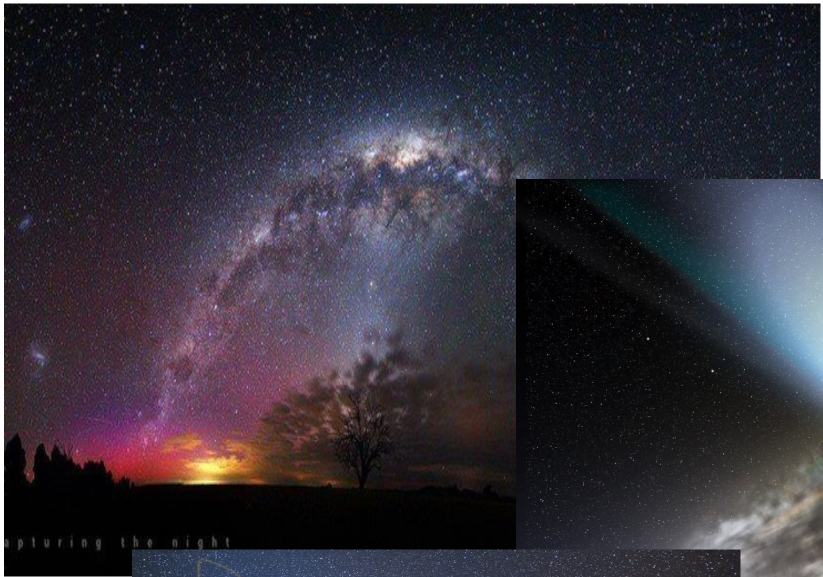
Acceleration of Charged Grains in Dusty Plasma

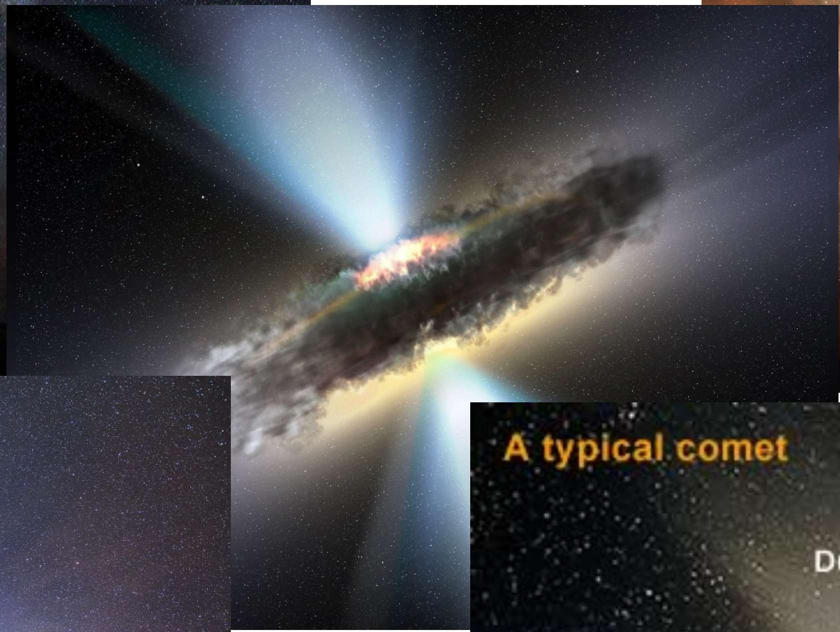
Thiem Hoang (KASI & UST)

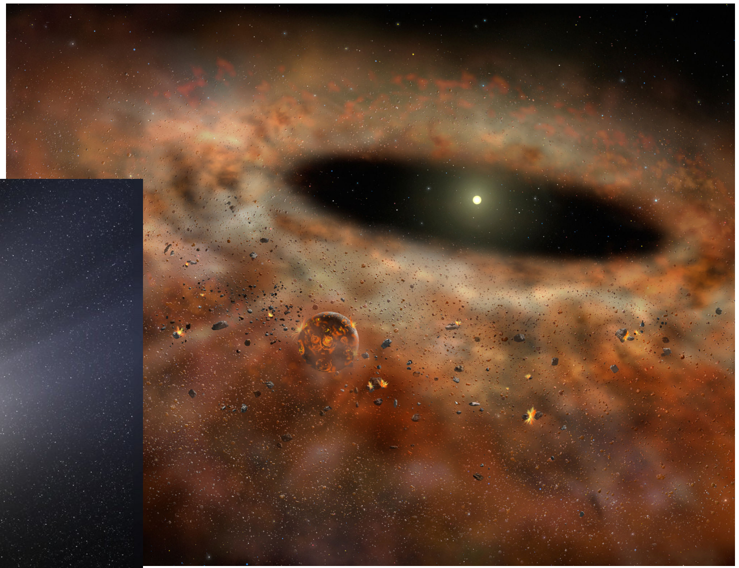
Thanks to A. Lazarian, R. Schlickeiser, A. Ivlev, & Avi Loeb

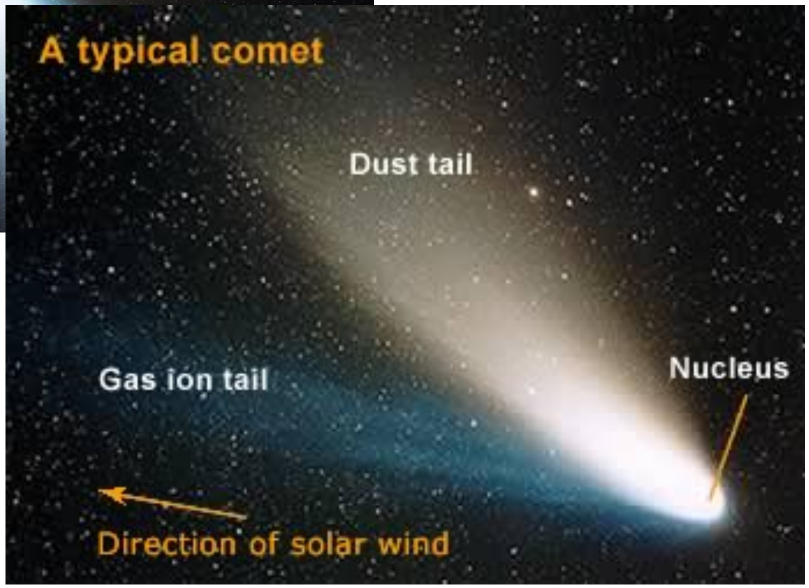
CNU, Daejeon, July 30-Aug 3, 2018

Space and Astrophysical Plasma is Dusty





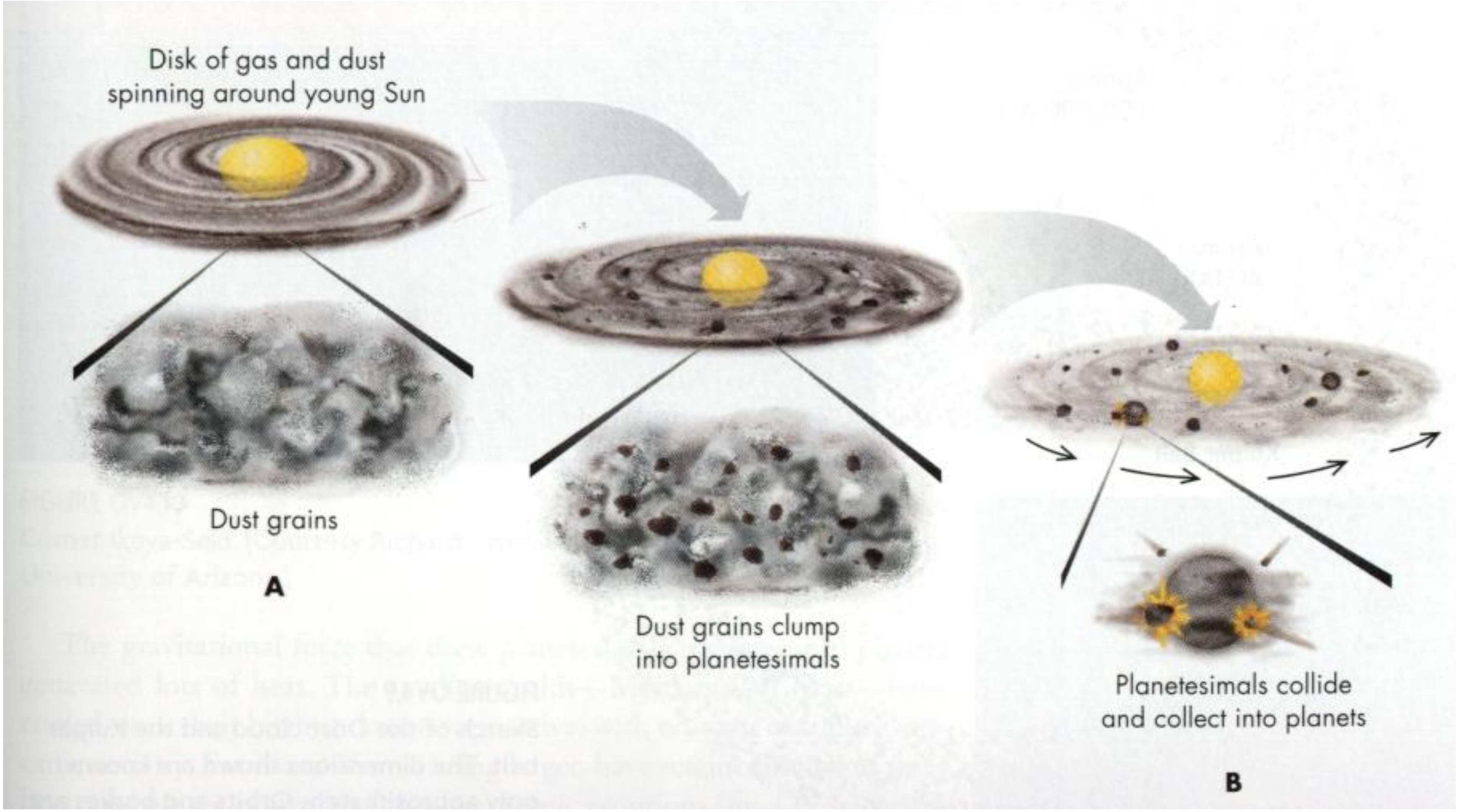




Outline

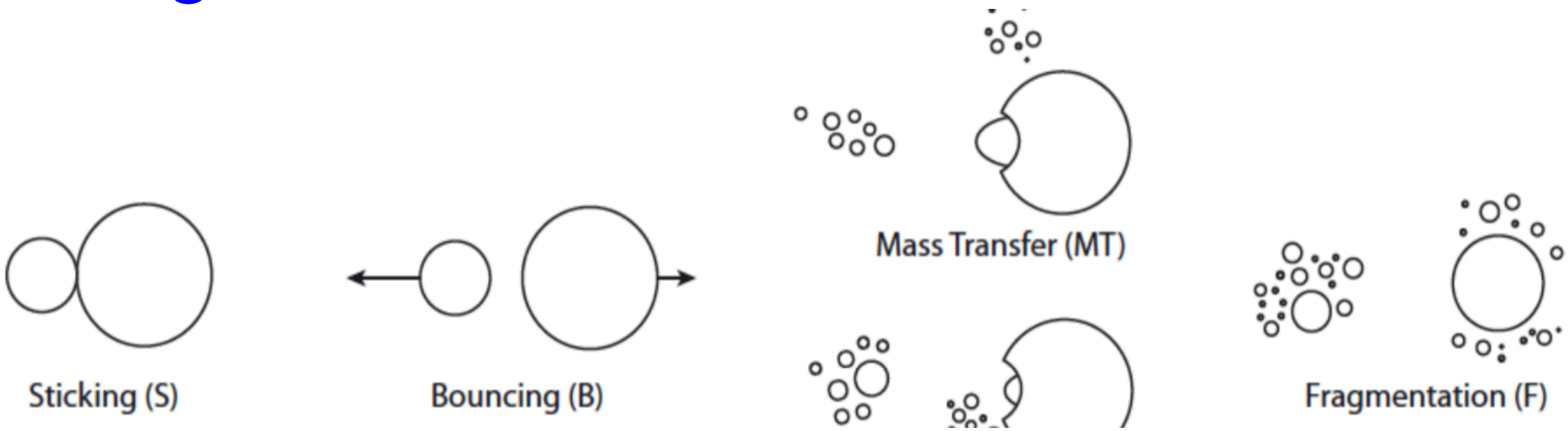
- Why do we care about dust grain motion?
- Acceleration of nanodust grains by charge fluctuations
- Acceleration of charged grains by MHD turbulence
- Acceleration by strong radiation pressure (grain and nanospacecraft)
- Summary and discussion

Grain Growth and Planetesimal Formation

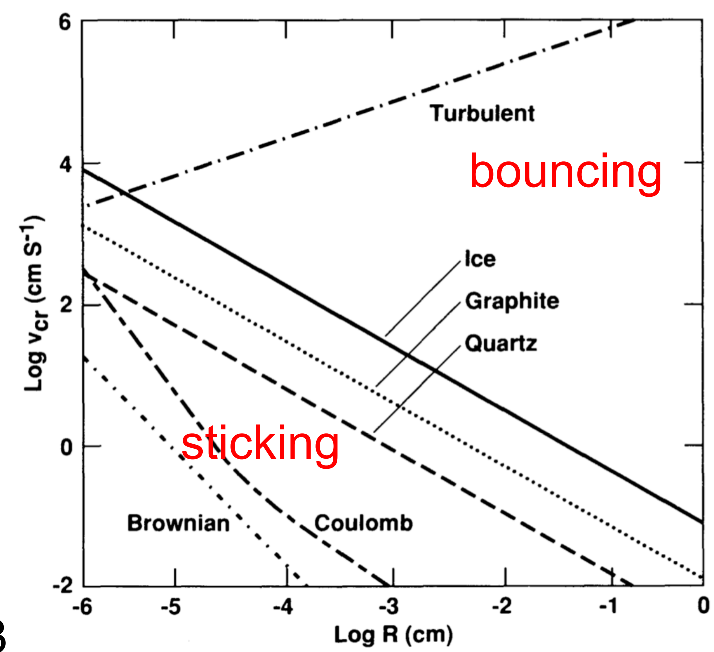


- Note: Planetesimal formation mechanism still unclear!

Grain velocity determines the outcome of grain collisions and dust evolution



relative velocity



Chokshi, Tielens & Hollenbach 1993

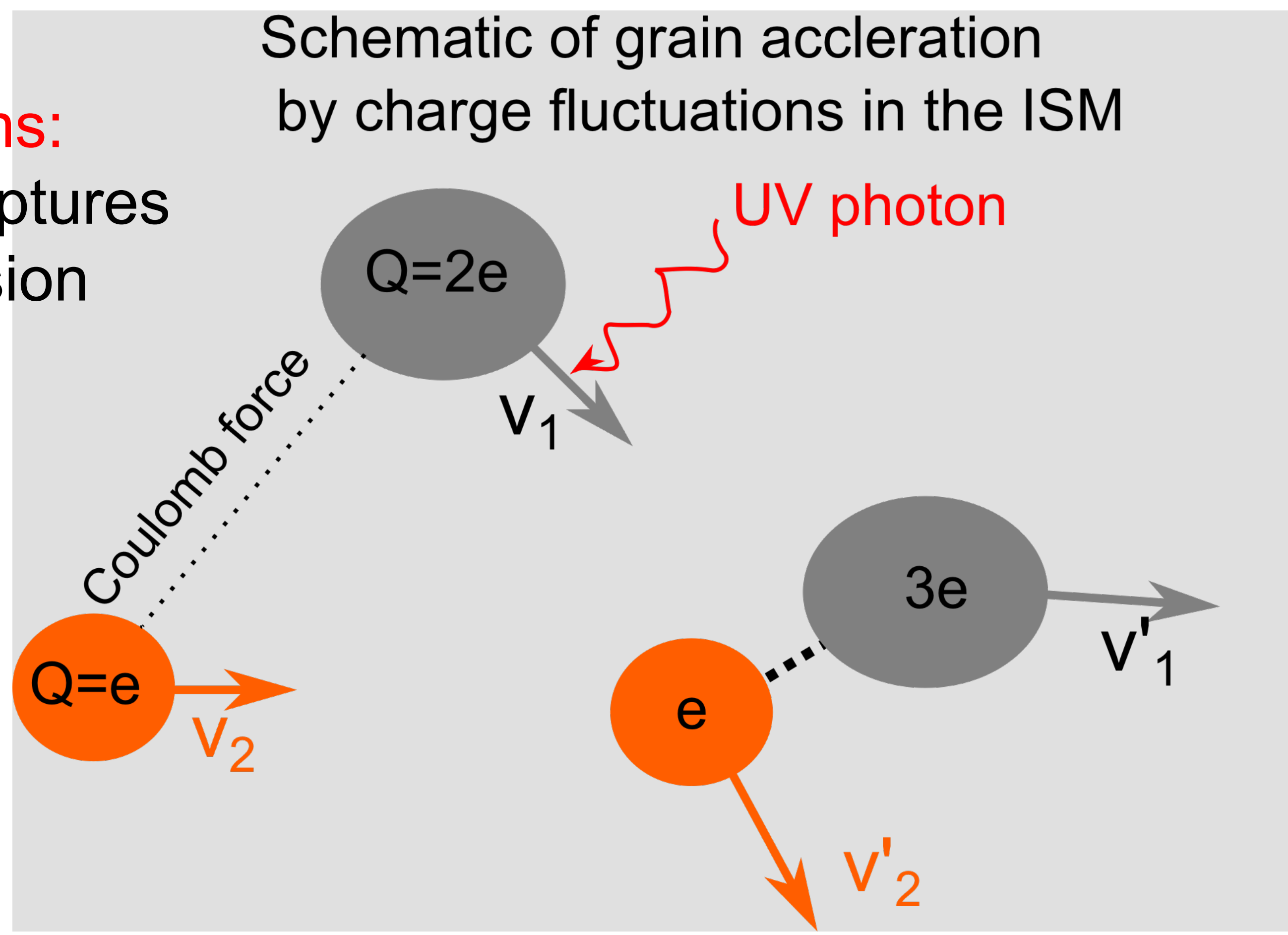
Acceleration of Nanodust Grains by Charge Fluctuations

Charging and Charge Fluctuations

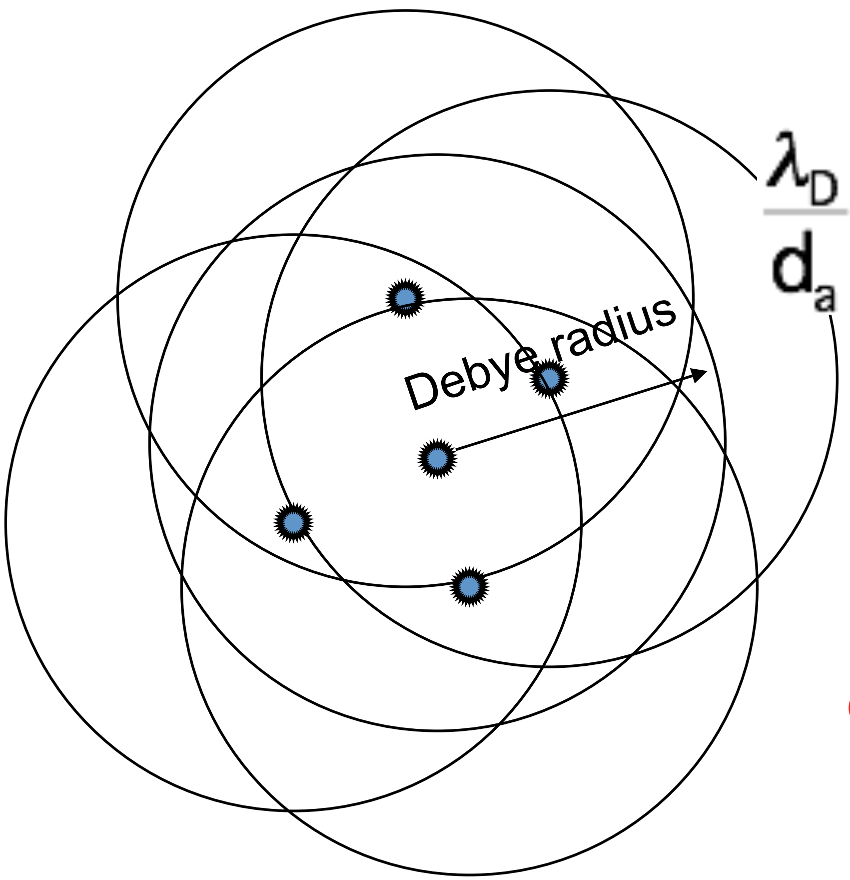
Charging mechanisms:

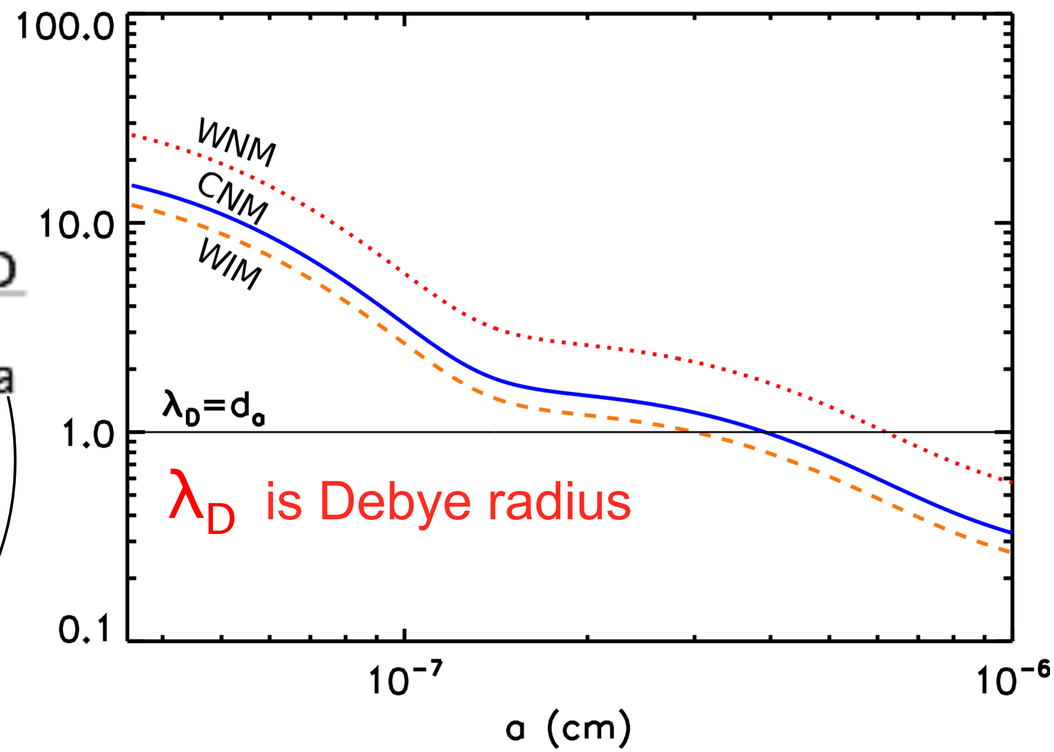
- Ion and electron captures
- Photoelectric emission
- CRs ionization

Dust grains have charge fluctuations due to discrete charging nature



Acceleration due to Charge Fluctuations





d_a is the mean distance between 2 grains

Grain experiences random electric force, resulting in acceleration, similar to 2nd Fermi mechanism

Ivlev, Lazarian, & Hoang, et al. 2010

Fokker-Planck Equation Approach

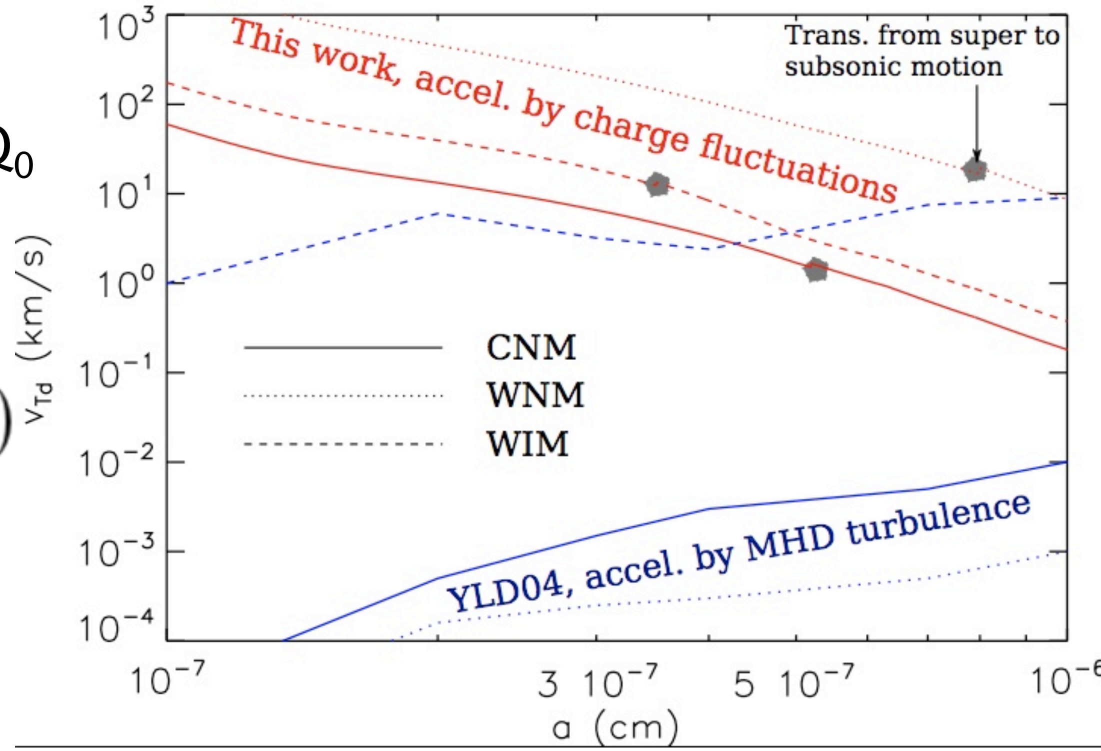
Ivlev, Lazarian, & Hoang 2010

- Assumptions:

➢ fast charge fluctuations,
➢ small charge dispersion: $\delta Q < Q_0$

$$\langle \delta Q(t+\tau)\delta Q(t)\rangle = \sigma_Q^2 e^{-\nu_{ch}|\tau|}$$

$$\delta\varepsilon_r \approx \frac{\sigma_Q^2}{m_d \nu_{ch}} \int \left|\frac{d\varphi_0}{dr}\right|^2 dt + O\left(\nu_{ch}^{-2}\right)$$



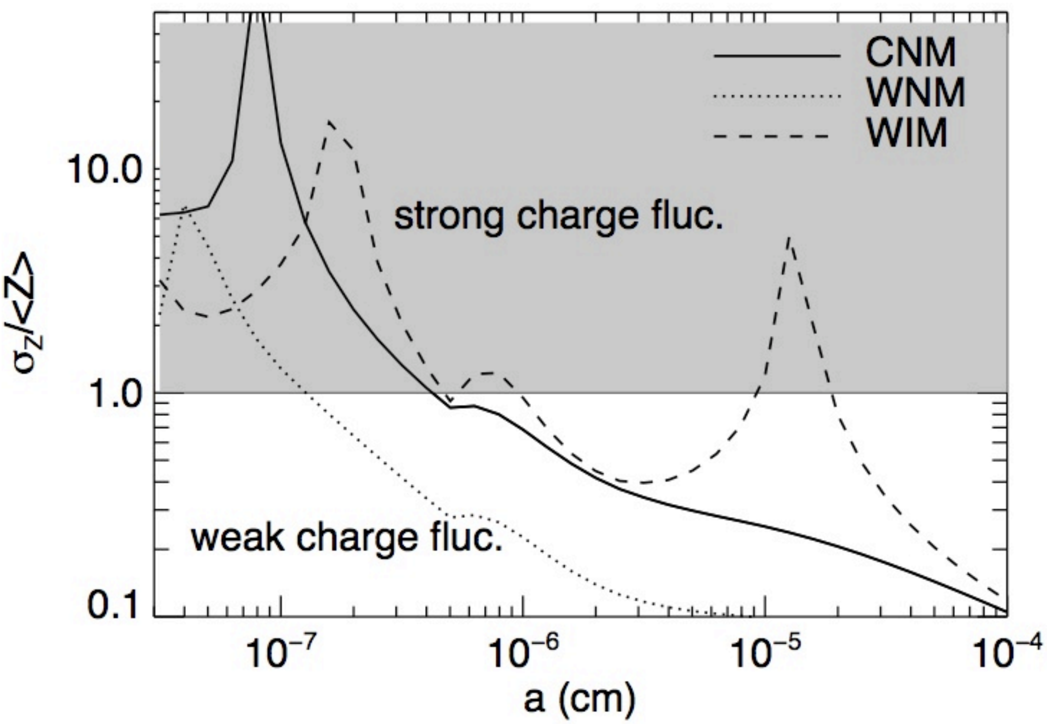
Terminal velocity:

$$\frac{T_d^\infty}{T_i} \sim \frac{n_i}{n_n}\frac{\lambda_D^4 n_d(a)}{a}$$

- Nanoparticles can move supernonic
- Nanoparticles easily destroyed upon collisions

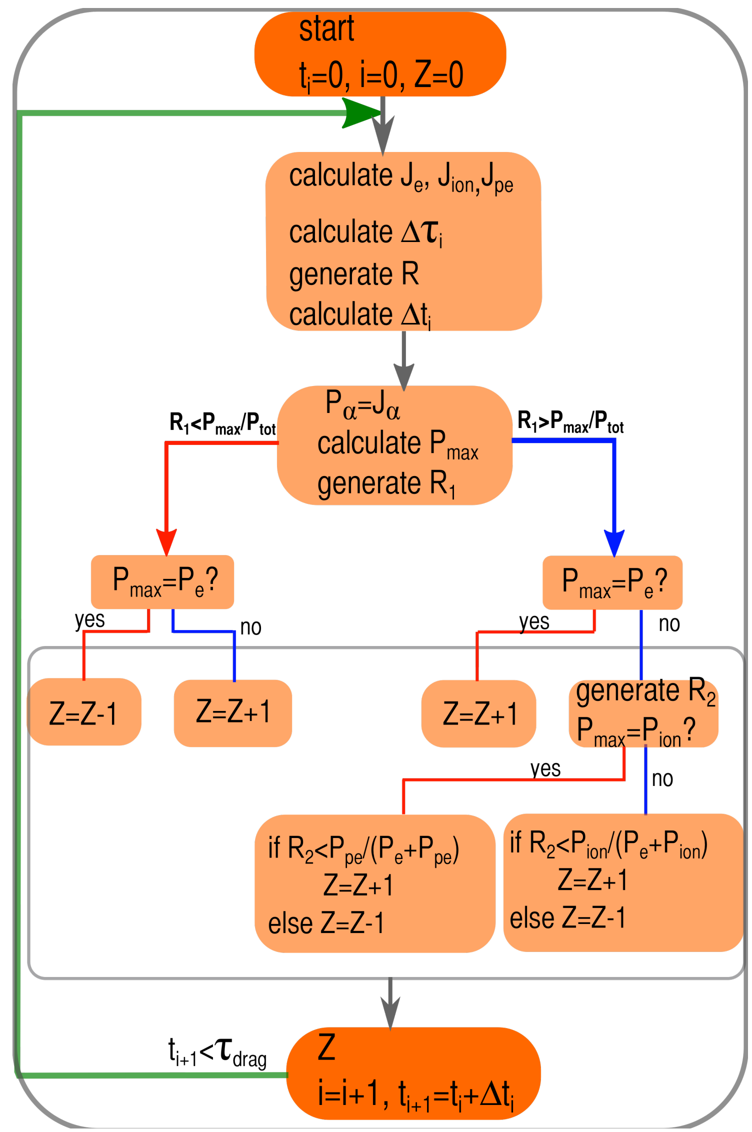
Strong, slow Charge Fluctuations

Charge fluctuations in the ISM

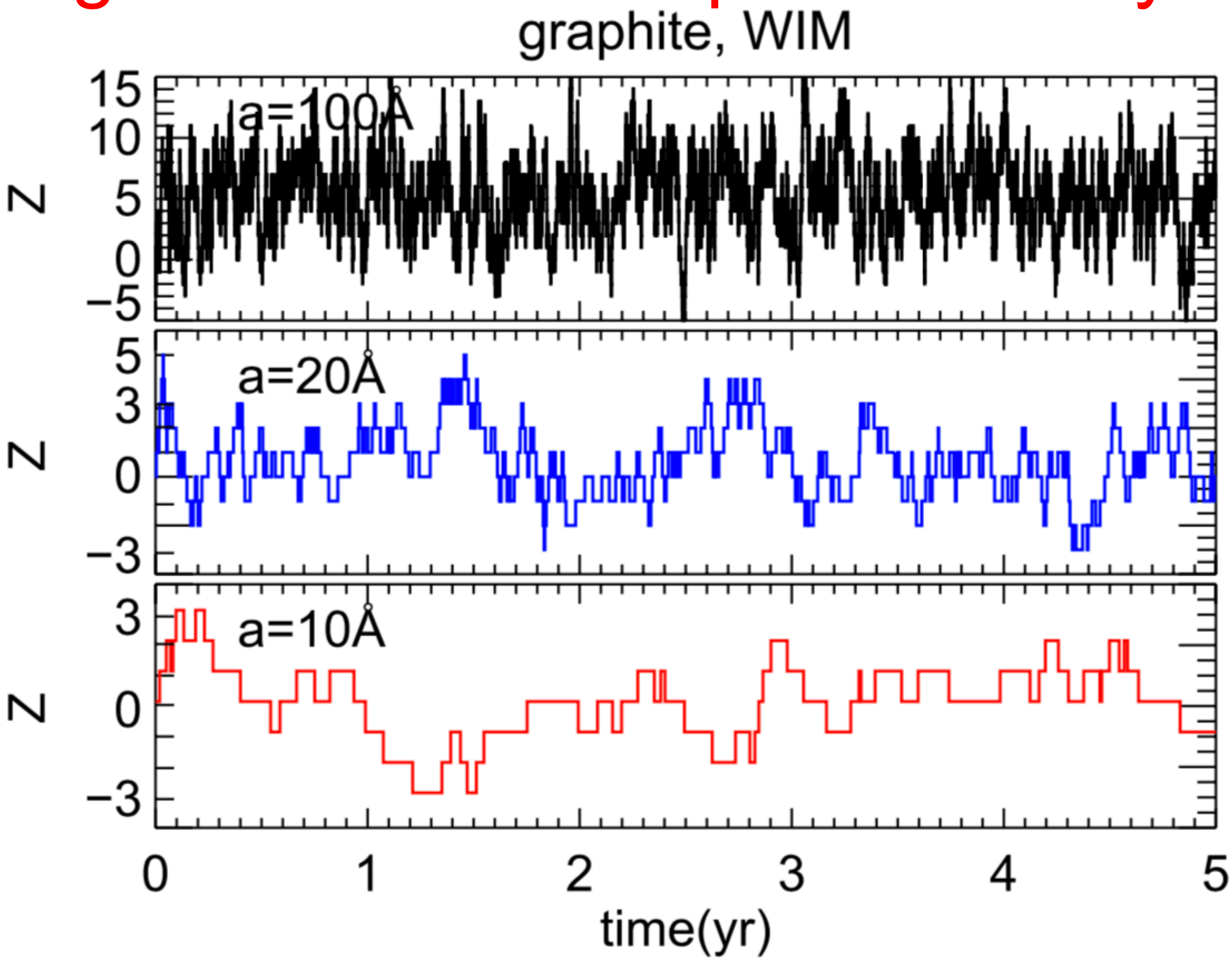


Hoang & Lazarian (2012)

Monte Carlo Simulation



- Charge state of a nanoparticle in 5 years



Hoang & Lazarian (2012)

Grain-in-Cell (GIC) Simulation

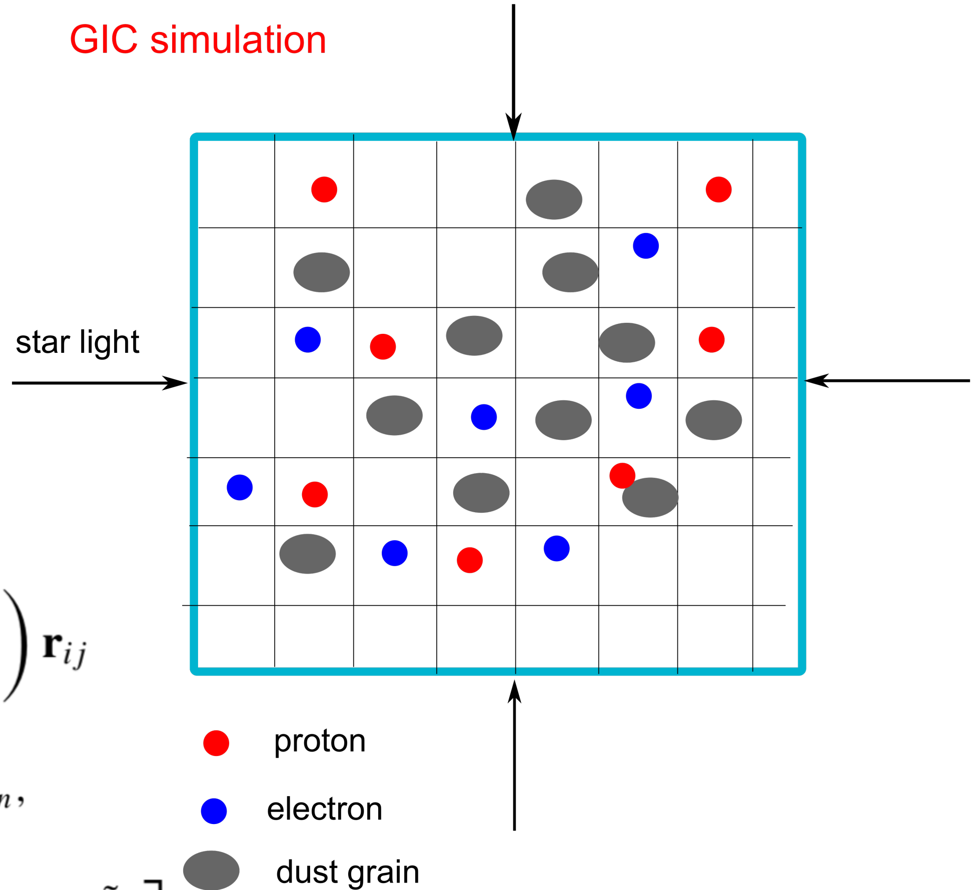
Equation of Motion

$$\frac{d\mathbf{v}_i}{dt} = -\frac{\mathbf{v}_i}{\tau_{\rm drag}} + R_i + \frac{\mathbf{F}_i}{m_i}$$

random Coulomb force:

$$\mathbf{F}_i(\mathbf{r}, t) = \sum_{j\neq i} \nabla \frac{Q_i(t)Q_j(t)\exp(-r_{ij}/\lambda)}{\mathbf{r}_{ij}}$$

$$= \sum_{j\neq i} Q_i(t)Q_j(t)\frac{\exp(-r_{ij}/\lambda)}{r_{ij}^2}\left(\frac{1}{\lambda}+\frac{1}{r_{ij}}\right)\mathbf{r}_{ij}$$



Numerical Algorithm

$$\tilde{\mathbf{r}}_{n+1} = \mathbf{r}_n + \mathbf{v}_n h_n,$$

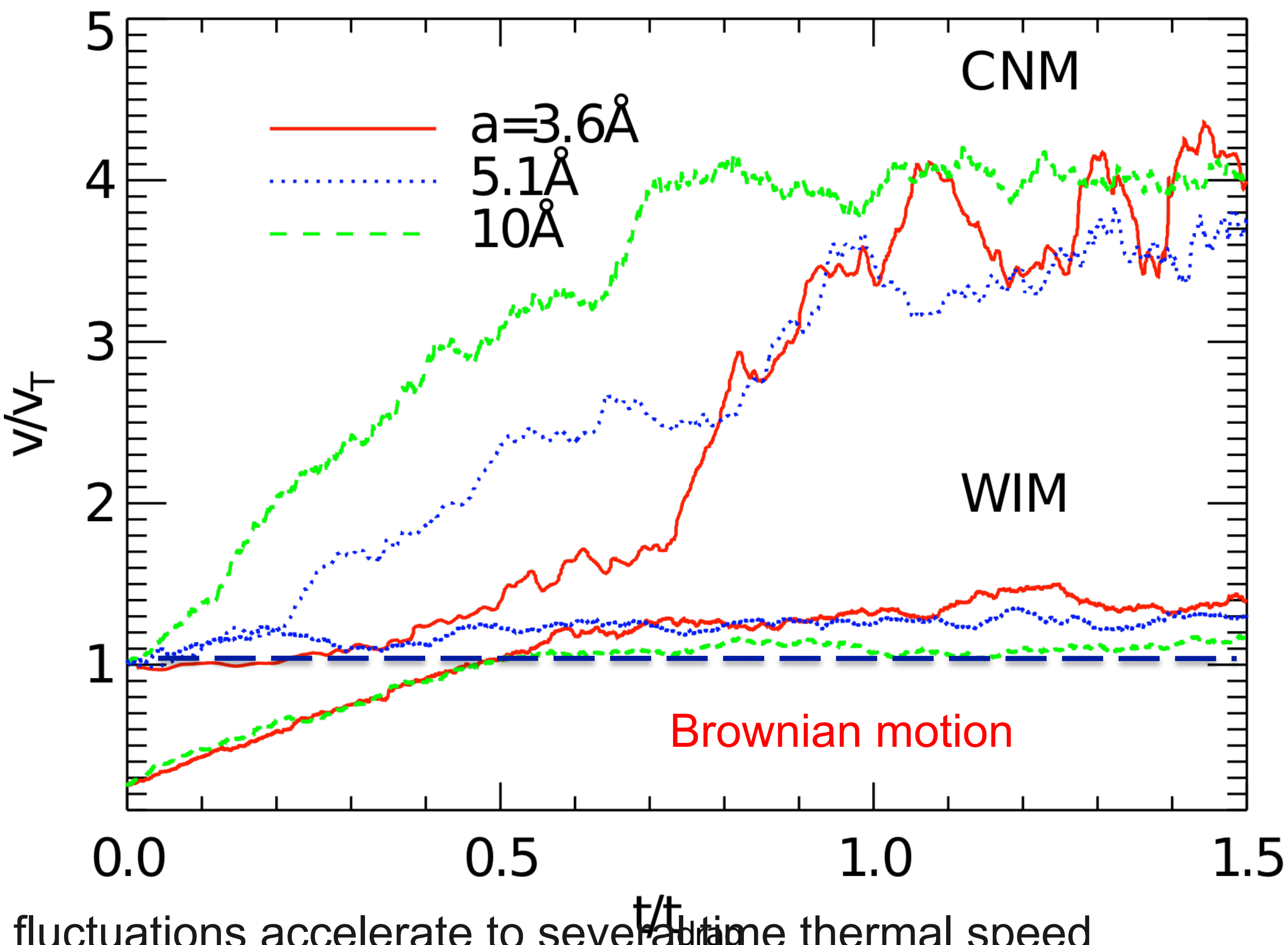
$$\mathbf{v}_{n+1} = \mathbf{v}_n + \left[-\frac{\mathbf{v}_n}{\tau_{\rm drag}} + R_i + \frac{\mathbf{F}_i + \tilde{\mathbf{F}}_i}{2m_i}\right] h_n$$

$$\mathbf{r}_{n+1} = \mathbf{r}_n + \frac{1}{2}\left(\mathbf{v}_n + \mathbf{v}_{n+1}\right) h_n,$$

$$\mathbf{F}_i = \mathbf{F}_i(\mathbf{r}_n, t_n) \text{ and } \tilde{\mathbf{F}}_i = \mathbf{F}_i(\tilde{\mathbf{r}}_{n+1}, t_n).$$

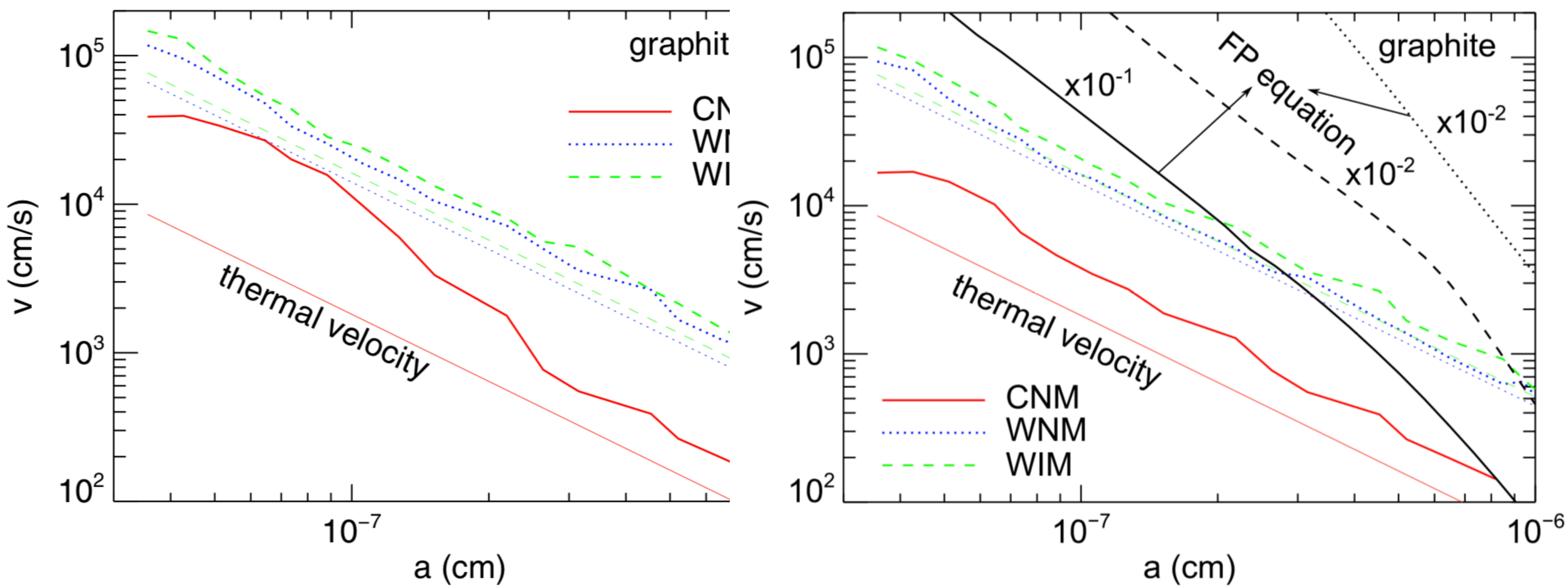
Hoang & Lazarian (2012)

Results from GIC Simulations



- Charge fluctuations accelerate to several time thermal speed
- The mechanism is more efficient for CNM than WIM because CNM have
  - -longer Debye screen length than WIM
  - -larger charge dispersion

GIC simulations vs. Fokker-Planck



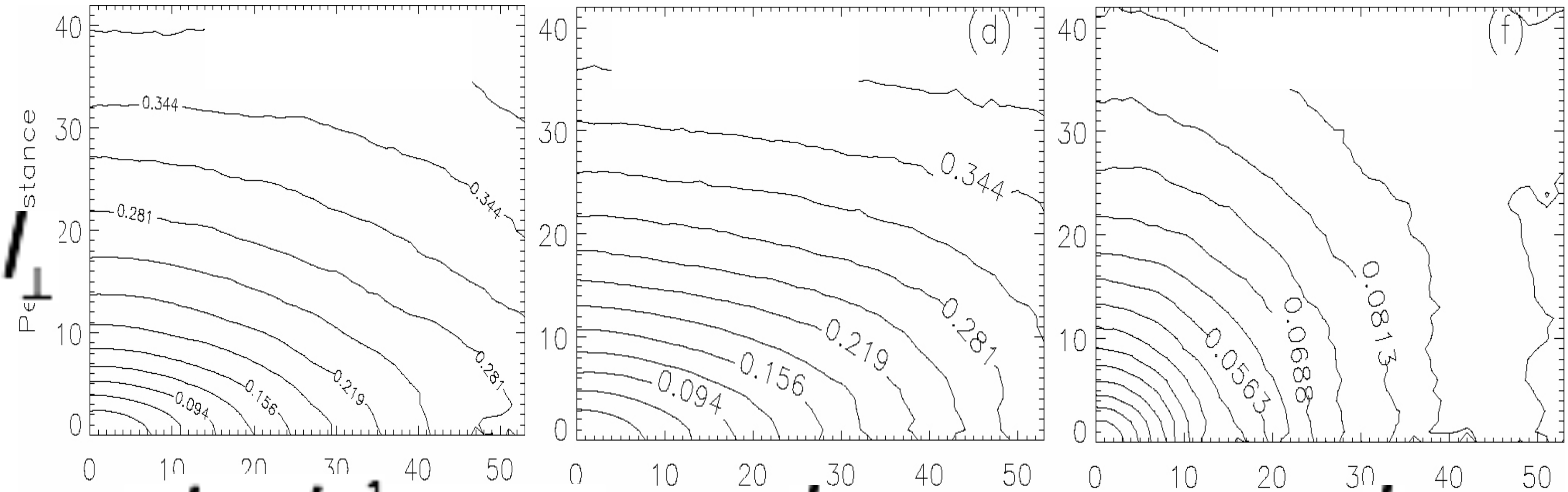
- GIC simulations predict lower efficiency than Fokker-Planck (FP) approach
- In the ISM, charge fluctuations are slow, but high dispersion, not valid for FP

Hoang & Lazarian (2012)

Acceleration of Charged Grains by MHD Turbulence

Alfven, slow and fast modes in MHD Turbulence

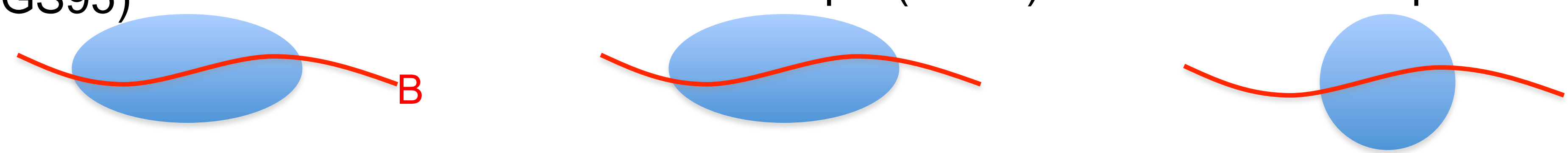
Alfven$\sim k^{-5/3}$ slow $\sim k^{-5/3}$ fast $\sim k^{-3/2}$



$l_\perp$

$l_\parallel \sim k_\parallel^{-1}$ $l_\parallel$ $l_\parallel$

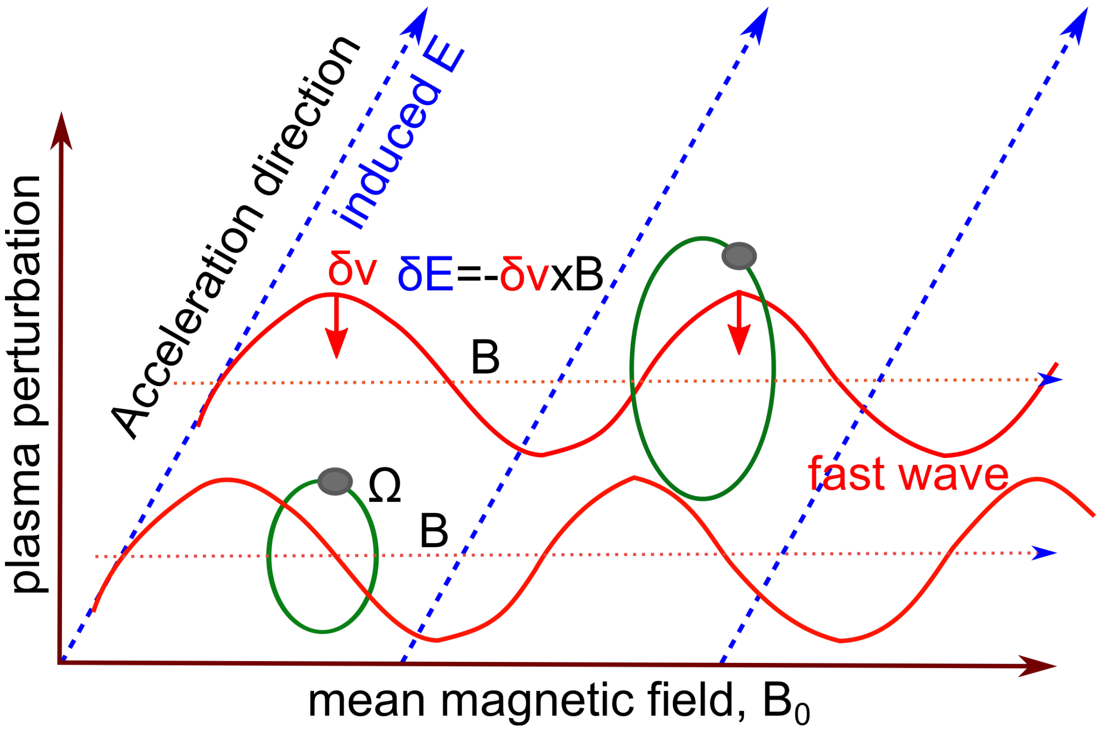
anisotropic (GS95) anisotropic (GS95) isotropic



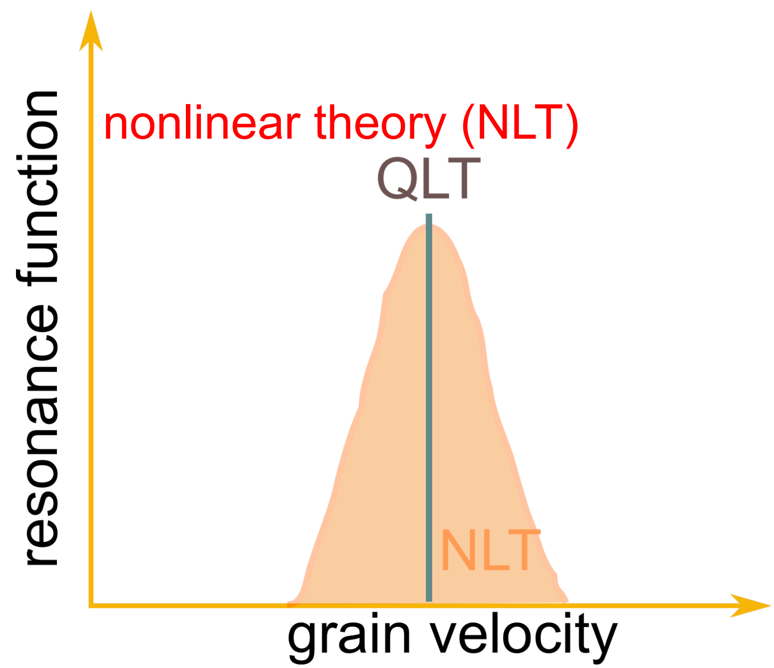
Contours of equal correlation are shown

Cho & Lazarian 02, 03

NLT Resonance Acceleration by MHD Turbulence



QLT:
Lazarian & Yan (2002), YL03
Yan, Lazarian & Draine (2004)



Resonance condition in quasilinear theory (QLT): $\omega - k_{\|} v \mu = n\Omega$

n=0, ±1,±2, …

See Brunetti's talk

Hoang, Lazarian, & Schlickeiser (2012)

NLT Gyroresonant Acceleration

Equation of Motion

$$m\frac{d\langle v^2\rangle}{dt} = -\frac{m\langle v^2\rangle}{t_{\rm damp}} + A(v),$$

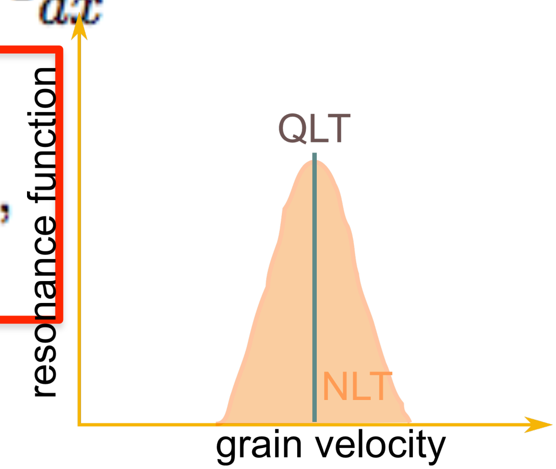
$$A(v) = \frac{1}{4p^2}\frac{\partial}{\partial p}\left(vp^2 D_p(p)\right),$$

$$D_p(p) = \frac{1}{2}\int_{-1}^{1} D_{pp}(\mu, p)d\mu.$$

$$D_{pp}(\mu,p)^{\rm G} = \frac{v\sqrt{\pi}\Omega^2(1-\mu^2)m^2V_{\rm A}^2M_{\rm A}^2}{2LR^2}\int_1^{k_cL}x^{-5/2}dx$$

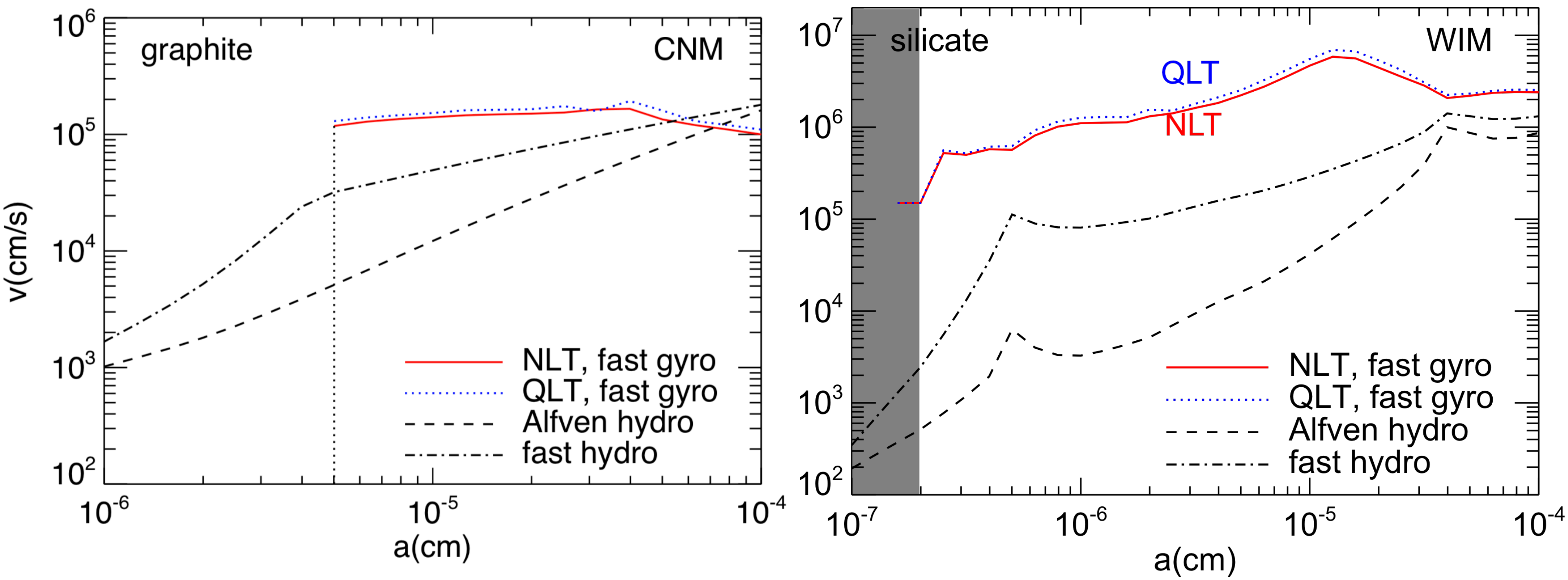
$$\times\int_0^1\frac{d\eta}{\eta\Delta\mu}[J_0^2(w)+J_2^2(w)]\exp\left[-\frac{(\mu-\frac{V_A}{\eta v}\pm\frac{1}{\eta xR})^2}{(\Delta\mu)^2}\right],$$

resonance function



Hoang, Lazarian & Schlickeiser (2012)

NLT Gyroresonant Acceleration



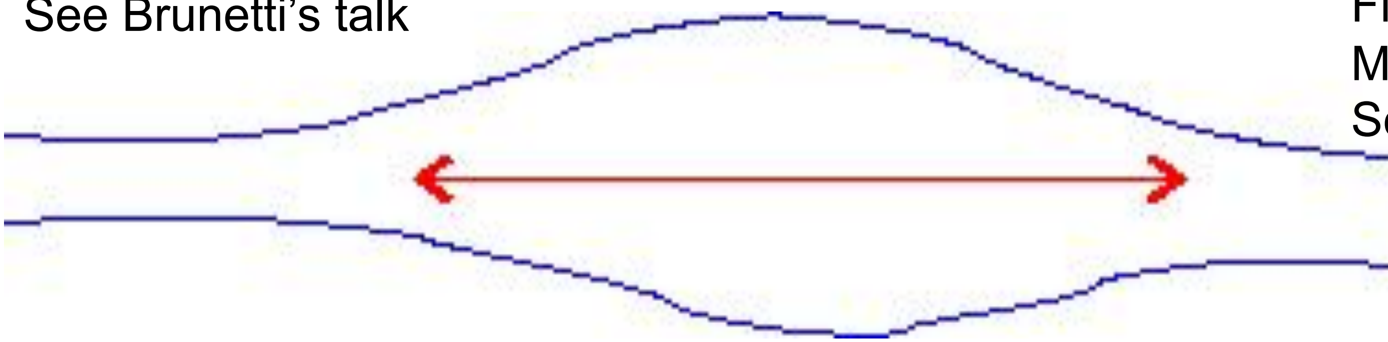
- *QLT is good approximation for gyroresonance acceleration*
- *QLT not adequate for TTD acceleration*

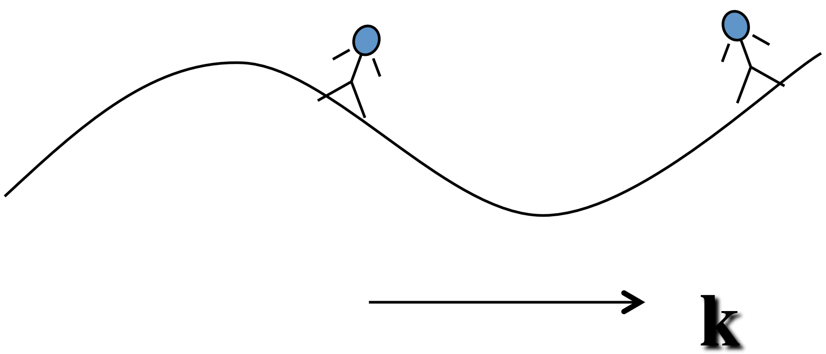
Hoang, Lazarian & Schlickeiser 2012

Transit-time Damping (TTD) Acceleration

See Brunetti's talk

Fisk 1976
Miller et al. 1996
Schlickeiser & Miller 1998





Random force:

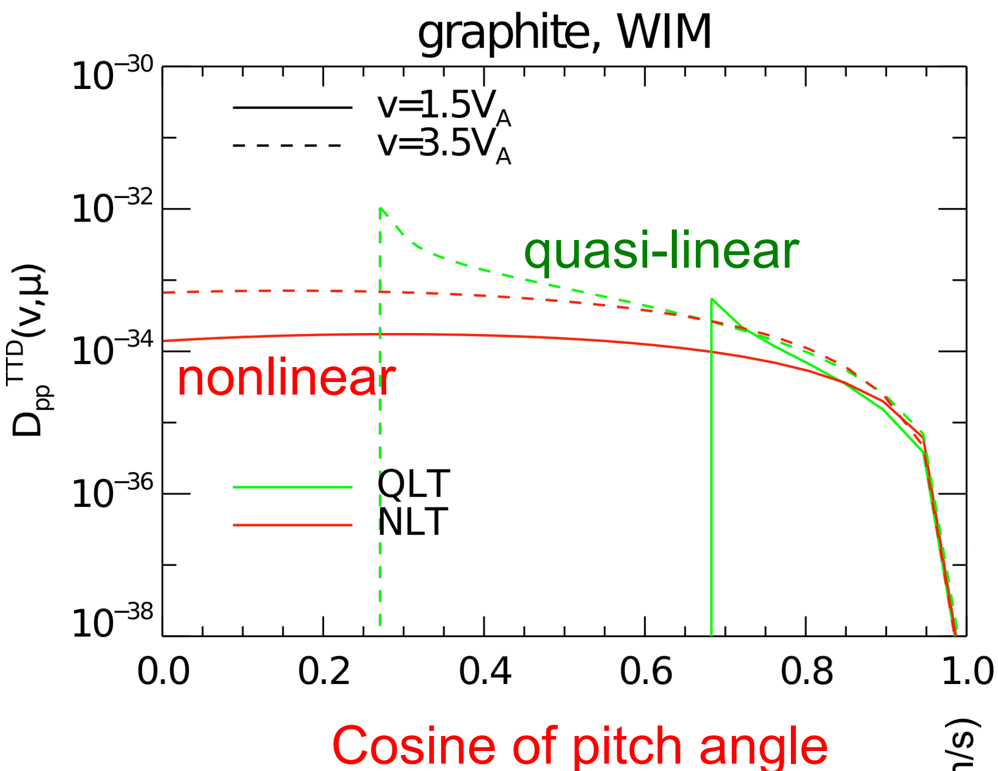
$$-(mv_\perp^2/2B)\nabla_\parallel \mathbf{B}$$

Landau resonance condition:

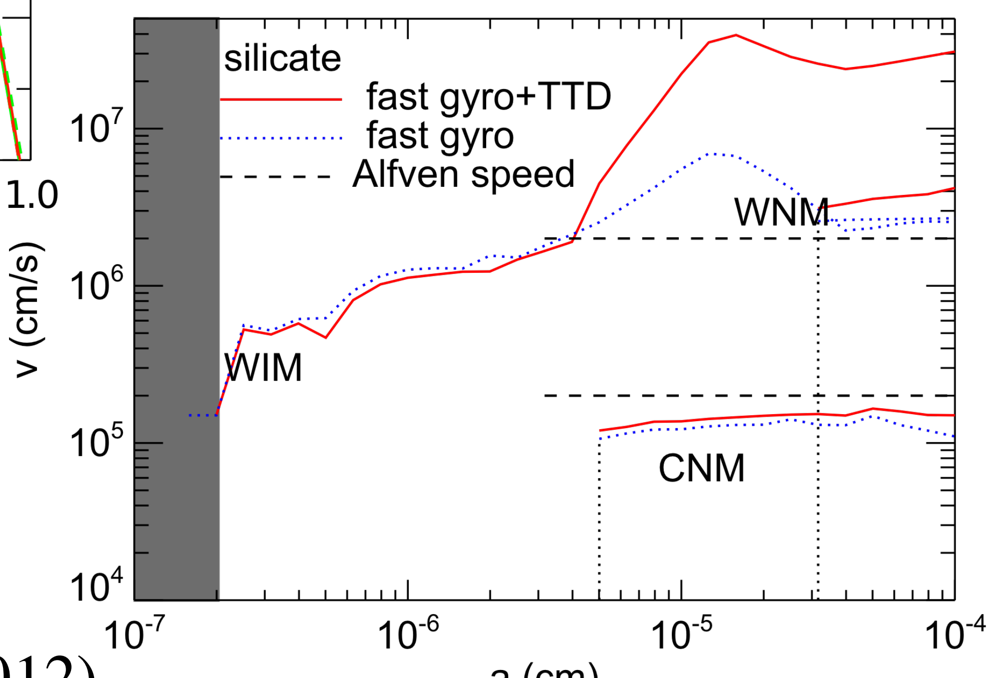
$$k_\parallel v\mu = \omega$$

- Particles must move along the mean field
- Reflection by magnetic mirror induces stochastic acceleration

TTD Acceleration by NLT



- TTD works when $v_{||}$ nonzero, but in QLT, $v_{||}=0$
- NLT: Broadening of resonance function enables TTD

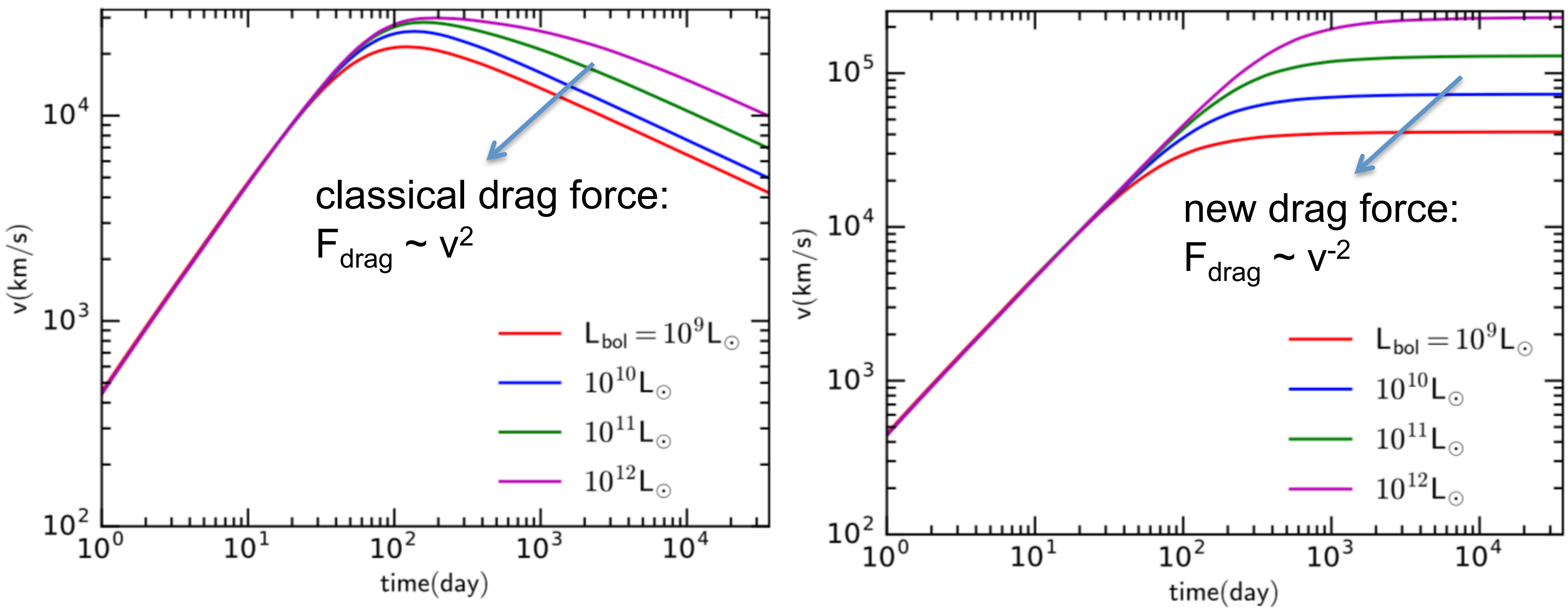


Hoang, Lazarian & Schlickeiser (2012)

Acceleration by Strong Radiation Pressure

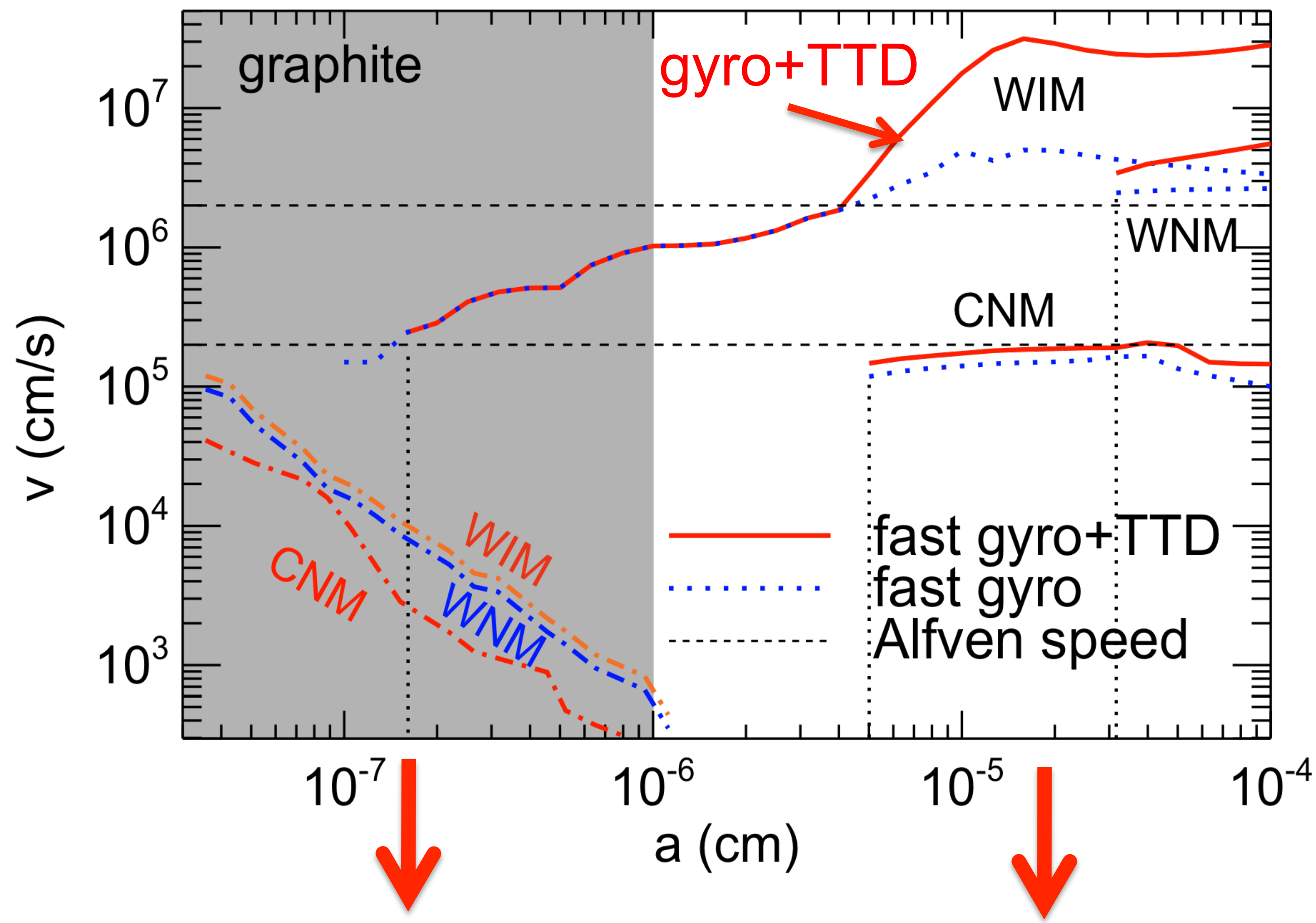
- Grains can be accelerated to relativistic speeds by radiation pressure in vicinity of SNe, AGN (Spitzer 1949, Hoang, Lazarian & Schlickeiser 2015)

- New drag force identified at high energy regime (Hoang 2017)



Hoang (2017)

Summary of grain motion in the ISM



Charge fluctuations

gyro and TTD acceleration

Summary and Implications

• We present a novel mechanism for the acceleration of charge particle in dusty plasma arising from the charge fluctuations. We show that the this mechanism is efficient for tiny grains smaller than 0.01 micron (e.g,., PAHs).

• Transit-time damping of fast MHD modes further accelerate large grains to super-Alfvènic velocities due to broadening of resonance conditions.

• The supersonic motion of dust grains have important effects on grain size distribution, grain coagulation, and planetesimal formations.

Summary and Implication

- Grains can be accelerated to relativistic speeds by radiation pressure.
- Chosen method to accelerated nanocraft to relativistic speeds by Breakthrough Starshot Mission
- New drag force is identified at high energy regime (Hoang 2017), important for reduced slowing down of relativistic lightsail (Hoang, Lazarian, Burkhart & Avi 2017)