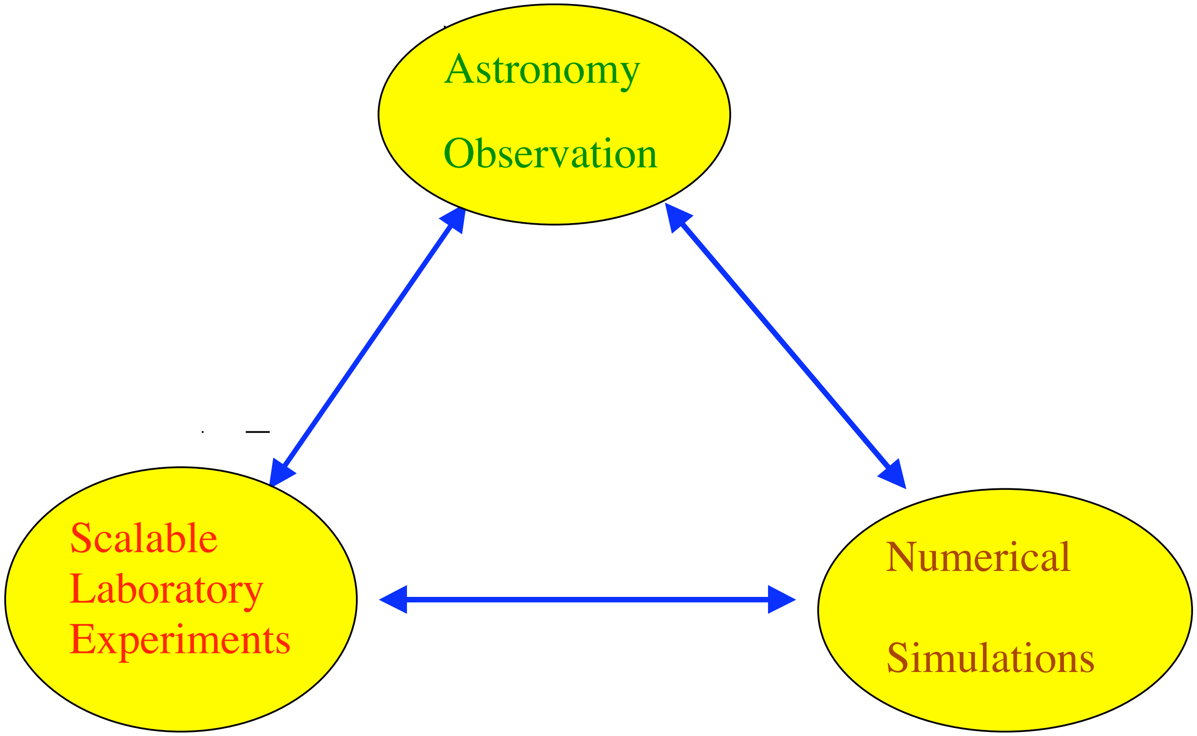
Laboratory Astrophysics with High Energy Density Facilities

Edison Liang, Rice University

Workshop on Science with High Power
Lasers and Pulse Power
Santa Fe, NM, July 2009



Astronomy Observation

Scalable Laboratory Experiments

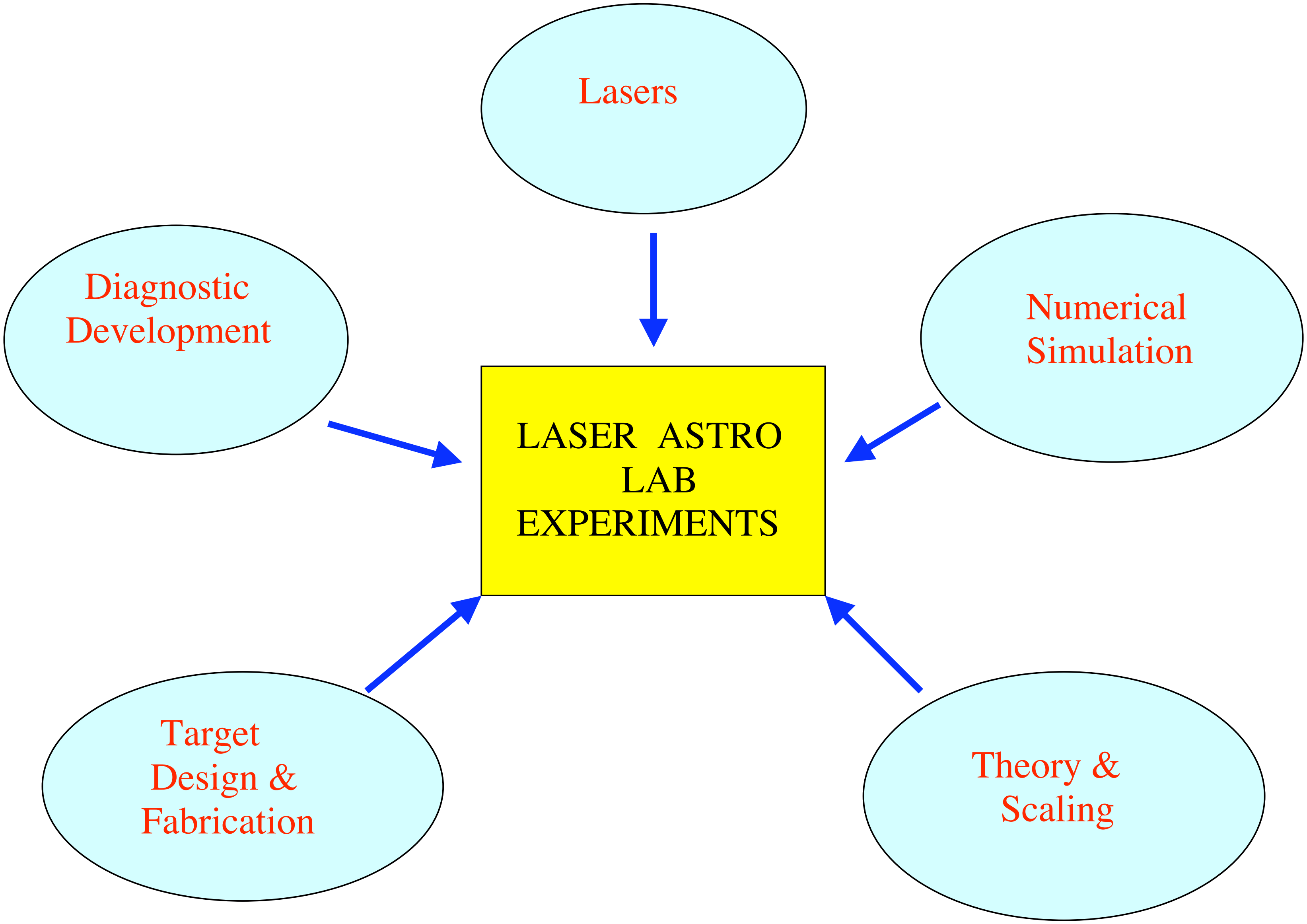
Numerical Simulations

EXAMPLES:

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

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

KEY ELEMENTS FOR FUTURE ADVANCES



Lasers

Diagnostic Development

Numerical Simulation

LASER ASTRO LAB EXPERIMENTS

Target Design & Fabrication

Theory & Scaling

Two Regimes of Laboratory Astrophysics

1. High Density/Collisional Astrophysics:
   Physical Processes: Rad Flow; Hydro; MHD; Atomic and Nuclear Processes; EOS; opacities
   Astro Context: SN;SNR;Accretion Disks; Stellar Physics;Solar flares;Jets and Bubbles; ISM and ICM; Nebulae
2. High Energy/Collisionless Astrophysics:
   Physical Processes: Plasma kinetics; Particle Acceleration; Pairs; Relativistic Outflows and Dissipation; Reconnection; Turbulence Cascade
   Astro Context: GRB;Blazars;Pulsars;PWN;Solar Flares;BH flares; Magnetars;Solar Wind and IPM; Cosmic Rays

Two Approaches to Lab Astrophysics

1. Scalable Experiments in which key Dimensionless parameters are similar for the lab and astro contexts

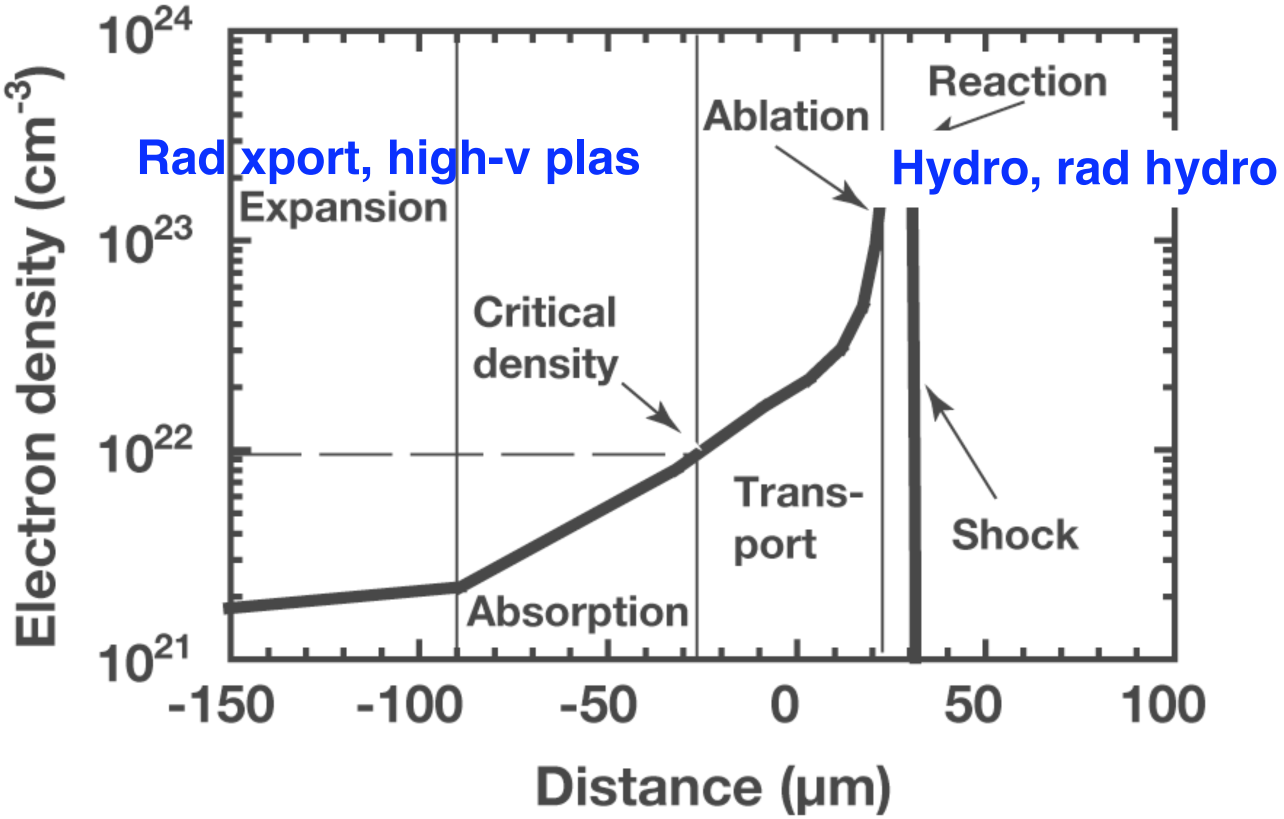
Examples: Ideal hydro Instabilities and Mixing and MHD; Shock dynamics; Hydro and MHD Jets and Interactions

2. Nonscalable experiments that provide meaningful tests and calibration of numerical codes. Once tested, such codes can then be applied to astrophysics simulations with "extrapolated" or parametrized physics.

Examples: Radiative Processes; Transport Processes; Reconnection; Turbulence Cascade; Relativistic and Pair Plasmas

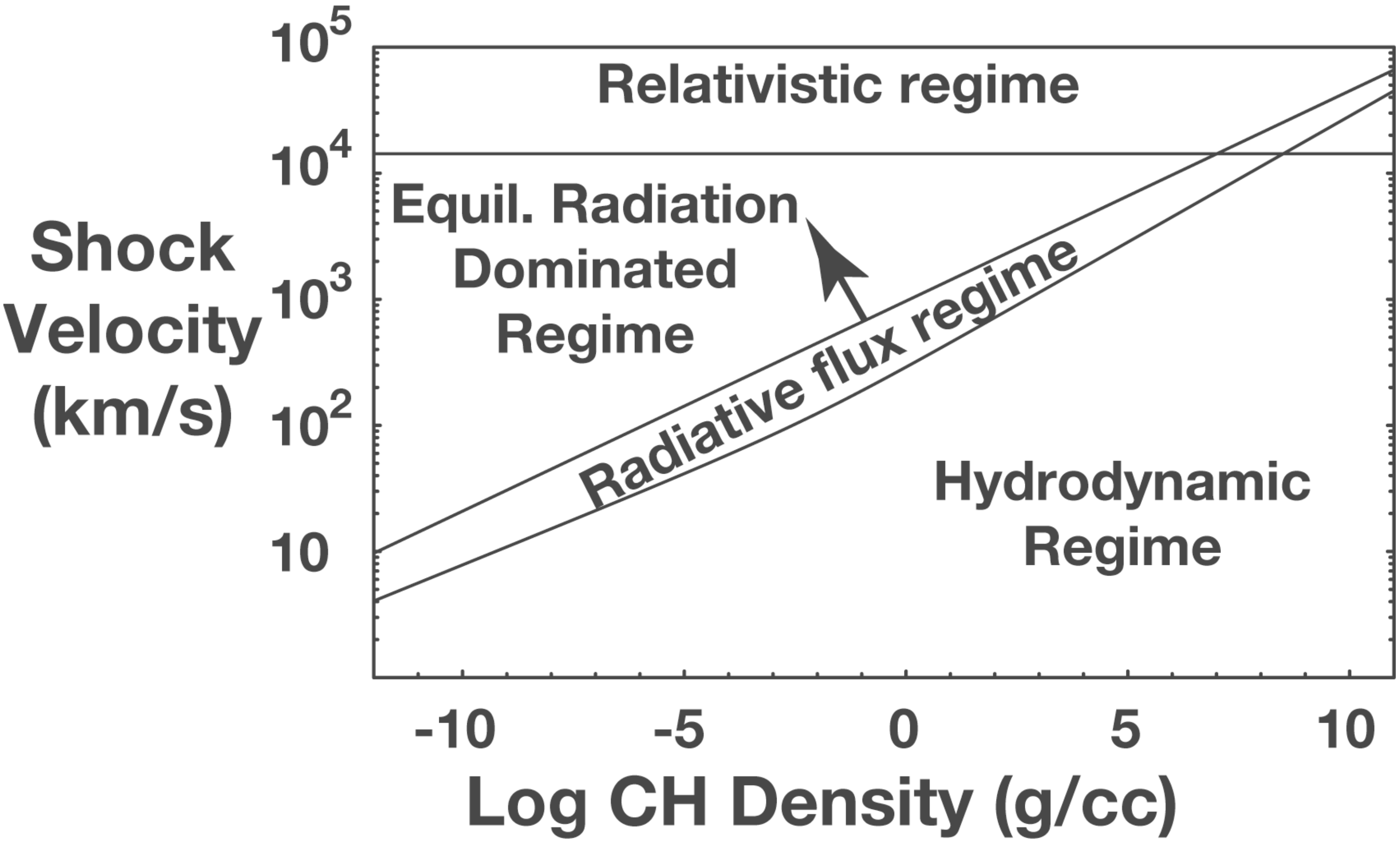
Here is what such lasers do to a material

- The laser is absorbed at less than 1% of solid density



From Drake, *High-Energy-Density Physics*, Springer (2006)

Shock waves establish the regime of an experiment

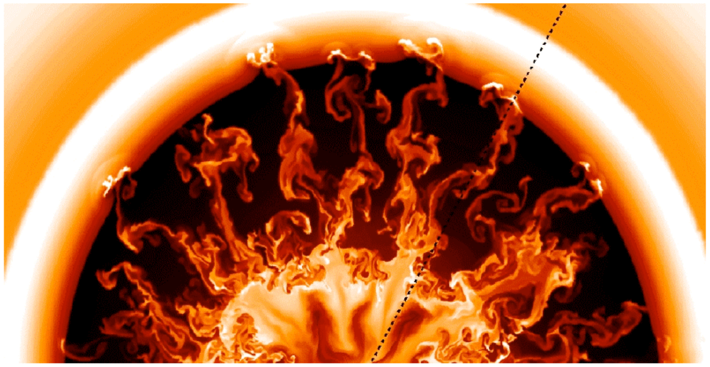


(from Drake et al)

Supernova 1987A motivates scaled hydrodynamic instability experiments

- SN 1987A
  - A core-collapse supernova
  - Early high-Z x-ray lines with large Doppler shifts
  - Early glow from radioactive heating
  - The issue is the post-core-collapse explosive behavior
- In 20 years of simulations
  - Only one (Kifonidis, 2006) makes fast enough high-Z material
  - 3D simulations coupling all the interfaces where initial conditions matter are not feasible
  - NIF experiments can do this
  - Omega experiments address a single interface

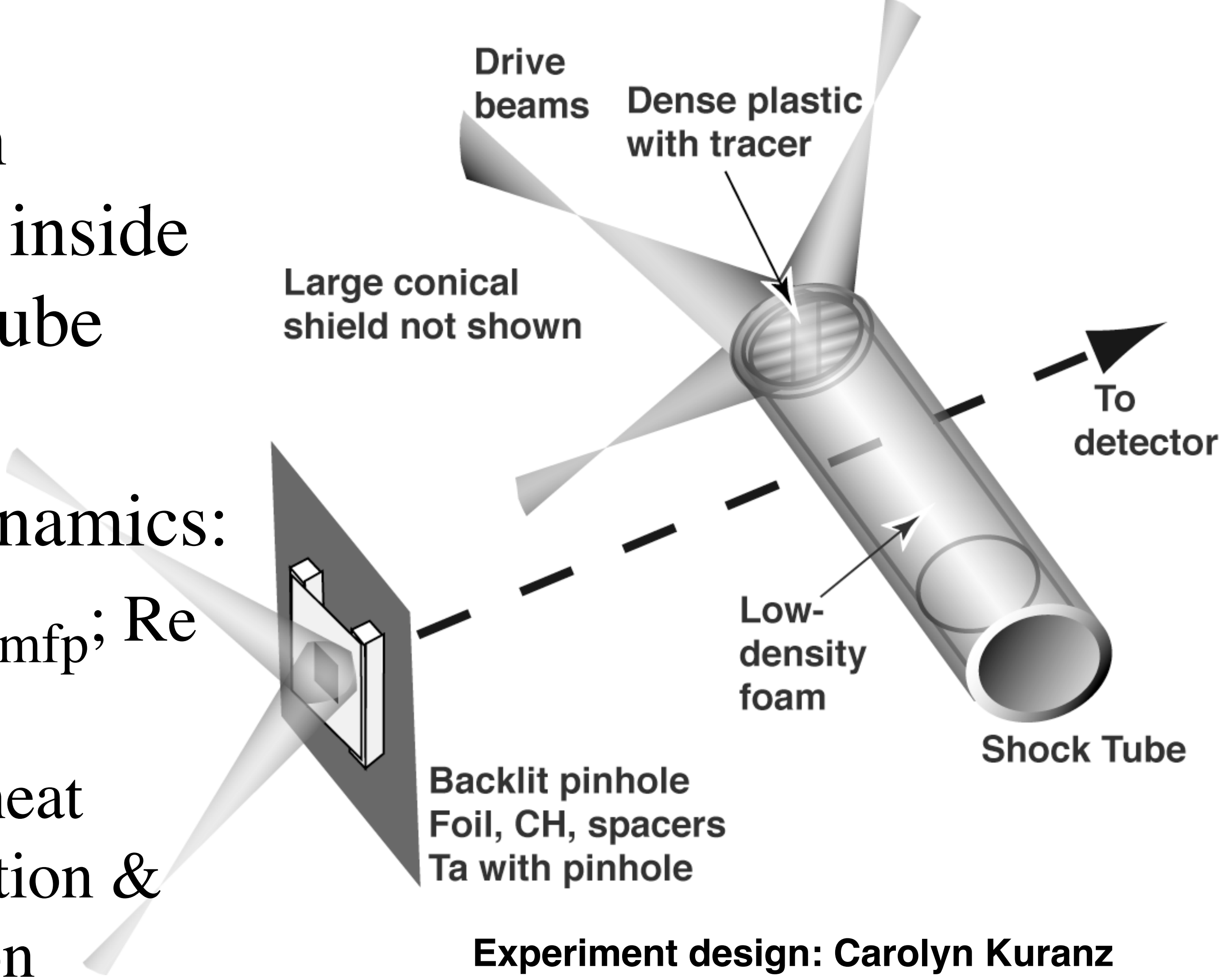
SN1987A, WFPC2, Hubble



Kifonidis, 2003

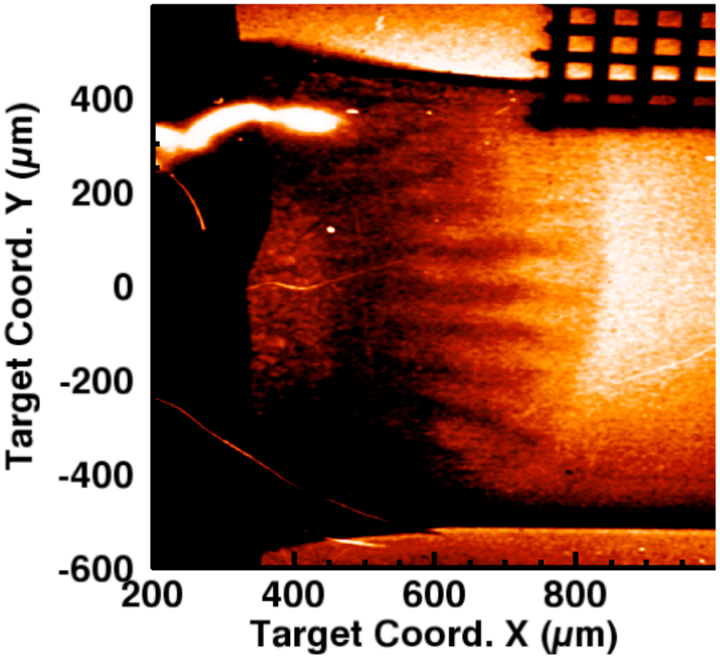
Here is a typical target for supernova hydrodynamics experiments

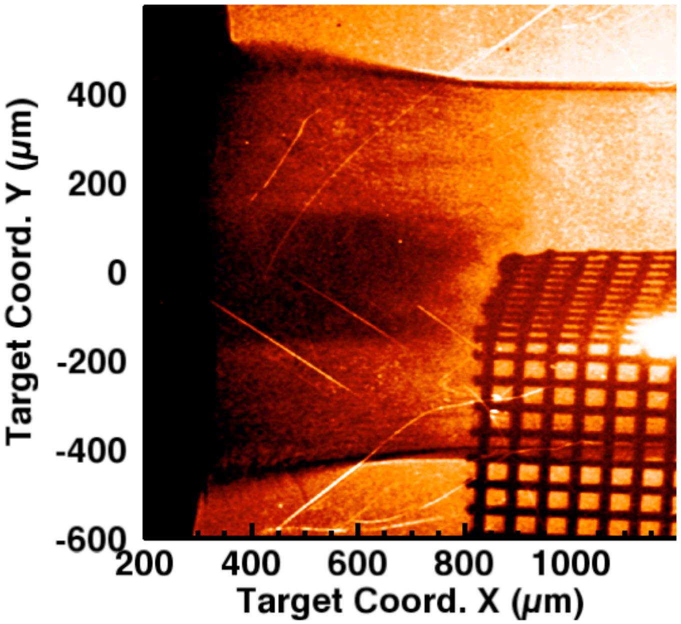
- Precision structure inside a shock tube
- Hydrodynamics:
  - $L \gg \lambda_{mfp}$; $Re > 10^5$;
  - small heat conduction & radiation



Experiment design: Carolyn Kuranz

Obtain data from two orthogonal directions

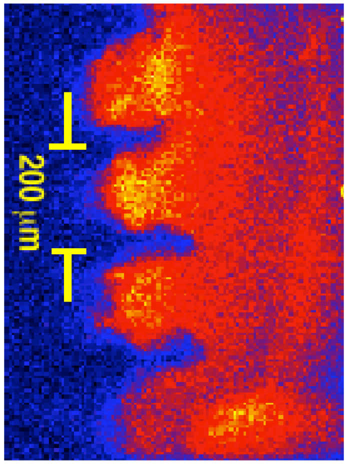




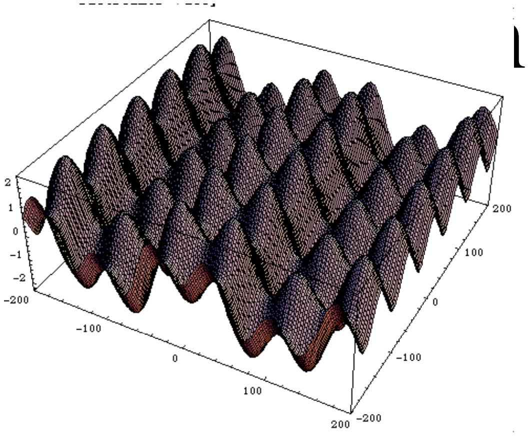
Dec. 06 data at 21 ns

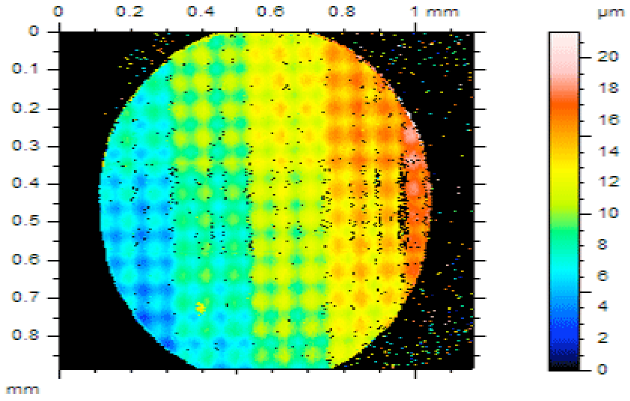
Data and analysis: Carolyn Kuranz

Mid-1990's data



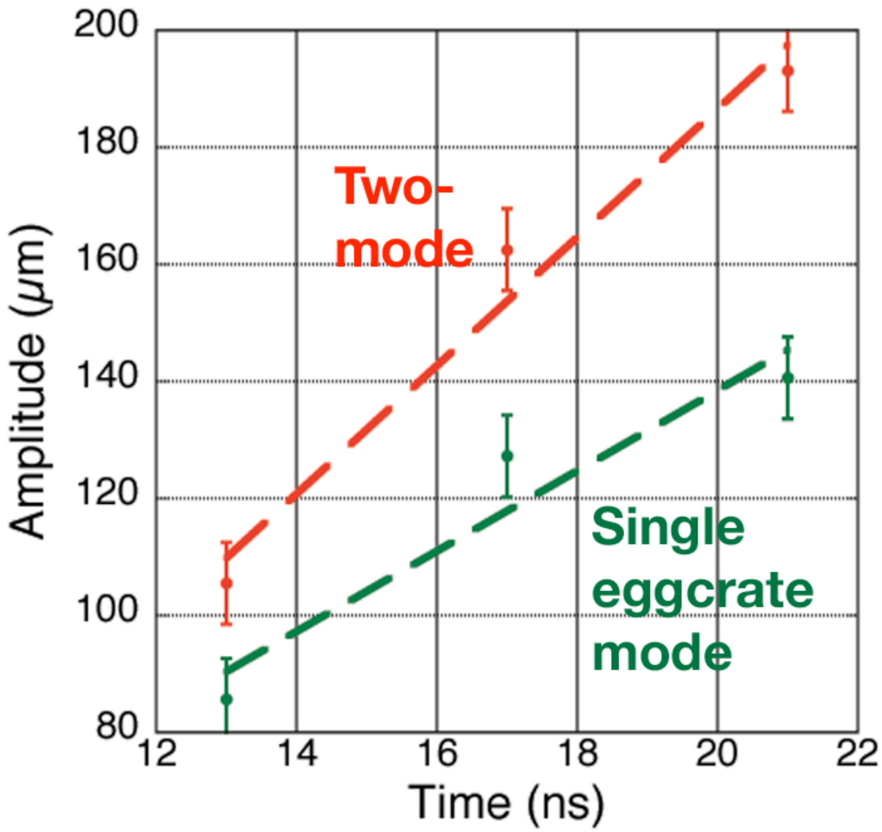
We are now observing the role of complex initial conditions in spike etration





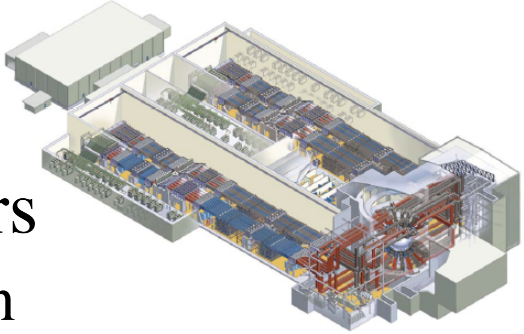
Interferogram of complex surface on component provided by GA (analysis: Kai Ravariere)

Preliminary data on mix layer thickness



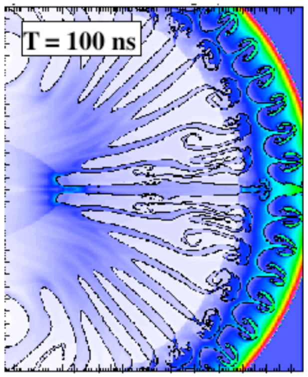
Data and analysis: Carolyn Kuranz

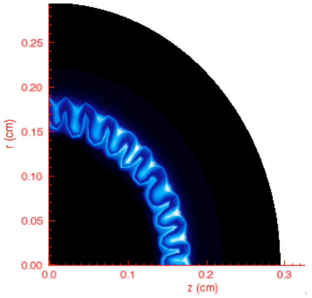
HED hydrodynamics beyond simulation on NIF



National Ignition Facility

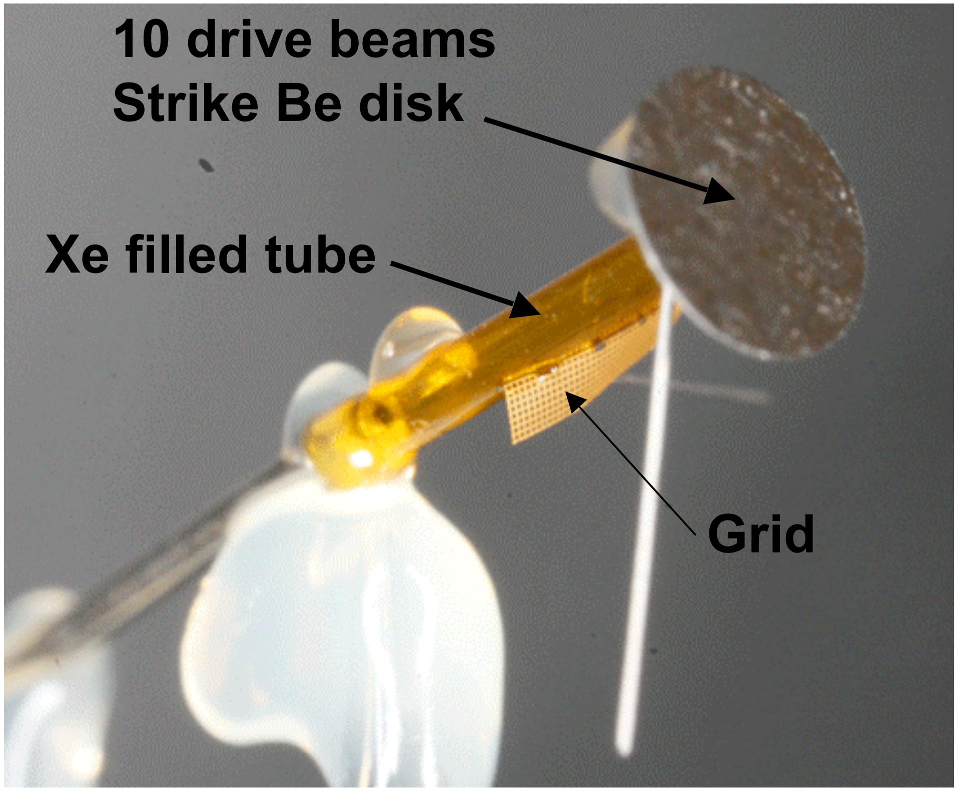
- The unresolved issue in exploding stars
  - The 3D behavior of a diverging explosion
  - With multiple, structured interfaces
- This problem cannot be fully simulated with computers
  - Too big, too complex, high Reynolds number
- NIF can do a very relevant experiment
  - Also can do transition to turbulence
- Preliminary design-related simulations
- At Michigan and LLNL
  - (Grosskopf) (Miles)





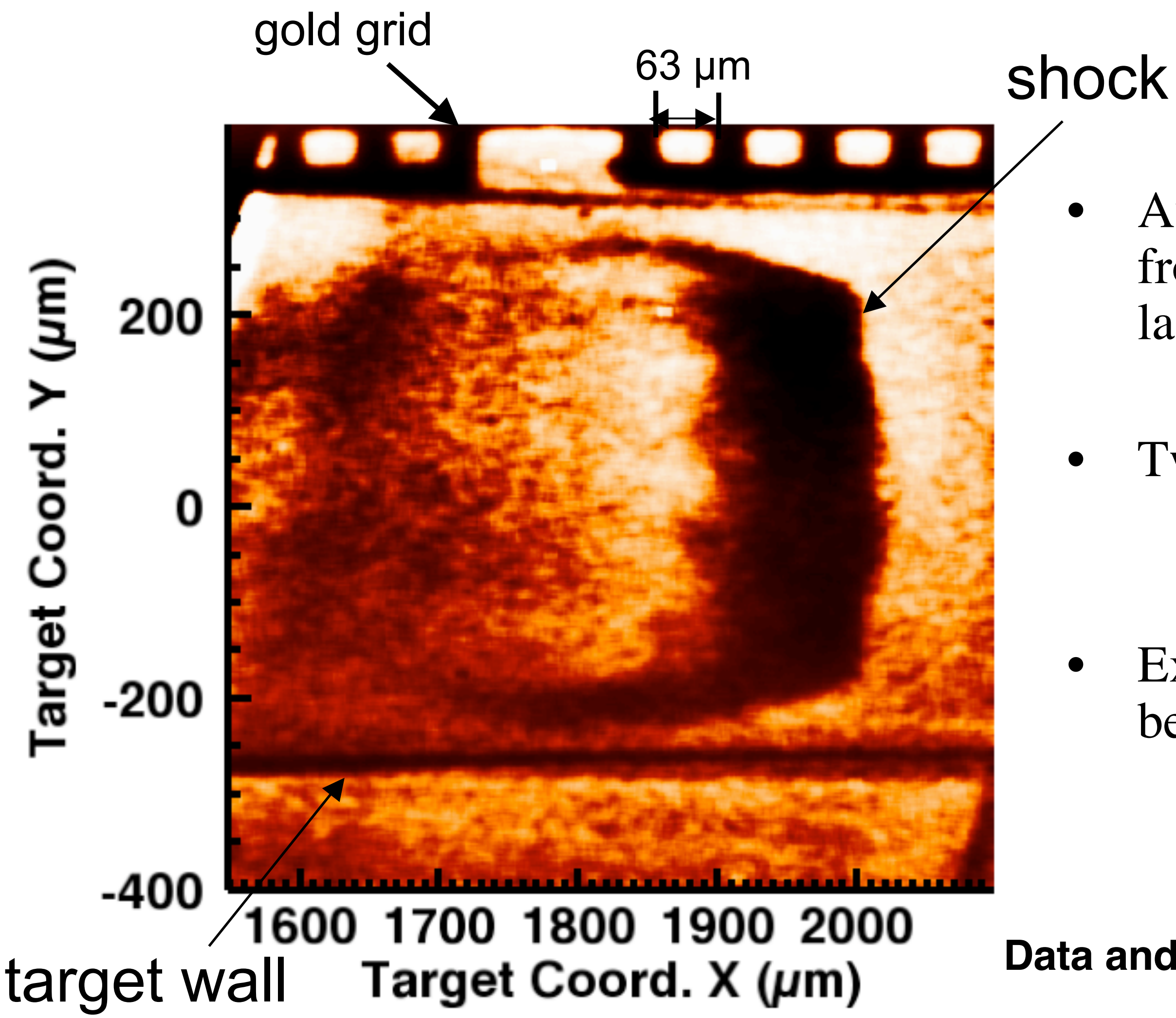
Create and study driven radiative shocks

- Laser beams launch Be piston into Xe or Ar gas at > 100 km/s
- Piston drives a planar shock
- Radiography detects dense xenon
- Gold grid provides spatial fiducial
- Parameters
  - 10^{15} W/cm^2
  - 0.35 μm light
  - 1 ns pulse
  - 600 μm tube dia.



Target: Mike Grosskopf, Donna Marion, Mark Taylor

Sample radiographic images of radiative shocks



Shot 39927

- Average velocity 140 km/sec from t = 0 to 14.6 ns from laser firing
- Two Phys. Plasmas papers
- Exploration of structure will be a next theme

Data and analysis: Amy Reighard

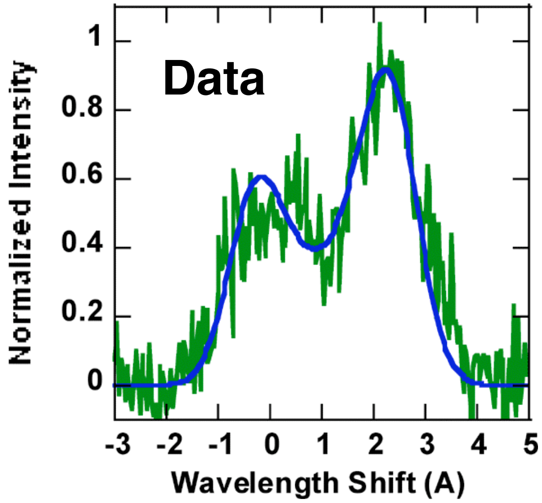
Advanced diagnostics will measure much more

- Thomson scattering
  - Collaboration with Dustin Froula and Siegfreid Glenzer of LLNL

Design: Amy Reighard

Paper in prep. for Phys. Rev. Lett.

Target: Trisha Donajkowski, Mike Grosskopf, Donna Marion

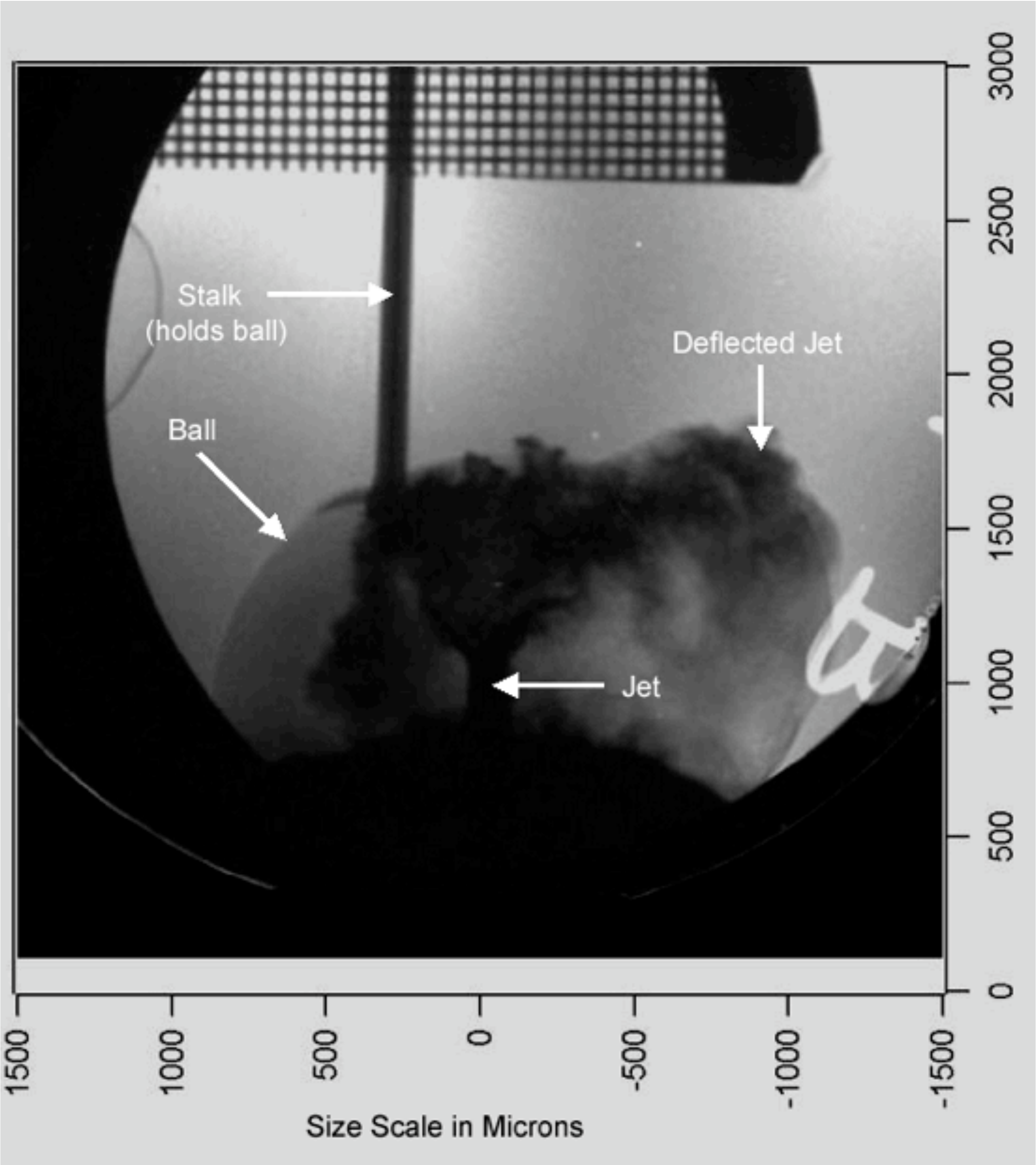


Data and analysis: Amy Reighard
With Dustin Froula

- **Fitting to data gives**
  - **–110 km/s fluid velocity**
  - **–ZT_e = 12 x 300 eV**
  - **–$T_e \leq T_i \leq$ 500 eV**

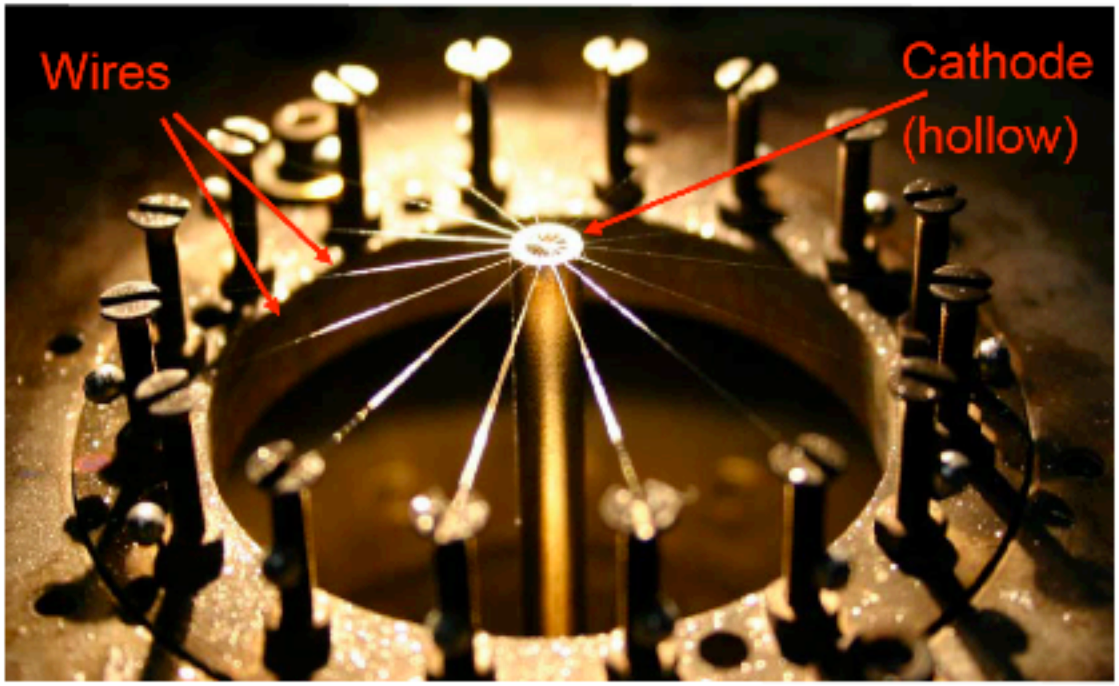
from Drake et al

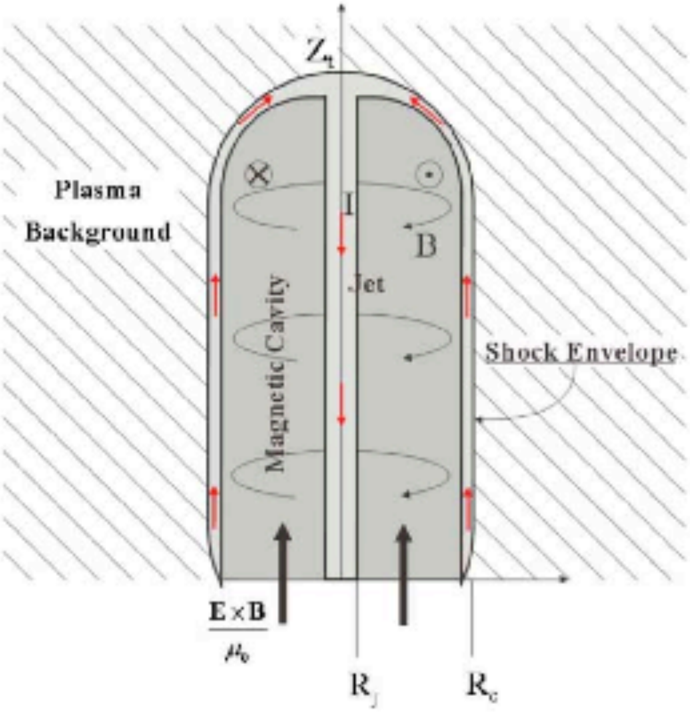
Sample x-ray image of stellar jet deflection experiments
at Omega by
Hartigan, Frank
and collaborators.



Schematic of the experiment

16 x 13μm W wires driven by 1MA, 250ns current pulse (~1 MG toroidal magnetic field)





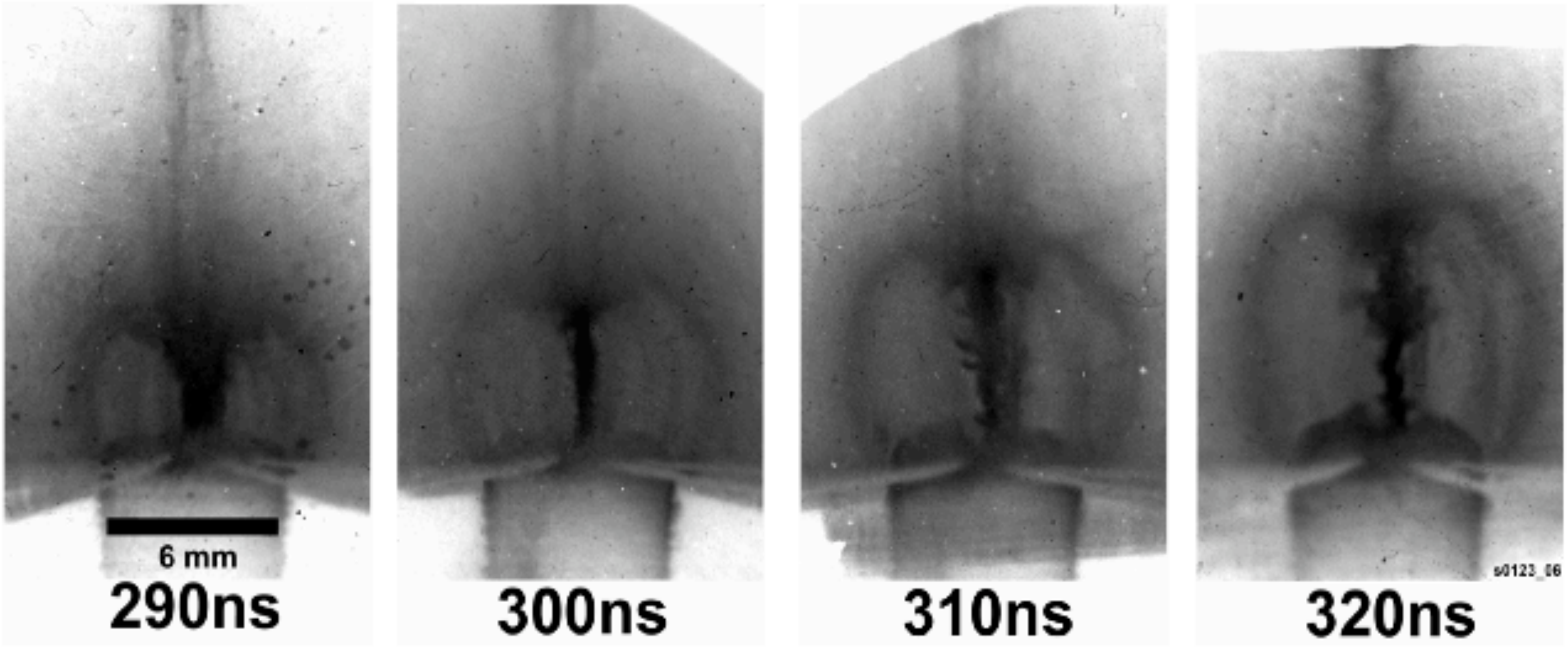
MHD Jets launched by Toroidal Fields from Lebedev’s Group in UK

S.V. Lebedev et al., Rice meeting Mau 14 2007

Evolution of the jet

W

XUV emission

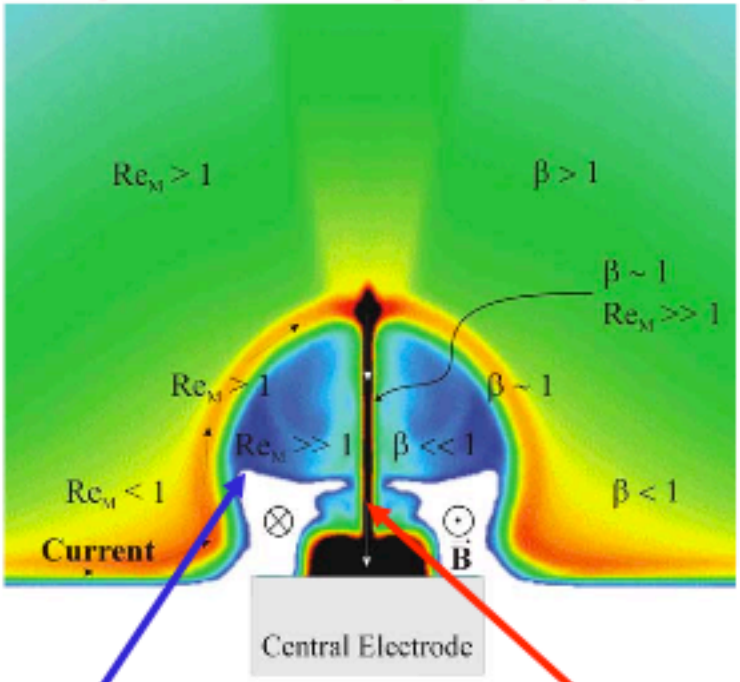


The jet demonstrates MHD instabilities typical for Laboratory plasmas (Z-pinch) but they do not destroy the jet

S.V. Lebedev et al., Rice meeting Mau 14 2007

Structure of the “magnetic tower”

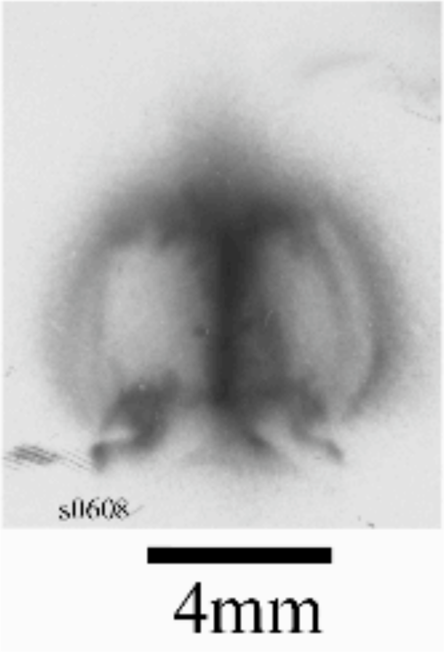
Dimensionless parameters from 2-D MHD simulations



Expanding magnetic bubble

Jet pinched by the toroidal magnetic field

Experiment:
X-ray emission (~300eV)

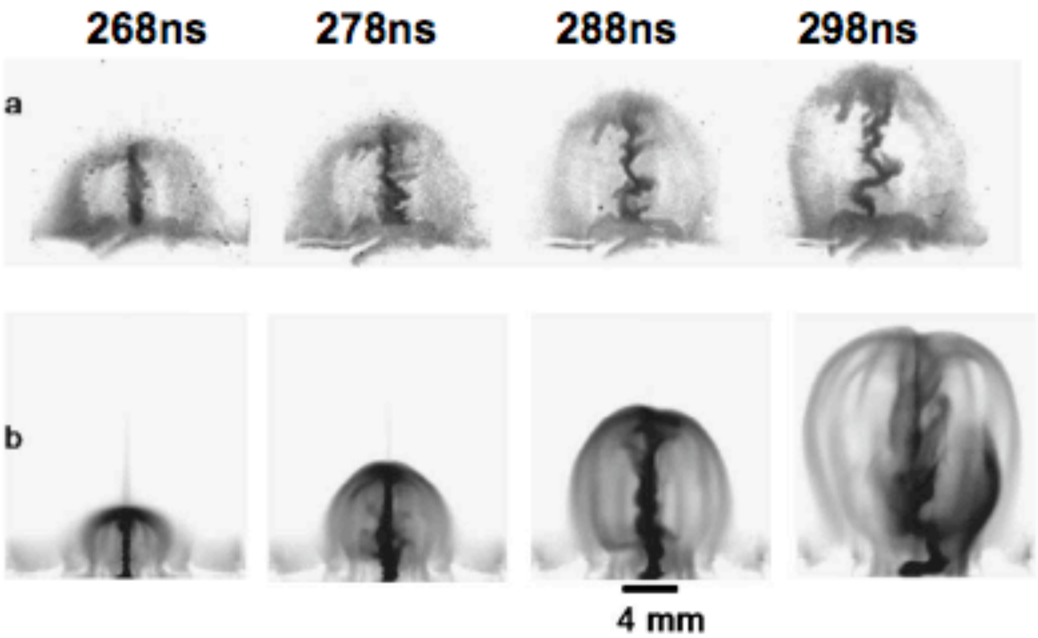


$n_i \sim 10^{19}$ cm^{-3}, T ~ 200 eV
I ~ 1 MA, B ~ 100 T
Re > 10^4 , $\lambda/R \sim 10^{-5}$, Pe > 10
$\beta \sim 1$, $Re_M \sim 50$

S.V. Lebedev et al., Rice meeting Mau 14 2007

Magnetic Tower jets in laboratory experiments

Experiment versus 3-D MHD



Jet driven by the pressure of the toroidal magnetic field

Collimation of the central jet by the hoop stress

Collimation of the magnetic bubble by the ambient medium

Instabilities do not destroy the jet but lead to variability of the flow

Variability of the jet emission

Two temporal scales for outflow variability:

- fast – instability growth time
- slow – bubble growth time

S.V. Lebedev et al., Rice meeting Mau 14 2007

In High Energy Astrophysics, Five Major Questions Posed by WG:

1. What is the role of e+e- pairs in the most energetic phenomena of the universe such as gamma-ray bursts, AGN jets and pulsar wind dynamics?

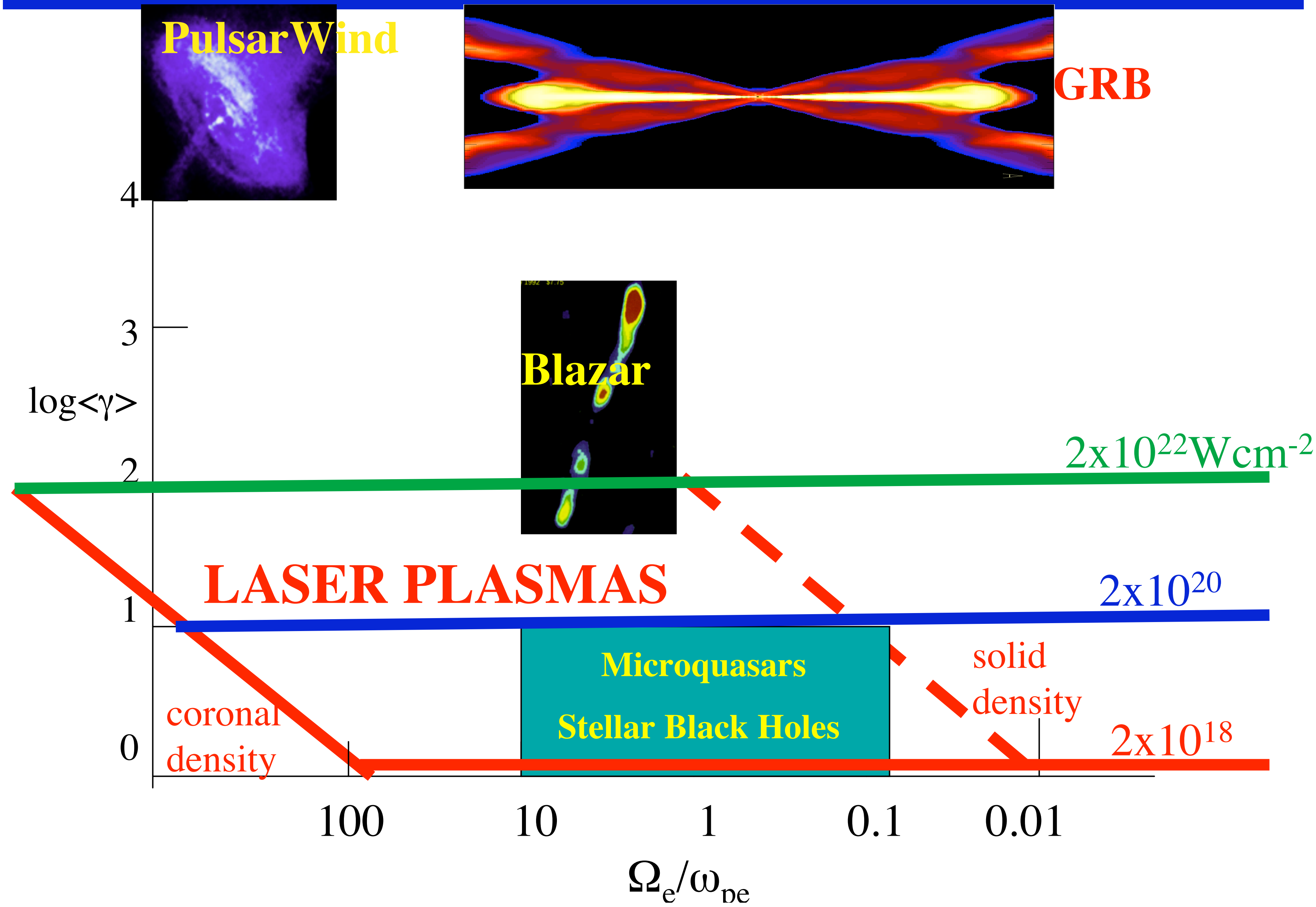
2. Why are astrophysical jets spectacularly collimated over enormous distances?

3. How does tenuous plasma interact with and dissipate ultra-relativistic or electromagnetic-dominated outflows such as pulsar winds and gamma-ray bursts?

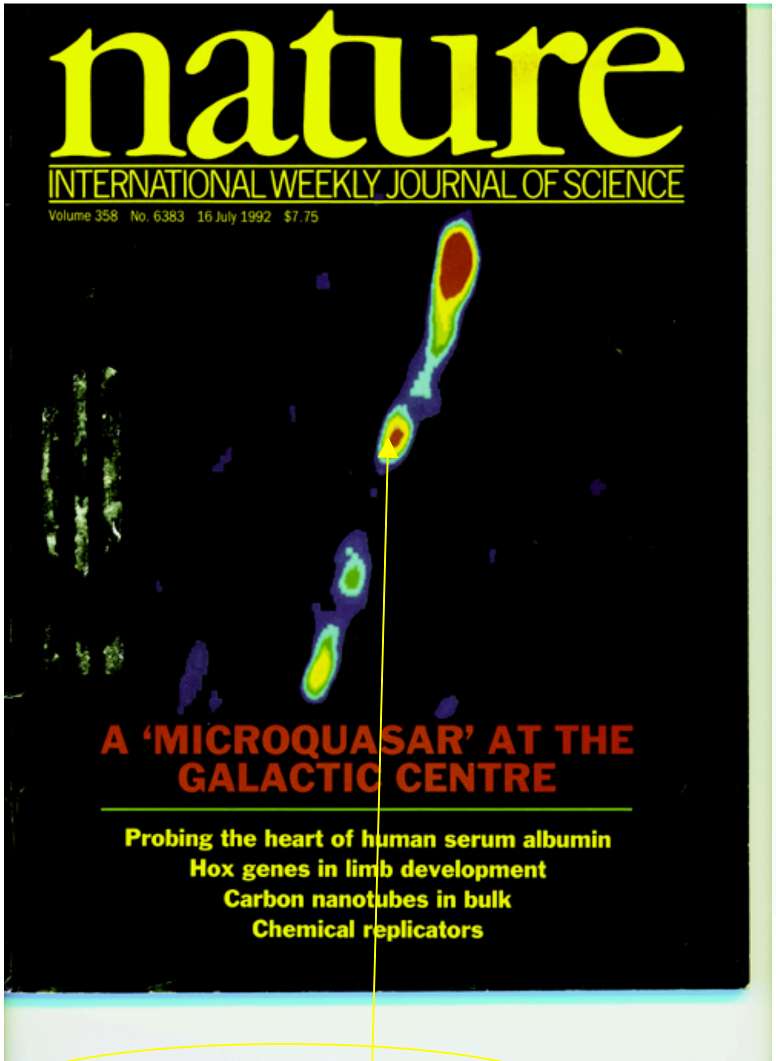
4. How do shock waves produce high energy cosmic rays?

5. How does magnetic turbulence dissipate energy in astrophysical plasmas?

Phase space of laser pair plasmas overlap some relevant high energy astrophysics regimes



relativistic e+e- plasmas are ubiquitous in the universe



nature

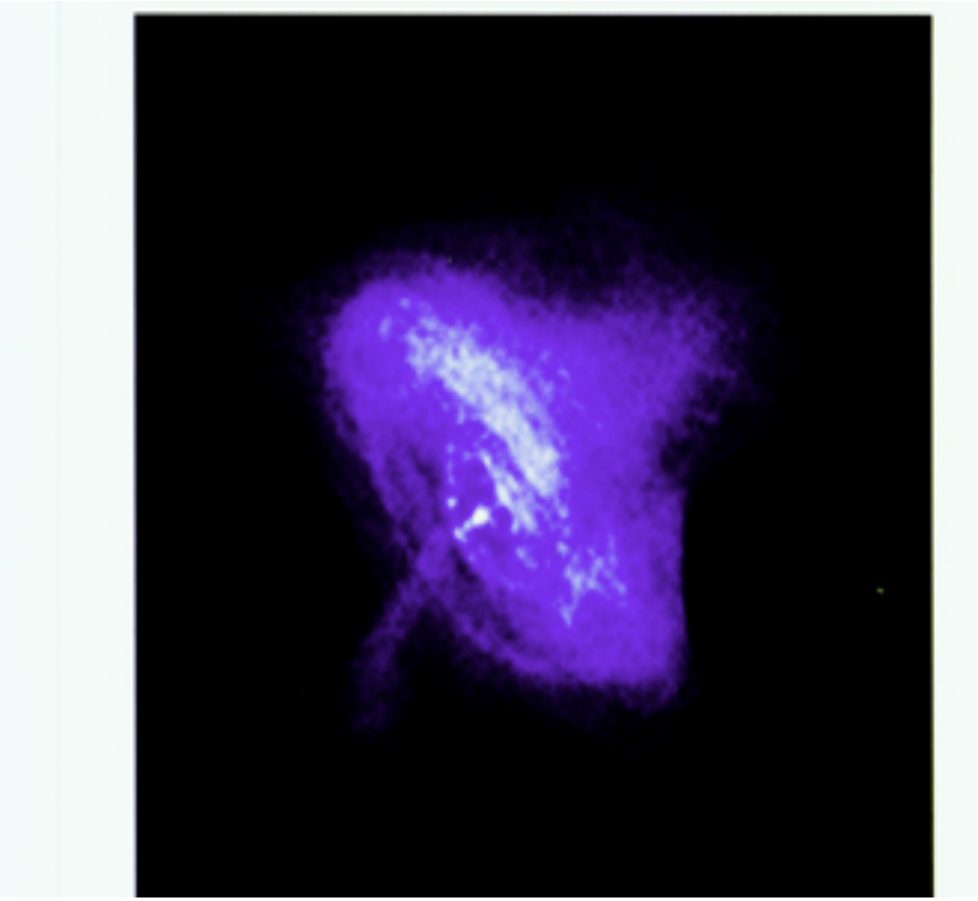
INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

Volume 358 No. 6383 16 July 1992 $7.75

A 'MICROQUASAR' AT THE GALACTIC CENTRE

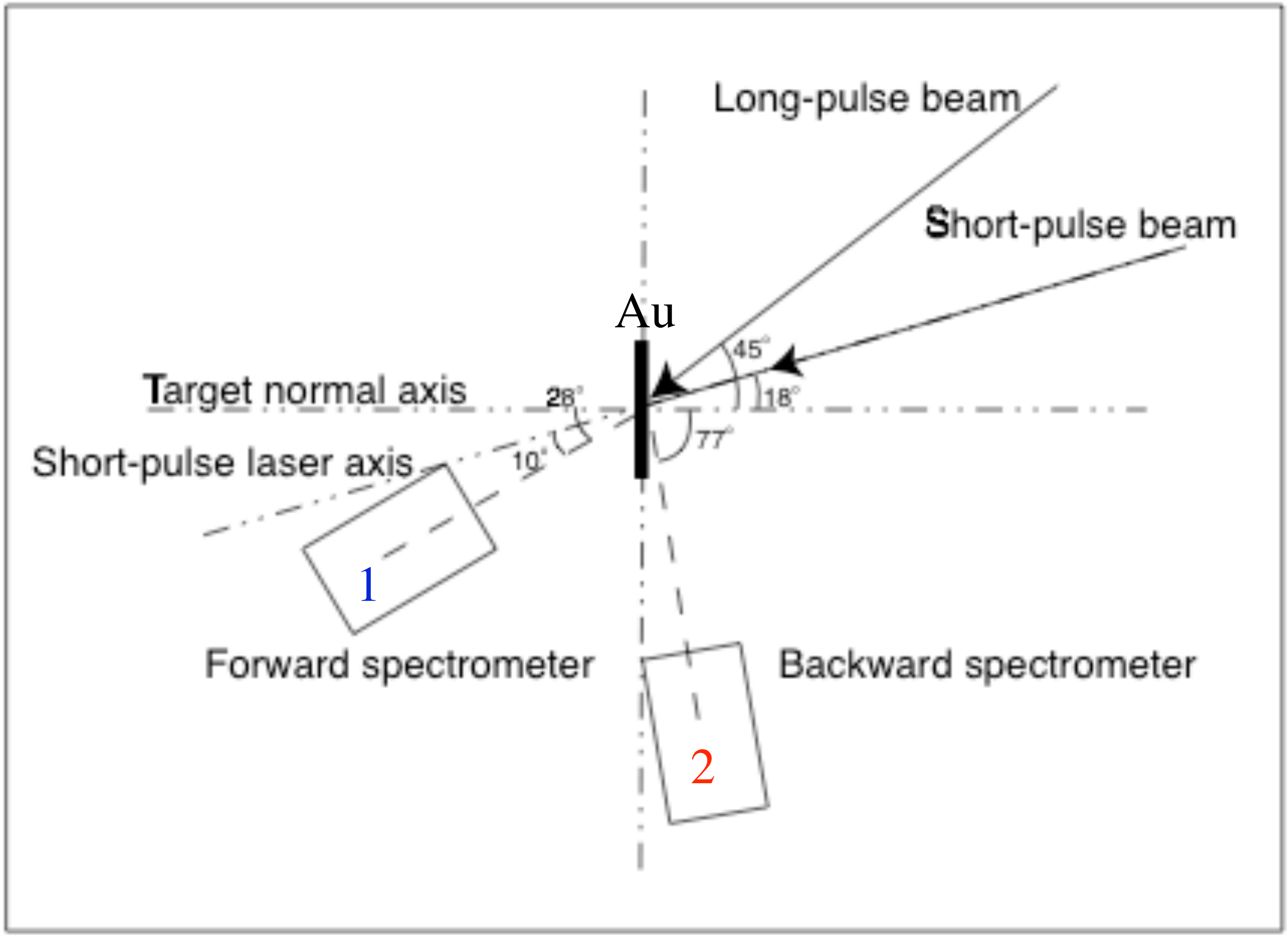
Probing the heart of human serum albumin
Hox genes in limb development
Carbon nanotubes in bulk
Chemical replicators

Thermal MeV pairs

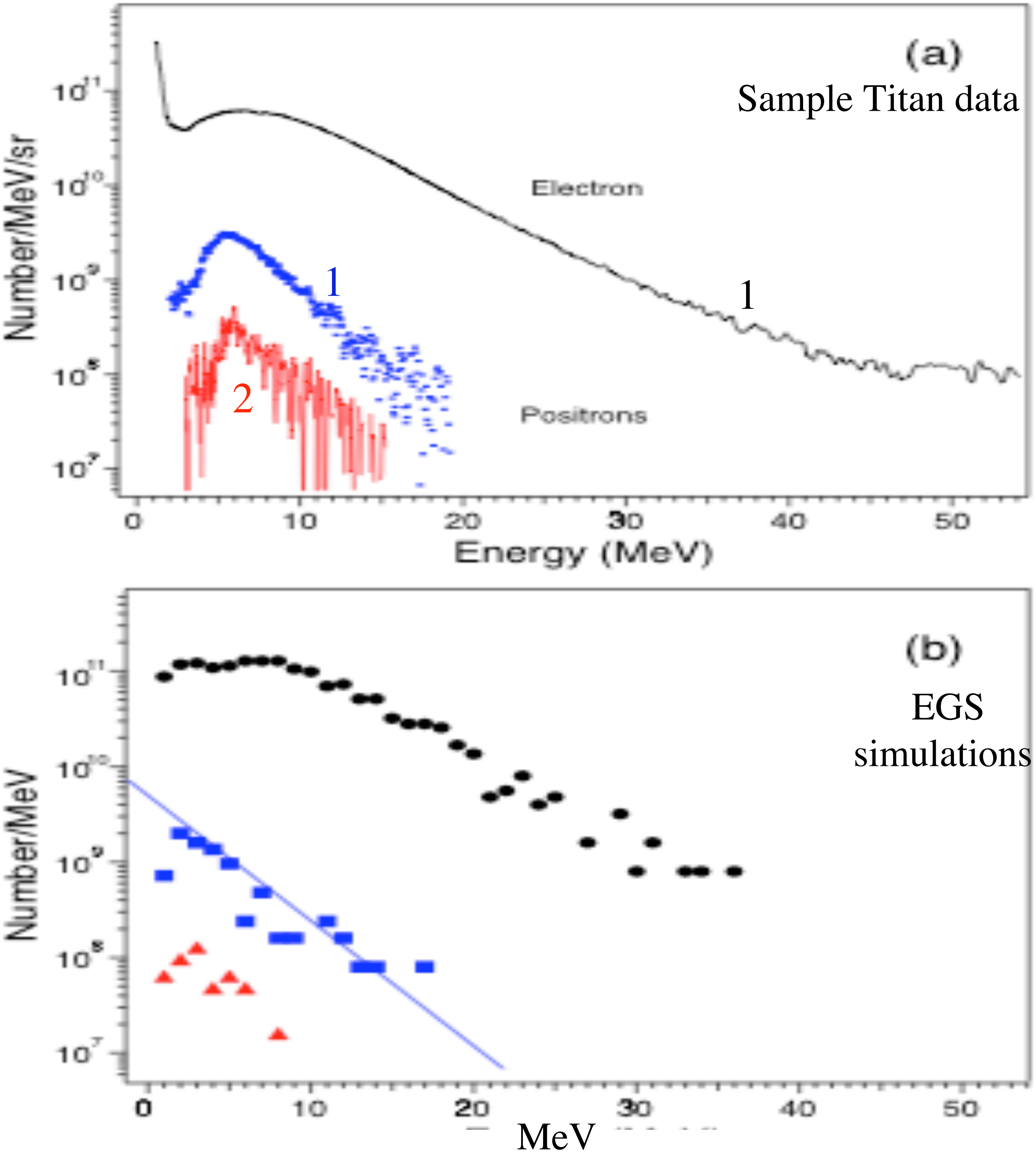


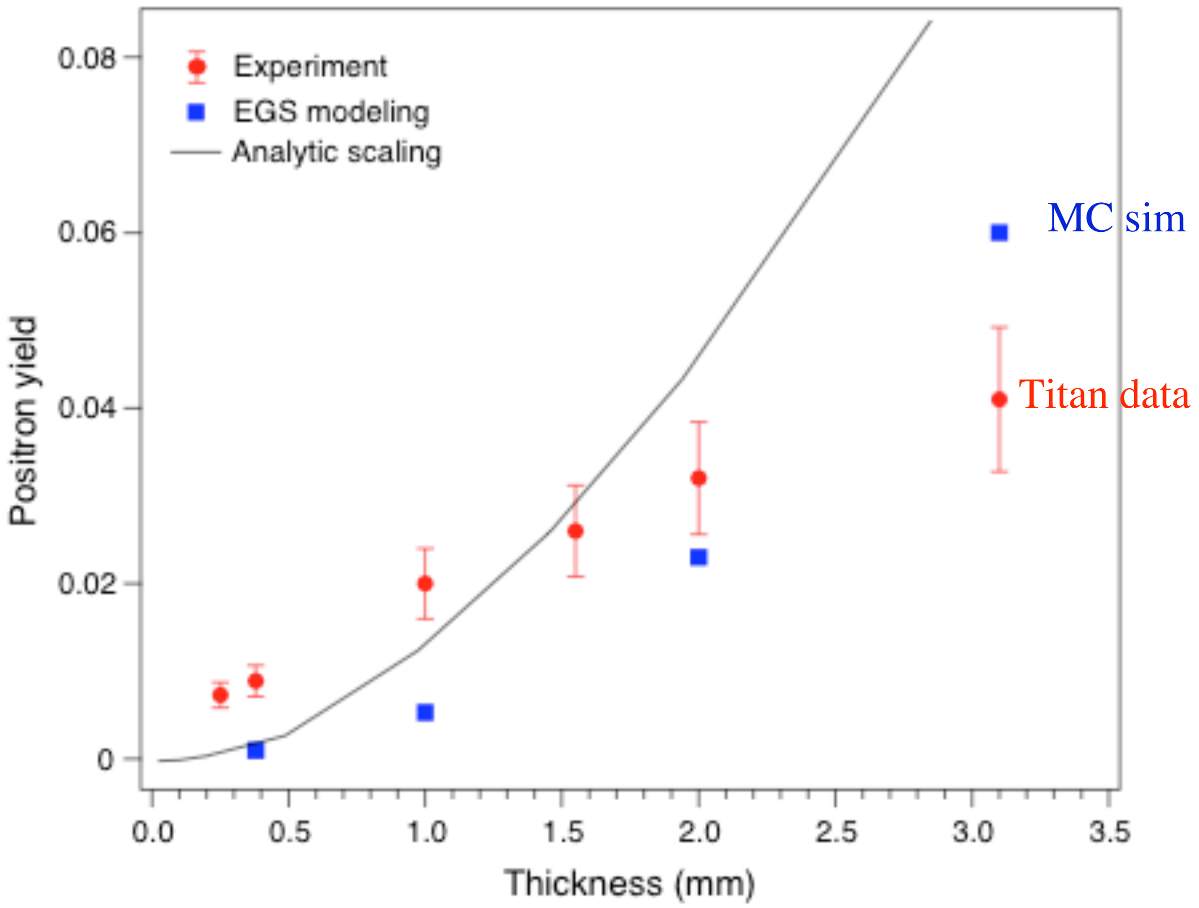
Nonthermal TeV pairs

Laser-produced pair plasmas can be used to study astrophysics



Set-up of Titan Laser Experiments (Chen et al PRL 2009)


(a)
Sample Titan data
Number/MeV/sr
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
Electron
1
1
2
Positrons
0
10
20
30
40
50
Energy (MeV)
(b)
EGS simulations
Number/MeV
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
0
10
20
30
40
50
MeV



e+ yield per emergent hot electron as function of Au thickness. Discrepancy is likely due to angular effects (from Chen et al 2009).

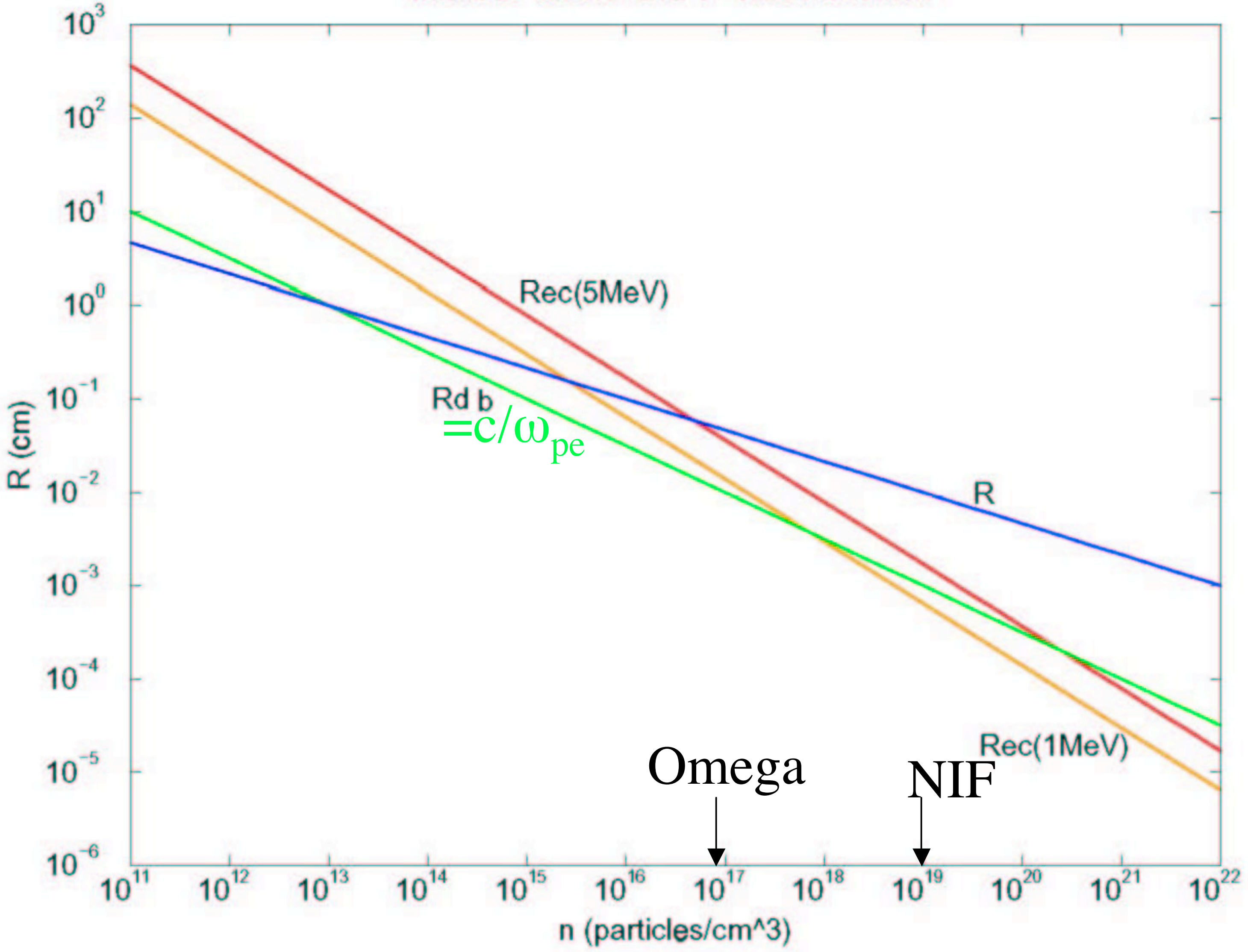
Assuming the conversion ratio of laser energy to hot electrons is ~ 30 %, and the hot electron temperature is ~ 5 -10MeV, the Titan results suggest that the optimized positron yield can reach

~ 10^{12} e+ per kJ of laser energy
with the Au target > 5-6 mm

The in-situ e+ density should reach $>10^{17}/\mathrm{cm}^3$ /kJ of laser energy

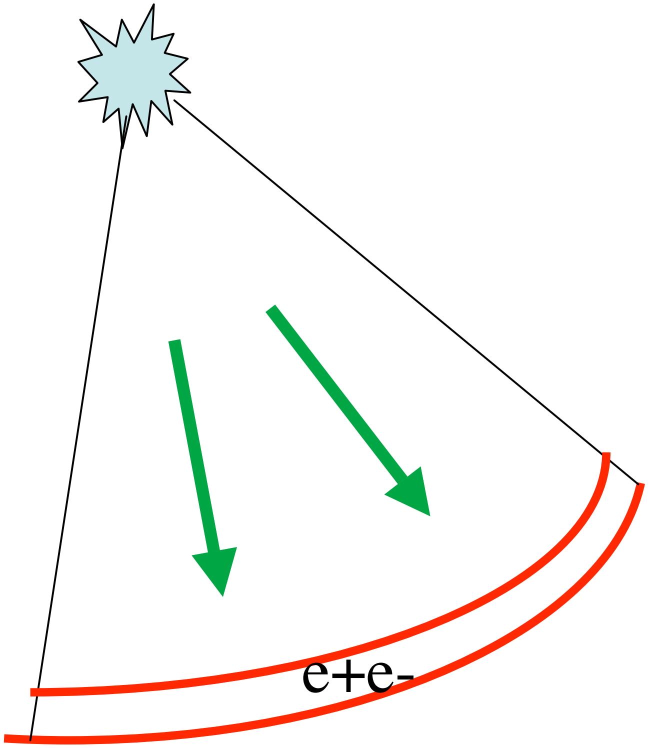
The peak e+ current should reach 10^{24}/sec

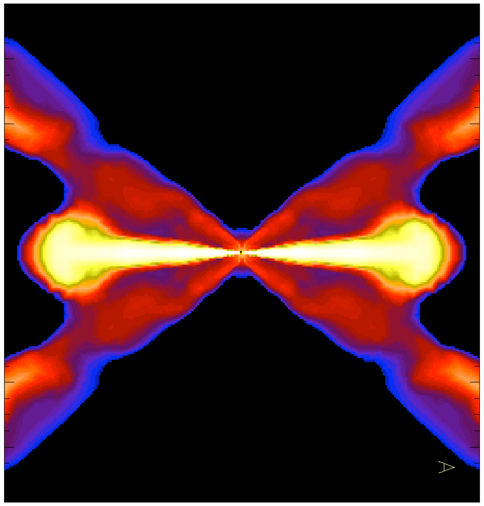
Pair content may reach 80% for thick targets



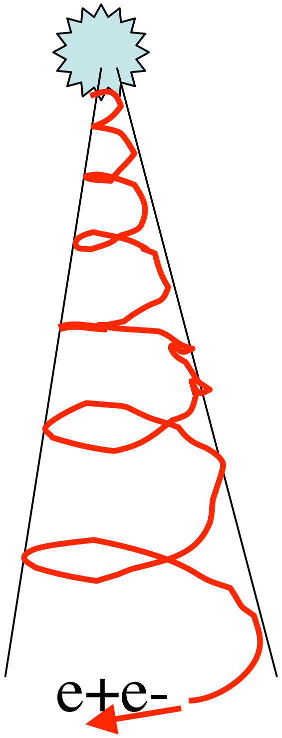
Comparsion of Debye radius and electron gyroradii with fireball radius
Initial B=9.e8G and T=1MeV & 5MeV

Gamma-Ray Bursts: High Γ favors an e+e- plasma outflow?





Woosley & MacFadyen,
A&A. Suppl. 138, 499 (1999)



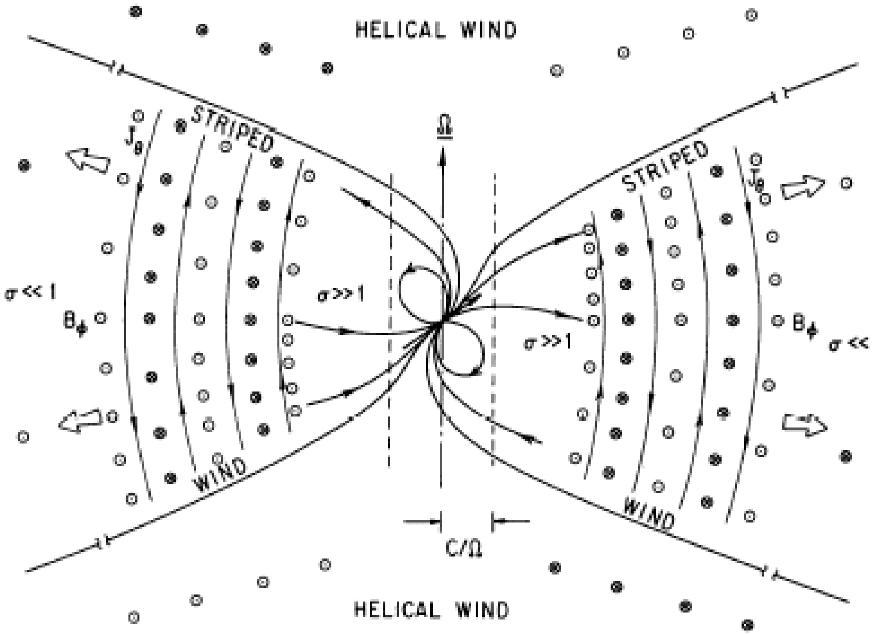
Internal shocks:
Hydrodynamic

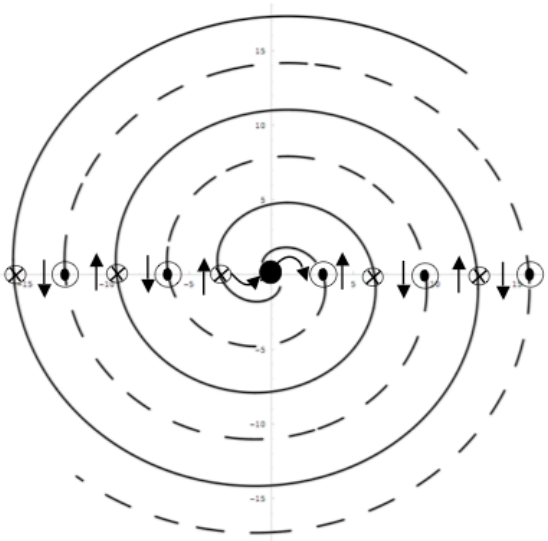
What is primary energy source?
How are the e+e- accelerated?
How do they radiate?

Poynting flux:
Electro-
magnetic

Pulsae Stripe Wind Dissipation

If wrinkled current dissipates, striped field dissipates, magnetic energy coverts to flow kinetic energy, “heat” & high frequency radiation, strong waves - partition?



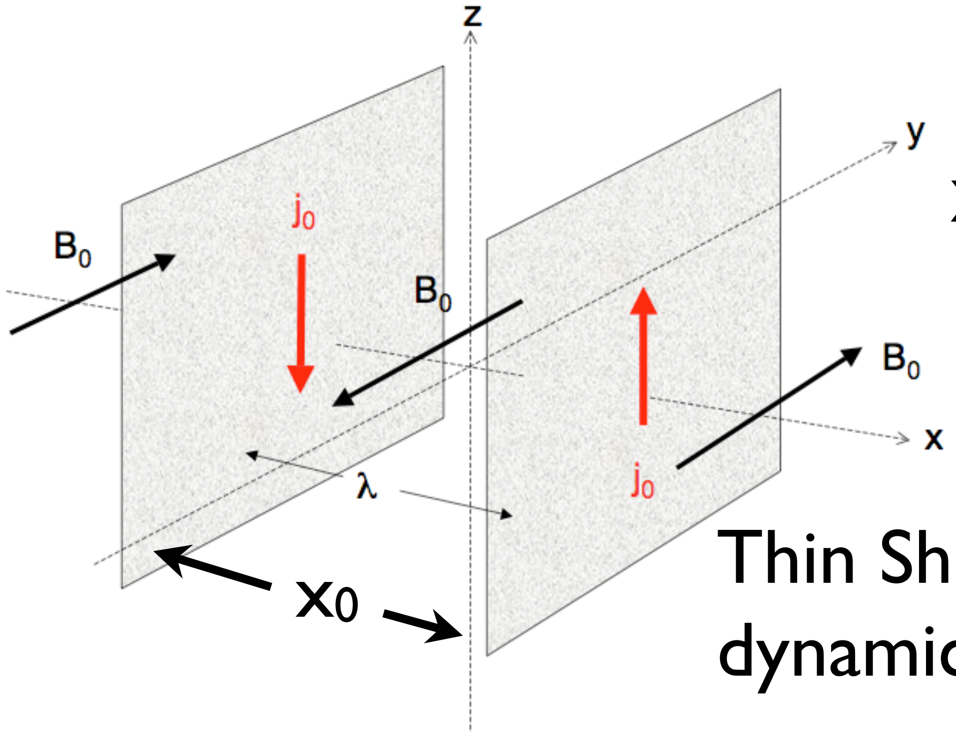


Sheet Dissipation: Tearing of **<u>one</u>** locally ~ plane sheet? (Coroniti; too slow? - Kirk & co.)

Cause: Current starvation? (everybody)

sheet → strong waves? - Melatos-vacuum)

Sheets Interact - Two Stream (Weibel-like) instability



$x_0 = R_L << r$

Thin Sheet ($kr_L<<1$)
dynamics as if each sheet is
unmagnetized
although intersheet
medium MHD $(B^2 \gg 4\pi\rho_0 c^2)$

$$\langle f(x_n)\rangle = \frac{1}{2}[f(x_n^{(+)}) + f(x_n^{(-)})]$$

$$mc\Sigma_b \frac{D(\gamma_b\beta_b)}{Dt} = q\Sigma_b(\langle E\rangle + \beta_b \times \langle B\rangle) = q\Sigma_b(\langle \delta E\rangle + \beta_b \times \langle \delta B\rangle),\ \langle B_0\rangle = 0 \quad 1$$

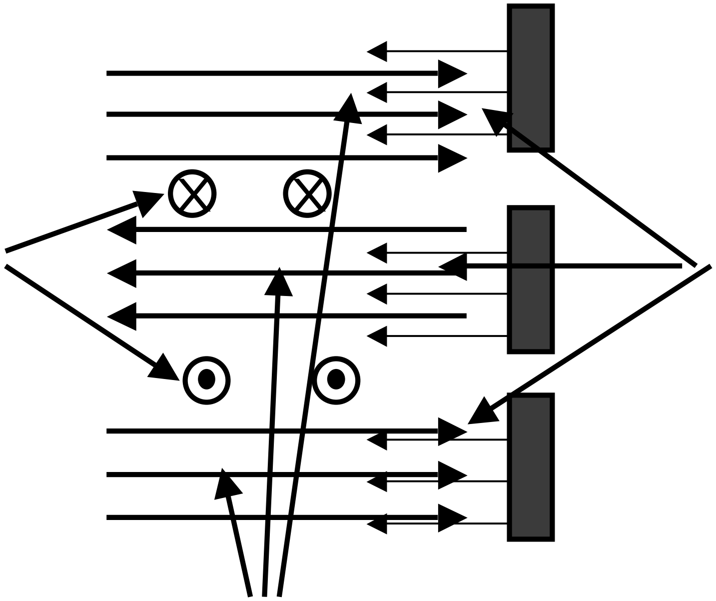
Possible Experiments

Computational: 3D PIC, must be MHD between sheets (frozen-in pairs)
resolve current layer: Larmor and c/ω_p scales of beam particles
could use rectangular geometry

Lab Experiment?

Use laser on dense slab to launch relativistic electron-positron plasma
onto field lines of reversed B (RFP?)
Launch beams into field reversal region?

$$R_m = R_L \left(\frac{q\Phi}{2 m_b c^2 \beta_b \gamma_b} \right)^2$$



Charged particle beam currents

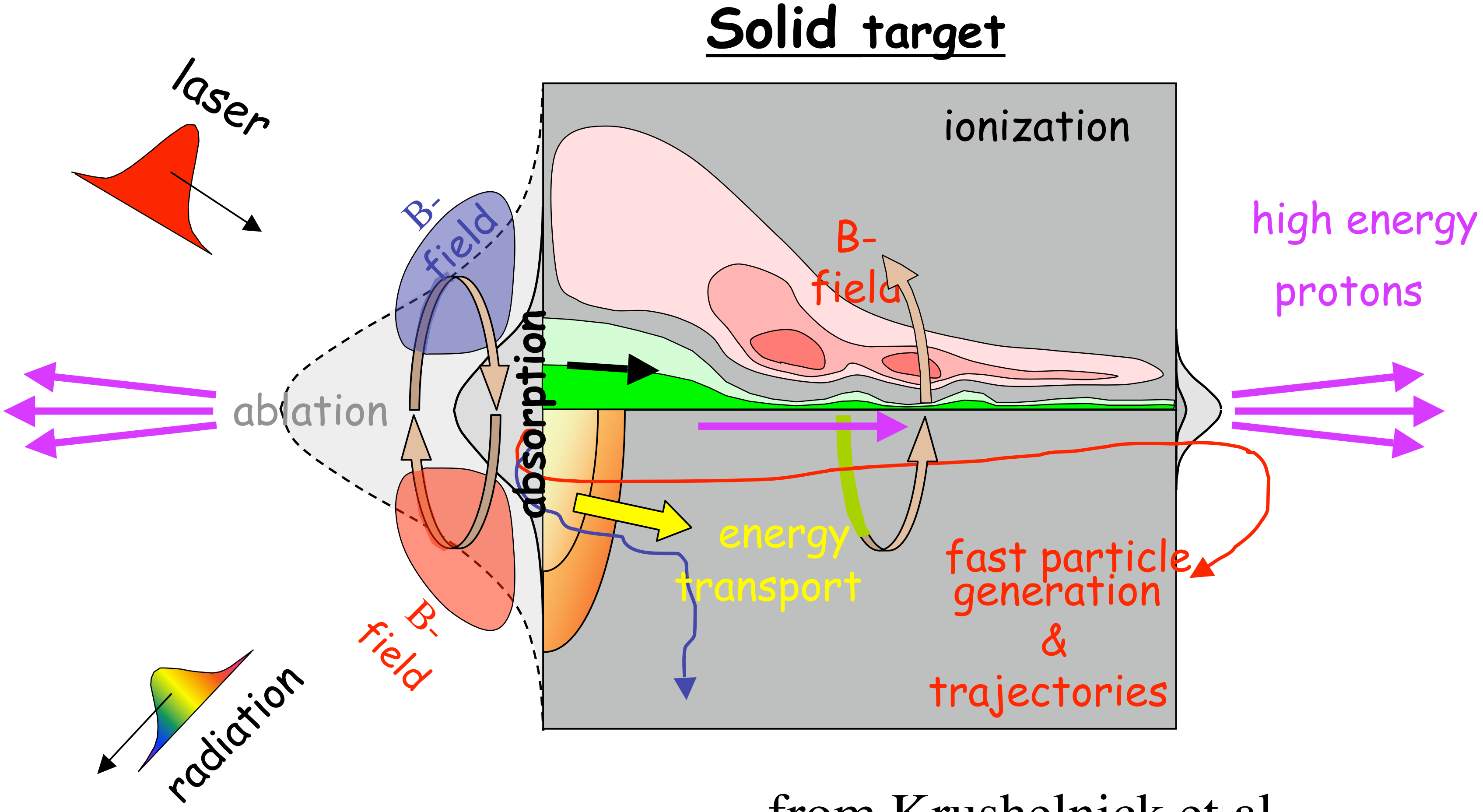
Laser generated MHD electron-positron plasma

Strong Background B

Perp E to give cross field plasma flow?

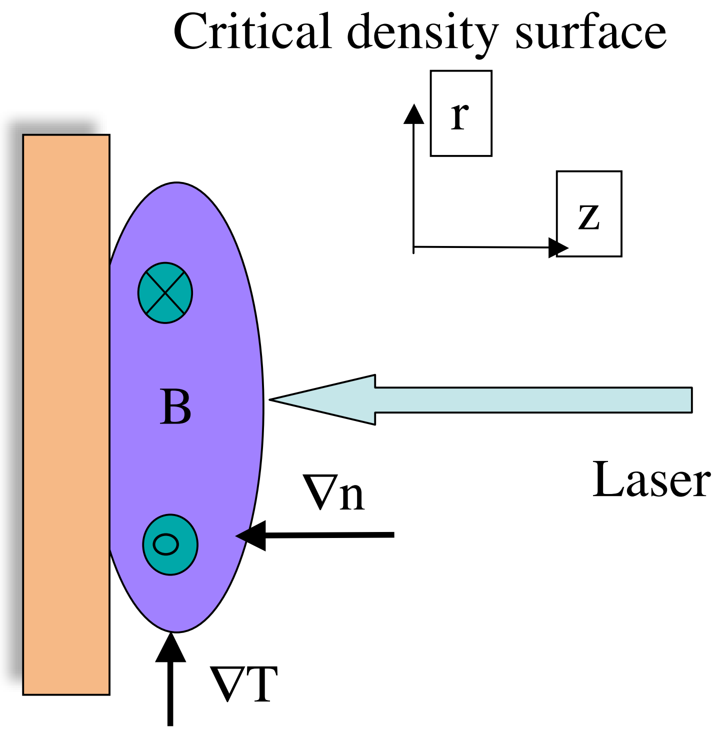
Expt improves on simulation?

Short pulse laser plasma interactions (solid targets) can generate ultra-strong fields > 10^9 gauss



from Krushelnick et al

Mechanisms of magnetic field generation in intense laser plasma interactions



1. Non parallel temperature and density gradients.

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

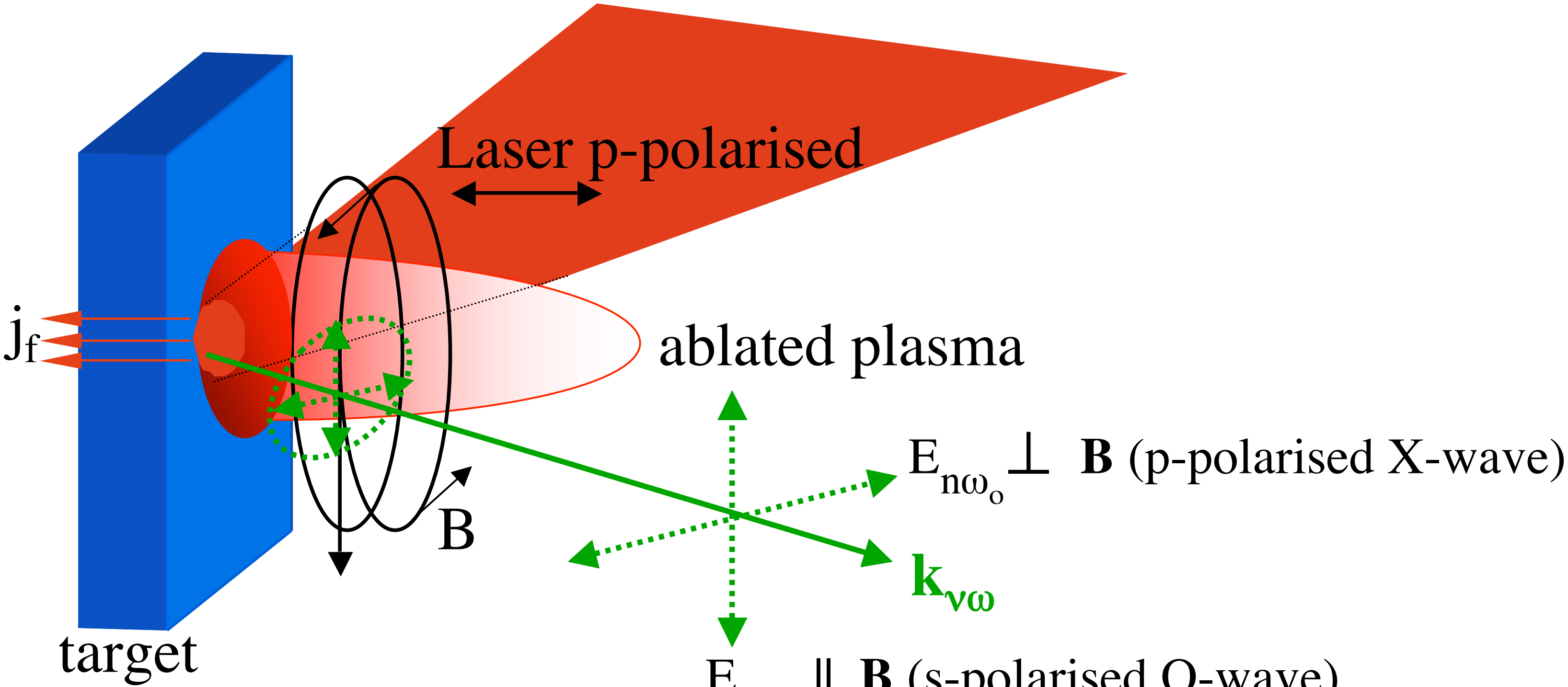
$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \left(\frac{\nabla p_e}{n_e e}\right) = \frac{k_e \nabla T_e \times \nabla n_e}{n_e e}$$

2. Current due to fast electrons generated during the interaction (Weibel instability)

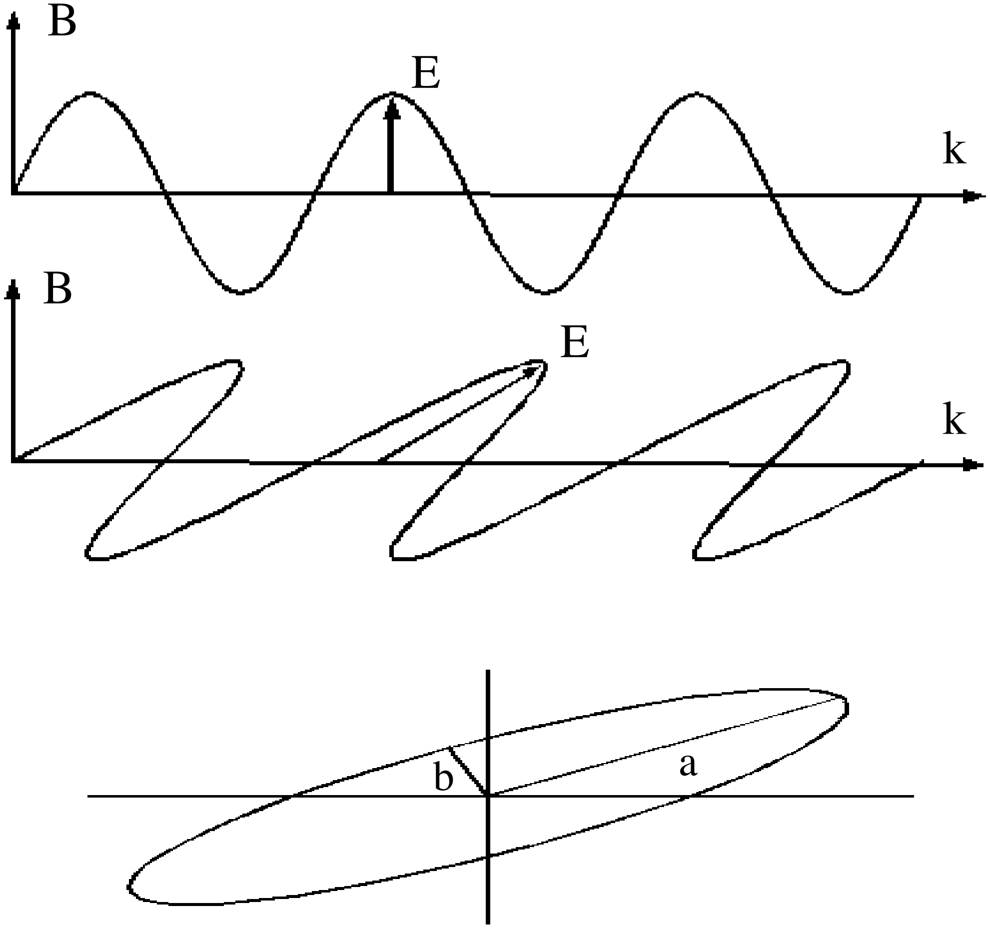
3. DC currents generated by the spatial and temporal variation of the ponderomotive force of the incident laser pulse $\mathbf{B}_{\mathrm{dc}} \sim \mathbf{B}_{\mathrm{laser}}$*

* *R.N.Sudan, Phys. Rev. Lett., **70,** 3075 (1993)*

Experimental schematic



EM wave propagation in magnetized plasma



- Ordinary Wave (O)

$$\mu_O^2 = 1 - \frac{\omega_{pe}^2}{\omega_0^2}$$

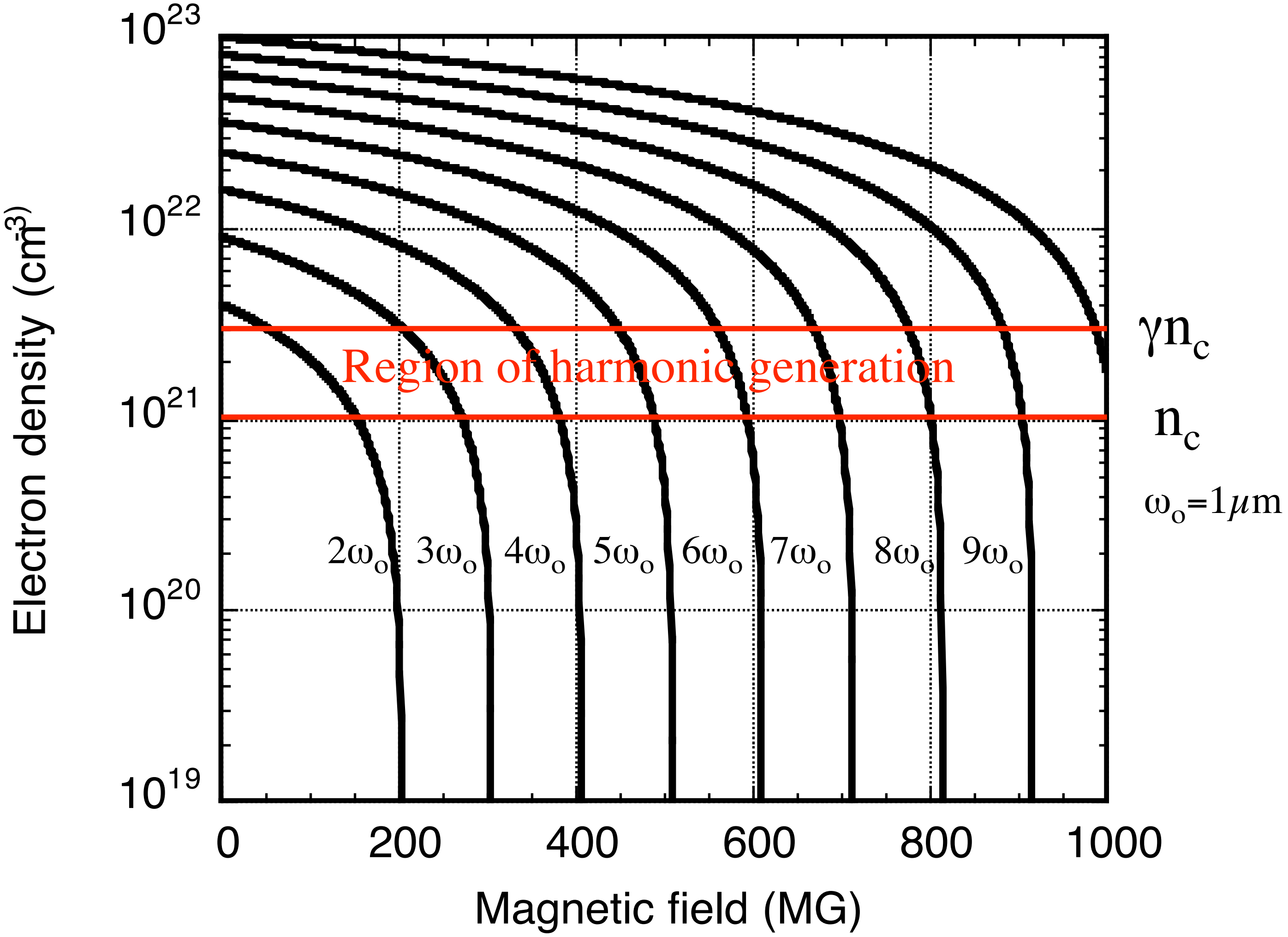
- Extraordinary Wave (X)

$$\mu_X^2 = 1 - \frac{\frac{\omega_{pe}^2}{\omega_0^2}\left(1 - \frac{\omega_{pe}^2}{\omega_0^2}\right)}{1 - \frac{\omega_{pe}^2}{\omega_0^2} - \frac{\omega_{ce}^2}{\omega_0^2}}$$

- Ellipticity

$$\frac{b}{a} = 2.49 \text{ x } 10^{-21} \lambda_{\mu m}^3 \int n B_{MG}^2 dl$$

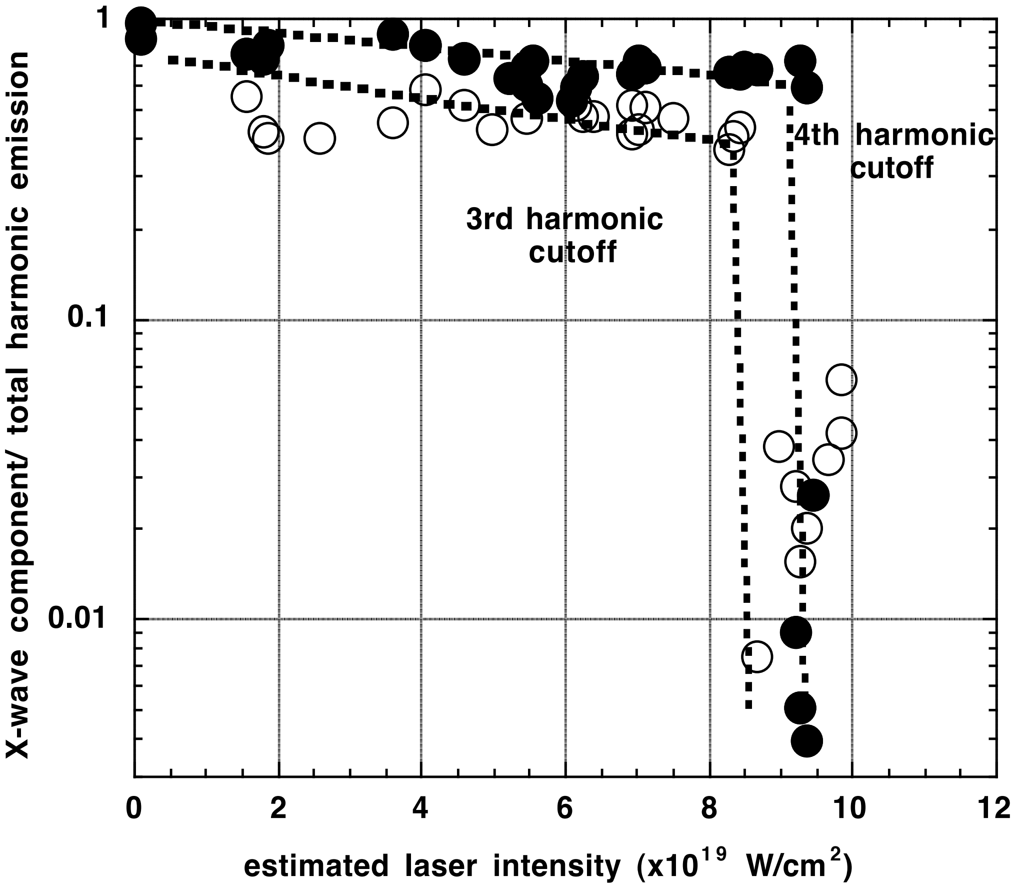
X-Wave cutoffs



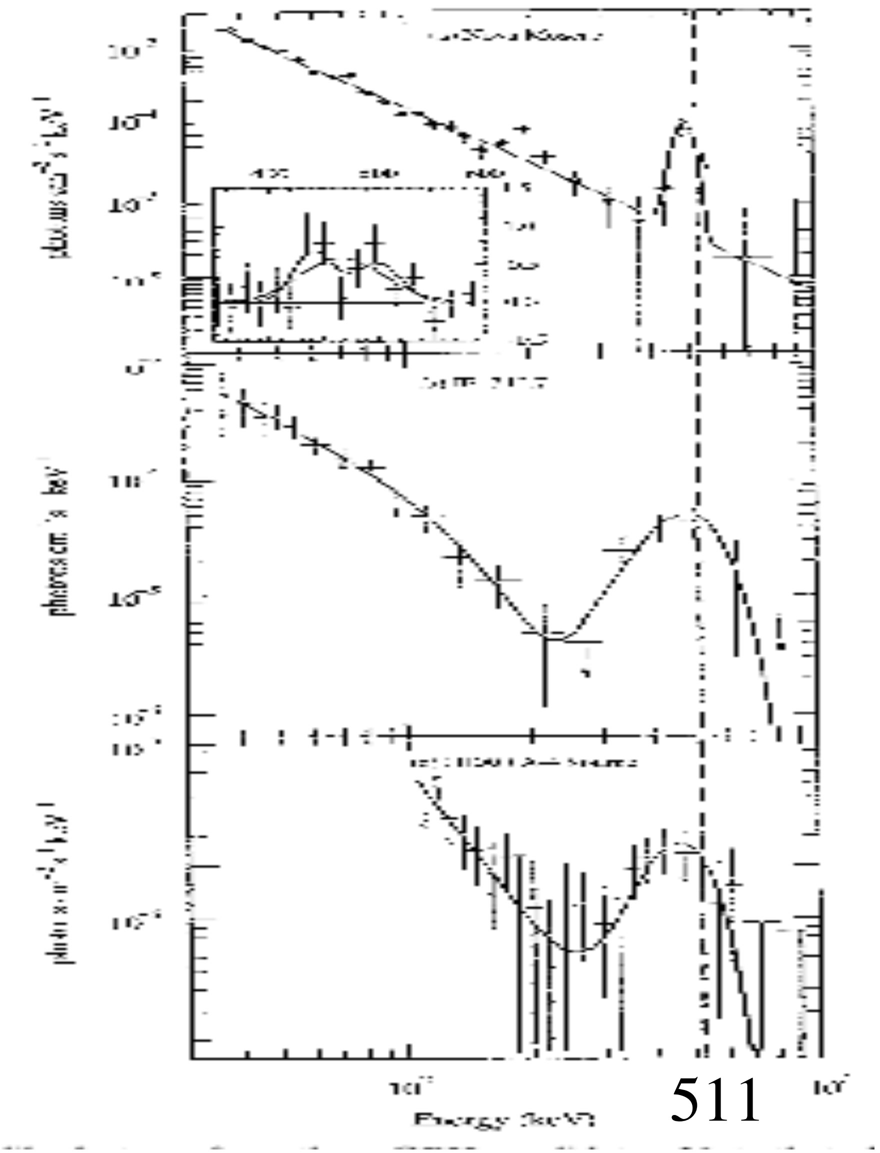
Observation of cutoffs

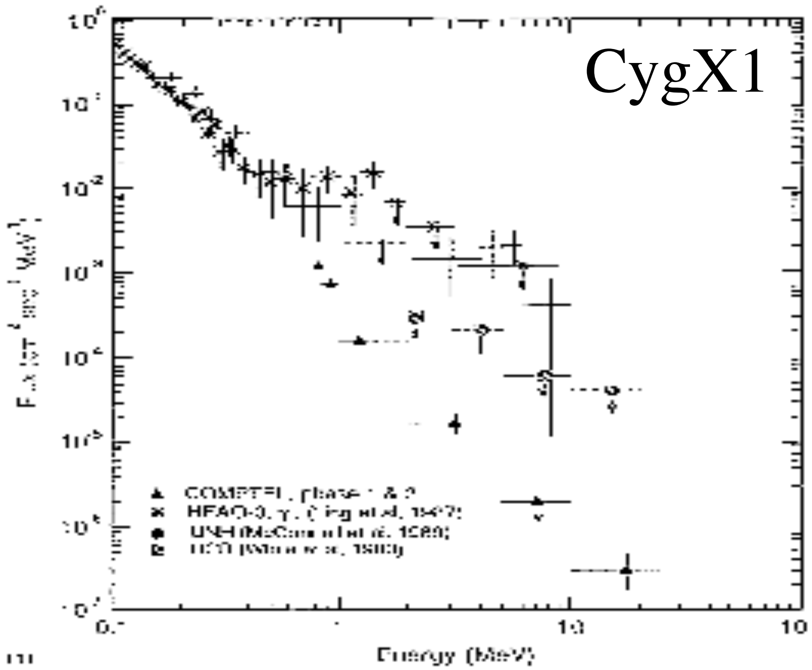
(Tatarakis *et al. Nature*, **415,** 280 (2002))

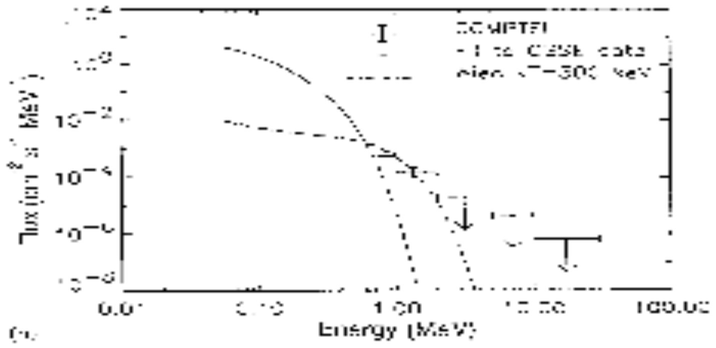
Indicates fields up to ~ 400 MG



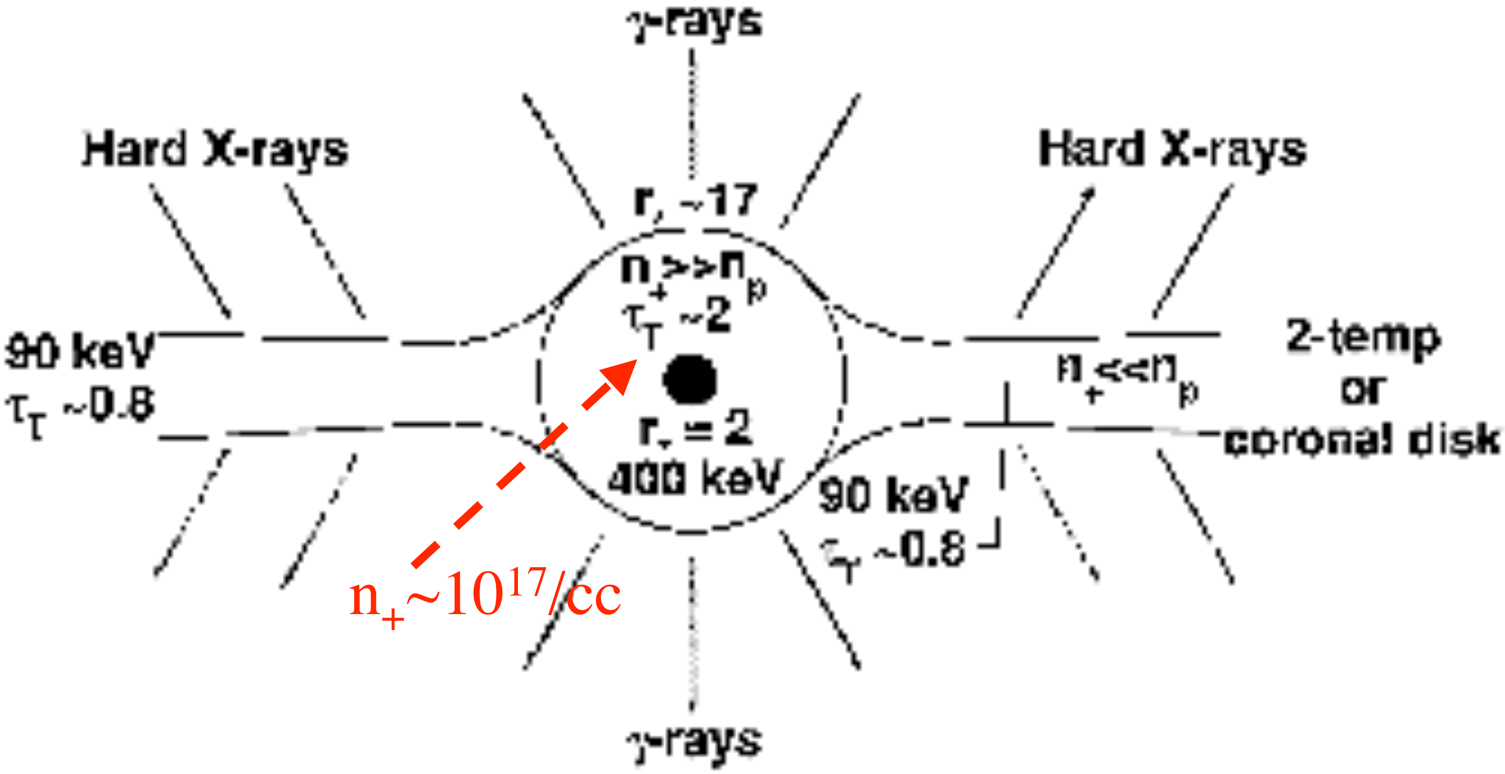
Pair annihilation-like features had been reported for several black hole candidates, but only CygX-1 has been confirmed





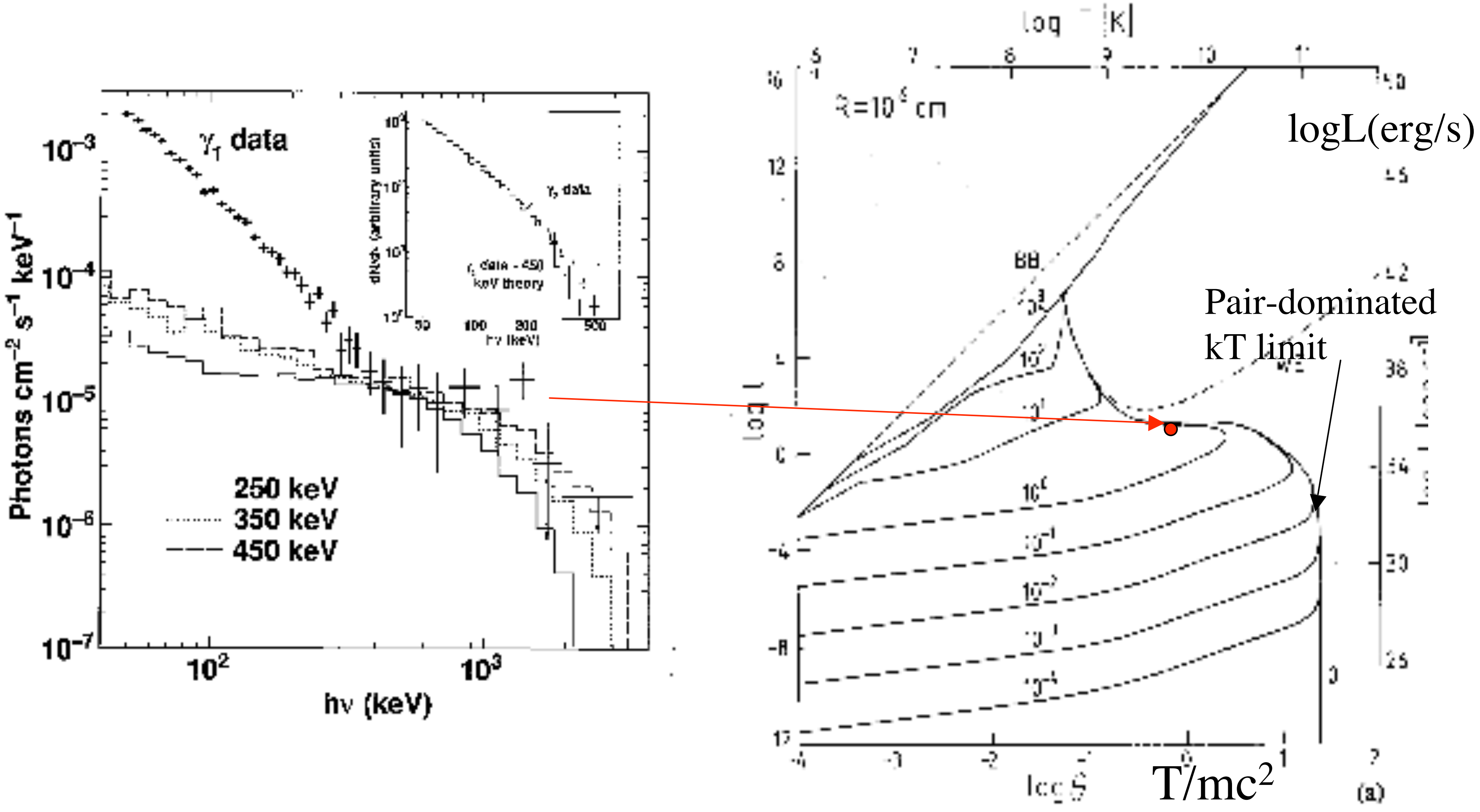


2D model of an e+e- pair-cloud surrounded by a thin accretion disk to explain the MeV-bump



$n_+ \sim 10^{17}$/cc

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?

Summary

1. Most successful experiments so far are in ideal hydro MHD regimes. Some radiative experiments have successfully compared with codes. Jets and their interactions are exciting new frontiers.

2. In the high energy/collisionless regime, creation of copious pairs and ultra-strong fields with PW class lasers have been demonstrated. Meaningful astrophysics experiments remain to be conceived and designed.

3. Diagnostics is the biggest challenge. Much more thought, manpower and resource need to be devoted to diagnostic development.