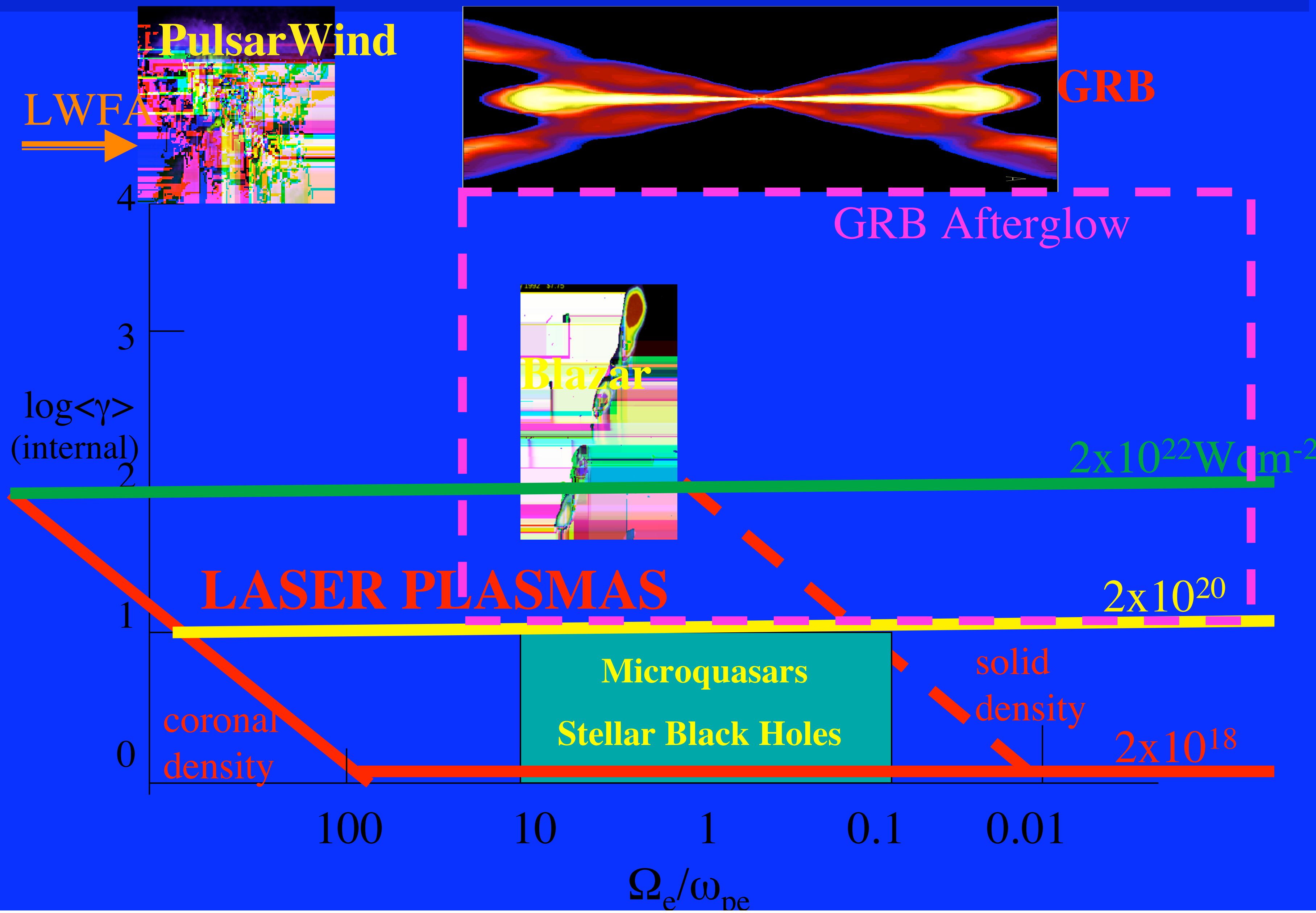
"Extreme Plasmas"

There is a great deal of synergism between astrophysical plasmas and laser plasmas in the relativistic, strong field regimes.
Our study group identified Six Thrust Areas that may provide the best opportunities for major advances via Laboratory Experiments (E) and Computer Simulations (S)

1. Relativistic Collisionless Shocks
2. Electron-positron Pair Plasmas (E)
3. Relativistic Jets
4. Beam Propagation and Dissipation
5. Ultra-strong Magnetic Fields (E)
6. Turbulence and Reconnection in Relativistic Plasmas (S)

Phase space of laser hot electrons/pairs overlap some relevant regimes of high energy astrophysics



“Extreme” Plasmas are different and special because:

1. As v-->c (or kT >> mc^2, or $(E^2,B^2) \gg \rho c^2$), qualitatively new properties emerge, especially when nonlinear collective plasma processes dominate.

2. When pair dominate, mobility of the charges allow the plasma to act very differently from e-ion plasmas.

3. Strong fields (“B_{cr}“~ 10^9G, 4×10^{13}G, 6×10^{15}G) lead to qualitatively new atomic, radiative and plasma properties.

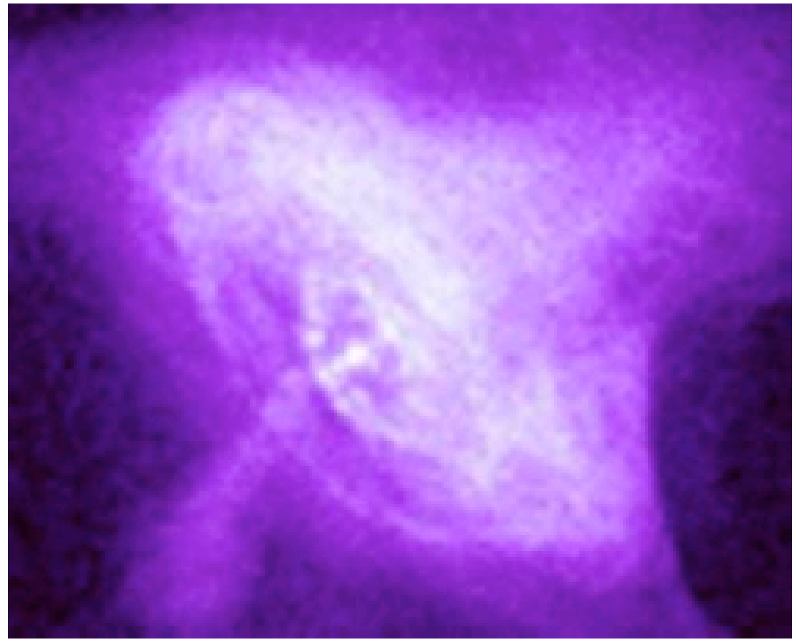
Relativistic Collisionless Shocks

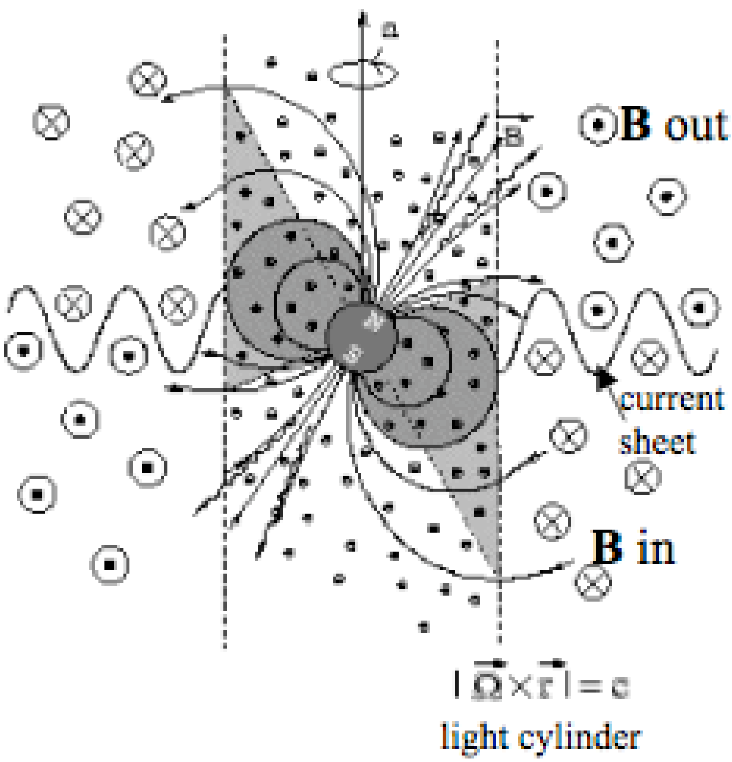
Major Questions:

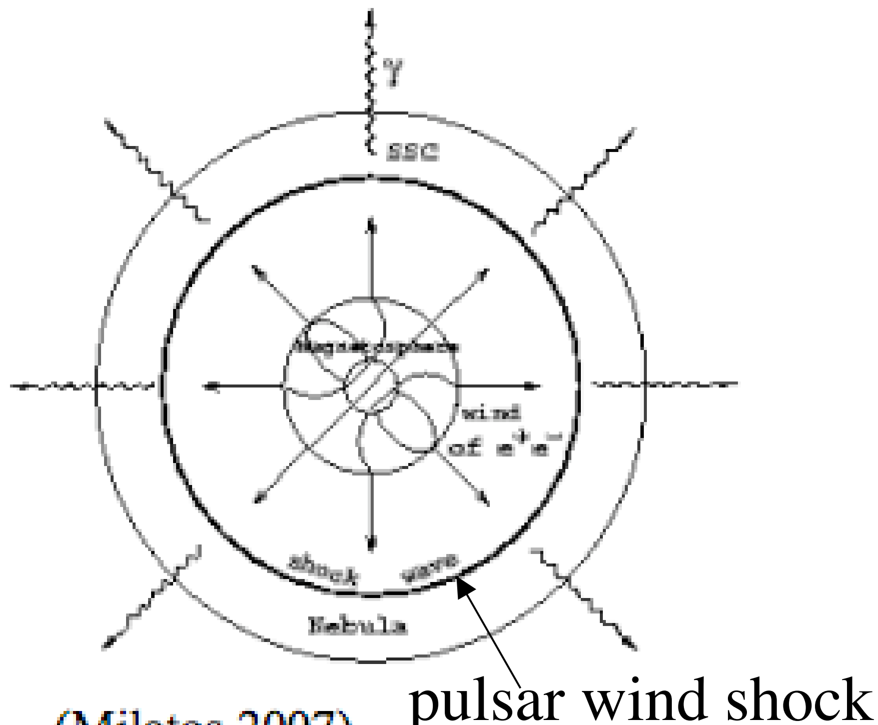
1. Shock Structure as function of upstream magnetization, flow speed, field geometry, composition (e-ion vs pairs vs hybrid)* and temperature
2. B-field generation and evolution in shocks
3. Particle Energization and Acceleration
4. Differences between relativistic and non-relativistic shocks*
5. Radiative properties & radiation damping*

Example of Relativistic Shock

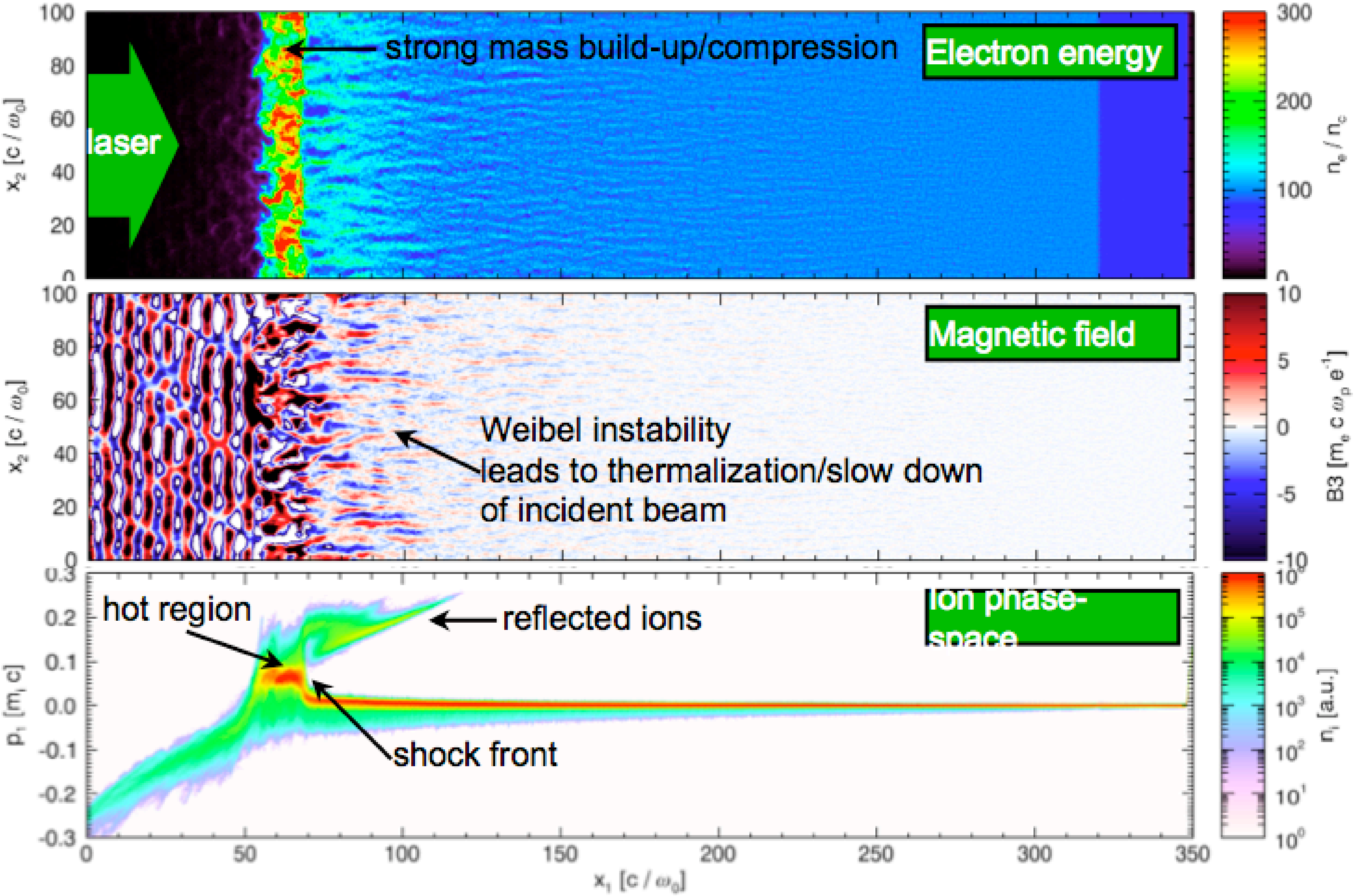
Chandra X-ray Image of Crab Pulsar Wind Nebula







(Milatos 2007)



2D PIC simulation of 10^{20}W.cm^{-2} laser driving a hot electron shock in a solid target. Relativistic hot electrons filament and generate magnetic turbulence via Weibel, leading to thermalization, heating and compression of incident electrons, which in turn results in heating and compression of ions. Shock speed is ~0.06c. (courtesy of fiuza et al. 2009 unpublished).

Laser-created Dense electron/Pair Jets provides new opportunity on Relativistic Shocks

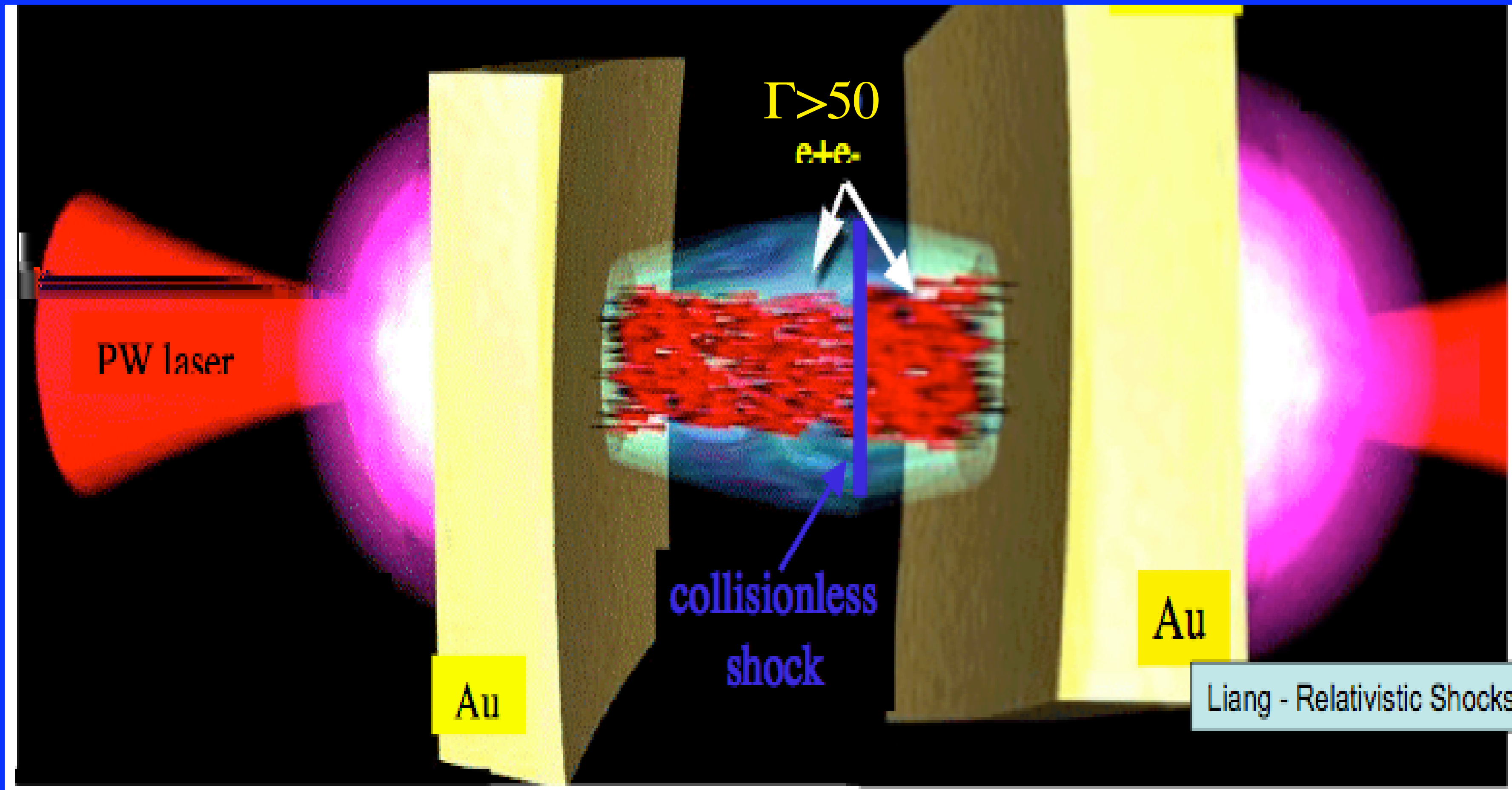


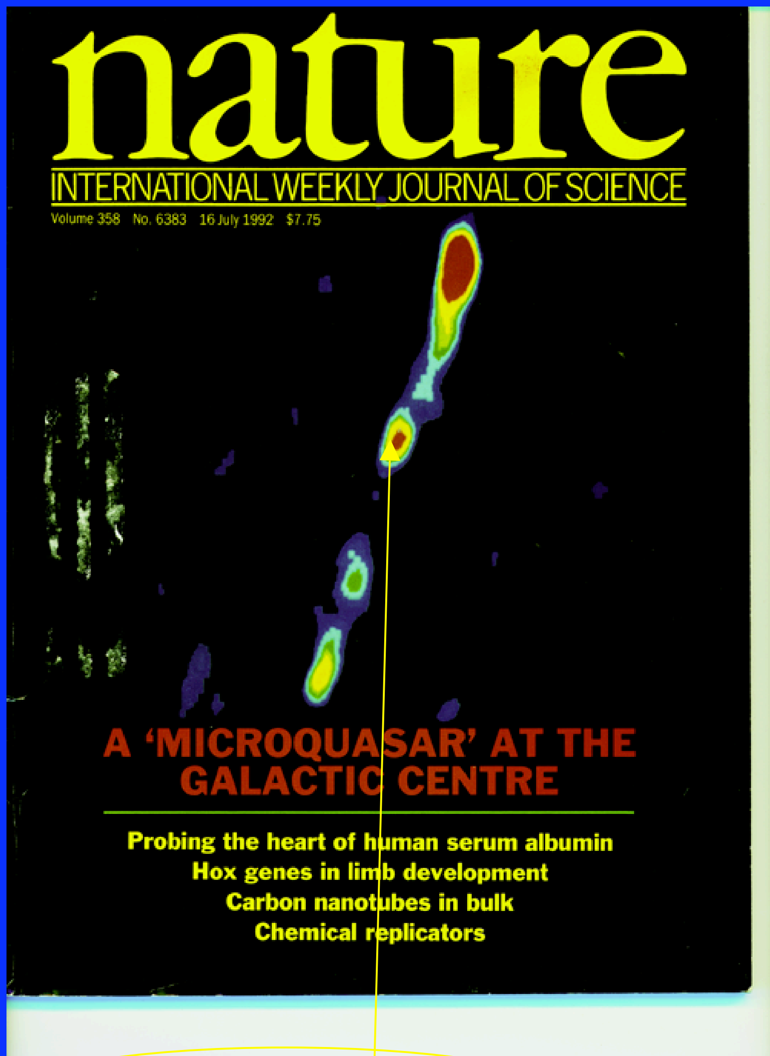
Fig.4 Artist conception of relativistic shock launched by head-on collision of two e+e- pair jets created by two high-energy PW-class lasers irradiating mm-thick gold targets.

Pair Plasmas

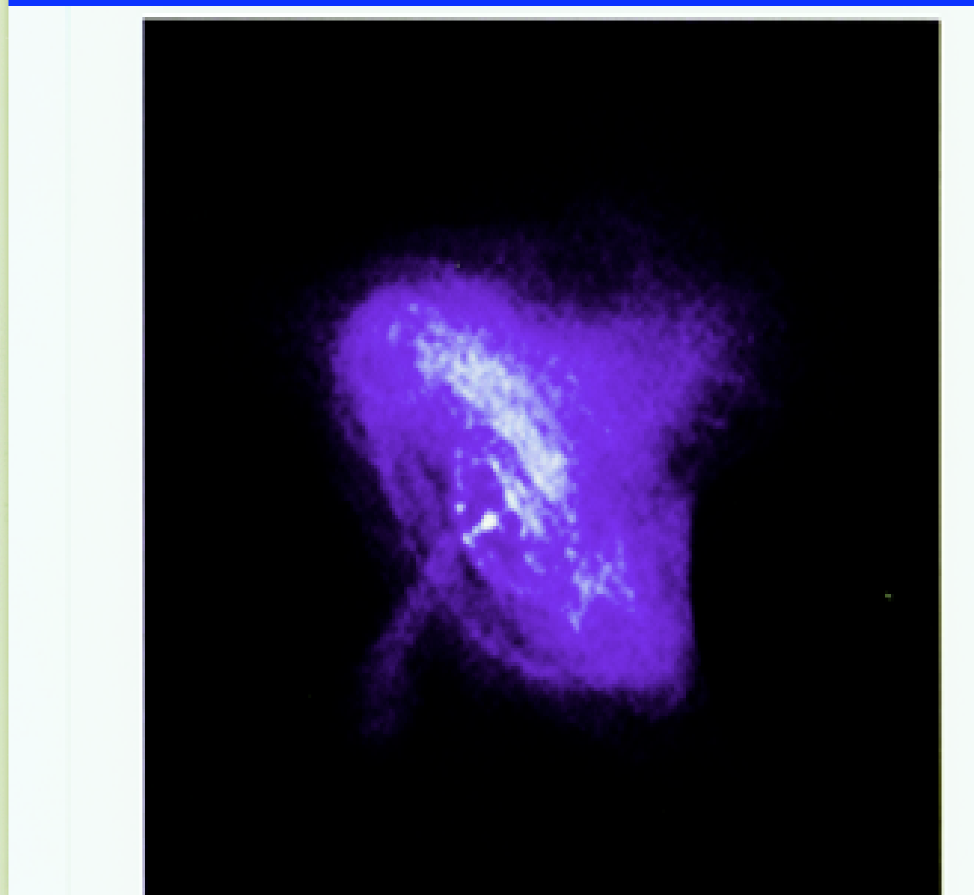
Major Questions

1. How can pair plasmas manifest themselves?
2. Key differences between fundamental plasma kinetics of pair-plasma vs. e-ion plasmas
3. Thermodynamics of pair-equilibrium plasmas, including creation-annihilation and radiation processes.
4. How can we create, sustain and study pair plasmas in the laboratory?

relativistic e+e- plasmas are ubiquitous in the universe



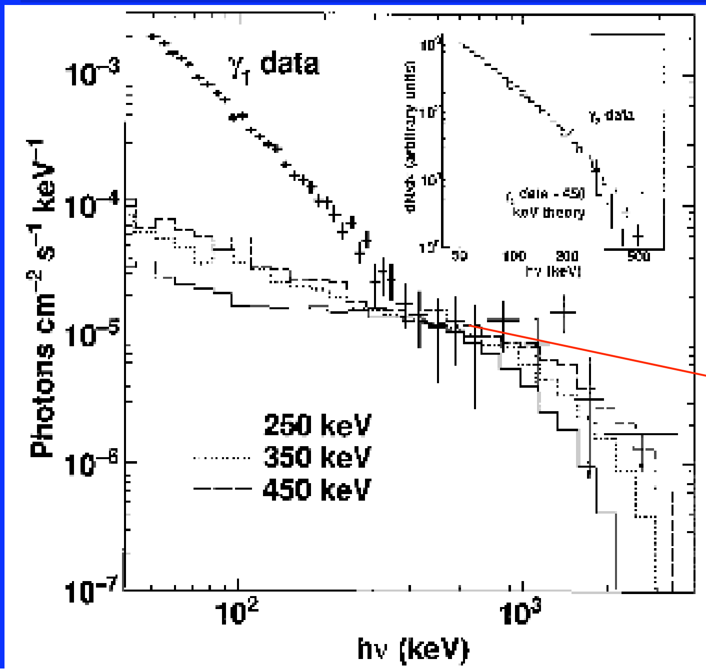
Thermal MeV pairs

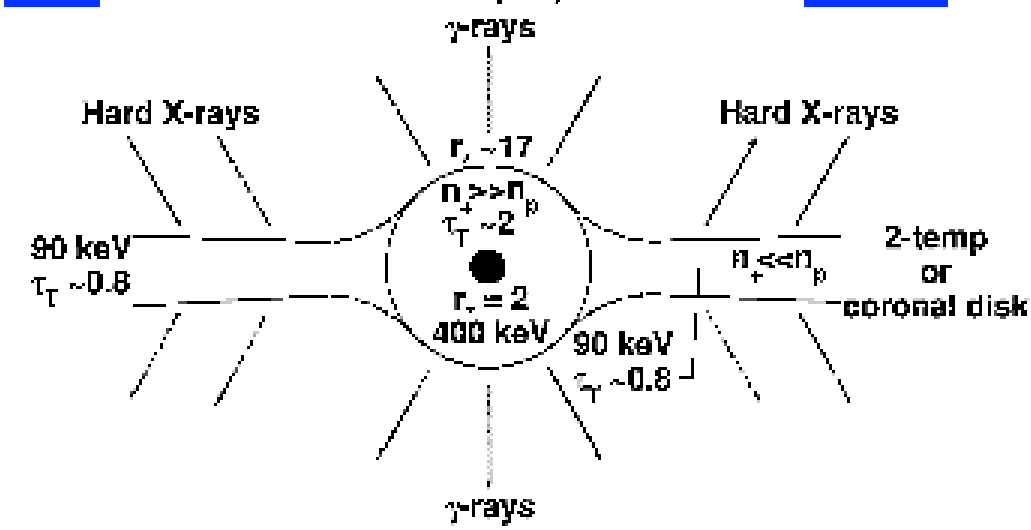


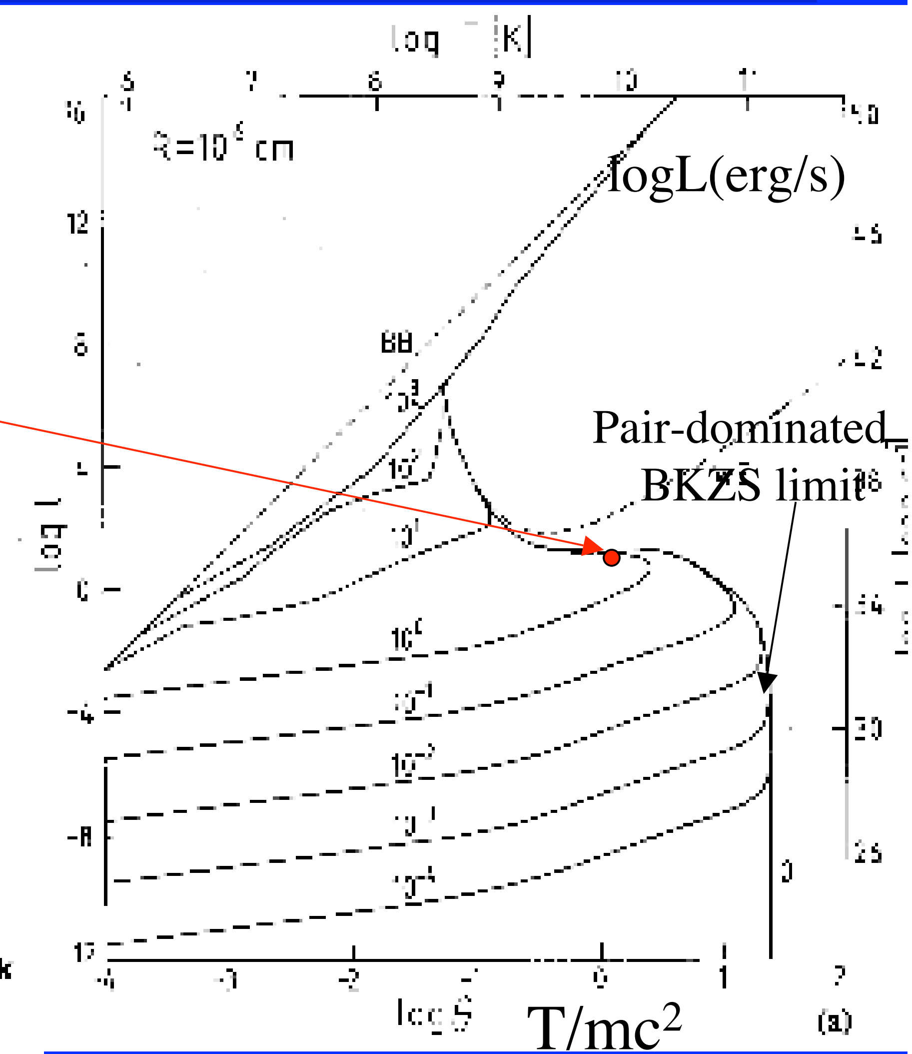
Nonthermal TeV pairs

Laser-produced pair plasmas can be used to study pairs in astrophysics

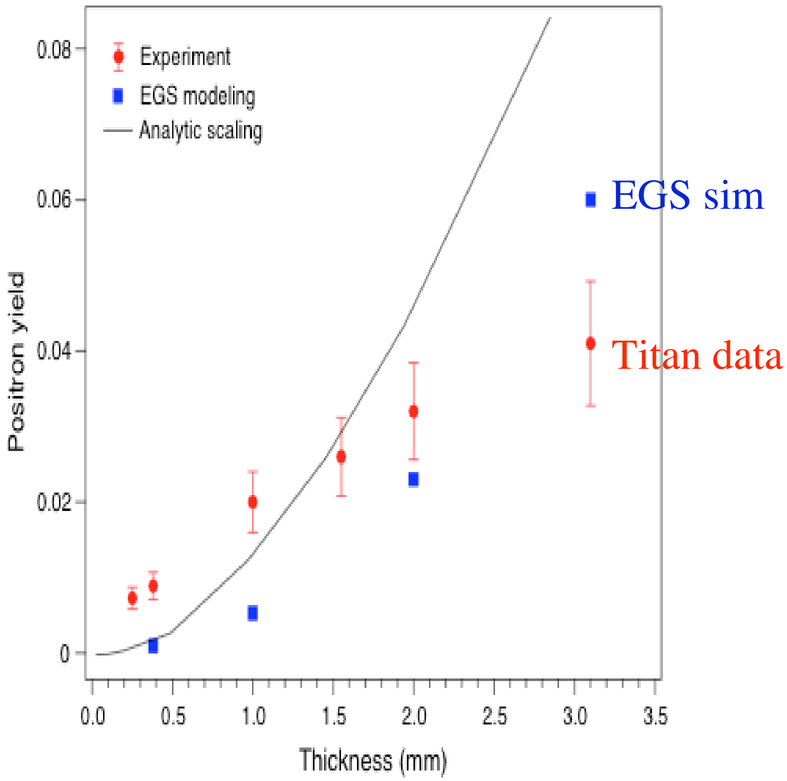
The Black Hole gamma-ray-bump can be interpreted as emissions from a pair-dominated MeV plasma with $n_+ \sim 10^{17} cm^{-3}$

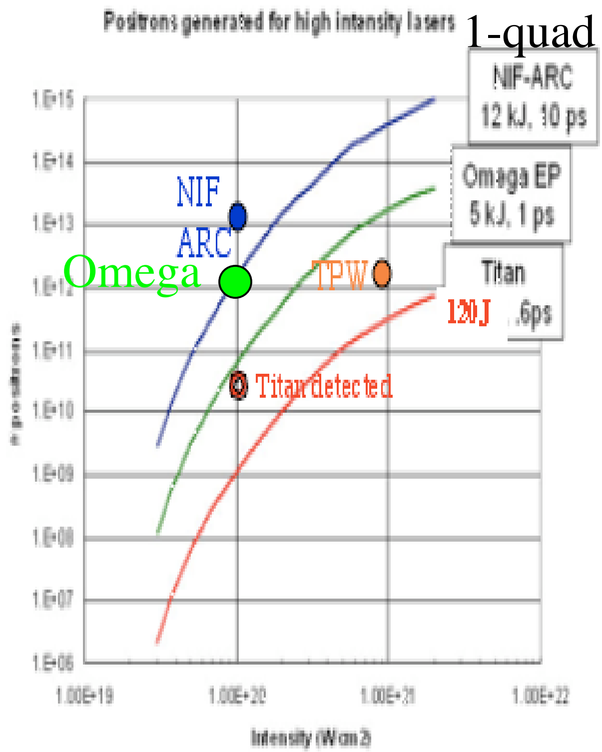






Can laser-produced pair plasmas probe the pair-dominated temperature limit?





Titan data suggests that NIF-ARC can easily exceed 10^{13} e+

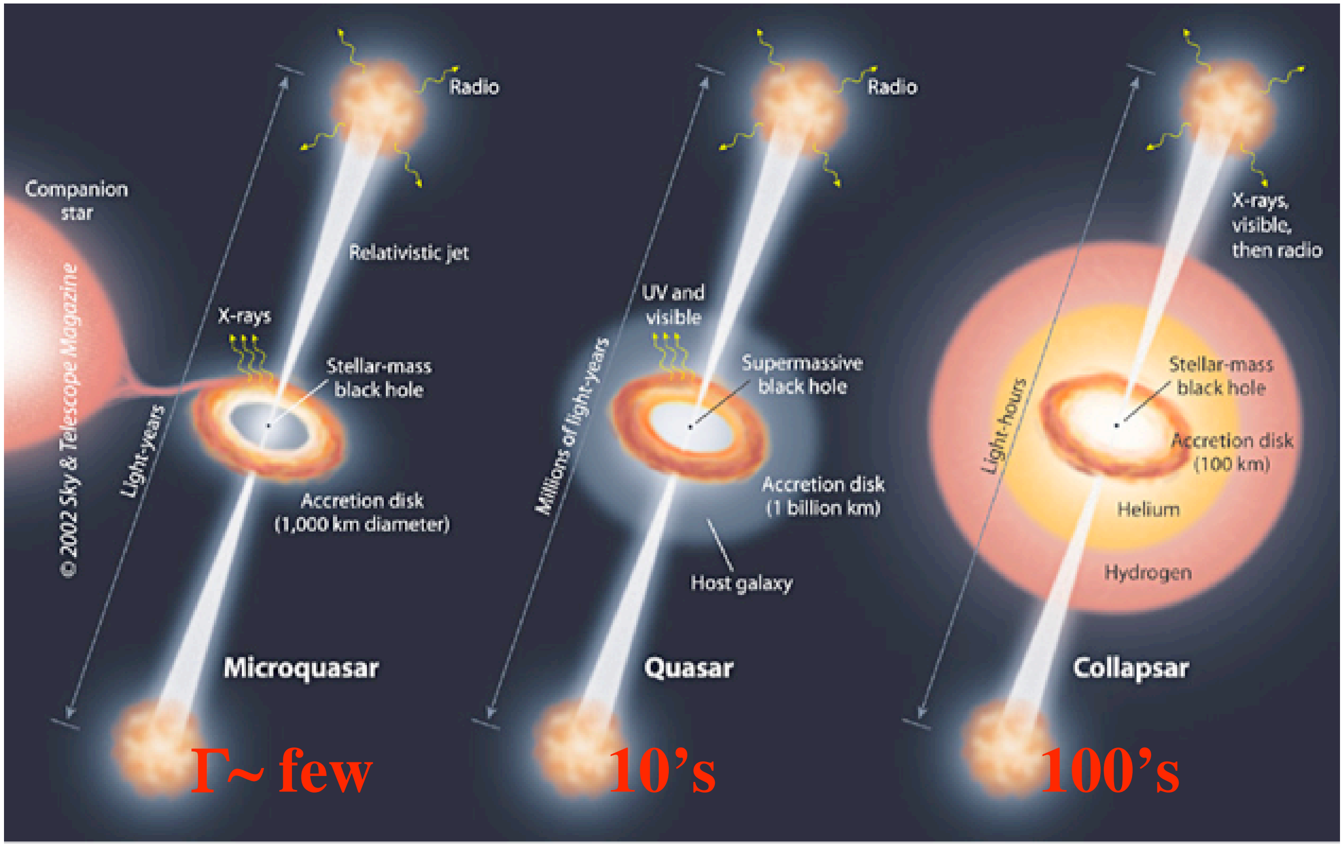
e+ yield per emergent hot electron increases with Au thickness in the Titan laser experiments (from Chen et al 2009). With NIF-ARC we estimate pair density reaching $\sim 10^{18}$ cm^{-3}.

Relativistic Jets

Major Questions*

1. What are the dominant component(s) of relativistic jets (e-ion, pairs, or Poynting flux)?
2. How are relativistic jets ($\Gamma >> 1$) launched and accelerated?
3. How are relativistic jets collimated?
4. Differences between relativistic and nonrelativistic jets
5. Differences between strongly and weakly magnetized jets
6. How do different regions of jets interact with each other (i.e. what are the internal dissipation mechanisms)?

A UNIVERSAL MECHANISM FOR RELATIVISTIC JETS?



Microblazar **Blazar** **GRB**

(Mirabel & Rodriguez; Sky & Telescope, May 2002)

Beam Propagation and Dissipation

Major Questions:

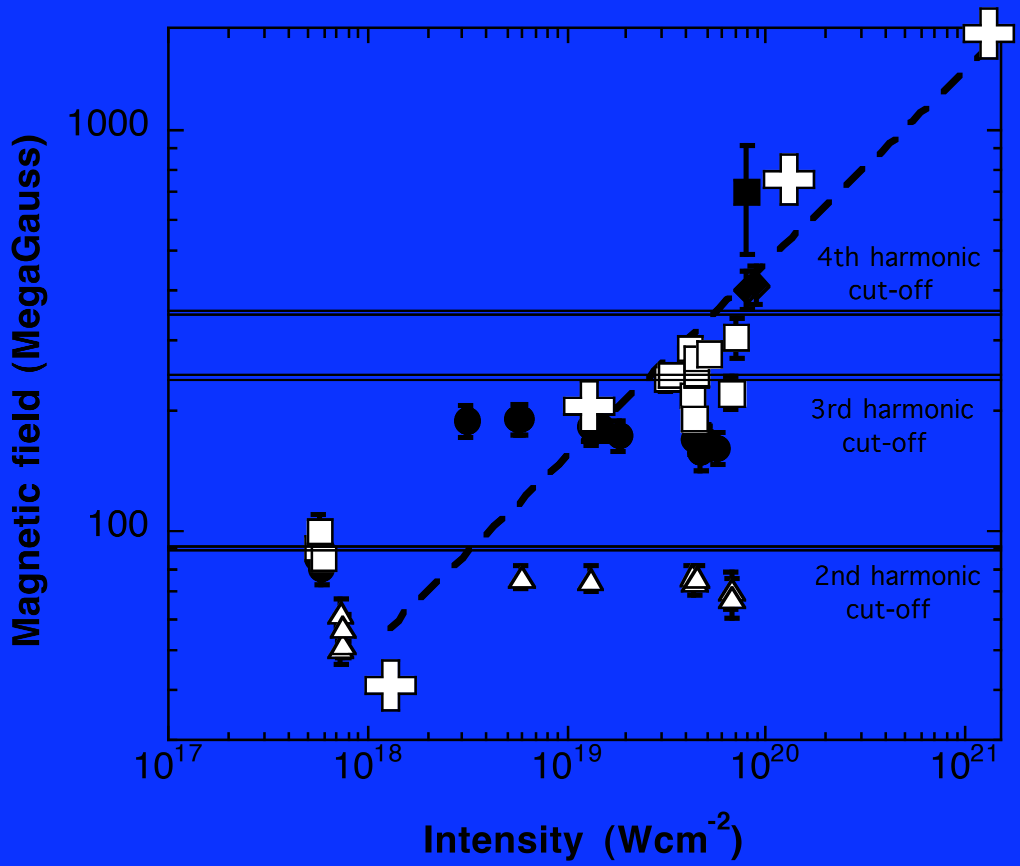
1. Dependence of Weibel-like instability on beam cross-section, Lorentz factor*, density, temperature, composition (pairs vs e-ions)* and magnetic field
2. Late-time evolution of saturated Weibel-generated fields
3. Particle acceleration and radiation processes
4. If Weibel is suppressed, how do beams dissipate?

Ultra-strong Magnetic Fields

Major Questions*

1. What are the atomic, radiative and plasma physics in ultra-strong magnetic fields?
2. Anisotropic radiation transport in strong fields
3. How to apply ultra-strong field experiments in the laboratory ($B > 100$ MG) to astrophysics ?
4. Photon-bubble instability in neutron star polar caps

B > GigaGauss has been created and measured in Laser plasmas. Experimental results are in agreement with "ponderomotive" source for fields

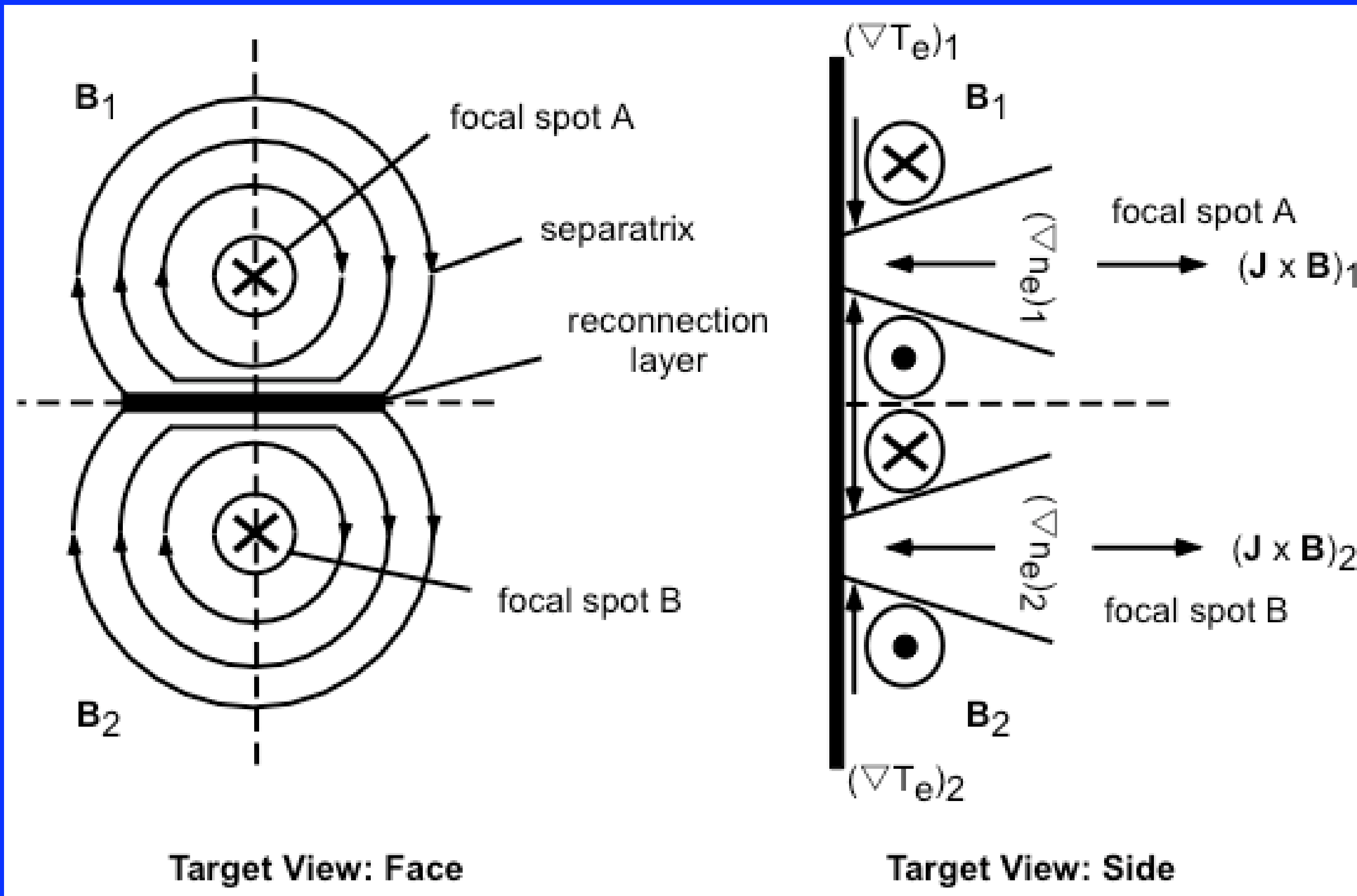


Turbulence & Reconnection in Relativistic Plasmas

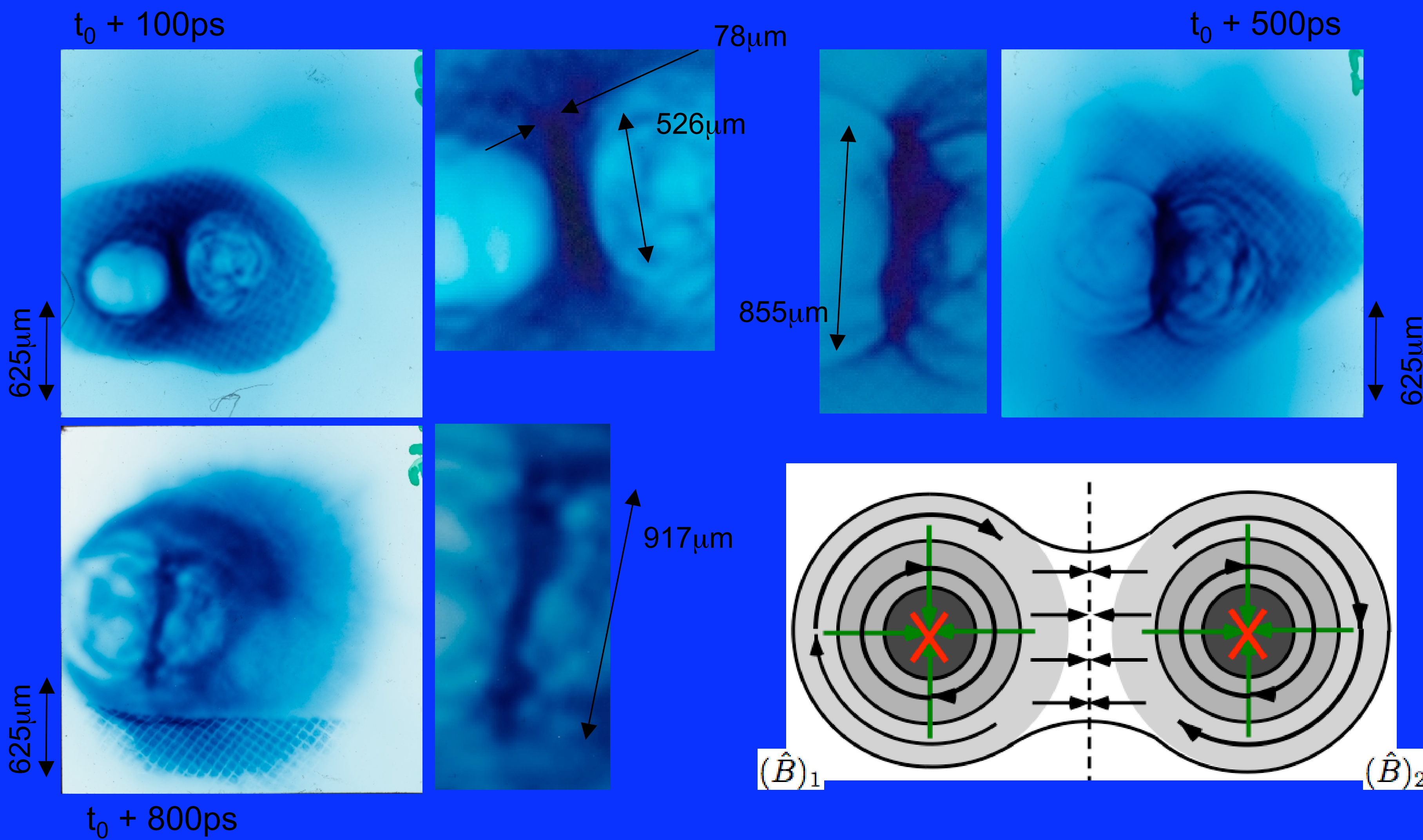
Major Questions

1. What are the differences between turbulence cascade in the relativistic vs. nonrelativistic regimes?*
2. What are differences between turbulence cascade in the strongly vs. weakly magnetized regimes? Pair plasmas vs. e-ion plasmas?*
3. Roles of current sheets and reconnection in nonlinear dissipation.
4. What are the particle energization and radiative processes?
5. The energy flow: kinetic, magnetic, thermal, nonthermal, electrons, ions, radiation.

Long-pulse (ns) solid target interactions
Magnetic field generation: dual beam geometry



Plasma dynamics: Al target
Rear projection proton imaging (fields ~ 1 MGauss)



Opportunities and Challenges of Laboratory Experiments

1. Requires Large National Facilities:big lasers, accelerators, pulse-power machines
2. Requires diagnostics mostly not yet available
3. How to scale lab results to astrophysical scales?
4. How to design "simple" experiments to meaningfully calibrate computer codes? (most lab experiments are too big and too complex for full-scale end-to-end computer simulations).