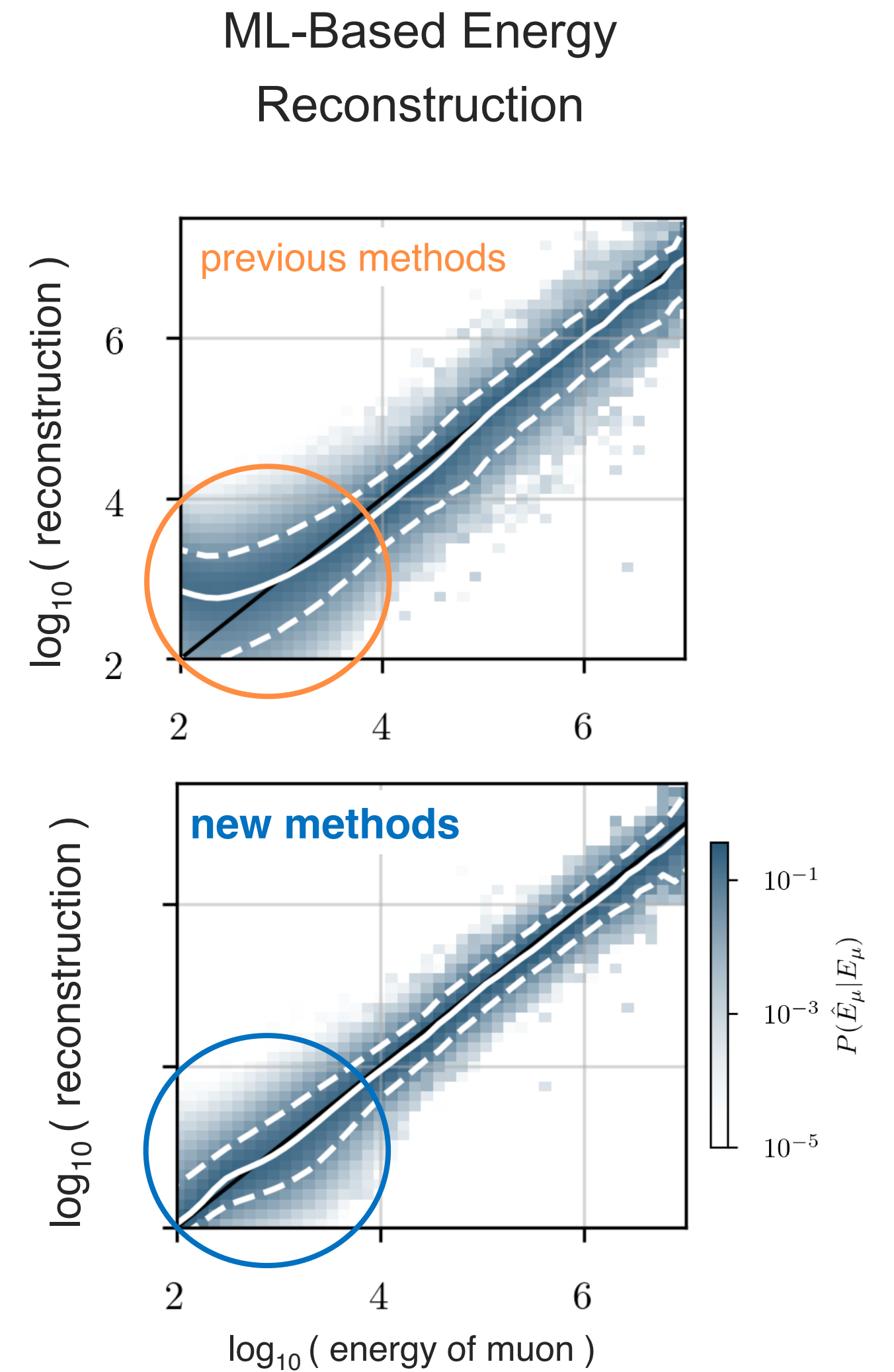# *Subir,*
I have a question for you
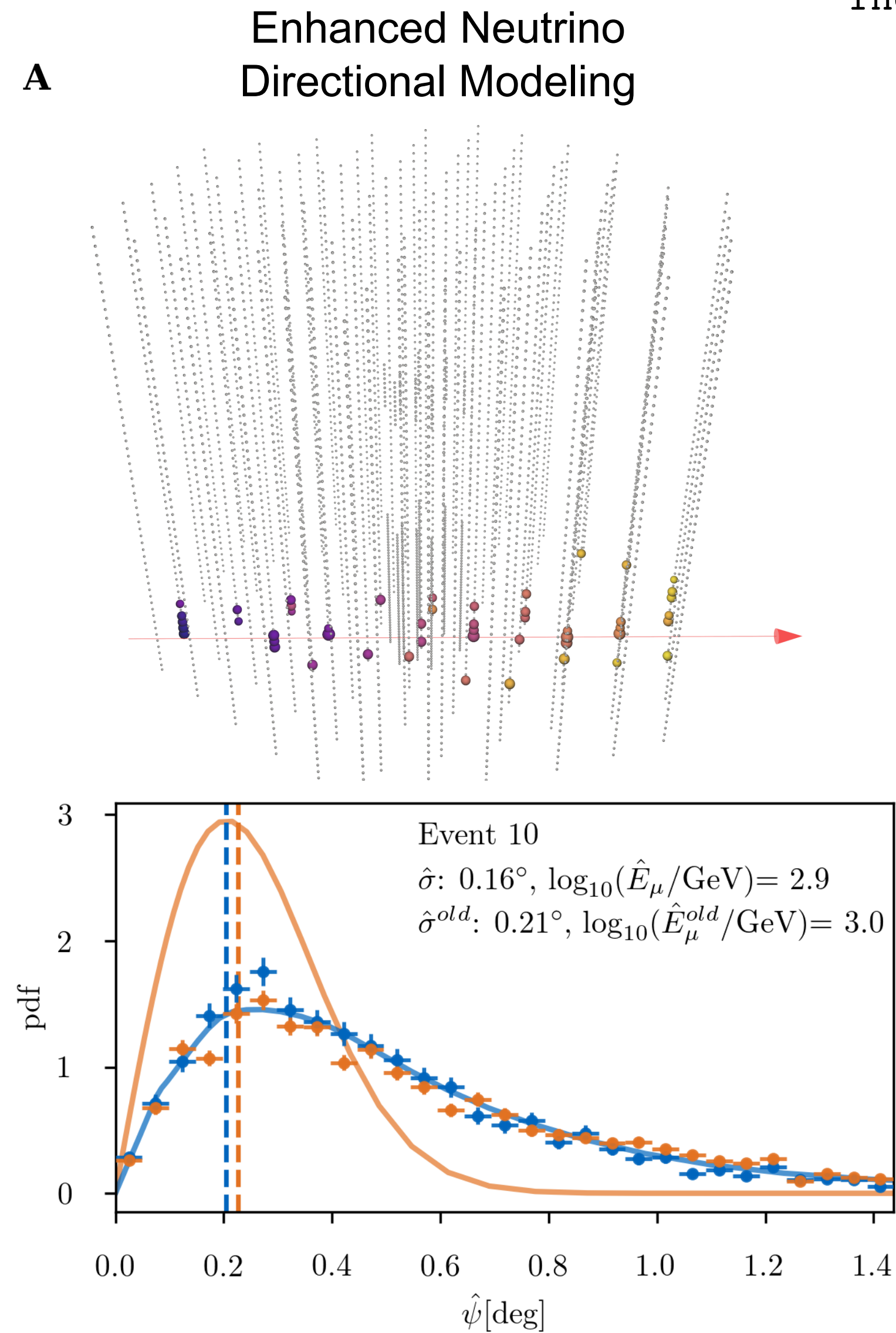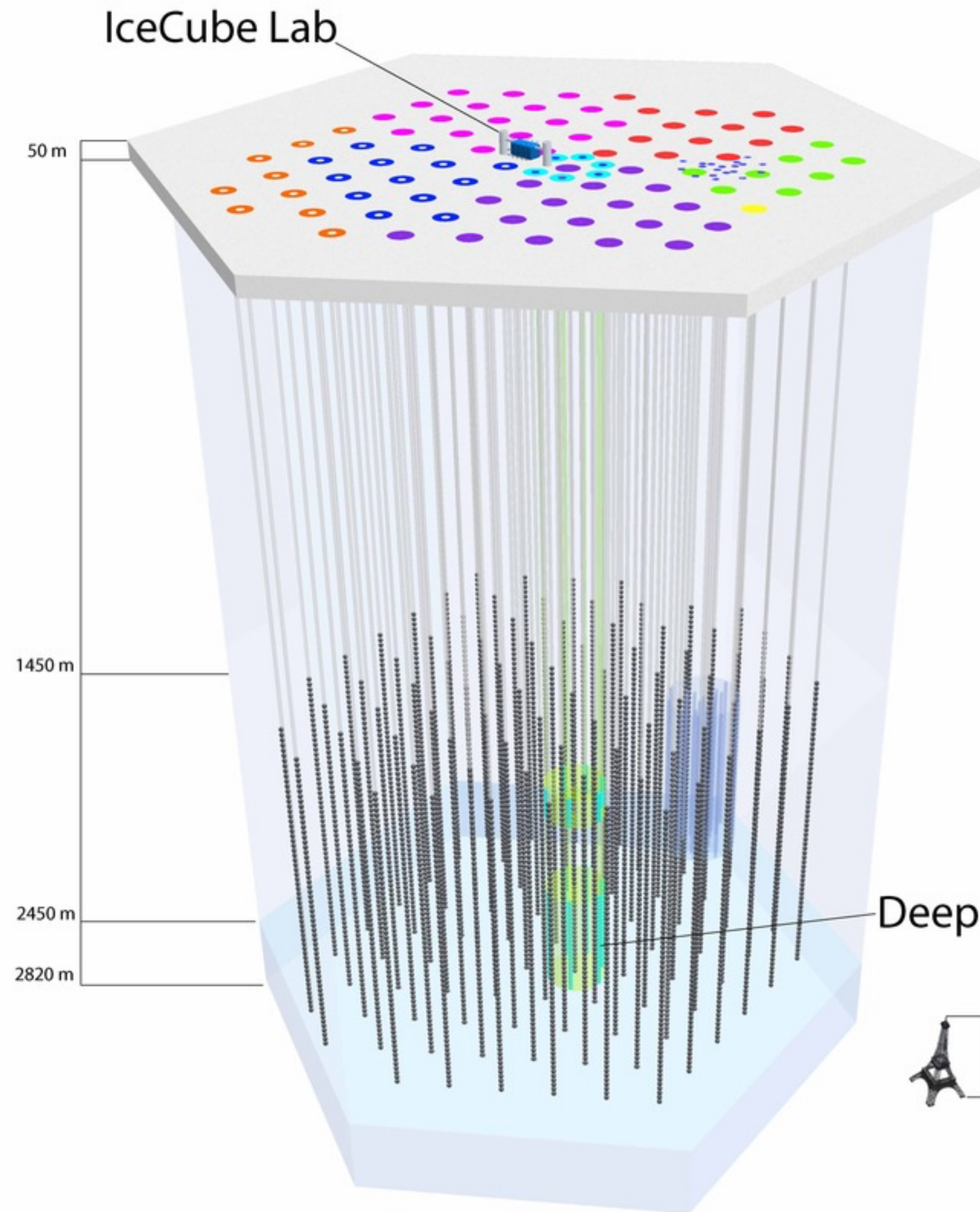
Elisa Resconi

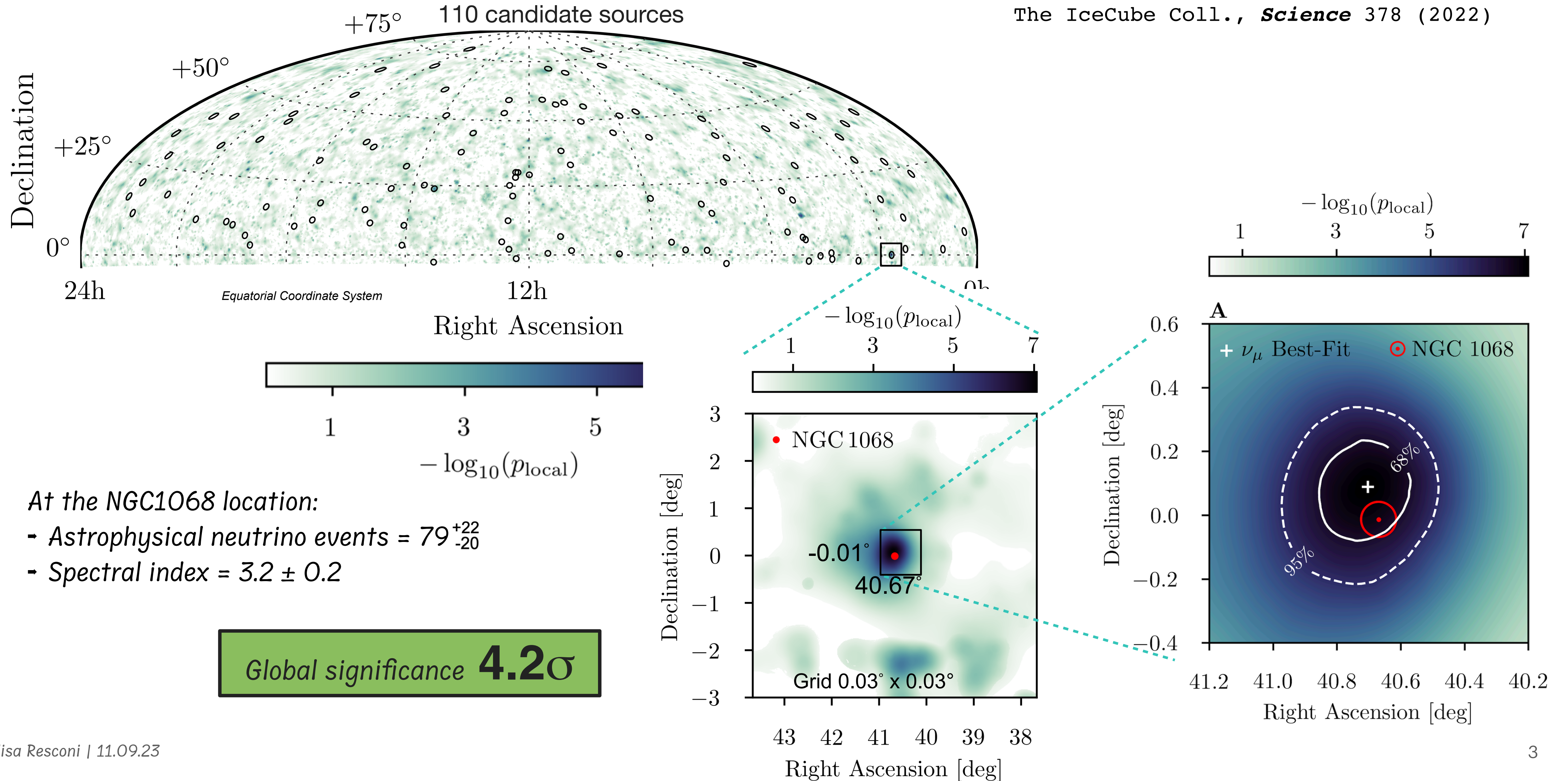*Technical University of Munich*

11.09.2023

IceCube's First Decade: Revealing Neutrino Sources

The IceCube Coll., *Science* 378 (2022)

Enhanced Neutrino Directional Modeling

A

ML-Based Energy Reconstruction

previous methods

new methods

Event 10
$\hat{\sigma}$: 0.16°, $\log_{10}(\hat{E}_\mu/\mathrm{GeV})= 2.9$
$\hat{\sigma}^{old}$: 0.21°, $\log_{10}(\hat{E}_\mu^{old}/\mathrm{GeV})= 3.0$

$\hat{\psi}$[deg]

$\log_{10}$ (reconstruction)

$\log_{10}$ (energy of muon)

$P(\hat{E}_\mu|E_\mu)$

IceCube Lab

Deep

Evidence of Neutrino Emission from NGC 1068

110 candidate sources

At the NGC1068 location:
- Astrophysical neutrino events = 79^{+22}_{-20}
- Spectral index = 3.2 ± 0.2

Global significance **4.2**σ

Indication of Neutrino Emission other Seyfert Galaxies

The IceCube Coll. (T. Glauch et al.), **ICRC'23,** https://pos.sissa.it/444/1052/pdf
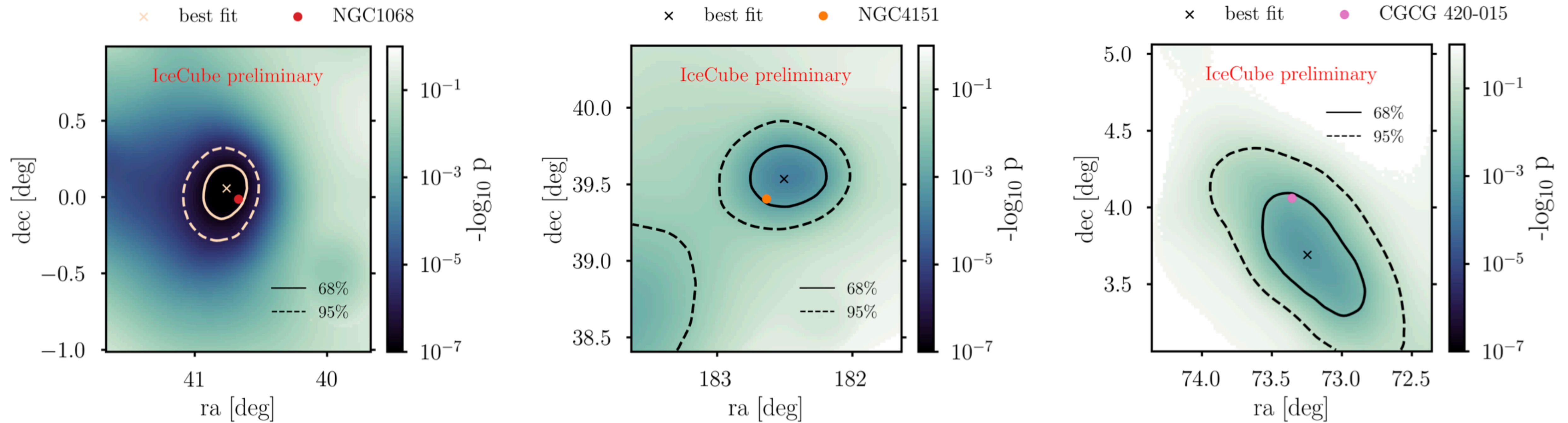
Global significance 2.7σ

New Test Planed on Four Years of Additional Statistics

The Multiwavelength Picture of NGC 1068

Gamma Ray Flux << Neutrino Flux: How?

Y. Inoue et al., ApJL'20

K. Murase et al., PRL'20

- IceCube (this work)
- Theoretical ν model (44,45)
- Theoretical ν model (46)
- Electromagnetic observations (26)
- 0.1 to 100 GeV gamma-rays (41,42)
- > 200 GeV gamma-rays (43)

$p + \gamma \longrightarrow n + \pi^+$

$p + \gamma \longrightarrow p + \pi^0$

same probability

$\pi^\pm \longrightarrow \mu^\pm + \nu_\mu$

$\mu^\pm \longrightarrow e^\pm + \nu_\mu + \nu_e$

$\pi^0 \longrightarrow \gamma + \gamma$ (absorbed)

NGC 1068

IceCube

Fermi - MAGIC

$E^2 \Phi$ [TeV cm^{-2} s^{-1}]

Energy [GeV]
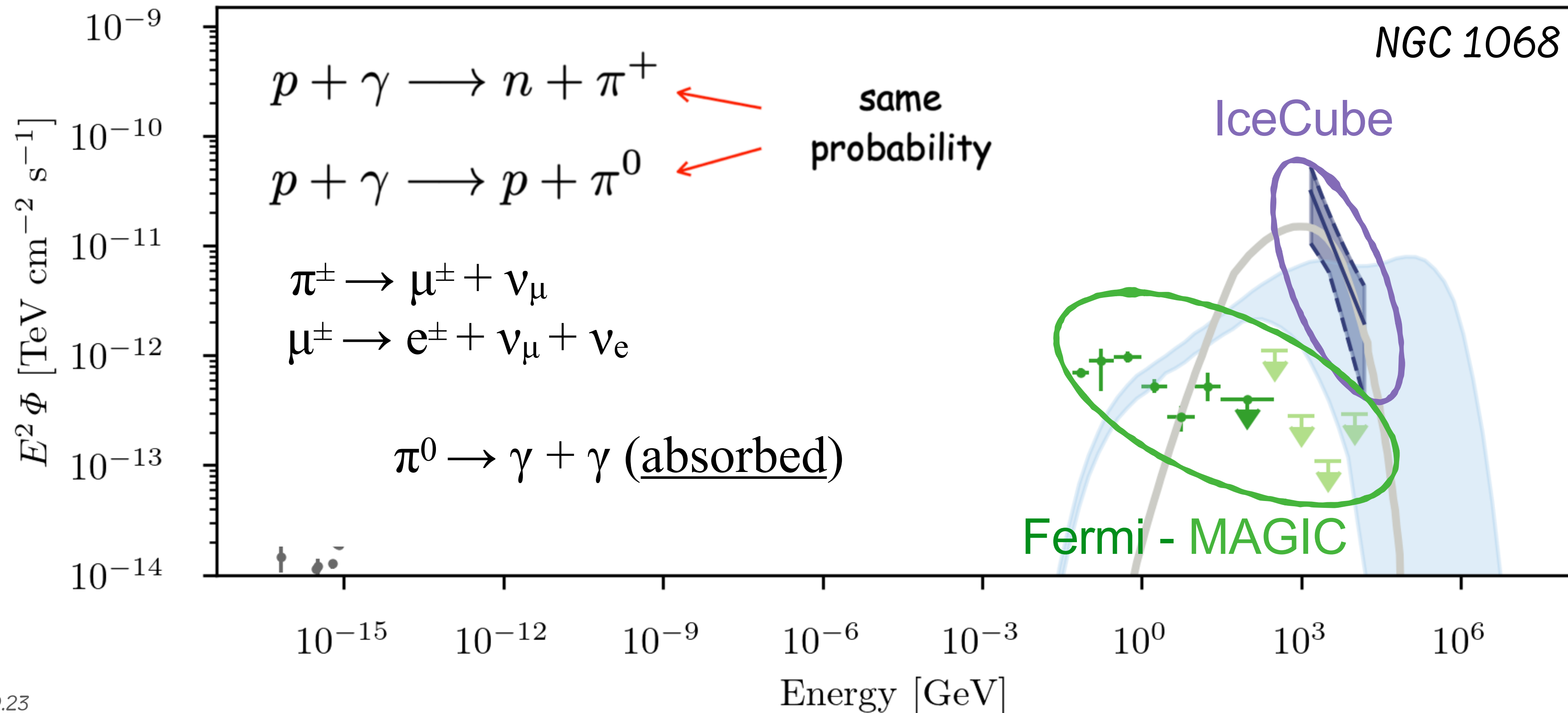
NGC 1068: An Archetype of _Obscured_ AGN

One of the nearest and most studied Seyfert 2

Halo

AGN

Circumnuclear disk (CND) ~200 pc in radius

Starburst activity: ~2 kpc starburst ring

Bar connecting CND and starburst ring

$+$ ν_μ Best-Fit   ⊙ NGC 1068

68%

95%
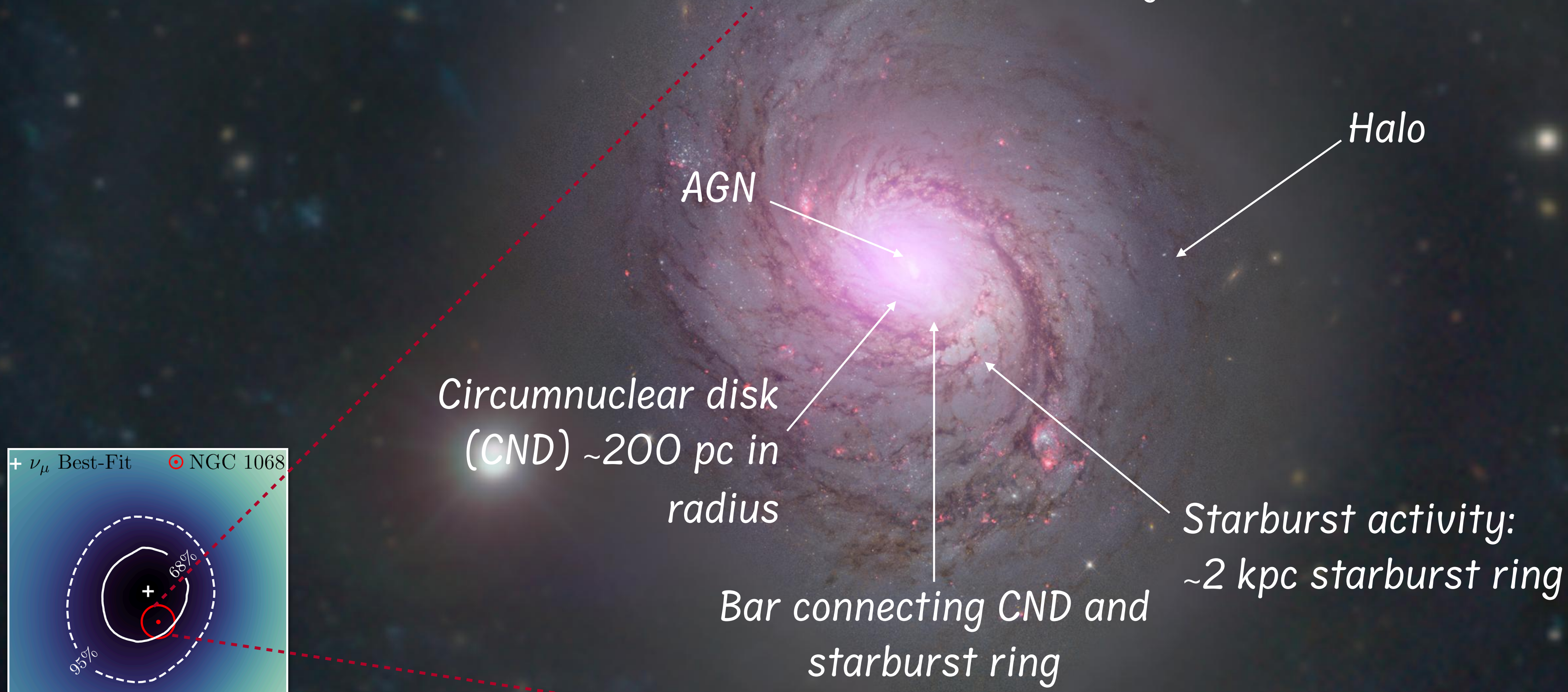
IceCube can't resolve different emission components

NASA/JPL-Caltech/Roma Tre Univ.

NGC 1068: An Archetype of <u>Obscured</u> AGN

- Usual Question:

  Origins of Neutrinos?

- Specific Query:

  Locations and Mechanisms of Gamma-ray Absorption?

NASA/JPL-Caltech/Roma Tre Univ.

Emission powers different components

	Scale	Power (erg/s)	L_γ (erg/s)	L_ν (erg/s)
Star formation	> Kpc	$10^{44.5}$	$\sim 10^{40.9}$	$\sim 10^{40.6}$
Jet	$\sim$ Kpc	$10^{42.9\pm1}$	$\sim 10^{41.7}$ (M87–like) [absorbed]	$\sim 10^{41.4}$
Outflow	$\sim$ 100 pc	$10^{41.4\pm1.0}$	$< 10^{39.5}$	$< 10^{39.2}$
BH vicinity	$\sim$ 0.03 millipc ($\sim$ 50 $R_{S)}$	$10^{44.7\pm0.5}$	?	?

Total: $\sim 10^{41.5}$

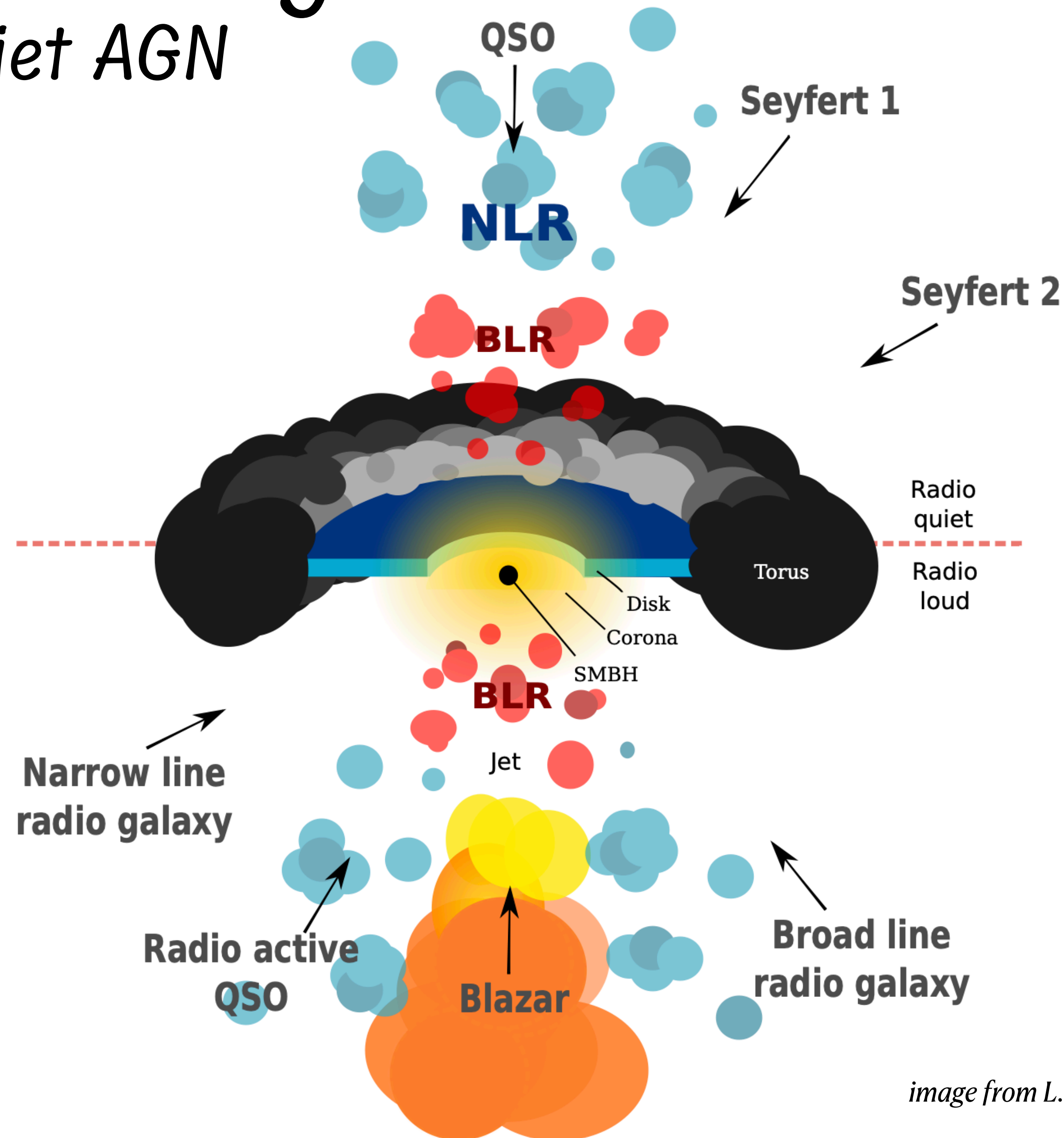Observed: $10^{40.92\pm0.03}$ $10^{42.1\pm0.2}$
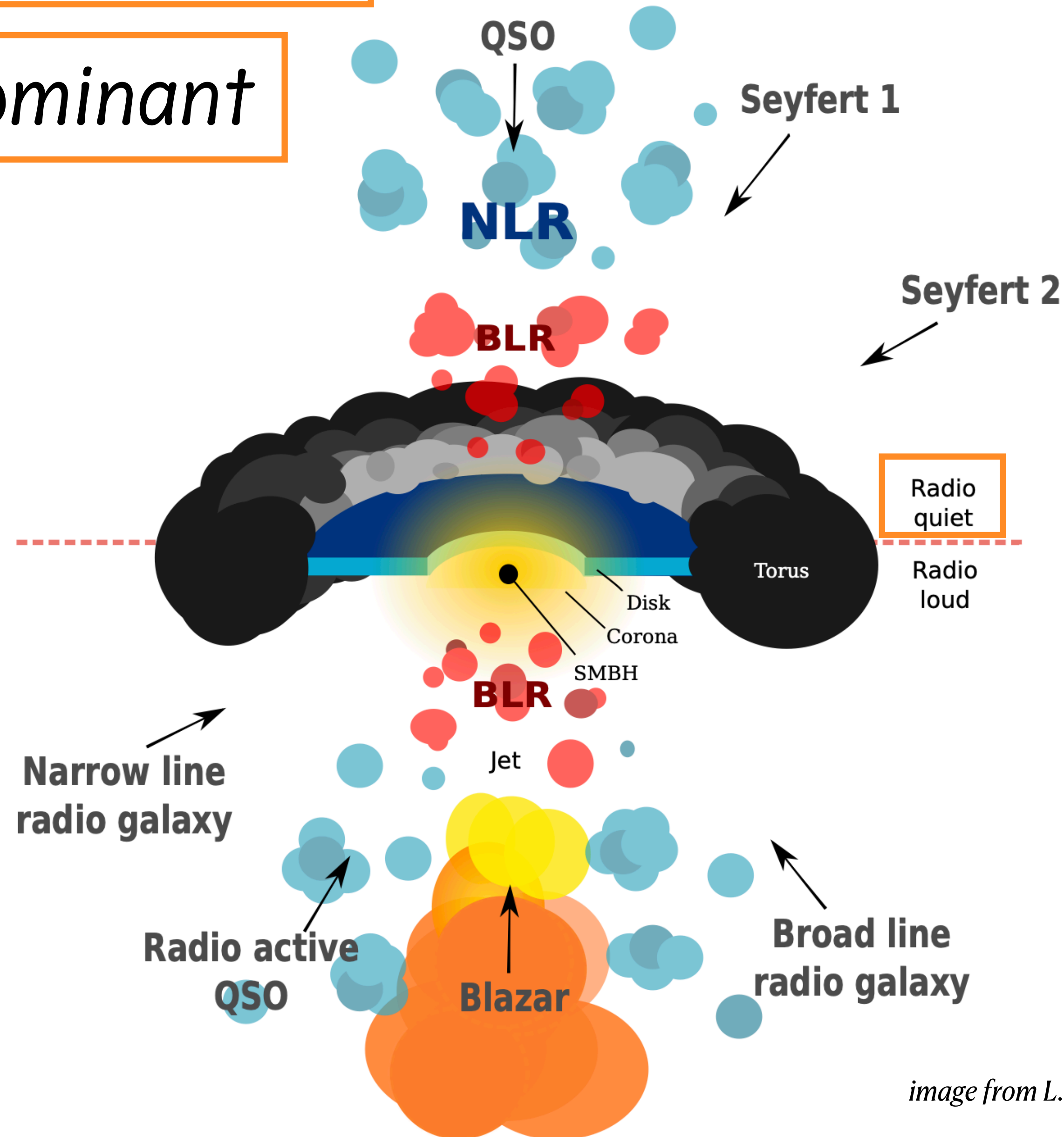
$$L_\nu = 1.4 \cdot 10^{42} \text{ erg/s}$$
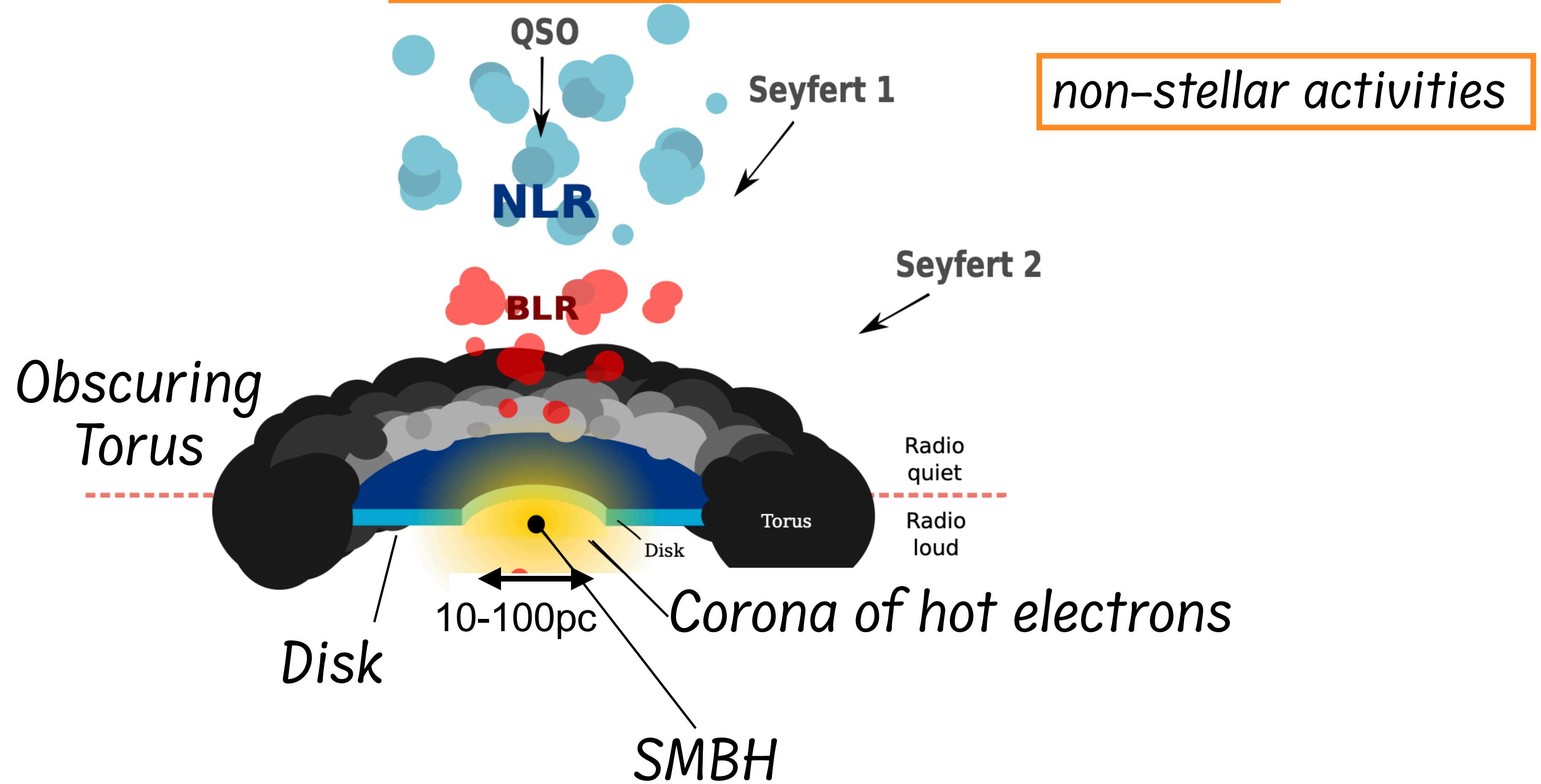
Black Hole vicinity
Seyferts: radio quiet AGN

image from L. Baronchelli

Seyferts = radio quiet Active Galactic Nuclei

jet not dominant

QSO

Seyfert 1

NLR

Seyfert 2

BLR

Radio quiet

Torus

Radio loud

Disk
Corona
SMBH

BLR

Jet

Narrow line radio galaxy

Radio active QSO

Blazar

Broad line radio galaxy

image from L. Baronchelli

Seyferts = radio quiet Active Galactic Nuclei

non-stellar activities

QSO

Seyfert 1

NLR

Seyfert 2

BLR

Obscuring Torus

Radio quiet

Radio loud

Torus

Disk

10-100pc

Corona of hot electrons

Disk

SMBH

image from L. Baronchelli

The Corona of hot electrons (and protons?)

QSO

Seyfert 1

NLR

BLR

Seyfert 2

Radio quiet

Radio loud

Torus

Disk

Compton thick
($N_H > 10^{24}$ atoms cm^{-2})

Corona of hot electrons (X-ray)

Disk: photons at optical and UV wavelengths

Inverse Compton Scattering

low-energy photon
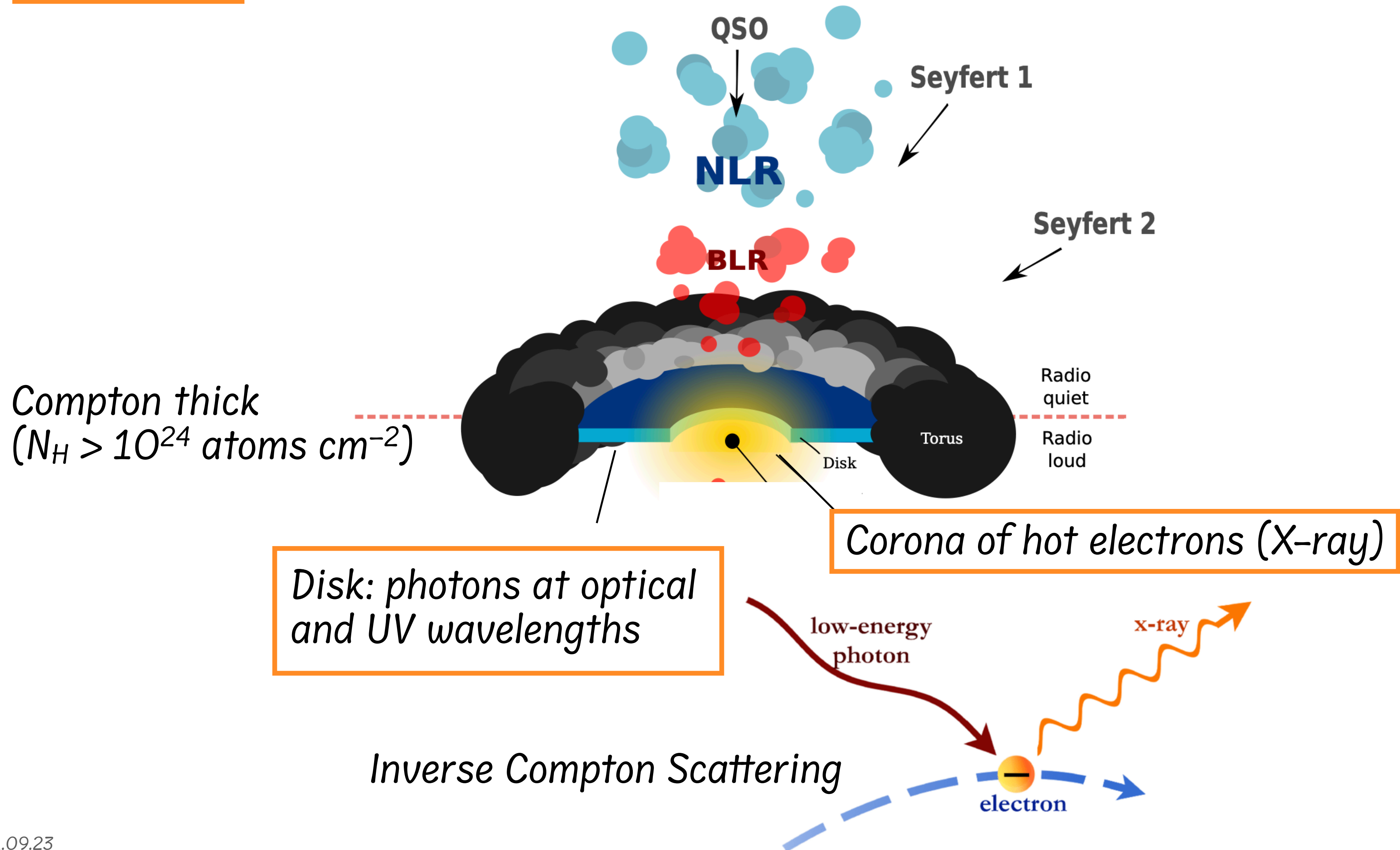
x-ray

electron

The 'naive' scenario

Step 1: acceleration of protons (and electrons)

Step 2: p–γ (also p–p) interaction

   e.g., $E_p \sim 100$ TeV

    target γ ~ X–ray domain

    (Corona component)
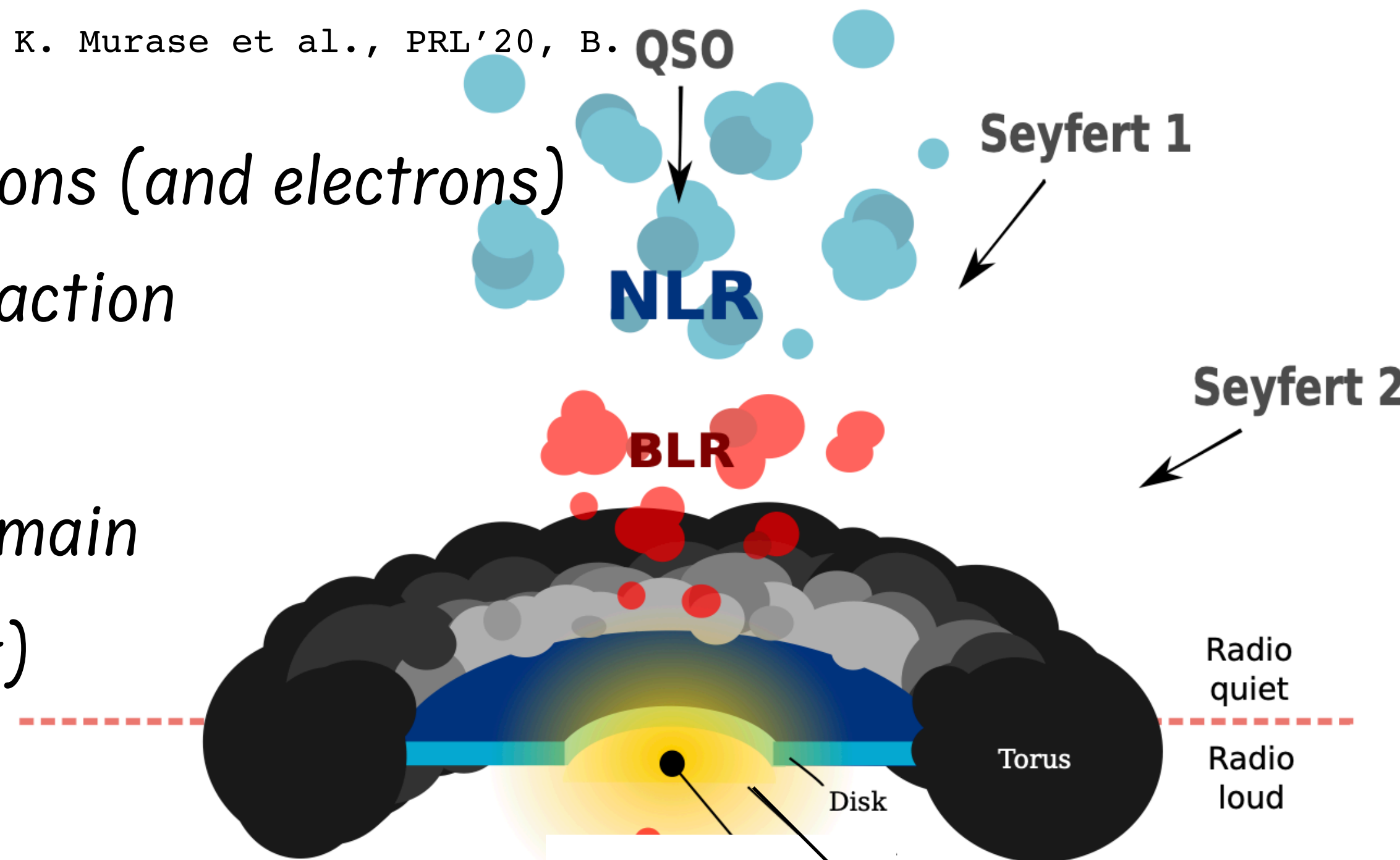
Step 3: mesons production

Step 4: γ–ray → degraded into MeV region

    neutrinos stream through

Note: the Fermi–LAT component most probably associated to the starburst component

QSO

Seyfert 1

NLR

Seyfert 2

BLR

Radio quiet

Radio loud

Torus

Disk

Corona of hot electrons (X-ray)

see Eichmann et al., Astrophys. J. 939 (2022)

The 'naive' scenario

see also Y. Inoue et al., ApJL'20, K. Murase et al., PRL'20, B.

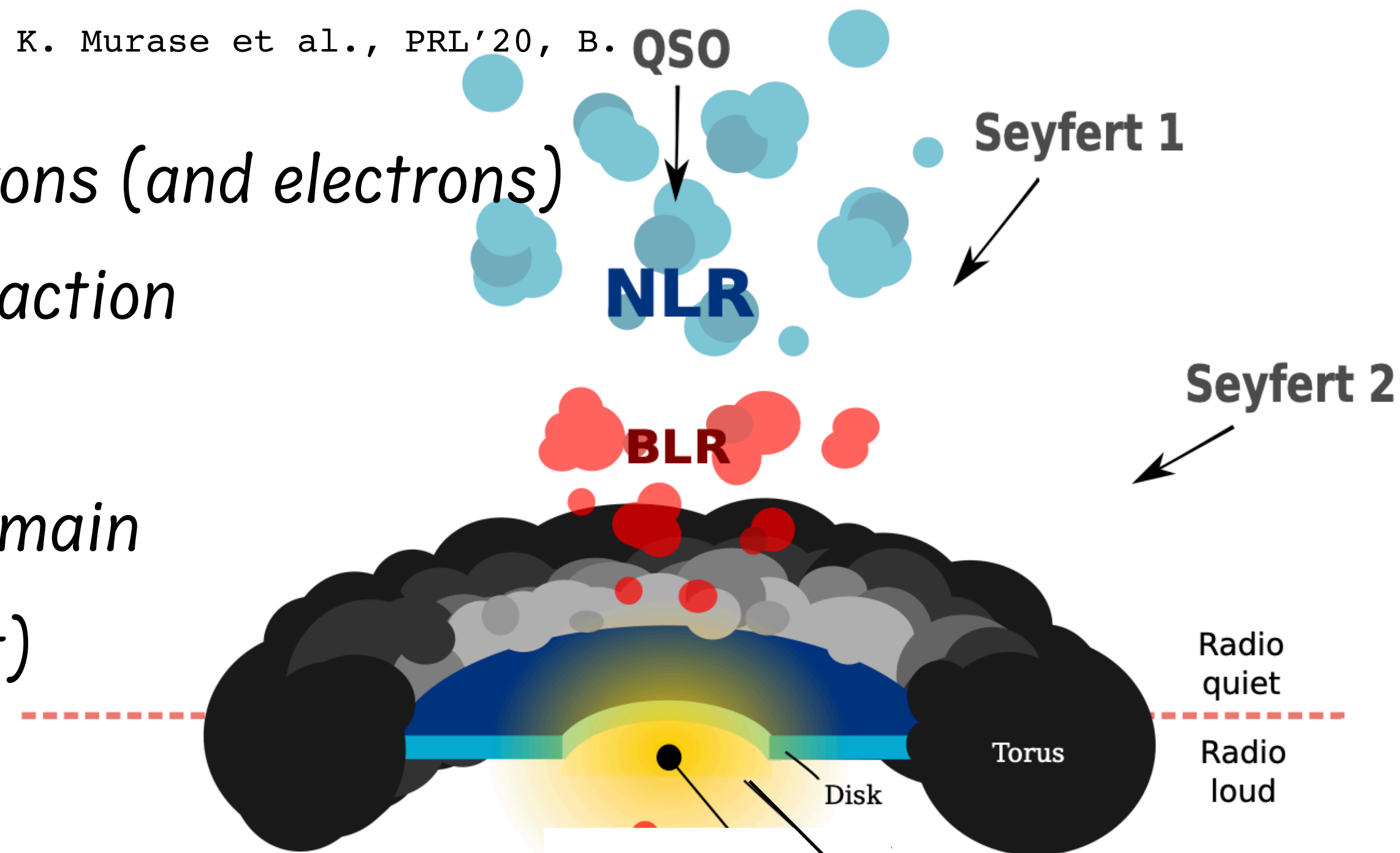*Step 1*: acceleration of protons (and electrons)

Step 2: p–γ (also p–p) interaction

     e.g., E_p ~ 100 TeV

      target γ ~ X–ray domain

      (Corona component)

Step 3: mesons production

Step 4: γ–ray → degraded into MeV region

     neutrinos stream through   *Crucial Signature for Neutrino Validation & Search*
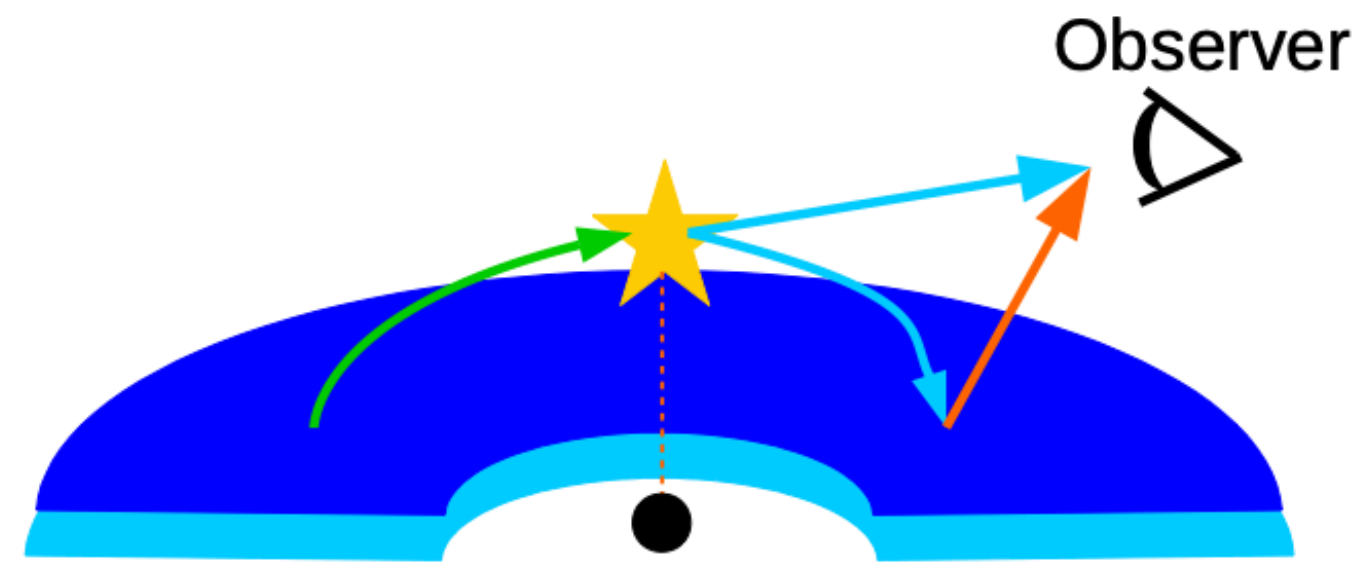
Note: the Fermi–LAT component most probably associated to the starburst component

Corona of hot electrons (X–ray)

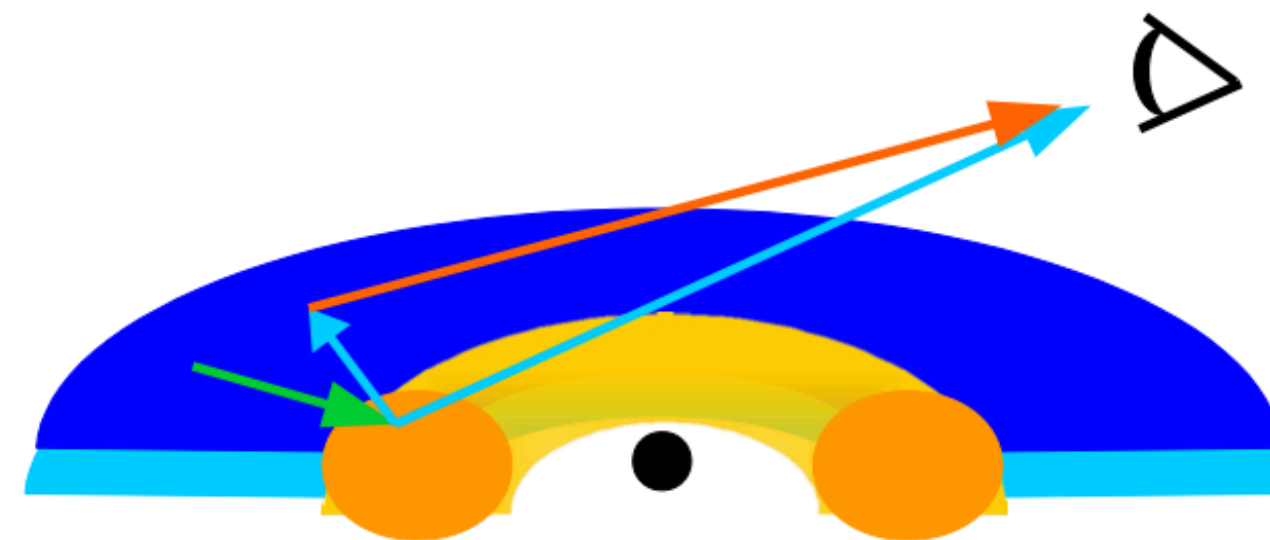see Eichmann et al., Astrophys. J. 939 (2022)

The Corona

- *NGC1068 X-ray Emission: Arises from scattered emission along our line of sight.*

- *Rapid X-ray Variability (2-10 keV): Implies a compact corona near the SMBH.*

- *Anisotropic Coronae: Influenced by corona position, black hole spin, and disc inclination.*
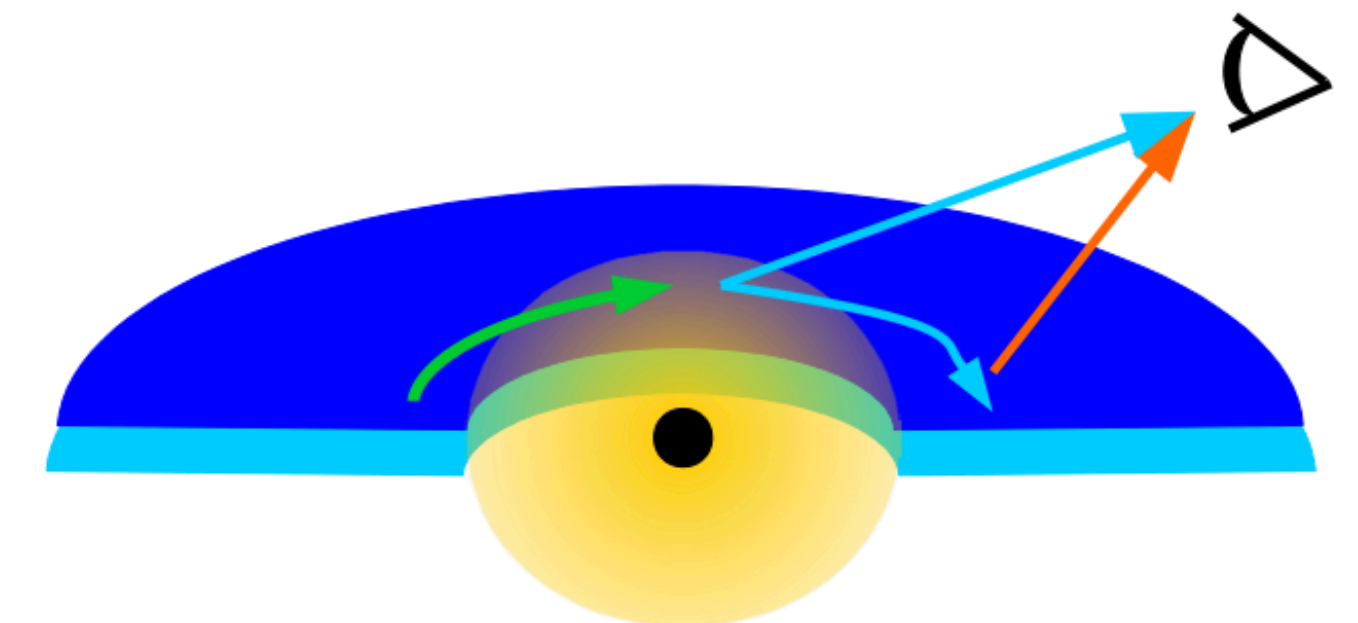

Observer

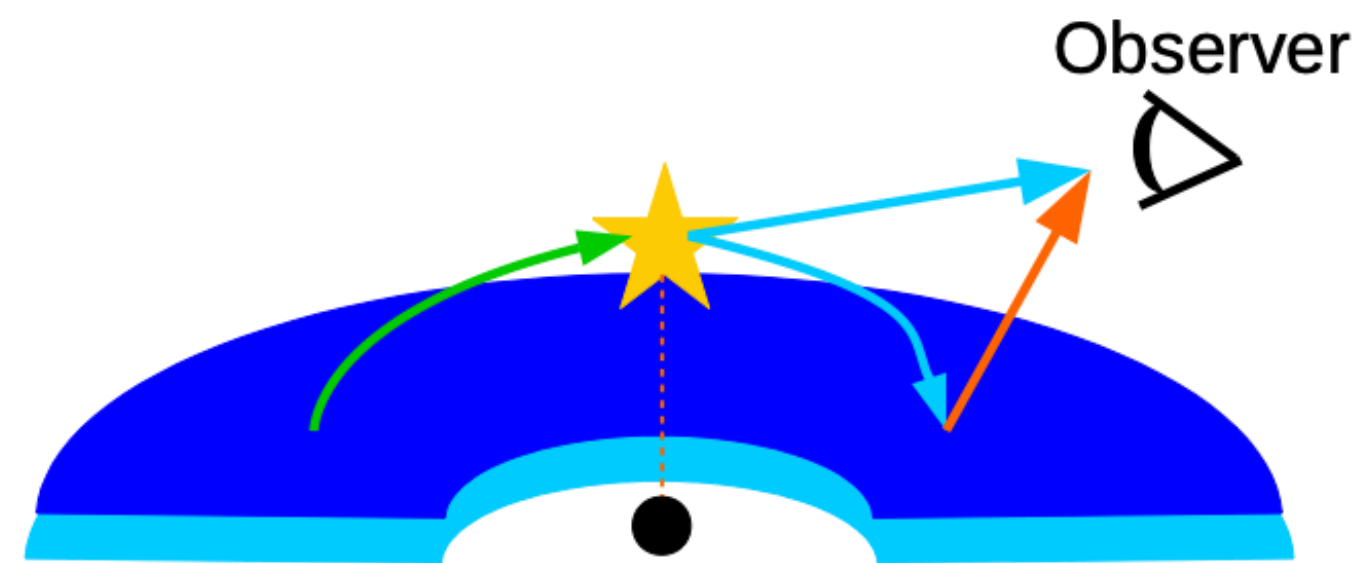1) Lamp post corona
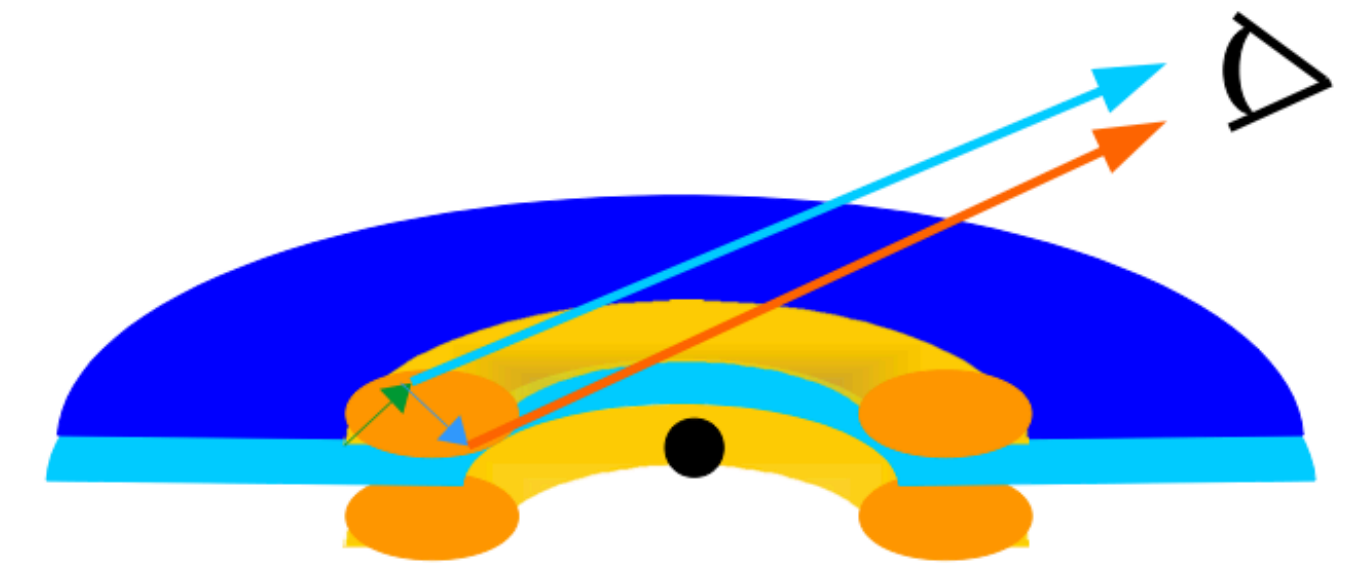
2) Sandwich corona

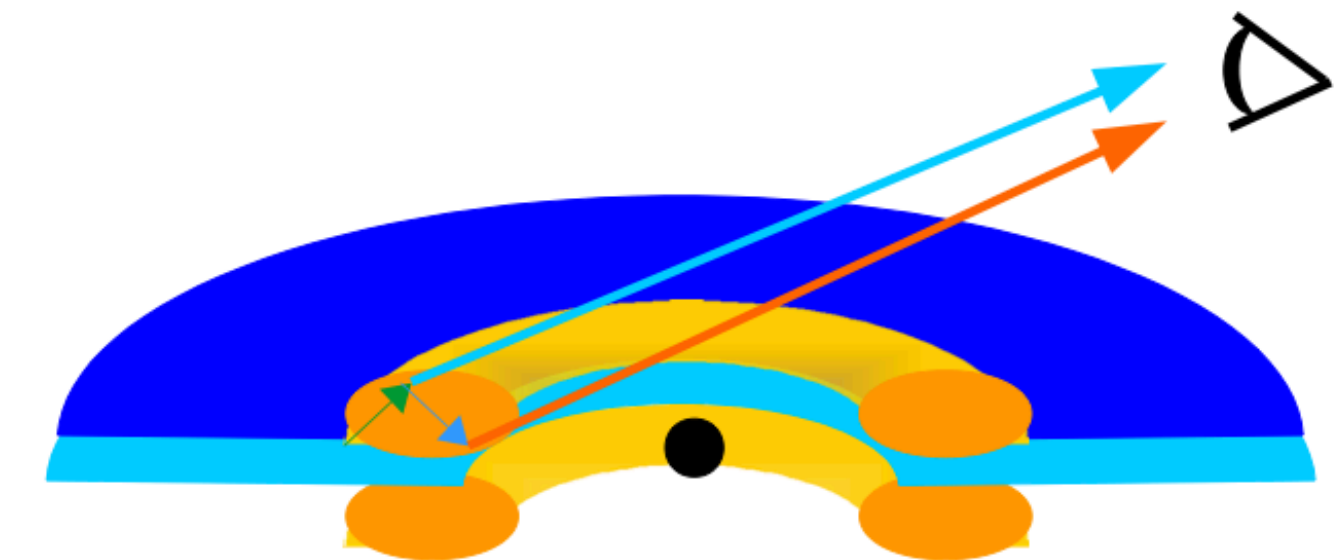3) Toroidal corona

4) Spherical corona
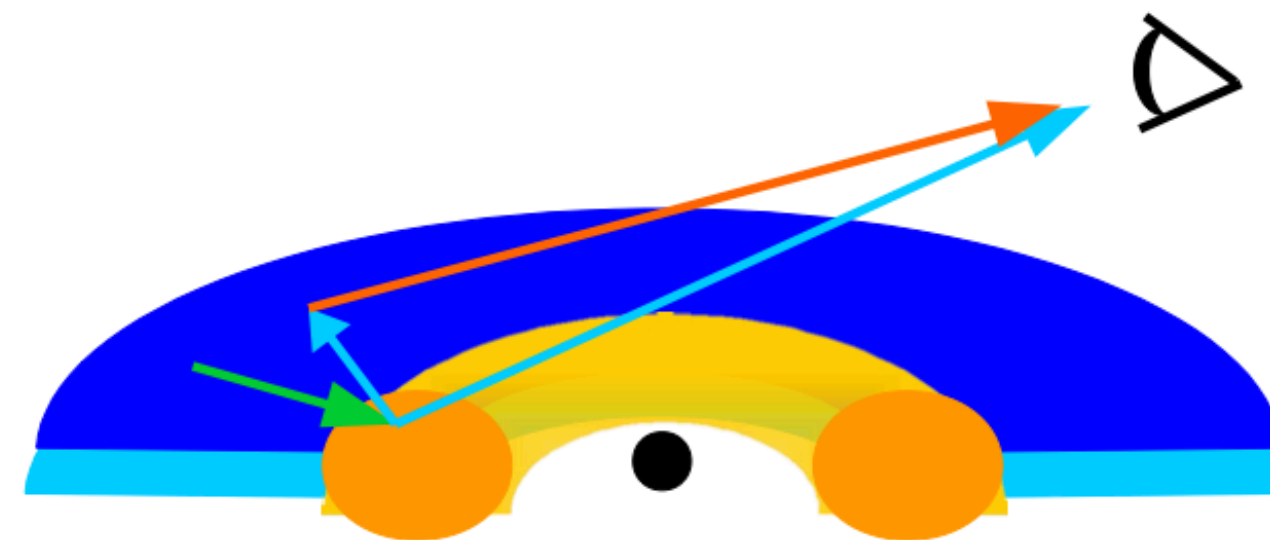
image from L. Baronchelli

The Corona

- *NGC1068 X-ray Emission: Arises from scattered emission along our line of sight.*

- *Rapid X-ray Variability (2-10 keV): Implies a compact corona near the SMBH.*

- *Anisotropic Coronae: Influenced by corona position, black hole spin, and disc inclination.*

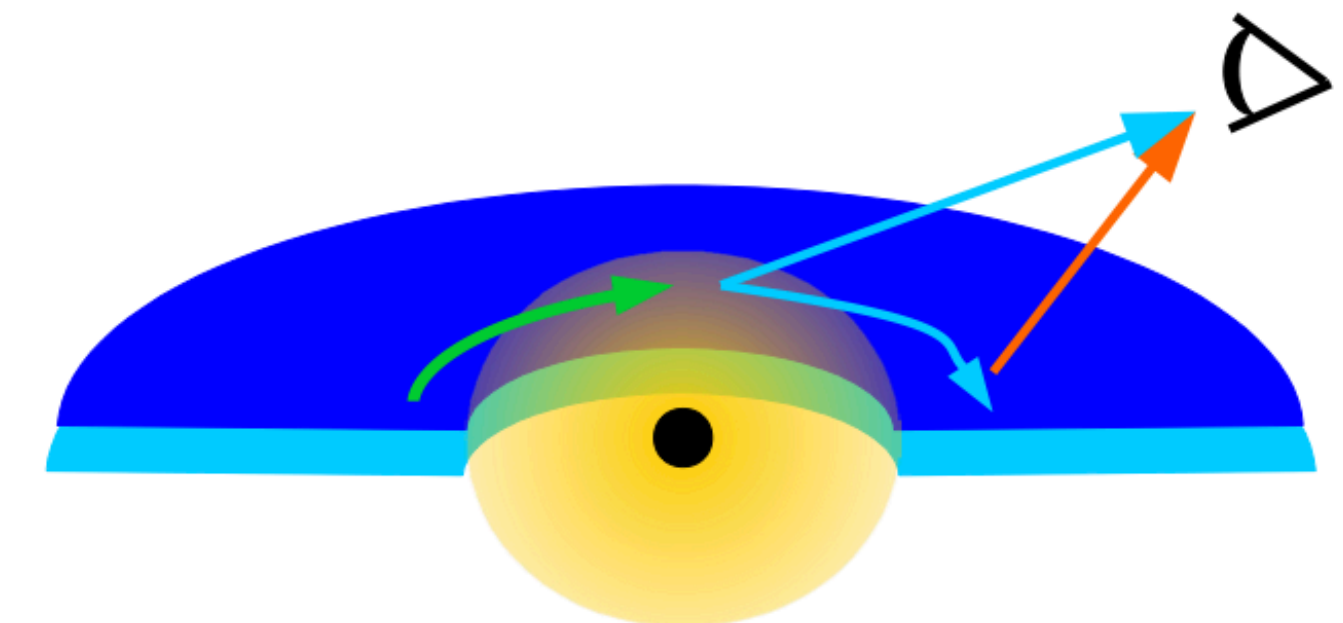- *Coronae Placement: Many of the coronae are positioned within regions where*

Observer

1) Lamp post corona

2) Sandwich corona

3) Toroidal corona

4) Spherical corona

image from L. Baronchelli

➡ *General Relativistic Effects might play Crucial Roles. Strong gravity regime.*

The 'naive' scenario

see also Y. Inoue et al., ApJL'20, K. Murase et al., PRL'20, B.
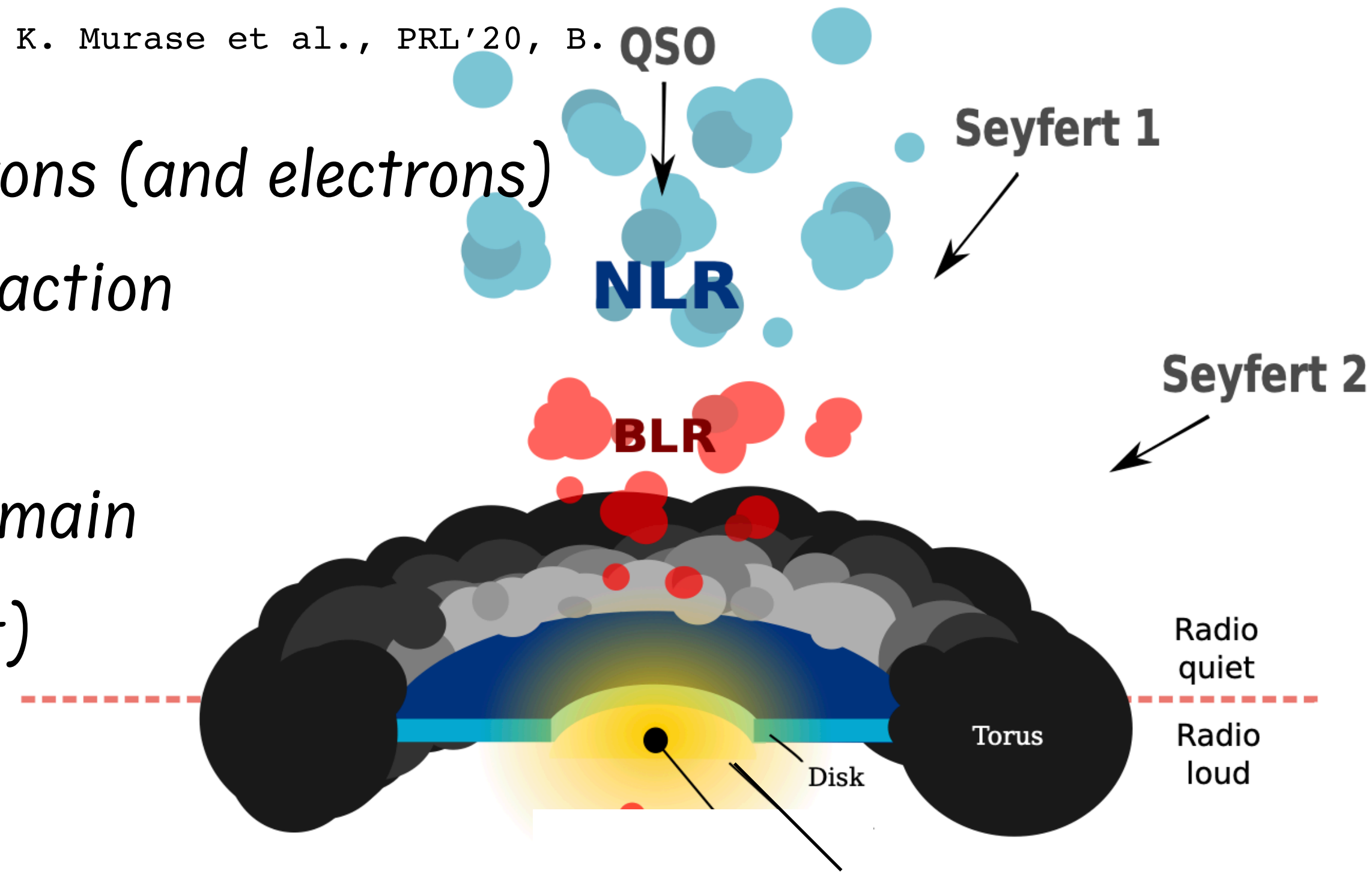
Step 1: acceleration of protons (and electrons)

Step 2: p–γ (also p–p) interaction

e.g., $E_p \sim 100$ TeV

target γ ~ X–ray domain

(Corona component)

What happens to the strong interactions in the realm of strong gravity?

I have asked several theorists:
What happens to the strong interactions in the realm of strong gravity?

Group 1:

"Possibly nothing, but I'm not an expert. This question seems quite exotic and not particularly well-defined. There are for sure papers you can consult."

Group 2:

"Nothing significant, as at the scale of strong interactions, spacetime can be approximated as flat."

I have asked several theorists:
What happens to the strong interactions in the realm of strong gravity?

Group 1:

"Possibly nothing, but I'm not an expert. This question seems quite exotic and not particularly well-defined. There are for sure papers you can consult."

Group 2:

"Nothing significant, as at the scale of strong interactions, spacetime can be approximated as flat."

Group 3:

"Ask Subir!"

Conclusions, questions and a proposal

IceCube Connection to NGC1068 & Other Seyfert Galaxies Point to:

- *Proton Acceleration near SMBH: Mechanisms?*

- *Hot Corona's Photon Field: Origin, Composition, & Morphology?*

- *Gamma-Ray Showering & Implications: Cascade to MeV Range?*

- *MeV Telescope Gap: How to Overcome Confirmation Challenges?*

- *Compact, Obscured Region Interactions: General Relativity Corrections?*

Ask Subir!

Conclusions, questions and a proposal

IceCube Connection to NGC1068 & Other Seyfert Galaxies Point to:

- *Proton Acceleration near SMBH: Mechanisms?*

- *Hot Corona's Photon Field: Origin, Composition, & Morphology?*

- *Gamma-Ray Showering & Implications: Cascade to MeV Range?*

- *MeV Telescope Gap: How to Overcome Confirmation Challenges?*

- *Compact, Obscured Region Interactions: General Relativity Corrections?*
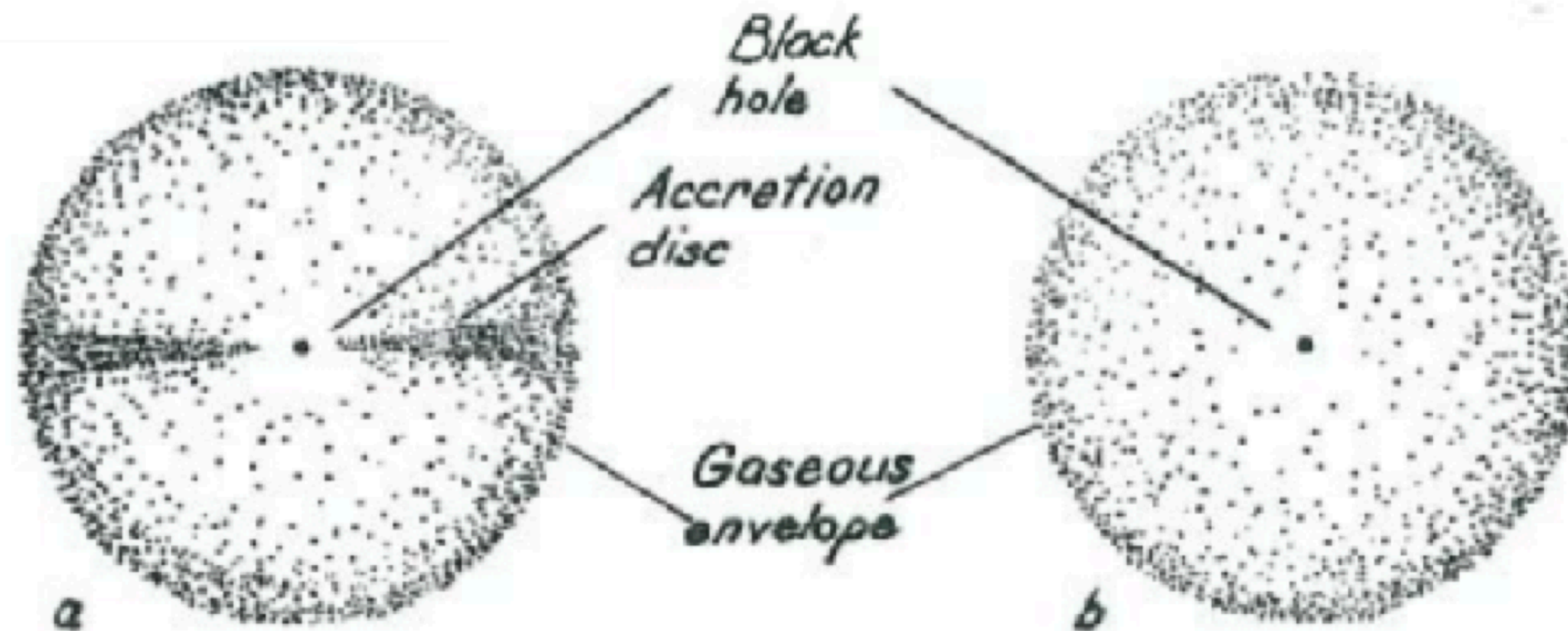
Ask Subir!

- *Berezinsky's 1981 Groundwork: Proposal to Label Seyfert Galaxies with Neutrino Component as 'Berezinsky Galaxies'*

The 'Hidden' source idea

VENYA BEREZINSKY

§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).

ASTROPHYSICS OF COSMIC RAYS

V.S. Berezinskii, S.V. Bulanov, V.A. Dogiel,
V.L. Ginzburg (editor) and V.S. Ptuskin

NORTH-HOLLAND

Berezinsky, Ginzburg, MNRAS 1981
Silberberg, Shapiro 1982