A Review of High-Energy-Density Laboratory Astrophysics
^ Relativistic

- Collimation and propagation dynamics in magnetized flows
- Radiative and reverse-radiative shock systems
- Collisionless shock interactions
- Instabilities in plasma – RT, RM, KH, MRI, MTI
- Equation of state – planetary and stellar interiors
- Nucleosynthesis - relevant Gamow energies in a 'thermal' plasma
- Relativistic electron-positron plasmas

Mario Manuel
Einstein Fellows Symposium
Harvard-Smithsonian Center for Astrophysics
October 27th, 2015

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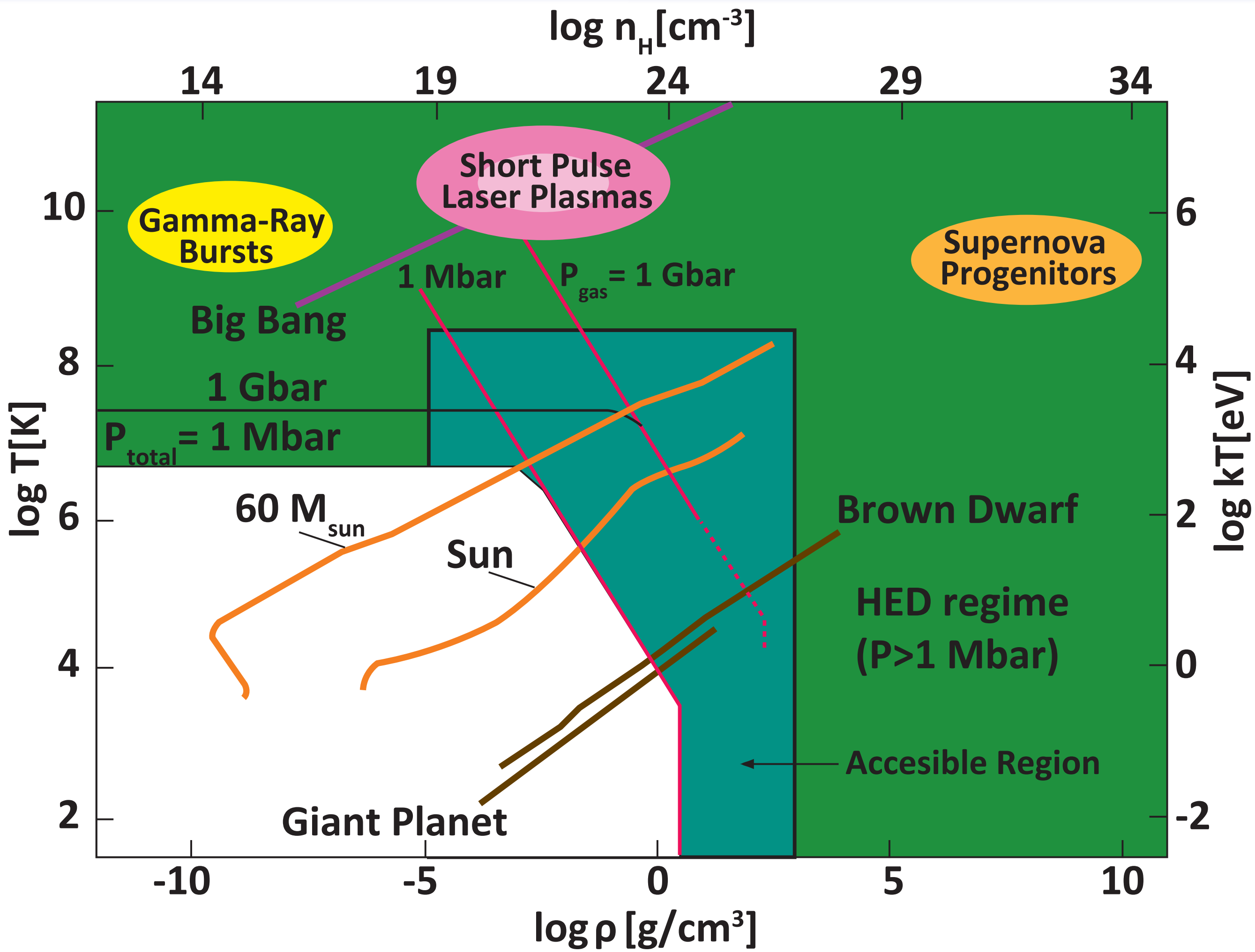
A Review of Relativistic High-Energy-Density Laboratory Astrophysics



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*Adapted from NRC committee on HEDP (2003)

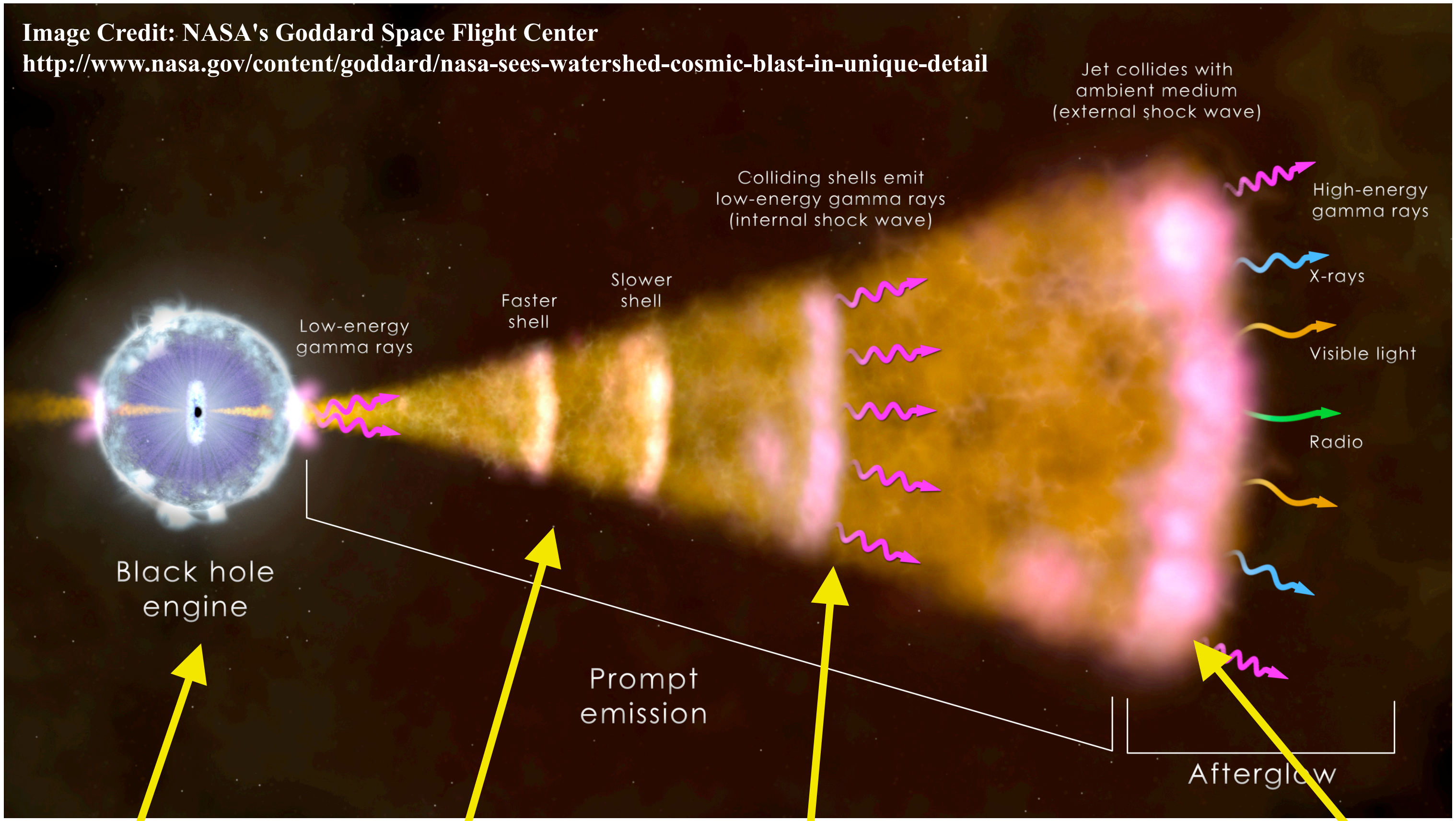
Relativistic plasmas is an emerging field in laboratory astrophysics

- Many of the most energetic events in our universe involve relativistic plasmas: GRBs, collisionless shocks – cosmic ray generation, etc.

- The plasma must be near neutral and exhibit collective behavior to study astrophysically relevant dynamics

- Intense lasers provide a unique opportunity to study the detailed physics of these relativistic systems under controlled conditions

Gamma-ray Bursts emit high-energy radiation in prompt and extended durations



(1) Relativistic energy source - the "engine"

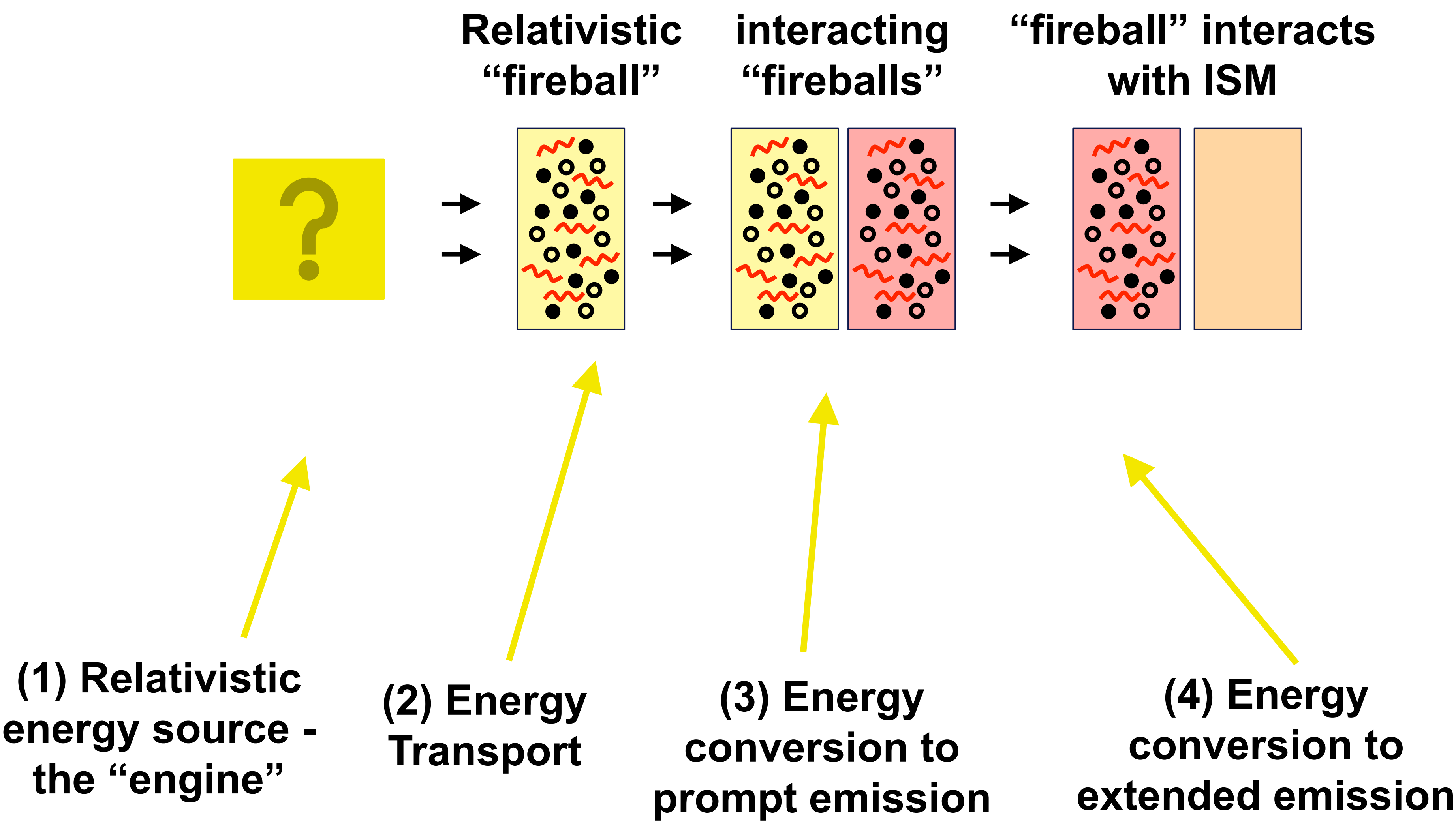
(2) Energy Transport

(3) Energy conversion to prompt emission

(4) Energy conversion to extended emission

Piran, PR 314 (1999)

Relativistic plasma physics relevant to GRBs can be studied in the laboratory



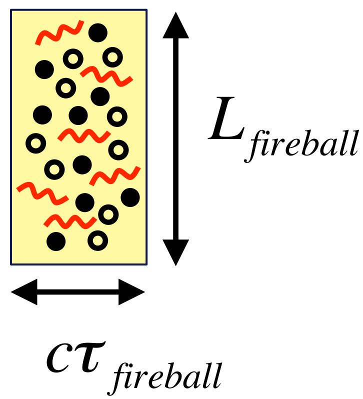
Piran, PR 314 (1999)

The laboratory "fireball" must behave as a plasma to be relevant to astrophysical dynamics

Relativistic "fireball"

Consider a relativistic e^- - e^+ plasma

$$\omega_p = \sqrt{\frac{e^2\left(n_{e-} + n_{e+}\right)}{\varepsilon_0 \gamma m_e}}$$



(1) Quasi-neutral

$$N_{e-} \approx N_{e+}$$

(2) Collective Behavior

$$L_{fireball} > \ell_{skin} = \frac{c}{\omega_p}$$

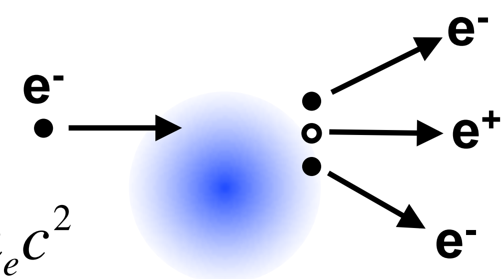
$$3.9 \times 10^{-4} \sqrt{\frac{N_{e-} + N_{e+}}{\gamma \tau_{fireball}\left[10^{-15}\,\mathrm{s}\right]}} > 1$$

A plasma with these characteristics may be created in the laboratory with ultra short-pulse laser systems.

Sarri, Nat. Comm. 15 (2015)

Relativistic pair-production in the laboratory requires relativistic electrons

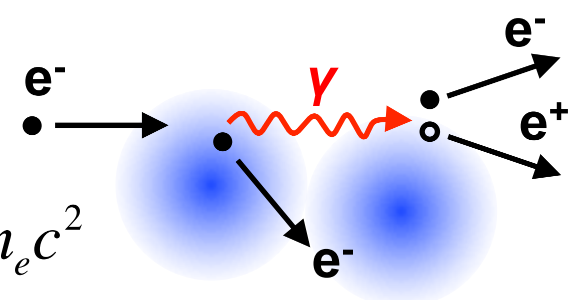
Trident Process



$$E_{e-} > 2m_e c^2$$

$$\sigma_T \propto Z^2$$

Bethe-Heitler (BH) Process



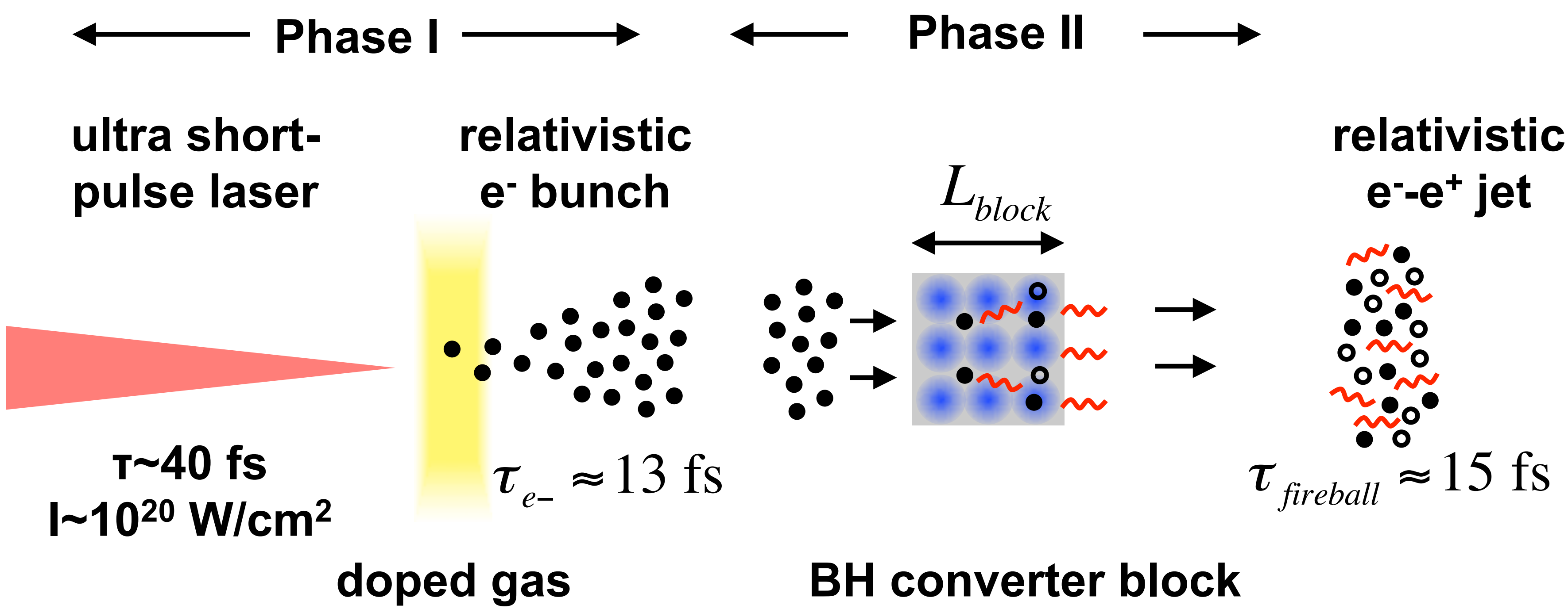
$$E_{e-} > 2m_e c^2$$

$$\sigma_{BH} \propto Z^4$$

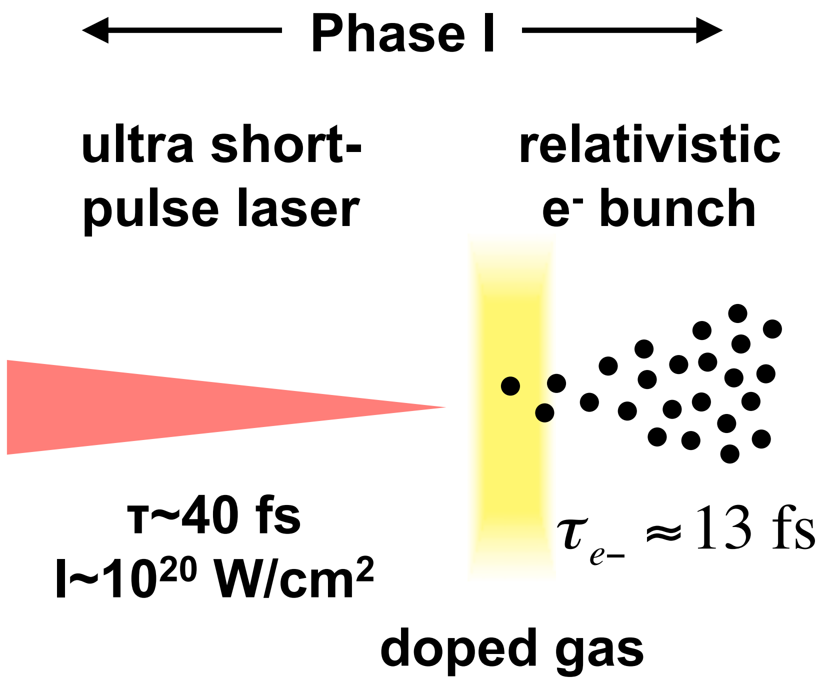
The Bethe-Heitler process dominates pair-production in materials with high atomic number (Z).

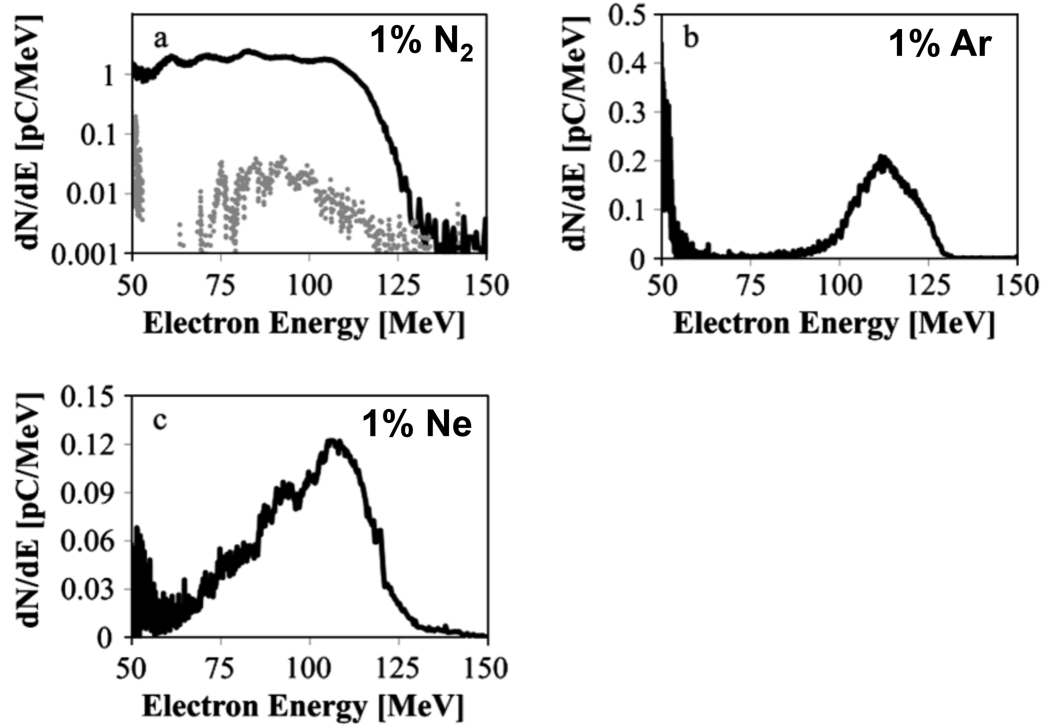
Shearer, PRA 8 (1973), Heitler (1954)

Creating a relativistic plasma jet in the lab is a 2-phase process



Creating a relativistic plasma jet in the lab is a 2-phase process
Phase I: Generate a relativistic electron bunch

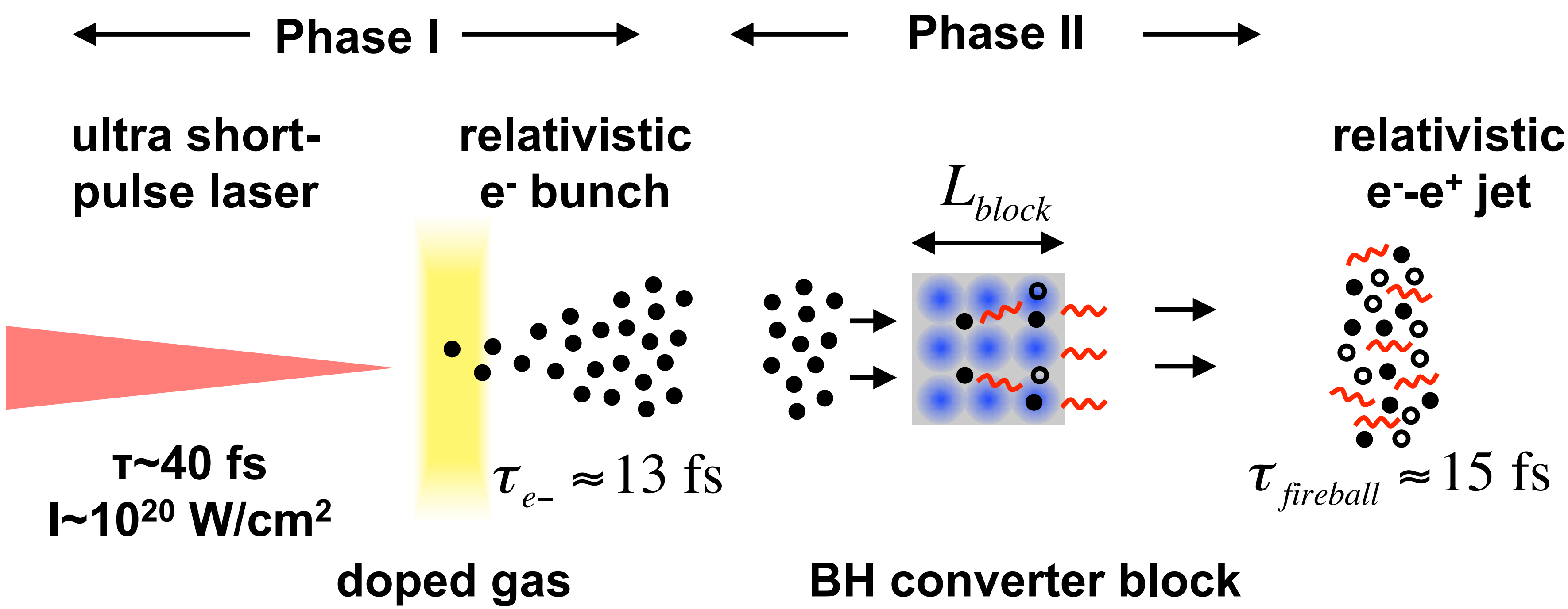




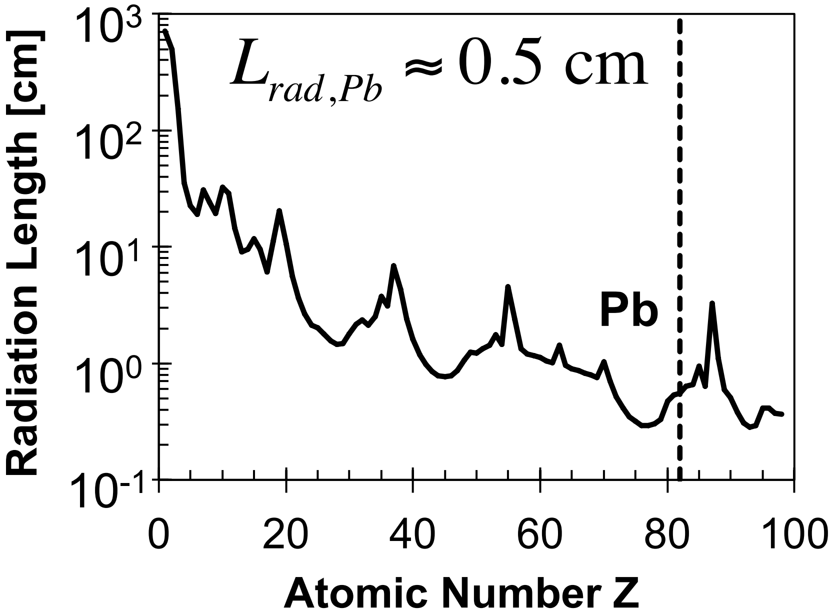
"Wakefield acceleration" provides an efficient mechanism to create tailored relativistic electron bunches

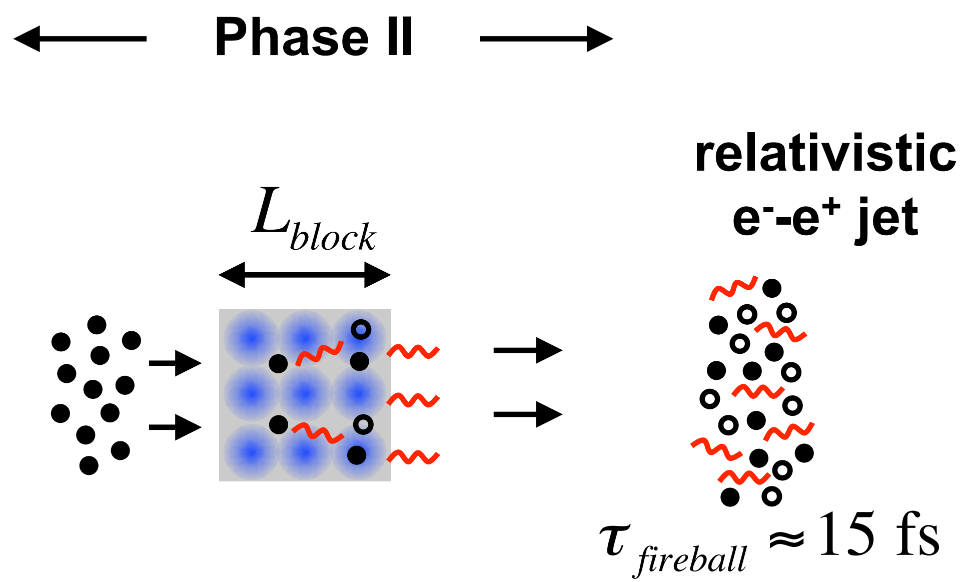
Tajima, PRL 43 (1979); McGuffey, PRL 104 (2010)

Creating a relativistic plasma jet in the lab is a 2-phase process



Creating a relativistic plasma jet in the lab is a 2-phase process
Phase II: Convert electrons to pairs





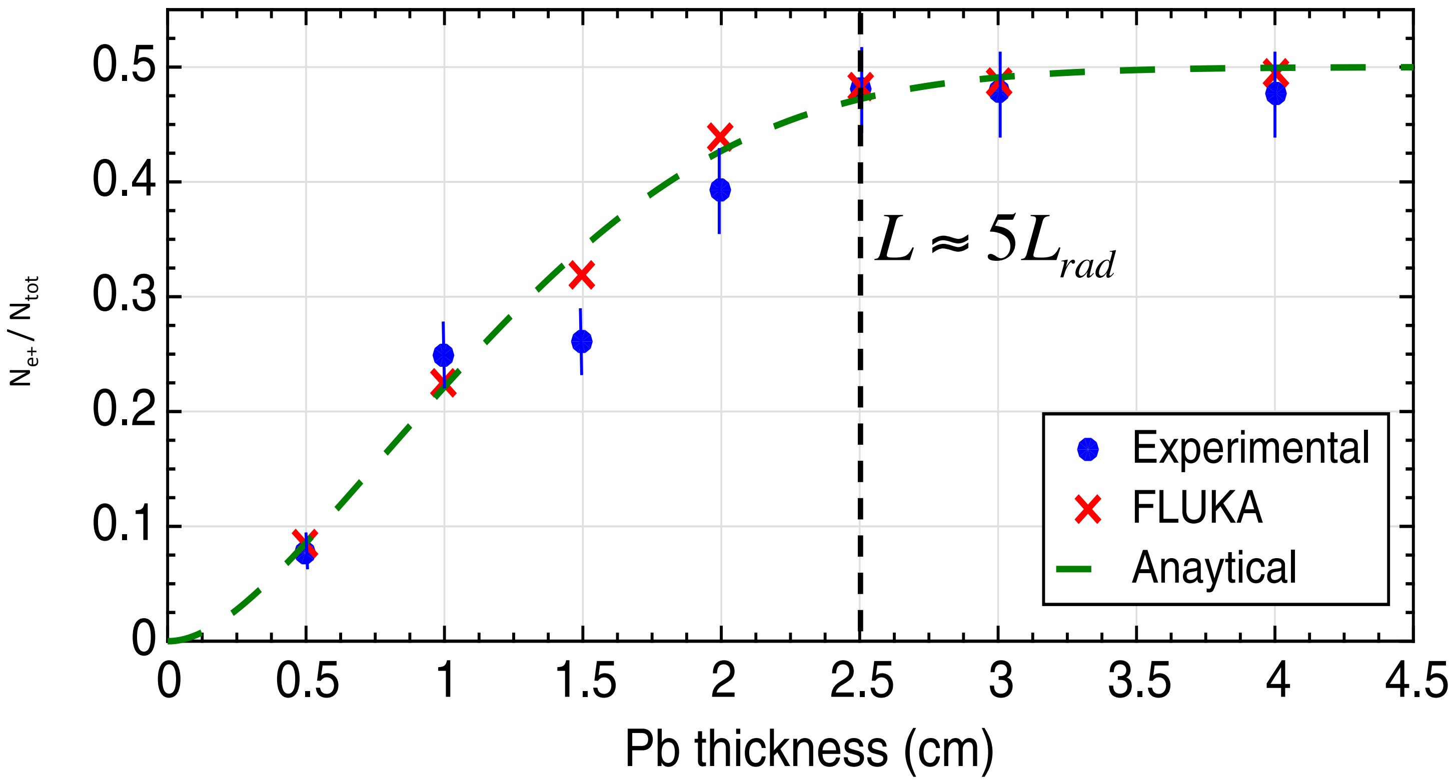
BH converter block

To create a quasi-neutral electron-positron jet,

$$L_{block} \geq 5L_{rad}$$

and scattering in the block must be accounted for.

Creating a relativistic plasma jet in the lab is a 2-phase process
Phase II: Convert electrons to pairs



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Sarri, Nat Comm 6 (2015)

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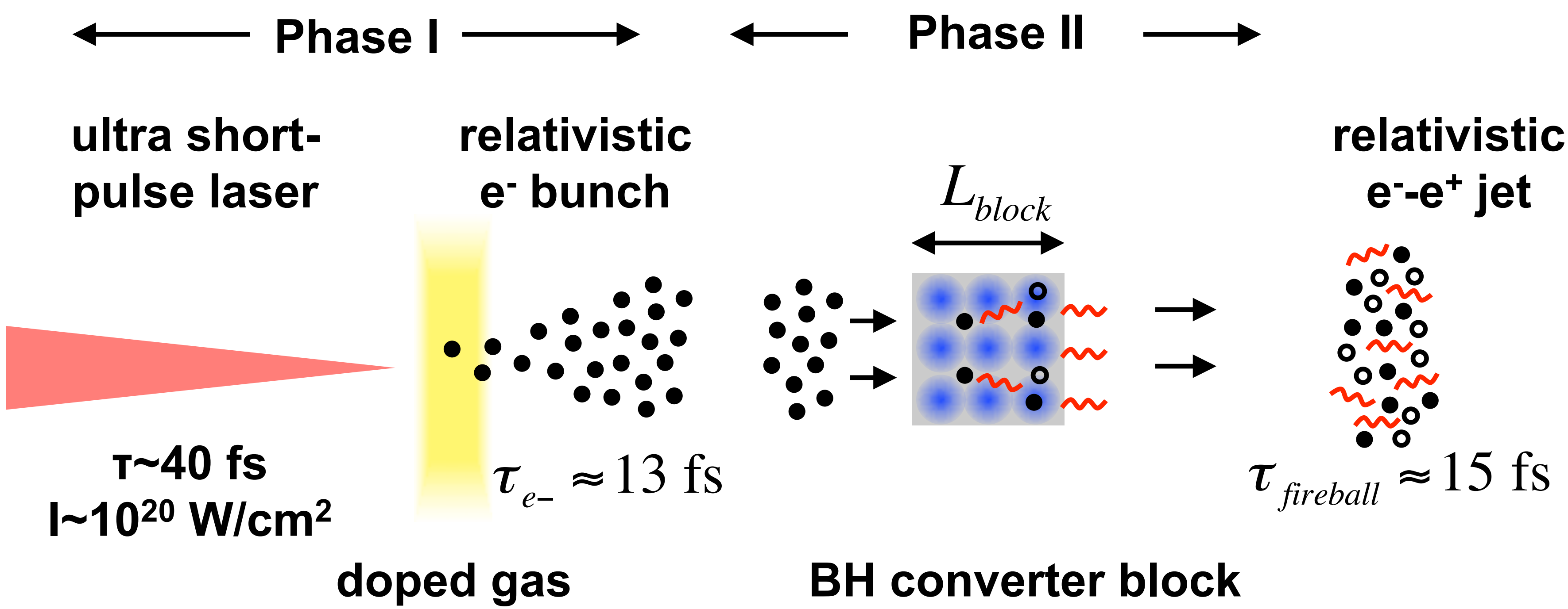
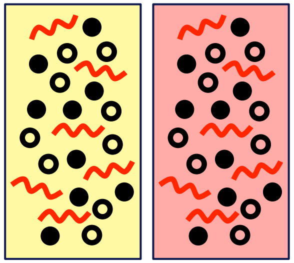


This technique can create a quasi-neutral relativistic plasma jet that behaves collectively.

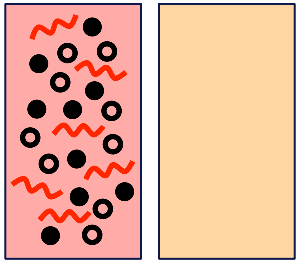
Relativistic electron-positron jets can be created to investigate physics relevant to GRBs

interacting "fireballs"



- double-peaked spectrum for the electron-positron plasma

"fireball" interacts with ISM

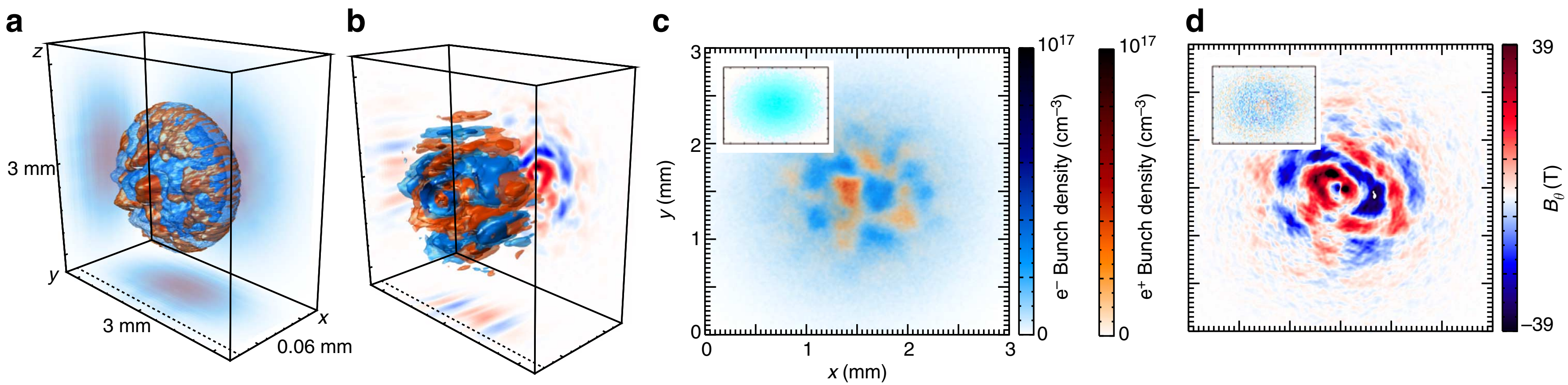


- Interaction with background plasma or gas

Measured γ-ray spectra from these well characterized systems will provide concrete data to benchmark models.

PIC simulations suggest that filamentary structure will form in a background plasma

50:50 electron:positron jet traversing a uniform electron-ion plasma



- Syncrotron emission from the self-generated/amplified fields
- Filament generation and characterization
- Collisionless shock formation
- Particle acceleration

Sarri, Nat Comm 6 (2015), Muggli arXiV:1306.4380v1

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