Fundamental Physics & Relativistic Laboratory Astrophysics with Extreme Power Lasers

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following the presentation given by

T. Zh. Esirkepov

(Advanced Beam Technology Division Japan Atomic Energy Agency)

at the European Conference on the Laboratory Astrophysics (ECLA)
Paris, France, 26-30 September 2011

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Collaboration & acknowledgments

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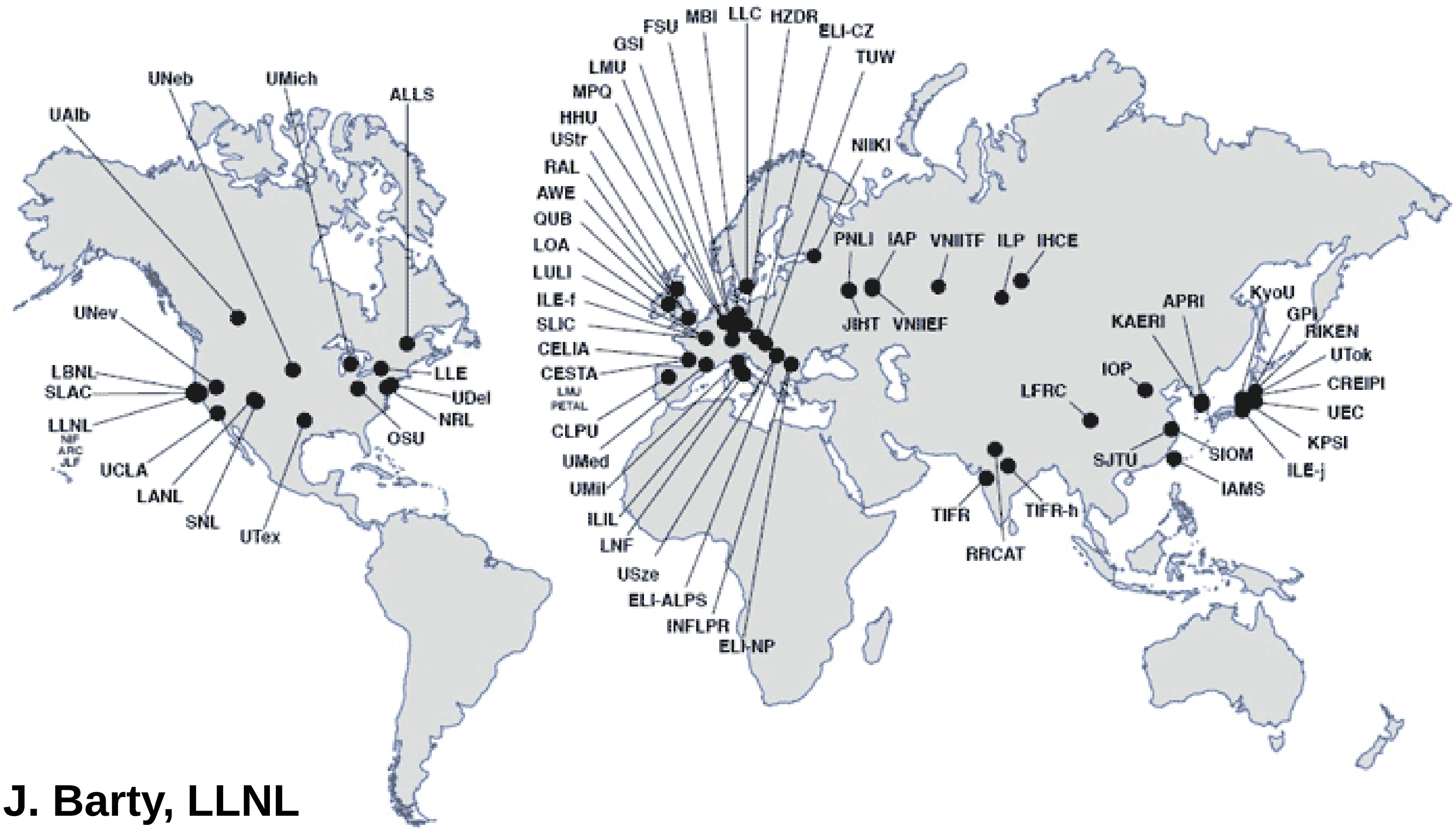
Financial support from MEXT, Japan

2010 World Map of Ultrahigh Intensity Laser Capabilities

The International Committee on Ultra-High Intensity Lasers, http://www.icuil.org/



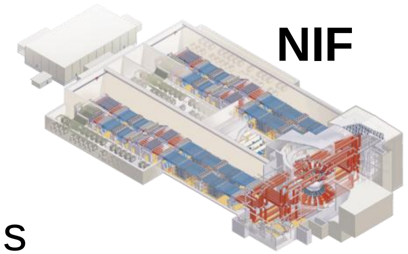
(71 site)

C. P. J. Barty, LLNL

- **the total peak power of all the CPA systems operating today is ~11.5 PW**
- **by the end of 2015 planned CPA projects will bring the total to ~127 PWs**
- **these CPA projects represent ~$4.3B of effort by ~1600 people (no NIF or LMJ)**
- **these estimates do not include Exawatt scale projects currently being planned**

Most Powerful Laser Facilities

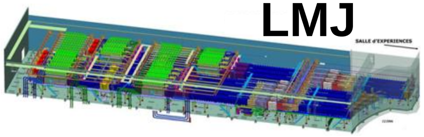
NIF

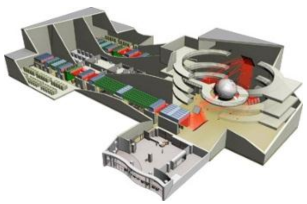


Primarily for inertial thermonuclear fusion;
also for laboratory astrophysics:

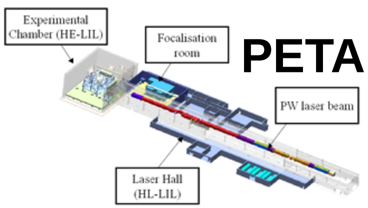
- **NIF, LLNL, USA**, demonstrated 1.41 MJ of 3ω with 192 beams (August, 2011). Designed for 1.8 MJ.
- **LMJ, Bordeaux, France**, will deliver 1.8 MJ with 240 beams

LMJ





HiPER



PETAL

For fast Ignition & fundamental science (including laboratory astrophysics):

- **HiPER – High Power laser Energy Research facility**
- **PETAL – PETawatt Aquitaine Laser** (coupled with LMJ)

  Long pulse beams of 200 kJ combined with ultra-high intensity beams of 70 kJ.

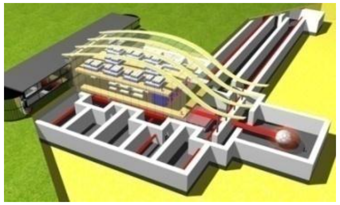
For high field science, laboratory astrophysics & hadron therapy:

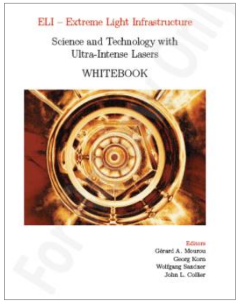
ELI – Extreme Light Infrastructure

Femtosecond pulse of 70 KJ
with the power > 100 petawatt
and the intensity > 10^{25} W/cm^2

Started (Czech Rep., Romania, Hungary, 2010).

ELI





ELI Whitebook

Collaboration of ~ 40 research institutions from 13 European countries

- Bulgaria
- Czech Republic
- France
- Germany
- Greece
- Hungary
- Italy
- Lithuania
- Poland
- Portugal
- Romania
- Spain
- United Kingdom

http://www.extreme-light-infrastructure.eu/

ELI will afford new investigations in particle physics, nuclear physics, gravitational physics, nonlinear field theory, ultrahigh-pressure physics, astrophysics and cosmology.

Budget >700 M€.
The first pillar of ELI in Czech Republic: ~290 M€ (approved by EU Commission, April 21, 2011).

Project Coordinator Gerard Mourou, CNRS
Deputy Coordinator Georg Korn, MPQ
Project Manager Jean-Paul Chambaret, CNRS
Deputy Project Manager Karoly Osvay, CNRS & U.Szeged

Leaders of
Support Actions Dimitris Charalambidis, FORTH
Scientific and Technical Activities John Collier, STFC
Coordination Actions Patrizio Antici, CNRS & INFN

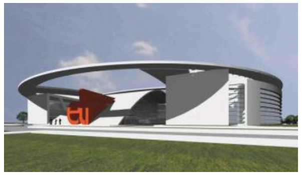
Four pillars

operational costs

- **High Energy Beam Science**
  Prague (Czech Republic)
  2015

short X-ray pulse generation and particles acceleration

21 M€/yr



- **Attosecond Laser Science**
  Szeged (Hungary)
  2015

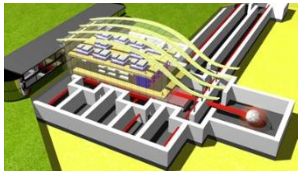
generation and application of supershort pulses

22 M€/yr

- **Laser-based Nuclear Physics**
  Magurele (Romania)
  2015

nuclear physics with gamma ray

29 M€/yr



- **Ultra High Field Science**
  To be decided in 2012
  2017

ultra high intensity inducing processes of nonlinear QED, High Energy Particle physics and Gravitational physics.

"The purposes of the facilities is to design, develop and build ultra-high-power lasers with focusable intensities and average powers reaching far beyond the existing laser systems and organize them as international user facilities for new up to now unconceivable revolutionary experiments in different scientific disciplines as well as in technology and medicine." (ELI Whitebook, 2011)

Paramount objective of ELI: to provide ultra-short energetic particle (10-100GeV) and radiation (1-10 MeV) beams produced from compact laser plasma accelerators.

Technical

- Power: Exawatt (10^{18} W)
- Irradiance: 10^{25} W/cm^2
- Duration: femtosecond (10^{-15} s) to attosecond (10^{-18} s)
- High repetition rate (10Hz–1 kHz)
- High contrast (background-to-peak irradiance, 10^{-15})
- Excellent mechanical & optical pump stablity (1%)
- Perfect focusability (λ/20)

Scientific

- Particle acceleration
  - Laser-driven hadron therapy
  - Compton scattering (γ-ray source)
  - Unruh radiation
- Quantum ElectroDynamics (QED)
  - Antimatter creation (e^+e^- pairs)
  - Vacuum polarization
    Vacuum birefringence
- Laboratory Astrophysics
- Physics of high-power lasers

Jules Henri Poincaré,
The Value of Science, Chapter VI. Astronomy.

Jules Henri Poincaré (1854-1912)

"Governments and parliaments must find that astronomy is one of the sciences which cost most dear... And all that for stars which are so far away, which are complete strangers to our electoral contests, and in all probability will never take any part in them."

Why we need astronomy?

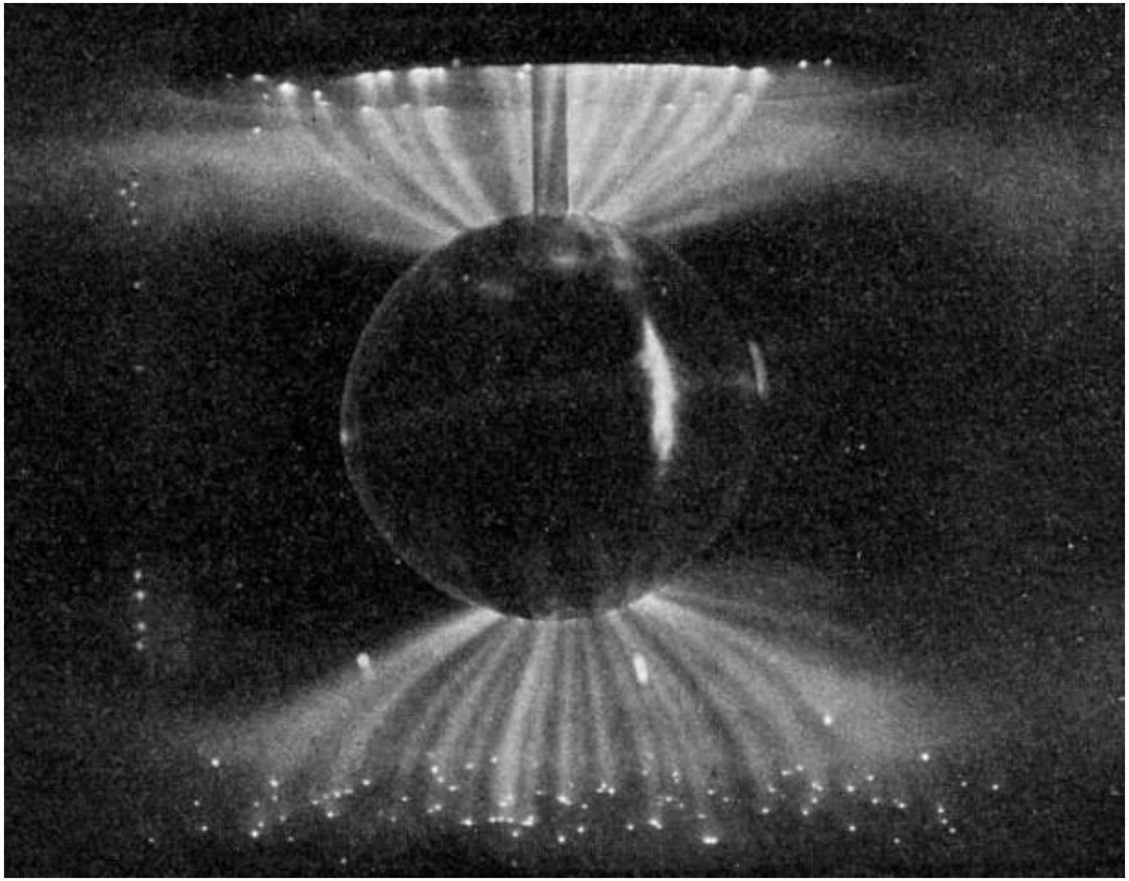
- **Navigation**
- **"Astronomy is useful because it raises us above ourselves... Thus we attain the consciousness of our power, and this is something which can not cost too dear, since this consciousness makes us mightier."**
- **"Astronomy has facilitated the work of the other sciences, more directly useful, since it has given us a soul capable of comprehending nature."**

"The stars are majestic laboratories, gigantic crucibles, such as no chemist could dream. There reign temperatures impossible for us to realize. Their only defect is being a little far away; but the telescope will soon bring them near to us, and then we shall see how matter acts there. What good fortune for the physicist and the chemist!"

Laboratory Astrophysics: First Attempt

Kristian Olaf Birkeland, Terrella experiment, 1908

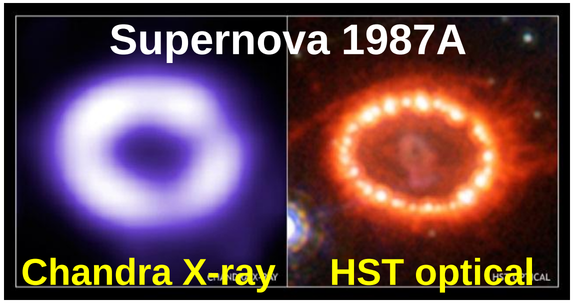
The modeling of the lights of the polar aurora



Kristian Olaf Birkeland
(1867-1917)

Supernova 1987A: Rayleigh-Taylor & Richtmyer-Meshkov Instabilities

Observation



Theory

Navier-Stokes equations

$$\frac{\partial \rho Y_i}{\partial t} + \nabla \cdot (\rho Y_i \mathbf{u} + \mathbf{J}_i) = 0, \quad i = 1, 2, \qquad (1)$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot [\rho \mathbf{u}\mathbf{u} + p\underline{\boldsymbol{\delta}} - \underline{\boldsymbol{\tau}}] = \rho \mathbf{g}, \qquad (2)$$

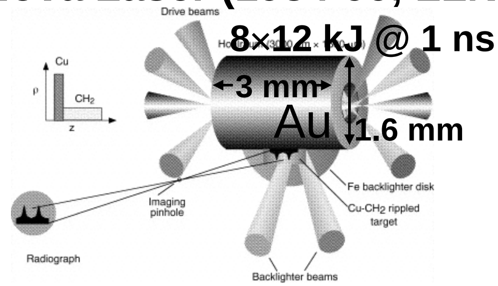
$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + p)\mathbf{u} - \underline{\boldsymbol{\tau}} \cdot \mathbf{u} + \mathbf{q}] = \rho \mathbf{g} \cdot \mathbf{u}, \qquad (3)$$

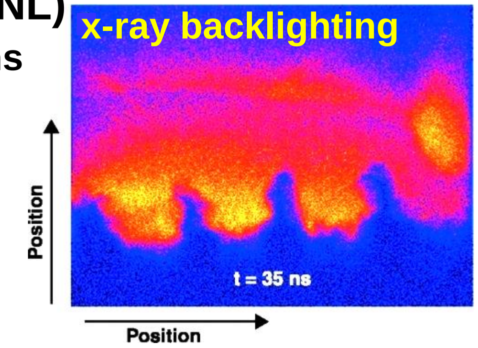
$$p = \rho R T, \quad T = (\gamma - 1)e/R, \quad R = R_o \sum_{i=1}^{2} \frac{Y_i}{W_i}, \qquad (4)$$

Similarity principles

Experiment
(modeling, simulation)

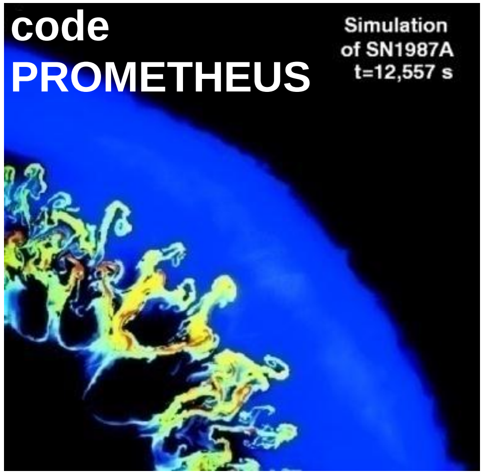
Nova Laser (1984-99, LLNL)





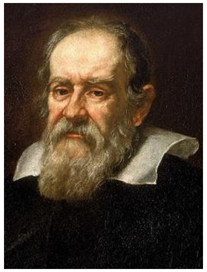
B. A. Remington, D. Arnett, R. P. Drake, H. Takabe. "Modeling Astrophysical Phenomena in the Laboratory with Intense Lasers", *Science 284,1488 (1999).*

Numerical Simulation



E. Muller, B. Fryxell, D. Arnett, Astron. Astrophys. 251, 505 (1991).

Dimensional analysis


Galileo Galilei (1564-1642)


Isaac Newton (1643-1727)


John William Strutt, 3rd Baron Rayleigh (1842-1919)


Edgar Buckingham (1867-1940)

Galileo Galilei, *Discorsi e dimostrazioni matematiche, intorno à due nuove scienze,* 1638.

Great Principle of Similitude (I. Newton, 1686)

Method of Dimensional Analysis (J. W. S. Rayleigh, 1872)

π Theorem (E. Buckingham, 1914)

Absolute similarity — *the same equations, the same dimensionless quantities*

Approximate (incomplete) similarity — *only few basic parameters are reproduced*

- **configuration simulation** — *global geometry & some physical processes therein.*
- **process simulation** — *local properties of physical processes at astrophysical conditions.*

Limited similarity (qualitative scaling)

"We must, for the above reasons, be content with a limited scaling. It is sufficient that the same phenomena dominate in the laboratory and in nature, i.e. dimensionless quantities in nature which are small compared to unity should be small in the model, but not necessarily by the same order of magnitude." *Lars P. Block, Planet. Space Sci. 15, 1479 (1967).*

Laboratory Astrophysics White Paper

(NASA Laboratory Astrophysics Workshop in Gatlinburg, TN, USA, 25-28 October 2010)

Laser:

Tool of Diagnostics

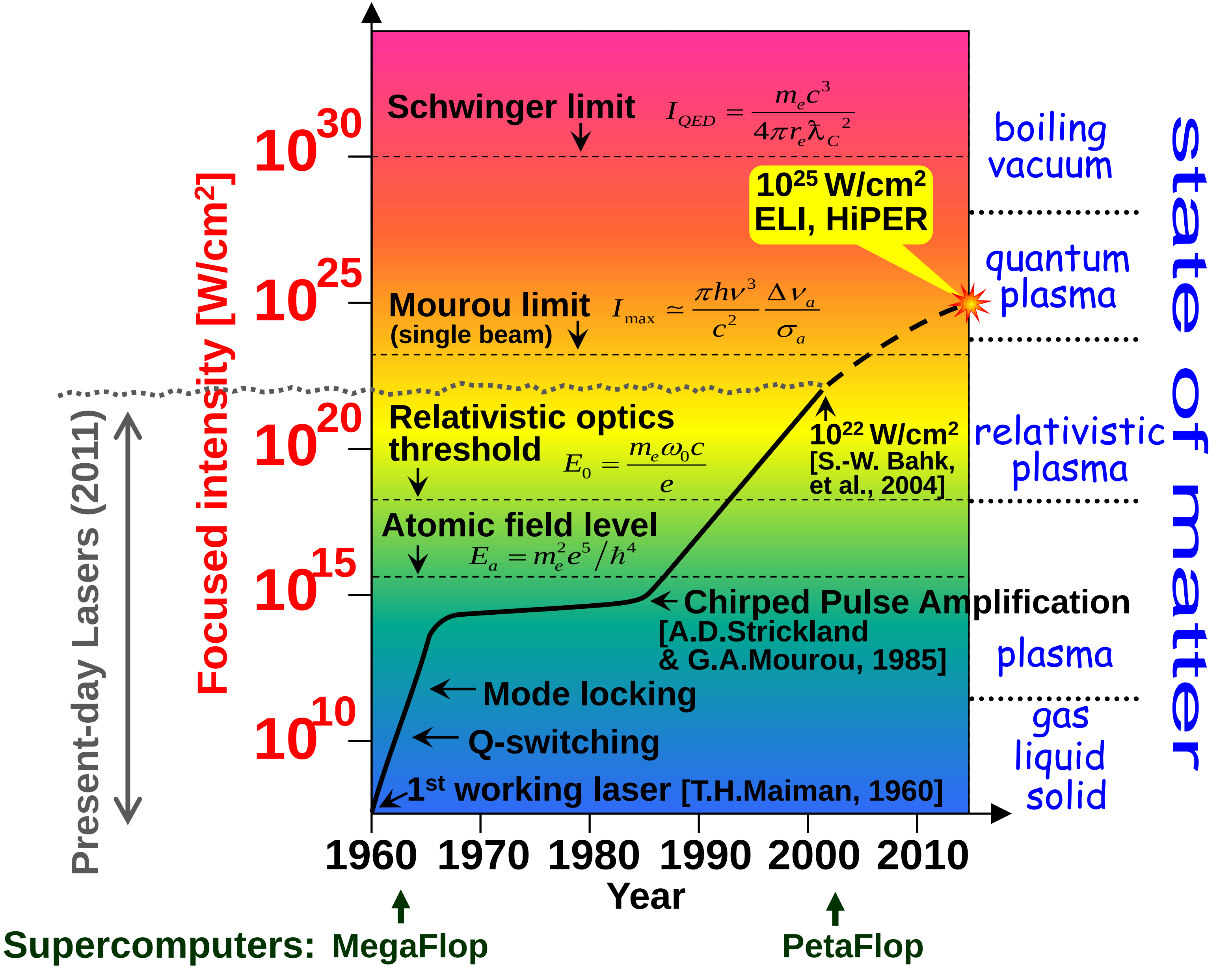
Process Driver

1. **Atomic Astrophysics**
   - Spectra and Structure (especially X-ray)
   - Electron-Impact Collisions
   - Heavy Particle Collisions
   - Photon Driven Processes (photoionization, innershell photo-excitation)
2. **Molecular Astrophysics**
   - Instrument and Technology Development
   - Spectral Complexity
   - Molecular Complexity (chemical models)
   - Spectral and Kinetic Databases
   - Science Interpretation (measurements for key reactions)
   - Computation and Theory
3. **Dust and Ices Astrophysics**
   - Ice, Dust, and polycyclic aromatic hydrocarbon (PAH) Identification at IR Wavelengths
   - Diagnostics of Surface Formation Pathways
   - Ice Formation and Destruction
   - PAH and Amorphous Carbon Particle Formation and Destruction
4. **Plasma Astrophysics**
   - Radiatively Driven Laboratory Experiments
   - Magnetically Driven Laboratory Experiments
   - Kinetically Driven Laboratory Experiments (jets & shocks)

+ 5. Cosmology

Laser
as Process Driver

Laser Technology Progress



T.Brabec & F.Krausz. **Intense few-cycle laser fields: Frontiers of nonlinear optics.** Rev. Mod. Phys. 72, 545-591 (2000).

G.A.Mourou, T.Tajima & S.V.Bulanov. **Optics in the relativistic regime.** Rev. Mod. Phys. 78, 309-371 (2006).

Electron in Laser Field

Hamiltonian

$$\mathcal{H}(t,x,P)=\sqrt{m_e^2c^4+c^2P_{\parallel}^2+\left(cP_{\perp}+e\,A_{\perp}(x-ct)\right)^2}.$$

laser field

is invariant of 1D Lie groups

$$(c\partial_x+\partial_t)\mathcal{H}(t,x,P)=0,\quad \partial_y\mathcal{H}(t,x,P)=0,\quad \partial_z\mathcal{H}(t,x,P)=0.$$

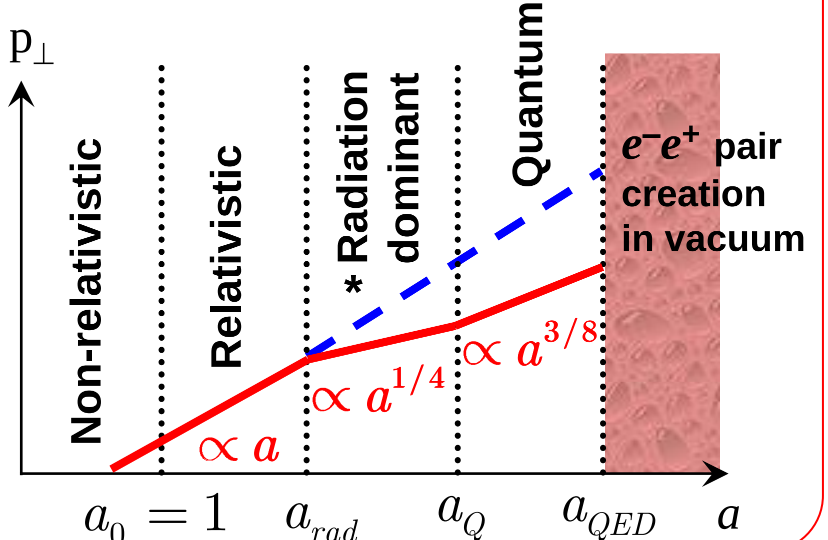
Noether's theorem gives motion integrals:

$$\mathcal{H}(t,x,P)-cP_{\parallel}=m_ec^2h_0\ \text{(const)},\quad P_{\perp}=P_{\perp0}\ \text{(const)}.$$

For $h_0=1, P_{\perp0}=0$, $a=\dfrac{eA_{\perp}}{m_ec^2}=\dfrac{eE_{\perp}}{m_e\omega c}$,

$$p_{\parallel}=m_ec\frac{a^2(x-ct)}{2},\quad p_{\perp}=m_eca(x-ct).$$

Electron Transverse Momentum in EM Wave



critical parameter

Laser intensity (for λ = 1μm) W/cm²	Dimensionless amplitude of EM wave
	e⁻ e⁺ pairs
2.3×10²⁹	$a_{QED}=\dfrac{m_ec^2}{\hbar\omega}$ ≈ **4.1×10⁵**
	quantum effects
5.5×10²⁴	$a_Q=\dfrac{2e^2m_ec}{3\hbar^2\omega}$ ≈ **2×10³**
	radiation friction
* **2.6×10²³**	$a_{rad}=\left(3\lambda/4\pi r_e\right)^{1/3}$ ≈ **440**
	relativistic p⁺
2.5×10²¹	$\sqrt{m_p/m_e}$ ≈ **43**
	relativistic e⁻
1.37×10¹⁸	$a_0=\dfrac{eE_0}{m_e\omega c}$ = **1**

Present-day lasers (2011): 10^{22} W/cm²

E = $3.2\times10^{12}\times a\times(1\mu m/\lambda)$ Volt/meter

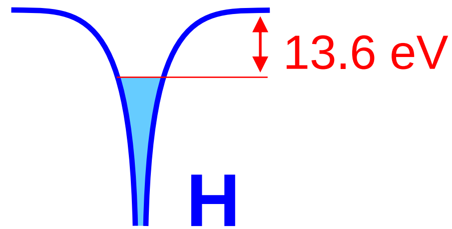
B = $1.1\times10^{8}\times a\times(1\mu m/\lambda)$ Gauss

* Ya. B. Zel'dovich, Sov. Phys. Usp. 18, 79 (1975);
S.V.Bulanov, T. Zh. Esirkepov, J. Koga, T. Tajima, Plasma Phys. Rep. 30, 196 (2004).

Laser driven plasma formation

Laser photon energy

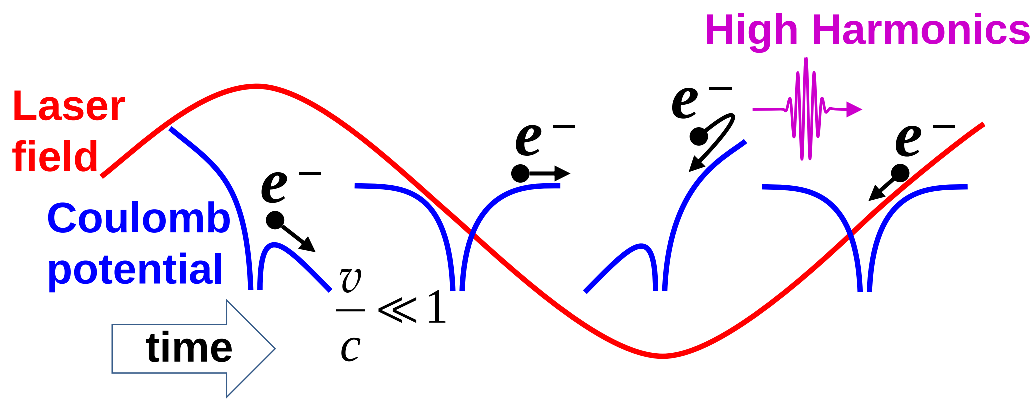
$$\mathcal{E} = 1.24\,\text{eV} \times \frac{1\,\mu\text{m}}{\lambda}$$

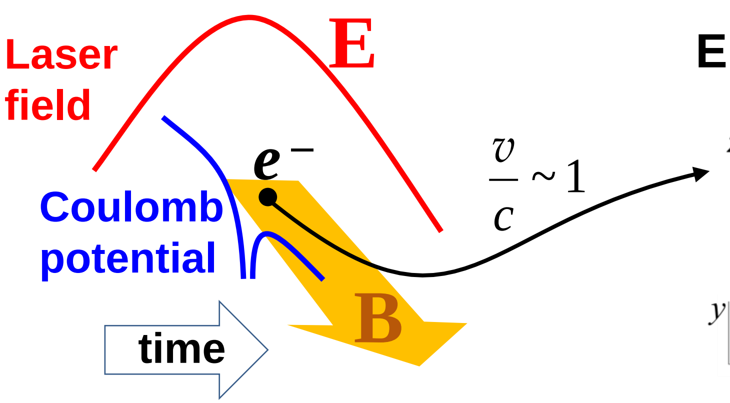


Multi-photon ionization

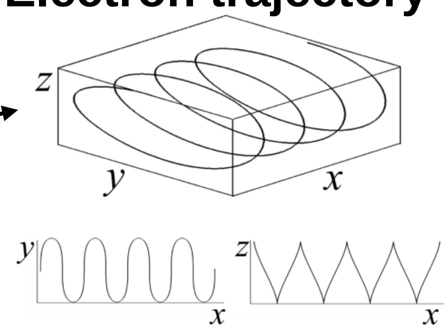
Tunnel ionization

Optical field ionization

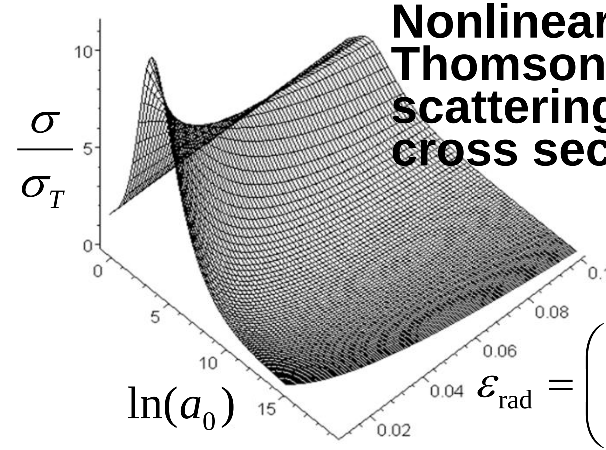




Electron trajectory

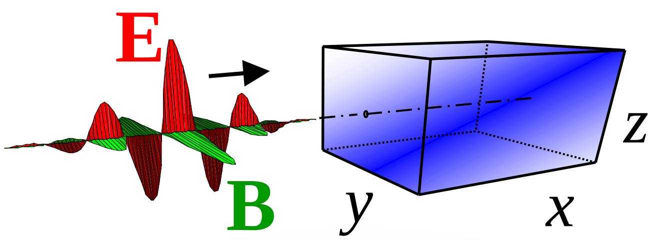


Nonlinear Thomson scattering cross section



$$\varepsilon_{\text{rad}} = \left(\frac{4\pi r_e}{3\lambda_0}\right)$$

Laser-plasma interaction



Optical Field Ionization
Collisional ionization
Turbulence development
Plasma heating

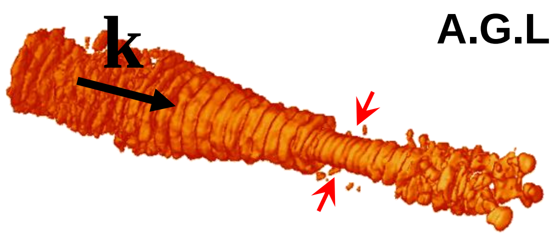
Laser pulse self-focusing
self-channeling
filamentation
change of frequency
depletion

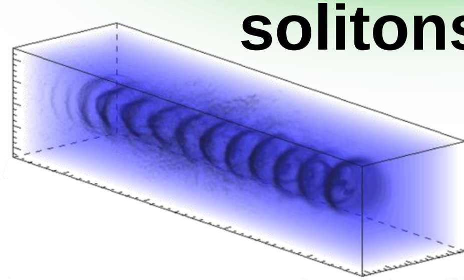
Generation of coherent structures
wake wave
electron vortices
solitons

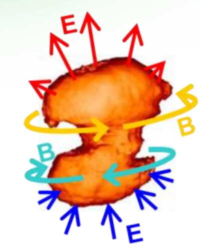
Relativistic self-focusing threshold

$$\mathcal{P}_{cr} \approx 17\left(n_{cr}/n_e\right)\ \text{GW}$$

A.G.Litvak, 1969



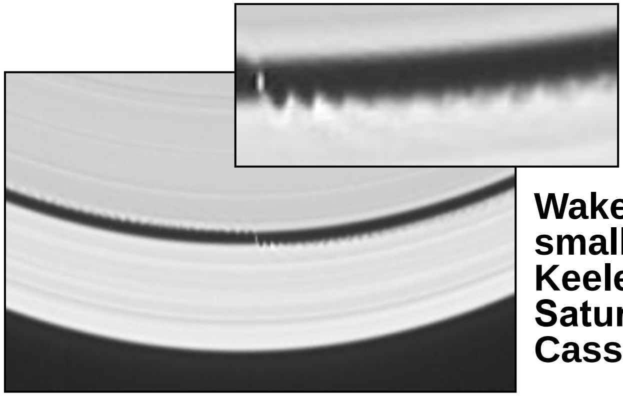




Similitude of Entities in Space and Laser Plasmas

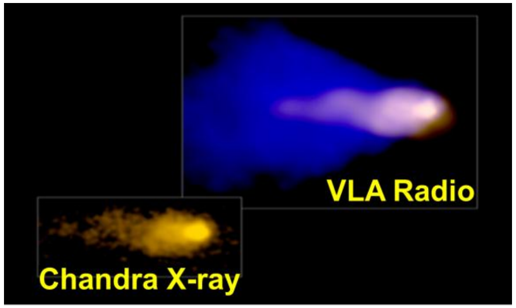
Similitude of Entities in Space and Laser Plasmas

Wake Wave



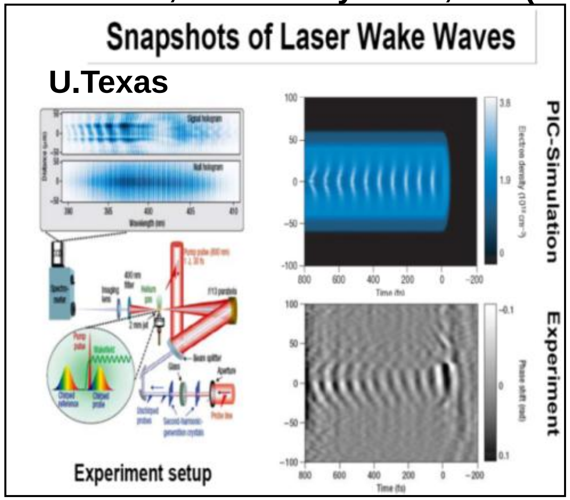
Wake behind a small moon in the Keeler gap in Saturn's rings. Cassini spacecraft.

Tail behind the Mira star. GALEX satellite.



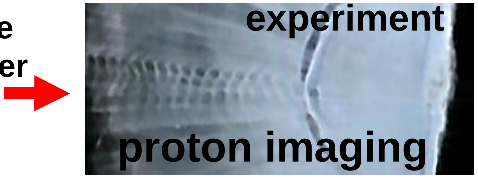
Tail behind the Mouse pulsar G359.23-0.82

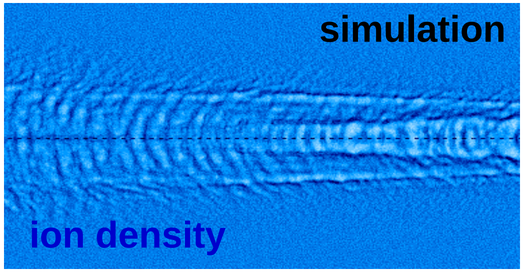
N.H.Matlis et al, Nature Physics 2, 749 (2006)



M. Borghesi, et al, PRL 94, 195003 (2005)

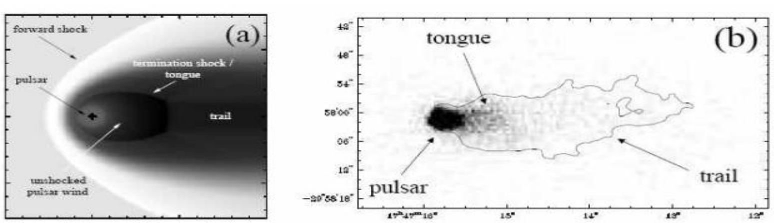
Ti:Sa Salle Jaune laser (LOA)
2J @ 35fs



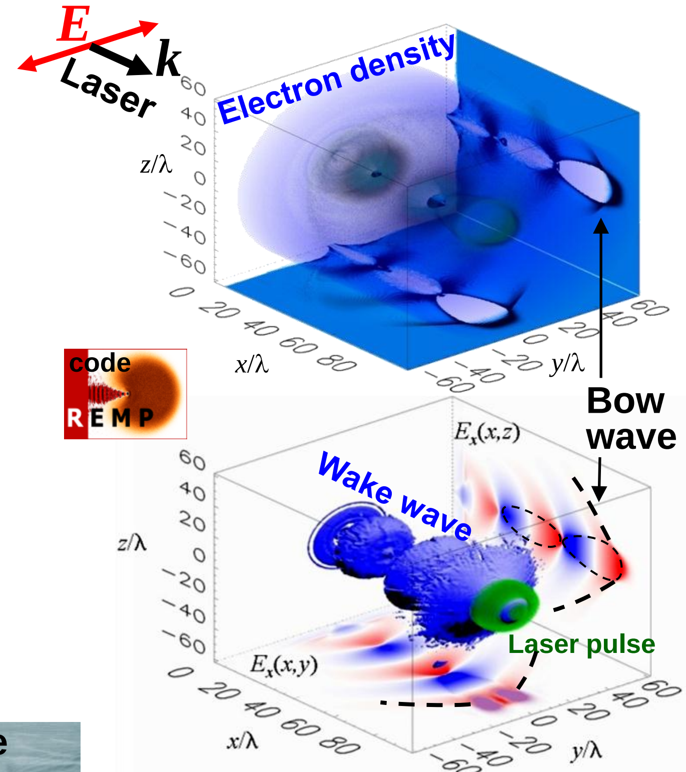


Similitude of Entities in Space and Laser Plasmas

Bow Wave



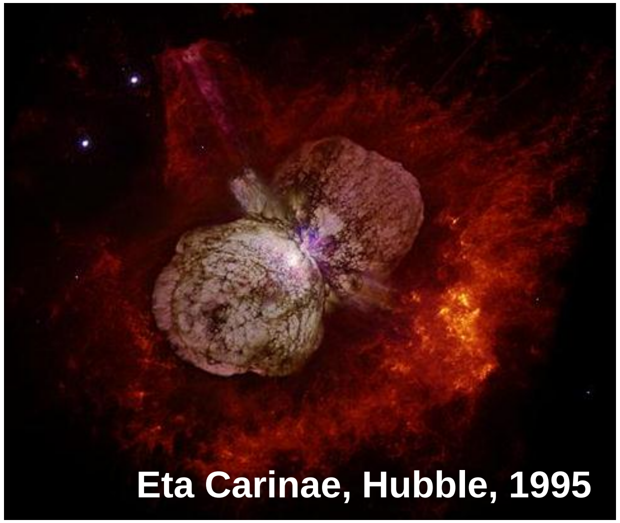
The Mouse Pulsar, B. M. Gaensler et al. (2004)



T. Esirkepov, Y.Kato, S.V.Bulanov, PRL 101, 265001 (2008).

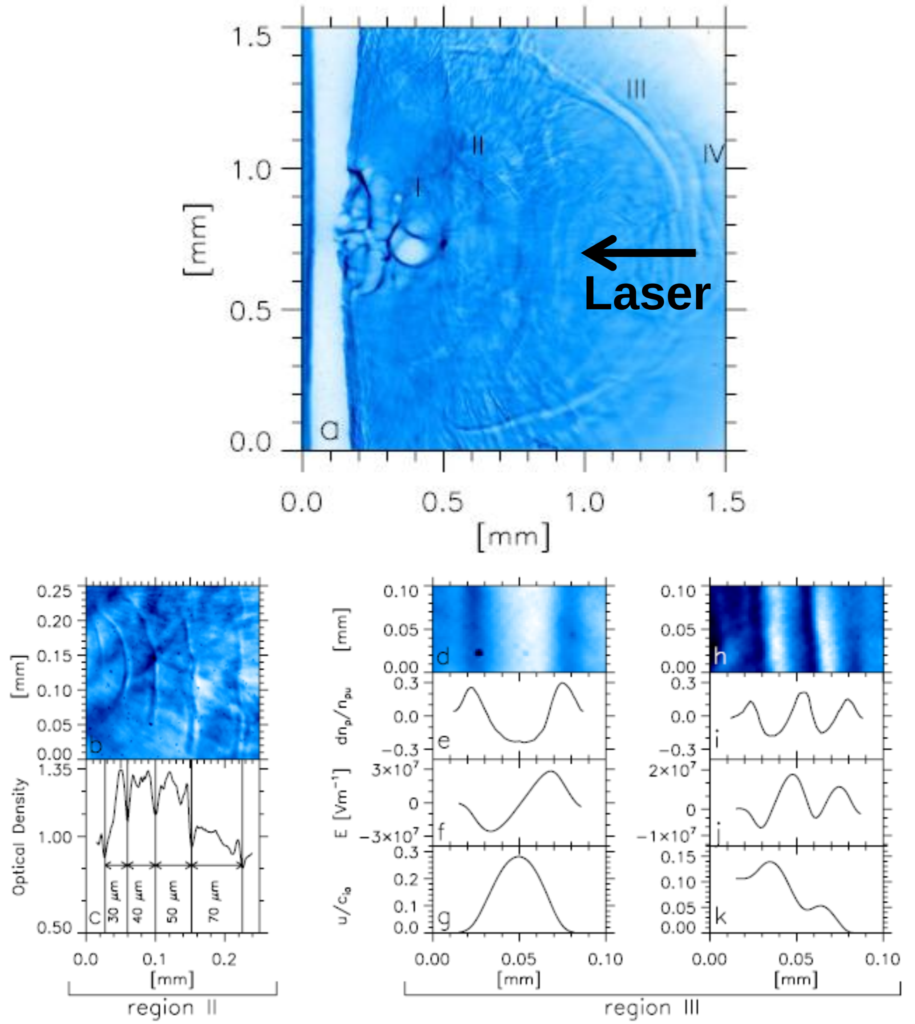
Similitude of Entities in Space and Laser Plasmas

Collisionless Shock Waves



Eta Carinae, Hubble, 1995

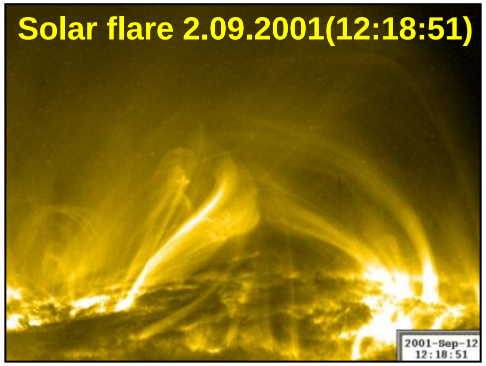
Cassiopeia A, false color.
Red: Spitzer (IR), orange: Hubble,
blue & green: Chandra (X-ray).

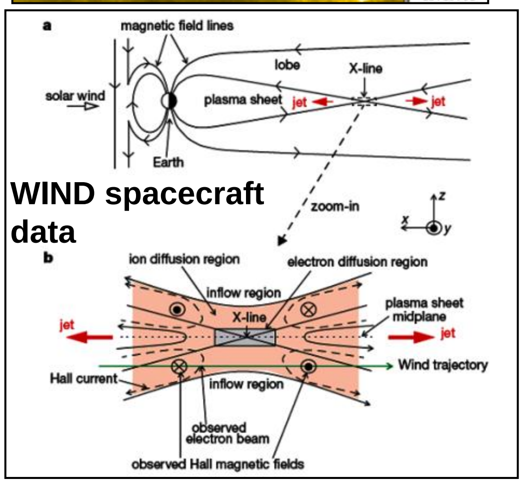


L.Romagnani, S.V.Bulanov, M.Borghesi, et al.,
PRL 101, 025004 (2008)

Similitude of Entities in Space and Laser Plasmas

Magnetic Field Lines Reconnection

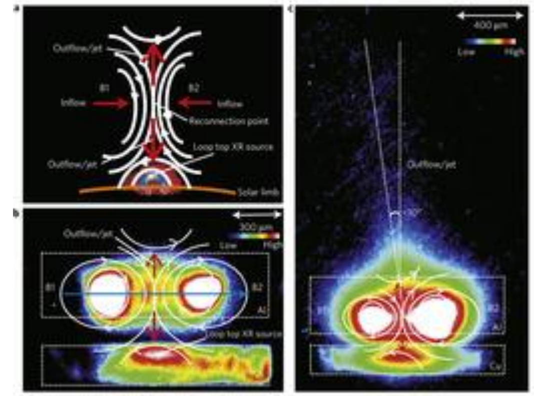




M. Øieroset, et al., Nature 412, 414 (2001)

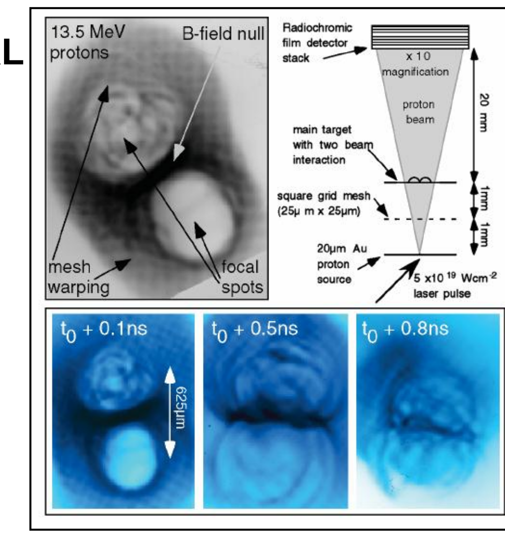
J. Zhong et al., Nature Phys. 6, 984 (2010)

Modelling loop-top X-ray source and reconnection outflows in solar flares with intense lasers



P. M. Nilson et al, PRL 97, 255001 (2006)

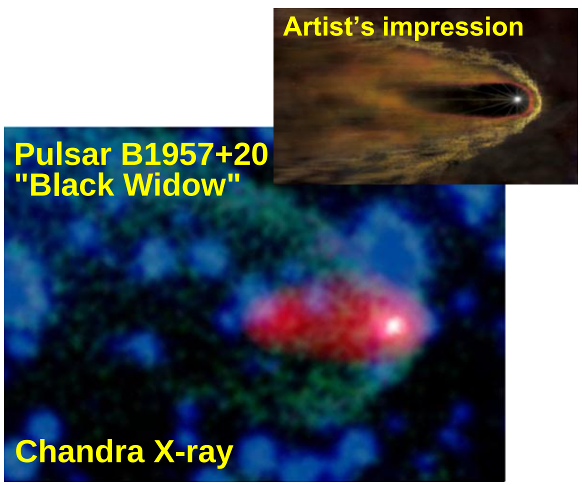
Magnetic reconnection and plasma dynamics in two-beam laser-solid interactions
10^{15} W/cm^2, 1ns

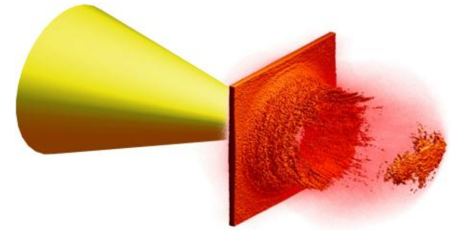


Magnetic reconnection in laser plasmas: G.A.Askar'yan, S.V.Bulanov, F.Pegoraro, A.M.Pukhov, “Magnetic Interaction of Self-Focused Channels and Magnetic Wake Excitation in High Intensity Laser Pulse” // Comments Plasma Physics and Controlled Fusion 17, 35 (1995).

Similitude of Entities in Space and Laser Plasmas

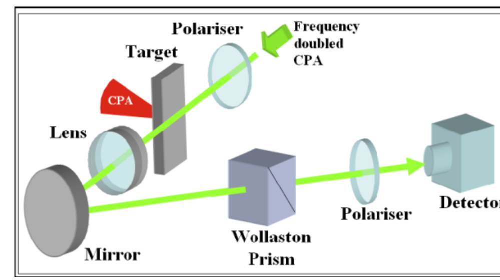
Radiation Pressure

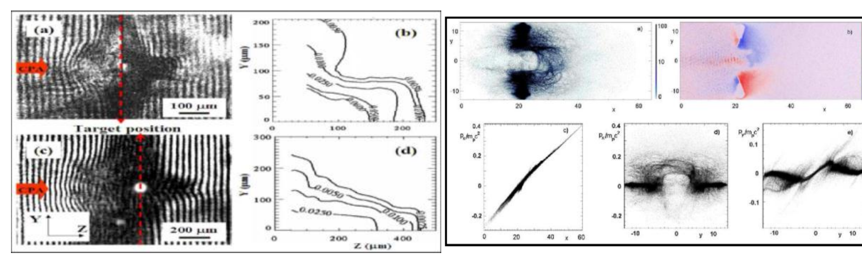




Plasma Jets Driven by Ultraintense-Laser Interaction with Thin Foils

VULCAN Nd-glass laser (RAL)
60 J @ 1ps &
250 J @ 0.7 ps;
foils (3, 5 mum, Al & Cu)



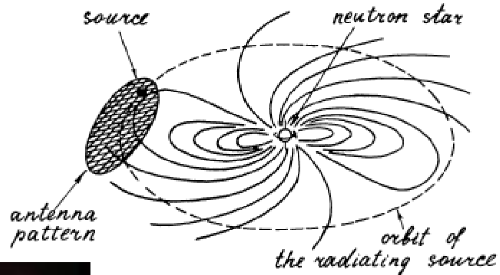


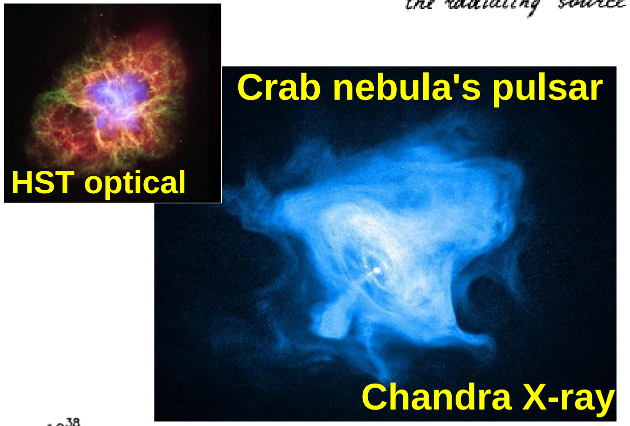
S. Kar, et al., Phys. Rev. Lett. 100, 225004 (2008).

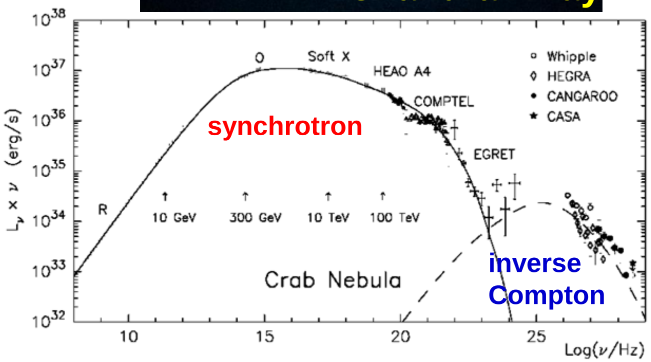
Similitude of Entities in Space and Laser Plasmas

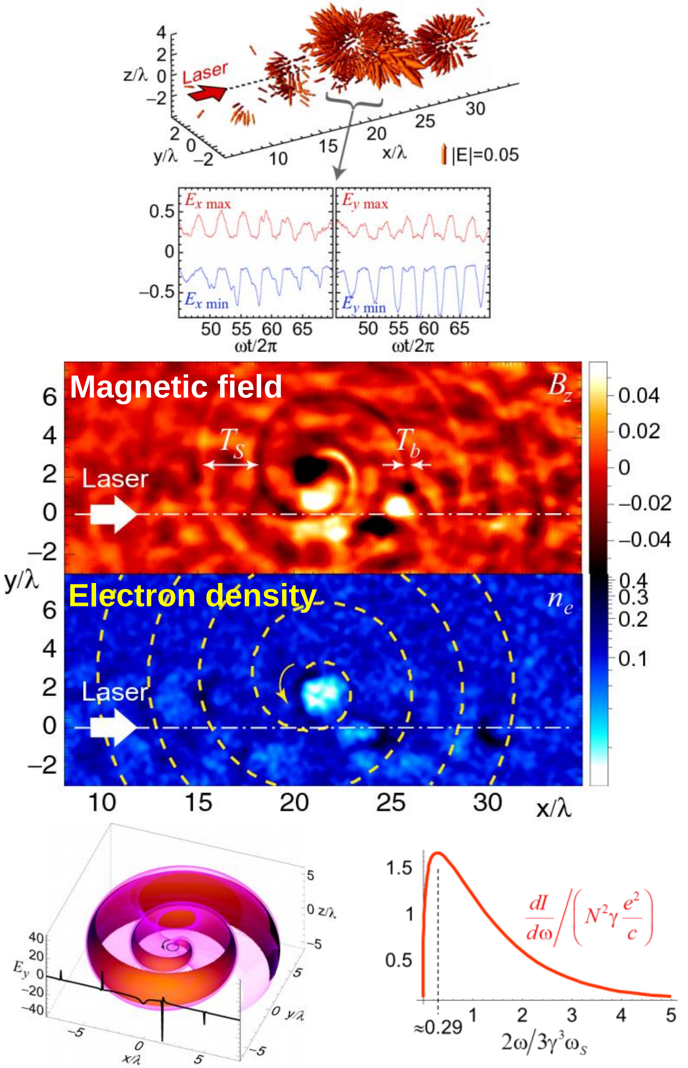
Relativistic Rotator

V. L. Ginzburg, V. V. Zheleznyakov. "On the Pulsar Emission Mechanisms" // Annual Review of Astronomy and Astrophysics, Vol. 13, 511-535 (1975)





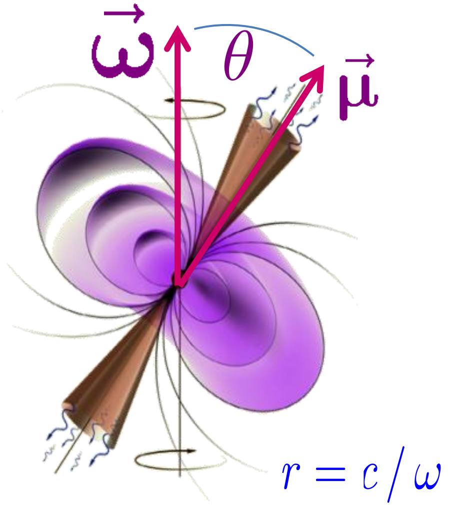




T.Esirkepov, S.V.Bulanov, K.Nishihara, T.Tajima, Phys. Rev. Lett. 92, 255001 (2004).

Astrophysical conditions

Astrophysical Conditions



Beskin, Gurevich, Istomin, 2005.
Gruzinov, 2005.

Example: EM Field near Pulsar

Magneto-dipole radiation of oblique rotator: a model for the pulsar radiation.

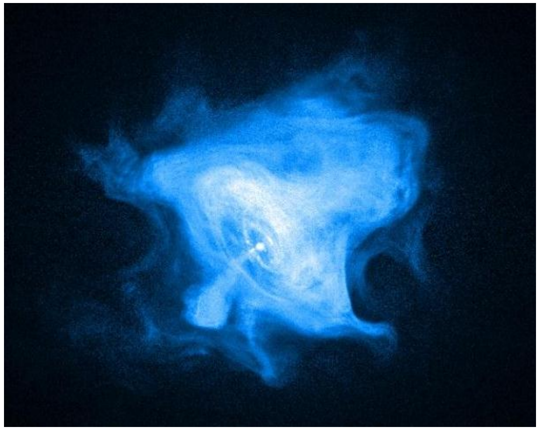
Power emitted by rotator $W = \dfrac{2}{3}\dfrac{\mu^2 \sin\theta^{\,2}\,\omega^4}{c^3}.$

Magnetic moment $\mu \approx B r_p^3$ and $\vec{\omega}$ form angle $\boldsymbol{\theta}$.

In the wave zone, $r = c/\omega$,
the dimensionless wave amplitude is $a_0 = \dfrac{e\mu\omega^2}{m_e c^4}.$

For typical magnetic field $B = 10^{12}\mathrm{G}$
rotation frequency $\omega = 200\,\mathrm{s}^{-1}$
pulsar radius $r_p = 10^6\,\mathrm{cm}$

we have $\mu = 10^{30}\mathrm{G}\cdot\mathrm{cm}^3$ and $a_0 \approx 10^{10}$.



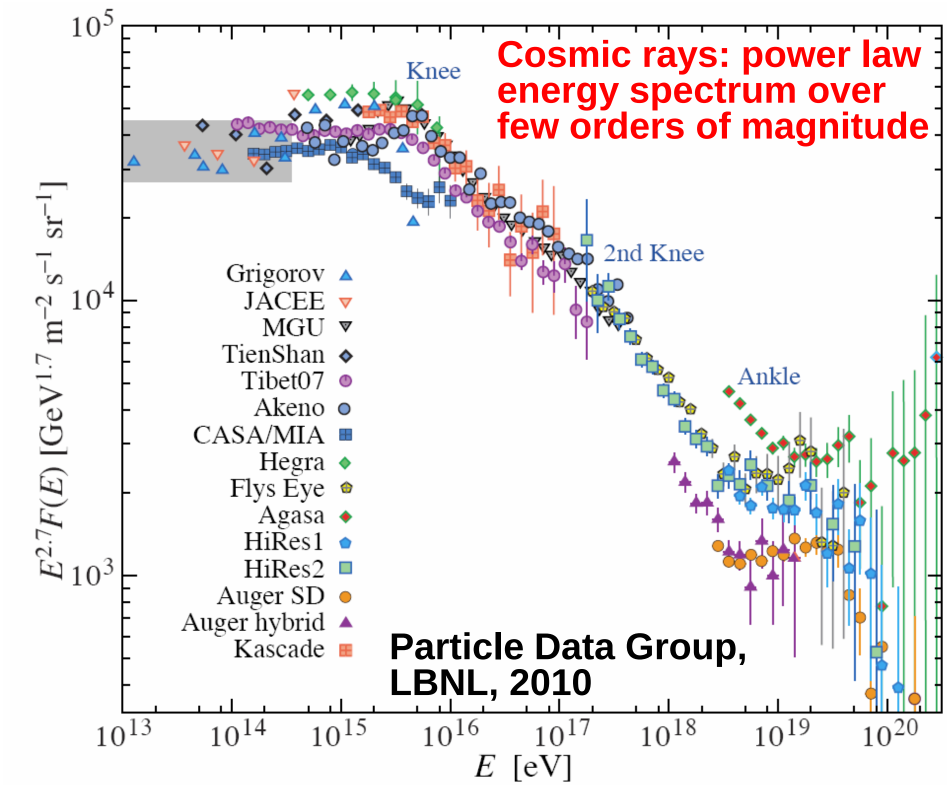
Crab nebula's X-ray-emitting pulsar.
Orbiting Chandra observatory, 2008.

For the Crab nebula's pulsar the radiation damping effects are crucially important since

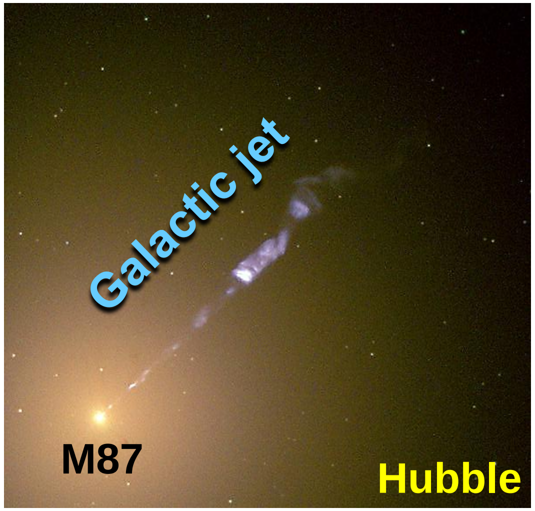
$$a_{rad} = \left(3c/2r_e\omega\right)^{1/3} \approx 10^7.$$

Astrophysical Conditions

Ultra-high-energy cosmic ray (UHECR)

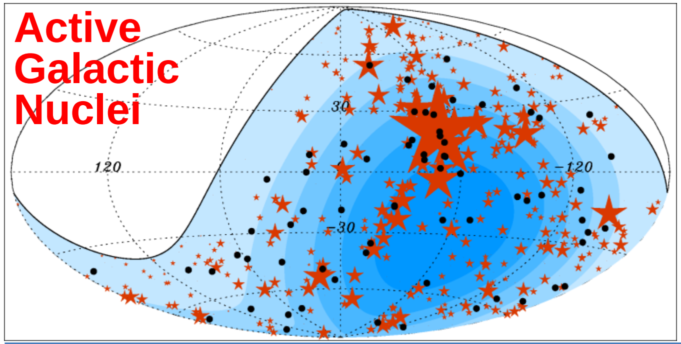


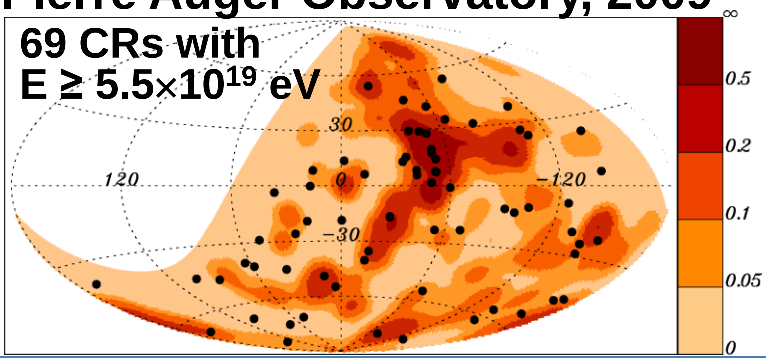
Greisen-Zatsepin-Kuzmin (GZK) limit: 5×10^{19} eV



Zevatron (10^{21} eV)?

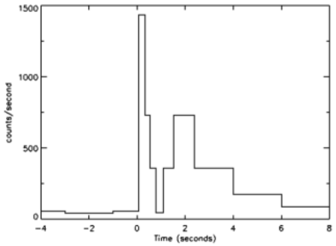
Pierre Auger Observatory, 2009



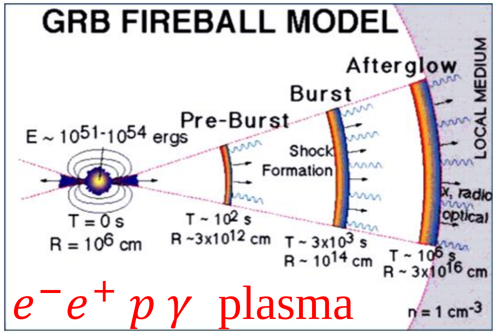


Astrophysical Conditions

Gamma Ray Bursts

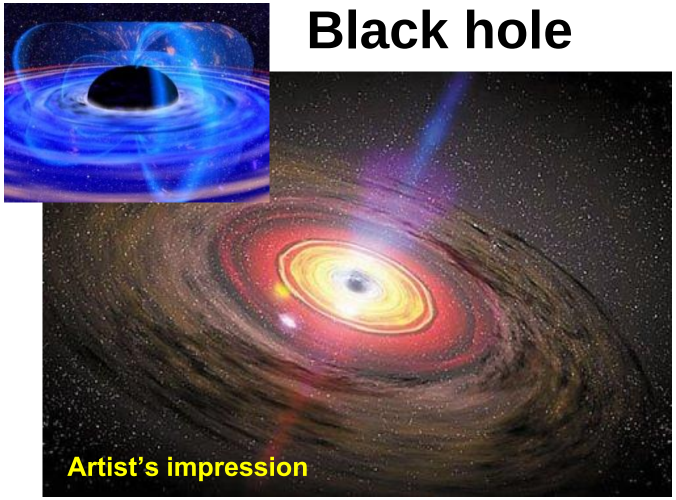


First GRB detected
(Vela satellites, 1967)

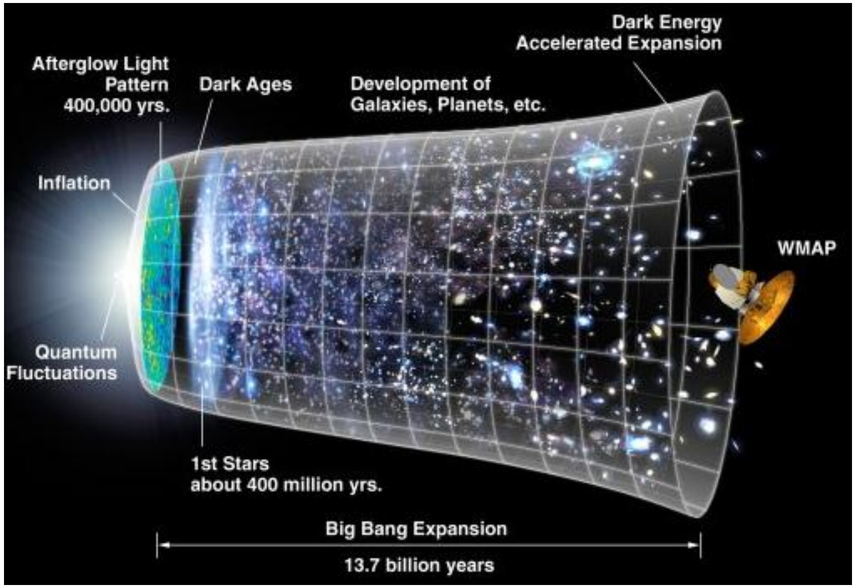


$e^{-}e^{+}\,p\,\gamma$ plasma

Black hole



Early Universe



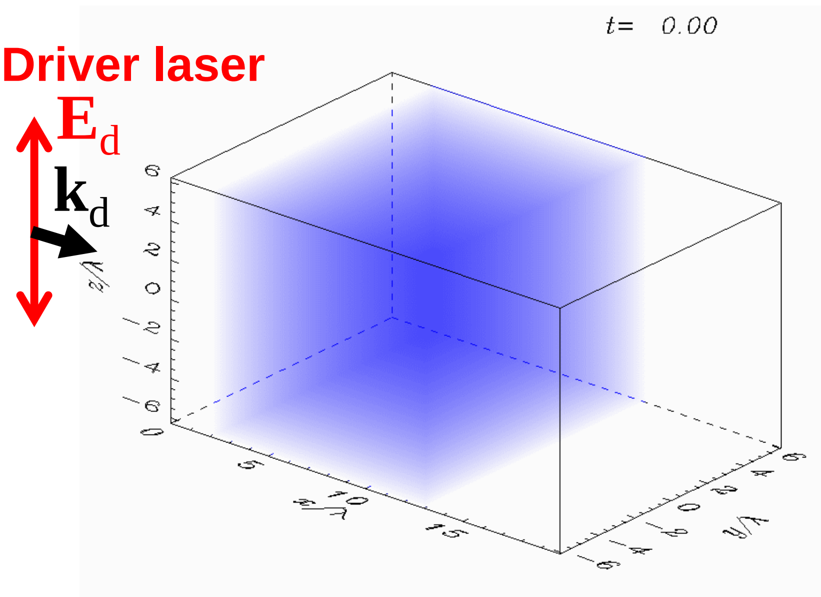
EM field strength
~ 1.3×10^{16} V/cm
Schwinger field
(QED critical EM field)

Towards Schwinger field

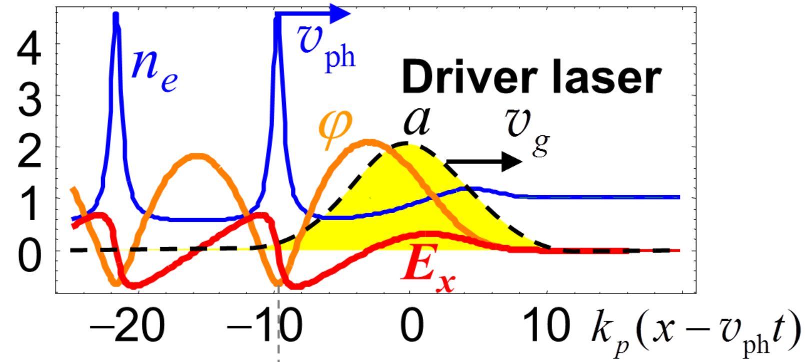
with Laser Driven Relativistic Flying mirrors

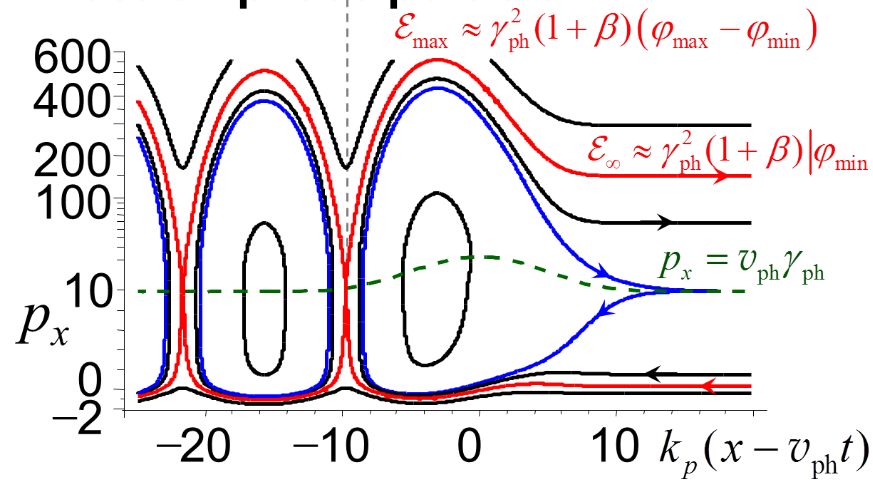
Laser Driven Relativistic Flying Mirror: towards Schwinger field

Wake Wave



A.I.Akhiezer & R.V.Polovin, Sov. Phys. JETP 3, 696 (1956)





At the wave-breaking ($\gamma_e \to \gamma_{ph}$) the electron density becomes singular:

$$n_e \propto \frac{1}{\left|x - x_{peak}\right|^{2/3}}$$

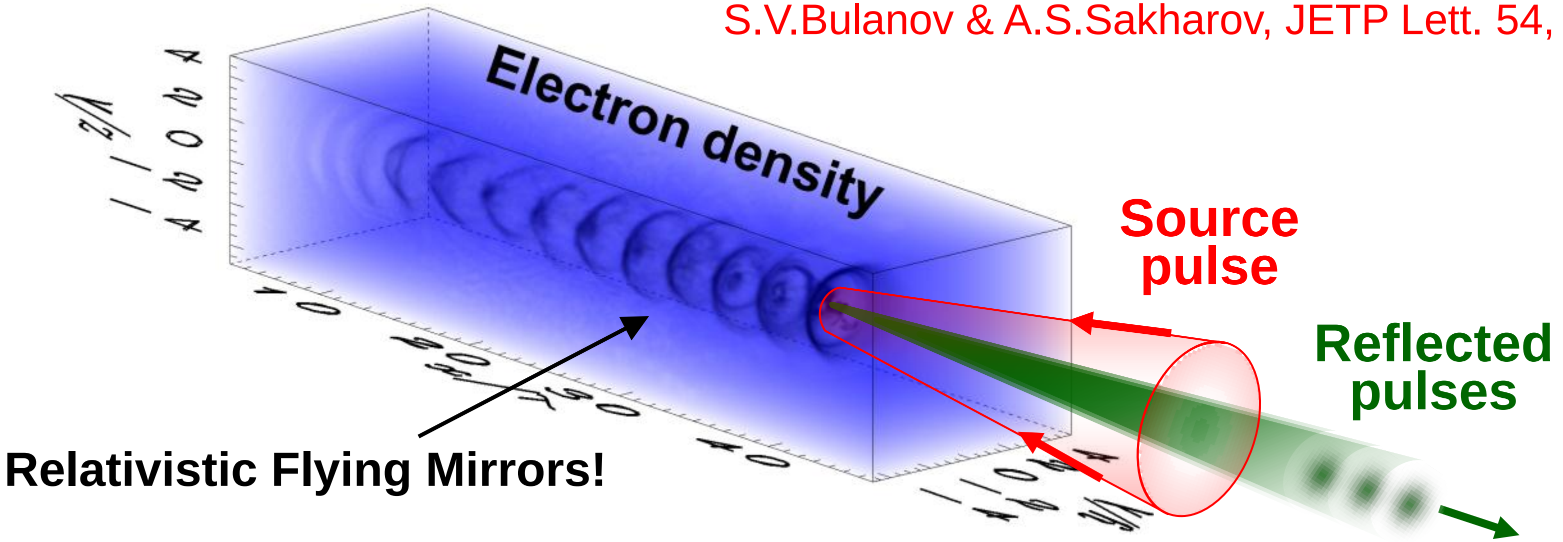
Hokusai (1760-1849)

Laser Wake Field Accelerator

T. Tajima, J.M. Dawson, Phys. Rev. Lett. 43, 267 (1979)

Laser Driven Relativistic Flying Mirror: towards Schwinger field

Due to dependence of wave frequency on amplitude, density shells are parabolic.
S.V.Bulanov & A.S.Sakharov, JETP Lett. 54, 203 (1991).



Reflection coefficient:

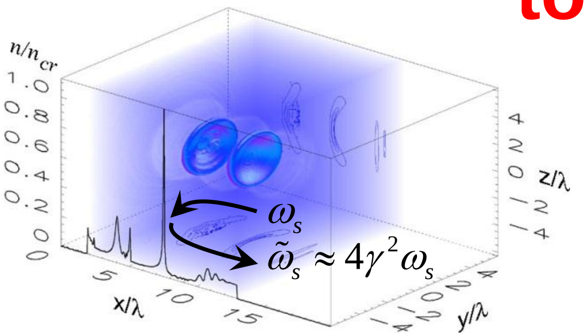
$$\kappa \approx \frac{\omega_d^2}{\omega_s^2} \frac{1}{2\gamma_{\text{ph}}^3}$$

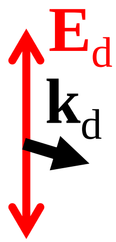
Reflected energy:

$$\mathcal{E}_r = \mathcal{E}_s \frac{c + v_{\text{ph}}}{c - v_{\text{ph}}} \left(1 - (1-\kappa)^N\right)$$

S. V. Bulanov, et al., Kratk. Soobshch. Fiz. ANSSSR 6, 9 (1991);
S. V. Bulanov, et al. in: Reviews of Plasma Physics. Vol. 22 (Kluwer Acad/Plenum Publ, 2001).

Laser Driven Relativistic Flying Mirror: towards Schwinger field

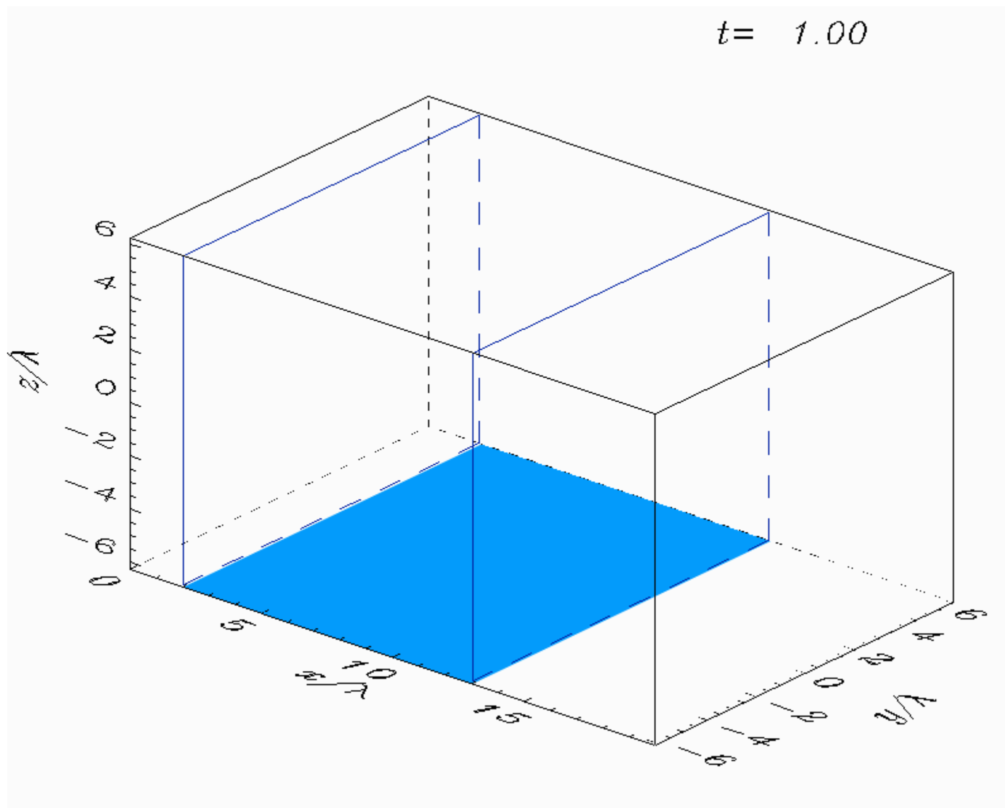




Driver pulse

a=1.7
size=3λx6λx6λ,
Gaussian
I_{peak}=4×10^18 W/cm²×(1μm/λ)²

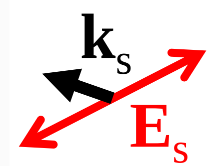
3D PIC simulation



Plasma:
ω_{pe}/ω_d = 0.3
n_e=10^20 cm^−3

Source pulse

a=0.05, λ_s = 2λ
size=6λx6λx6λ,
Gaussian
I_{peak}=3.4×10^15 W/cm²×(1μm/λ)²



XY,Blue: n_e
Red: $W=E^2+B^2$

$$v_{ph} \approx 0.87 \qquad \gamma_{ph} \approx 2 \qquad \frac{\tilde{\omega}_s}{\omega_s} \approx 14 \qquad \tilde{I}_{s\max} \approx 256\, I_s$$

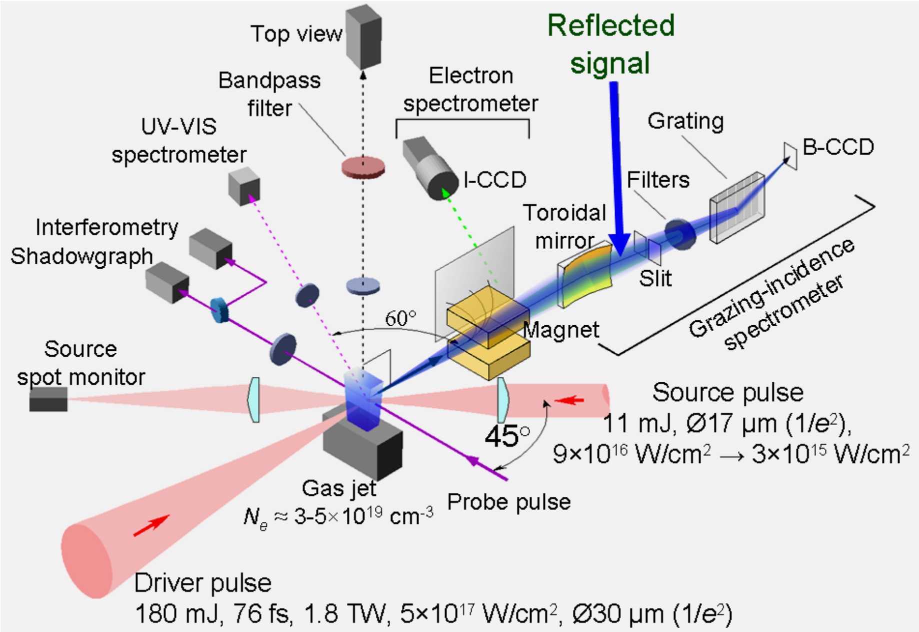
REMP

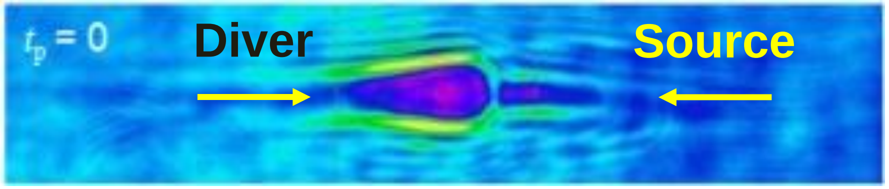
λ=86dx, N_p=10^10,
grid: 1720x1050x1080
HP αServer (720 CPU)

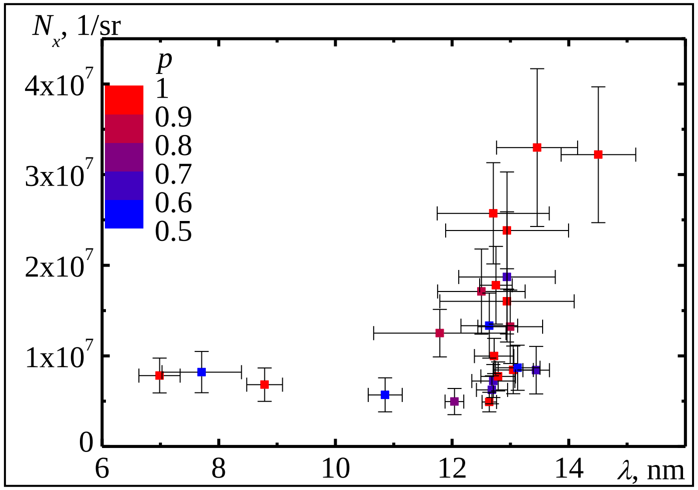
S.V.Bulanov, T. Esirkepov, T. Tajima, Phys.Rev.Lett. 91, 085001 (2003).

Laser Driven Relativistic Flying Mirror: towards Schwinger field

Proof-of-Principle Experiment



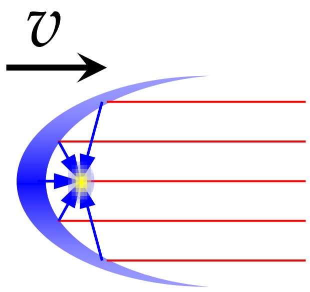




Reflected wavelength: λ_x = 14.3 nm ± 1%
Photon number: 10^{10} per sr
Reflected pulse duration: τ_x ~ 1.4 fs

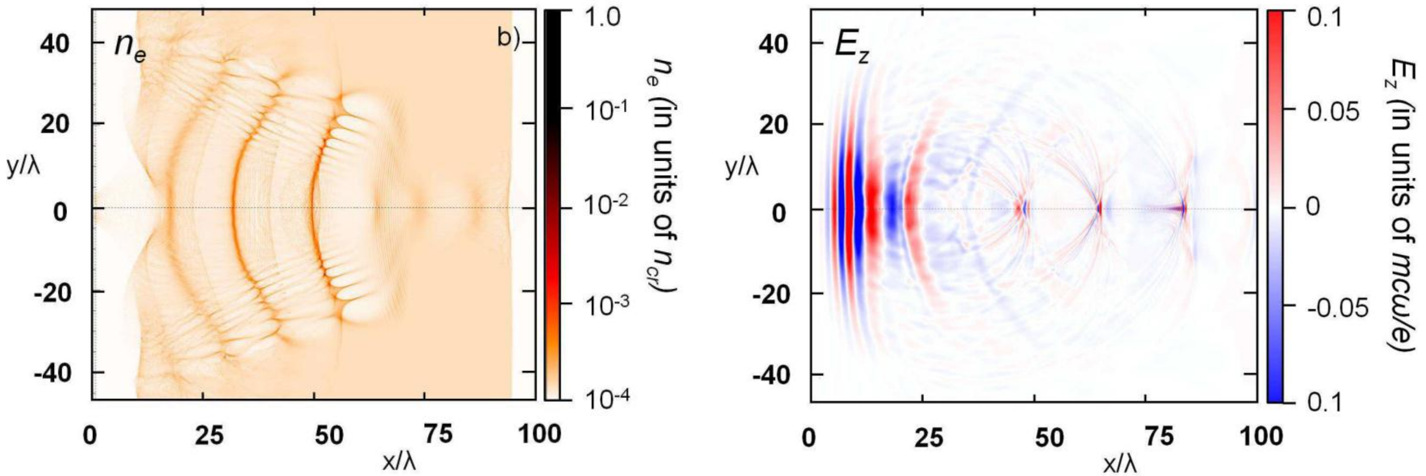
M. Kando, et al., Phys. Rev. Lett. 99, 135001 (2007)
A. S. Pirozhkov, et al., Phys. Plasmas 14, 080904 (2007)
M. Kando, et al., Phys. Rev. Lett., 103, 235003 (2009)

Laser Driven Relativistic Flying Mirror: towards Schwinger field



Parabolic mirror focused intensity $I_r \approx 32\gamma_{\mathrm{ph}}^3 \frac{\omega_d^2}{\omega_s^2} \frac{D^2}{\lambda_s^2} I_s$

Spherical mirror focused intensity $I_r \approx 128\gamma_{\mathrm{ph}}^5 \frac{\omega_d^2}{\omega_s^2} \frac{D^2}{\lambda_s^2} I_s$

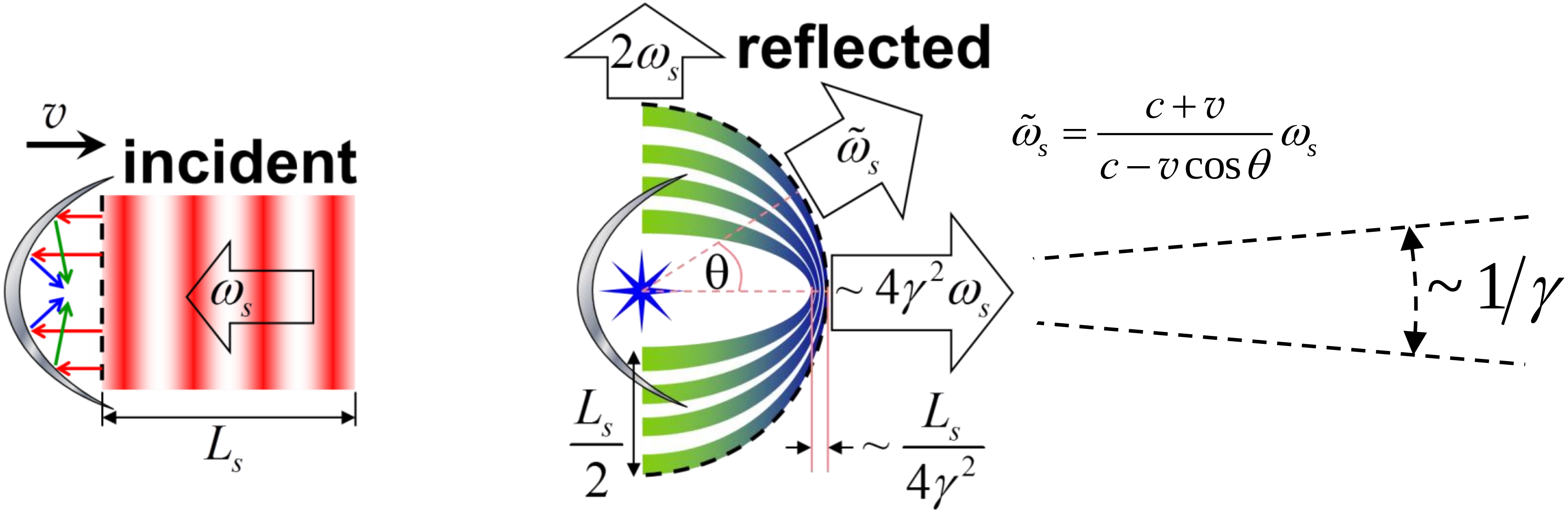


S. S. Bulanov, et al., "Relativistic spherical plasma waves", arXiv:1101.5179v1 (2011).

Laser Driven Relativistic Flying Mirror: towards Schwinger field ...and beyond.

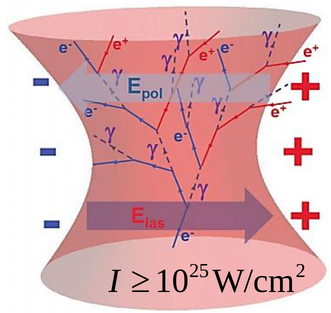
In a plane EM wave, both the invariants $\mathcal{F} = \frac{\mathbf{E}^2 - \mathbf{B}^2}{2} = \text{inv}, \quad \mathcal{G} = (\mathbf{E} \cdot \mathbf{B}) = \text{inv}$ **are zero, therefore $e^- e^+$ pairs are not created for an arbitrary magnitude of the EM field.**

Relativistic flying mirror can create field γ_{ph} times greater than QED critical field.

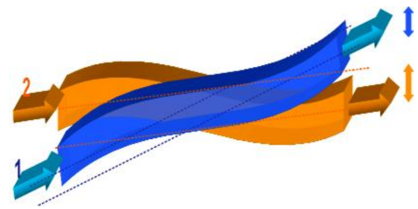


The mirror curvature can be controlled by the shape of the laser pulse.

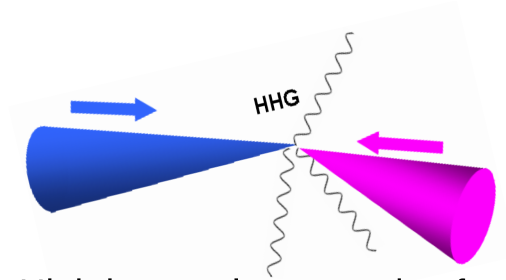
Quantum ElectroDynamics Effects near Schwinger Field



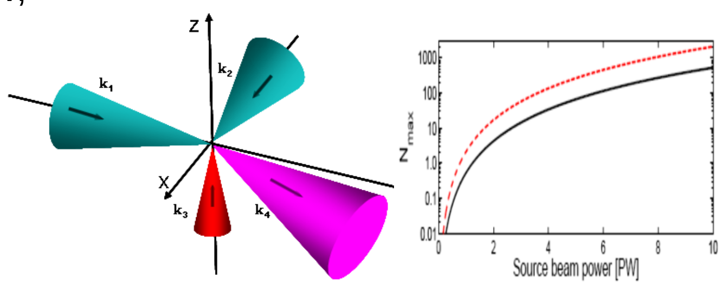
Electron-positron pair creation at the laser focus (SS Bulanov, Narozhny, Mur, VS Popov, 2006; Bell & Kirk, 2008).



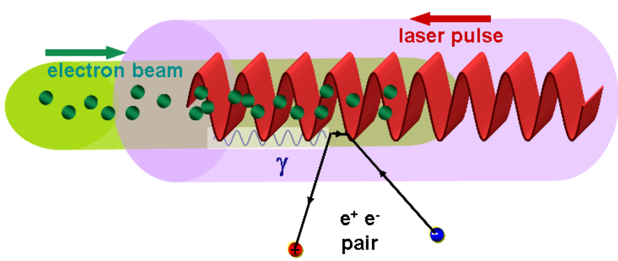
Birefringence of vacuum (Rozanov, 1993)



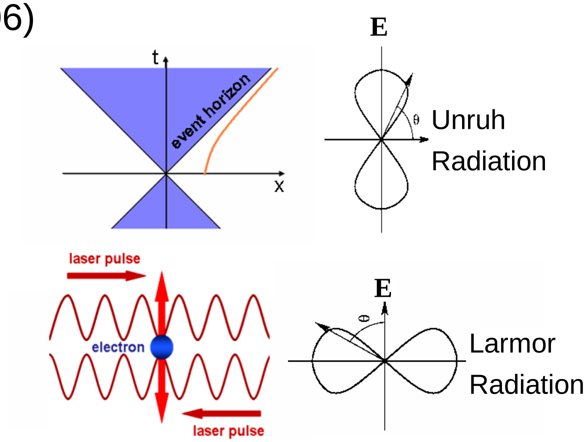
High harmonic generation from quantum vacuum (Di Piazza, Hatsagortsyan, Keitel, 2005;2009; Fedotov & Narozhny, 2006)



4-wave mixing (Lundström et al, 2006)



Electron-positron pair creation in the laser-electron collision: $e^- + n\gamma \rightarrow \gamma,\ \gamma + n\gamma' \rightarrow e^+ + e^-$ (Bula et al, 1996; Burke et al,1997)

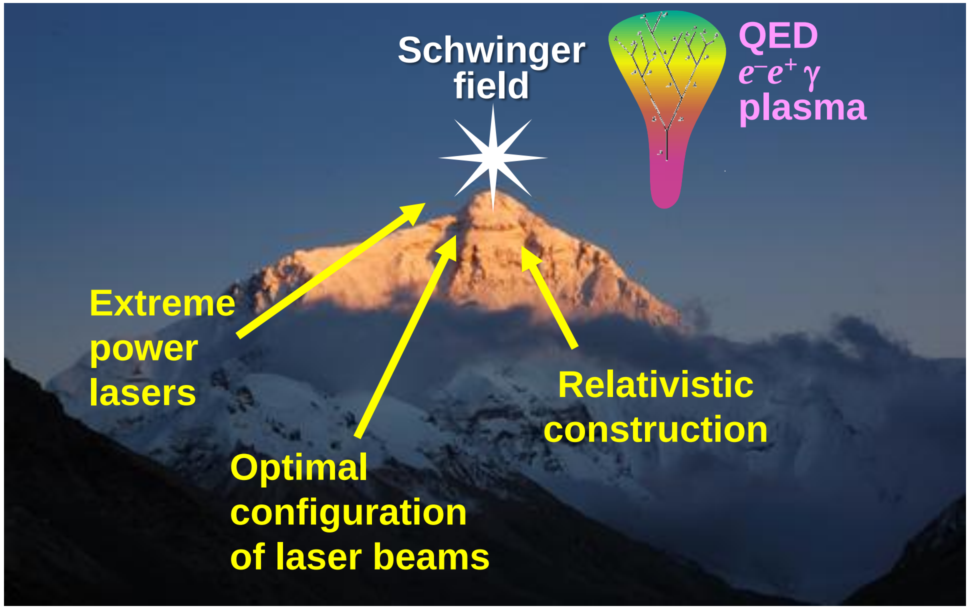


Unruh radiation (Chen&Tajima,1999)

Creation of $e^{-}e^{+}\gamma$ Plasma

with Lasers

Laser Driven $e^-e^+\gamma$ Plasma

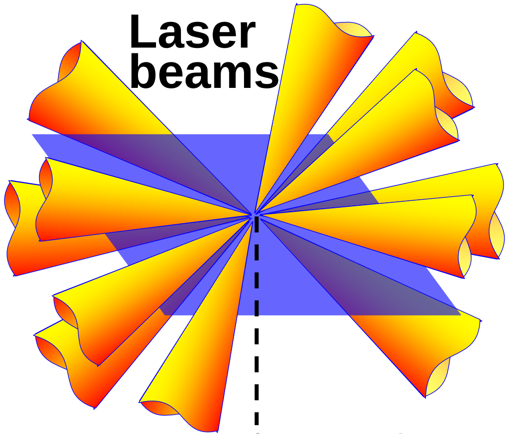


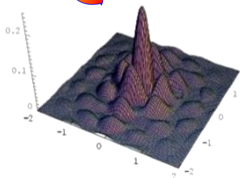
Electron-positron pairs can be created before the laser field reaches the Schwinger limit, due to a large phase volume occupied by a high-intensity EM field.

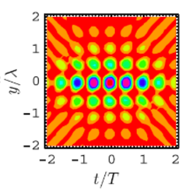
S. S. Bulanov, N. B. Narozhny, V. D. Mur, V.S. Popov, "Electron-positron pair production by electromagnetic pulses". JETP, 102, 9 (2006).

A. R. Bell & J. G. Kirk, "Possibility of Prolific Pair Production with High-Power Lasers". Phys. Rev. Lett. 101, 200403 (2008).

A. M. Fedotov, N. B. Narozhny, G. Mourou, G. Korn, "Limitations on the Attainable Intensity of High Power Lasers". Phys. Rev. Lett. 105, 080402 (2010).





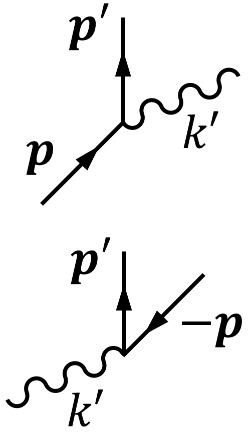


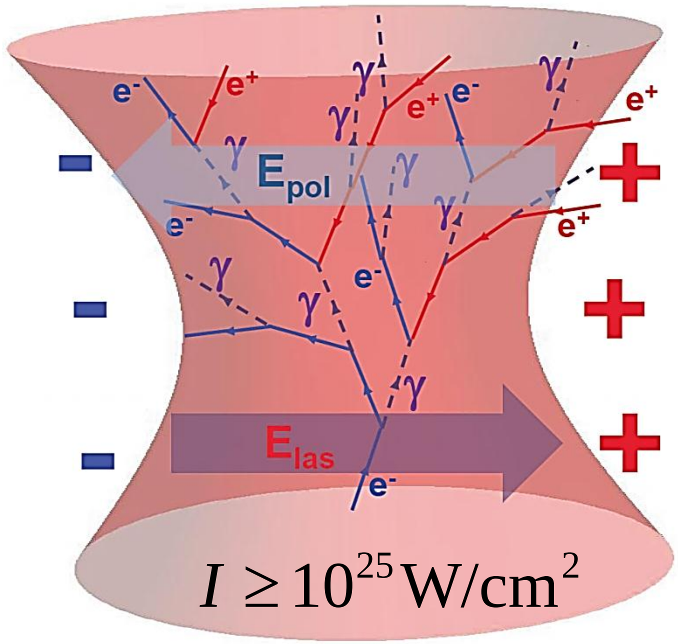
Multiple 10kJ beam system provides necessary conditions for e^-e^+ pairs creation.

Number of pulses	Number of e^-e^+ with 10kJ pulses	Required power (kJ) to create one pair
2	9×10^{-19}	40
4	3×10^{-9}	20
8	4	10
16	1.8×10^{3}	8
24	4.2×10^{6}	5.1

S.S.Bulanov, V.D.Mur, N.B.Narozhny, J.Nees, V.S.Popov, Phys. Rev. Lett. 104, 220404 (2010).

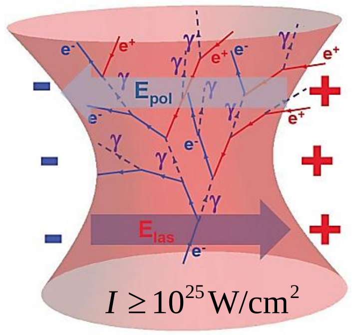
Creation of $e^-e^+\gamma$ Plasma by Superintense Laser Field





$$\gamma_e \frac{E}{E_S} \gg 1 \quad \rightarrow \quad n_+ \approx n_- = \frac{E}{4\pi e \lambda_0}$$

- **A. R. Bell and J. G. Kirk, "Possibility of Prolific Pair Production with High-Power Lasers" Phys. Rev. Lett. 101, 200403 (2008)**
- **A. M. Fedotov, N. B. Narozhny, G. Mourou, G. Korn, "Limitations on the Attainable Intensity of High Power Lasers" Phys. Rev. Lett. 105, 080402 (2010)**
- **S.S.Bulanov, T. Zh.Esirkepov, A.Thomas, J.Koga, S.V.Bulanov, "On the Schwinger limit attainability with extreme power lasers" Phys. Rev. Lett. 105, 220407 (2010)**
- **E. N. Nerush, I. Yu. Kostyukov, A. M. Fedotov, N. B. Narozhny, N. V. Elkina, H. Ruhl, "Laser Field Absorption in Self-Generated Electron-Positron Pair Plasma" Phys. Rev. Lett. 106, 035001 (2011)**
- **N. V. Elkina, A. M. Fedotov, I. Yu. Kostyukov, M. V. Legkov, N. B. Narozhny, E. N. Nerush, H. Ruhl "QED cascades induced by circularly polarized laser fields" Phys. Rev. ST Accel. Beams 14, 054401 (2011)**



Creation of $e^- e^+ \gamma$ Plasma by Superintense Laser Field

Key Parameters (dimensionless Lorentz invariants)

$$a = \frac{e\sqrt{(A_\mu)^2}}{m_e \omega c} = \frac{eE}{m_e \omega c}$$ **Laser dimensionless amplitude.**

$$\chi_e = \frac{e\hbar\sqrt{(F^{\mu\nu}p_\mu)^2}}{m_e^3 c^4} = \sqrt{\left(\gamma_e \frac{\boldsymbol{E}}{E_S} + \frac{\boldsymbol{p}\times\boldsymbol{B}}{m_e c E_S}\right)^2 - \left(\frac{\boldsymbol{p}\cdot\boldsymbol{E}}{m_e c E_S}\right)^2} \approx \frac{E}{E_S}\frac{2p_\perp}{m_e c}$$

characterizes the probability of the photon emission by the electron; in the electron rest frame of reference: $\chi_e \sim E/E_S$.

$$E_S = 1.3\times 10^{16}\ \text{V/cm}$$

$$\chi_\gamma = \frac{e\hbar^2\sqrt{(F^{\mu\nu}k_\mu)^2}}{m_e^3 c^4} \approx \frac{E}{E_S}\frac{2\hbar\omega_\gamma}{m_e c^2} \qquad \left[N\omega_0 + \omega_\gamma \rightarrow e^+ e^-\right]$$

characterizes the probability of the $e-e+$ pair creation due to a collision between the high energy photon and EM field.

- O. Klein (1929)
- F. Sauter (1931)
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- E.Brezin, C.Itzykson (1970)
- V. S. Popov (1971)
- V.I.Ritus (1979)
- A. Ringwald (2001)
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- N. B. Narozhny et al., Phys. Lett. A 330, 1 (2004)
- S. S. Bulanov et al., Phys. Rev E 71, 016404 (2005)
- S. S. Bulanov et al., JETP, 102, 9 (2006)
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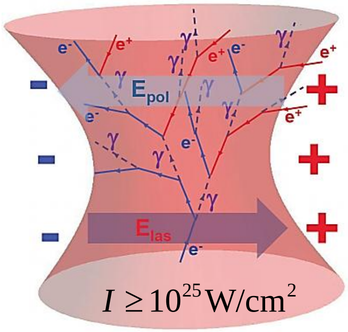


Creation of $e^-e^+\gamma$ Plasma by Superintense Laser Field

Probability of e^-e^+ pair creation

$$W_{\parallel}(\chi_\gamma) = \frac{3}{32}\frac{e^2 m_e^2 c^3}{\hbar^3 \omega_\gamma}\left(\frac{\chi_\gamma}{2\pi}\right)^{3/2}\exp\left(-\frac{8}{3\chi_\gamma}\right) \quad \text{for } \chi_\gamma \ll 1$$

$$W_{\parallel}(\chi_\gamma) = \frac{27\,\Gamma^7(2/3)}{56\pi^5}\frac{e^2 m_e^2 c^3}{\hbar^3 \omega_\gamma}\left(\frac{3\chi_\gamma}{2}\right)^{2/3} \quad \text{for } \chi_\gamma \gg 1$$

The number of absorbed laser photons: $N_l \approx a$

Photon mean-free-path before the pair creation: $\ell_{\text{mfp}} = \frac{\lambda_0}{0.2\pi\alpha a} \approx 220\frac{\lambda_0}{a}$

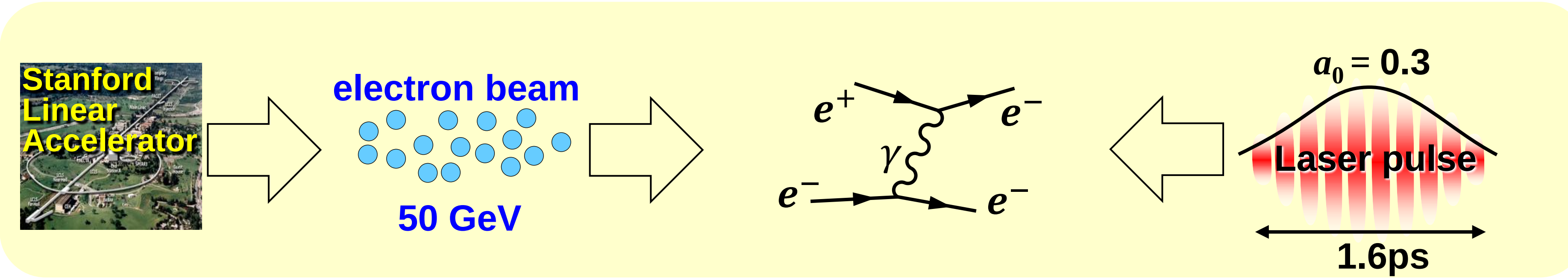
Favorable parameters for pair creation: $\chi_e \gtrsim 1$ and $\chi_\gamma \gtrsim 1$.

Size of the EM wave focus region should be $\gtrsim 220\lambda_0/a$.

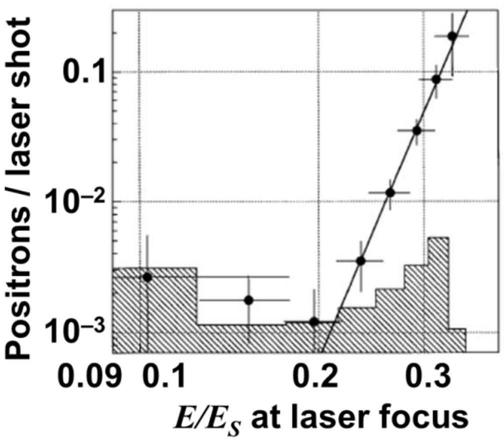
- H. Reiss, J. Math. Phys. 3, 59 (1962)
- A. I. Nikishov, and V. I. Ritus, 'Interaction of Electrons and Photons with a Very Strong Electromagnetic Field', Sov. Phys. Usp. 13, 303 (1970)
- V. I. Ritus, 'Quantum Effects of the Interaction of Elementary Particles with an Intense Electromagnetic Field', Tr. Fiz. Inst. Akad. Nauk SSSR 111, 5 (1979)
- K. T. McDonald, "Fundamental Physics During Violent Acceleration", AIP Conf. Proceed. 130, 23 (1985)

Creation of $e^-e^+\gamma$ Plasma in Ultrarelativistic Electron Collision with EM Wave

Conventional Accelerator + Laser



D. L. Burke, et al., Phys. Rev. Lett. 79, 1627 (1997)



$E_S = 1.3\times10^{16}$ V/cm

Breit-Wheeler process $\hbar\omega + \hbar\omega' \to e^+ + e^-$

$$\sigma_{\omega\omega\to e^+e^-} \approx \alpha^2 r_e^2 \quad \text{if} \quad \hbar^2\omega\omega' > m_e^2 c^4$$

G. Breit, J. A. Wheeler, Phys. Rev. 46, 1087 (1934)

Multiphoton inverse Compton scattering

$$e^- + N\hbar\omega_0 + \to \hbar\omega_\gamma + e^-$$

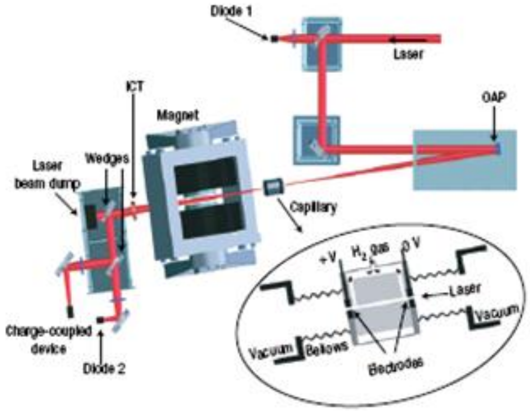
Multiphoton Breit-Wheeler process

$$\hbar\omega_\gamma + N\hbar\omega_0 \to e^+ + e^-$$

Key Parameters: $\chi_e = \dfrac{E}{E_S}\gamma_e \approx 0.3, \quad \chi_\gamma = \dfrac{E}{E_S}\dfrac{\hbar\omega_\gamma}{m_e c^2} \approx 0.15$

Creation of $e^-e^+\gamma$ Plasma in Ultrarelativistic Electron Collision with EM Wave

Conventional Accelerator → Laser Wake Field accelerator

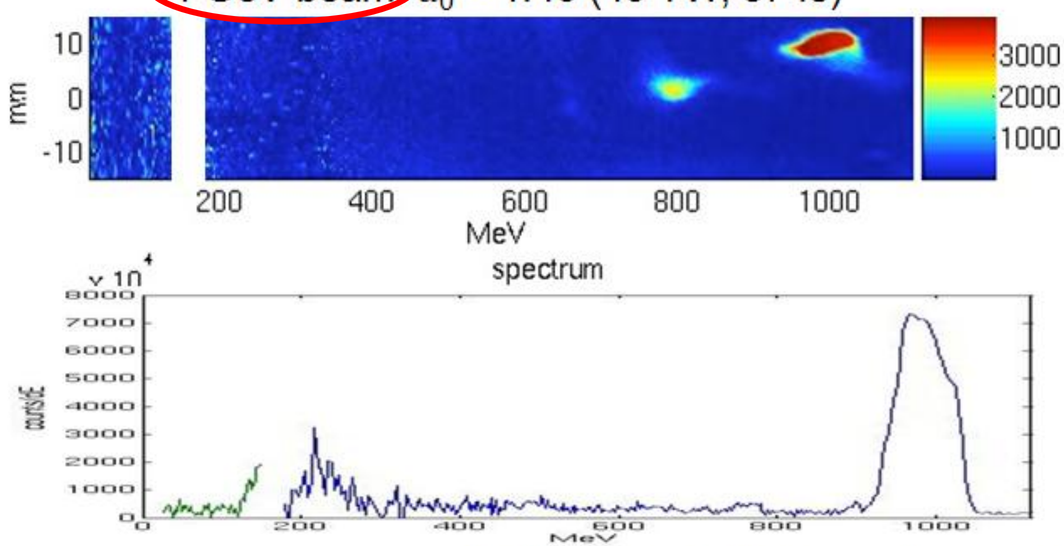


Laser: 1.5 J/pulse

Density: 4x10^{18} cm^{-3}

Capillary: 312 mm diameter and 33 mm length

1 GeV beam: a_0 ~ 1.46 (40 TW, 37 fs)

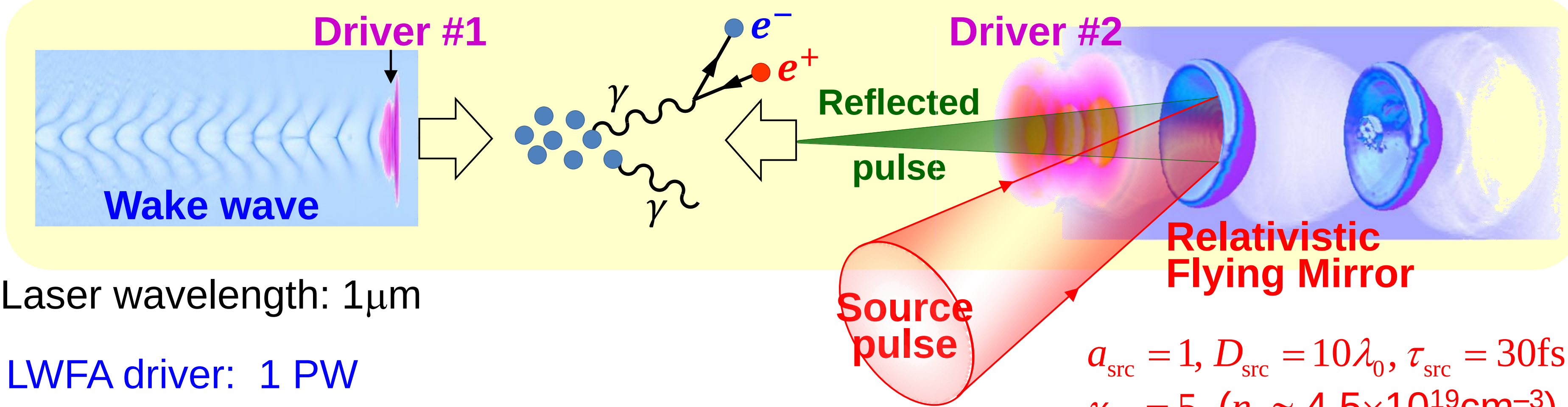


Peak energy: 1000 MeV
Divergence(rms): 2.0 mrad
Energy spread (rms): 2.5%
Charge: > 30.0 pC

W.P.Leemans et al, Nature Physics, 418 (2006)

Creation of $e^-e^+\gamma$ Plasma in Ultrarelativistic Electron Collision with EM Wave

Laser Wake Field Accelerator + Relativistic Flying Mirror



Laser wavelength: 1μm

LWFA driver: 1 PW

electron energy = 1.25 GeV $(\gamma_e = 2500)$

$a_{\rm src} = 1,\ D_{\rm src} = 10\lambda_0,\ \tau_{\rm src} = 30{\rm fs}$

$\gamma_{\rm ph} = 5\ \ (n_e \approx 4.5\times10^{19}{\rm cm}^{-3})$

Reflected focus: $I_{FM} = 32\gamma_{\rm ph}^3 \dfrac{D_{\rm src}^2}{\lambda_0^2} I_{\rm src}$

$$\frac{E_{FM}}{E_S} = 2^{5/2}\gamma_{\rm ph}^{3/2}\frac{D_{\rm src}}{\lambda_0}\frac{E_{\rm src}}{E_S} \approx 1.5\times10^{-3}$$

Key Parameters:

$$\chi_e \approx 2\gamma_e \frac{E_{FM}}{E_S} = 7.7$$

and, in multi-photon inverse Compton scattering regime,

$$\chi_\gamma \approx \frac{2\hbar\omega_\gamma}{m_e c^2}\frac{E_{FM}}{E_S} \approx 1.2\gamma_e \frac{E_{FM}}{E_S} = 4.6$$

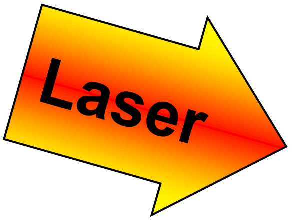
The condition that the electron is not expelled from the focus region by the ponderomotive force:

$$\gamma_e > \frac{c\tau_{FM}a_{FM}}{2D_{FM}} = \frac{c\tau_{\rm src}a_{\rm src}}{(2\gamma_{\rm ph})^{3/2}\lambda_0} \approx 0.3$$

Towards
Quark-Gluon Plasma

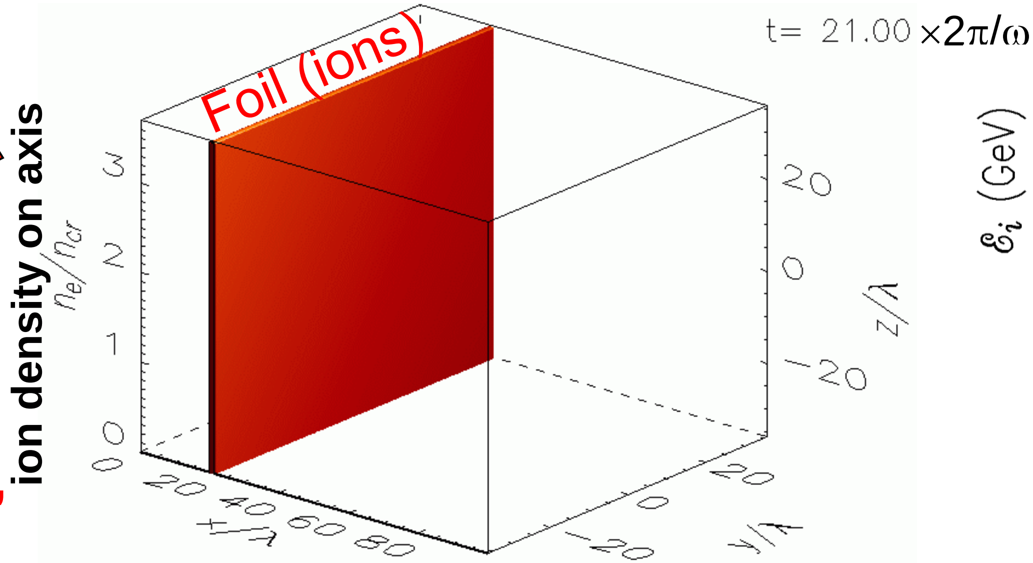
with Laser Radiation Pressure Dominant Acceleration

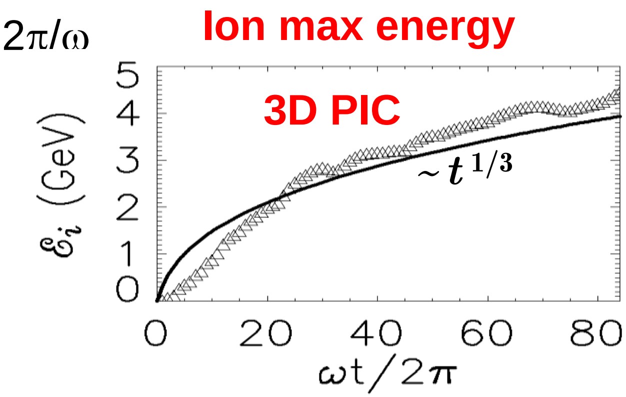
Laser Radiation Pressure Dominant Acceleration: towards Quark-Gluon Plasma



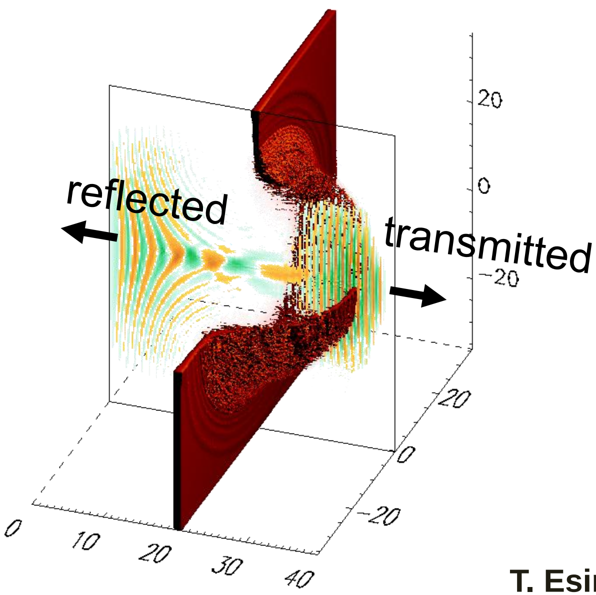
Laser:
***a*=316,**
***I*=1.37×10²³ W/cm²,**
8λ×25λ×25λ,
$\mathcal{E}_L$=10kJ

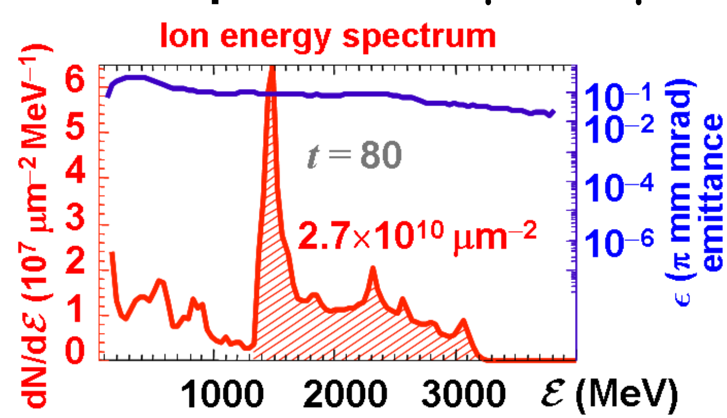
Foil: H, 1λ, 50n_{cr}





Ion beam
density: 3×10²¹ cm⁻³
Duration: 20 fs
Spot size: 20μm×10μm





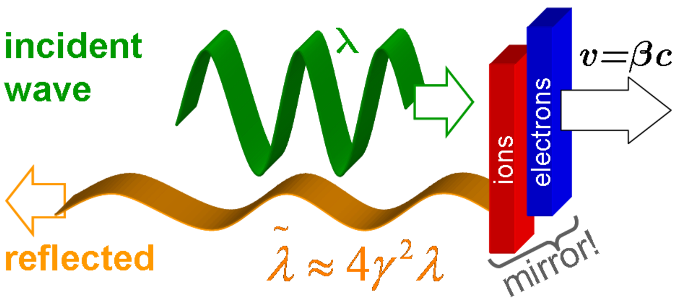
code REMP

Grid 2500×1800×1800;
4.4×10⁹ quasi-particles

Laser→ion energy transformation efficiency to all ions: 30% ; to ions > 1GeV: 12%

T. Esirkepov, M. Borghesi, S. V. Bulanov, et al., PRL 92, 175003 (2004).

Laser Radiation Pressure Dominant Acceleration: towards Quark-Gluon Plasma



Electromagnetic radiation pressure:

$$\mathcal{P} = \frac{E_\perp'^2}{2\pi}\left|\rho\left(\omega'\right)\right|^2$$

relativistic invariant

(′) means moving reference frame

$$\frac{E_\perp'^2}{E_\perp^2} = \frac{\omega'^2}{\omega^2} = \frac{c-v}{c+v};\quad v = \frac{pc}{\sqrt{m_i^2c^2+p^2}}$$

The foil motion under the radiation pressure:

$$\frac{dp}{dt} = \frac{E_\perp^2}{2\pi n_e \ell}\left|\rho\left(\omega'\right)\right|^2 \frac{\sqrt{m_i^2c^2+p^2}-p}{\sqrt{m_i^2c^2+p^2}+p}$$

Cf.: the average force of the EM wave scattered by electron [L. D. Landau & E. M. Lifshitz, *The Classical Theory of Field* (Addison-Wesley Press, U. of Michigan, 2nd ed., 1951), chapter 9, problem 6: p. 236.
Just substitute $1/2n_e\ell$ for the Thomson cross section :

$$\sigma_T = 8\pi r_e^2/3 \;\to\; \sigma = 1/2n_e\ell$$

“Fluence”: $$w = \int_{-\infty}^{t-x(t)/c} \frac{E_\perp^2(\zeta)}{4\pi n_e \ell m_i c}\left|\rho\left(\omega'\right)\right|^2 d\zeta.$$

accepted fluence

$$\max w = \mathcal{E}_L / \mathrm{N}_i m_i c^2 .$$

When $v \to c$, then $\left|\rho\ \omega'\right|^2 \to 1$

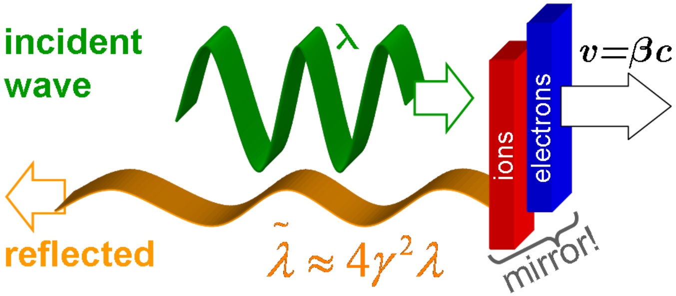
Solution for $p|_{t=0}=0$**:** $$\mathcal{E}_{i\,\mathrm{kin}} = m_i c^2 \frac{w^2}{w+1/2}$$

Asymptotically at $t \to \infty$ **:** $$\max \mathcal{E}_{i\,\mathrm{kin}} \approx \mathcal{E}_L / \mathrm{N}_i$$

Laser-to-ion energy conversion efficiency:

$$\kappa_{\mathrm{eff}} = \frac{\mathrm{N}_i \mathcal{E}_{i\,\mathrm{kin}}}{\mathcal{E}_L} = \frac{1}{1+1/2w}$$

Laser Radiation Pressure Dominant Acceleration: towards Quark-Gluon Plasma



Energy Scaling

$\gamma_\alpha - 1 \ll 1$ **Nonrelativistic Limit**

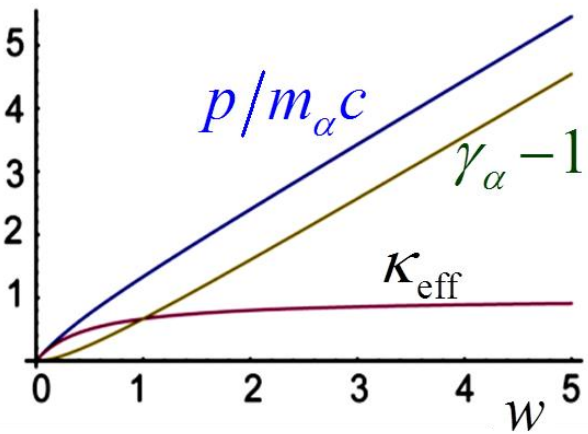
$$\mathcal{E}_\alpha = 8 \times \left(10^{11}/N_{tot}\right)^2 \left(m_p/m_\alpha\right)\left(\mathcal{E}_{las}/1\text{J}\right)^2 \text{ MeV}$$

$\gamma_\alpha \gg 1$ **Ultrarelativistic Limit**

$$\mathcal{E}_\alpha = 6.25 \times \left(10^{11}/N_{tot}\right)\left(\mathcal{E}_{las}/100\text{J}\right) \text{ GeV}$$

Efficiency

$$\kappa_{\text{eff}} = \frac{1}{1+1/2w} \xrightarrow[w\to\infty]{} 1$$

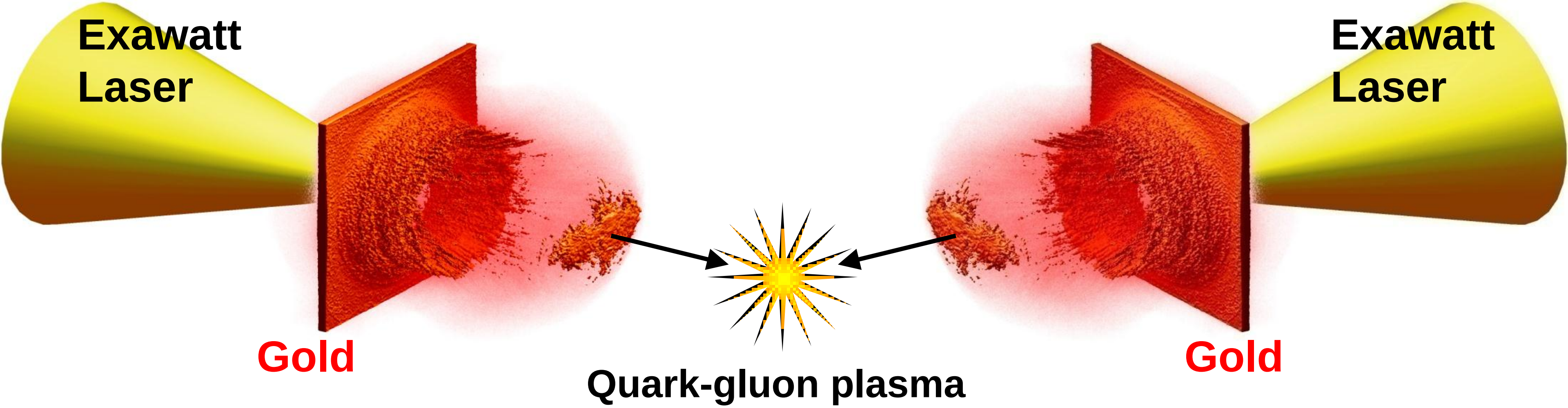


Laser-to-ion energy conversion can be formally 100%.

30 KJ laser pulse can accelerate 10^{12} protons up to 200 GeV.

Laser Radiation Pressure Dominant Acceleration: towards Quark-Gluon Plasma

Laser Driven Ion Collider



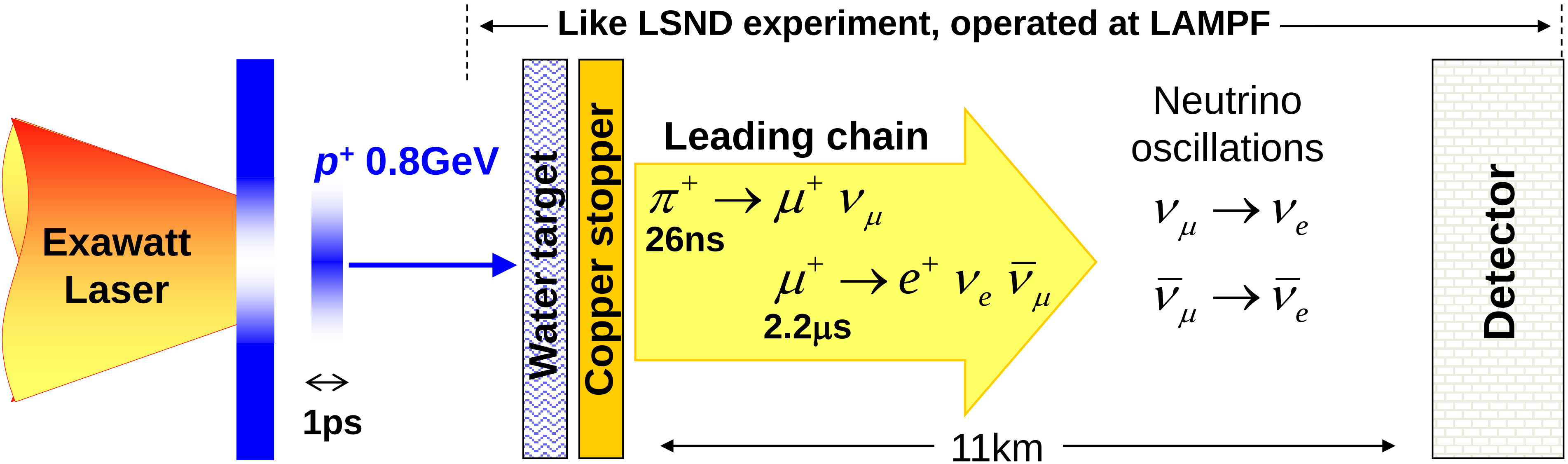
Luminosity $\mathcal{L} = f\left(\frac{N_1 N_2}{4\pi\sigma_y\sigma_z}\right) = 10^{34}\left(\frac{f}{10\mathrm{KHz}}\right)\left(\frac{N_{tot}}{10^{12}}\right)^2\left(\frac{10^{-4}\mathrm{cm}}{\sigma_\perp}\right)^2 \mathrm{cm}^{-2}\mathrm{s}^{-1}$

For 100 GeV, 10^{12}-10^{14} particles $\sim$ 10^7-10^{11} events per 1 shot

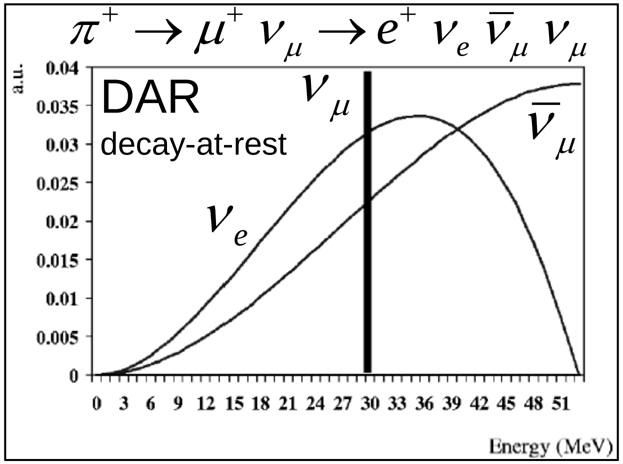
Cf.: with RHIC/BNL collider (Au+Au,100 GeV/nucleon)

Laser Radiation Pressure Dominant Acceleration:

Beam Dump Facility for Neutrino $\bar{\nu}_\mu \to \bar{\nu}_e$ Oscillations Studies



$\nu_e, \bar{\nu}_e$ **contaminations suppressed**

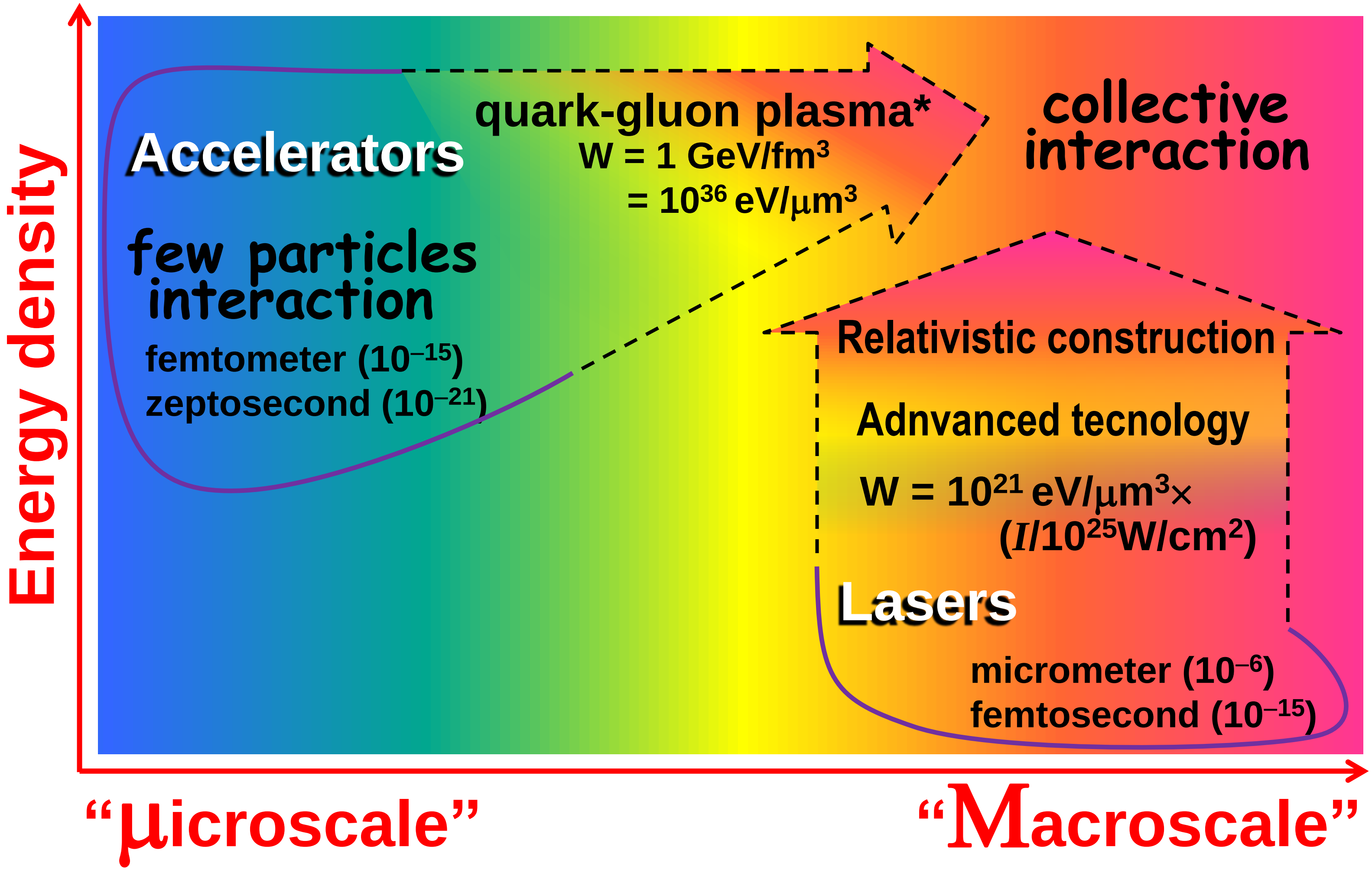


1. **Multipurpose facility for high precision studies of neutrino oscillations.**
2. **The facility could allow for the first time the study of subdominant $\nu_\mu \to \nu_e$ oscillations at the atmospheric scale with neutrinos produced by π^+ decays at rest or in flight.**

S.V.Bulanov,T.Esirkepov,P.Migliozzi,F.Pegoraro,T.Tajima,F.Terranova,Nucl.Instrum.Meth. A540, 25-41 (2005)

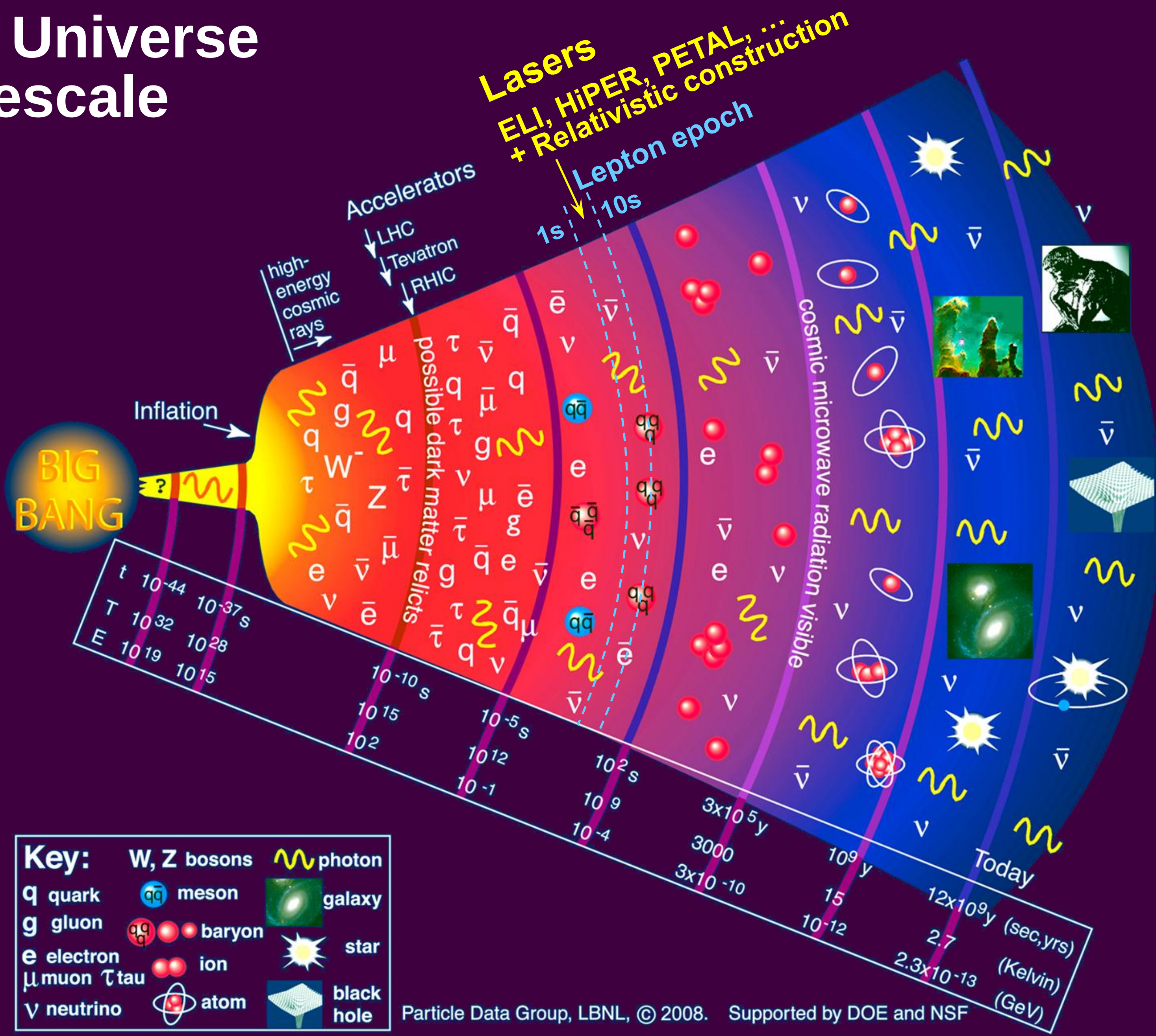
Towards
Collective
High Energy Physics

High Energy Physics



* Super Proton Synchrotron (CERN, p) 1994…2000.
Relativistic Heavy Ion Collider (BNL, Au) 2004…2010.
Large Hadron Collider (CERN, Pb) 2010…2011.

The Universe timescale



Conclusion

Development of Superintense Lasers ELI, PETAL, HiPER, ... will allow

- **exploring novel phenomena in fundamental physics and**
- **modeling processes in relativistic astrophysics.**

The experiments in this field will allow creating in a terrestrial laboratory the state of matter characteristic to

- **cosmic Gamma Ray Bursts,**
- **the Lepton Era and**
- **Hadron Era of the Universe.**