LABORATORY ASTROPHYSICS USING HIGH INTENSITY PARTICLE AND PHOTON BEAMS

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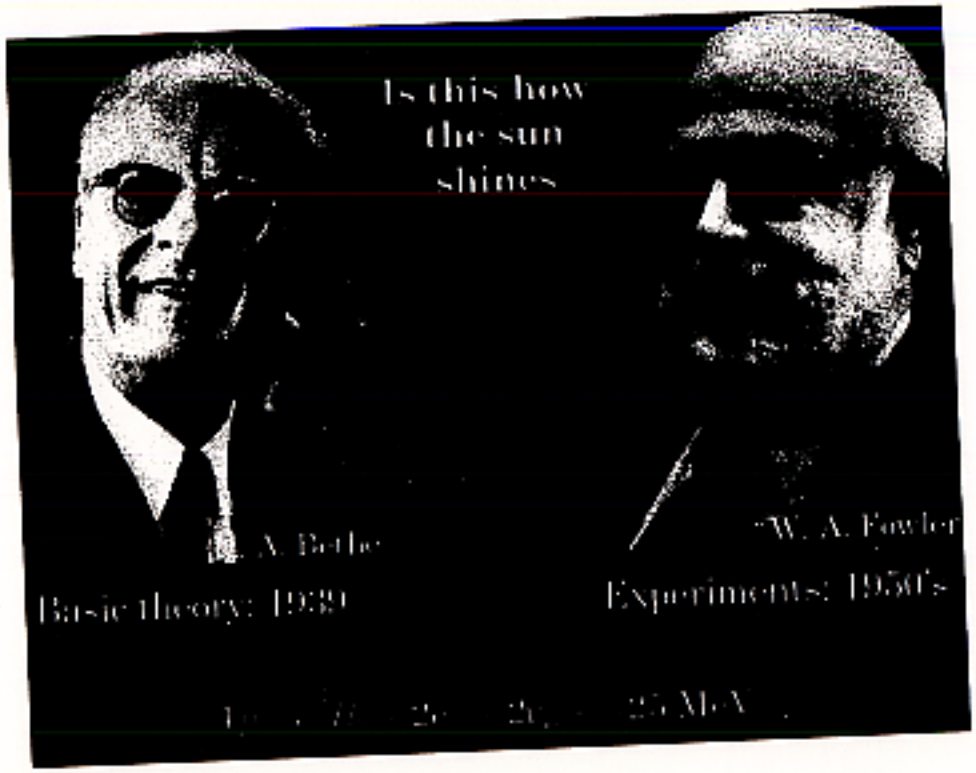
- The Universe as a Laboratory
- Laboratory Studies of the Universe
- A Laboratory Astrophysics Facility at SLAC
- Possible laboratory astrophysics experiments
- Summary

11-29-01

Laboratory Determination of Stellar Evolution

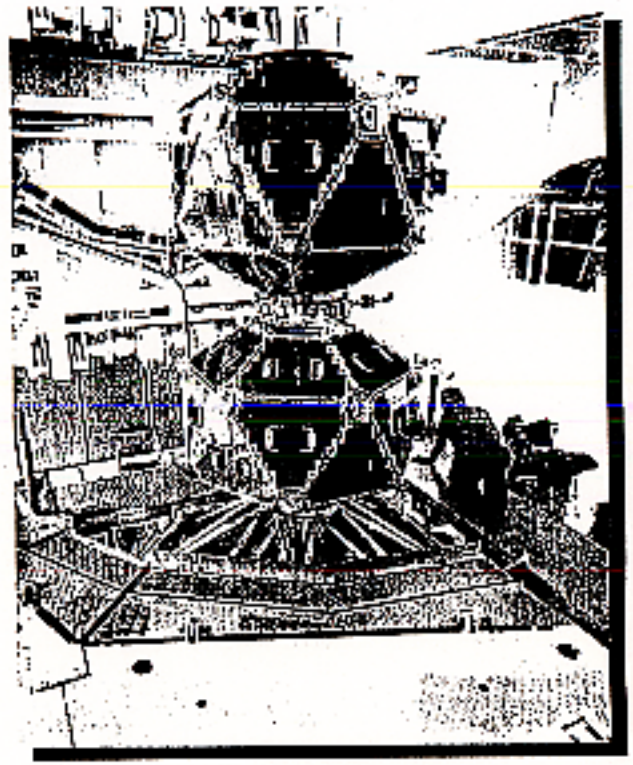


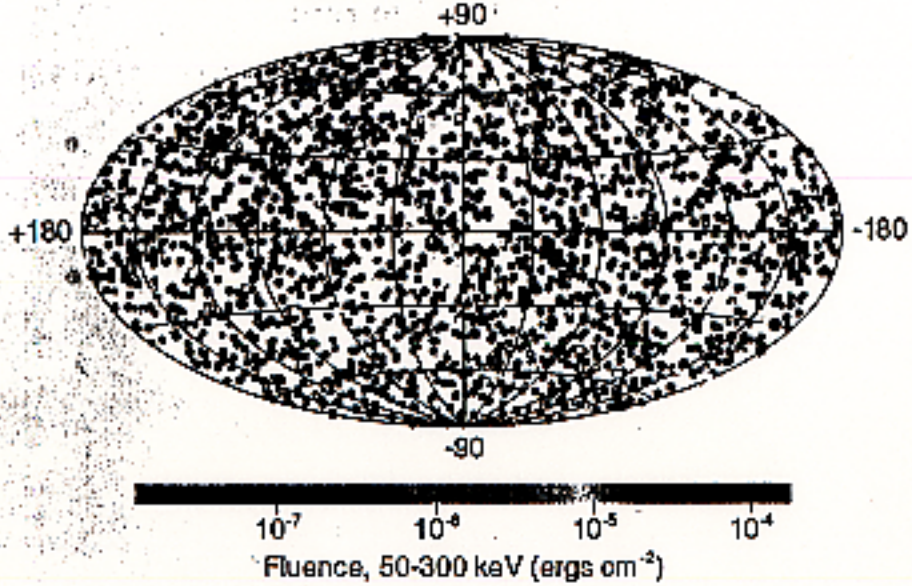
UNIVERSE AS A LABORATORY

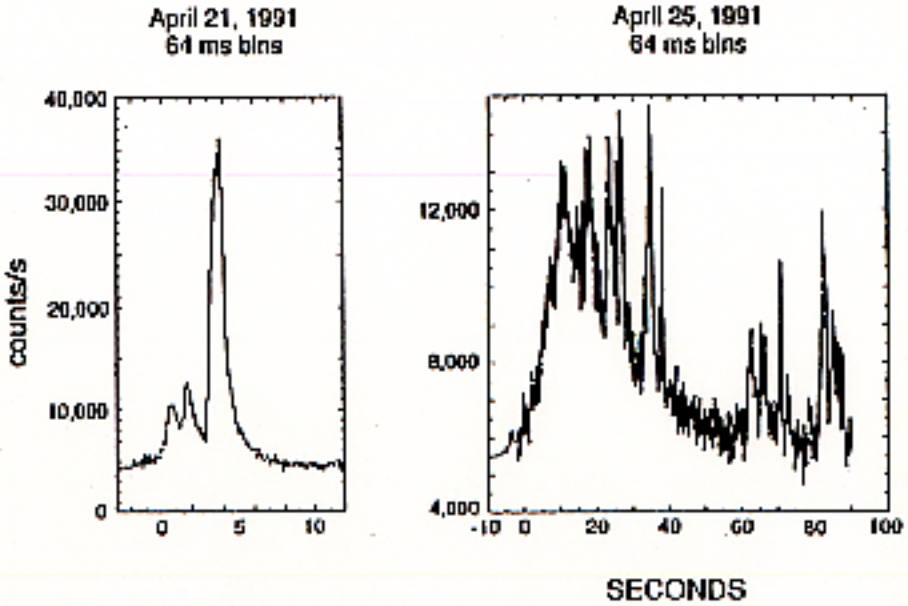
- Very High Intensity and Temperature Processes
  - Gamma Ray Bursts (~ 10^{52} erg/sec)
  - Supernova Explosions
- Extremely High Energy Events
  - Ultra High Energy Cosmic Rays (> 10^{20} eV)
  - Blazars: Emission of High Energy Photons (> TeV)
- Ultra Strong Field Environments
  - Black Holes and Neutron Stars: Strong Gravity and EM Fields (B ~ 10^{13} G)

GRB History

- Discovered by Vela satellites in late 1960's
- Study in detail in 1991-2000 by CGRO/BATSE that detected 2500 GRBs
- BeppoSAX discovered X-ray afterglow in 1997 and enabled radio/optical afterglows discoveries proving cosmological distances



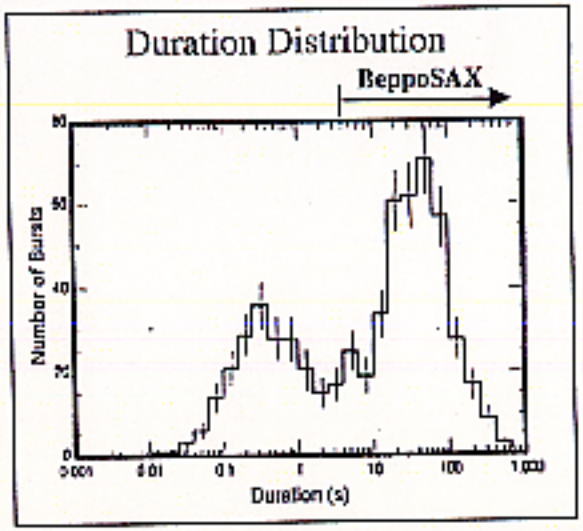


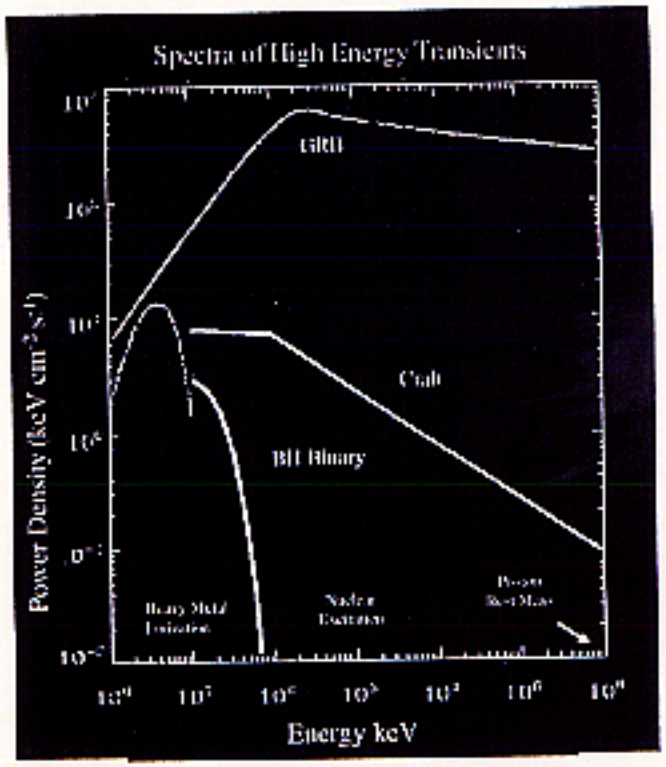


GRB Properties

- Time profiles highly varied
- → Duration distribution is bimodal
  - Short GRBs have different "variability" and log N- log S
- Full sky rate was 1.7 day^{-1} for BATSE, will be 3-5 day^{-1} for Swift
- → Spectra peak at ~1 MeV with non-thermal high-energy tail
- Distribution on sky is isotropic
- Fluxes range from 0.1 to 1000 photons cm^{-2}s^{-1} in 50-200 keV band(Crab = 0.1)

Tremendous energy release :
~10^{52} erg/sec !!



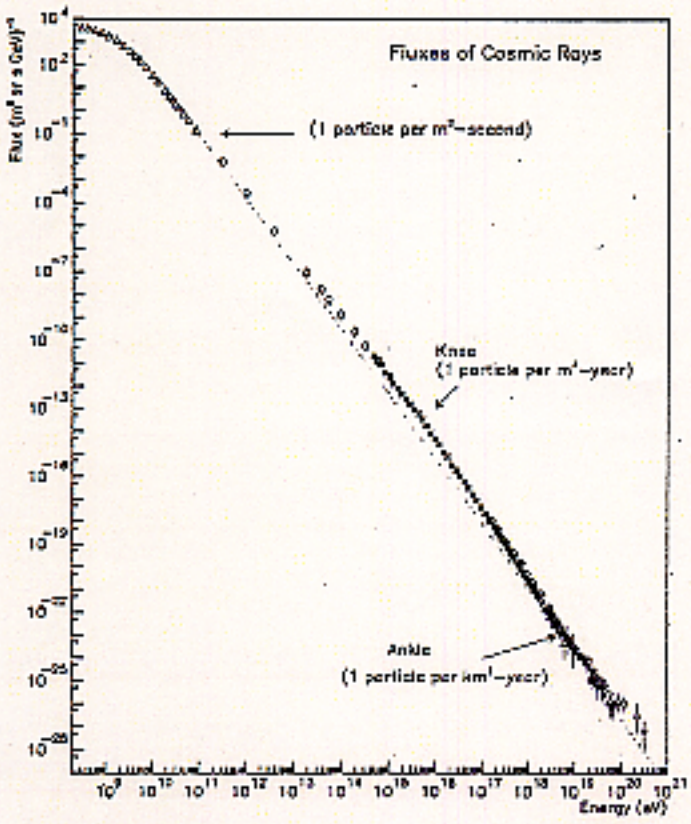


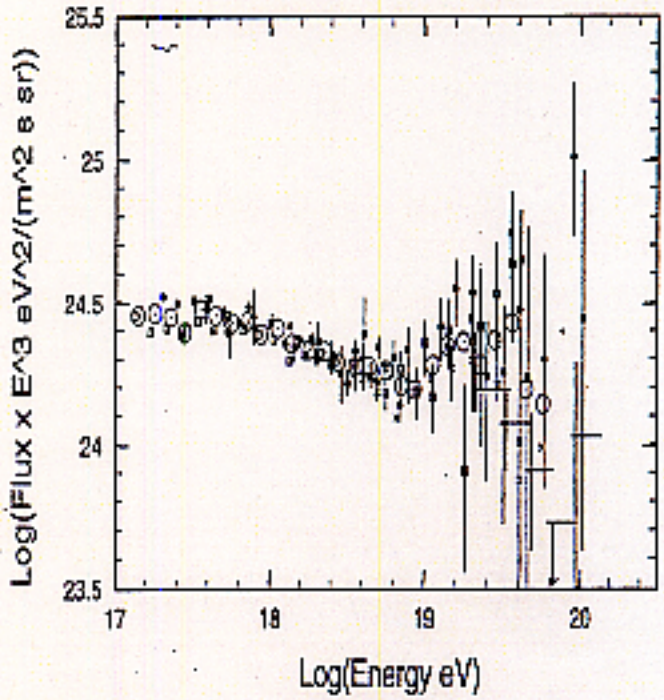
AUGER : Les Rayons Cosmiques

Découverts en 1912 par Victor Hess.

Énergie estimée au delà de 10^{15} eV par Pierre Auger (années 30).

Événements détectés au delà de 10^{20} eV depuis les années 60.





Spectre des Rayons Cosmiques.

Soulèvent des problèmes :

- – coupure GZK

High energy protons prapagate through cosmic distance will annihilate with CMB γ's:

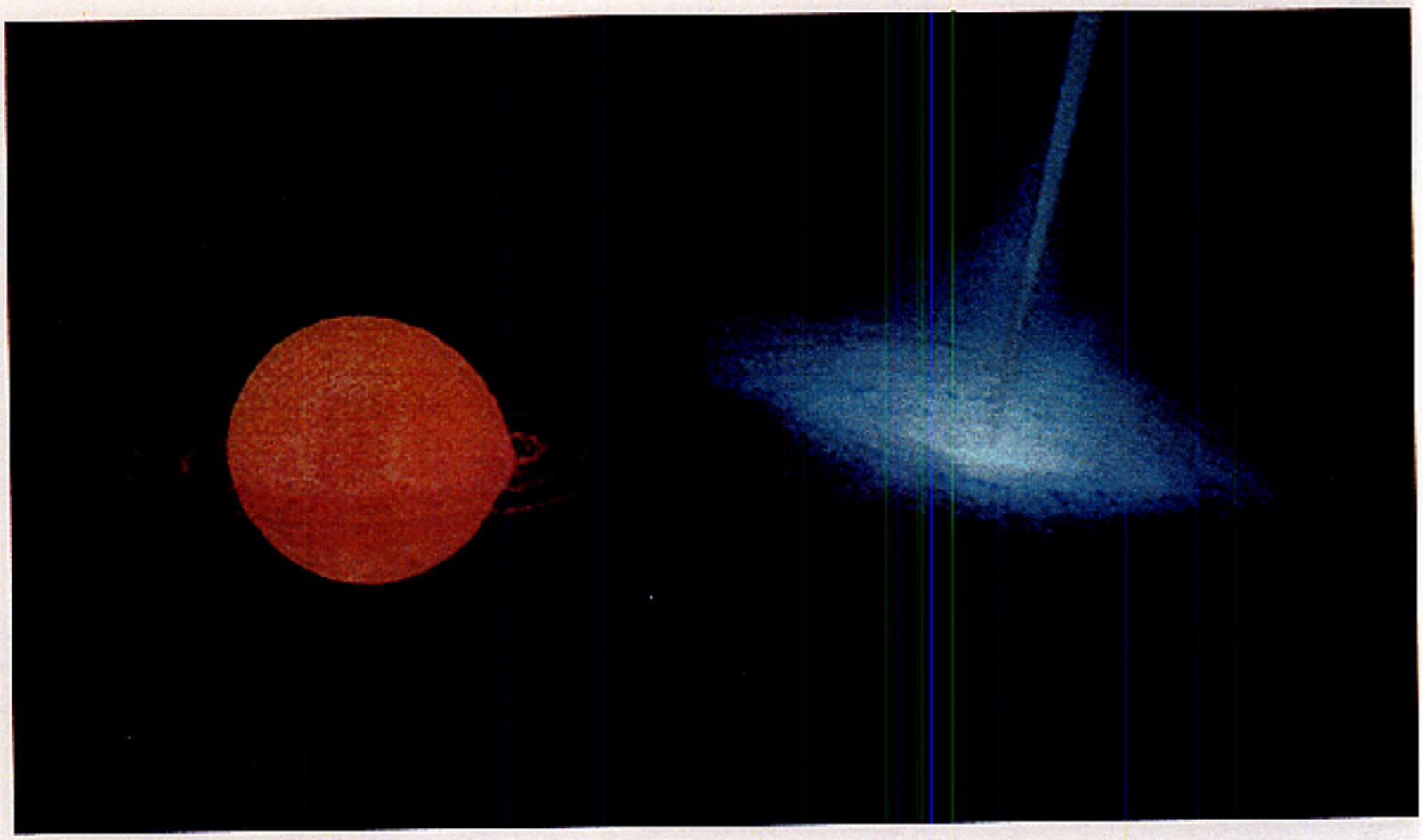
$$p + \gamma(\text{CMB}) \rightarrow \Delta^+ \rightarrow n + \pi^+ \hookrightarrow \mu^+ + \nu$$

($T \sim 3^\circ K \Rightarrow \sim 3 \times 10^{-4}$ eV)

threshold $\Rightarrow 5 \times 10^{19}$ eV

- – sources

{Top-down scenario
{Bottom-up scenario



X-RAY PROBES OF STRONG GRAVITY

Presentation to CPU
Pasadena, June 6, 2001

Mitchell Begelman
JILA, University of Colorado

THE QUESTION:

Did Einstein have the last word on gravity?

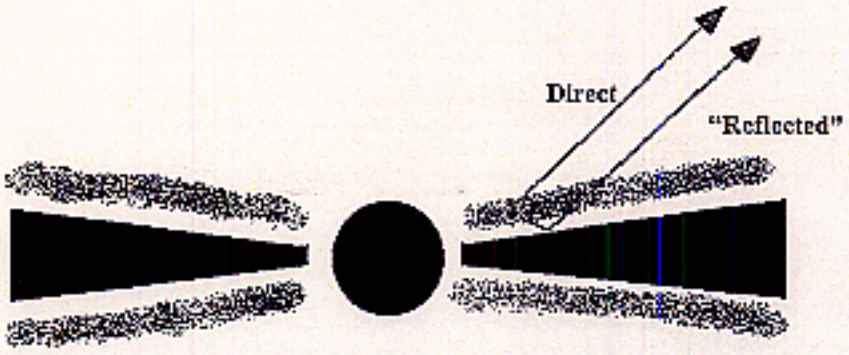
TOWARD AN ANSWER:

X-ray observations will allow us to probe the spacetimes of black holes in detail.

THREE "LUCKY BREAKS" OF BLACK HOLE ACCRETION

1. (many) accretion flows are "cold"
2. accretion disks are not fully ionized
3. **accretion disks are illuminated by flaring coronae**
   - flares excite different regions of disk at different times
   - by watching evolving echoes of flares we map different slices of spacetime
   - major deconvolution challenge

IRON LINES ARE EXCITED BY X-RAY IRRADIATION FROM DISK CORONA



…"reflected" X-rays imprinted with iron lines

LABORATORY STUDIES OF THE UNIVERSE

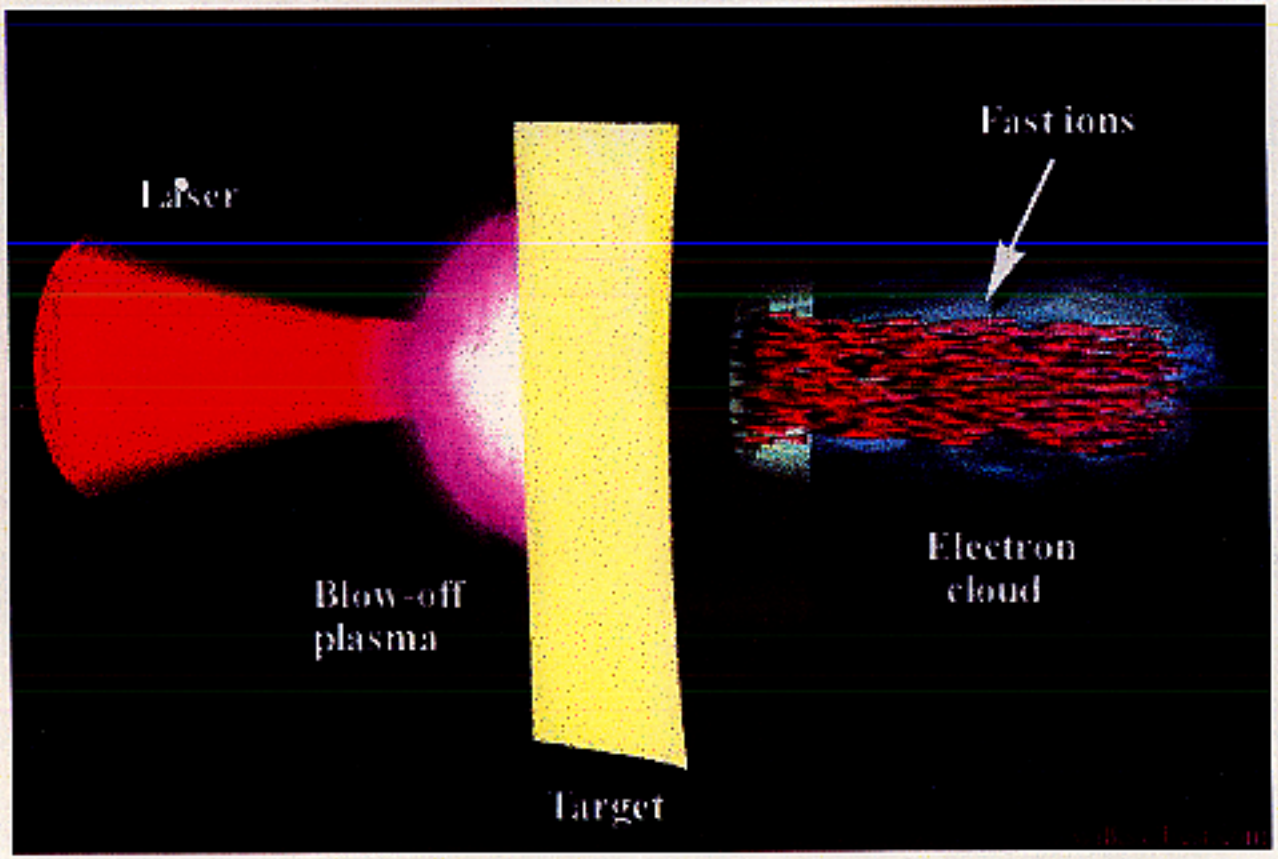
- Many astrophysical processes involve extreme conditions:
  High energy particles coupled with high intensities, high densities, high temperatures, high gravitational and EM fields plasmas
- *Insights into underlying fundamental physical mechanisms require controlled laboratory experiments*
- Complementarity between laser & particle beams:

  Both can deliver high EM powers and can couple effectively to plasmas, while

  Lasers: more effective in loading energy to material → SN studies

  Particle Beams: more penetrating → High energy astrophysics

We have begun a promising new study of low-emittance ion beam generation from laser-irradiated foils



Our work on Laser Acceleration of extremely high intensity proton beams was featured at the 1999 APS Division of Plasma Physics Meeting

This relativistic extension of a well-established phenomenon has broad potential: High brightness ion beams; Compact ion accelerators; High energy density neutral beams and fusion physics; and Plasma jets of interest to astrophysics.

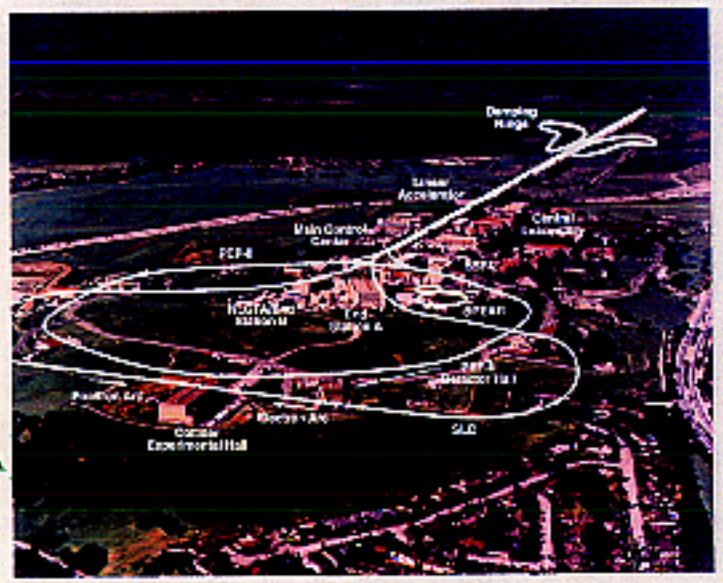
T.E. Cowan, M. Roth, S. Wilks, S.P. Hatchett, M.D. Perry, M. Allen, S. Karsch *et al.*

BENCH-MARKING OF ASTROPHYSICS SIMULATIONS

- Complexity of most astrophysical systems renders fully theoretical treatment difficult:
  Relativistic magnetohydrodynamics (MHD), high-density plasmas and high-intensity EM fields coupled with high energy particles, etc.
- Large scale computer simulations indispensable
- Laboratory experiments can help to verify the validity of simulations designed for environments far from accessible in terrestrial conditions

UNIQUE LABORATORY ASTROPHYSICS OPPORTUNITY

- High intensity e^-/e^+ beams
  ultra-fast (< 50 fsec), high energy (~30GeV/e)
  ultra-high intensity (~ 10^{22} W/cm^2)
  very high repetition rate (10 Hz)
- High fluence photon beams
  1. X-ray from undulator (~ 10^9 γ/pulse at 1.5 Å
  2. Terawatt laser (at ~ 1 μm)
  3. Gamma-ray (up to ~ 15 GeV) through laser-particle beam Compton-backscattering



* Experiments can be performed with different combinations of these beams

RELATED EXPERIMENTS DONE AT SLAC

- E-144: Nonlinear QED Processes

  45 GeV electron beam colliding with terawatt laser [Bula, et al., Phys. Rev. Lett. 76, 3116 (1996)]

  → Relevant to compact-object environments

- E-150: Plasma Lens Experiment

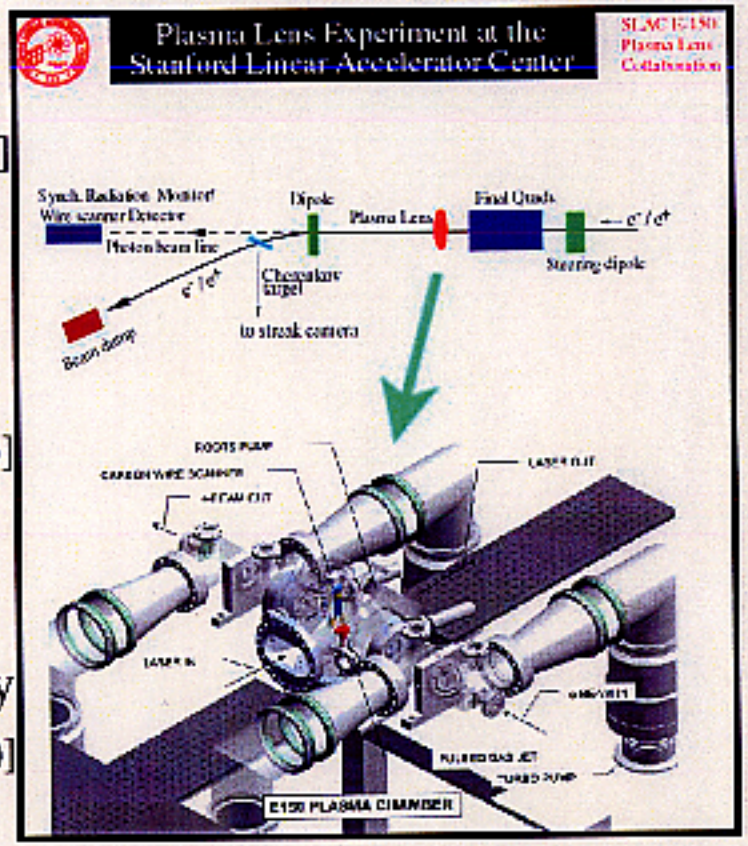
  30 GeV e^-/e^+ beams focused by high-density ($\sim 10^{18}$/c.c.) plasma [Ng, et al., Phys. Rev Lett (2001)]

  → Relevant to jet dynamics & collimation

- E-157/162: Plasma Wakefield Accel.

  High gradient self-acceleration of e^-/e^+ beams by plasma [Hogan, et al., Phys. Plas. 7, 2441 (2000)]

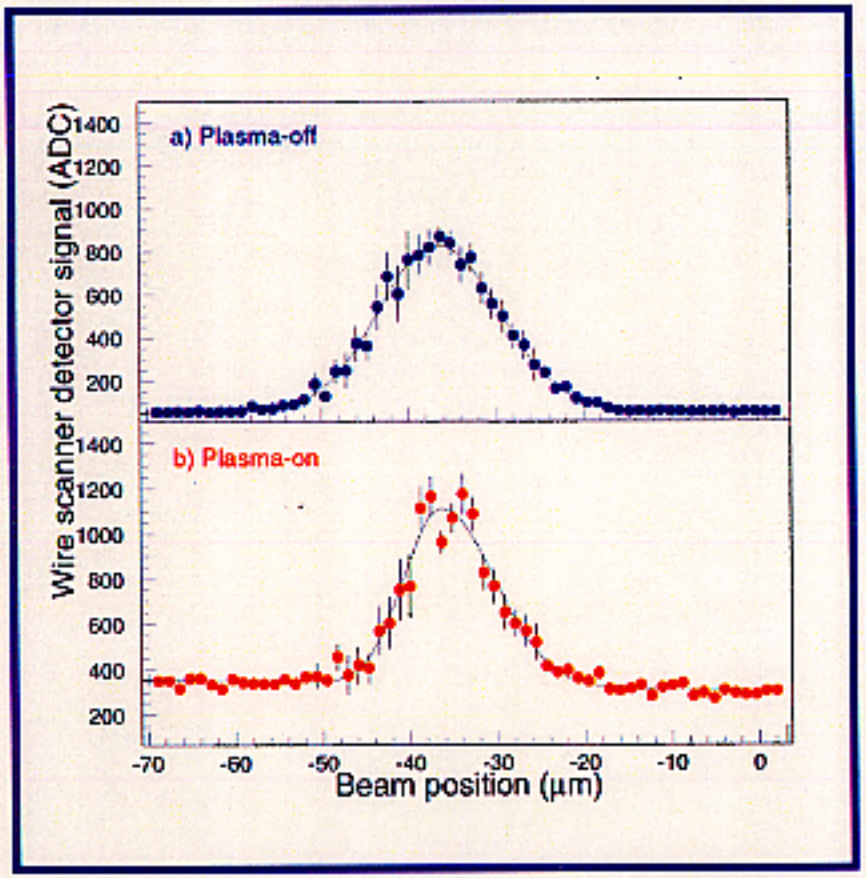
  → Relevant to cosmic acceleration



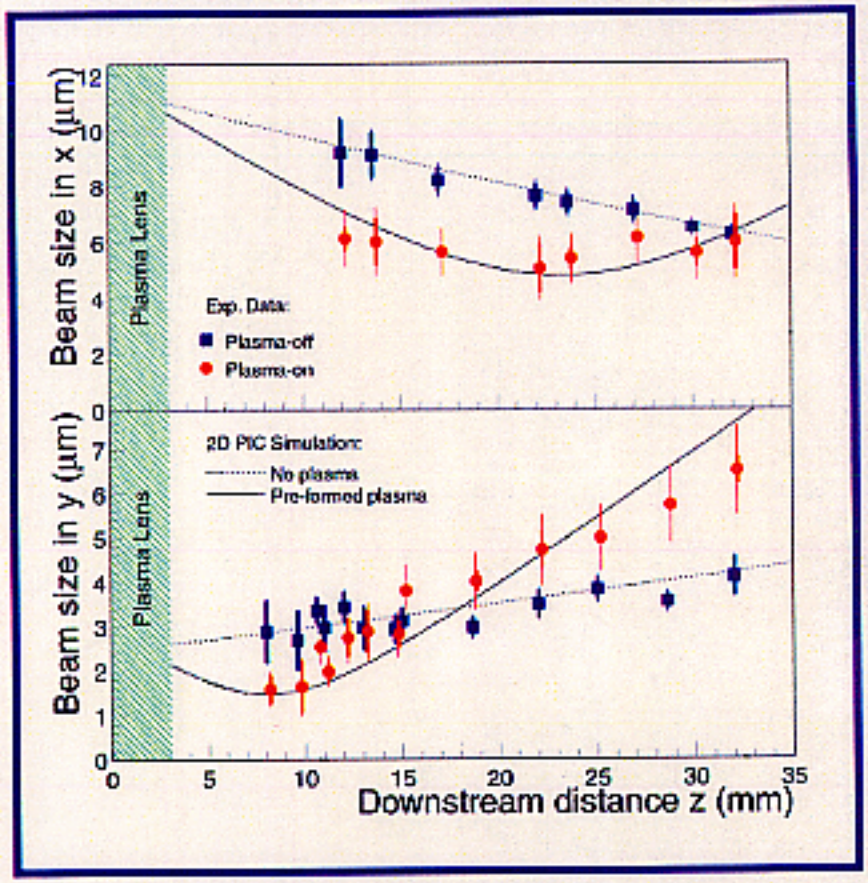
These have demonstrated promising capability for laboratory astrophysics studies

Plasma Focusing of a 28.5 GeV Positron Beam

[J.S.T. Ng *et al.*, Phys. Rev. Lett., **87**, No. 24, 10-Dec-2001.]



Transverse beam profile



Beam envelope

The Pehong and Adele Chen

Particle Astrophysics and Cosmology Institute at Stanford University

Pehong Chen, founder and CEO of BroadVision, and his wife, Adele, will donate $15 million to Stanford to establish a new institute for the study of particle astrophysics and cosmology, President John Hennessy announced Tuesday. The institute will capitalize on the strengths and worldwide reputation of the Stanford Linear Accelerator Center (SLAC) and the university's Physics and Applied Physics Departments.

(L-R) SLAC Director - Jonathan Dorfan, Pehong and Adele Chen, Daphne and Pisin Chen, Stanford President - John Hennessy

STATUS OF THE CHEN INSTITUTE

- The Institute is an independent laboratory at Stanford University reporting to the Vice Provost for Research
- Search Committee for the 1st Institute Director and holder of the Chen Chair, co-chaired by M. Perl and D. Osheroff, has narrowed down to a list of top 10 candidates
- Institute will consist 10 faculty as *Members* of the Institute, and a total of about 90 people
- Other Stanford faculty in related research area be associated members
- Affiliated members for scientists from other institutions
- Institute building (to be located at SLAC) design underway

POSSIBLE LABORATORY ASTROPHYSICS EXPERIMENTS

Suggested in a recent Workshop on Laboratory Astrophysics (very preliminary):

1. Cline (UCLA):	Primordial Black Hole Induced Plasma Instability Expt.
2. Sokolsky (Utah):	High Energy Shower Expt. for UHECR
3. Kirkby (CERN):	CLOUD Expt. on Climate Variation
4. Chen-Tajima (SLAC-Austin):	Ponderomotive Acceleration Expt. for UHECR and Blazars
5. Nakajima (KEK):	Laser Driven Dirac Acceleration for UHECR Expt.
6. Odian (SLAC):	Non-Askaryan Effect Expt.
7. Rosner (Chicago):	Astro Fluid Dynamics Computer Code Validation Expt.
8. Colgate-Li (LANL):	Magnetic Flux Transport and Acceleration Expt.
9. Kamae (SLAC):	Photon Collider for Cold e^+e^- Plasma Expt.
10. Begelman-Marshall (CO-MIT):	X-Ray Iron Spectroscopy and Polarization Effects Expt.
11. Ng (SLAC):	Relativistic e^+e^- Plasma Expt.
12. Katsouleas (USC):	Beam-Plasma Interaction Induced Photon Burst Expt.
13. Blandford (CalTech):	Beam-Plasma Filamentation Instability Expt.
14. Scargle (NASA-Ames):	Relativistic MHD Landau Damping Expt.

Pisin Chen (10-22-01)

COSMIC ACCELERATION

one of the "Eleven Science Questions for the New Century"
raised by NRC Committee on the Physics of the Universe

- Conventional cosmic acceleration mechanisms encounter limitations

  * Fermi acceleration (= stochastic accel. due to irragular magnetic fields)

  * Relativistic shock acceleration (a variant of Fermi mechanism)

    → Limitations for producing ultra-high energies:

      – Magnetic field strength

      – Bouncing off high energy particles not easy

      – Radiation loss and collisional loss severe at ultra high energies

  * Eddington acceleration (= accleration by photon pressure)

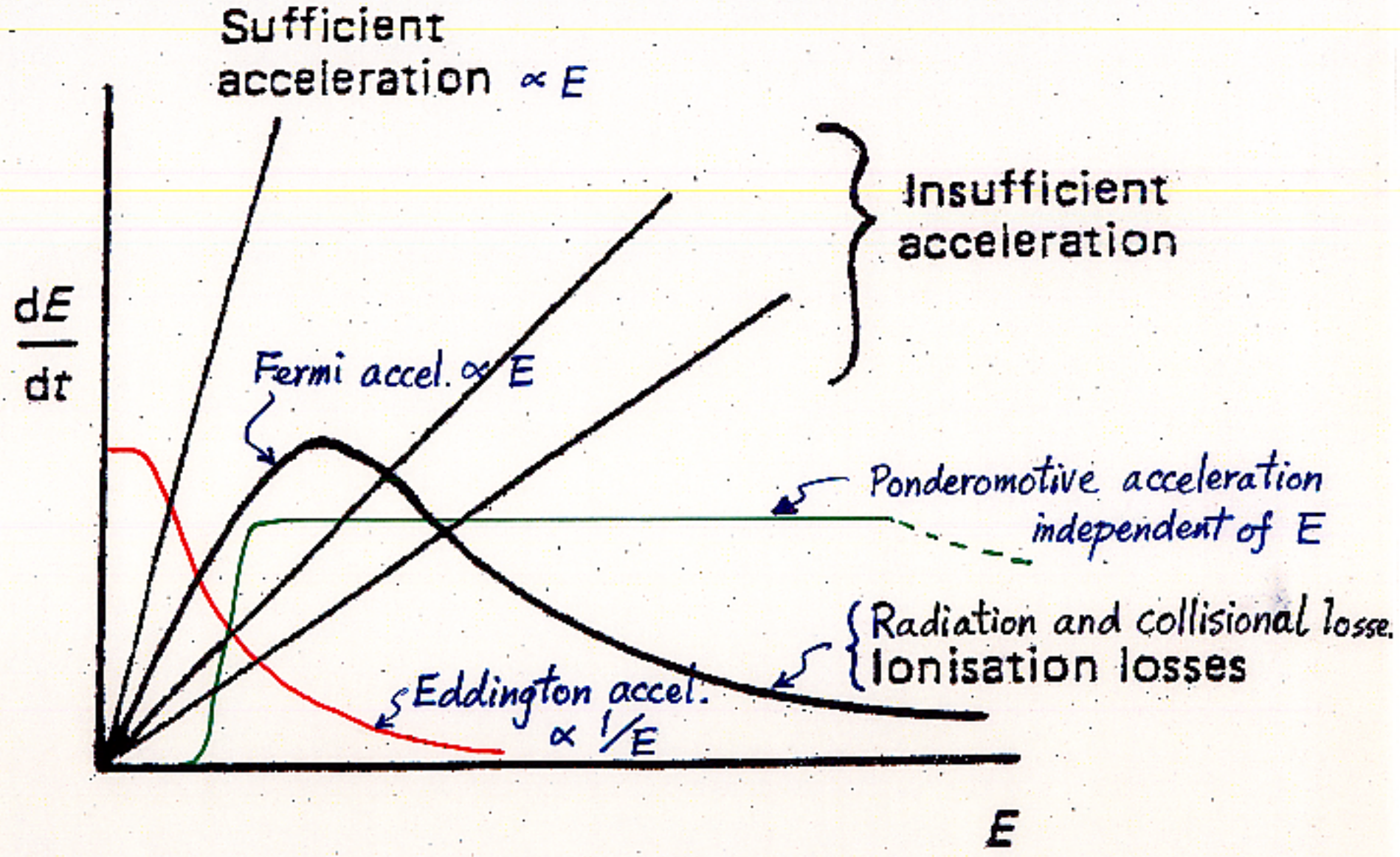
    → Limitation: Acceleration diminishes as $1/\gamma$

- New thinking: Ponderomotive acceleration in relativistic plasmas (Chen-Tajima)

  – Ponderomotive field Lorentz invariant → Accel gradient independent of γ

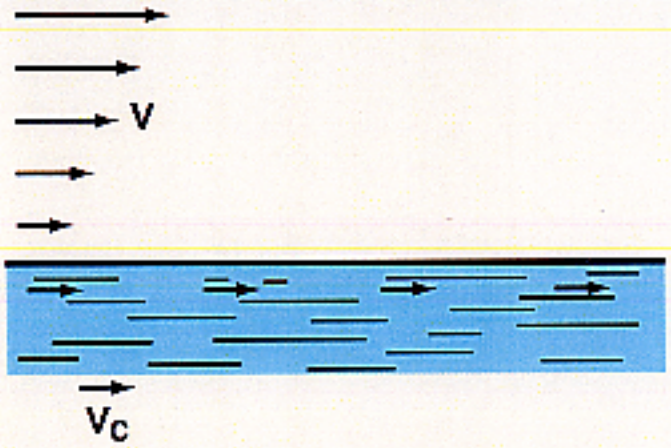
  – Ultra-high acceleration gradient → cosmic accelerator "compact'

  – Setting for ponderomotive accel cosmically abundant: GRB, AGN, BH, etc.


Sufficient acceleration ∝ E
Insufficient acceleration
dE/dt
Fermi accel. ∝ E
Ponderomotive acceleration independent of E
Radiation and collisional losses
Ionisation losses
Eddington accel. ∝ 1/E
E

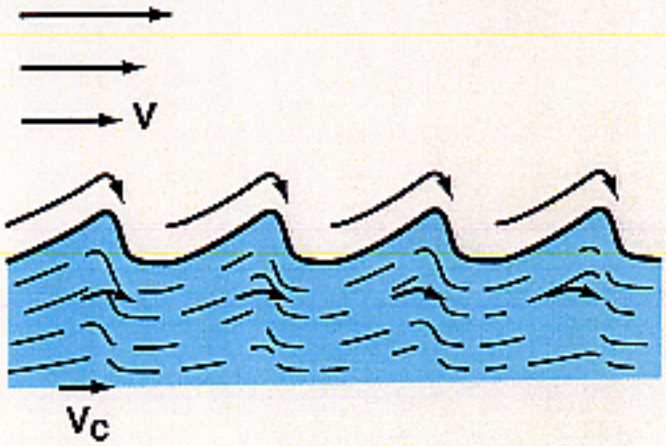
Wind-driven Water Flow vs. Ponderomotive Particle Acceleration

$v < v_c$ (laminar flow)

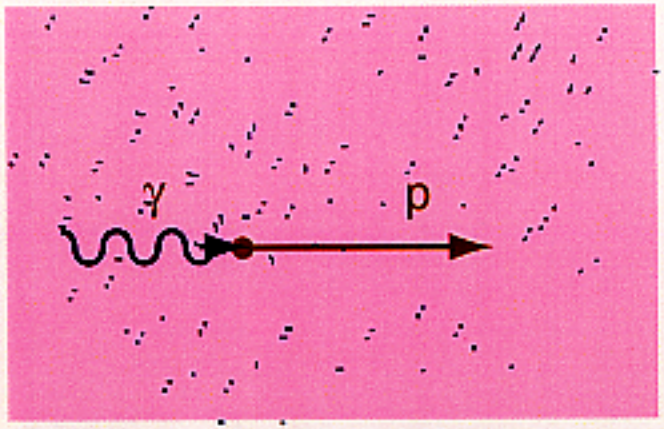


Viscosity of Molecules

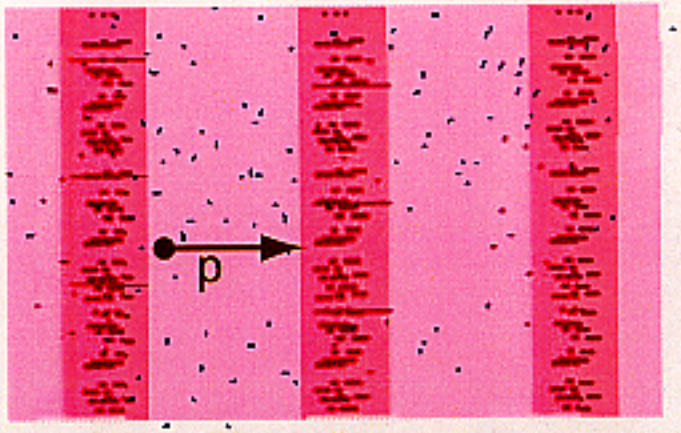
$v > v_c$ (Kelvin-Helmholtz Instability)



Eddington Acceleration



Photons Collide with Charged Particles



Photons (EM) Excite Waves that Accelerate Particles

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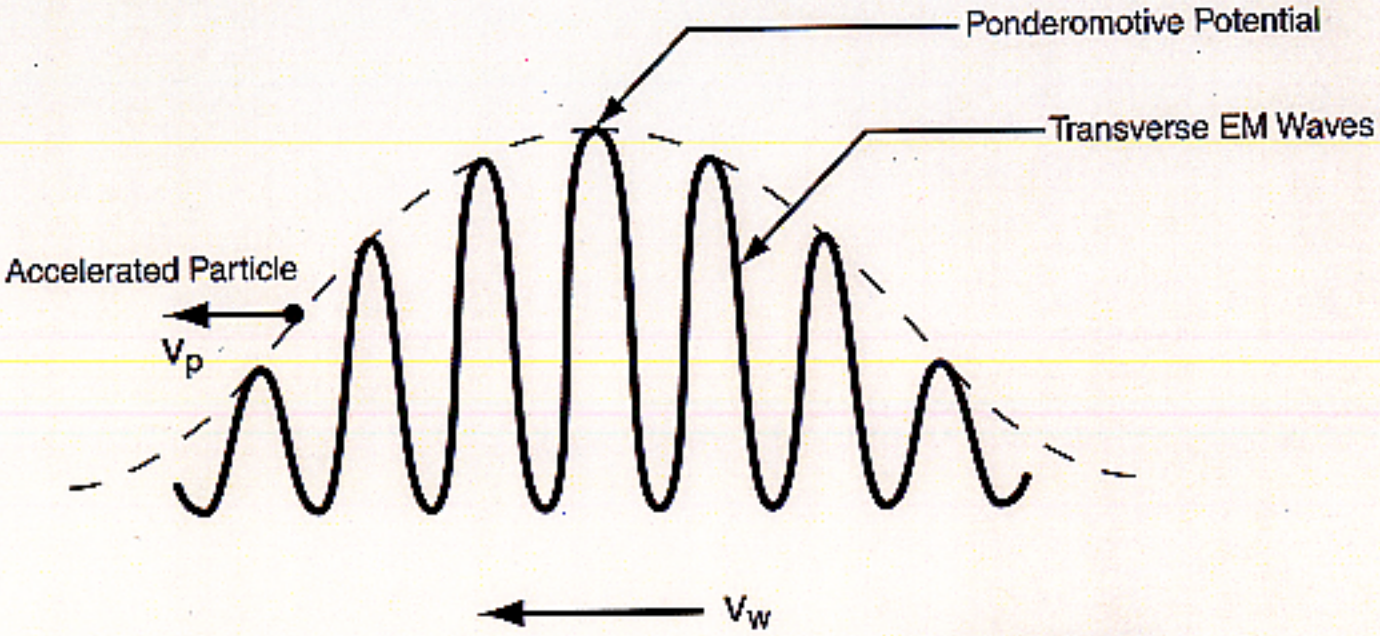
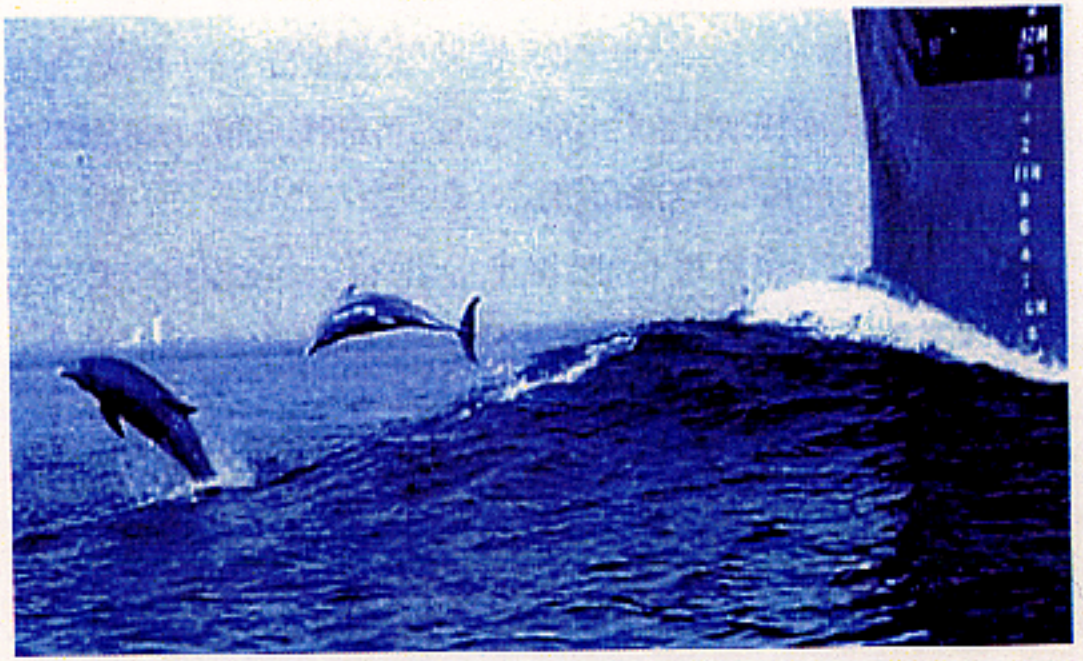
PONDEROMOTIVE ACCELERATION BY EM WAVES





Dolphins Surf Wave

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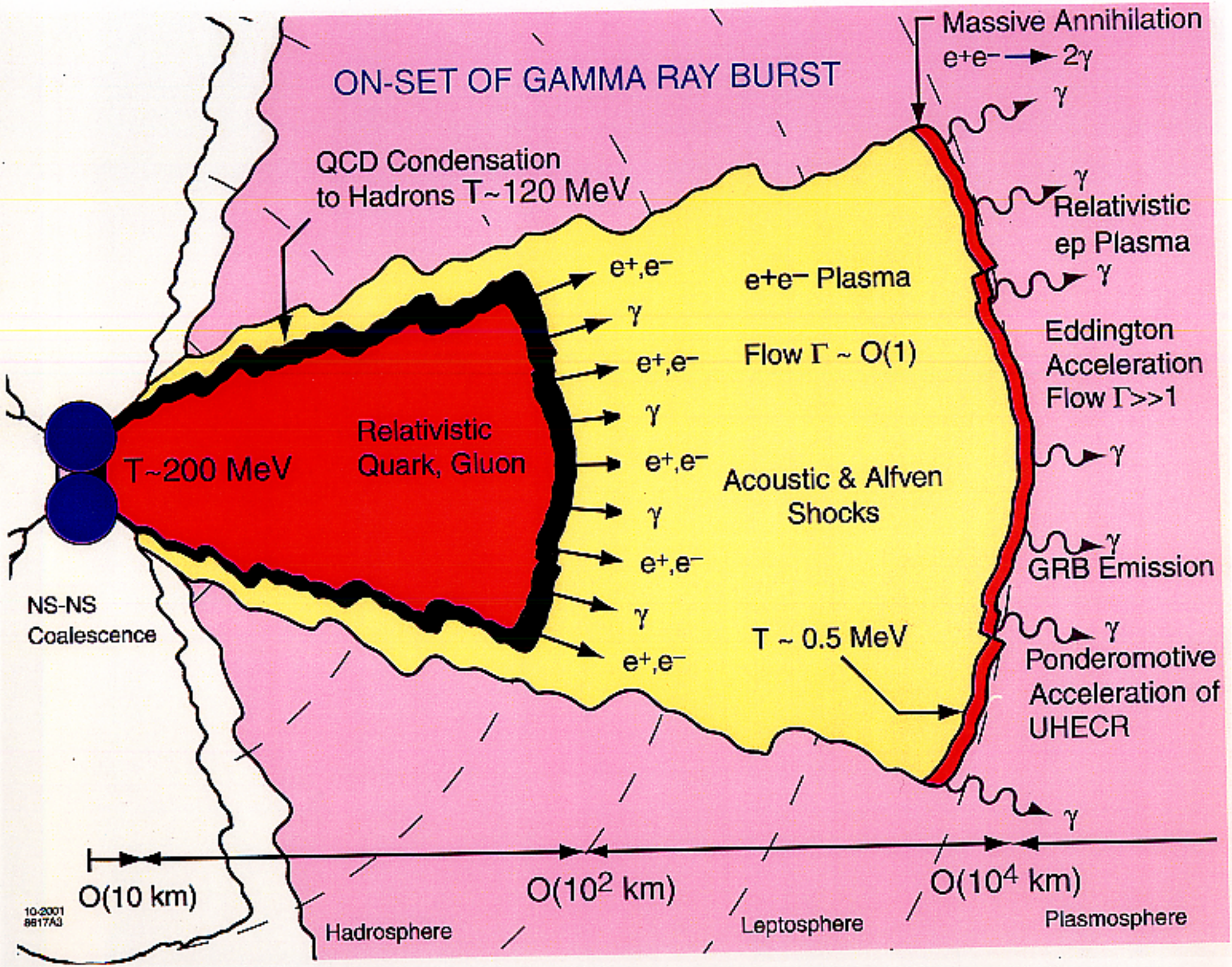
ON-SET OF GAMMA RAY BURST
Massive Annihilation
e+e− → 2γ
γ
QCD Condensation
to Hadrons T~120 MeV
γ
Relativistic
ep Plasma
γ
e+,e−
e+e− Plasma
γ
Eddington
Acceleration
Flow Γ >>1
e+,e−
Flow Γ ~ O(1)
γ
T~200 MeV
Relativistic
Quark, Gluon
e+,e−
γ
Acoustic & Alfven
Shocks
γ
GRB Emission
e+,e−
γ
T ~ 0.5 MeV
γ
Ponderomotive
Acceleration of
UHECR
e+,e−
NS-NS
Coalescence
γ
O(10 km)
O(10² km)
O(10⁴ km)
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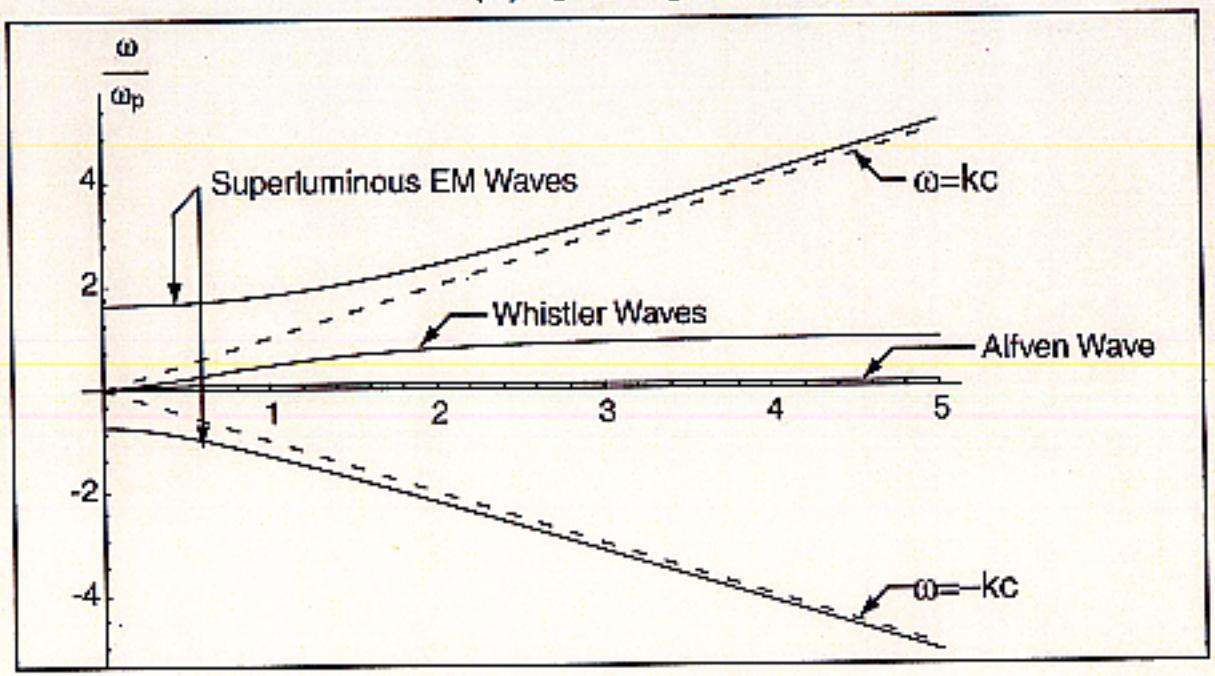
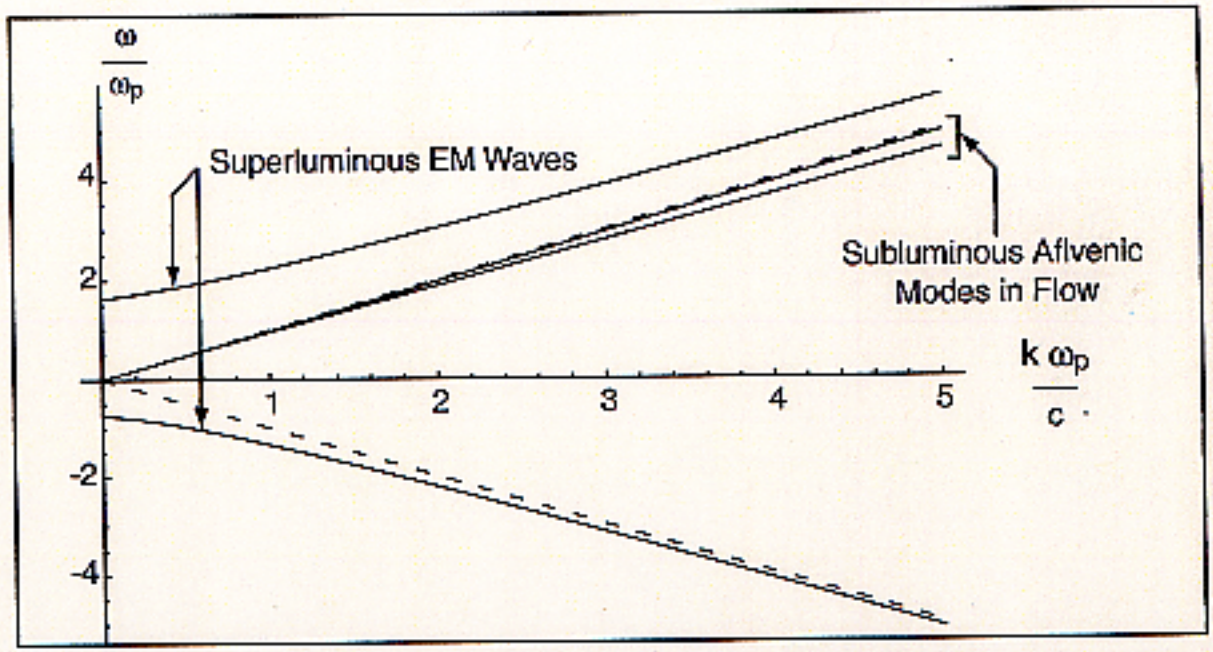
Hadrosphere
Leptosphere
Plasmosphere

PLASMA DISPERSION RELATIONS

$\omega(k)$ $[v_0=0]$



$\omega(k)$ $[v_0=0.9c]$



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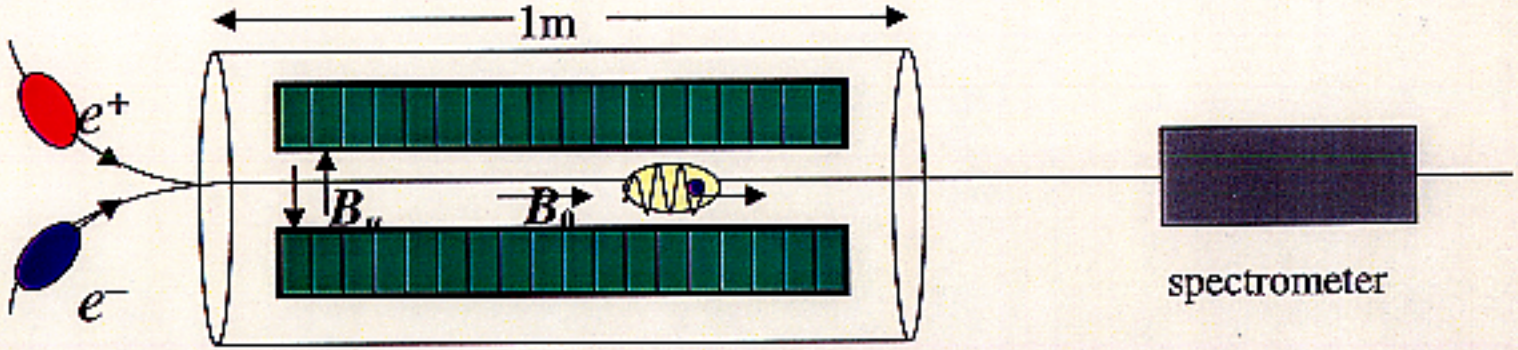
A POSSIBLE COSMIC ACCELERATION EXPERIMENT (P. Chen and T. Tajima)

To investigate

- Generation of sub-luminous waves in relativistic plasma flows
- Generation of high gradient nonlinear ponderomotive potential
- Ponderomotive acceleration of trapped e^+/e^- to higher energies
- Energy spectrum of stochastic acceleration process



e^+ energy: 30 GeV, e^- energy: 50 MeV, solenoidal field: B_0 = 10 Tesla, undulator field: B_u = 1 Tesla, beam density: n ~10^{16}/cc, Alfven velocity (comoving frame): $v_A/c \sim 10^{-2}$, acceleration gradient: G ~ 3 GeV/m

SUMMARY

- History has shown that symbiosis between *direct observation* and *laboratory investigation* instrumental in the progress of astrophysics
- Astro frontiers mostly involve high energy particles interacting with plasmas with high density, high temperature, high fields

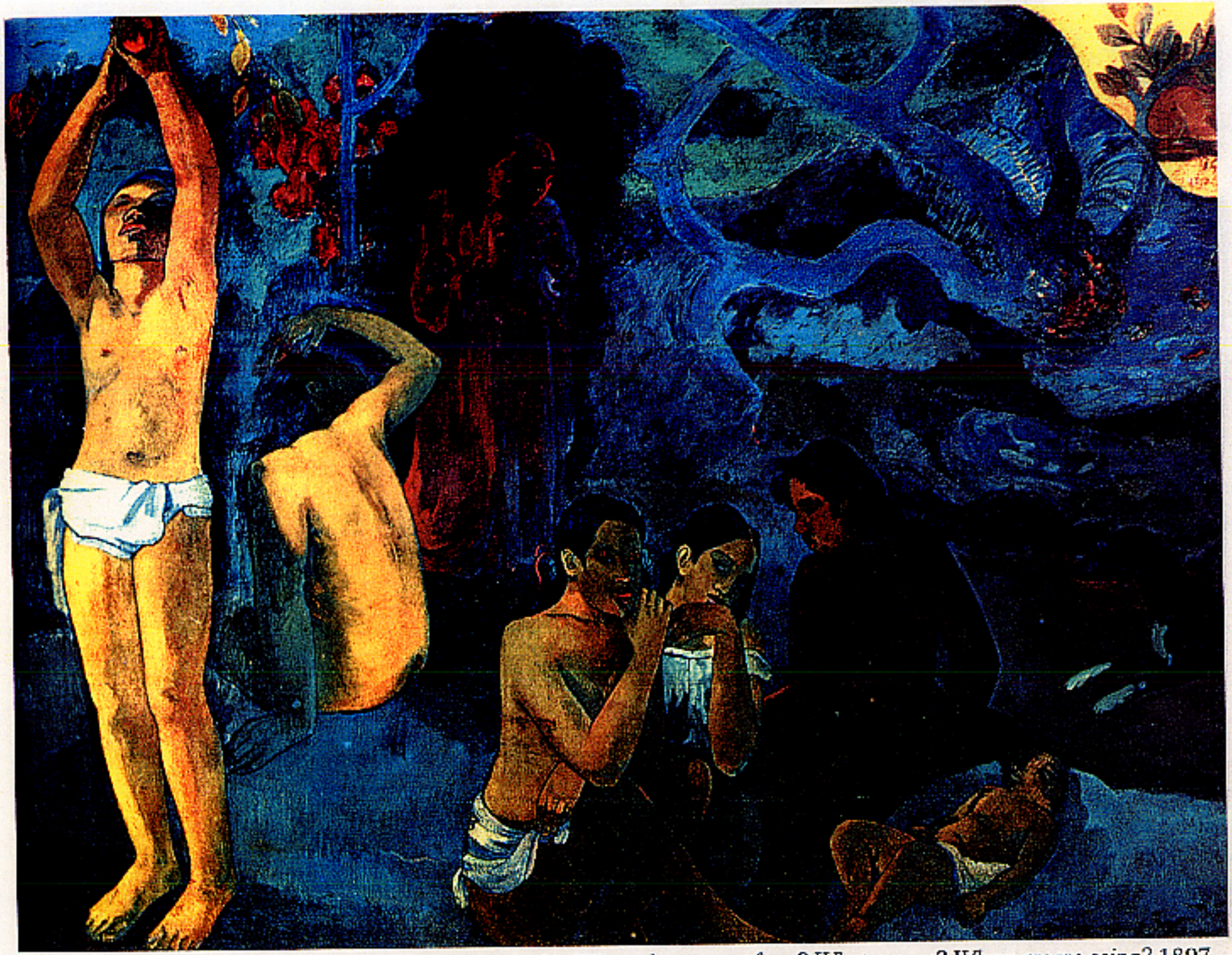
→ Insights into underlying fundamental physical mechanisms and processes require controlled laboratory experiments

- Complexity of such systems render fully theoretical treatment difficult; Large scale *simulations* indispensable

→ Validation of simulation codes relies on laboratory experiments

- SLAC can provide a unique leverage in this area of frontier research

Pisin Chen (10-22-01)



Paul Gauguin: *Where do we come from? What are we? Where are we going?* 1897