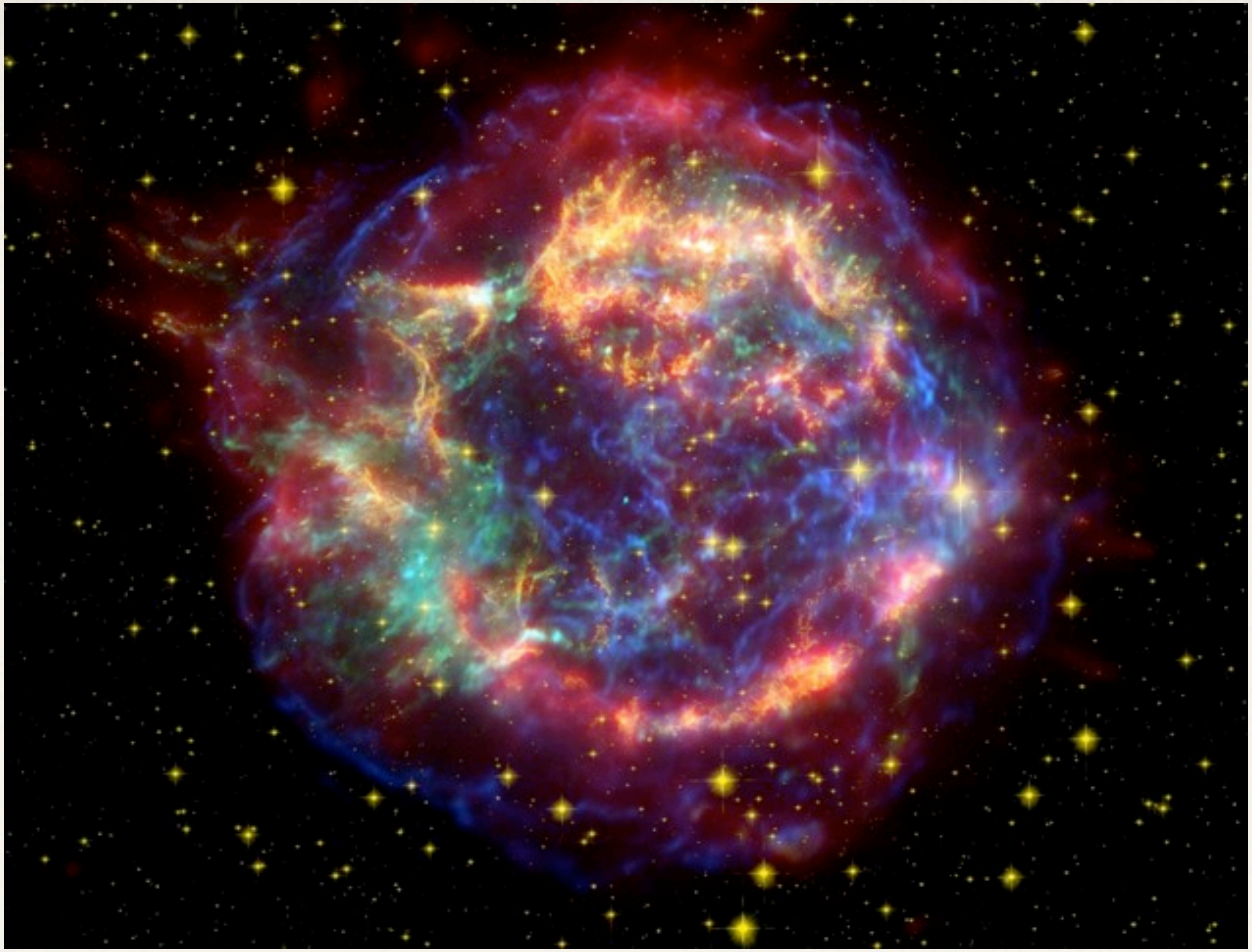
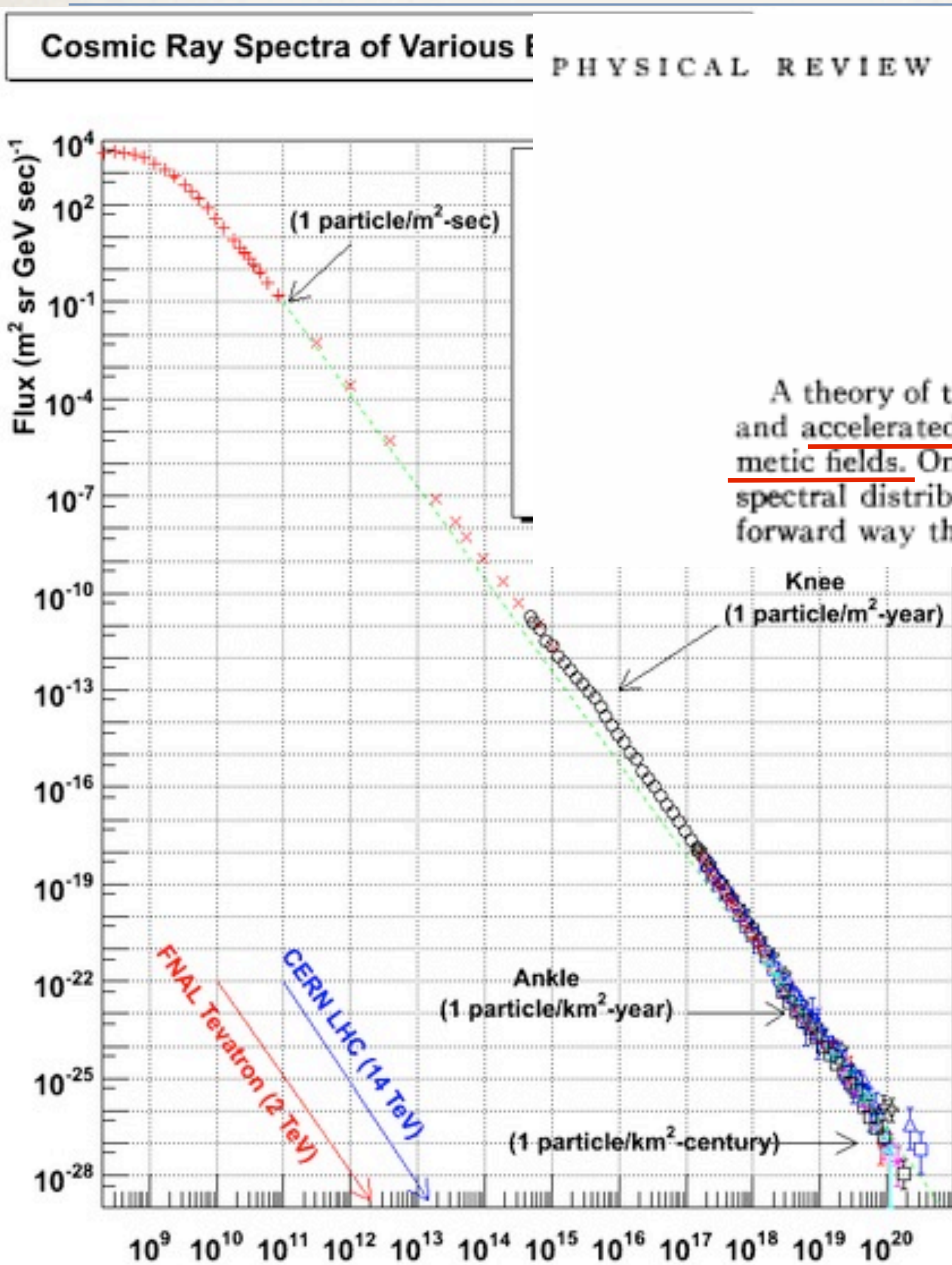


Energization of charged particles by turbulence

Dhrubaditya Mitra

July 2014, Pencil Code Meeting

Fermi's theory of cosmic rays

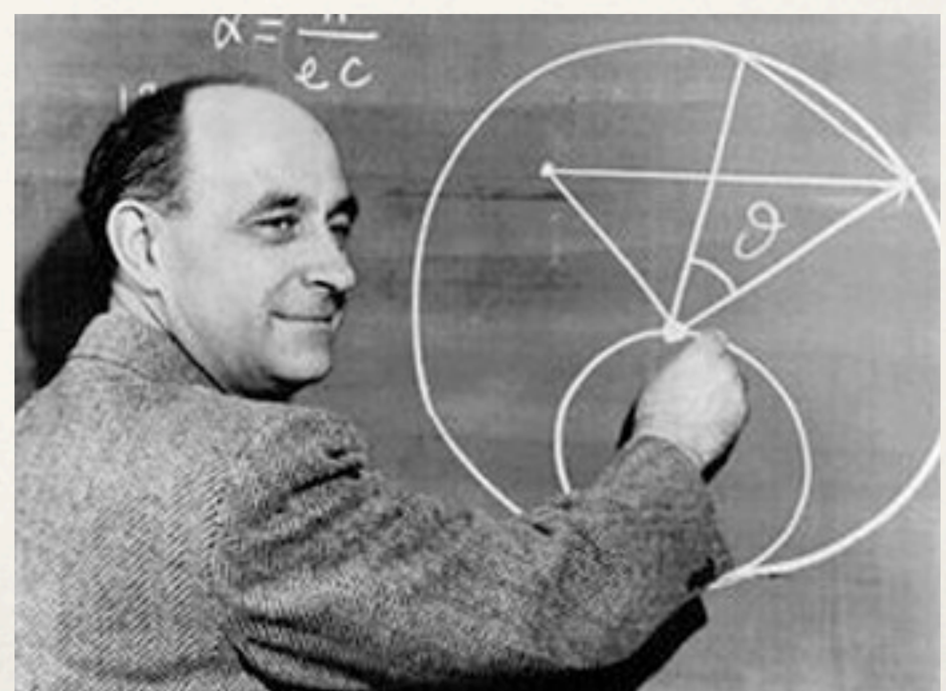


PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 19

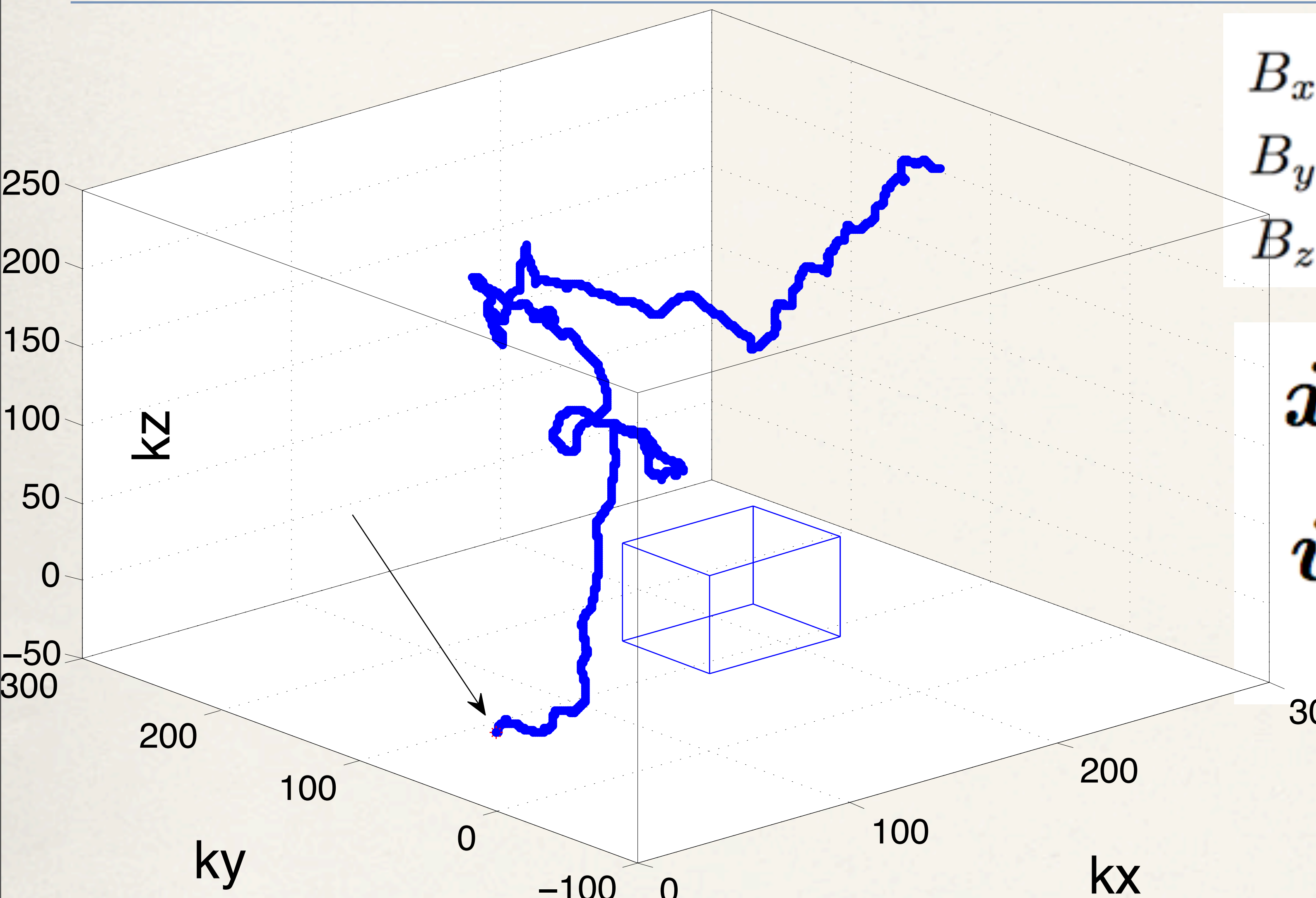
On the Origin of the Cosmic Radiation

ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magmetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.



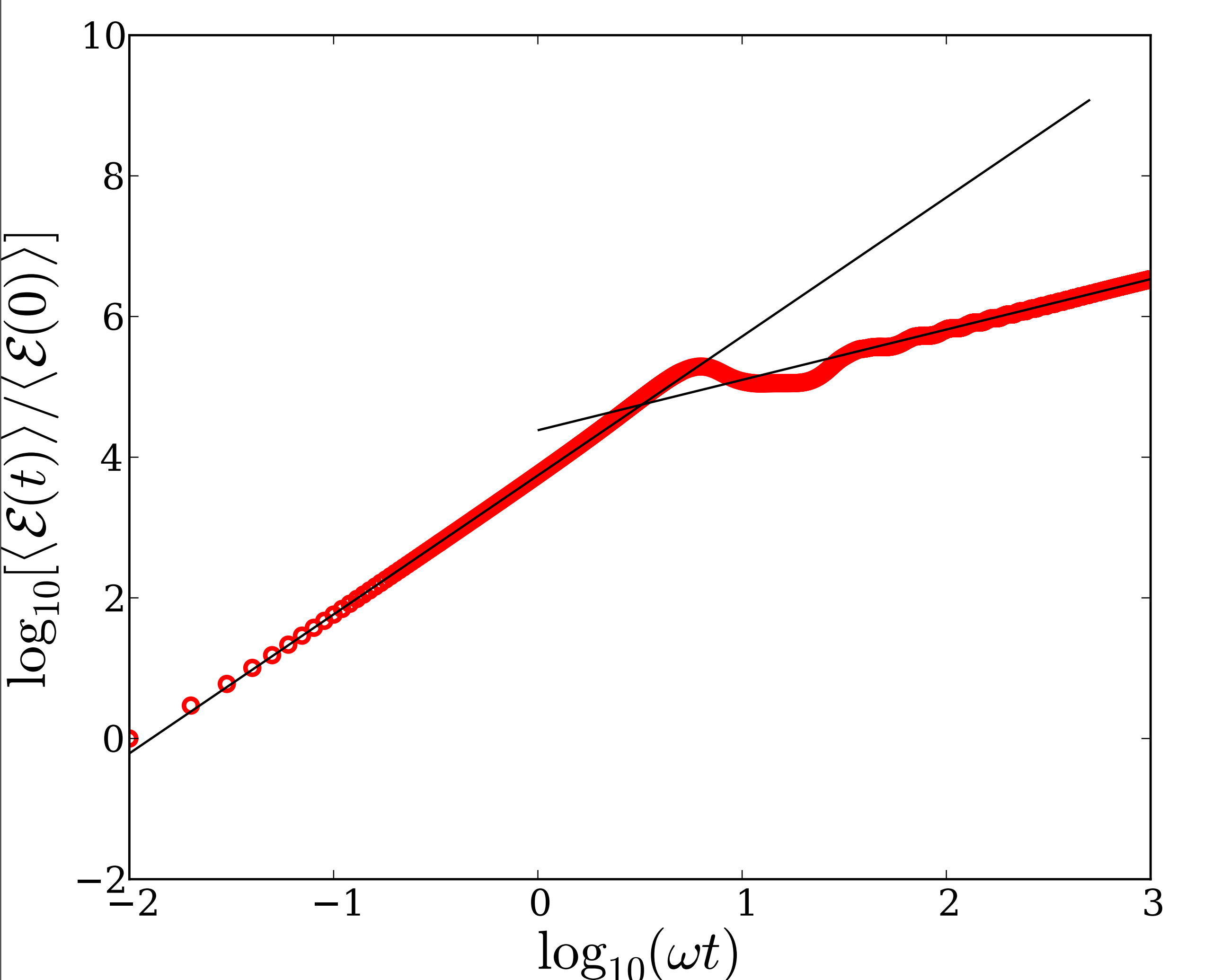
Model for moving magnetic field

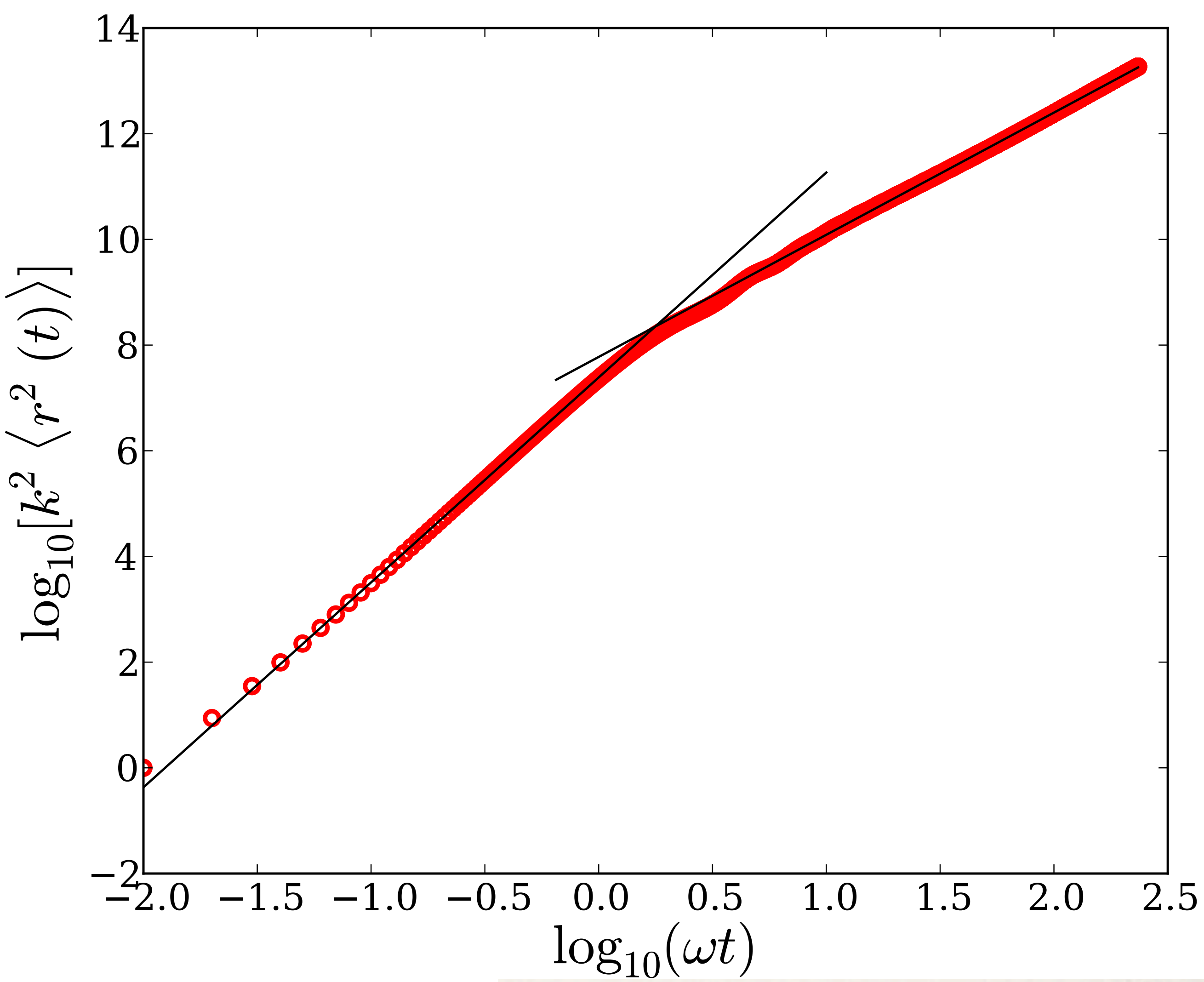


$$B_x = B_0(A\sin kz + C\cos ky)\sin\omega t,$$
$$B_y = B_0(B\sin kx + A\cos kz)\sin\omega t,$$
$$B_z = B_0(C\sin ky + B\cos kx)\sin\omega t,$$

$$\dot{\boldsymbol{x}} = \boldsymbol{v},$$
$$\dot{\boldsymbol{v}} = \frac{q}{m}\left(\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B}\right).$$

Energization





Run	R1	R2	R3	R4
ω	1/10	1/16	1/32	1/64
ξ	0.45	0.77	0.8	0.9

Charged particle in turbulence

$$\partial_t \boldsymbol{B} = \boldsymbol{\nabla} \times (\boldsymbol{U} \times \boldsymbol{B} - \eta \boldsymbol{J})$$

$$-\boldsymbol{\nabla} \times \boldsymbol{B} = \partial_t \boldsymbol{E}$$

$$\begin{aligned} \boldsymbol{E} &= -\partial_t \boldsymbol{A} \\ &= -(\boldsymbol{U} \times \boldsymbol{B} - \eta \boldsymbol{J}) \end{aligned}$$

$$\begin{aligned} \partial_t \boldsymbol{v} &= \frac{q}{m} [\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}] \\ &= \frac{q}{m} [(\boldsymbol{v} - \boldsymbol{U}) \times \boldsymbol{B} + \eta \boldsymbol{J}] \end{aligned}$$

Implementation in pencil code

```
logical :: lee_as_aux=.false.
logical :: lbb_as_aux=.false.,
```

```
if (lbb_as_aux .or. lbb_as_comaux) call register_report_aux('bb', ibb, ibx, iby, ibz,
```

```
dAdt = dAdt+ p%uxb+fres
```

```
if (lEE_as_aux ) f(l1:l2,m,n,iEEx :iEEz  )= -dAdt
```

```
! $Id: particles_charged dhruba.mitra@gmail.com$
!
!  This module takes care of everything related to
!
!** AUTOMATIC CPARAM.INC GENERATION **************
!
! Declare (for generation of cparam.inc) the numbe
! variables and auxiliary variables added by this
!
! MPVAR CONTRIBUTION 6
! MAUX CONTRIBUTION 2
! CPARAM logical, parameter :: lparticles=.true.
```

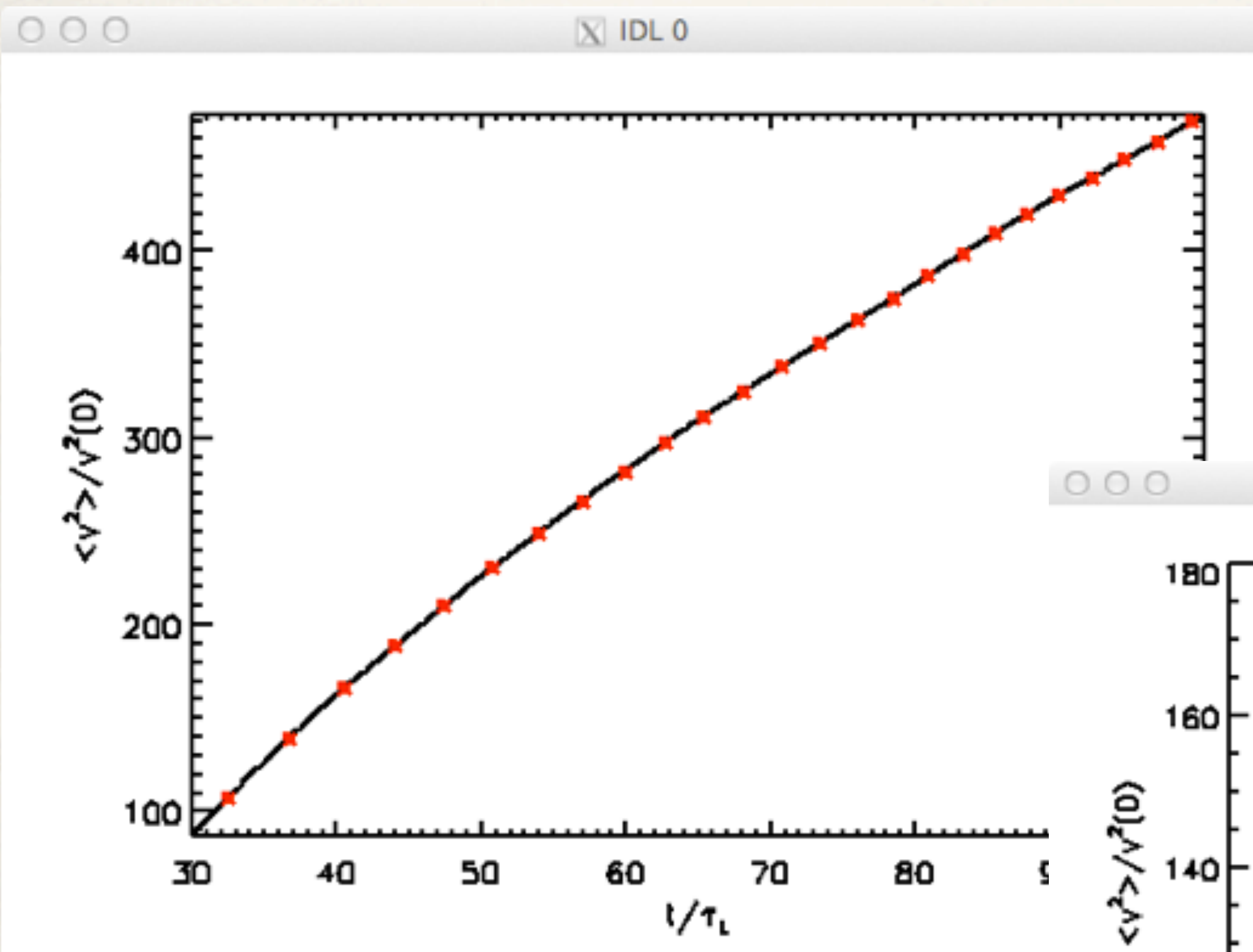
```
 subroutine dvvp_dt_pencil(f,df,fp,dfp,p,ineargrid)

Evolution of dust particle velocity (called from main pencil lo

25-apr-06/anders: codedg
```

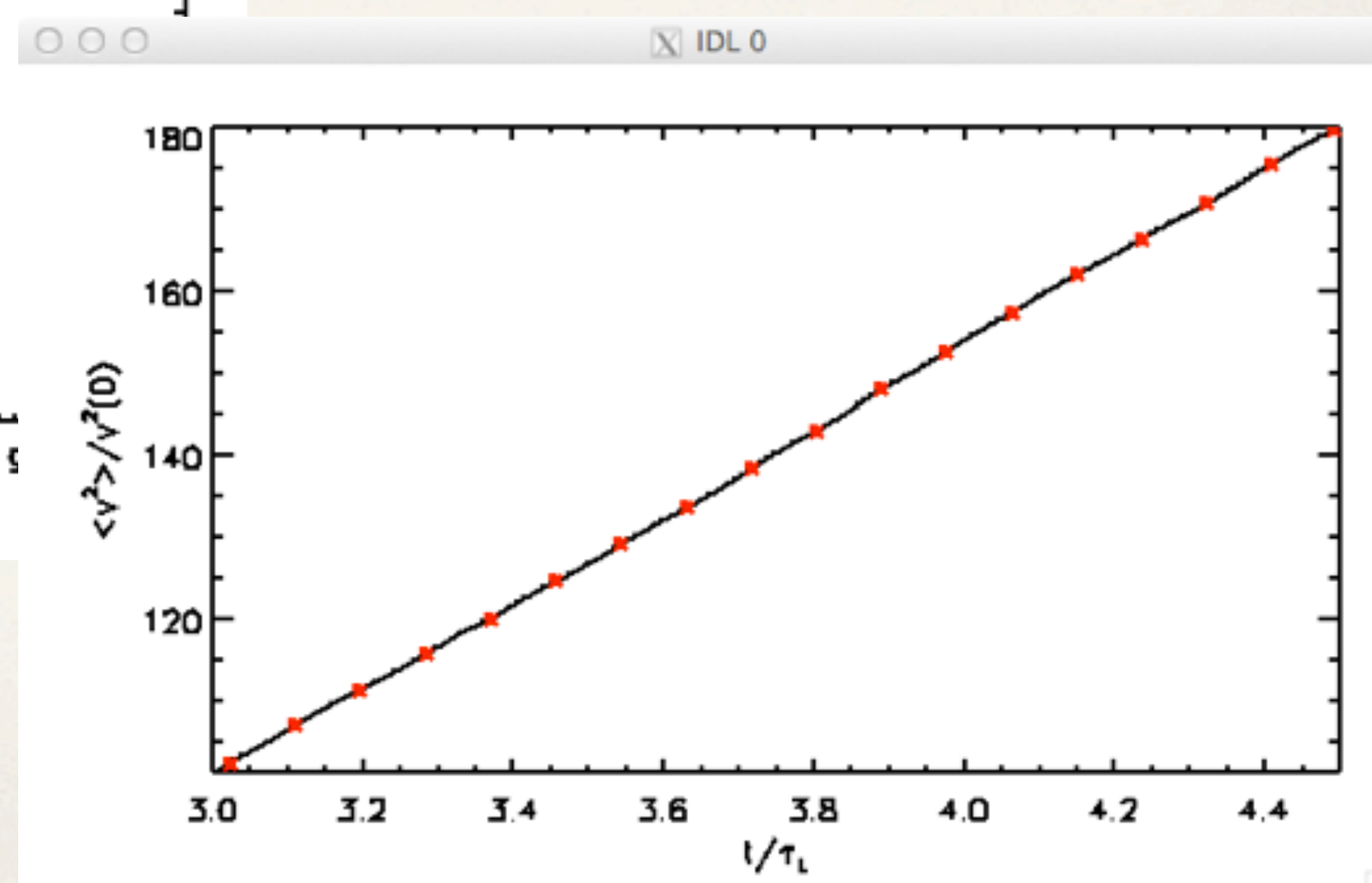
```
subroutine dvvp_dt_pencil(f,df,fp,dfp,p,ineargrid)

Evolution of dust particle velocity (called from main pencil loop).

25-apr-06/anders: codedg
```

```
    do k=k1_imn(imn),k2_imn(imn)

      ix0=ineargrid(k,1)
      iy0=ineargrid(k,2)
      iz0=ineargrid(k,3)

The interpolated gas velocity is either precalculated, and stored in
interp_uu, or it must be calculated here.

      call interpolate_linear(f,iEEx,iEEz,fp(k,ixp:izp), EEp,ineargrid(k,:),0,ipar(k))
      call interpolate_linear(f,ibx,ibz,fp(k,ixp:izp), bbp,ineargrid(k,:),0,ipar(k))
```

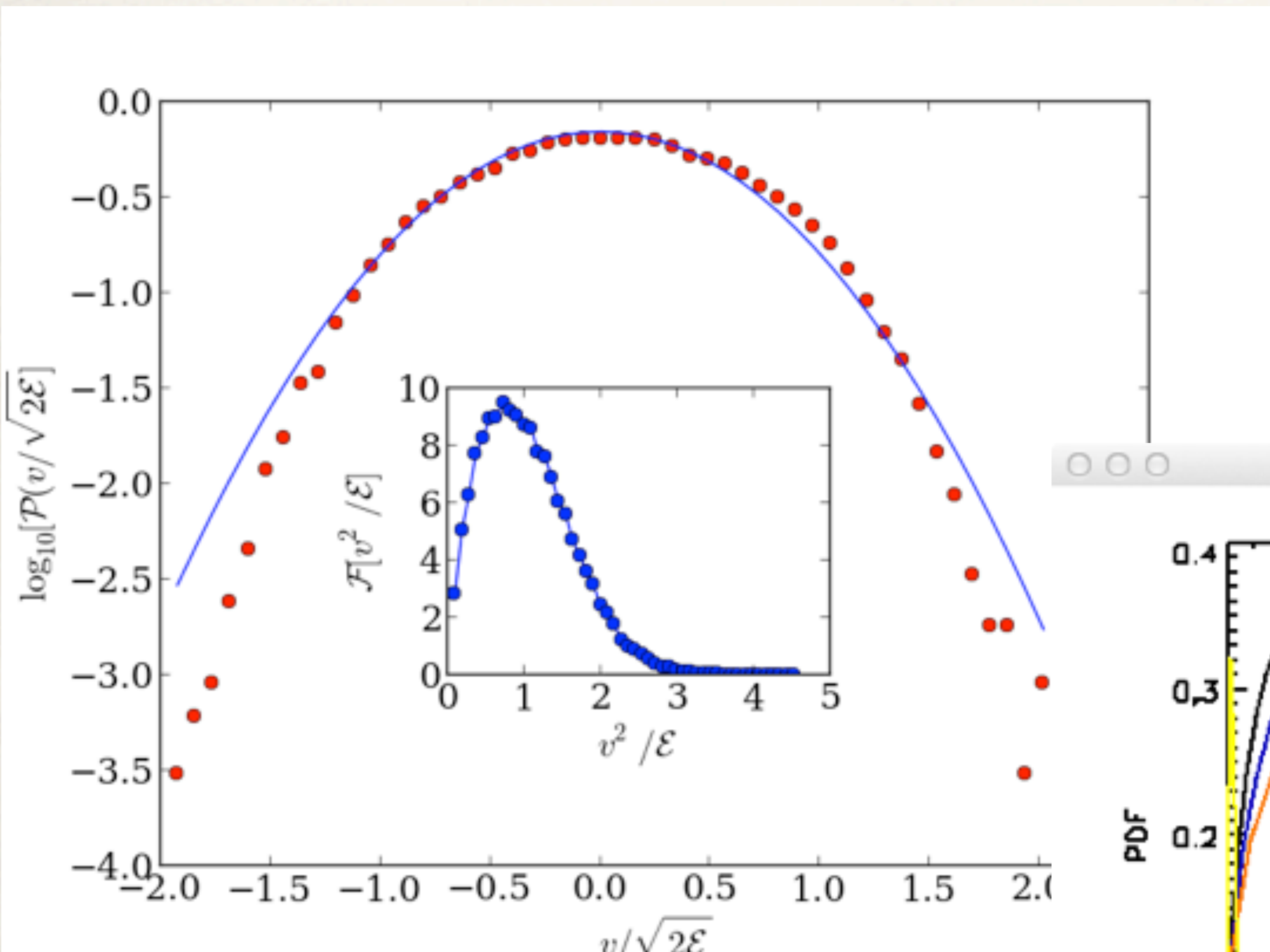
```
  velocity=fp(k,ivpx:ivpz)
  vsqr=velocity(1)*velocity(1) + &
    velocity(2)*velocity(2) + velocity(3)*velocity(3)
  vsqr_max=max(vsqr_max,vsqr)
  if (lonly_eforce) then
    accn = qbym*EEp
  else
    call cross(velocity,bbp,fmagnetic)
    accn = qbym*(EEp+fmagnetic)
  endif

  dfp(k,ivpx:ivpz) = dfp(k,ivpx:ivpz) + accn
```

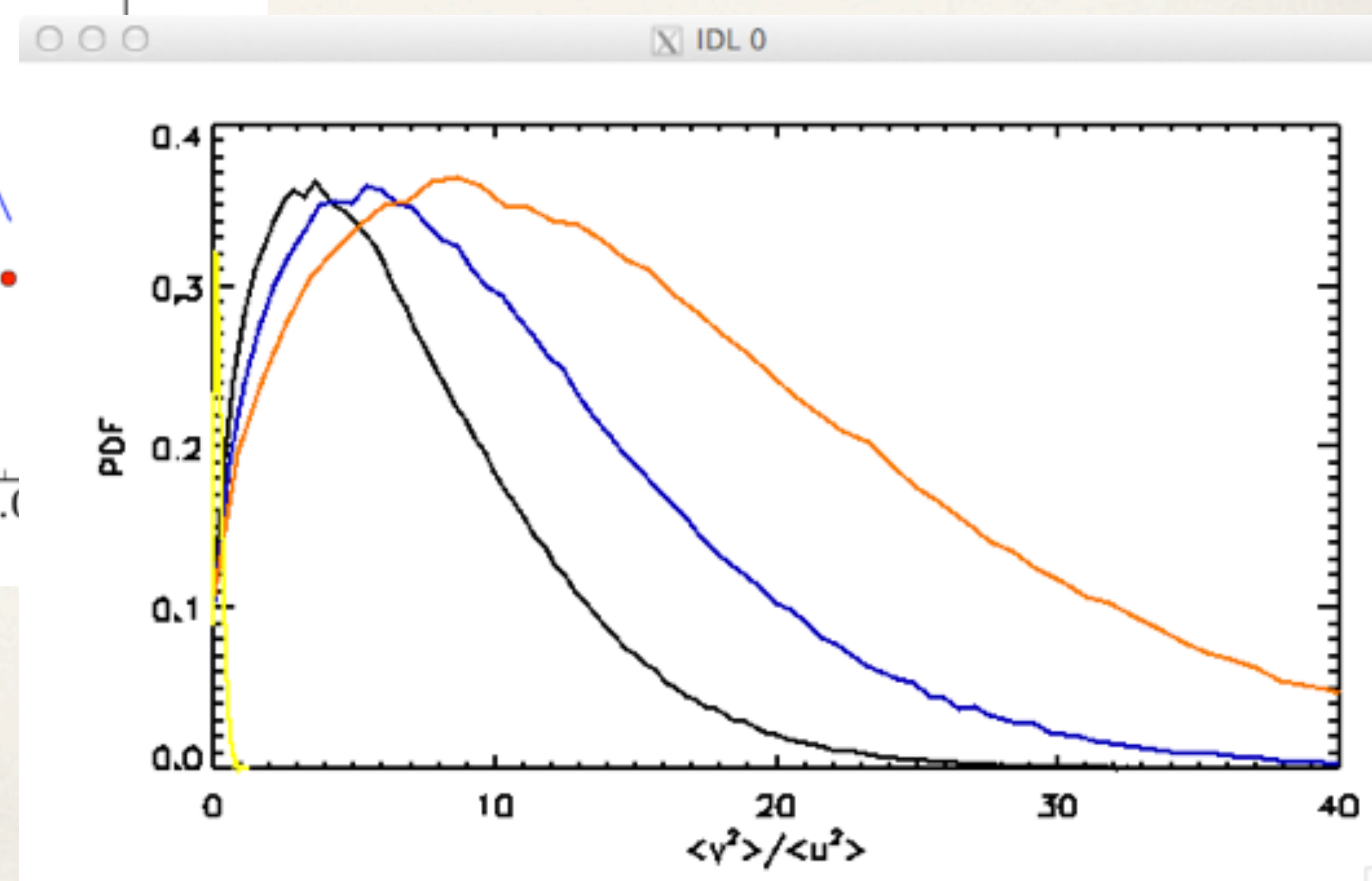
Energization by turbulence



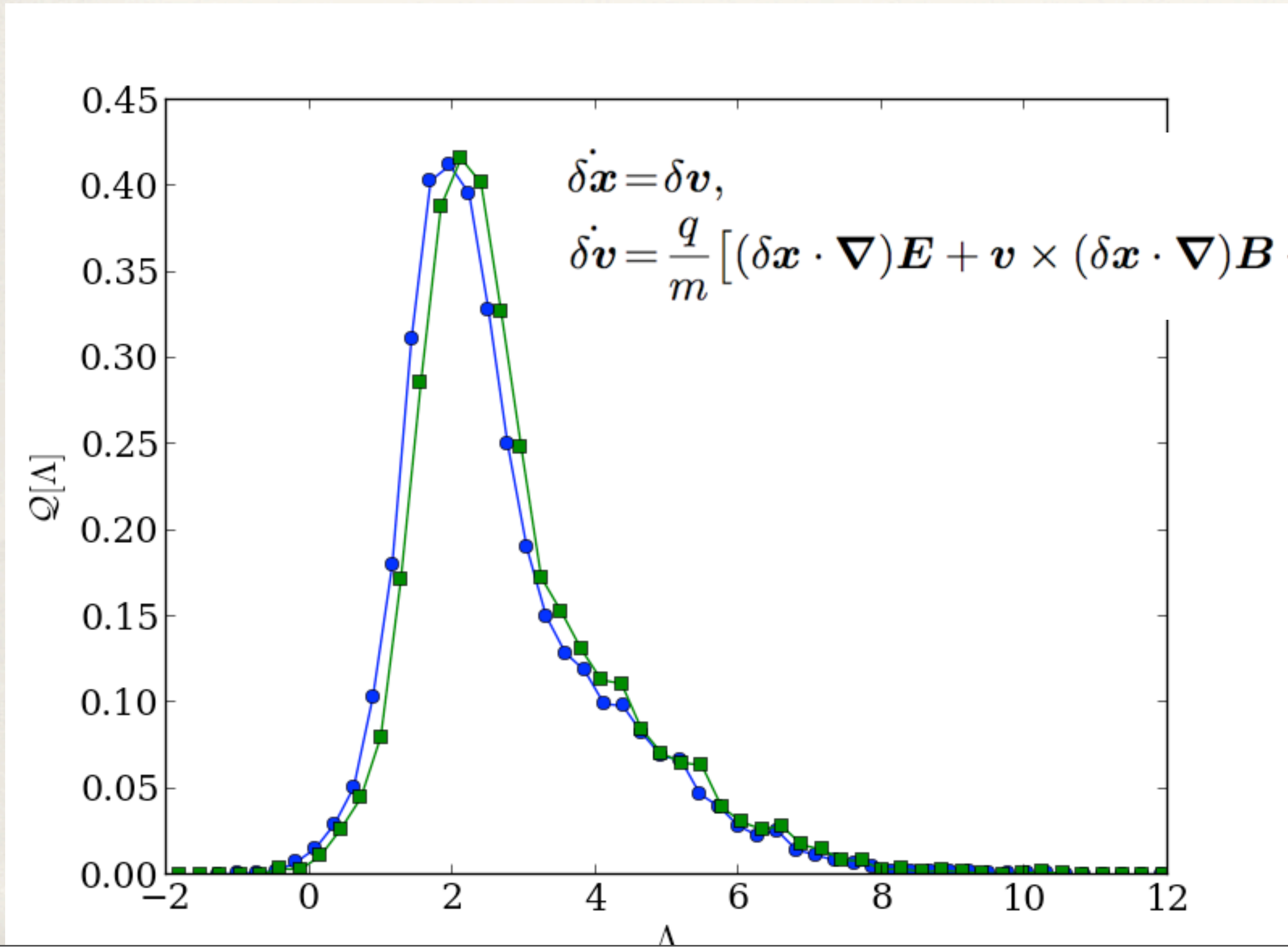


PDF of energies





chaotic motion ?



$$\dot{\delta \boldsymbol{x}} = \delta \boldsymbol{v},$$
$$\dot{\delta \boldsymbol{v}} = \frac{q}{m}\left[(\delta \boldsymbol{x} \cdot \boldsymbol{\nabla})\boldsymbol{E} + \boldsymbol{v} \times (\delta \boldsymbol{x} \cdot \boldsymbol{\nabla})\boldsymbol{B} + \delta \boldsymbol{v} \times \boldsymbol{B}\right].$$

Speculations

- The properties of the dynamical system defined by the charged particles.
- Do they cluster, in real space or phase space ?
- Analogies with equation of dust particles.

$$\begin{aligned}
\partial_t \boldsymbol{x} &= \boldsymbol{v} \\
\partial_t \boldsymbol{v} &= \frac{q}{m}(\boldsymbol{v} - \boldsymbol{U}) \times \boldsymbol{B} \\
\partial_t \boldsymbol{v} &= \frac{1}{\tau_{\mathrm{p}}}(\boldsymbol{U} - \boldsymbol{v})
\end{aligned}$$