# Enhanced Particle Slowing from 1D Long-Range Like-Sign Collisions

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Supported by:  AFOSR FA9550-19-1-0099 and DOE DE-SC-0018236

# Abstract

## Enhanced Particle Slowing from 1D Long-Range Like-Sign Collisions*

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Recent theory [1] predicts enhanced collisional slowing rates for like-sign particle collisions in strong magnetic fields, in density and temperature regimes where binary Boltzmann collisions dominate over statistical Fokker-Planck collisions. Here, the enhancement is from "long-range" collisions, with impact parameters greater than the cyclotron radius. For protons (or anti-protons) at $n \sim 10^8 \mathrm{cm}^{-3}$ and $B \sim 3\mathrm{T}$, the enhancement is large for $T < 1.\mathrm{eV}$; and for $\mathrm{Mg}^+$ ions at $n \sim 10^7 \mathrm{cm}^{-3}$ studied here, the enhancement is large for $T < 0.01\mathrm{eV}$.

Prior experiments have *indirectly* measured $\mathrm{Mg}^+$ and $\mathrm{MgH}^+$ collisions causing damping of plasma waves well into the enhancement regime [2], obtaining damping rates consistent with enhanced inter-species collisional drag.

Two recent experimental campaigns have utilized LIF to *directly* measure $\mathrm{Mg}^+$ test-particle distributions $f(\mathrm{v})$ colliding with warmer equilibria, with test-particle energies $T > 0.1\mathrm{eV}$. Here, the measurements are *consistent* with the predicted factor-of-two enhancement, but the (increasing) rates have not yet been measured into the strong enhancement regime.

[1] D.H.E. Dubin, *Phys Plasmas* **21**, 052108 (2014)

[2] M.Affolter et al, *Phys. Rev. Lett* **117**, 155001 (2016)

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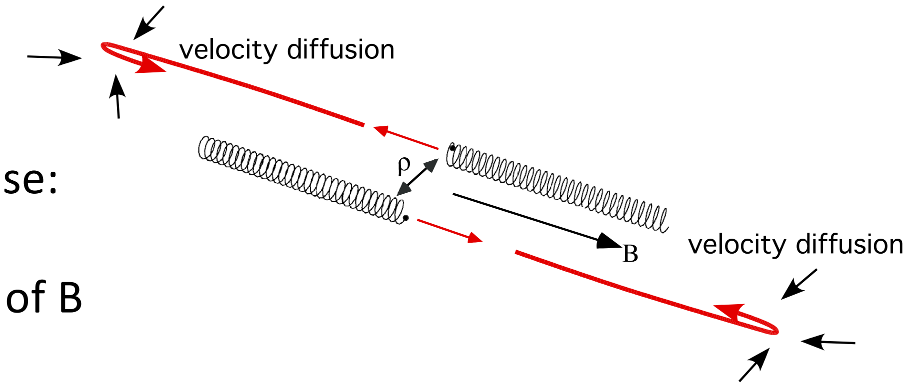
# Novel effects in Slowing due to Long Range Collisions

The UCSD group has developed wide-ranging theory and experiments describing transport from long range collisions with impact parameter $\rho$ larger than the cyclotron radius $r_c$

These collisions are in addition to the standard short-range collisions with $b<\rho<r_c$



In nonneutral plasmas the long range collisions cause:

- Cross-field diffusion enhanced by 10x
- Heat transport enhanced by 100x, independent of B
- Viscosity enhanced by $10^5$x, increasing with B

We have now shown that long range collisions also can strongly enhance collisional slowing $\nu_s$

D. Dubin, *Phys. Plas.* 21, 052108 (2014); M Affolter et. Al, *Phys. Rev. Lett.* **117**, 155001 (2016)

A new fundamental length scale $d$ was identified: $d = b\left(\bar{v}^2 / b^2 \nu_s^2\right)^{1/5}$ $b = e^2/T,\ \bar{v} = \sqrt{T/m}$

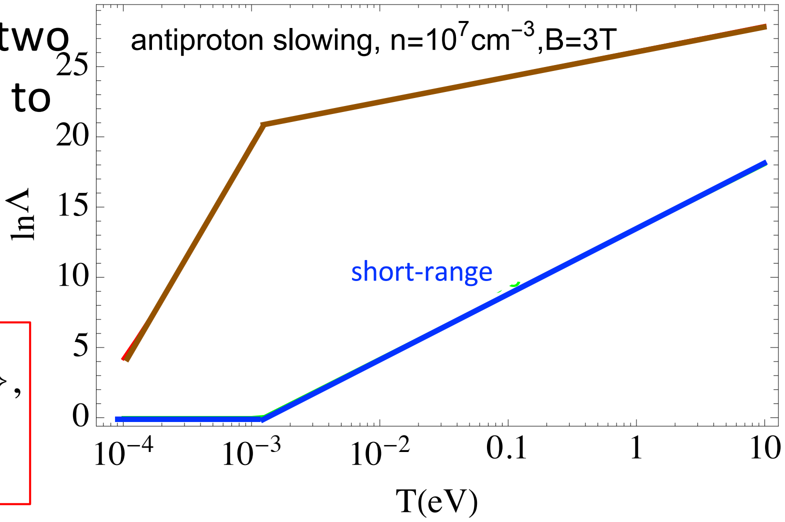
For $\rho<d$: long range collisions are two-body and point-like; particles either reflect or pass by

For $\rho>d$: multiple weak collisions occur simultaneously; particles diffuse in velocity

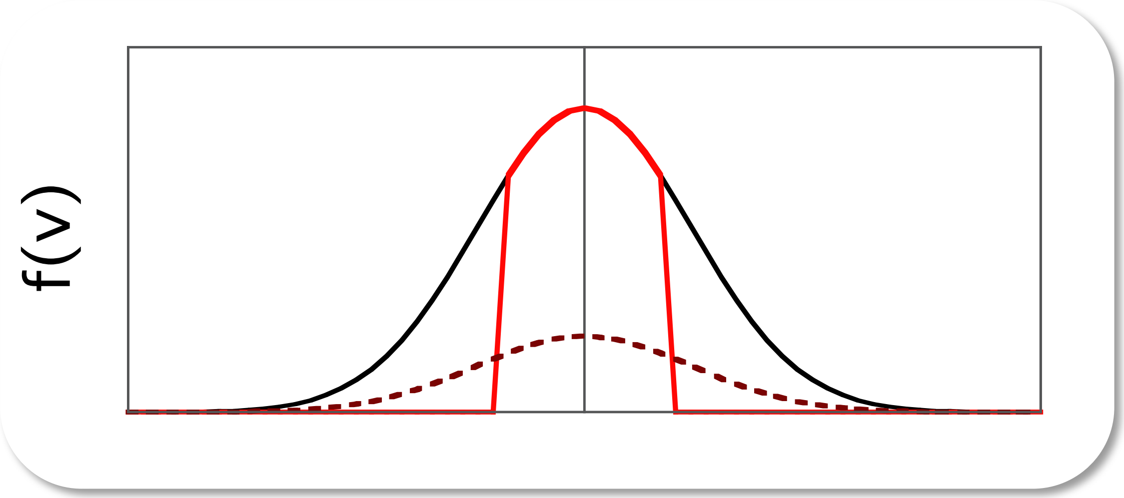
The short range Coulomb logarithm (blue) is enhanced by two new terms from long-range collisions (brown). This applies to Penning trap plasmas for both matter and antimatter, for some astrophysical plasmas, and even for the edge region of tokomak plasmas.

$$\nu_s = \sqrt{\pi}\, n \bar{v} b^2 \ln\Lambda;\ \text{where}\ \ln\Lambda = \left\{ h\ln(d/r_c) + 2\ln(\lambda_D/d) + \frac{4}{3}\ln(r_c/b) \right\},$$

$h = 5.899$ for repulsive collisions; $h = 0$ for attractive collisions



# Measure particle velocity diffusion



- Use electronic **spin orientation** of magnesium ion to label (tag) a group of ion.
- Tag part of the parallel velocity distribution (shown in red).
- Observe tagged particle relaxing with the background due to collisions $\nu_s = \sqrt{\pi}\ n \bar{\mathrm{v}} b^2 \ln \Lambda$

- Accurate (but indirect measurements) were performed using wave damping due to drag between species:

*M. Affolter, F. Anderegg, D.H.E. Dubin and C.F. Driscoll, "Measurements of long-range enhanced collisional velocity drag through plasma wave damping", Physics of Plasmas* ***25****, 055701 (2018).*

*M.Affolter, F.Anderegg, D.H.E.Dubin and C.F. Driscoll, "First Test of Long-Range Collisional Drag via Plasma Wave Damping," Phys. Rev. Lett* ***117****, 155001 (2016).*

- Also, similar measurements were made in neutralized plasma.

*J. Bowles, R. McWilliams, and N. Rynn, "Direct measurenet of velocity space transport in fully ionined plasmas" Phys. Rev. Lett* ***68****, 1144 (1992).*

Subtle Coulomb log effect

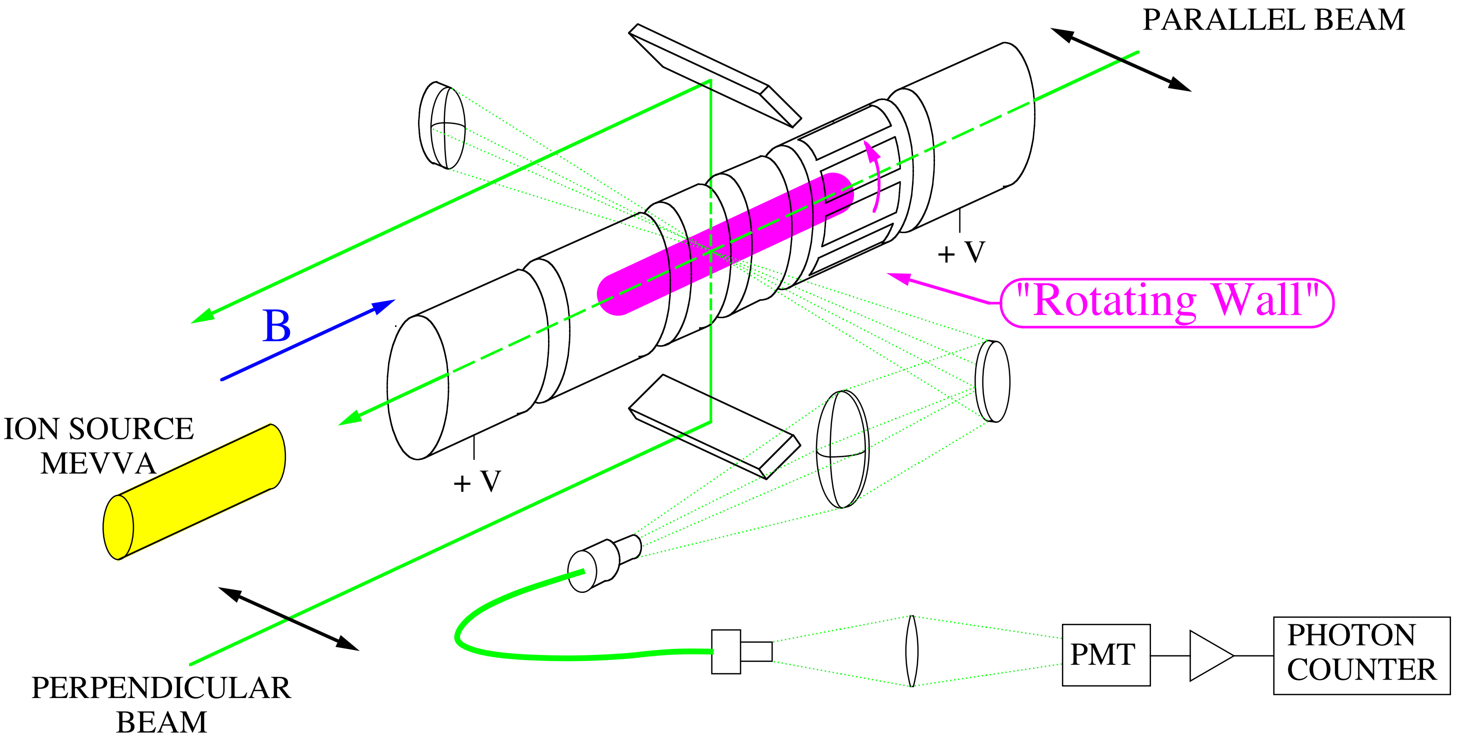
$$v_s = \sqrt{\pi}\; n \bar{v} b^2 \ln\Lambda$$

$\boldsymbol{h = 5.899}$ same sign of charge
$h = 0$ for attractive collision

$$\ln\Lambda = \underbrace{\tfrac{4}{3}\,\mathrm{lnm}\left(\frac{\min\left[r_c,\lambda_D\right]}{b}\right)}_{\text{Classical 3D (short range)}} + \underbrace{h\,\mathrm{lnm}\left(\frac{d}{\max\left[b,r_c\right]}\right)}_{\text{1D long range Boltzmann}} + \underbrace{2\,\mathrm{lnm}\left(\frac{\lambda_D}{\max\left[d,r_c\right]}\right)}_{\text{1D long range Fokker-Plank}}$$

*D.H.E. Dubin "Parallel Velocity Diffusion and Slowing-Down Rate from Long-Range Collisions in a Magnetized Plasma," Phys. Plasmas* ***21****, 052108 (2014)*

# Magnesium ion plasma in Penning-Malmberg trap



$$B = 3 \text{ Tesla}$$

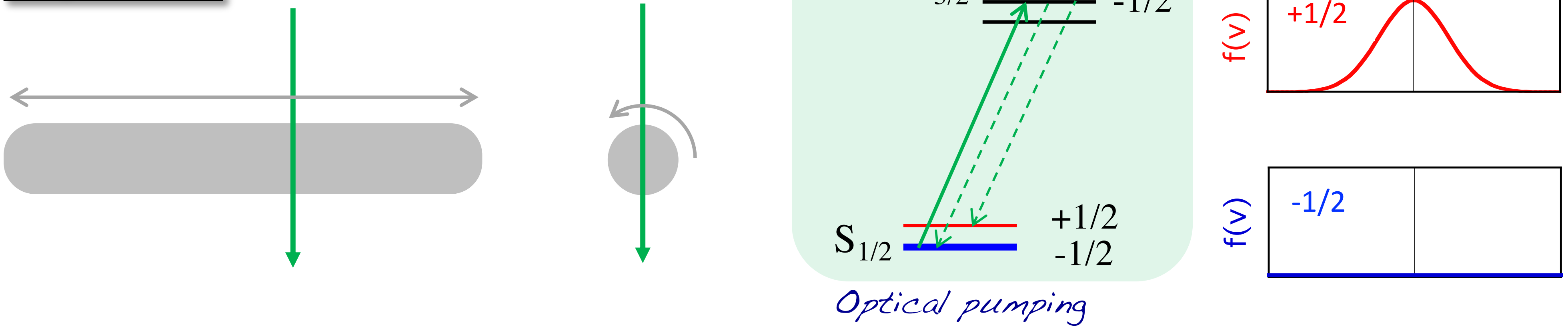
$$n \simeq 10^7 \text{ cm}^{-3}$$

$$L_p \simeq 10. \text{ cm}$$

$$10^{-5} \text{ eV} \le T \le 1 \text{ eV}$$

This work $0.07 \text{ eV} \le T \le 1.2 \text{ eV}$

Tag all ions



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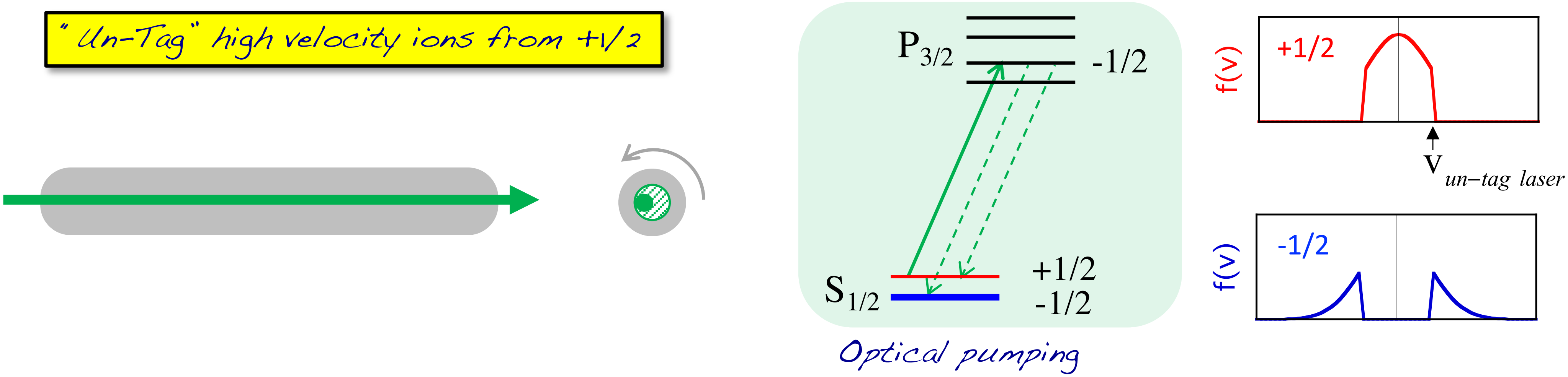
" Un-Tag " high velocity ions from +1/2



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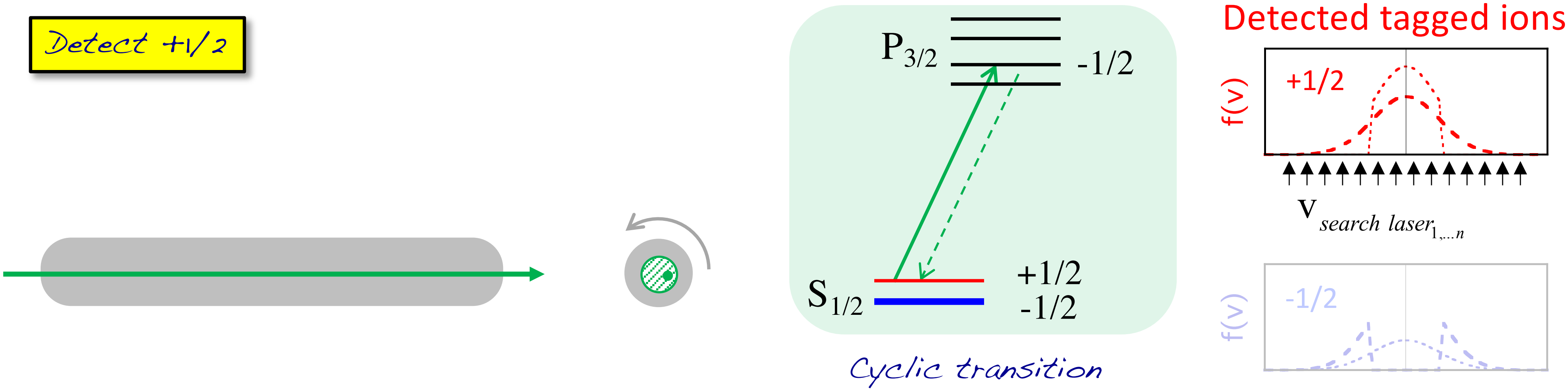
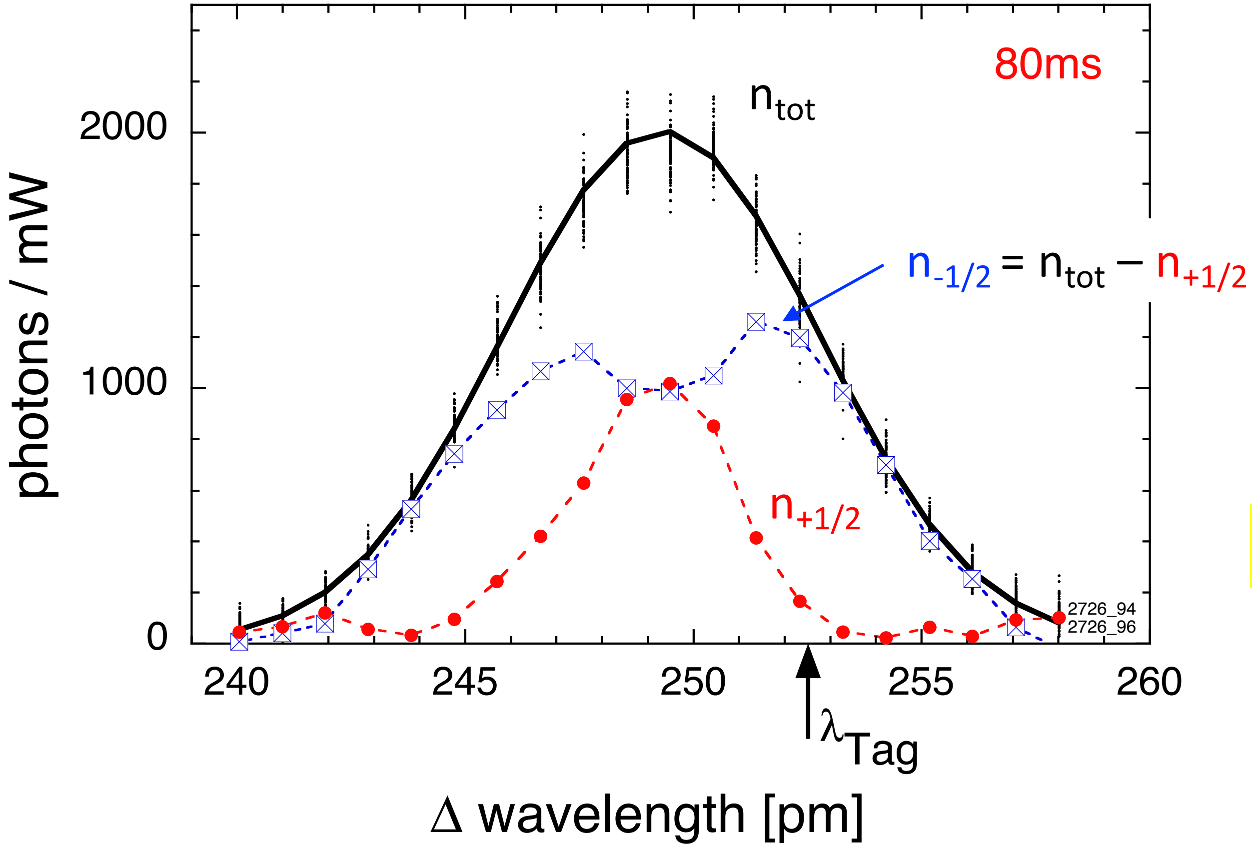
Detect +1/2



# Test particle with large velocity particle removed

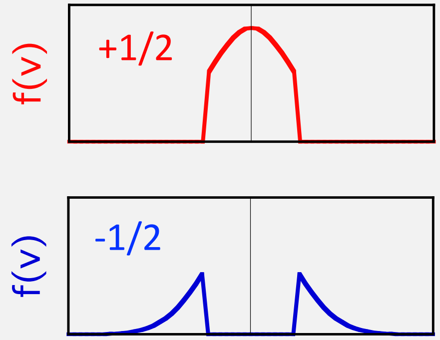
*This is what we have done*

- Un-Tag for 50ms (ie remove large velocity particle)
- Wait 30ms
- Search $n_{+1/2}$ for 8ms



*Distribution offset subtracted*

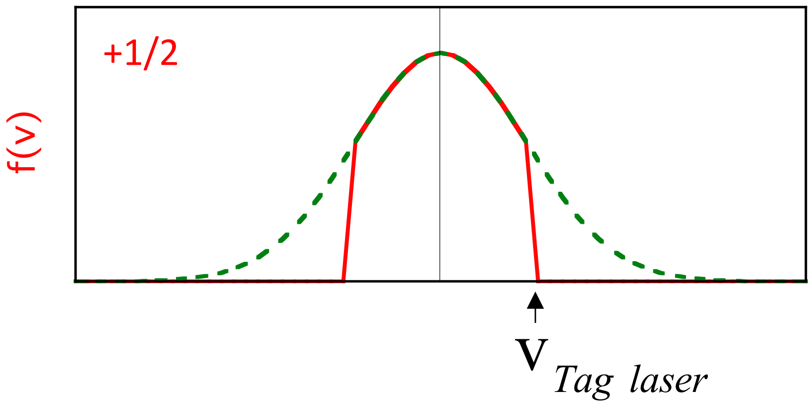
*This is what we would like to do*

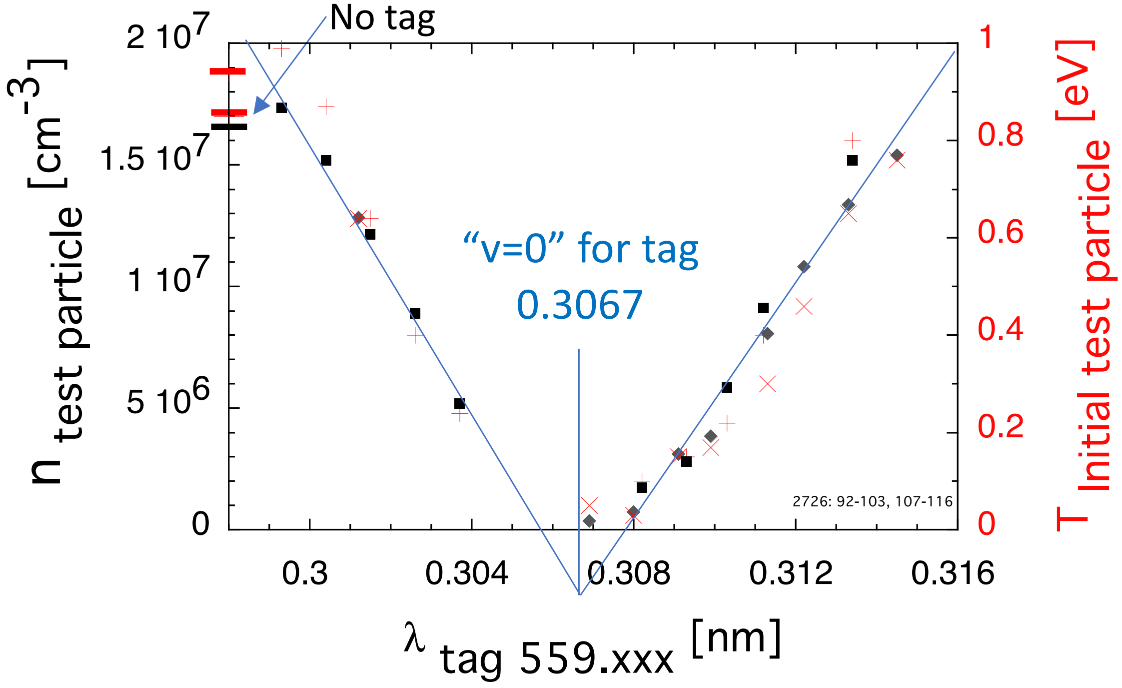


No more large velocity in +1/2 state

✓

# Initial Density and Temperature of test particle vs tagging wavelength





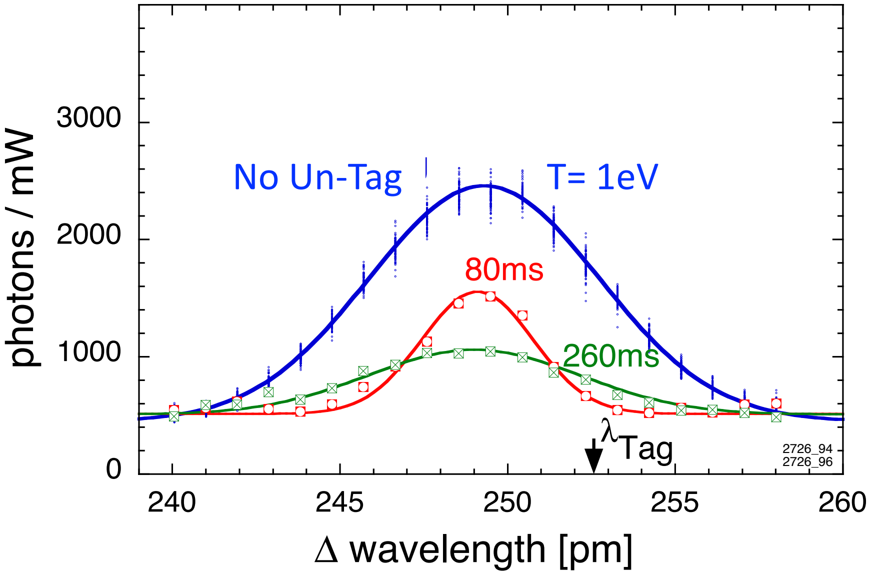
- Un-Tag for 50ms
  *remove large velocity particle*
- Wait 30ms
- Search $n_{+1/2}$ for 8ms

The tagging laser removes high velocity particle from +1/2 state leaving "cold" test particle

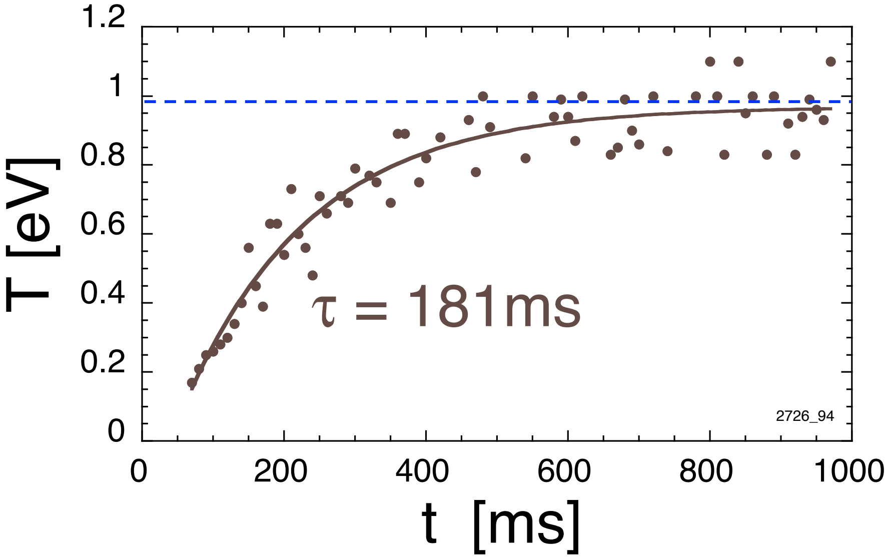
✓

# Temperature of test particle vs time

Ignore detail of f(v) consider temperature T(t) only



Test particles in +1/2 state equilibrate with the rest of the plasma



Test particles in +1/2 state re-heat due to collisions with the rest of the plasma

Exponential relaxation

Define collision rate $\nu_s = 1/\tau_{\text{re-heating}}$

# Collision rate  theory prediction

*D.H.E. Dubin, Phys. Plasmas* ***21****, 052108 (2014)*

$\mathrm{lnm}\,(x) = \ln\left(\max[1,x]\right)$

$$\nu_s = \sqrt{\pi}\; n\bar{v}\, b^2 \ln\Lambda$$

***h* = 5.899** same sign of charge

*h* = 0 for attractive collision

$$\ln\Lambda = \underbrace{\tfrac{4}{3}\,\mathrm{lnm}\left(\frac{\min\left[r_c,\lambda_D\right]}{b}\right)}_{\text{Classical 3D collisions (short range)}} + \underbrace{h\,\mathrm{lnm}\left(\frac{d}{\max\left[b,r_c\right]}\right)}_{\text{1D long range 2-body Boltzmann}} + \underbrace{2\,\mathrm{lnm}\left(\frac{\lambda_D}{\max\left[d,r_c\right]}\right)}_{\text{1D long range “Noisy” Fokker-Plank collisions}}$$

$\rho < d$

$\rho > d$

Impact parameter

$r_c$ : cyclotron radius

$b$ : distance of closest approach

$\lambda_D$ : Debye length

$d$ : new scale length

$$d \equiv b\left(\frac{\bar{v}^2}{b^2\nu_s^2}\right)^{1/5}$$

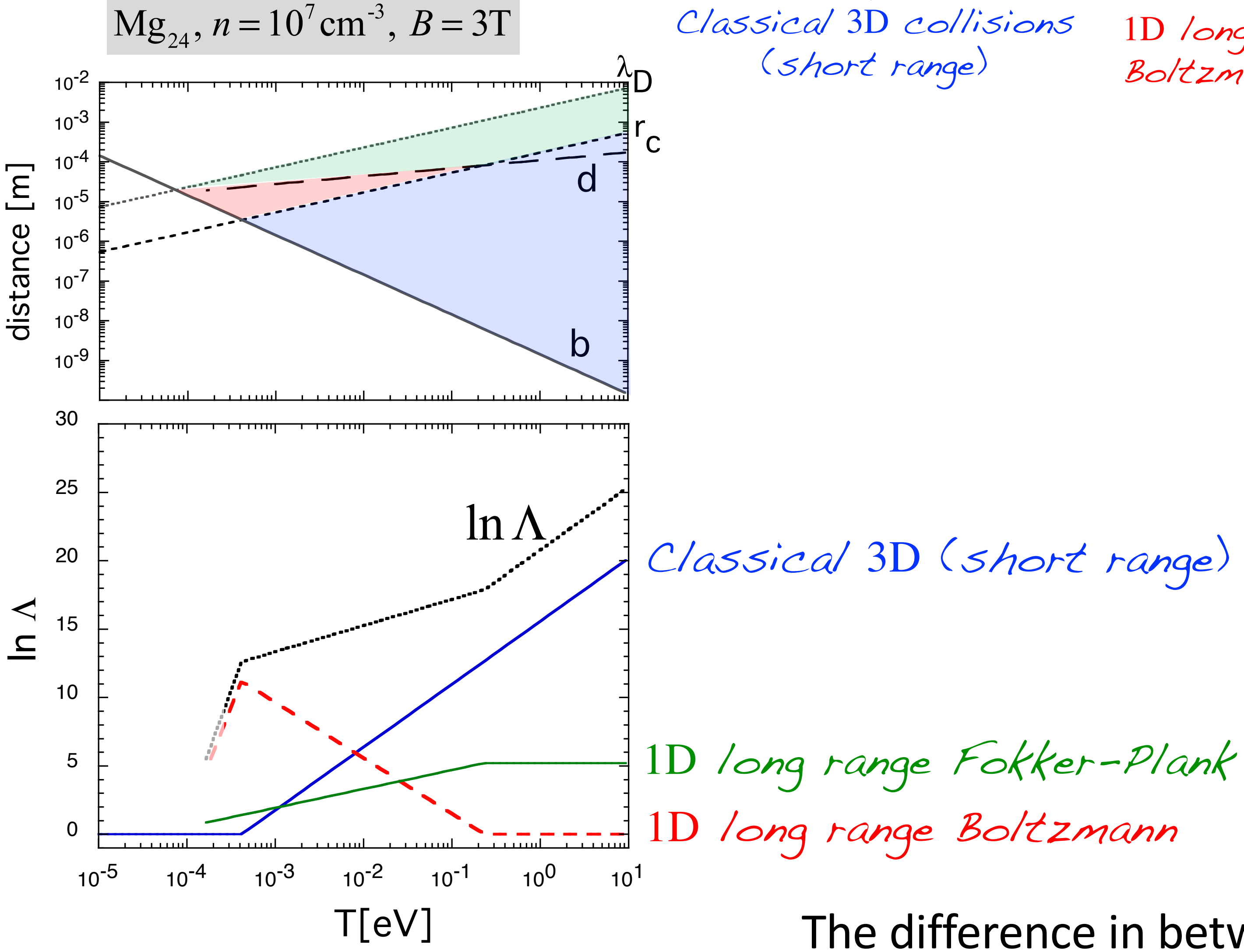
Impact parameter

For ρ<*d*: long range collisions are two-body and point-like; **particles either reflect or pass by**

For ρ>*d:* multiple weak collisions occur simultaneously; **particles diffuse in velocity**

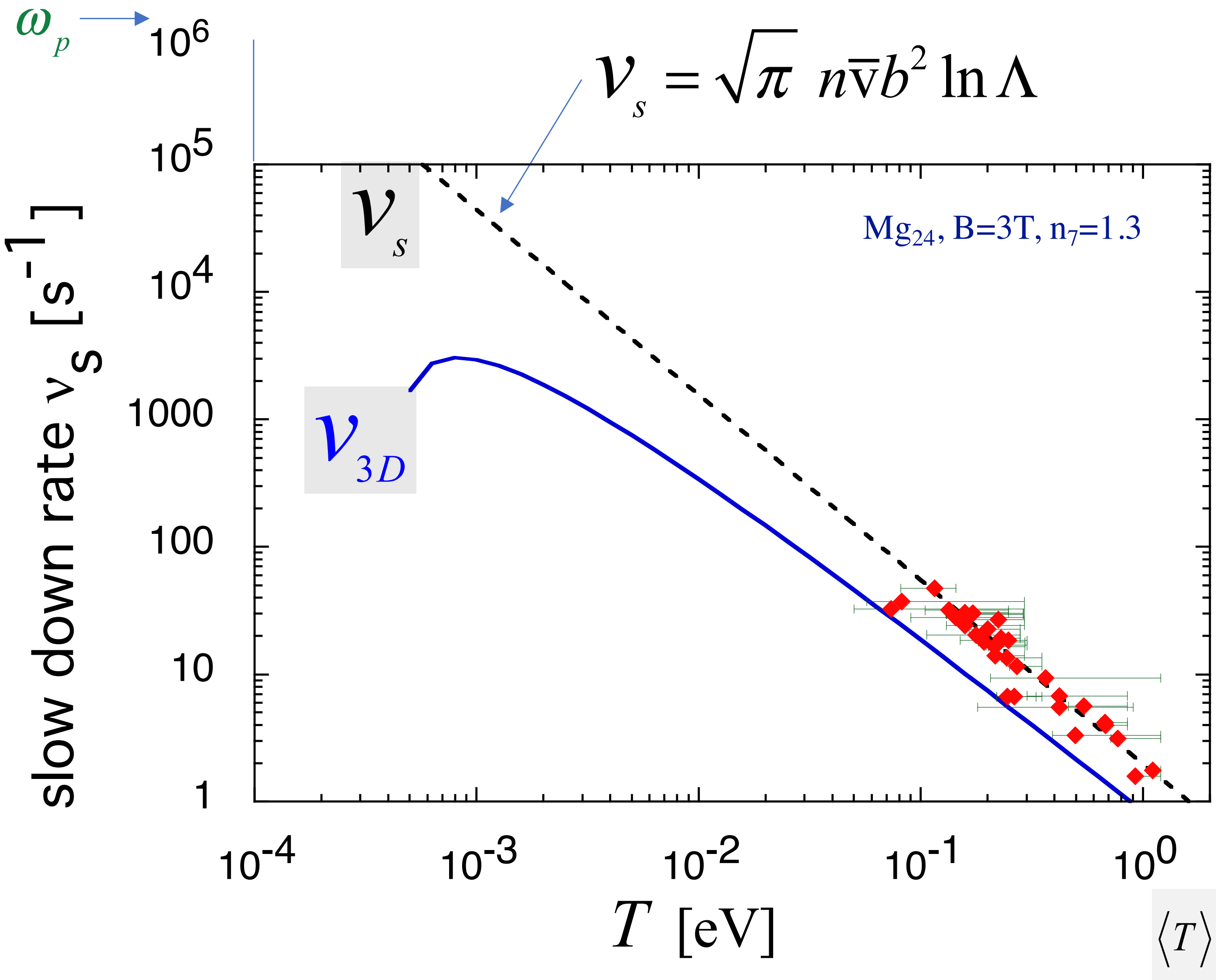
# Coulomb log vs temperature

$$\ln\Lambda = \underbrace{\frac{4}{3}\,\mathrm{lnm}\left(\frac{\min\left[r_c,\lambda_D\right]}{b}\right)}_{\text{Classical 3D collisions (short range)}} + \underbrace{h\,\mathrm{lnm}\left(\frac{d}{\max\left[b,r_c\right]}\right)}_{\text{1D long range Boltzmann}} + \underbrace{2\,\mathrm{lnm}\left(\frac{\lambda_D}{\max\left[d,r_c\right]}\right)}_{\text{1D long range Fokker-Plank}}$$



The difference in between 3D and 1D of the Coulomb log is larger at low temperature

# Slowing down rate  theory and experiments



$$\nu_s = \sqrt{\pi}\; n\bar{v}b^2 \ln\Lambda$$

Theory has no adjustable parameter

$$\langle T \rangle \equiv \left( \rho_{\text{red}}\, T_{\text{red initial}}^{-3/2} + \left(1 - \rho_{\text{red}}\right) T_{\text{eq}}^{-3/2} \right)^{-2/3}$$

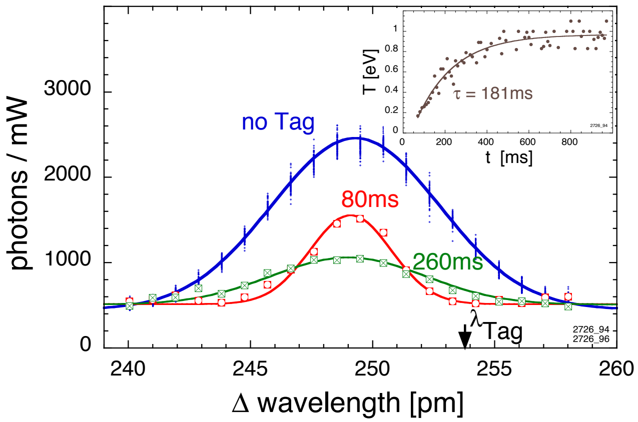
$$T_{\text{low}} \equiv T_{\text{red initial}} \qquad T_{\text{high}} \equiv T_{\text{eq}}$$

1D **long range** Fokker-Plank collisions enhance slow down rate over the short range 3D case.

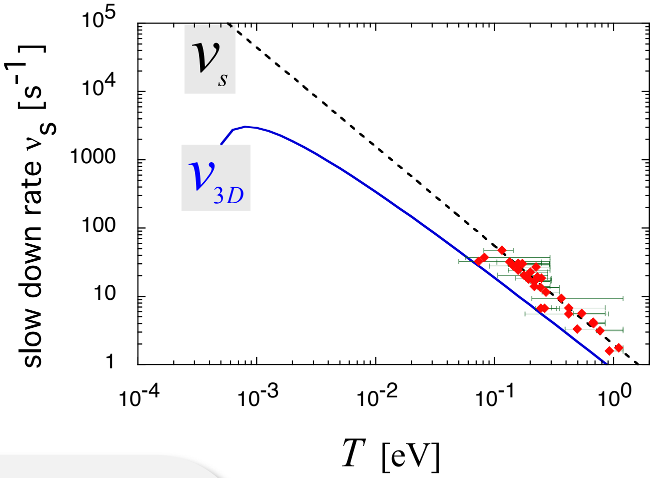
# Summary

We have created test particles where the high velocity particle are removed.

We measured how these test particles equilibrate with the rest of the plasma.



1D long range Fokker-Plank collisions enhance slow down rate over the short range 3D case



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