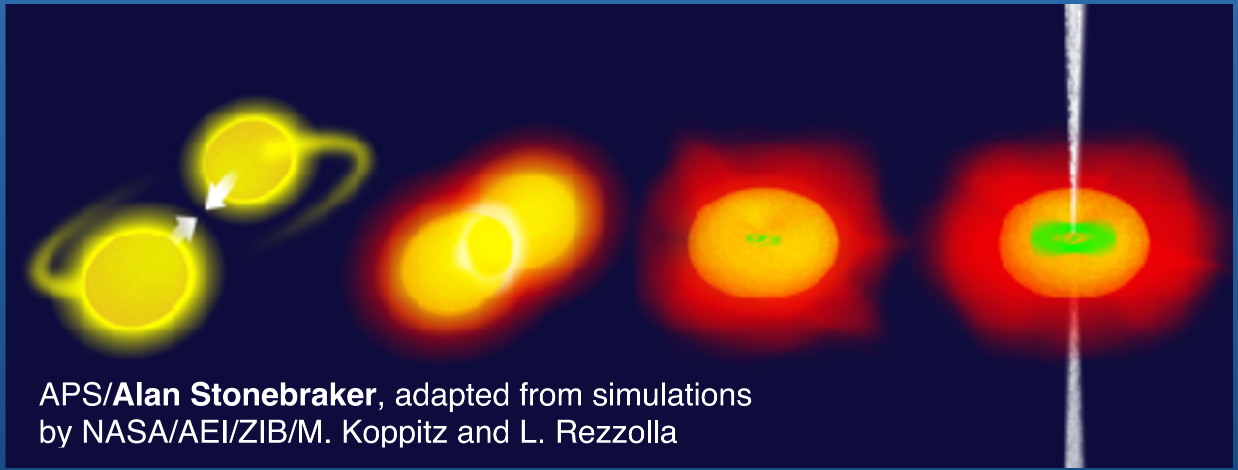
Wakefield Acceleration in a Jet from a NDAF around a BH

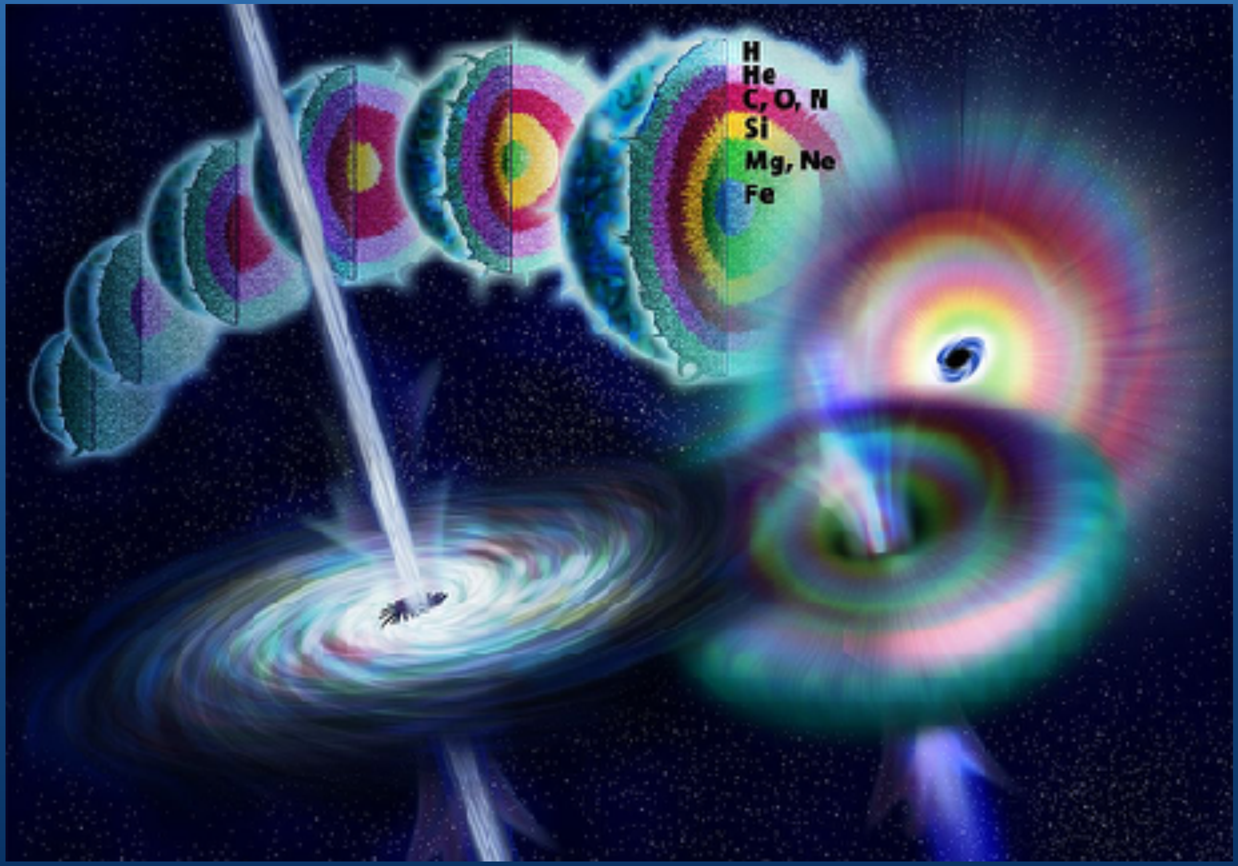
NDAF = Neutrino Driven Accretion Flow

Merging NS-NS



Taken from an article on October 16, 2017 *Physics* 10, 114 by Maura McLaughlin

Collapsing massive stars



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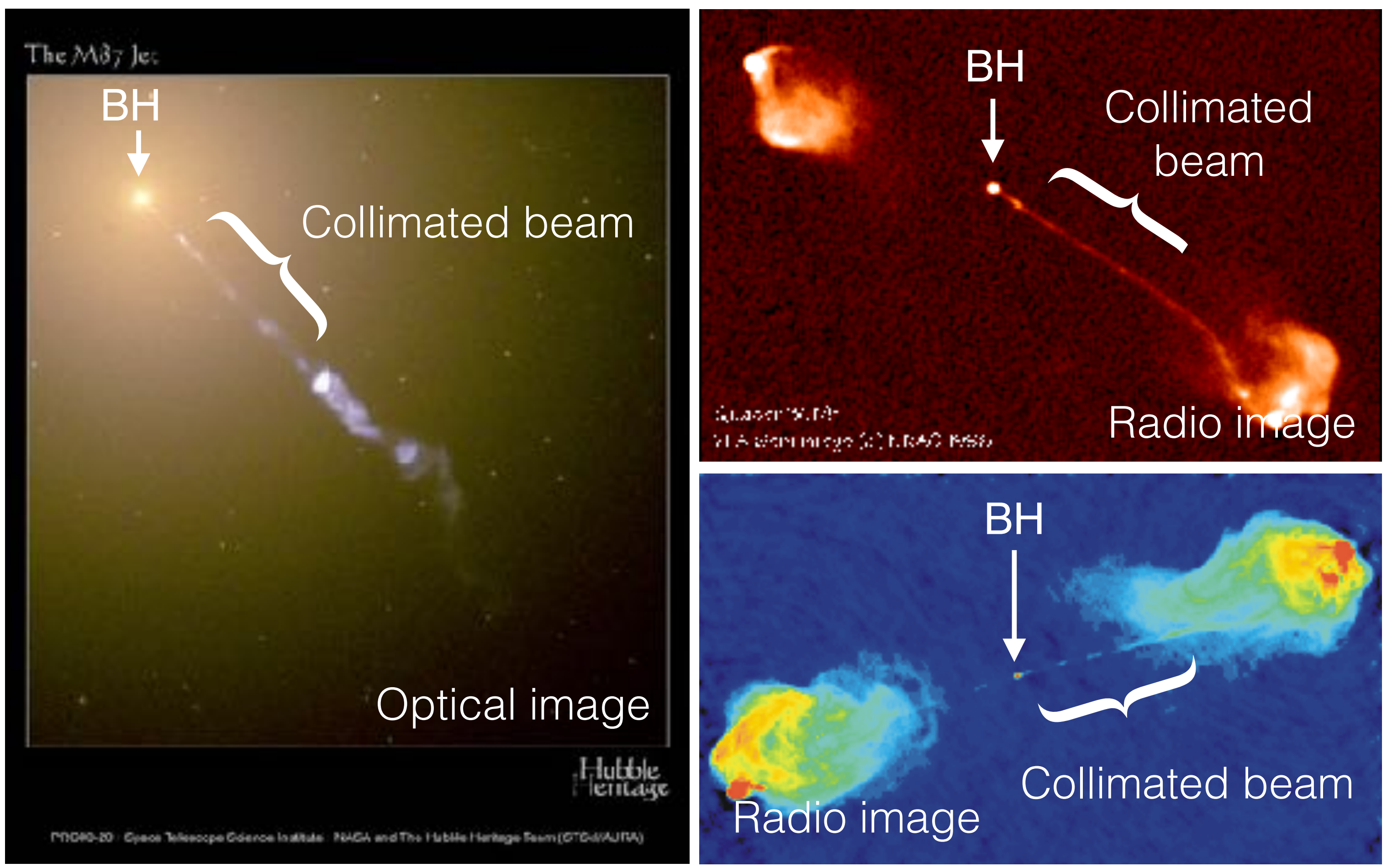
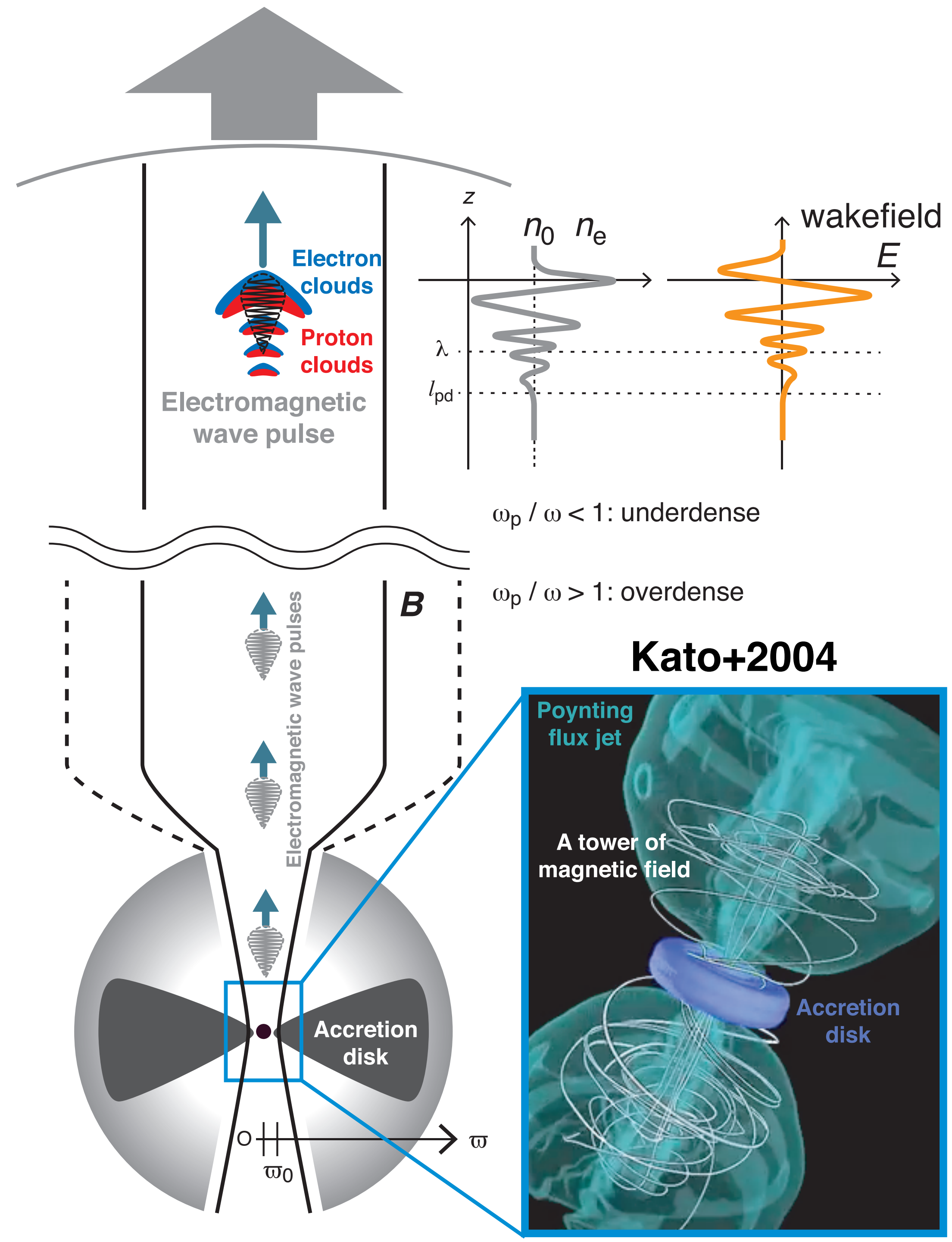
Astrophysical Wakefield Acceleration

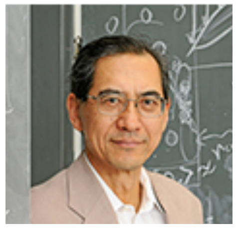
Ebisuzaki & Tajima 2014; Tajima, Nakajima, and Mourou 2017; Ebisuzaki & Tajima 2019

Astrophysical jets = Collimated beams



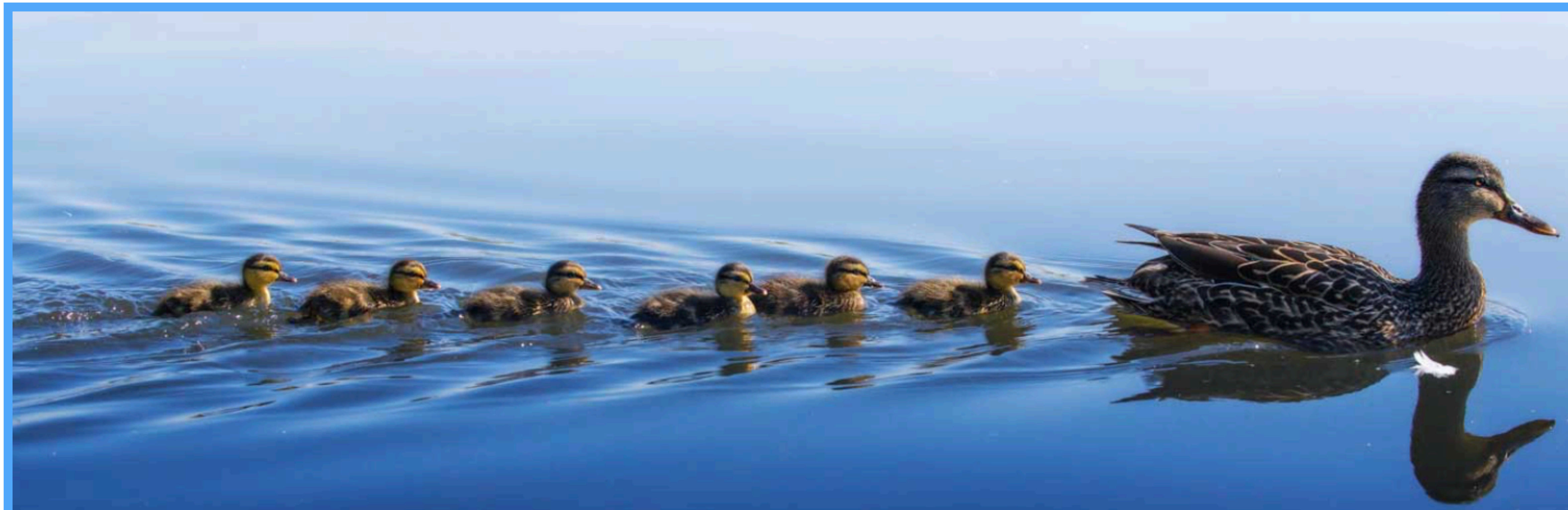
The largest structure in the Universe!





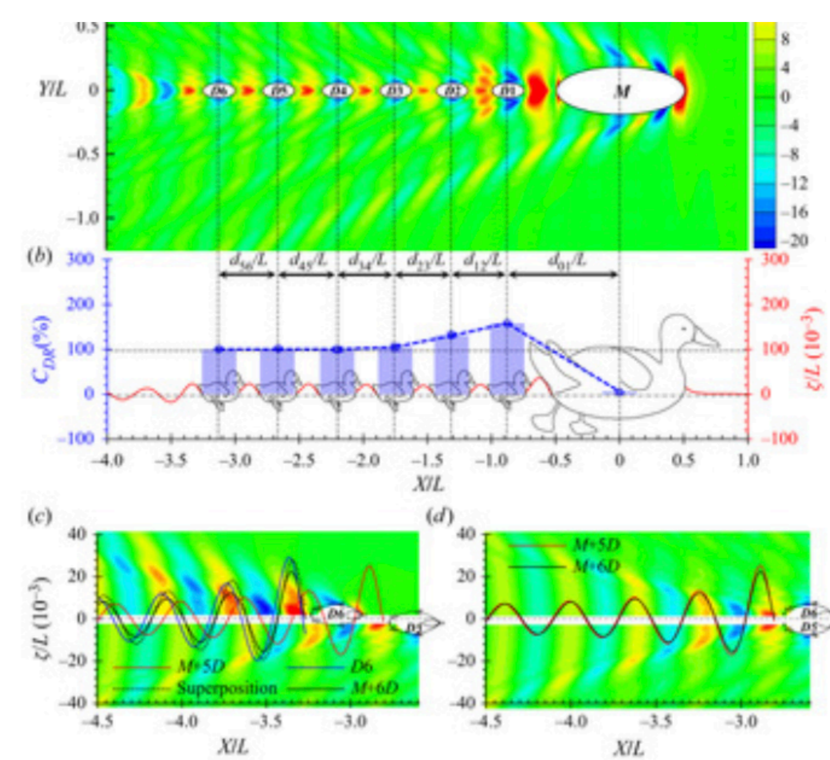
Wake acceleration

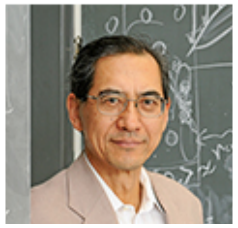
Prof. Tajima’s lecture “Plasma Accelerator Physics” (PHY249) at UCI



Bow wake and stern wake
Nature (or mother duck) shows us.

Yuan+2021



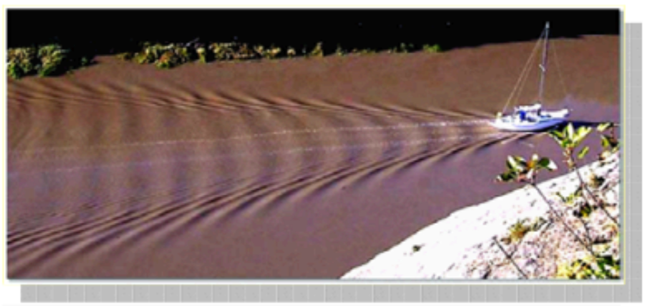


Laser wakefield acceleration

Prof. Tajima’s lecture “Plasma Accelerator Physics” (PHY249) at UCI

Wake

Kelvin’s Ship Wake



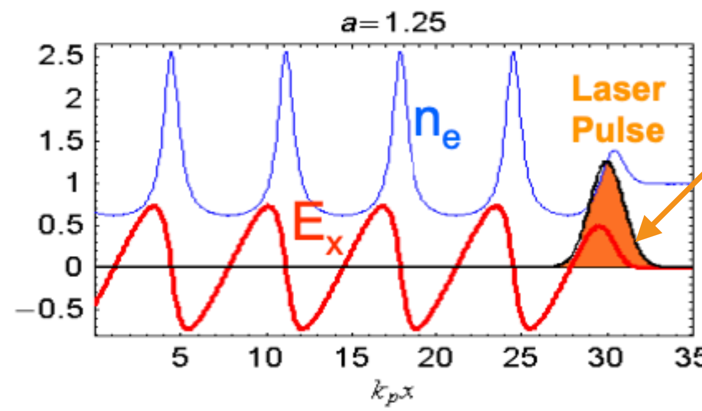
$$\omega = \sqrt{kg}$$

$$x = X_1 \cos\theta \left(1 - \frac{1}{2}\cos^2\theta\right)$$

$$y = X_1 \cos^2\theta \sin\theta$$

$$-\pi/2 < \theta < \pi/2$$

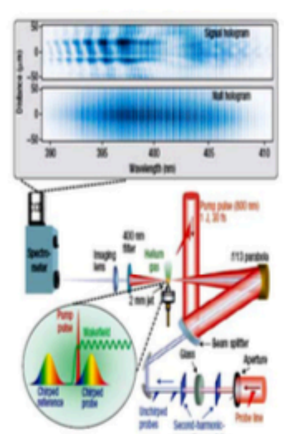
Laser Plasma Wake



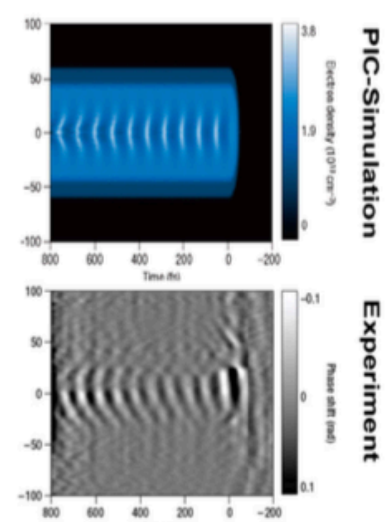
$$\lambda_p = 2\pi / k_p \qquad k_p v_{ph} = \omega_{pe}$$

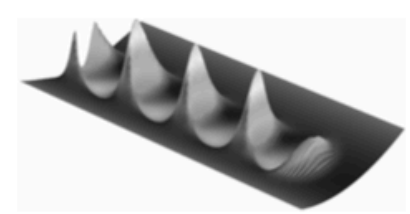
$$\omega_{pe} = \left(4\pi n e^2 / m_e\right)^{1/2}$$

Snapshots of Laser Wake Waves



Experiment setup





Paraboloidal Form of the Wake

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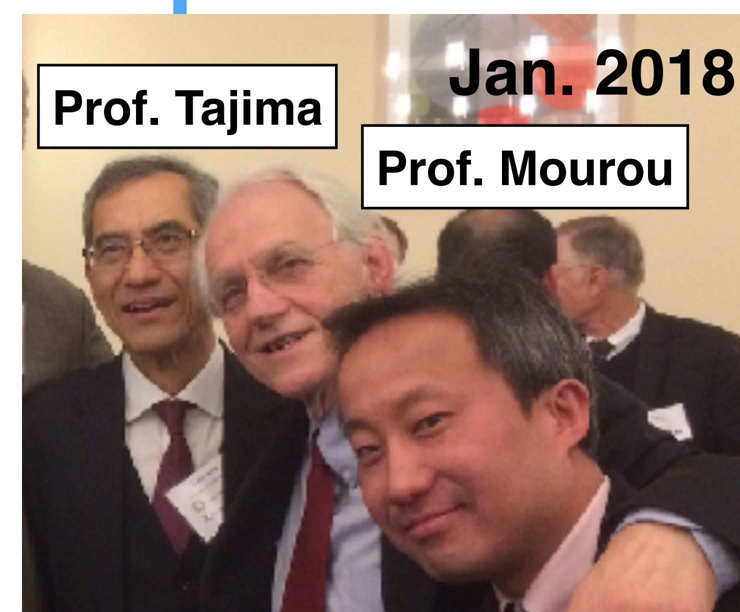
N. H. Matlis et al, Nature Phys. (2006)

Chirped Pulse Amplification (CPA)



Analytical Solution of NDAF disks

Previous studies: Popham+1999; Di Matteo+2002; Kawanaka+2013

- Standard Accretion Disk Model (Shakura & Sunyaev1973)

$$\dot{M} = -2\pi\varpi\Sigma(\varpi)v_{\varpi}(\varpi) = \mathrm{const.}, \qquad Q_{\mathrm{vis}}(\varpi) = \frac{3\dot{M}}{4\pi}\Omega_{\mathrm{K}}^{2}(\varpi).$$

$$\dot{M}\varpi^{2}\Omega_{\mathrm{K}}(\varpi) = -2\pi\varpi^{2}\mathcal{S}_{\varpi\varphi} + \mathrm{const.}, \qquad \mathcal{F}_{\nu}(\varpi) = Q_{\nu}(\varpi)/2 = \frac{3\dot{M}}{8\pi}\Omega_{\mathrm{K}}^{2}(\varpi). \qquad \epsilon_{0}(\varpi) = \frac{3}{4}\frac{\mathcal{F}_{\nu}(\varpi)}{c}\bar{\kappa}_{\nu}(\varpi)\Sigma(\varpi)$$

- Energy density and temperature (Di Matteo+ 2002)

$$\epsilon_{0}(\varpi) = (11/4)aT_{0}^{4}(\varpi) + (7/8)aT_{0}^{4}(\varpi) = (29/8)aT_{0}^{4}(\varpi)$$

- Rosseland mean opacity of neutrino (Bahcall 1964)

$$\bar{\kappa}_{\nu}(\varpi) = \kappa_{\nu 0}\left(\frac{k_{\mathrm{B}}T_{0}(\varpi)}{m_{\mathrm{e}}c^{2}}\right)^{2} \quad \text{where } \kappa_{\nu 0} = 5.22\times 10^{-20}\,\mathrm{cm^{2}g^{-1}} \text{ for } k_{\mathrm{B}}T_{0}(\varpi) \gg m_{\mathrm{e}}c^{2}$$

- Magnetic field strength is determined by plasma-β

$$\beta \equiv p_{0}(\varpi)/p_{0,\mathrm{mag}}(\varpi)$$

Properties of NDAFs

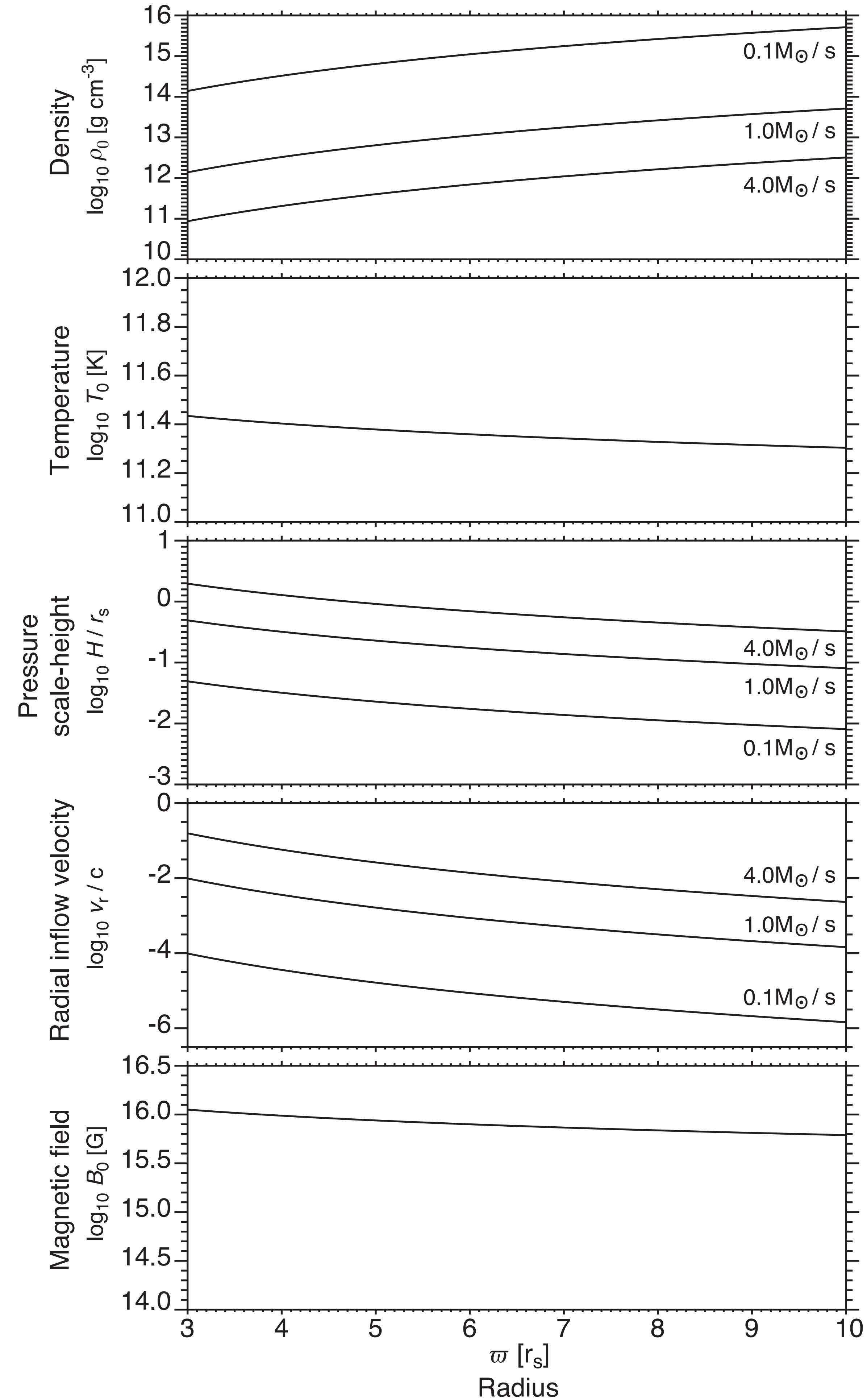
- Magnetic field strength

$$B_0(\varpi) = \left(\frac{8\pi}{3\beta}\right)^{1/2} \left(\frac{58\pi^3 a m_e^4 c^{10}}{\alpha^2 \kappa_{\nu 0}^2 k_B^4}\right)^{1/6} \Omega_K^{1/3}(\varpi)$$
$$= 1.95 \times 10^{16} \left(\frac{\beta}{10}\right)^{-1/2} \left(\frac{\alpha}{0.1}\right)^{-1/3} \left(\frac{M}{M_\odot}\right)^{-1/3} \left(\frac{\varpi}{r_s}\right)^{-1/2} \; [\mathrm{G}].$$

- Neutrino luminosity

$$L_\nu = \int_{\varpi_{in}}^{\infty} 2\mathcal{F}_\nu(\varpi) 2\pi\varpi d\varpi = \frac{3\dot{M}}{2}\frac{GM}{\varpi_{in}} = \frac{1}{4}\dot{M}c^2$$
$$= 4.47 \times 10^{53} \left(\frac{\dot{M}}{\dot{M}_\odot}\right) \; [\mathrm{erg\,s^{-1}}].$$

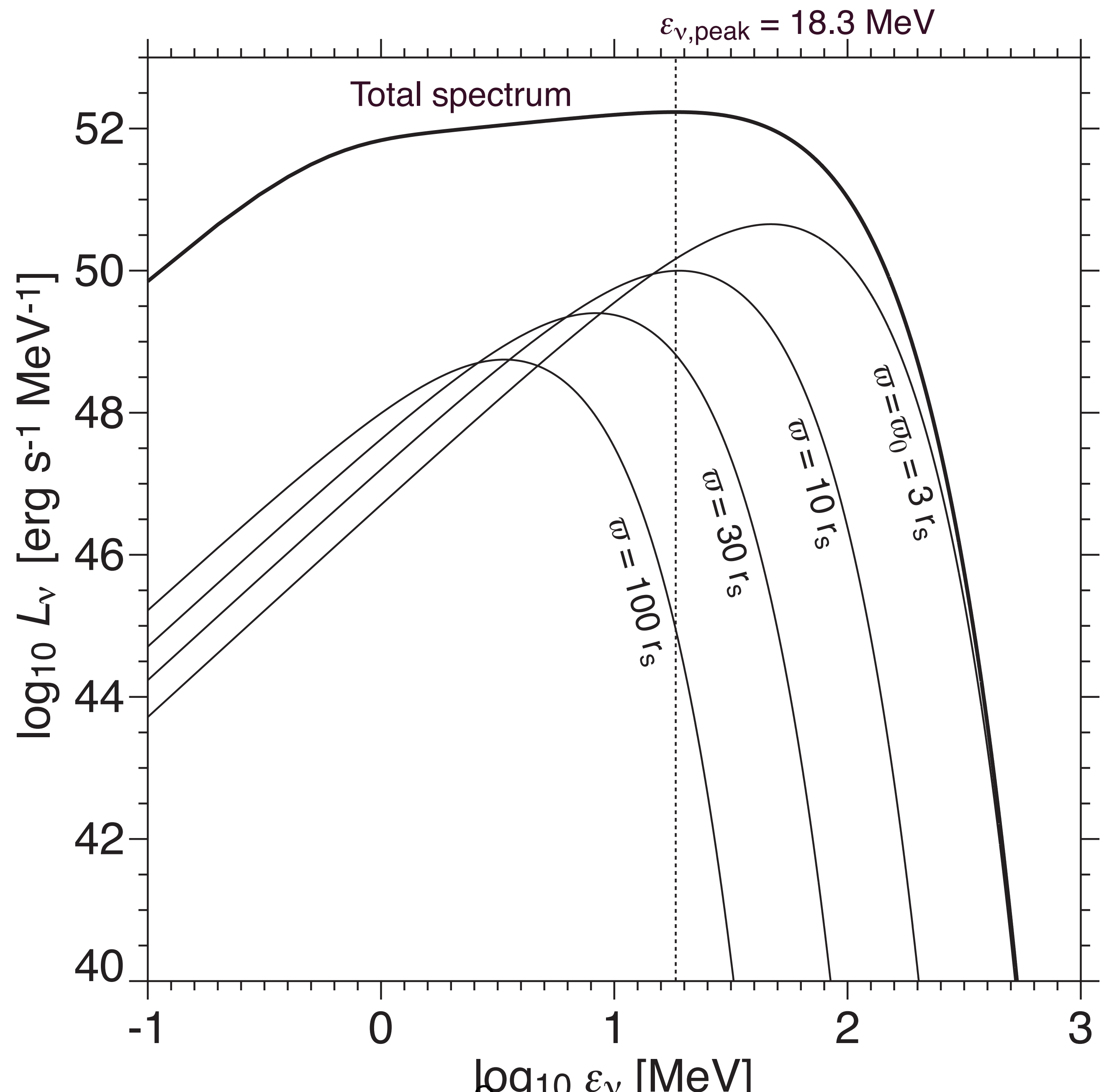
Our model is consistent with Kawanaka+2013



Neutrino spectra of NDAF disks

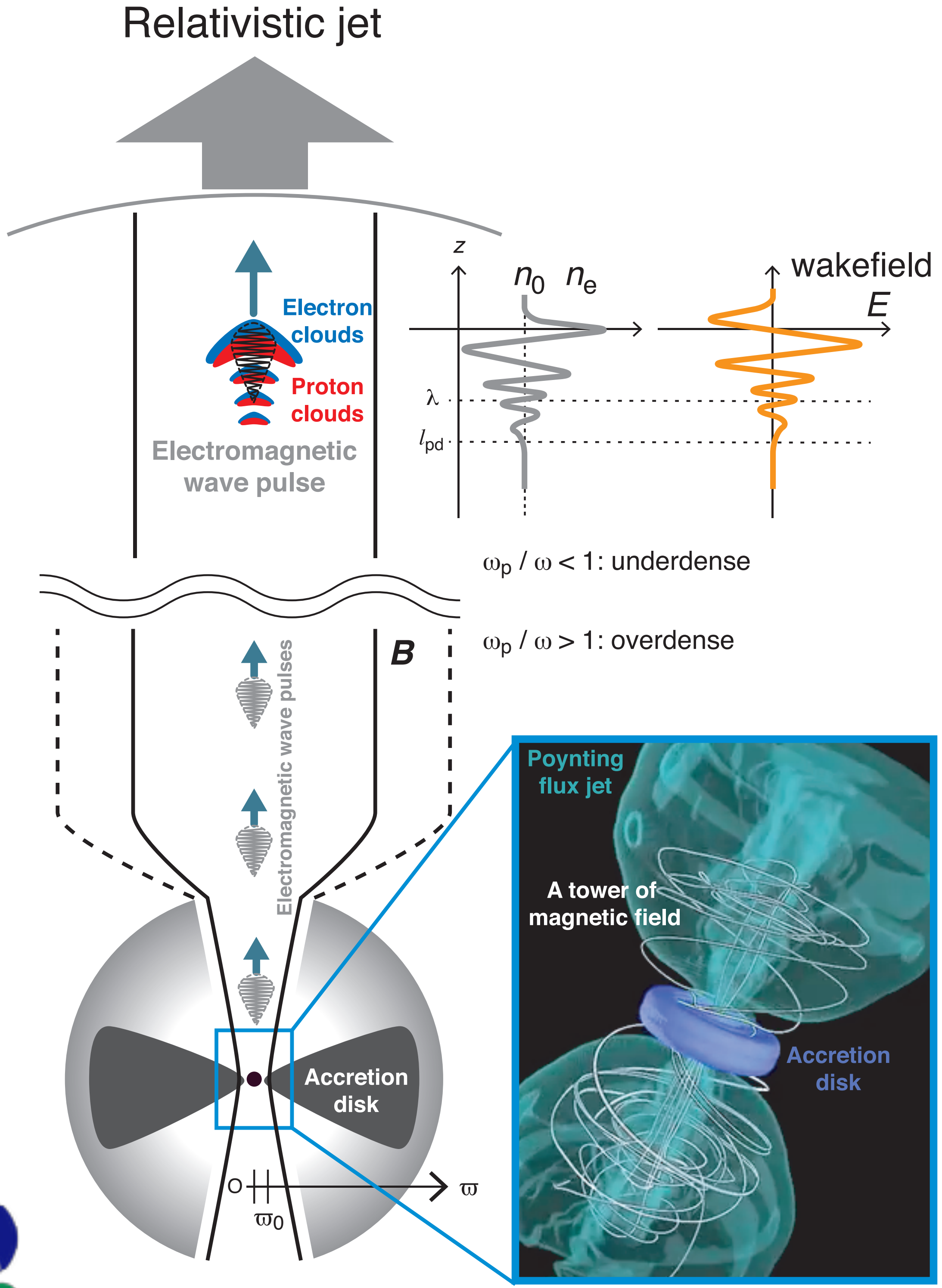
$$\mathcal{B}_\nu(\varepsilon_\nu, T_\nu(\varpi)) = \frac{4\varepsilon_\nu^3/h^3c^2}{\exp\left[\left(\varepsilon_\nu - \mu_\nu\right)/k_\mathrm{B}T_\nu(\varpi)\right] + 1}.$$

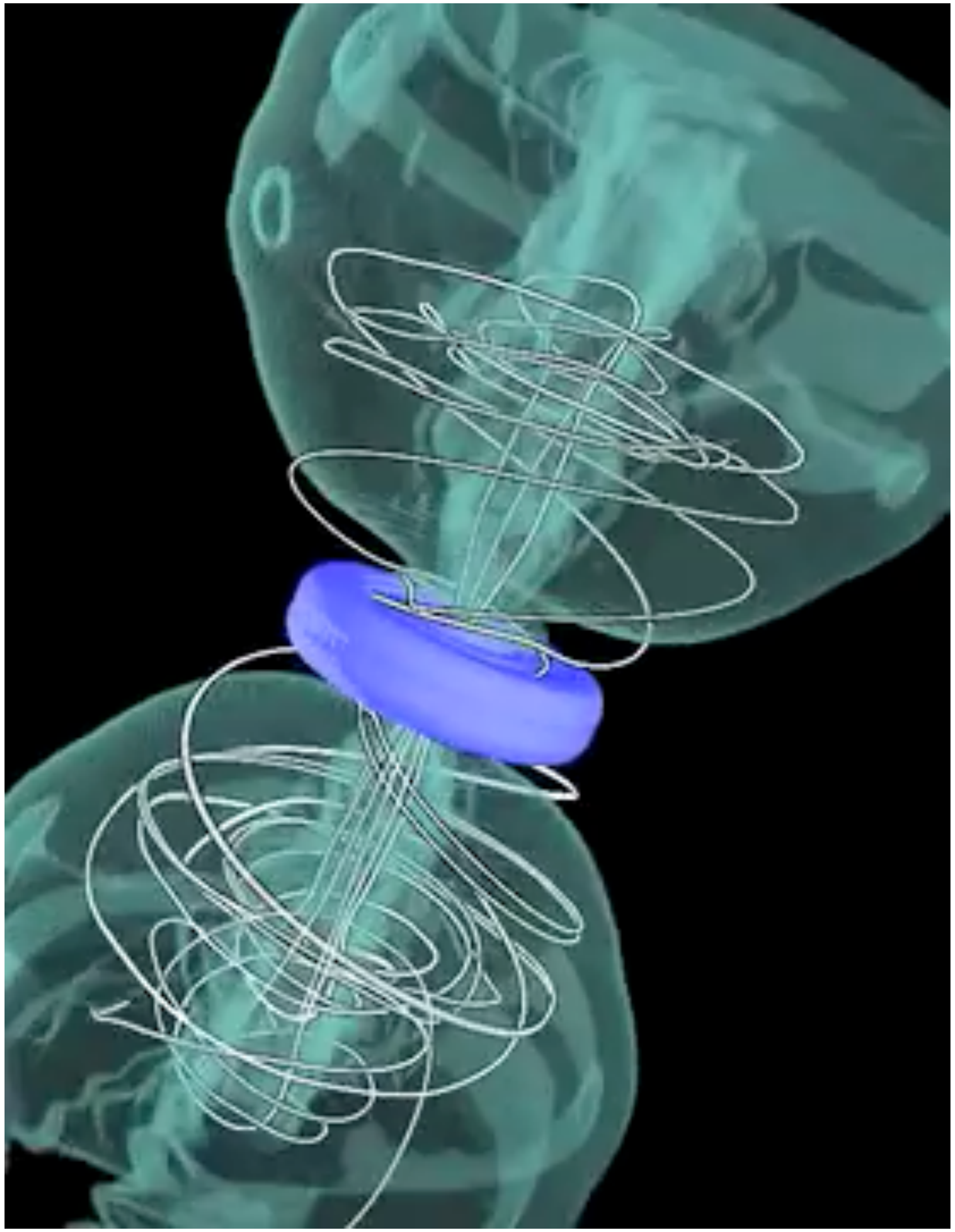
$$L_\nu(\varepsilon_\nu) = 4\pi^2\mathcal{B}_\nu(\varepsilon_\nu, T_\nu(\varpi))\varpi d\varpi \qquad \mathcal{F}_\nu(\varpi) = (7/8)aT_\nu^4(\varpi)$$



Magnetic tower

Lynden-Bell 1996; Kato, Mineshige, and Shibata 2004





Properties of jets at the base

- Magnetic field strength at the base

$$B_0(\varpi) = \left(\frac{8\pi}{3\beta}\right)^{1/2}\left(\frac{58\pi^3 a m_e^4 c^{10}}{\alpha^2\kappa_{\nu 0}^2 k_B^4}\right)^{1/6}\Omega_K^{1/3}(\varpi)$$
$$= 1.95\times 10^{16}\left(\frac{\beta}{10}\right)^{-1/2}\left(\frac{\alpha}{0.1}\right)^{-1/3}\left(\frac{M}{M_\odot}\right)^{-1/3}\left(\frac{\varpi}{r_s}\right)^{-1/2}\ [\mathrm{G}].$$

- Neutrino luminosity

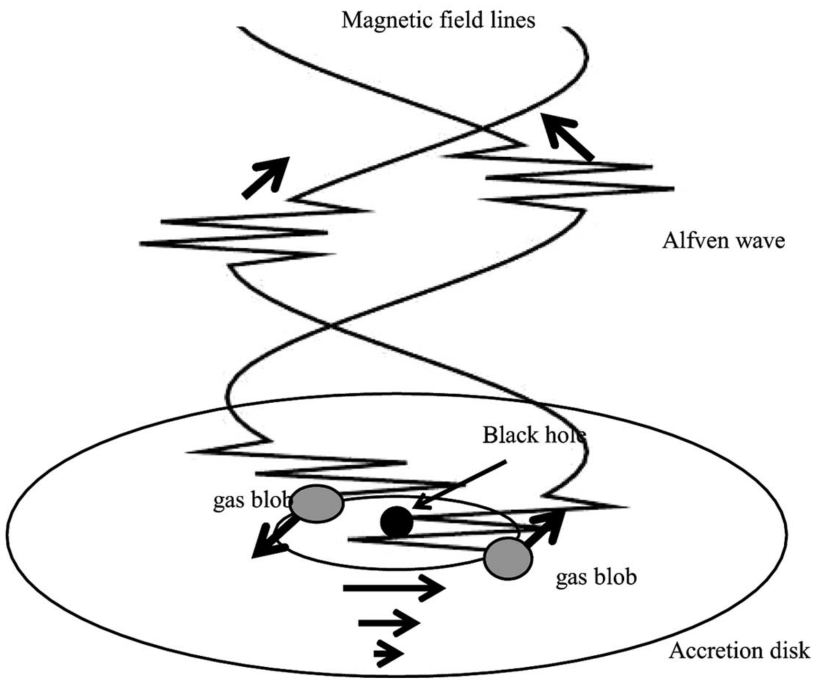
$$L_\nu = \int_{\varpi_{in}}^{\infty} 2\mathcal{F}_\nu(\varpi)2\pi\varpi d\varpi = \frac{3\dot{M}}{2}\frac{GM}{\varpi_{in}} = \frac{1}{4}\dot{M}c^2$$
$$= 4.47\times 10^{53}\left(\frac{\dot{M}}{\dot{M}_\odot}\right)\ [\mathrm{erg\,s^{-1}}].$$

- Luminosity of EM wave pulses

$$L_{wave} = \int_{\varpi_{in}}^{\infty} 2\mathcal{F}_{wave}(\varpi)2\pi\varpi d\varpi = \frac{\dot{M}}{\alpha}\left(\frac{2}{\beta^3}\right)^{1/2}\left(\frac{GM}{\varpi_{in}}\right) = \left(\frac{1}{18\alpha^2\beta^3}\right)^{1/2}\dot{M}c^2$$
$$= 1.33\times 10^{53}\left(\frac{\beta}{10}\right)^{-3/2}\left(\frac{\alpha}{0.1}\right)^{-1}\left(\frac{\dot{M}}{\dot{M}_\odot}\right)\ [\mathrm{erg\,s^{-1}}].$$

- The wakefield strength parameter

$$a_0(\varpi) = 5.19\times 10^{17}\left(\frac{\beta}{10}\right)^{-5/4}\left(\frac{\alpha}{0.1}\right)^{-4/3}\left(\frac{\dot{M}}{\dot{M}_\odot}\right)^{3/2}\left(\frac{M}{M_\odot}\right)^{-4/3}\left(\frac{\varpi}{r_s}\right)^{-2}.$$



Ebisuzaki & Tajima 2014

$$E_0(\varpi) = \sqrt{\frac{4\pi\mathcal{F}_{wave}(\varpi)}{c}}.$$

the amplitude of the vector potential

$$A_0 \equiv cE_0(\varpi)/\omega$$

$$a_0 = eA_0/m_e c^2$$

Properties of jets

- Radius of the jet has either a parabolic-shape or a conical-shape

$$R(\varpi_0, z) = \varpi_0 \left[1 + (z/\varpi_0)^{\phi}\right]$$

- Area of the jet

$$\mathcal{A}(z) = \pi R^2(\varpi_0, z)$$

- Magnetic field strength

$$B(z) = B_0 \mathcal{A}(0)/\mathcal{A}(z).$$

- Number density

$$L_{\rm kinetic} = n_{\rm p} \mu m_{\rm p} c^3 \Gamma^2 \mathcal{A}(z) = \xi L_\nu \qquad \xi = 0.1.$$

we set $\Gamma = 200$ is the jet bulk Lorentz factor (Ghirlanda et al. 2018)

- The wakefield strength parameter

$$a(z) = a_0 \sqrt{\mathcal{A}(0)/\mathcal{A}(z)} \gg 1.$$

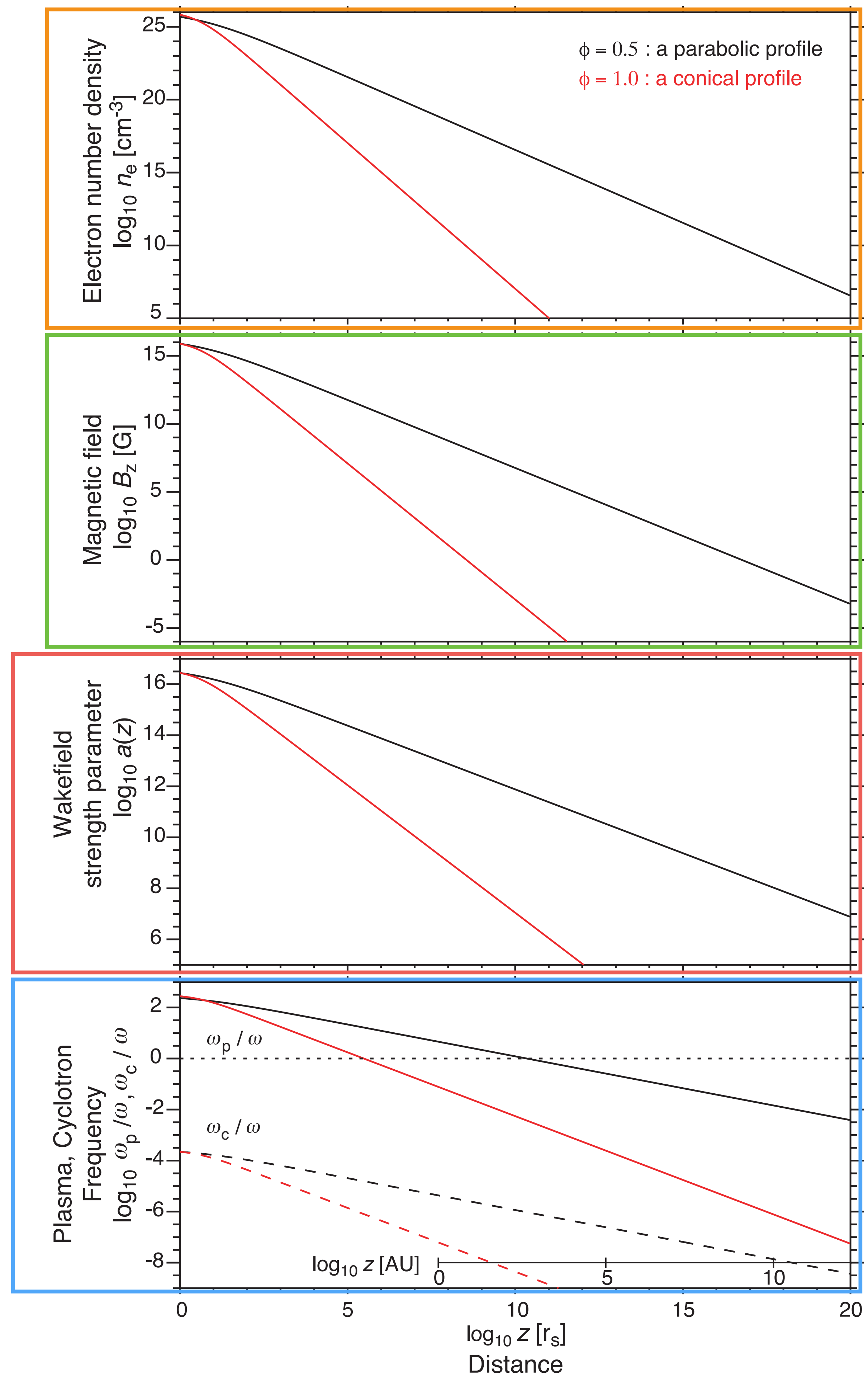
- Propagation region

$\omega_{\rm p}/\omega > 1$: overdense

$\omega_{\rm p}/\omega < 1$: under-dense

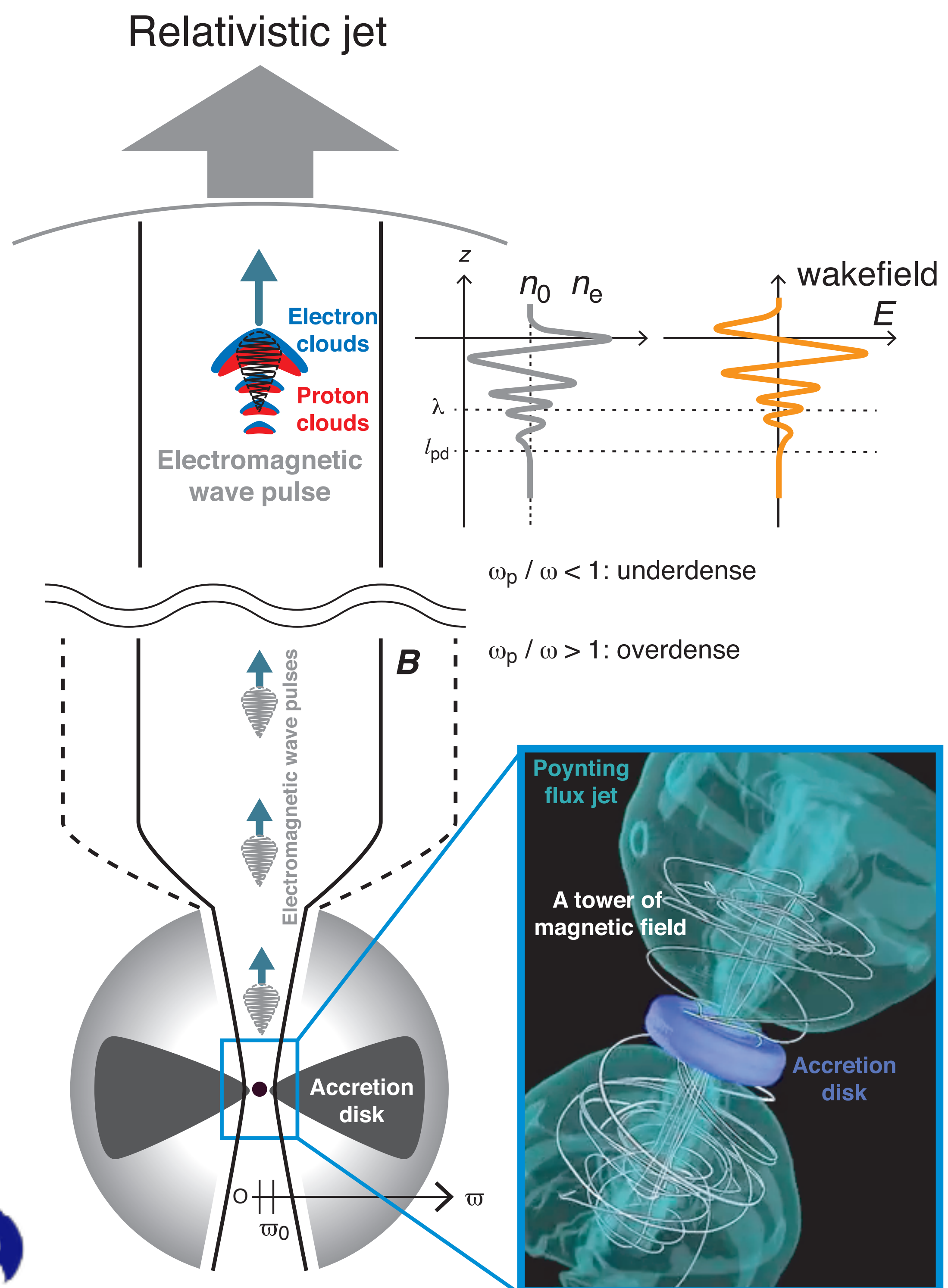
$$\omega^2 = \omega_{\rm p}^2 + k^2 c^2$$

the generation of wakefield by EM wave pluses



The wakefield acceleration in the jets

Kato, Ebisuzaki, & Tajima in prep.



Our assumptions

Z

Tajima & Dawson 1979; Tajima+2017

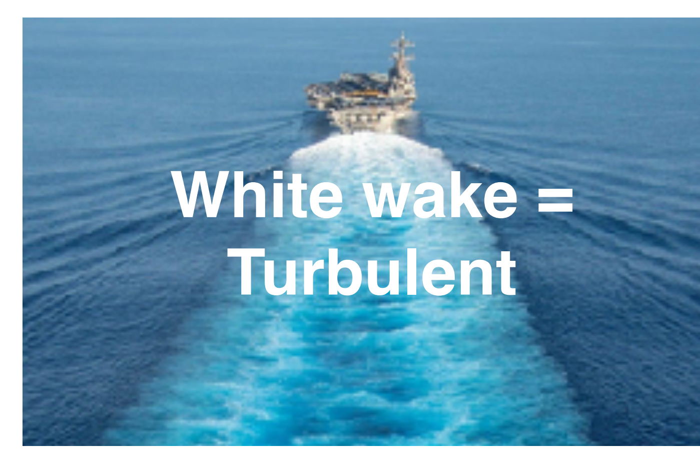
Wakefield force: $F_\mathrm{w} = \mathcal{Z}\Gamma m_\mathrm{e} a(z)\omega_\mathrm{p}(z)c$

Acceleration distance:

$$\Delta z_\mathrm{w} = l_\mathrm{pd}/2 = \sqrt{2}c\left[\omega_0^2/\omega_\mathrm{p}^3(z_\mathrm{w})\right]a(z_\mathrm{w})$$

Acceleration site: z_w

z= 0



Maximum energy gained for a proton

- The wakefield force (Tajima+2017)

$$F_{\rm w} = \mathcal{Z}\Gamma m_{\rm e} a(z)\omega_{\rm p}(z)c.$$

- Maximum energy of a proton

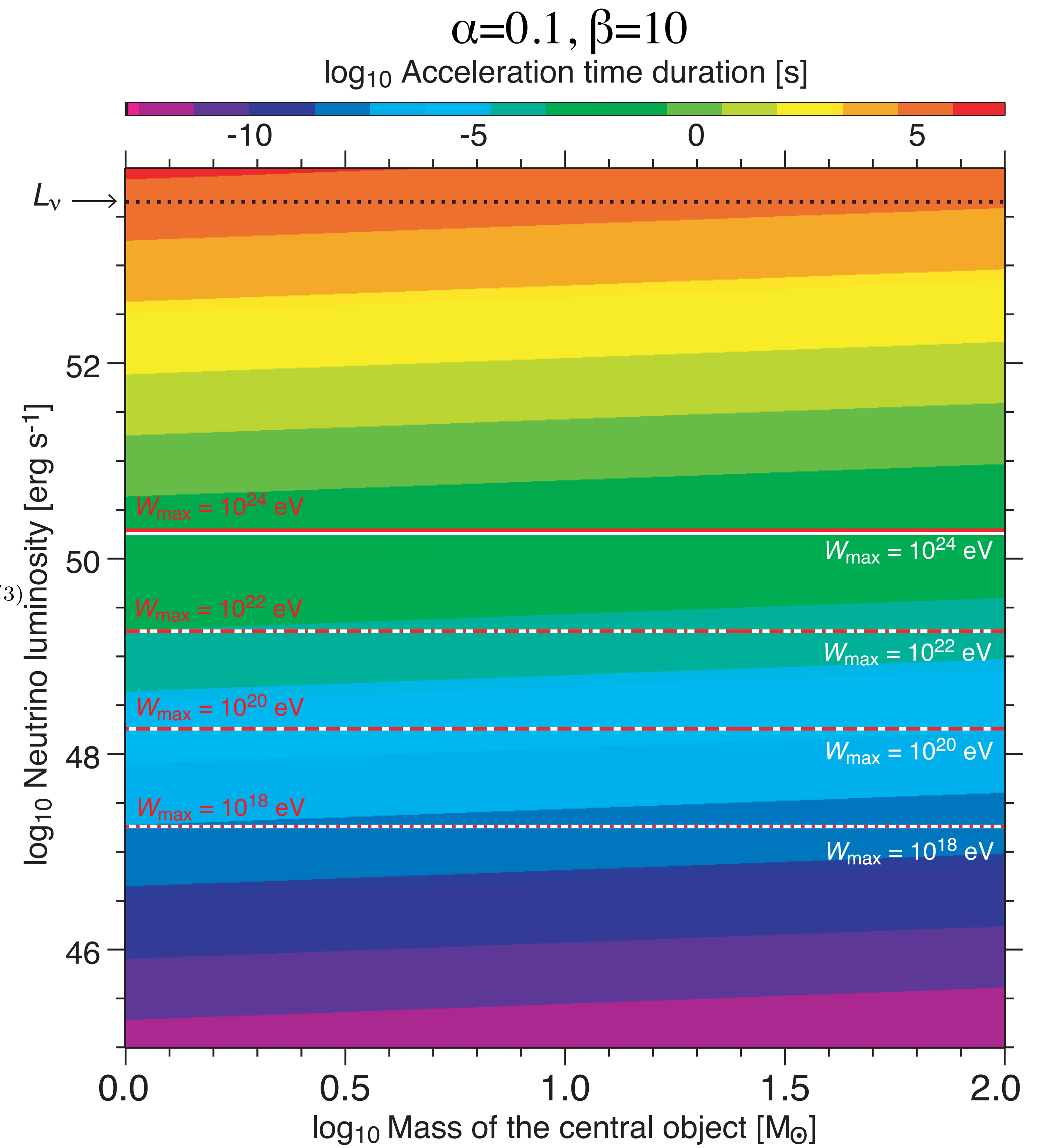
$$\mathcal{W}_{\rm max} = \int_{z_{\rm w}}^{z_{\rm w}+\Delta z_{\rm w}} F_{\rm w} dz = \mathcal{Z}\Gamma m_{\rm e} c \int_{z_{\rm w}}^{z_{\rm w}+\Delta z_{\rm w}} \omega_{\rm p}(z) a(z) dz.$$

the acceleration distance $\Delta z_{\rm w} = l_{\rm pd}/2 = \sqrt{2}c\left[\omega_0^2/\omega_{\rm p}^3(z_{\rm w})\right] a(z_{\rm w})$
where $z_{\rm w}$ is the acceleration point on which the plasma becomes the underdense condition $(\omega > \omega_{\rm p})$ from the overdense condition $(\omega < \omega_{\rm p})$

$$\mathcal{W}_{\rm max} = \mathcal{W}_0\phi_0^{-1}\left[(z_{\rm w}+\Delta z_{\rm w})^{\phi_0} - z_{\rm w}^{\phi_0}\right]\left(\frac{c^2}{6}\right)^{\phi_0+1}\dot{M}^{3/4}(GM)^{-(\phi_0+2/3)}$$

- Relation between neutrino luminosity and maximum energy of a proton

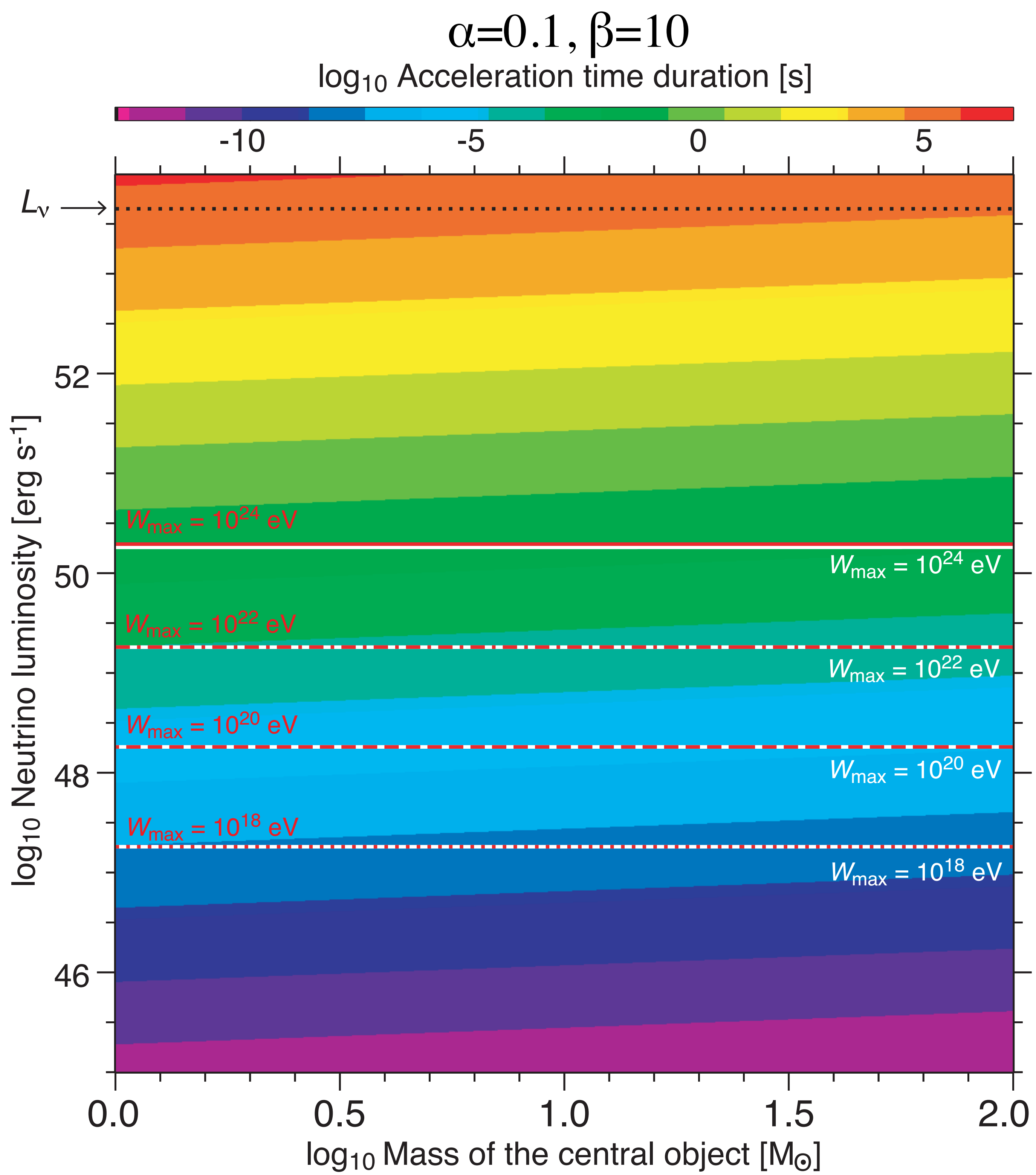
$$\mathcal{L}_\nu = \left\{\frac{2^{(\phi_0-1/2)}3^{(\phi_0+1)}c^{-(2\phi_0+1/2)}\mathcal{W}_{\rm max}(G\mathcal{M})^{(\phi_0+2/3)}}{\mathcal{W}_0\phi_0^{-1}\left[(z_{\rm w}+\Delta z_{\rm w})^{\phi_0} - z_{\rm w}^{\phi_0}\right]}\right\}^{4/3}$$

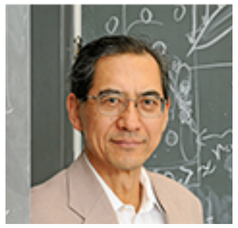


Observational signatures

which could have been detected in the future

- Charged particles < 10^{14} eV can be generated less than a pico-second (< 10^{-12} s)
  - A plausible source of gamma-ray emissions ~ 1 MeV via synchrotron radiation
- Protons of 10^{16-20} eV can be generated less than a micro-second (< 10^{-6} s)
  - A possible source of 10^{14} eV neutrinos via pion-production though photo-meson interaction (Waxman & Bahcall 1997)





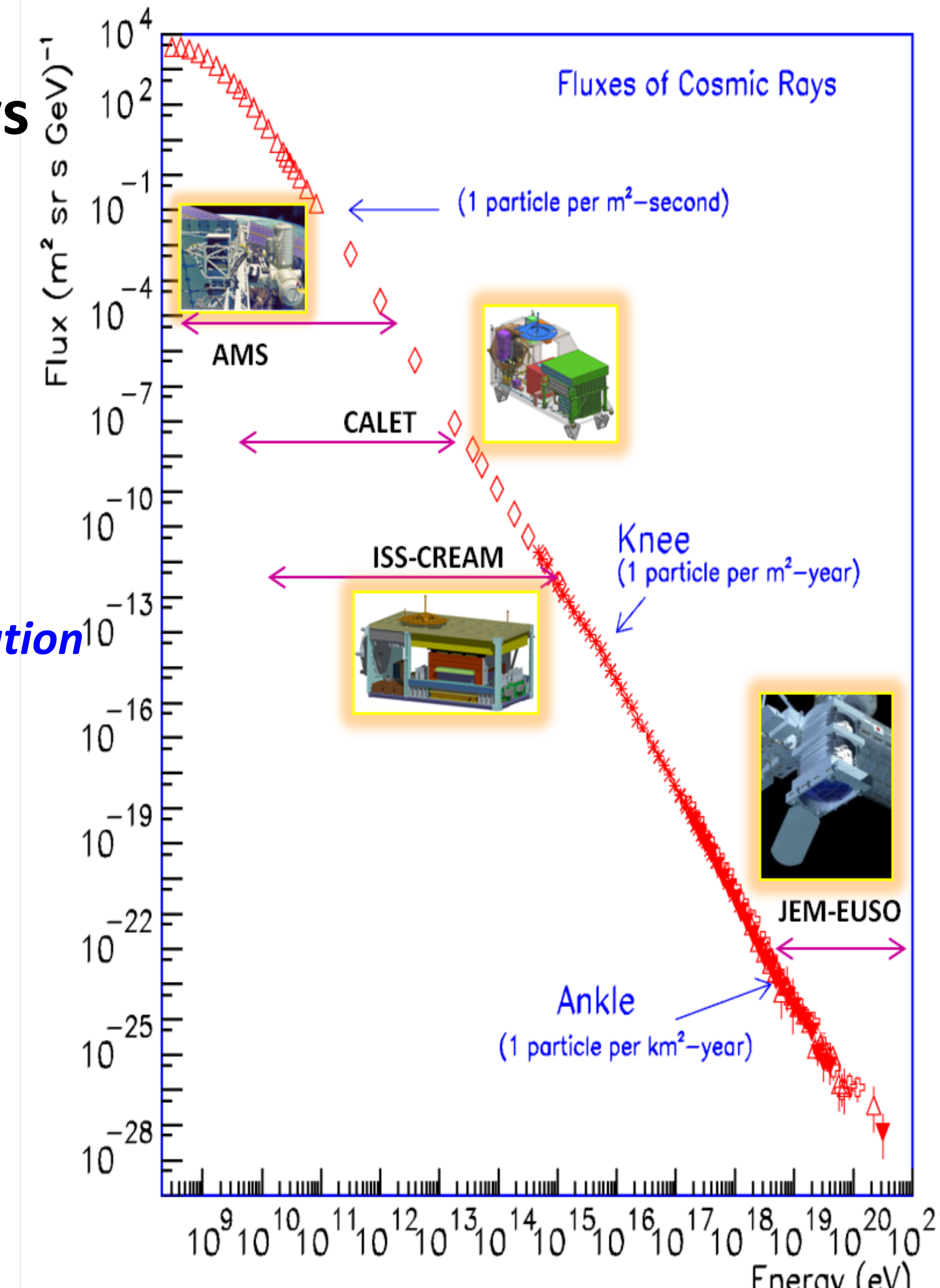
Fluxes of Cosmic Rays

Prof. Tajima’s lecture “Plasma Accelerator Physics” (PHY249) at UCI

Ultrahigh Energy Cosmic Rays (UHECR)

Fermi mechanism runs out of steam
- beyond 10^{19} eV
- due to *synchrotron radiation*

Wakefield acceleration
- comes in rescue
- prompt, intense, *linear acceleration*
- small synchrotron radiation
- radiation damping effects?



Summary

- We have demonstrated that the wakefield acceleration in the jets from NDAF as a model of GRBs.
- The wakefield acceleration postulates various observational signatures:
  - ✓ The time-variability of neutrino emissions < 100 MeV (peak ~ 20 MeV) from NDAF disks may discriminate the nature of generation of EM wave pulse,
  - ✓ The tracing of gamma-ray emission from high energy electrons and subsequent burst of ~ 10^{14} eV neutrinos may disclose the onset of the wakefield acceleration,
  - ✓ The detection of the extremely high energy cosmic rays (EHECRs) of $10^{21\text{-}22}$ eV and super-EHECRs of $10^{22\text{-}23}$ eV within several hours after both gamma-ray emissions and neutrino bursts could be a smoking gun for the astrophysical wakefield acceleration.
- The wakefield acceleration will be a key player for the multi-messenger astronomy.