Wakefield Acceleration (WFA) in Laboratories and Beyond

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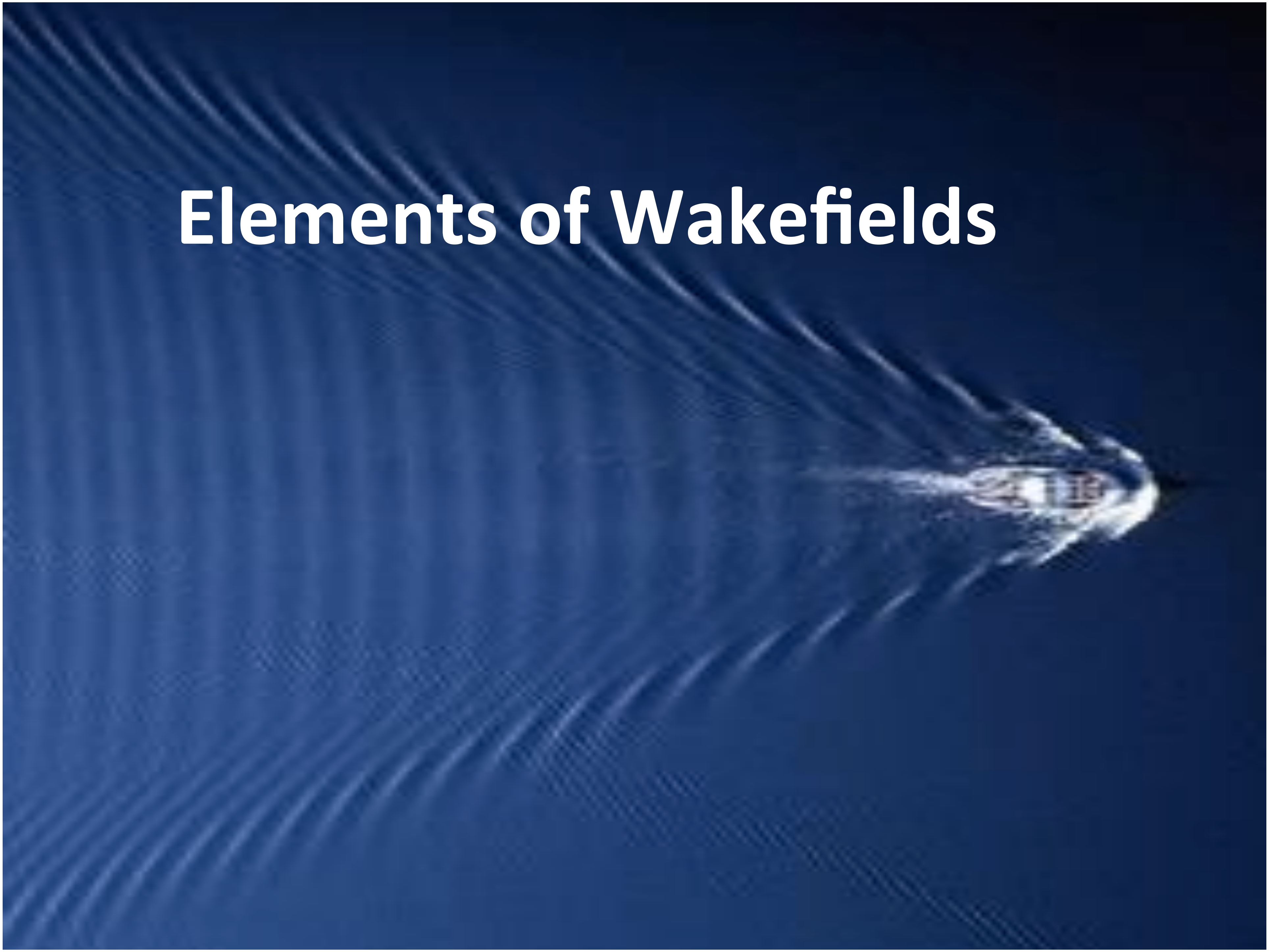
Wilson Prize Lecture
APS, Denver
April 13, 2019

abstract

1. **Wakefield (1979): robustly elevated energy state, relativistic coherence, Higgs' state of plasma driven by laser with high phase velocity wave**
2. **CPA (1985) → Demonstration of Laser Wakefield Acceleration: Nakajima,….Tajima (1994, 95)**
3. **Gamma-ray bursts (Blazars): signature of wakefields found in nature (2013)**
4. **Applications of LWFA: e.g. endoscopic cancer therapy (2018)**
5. **What may lie ahead: New technology thin film compression (2014) → "TeV on a chip" (X-ray LWFA)**

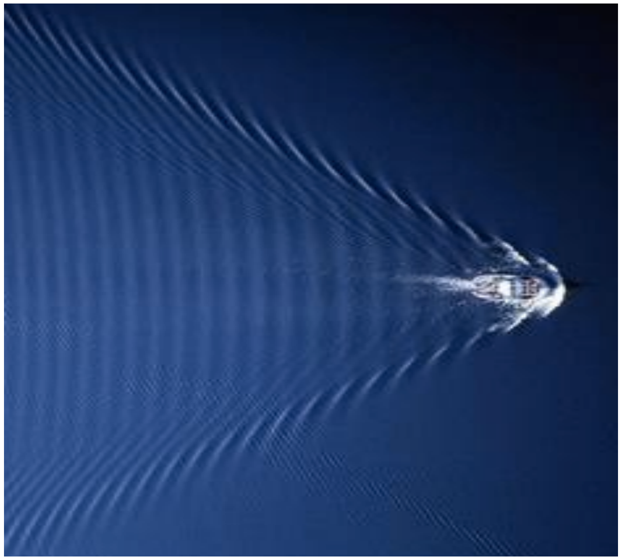
Elements of Wakefields



Laser Wakefield (LWFA):

Wake phase velocity >> water movement speed maintains **coherent** and **smooth** structure

Tsunami phase velocity becomes ~0, causes **wavebreak** and **turbulence**

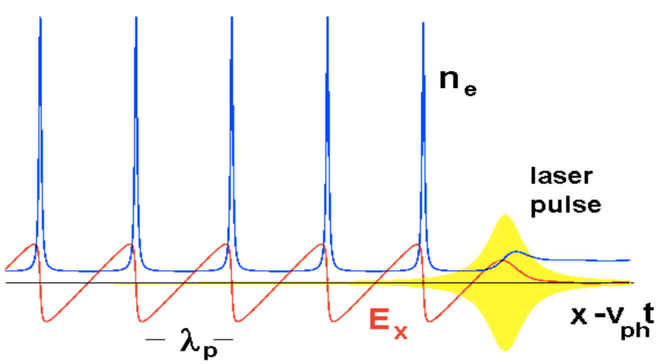


vs

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

No wave breaks and wake **peaks** at v≈c

Wave **breaks** at v<c

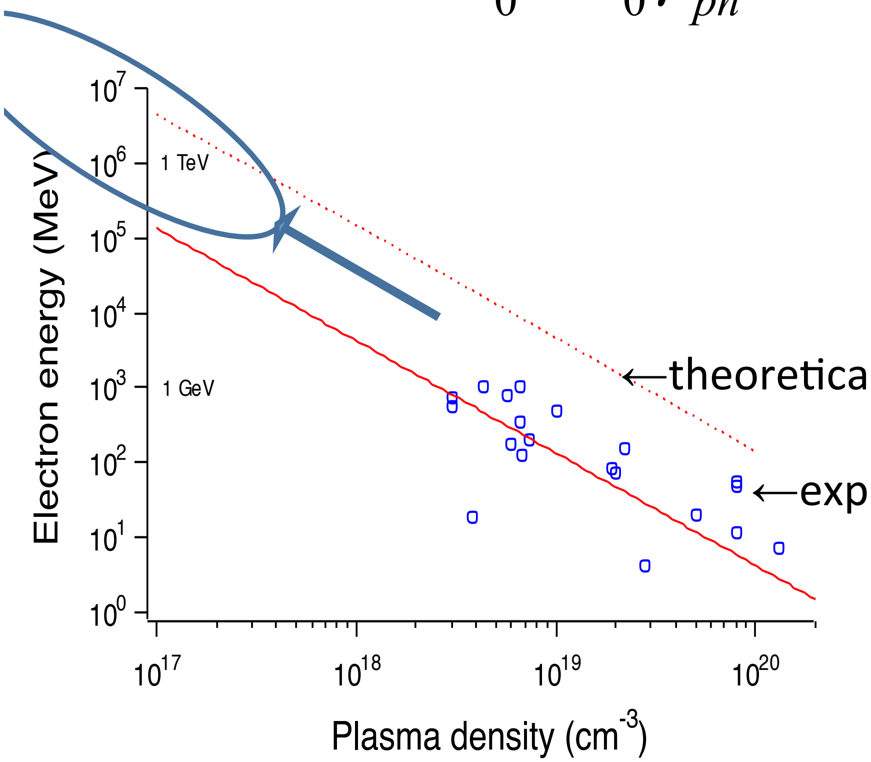


← relativity regularizes (***relativistic coherence***)

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

Theory of wakefield toward extreme energies

$$\Delta E \approx 2m_0c^2a_0^2\gamma_{ph}^2 = 2m_0c^2a_0^2\left(\frac{n_{cr}}{n_e}\right),$$ (when 1D theory applies)



In order to avoid wavebreak,

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

where

$$\gamma_{ph} = (\omega_0 / \omega_p)$$

$n_{cr} = 10^{21}$

$n_e = 10^{16}$

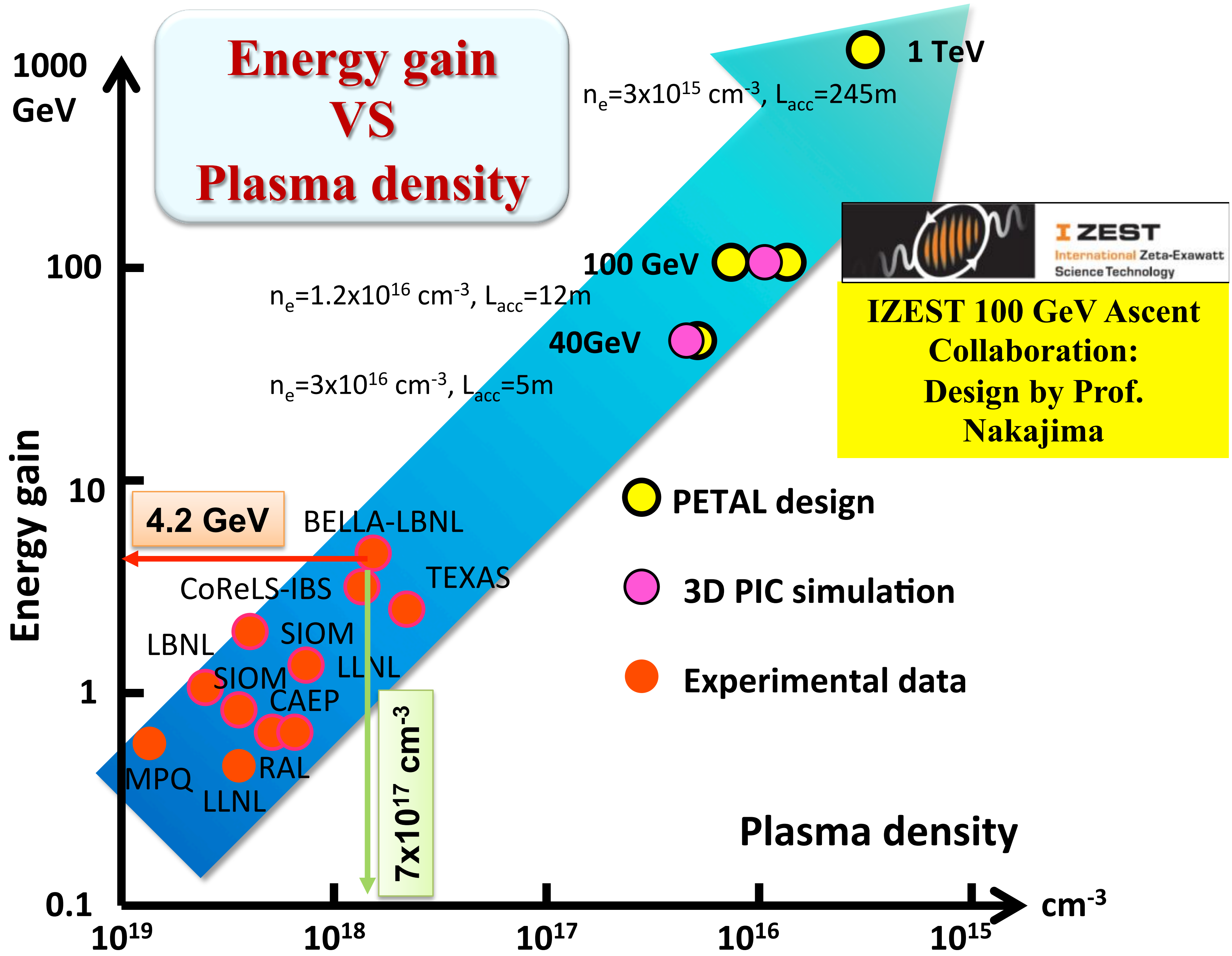
$$L_d = \frac{2}{\pi}\lambda_p a_0^2\left(\frac{n_{cr}}{n_e}\right),$$

dephasing length

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

pump depletion length

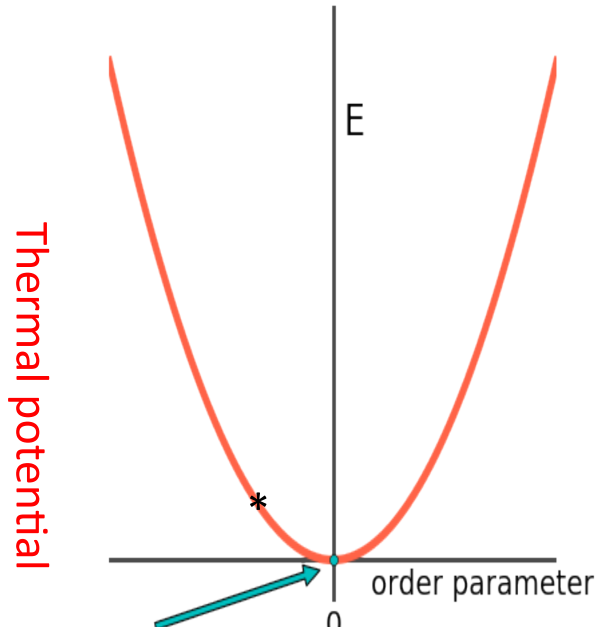
where $\lambda_p = 2\pi c/\omega_p$

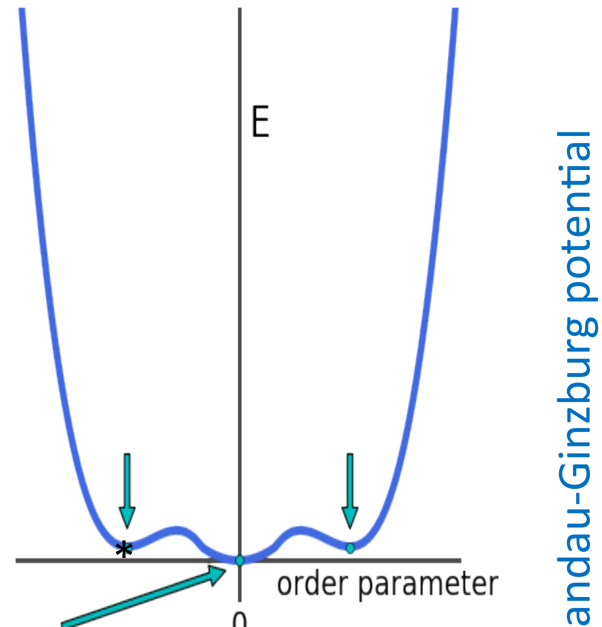


Energy gain
VS
Plasma density
1000 GeV
100
10
1
0.1
Energy gain
1 TeV
n_e=3x10^{15} cm^{-3}, L_{acc}=245m
100 GeV
n_e=1.2x10^{16} cm^{-3}, L_{acc}=12m
40GeV
n_e=3x10^{16} cm^{-3}, L_{acc}=5m
IZEST
International Zeta-Exawatt Science Technology
IZEST 100 GeV Ascent Collaboration: Design by Prof. Nakajima
4.2 GeV
BELLA-LBNL
CoReLS-IBS
TEXAS
LBNL
SIOM
SIOM
LLNL
CAEP
RAL
MPQ
LLNL
7x10^{17} cm^{-3}
PETAL design
3D PIC simulation
Experimental data
Plasma density
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
cm^{-3}

Thermal plasma vs. Wakefields and Higgs

Trivial vacuum vs. Laundau-Ginzburg potential → BCS → Nambu → Higgs vacuum
Thermal plasma and Landau damping → wakefields , plasma with elevated energy





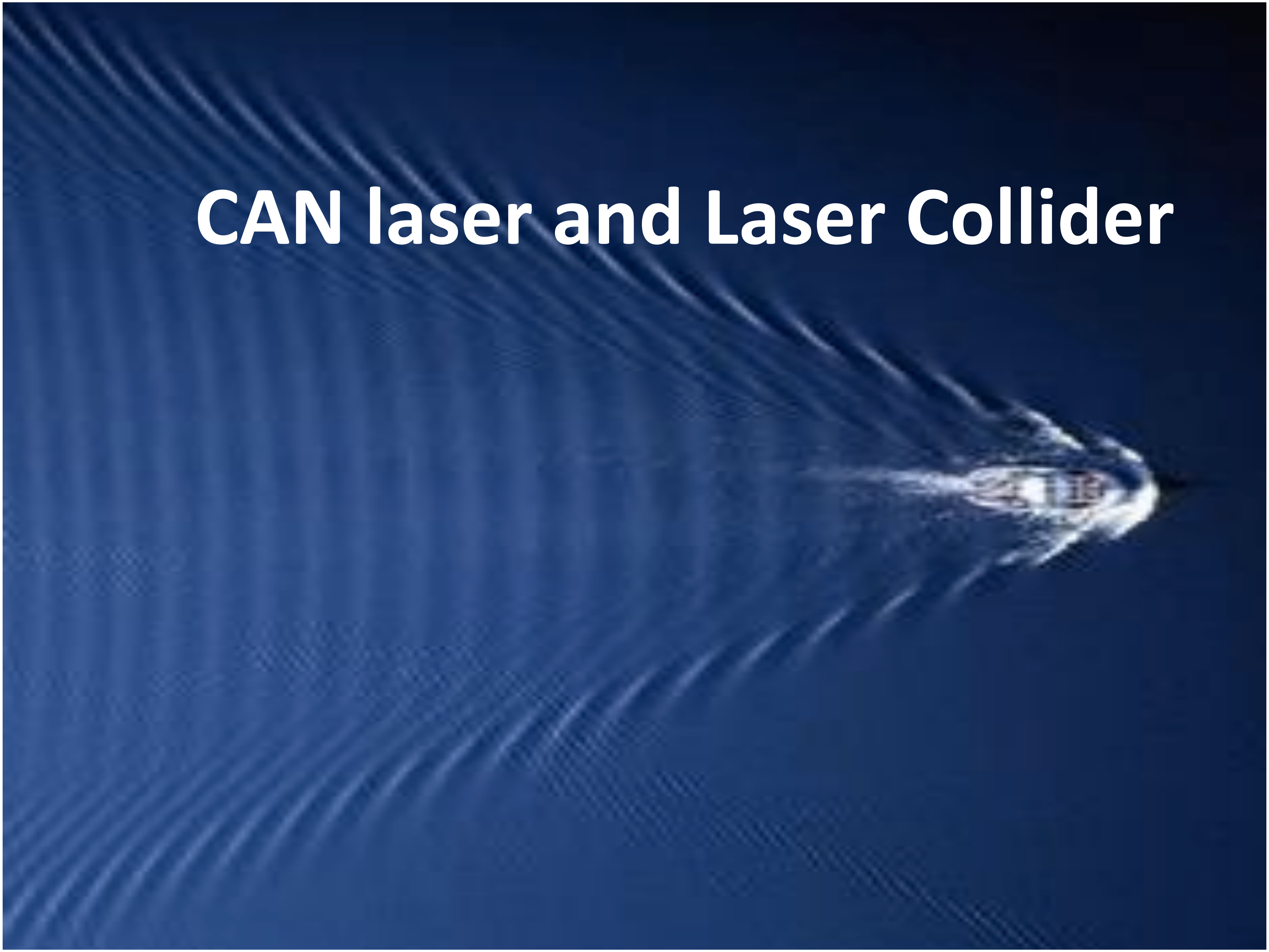
[**Landau damping**: decay of excited waves to equilibrium (left picture)]

Wakefield: no damping; distinct excited <u>stable state</u> ←no particles to resonate (@ *v* = *c*)
= plasma's elevated Higgs state

| 0 > vs. | *H* > (cf . | *H* > → | 0 >)

thermo-equilibrium wakefield state tsunami onshore

CAN laser and Laser Collider

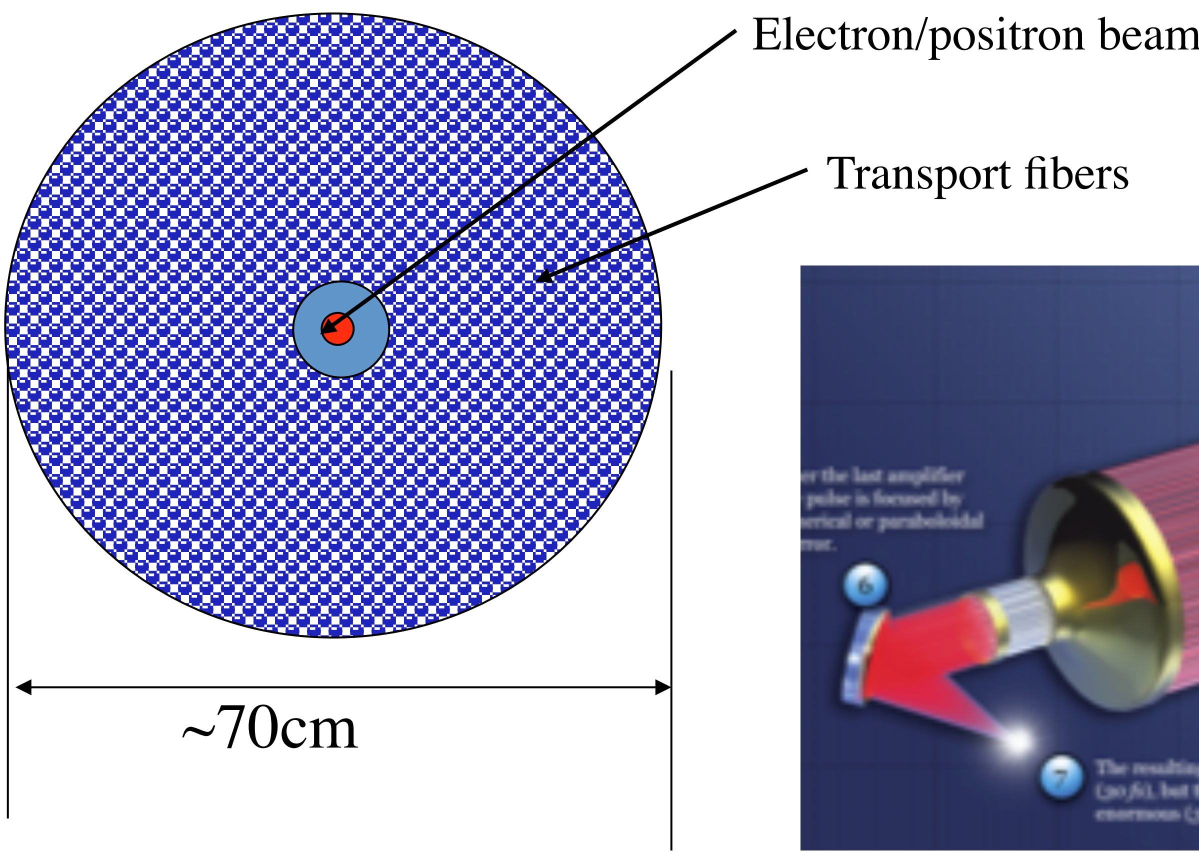


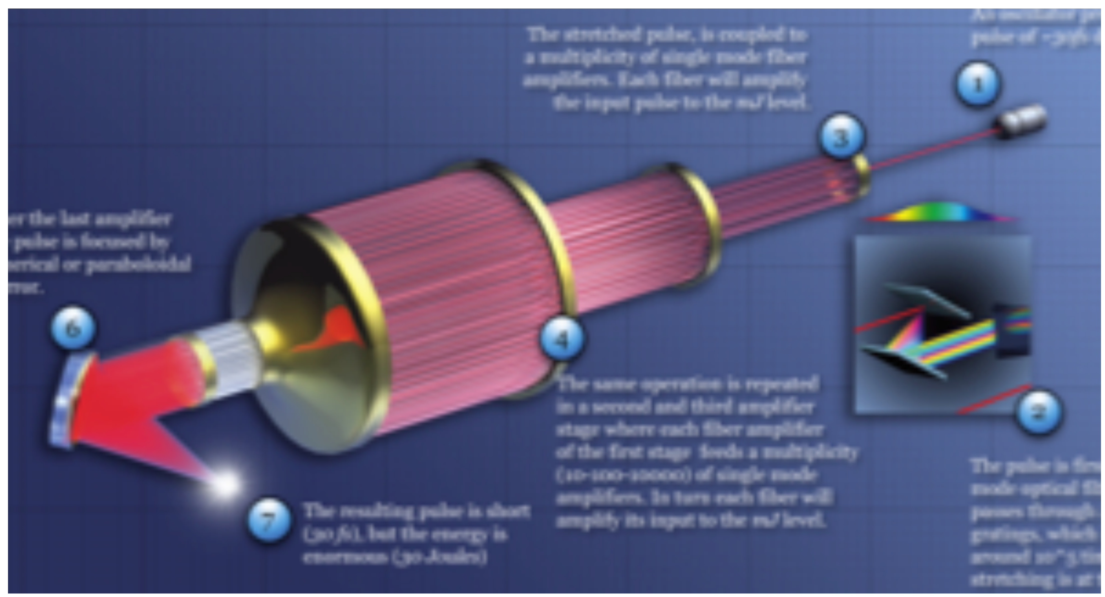
Coherent Amplification Network

Efficient (>30%), high rep rated (~kHz –MHz), light, digitally controllable

CAN laser makes laser collider possible

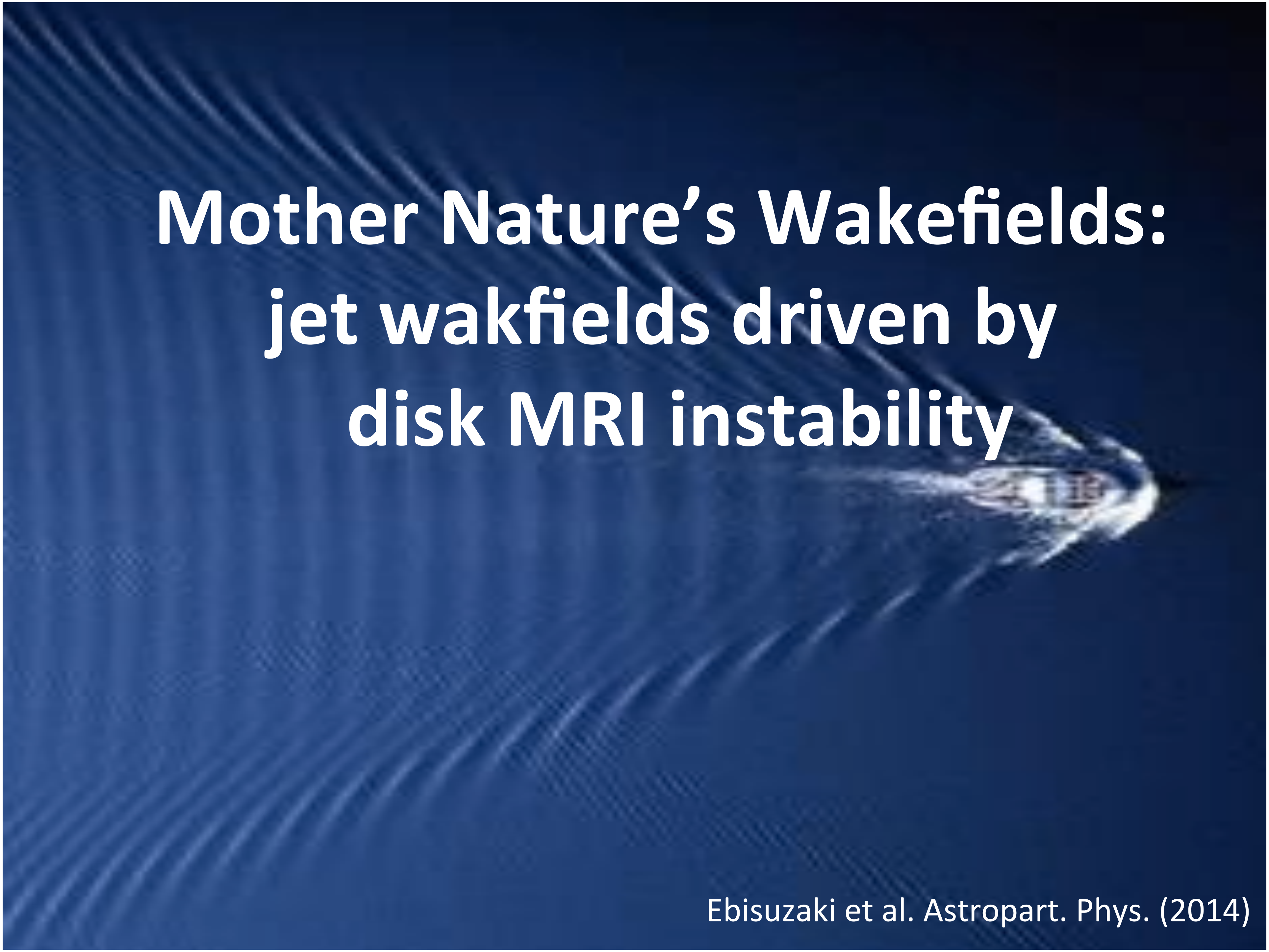
See Nakajima et al. (2018)

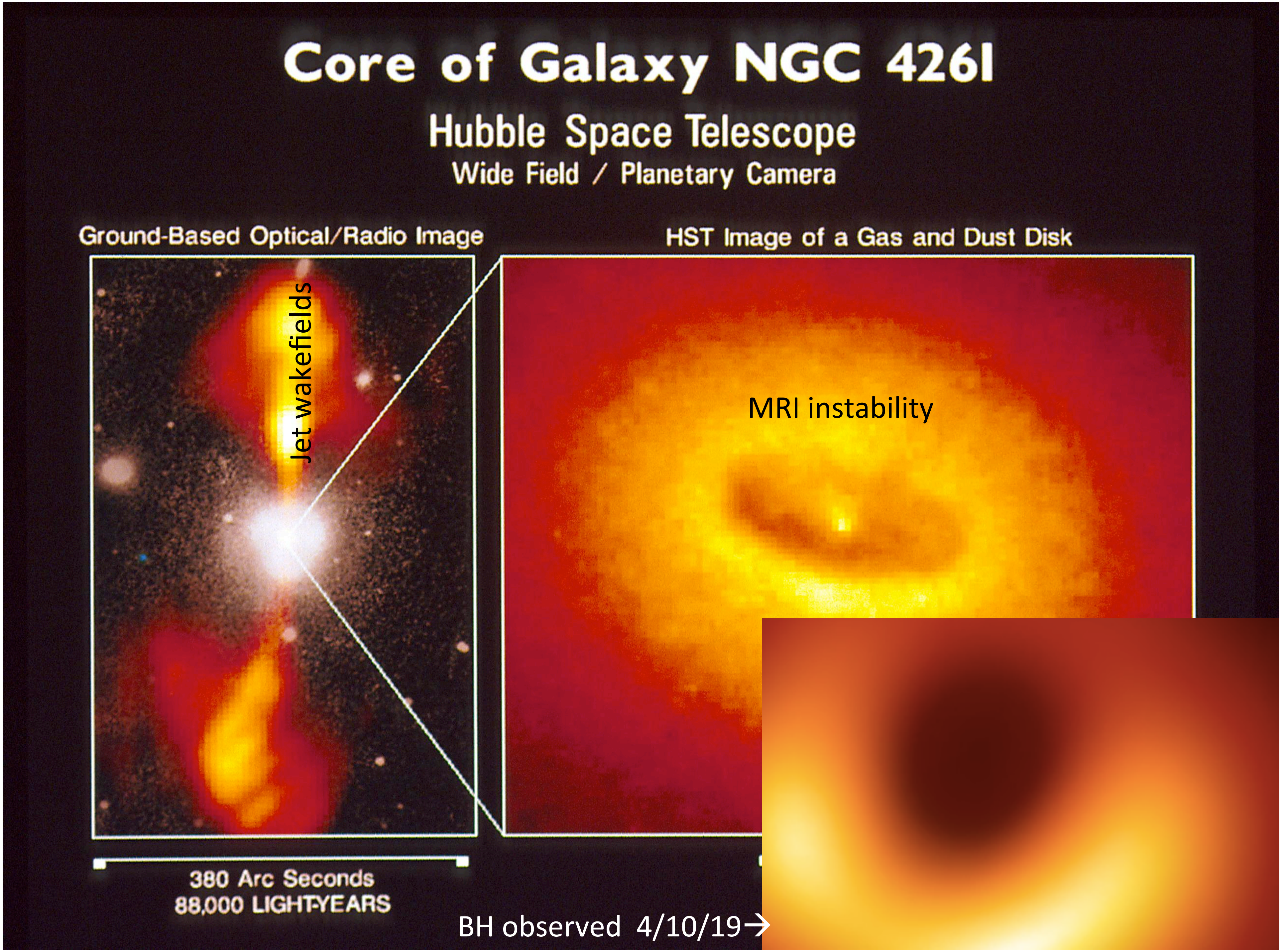




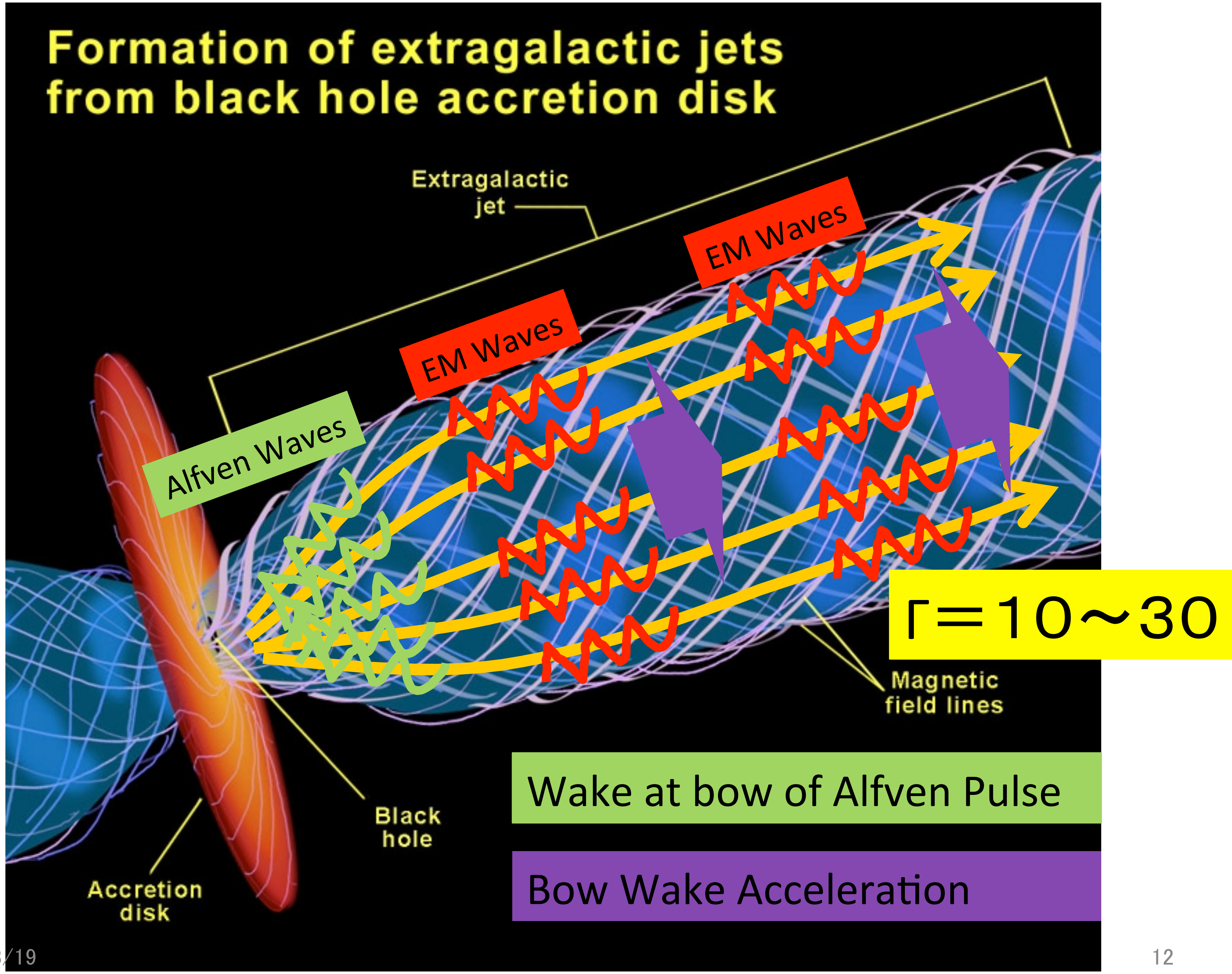
Mourou*, Brocklesby, Tajima, Limpert, Nature Photonics (2013)

*) Nobel Laureate (2018)


Mother Nature's Wakefields:
jet wakfields driven by
disk MRI instability
Ebisuzaki et al. Astropart. Phys. (2014)



Core of Galaxy NGC 4261
Hubble Space Telescope
Wide Field / Planetary Camera
Ground-Based Optical/Radio Image
HST Image of a Gas and Dust Disk
Jet wakefields
MRI instability
380 Arc Seconds
88,000 LIGHT-YEARS
BH observed 4/10/19→



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

Gravitational wave and Gamma bursts

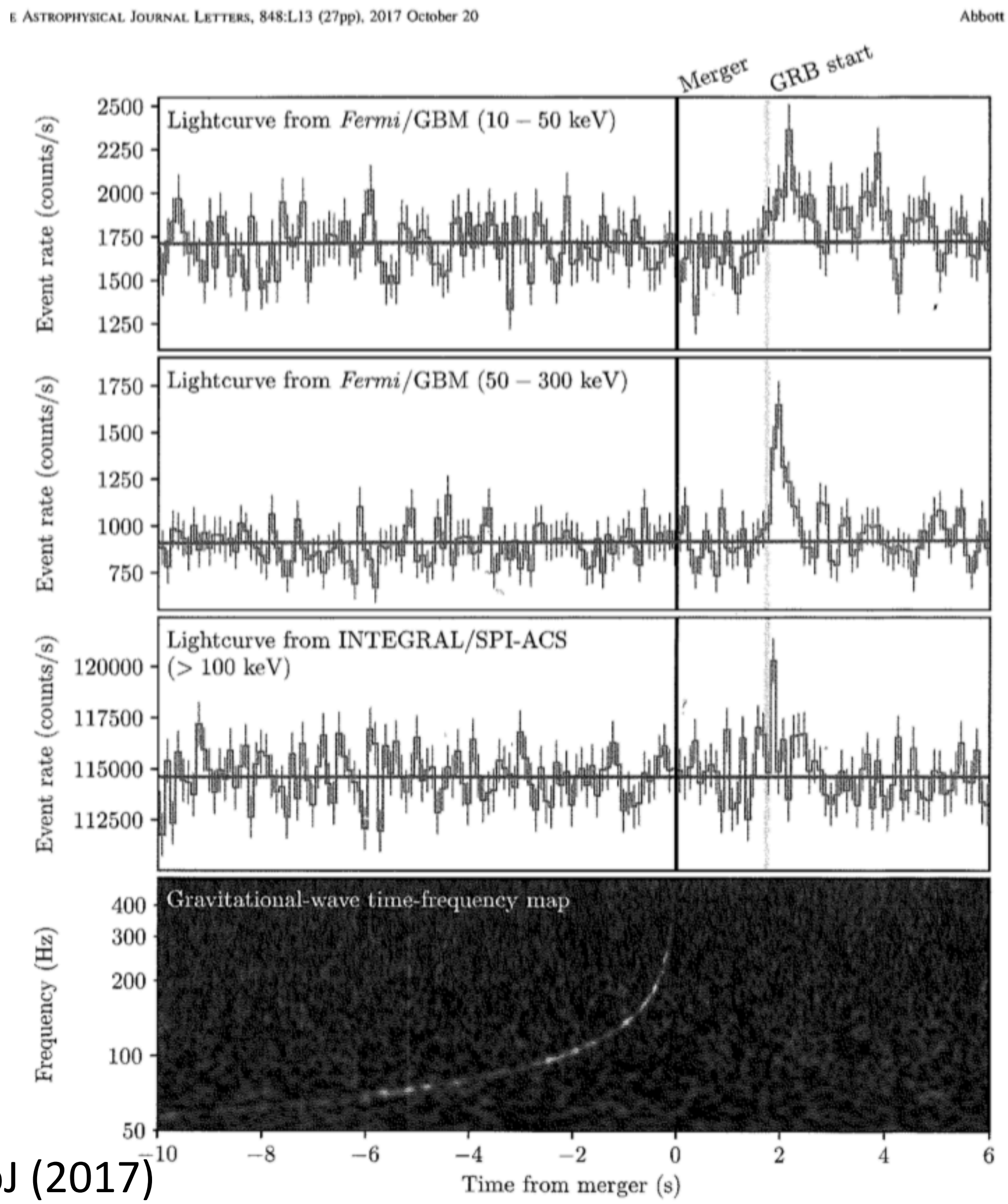
LIGO x Fermi satellite

- gamma bursts synchronize with GW
- GW precedes gamma bursts

see (Ebisuzaki's talk)
Neutron star-Neutron star collision
→ similar wakefields
(Takahashi et al. 2000)

Simultaneous Gravitational Waves →
(Barish**'s talk at UCI, 2018)

**) Nobel Laureate (2017)



Abbott et al. ApJ (2017)

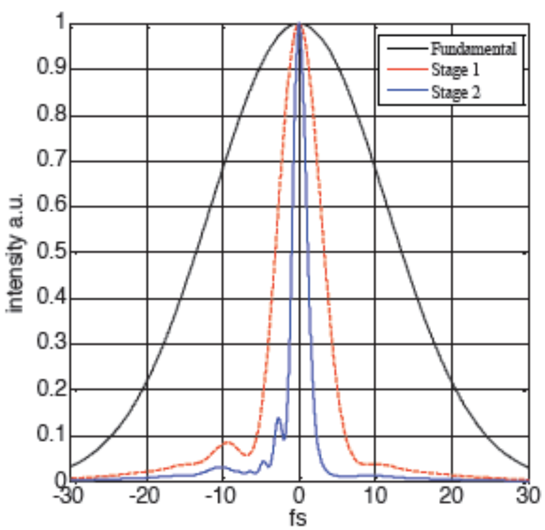
Thin Film Compression and Relativistic Compression: Path toward X-ray laser Wakefield Accelerator

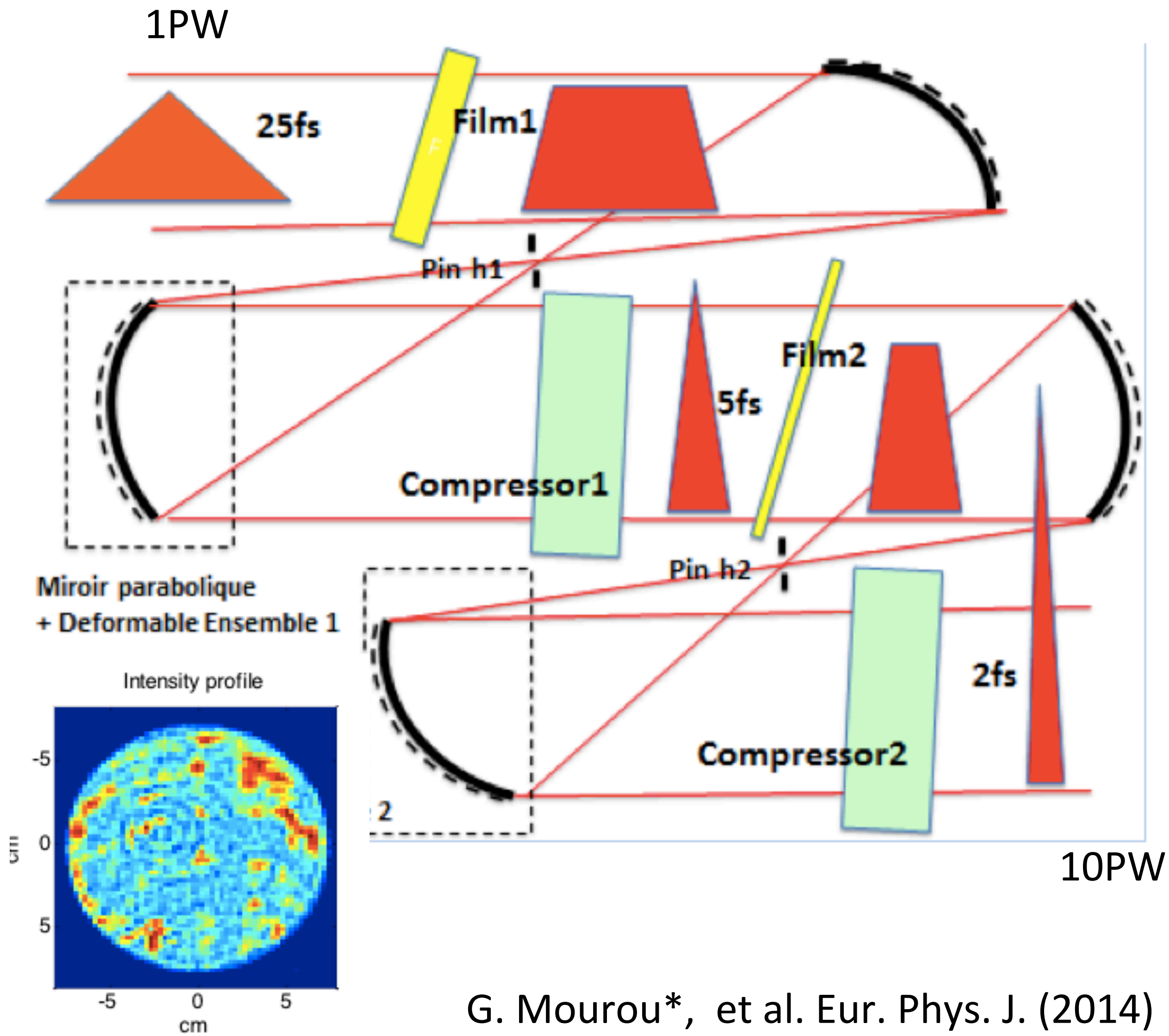
Mourou* et al. (2014)

Single-cycle laser (new Thin Film Compression)

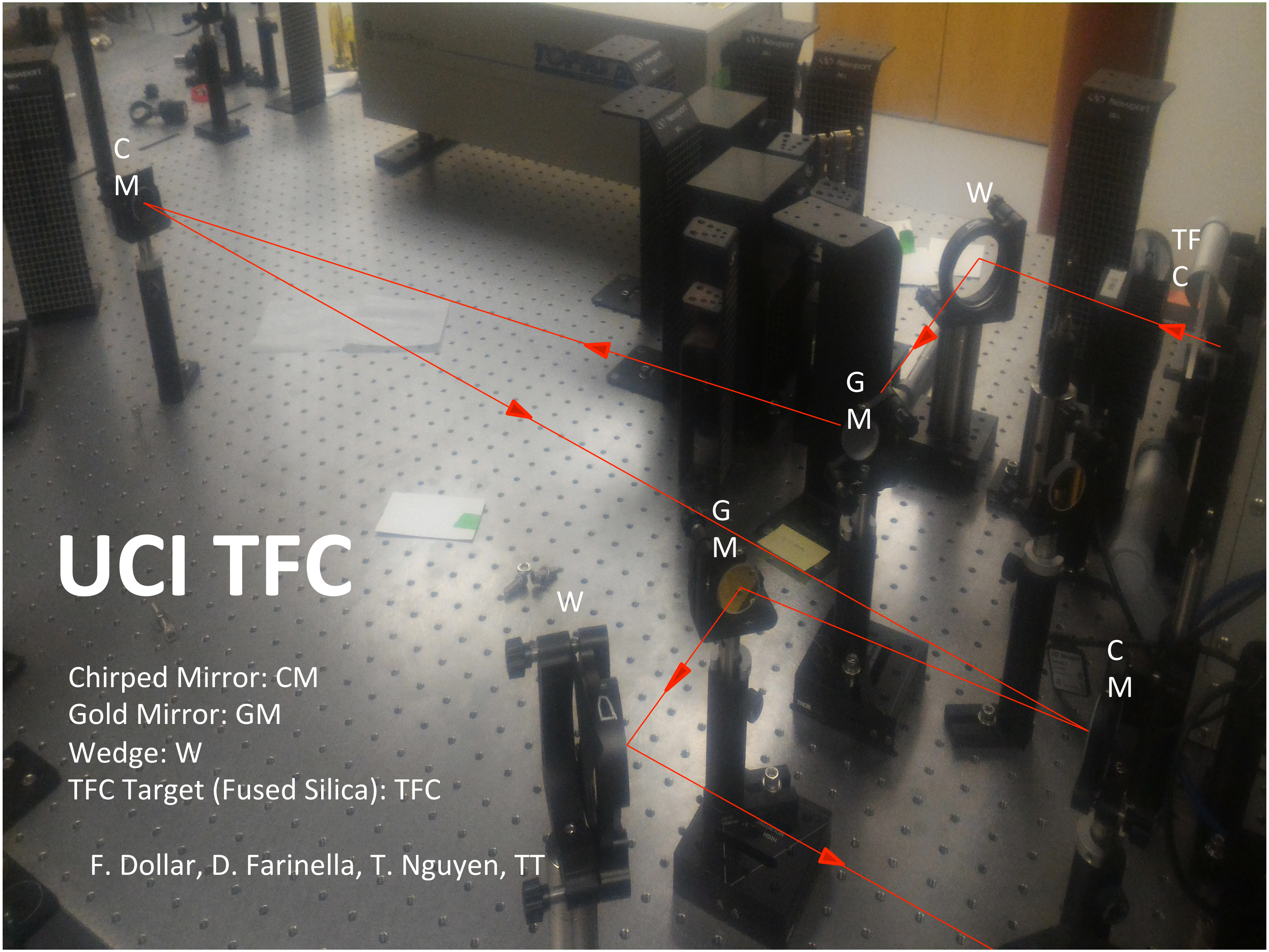
Laser power = energy / pulse lnegth

Optical nonlinearity of thin film → pulse frequency width bulge, pulse compression

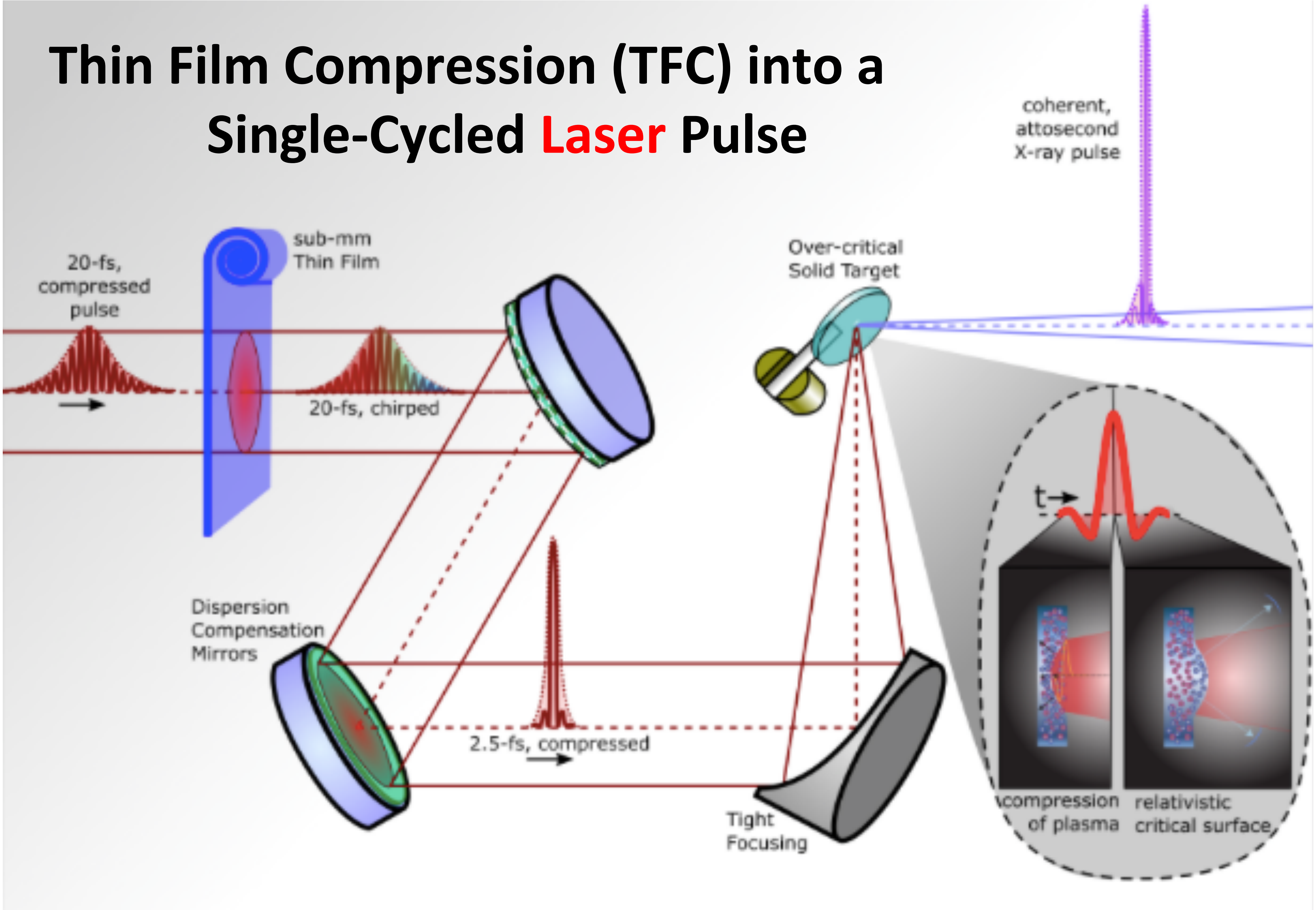




G. Mourou*, et al. Eur. Phys. J. (2014)


C
M
W
TF
C
G
M
G
M
UCI TFC
W
C
M
Chirped Mirror: CM
Gold Mirror: GM
Wedge: W
TFC Target (Fused Silica): TFC
F. Dollar, D. Farinella, T. Nguyen, TT

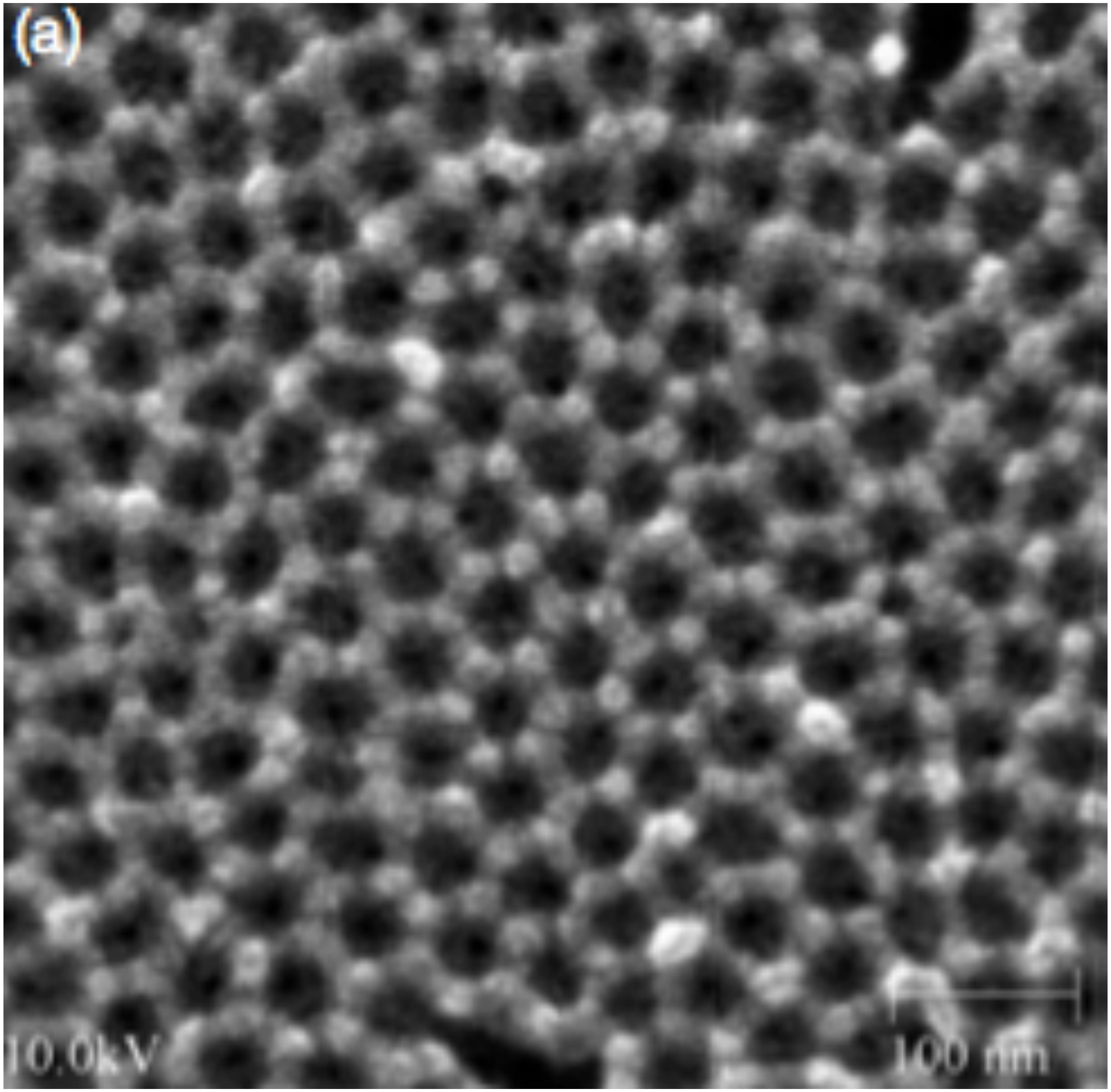
Thin Film Compression (TFC) into a Single-Cycled Laser Pulse



Mourou* et al. (2014)

Porous Nanomaterial:

rastering possible



Nano holes:
reduce the stopping power
keep strong wakefields

➔ Marriage of *nanotech* and *high field science*

Spatia (nm), time(as-zs), density 10^{24} /cc), photon (keV) scales:
Transverse and longitudinal **structure of nanotubes**: act as e.g., accelerator structure (the structure intact in time of ionization, material breakdown times fs > x-ray pulse time zs-as)

Porous alimina on Si substrate Nanotech. **15**, 833 (2004);
P. Taborek (UCI): porous alumina (2007)

X-ray wakefield acceleration in nanomaterials tubes

T. Tajima, EPJ (2014)

X-ray laser with short length and small spot:

NB: electrons in outers-shell bound states, too, interact with X-rays

Simulation:

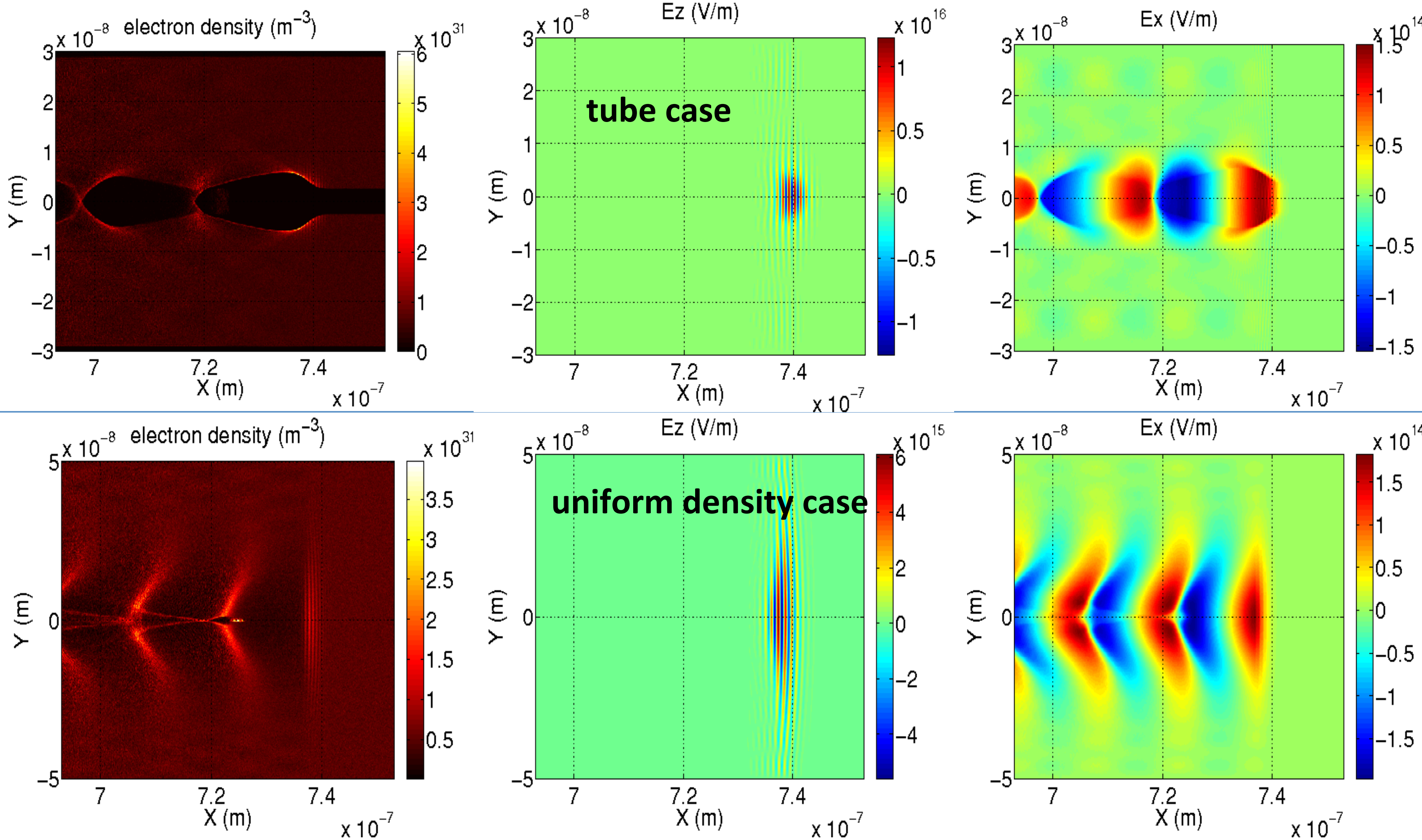
X.M. Zhang, et al.PR AB (2016)

Laser pulse with small spot can be well controlled and guided with a tube. Such structure available e.g. with **carbon nanotube,** or **alumina nanotubes** (typical simulation parameters)

$$\lambda = 1nm, a_0 = 4, \sigma_L = 5nm, \tau_L = 3nm / c$$

$$n_{tube} = 5 \times 10^{24} / cm^3, \sigma_{tube} = 2.5nm$$

Wakefield comparison between the cases of a tube and a uniform density



X. M. Zhang

Conclusions

- **Robust** heightened energy state of plasma, Higgs' state: Wakefields
- Wakefields: **Nature creates** naturally and ubiquitously: jets from Blackhole (AGN)
- **X-ray LWFA in crystal**: accelerating gradient (from GeV/cm in gas) →TeV/cm in nanomaterial
- Applications →including microscopic endoscopic LWFA by fiber laser


(Y.Shin)
Thank you!
You taught me.
Your community nurtured me.
Morning-shone mountains
With glittering snowwhite caps
Welcome me on board
To the Denver APS
Over rocky etched carpets
Toshi Tajima