Radio Frequency Emission From Hypervelocity Impact Plasma

Alex Fletcher
Donovan Mathias
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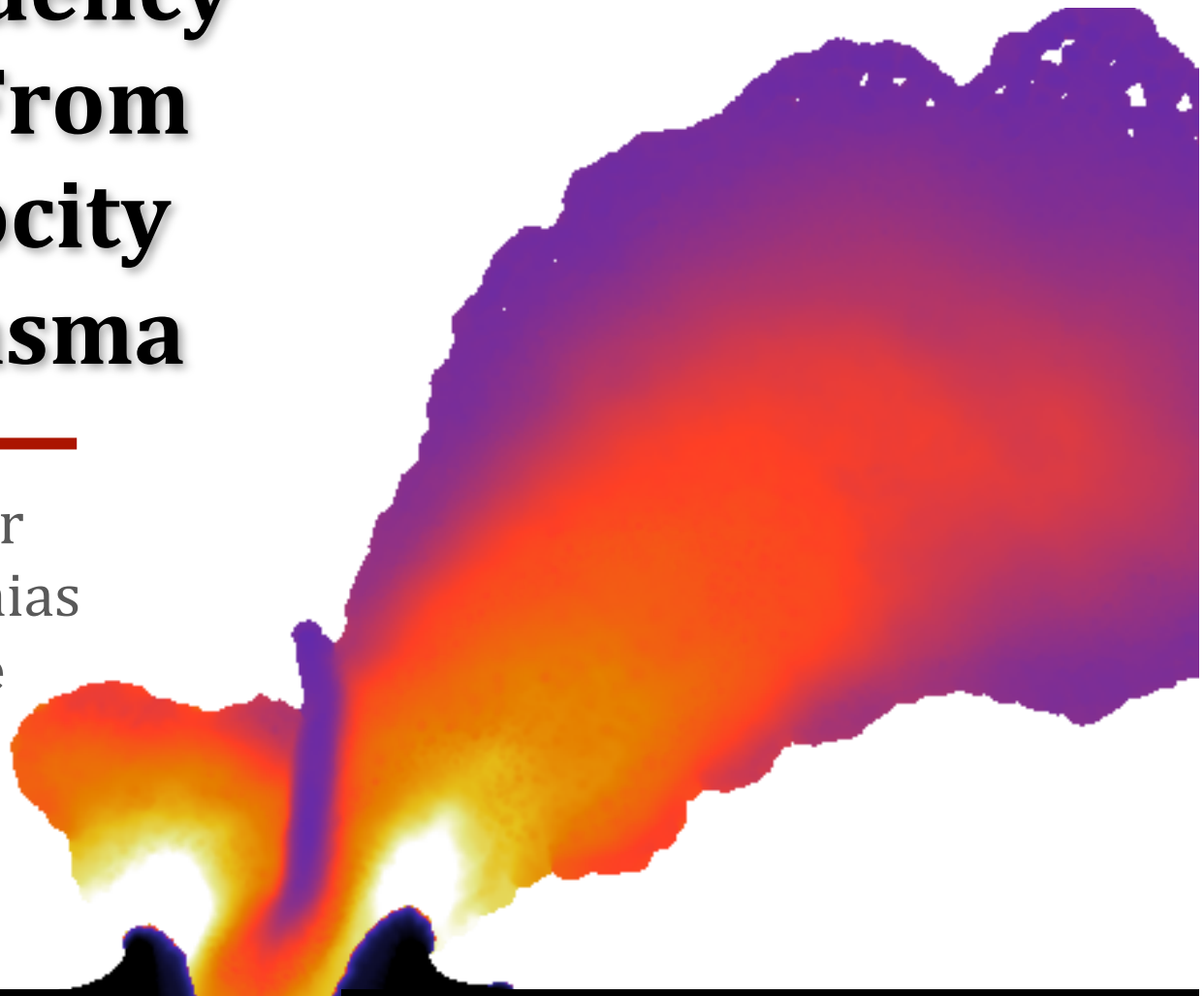
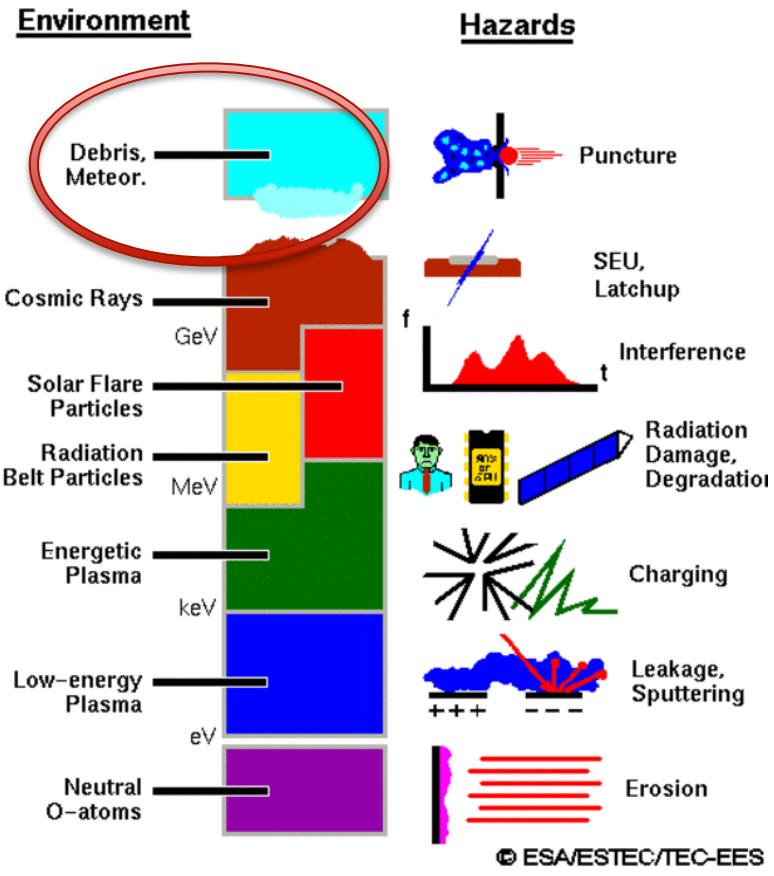


Aeronautics and Astronautics
Space Environment and Satellite Systems

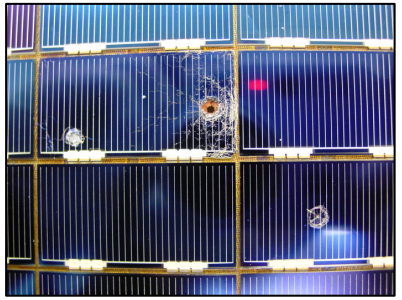
NASA Ames Research Center
Engineering Risk Assessment

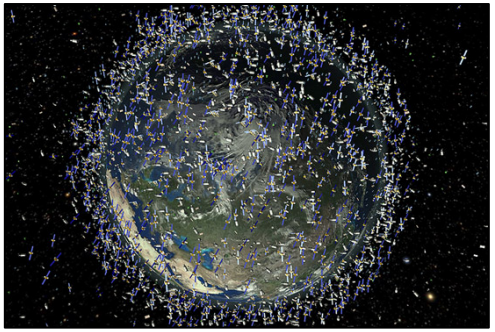
Applied Modelin & Simulation (AMS) Seminar Series
NASA Ames Research Center,, May 5, 2015

Dangers in the Space Environment



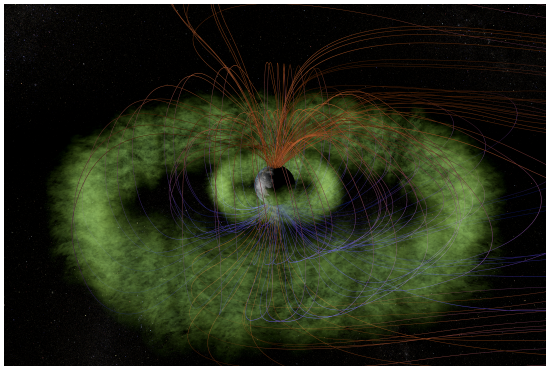
Recovered Solar Panel from Hubble ➔





➔ **Tracked Orbital Debris**

Van Allen Radiation Belts ➔



Electrical Anomalies

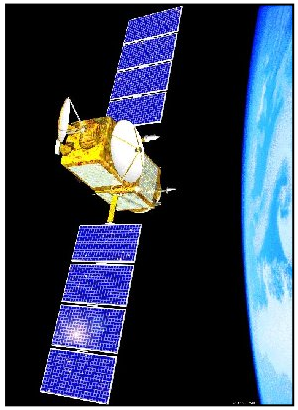
Olympus
1993

ESA

ADEOS II
2003

JAXA

JASON-1
2005

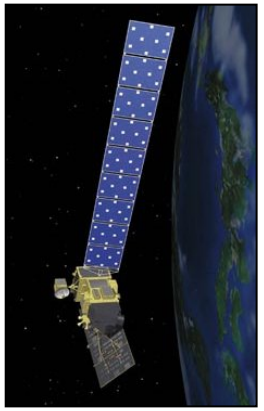


NASA

Landsat 5
2009

NASA

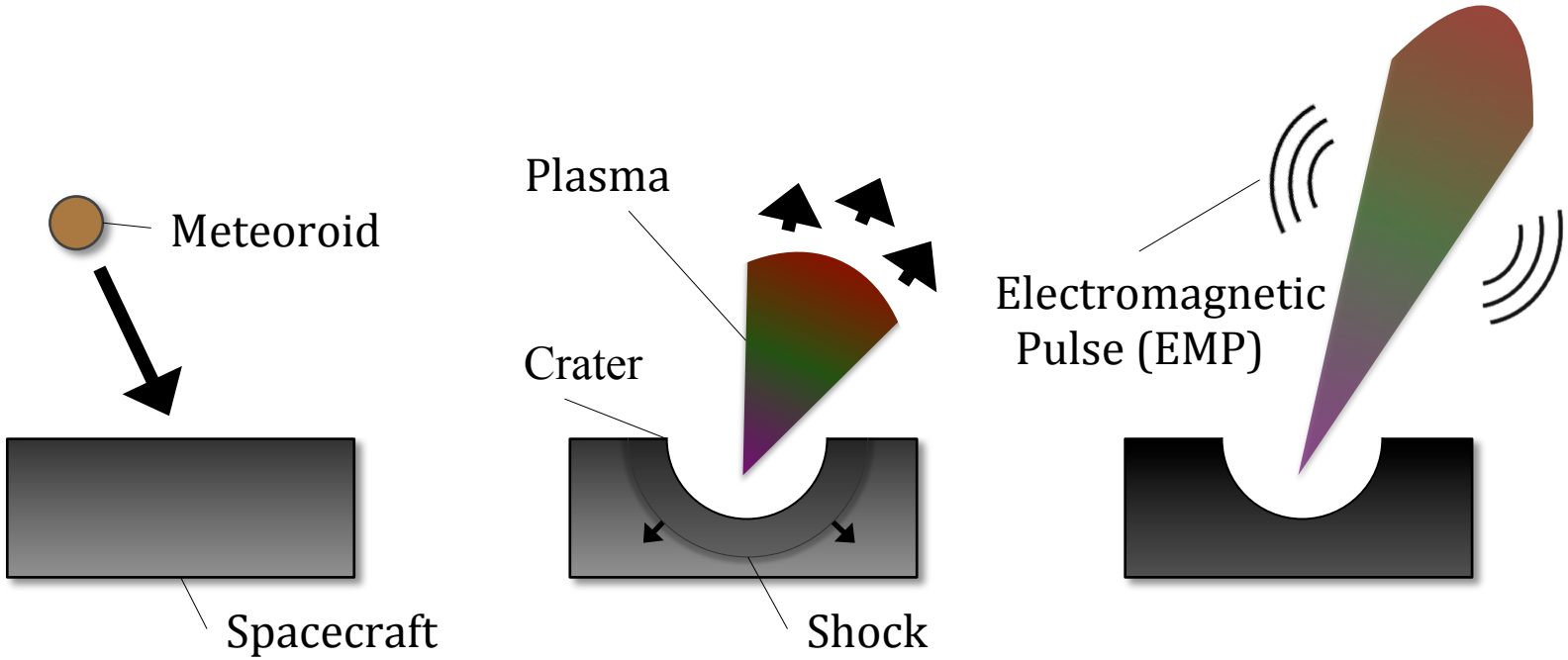
ALOS
2011



JAXA

NGDC Database: Anomaly Diagnosis	
Deep Dielectric Charging	490
Electrostatic Discharge	1072
Single Event Upset	822
Radio Frequency Interference	8
Unknown	**2587**

A New Failure Mechanism



Objective: Characterize electrical damage mechanism to diagnose current anomalies and inform future design decisions

- Motivation
- **Plasma Primer**
- Impact Physics
- Computational Approach
- Simulation Results
- Concluding Remarks

What is a plasma?

- System of charged particles (**ions, electrons**, and neutrals), but quasi-neutral overall
- Long range electromagnetic forces cause **collective behavior**

Plasma Density [m^{-3}]	n_e
Plasma Frequency	$\omega_p \propto \sqrt{n_e}$
Debye Length	$\lambda_d \propto \sqrt{\frac{T_e}{n_e}}$
Electron-ion collision frequency	$\nu_{ei} \propto \frac{Z_i n_i}{T_e^{3/2}} ln\Lambda$

What is a plasma?

- ***Collisional*** **or** ***collisionless*** depending on the mean collision time relative to dynamic time of interest
- ***Equilibrium*** **or** ***non-equilibrium*** describing validity of temperature/Maxwellian distributions or change in ionization state
- ***Ideal*** **or** ***non-ideal*** depending on the importance of three-body collisions
- ***Electrostatic*** **or** ***electromagnetic*** depending on the importance of the magnetic field produced by the plasma

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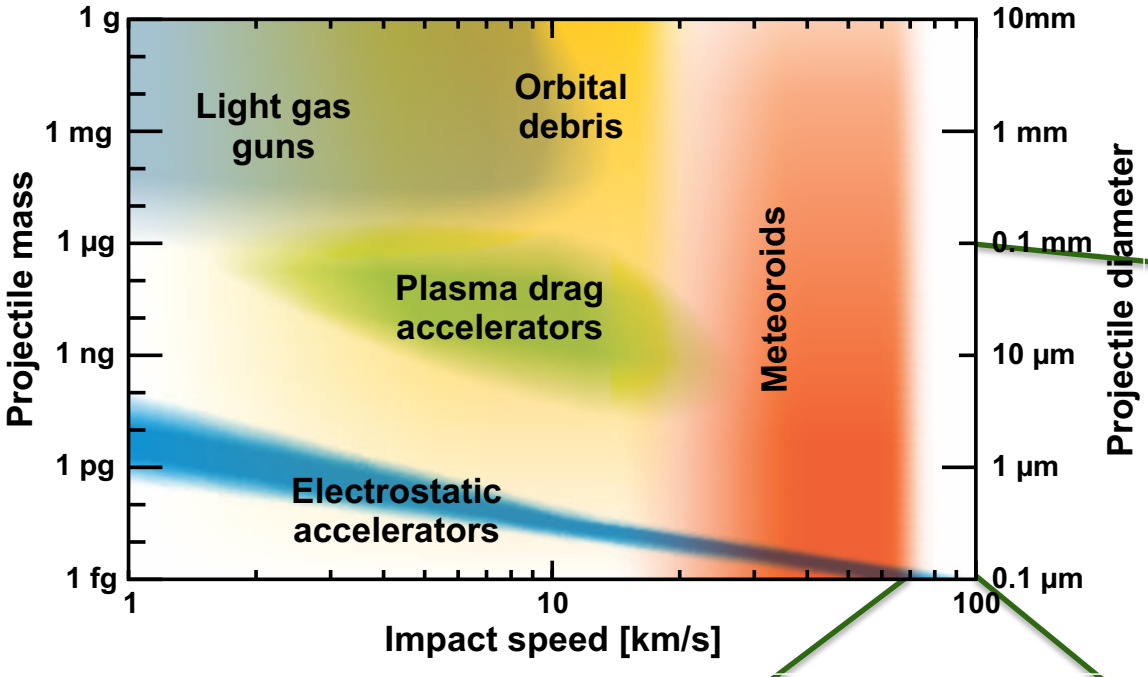
Hypervelocity Impactors



~100 *µm* (dust mite)

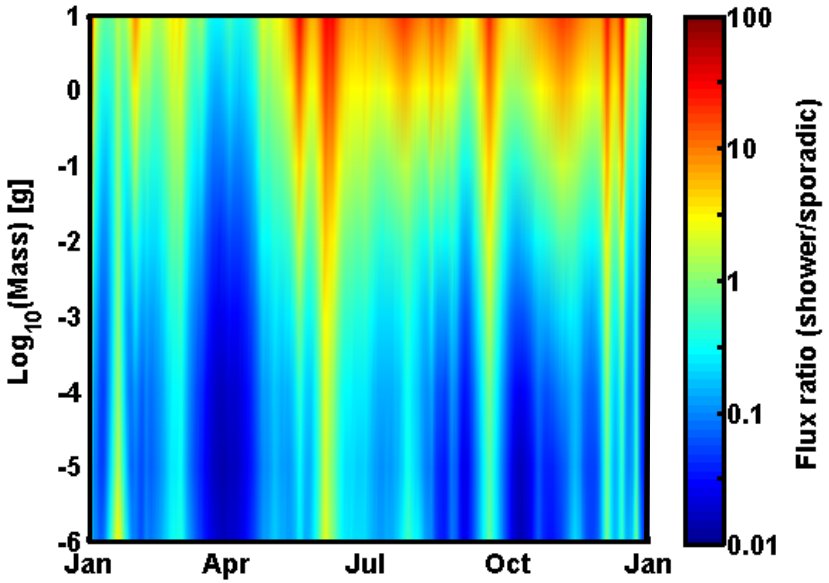
~100 *nm* (spider web)

72 *km/s* = Mach 210

Lee, N. (2012), Understanding Spacecraft Electrical Anomalies: Theory and Experiments Characterizing Hypervelocity Impact Plasma Dynamics. Ph.D. Thesis, Stanford University.

Meteoroids and Orbital Debris

	Meteoroids	Orbital Debris
Speed	11 – 72 *km/s*	< 12 *km/s*
Size	< 0.3 *m*	< 0.1 *m*
Origin	Comets and Asteroids	Human-Made
Orbit	Any	Mostly LEO

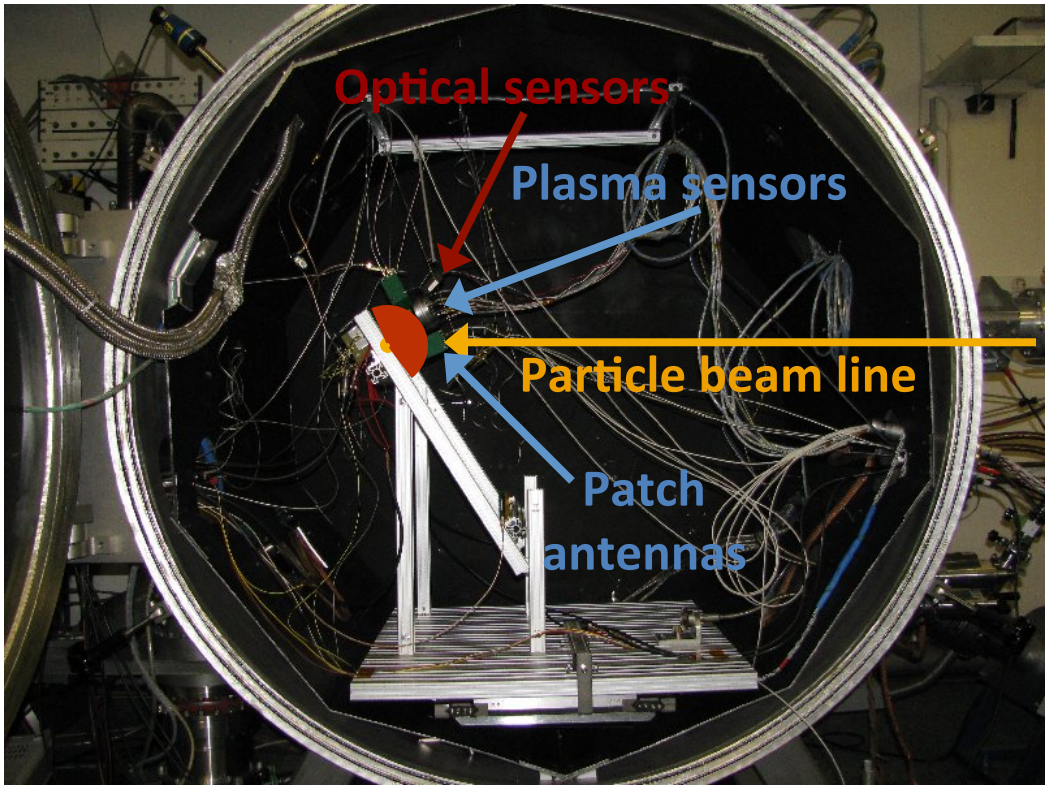


Hypervelocity Impacts

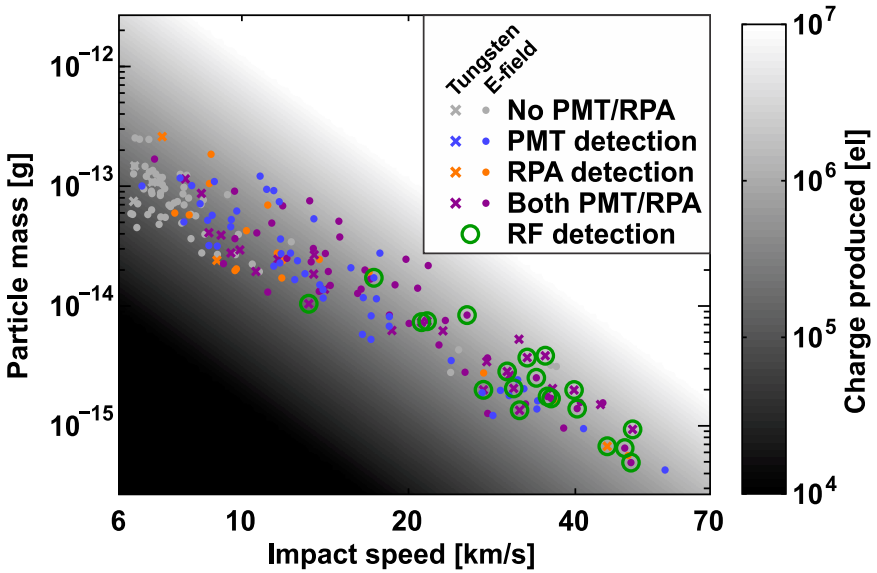
- **Hypervelocity** means faster than the speeds of sound of the target (~8 *km/s*)
- Creates a **shock wave** in target and impactor
- Enough energy to ionize material, forming **plasma***
- Tiny but *fast* meteoroids - speed is the dominant parameter

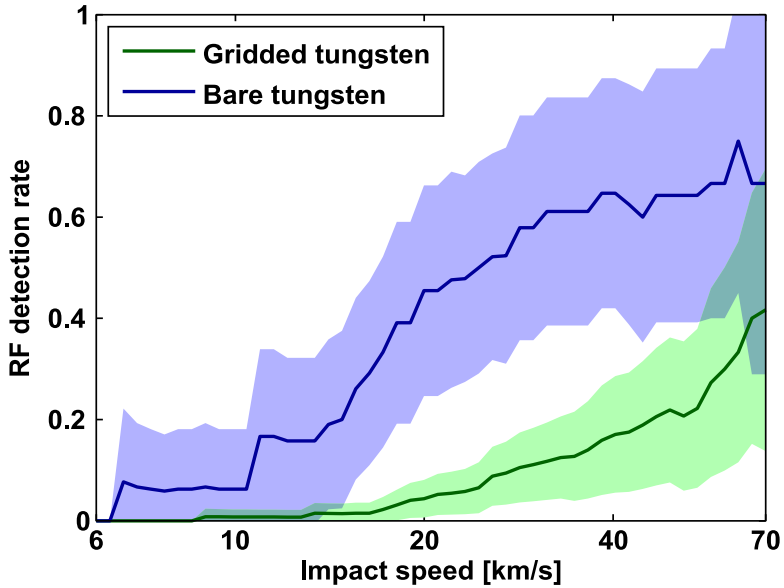
1.7 g 6.8 *km/s* ESA

Van de Graaff Experiments



Electromagnetic Radiation Measurements



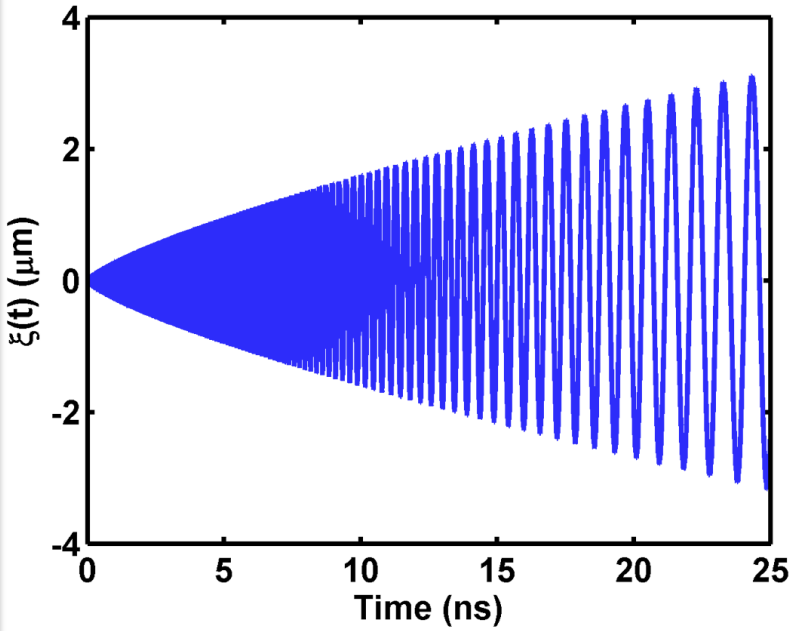


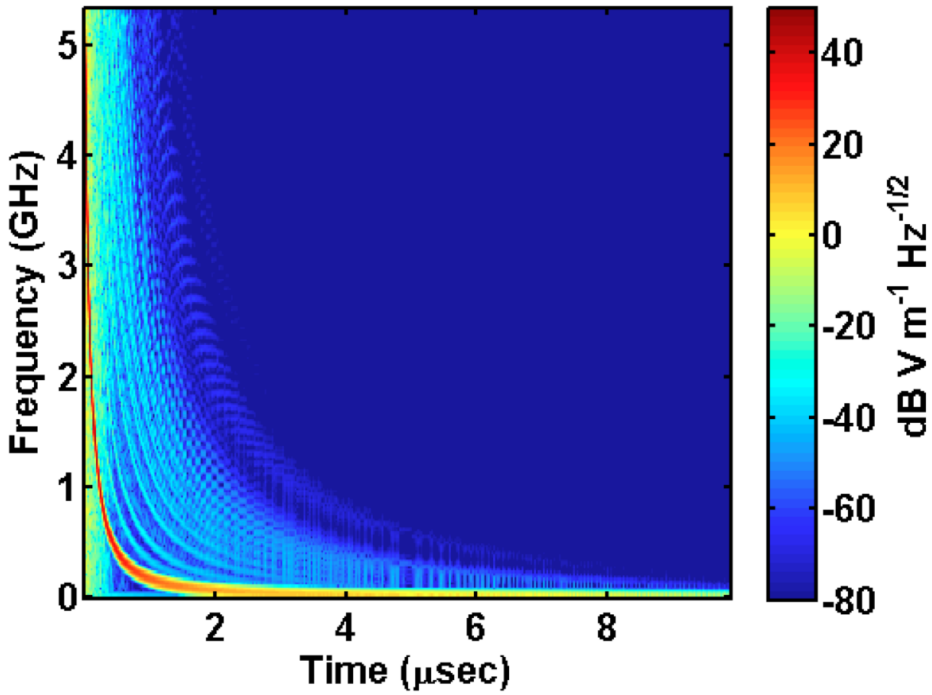
- No plasma below **8 *km/s*** & no RF below **15 *km/s***
- **0.4%** RF detection rate overall but **24.1%** above 15 *km/s*

Close, S. I. Linscott, N. Lee, T. Johnson, D. Strauss, et al., (2013) Detection of electromagnetic pulses produced by hypervelocity micro particle impacts, *Phys. Plasmas*, *20*, doi: 10.1063/1.4819777

Radiation from Coherent Oscillations

$$\xi(t) = c_1 \frac{c_s}{2r_0}\left(1+\frac{c_s t}{r_0}\right)^{1/2} J_1\left(\omega_{p,0}\frac{2r_0}{c_s}\left[1+\frac{c_s t}{r_0}\right]^{-1/2}\right) + c_2 \frac{c_s}{2r_0}\left(1+\frac{c_s t}{r_0}\right)^{1/2} Y_1\left(\omega_{p,0}\frac{2r_0}{c_s}\left[1+\frac{c_s t}{r_0}\right]^{-1/2}\right)$$





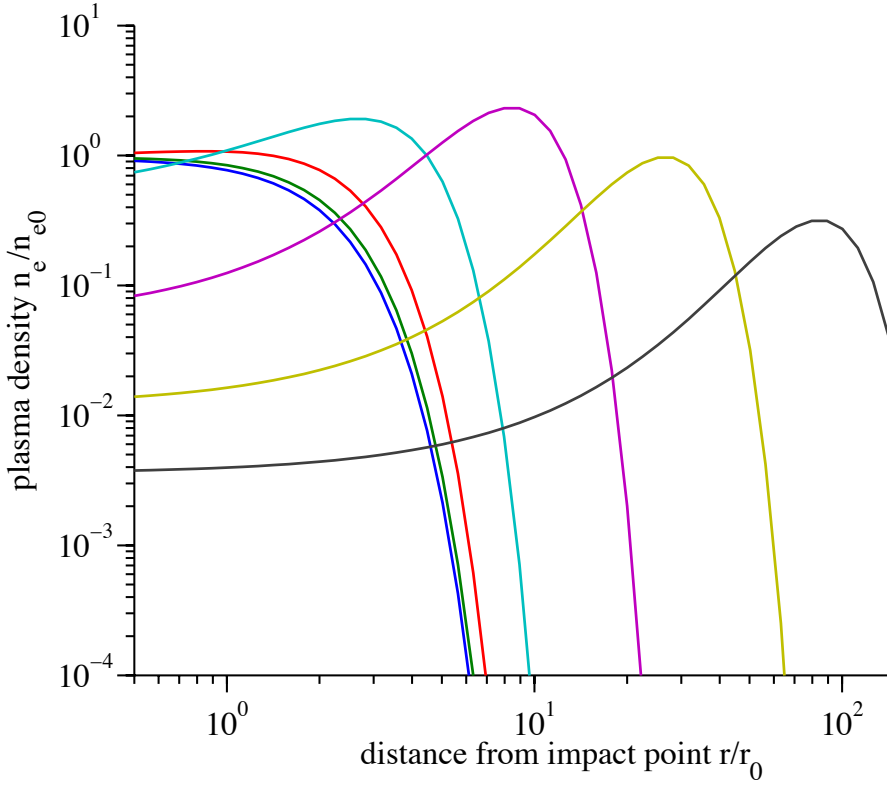
S. Close, P. Colestock, L. Cox, M. Kelley, and N. Lee. Electromagnetic pulses generated by meteoroid impacts on spacecraft. J. Geophys. Res., 115, 2010.

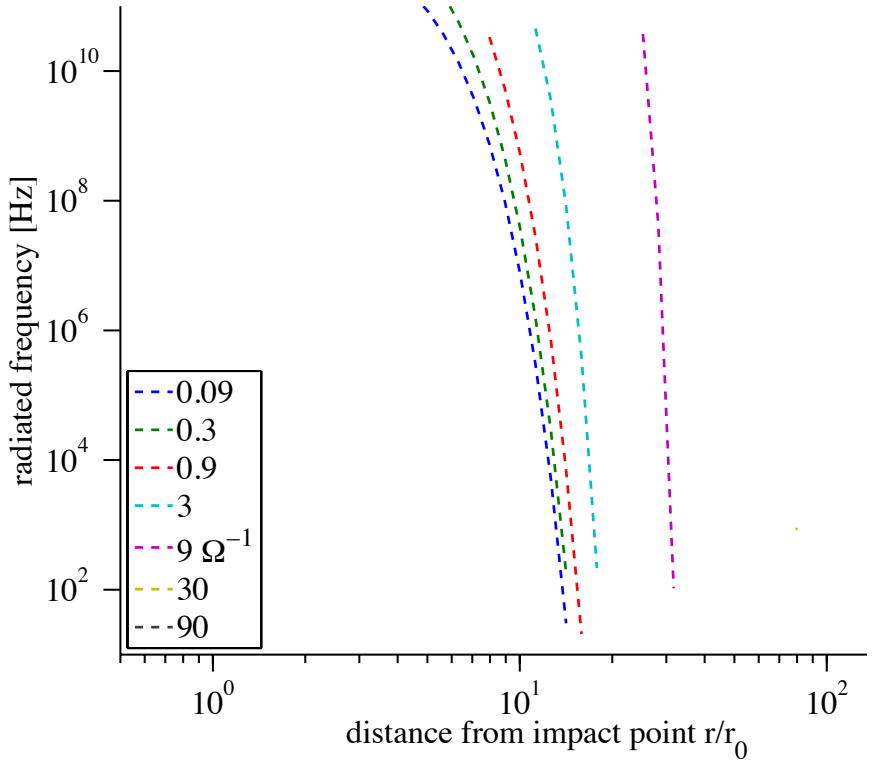
Fletcher, A., Close, S., MacCormack, R. W., Modeling Plasma Formation from Hypervelocity Meteoroid Impacts. URSI, 2012.

Radiation from Plasma Instabilities

$$f_{1D} = n\left(\frac{x-u_0 t}{\sqrt{1+\Omega^2 t^2}}\right)\frac{1}{v_{th}\sqrt{\pi}}\exp\left(-\frac{I}{v_{th}^2}\right)$$

$$I = \frac{1}{2}\left[(v-u_0)^2 - \Omega^2\left(\frac{x^2}{1+\Omega^2 t^2} - (x-vt)^2\right)\right] + \frac{1}{2}\left[\frac{x^2\Omega^2}{1+\Omega^2 t^2} - u_0^2\right] + \frac{q}{m}\Phi$$





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Why is this hard to simulate?

- **Multi-physics**
  - Continuum dynamics (solid, gas, plasma, etc)
  - Elasticity and plasticity
  - Non-ideal plasma
  - Transition regions
  - Kinetic behavior
  - Electromagnetic fields
- **Multi-scale**
  - Length scales from ~1 *micron* to ~1 *meter*
  - Number density scales from ~10^{20} m^{-3} to ~10^{29} m^{-3}
  - Velocity scales from ~1 *km/s* to speed of light

➔ **Split computational domain into two regions**

1 – How is the impact plasma formed?

2 – What is the radiation mechanism?

Smoothed Particle Hydrodynamics (SPH)

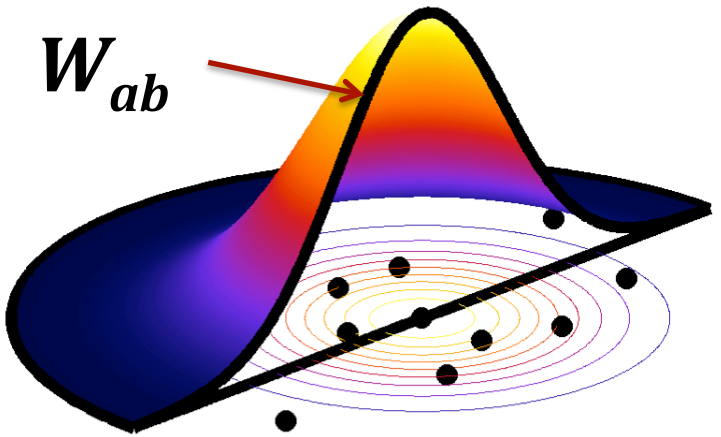
How are hypervelocity impact plasmas formed?

$$\frac{D\rho}{Dt} = -\rho\frac{\partial v^i}{\partial x^i}$$
$$\rho\frac{Dv^i}{Dt} = \frac{\partial \sigma^{ij}}{\partial x^j}$$
$$\rho\frac{De}{Dt} = \frac{\partial v^i \sigma^{ij}}{\partial x^j}$$

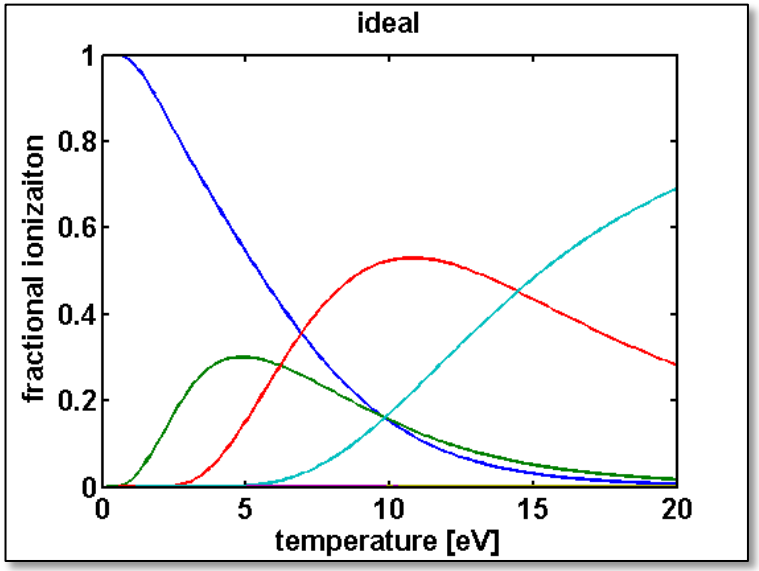
➔

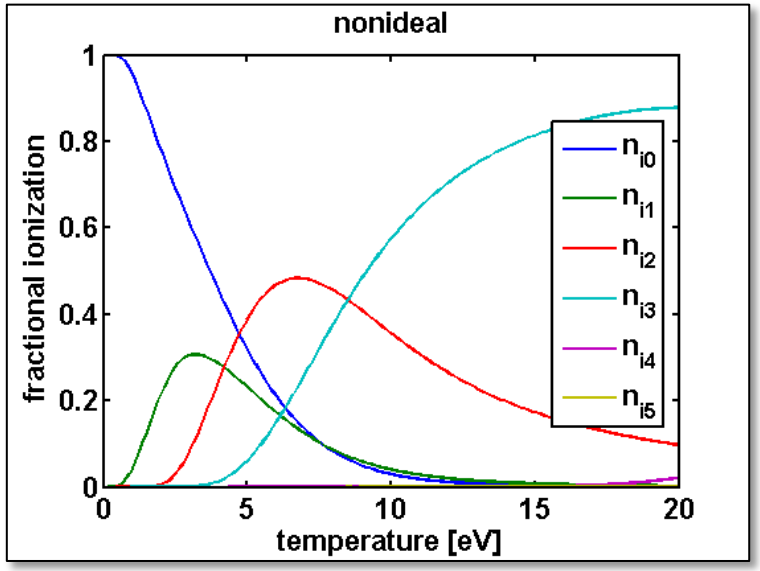
$$\rho_a = \sum_b m_b W_{ab}(h_a)$$
$$\frac{dv_a^i}{dt} = \sum_b m_b \left[\frac{\sigma_a^{ij}}{\rho_a^2} + \frac{\sigma_b^{ij}}{\rho_b^2}\right] \left.\frac{\partial W_{ab}}{\partial x_a^j}\right|_{h^*}$$
$$\frac{de_a}{dt} = \sum_b m_b \left[\frac{v_b^i \sigma_a^{ij}}{\rho_a^2} + \frac{v_a^i \sigma_b^{ij}}{\rho_b^2}\right] \left.\frac{\partial W_{ab}}{\partial x_a^j}\right|_{h^*}$$

- Easy to add additional physics (…relatively)
- Can handle free boundary
- Transitions well to next method
- Automatically adaptive to different scales (to a point)



Ionization in Non-Ideal Plasmas





Non-ideal Saha Equation

$$\frac{n_{r+1}n_e}{n_r} = 2\frac{U_{r+1}}{U_r}\left[\frac{2\pi m_e kT_e}{h^2}\right]^{\frac{3}{2}} \exp\left(-\frac{I_r - \Delta I_r}{kT_e}\right)$$

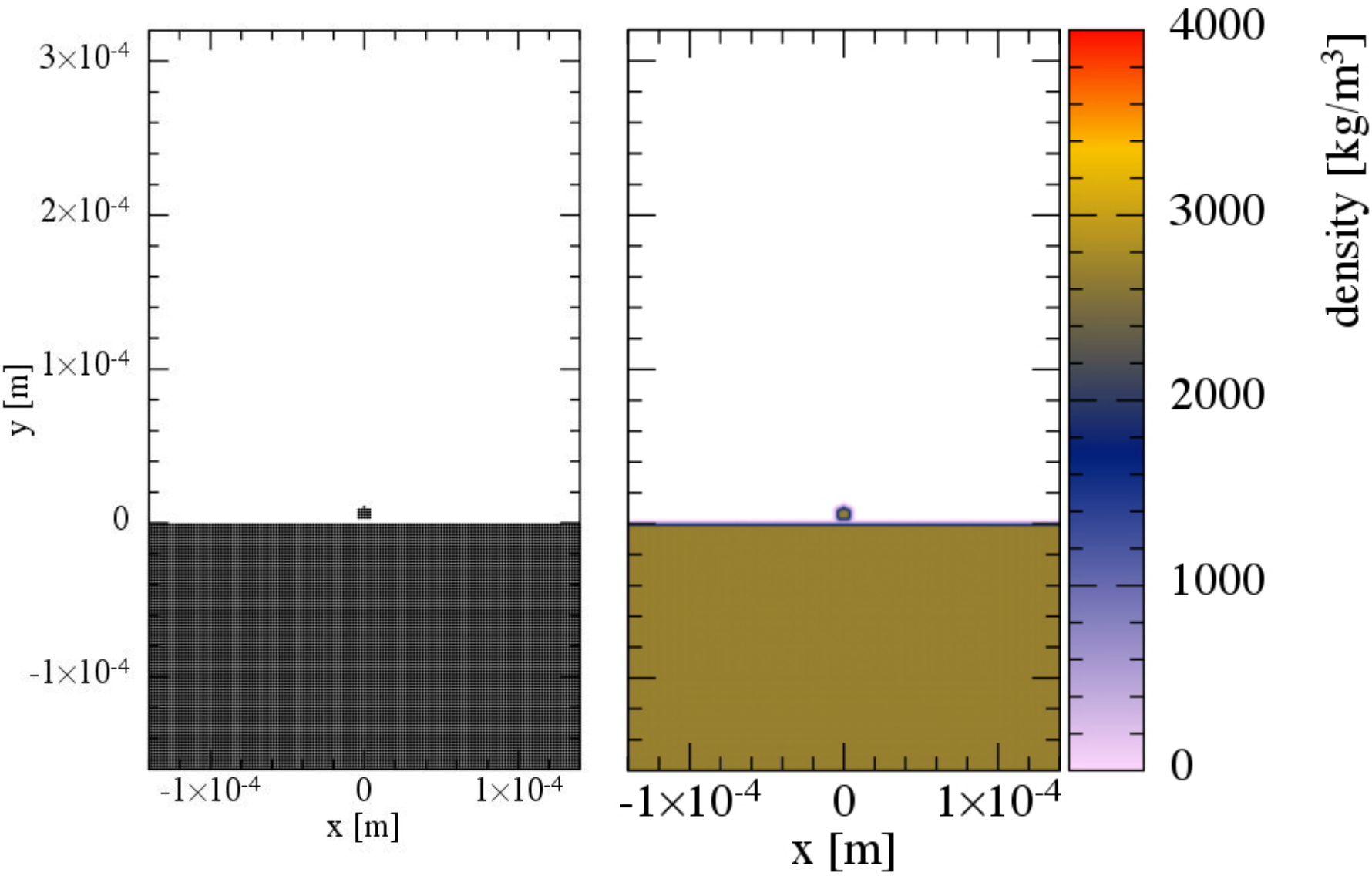
Change in ionization energy

$$\Delta I_r = \frac{(r+1)e^2}{4\pi\epsilon_0 a_r}$$

Equation of State

$$P[n_e, n_r, T, \lambda_D, \ldots] = (1 + Z_{av})n_H k_B T - \triangle P$$

SPH Particles in Density Gradients



A Stable Particle Splitting Algorithm

1) **Split:** place child particles near parent with random orientation

$$m_{child} = \frac{m_{parent}}{n_{children} + 1}$$

$$h_{child} = \frac{h_{parent}}{(n_{children} + 1)^{1/D}}$$

$$r = 0.75\eta h_{parent}$$

2) **Adjust:** treat nearby particles like a truss force

$$f_a = \sum_b (l_0 - l_{ab}) \begin{cases} k_1 & : l_{ab} < l_0 \\ \delta_{ap} k_2 & : l_{ab} \geq l_0 \end{cases}$$

3) **Constrain:** limit motion so influence of child doesn't extend past parent

$$r_l = \eta * h_{child} \left[(n_{children} + 1)^{1/D} - 1 \right]$$

4) **Interpolate:** find child's parameters by interpolating over the parent's neighbors

$$\bar{v}(\bar{r_a}) = \sum_b m_b \frac{\bar{v}_b}{\rho_b} K(l_{ab}, h_a, h_b)$$

Electromagnetic Particle-in-Cell (PIC)

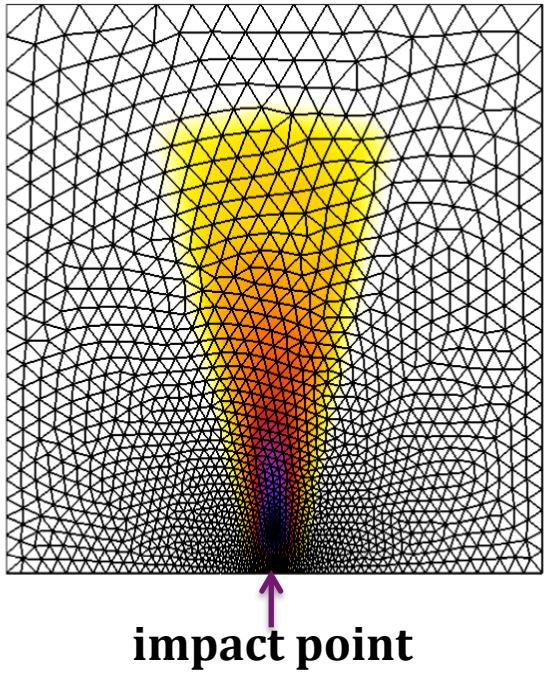
Is there a radiation mechanism? What is it?

$$\frac{\partial \mathbf{E}}{\partial t} = c^2 \nabla \times \mathbf{B} - \frac{1}{\epsilon_0} \sum_s q_s \int \mathbf{v} f_s d\mathbf{v} \qquad \nabla \cdot \mathbf{E} = \frac{1}{\epsilon_0} \sum_s q_s \int f_s d\mathbf{v}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \qquad \nabla \cdot \mathbf{B} = 0$$

$$\frac{\partial f_s}{\partial t} + \mathbf{v} \cdot \nabla f_s + \frac{q_s}{m_s} (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \nabla_{\mathbf{v}} f_s = 0$$

- Unstructured grid adapts to disparate length scales
- No numerical Cherenkov radiation
- Naturally parallelizable
- Higher-order



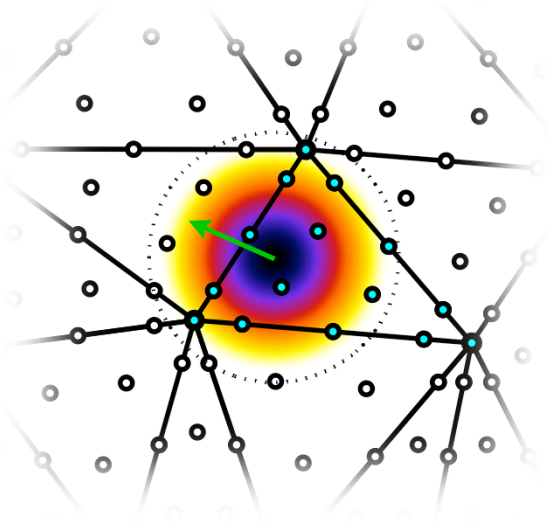
Discontinuous Galerkin (DG) PIC

Weight Particles to Grid

$$S(r) = \frac{\zeta + 1}{\pi R^2}\left[1 - \left(\frac{r}{R}\right)^2\right]^{\zeta}$$

$$\rho_n = \sum_{i=1}^{N_p} q_i S(|\mathbf{x}_{p,i} - \mathbf{x}|)$$

$$\mathbf{j}_n = \sum_{i=1}^{N_p} q_i \mathbf{v}_i S(|\mathbf{x}_{p,i} - \mathbf{x}|)$$



Solve (modified) Maxwell's Equations with DG

$$\hat{\mathbf{n}} \cdot [\mathbf{F} - \mathbf{F}^*] = \frac{1}{2}\begin{bmatrix} \hat{\mathbf{n}} \times (\hat{\mathbf{n}} \times [[\mathbf{E}]] - [[\mathbf{B}]]) - \chi\hat{\mathbf{n}}(\hat{\mathbf{n}} \cdot [[\mathbf{E}]] - [[\Phi]]) \\ \hat{\mathbf{n}} \times (\hat{\mathbf{n}} \times [[\mathbf{B}]] + [[\mathbf{E}]]) - \gamma\hat{\mathbf{n}}(\hat{\mathbf{n}} \cdot [[\mathbf{B}]] - [[\Psi]]) \\ \chi(\hat{\mathbf{n}} \cdot [[\mathbf{E}]] - [[\Phi]]) \\ \gamma(\hat{\mathbf{n}} \cdot [[\mathbf{B}]] - [[\Psi]]) \end{bmatrix}$$

Weight Fields to Particles

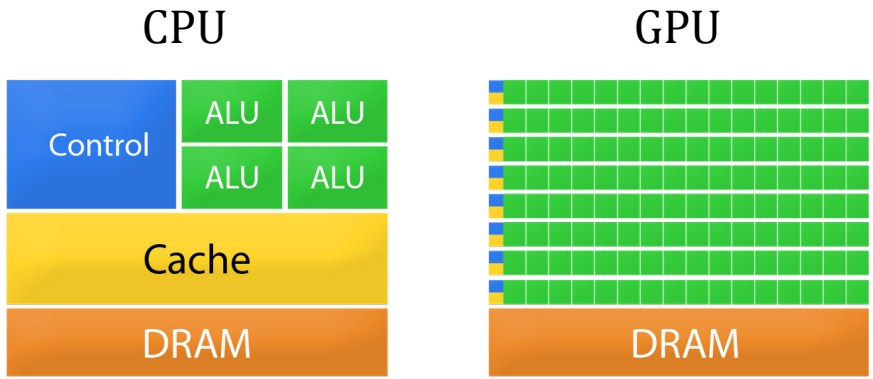
Step Forward in Time

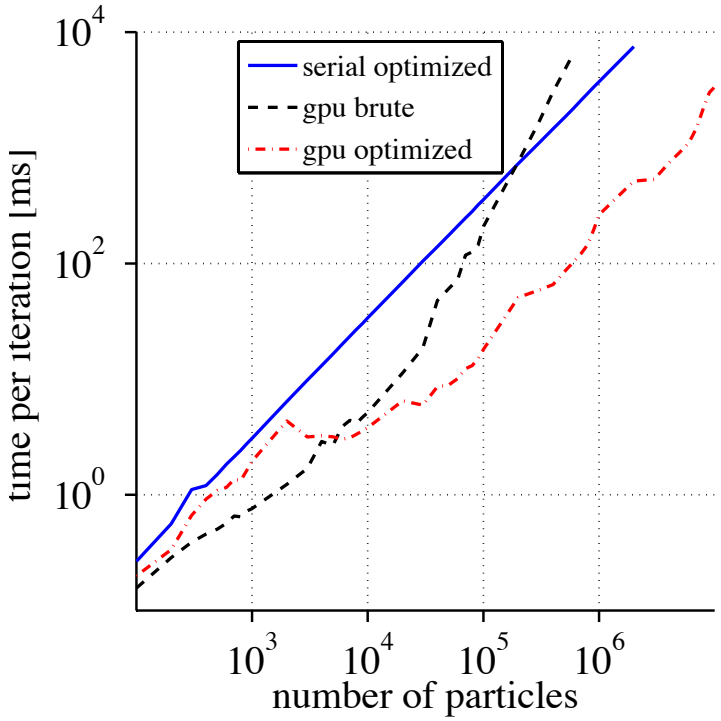
$$\mathbf{w}^{(i)} = \mathbf{w}^{(n)} + \Delta t \Sigma_{\nu=1}^{N} \Sigma_{j=1}^{s} a_{ij}^{\nu} \mathbf{R}^{\nu}(t^{(n)} + c_j \Delta t, \mathbf{w}^{(j)})$$

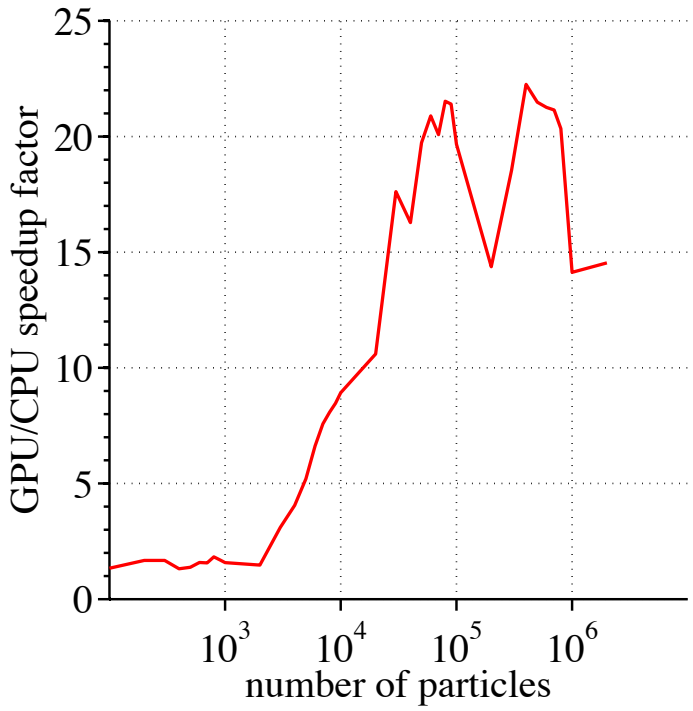
$$\mathbf{w}^{(n+1)} = \mathbf{w}^{(n)} + \Delta t \Sigma_{\nu=1}^{N} \Sigma_{i=1}^{s} b_{i}^{\nu} \mathbf{R}^{\nu}(t^{(n)} + c_i \Delta t, \mathbf{w}^{(i)})$$

Parallelization on a GPU

- Parallel octree construction
- Each particle traverses tree in a separate thread
- **DG:** parallel matrix ops
- Plasma state stored in textures







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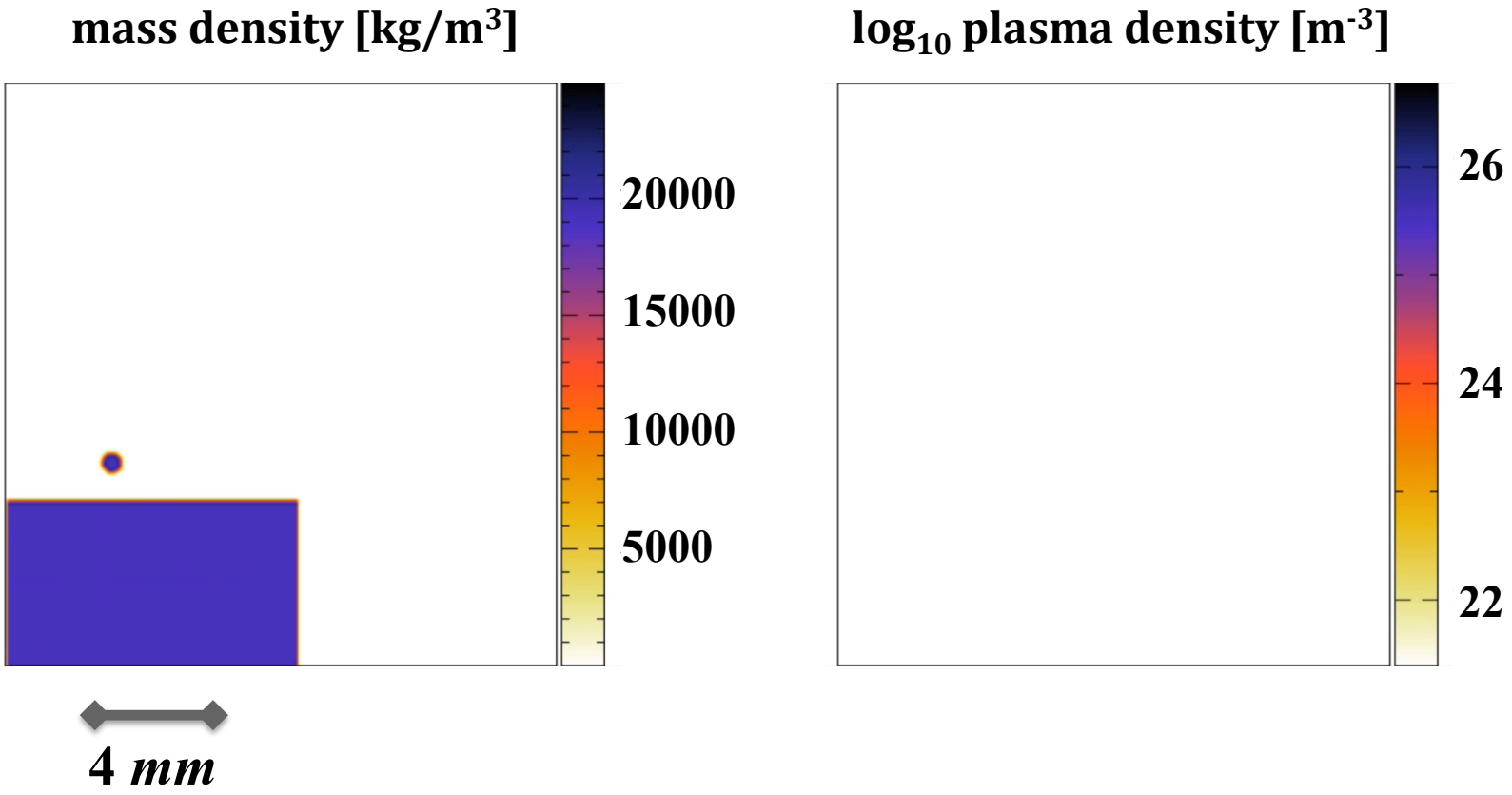
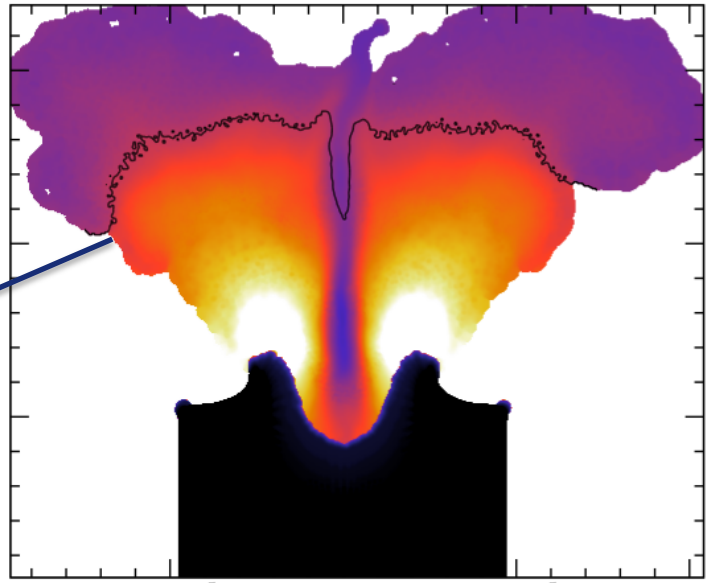
Plasma Production

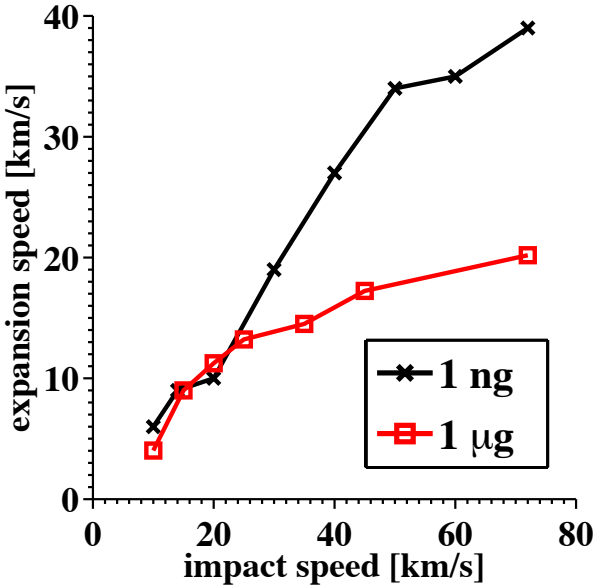


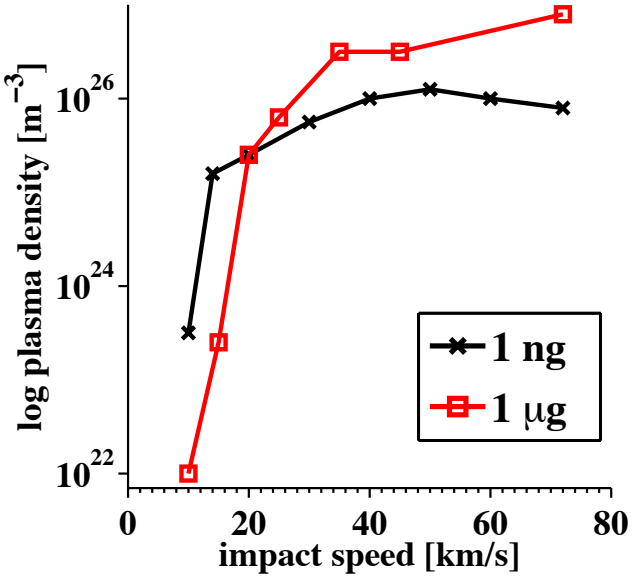
A **microgram** hypervelocity particle traveling **18 *km/s*** striking tungsten

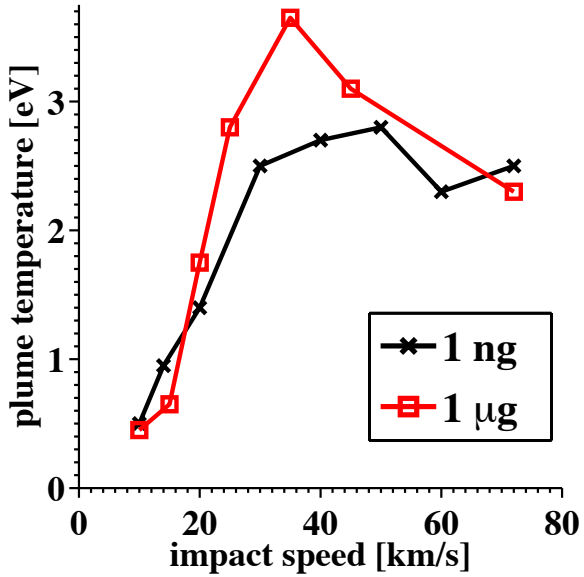
Speed and Mass Dependence



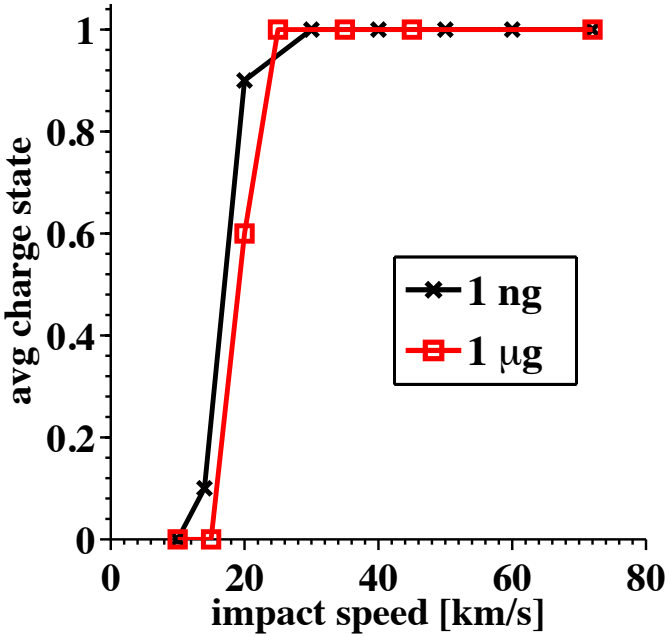
$$\frac{\omega_p}{\nu_{ei}} \sim 1$$

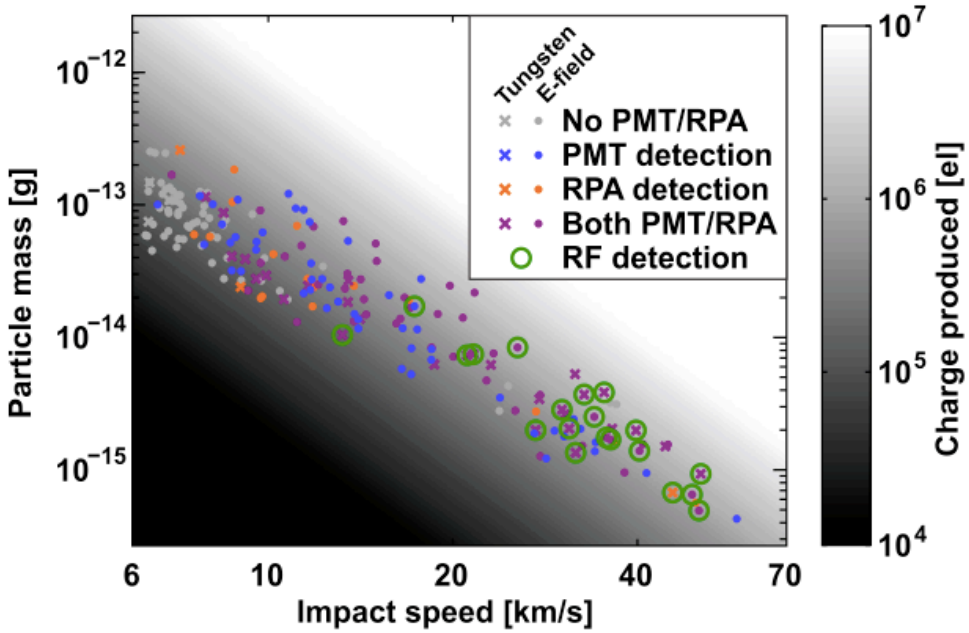






Ionization and Electromagnetic Radiation



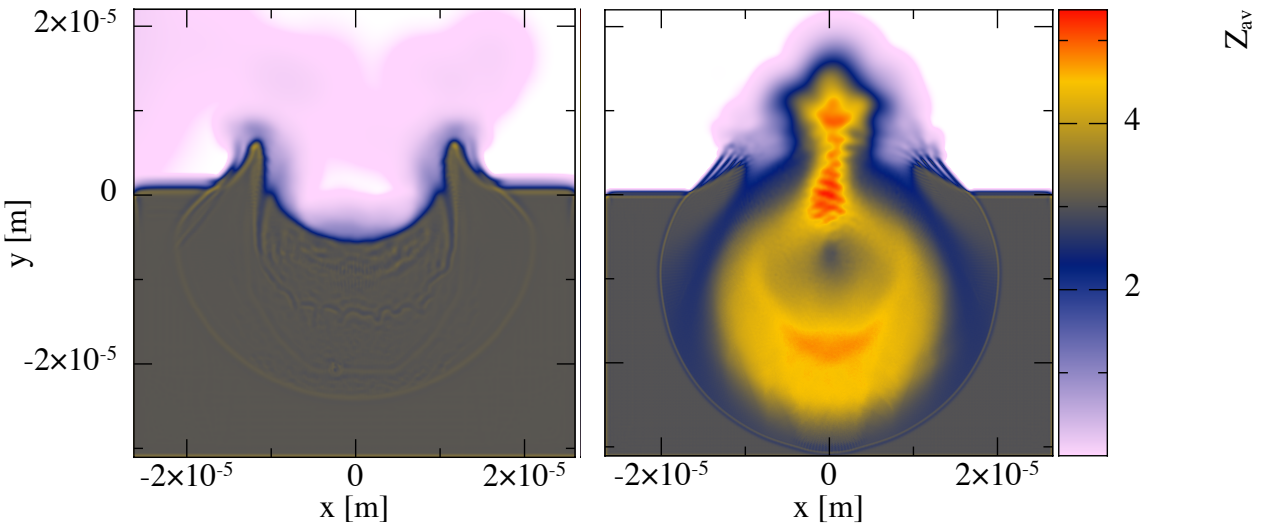


- Weakly ionized➔fully ionized at an impact speed of **~18 *km/s***
- Van de Graaff experiments produced the *same* abrupt speed threshold for radio frequency emission

Close, S. I. Linscott, N. Lee, T. Johnson, D. Strauss, et al., (2013) Detection of electromagnetic pulses produced by hypervelocity micro particle impacts, *Phys. Plasmas*, *20*, doi: 10.1063/1.4819777

Comparison to Experiment

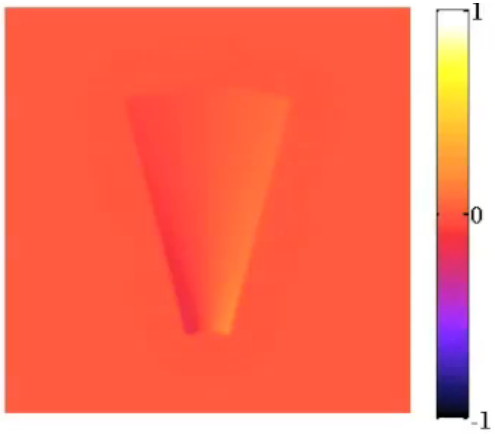
- Non-ideality causes:
  - Very high charge states in crater and at expansion boundary
  - Increased crater pressure and expansion velocity
- Total charge produced *is not* the same as total charge expanding into vacuum
- Multiple temperature measurements in different regimes match simulation



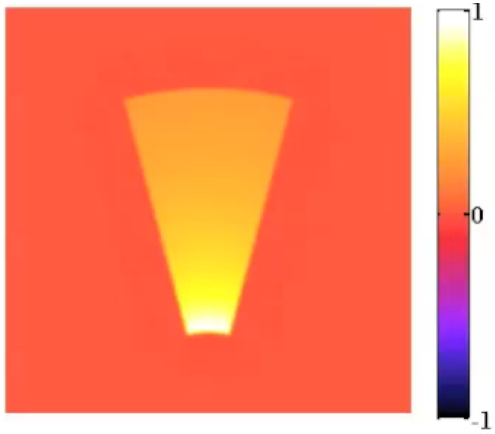
10 km/s 72 km/s

EMP at Collisionless Transition

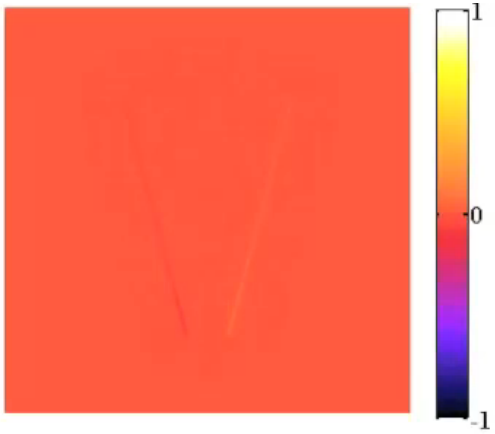
x Electric Field



y Electric Field



z Magnetic Field



- Nondimensionalized electric field (***x***), electric field (***y***), and magnetic field (***z***) from 50 *km/s* nanogram meteoroid
- Assuming perfect initial conditions (from theory), simulation produces a strong EMP
- Large initial pulse that rapidly decays temporally and spatially, supports theory

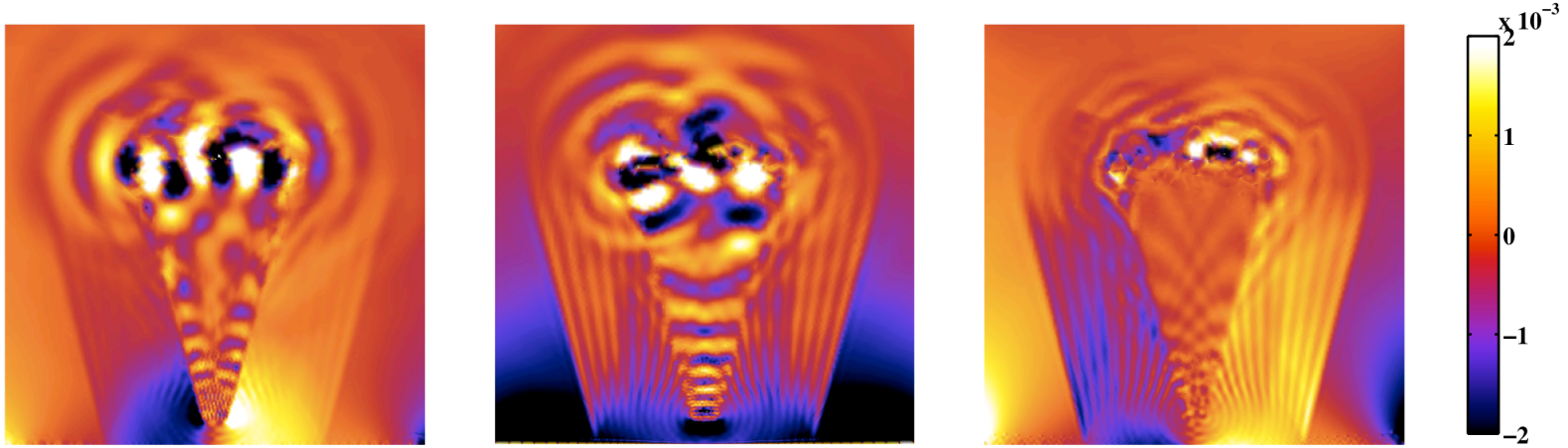
Fletcher, A., Close, S., Simulating hypervelocity plasmas and their effects on spacecraft, *Union of Radio Scientists U.S.A. National Radio Science Meeting*, 2014.

EMP from Charged Spacecraft

x Electric Field

y Electric Field

z Magnetic Field

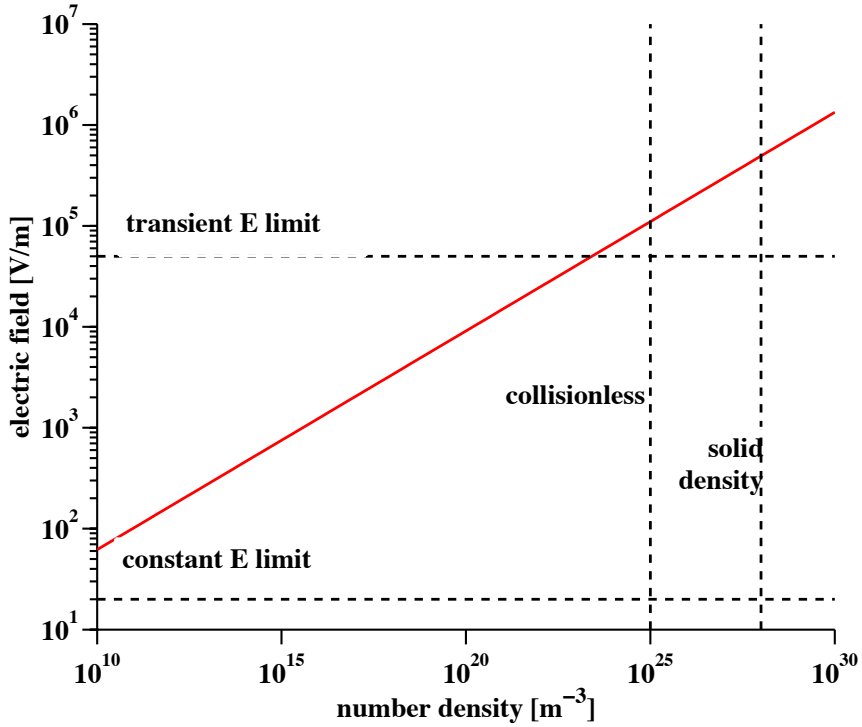


- Nondimensional electric field (***x***), electric field (***y***), and magnetic field (***z***) from 50 *km/s* nanogram meteoroid
- Removing ideal initial conditions from theory
- Add 1 *kV* potential to impact surface

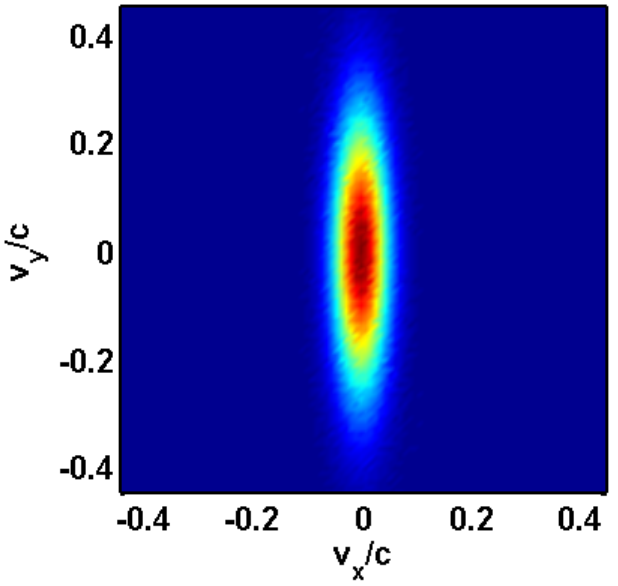
Threat to Spacecraft Electronics

- Standing waves in plasma couple to electromagnetic radiation
- Peak electric field amplitude reaches $\mathbf{10^5}$ $\boldsymbol{V/m}$ (!)
- Currently spacecraft are designed to $\sim\mathbf{10}$ $\boldsymbol{V/m}$ (static) or $\mathbf{10^4}$ (transient)

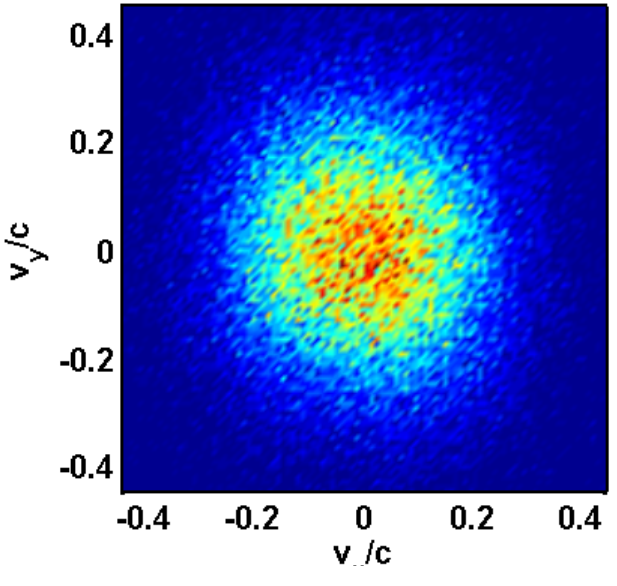
- … but the field is very spatially localized
- Falls to < 10 V/m within 10 cm for this worst realistic case
- ~1 catastrophic event per 22 years per satellite



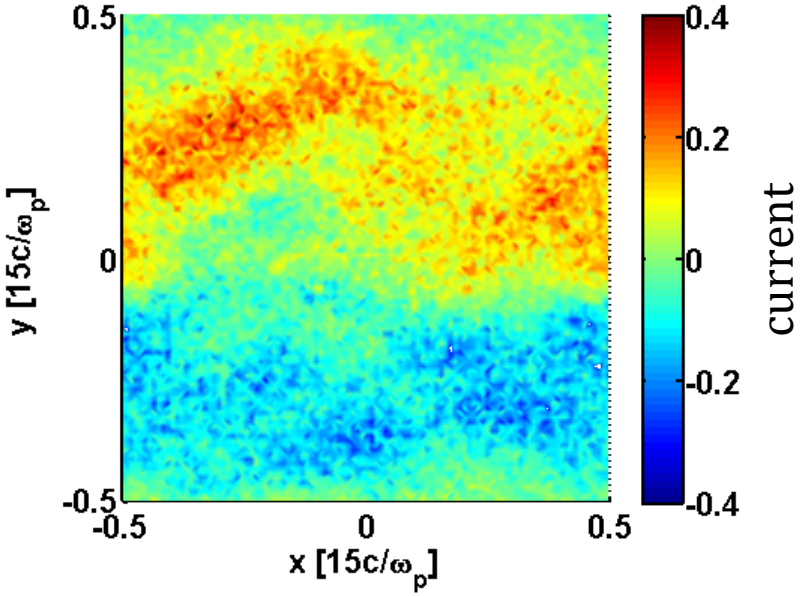
Weibel Instability (preliminary)

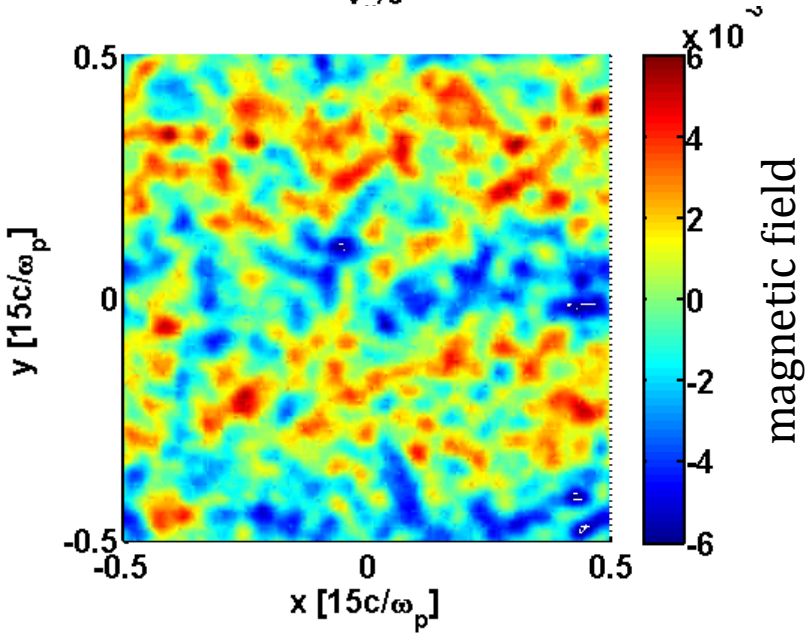


f(v,t=0)

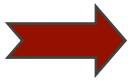


f(v,t>0)





- Motivation
- Plasma Primer
- Impact Physics
- Computational Approach
- Simulation Results



- **Concluding Remarks**

Contributions

- **Hypervelocity impact plasmas:**
  - Created the first comprehensive (multi-physics and multi-scale) computational simulation of hypervelocity impact plasmas; compares favorably with multiple experiments
  - Explained a mysterious result from impact experiments, showing that radio frequency emission is correlated to plasma formation
  - Showed that faster impacts (>30 *km/s*) are remarkably similar over a large range of parameters, and speed is the dominant parameter
  - Supported a theoretical model of radio frequency emission from impact plasmas
  - Developed particle refinement algorithm and GPU parallelism for SPH and PIC

Future Work

- Simulate other materials, understand beta factor
- Are there differences in predictions of non-ideality models (that are detectable in experiments)?
- Electrostatic simulation to test validity of theoretical assumptions used for EMP mechanism
- Understand the coupling between electrostatic and electromagnetic waves that is observed in the PIC
- Two other possible mechanisms:
  - Instabilities (in particular the Weibel instability)
  - MHD EMP from expanding charge front and ringing B-field
- Refine estimate for damage to spacecraft electronics

Thank you! Questions??

"Indeed, the plasma has taught me that it is so complicated that it should be regarded as a living being than a dead mechanical system. … This creature does not understand differential equations and vectors and tensors and does not care for such nonsense. It always finds new ways to cheat the mathematical physicist. This means that unless a scientist purges his brain of all such stuff he has little chance of understanding this naughty and whimsical child who loves to revolt against what the theoreticians have prescribed that it should do."

-Hannes Alfvén

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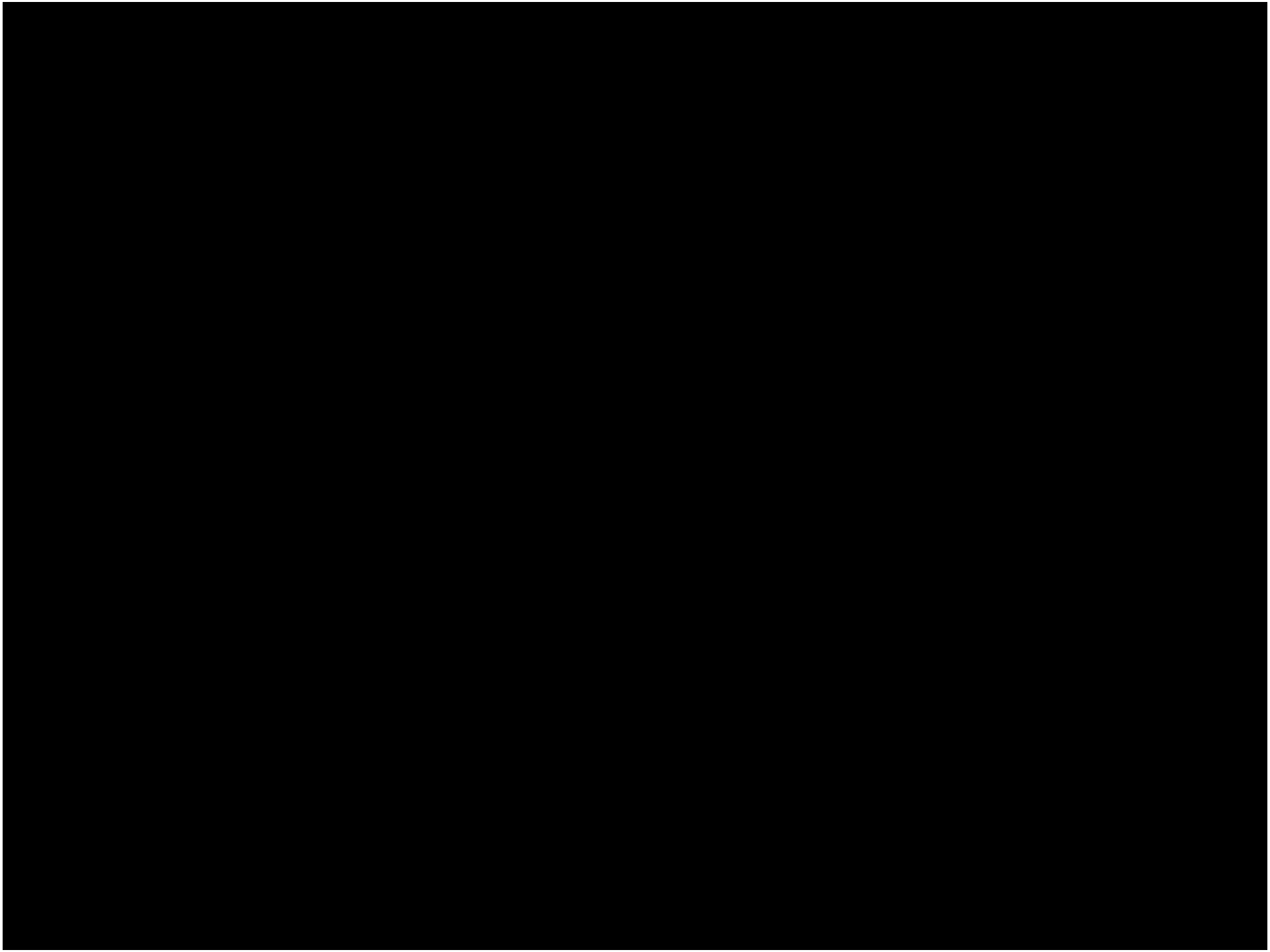
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