High Energy Astrophysics Experiments In The Laboratory & On Supercomputers*

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Collaborators: Rice students & postdocs plus UT Austin, LANL, LLNL, UCUI, OU

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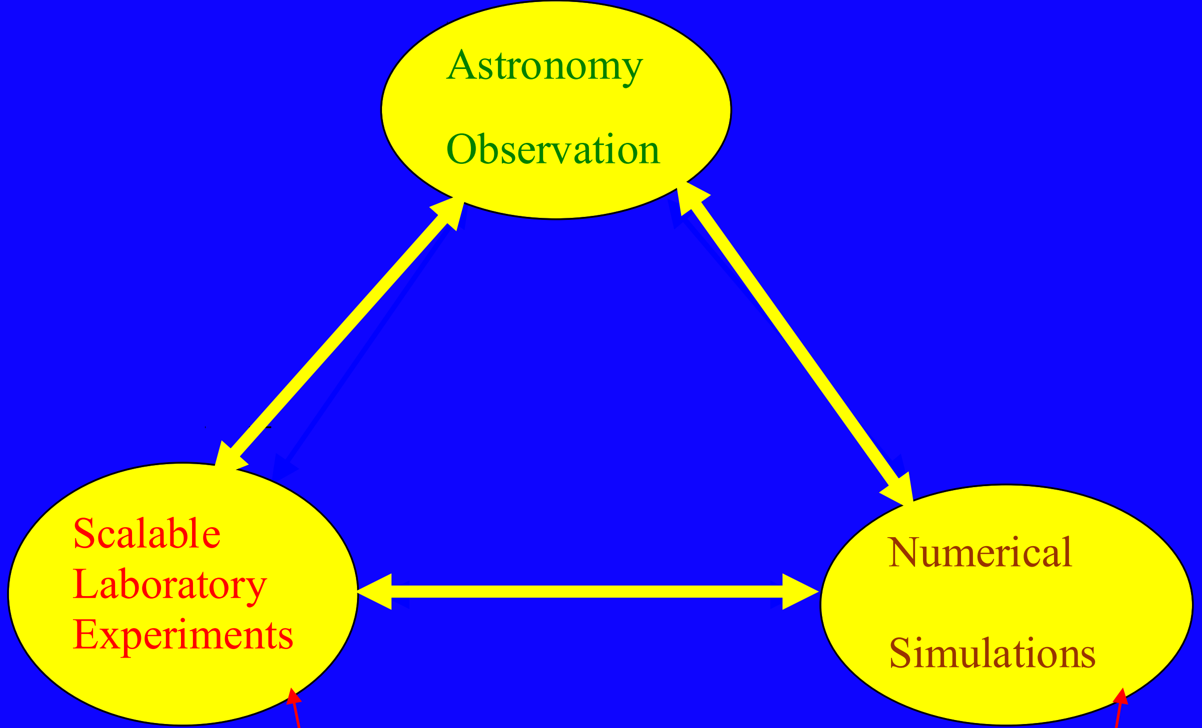
* *Work supported by NSF, DOE & NASA*



made possible by recent advances in High Energy Density Physics

HPC

EXAMPLES:

Gamma-Ray Bursts ---- Laser-Generated Relativistic Shocks and Fireballs

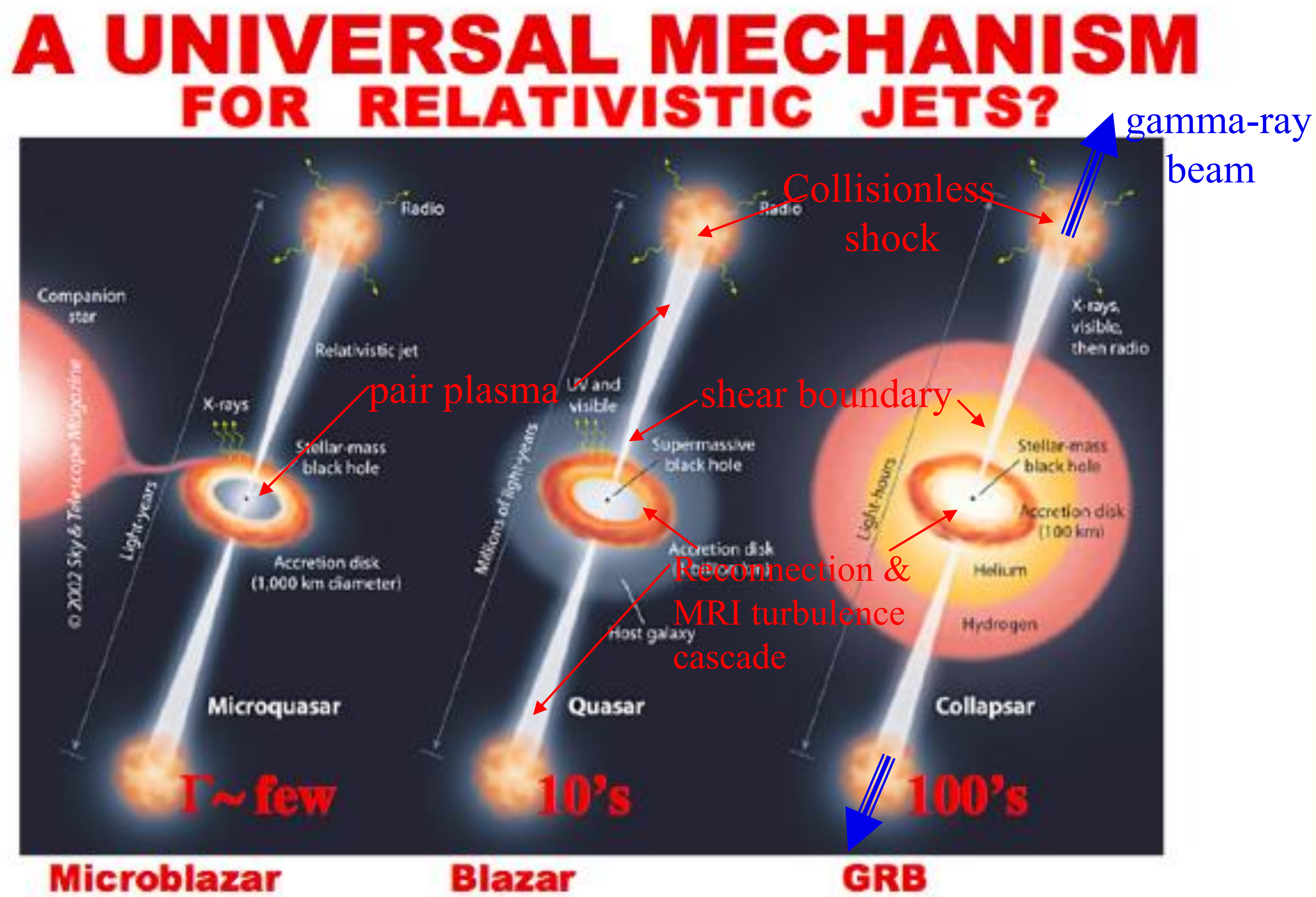
Black Hole Annihilation Flares ---- Laser-Generated Pair-Plasmas

Sample HEA processes accessible using relativistic laser experiments

1. e+e- Pair plasmas
2. Intense X-Gamma-ray Environments ~ GRBs
3. Collisionless Shocks & Shear Flows
4. >10^9G B-fields Generation
5. Magnetic Reconnection
6. Poynting Flux & Particle Energization

Plus many others under consideration

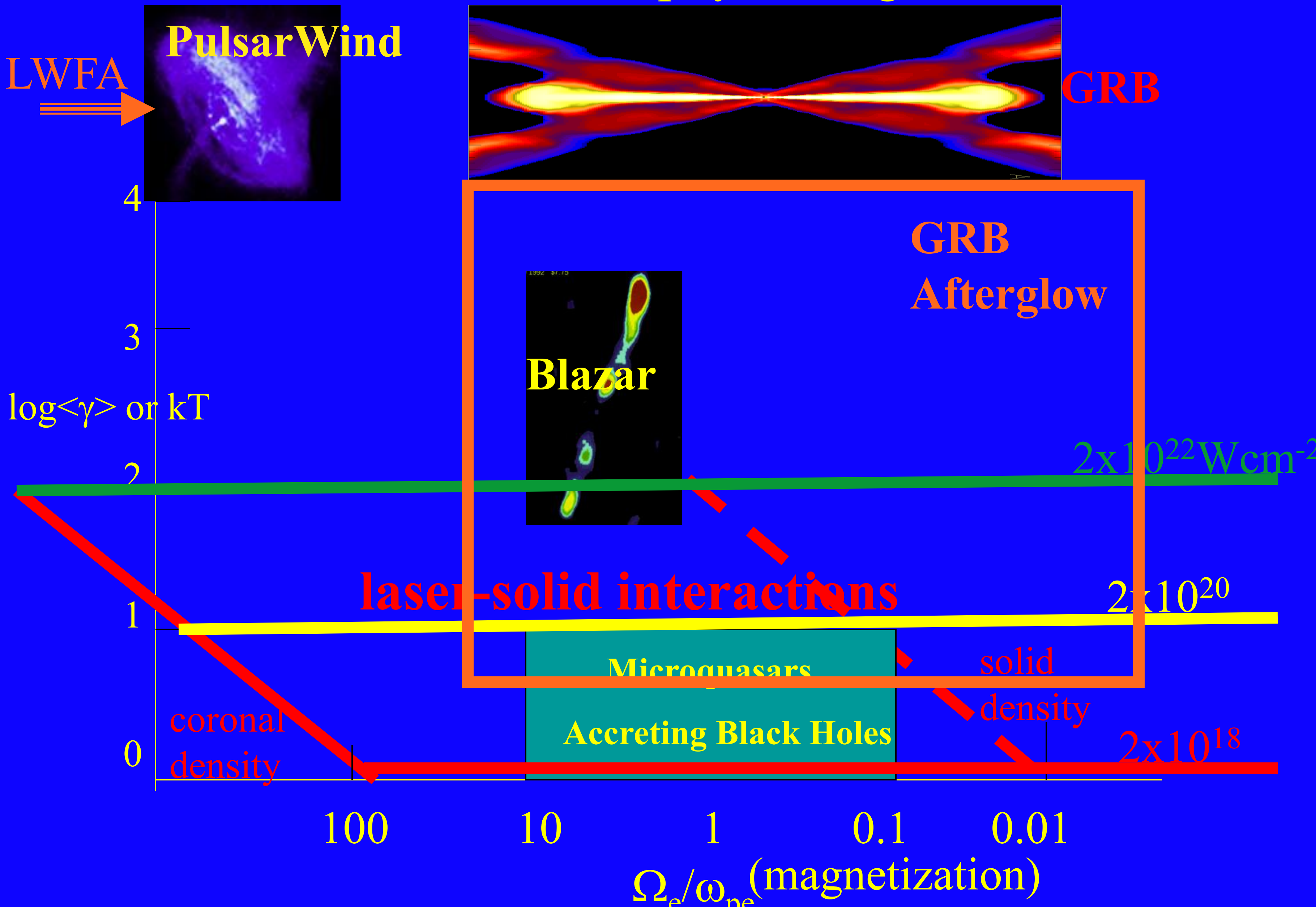
Lab experiments cannot reproduce global features. But they can mimic the local physical processes and their radiation output



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

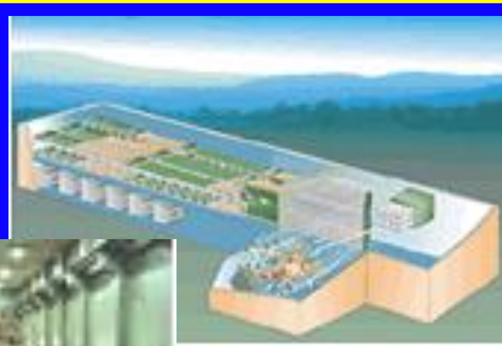
Important Issue: what are the "scalable" processes & phenomena?

Phase space of laser plasmas overlap some relevant relativistic astrophysics regimes

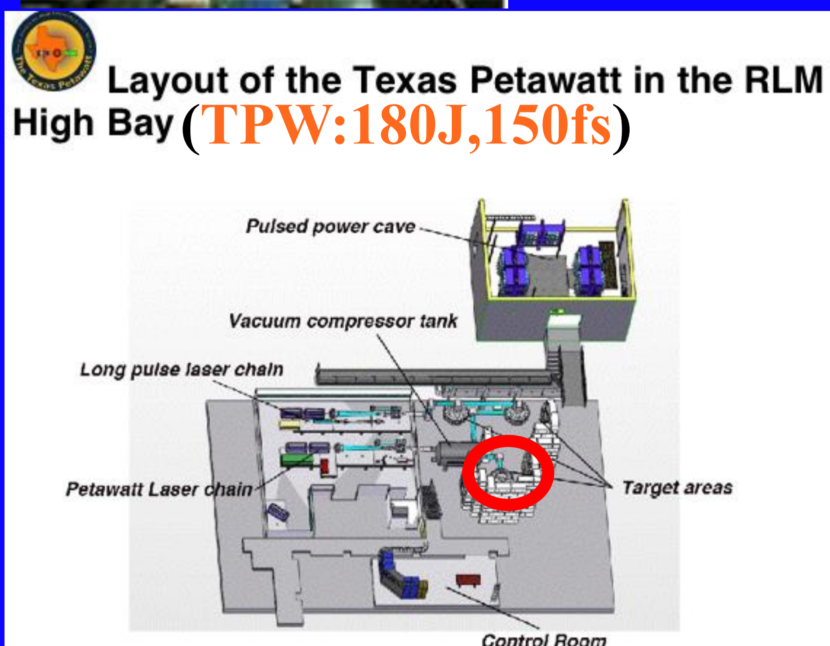


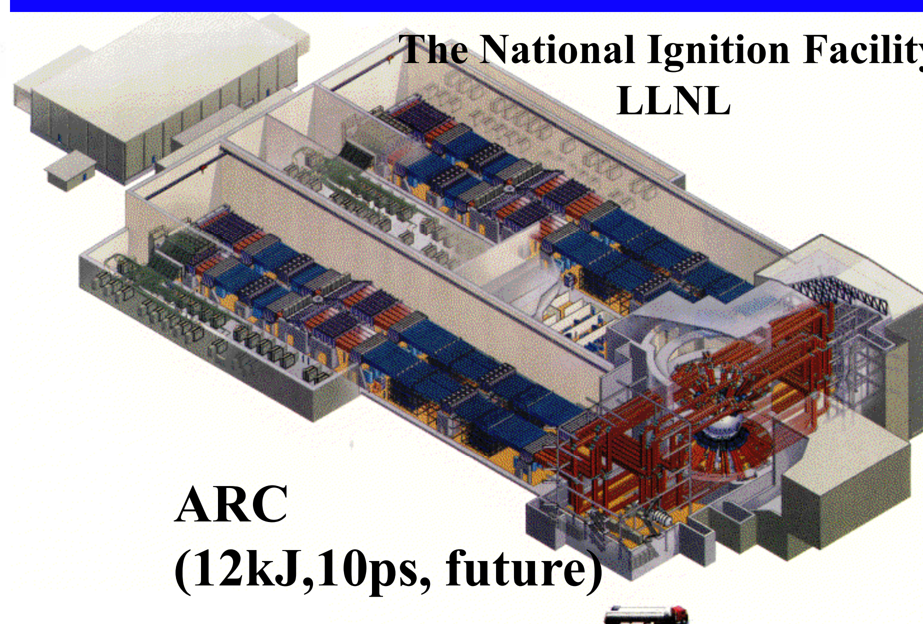
Many new 0.1-1 kJ-class PW lasers are coming on line in the US, Europe and Asia

FIREX
Gekko



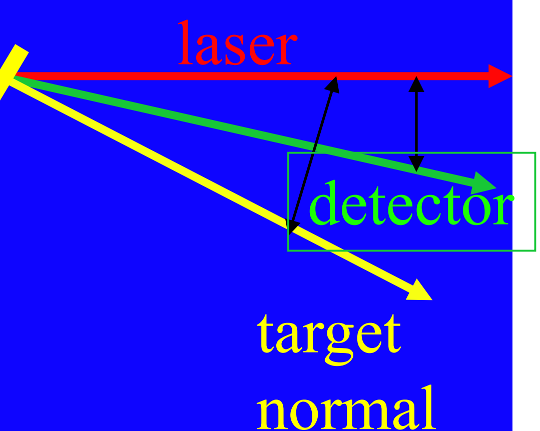
ILE Osaka

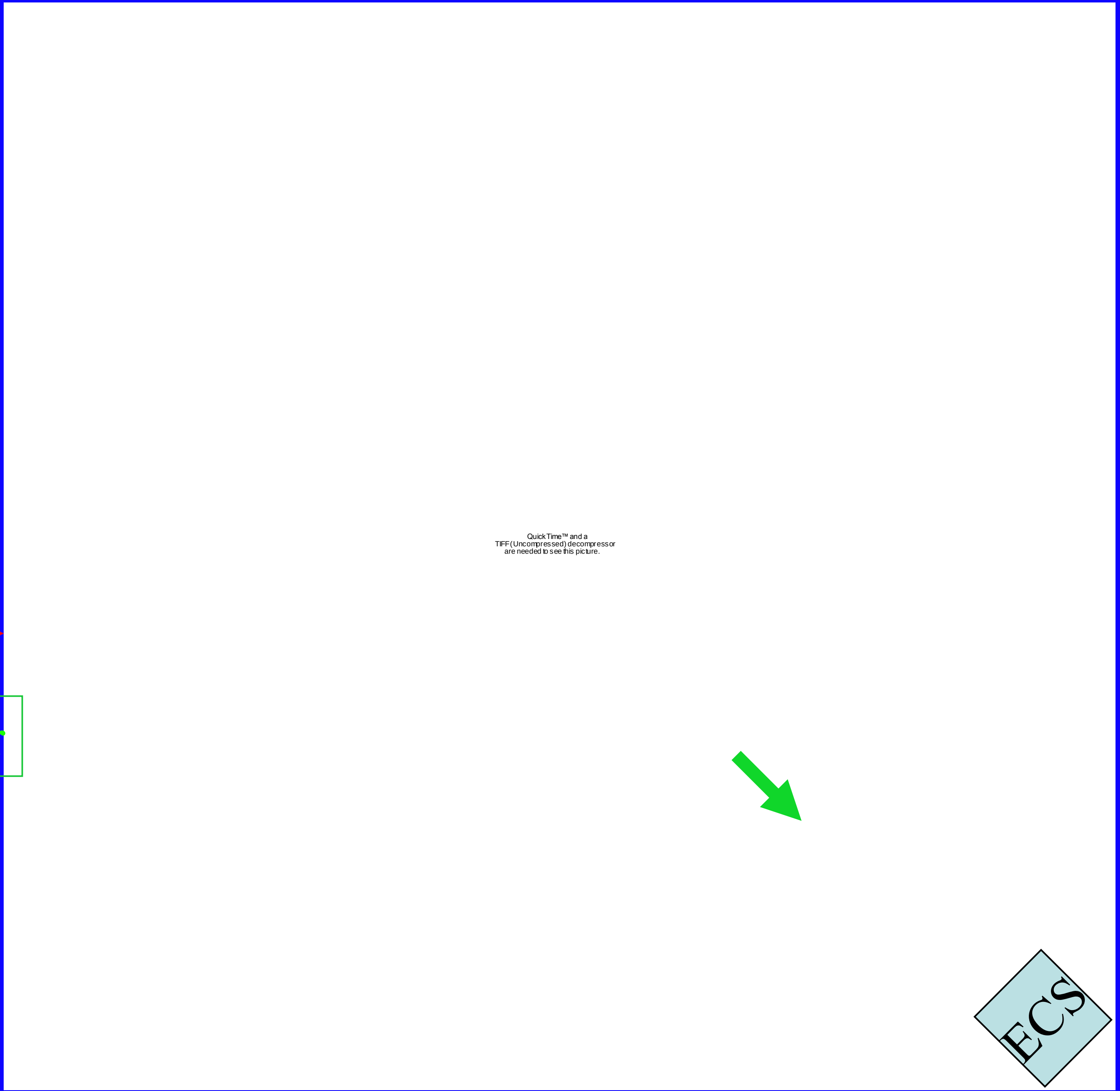




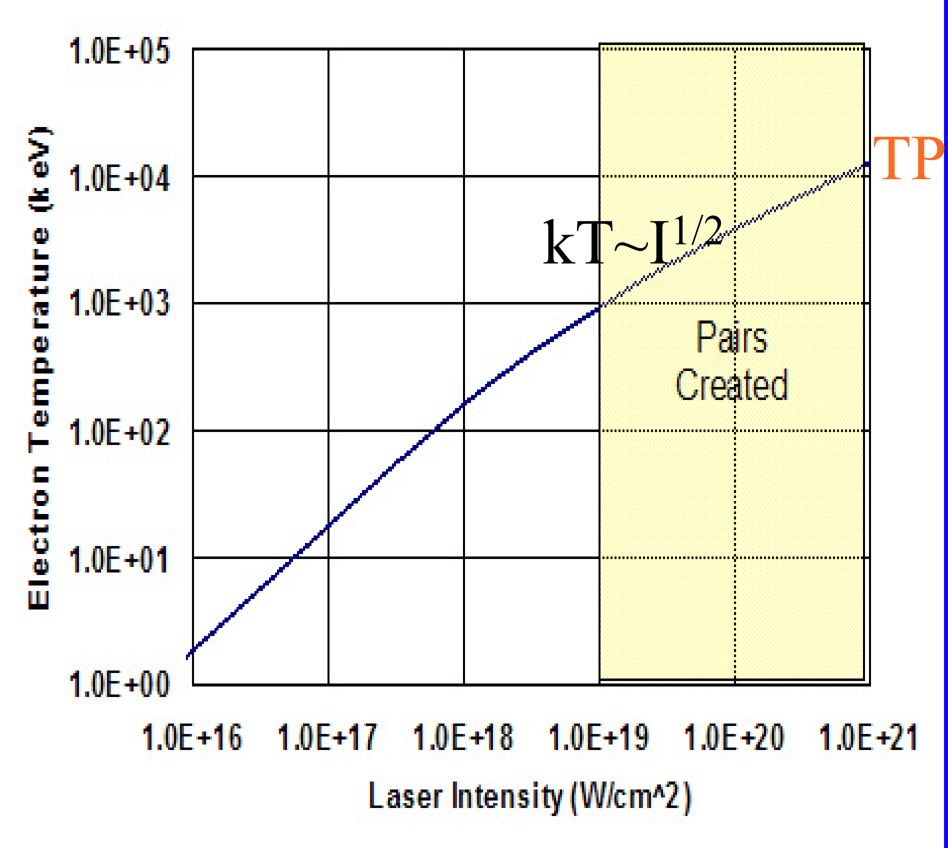
typical diagnostics and target setup

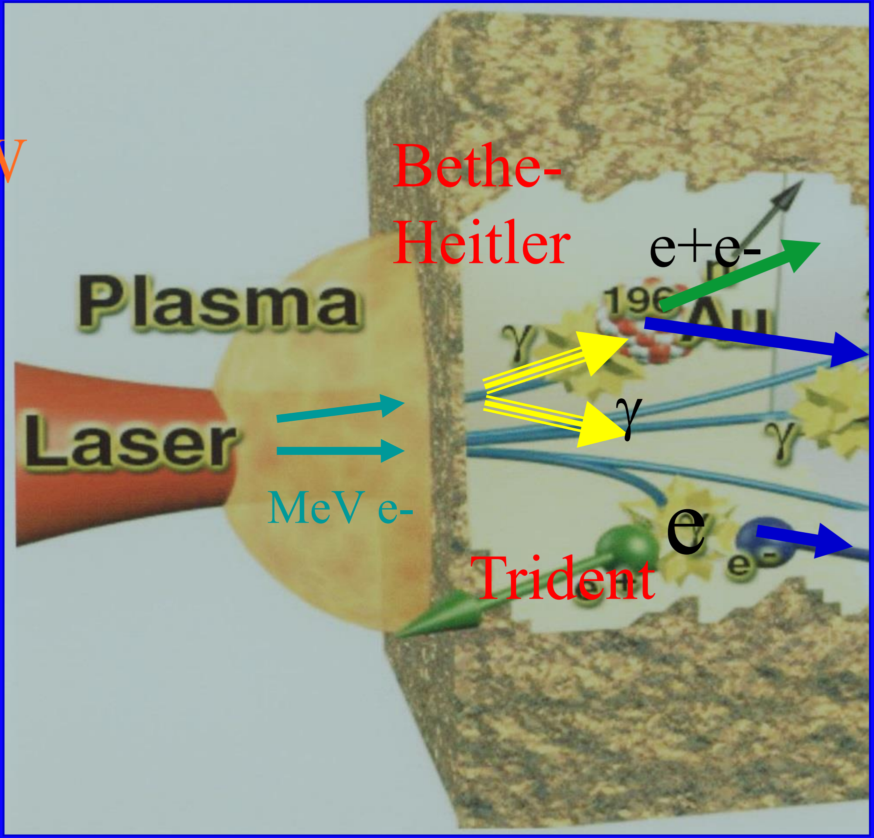
TC1 with f/3 mirror





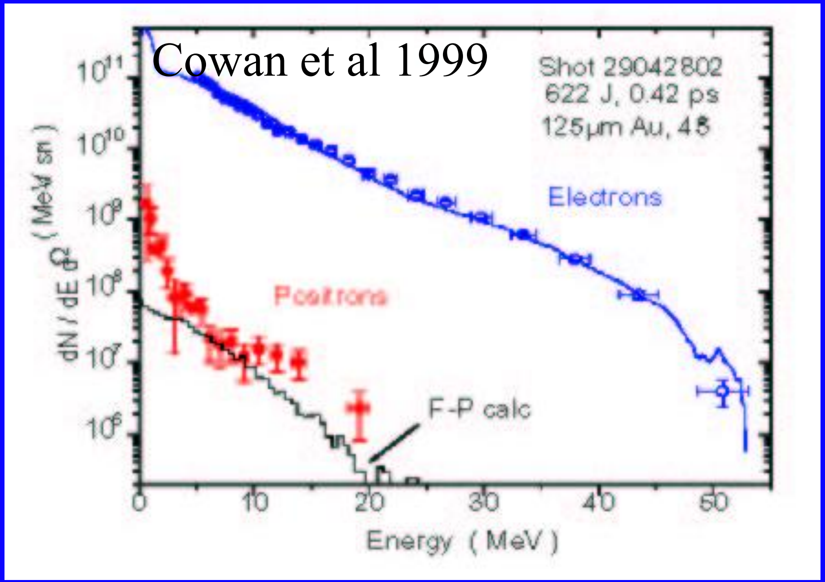
Ultra-intense laser is the most efficient tool to make **e+e- pairs (mc^2~1MeV)** in the laboratory

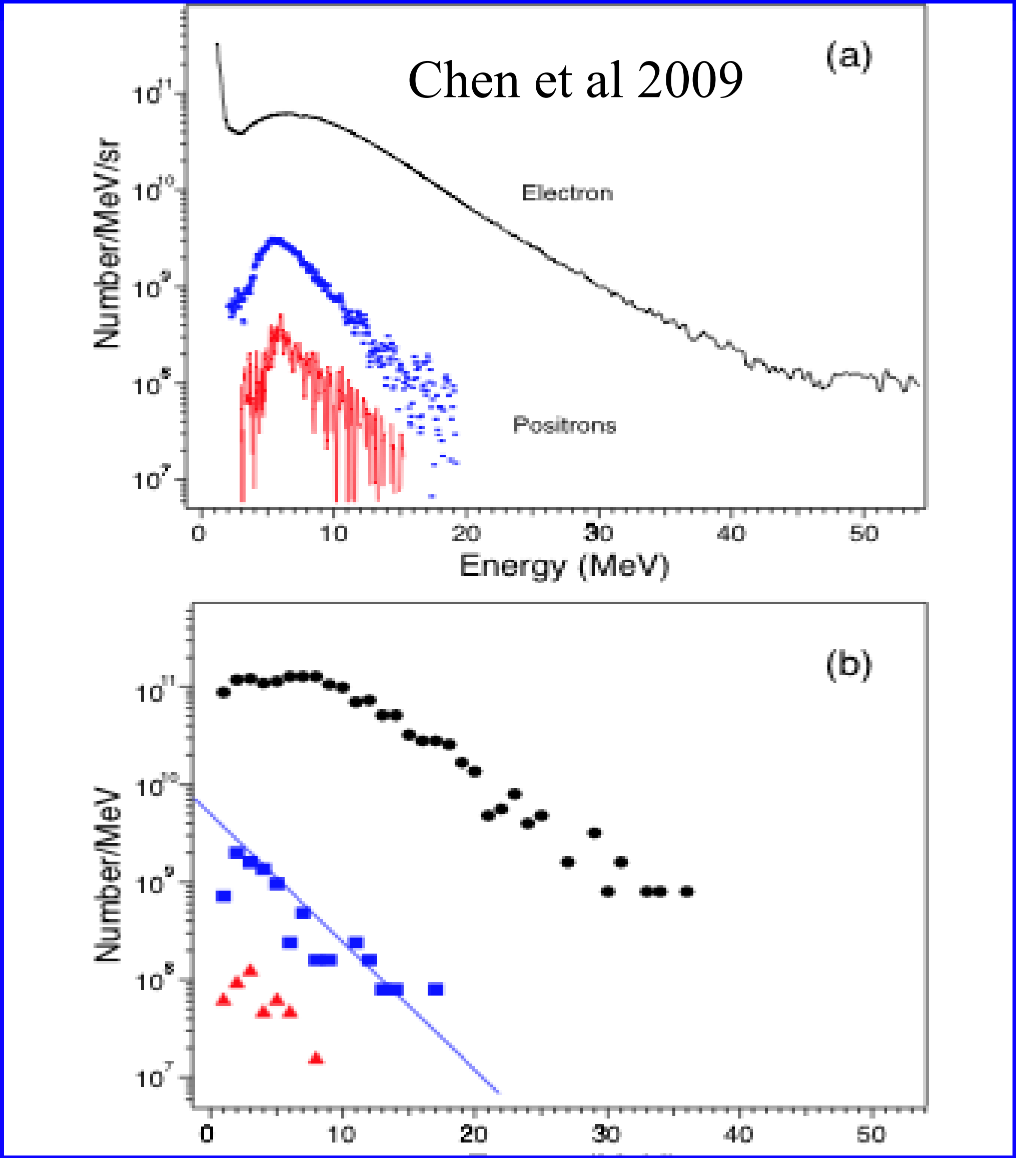




Lasers with intensity > 10^{19} W.cm^{-2} couple 10-50% of their energy to "hot electrons" with kT_e > MeV.

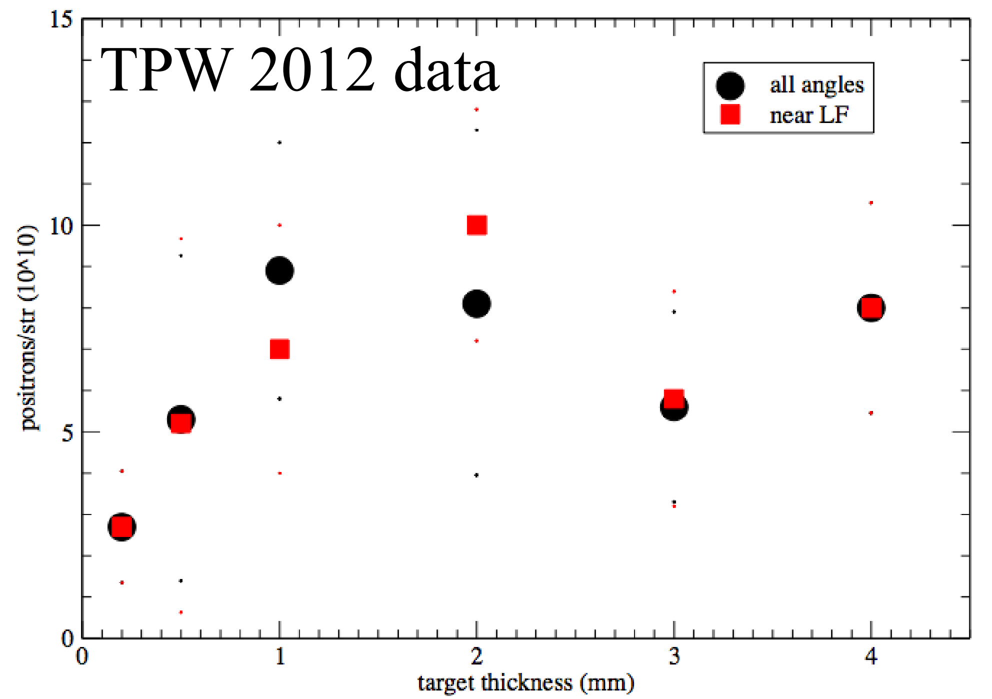
Laser pair creation was first demonstrated by Cowan et al in 1999 and greatly improved by Chen et al (2009, 2010) using laser intensities ~ few x10^{19} - 10^{20} W.cm^{-2}.





in 10 years the e+/e- ratio has increased by ~100

Measured e+e- pair yield follows same trend as theory predictions



kT_e

QuickTime™ and a
Graphics decompressor
are needed to see this picture.

(Henderson et al 2011)

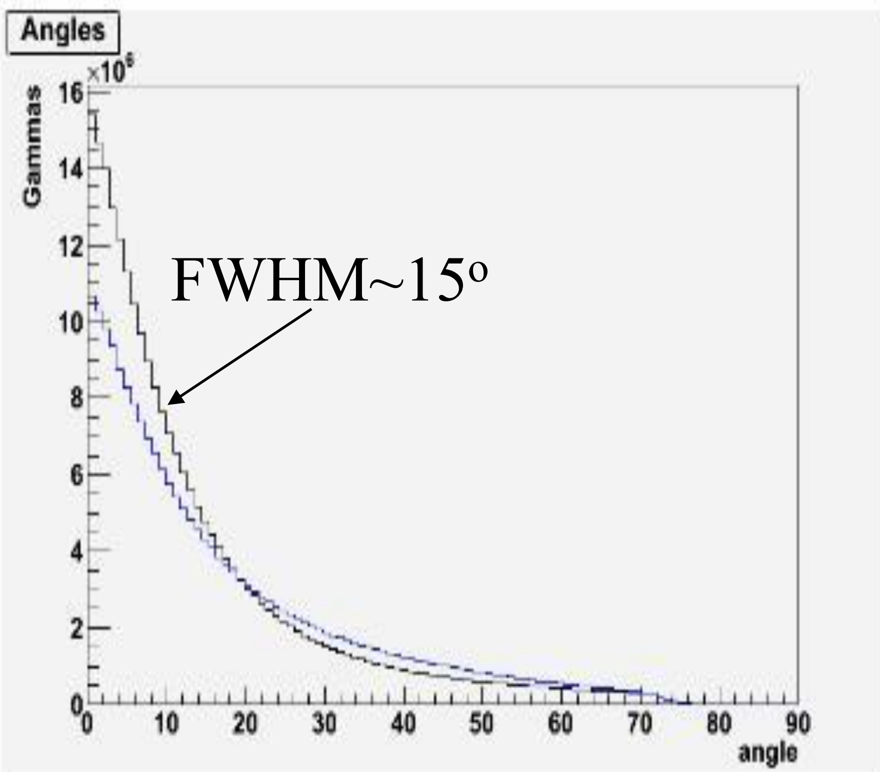
Intense lasers create **intense flux of >MeV gamma-rays**.

gamma-ray output ~5-10% of Laser Energy, with beam angle $\leq 15^{o}$.

Maximum γ-density ~ inside the GRB.

Total γ-fluence ~ ISM at 10 pc from a GRB.

1. Interaction of pairs with gamma-rays and strong-B fields
2. Interaction of gamma-rays with ISM, e.g. dust grain destruction with observable IR signatures.



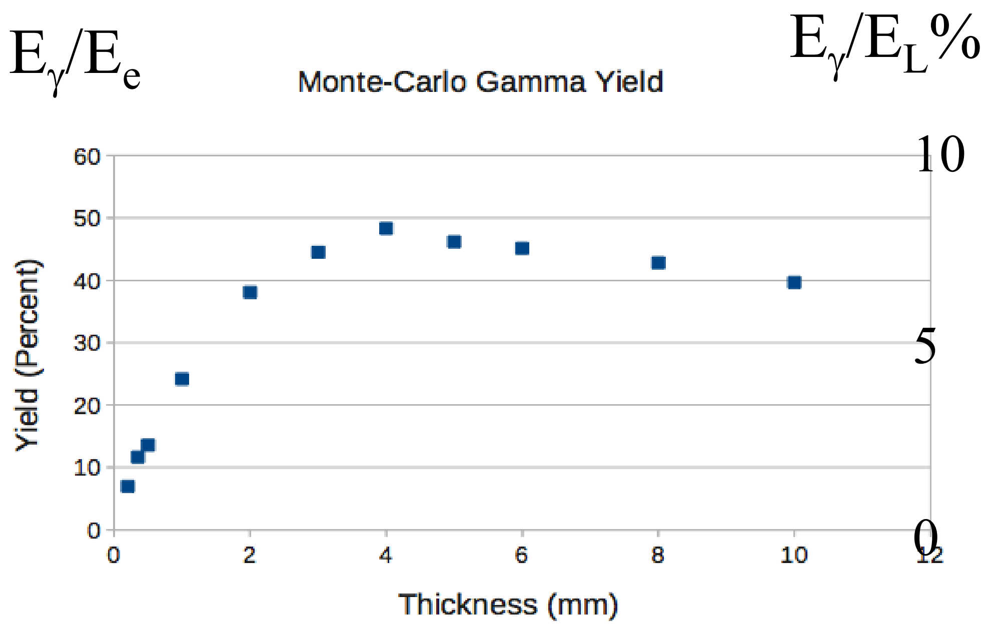
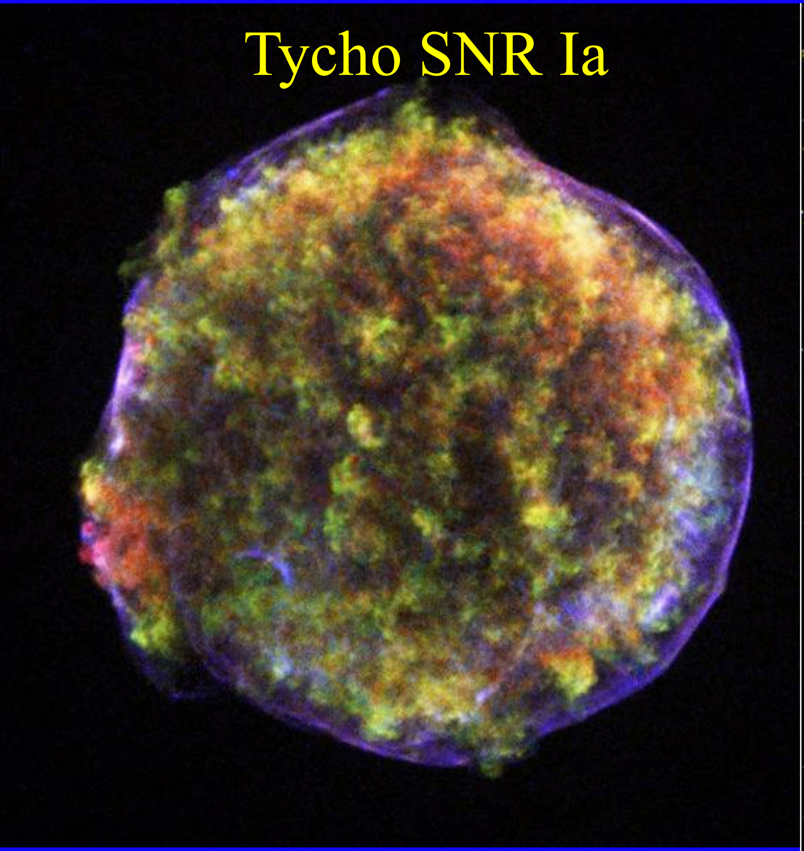
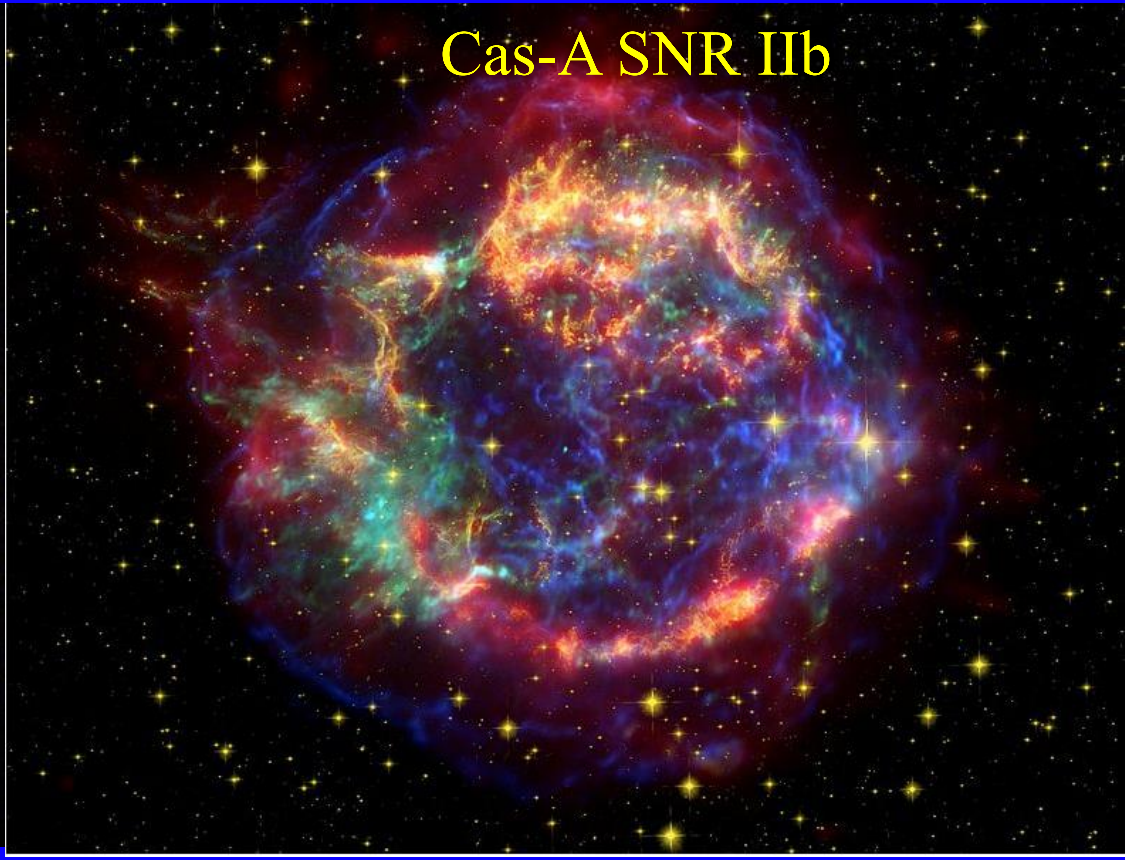


Figure X: Gamma Yield Versus Thickness. The GEANT4 Monte-Carlo simulation used the incident electron spectrum seen in figure X.

Collisionless Shocks are ubiquitous in the universe

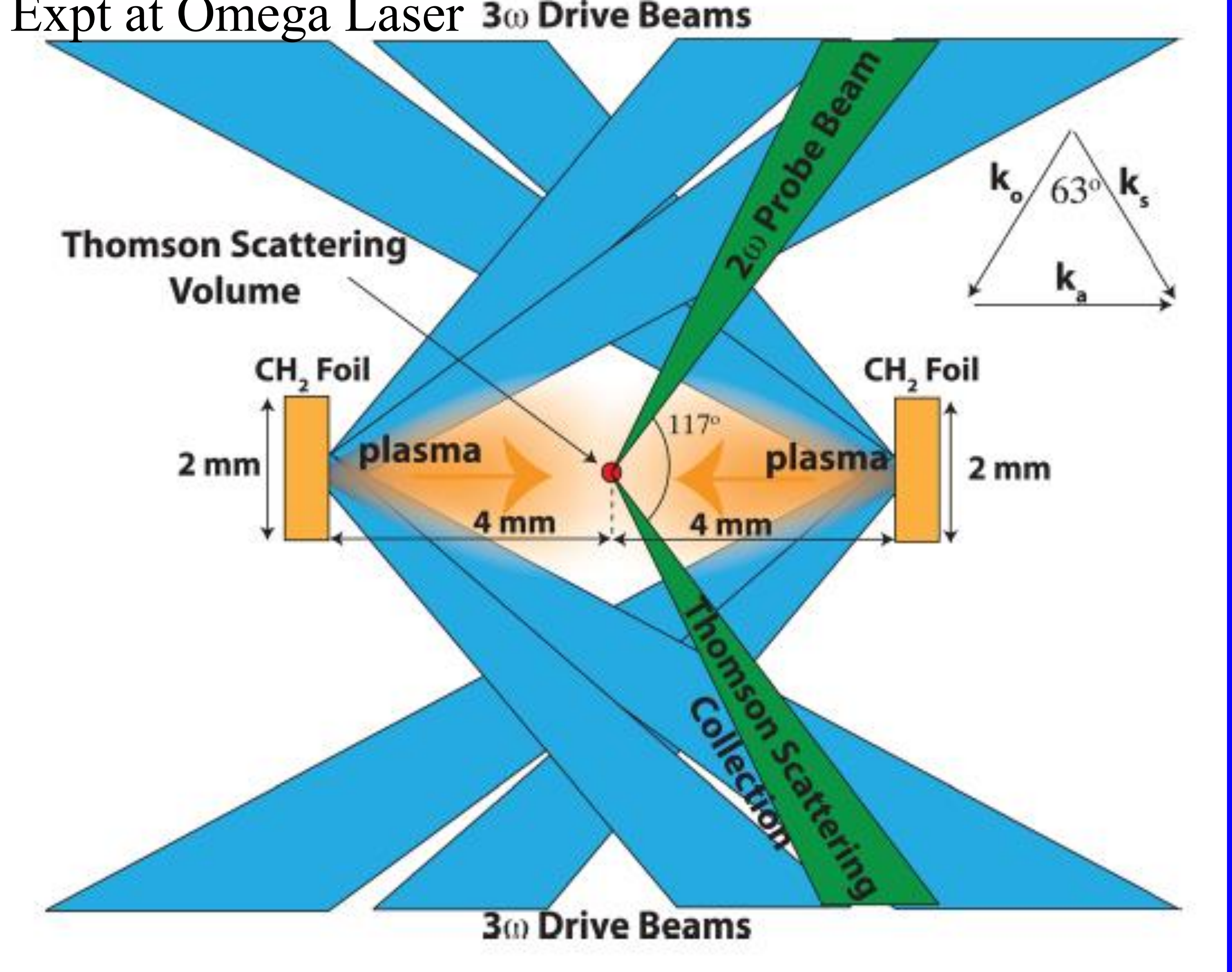




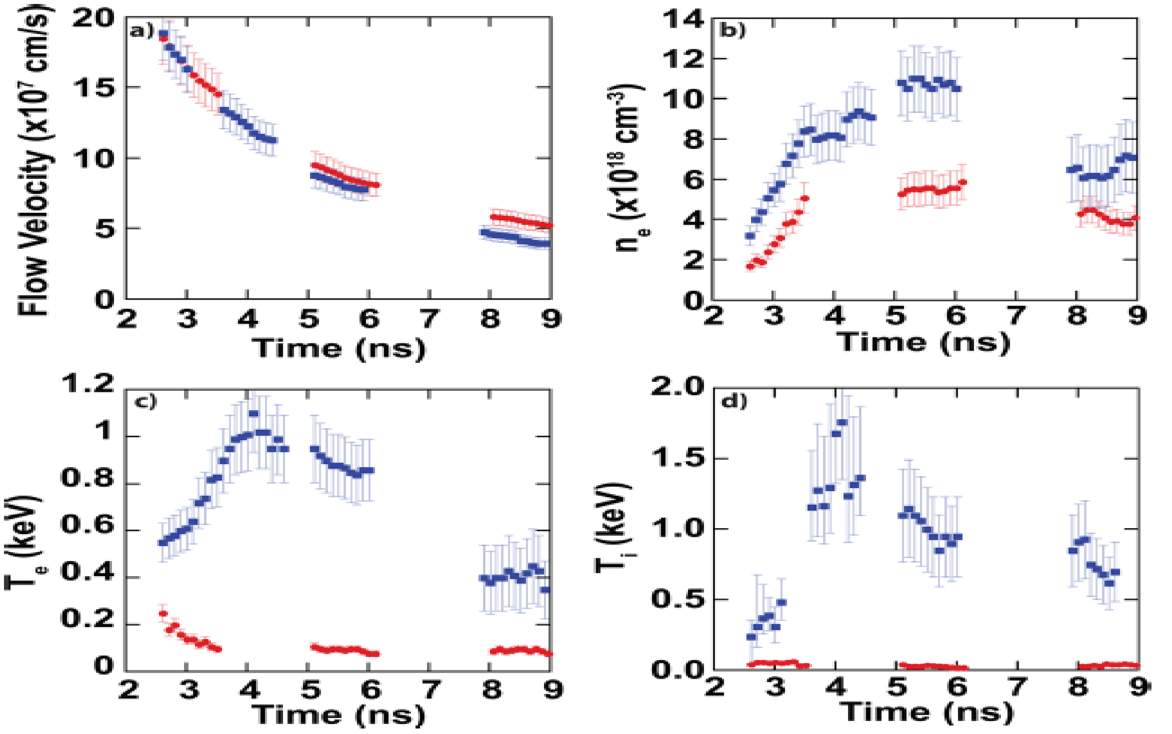
Collisionless Shocks likely Acceleration Sites for Cosmic Rays:
How do they efficiently generate magnetic fields and relativistic particles?

Creation and Diagnostic of **Collisionless Shocks** using lasers are very challenging, but great progress has been made in the past few years by the ACSEL team

Expt at Omega Laser

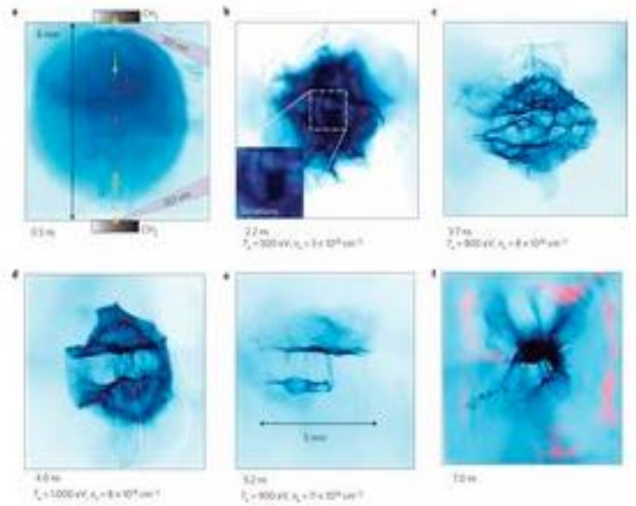


density and temperature data are consistent with theory predictions for collisionless shocks



Discovery of self-organized B-fields was unexpected and most exciting. Such fields may be important to particle acceleration in shocks.

Figure 2: Side-view time sequence of proton images showing the evolution of self-organized electromagnetic field structures.



Future Ideas

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

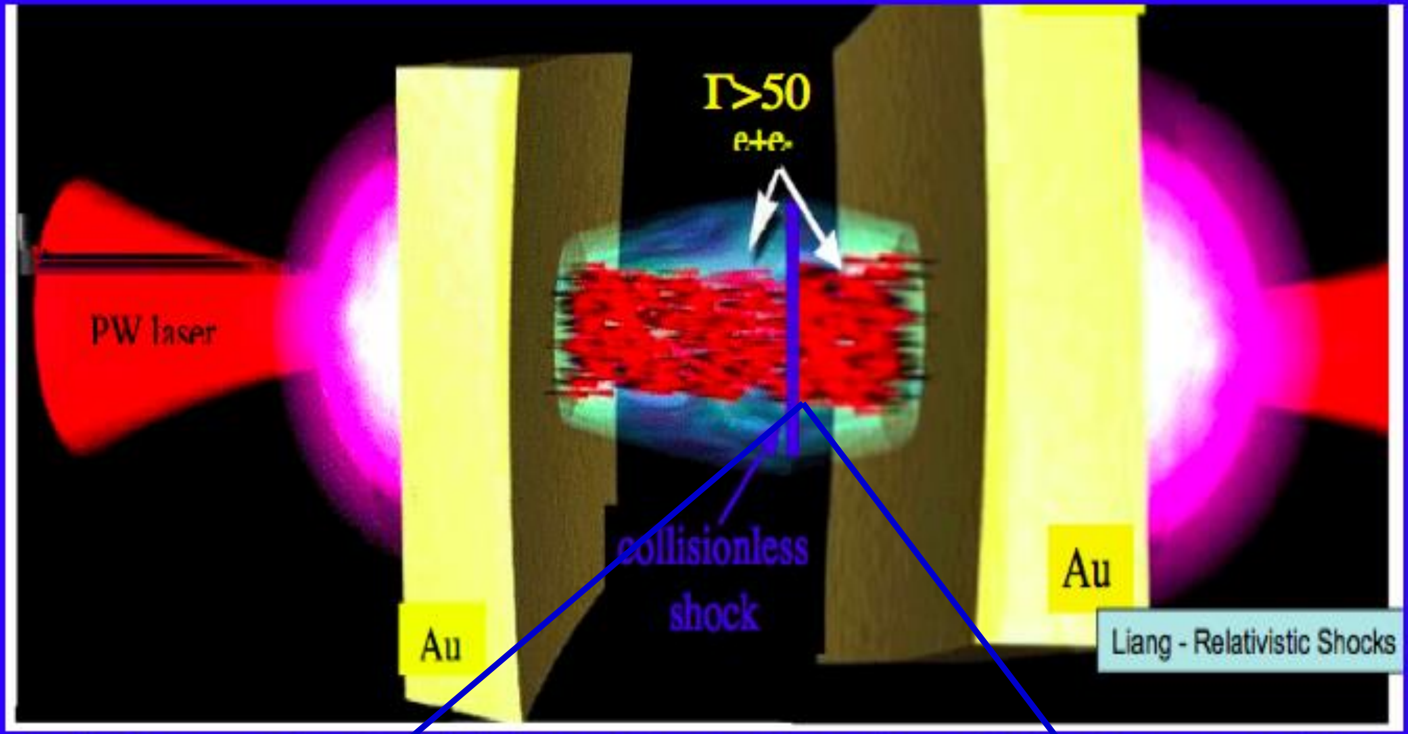
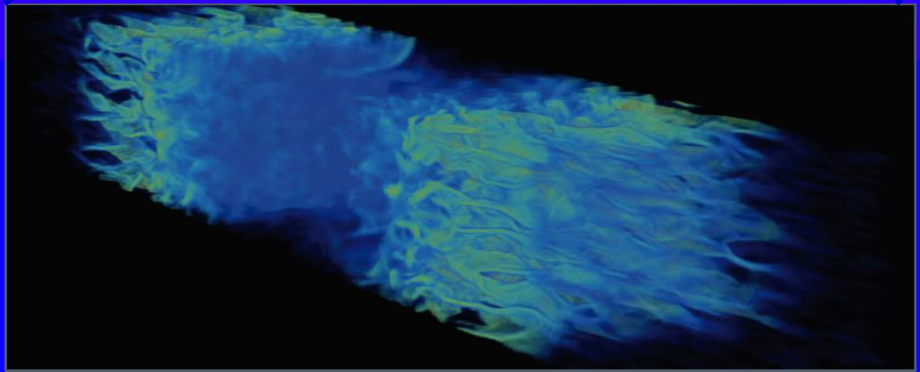
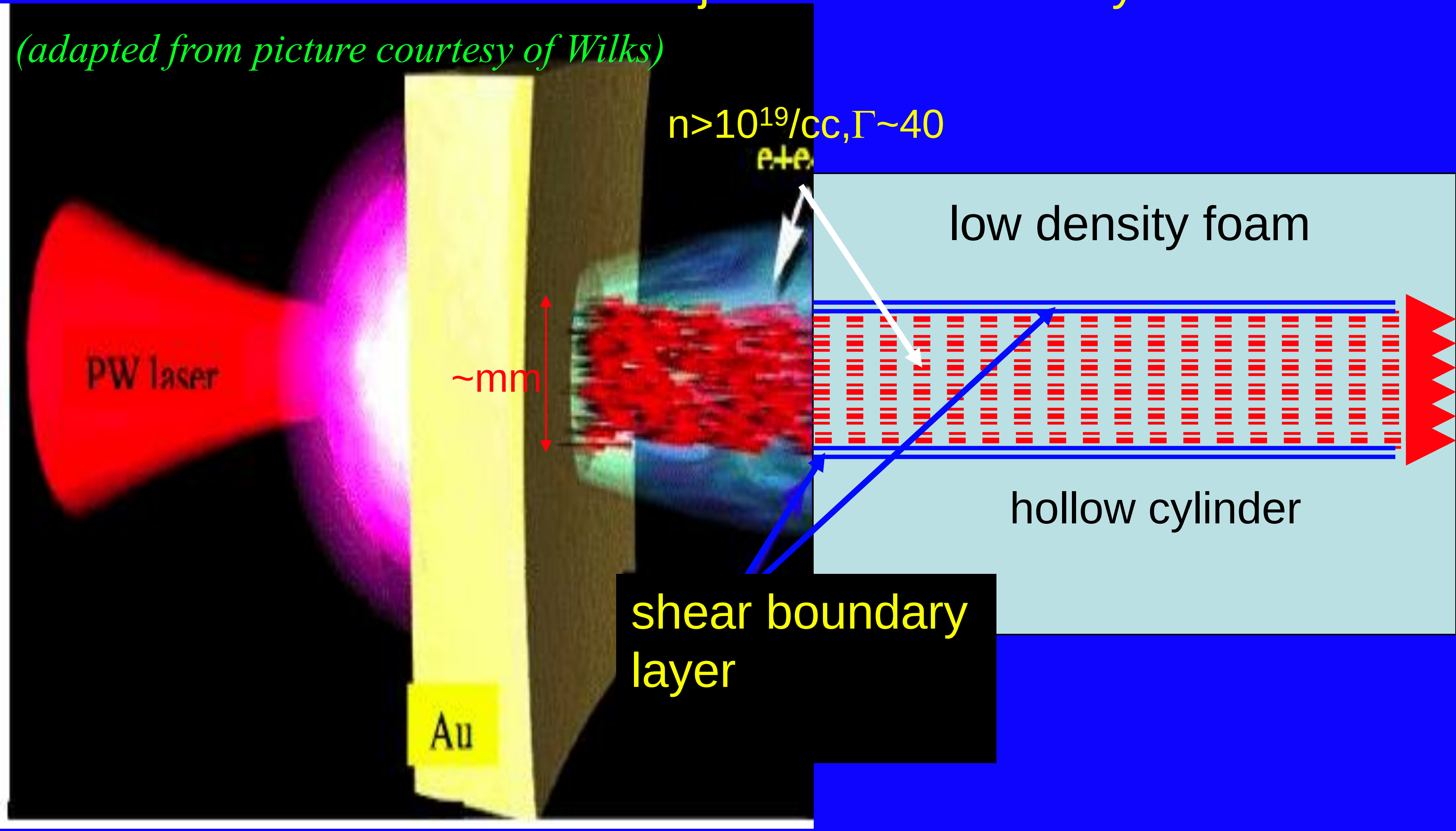


Fig.4 Artist conception of relativistic shock launched by head-on collision of two e+e- pair jets created by two high-energy PW-class lasers irradiating mm-thick gold targets.

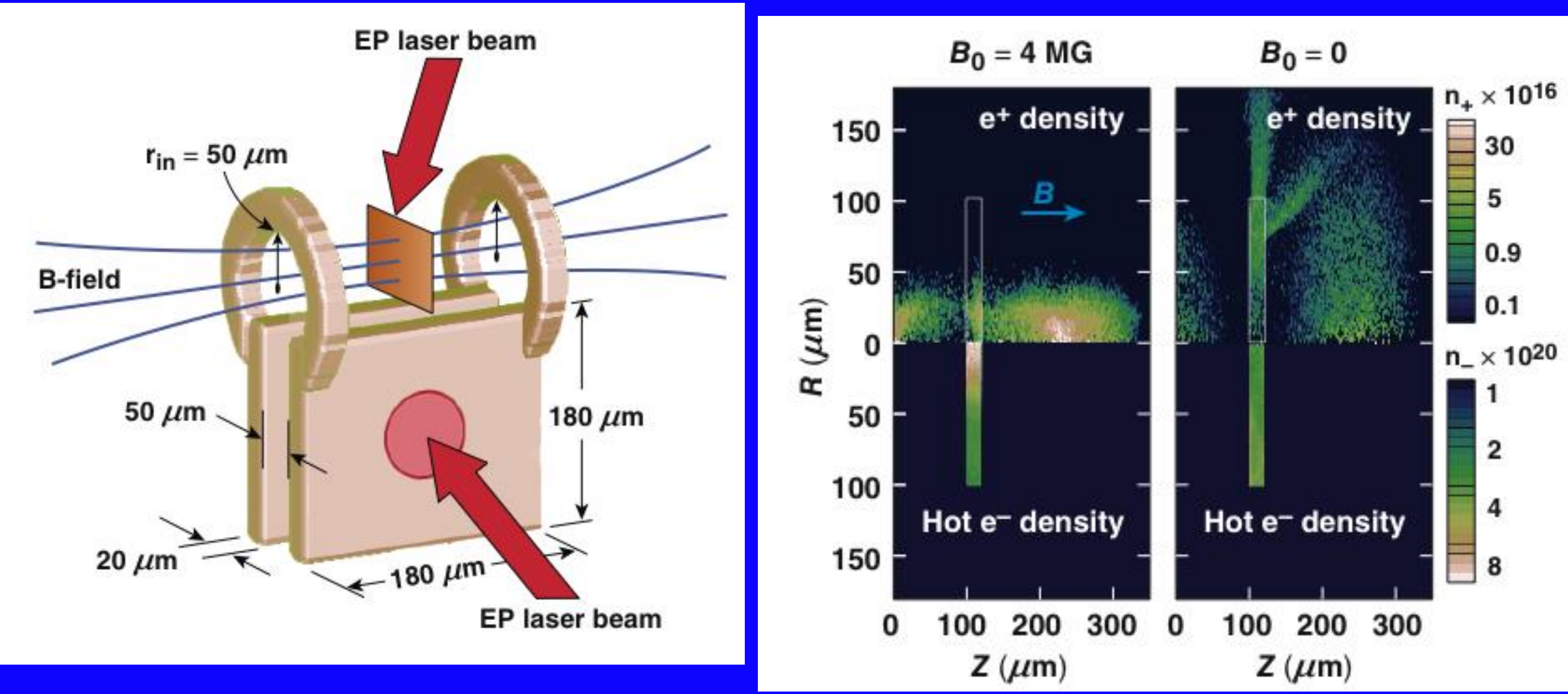


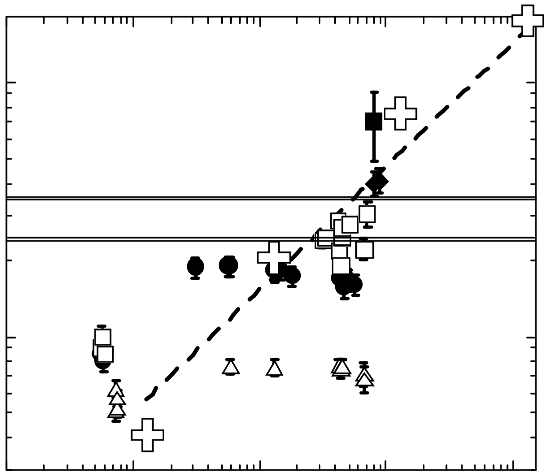
relativistic shear boundary layer may be formed by injecting laser-created relativistic e+e- jet into a low density foam



shear boundary layer may be easier to form, observe and diagnose than collisionless shocks

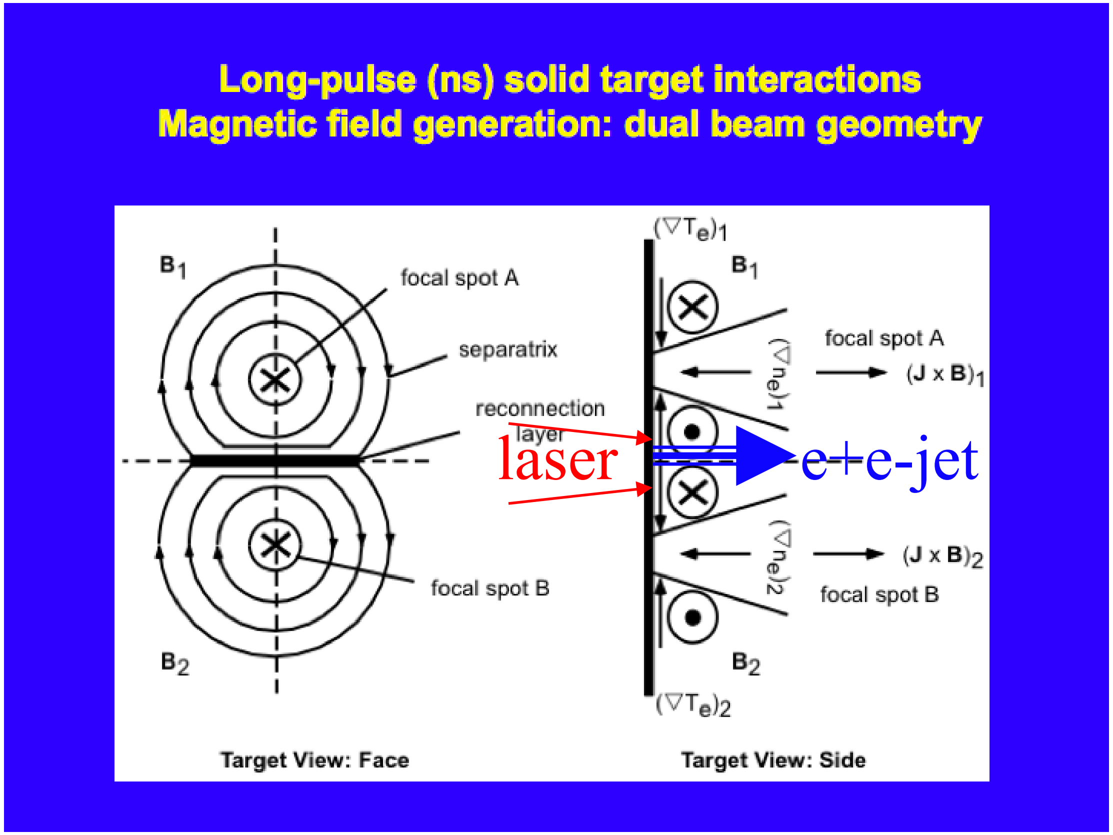
Laser-coupled Helmholtz Coils can generate vacuum axial **B** ~ 10^7G. It can be used to confine e+e- pair plasma to study pulsar & GRB.





<u>Physics of superstrong B</u> can also be studied in the lab using intense lasers:. Measured magnetic fields <u>inside</u> laser targets are now approaching ~ 10^9 gauss

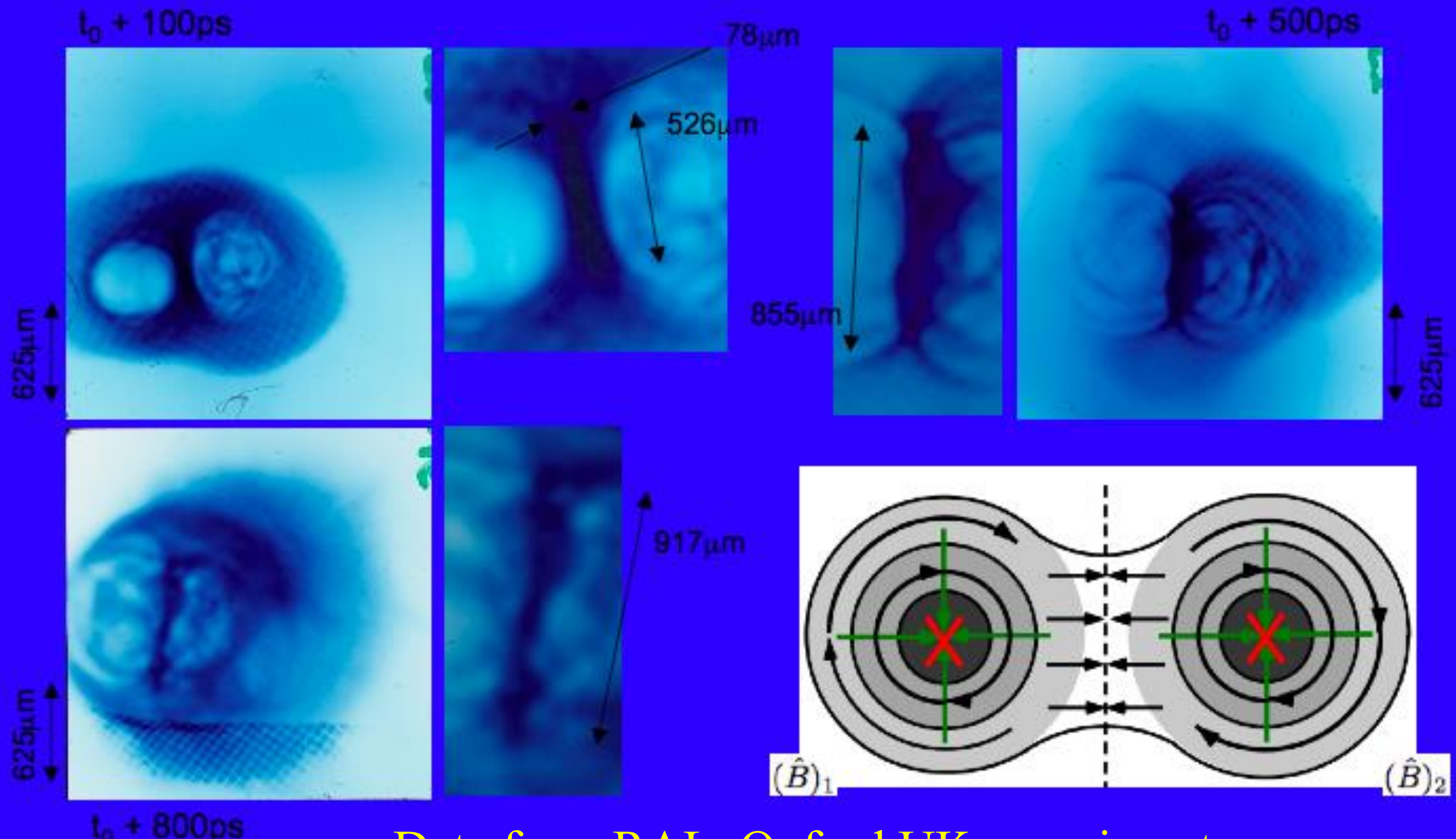
Magnetic reconnection and current sheets dissipation can be studied using two adjacent lasers



Reconnection Physics have been studied using two lasers

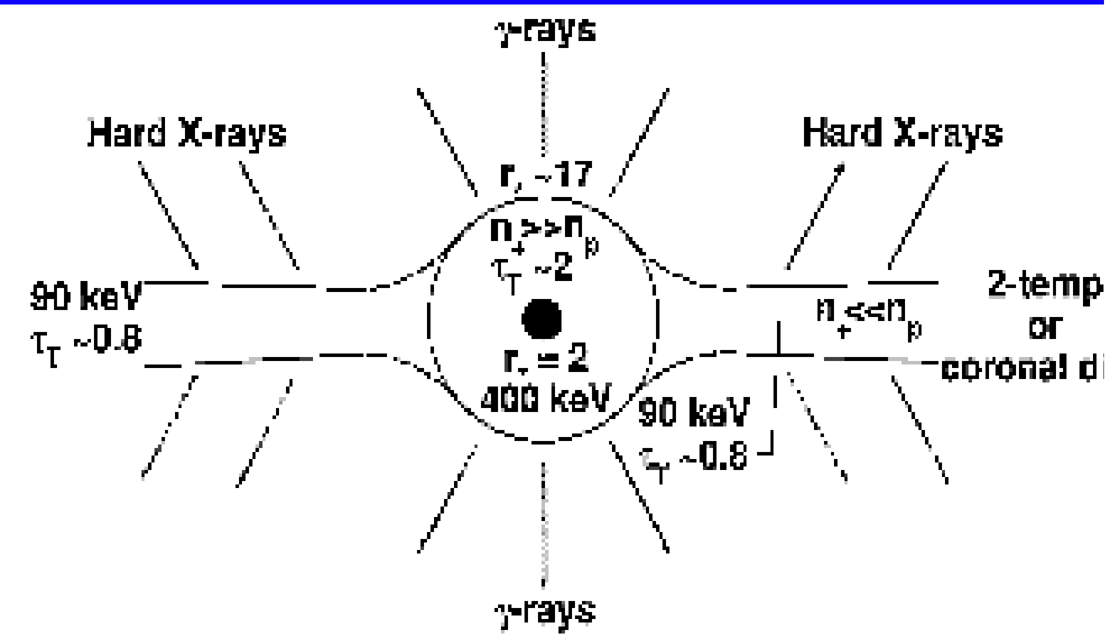
Plasma dynamics: Al target

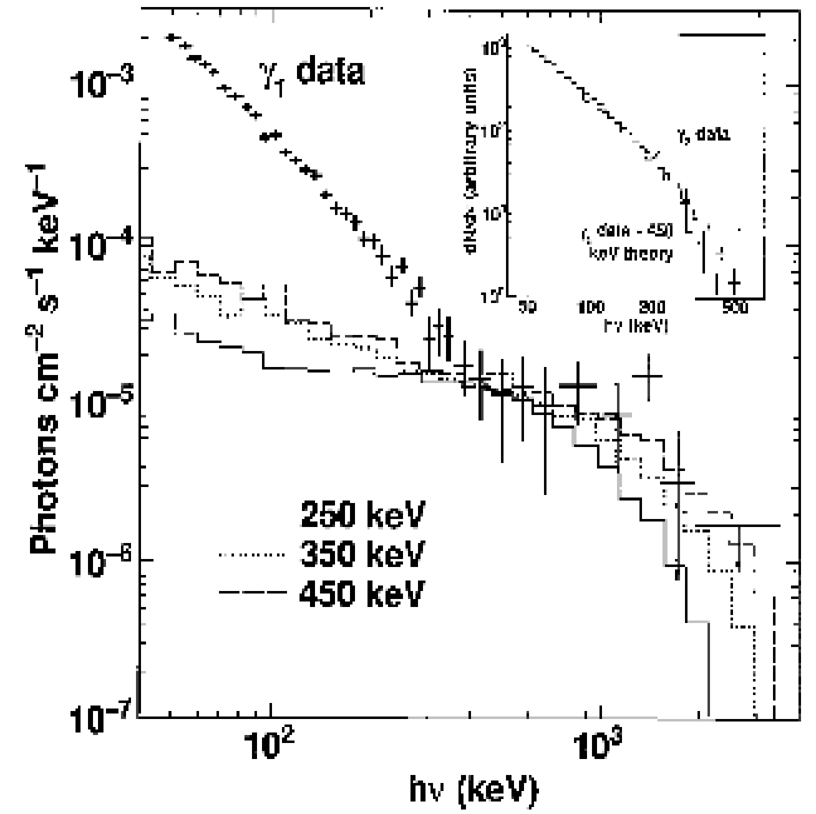
Rear projection proton imaging (fields ~ 1 MGauss)



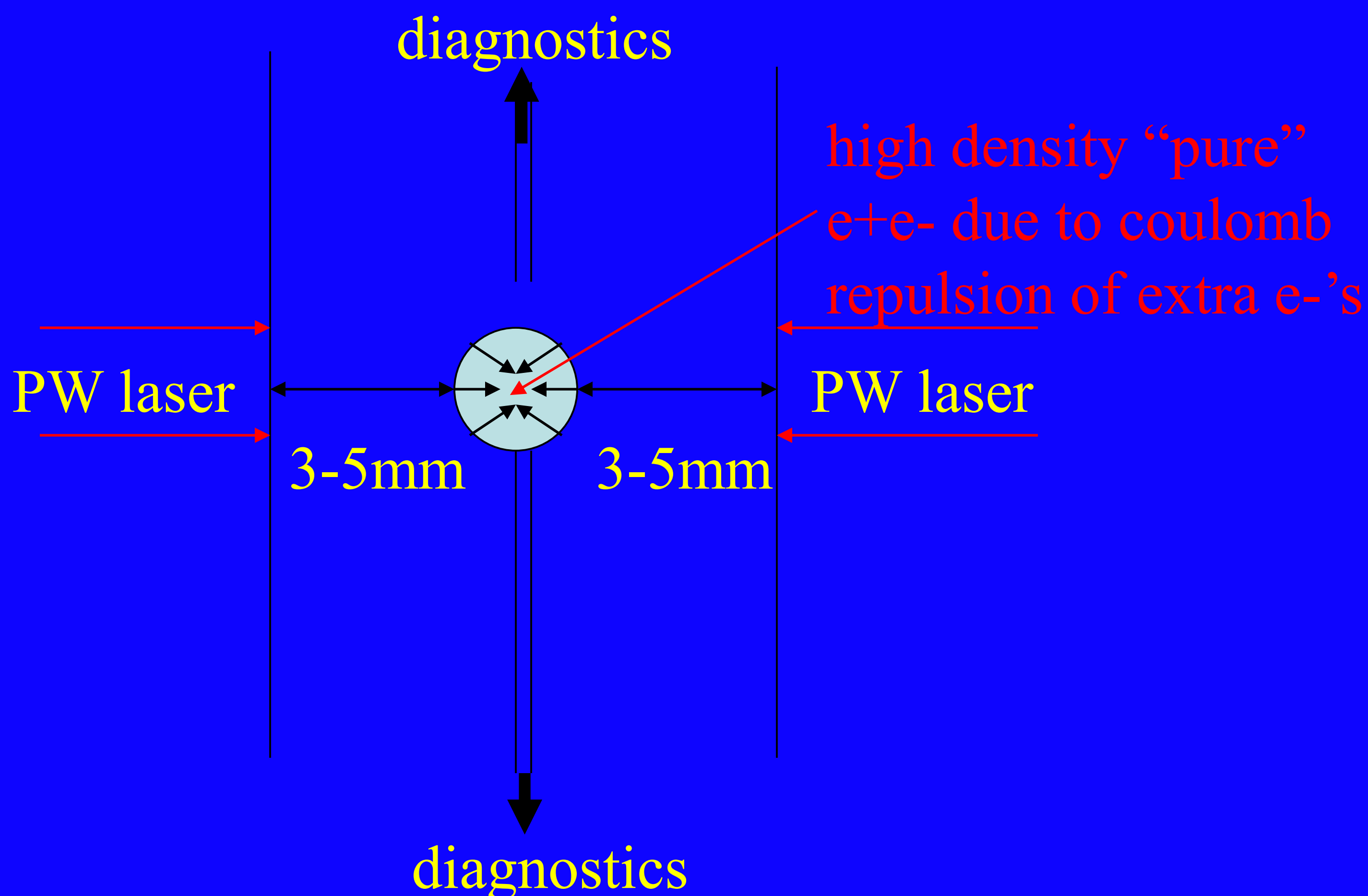
Data from RAL, Oxford UK experiments.

2D model of a pair-cloud surrounded by a thin accretion disk to explain the MeV-bump of Cyg X-1



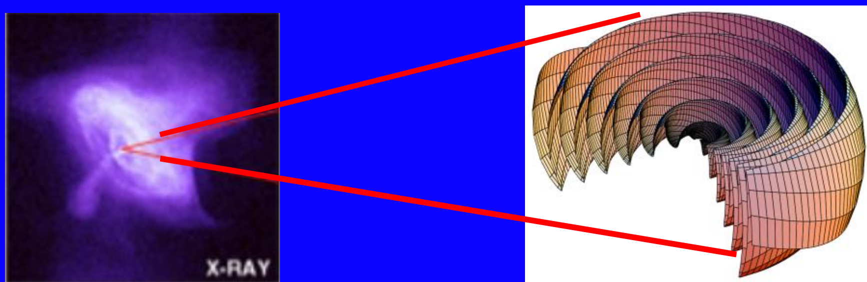


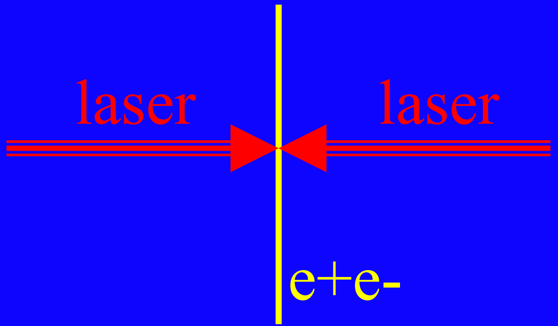
Double-sided irradiation plus sheath focusing may provide astrophysically relevant pair "fireball" in the center of a thick target cavity: ideal lab for GRB & BH γ-flares

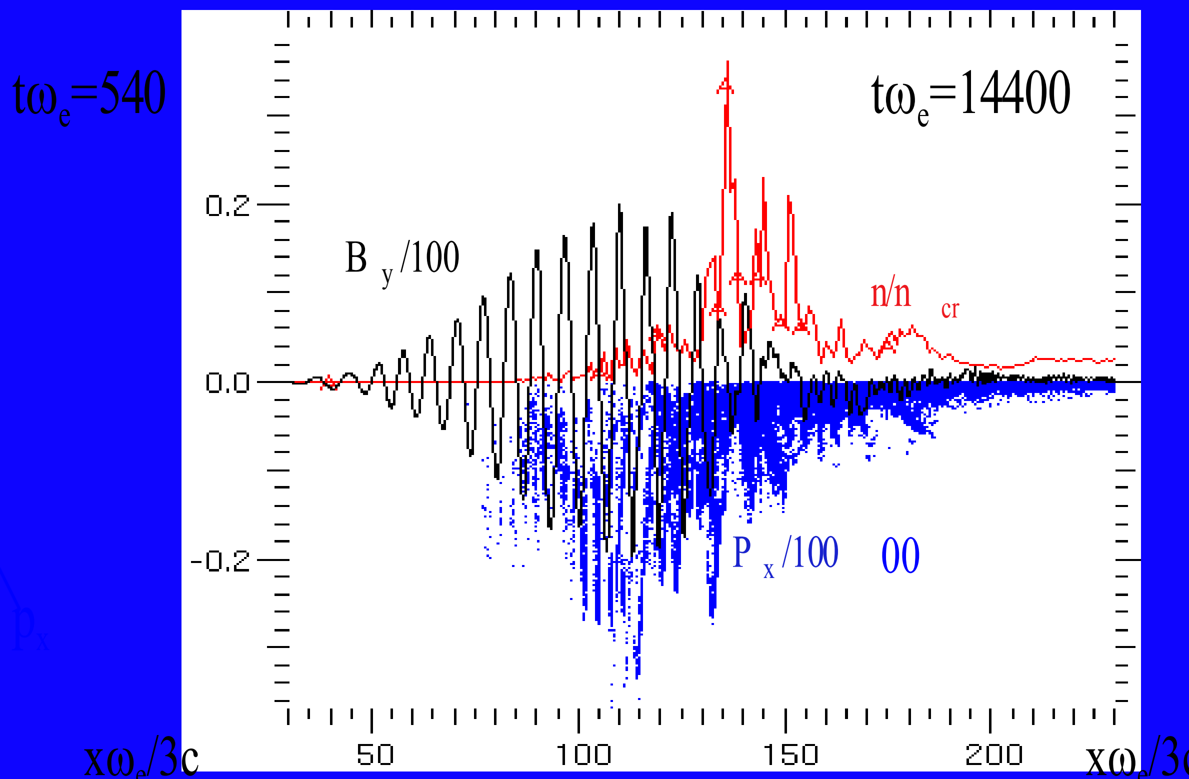


Thermal equilibrium pair plasma and BKZS limit may be replicated if we have multiple ARC beams staged in time sequence.

Pulsar Wind = Linearly Polarized EM Wave but Loaded with "overdense" Pair Plasma. How to do this with lasers?







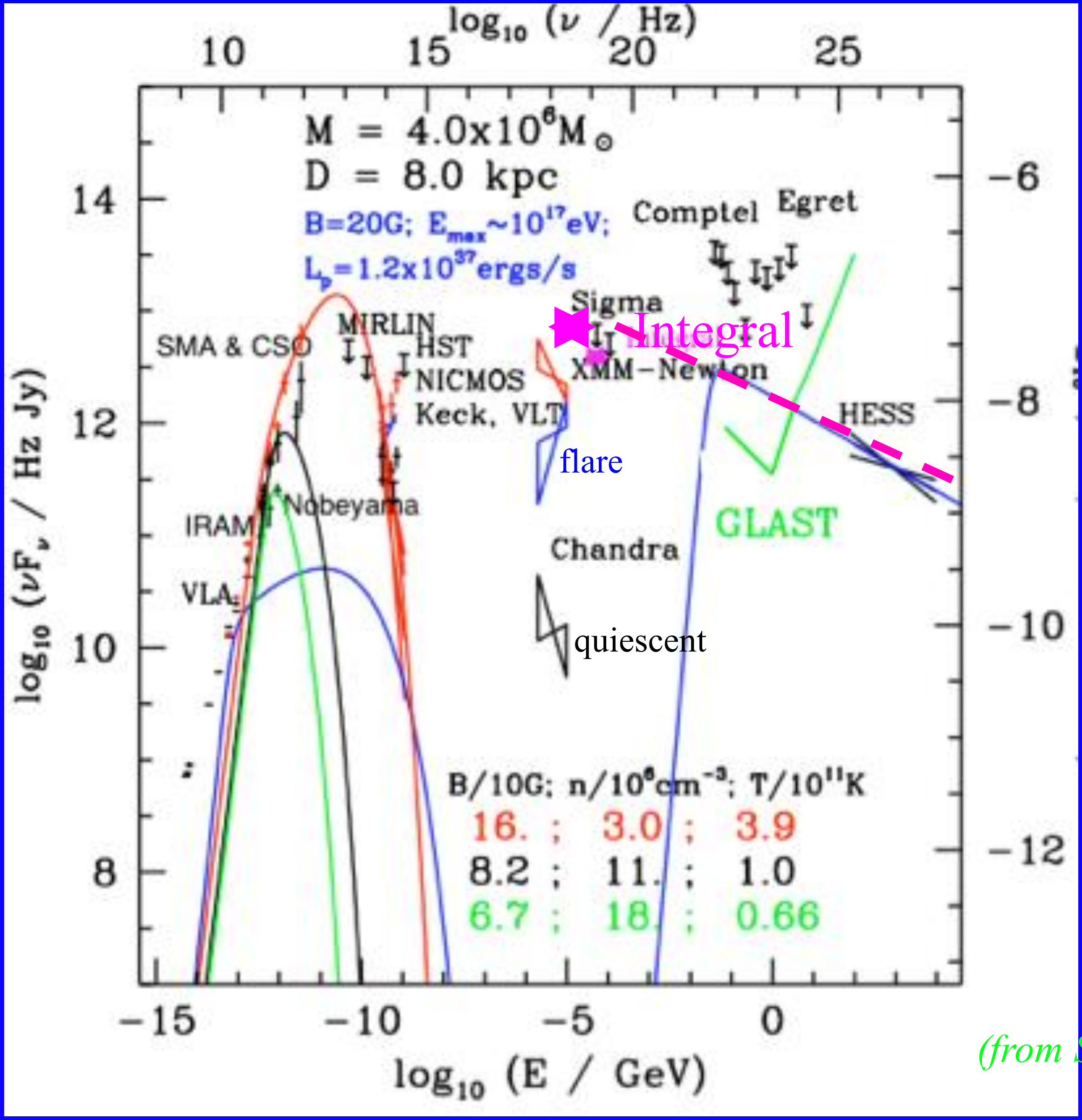
colliding laser pulses can load overdense e+e- plasma and accelerate them

In Astrophysics, we need multi-physics, multi-scale Computer Simulations that Include:

1. MHD for global dynamics
2. Radiation Transport for observable signatures
3. GR for strong gravity effects
4. Particle-in-Cell (PIC) Simulations for field generation, dissipation and particle energization.

Our group is involved in all four types of simulations and efforts to link simulations of different types

High-energy emission of low-luminosity black hole such as SgrA* examplifies accretion which requires energization above the level predicted by thermal SSC model with only e-ion coulomb coupling



(from S. Liu et al)

weakly magnetized initial torus around BH

MRI-induced accretion flow with
saturated MHD turbulence

thermal MRI
disk models

GRMHD

new approach

turbulence energization of
nonthermal electrons and ions

PIC

synchrotron emission by
nonthermal electrons

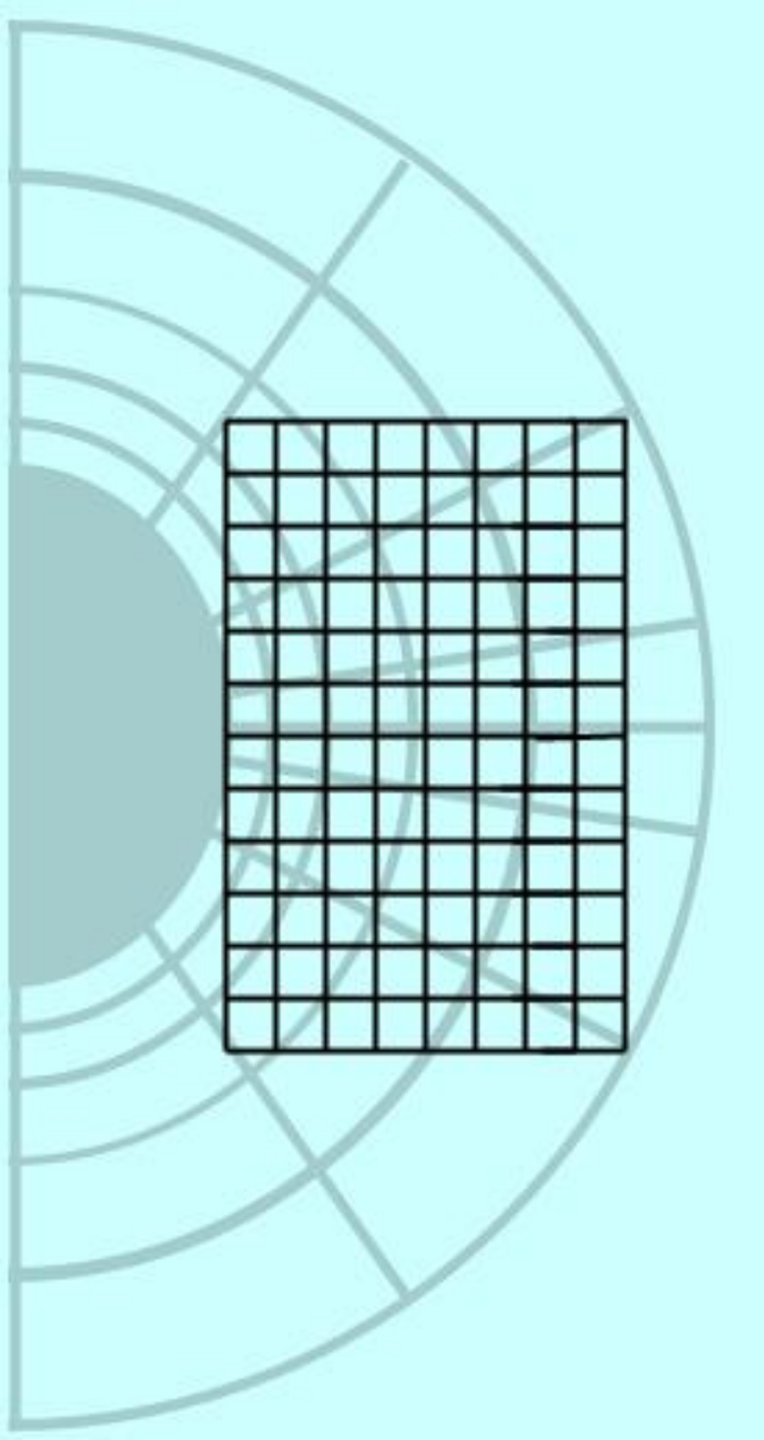
MC

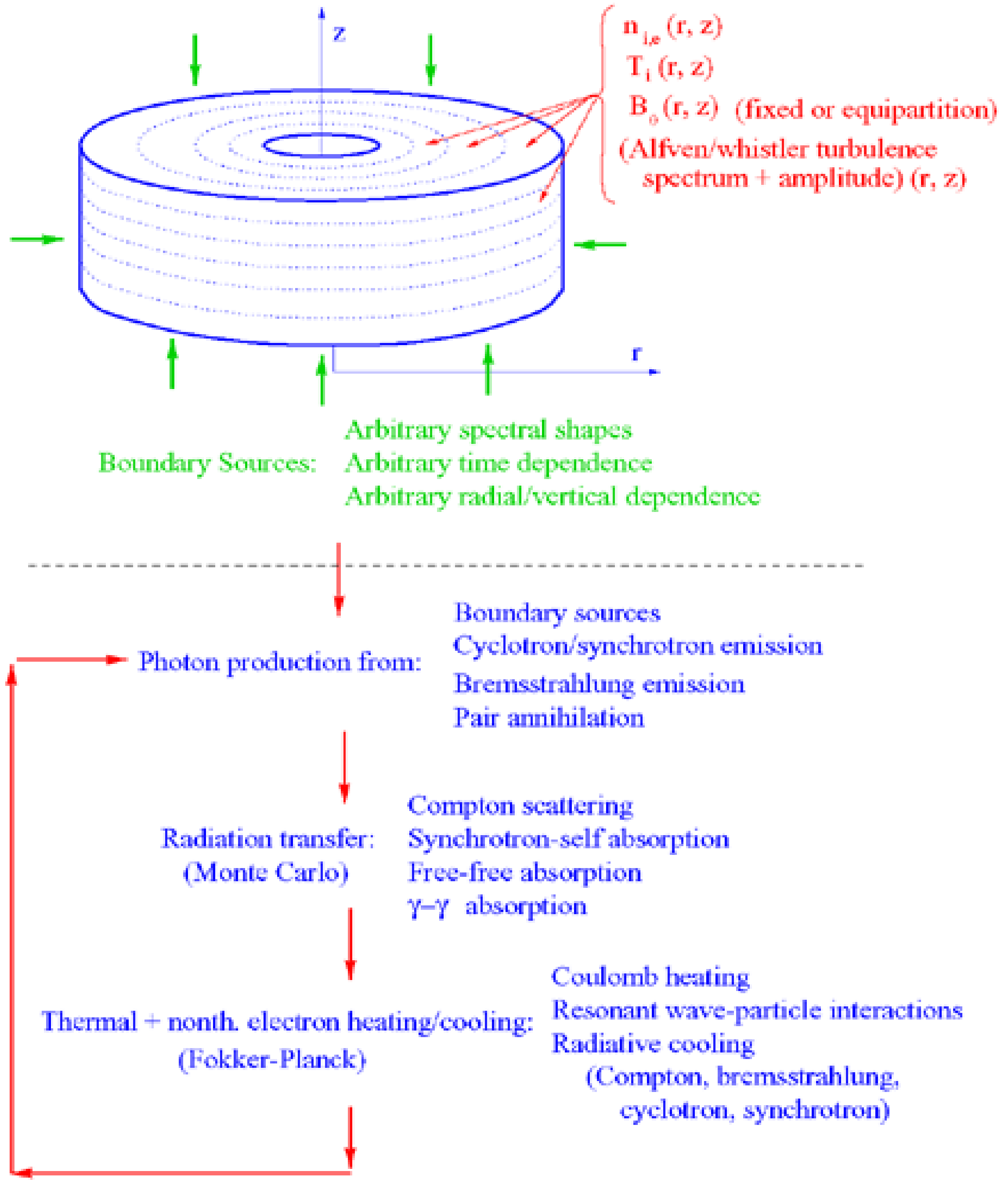
SSC+EC of nonthermal
electrons

GEANT4

pion decay emission of
Nonthermal ions

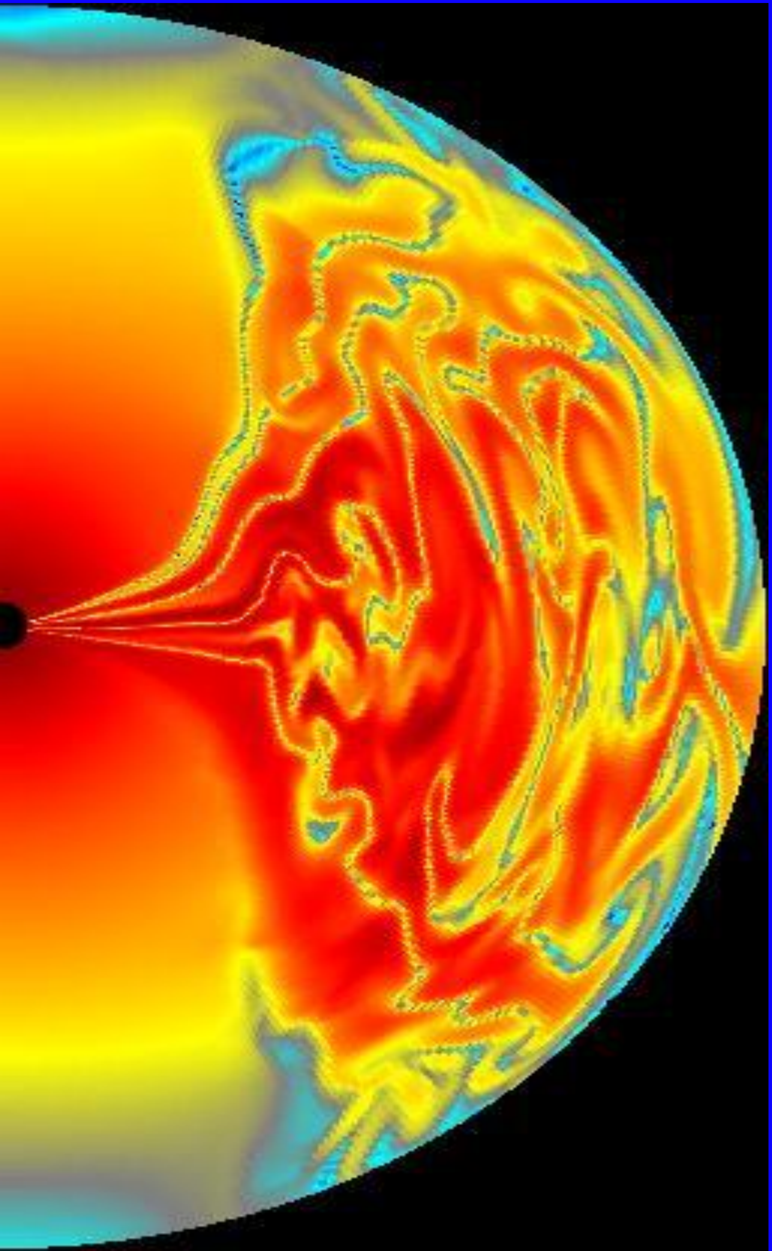
Model setup MC photon transport





MRI-induced flow from global GRMHD simulations

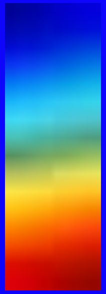
B^2



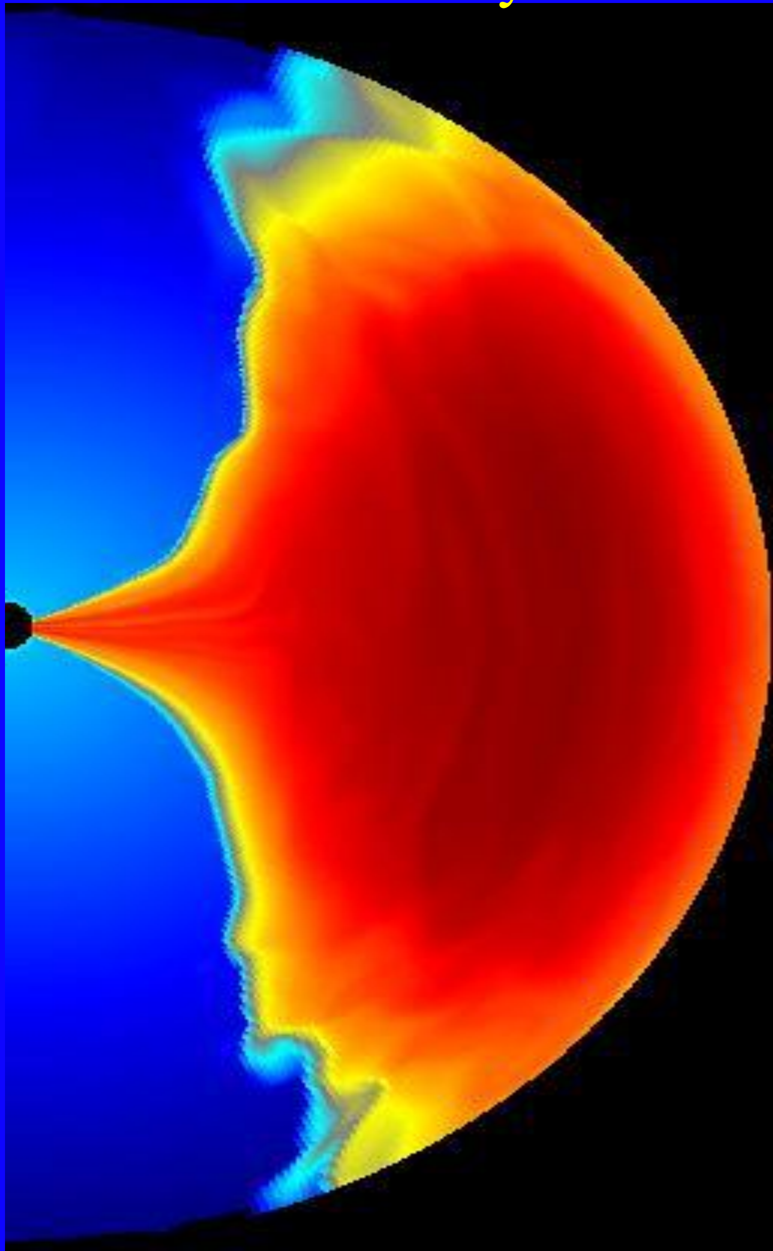
HARM code

256x256

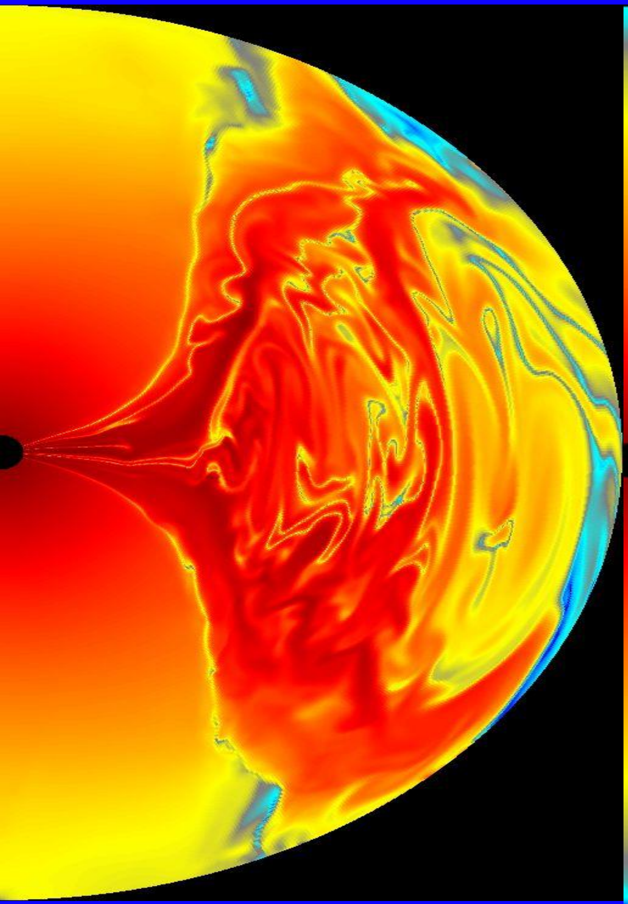
t=2002

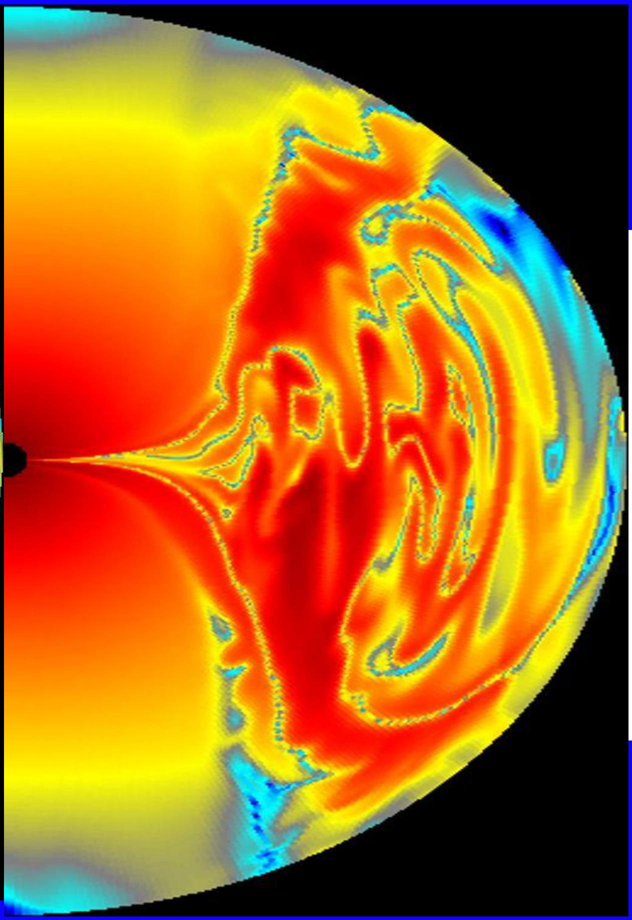


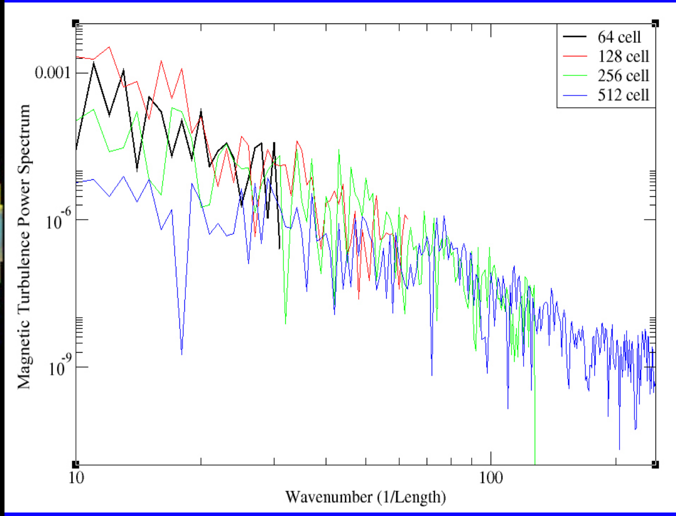
density



Alternating current sheets get thinner with increasing resolution but pattern maintains self-similarity







512x512

HARM code

256x256

B^2

High-Resolution 3D-MHD simulations show persistence of heavily folded current sheets

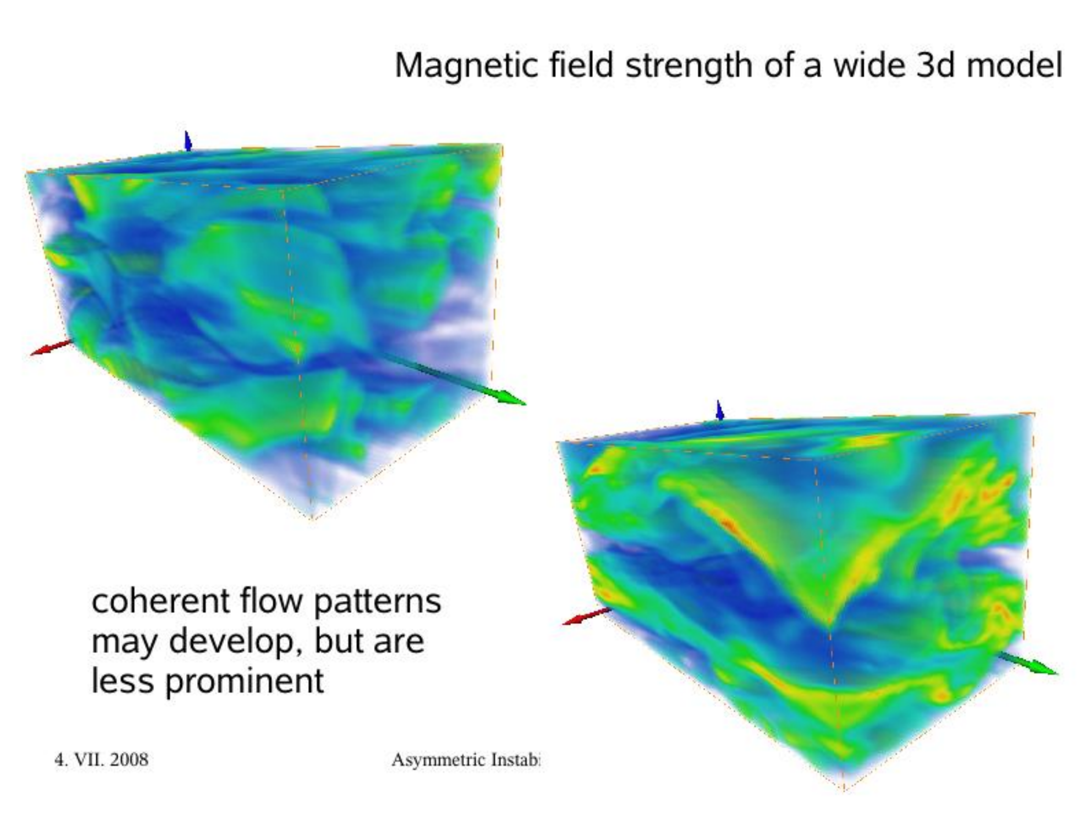
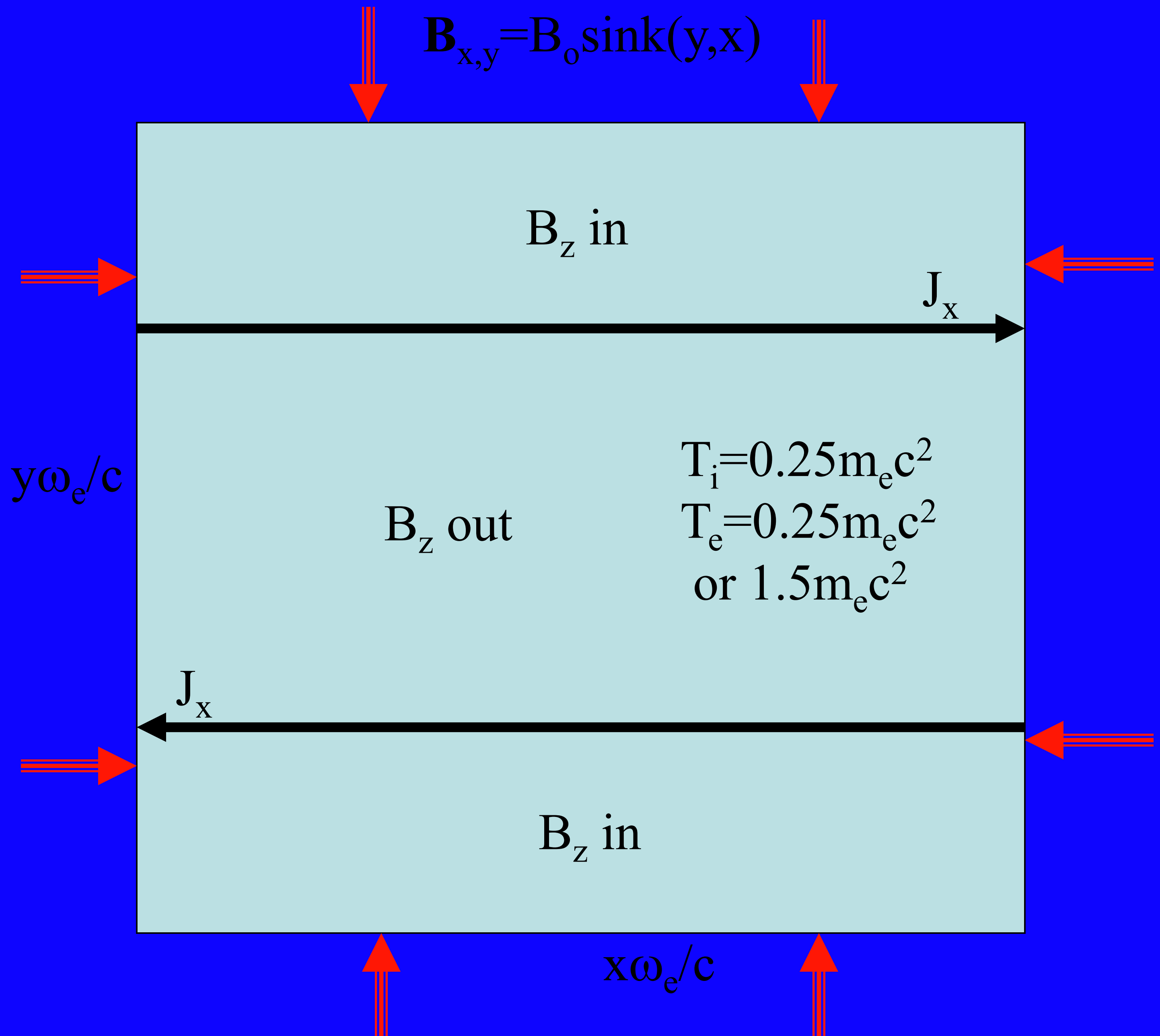


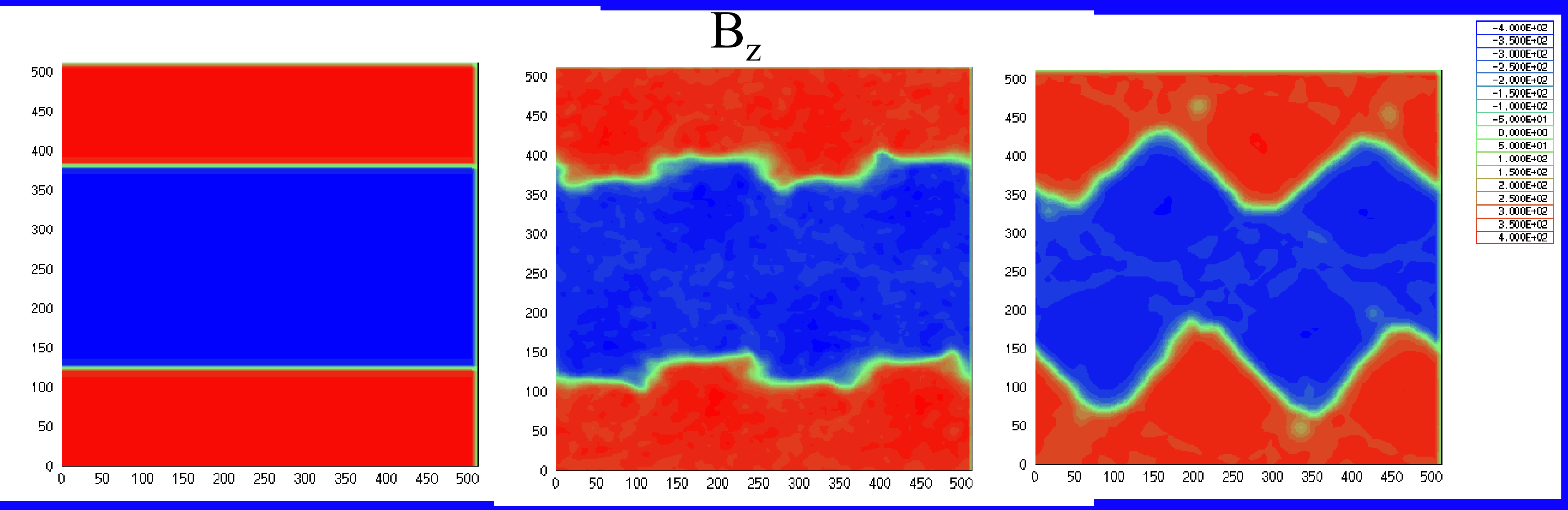
Fig.16 *A high resolution local MRI run showing the bending and folding of current sheets in 3D (from Obergaulinger et al 2005).*

2.5 D PIC 1024x1024 doubly periodic grid, ~10^8 particles, m_i=100m_e



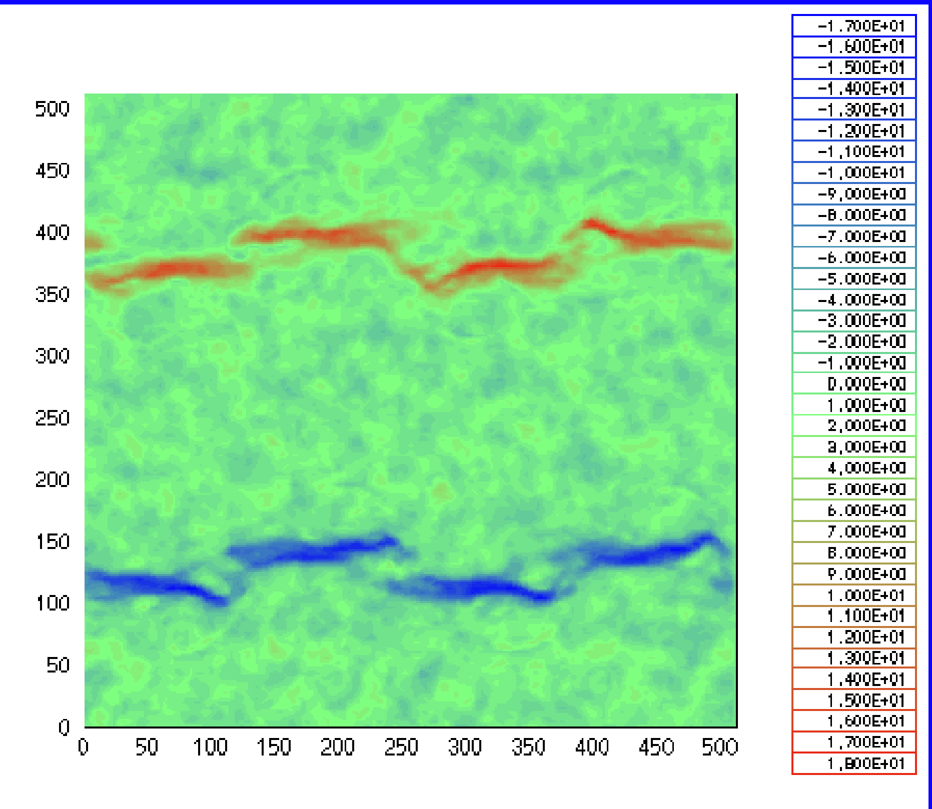
Single mode $kL=4\pi$ $T_e=1.5m_ec^2$ $B_z=10B_o$ $\Omega_e=5\omega_{pe}$

current sheet thickens and bents due to wave perturbations

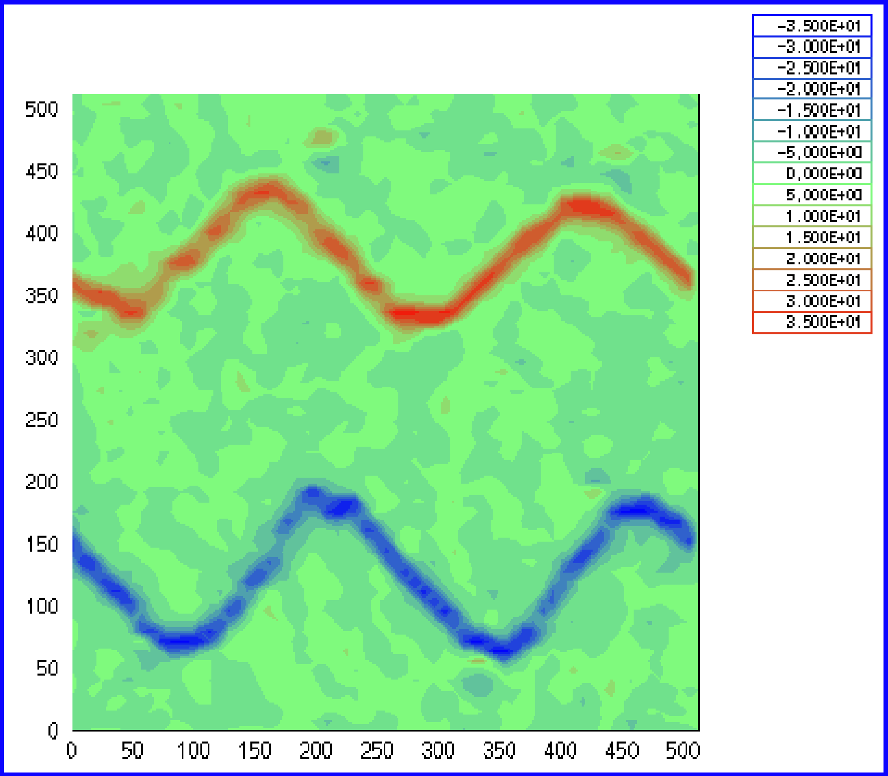


$t\omega_e=0$ 1000 4000

J_x

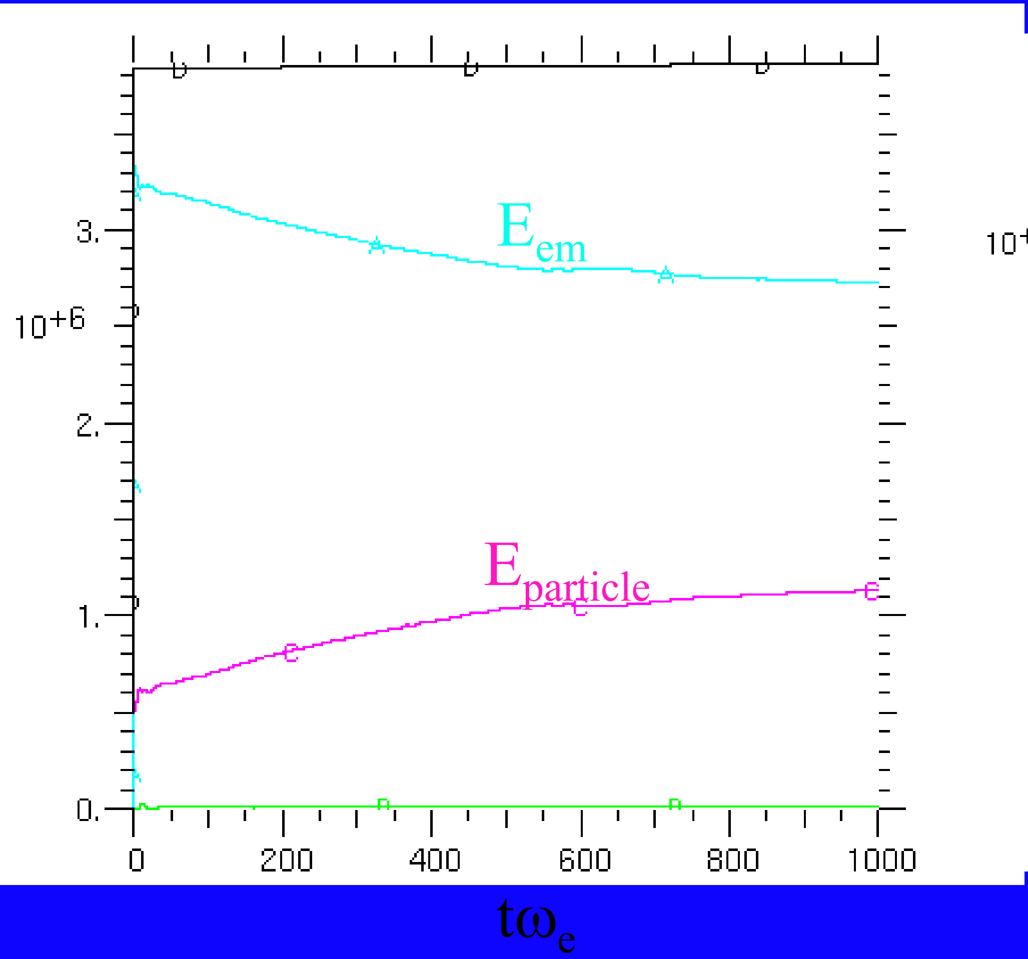


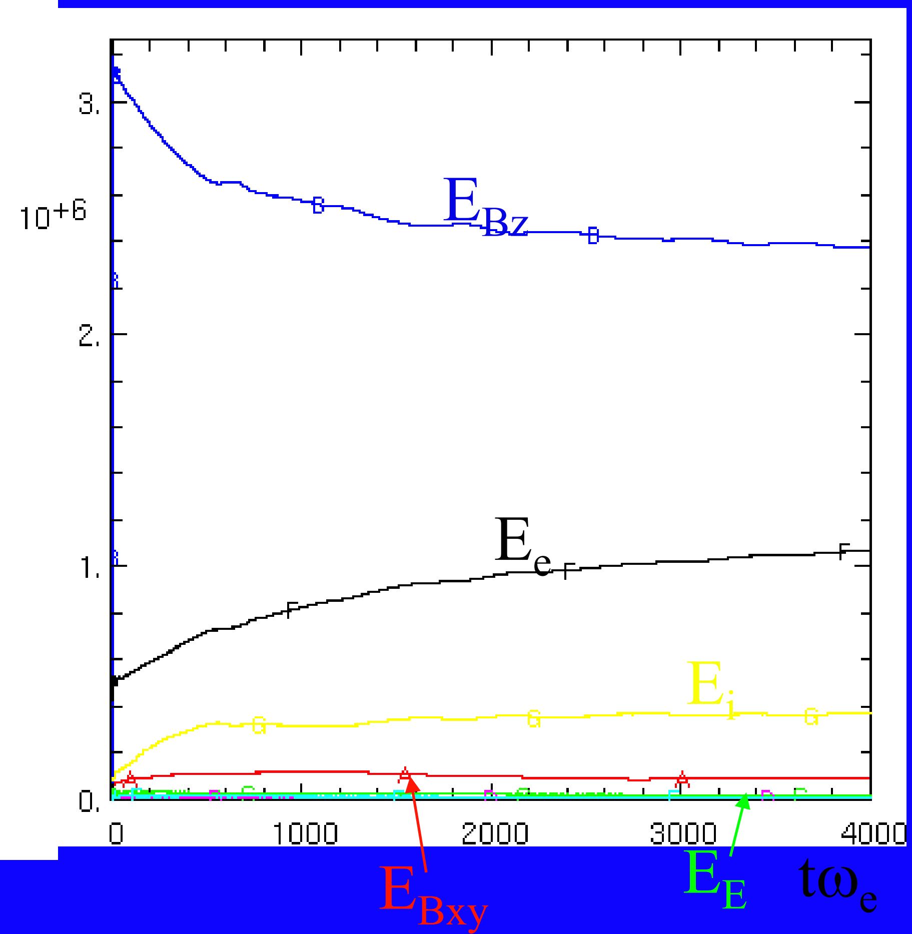
$t\omega_e$=1000

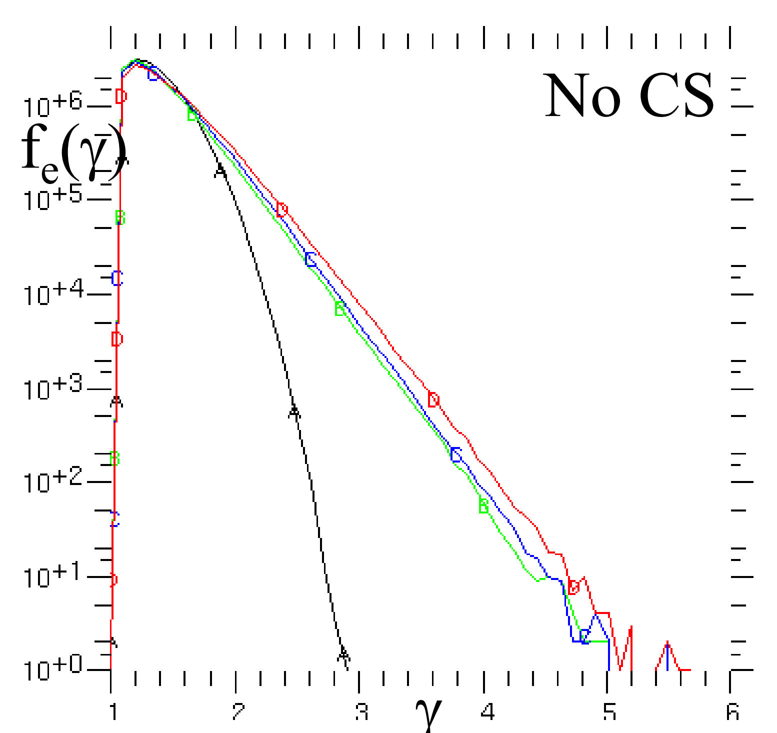


4000

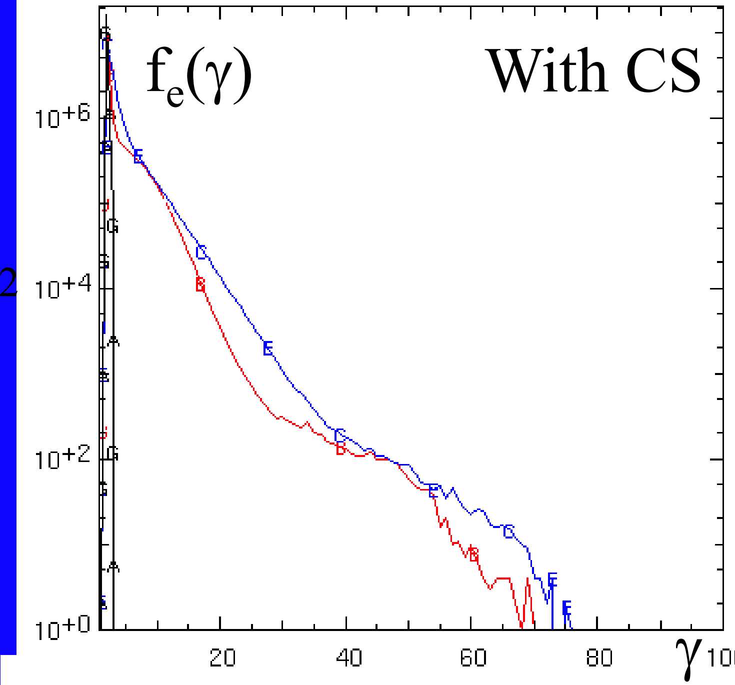
Magnetic energy is efficiently converted to hot electrons due to current sheet dissipation

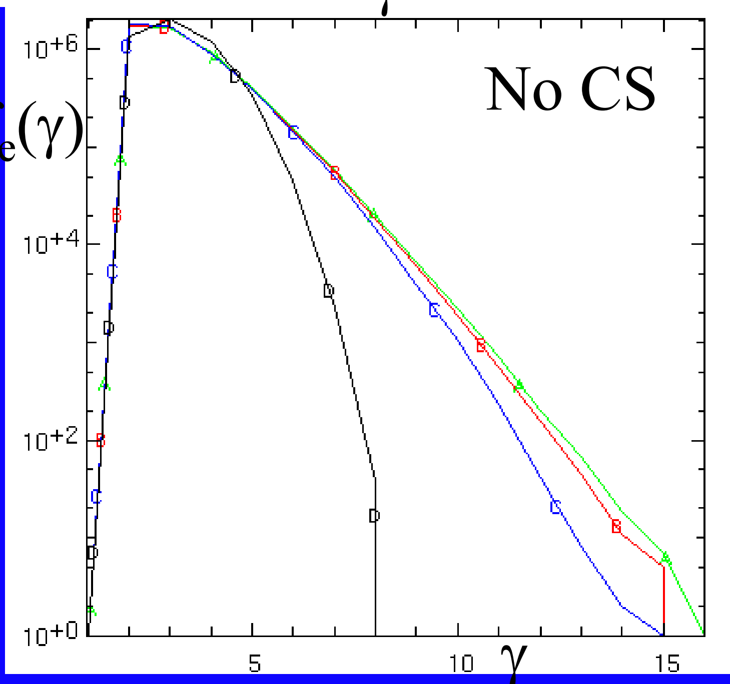




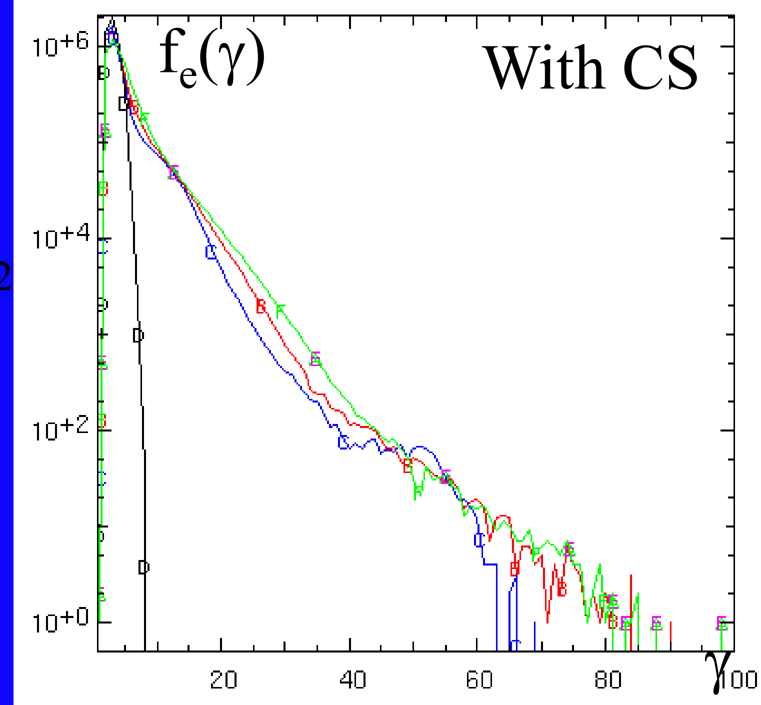


$T_e=0.25m_ec^2$

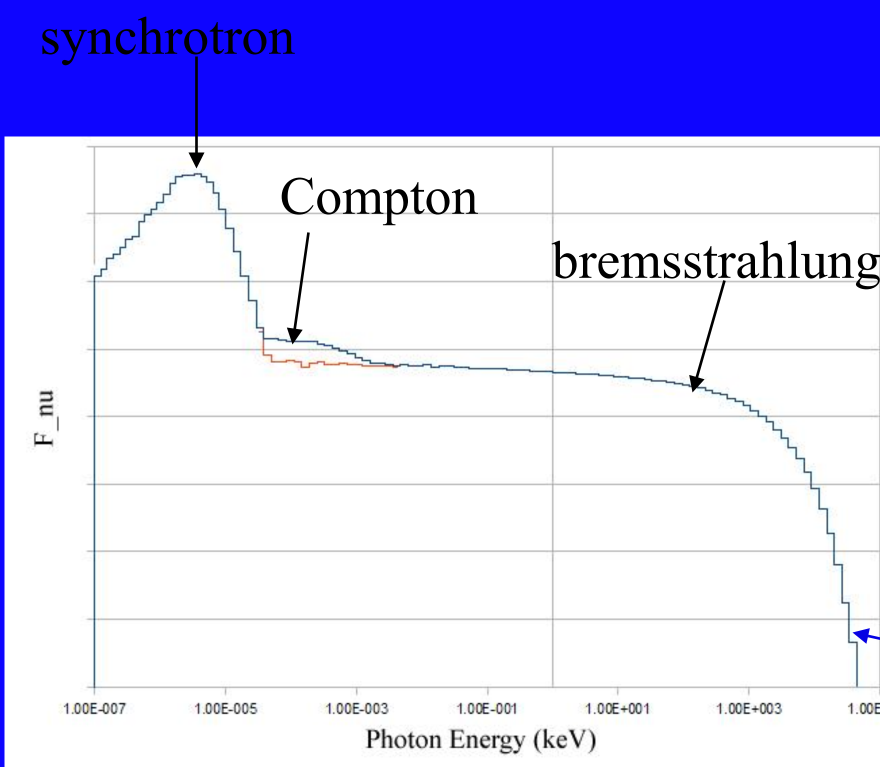


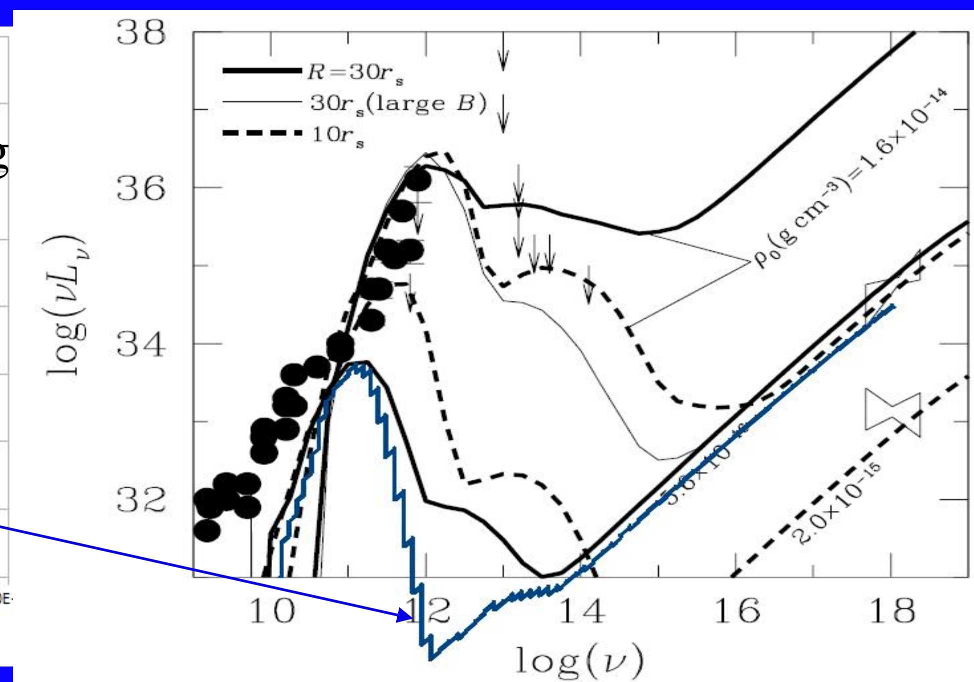


$T_e=1.5m_ec^2$



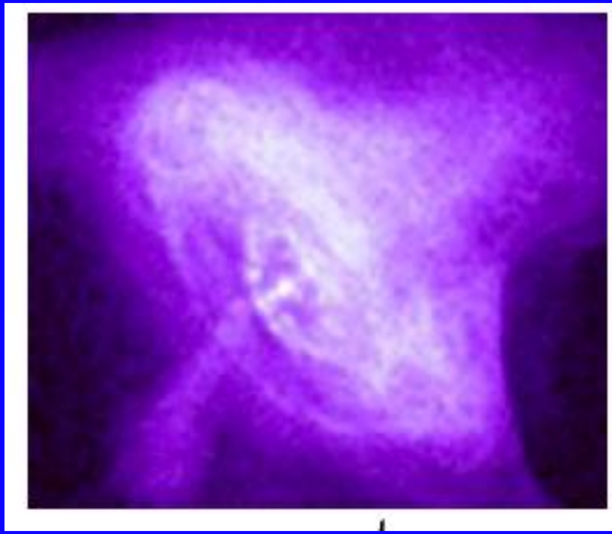
Photon spectrum using HARM output as input for the 2D-MC code (95x95 grid) with density normalized by the Chandra flare as due to bremsstrahlung. Note that our Compton hump is lower than the result of Ohsuga et al 2005.

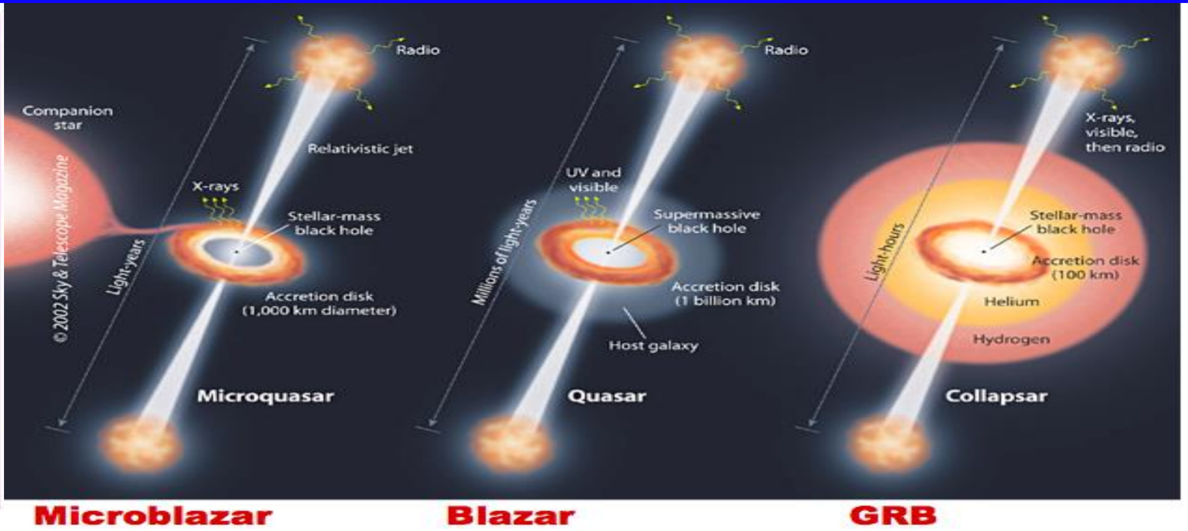




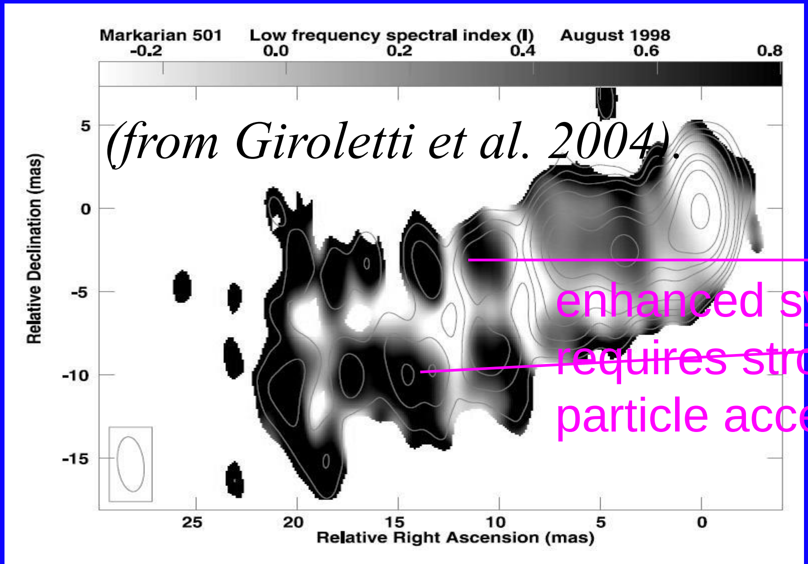
Ohsuga et al 2005

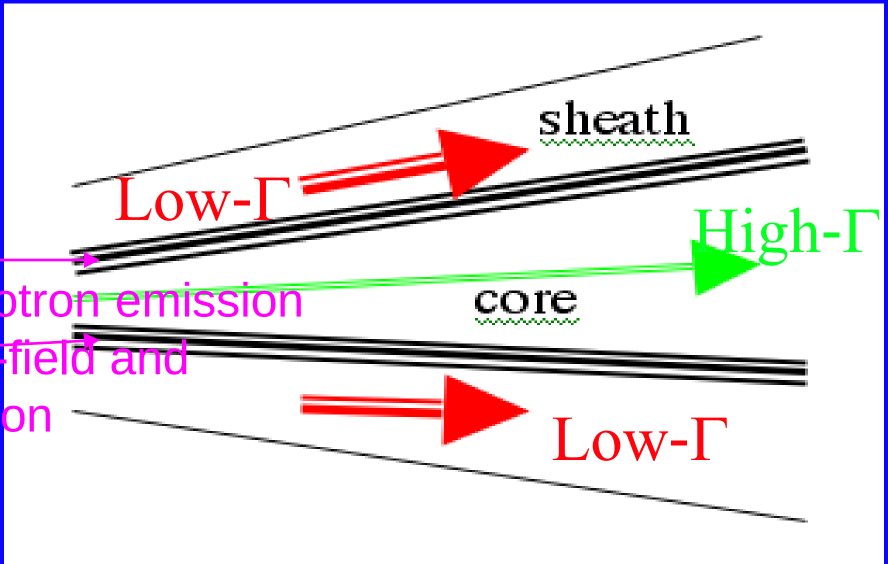
Relativistic shear boundary layer (SBL) dissipation likely occur in many astrophysical platforms and settings



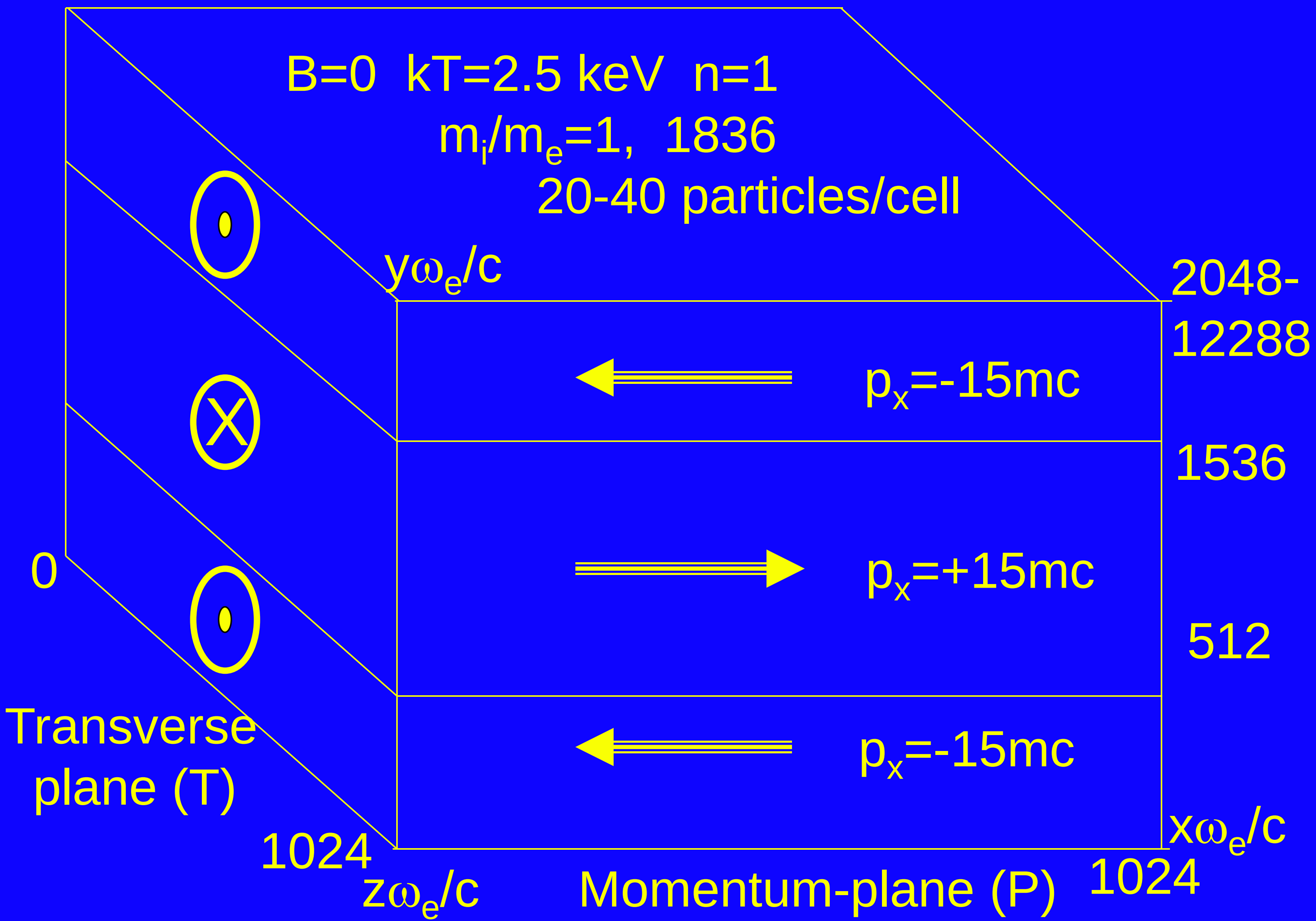


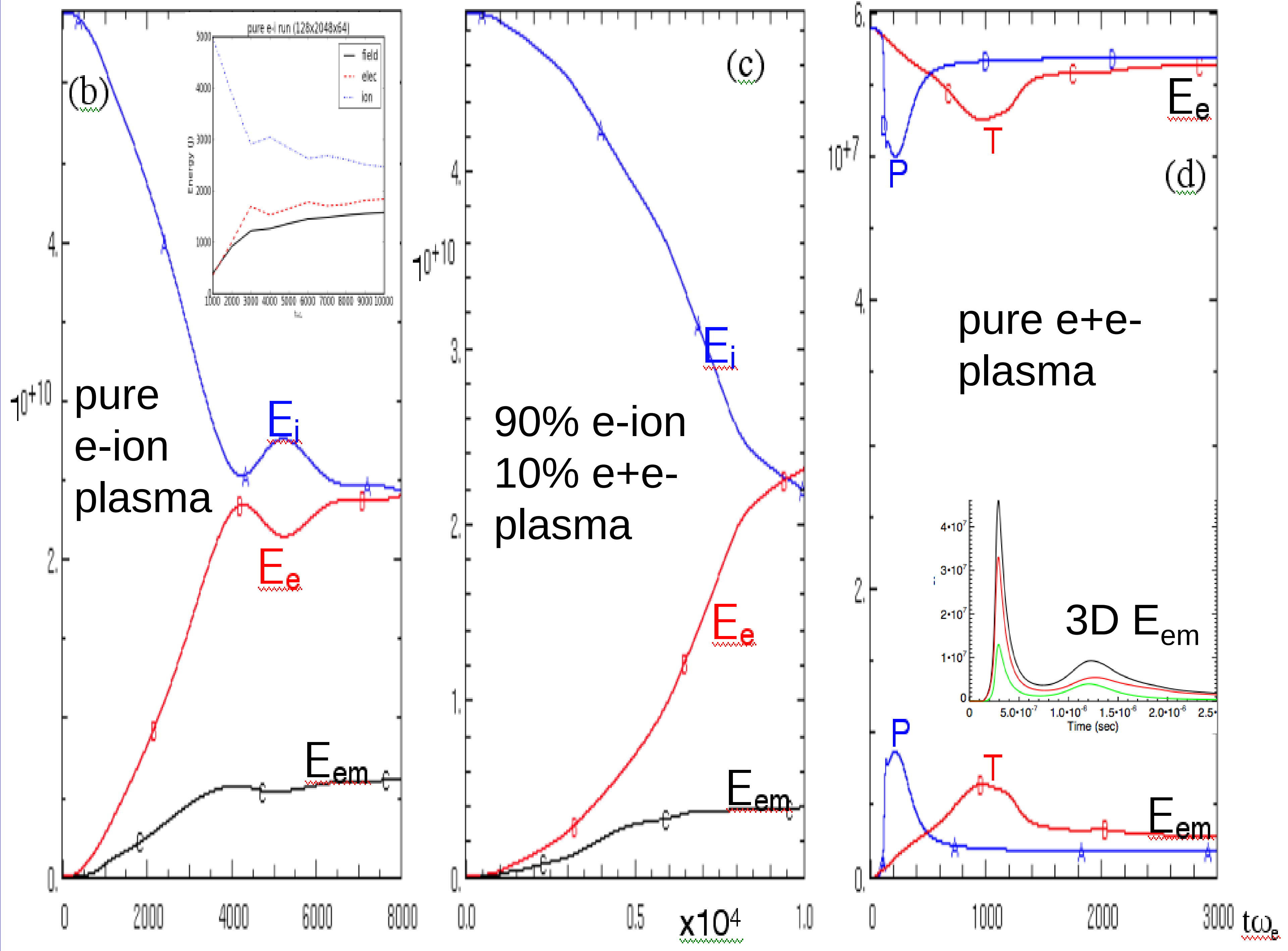
Limb-brightening of radio galaxies in VLBI observations consistent with boundary layer emission of core-sheath jets





We run 2-D simulations in both x-y and y-z planes plus small 3-D runs to check the essential features of 2-D results



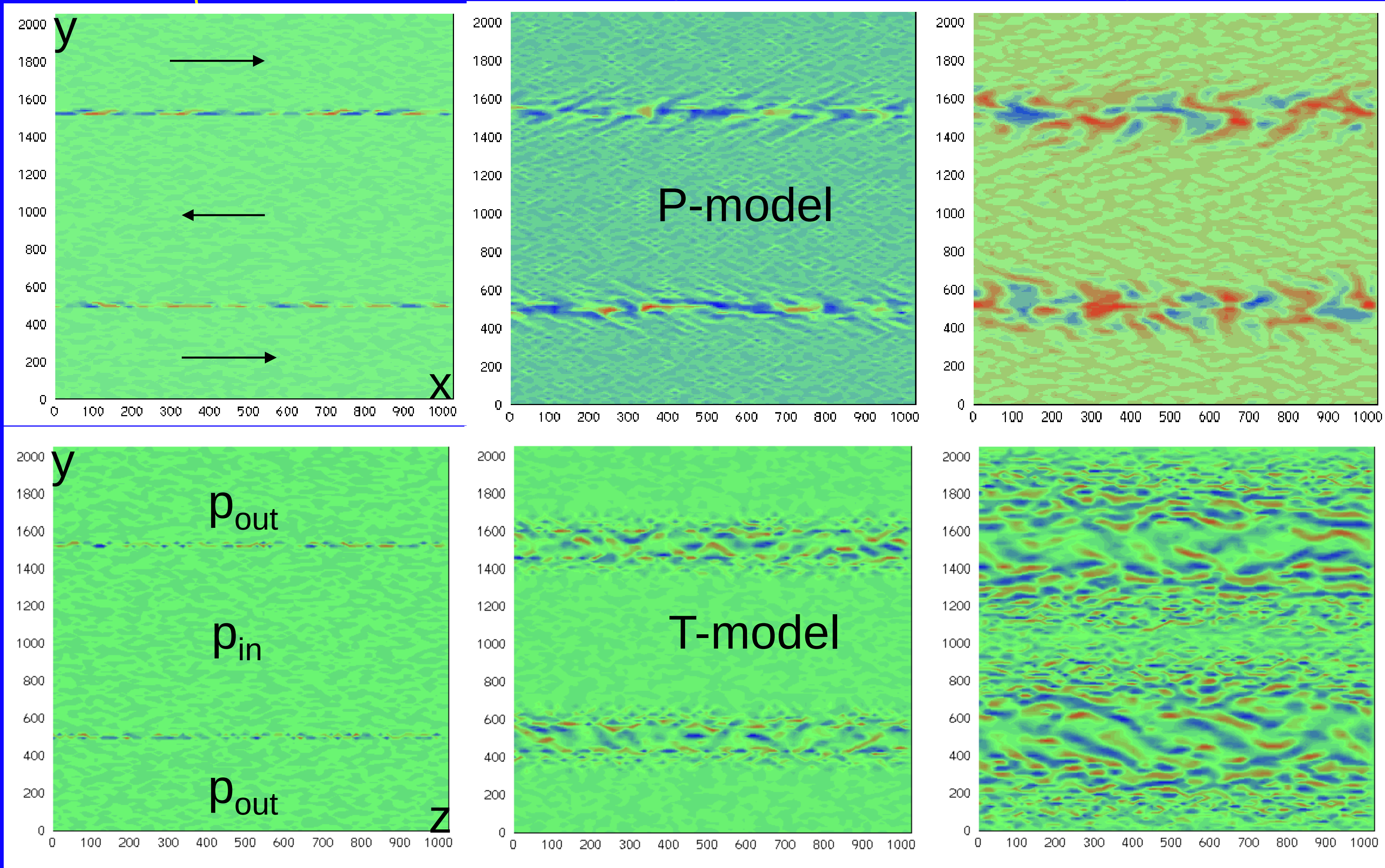


(b)
pure e-ion plasma
E_i
E_e
E_{em}
pure e-i run (128x2048x64)
field
elec
ion
Energy (J)
(c)
90% e-ion 10% e+e- plasma
E_i
E_e
E_{em}
x10⁴
(d)
pure e+e- plasma
E_e
P
T
3D E_{em}
Time (sec)
E_{em}
$t\omega_e$

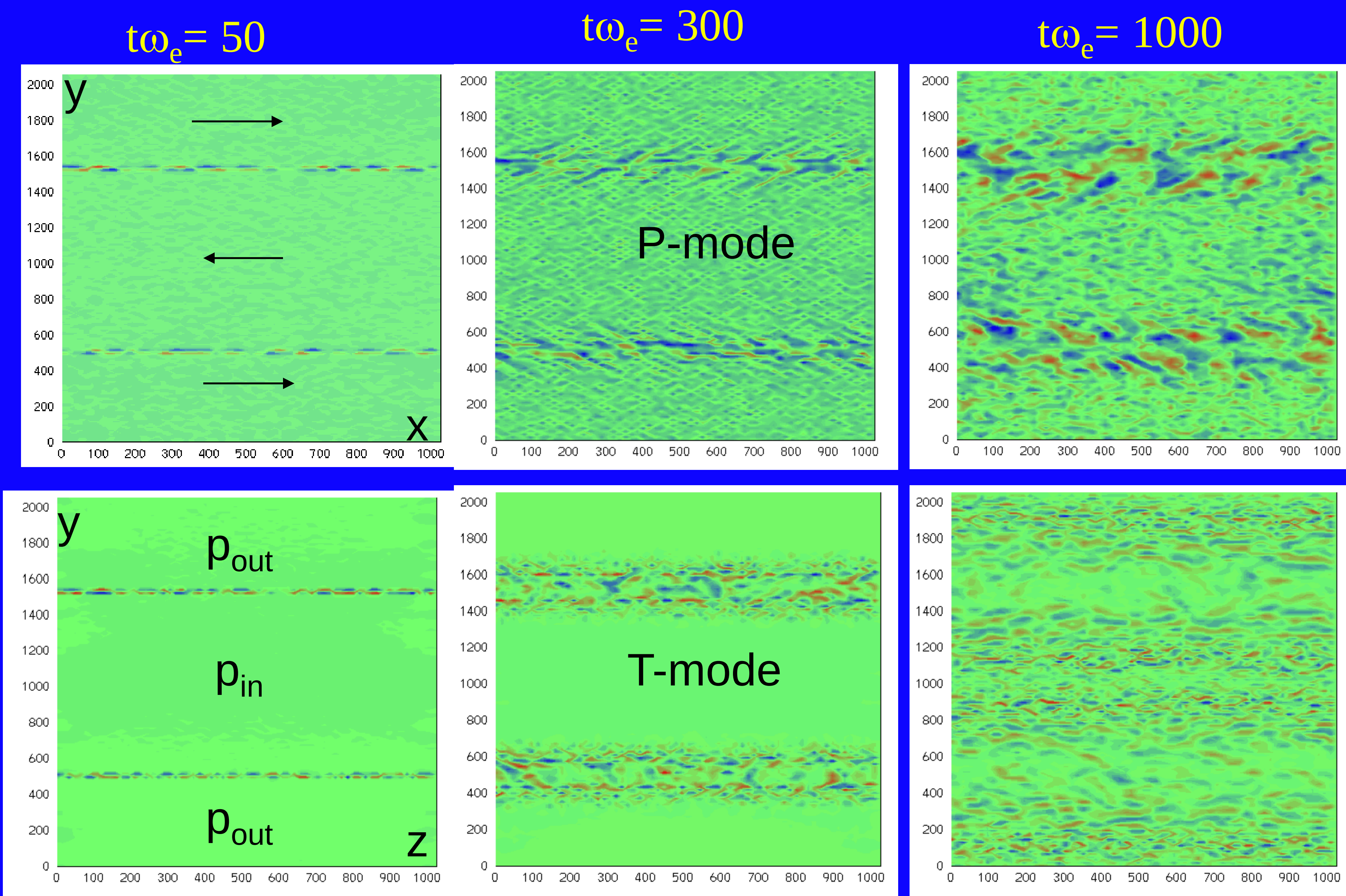
Evolution of B_z contours (in and out of the plane) for e+e- case.

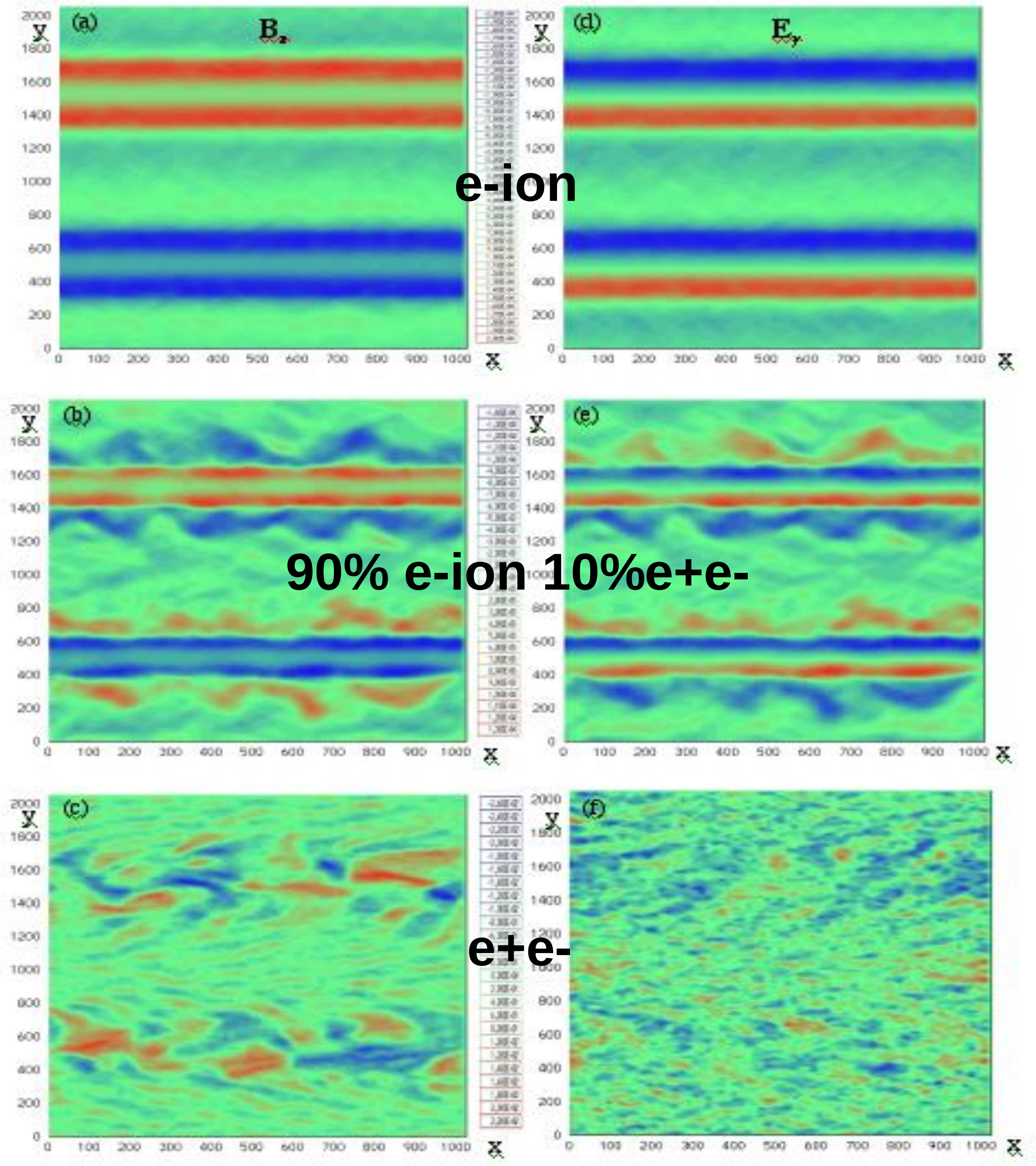
Maximum B_z is close to equipartition values ($B^2/4\pi \sim np_o c$)

$t\omega_e = 50$ $t\omega_e = 300$ $t\omega_e = 1000$

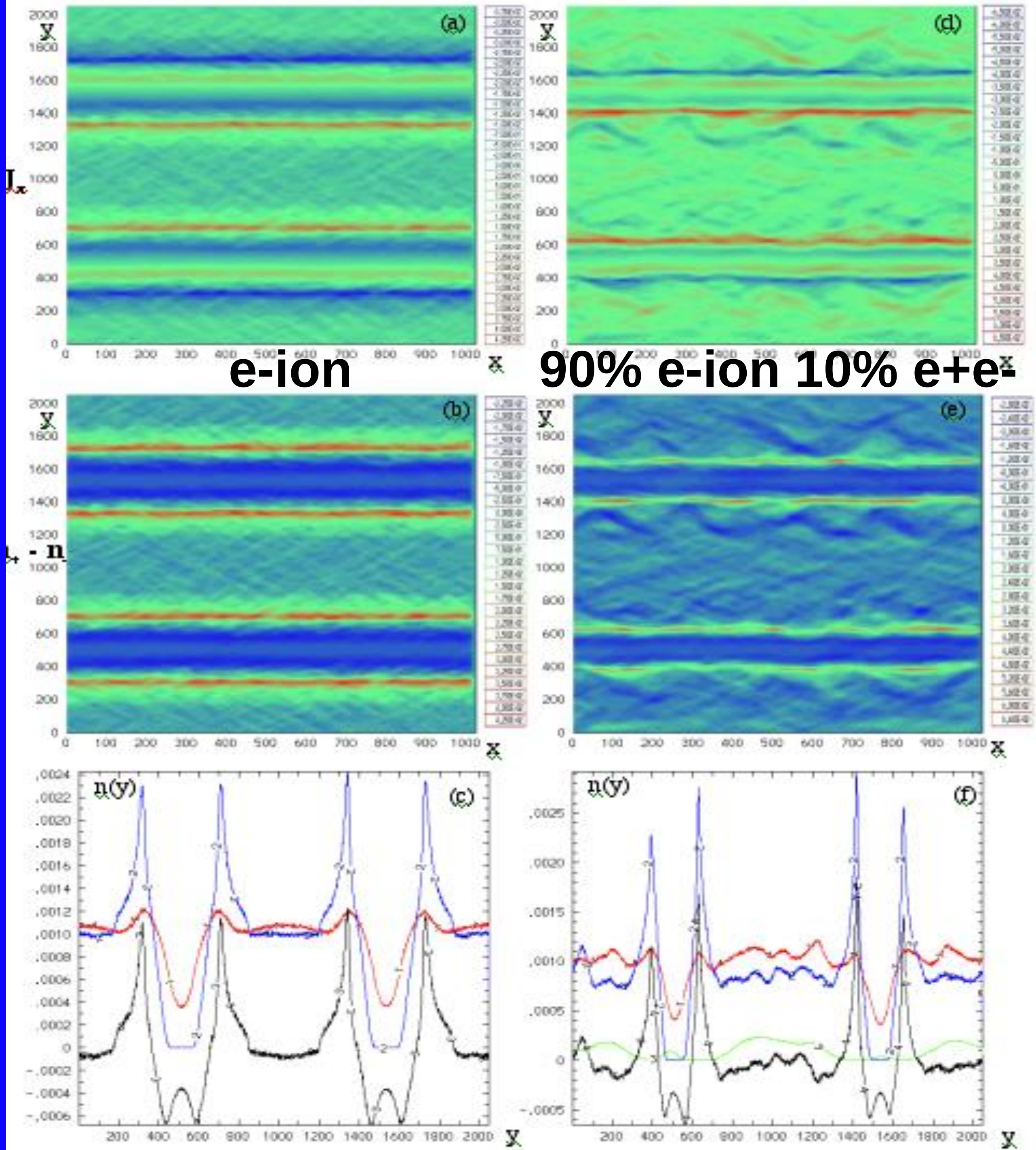


Evolution of E_y contours





In 3D runs, oblique modes generate (By,Ez), but they are < (Bz, Ey)



(a)
(d)
e-ion
90% e-ion 10% e+e-
(b)
(e)
(c)
(f)
n(y)
x
y

QuickTime™ and a
Graphics decompressor
are needed to see this picture.

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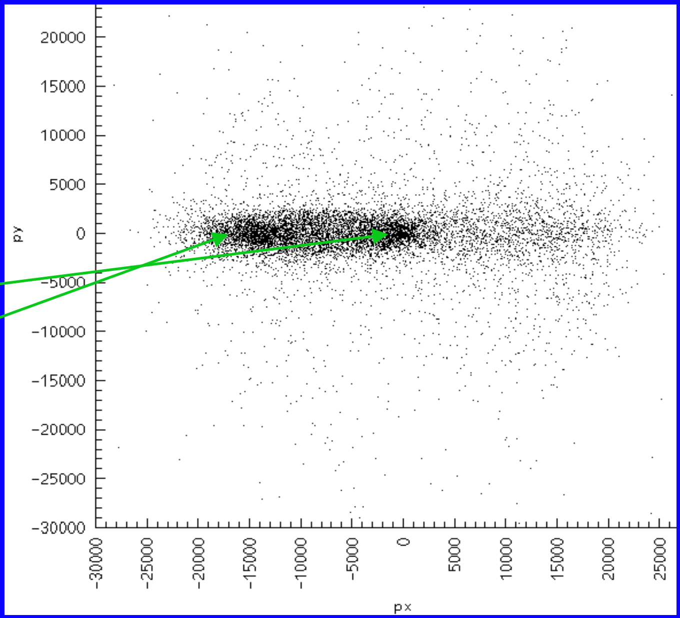
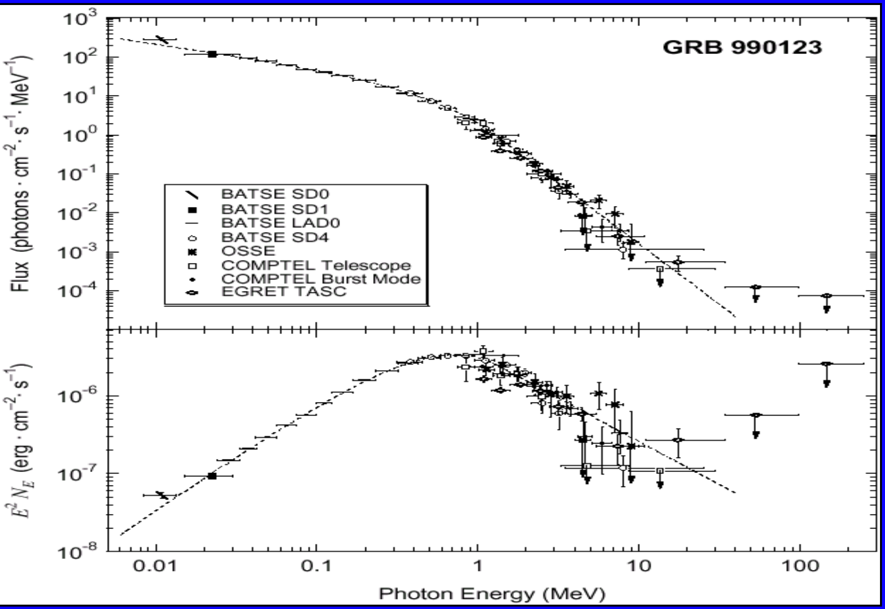
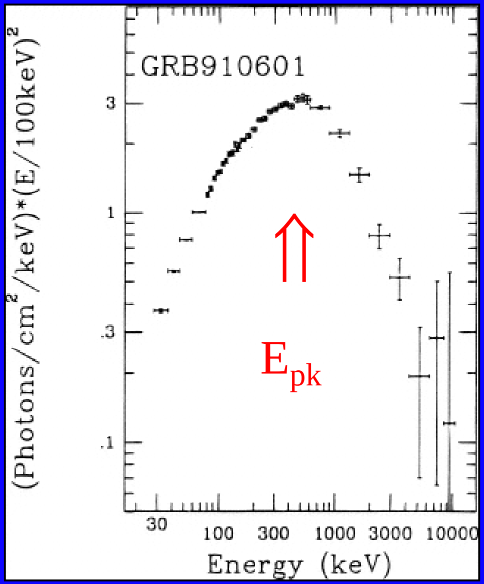
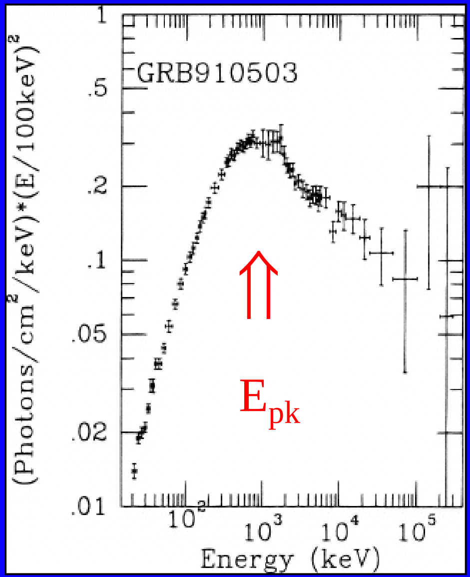


50GeV

Spectral Properties of GRBs







Band Function

Schaefer et al. (1998)

Observed GRB spectra strongly resemble hybrid shear boundary layer spectra. predicted peak frequency location is consistent with observed with Epk values