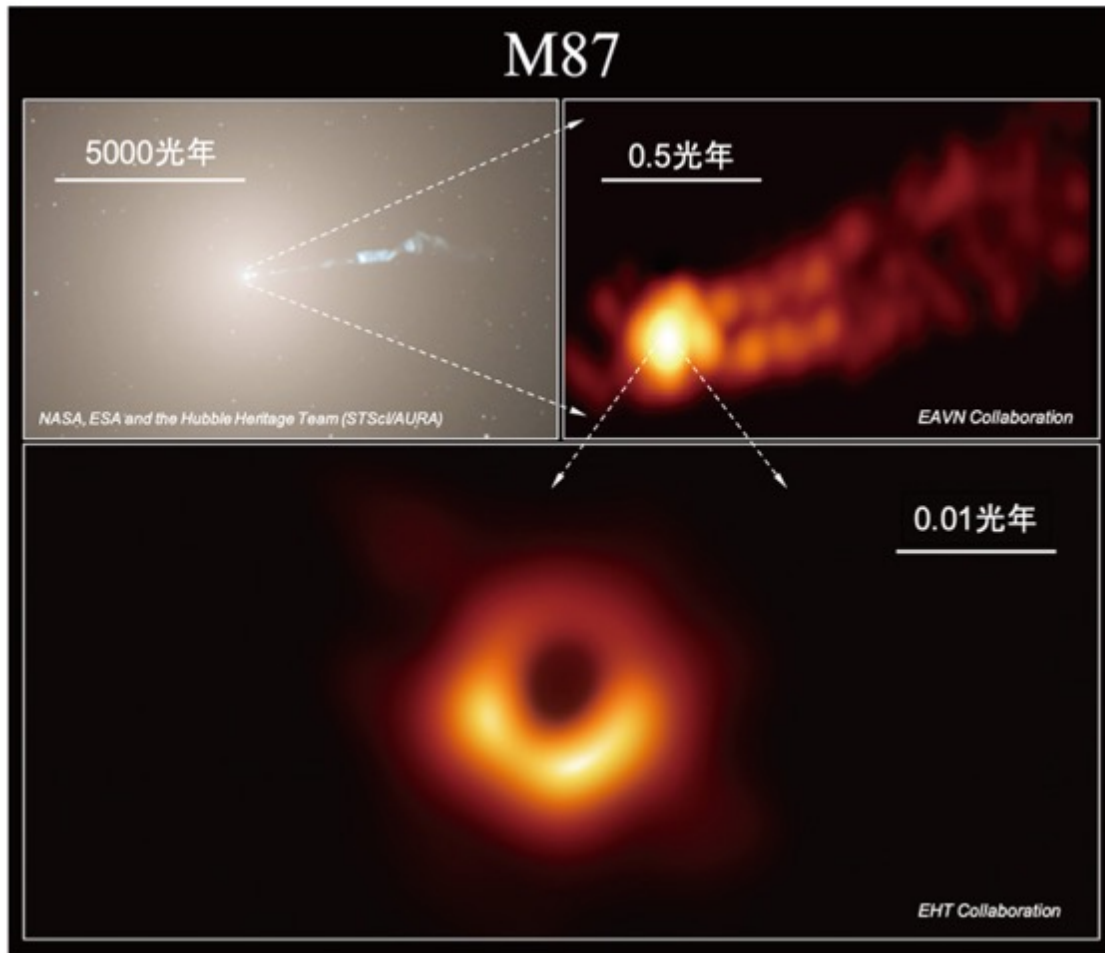


Plasma Astrophysics

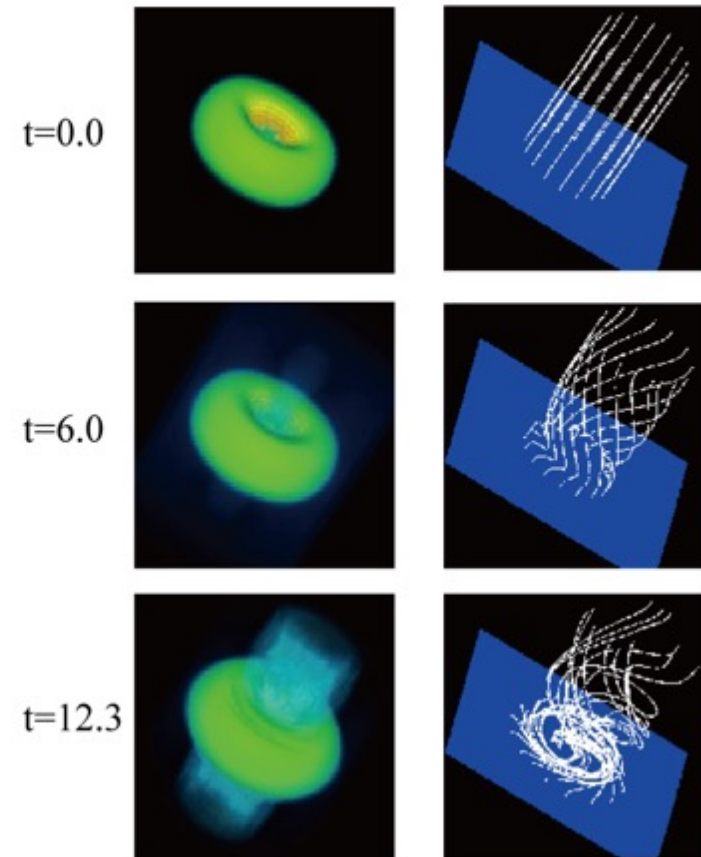
Toshiki Tajima, UCI

Class 4:PHY249 (2020Spring)



Event Horizon Telescope (2020)

3D Structure of Disk and Jet



Tajima Shibata (1997) p. 387

Plasma Astrophysics (Tajima, 2020)

----- general overview

- Class 1: Introduction to “plasma astrophysics”

instabilities vs. [structure formation](#) of plasma

exemplary processes in plasma astrophysics, plasma β

- Class 2: Gravity + Plasma + **B**

[magnetic Buoyancy](#), magneto-rotational instability (MRI)

explosive evolution of [flux tubes](#), [filamentary](#) Universe

- Class 3: Accretion disk and jets

MRI on accretion disk, [anomalous viscosity](#), [jet](#) formation

[Stimulus to evolution](#) of the Universe

----- now specific realizations

- Class 4: Neutron star-neutron star collision

[gravitational wave](#) and γ -bursts

- Class 5: “Physiology” of accretion disks

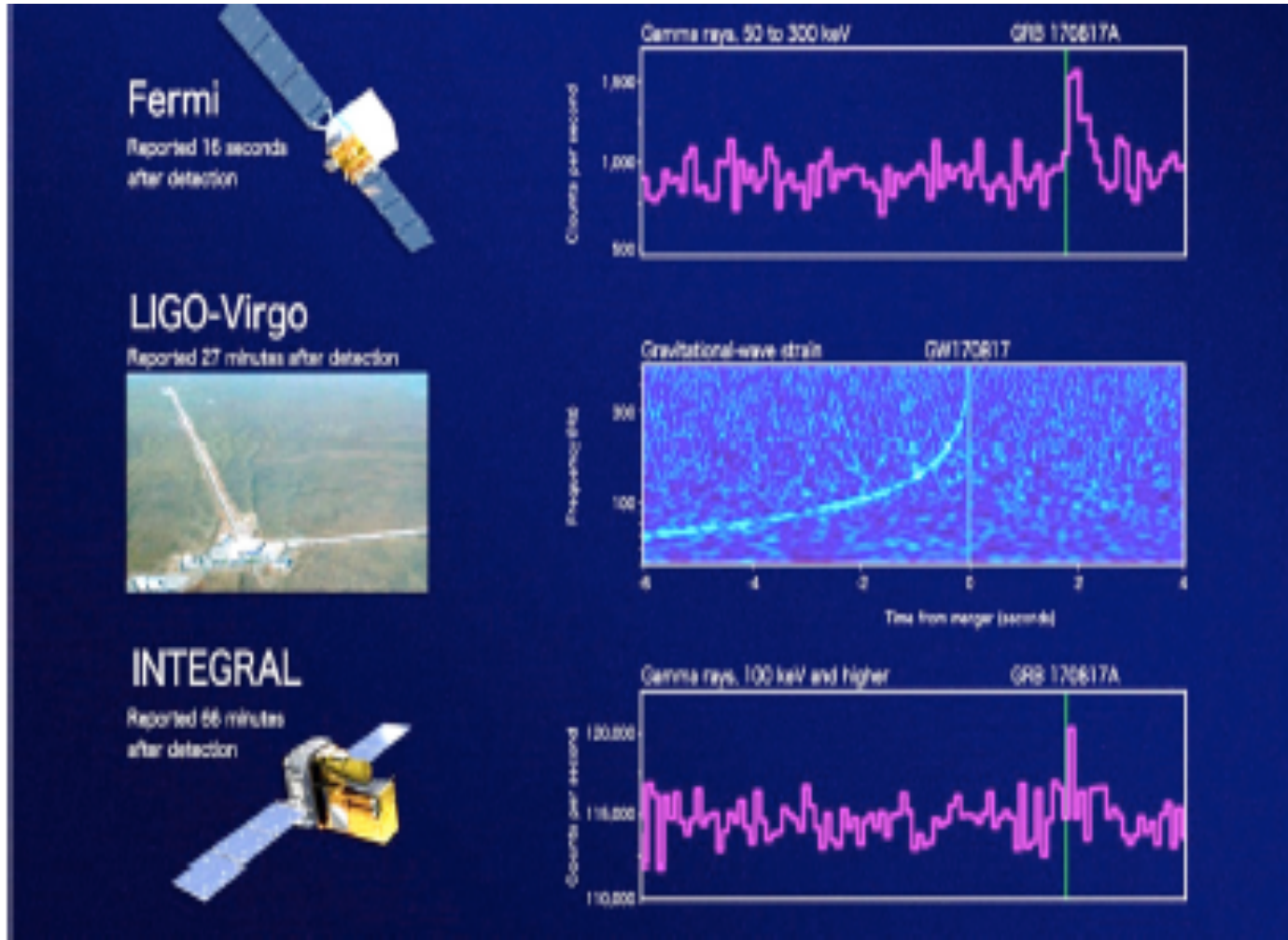
(Episodic eruptions and extreme high energy cosmic rays)

Mother [Nature’s accelerator](#) (from Fermi → new paradigm)

Collision of Neutron star-neutron star

- Collisions of **galaxies** (or **AGNs**) and those of **stars** happen often. Why?
- **Accelerate** the evolution of the Universe
- **Triggers violent and collective plasma** processes
- **Gravity + plasma + B**: essential ingredients
e.g. **jets** (the largest structure, why? ← collective modes)
- The more **violent** excited waves are, the more **coherent** they become: plasma loves violent waves = **jets** (knotted twisted Alfven waves) and **wakefields**
- **In 2017 Mother Nature emitted her important signal**

Neutron star-neutron star collision



from accretion disk

and jets emanated from NS-NS collision →

GW emission and gamma emission

LIGO

(Laser Interferometric Gravitational wave Observatory)

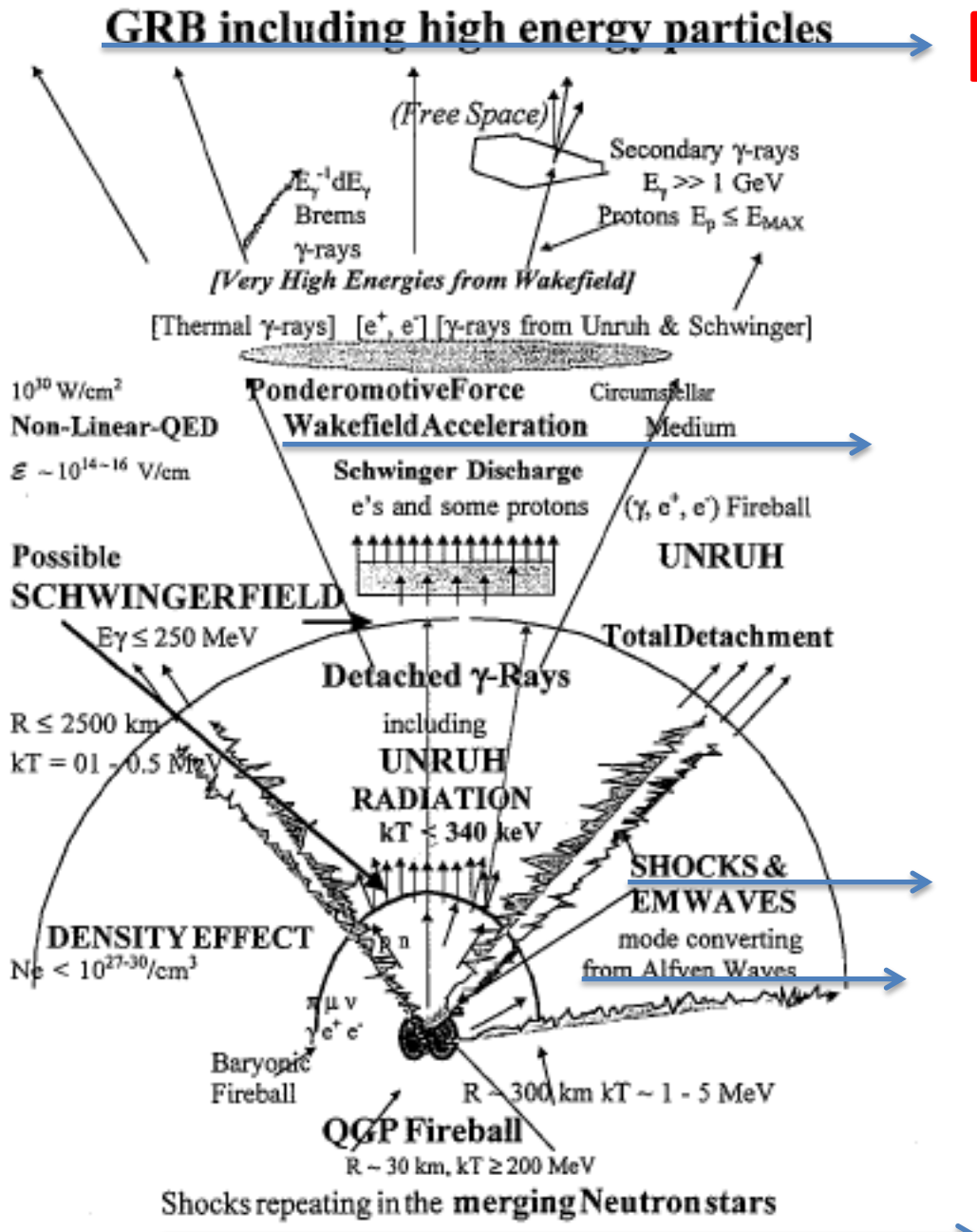
Fig. 5. Gamma-ray emission detected by Fermi and Integral satellites from the neutron star merging event (GW170817) delayed by 1.7 seconds compared with gravitational wave burst [79]. This time difference may be explained by the time to build-up the system for the acceleration of charged particles, described in the present

Barry Barish: 2017 Nobel Observation of Gravitational Waves



With Professor B. Barish at **LIGO**, Caltech

Takahashi et al. (2000)



Prophetic picture (2000)

NS-NS collision triggers →

- QGP (Quark-Gluon plasma)
- Shocks / **gravitational waves**
- Accretion disk
- Jets
- Alfvén waves and EM waves
- Wakefield acceleration
- GRB (gamma bursts)

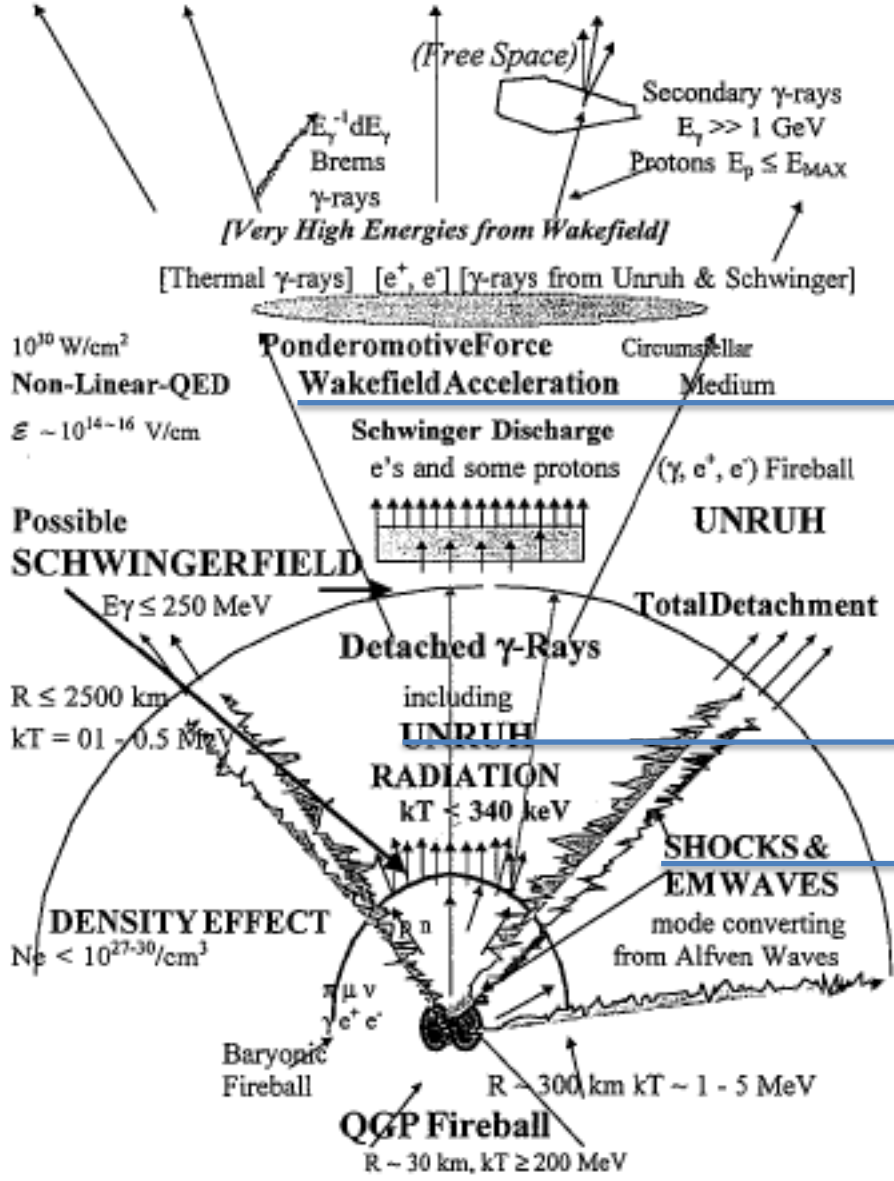
.....

Figure 8. A schematic illustration of the proposed concept.

GRB including high energy particles

Time scales of NS-NS collision

← n_e density decreases



Accretion disk

Jets/

Alfvén waves and EM waves/
Wakefield acceleration / $3 \times 10^5 \text{ km}$
GRB (gamma ray bursts) $t = 1 \text{ s}$

Unruh radiation 3000 km $t = 10 \text{ ms}$

Baryon fireball 300 km $t = 1 \text{ ms}$

Shocks / gravitational waves
QGP (Quark-Gluon plasma)

30 km $t = 0$

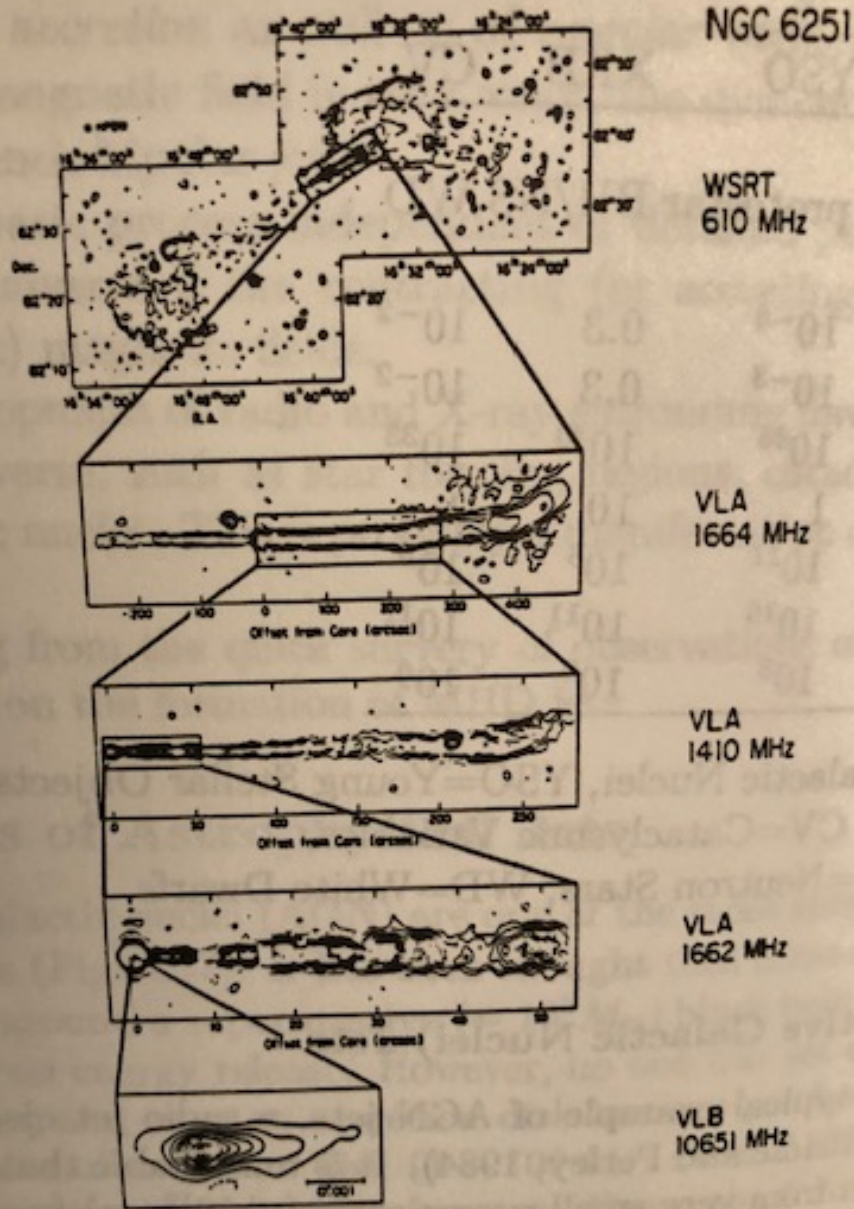
Shocks repeating in the merging Neutron stars

Figure 8. A schematic illustration of the proposed concept.

Extended structure of jets

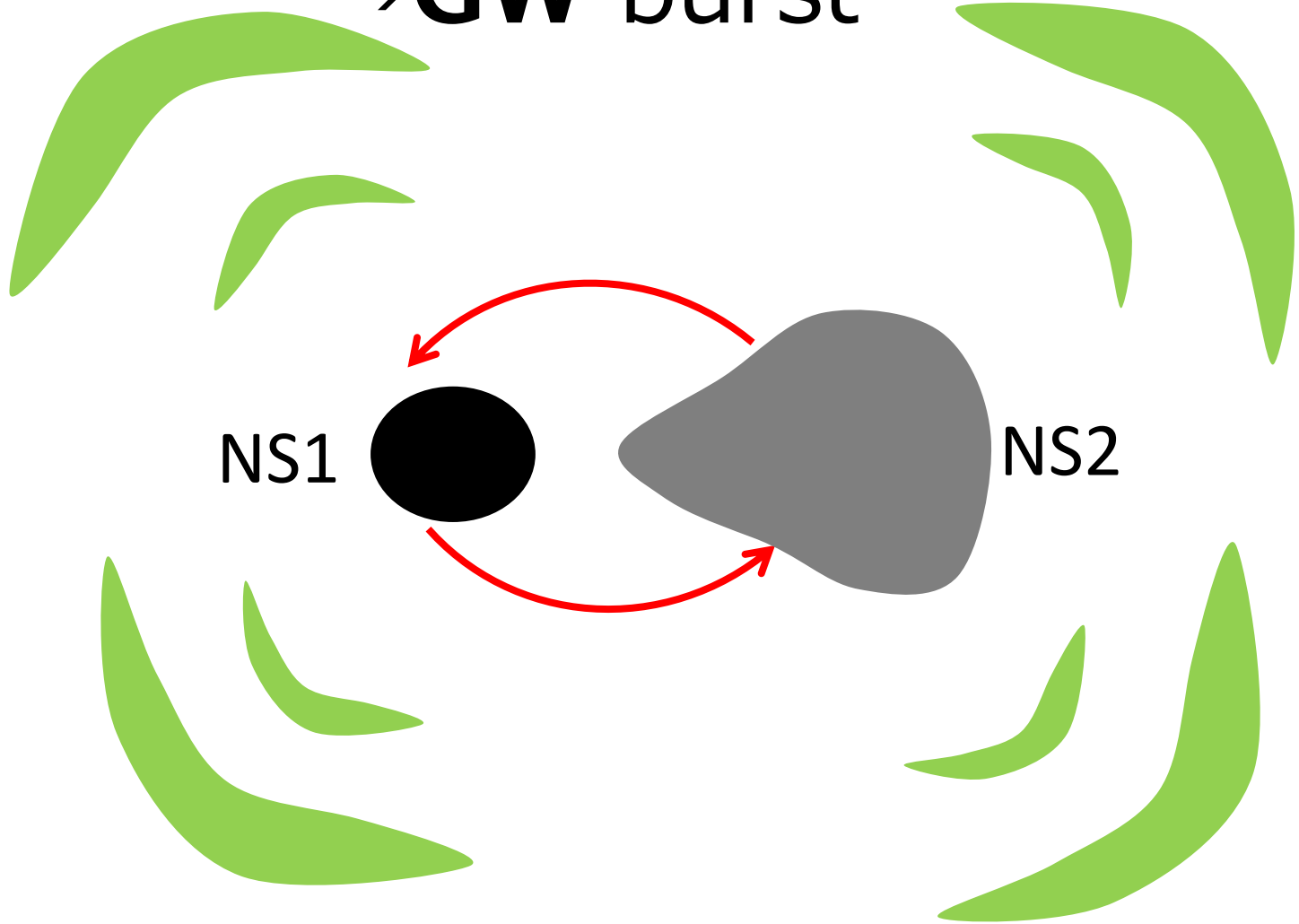
Jets deliver the momentum,
energy, and mass to the furthest

Jets and accretion disks: also
introduce **dissipative** parts in
collective modes
→ **accelerates** evolution of
Universe



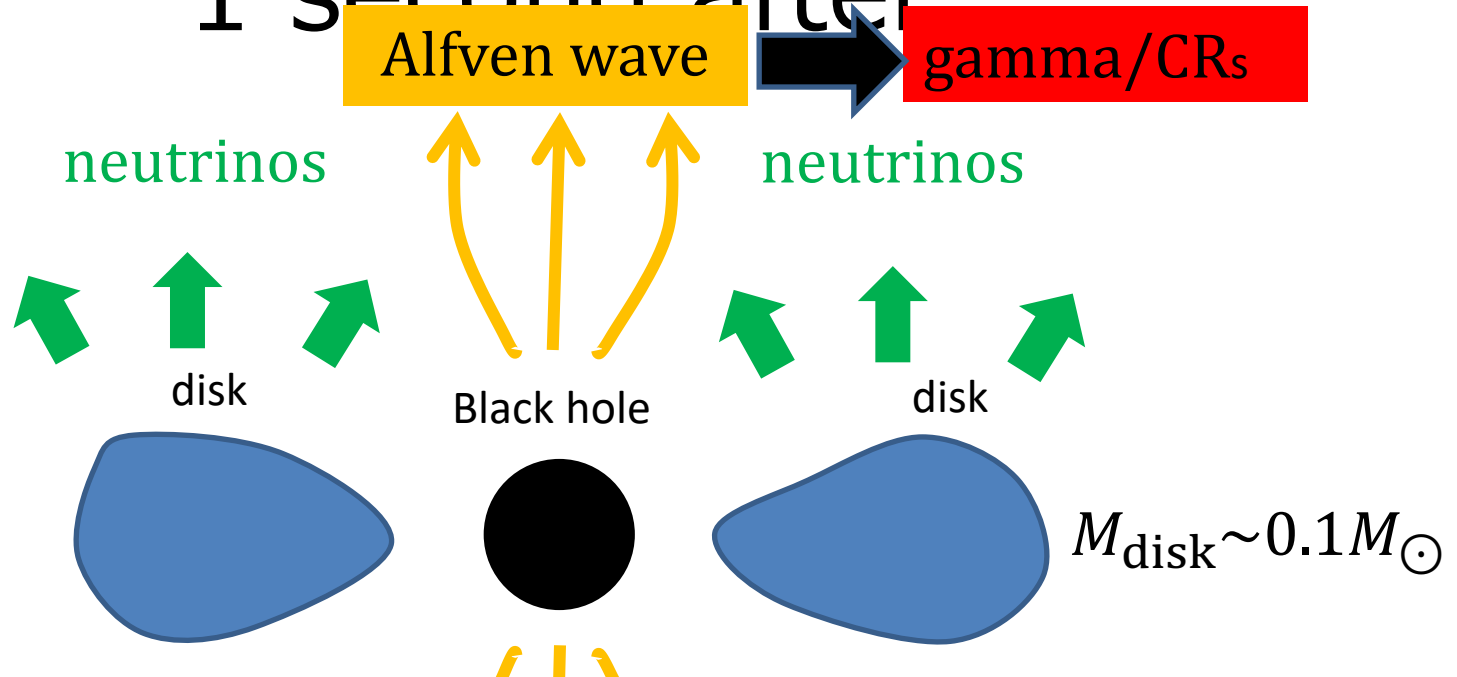
Radio images of jets ejected from nucleus of radio galaxy, NGC6251 (from Bridgman et al. 1997)

NS-NS merger → **GW** burst



NS-NS merger → BH + Disk

1 second after



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

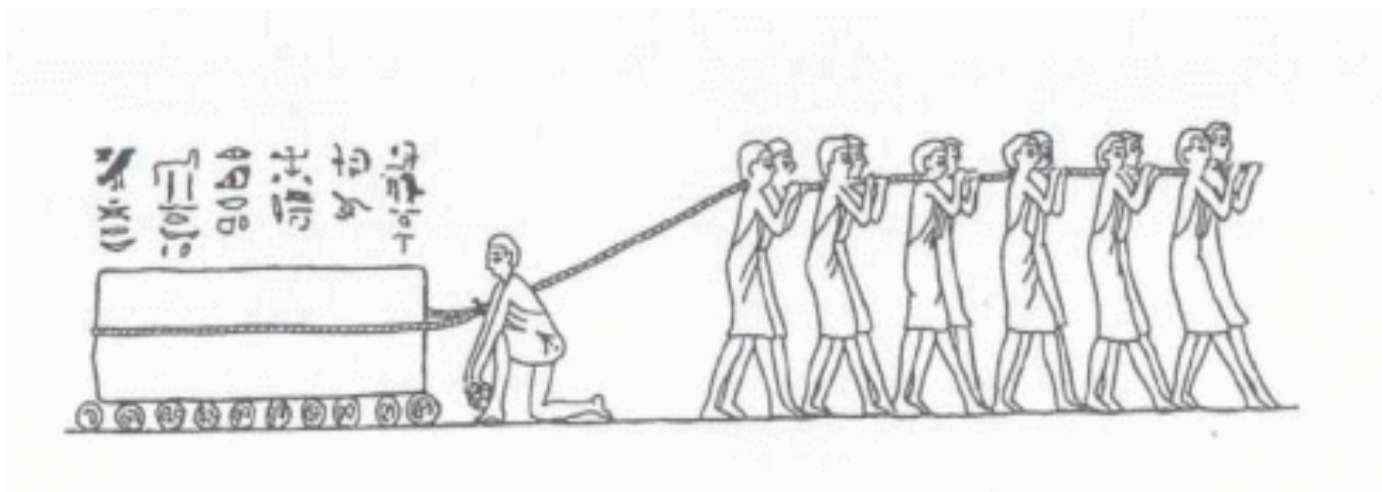
Central Engine of GRB/Hypernova

Alfven wave

Plasma's **Collective** Force / Modes

Collective force $\sim N^2$ (nonlinear \leftarrow linear force $\sim N$)

Coherent and smooth structure (not stochastic)



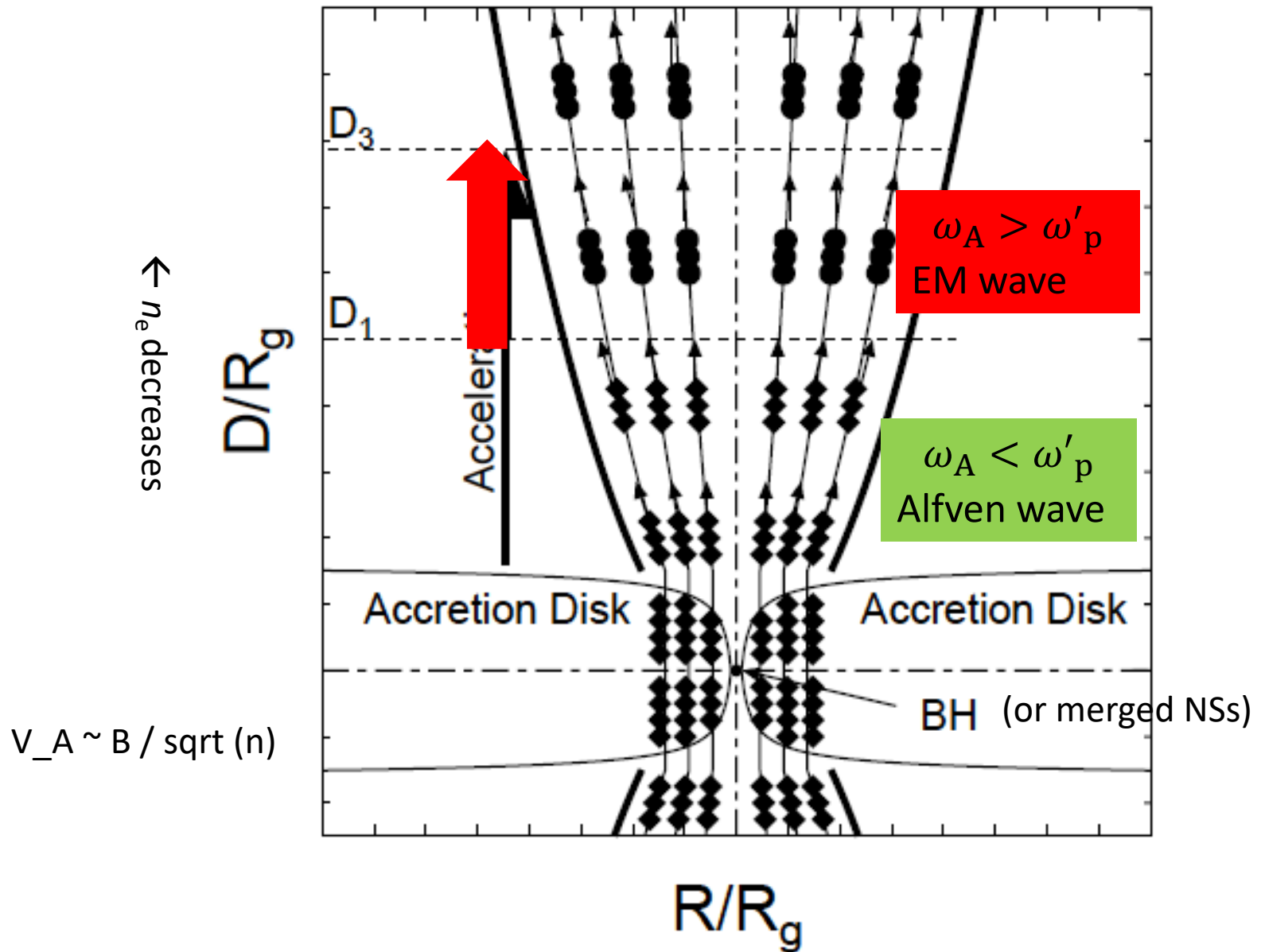
enhancement by $10^3 - 10^4$ (even by 10^{6-12}) \gg interaction of one particle x one particle

Collective mode delivery (EM x plasma x B) \leftrightarrow **long-ranged** force (gravity, EM)
what difference?

e.g. **jet**

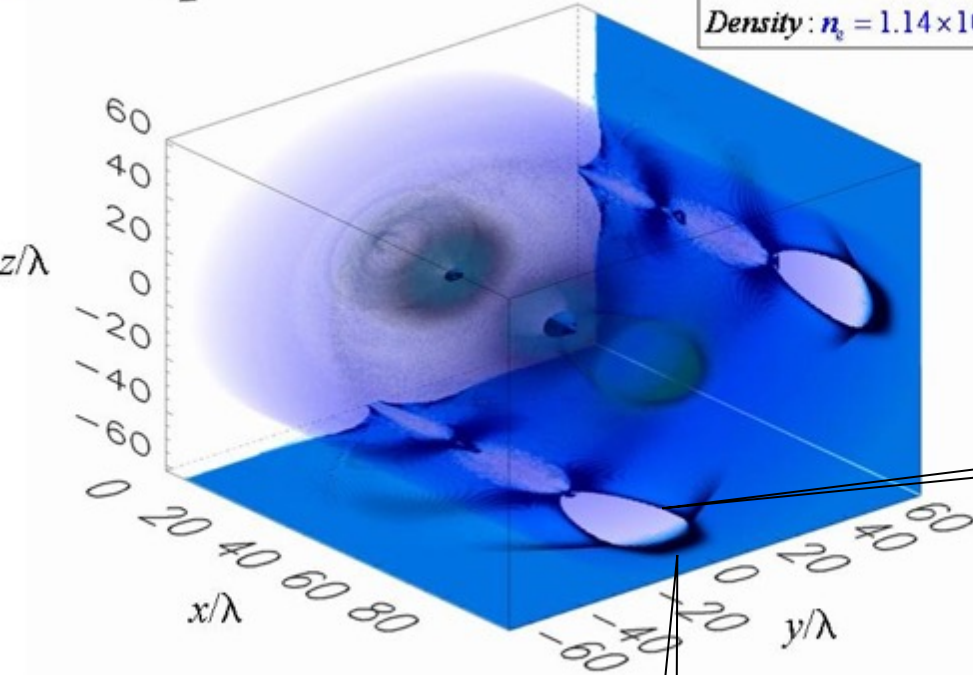
e.g. galaxy-galaxy interaction

Wakefield generation in Jet



EM pulse-driven bow and stern wakes

Density: $n_e = 1.14 \times 10^{18} \text{ cm}^{-3}$



Wakefield

(Tajima Dawson
1979)

Wake Wave



Bow Wave

Ponderomotive acceleration

(Bulanov, Esirkepov)

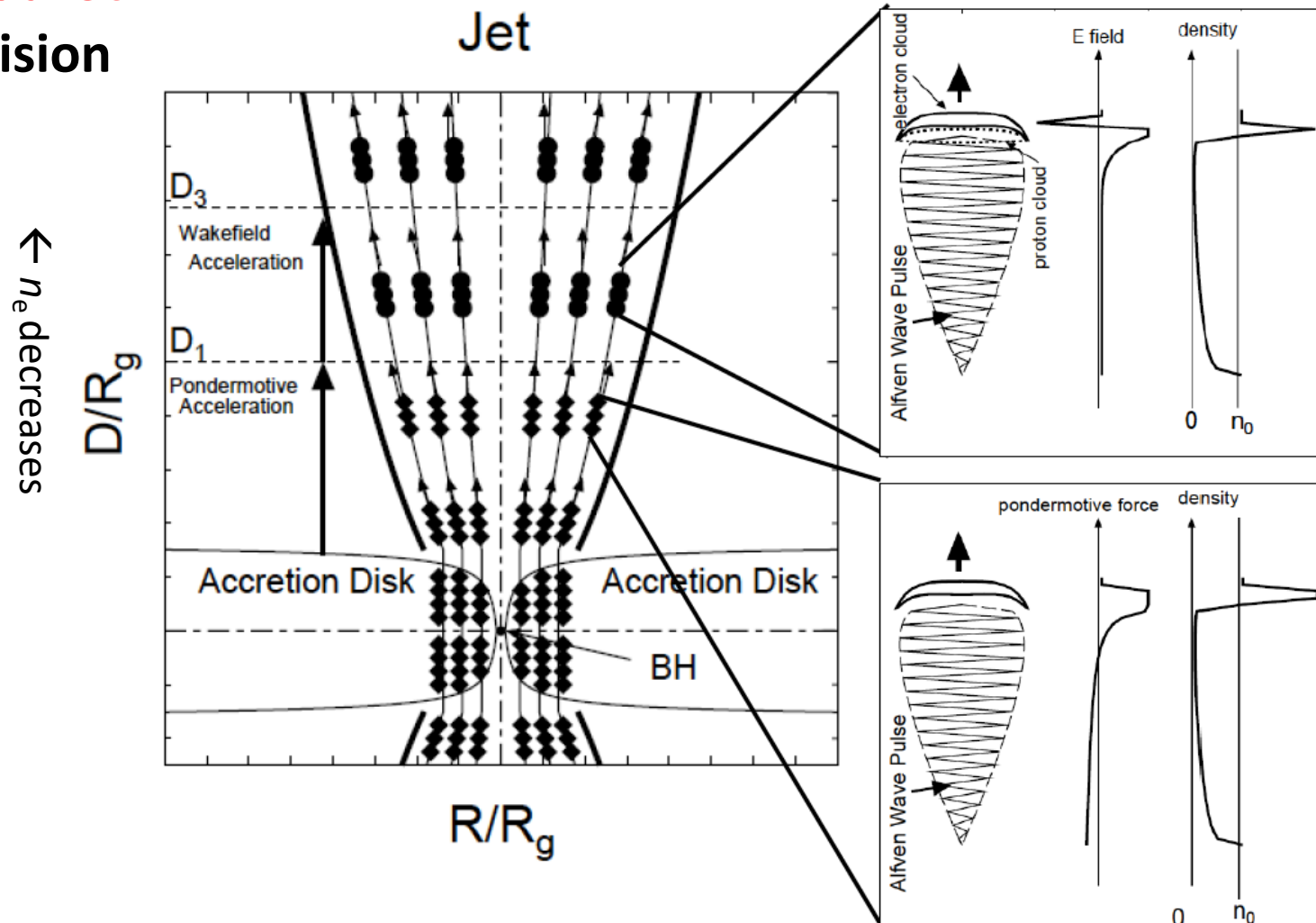
Intense Alfvén Shock from root of jet

→ Intense **EM** pulse

→ **wakefield** generation → Electron acceleration

→ **γ burst**

from NS-NS collision



Spacetime scales of the collision

Accretion disk

Jets/

Alfven waves and EM waves/

Wakefield acceleration / $3 \times 10^5 \text{ km}$

GRB (gamma ray bursts) $t = 1 \text{ s}$

Unruh radiation 3000 km $t = 10 \text{ ms}$

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Shocks / gravitational waves

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30 km

$t = 0$

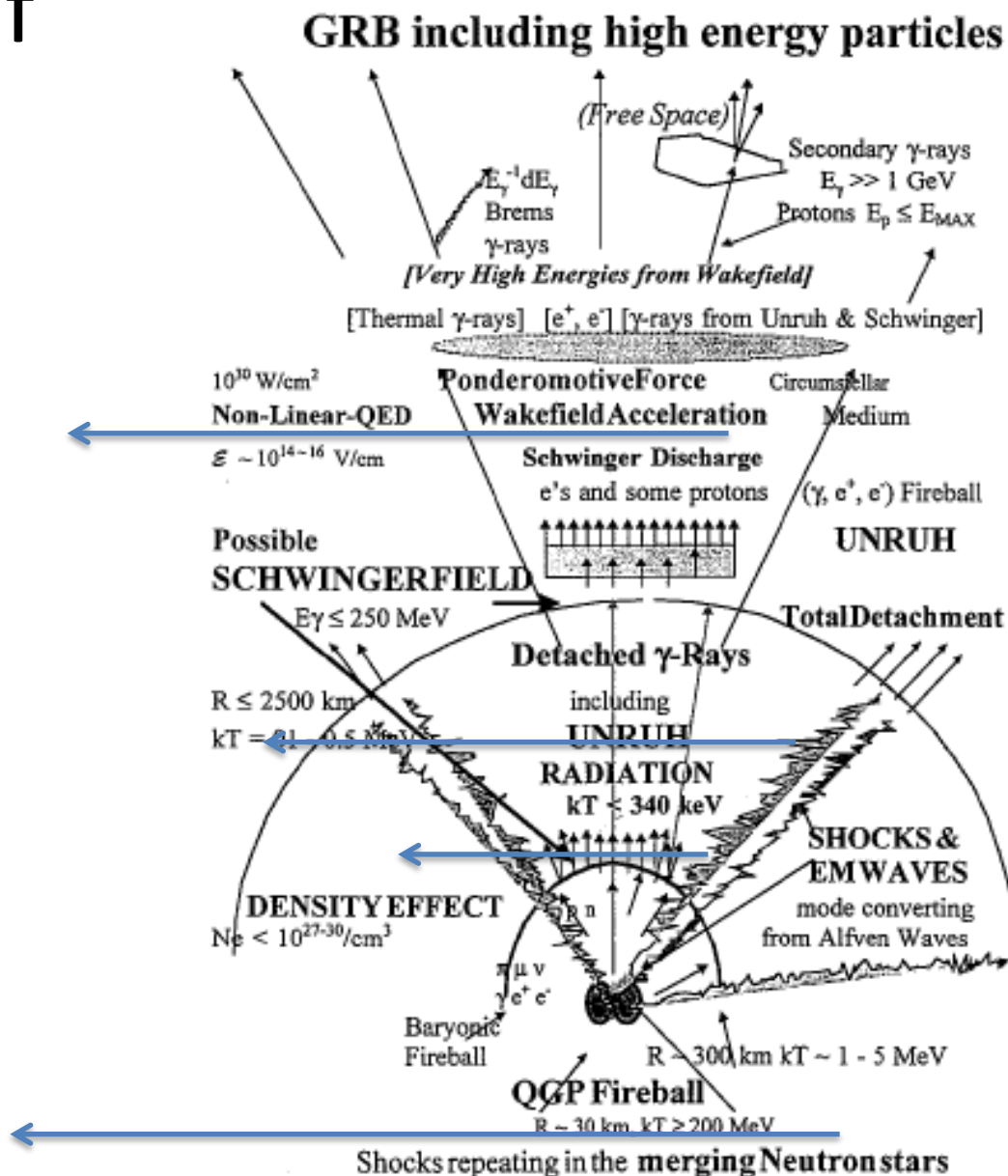
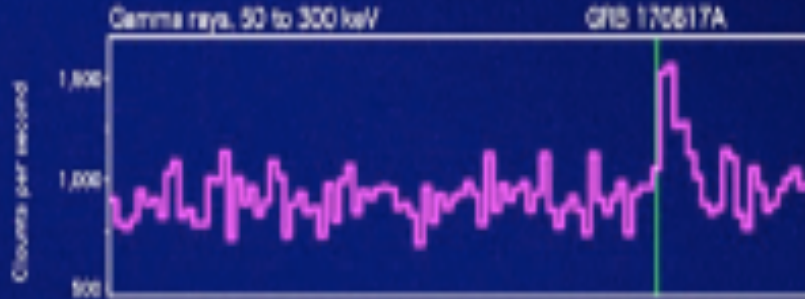


Figure 8. A schematic illustration of the proposed concept.

Takahashi, Y., Hillman, L.W., Tajima, T., *Relativistic Lasers and High Energy Astrophysics: Gamma Ray Bursts and Highest Energy Acceleration*, in *High Field Science*, Eds., T. Tajima, K., Mima, and H. Baldis (Kluwer, NY, 2000).pp171-221.

Fermi

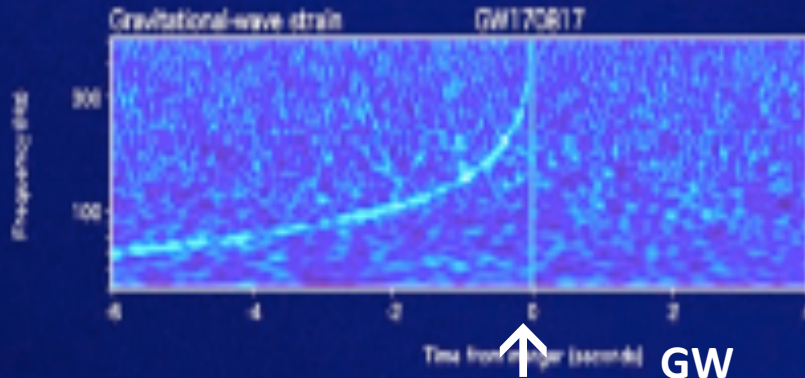
Reported 16 seconds
after detection



↑ γ -burst (from wakefield
electrons
1.7sec
later)

LIGO-Virgo

Reported 27 minutes after detection



↑ GW

INTEGRAL

Reported 66 minutes
after detection

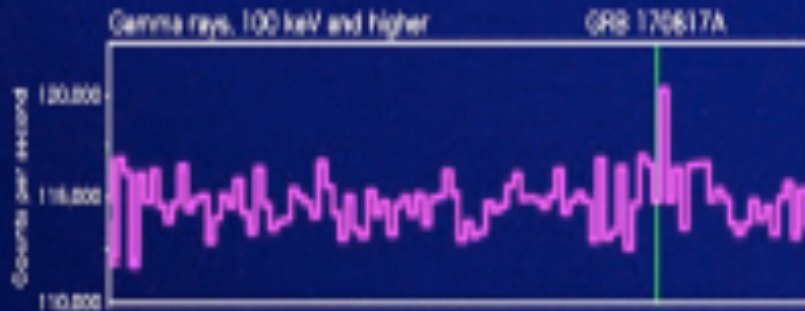


Fig. 5. Gamma-ray emission detected by Fermi and Integral satellites from the neutron star merging event (GW178017) delayed by 1.7 seconds compared with gravitational wave burst [79]. This time difference may be explained by the time to build-up the system for the acceleration of charged particles, described in the present