

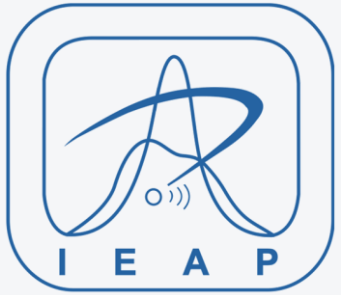
CZECH TECHNICAL UNIVERSITY IN PRAGUE

28th RAGtime Workshop

Research Centre for Theoretical Physics and Astrophysics,

Institute of Physics, Silesian University in Opava

Opava, Czech Republic, 2-6 November, 2026



Neutrino-Induced Polarization Rotation in Astrophysical Plasmas

Henrique Brito Câmara

henrique.camara@cvut.cz

IEAP-CTU, Prague

Presentation based on the works:

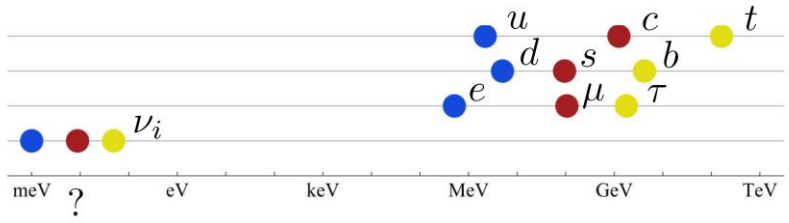
Phys. Rev. D 113, 113003 (2026) (arXiv: 2601.15910 [hep-ph])

arXiv: 26XX.XXXX [hep-ph]

In collaboration with: A. Smetana and A.A. Tursunov

Introduction and Outline

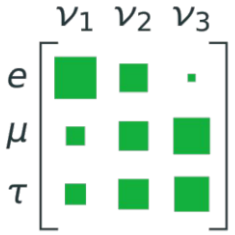
Neutrino flavour oscillations



Massive neutrinos

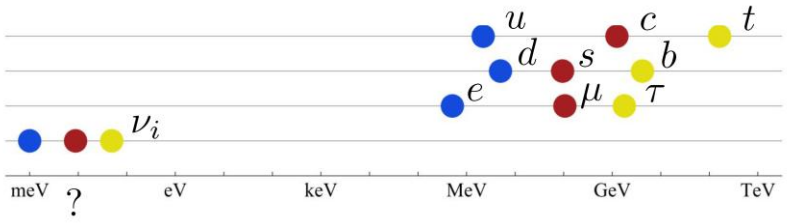
Lepton Mixing

$$U_{\mathrm{PMNS}} \sim$$



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Neutrino flavour oscillations



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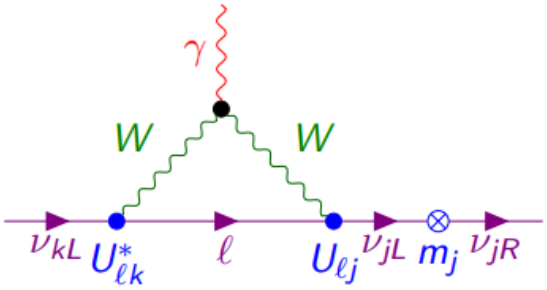
$$U_{\mathrm{PMNS}} \sim \begin{array}{c} \\ e \\ \mu \\ \tau \end{array} \begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \begin{bmatrix} \blacksquare & \blacksquare & \cdot \\ \cdot & \blacksquare & \blacksquare \\ \cdot & \blacksquare & \blacksquare \end{bmatrix} \end{array}$$

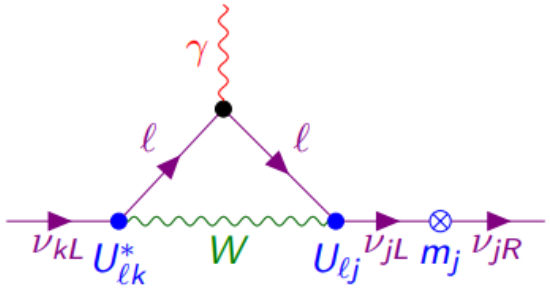
Schechter and Valle, Phys. Rev. D 24, 1883-1889 (1981)
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Electromagnetic properties of neutrinos

Magnetic moment

Taken from C. Giunti Talk at IRN Neutrino Meeting 2021





Dirac neutrinos

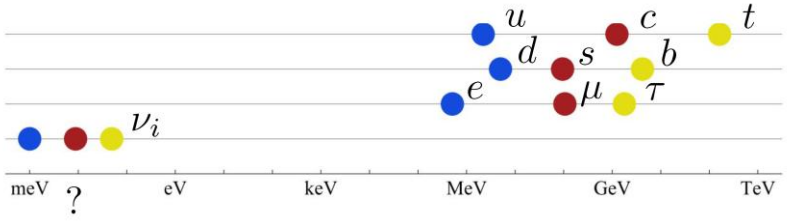
$$\mu^{\mathrm{D}}_{kk} \simeq 3.2 \times 10^{-19} \mu_{\mathrm{B}} \left(\frac{m_k}{\mathrm{eV}} \right)$$

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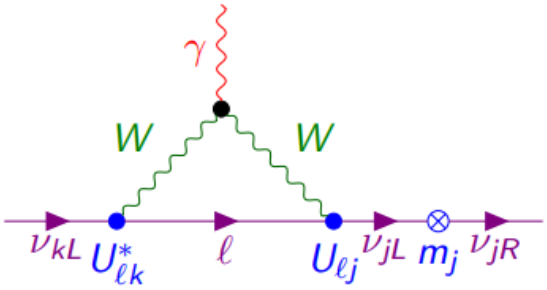
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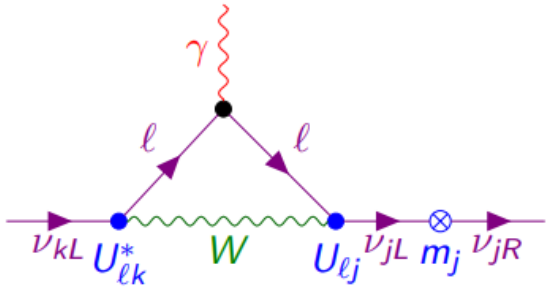
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- **Outline**
  - **Propagation of electromagnetic waves in media**: Birefringence, neutrino chiral media, plasma
  - **Active Galactic Nuclei** plasmas: jets and accretion disk **(arXiv: 2601.15910 [hep-ph])**
  - **Hyperaccreting stellar-mass black hole** scenario **(Preliminary results)**

Propagation of electromagnetic waves in media

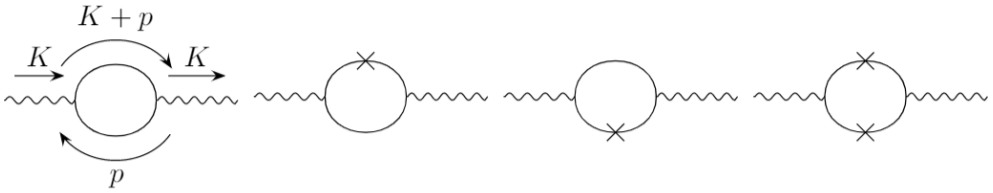
Forward photon scattering

The **effect of a medium on wave propagation** arises from the **forward scattering of photons on the particles of the medium.**

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Photon polarization tensor

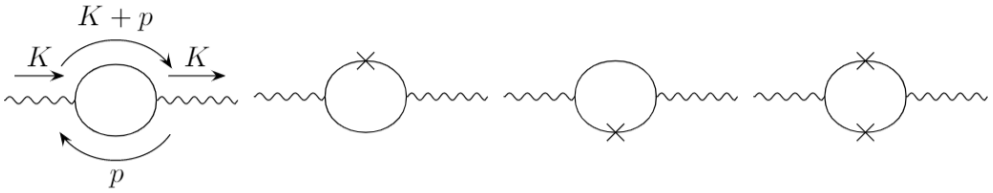


$$i\Pi_{\mu\nu} = (-1)\int \frac{d^4p}{(2\pi)^4} S(p+K)\Lambda_\mu(K)S(p)\Lambda_\nu(K)$$

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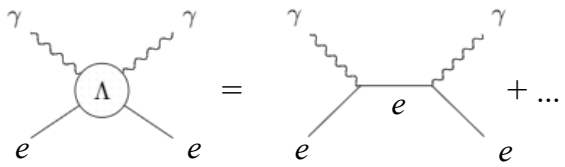
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Real time formalism

$$S(p) = S^{vac}(p) + (\hat{p}+m)\Gamma_F(p,\mu)$$

$$S^{vac}(p) = \frac{1}{\hat{p}-m+i\epsilon},$$
$$\Gamma(p) = 2\pi i\delta(p^2-m^2)[\theta(p_0)n_F(p,\mu) + \theta(-p_0)n_F(p,-\overline{\mu})]$$

Scattering on electrons



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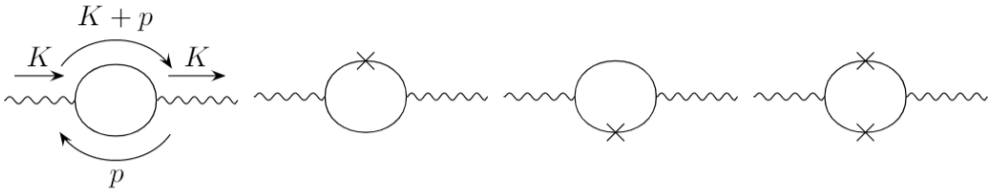
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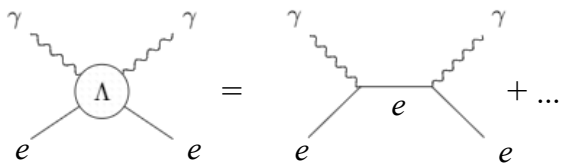
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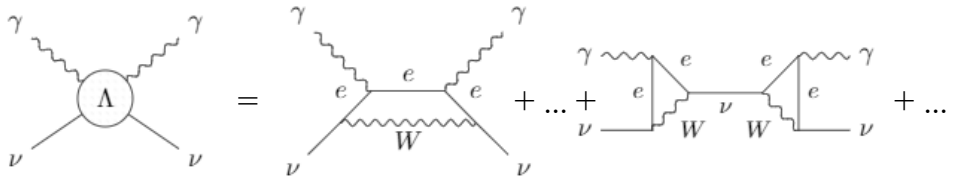
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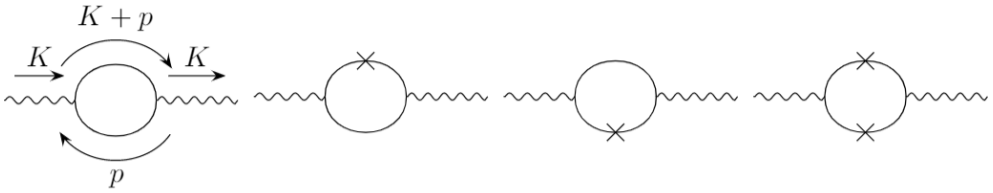
Scattering on neutrinos via weak interactions



Forward photon scattering

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Photon polarization tensor



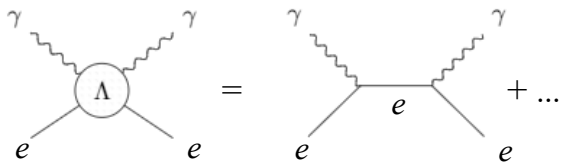
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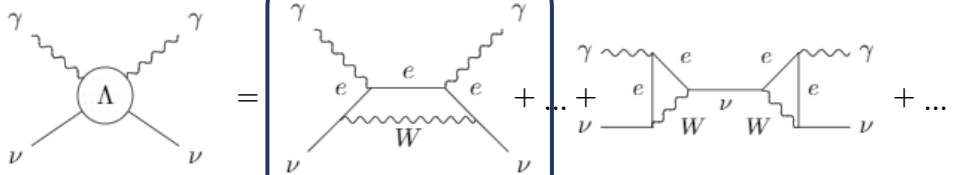
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Scattering on neutrinos via weak interactions



Parity-violating

Parity violation and Birefringence

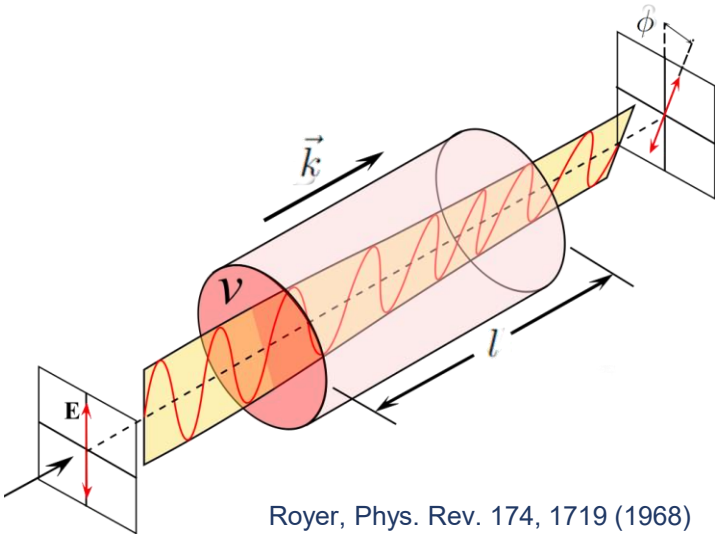
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Classical plane-wave framework

$$\frac{\phi}{l} \equiv \frac{1}{2}(|\mathbf{k}_-| - |\mathbf{k}_+|)$$



Royer, Phys. Rev. 174, 1719 (1968)

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Parity-violating media: polarization tensor develops a parity-violating part

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$$\Pi^{\mu\nu} = \Pi_{\mathrm{T}} P_{\mathrm{T}}^{\mu\nu} + \Pi_{\mathrm{L}} P_{\mathrm{L}}^{\mu\nu} + \Pi_{\mathrm{P}} P_{\mathrm{P}}^{\mu\nu}$$

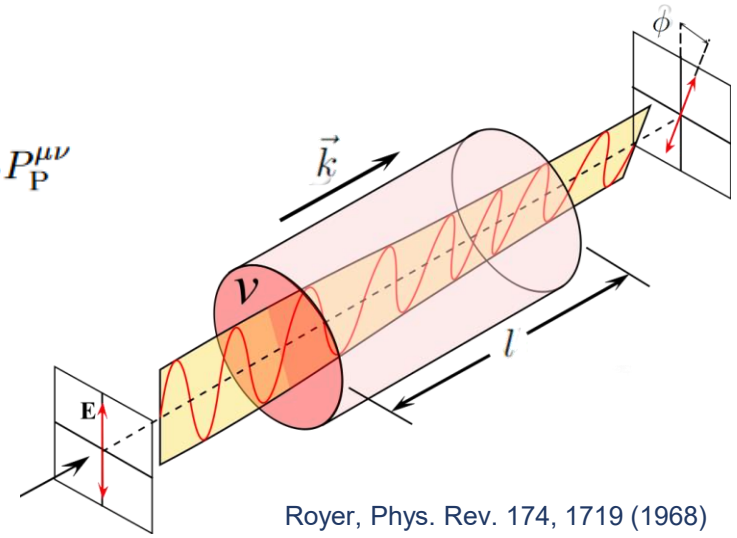
$$P_{\mathrm{L}}^{\mu\nu} = \frac{\tilde{u}^\mu \tilde{u}^\nu}{\tilde{u}^2}\,,$$

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$$P_{\mathrm{P}}^{\mu\nu} = \frac{\mathrm{i}}{K} \varepsilon^{\mu\nu\alpha\beta} k_\alpha \tilde{u}_\beta\,,$$

$$P_{\mathrm{P}\nu}^{\mu} e_{1,2}^{\nu} = \pm \mathrm{i} e_{2,1}^{\mu}\,.$$

$$P_{\mathrm{T}\nu}^{\mu} e_{1,2}^{\nu} = e_{1,2}^{\mu}\,, \quad P_{\mathrm{T}\nu}^{\mu} e_{3}^{\nu} = 0\,,$$
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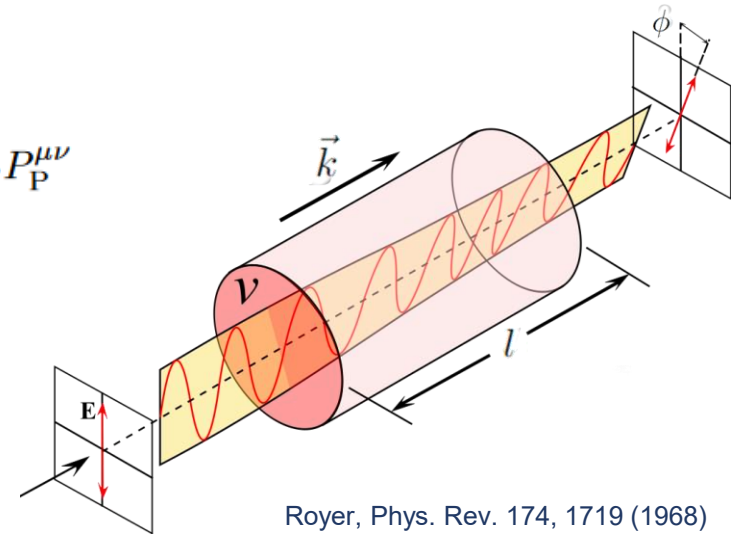
Chiral asymmetric neutrino gas

Left and Right circular get different dispersion relation leading to birefringence

$$\frac{\phi}{l} \equiv \frac{1}{2}(|\mathbf{k}_-| - |\mathbf{k}_+|)$$

$$\Pi^{\mu\nu} = \Pi_{\mathrm{T}} P^{\mu\nu}_{\mathrm{T}} + \Pi_{\mathrm{L}} P^{\mu\nu}_{\mathrm{L}} + \Pi_{\mathrm{P}} P^{\mu\nu}_{\mathrm{P}}$$

$$P^{\mu\nu}_{\mathrm{L}} = \frac{\tilde{u}^{\mu}\tilde{u}^{\nu}}{\tilde{u}^2} \,,$$
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Nieves and Pal, Phys. Rev. D 39, 652 (1989) Mohanty et al, Phys. Rev. D 58, 093007 (1998)

$$k^2 = \Pi_T \pm \Pi_P \qquad \begin{pmatrix} -k^2 + \Pi_T & -i\Pi_P \\ i\Pi_P & -k^2 + \Pi_T \end{pmatrix} \begin{pmatrix} A_1 \\ A_2 \end{pmatrix} = 0$$

$$k^2 = \omega^2(1 - n^2)$$

$$\frac{\phi}{l} \simeq \frac{\Pi_{\mathrm{P}}}{2\sqrt{\omega^2 - \Pi_{\mathrm{T}}}} = \frac{\Pi_{\mathrm{P}}}{2\omega n}$$

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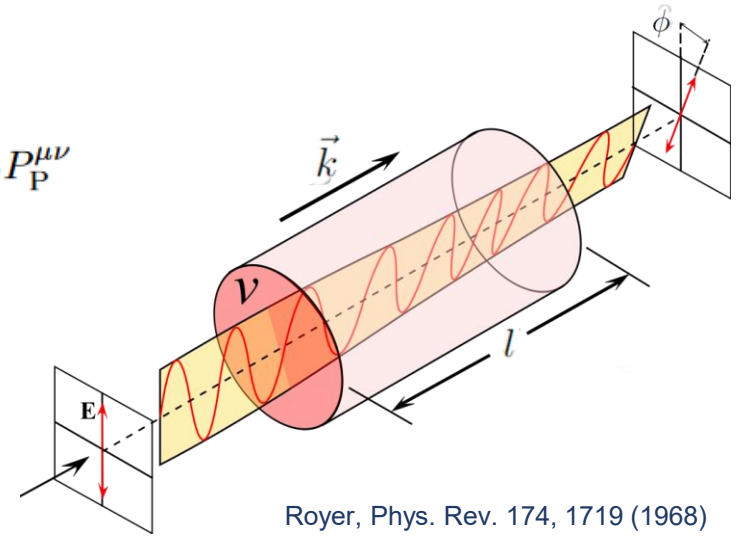
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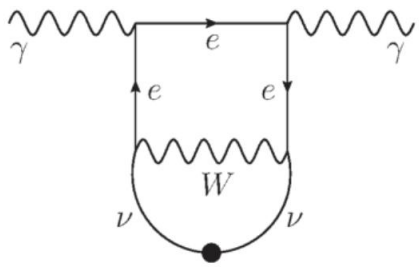
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Photon polarization and directionality factor

Electromagnetic wave propagates through two background media: a refractive medium permeated by a neutrino flux

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General covariant formalism

$$\tilde u^\mu = u^\mu - \frac{(k\cdot u)}{k^2}k^\mu - \frac{(e_1\cdot u)}{e_1^2}e_1^\mu - \frac{(e_2\cdot u)}{e_2^2}e_2^\mu$$

Longitudinal photon polarization vector

$$e_3^\mu = \frac{\tilde u^\mu}{\sqrt{-\tilde u^2}}$$



- Electromagnetic wave 4-momentum:
  $k = (\omega, \mathbf{k}) = \omega(1, n\hat{\mathbf{k}})\,, \quad k^2 = \omega^2(1-n^2)\,,$
- Neutrino medium 4-velocity:
  $u = (u_0, \mathbf{u}) = \gamma(1, \beta\hat{\mathbf{u}})\,, \quad u^2 = 1\,,$
- Transverse polarization:
  $e_{1,2} = (e^0_{1,2}, \mathbf{e}_{1,2}) = (0, \hat{\mathbf{e}}_{1,2})\,, \quad e^2_{1,2} = -1.,$
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$$K = \sqrt{(k.u)^2 - k^2(1 + (e_1\cdot u)^2 + (e_2\cdot u)^2)}$$

$$(k.u) = \omega\gamma(1 - n\beta\cos\theta_{ku})$$

$$(e_1.u) = -\gamma\beta\sin\theta_{ku}\cos\phi_{eu}$$

$$(e_2.u) = -\gamma\beta\sin\theta_{ku}\sin\phi_{eu}$$

Directionality factor

Petropavlova & Smetana, Phys. Rev. D 106, 053003 (2022)

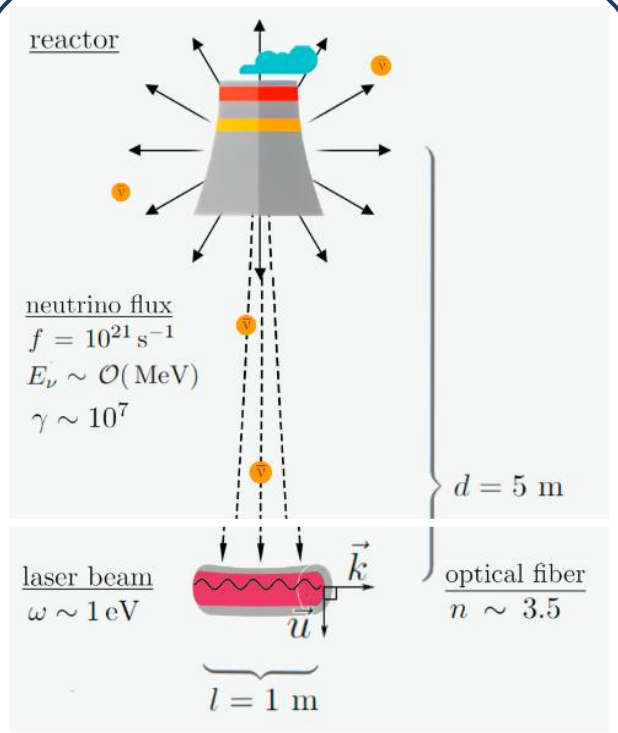
$$K = \omega\gamma(n - \beta\cos\theta_{ku})$$

Neutrino-induced polarization rotation

$$\frac{\phi}{l} = \frac{G_F \alpha}{3\sqrt{2}\pi} \frac{\omega^2 (1 - n^2)}{m_e^2} \gamma (n_\nu - n_{\bar{\nu}}) \left(1 - \frac{\beta}{n} \cos \theta_{ku} \right)$$

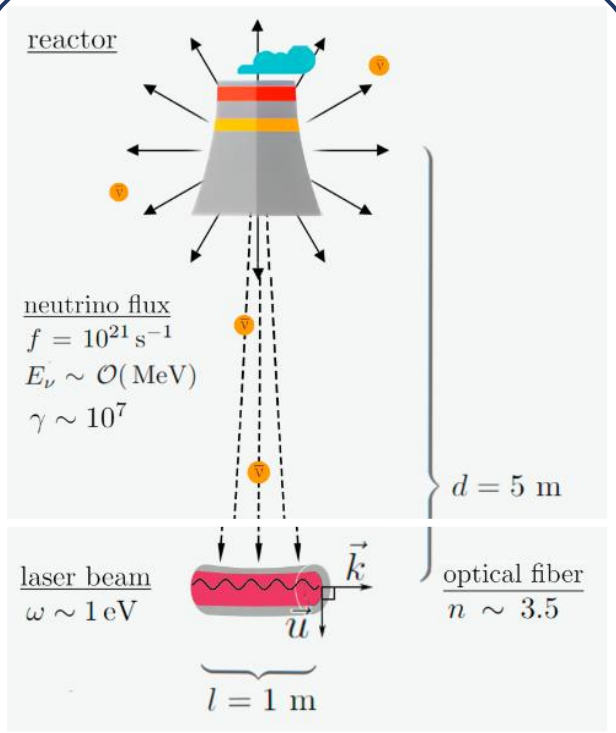
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$$\phi \sim 4.6 \times 10^{-39} \text{ rad}$$

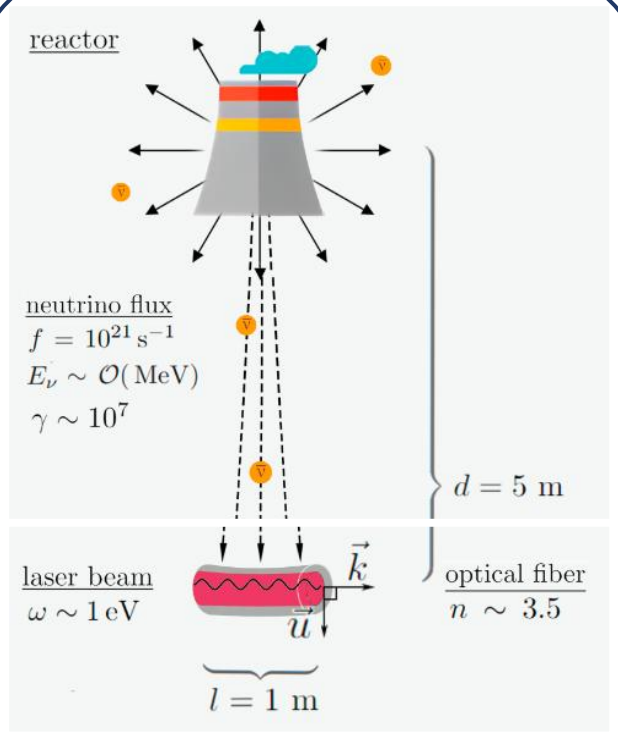
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Case where the refractive media is a plasma

Index of refraction of a non-relativistic non-magnetized **plasma**

$$k^2 = \omega_p^2 = \frac{4\pi\alpha n_e}{m_e} \qquad n(\omega, \omega_p) = \sqrt{1 - \frac{\omega_p^2}{\omega^2}}$$



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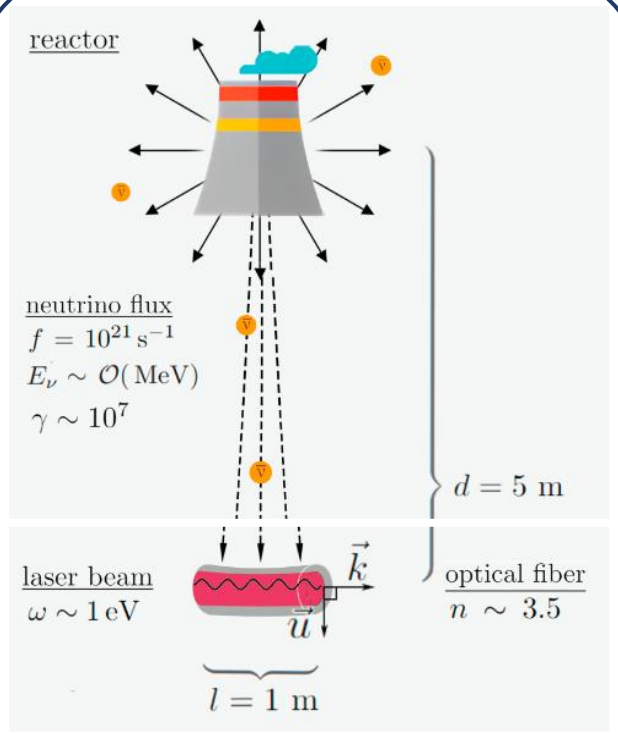
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Differential neutrino-induced polarization angle in terms of neutrino flux

$$\frac{1}{l}\frac{d\phi(E_\nu)}{dE_\nu} = C_\phi \frac{\omega_p^2}{m_e^2} \Phi_\nu(E_\nu)\,[1 - r_\nu(E_\nu)] \left(1 - \frac{\beta(E_\nu)}{n(\omega, \omega_p)} \cos\theta_{ku}\right)$$

$$r_\nu = n_{\bar{\nu}}/n_\nu$$

Neutrino-induced polarization rotation

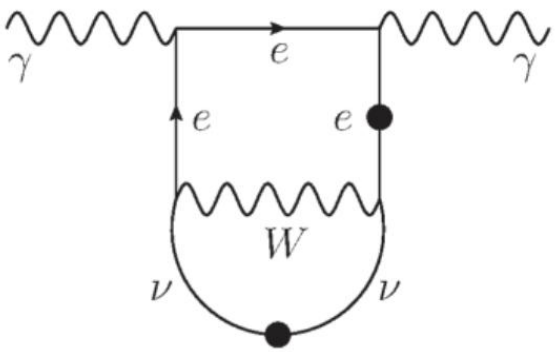
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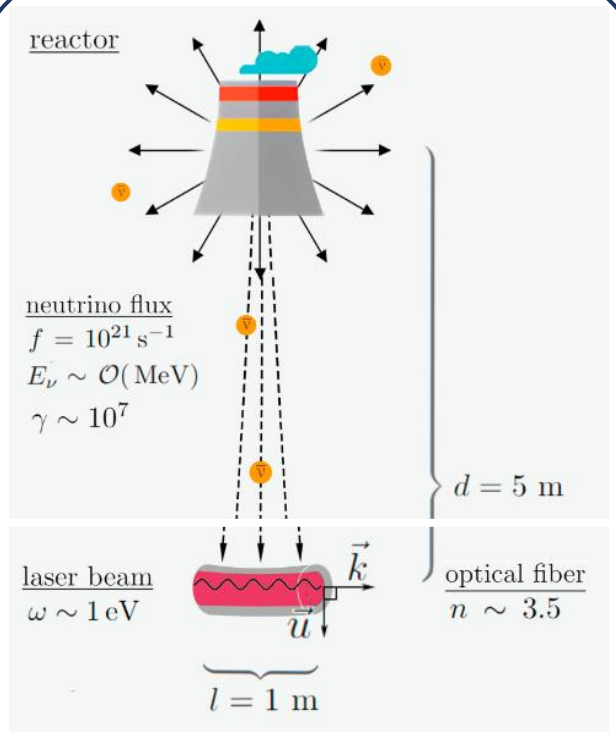
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Improved thermal approach enhancement:



Dvornikov and Semikoz, JCAP 2021 (03), 028

$$C_\phi = \frac{7\pi}{2\alpha} \times \frac{G_F\,\alpha}{3\sqrt{2}\,\pi}$$



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Active Galactic Nuclei

HBC, A. Smetana, A.A. Tursunov,

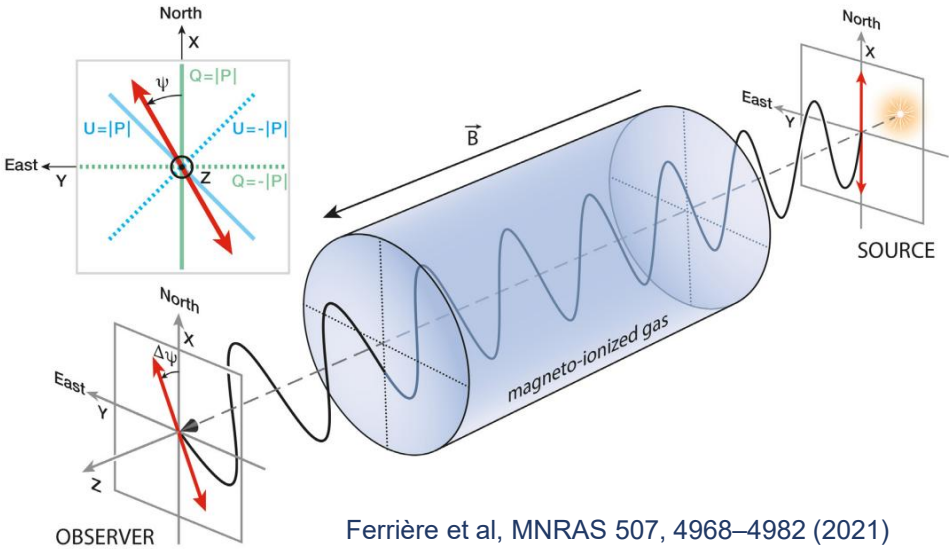
Neutrino-Induced Polarization Rotation in Active Galactic Nuclei Plasmas,

Phys. Rev. D 113, 113003 (2026) (arXiv: 2601.15910 [hep-ph])

Faraday rotation and Polarimetric experiments

Faraday rotation

$$\frac{\phi}{l} = \frac{\phi_0}{l} + \frac{\mathrm{RM}}{l}\,\omega^{-2}$$



Ferrière et al, MNRAS 507, 4968–4982 (2021)

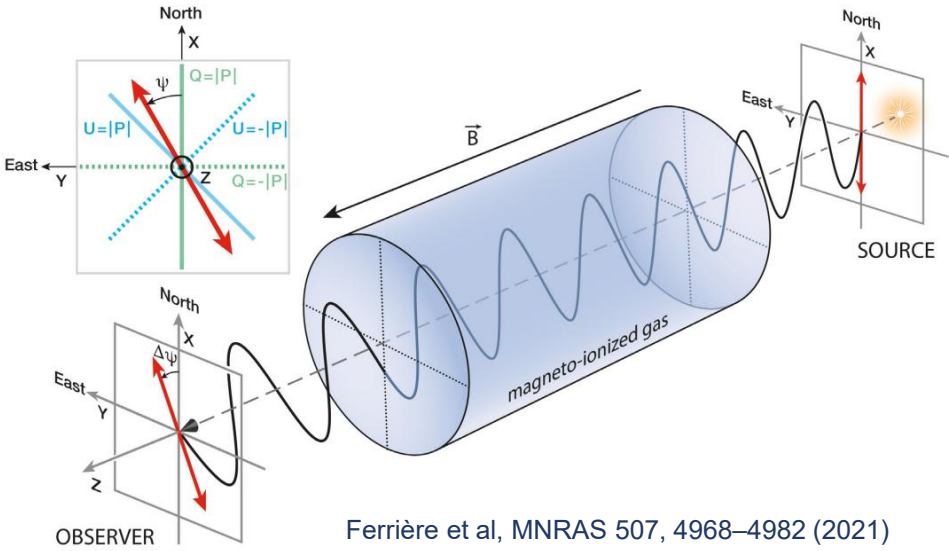
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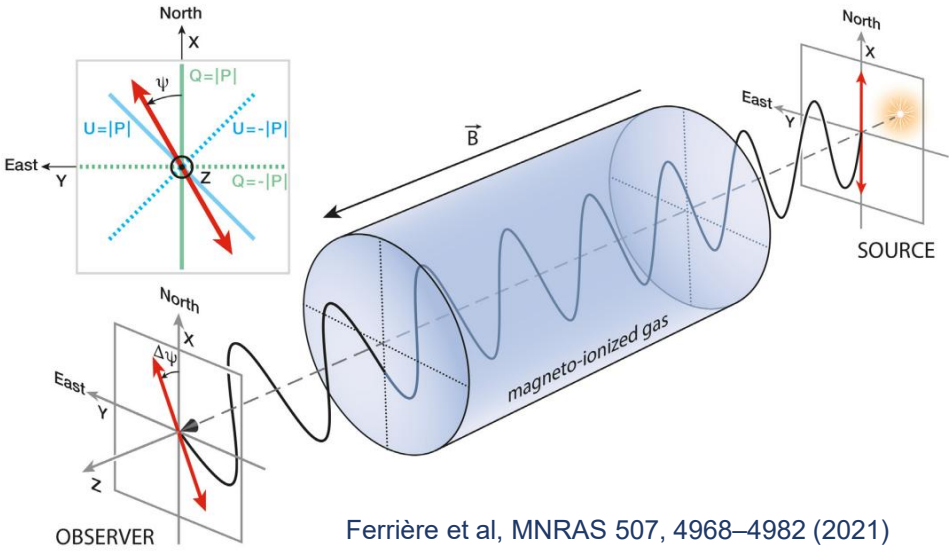
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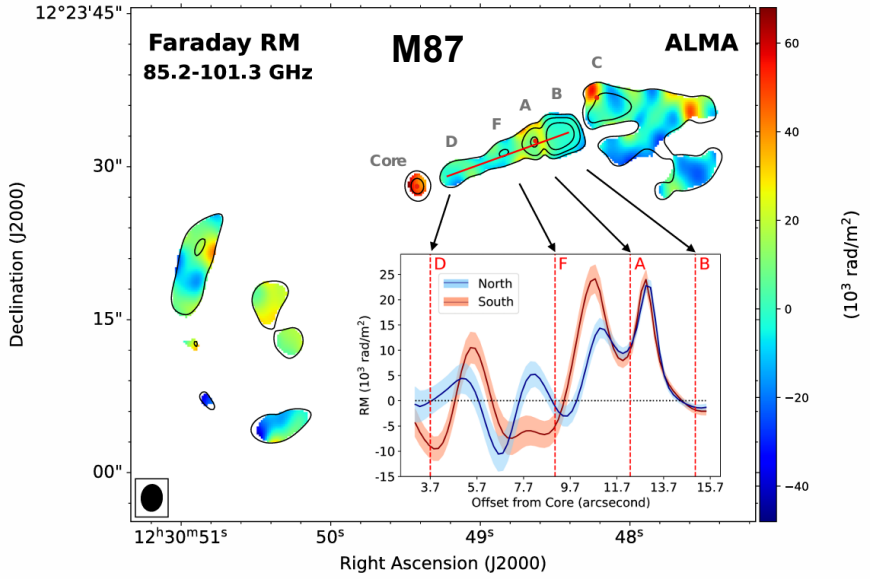
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Polarimetric experiments measure RM,
Electric Vector Position Angle (EVPA),
Stokes Parameters,
Polarization Angle (PA), Polarization Degree (PD), etc.
Infer properties of jets and accretion disk plasmas.



Ferrière et al, MNRAS 507, 4968–4982 (2021)

Atacama Large Millimeter/submillimeter Array (ALMA)



Peng et al, *Astrophys.J.* 975, 1, 103 (2024)

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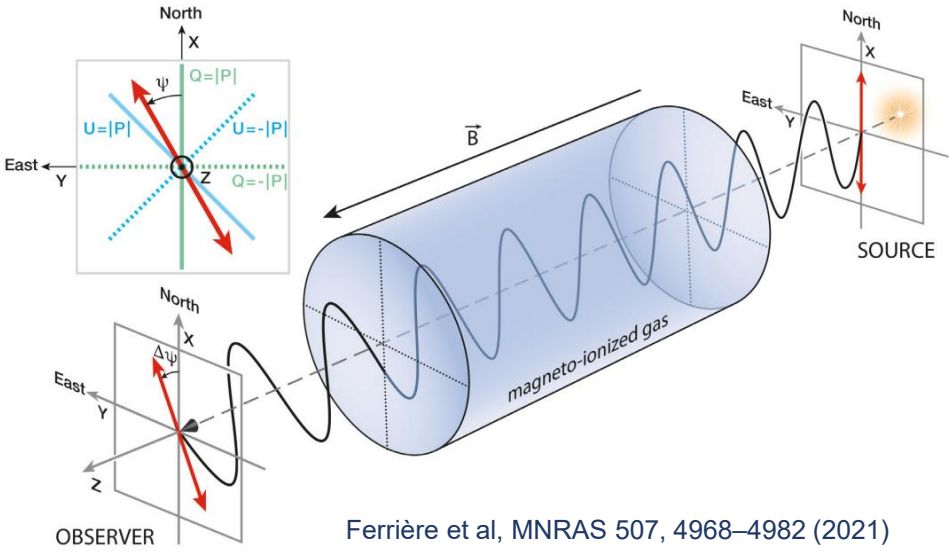
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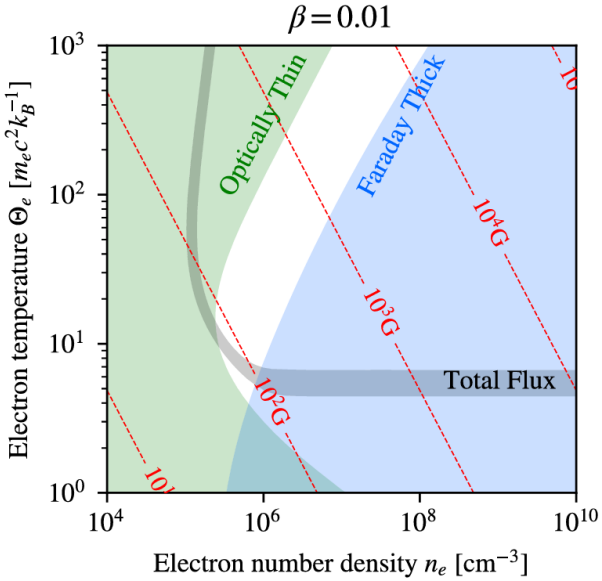
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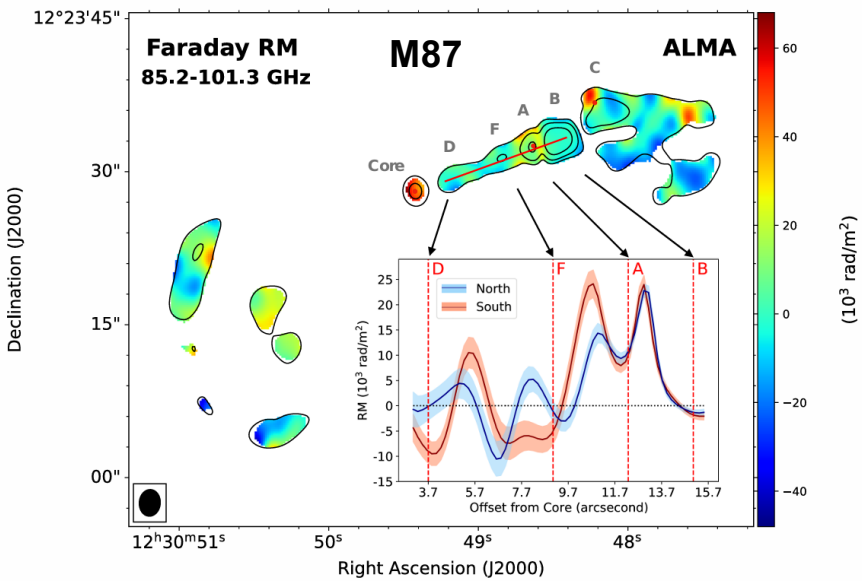


Ferrière et al, MNRAS 507, 4968–4982 (2021)



Event Horizon Telescope (EHT), *ApJL* 964 L26 (2024)

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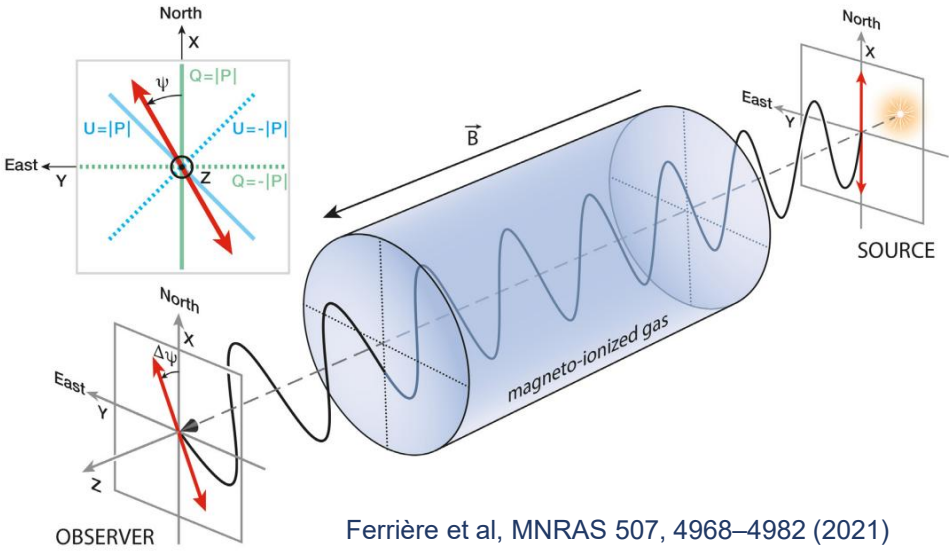
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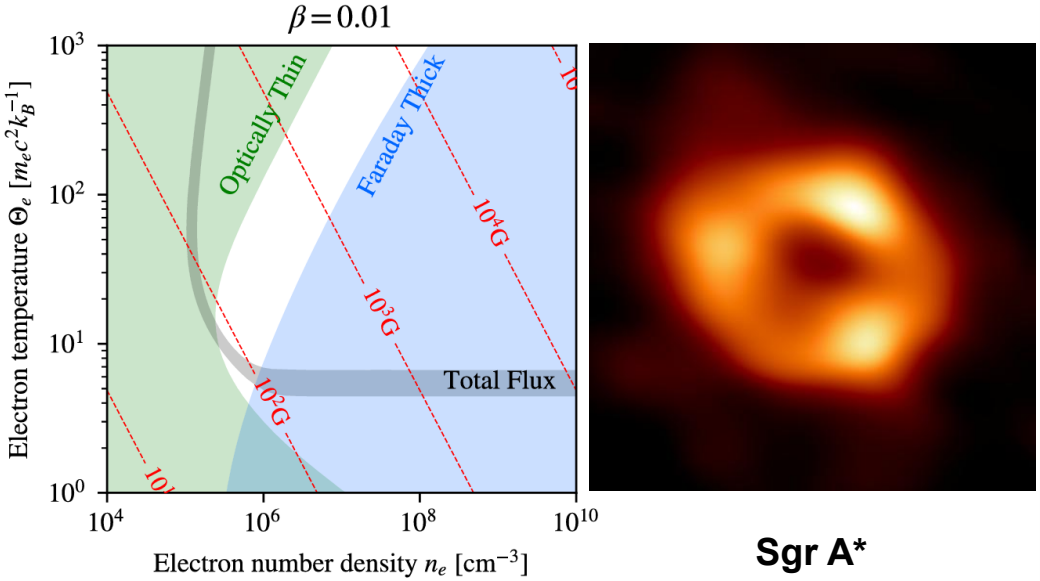
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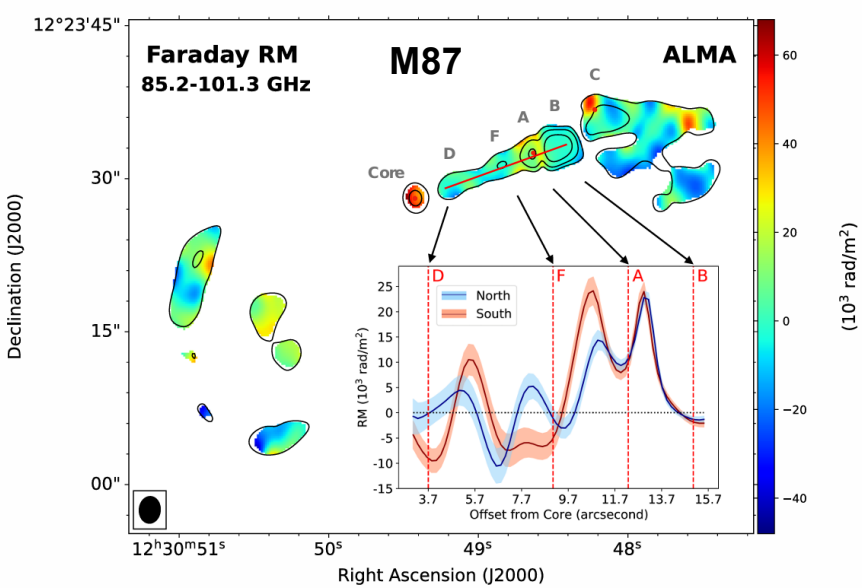
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Sgr A*

Event Horizon Telescope (EHT), *ApJL* 964 L26 (2024)

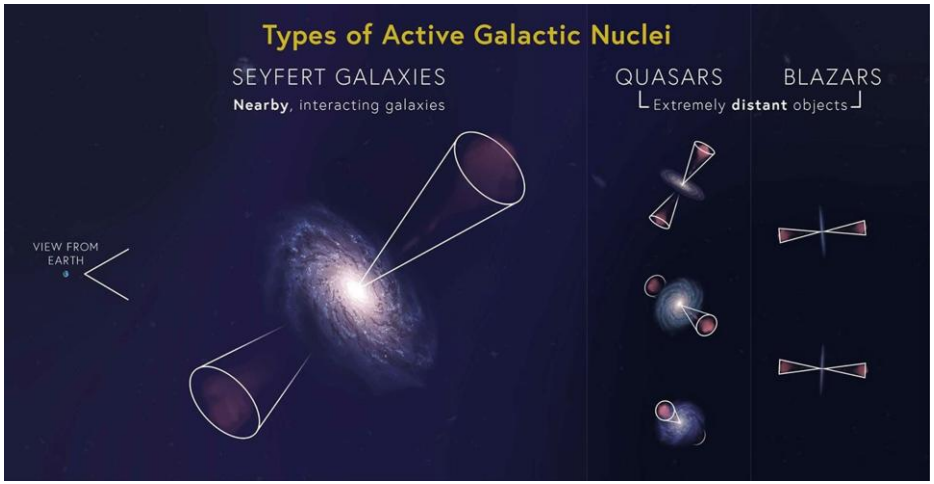


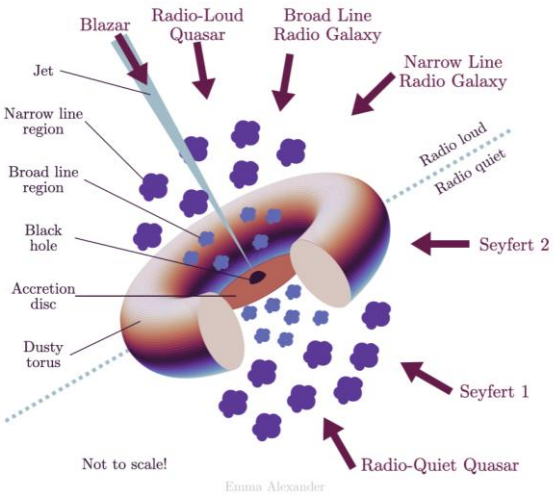
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Properties of Active Galactic Nuclei

Active galactic nuclei (AGN) are active supermassive black holes (BHs) that emit light via bright jets, winds and accretion disks, visible across radio wavelengths to X-rays.

Credit: NASA, ESA, CSA, and L. Hustak (STScI)

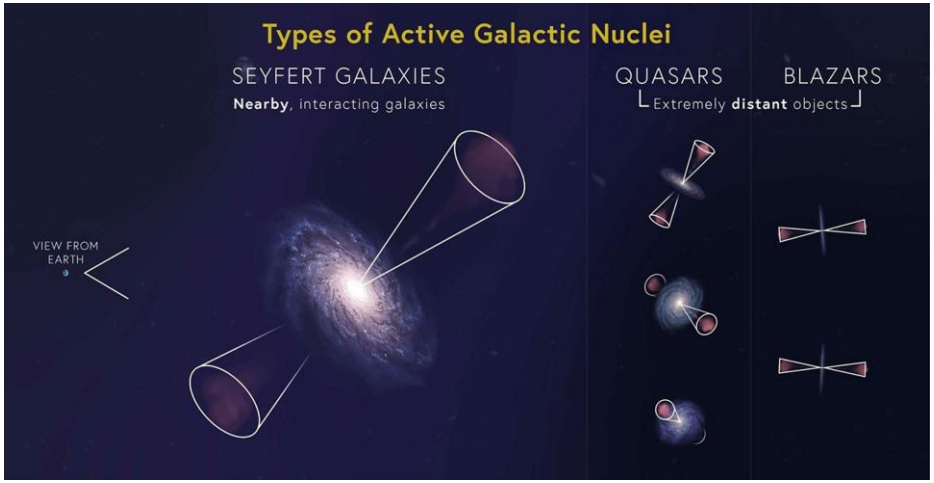


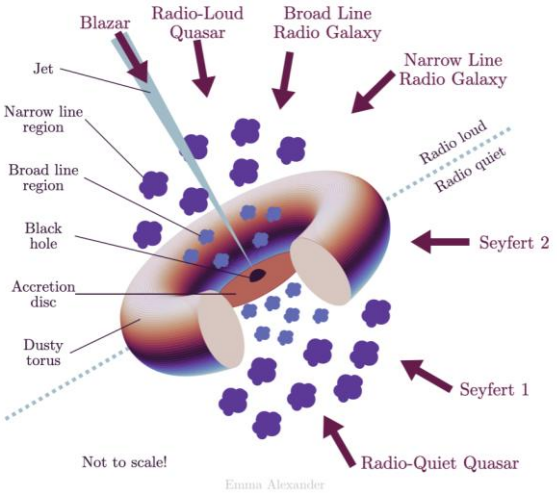


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Characteristics of luminous Seyfert/Quasar

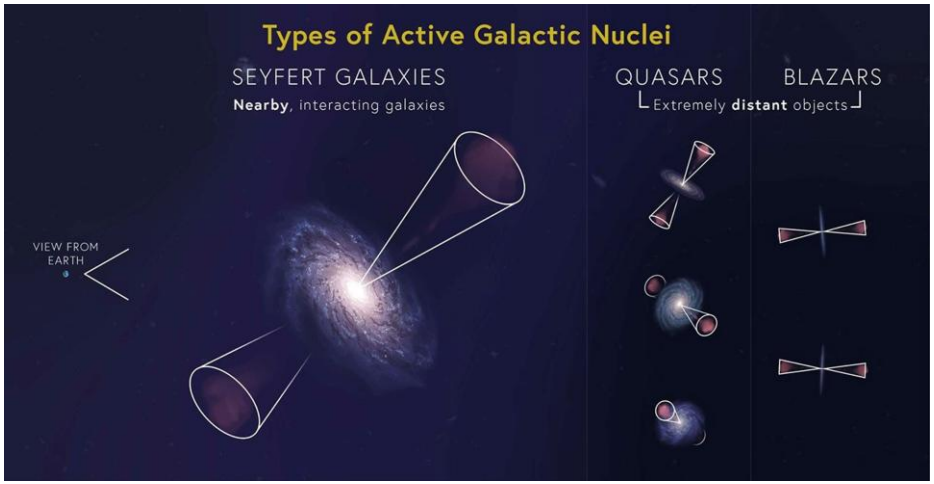
Supermassive BH $M_{\rm BH} \sim 10^8 - 10^9\, M_\odot$

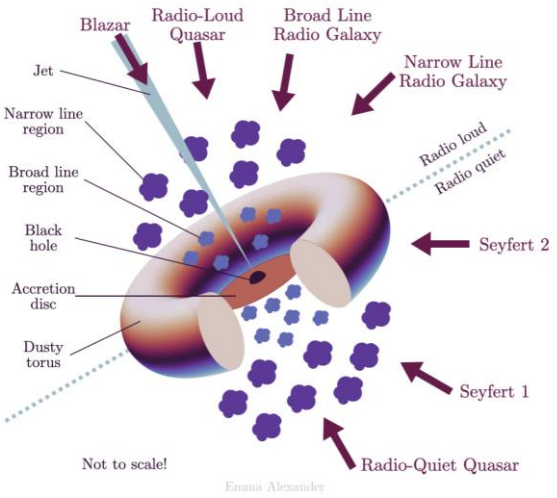
$r_g \equiv GM/c^2$ $r_g = 4 \times 10^{-5}$ pc

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Jet

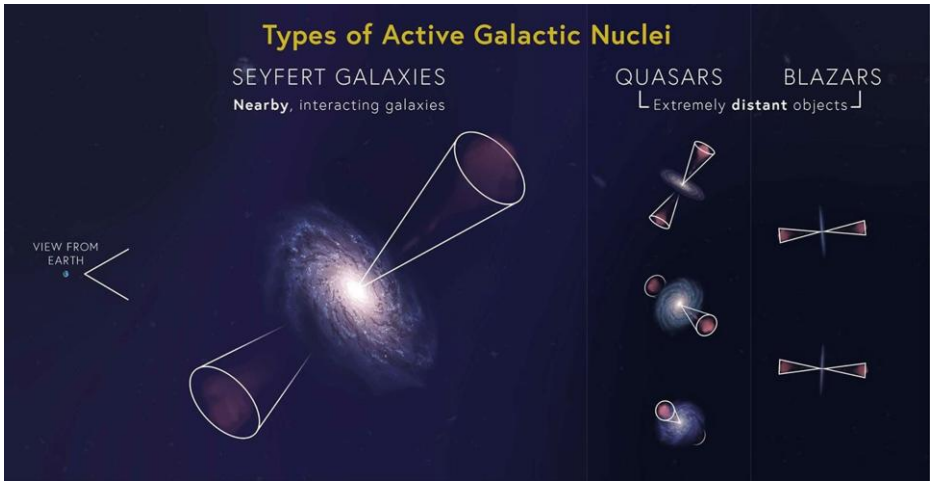
- **propagation scale:**
  sub-pc/pc scales out to **100 kpc**
- **plasma composition:**
  electron–proton $(e^- p)$ or pair-rich $(e^- e^+)$

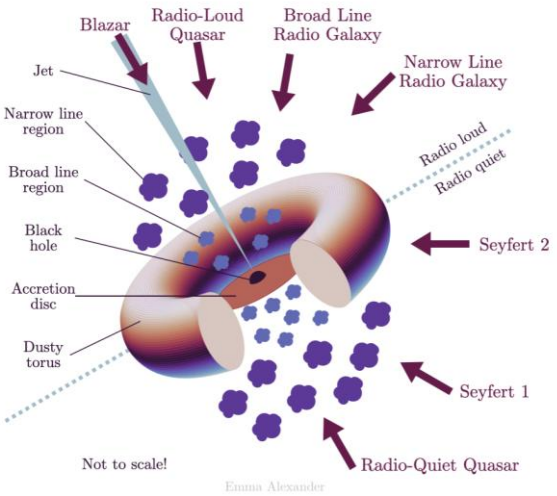
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Accretion disk

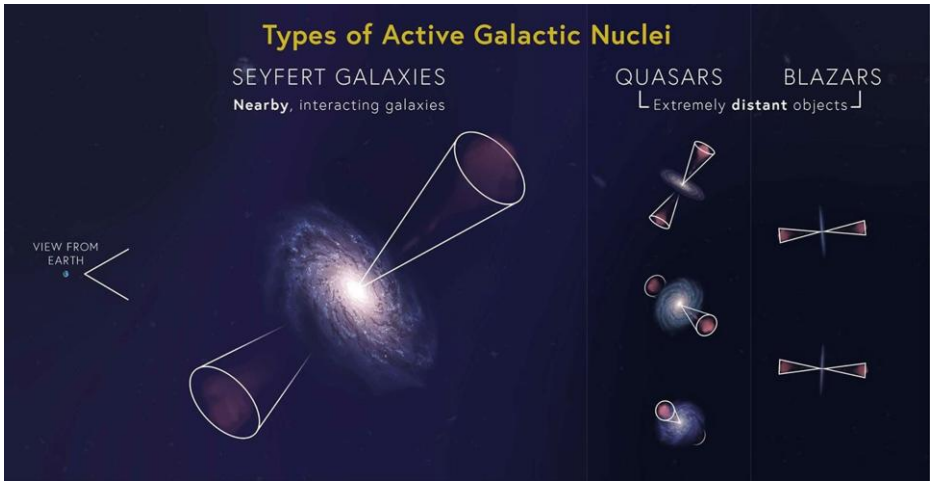
- **size** (bulk of the accretion luminosity): $\sim 10\, R_{\rm S}$
- **plasma composition**:
  ionized hydrogen/helium plasma
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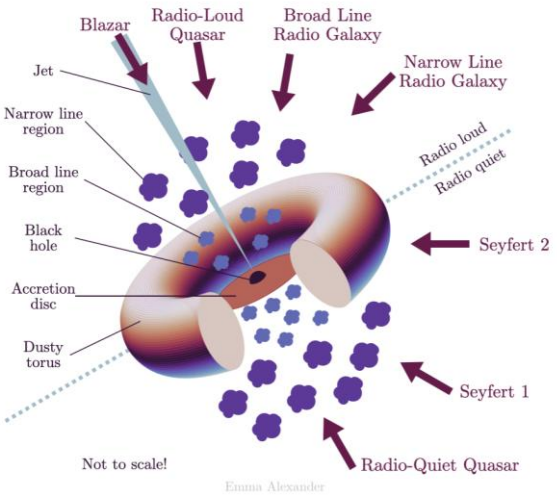
$10^4 - 10^5$ K $\quad n \sim 10^{14} - 10^{17}\ \mathrm{cm}^{-3}$

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Three cases of AGN **plasma + asymmetric chiral neutrino media**:

1. **Jet plasma + Cosmic Neutrino Background**
2. **Jet plasma** + Ultra-high energy **neutrinos produced within the jet**
3. **Accretion disk + Cosmic Neutrino Background**

Jet and Cosmic Neutrino Background

Cosmic neutrino background

$$n_\gamma \simeq 411 \text{ cm}^{-3}$$

$$\eta_{\nu_\alpha} \equiv \frac{n_{\nu_\alpha} - n_{\bar{\nu}_\alpha}}{n_\gamma} = \frac{\pi^2 \xi_\alpha}{12\zeta(3)} \left(1 + \frac{\xi_\alpha^2}{\pi^2}\right) \left(\frac{T_{\nu_\alpha}}{T_\gamma}\right)^3$$

$$T_{\nu_\alpha}/T_\gamma = (4/11)^{1/3}$$

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$$\xi_\nu \sim \mathcal{O}(0.05)$$

Li and Yu, *JHEP* 06, 213 (2025)

$$n_\nu - n_{\bar{\nu}} \sim \mathcal{O}(5) \text{ cm}^{-3}$$

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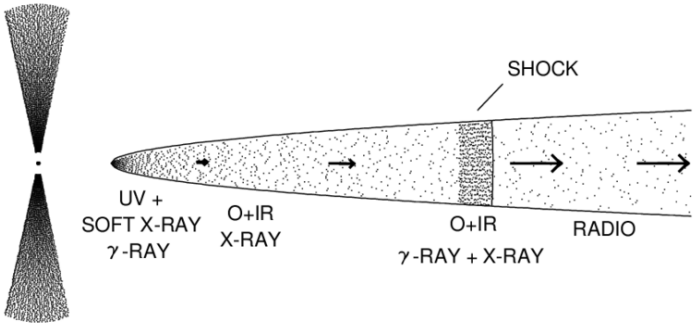
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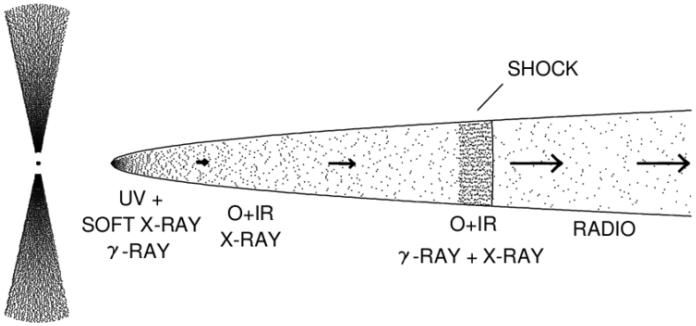
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Geometry

Lab frame

ν $u^\mu = (1, 0, 0, 0)$

plasma

polarized EM wave k^μ

Plasma rest frame

ν u^μ

$\theta_{ku} = \pi$

polarized EM wave k^μ

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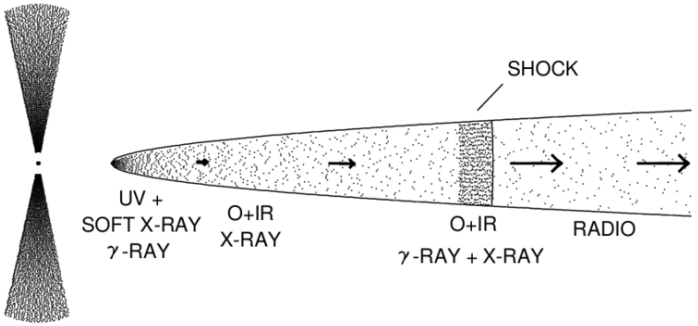
$$\xi_\nu \sim \mathcal{O}(0.05)$$

Li and Yu, *JHEP* 06, 213 (2025)

$$n_\nu - n_{\bar{\nu}} \sim \mathcal{O}(5) \text{ cm}^{-3}$$

Jet + Cosmic neutrino background

$$n_e = 10^4 \text{ cm}^{-3},\ l = 1 \text{ pc}$$



$$\beta = 0.9 \qquad \left(1 + \frac{\beta(E_\nu)}{n(\omega, \omega_p)}\right) \approx 1$$

$$\frac{\phi}{l} = C_\phi \frac{\omega_p^2}{m_e^2} \gamma \left(1 + \frac{\beta}{n}\right) \eta_{\nu_e} n_\gamma$$

Geometry

Lab frame

ν $u^\mu = (1, 0, 0, 0)$

plasma

polarized EM wave k^μ

Plasma rest frame

ν u^μ

$\theta_{ku} = \pi$

polarized EM wave k^μ

Jet and Cosmic Neutrino Background

Cosmic neutrino background

$$n_\gamma \simeq 411 \text{ cm}^{-3}$$

$$\eta_{\nu_\alpha} \equiv \frac{n_{\nu_\alpha} - n_{\bar{\nu}_\alpha}}{n_\gamma} = \frac{\pi^2 \xi_\alpha}{12\zeta(3)} \left(1 + \frac{\xi_\alpha^2}{\pi^2}\right) \left(\frac{T_{\nu_\alpha}}{T_\gamma}\right)^3$$

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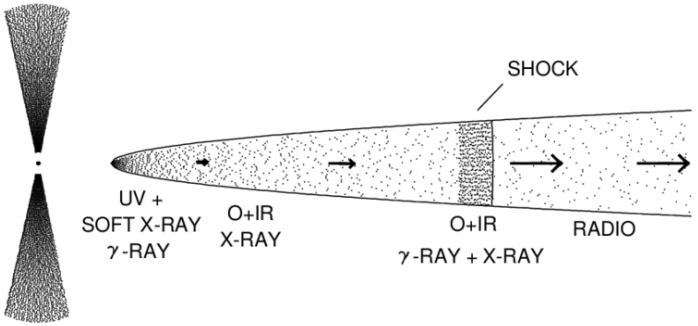
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$$\phi_{\text{j}}^{\text{C}\nu\text{B}} \sim 10^{-41} \text{ rad}$$

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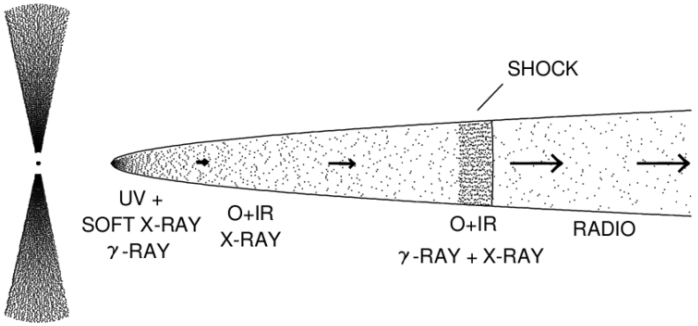
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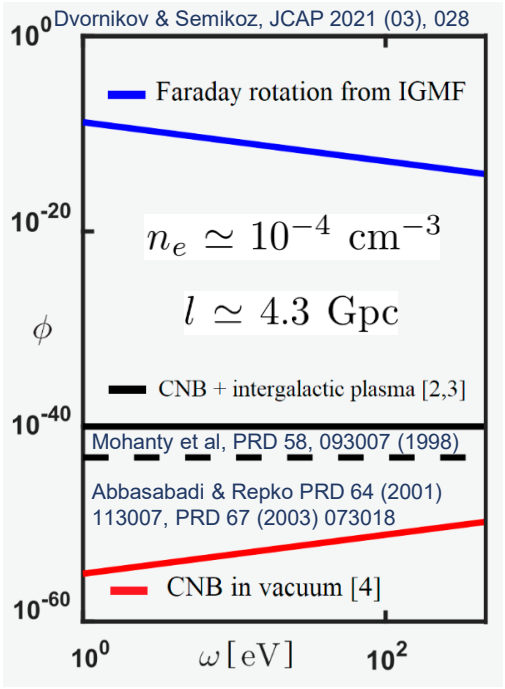
polarized EM wave k^μ

Plasma rest frame

ν u^μ

$\theta_{ku} = \pi$

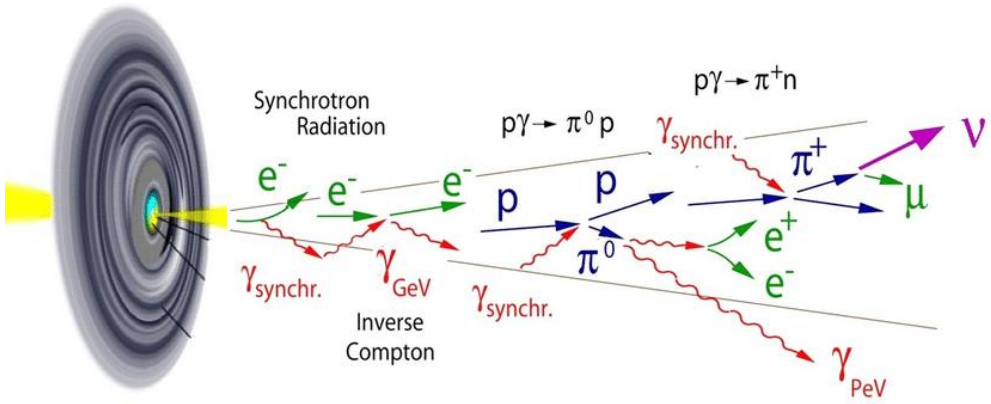
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Jet and neutrinos produced in the jet

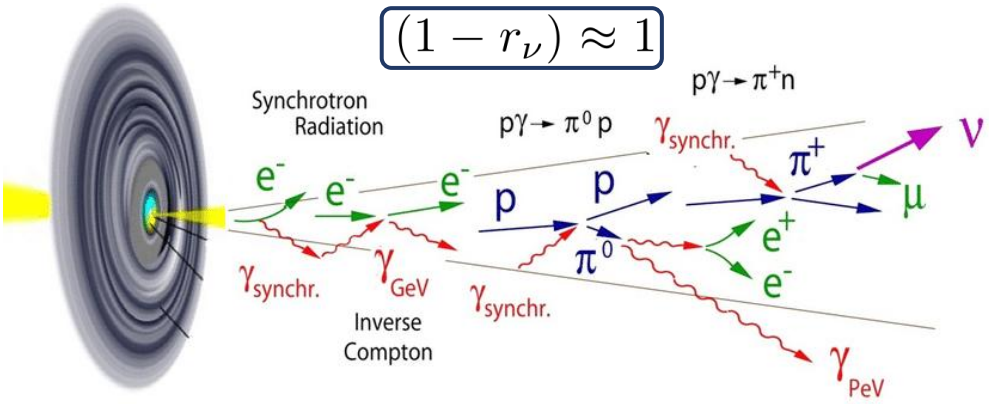
Ultra-high energy neutrino production



Jet and neutrinos produced in the jet

Ultra-high energy neutrino production

$$(1 - r_\nu) \approx 1$$



Jet and neutrinos produced in the jet

Ultra-high energy neutrino production

Geometry

Lab frame

ν $u^\mu = (\gamma, 0, 0, \gamma\beta)$

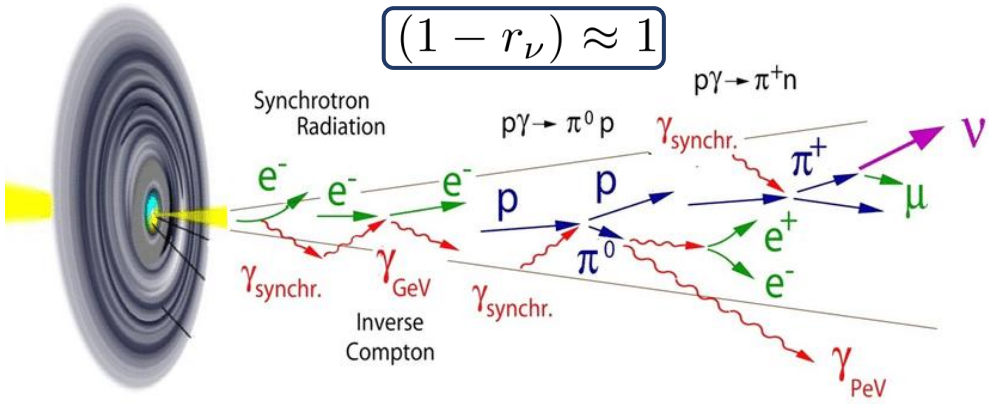
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Plasma rest frame

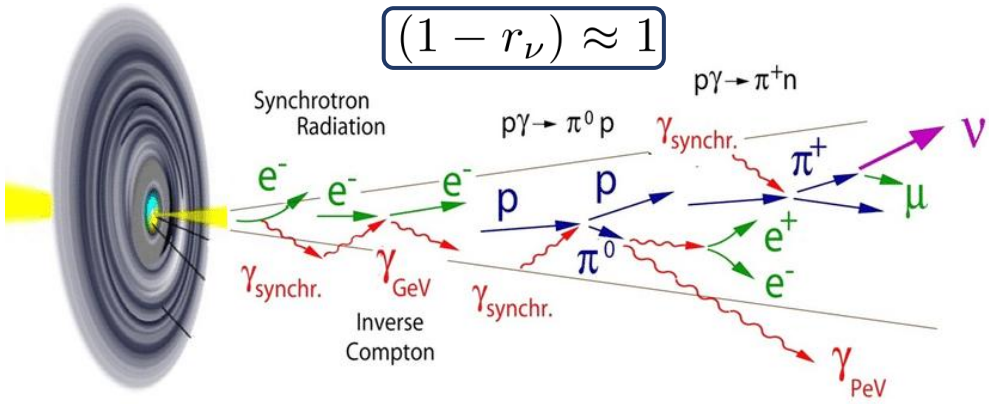
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Jet and neutrinos produced in the jet

Ultra-high energy neutrino production



Geometry

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plasma

polarized EM wave k^μ

Plasma rest frame

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polarized EM wave k^μ

Jet and neutrinos produced in the jet

Ultra-high energy neutrino production

Geometry

Lab frame

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plasma

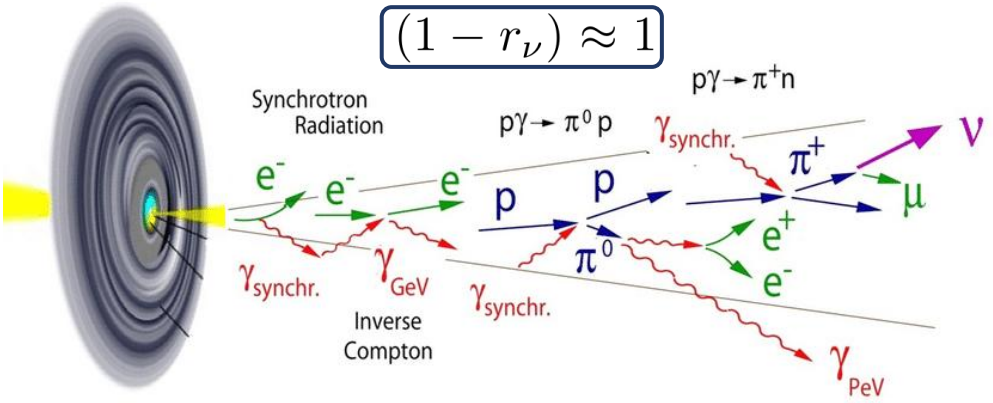
polarized EM wave k^μ

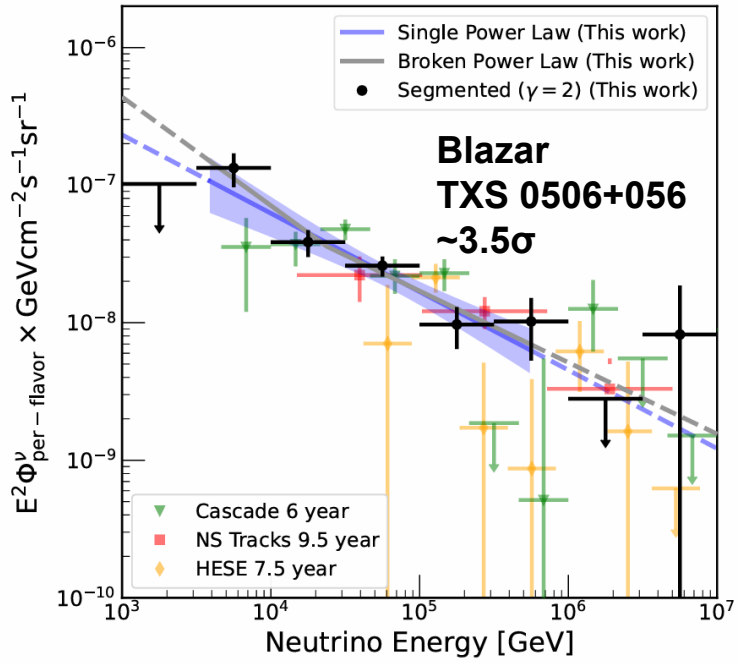
Plasma rest frame

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polarized EM wave k^μ





IceCube, Phys. Rev. D 110, 022001 (2024)

Jet and neutrinos produced in the jet

Ultra-high energy neutrino production

Geometry

Lab frame

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plasma

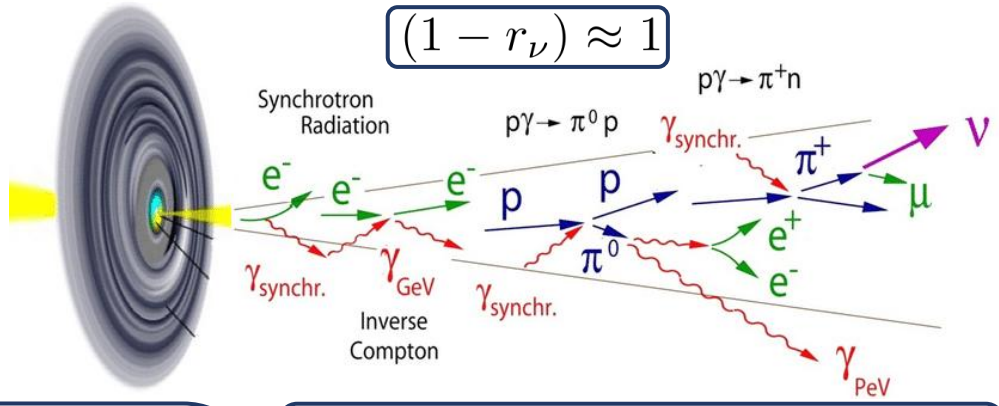
polarized EM wave k^μ

Plasma rest frame

ν u^μ

$\theta_{ku} = 0$

polarized EM wave k^μ



Single power law fit data from IceCube for TXS 0506+056

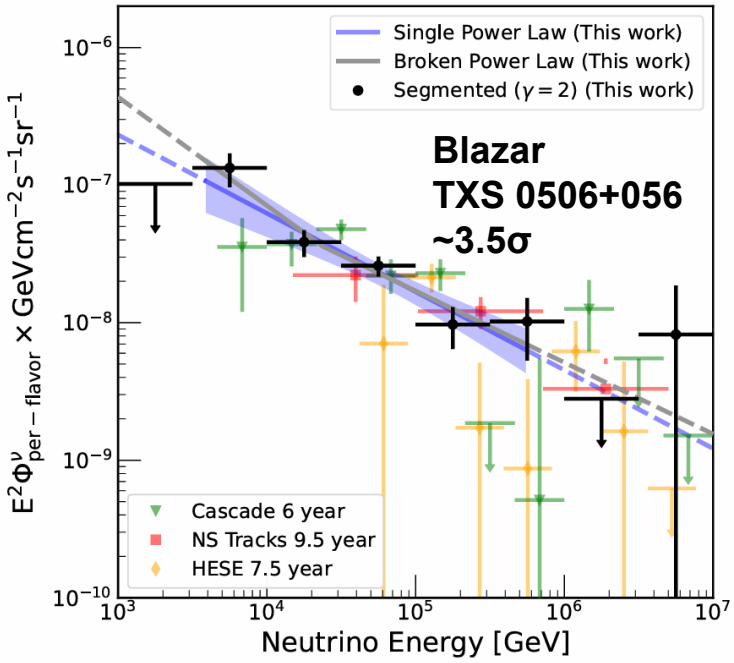
$\sigma = 2.58$

$(E_\nu^{\min}, E_\nu^{\max}) \in (3, 550)$ TeV

$E_0 = 100$ TeV

$\Phi_0 = 1.68 \times 10^{-18}$ GeV^{-1} cm^{-2} s^{-1} sr^{-1}

$$\Phi_\nu = \Phi_0 \left(\frac{E_\nu}{E_0}\right)^{-\sigma} \theta(E_\nu - E_\nu^{\min})\, \theta(E_\nu^{\max} - E_\nu)$$



IceCube, Phys. Rev. D 110, 022001 (2024)

Jet and neutrinos produced in the jet

Ultra-high energy neutrino production

Geometry

Lab frame

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plasma

polarized EM wave k^μ

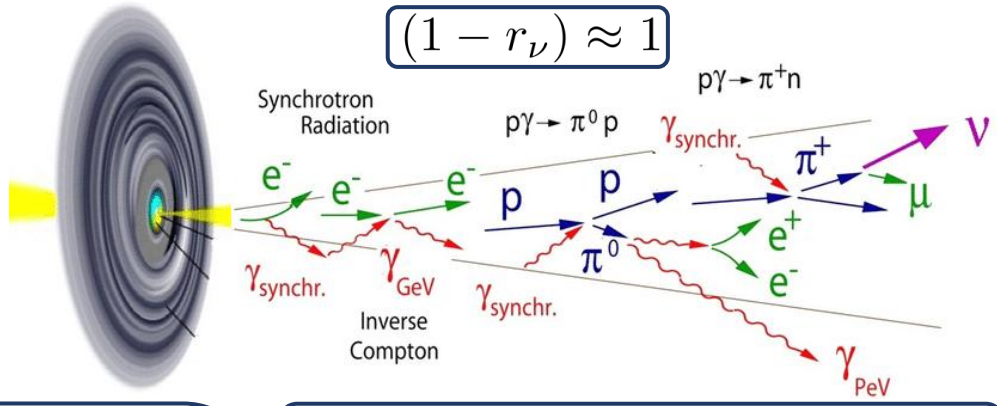
Plasma rest frame

ν u^μ

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polarized EM wave k^μ

$$\frac{\phi}{l} = C_\phi \frac{\omega_p^2}{m_e^2} \Phi_0 \int_{E_\nu^{\min}}^{E_\nu^{\max}} \mathrm{d}E_\nu \left(\frac{E_\nu}{E_0}\right)^{-\sigma} \left(1 - \frac{\beta(E_\nu)}{n}\right)$$



Single power law fit data from IceCube for TXS 0506+056

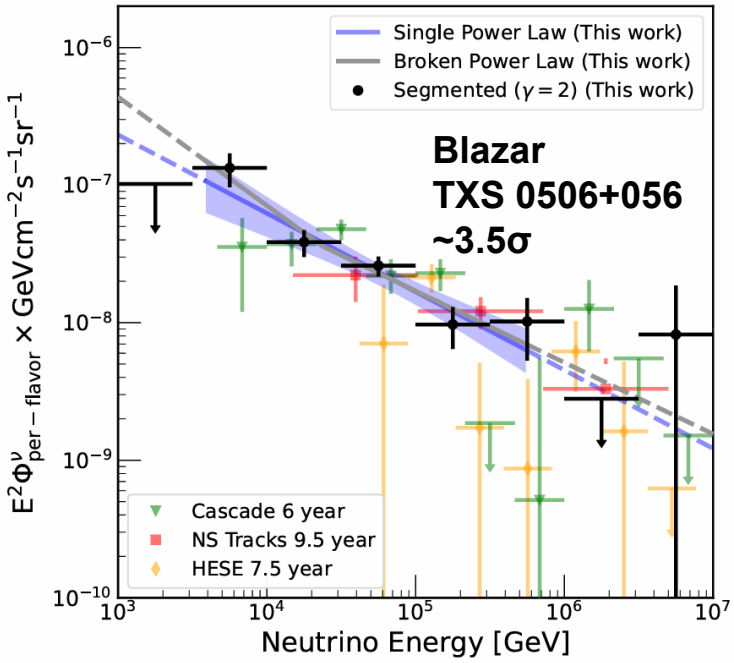
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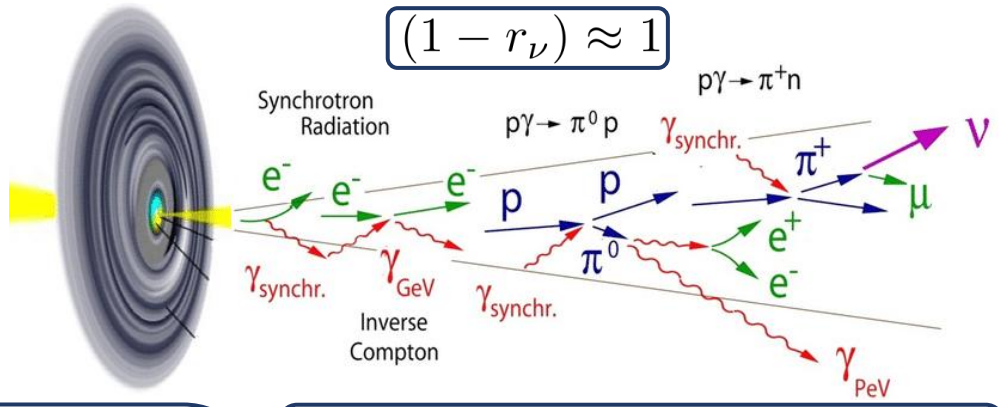


IceCube, Phys. Rev. D 110, 022001 (2024)

Jet and neutrinos produced in the jet

Ultra-high energy neutrino production

$(1 - r_\nu) \approx 1$



Geometry

Lab frame

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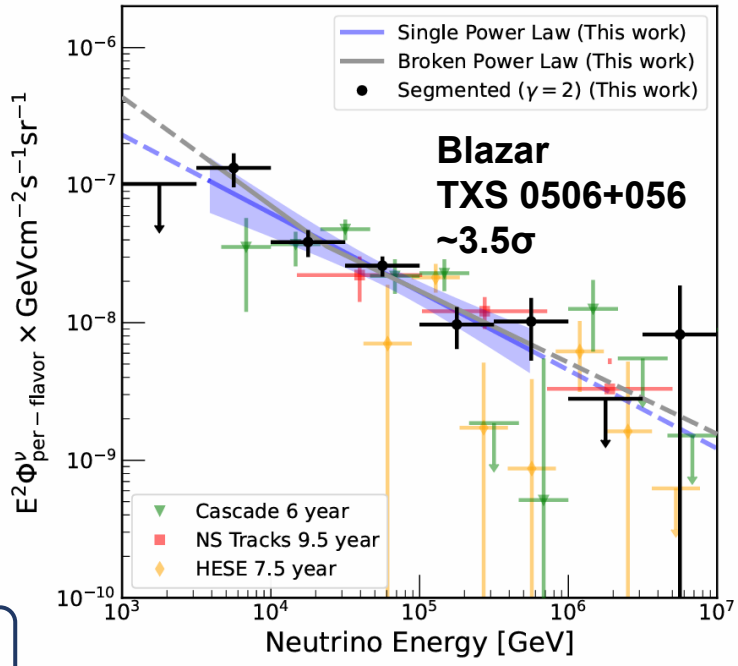
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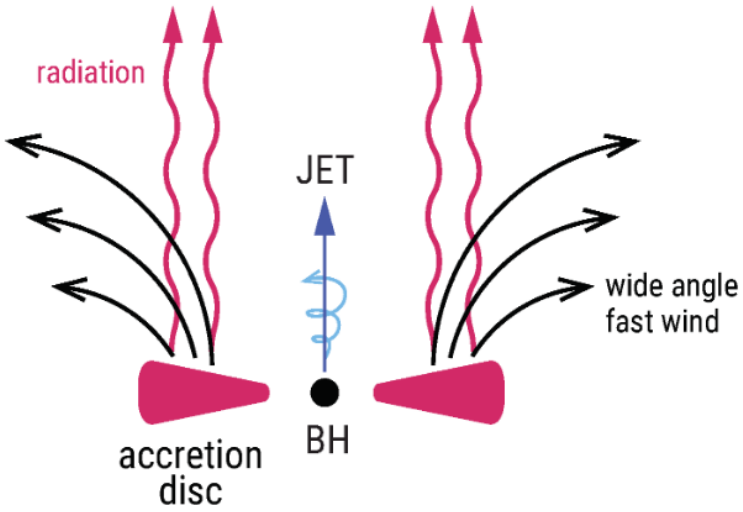
$$\frac{\phi}{l} = C_\phi \frac{\omega_p^2}{m_e^2} \Phi_0 \int_{E_\nu^{\min}}^{E_\nu^{\max}} \mathrm{d}E_\nu \left(\frac{E_\nu}{E_0}\right)^{-\sigma} \left(1 - \frac{\beta(E_\nu)}{n}\right)$$

$n_e = 10^4$ cm^{-3}, $l = 1$ pc

$\omega = 1$ GHz

$\phi_{\mathrm{j}}^{\mathrm{UHE}} \sim 5 \times 10^{-44}$ rad

Accretion disk and Cosmic Neutrino Background



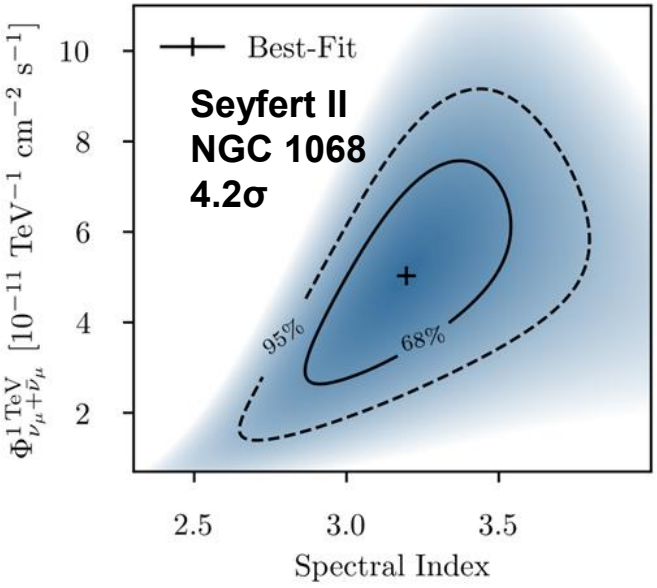
$$\frac{\phi}{l} = C_\phi \frac{\omega_p^2}{m_e^2} n_\nu (1 - r_\nu)$$

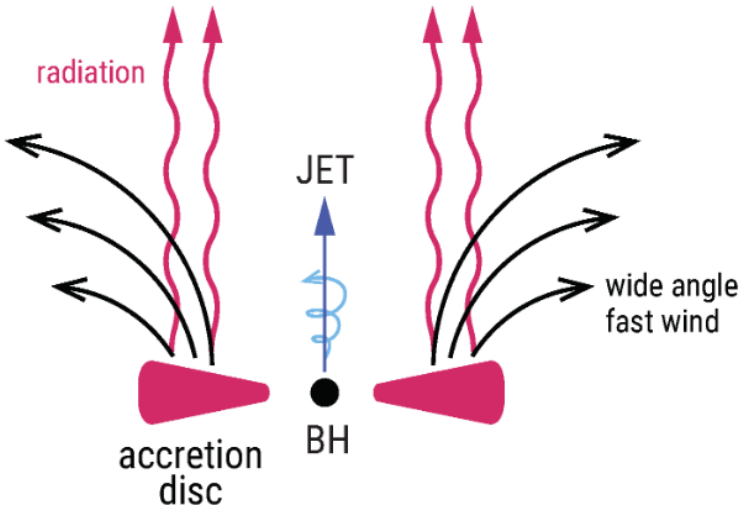
No preferred bulk motion

$$\beta = 0 \text{ and } \gamma = 1$$

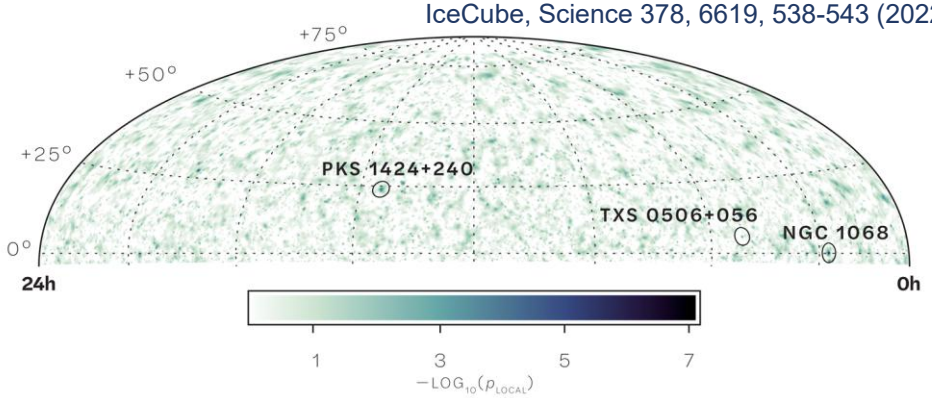
Accretion disk and Cosmic Neutrino Background

Ultra-high energy neutrino production





IceCube, Science 378, 6619, 538-543 (2022)



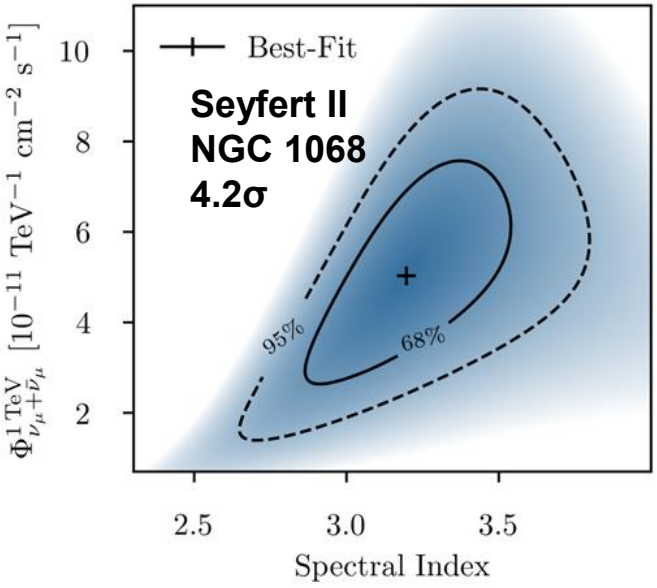
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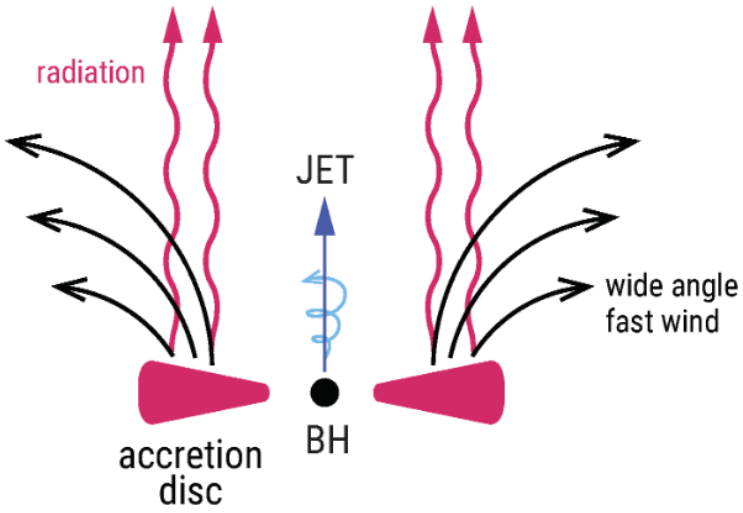
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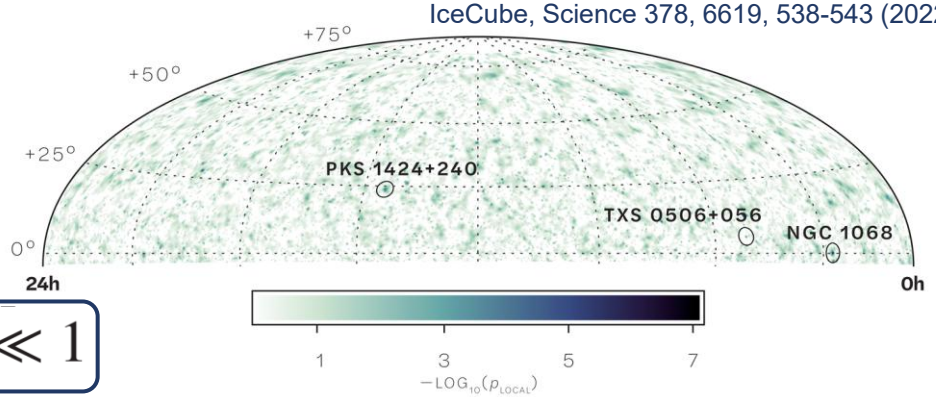
Accretion disk and Cosmic Neutrino Background

Ultra-high energy neutrino production





IceCube, Science 378, 6619, 538-543 (2022)



$$(1 - r_\nu) \ll 1$$

UHE neutrino production proceeds via pp interactions in dense disk.
This produces roughly equal numbers of charged pions.

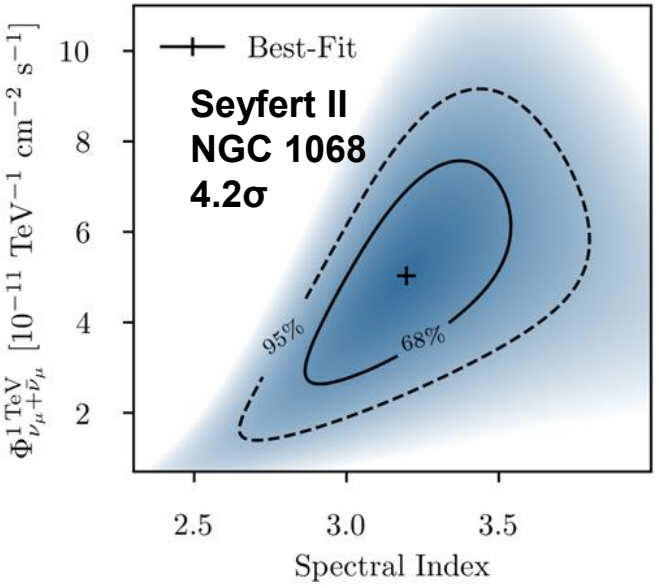
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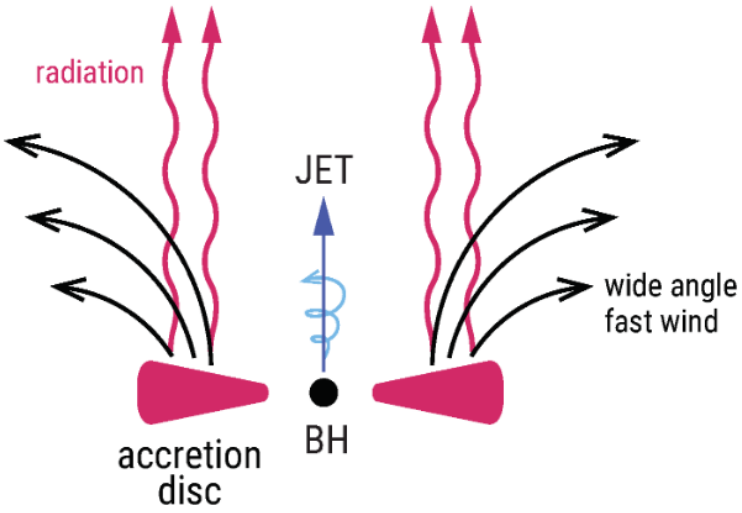
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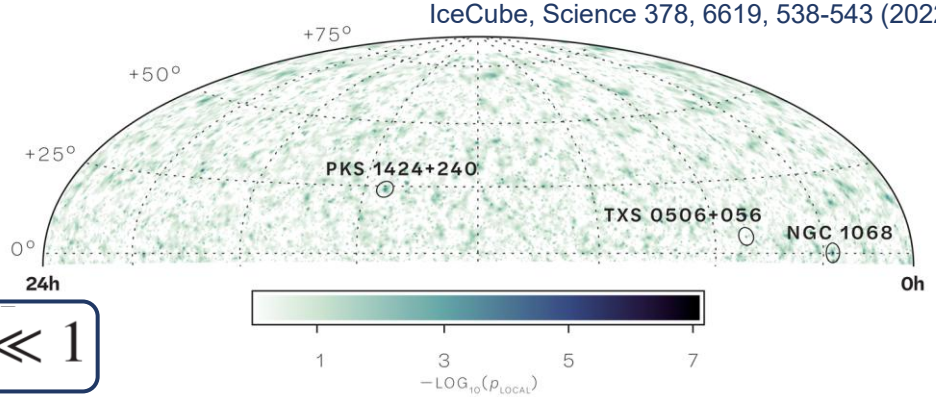
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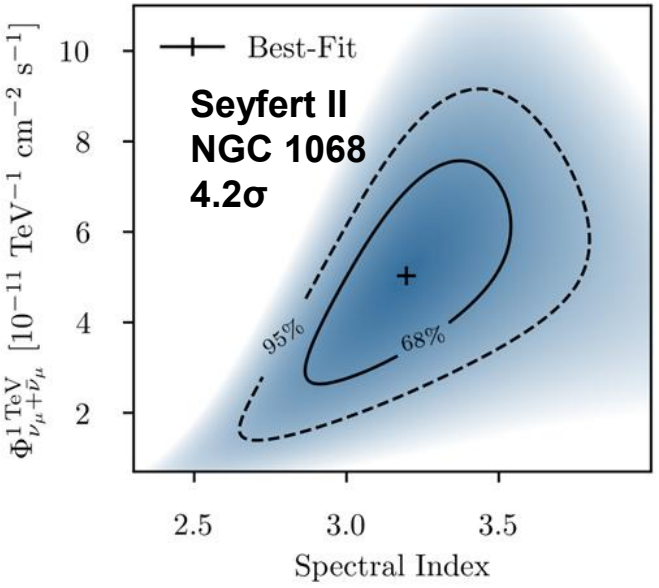
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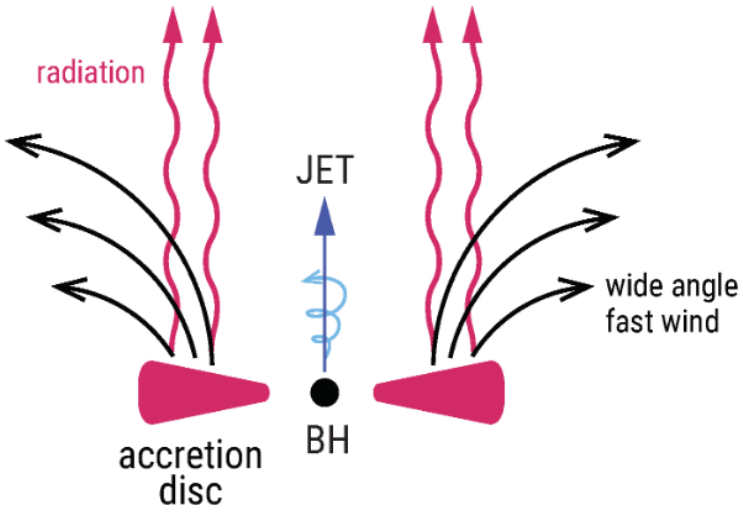
Cosmic neutrino background

$$n_\nu - n_{\bar{\nu}} \sim \mathcal{O}(5)\ \mathrm{cm}^{-3}$$

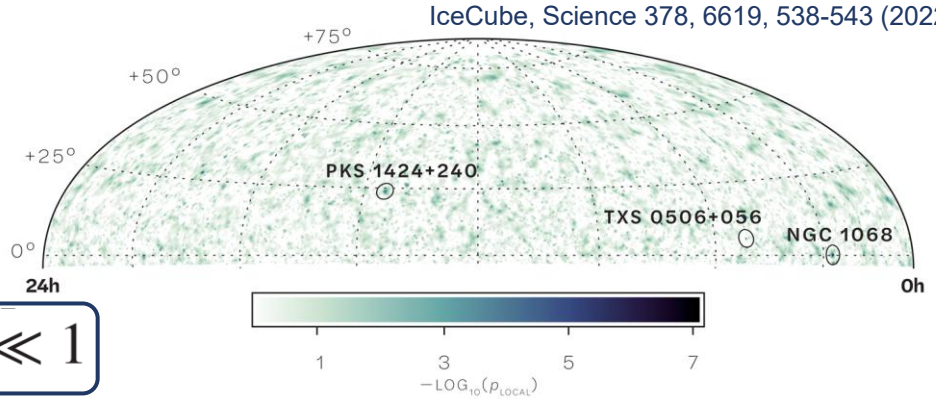
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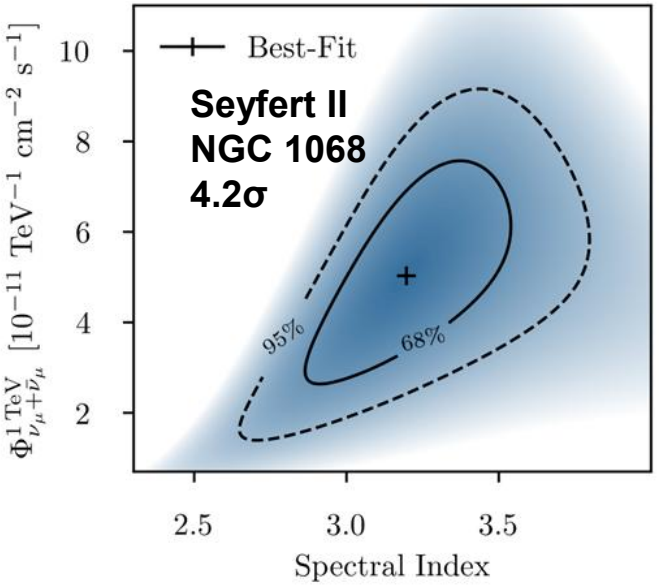
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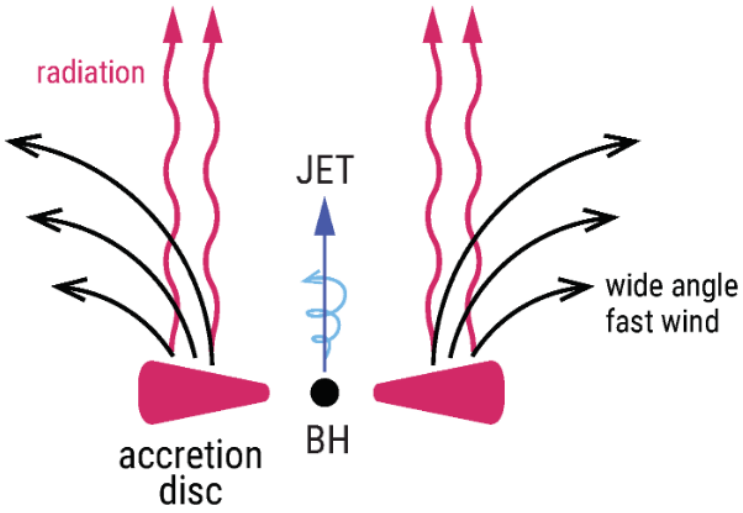
$$M = 10^9 M_\odot \qquad n_\nu - n_{\bar{\nu}} \sim \mathcal{O}(5)\ \mathrm{cm}^{-3}$$

$$l \equiv r_g = 4 \times 10^{-5}\ \mathrm{pc} \qquad n_e = 10^{15}\ \mathrm{cm}^{-3}$$

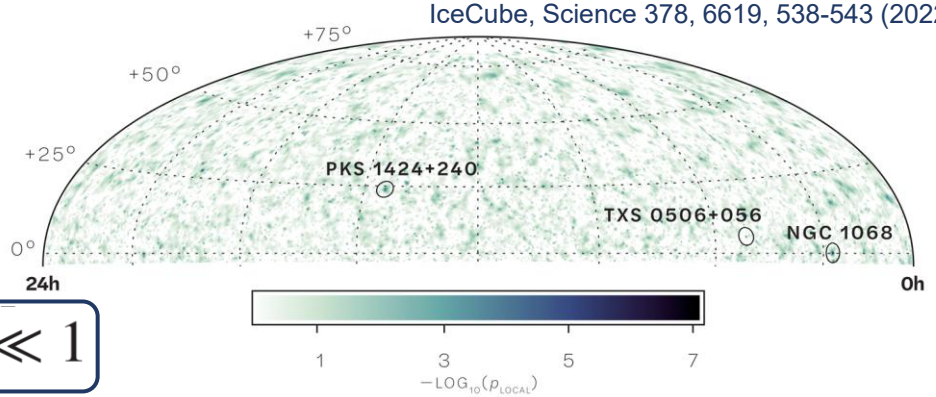
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$$l \equiv r_g = 4 \times 10^{-5}\ \mathrm{pc} \qquad n_e = 10^{15}\ \mathrm{cm}^{-3}$$

At X-ray frequencies

$$\phi_\mathrm{d} \sim 10^{-35}\ \mathrm{rad}$$

Largest neutrino induced polarization-rotation angle reported in the literature.

Hyperaccreting stellar-mass black hole

Preliminary results

Neutrino dominated accretion flows (NDAF)

NDAF extreme conditions:
Hyperaccreting stellar-mass black hole

Popham et al, Astrophys.J.518, 356-374,(1999)
Ramesh Narayan et al, Astrophys.J. 557, 949 (2001)
Di Matteo et al, Astrophys.J. 579, 706-715 (2002)
Chen and Beloborodov, Astrophys.J.657, 383-399 (2007)

$$M = 3\,M_\odot$$
$$\dot{M} \sim 10^{-3}\text{–}10\,M_\odot\,\mathrm{s}^{-1}$$
$$n_b \simeq \rho/m_p \sim 10^{32}\text{–}10^{37}\,\mathrm{cm}^{-3}$$
$$T \sim 10^{10}\text{–}10^{11}\,\mathrm{K}$$
$$n_e \sim 10^{33}\text{–}10^{36}\,\mathrm{cm}^{-3}$$

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Neutrino dominated accretion flows (NDAF)

NDAF extreme conditions:
Hyperaccreting stellar-mass black hole

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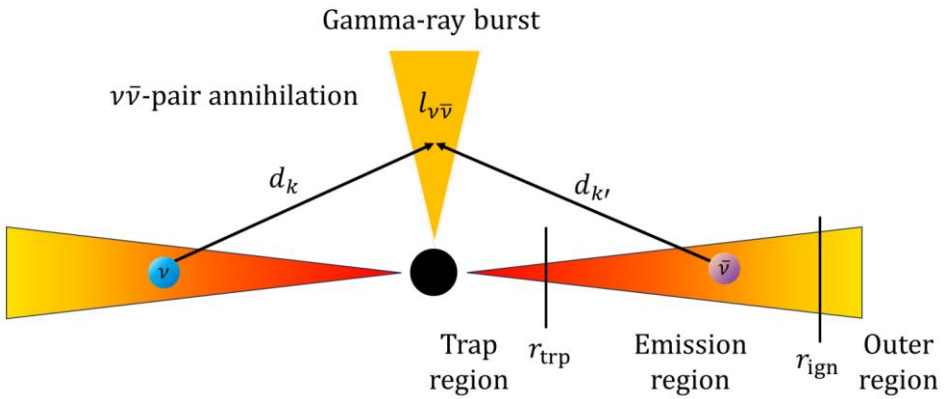
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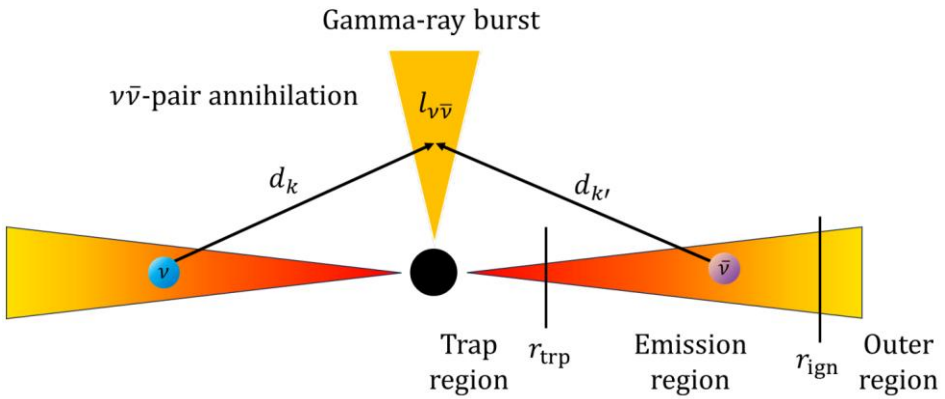
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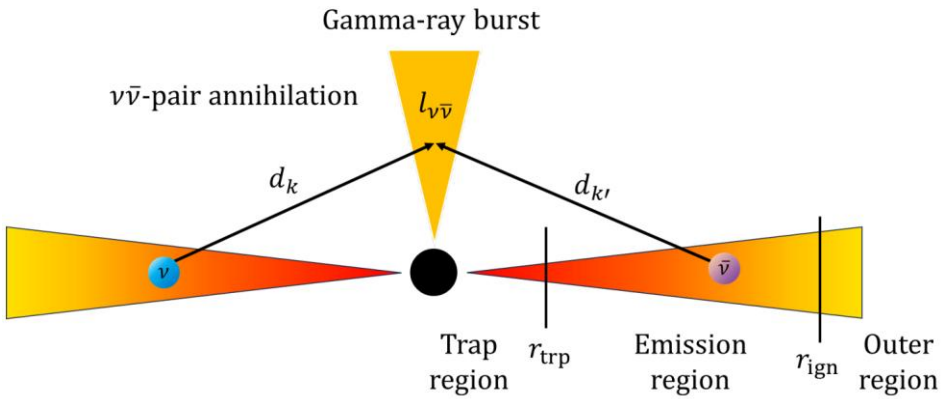
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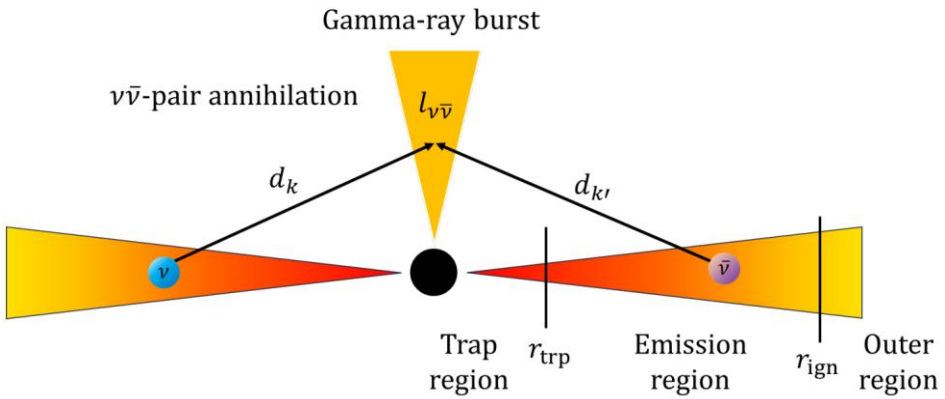
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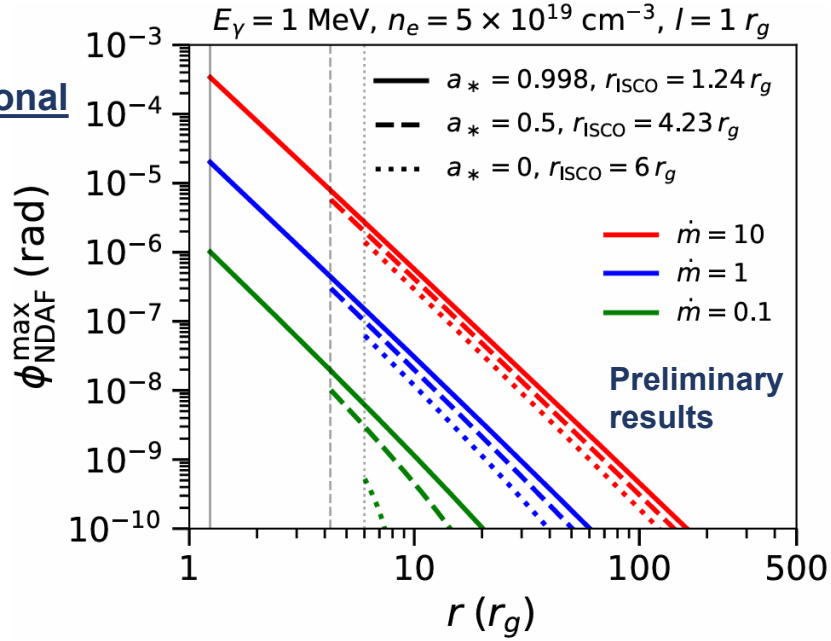
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Enchanced effect !

$$\phi^{\mathrm{max}}_{\mathrm{NDAF}} \sim 10^{-6} - 10^{-3}\ \mathrm{rad}$$

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Thank you !