

Modeling and Rendering Glow Discharge

Venkataram Sivaram, Ravi Ramamoorthi, Tzu-Mao Li

University of California, San Diego

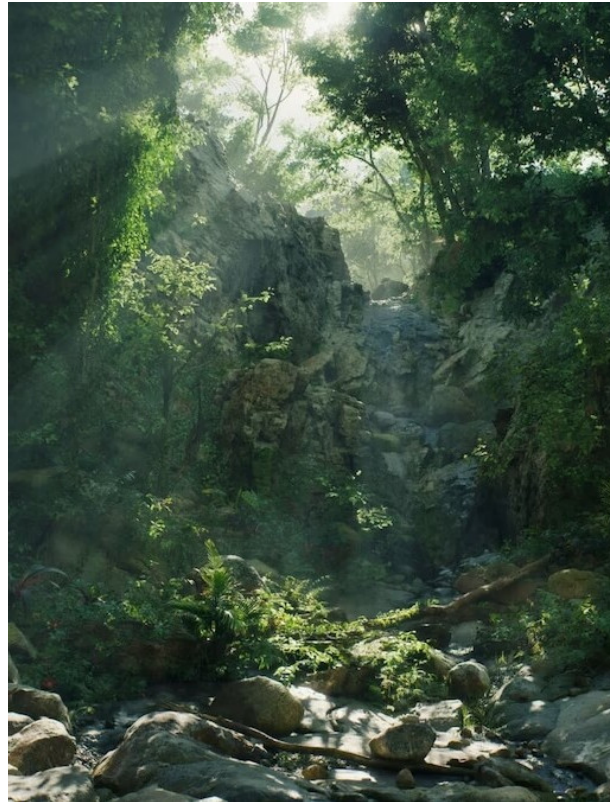
Goal: interactive rendering of glow discharge



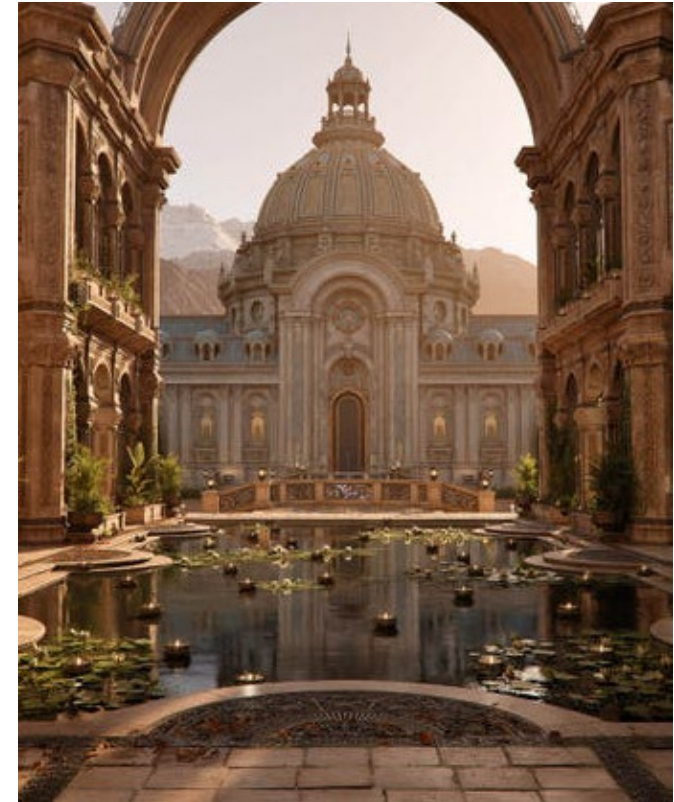
Why do we care about realistic light sources?



Futuristic (Cyberpunk 2077)



Natural (Electric Dreams)



Architectural (Zorah)

What is so interesting about glow discharge?



Gas discharge lamp



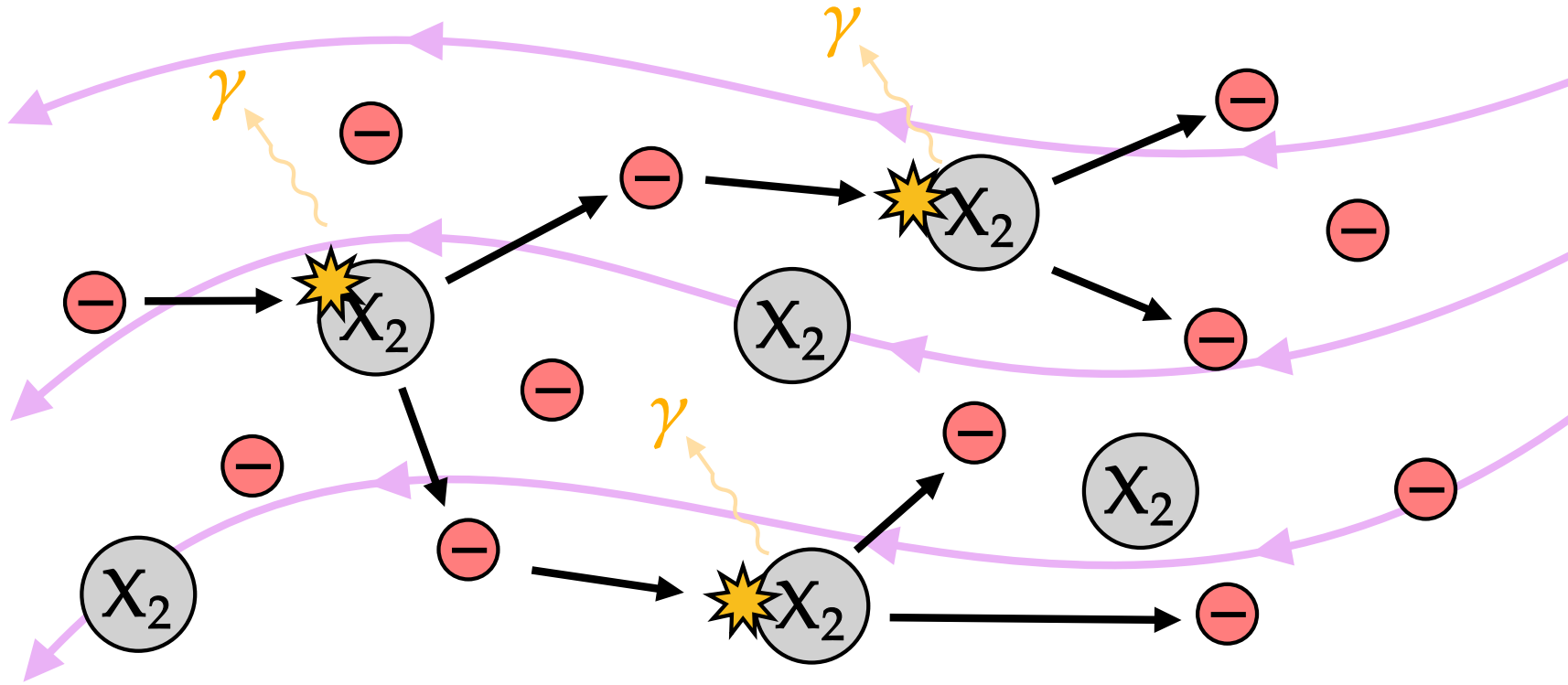
Neon signs



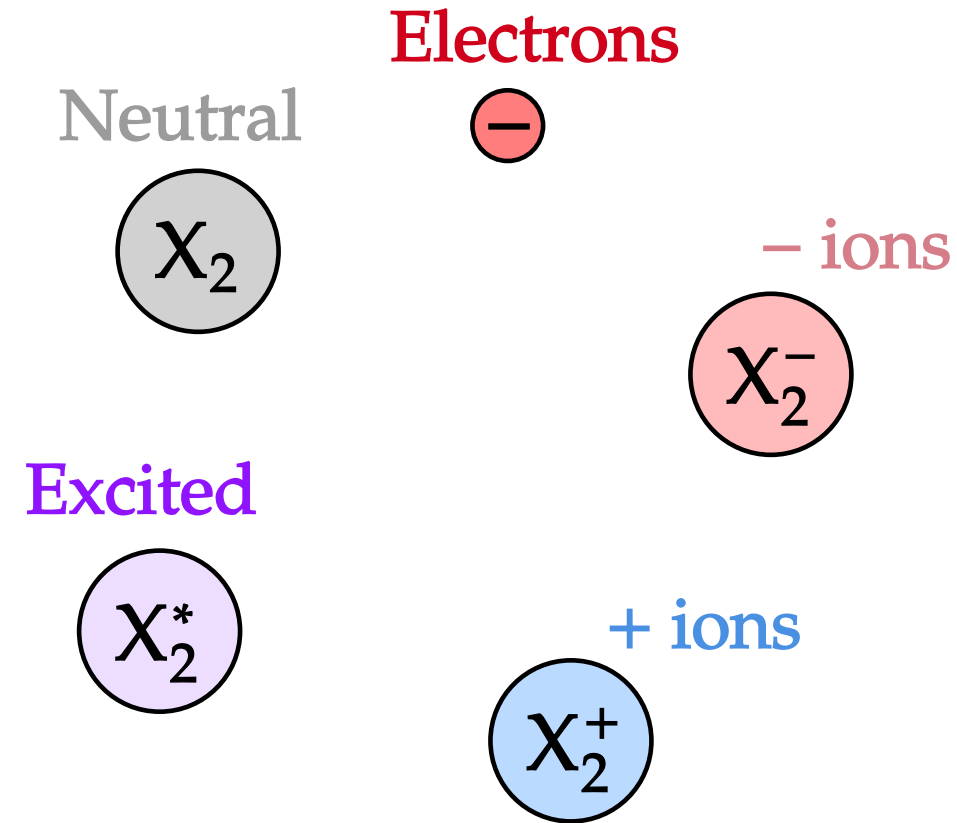
Kirlian photography

Physics of Glow Discharge

Glow discharge at a glance



Particles involved in glow discharge

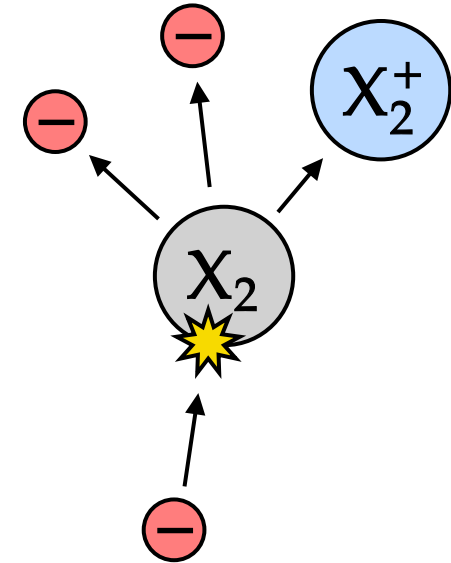


Ionization

High-energy electron collides with neutral molecule:

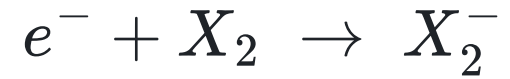


Produces an additional free electron into the system

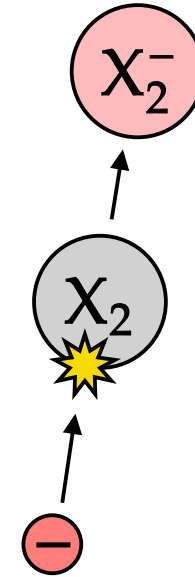


Attachment

Free electron attaches to neutral molecule:

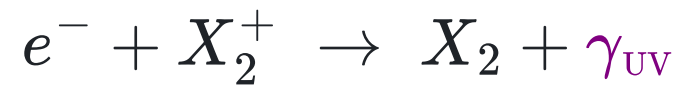


Adds a negative ion, removes free electron

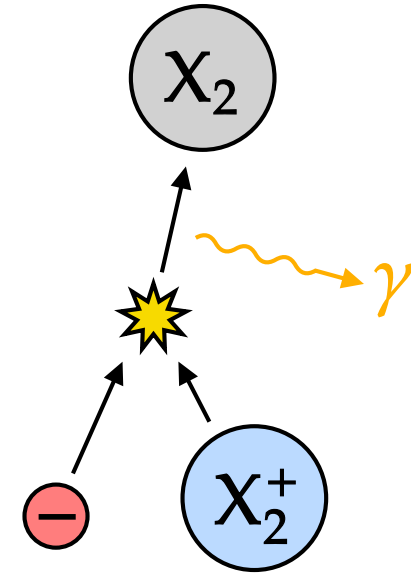


Recombination (electron-ion)

Electron neutralises positive ion:



Emits mostly non-visible UV photons (often re-absorbed)

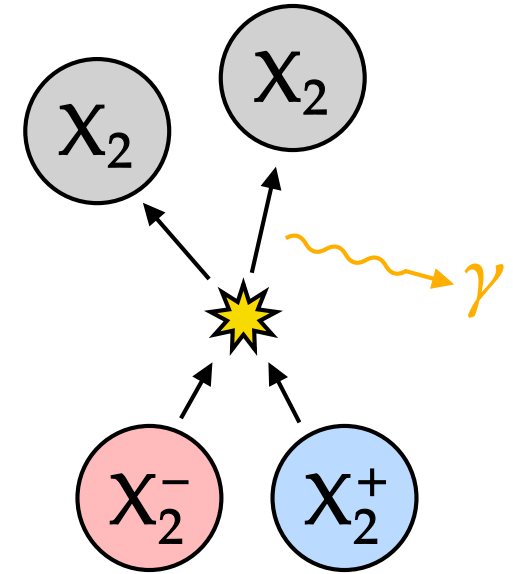


Recombination (ion-ion)

Negative and positive ions neutralise each other:

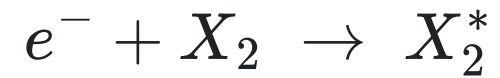


Also emits mostly non-visible UV photons

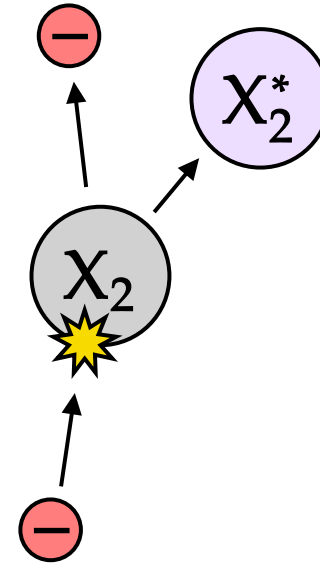


Excitation

Neutral molecule absorbs energy of electron:

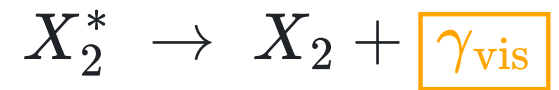


Elevates molecule to an excited state

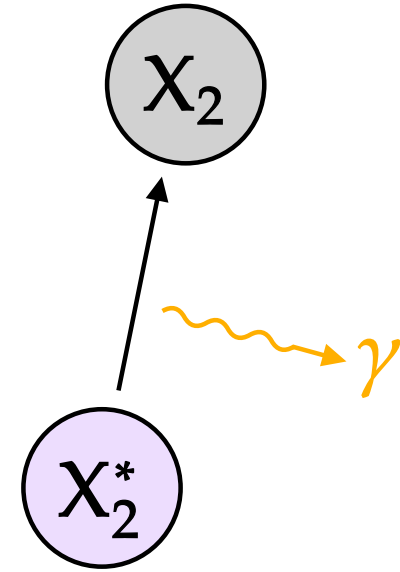


Deexcitation

Excited molecule returns to ground state:



Emits most of the visible light!



Mathematical Model

Reference model from computational physics

Starting point is a PDE from computational physics:

- Coupled system of number densities E, P, N
- Particle drift velocities $\vec{v}_E, \vec{v}_P, \vec{v}_N$

Density evolution: electrons

$$\partial_t E = \text{Ionization} - \text{Attachment} - \text{Recombination} + \text{Advection}$$

Density evolution: electrons

$$\partial_t E = \underbrace{\alpha \|\vec{v}_E\| E}_{\text{Ionization}} - \underbrace{\eta \|\vec{v}_E\| E}_{\text{Attachment}} - \underbrace{\beta EP}_{\text{Recombination}} + \underbrace{\nabla \cdot (E \vec{v}_E)}_{\text{Advection}}$$

Density evolution: positive ions

$$\partial_t P = \text{Ionization} - \text{Recombination} + \text{Advection}$$

Density evolution: positive ions

$$\partial_t P = \underbrace{\alpha \|\vec{v}_E\| E}_{\text{Ionization}} - \underbrace{\beta EP}_{\text{Recombination}} - \underbrace{\nabla \cdot (P \vec{v}_P)}_{\text{Advection}}$$

Density evolution: negative ions

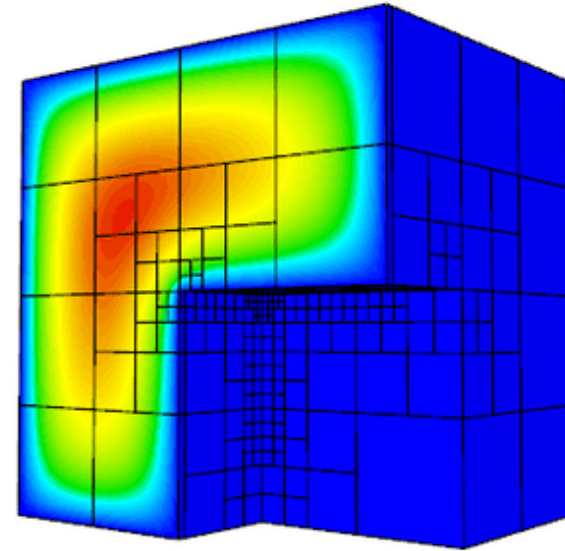
$$\partial_t N = \text{Attachment} - \text{Recombination} + \text{Advection}$$

Density evolution: negative ions

$$\partial_t N = \underbrace{\eta \|\vec{v}_E\| E}_{\text{Attachment}} - \underbrace{\beta NP}_{\text{Recombination}} - \underbrace{\nabla \cdot (N \vec{v}_N)}_{\text{Advection}}$$

Challenges for interactive rendering

- Coupled PDEs require global FEM/FD solves
- Fine spatial scales need dense meshes
- Scene and parameter tweaks require re-solve



Towards interactive rendering

Steady state dynamics

Assume that $\partial_t E = \partial_t P = \partial_t N = 0$ to eliminate the time dependence:

$$0 = \alpha \|\vec{v}_E\| E - \eta \|\vec{v}_E\| E - \beta EP + \nabla \cdot (E \vec{v}_E)$$

$$0 = \alpha \|\vec{v}_P\| P - \beta EP + \nabla \cdot (P \vec{v}_P)$$

$$0 = \eta \|\vec{v}_N\| N - \beta NP + \nabla \cdot (N \vec{v}_N)$$

Homogenizing the drift velocity

Use a common field $\vec{\mu}$ to represent the drift velocity to form a system of ODEs:

$$0 = \alpha \|\vec{\mu}\| E - \eta \|\vec{\mu}\| E - \beta EP + \nabla \cdot (E \vec{\mu})$$

$$0 = \alpha \|\vec{\mu}\| P - \beta EP + \nabla \cdot (P \cdot \rho \vec{\mu})$$

$$0 = \eta \|\vec{\mu}\| N - \beta NP + \nabla \cdot (N \cdot \rho \vec{\mu})$$

For ions, scale the field strength by ρ , so that $\vec{v}_P = \vec{v}_N = \rho \vec{\mu}$

Log-space densities

Parameterize number densities E , P , N with their logarithms:

$$E = \exp \tilde{E}, \quad P = \exp \tilde{P}, \quad N = \exp \tilde{N}$$

Helps to resolve numerical instabilities during integration.

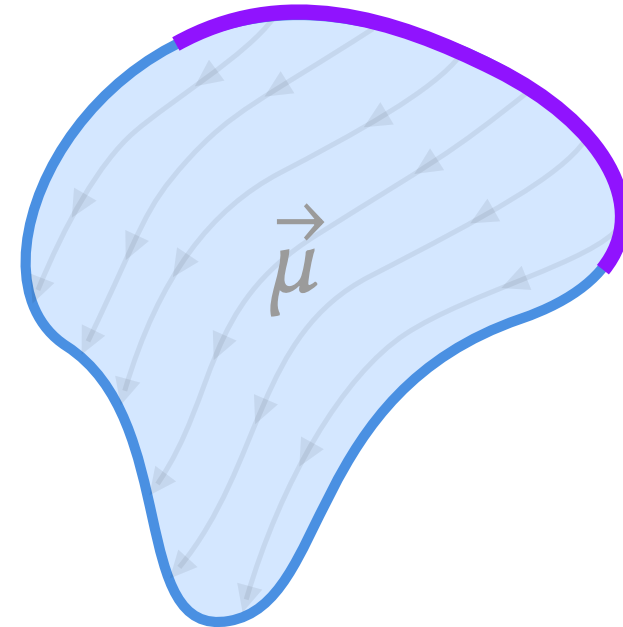
Boundary conditions

Inflow boundary condition along Γ :

$$\tilde{E} = \tilde{P} = \tilde{N} = 0$$

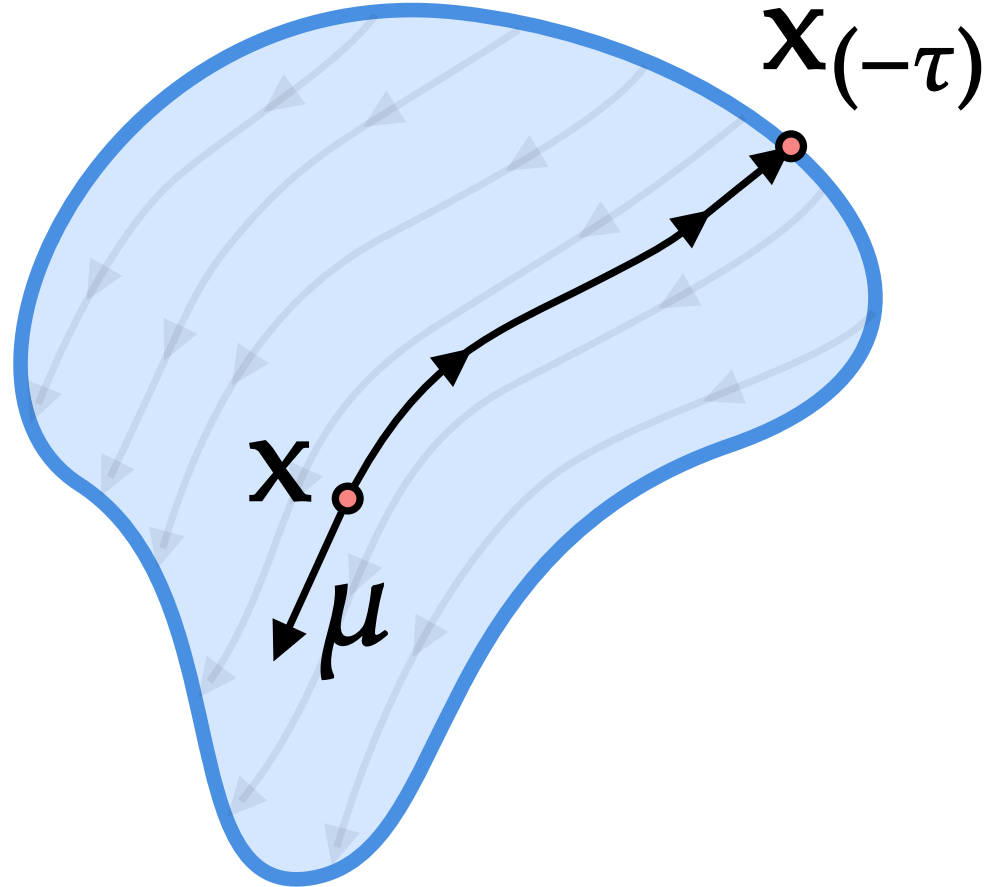
Acts as seed electrons/ions entering active region

$$\Gamma: \vec{\mu} \cdot \vec{n} < 0$$

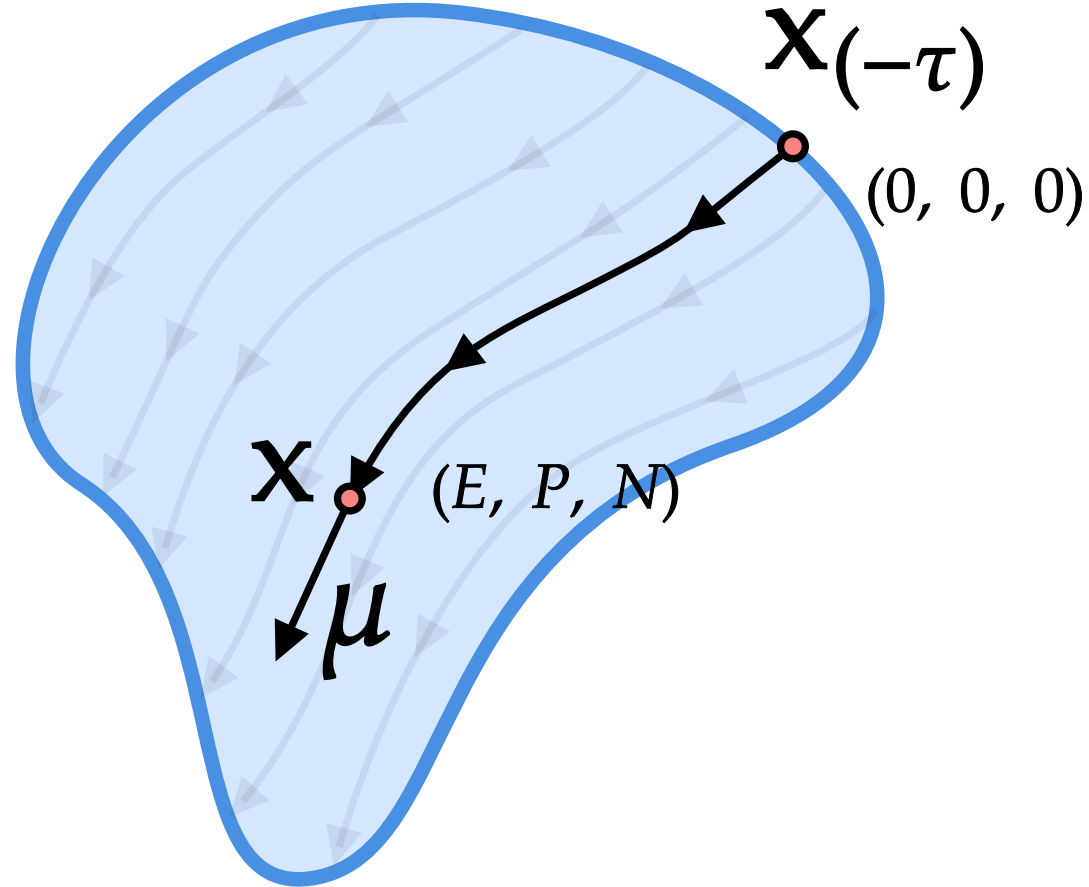


Solver and Renderer

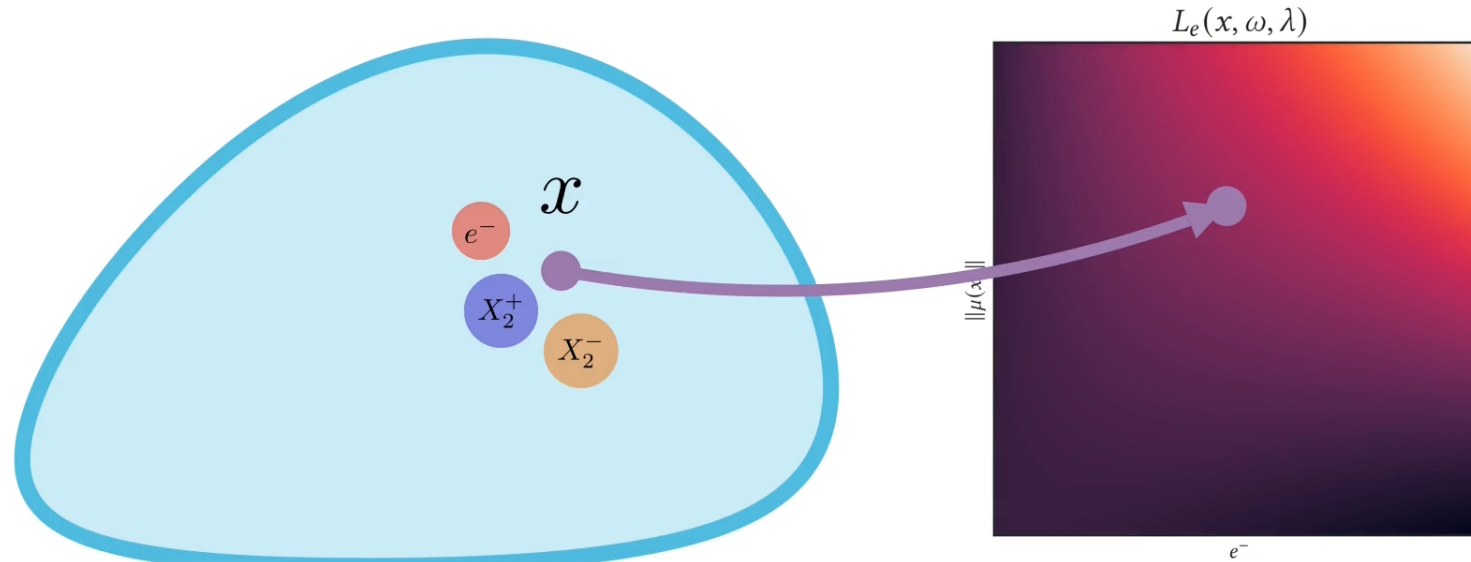
Point-wise solver: backward tracing



Point-wise solver: forward integration



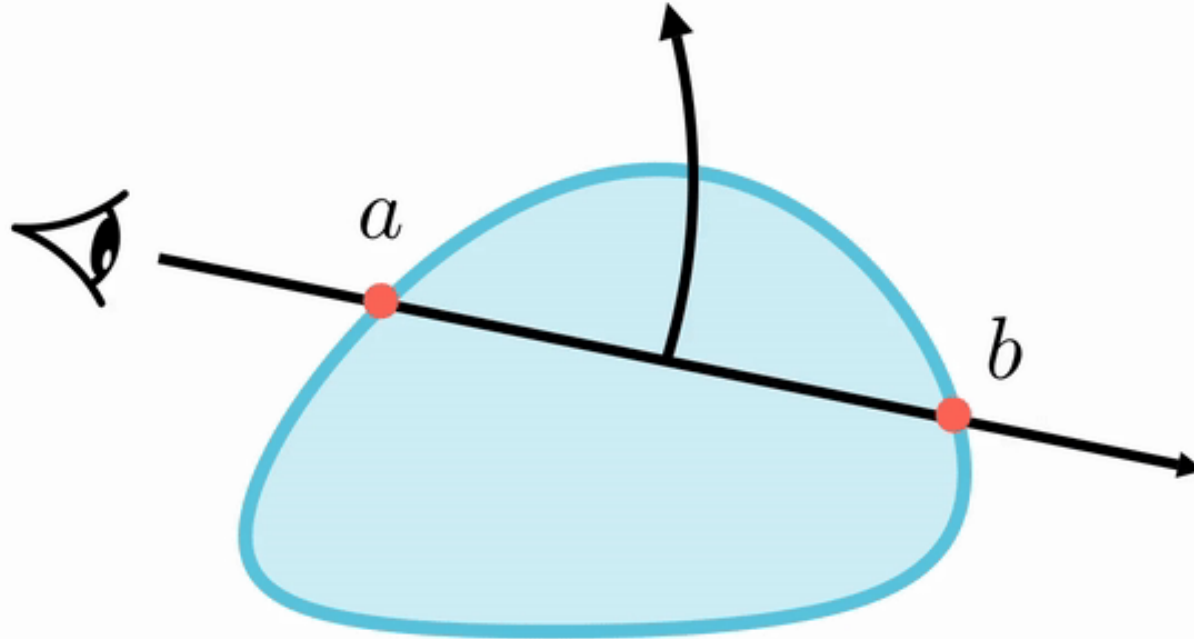
Physical to rendering quantities



$$L_e(\mathbf{x}, \boldsymbol{\omega}, \lambda) = \left(\frac{P_\lambda \sigma_0}{4\pi} \right) \|\vec{\mu}\| E(\mathbf{x}) \propto \sigma_0 \|\vec{\mu}\| E(\mathbf{x})$$

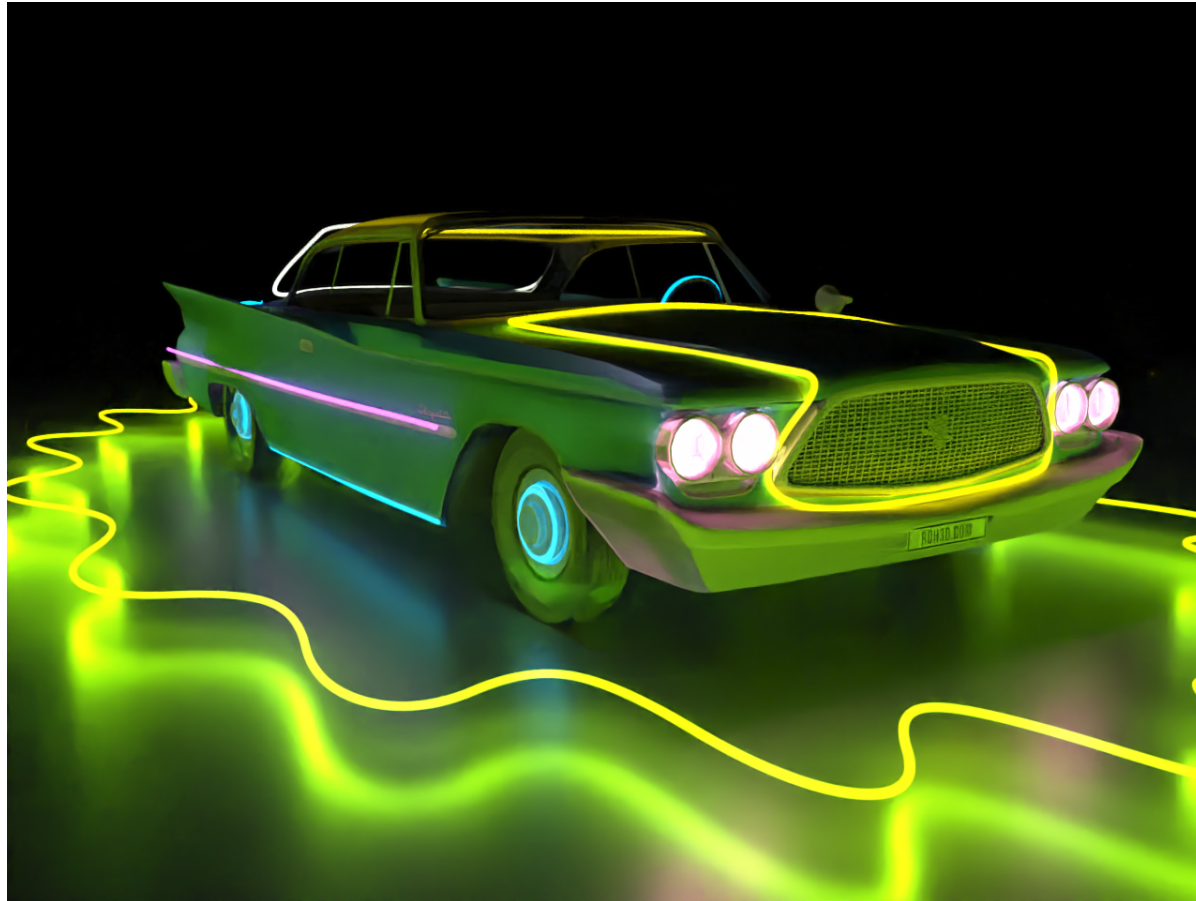
Monte Carlo estimator

$$L_o(x, \omega, \lambda) = \int_a^b L_e(x(t), \omega, \lambda) dt$$



Results and Evaluation

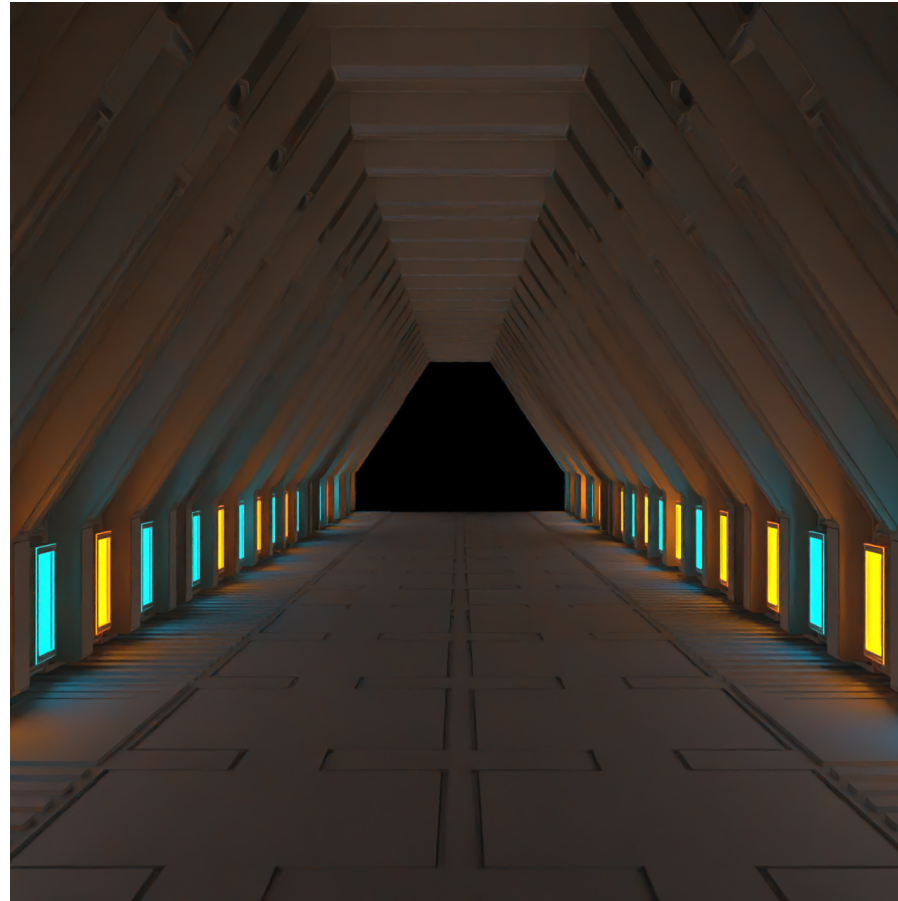
Rendering with only glow discharge primitives



Rendering with only glow discharge primitives



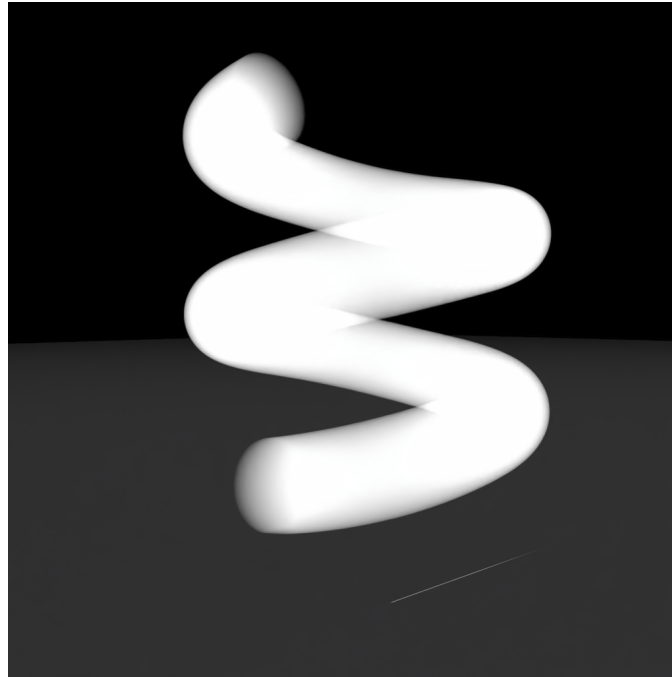
Rendering with only glow discharge primitives



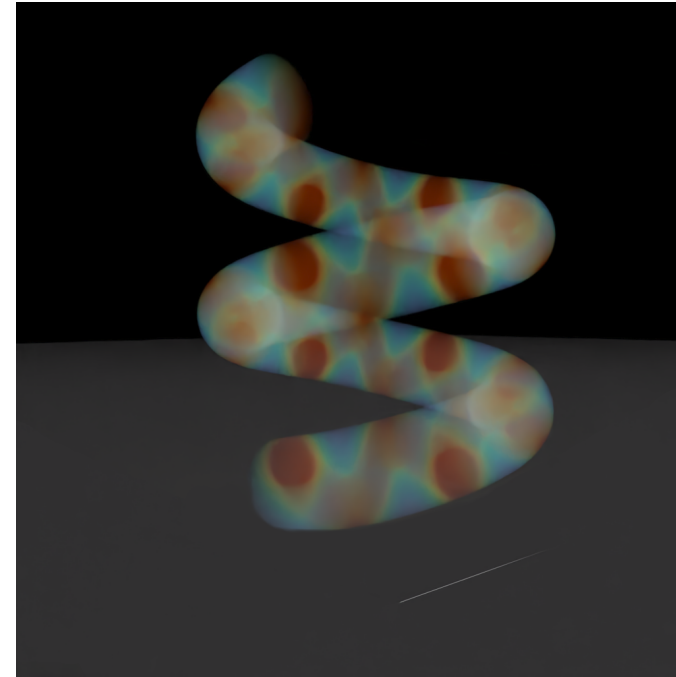
Rendering different gases



Parameter interpretation: scene configuration



Active region

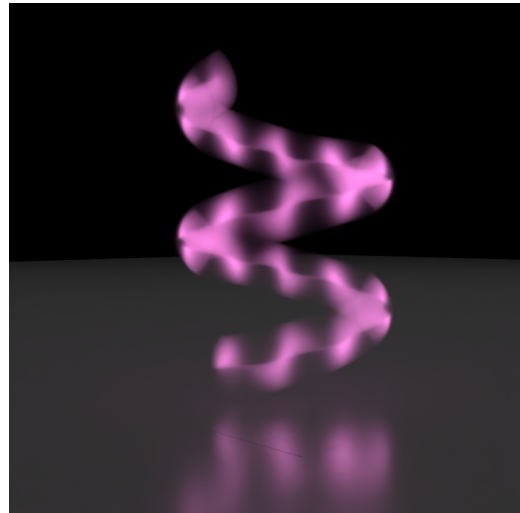


Drift velocity field

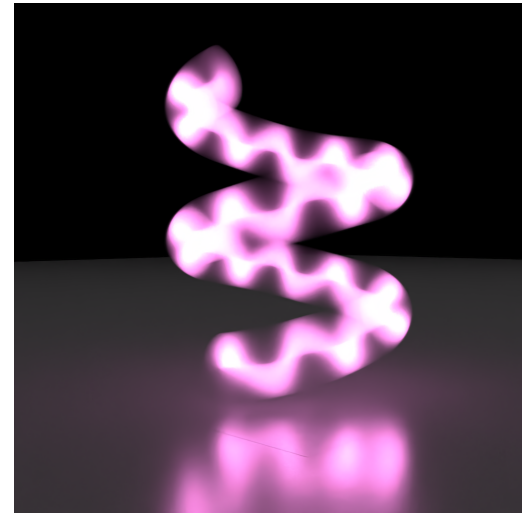
Parameter interpretation: ionization rate



$$\alpha = 10^2$$



$$\alpha = 5 \cdot 10^2$$

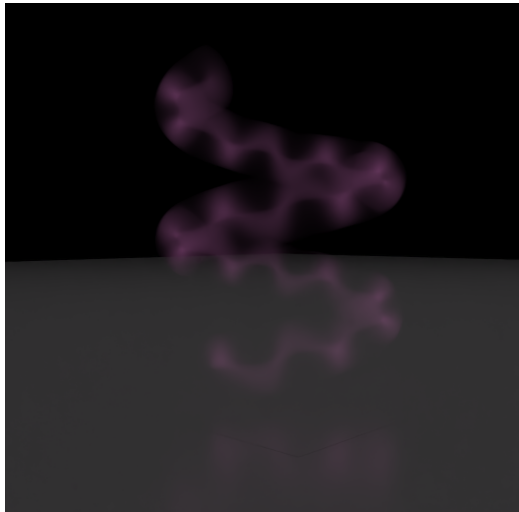


$$\alpha = 10^3$$

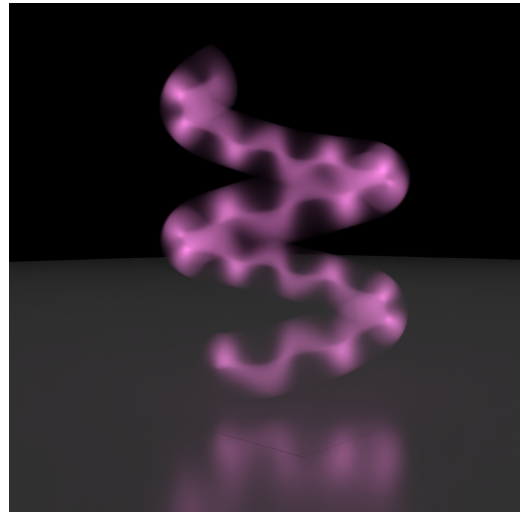


$$\alpha = 5 \cdot 10^3$$

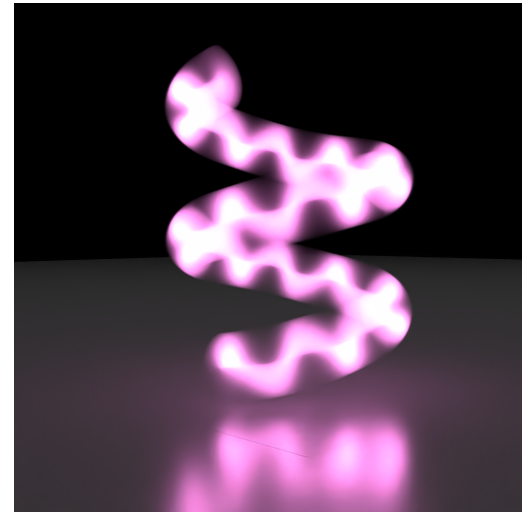
Parameter interpretation: recombination rate



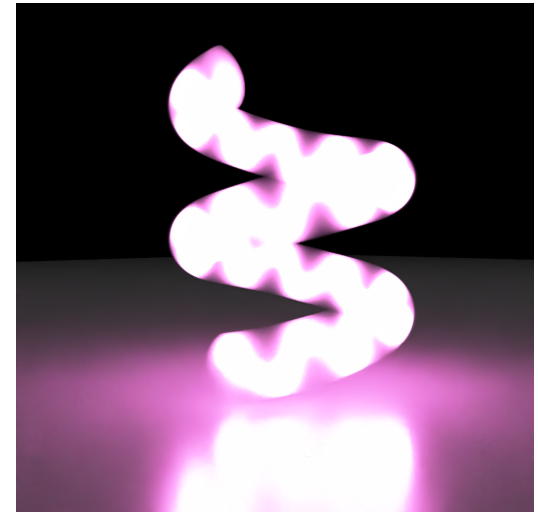
$$\beta = 10^{-8}$$



$$\beta = 10^{-9}$$

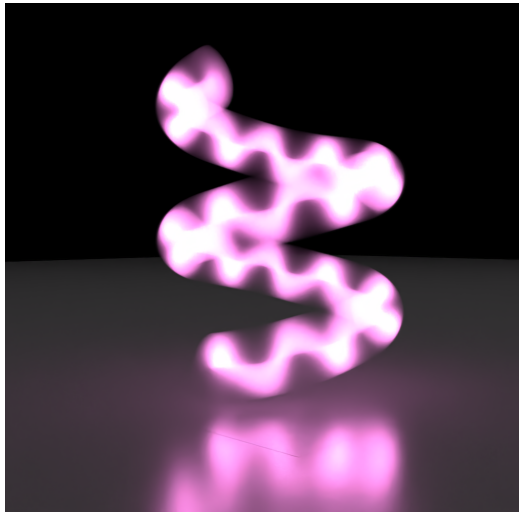


$$\beta = 10^{-10}$$

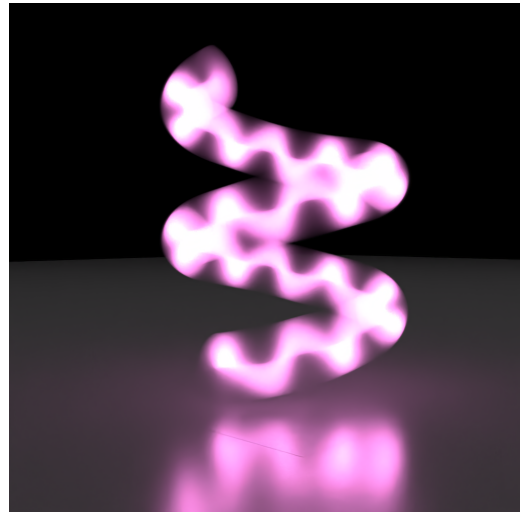


$$\beta = 10^{-11}$$

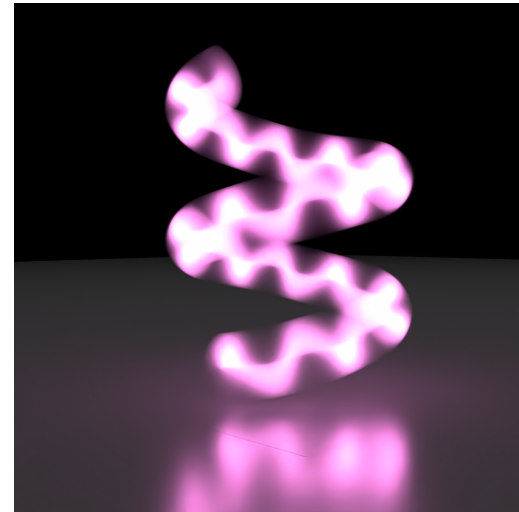
Parameter interpretation: attachment rate



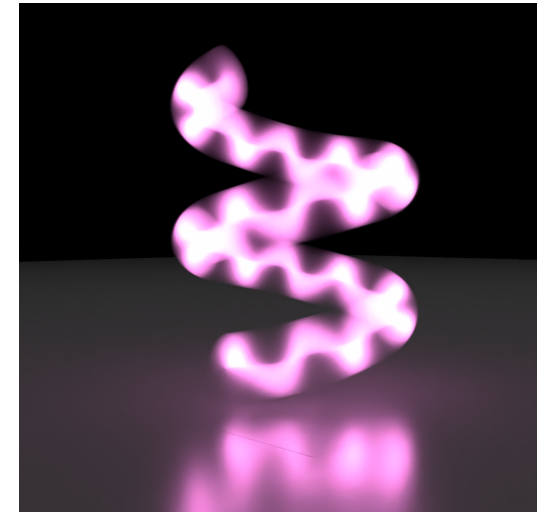
$$\eta = 0.25$$



$$\eta = 0.5$$

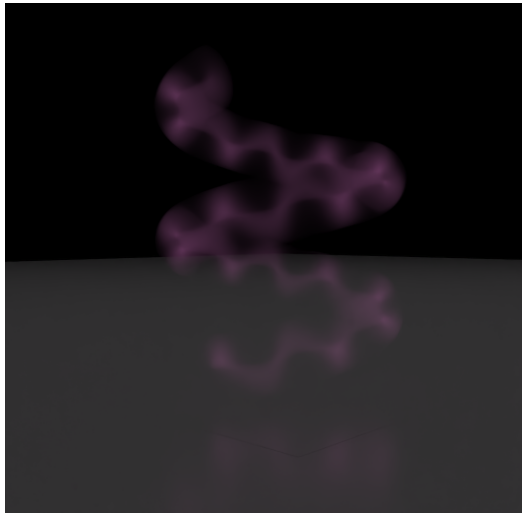


$$\eta = 1.0$$

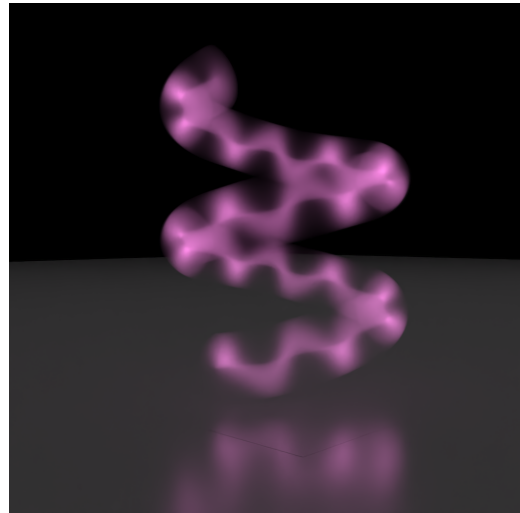


$$\eta = 2.0$$

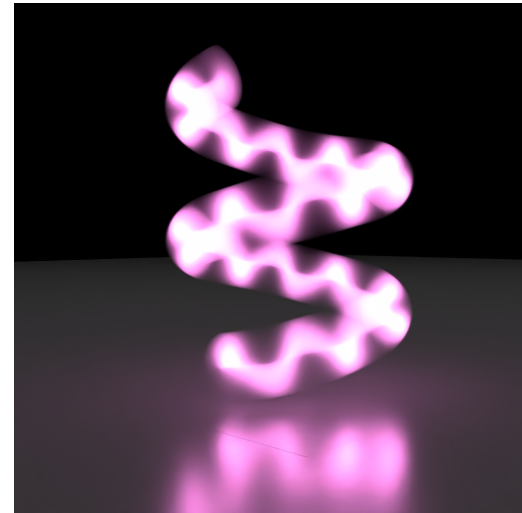
Parameter interpretation: scaling factor



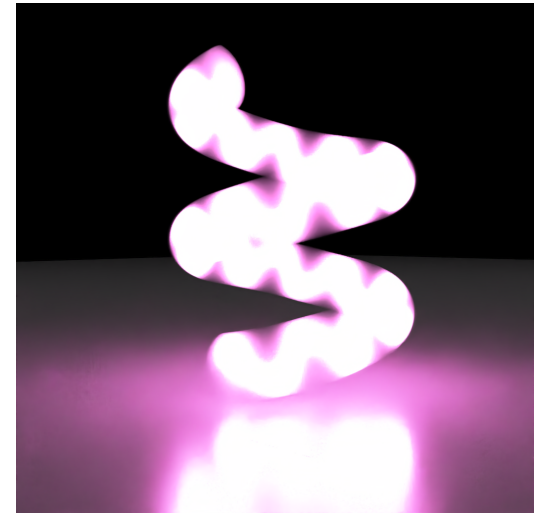
$$\rho = 10$$



$$\rho = 10^2$$

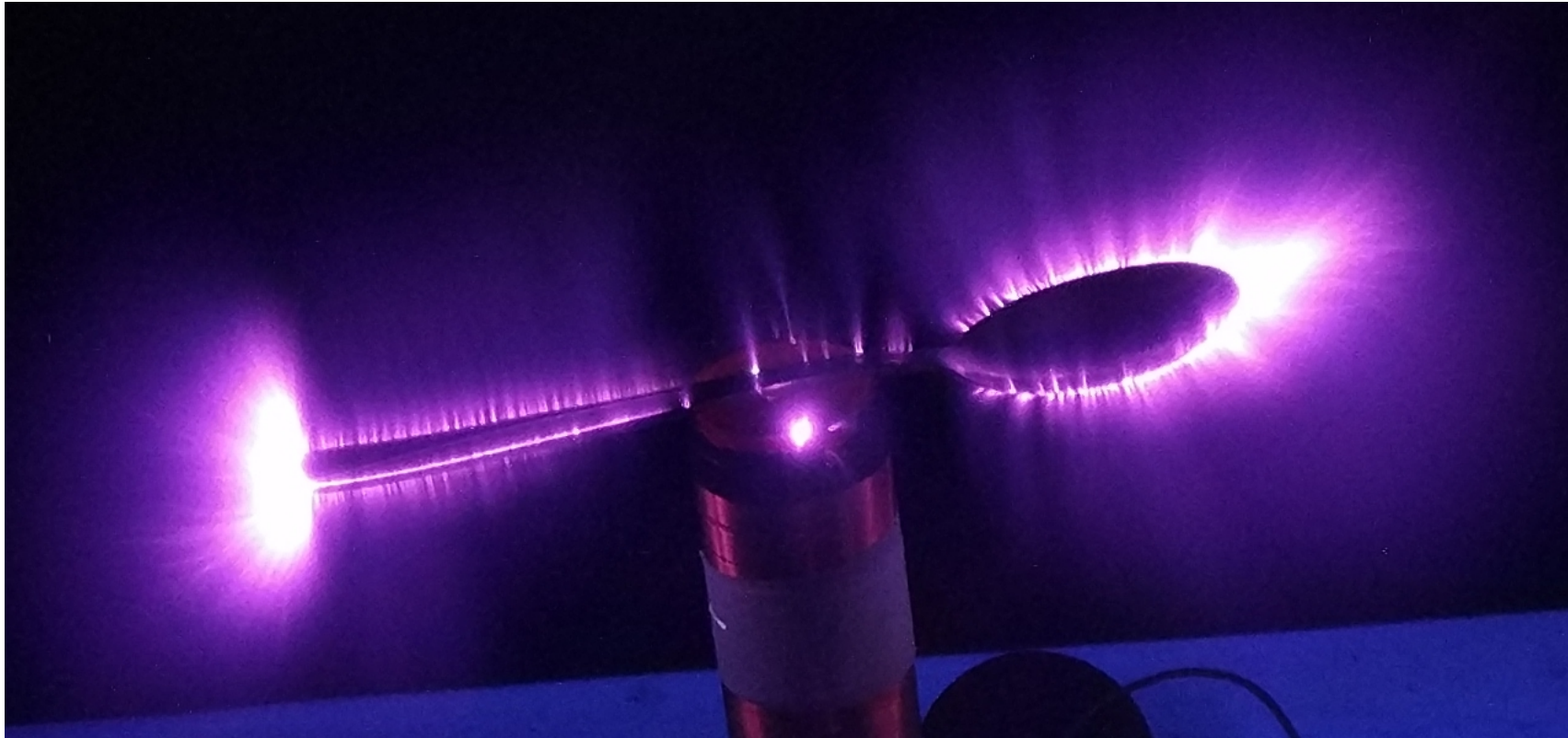


$$\rho = 10^3$$

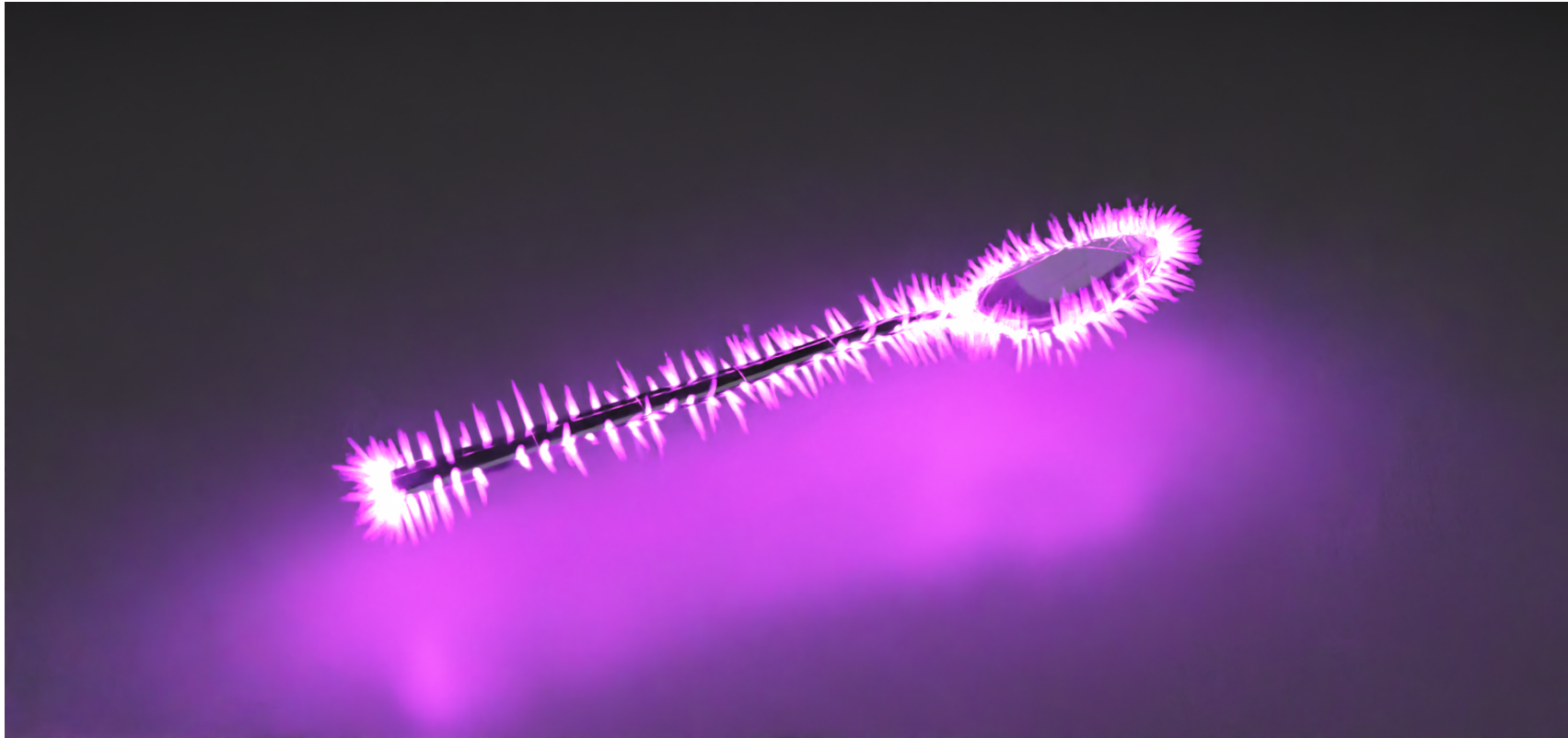


$$\rho = 10^4$$

Real world comparison: ground truth

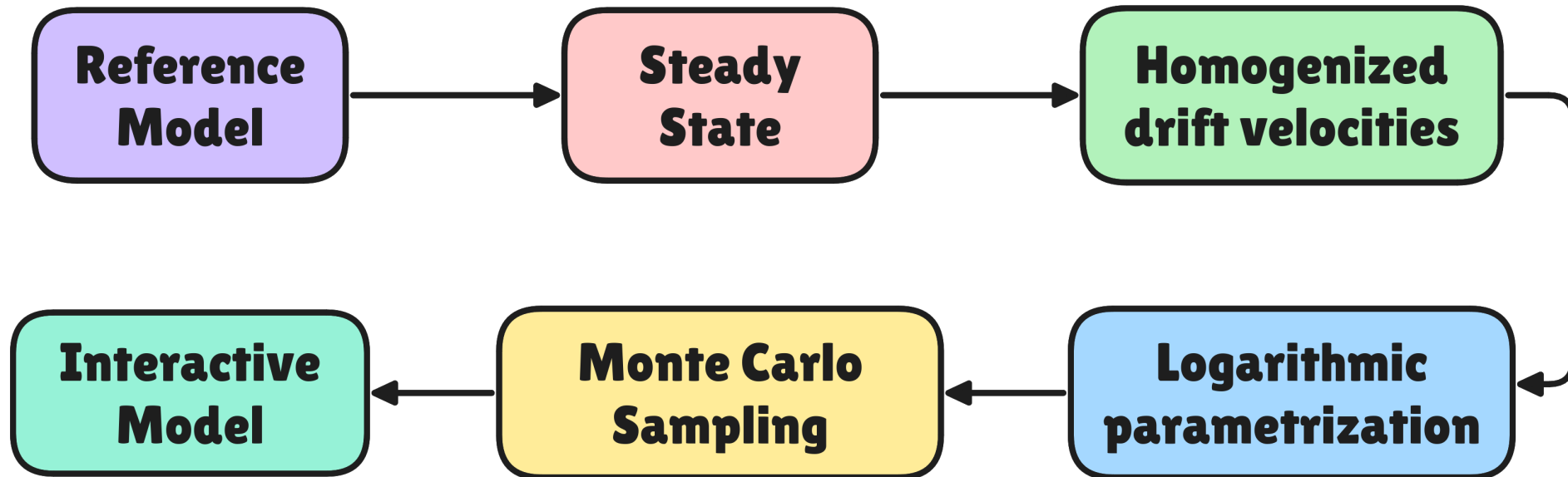


Real world comparison: our model



Summary and Future Work

A tractable model for glow discharge rendering



Limitations and future work

- Coefficients and gas properties are manually set
- Smarter sampling strategies (e.g. NEE or MIS)
- Extend to dynamic discharges and scenes
- Apply a similar approach to other phenomena

