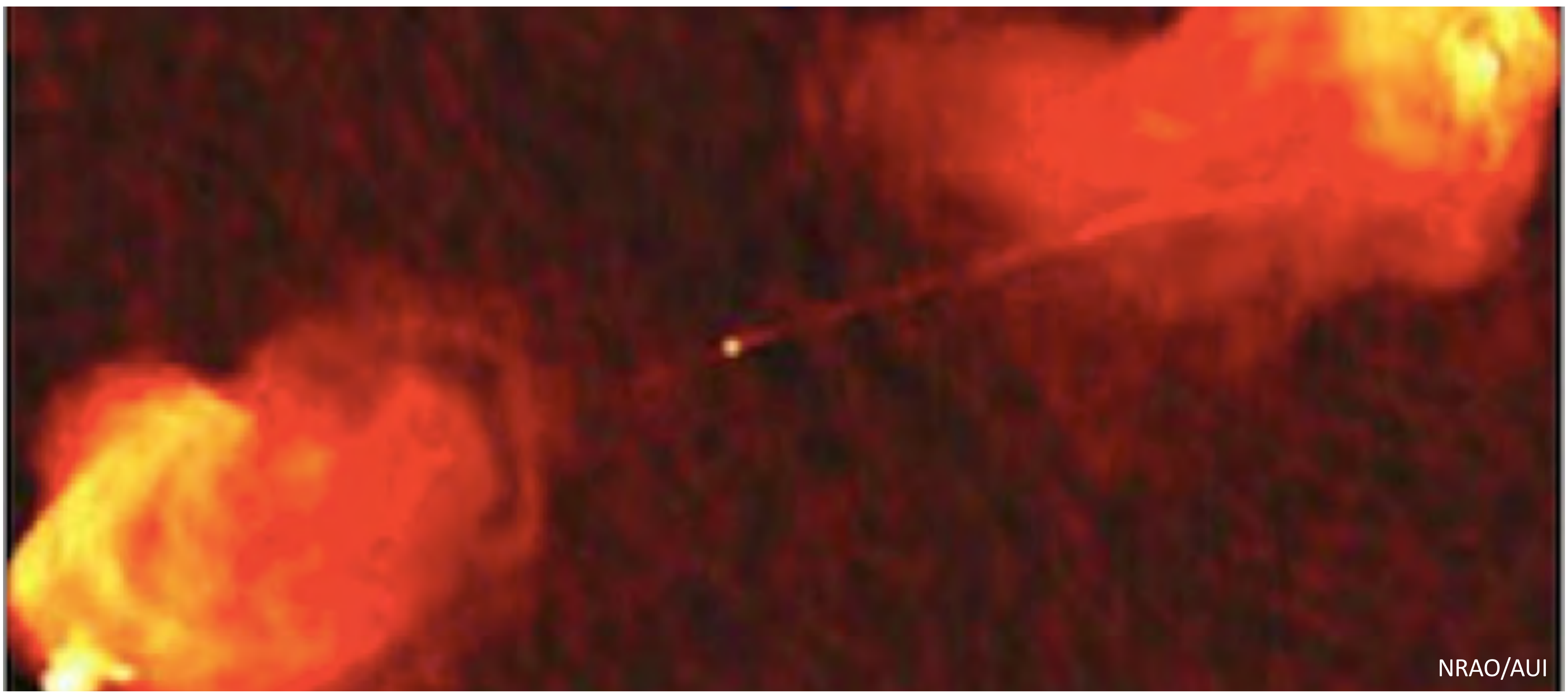
Plasma Accelerator Physics

Toshiki Tajima, Norman Rostoker Chair Professor, UCI

Class 3:PHY249 (2021Fall)



Cross paths with Dr. F. Albert

Dr. Felicie Albert:

Deputy Director, LLNL, Center for High Energy density Science

APS K. Weimer Award (2017), etc.

APS fellow, etc.

ICUIL Member, etc.

……..

PhD: Ecole Polytechnique (2007)

……..

……..

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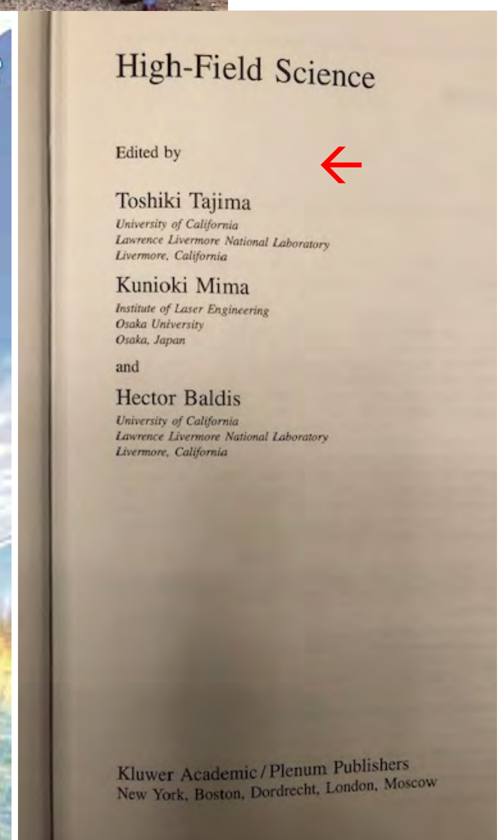
High-Field Science

Edited by

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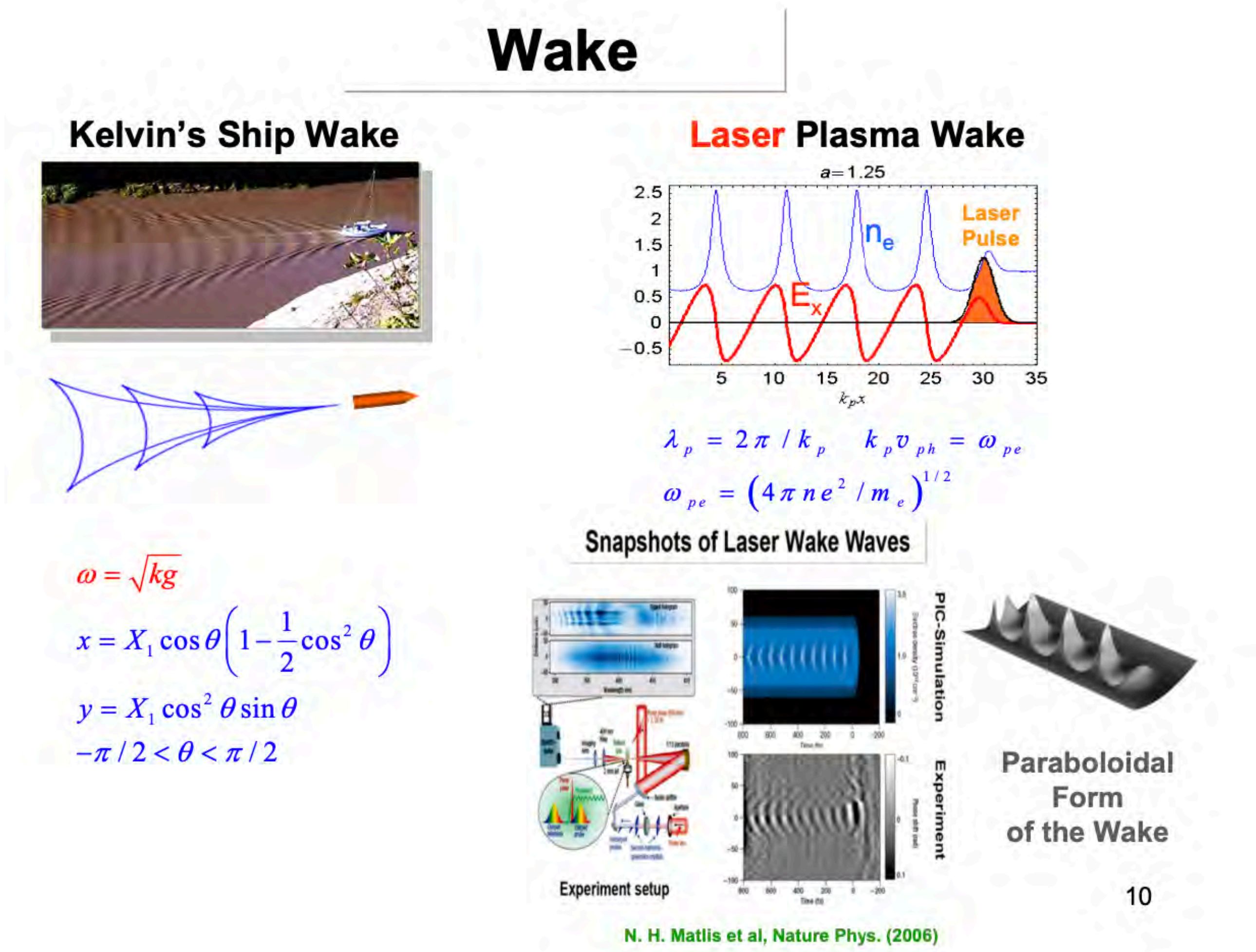
Kluwer Academic / Plenum Publishers
New York, Boston, Dordrecht, London, Moscow

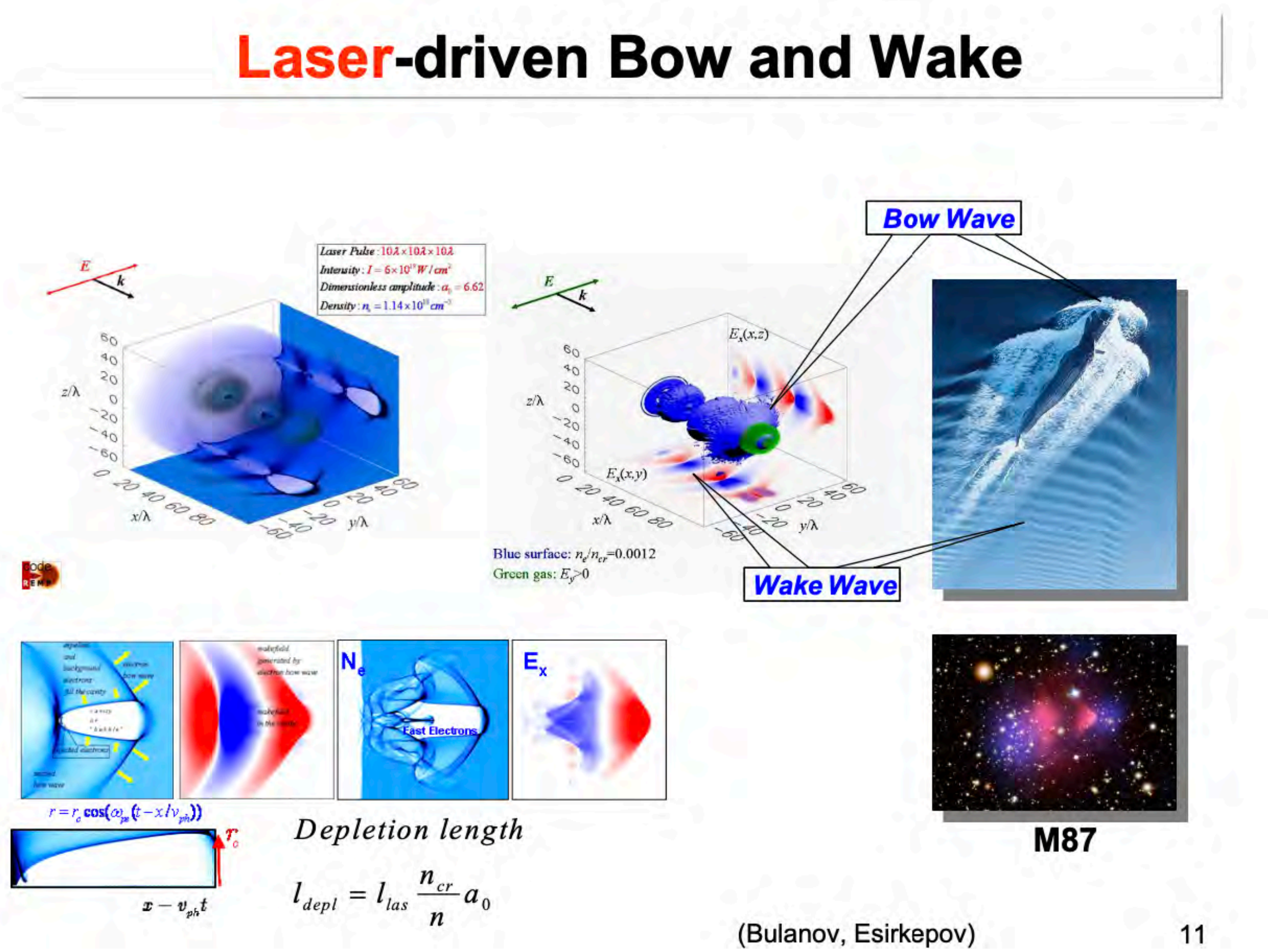
TT:

L LNL (1998-2001)
APS Wilson Prize
APS fellow, etc.
ICUIL co-founder (2004) Chair (2008-2016)
Pascal Chair: Ecole Polytechnique (2008-2009)

Comparison of wakes



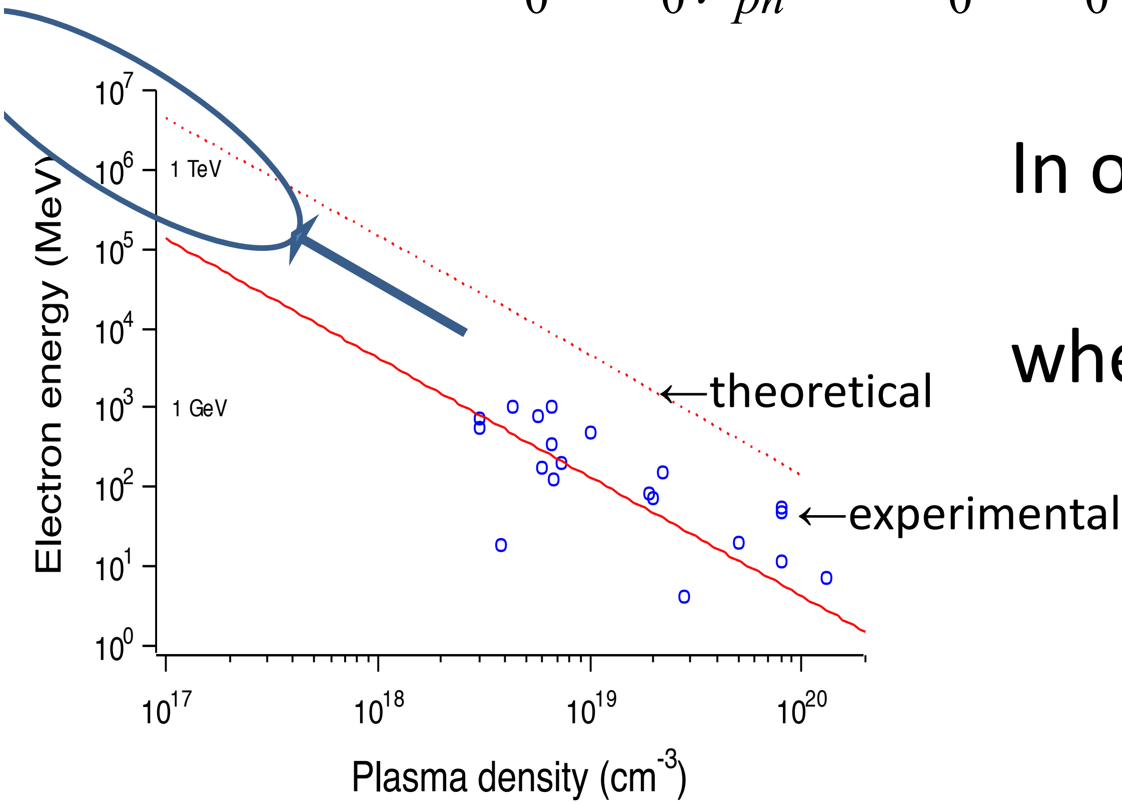
Bow and Stern wakes



Theory of wakefield toward extreme energy

$$\Delta E \approx 2m_0c^2a_0^2\gamma_{ph}^2 = 2m_0c^2a_0^2\left(\frac{n_{cr}}{n_e}\right),$$

(when 1D theory applies
Tajima / Dawson, 1979)



In order to avoid wavebreak,

$$a_0 < \gamma_{ph}^{1/2},$$

where

$$\gamma_{ph} = [n_{cr}(\omega) / n_e]^{1/2}$$

n_{cr} =10^{21}/cc (1eV photon)
→ 10^{29} (10keV photon)

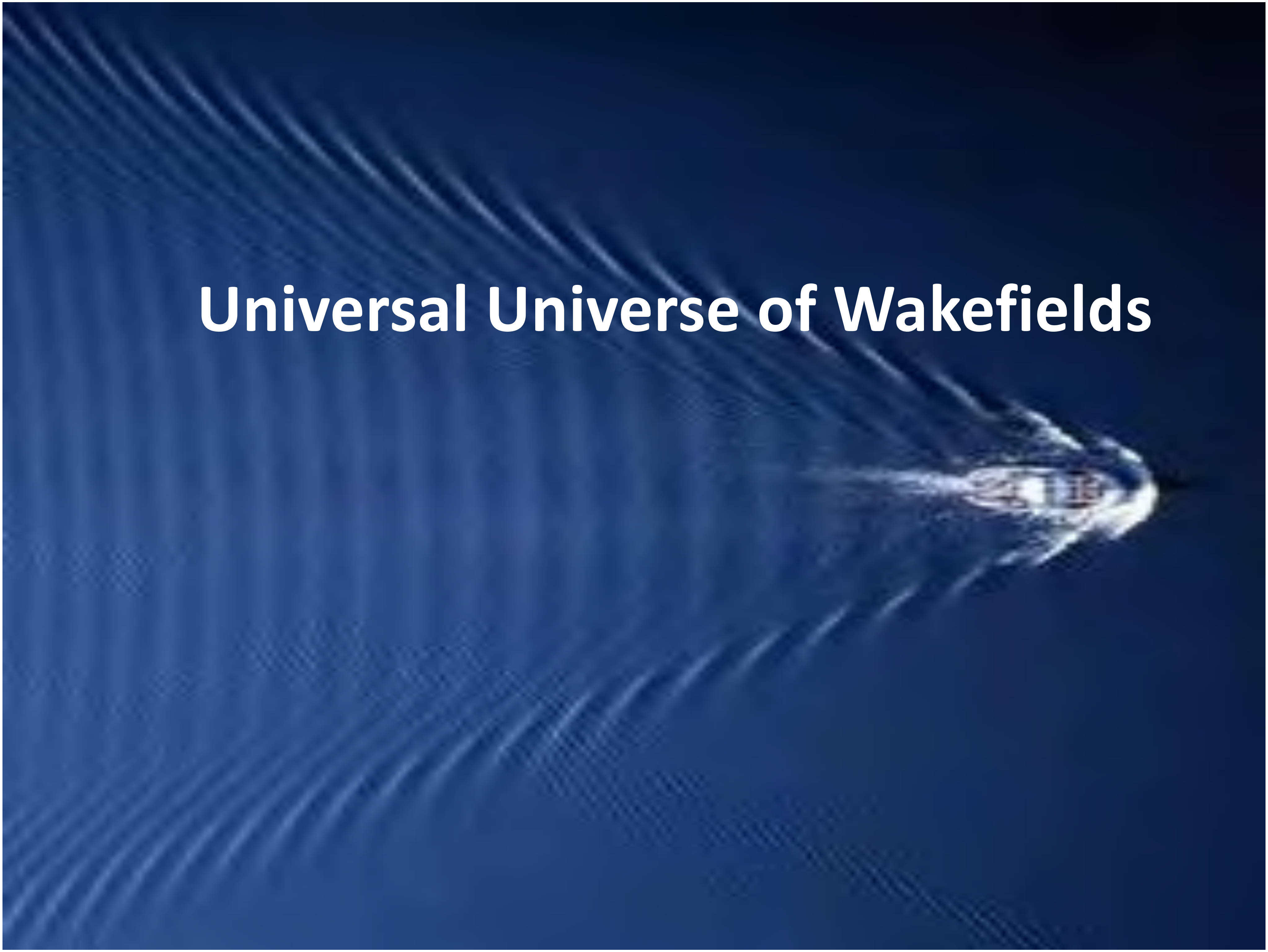
n_e = 10^{16} (gas) → 10^{23} /cc(solid)

$$L_d = \frac{2}{\pi}\lambda_p a_0^2\left(\frac{n_{cr}}{n_e}\right),$$

dephasing length

$$L_p = \frac{1}{3\pi}\lambda_p a_0\left(\frac{n_{cr}}{n_e}\right),$$

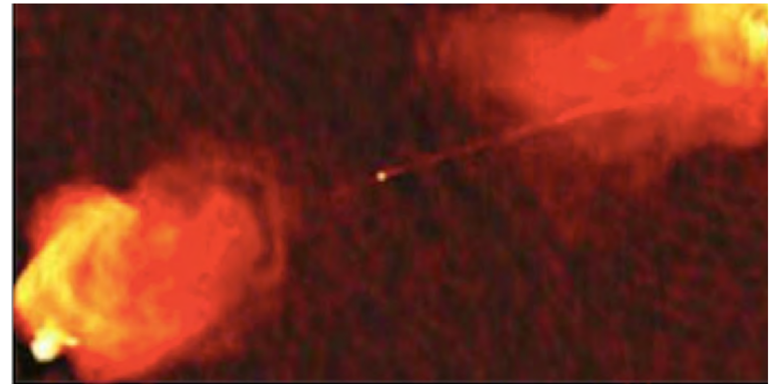
pump depletion length

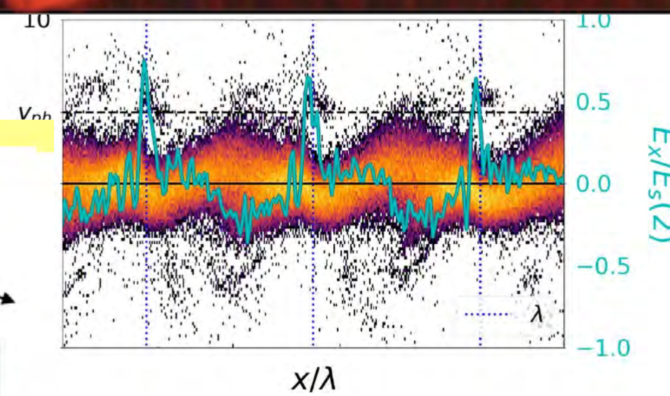

Universal Universe of Wakefields

Ranges of wakefields

λ : 10^{-13} cm ← → 10^{19} cm

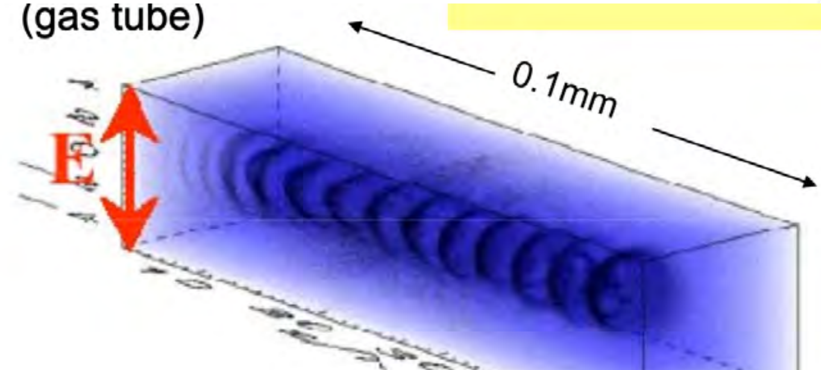
λ = 10^{19} cm
(AGN jets)

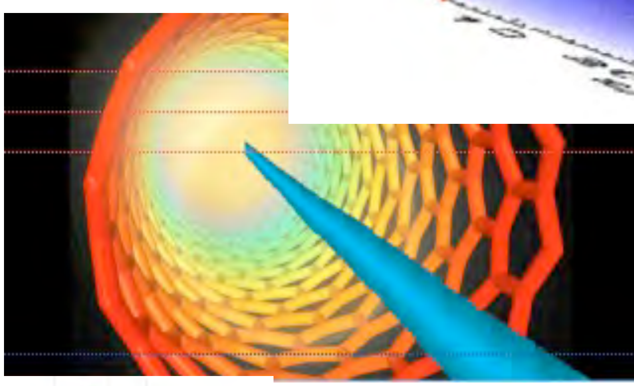




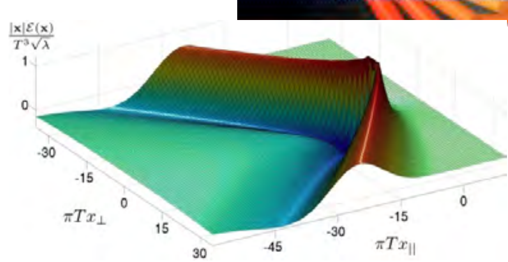
λ = 1 cm (fusion plasma)

λ = 10^{-4} cm
(gas tube)

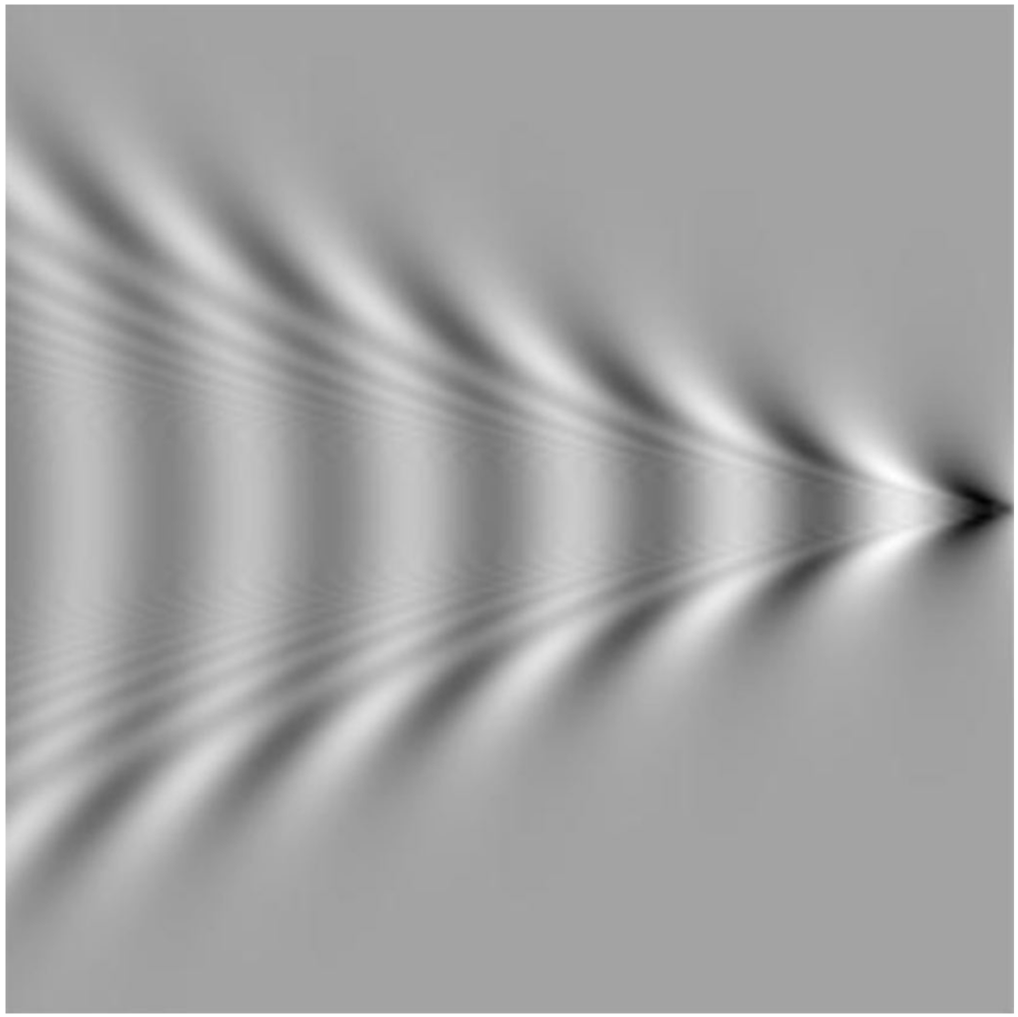




λ = 10^{-7} cm
(nanotube)



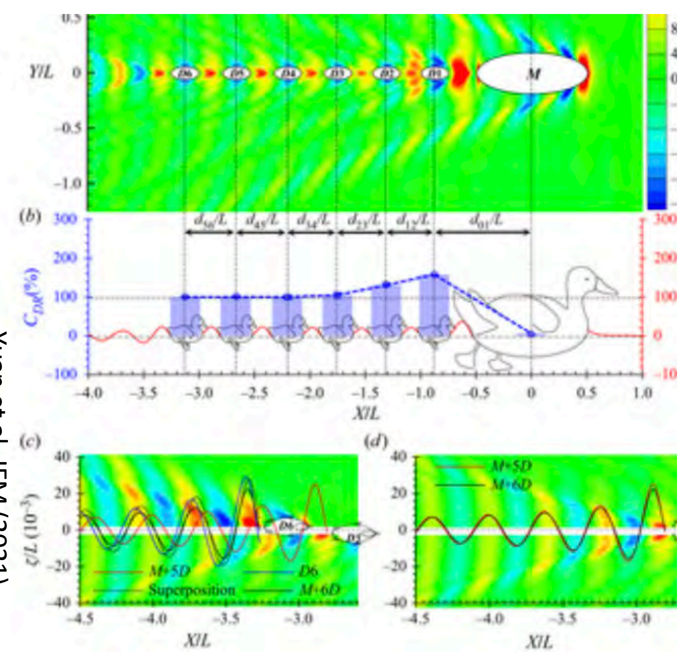
λ = 10^{-13} cm (nuclear QCD plasma)



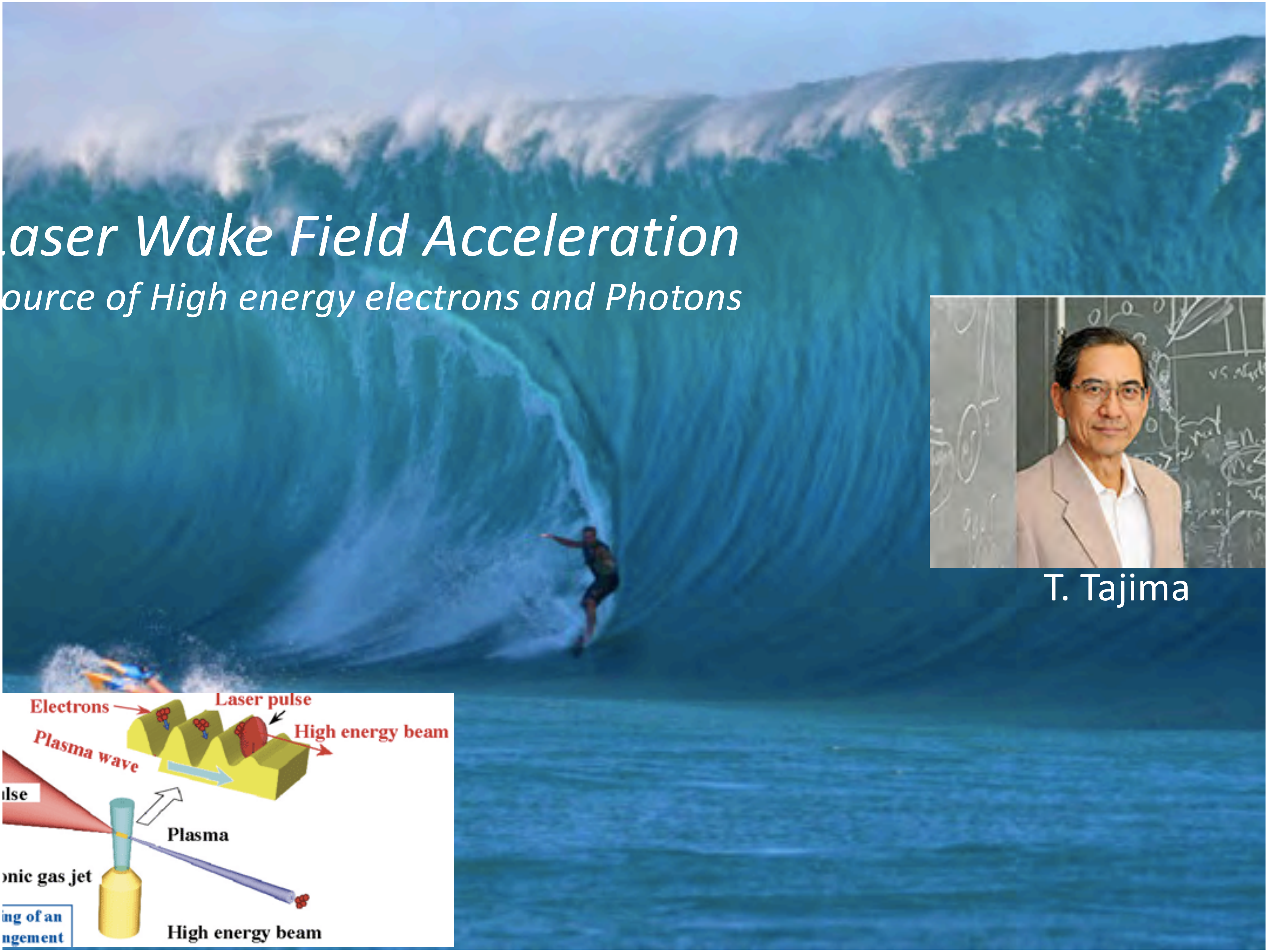
Wake acceleration

Bow wake and stern wake

Nature (or mother duck) shows us.



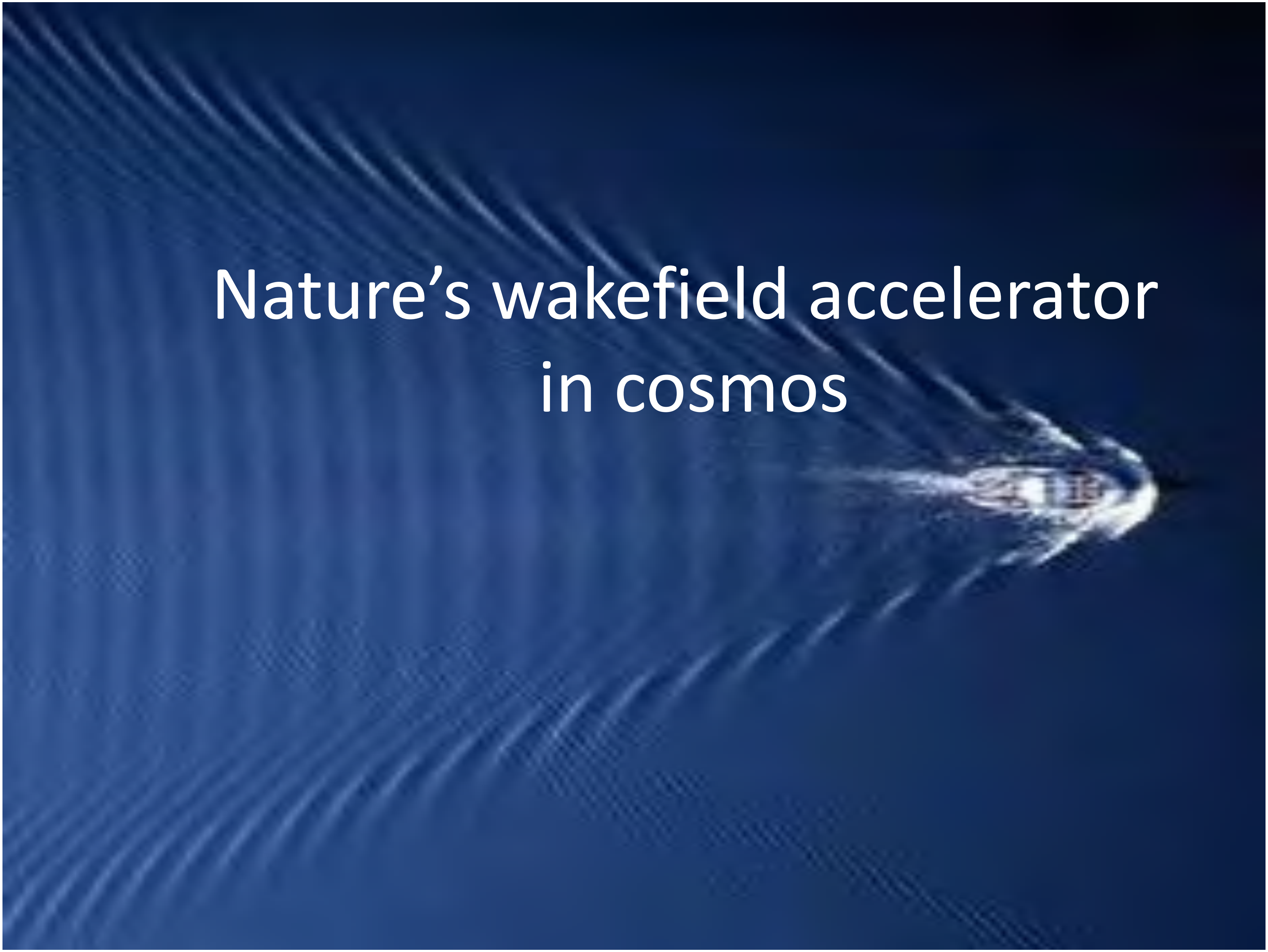
Yuan et al. JFM (2021)



Laser Wake Field Acceleration

ource of High energy electrons and Photons

T. Tajima


Nature’s wakefield accelerator
in cosmos

Relativistic aspects of LWFA

1. **High phase velocity paradigm**: Tajima-Dawson (1979) v_{ph} → large (close to c)

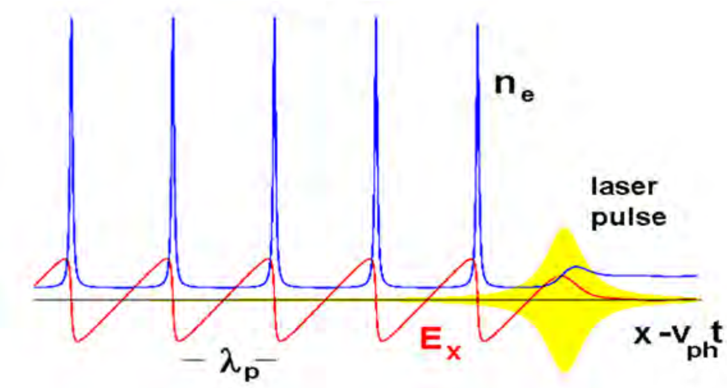
2. **Relativistic amplitude of LWFA** : a_0 >> 1

Strong beam (of laser / particles) drives plasma waves to saturation amplitude: $E = m\omega_p v_{ph} /e$

Relativistic coherence enhances beyond the Tajima-Dawson field: $E = m\omega_p c\, a_0 /e$ (~ GeV/cm)

<u>No wave breaks and wake **peaks** at relativistuic regime v≈c</u>

Wave **breaks** at v<c at non-relativistic regime

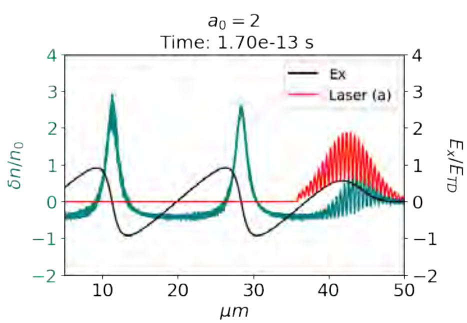


← relativity regularizes (*relativistic coherence*)

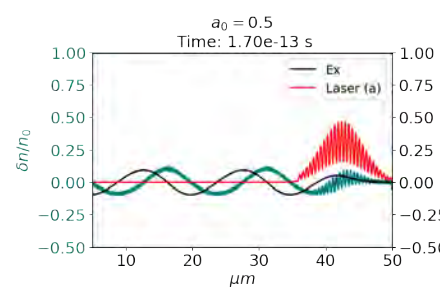
Tajima PJA B86, 147 (2010)

1 + 2→

Relativistic coherence (Tajima, 2010) ← →**Quantum coherence** (Bose-Einstein condensation)



vs

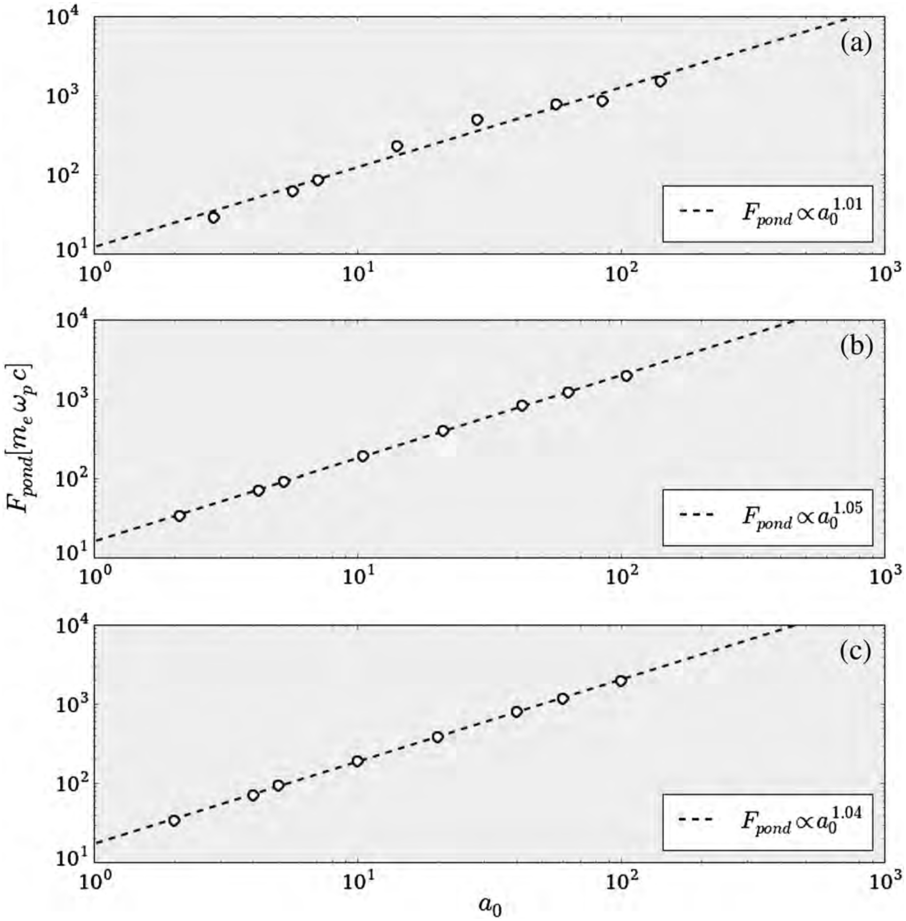


Ernesto

Relativistic astrophysical jets

Ponderomotive force: independent of M / m

Charge force less, as we reduce M / m

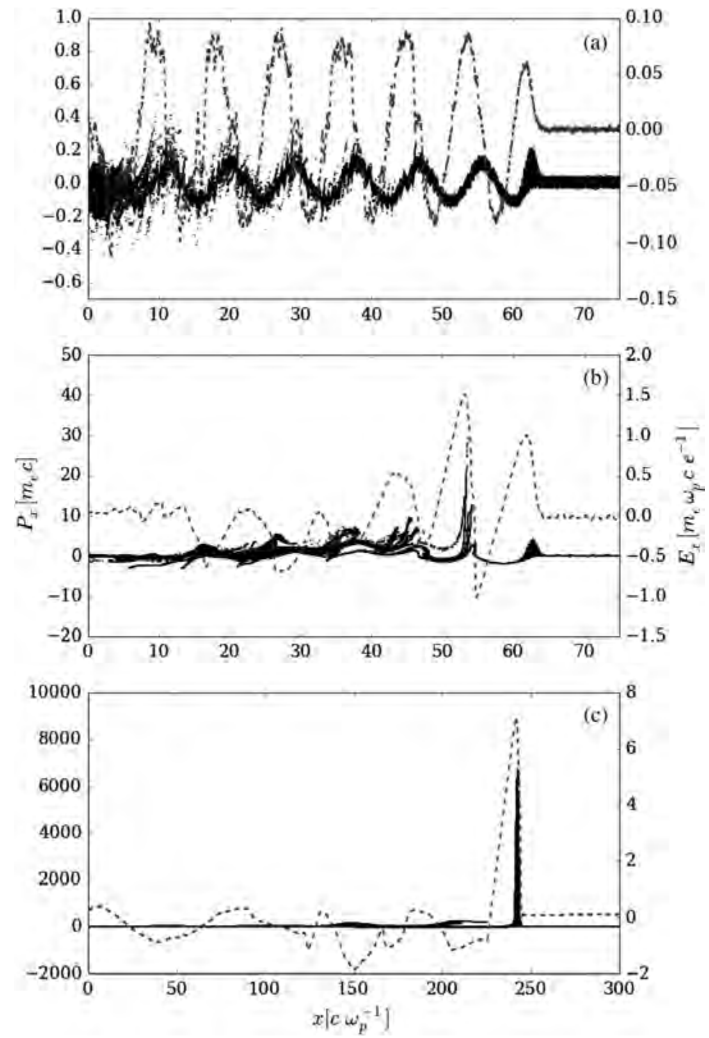


M / m : 1, 10^2 , 10^3

↑

$e^- e^+$

Lau et al. (2015)



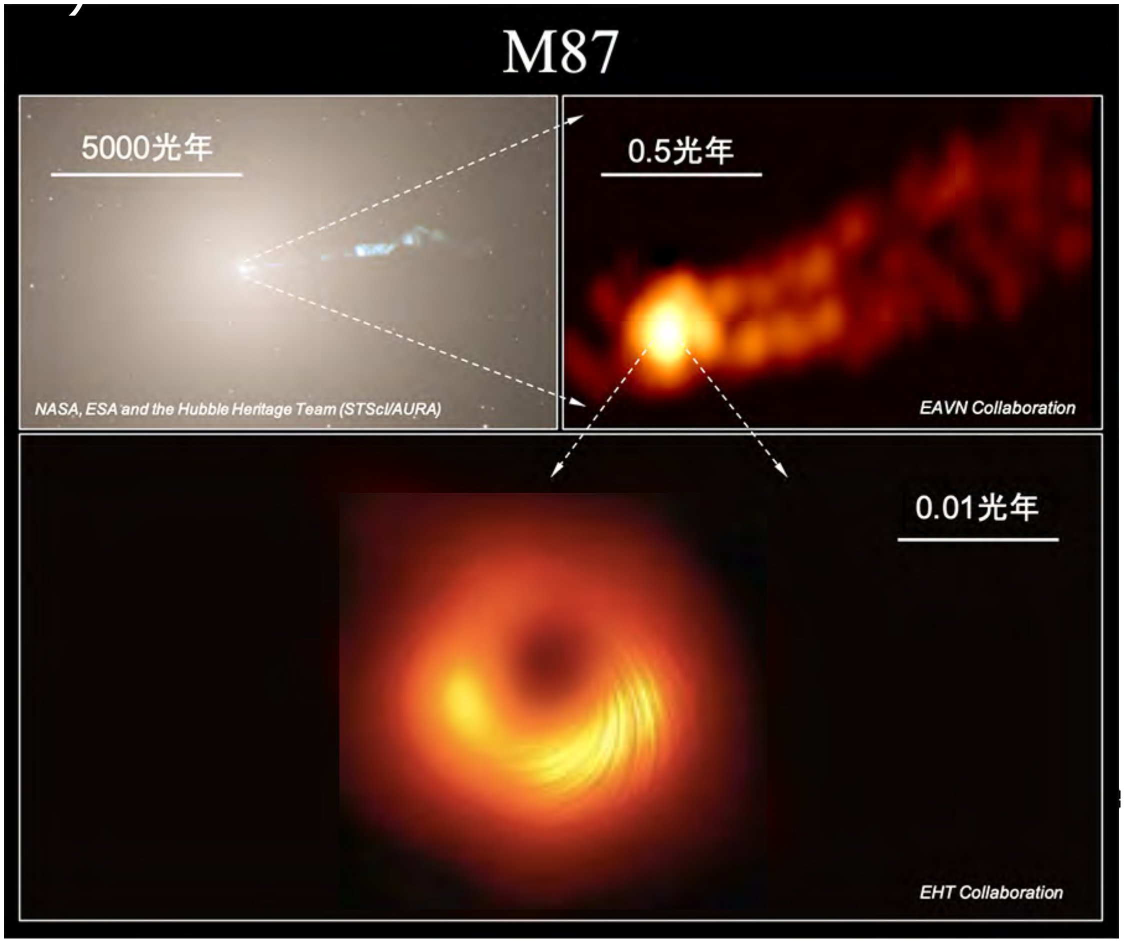
Bow wake (or shock) (rather than **stern wake**)

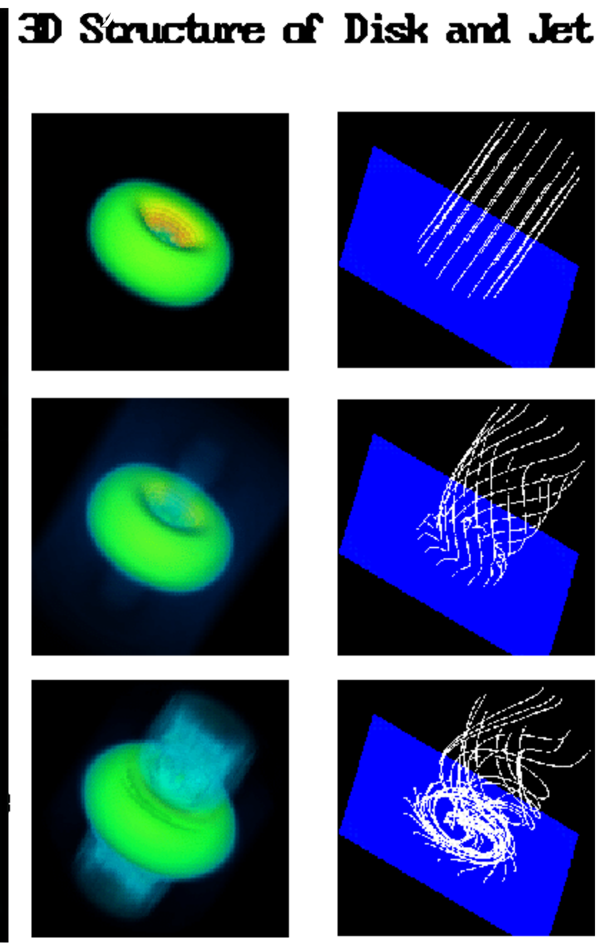
Ponderomotive acceleration

a_0 : 0.4, 2, 60

Energy gain : $W_{max} = 2mc^2 (\omega/\omega_p)^2 a_0^2$

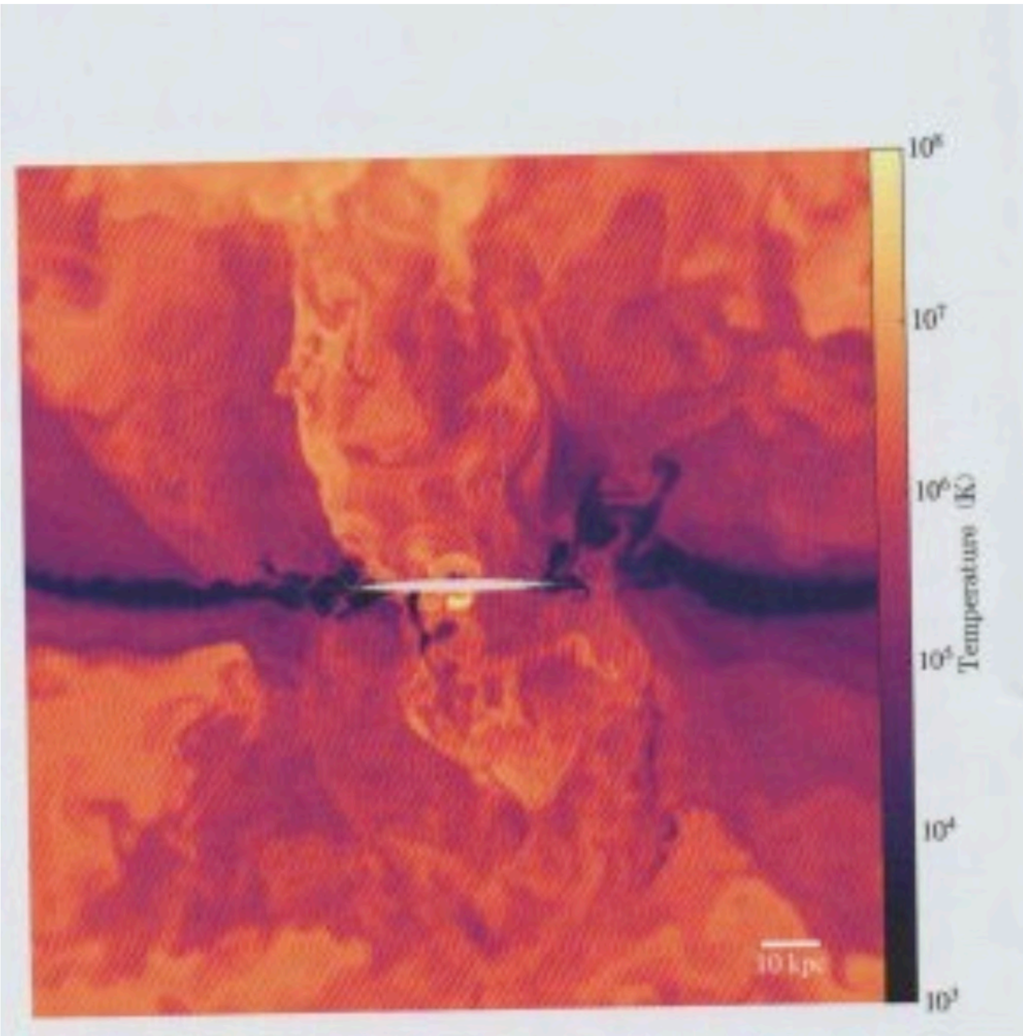
Jet of M87 Galaxy



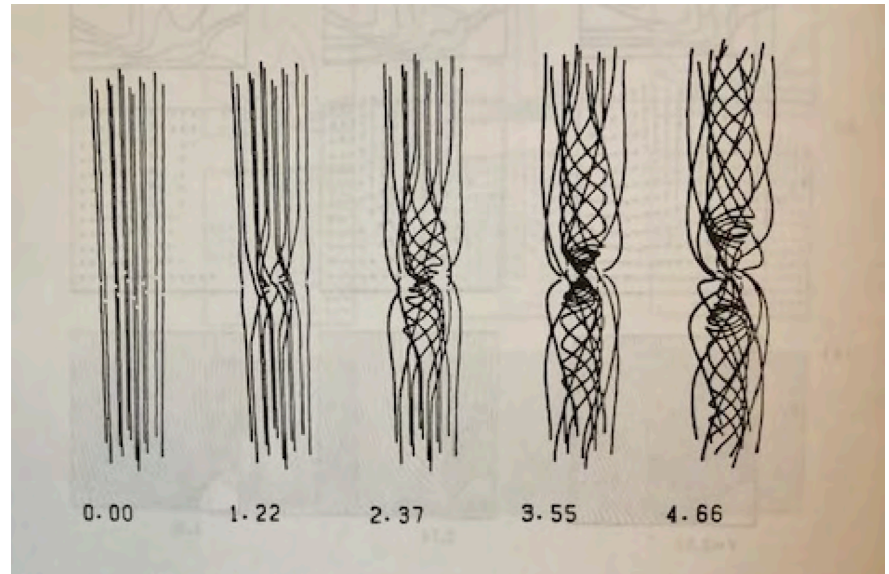


T. Tajima and K. Shibata, Plasma Astrophysics (Perseus Publishing, Cambridge Masachusetts 1997).

Compare Shibata's simulation with non-magnetic simulation to understand the importance of Magnetic fields in astrophysical jets and acceleration



A simulated galaxy cut in half, showing hot outflowing and cold inflowing gas. Colors represent increasing temperature in degrees Kelvin. Darker colors are cooler. The galaxy disk is seen edge-on at the center, with each star marked as a pale dot. The scale bar signifies size in thousands of parsecs. Credit: Claire Kopenhafer



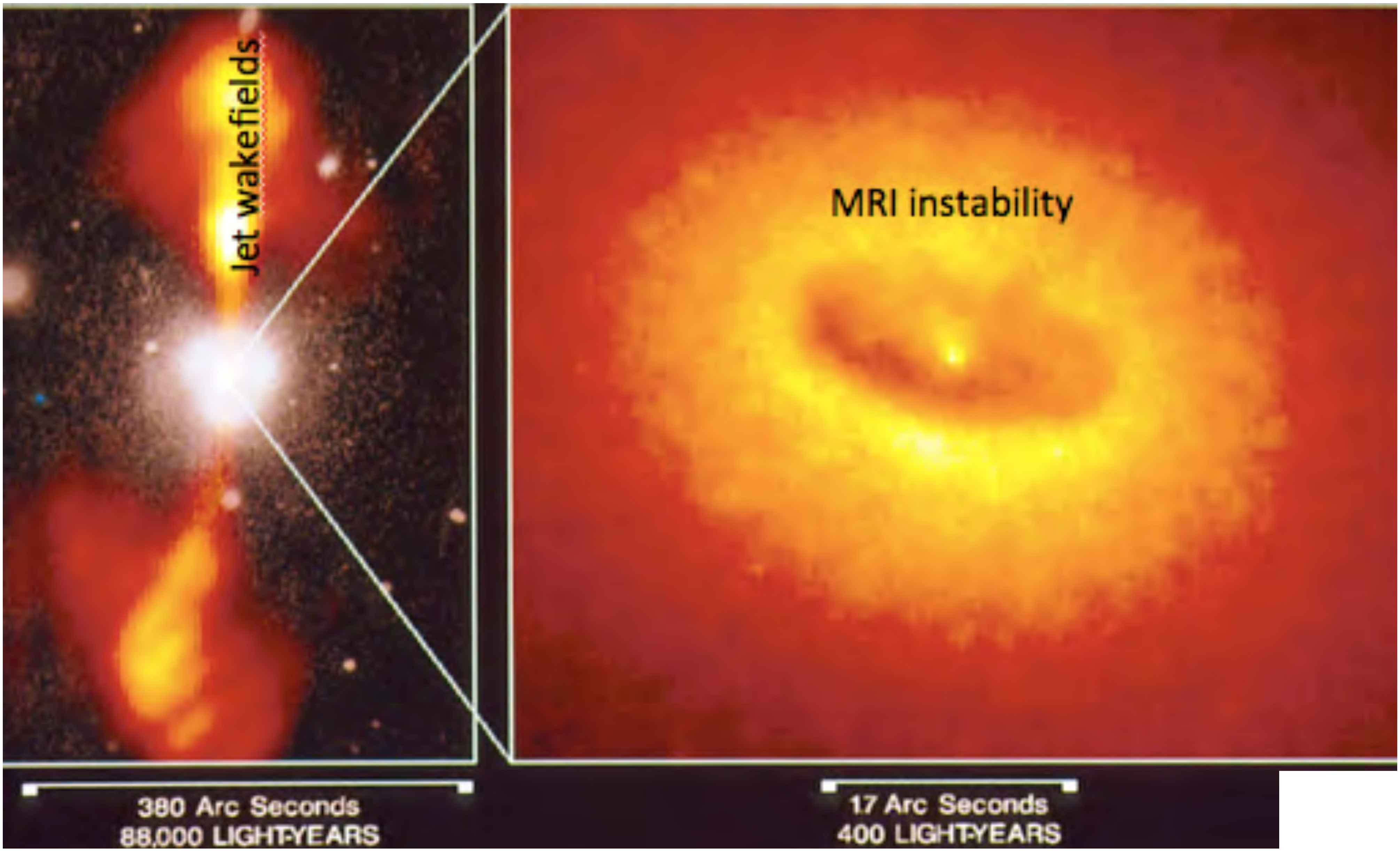
4.57 3D magnetic field configuration of *magnetic-twist* jet developed by Shibata and Uchida (1990).

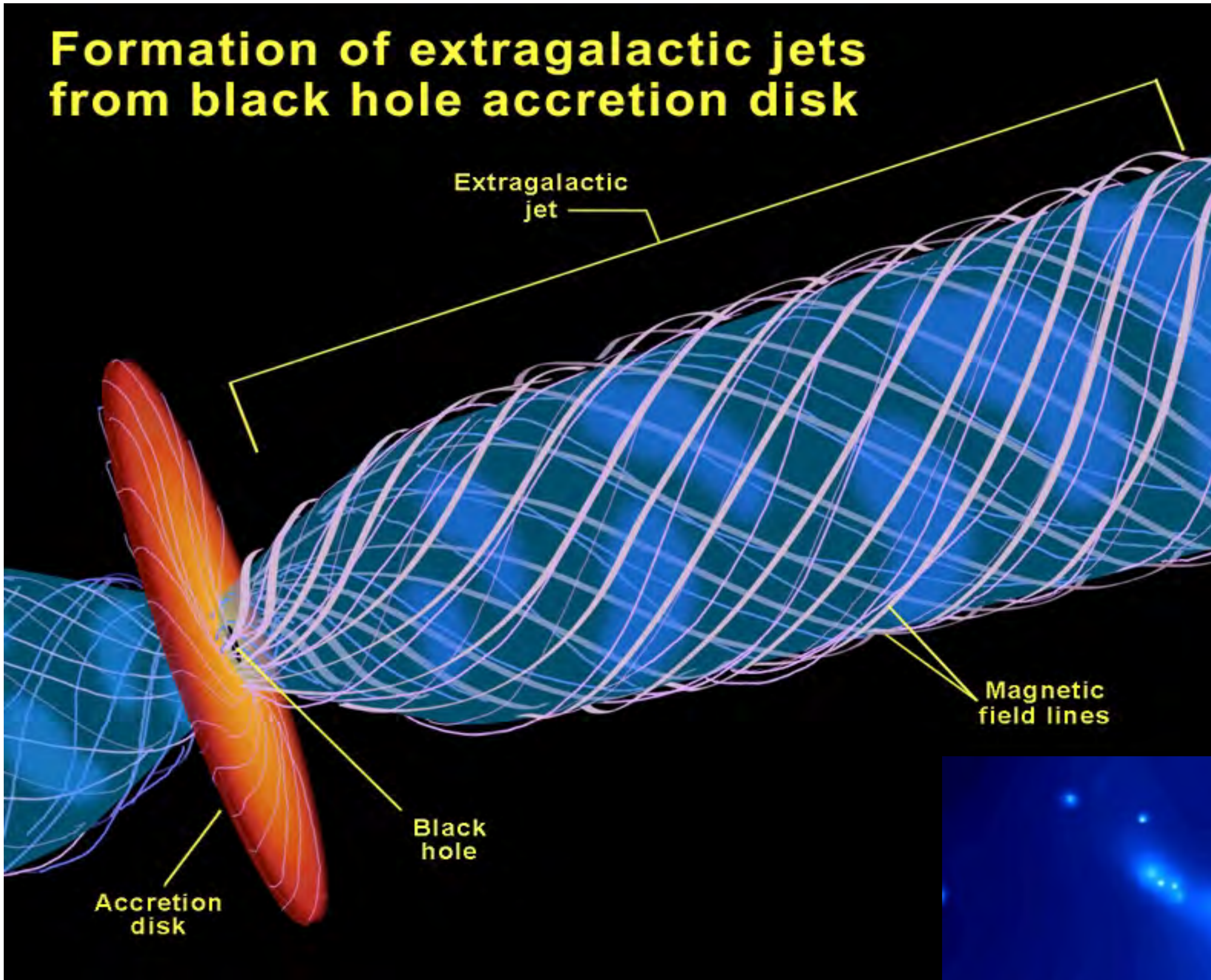
↑ With magnetic fields
same book above Tajima-Shibata p. 384

<--A gravitational simulation without B-fields
C. Kopenhafer (in Dexis, DoE p. 10 (2021))

Hubble Space Telescope image of jets and disk

Ground-based optical/radio image HST image of a gas and dust disk

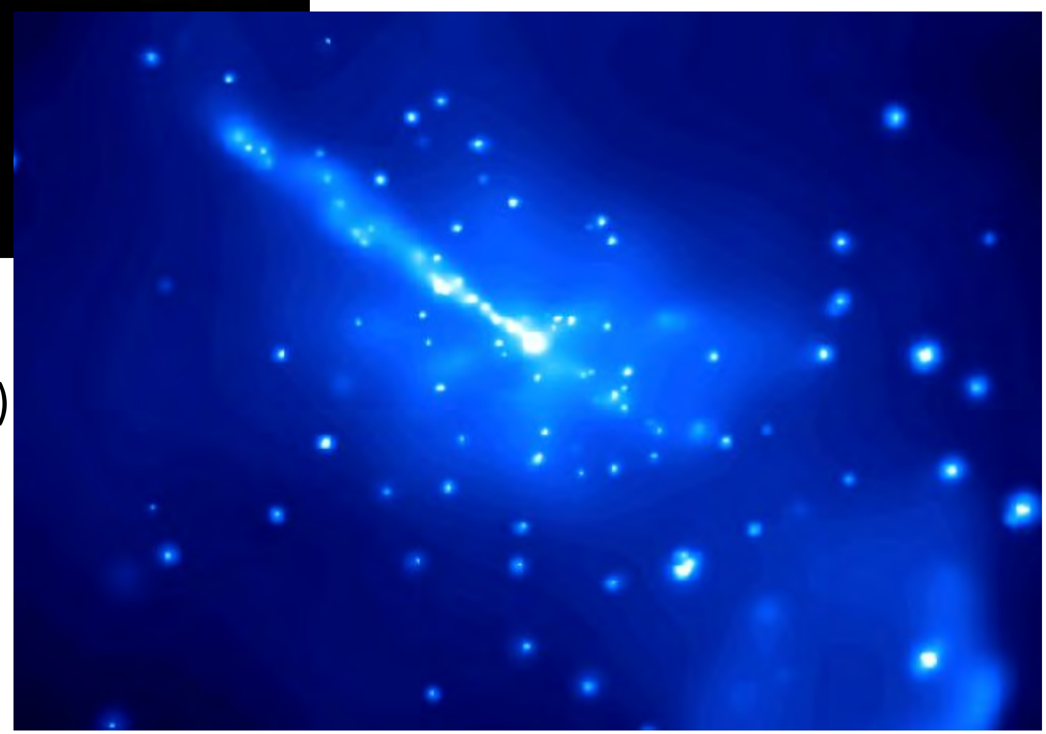




Fermi's '**Stochastic Acceleration'**
(large synchrotron radiation loss)

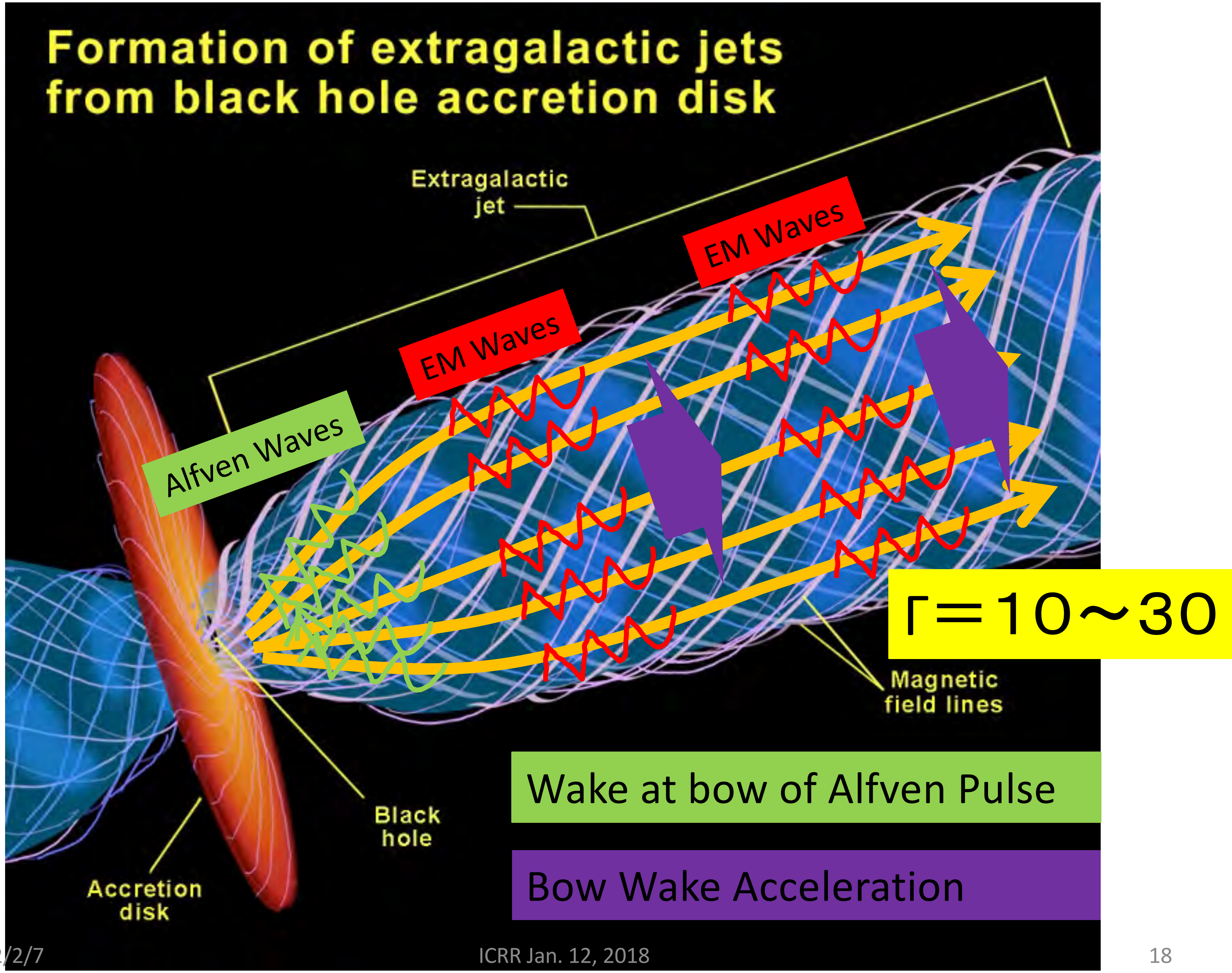
↓

Coherent wakefield acceleration
(no limitation of the energy)

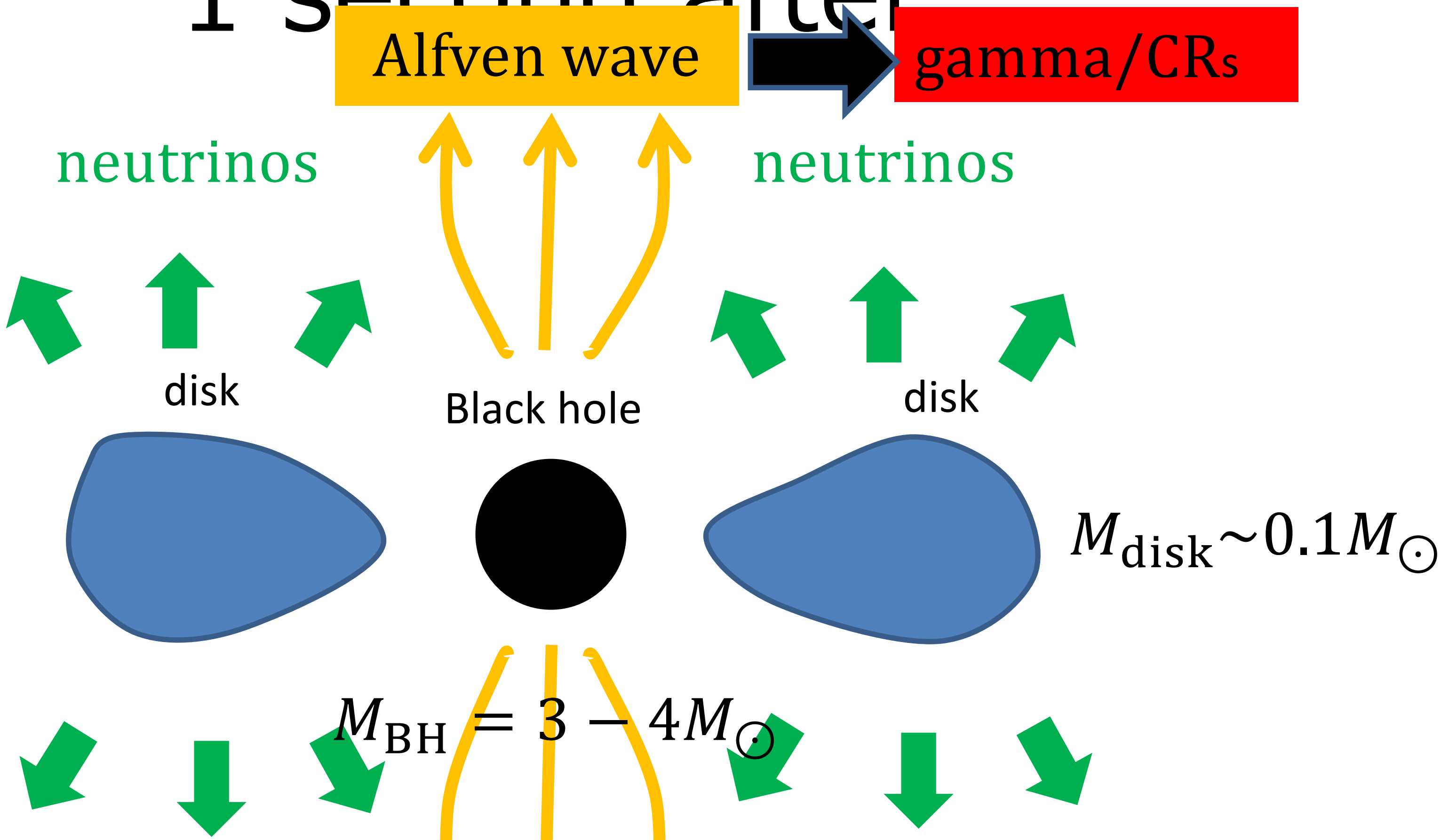


Nature's LWFA : Blazar jets
extreme high energy cosmic rays (~10^{21} eV)
episodic γ-ray bursts observed
consistent with LWFA theory

Ebisuzaki-Tajima (2014)


Formation of extragalactic jets
from black hole accretion disk
Extragalactic
jet
EM Waves
EM Waves
Alfven Waves
Γ＝10～30
Magnetic
field lines
Wake at bow of Alfven Pulse
Bow Wake Acceleration
Black
hole
Accretion
disk

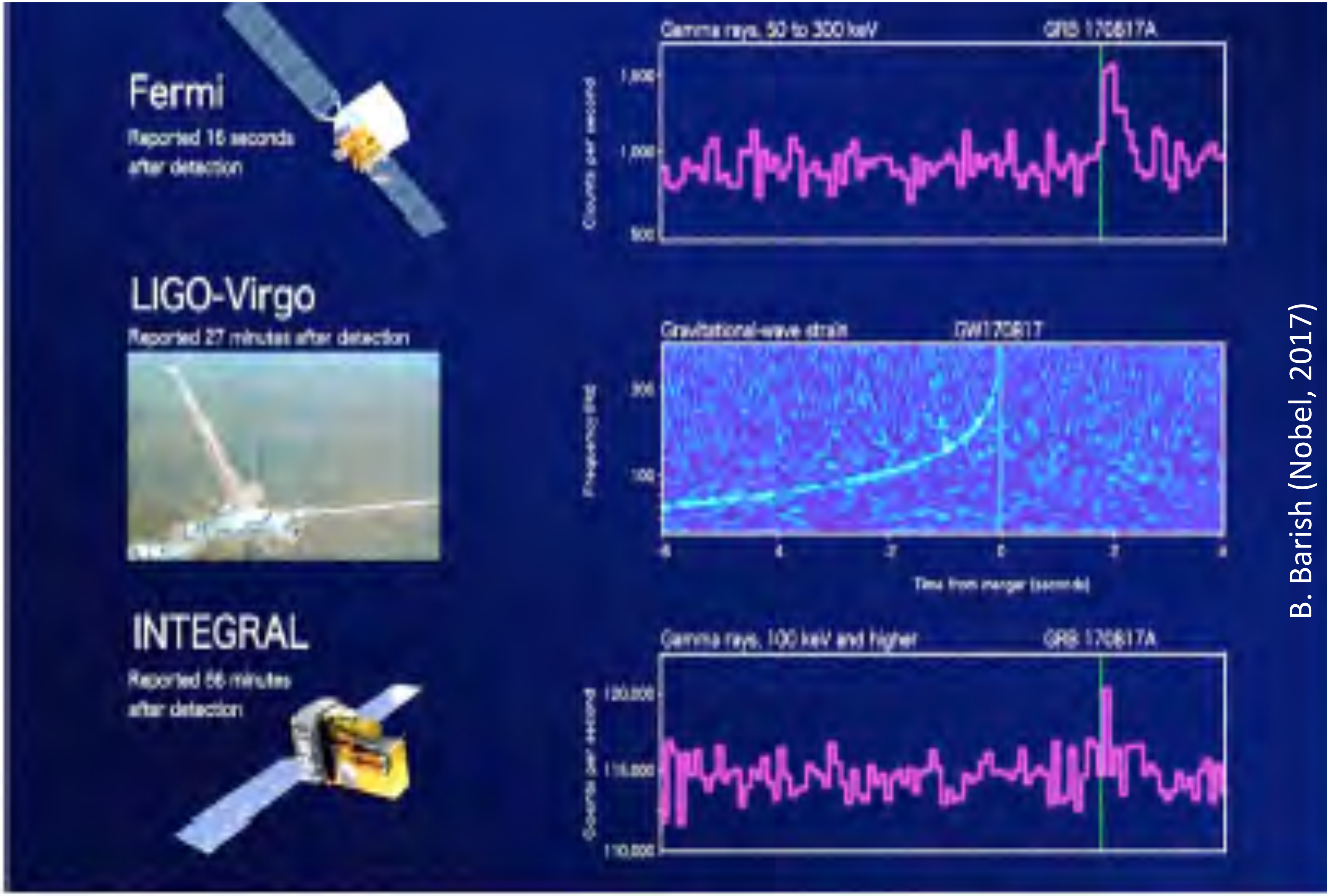
NS-NS merger→BH + Disk
1 second after



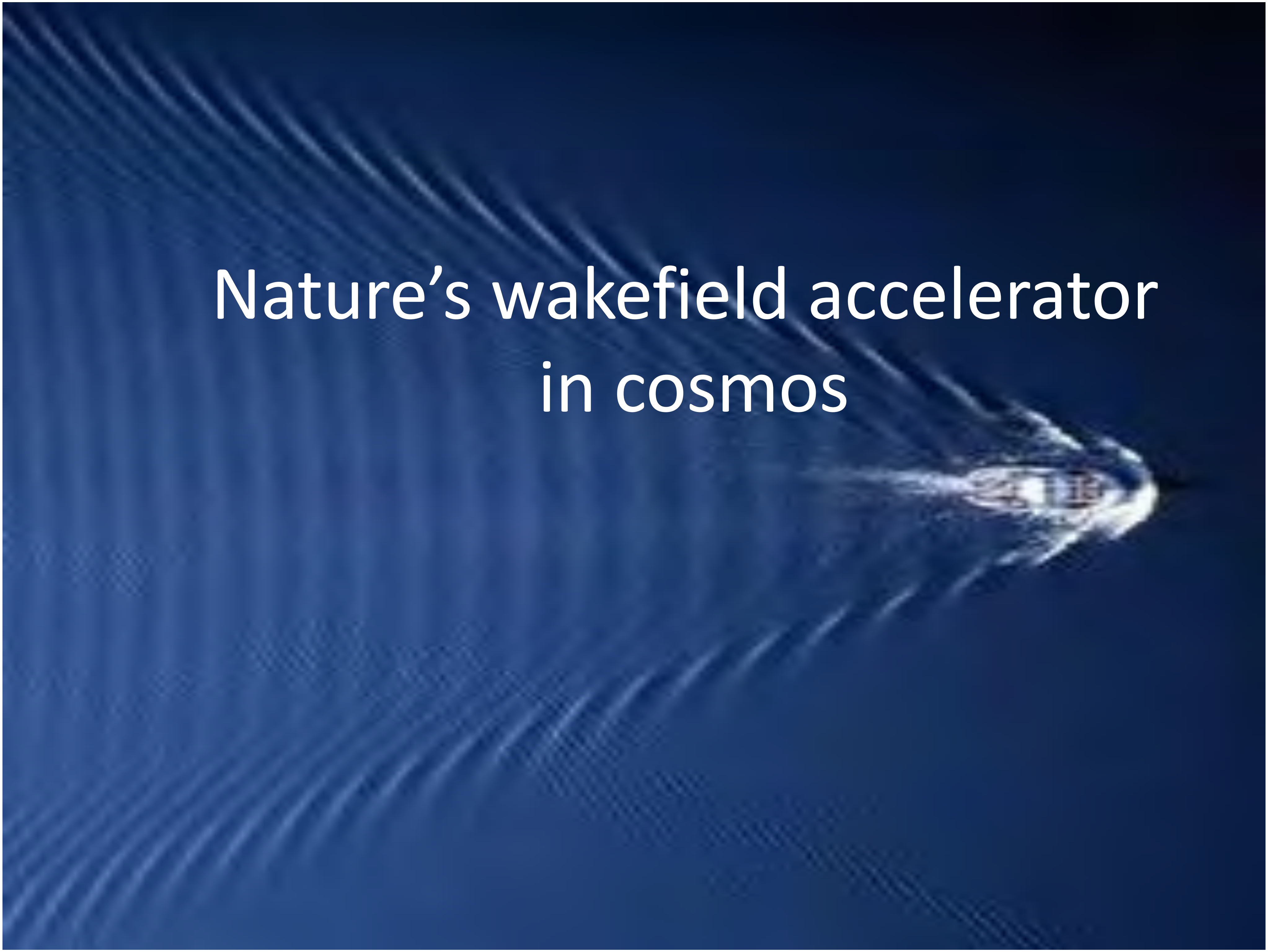
$L_\nu \sim 10^{52}$ erg/s$\sim L_A$

Central Engine of GRB/Hypernova

Gravitational wave and Gamma bursts



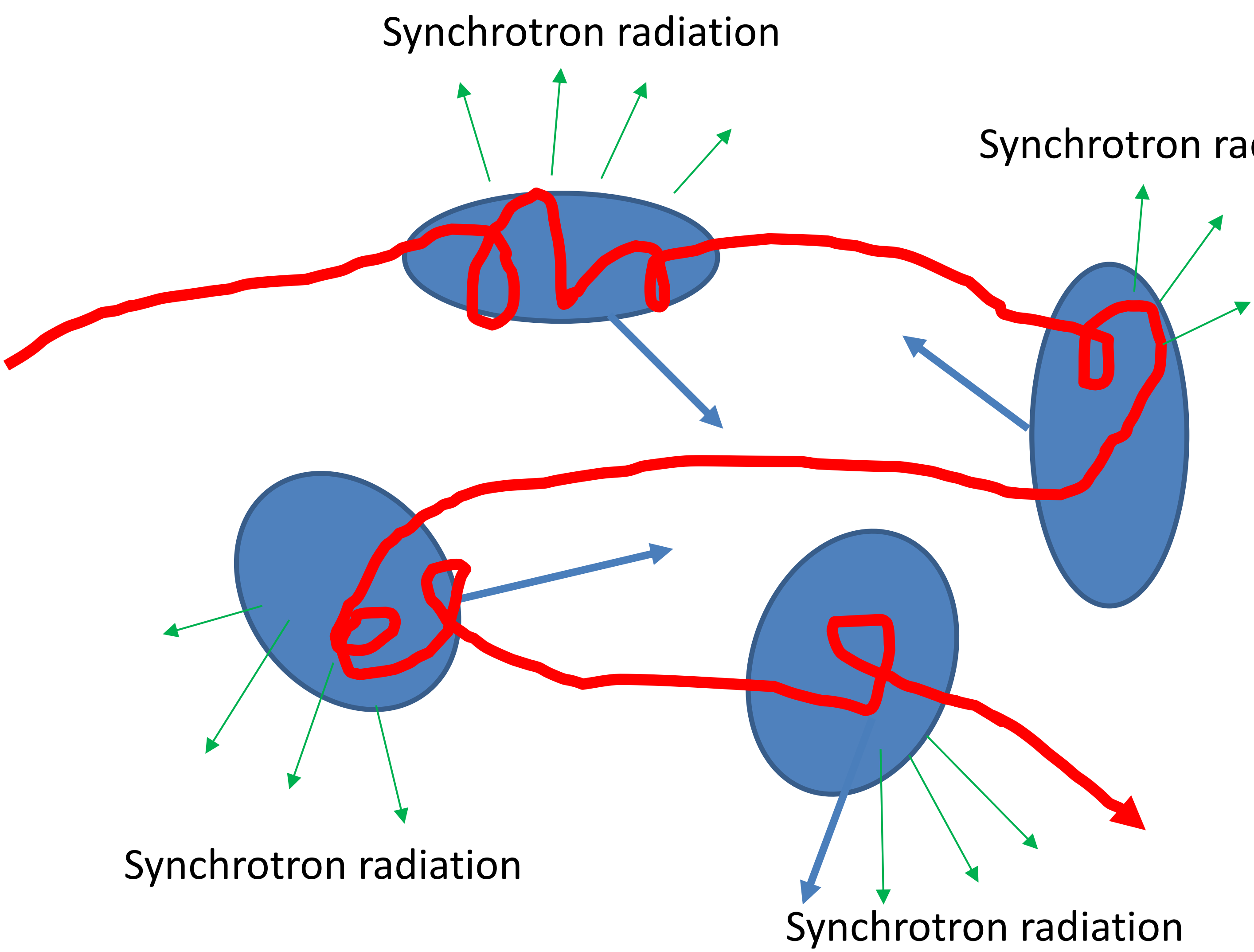
B. Barish (Nobel, 2017)

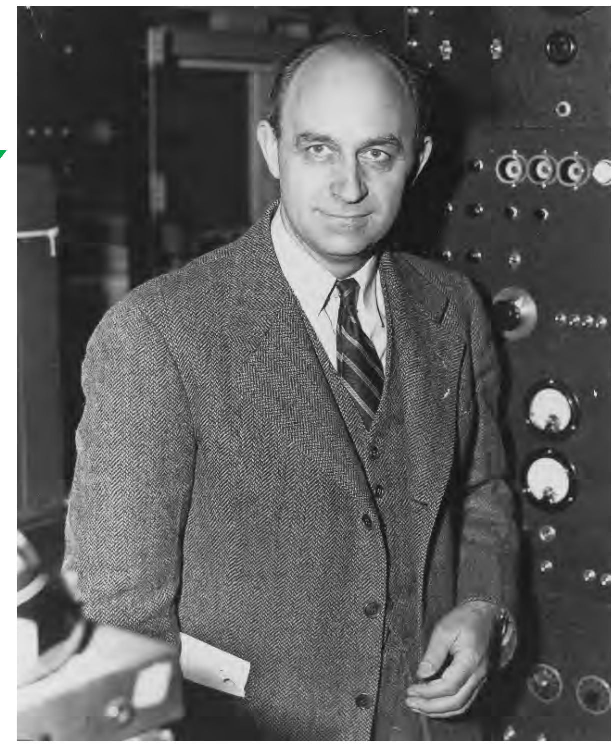

Nature's wakefield accelerator
in cosmos

Fermi mechanism

incoherent

requires bending→synchrotron loss



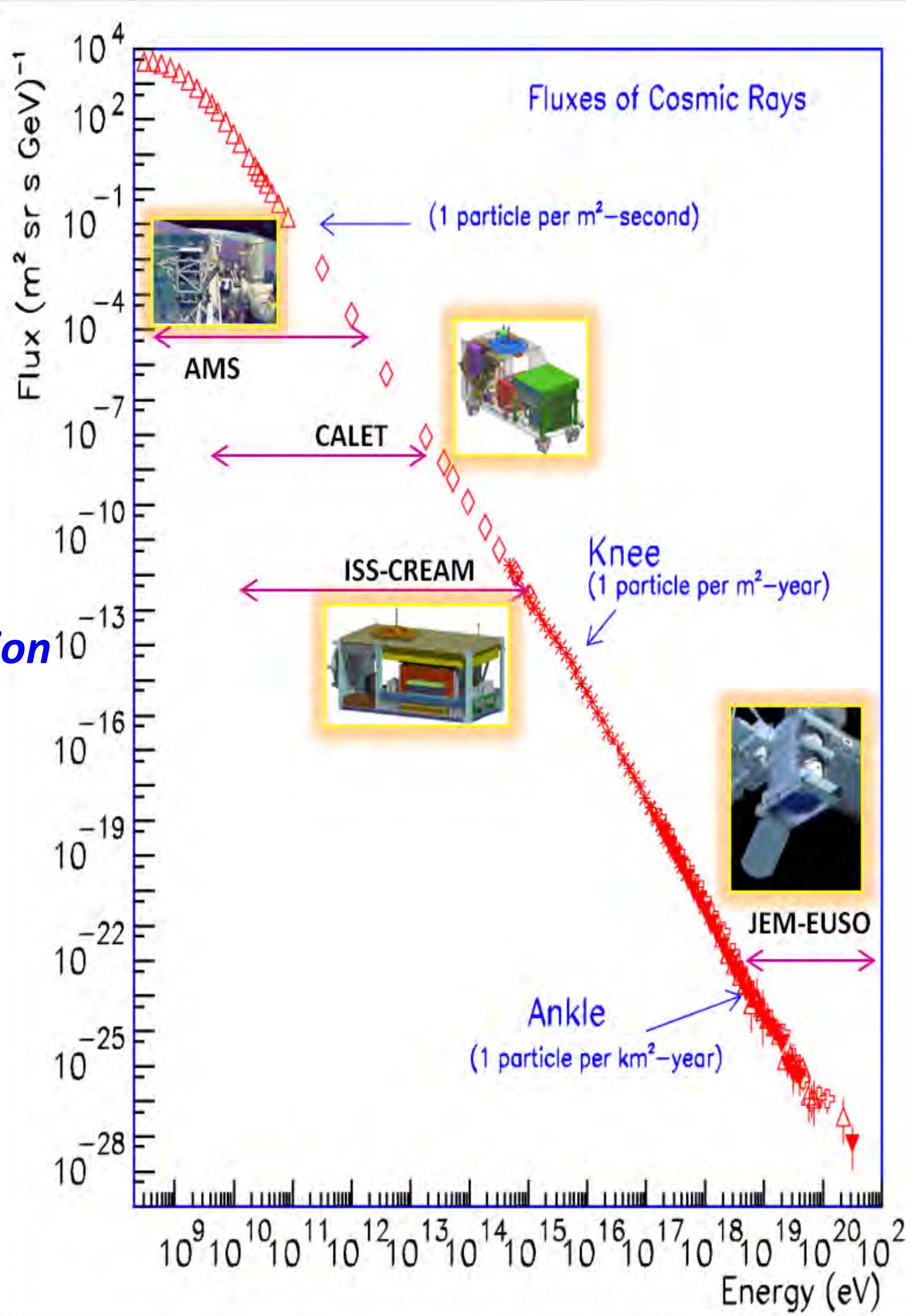


(Department of Energy. Office of Public Affairs)

E. Fermi, ApJ 119 (1954) 1.

Ultrahigh Energy Cosmic Rays (UHECR)

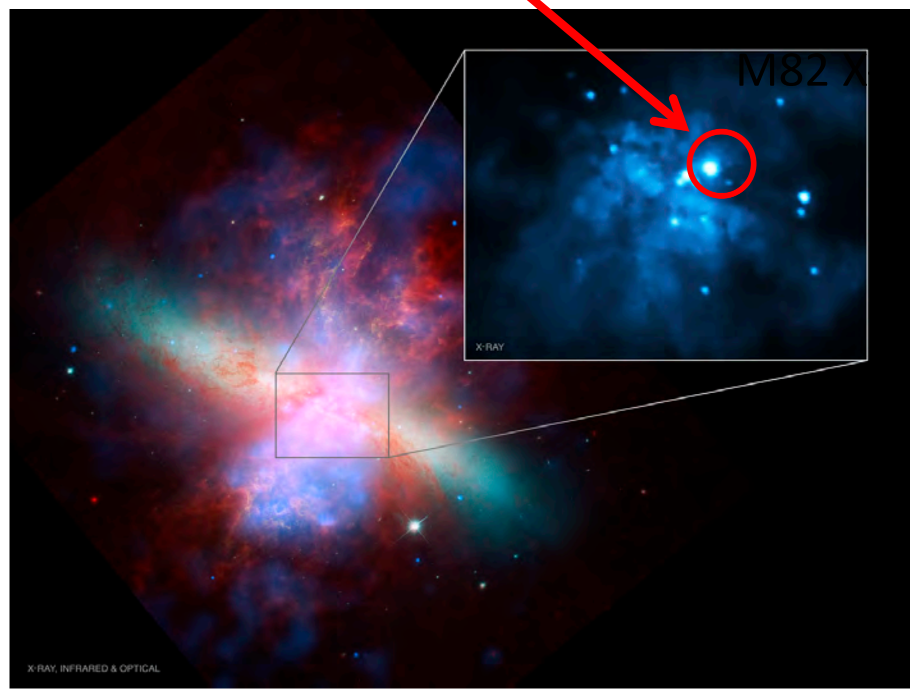
- Fermi mechanism runs out of steam
  - beyond 10^{19} eV
  - due to *synchrotron radiation*
- Wakefield acceleration
  - comes in rescue
  - prompt, intense, *linear acceleration*
  - small synchrotron radiation
  - radiation damping effects?



M82: Nearest Starburst Galaxy

M82 X-1: 1000-10000 Ms BH

Just after the collision with M81

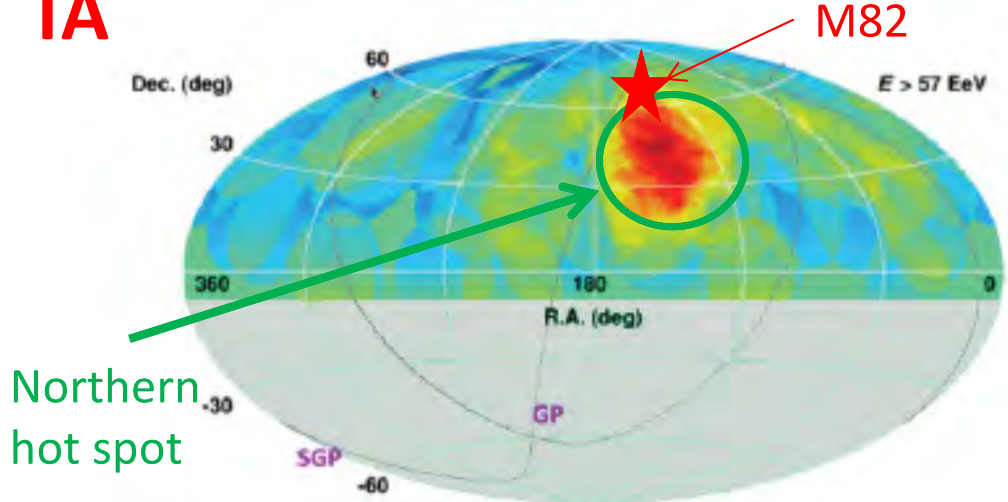


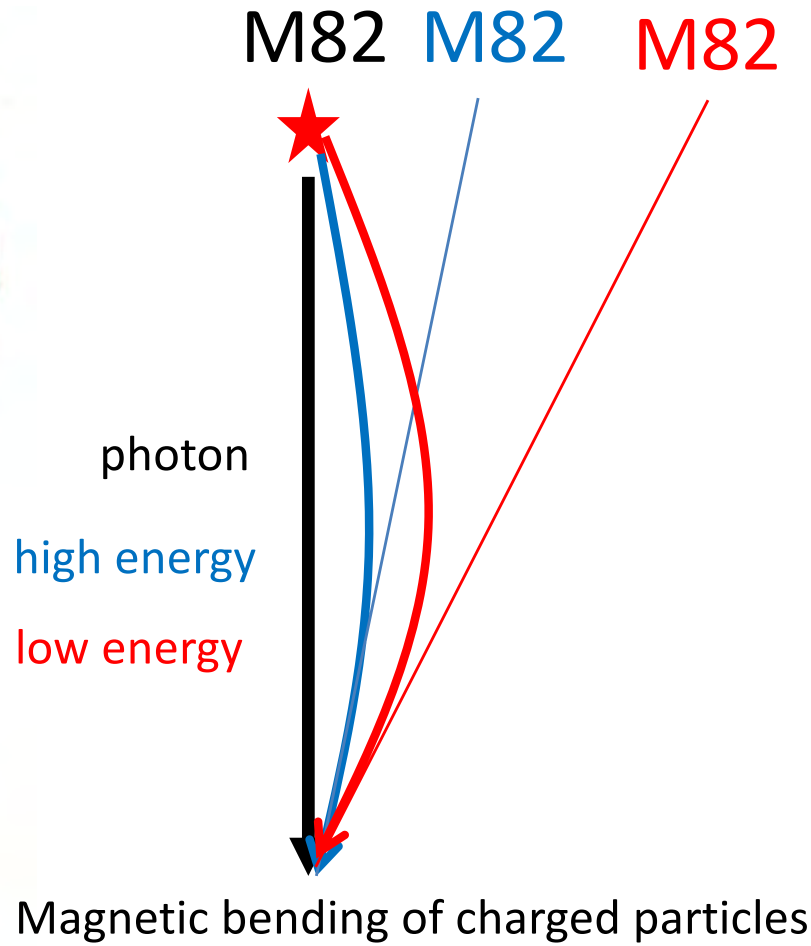
Composite of X-ray, IR, and optical emissions

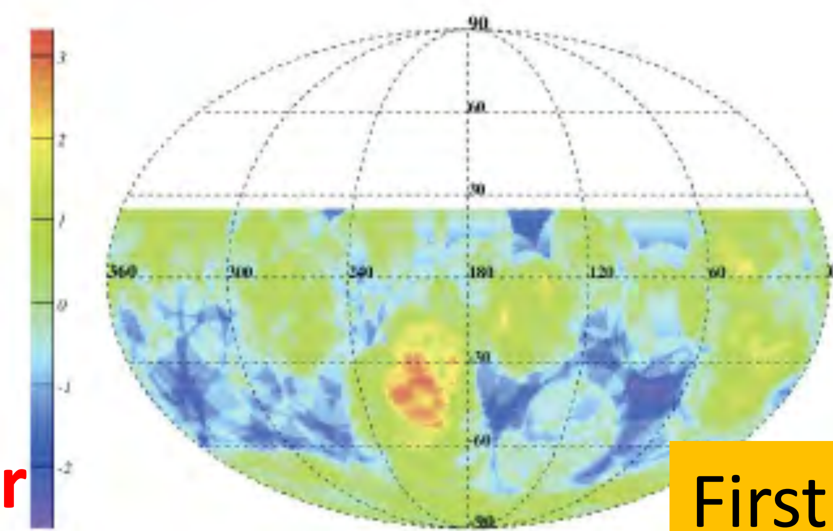
NASA / CXC / JHU / D. Strickland; optical: NASA / ESA / STScI / AURA/ Hubble Heritage Team; IR: NASA / JPL-Caltech /Univ. of AZ / C. Engelbracht; inset – NASA / CXC / Tsinghua University / H. Feng et al.

Arrival Direction Map
(cosmic rays>5×10^{19} eV)

TA







Auger

First Identification of CR sources?

First sign of anisotropy in charged particles

Anti-correlation between the luminosity and the power index from Blazars

Anti-correlation of Luminosity ***L*** and Power index ***p*** in time

↑

Wakefield theory anticipated (Ebisuzaki 2014)

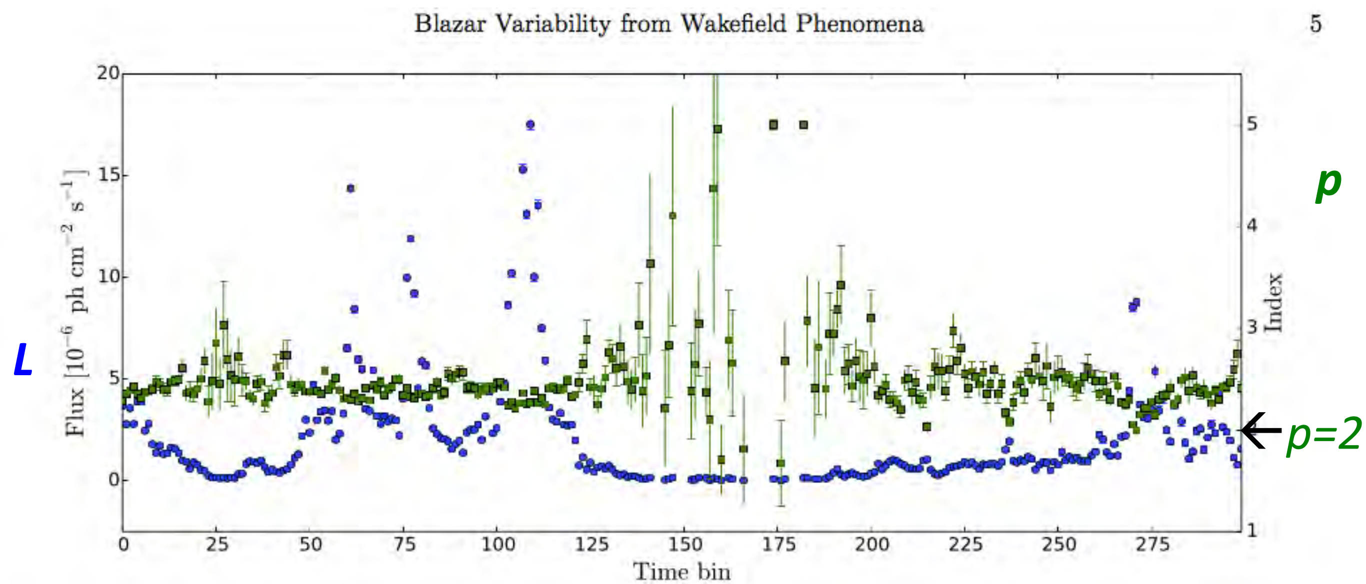


FIG. 2.— Shown are the flux (blue circles, left axis) and spectral index (green squares, right axis) for 3C 454.3 in 300 time bins of 7.9 days duration. An anti-correlation can be seen: the peaks in flux correspond to dips in the spectral index and vice versa.

Power index ***p*** vs. Luminosity ***L*** for several Blazars (more in **Abazajian** et al. arXiv **2017**)