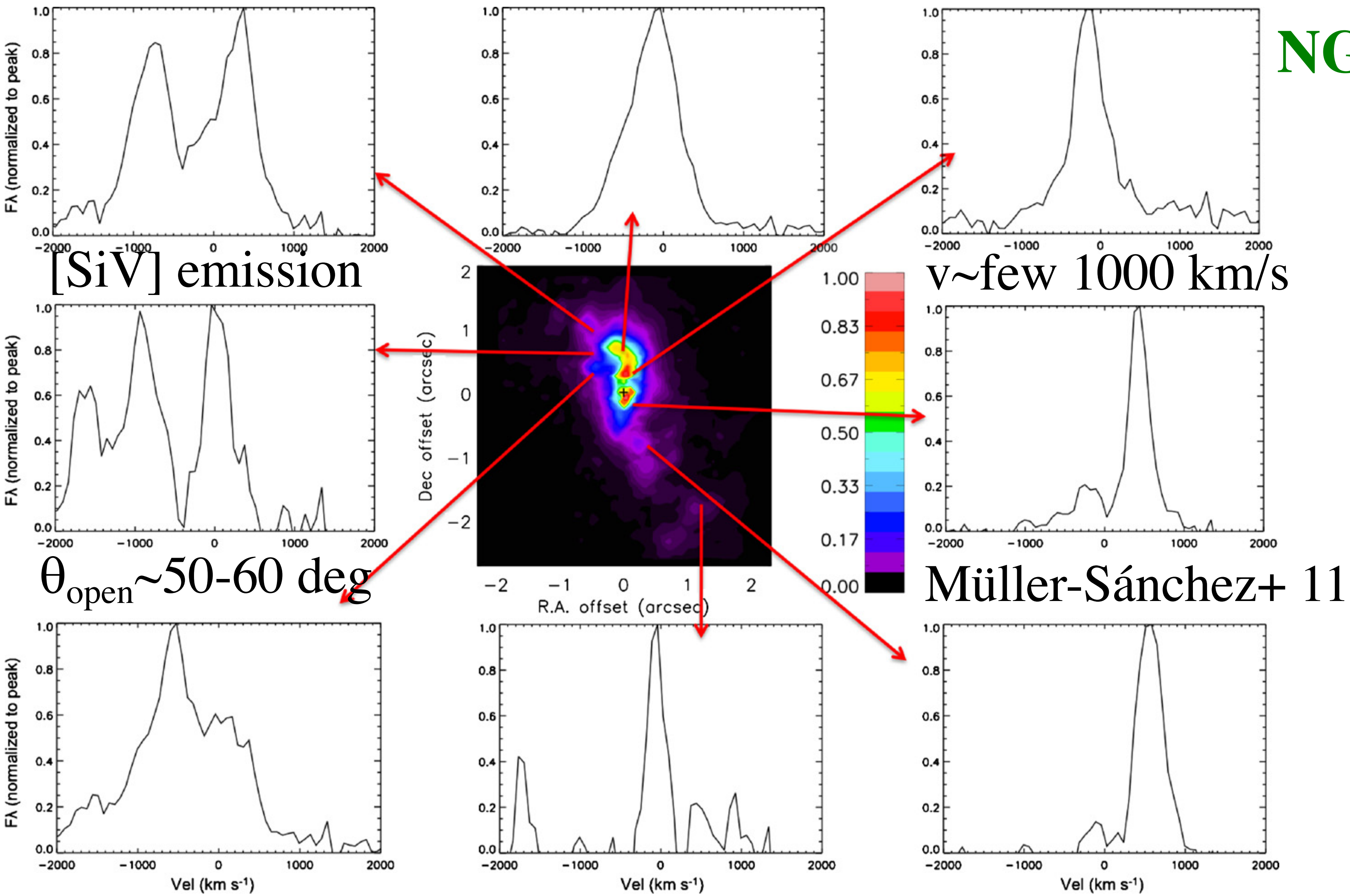
ν+γ emission from NGC 1068
- disk coronae?
- weak jets?
- winds? inner failed wind: pp(+pγ) neutrinos
  +cascade sub-GeV, submm (future MeV)
  outer wind-torus: GeV-TeV γ, GHz radio
- tests: MM variability correlations
  other AGN: NGC 4151 (unobscured), Circinus...
  contribution to diffuse ν background
- unique info on AGN inner regions

future prospects
- more realistic studies of winds, weak jets

backup slides

evidence for AGN winds
subkpc - fast, highly ionized winds

NGC 1068



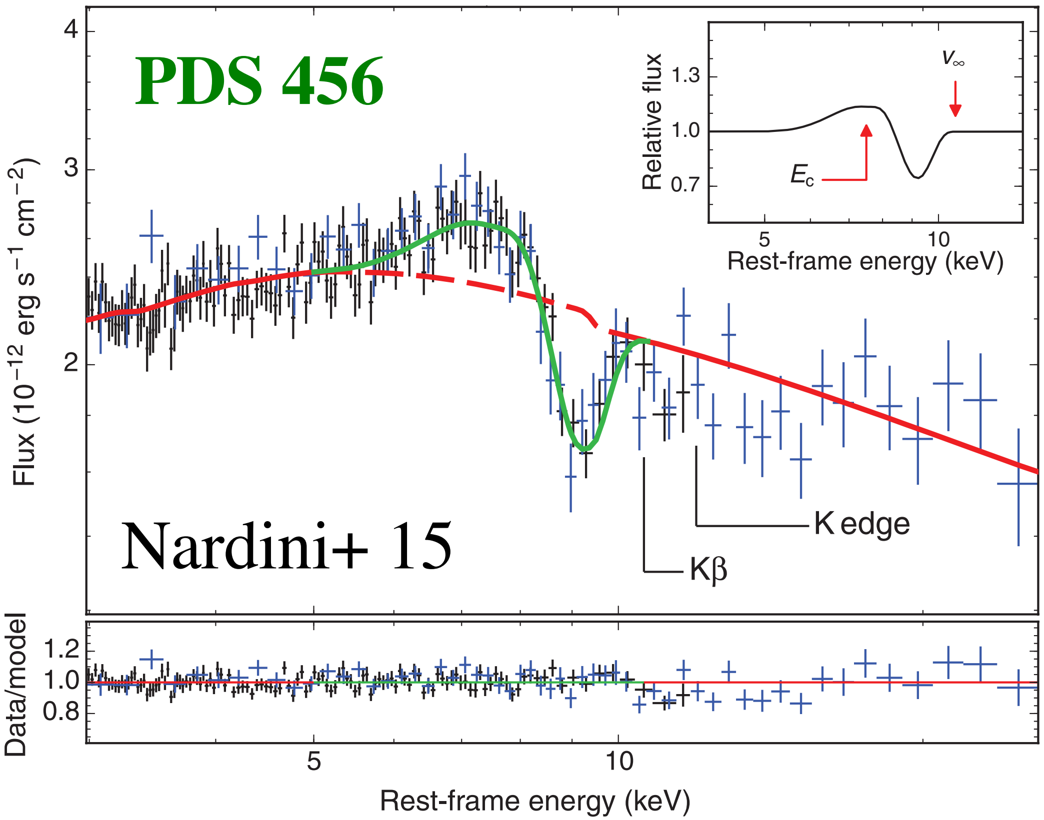
evidence for AGN winds

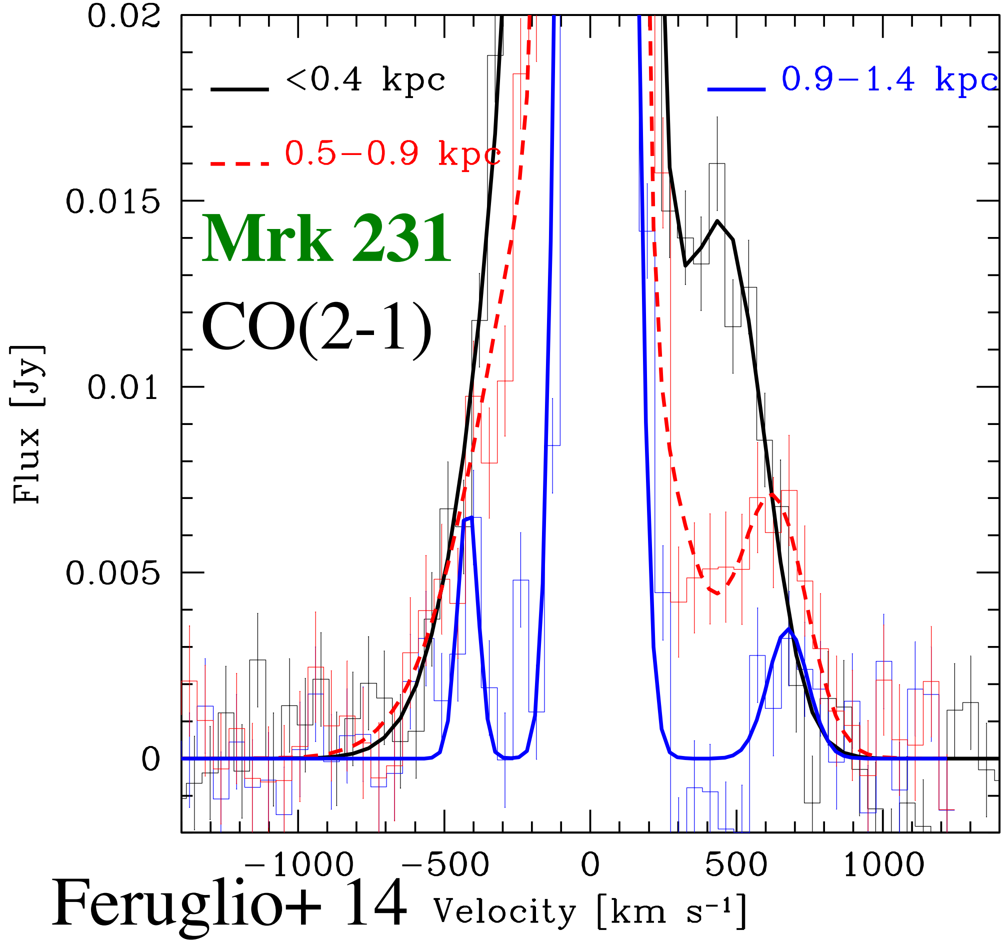
subpc:
ultra-fast outflows (UFOs)

- blue-shifted X-ray absorption lines, variable
- v~0.05-0.3c
- L_{kin}~0.01-0.4 L_{edd}
- >~40 % of all AGNs <-> jets

>~kpc:
massive molecular outflows

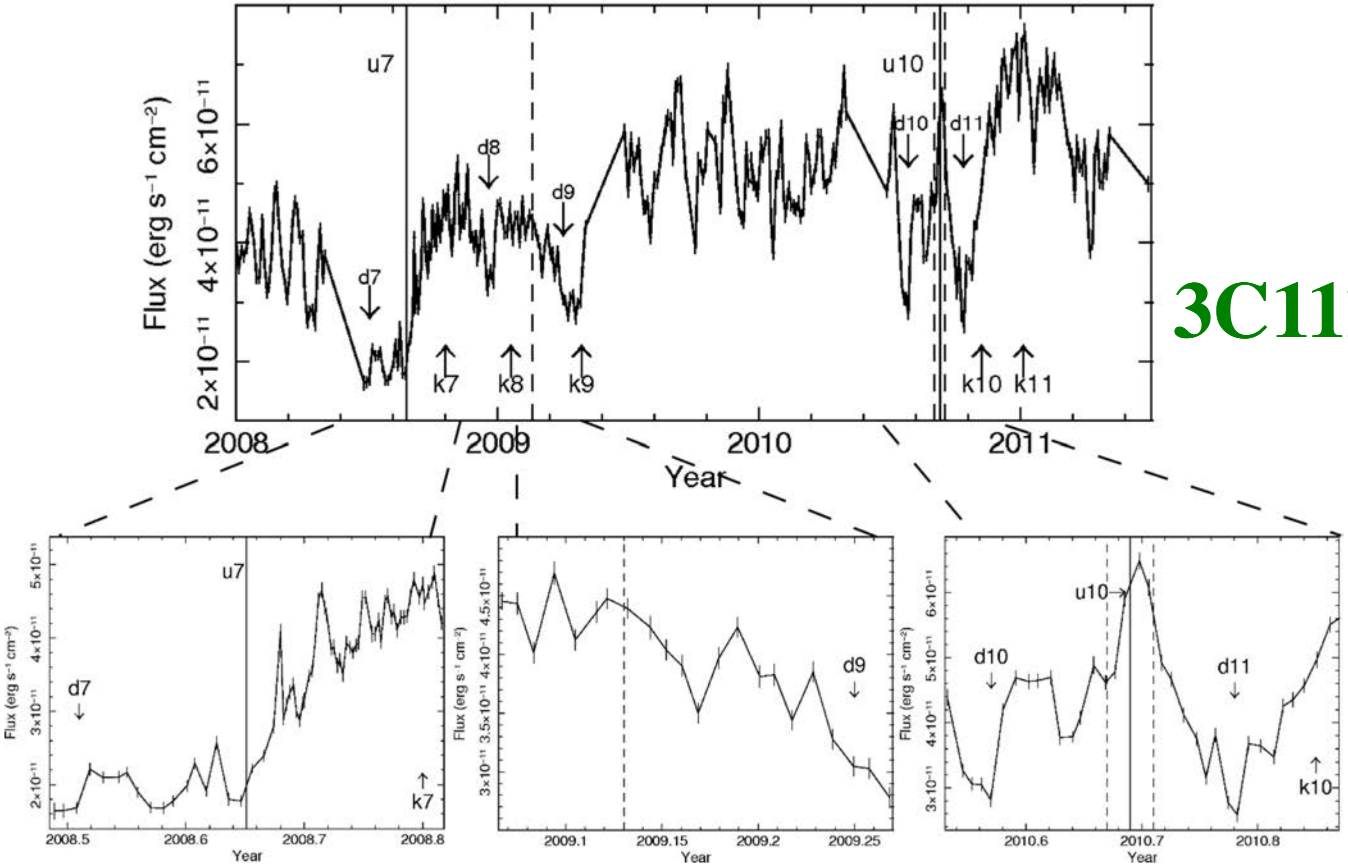
CO, OH etc. emission
-> v~100-1000 km/s,
$\dot{M}$~few 10-100 M_{Θ}/yr, L_{kin}~<L_{bol}





radio-loud AGN with UFOs: collimation by winds?

- 7 UFOs/27 radio-loud AGN   Tombesi+ 10,14
  -> 50+-20% accounting for selection effects
- jet vs UFO comparison in individual objects
  evidence for coexistence   Tombesi+ 12,13
  rough pressure equilibrium $P_{UFO,th} \sim P_{jet,ram}$



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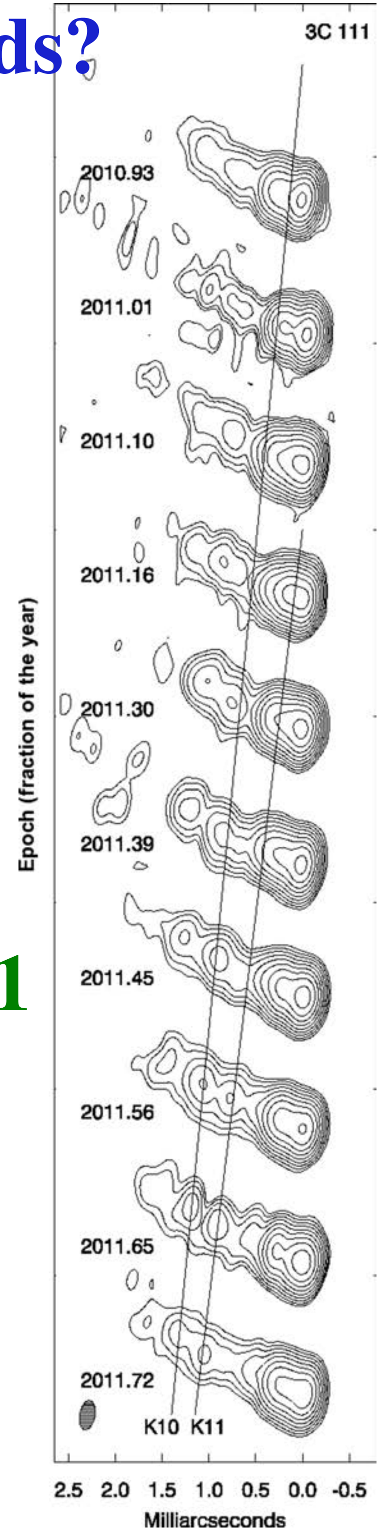
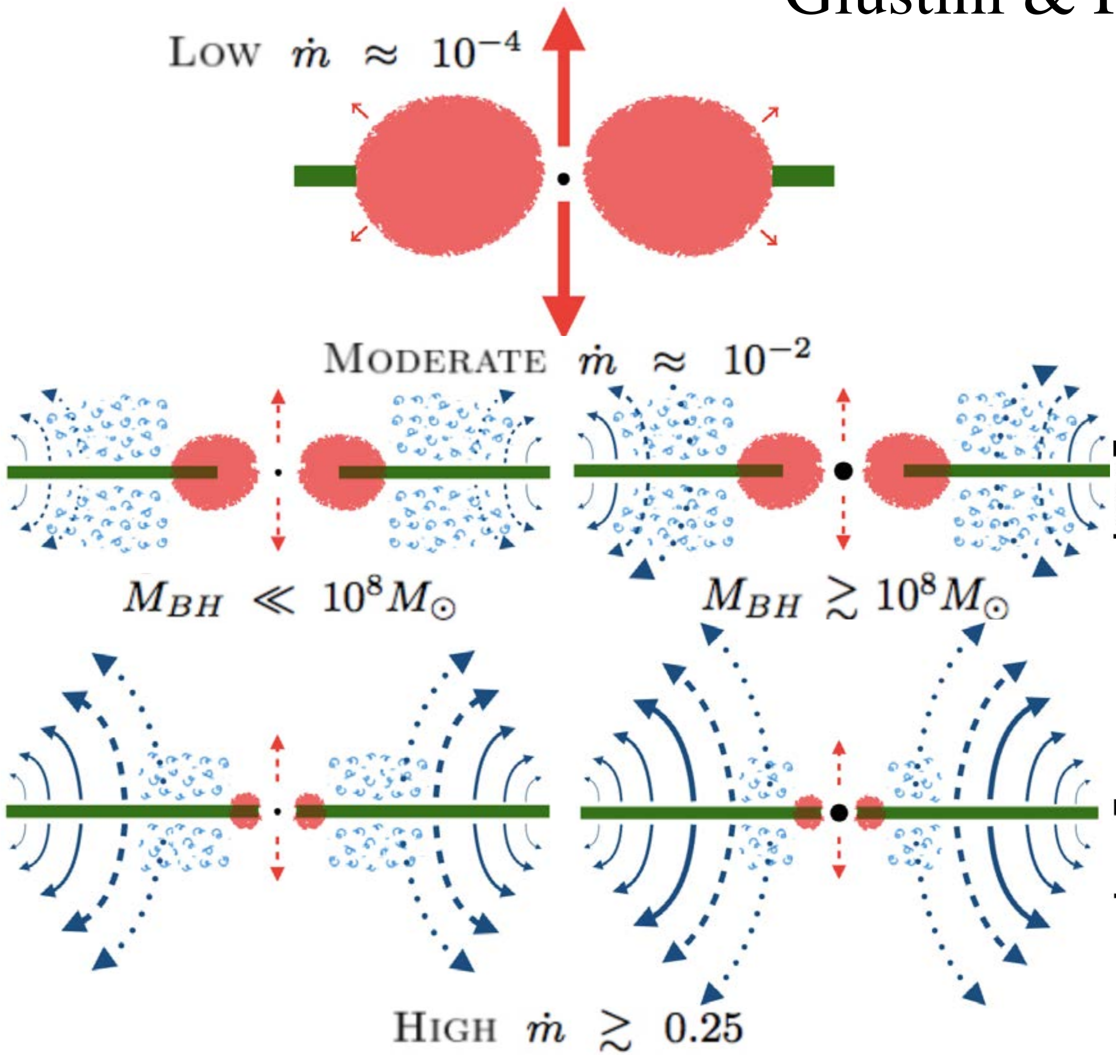
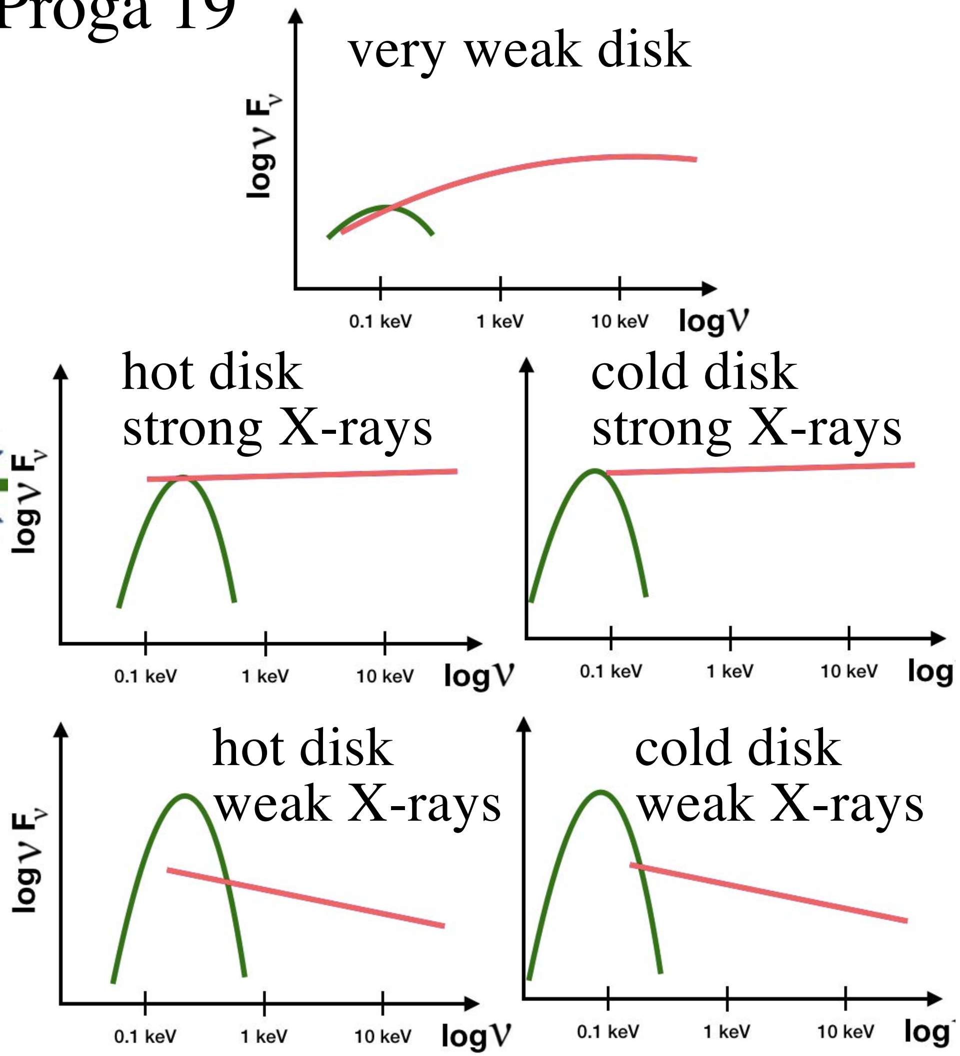


successful/failed winds vs accretion rate, BH mass

Giustini & Proga 19

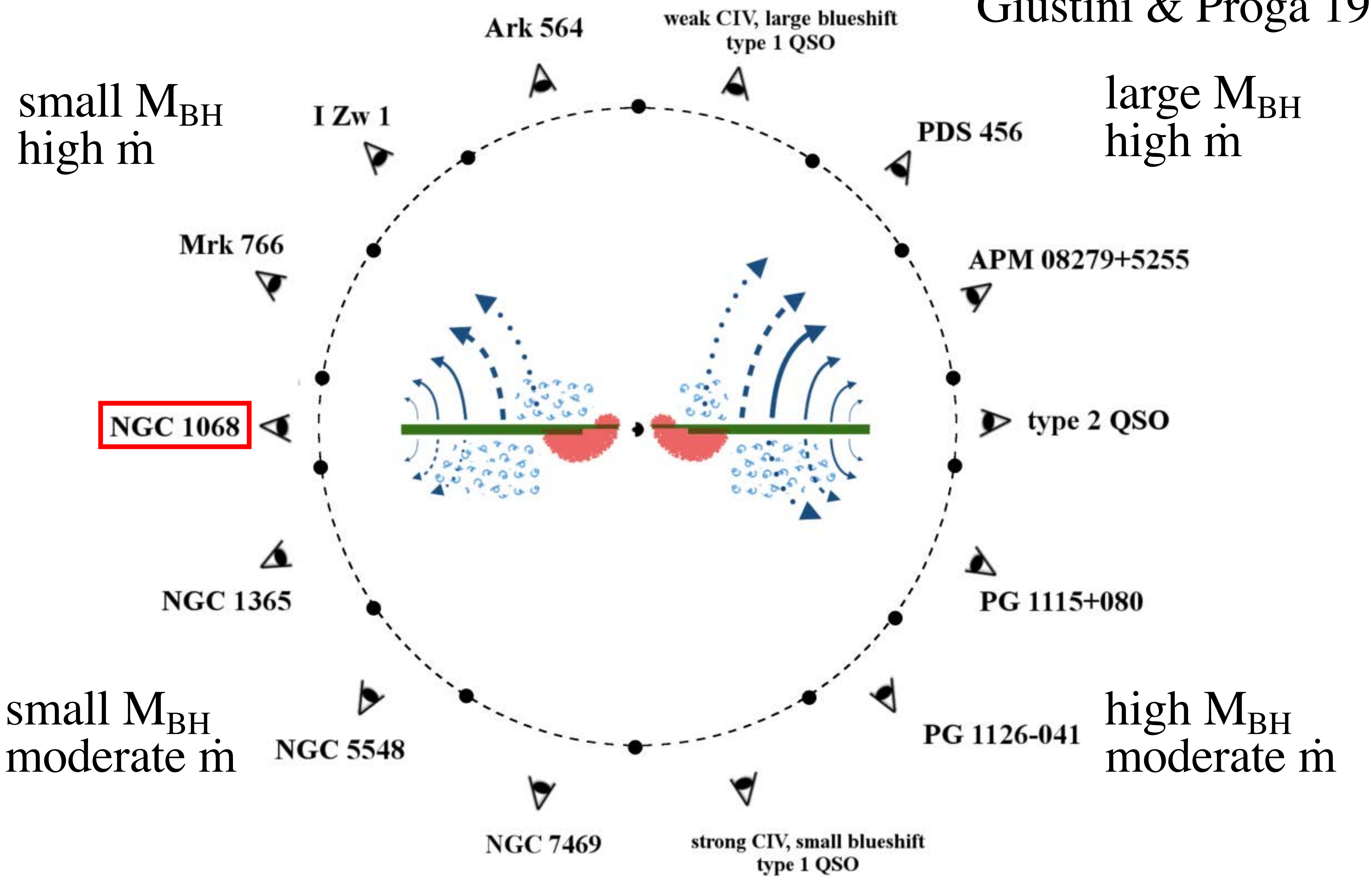




- qualitative scenario assuming ṁ scaling of thin disk+corona
- consistent with observed AGN SEDs, wind signatures
- robust failed winds at inner R for moderate to high ṁ: origin of BLR, X-ray obscurers (e.g. NGC 5548)?

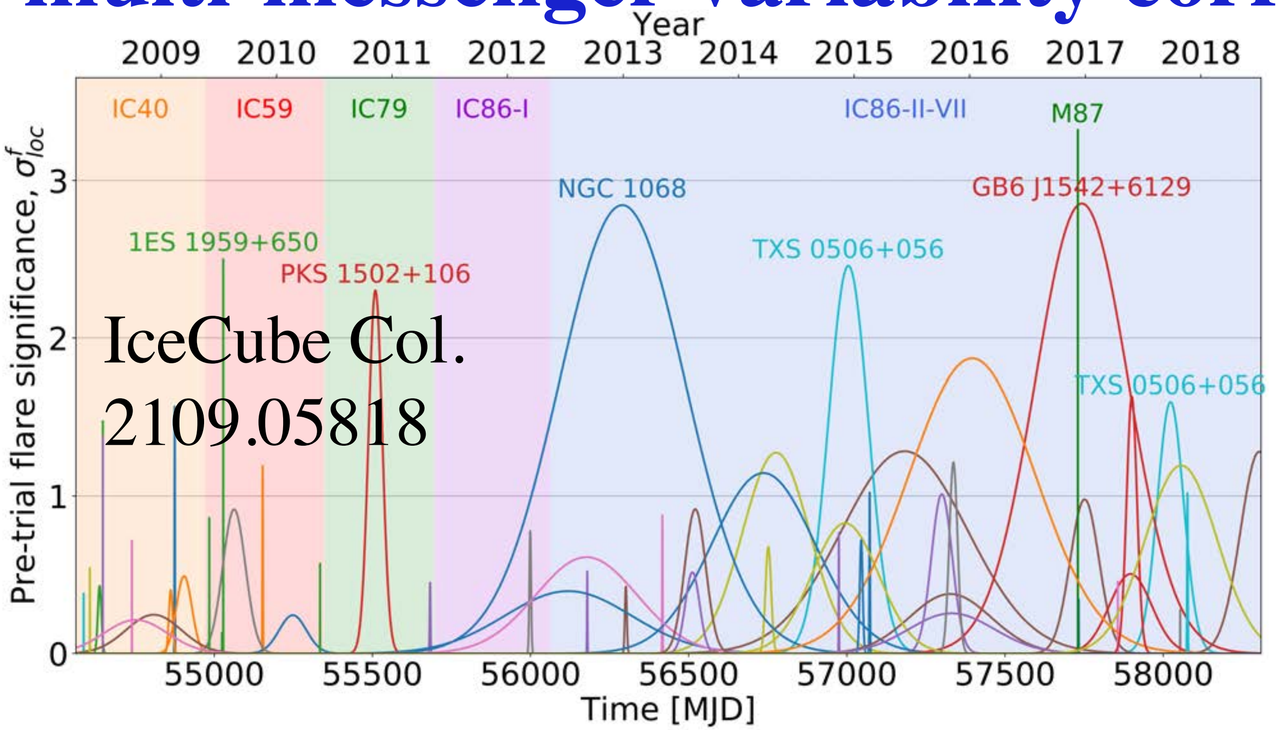
failed winds in inner regions of NGC 1068?

Giustini & Proga 19

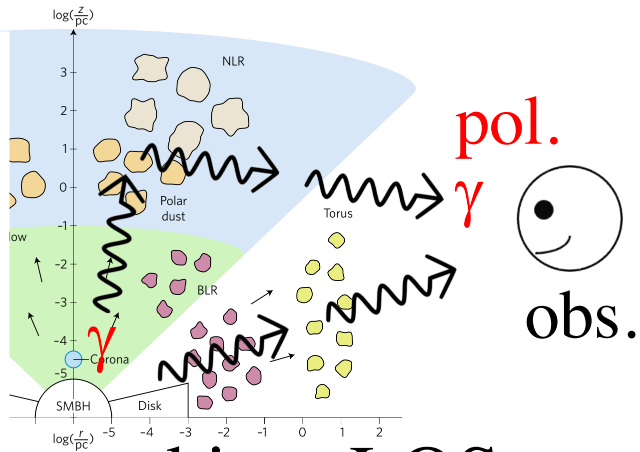


- NGC 1068: $\log M_{BH}/M_{\odot}$~7.2, $\dot{m}$~0.5
  -> failed winds in inner regions expected

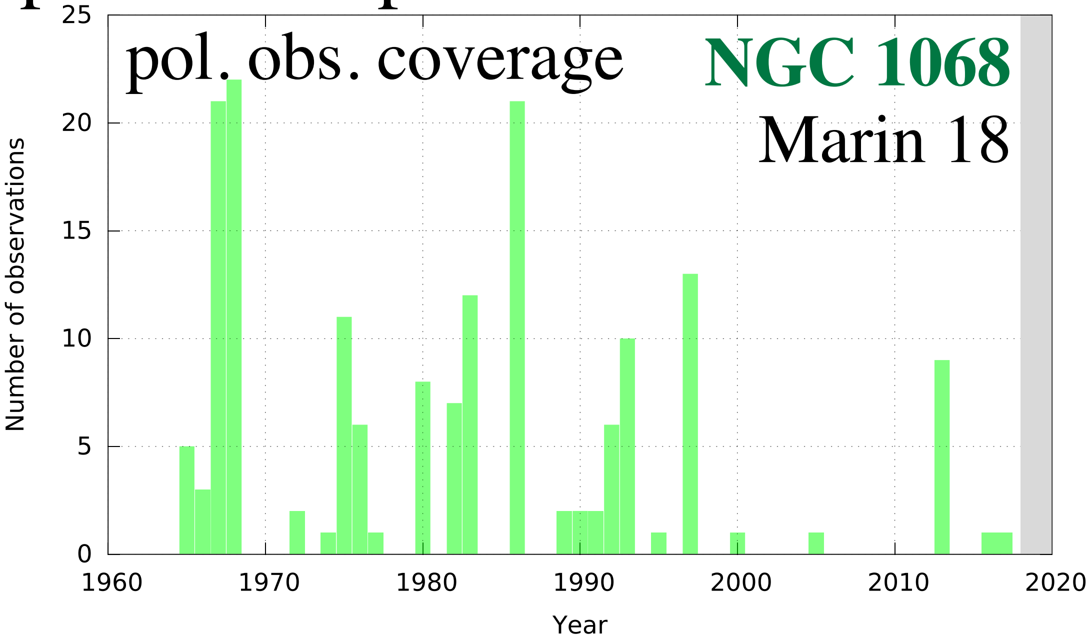
multi-messenger variability correlation



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



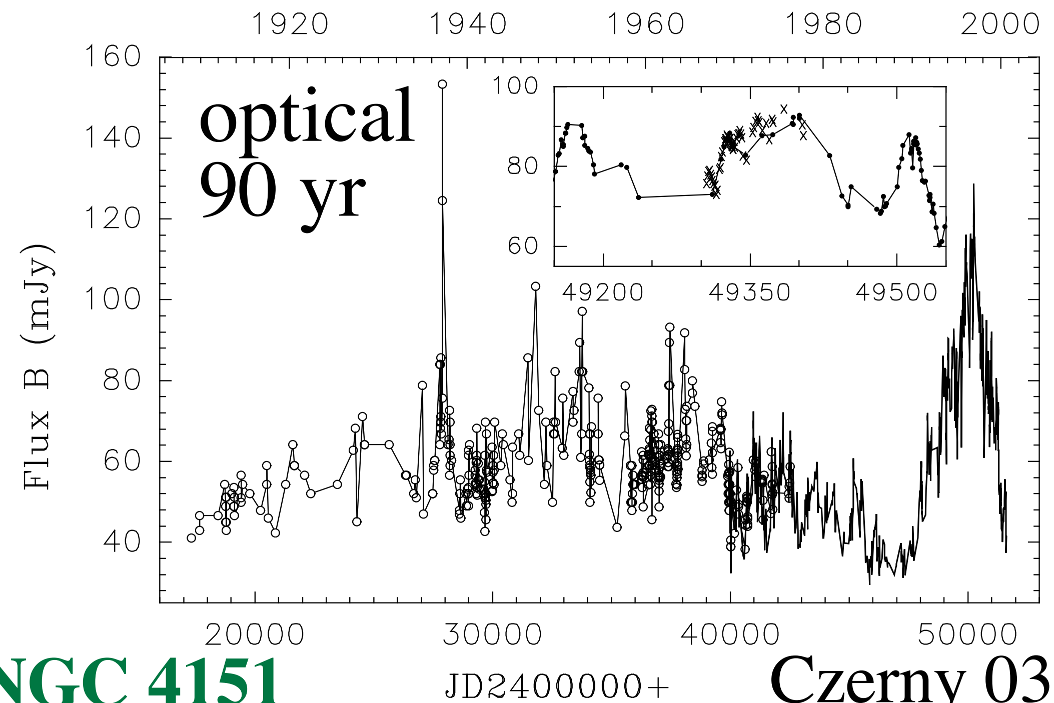
polarized optical-NIR: nuclear emission scattered into LOS



also escaping hard X-rays

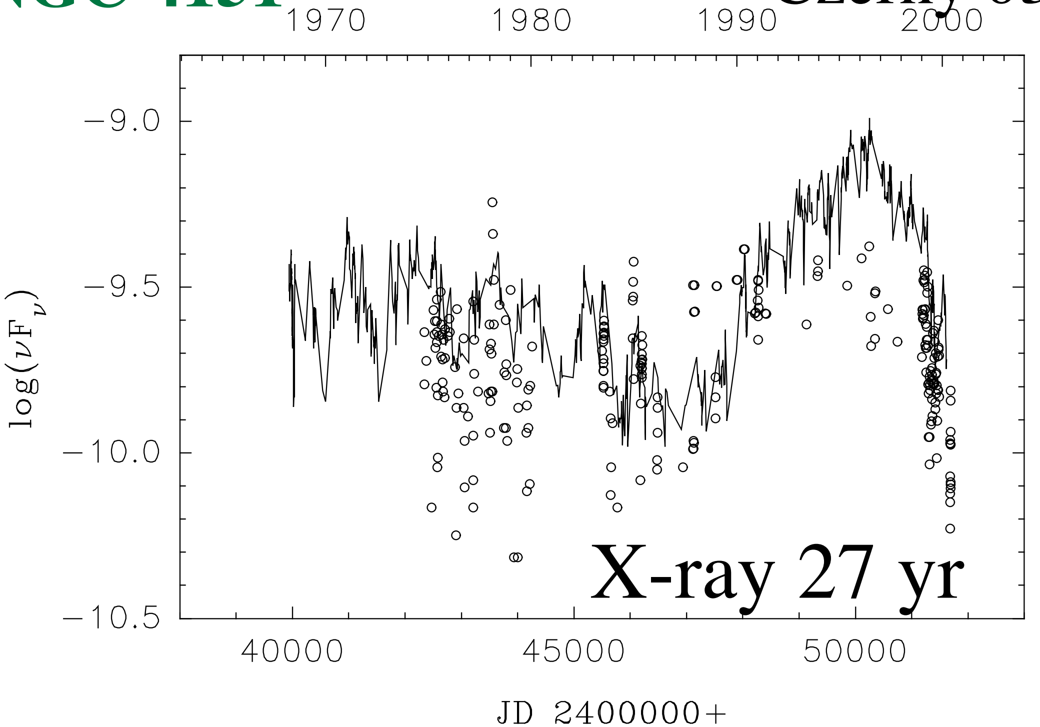
even better:
unobscured Seyfert 1

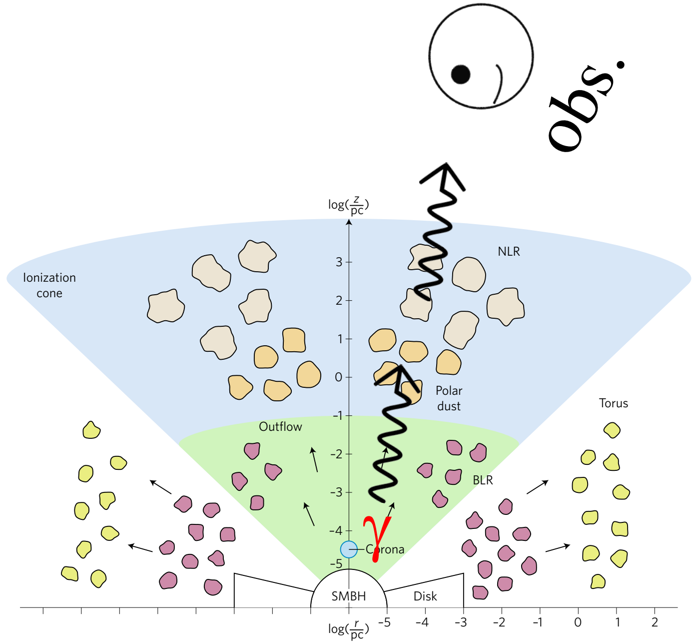
variability in unobscured Seyfert I with wind



NGC 4151

Czerny 03

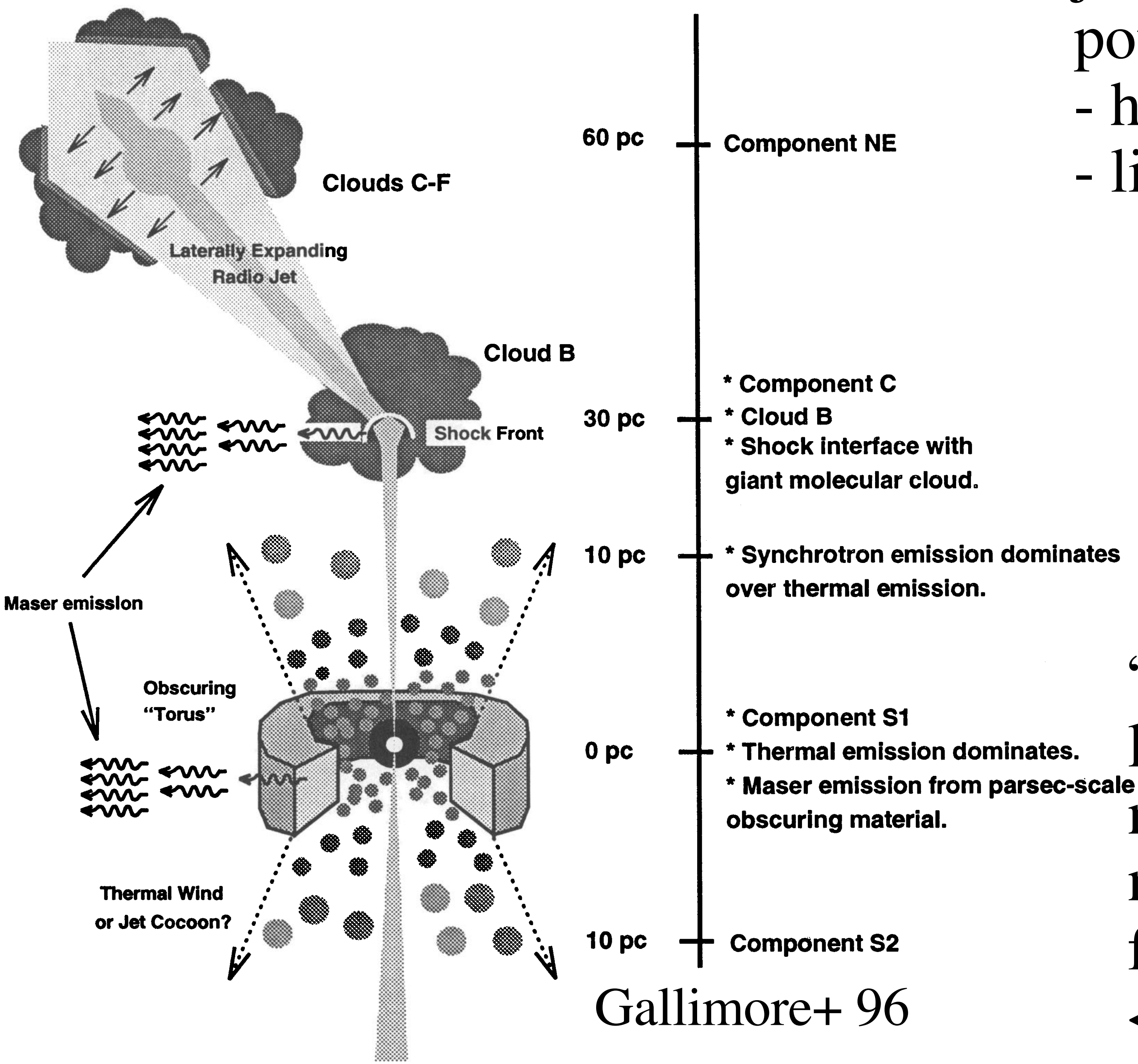




kpc-scale (“mini”-)jet in NGC 1068

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

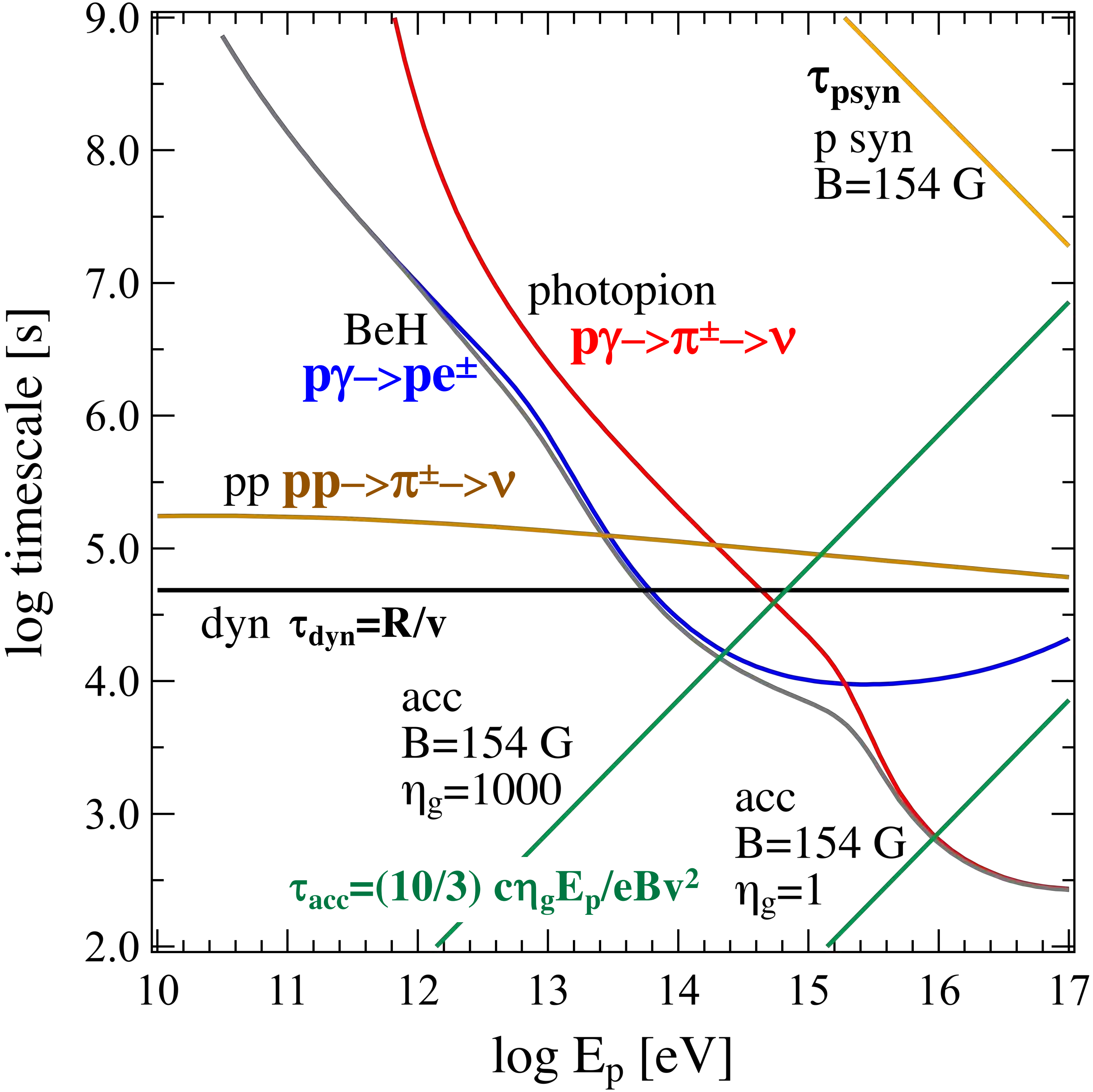
v_{jet}~0.06c at ~60 pc
likely higher at base
Bicknell+ 08



Gallimore+ 96

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

inner region (failed wind): timescales



$R=30R_s=2.7x10^{14}$ cm
$L_p=10^{44}$ erg/s
-> $t_{dyn}=4.9x10^4$ s
$n=1.2x10^{10}$ cm^{-3}

B=154 G ($\varepsilon_B=0.5$)
$\eta_g=1000$
-> $E_{p,max}=150$ TeV