Line Integration For Rendering Heterogenous Emissive Volumes

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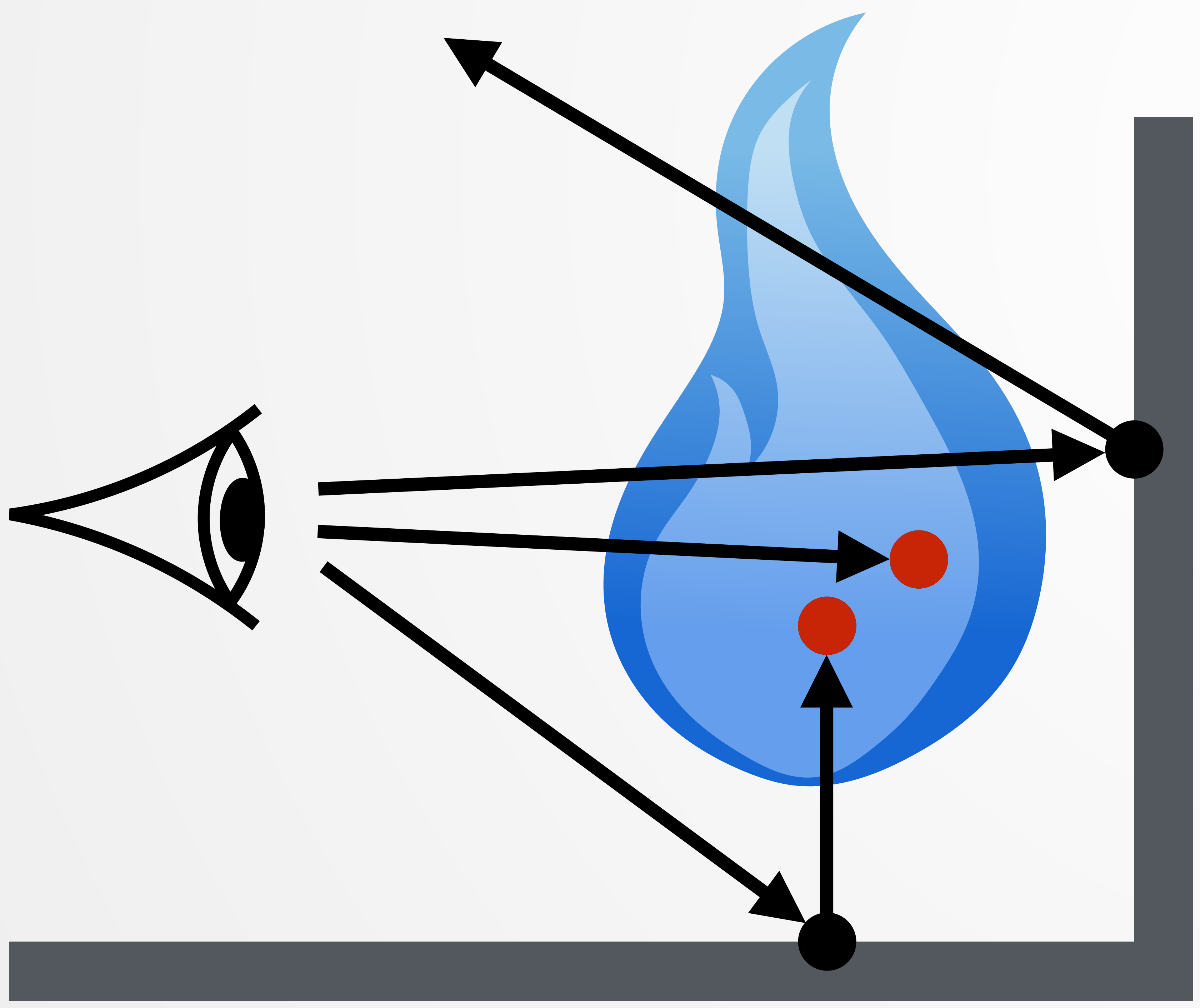
weta DIGITAL

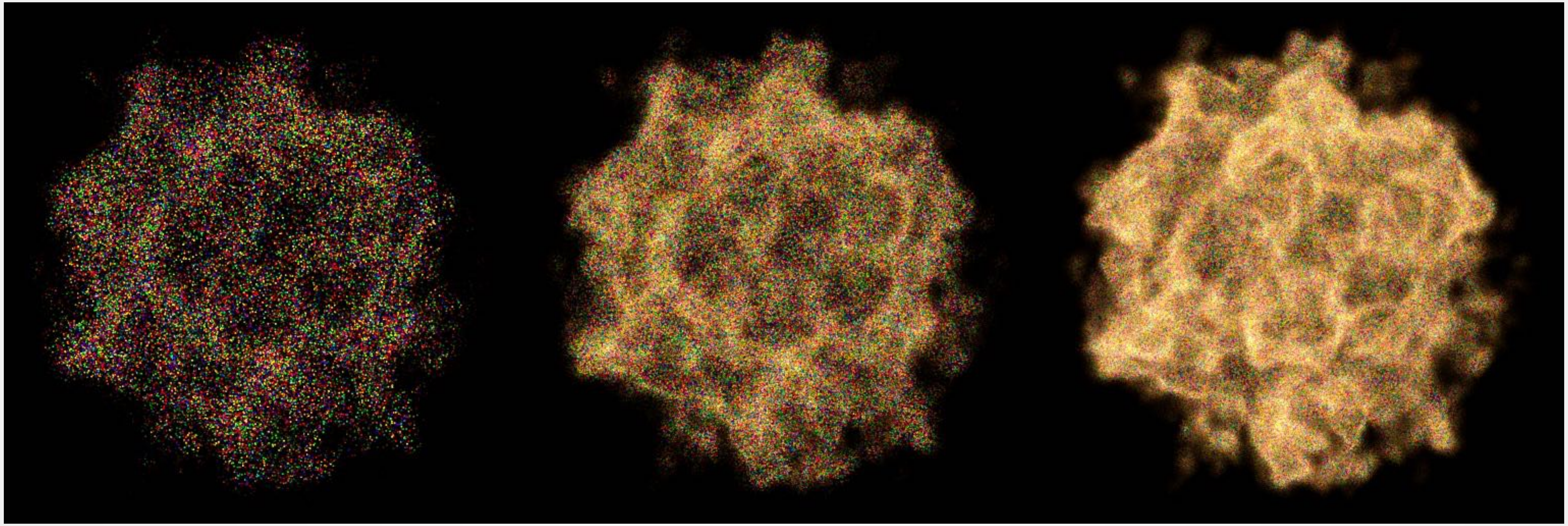
The Idea

- Path tracing evaluates volumetric emission only at points



The Idea

- Path tracing evaluates volumetric emission only at points

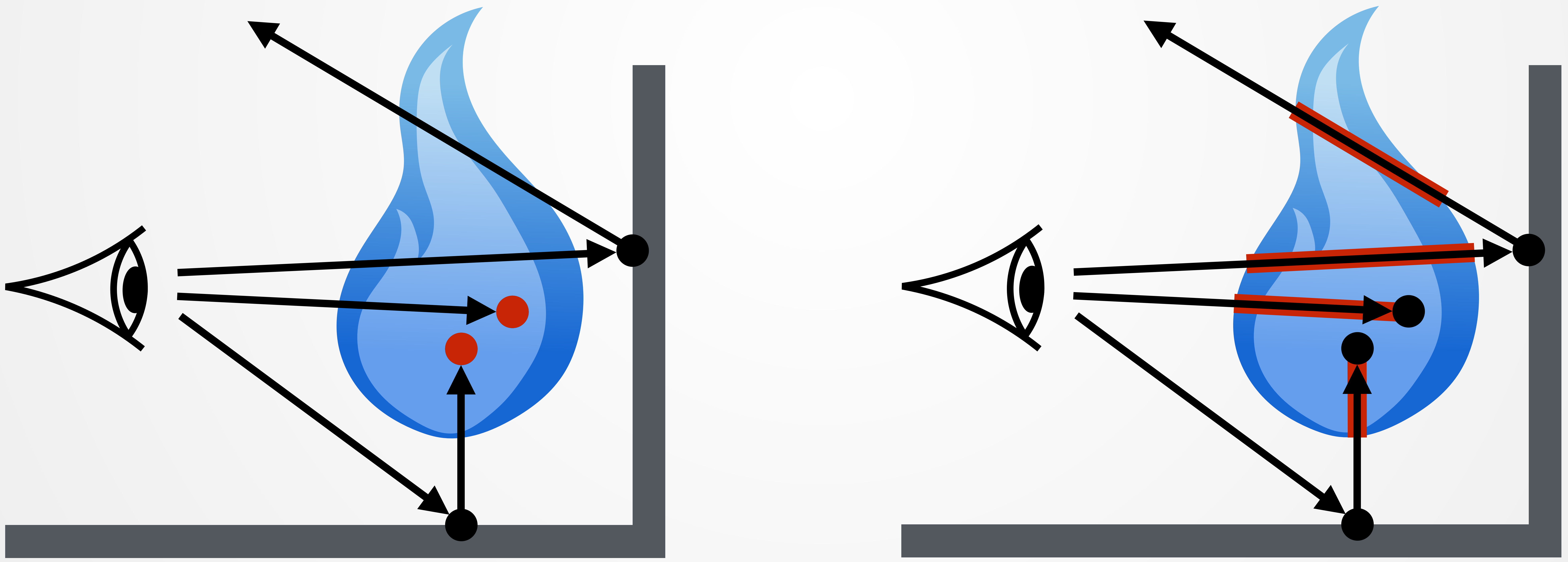


decreasing density

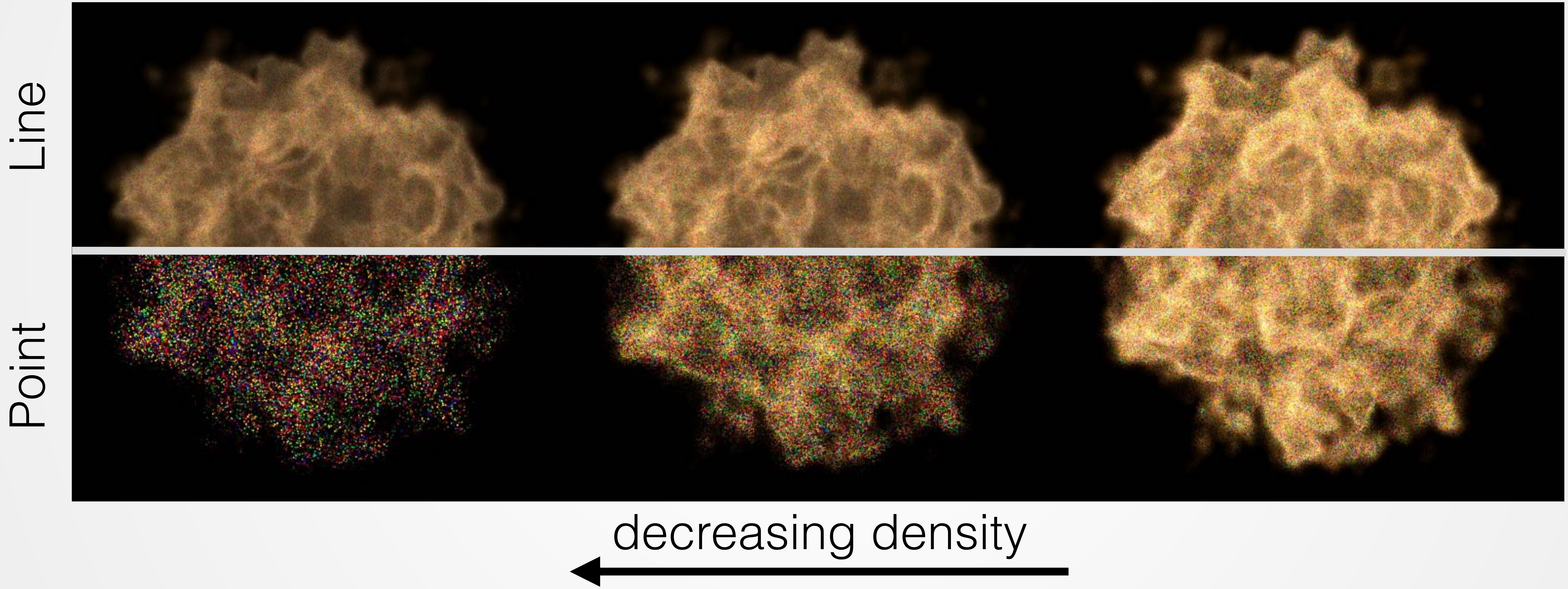
128spp for all images

The Idea

- Path tracing evaluates volumetric emission only at points
- Line Integration extends this to emission of segments



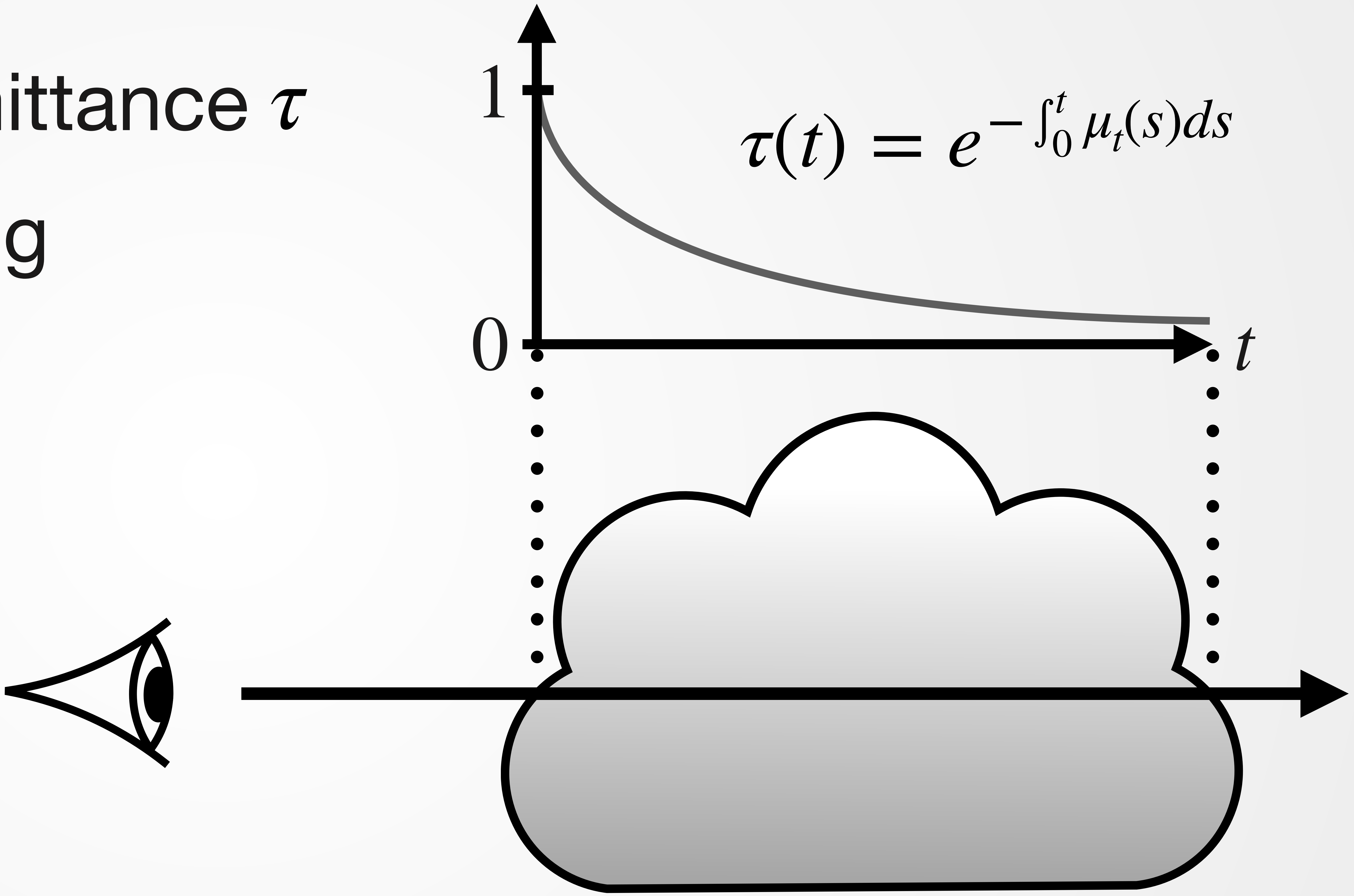
Line Integration



128spp for all images

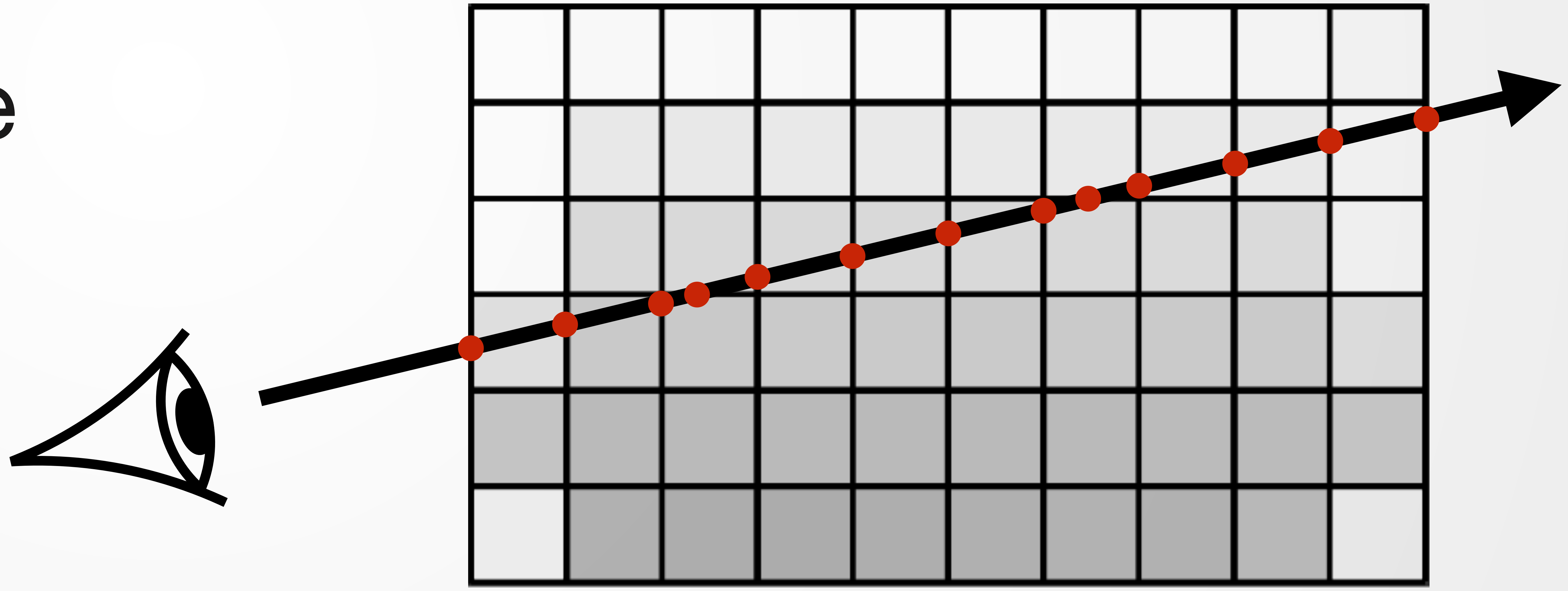
Free Path Sampling

- Proportional to transmittance τ
- Delta/Residual Tracking
  - Szirmay-Kalos et al. 2011
  - Kutz et al. 2017
- Regular Tracking



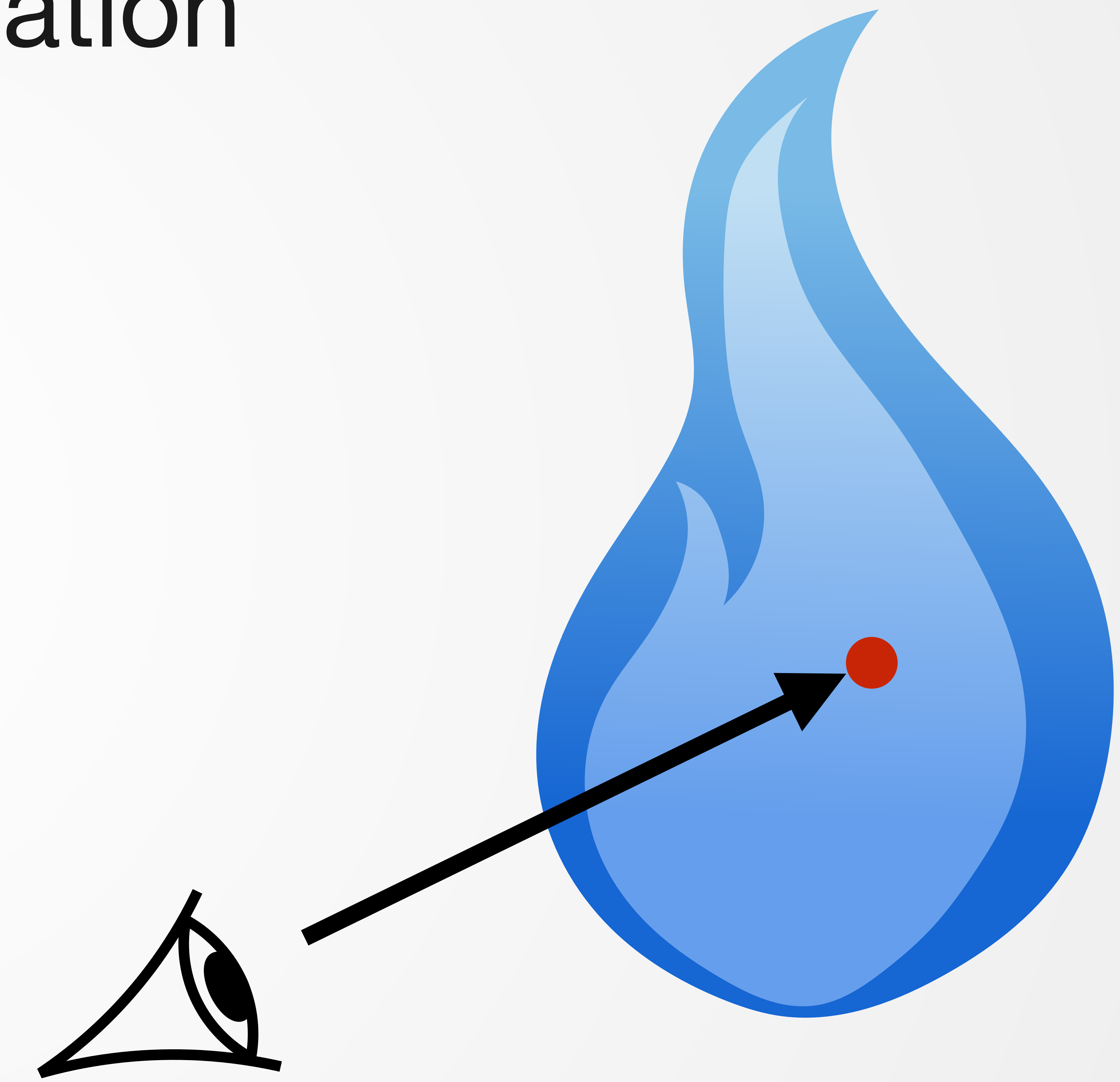
Regular Tracking

- Piecewise constant volume
- Step from voxel to voxel
- Integrate transmittance
- Stop when transmittance below random threshold



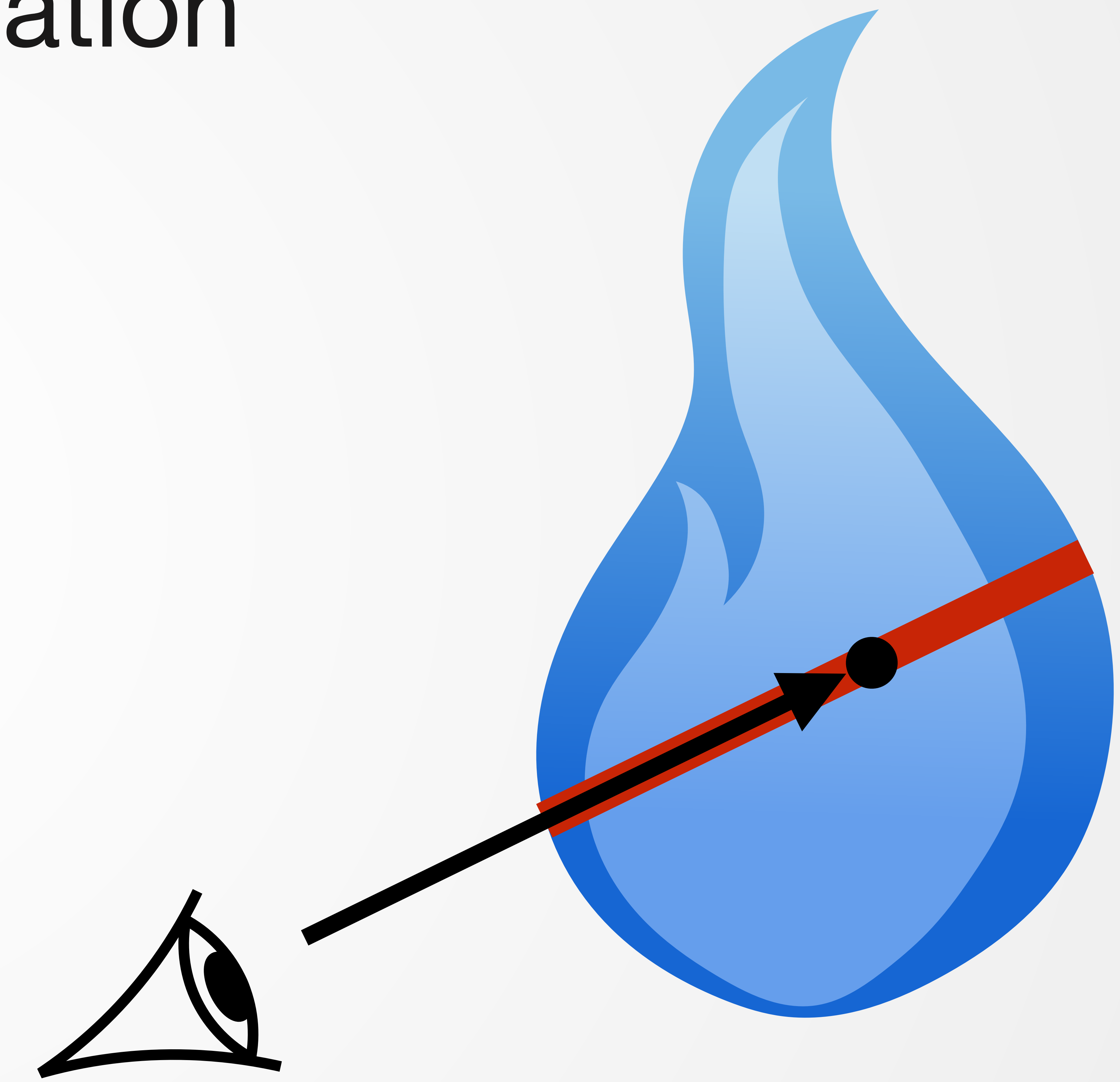
Handling Emission

- At scattering events = point integration



Handling Emission

- At scattering events = point integration
- Alternative:
  - Deterministic integration of emission
  - Inefficient for dense volumes
  - MIS with next event estimation?
    (more on that later)



Line Integration

- Integrate emission only up to scattering event
- Advantages:

Line Integration

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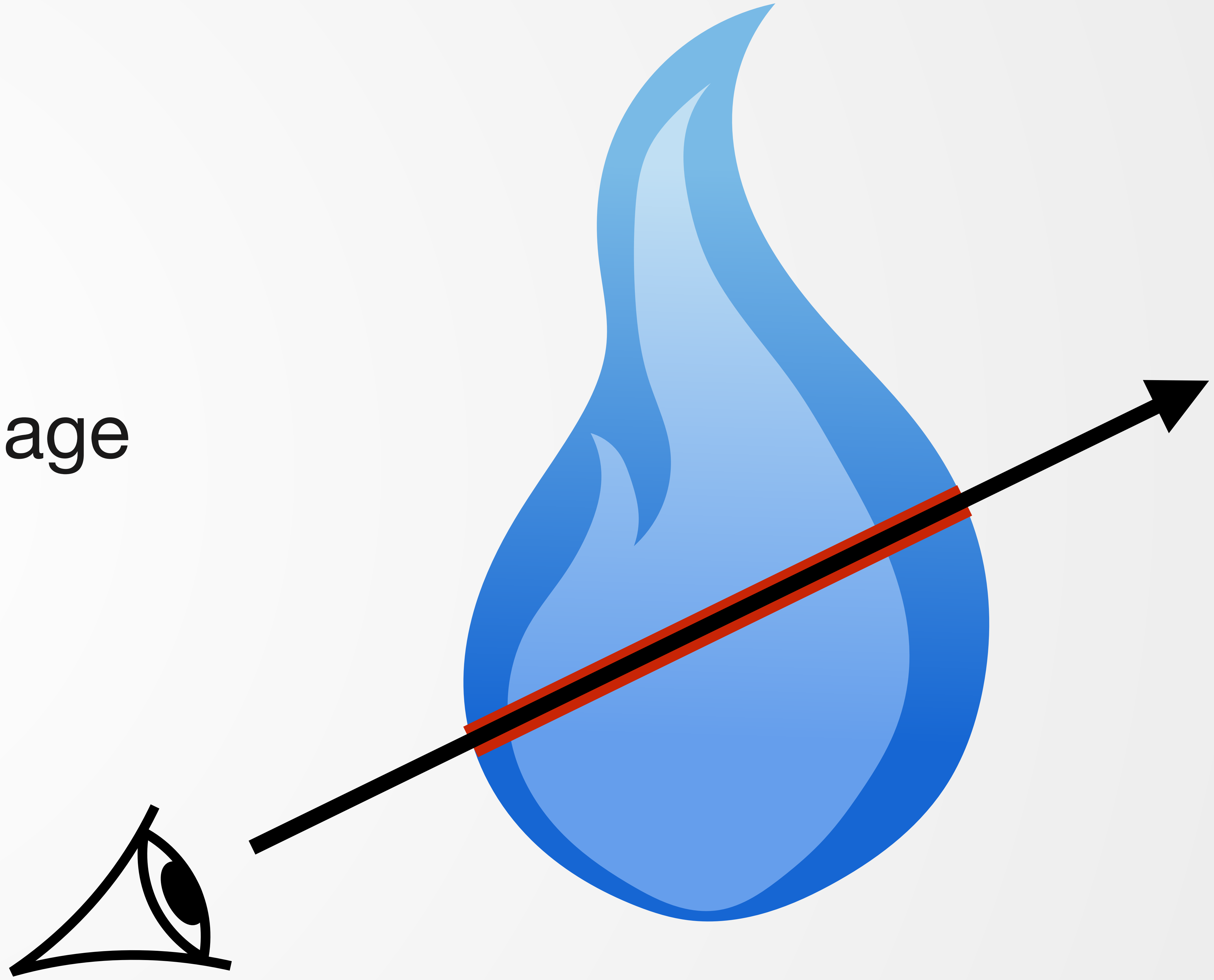
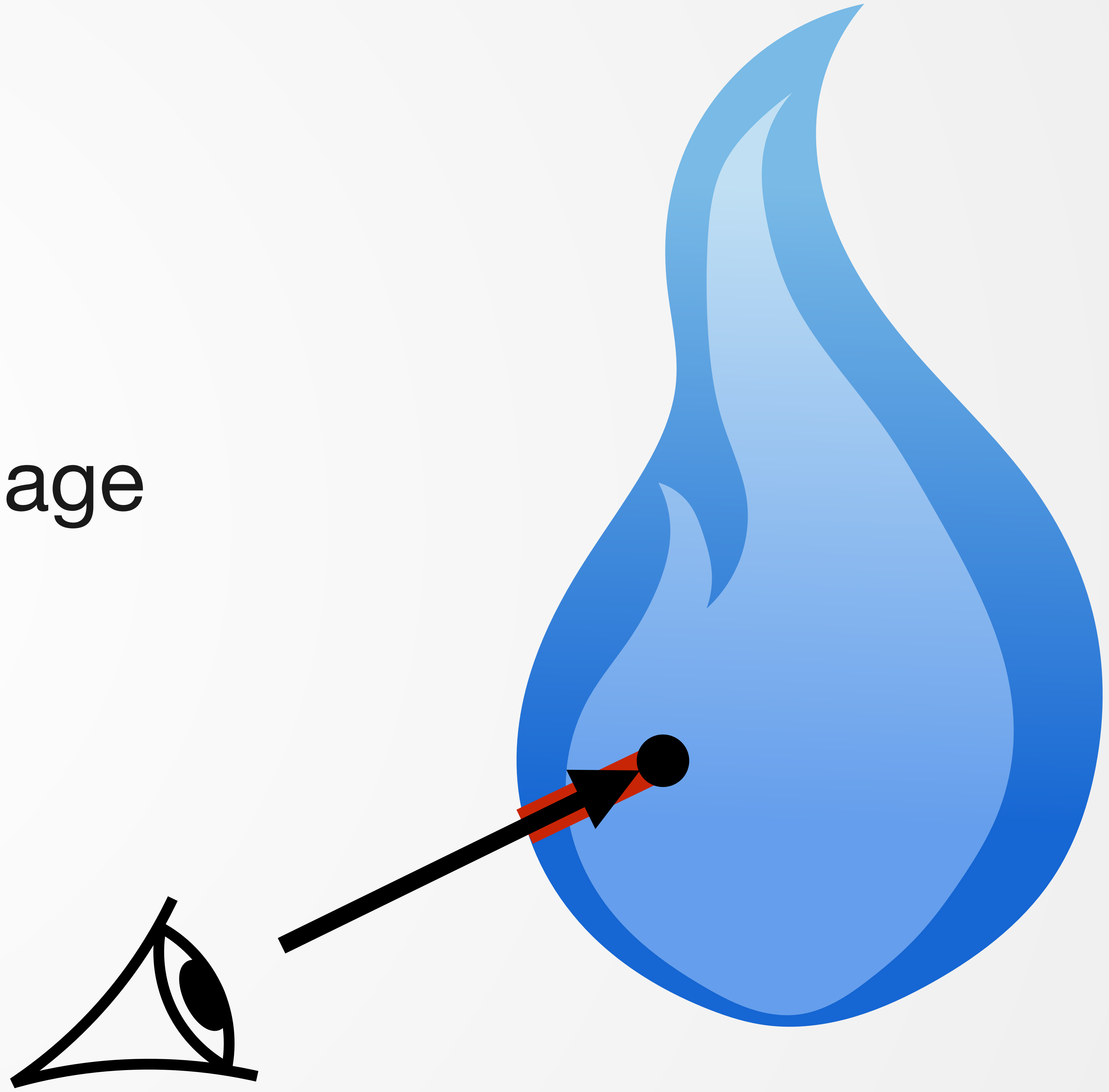
- Integrate emission only up to scattering event
- Advantage:
  - No-collision paths also contribute to the image



Line Integration

- Integrate emission only up to scattering event
- Advantage:
  - No-collision paths also contribute to the image
  - Early out in dense volumes



Line Integration

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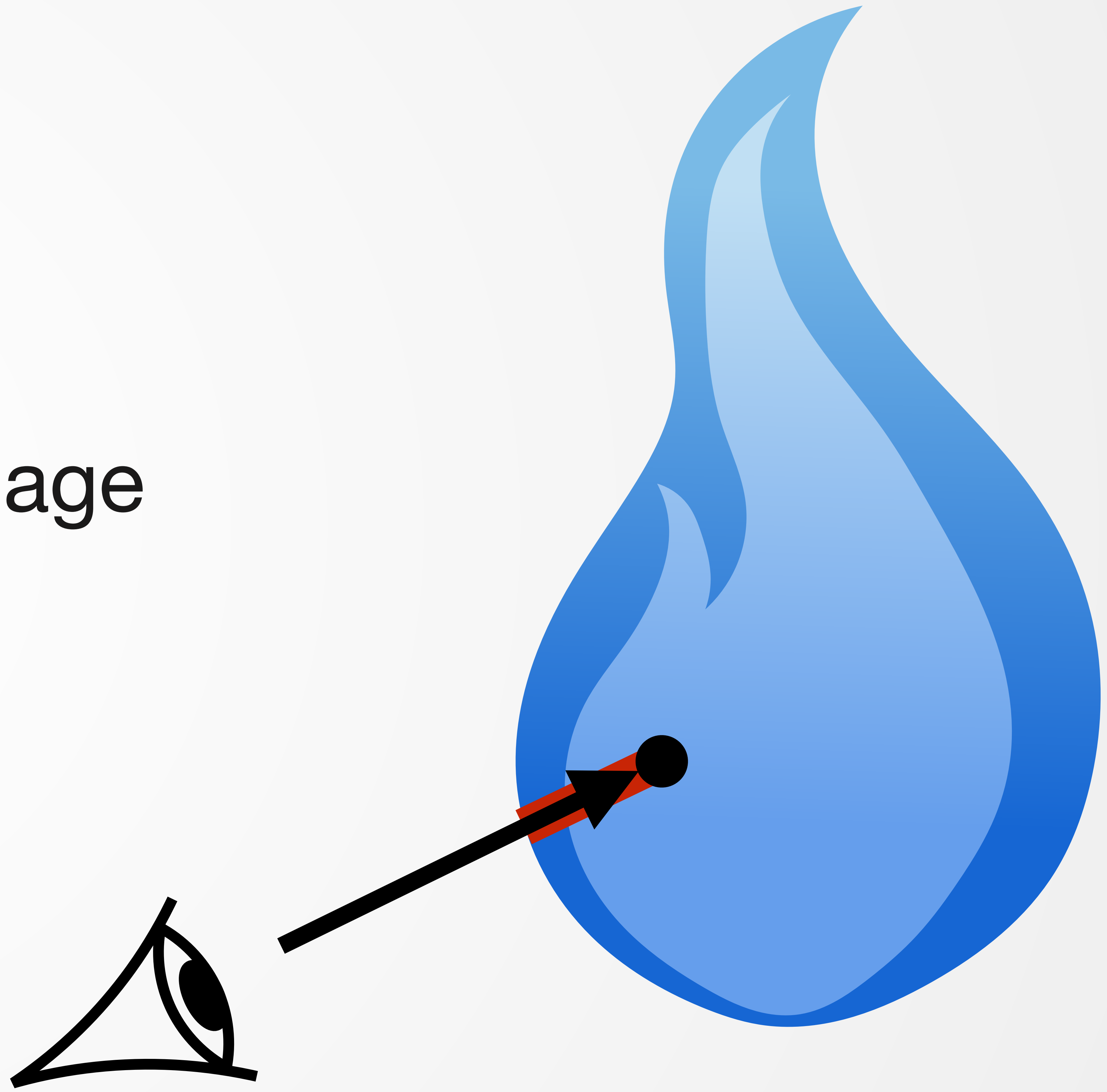
How?

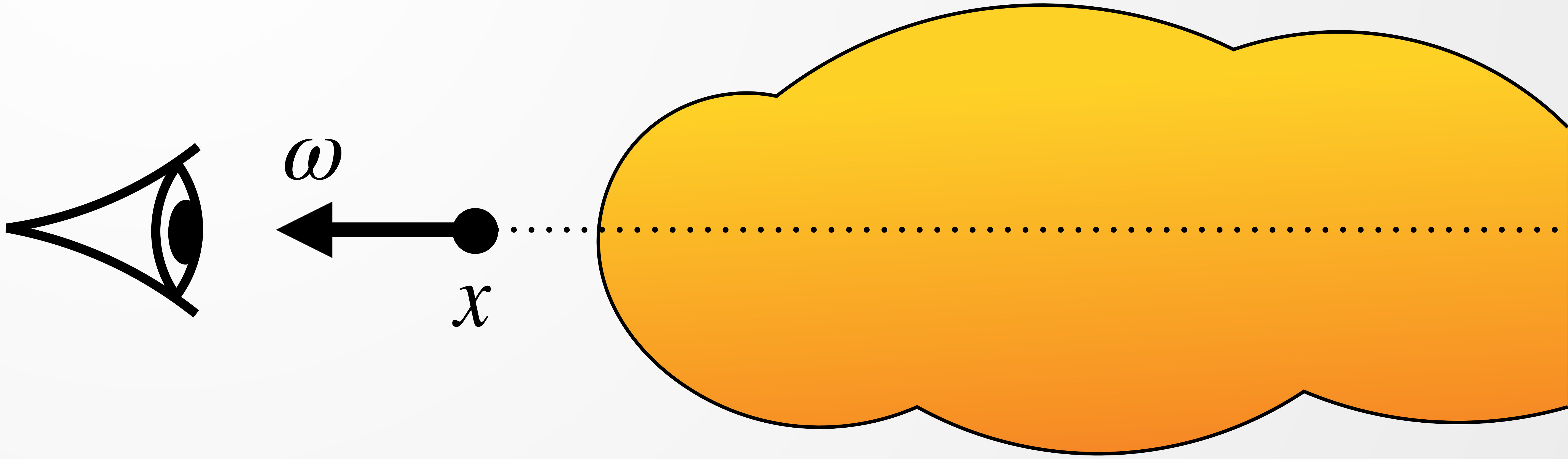


Volumetric Emisson

- Radiance at x in direction ω due to direct volumetric emission:

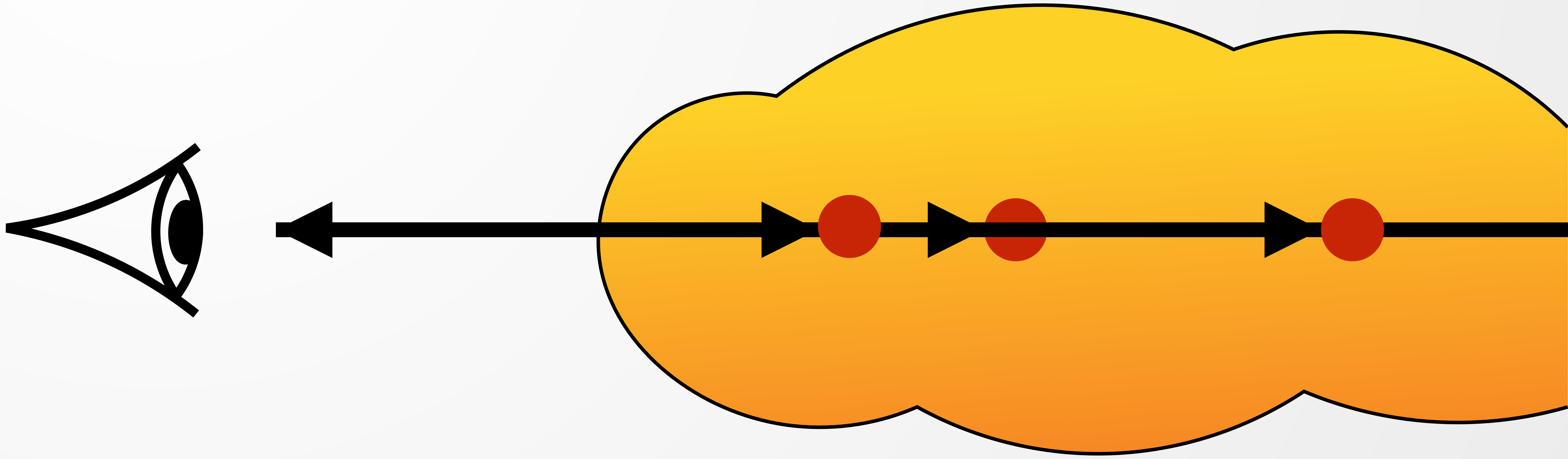
$$L(x,\omega) = \int_0^\infty \tau(x-\omega t)\, L_e(x-\omega t)\, dt$$

$$= \int_0^\infty \tau(t)\, L_e(t)\, dt$$



Point Integration

$$\int_0^\infty \tau(t)\, L_e(t)\, dt \;\approx\; \frac{1}{N}\sum_{i=1}^{N} \frac{\tau(t_i)\, L_e(t_i)}{p(t_i)}$$



Line Integration

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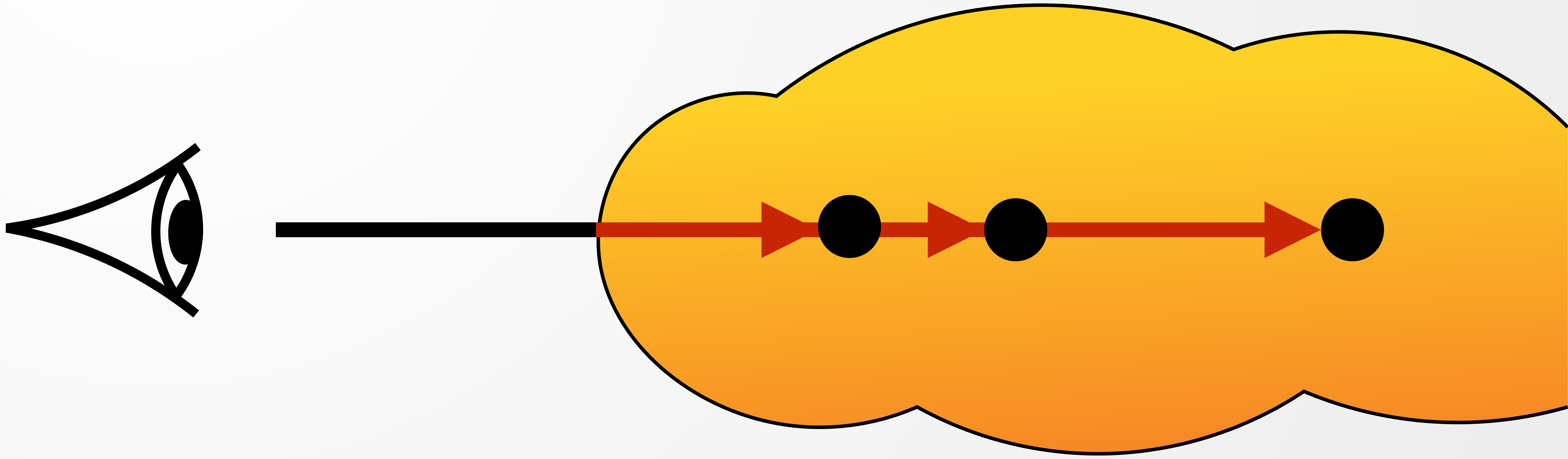
$$\int_0^\infty \int_0^t \tau(s)\, L_e(s)\, ds\, dt \;\approx\; \frac{1}{N}\sum_{i=1}^{N} \frac{\int_0^{t_i} \tau(s)\, L_e(s)\, ds}{p(t_i)}$$



Line Integration

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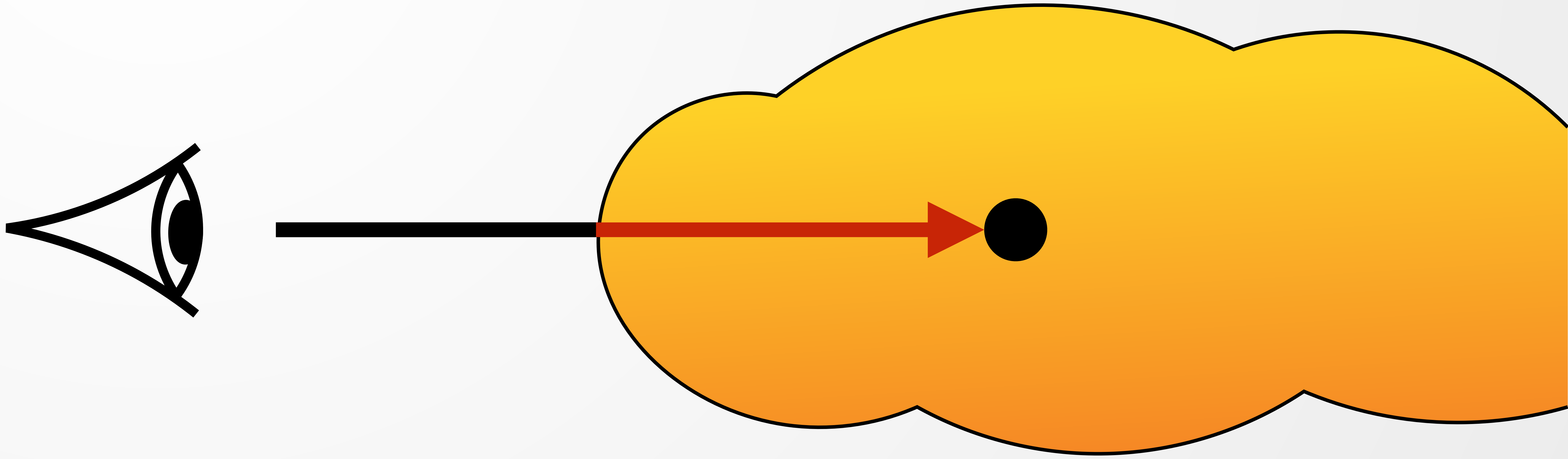
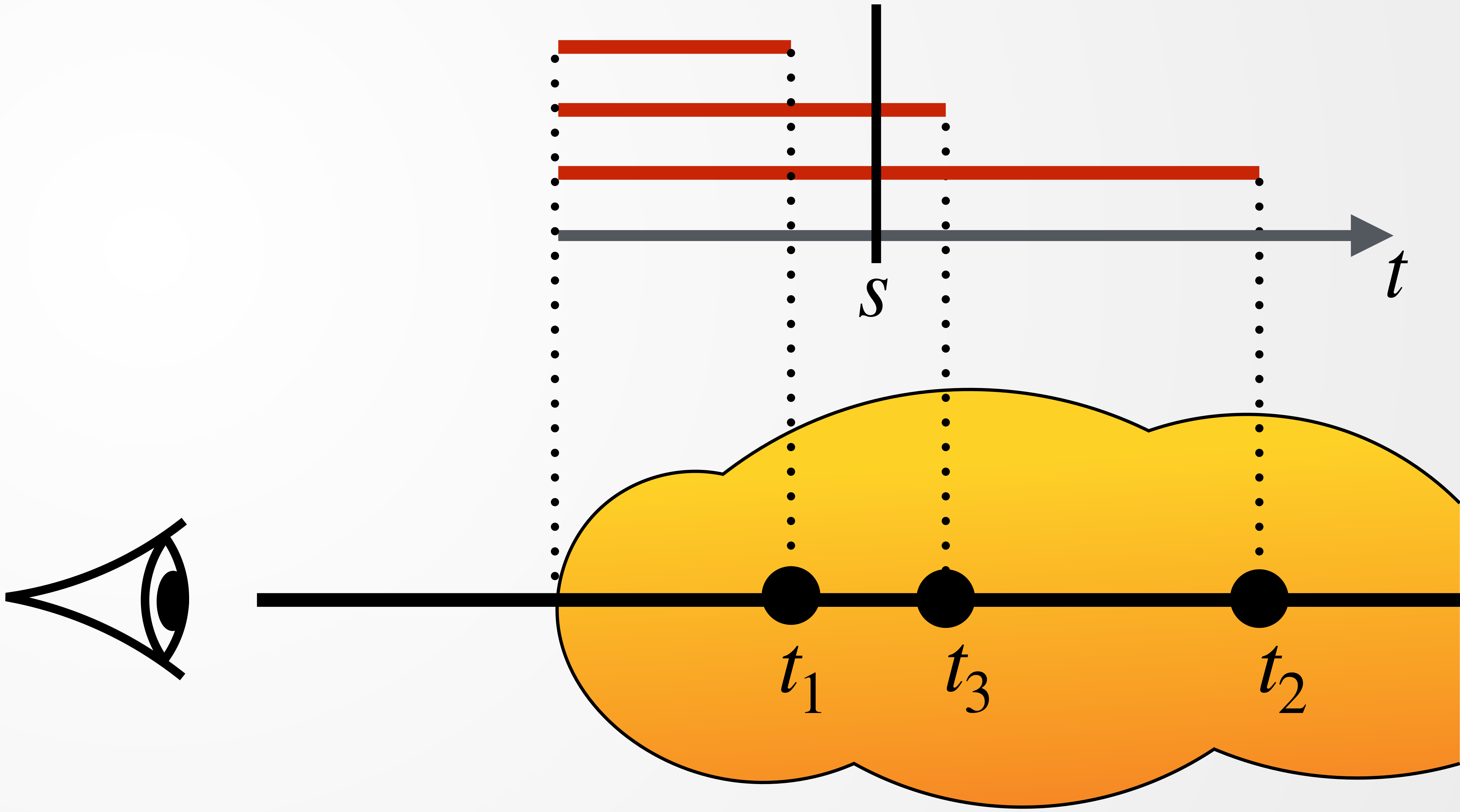
$$\neq$$

$$\int_0^\infty \int_0^t \tau(s)\, L_e(s)\, ds\, dt \;\approx\; \frac{1}{N}\sum_{i=1}^{N} \frac{\int_0^{t_i} \tau(s)\, L_e(s)\, ds}{p(t_i)}$$



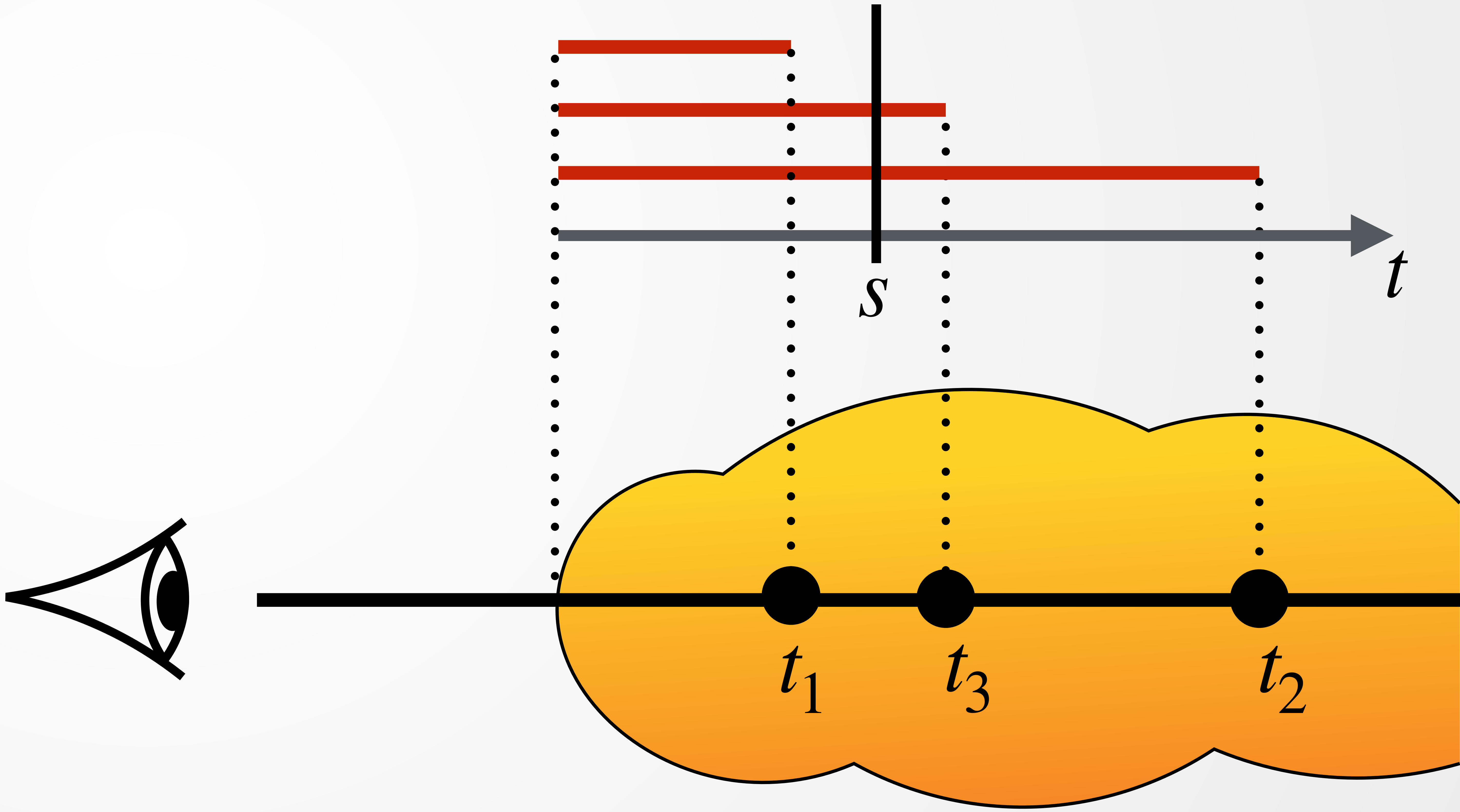
Line Integration

$$\int_0^\infty \tau(t)\, L_e(t)\, dt \neq \int_0^\infty \int_0^t \tau(s)\, L_e(s)\, ds\, dt$$



Line Integration

$$\int_0^\infty \tau(t)\, L_e(t)\, dt \overset{!}{=} \int_0^\infty \int_0^t w_t(s)\, \tau(s)\, L_e(s)\, ds\, dt$$



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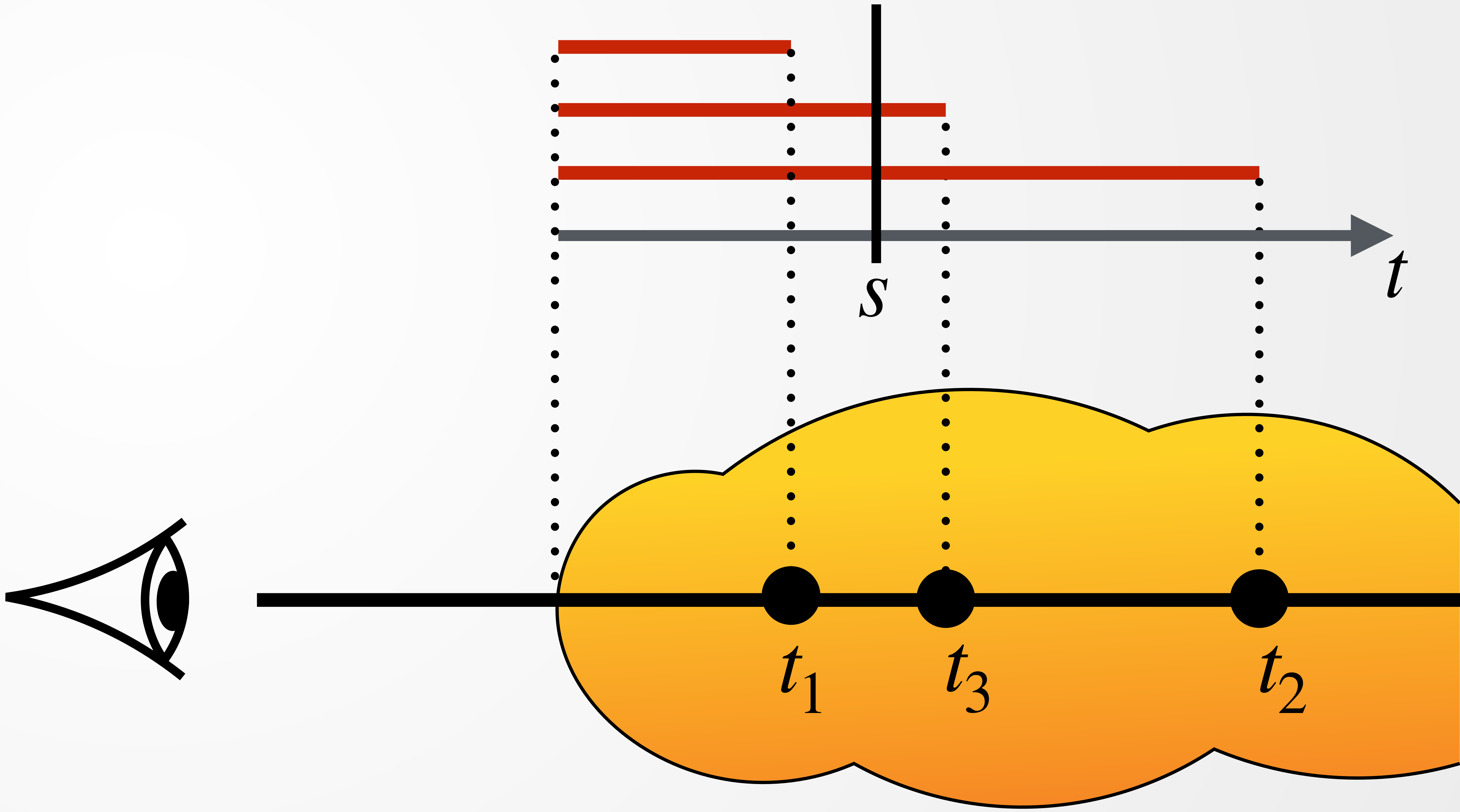
- $w_t(s) = 0$ for all $s > t$



Line Integration

$$\int_0^\infty \tau(t)\, L_e(t)\, dt \stackrel{!}{=} \int_0^\infty \int_0^{\color{red}\infty} w_t(s)\, \tau(s)\, L_e(s)\, ds\, dt$$

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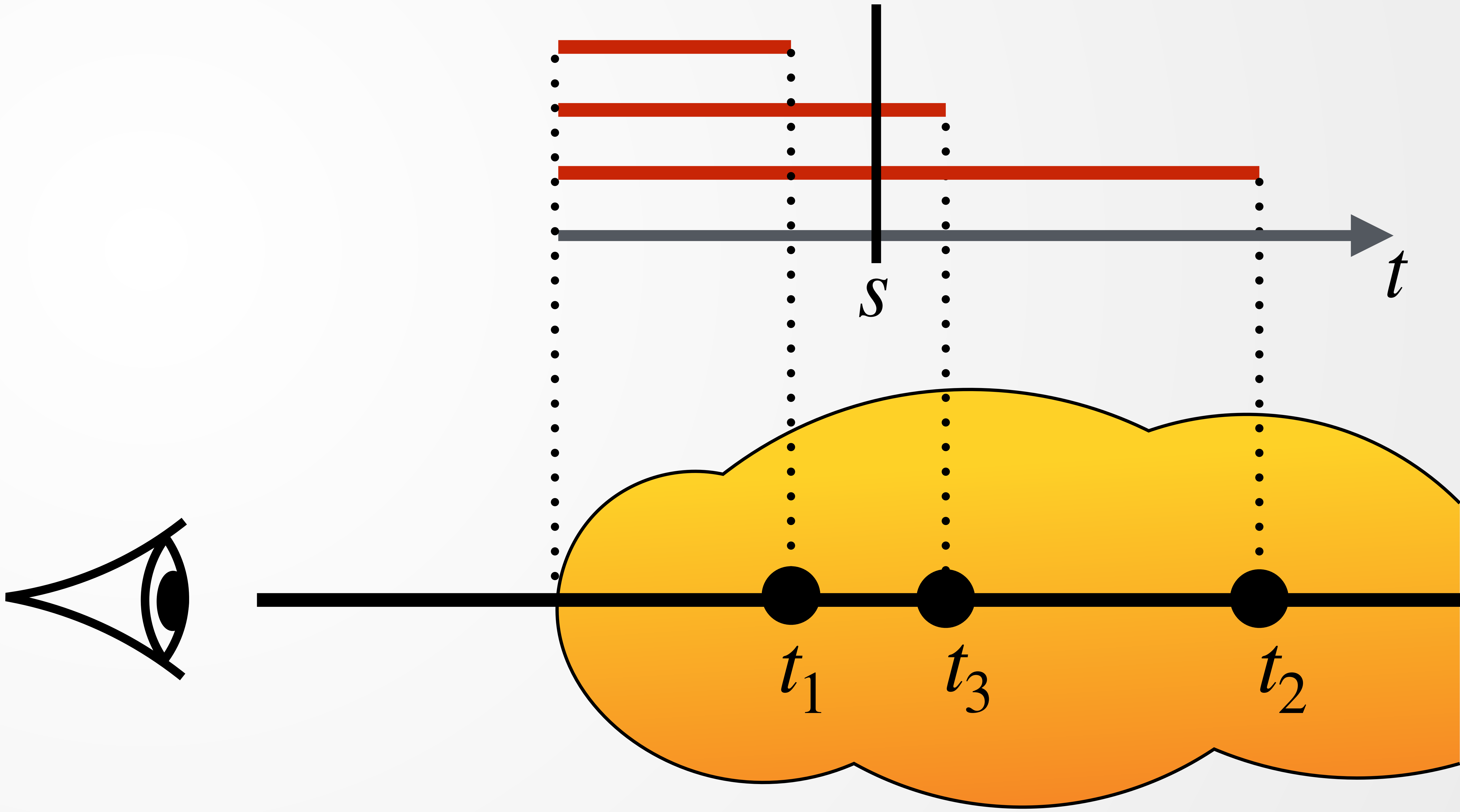

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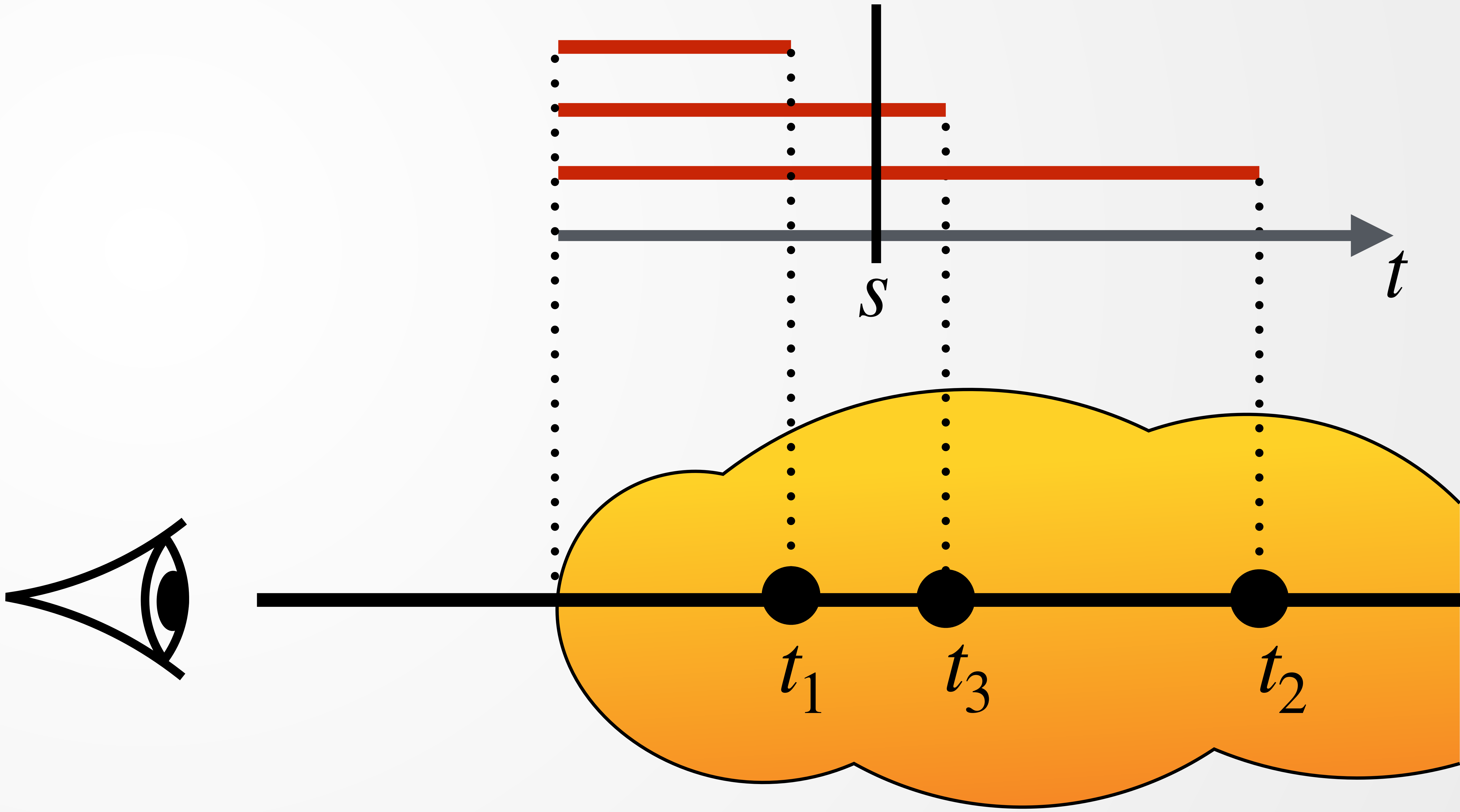
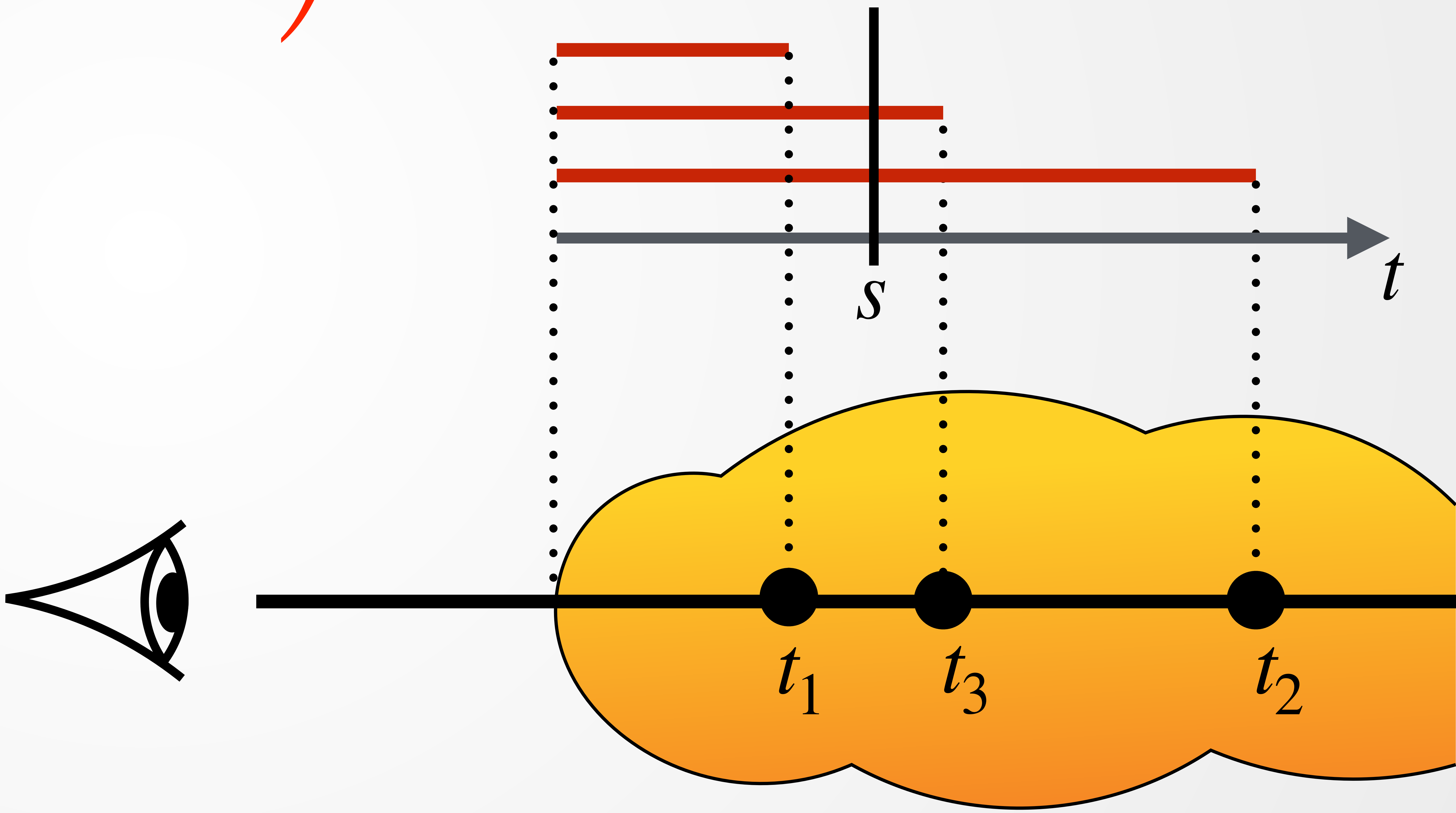


Line Integration

$$\int_0^\infty \tau(t)\, L_e(t)\, dt \overset{!}{=} \int_0^\infty \left(\int_0^\infty w_t(s)\, dt \right) \tau(s)\, L_e(s)\, ds$$

- $w_t(s) = 0$ for all $s > t$



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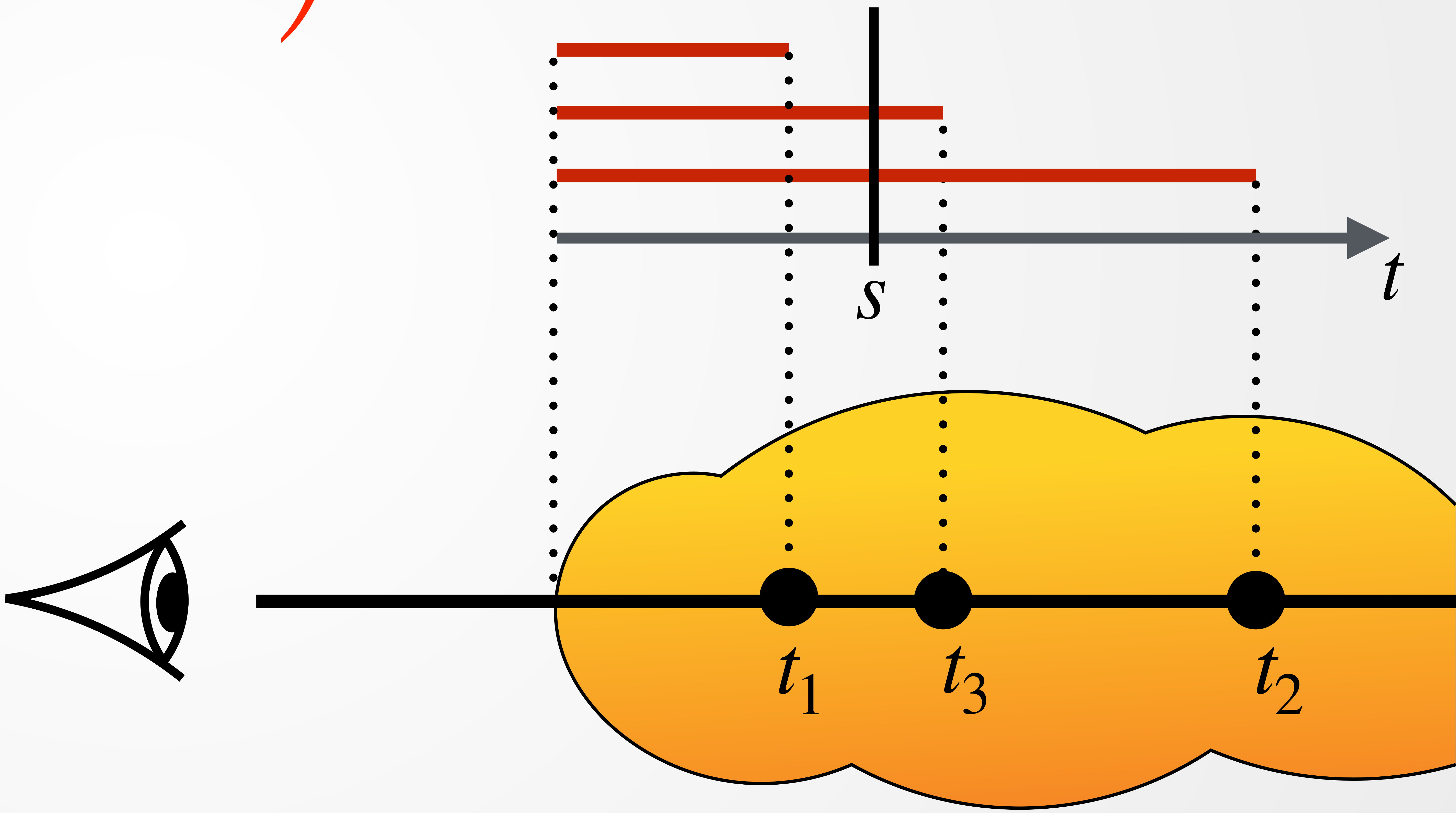
- $w_t(s) = 0$ for all $s > t$
- $\int_0^\infty w_t(s)\, dt = 1$ for all s



Line Integration

$$\int_0^\infty \tau(t)\, L_e(t)\, dt = \int_0^\infty \tau(s)\, L_e(s)\, ds$$

- $w_t(s) = 0$ for all $s > t$
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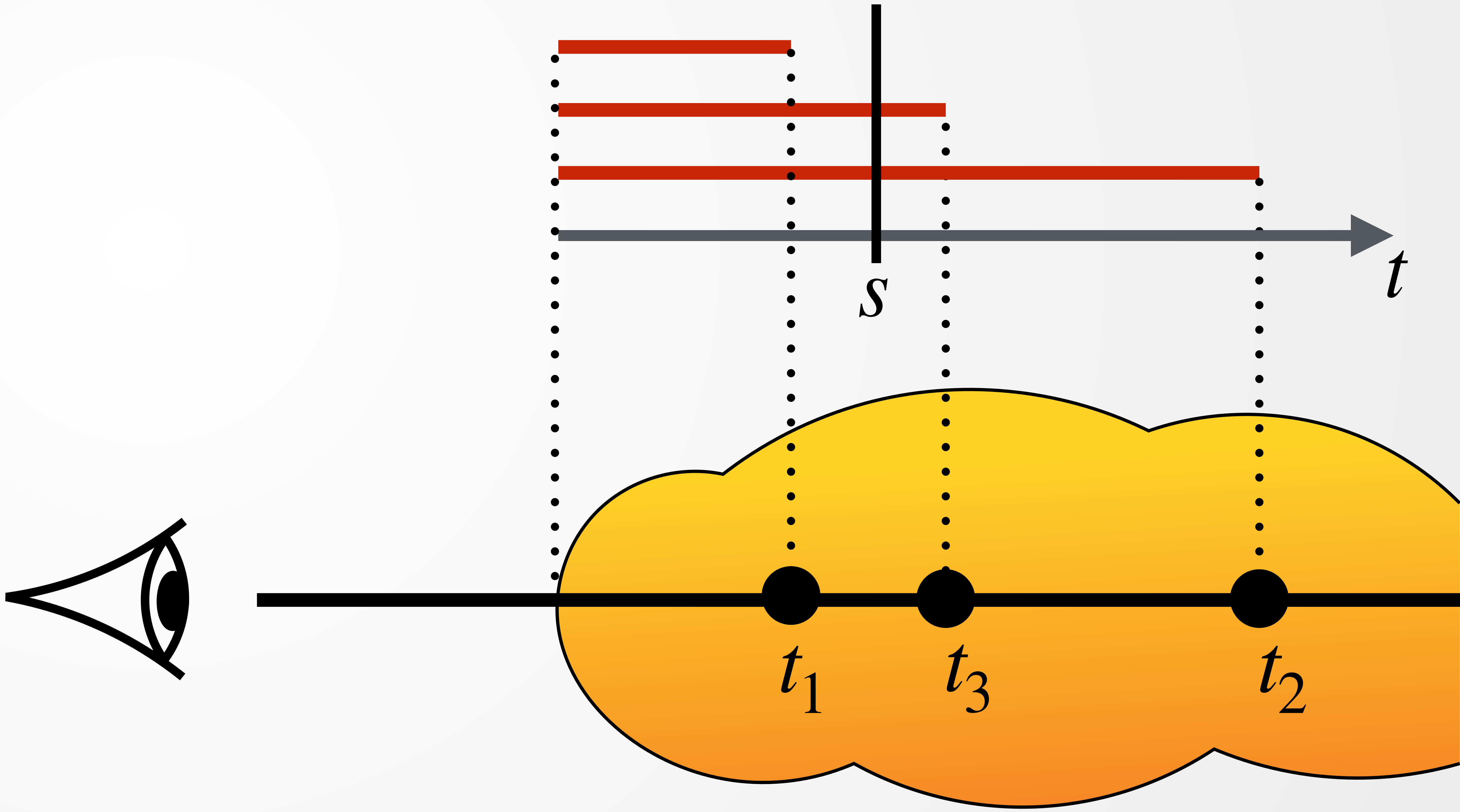
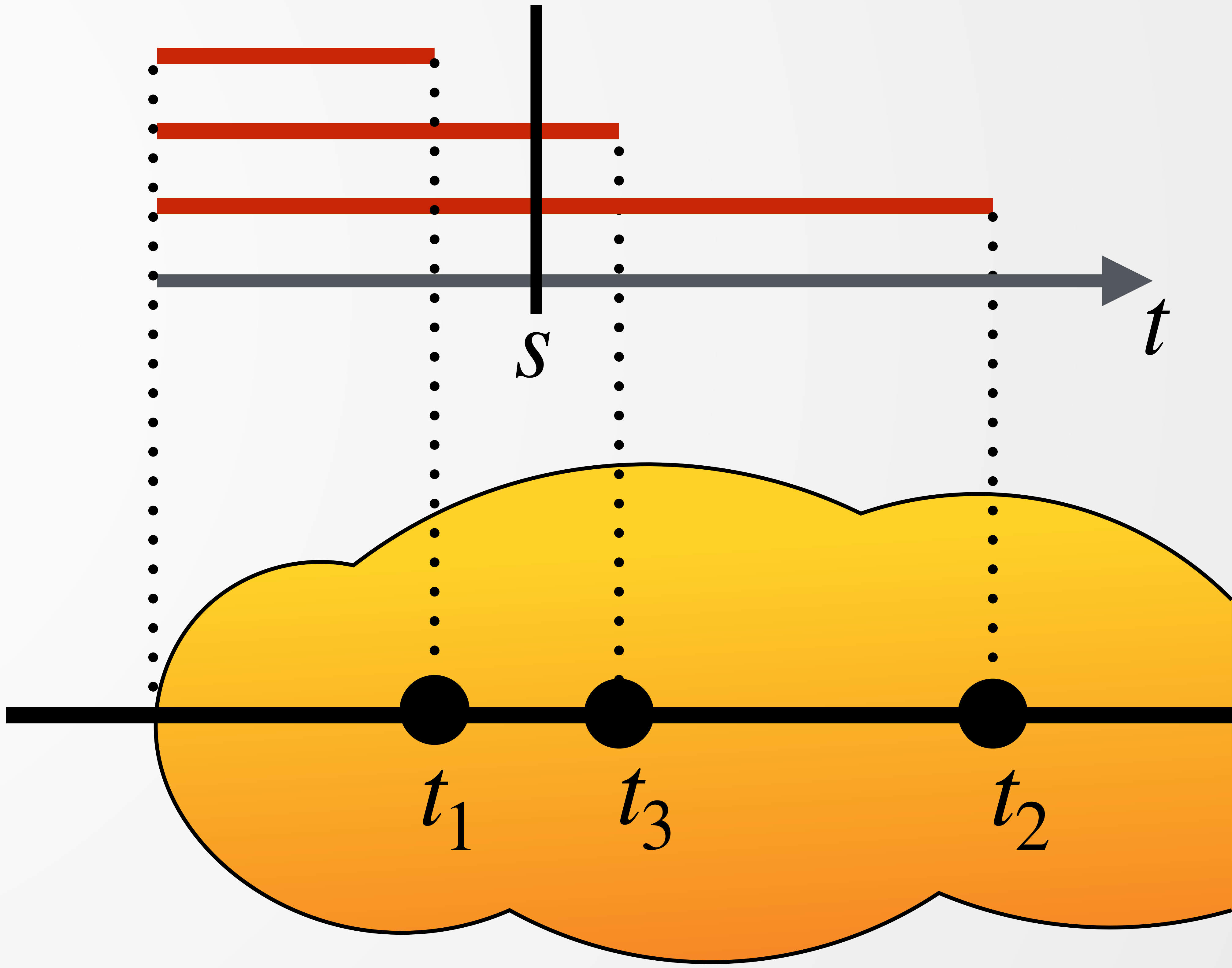


Weight Function

- Intuition:
  - $\Pr(t \geq s) = \tau(s)$
  - $w_t(s) \propto 1/\tau(s)$

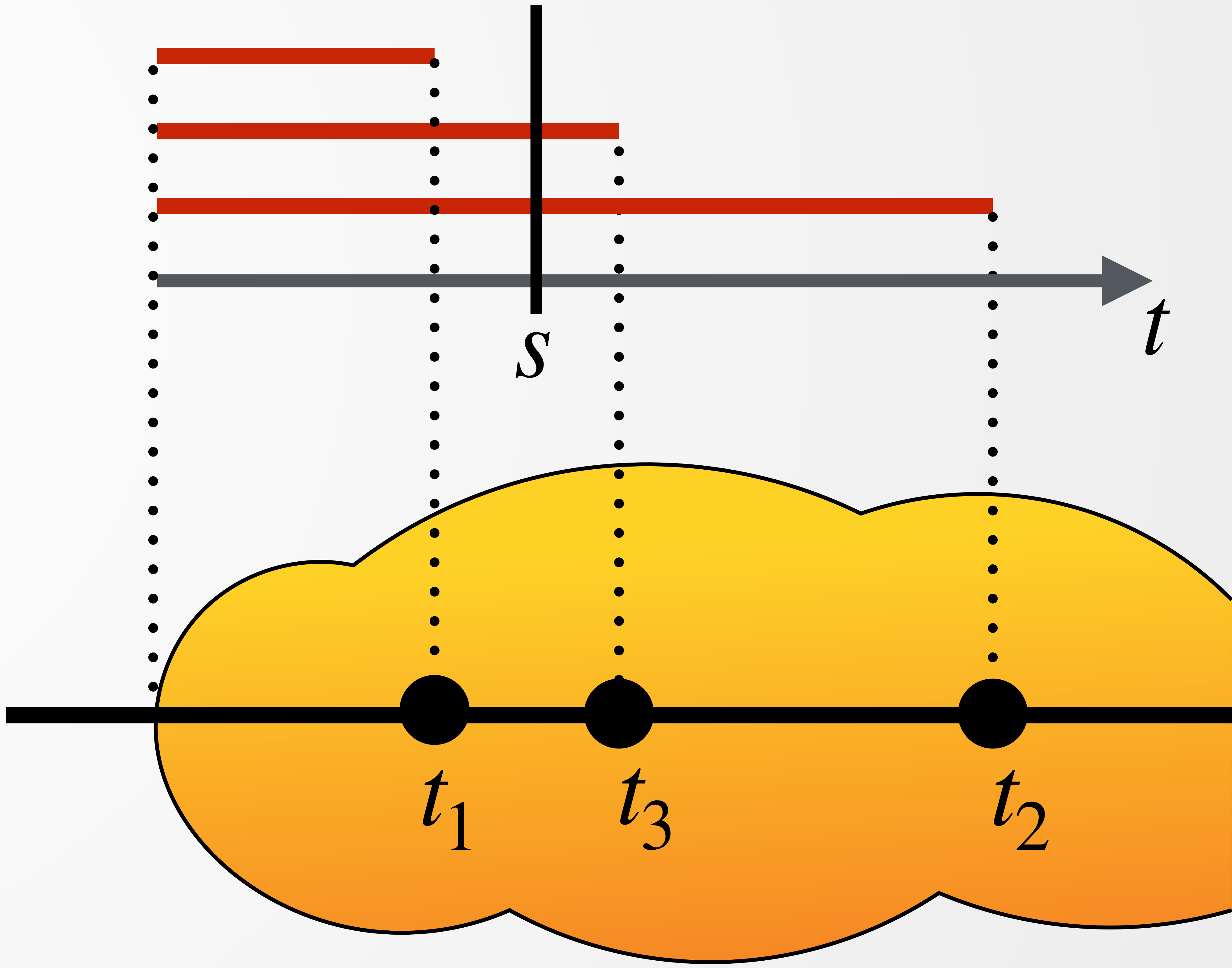


Weight Function

- Intuition:
  - $\Pr(t \geq s) = \tau(s)$
  - $w_t(s) \propto 1/\tau(s)$

- Weight function:

$$w_t(s) = \begin{cases} \dfrac{\mu_t(t)\tau(t)}{\tau(s)}, & \text{if } s \leq t \\ 0, & \text{otherwise} \end{cases}$$



Next Event Estimaton

- Crucial for efficient path tracing
- Sample light vertex directly on a light source
- Importance sampling volumes: Villemin and Hery 2013
- Combined with forward sampling (e.g. BSDF) using MIS

Next Event Estimation

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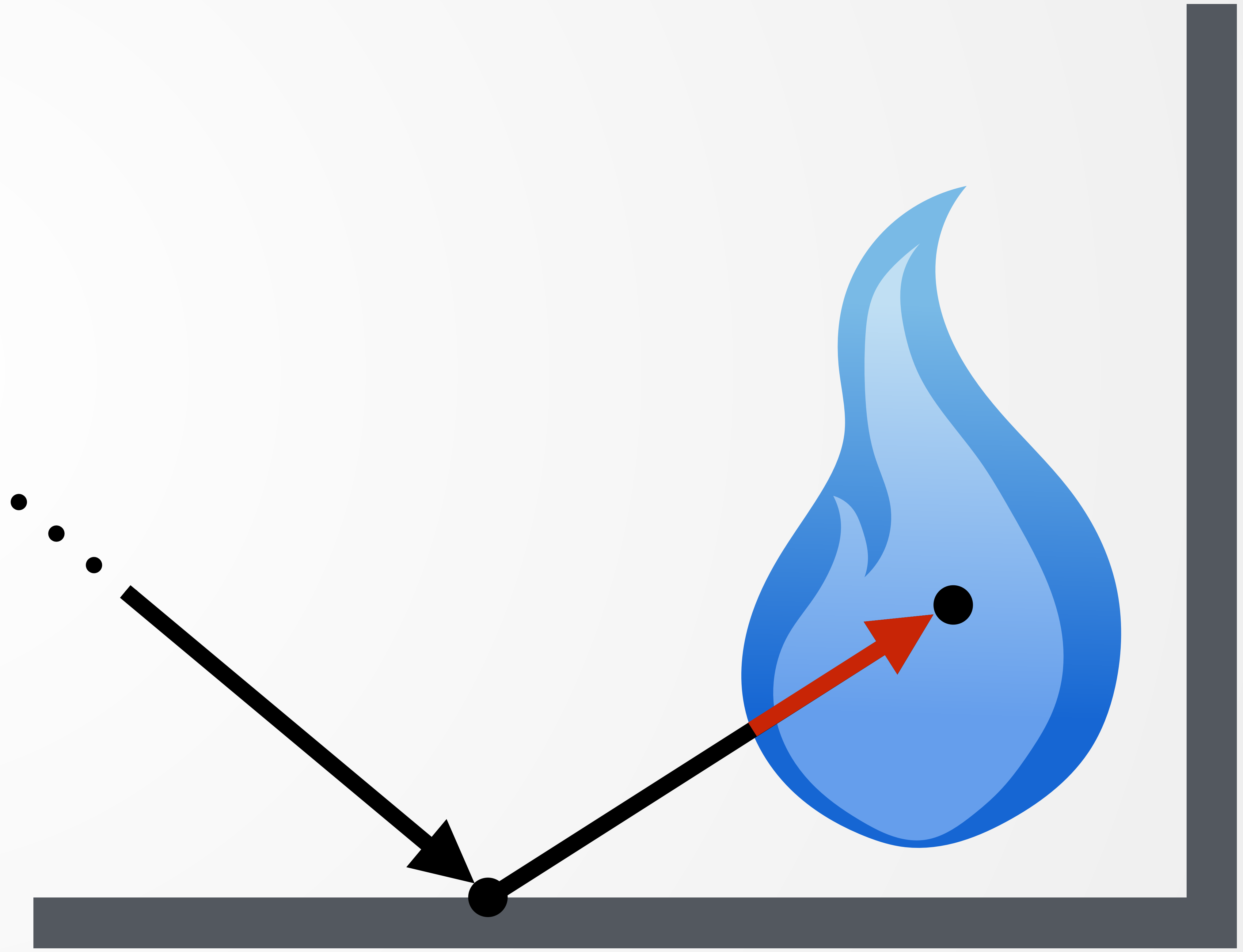
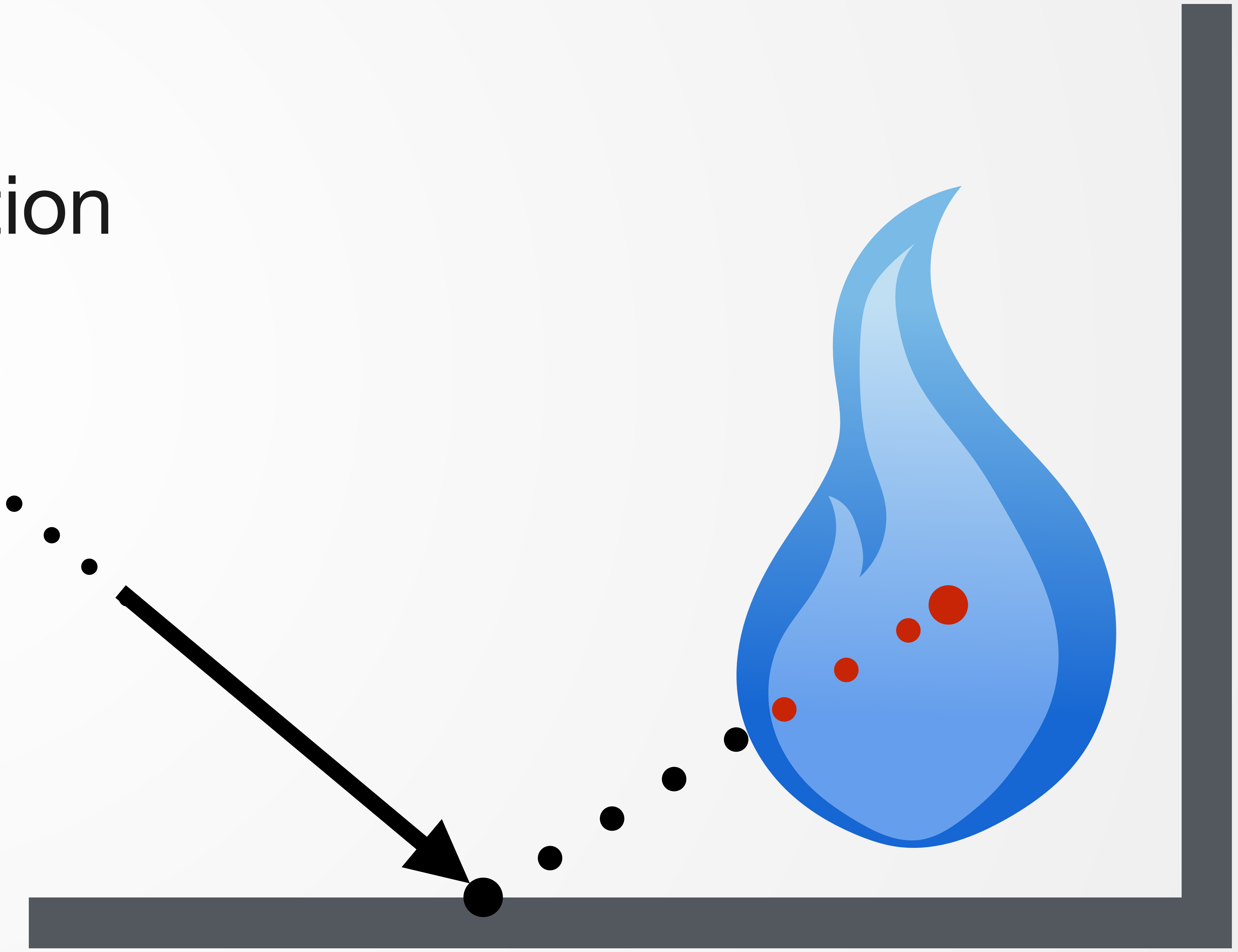
- Scattering events inside the volume



forward sampling

Next Event Estimation

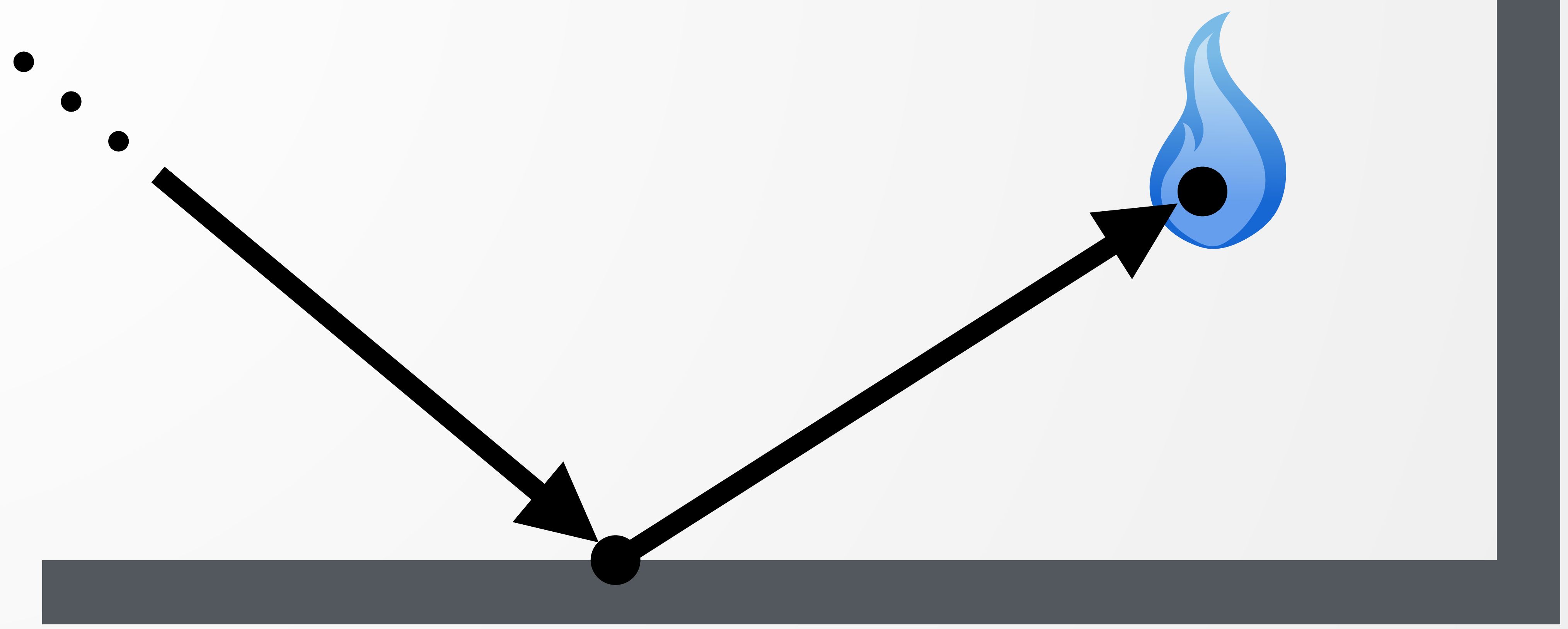
- Scattering events inside the volume
- Can also be sampled with NEE
  - Line integration with same weight function



next event estimation

Next Event Estimation

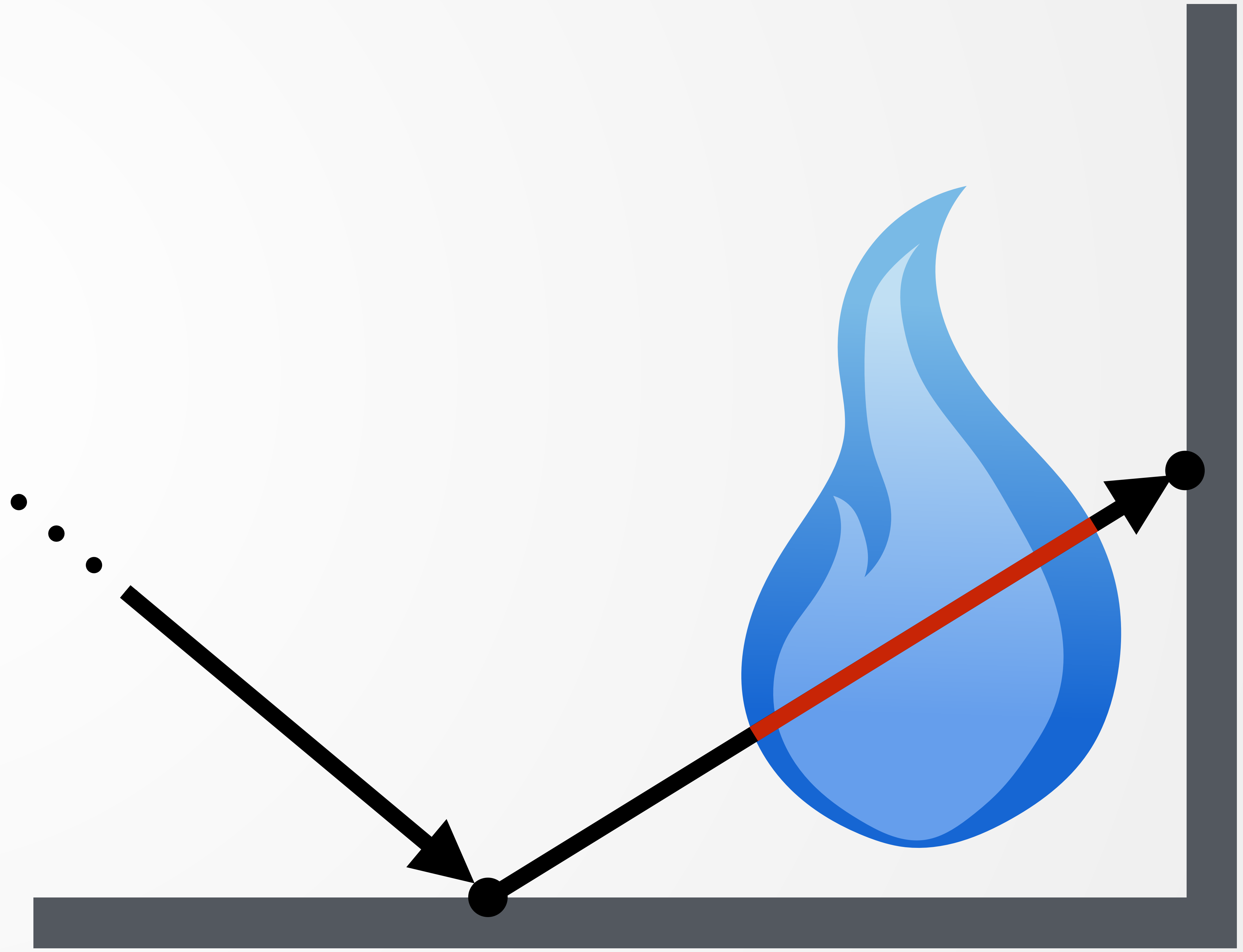
- Scattering events inside the volume
- Can also be sampled with NEE
  - Line integration with same weight function
- MIS is important for unlikely forward paths



forward sampling

Next Event Estimation

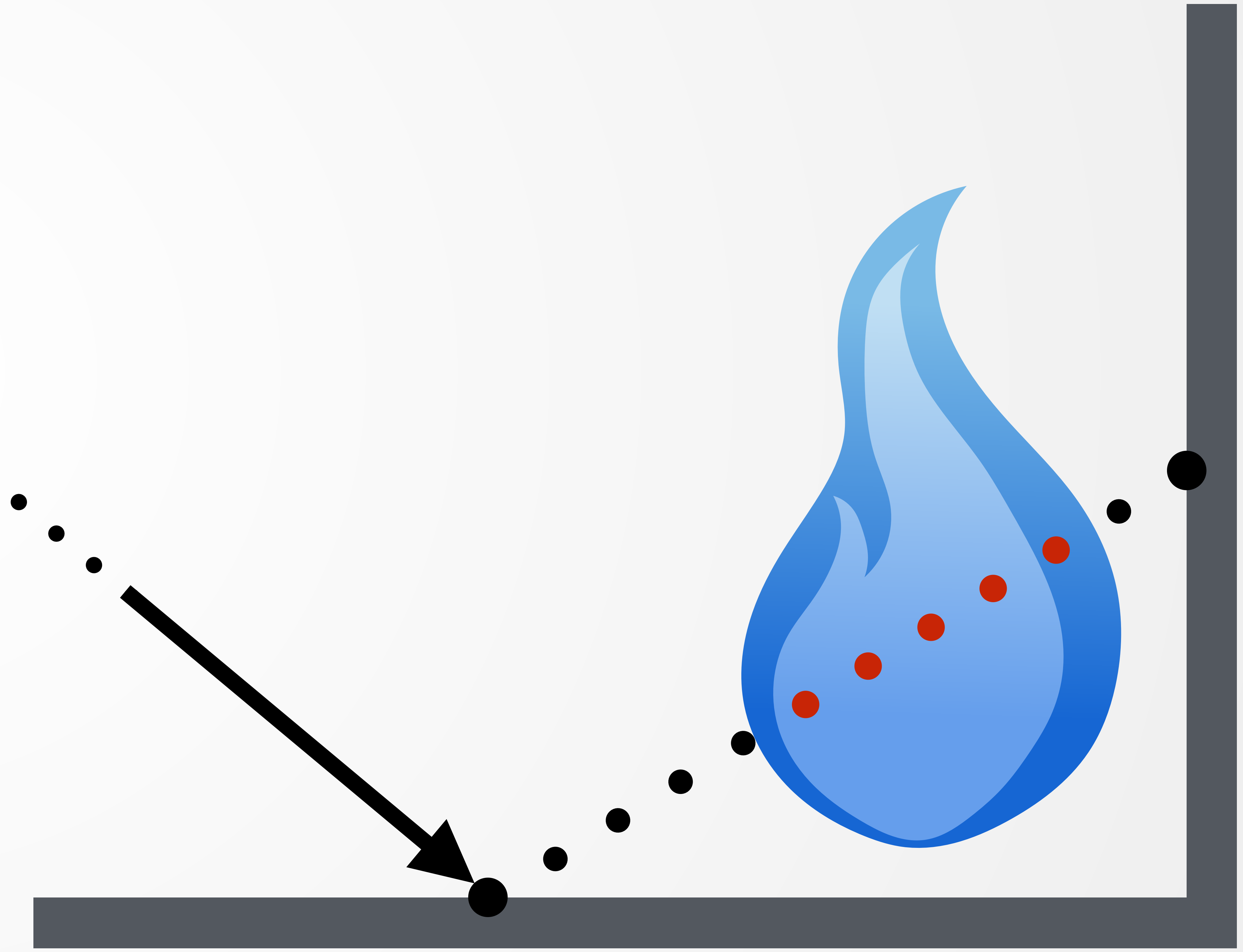
- No-collision paths contribute due to line integration



forward sampling

Next Event Estimation

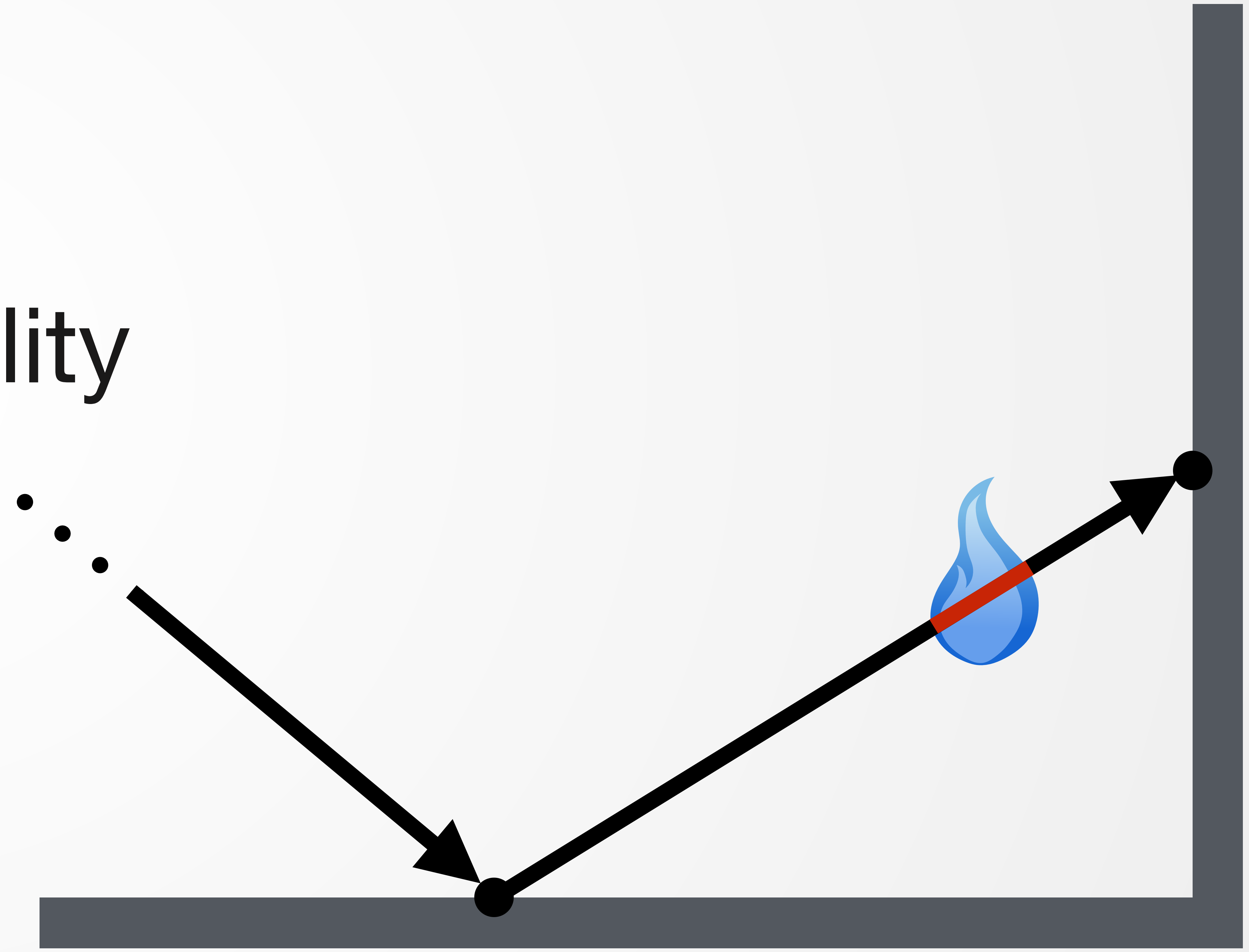
- No-collision paths contribute due to line integration
- But cannot be created by NEE



next event estimation ☒

Next Event Estimation

- No-collision paths contribute due to line integration
- But cannot be created by NEE
- Full contribution of low probability paths

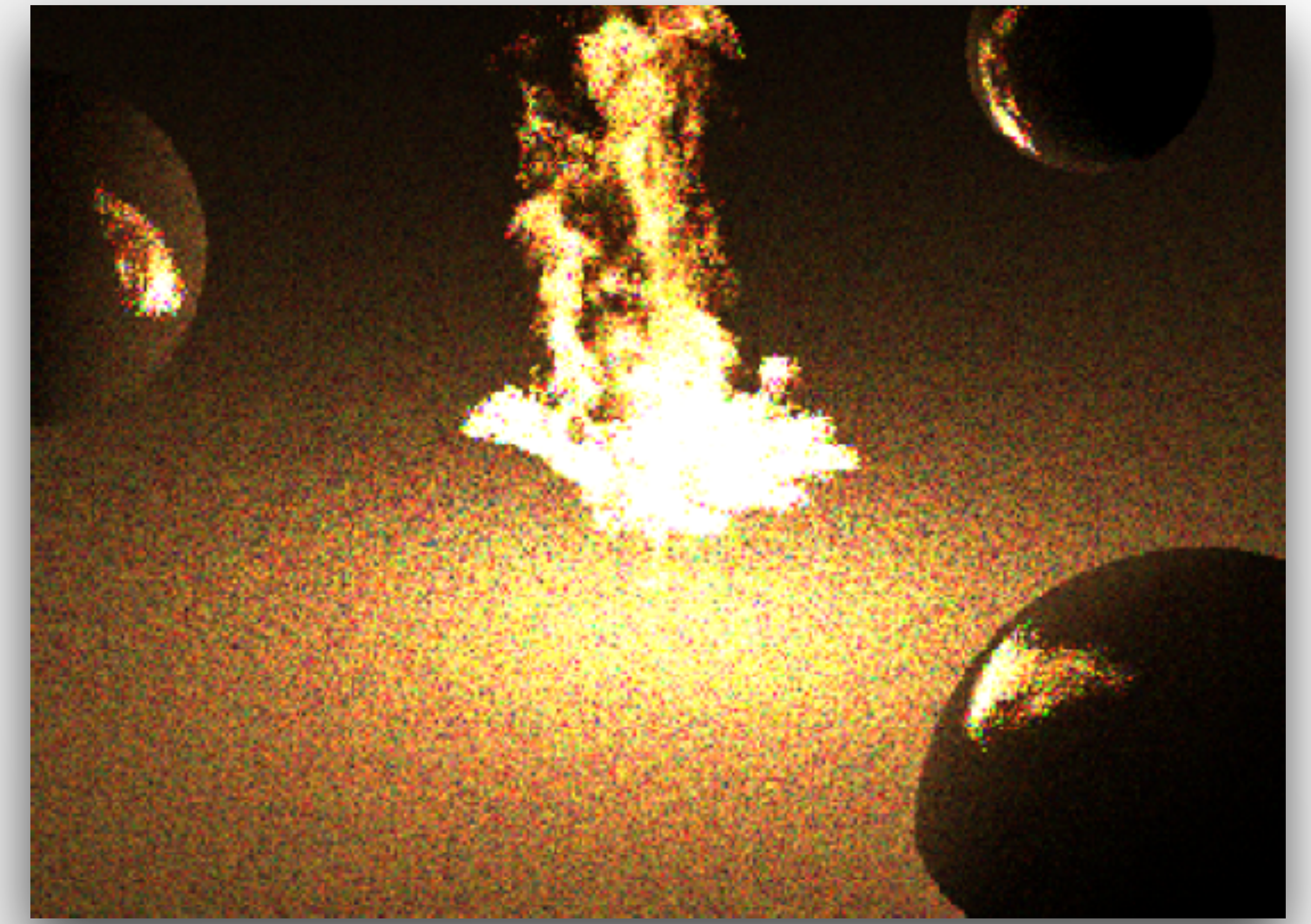


forward sampling

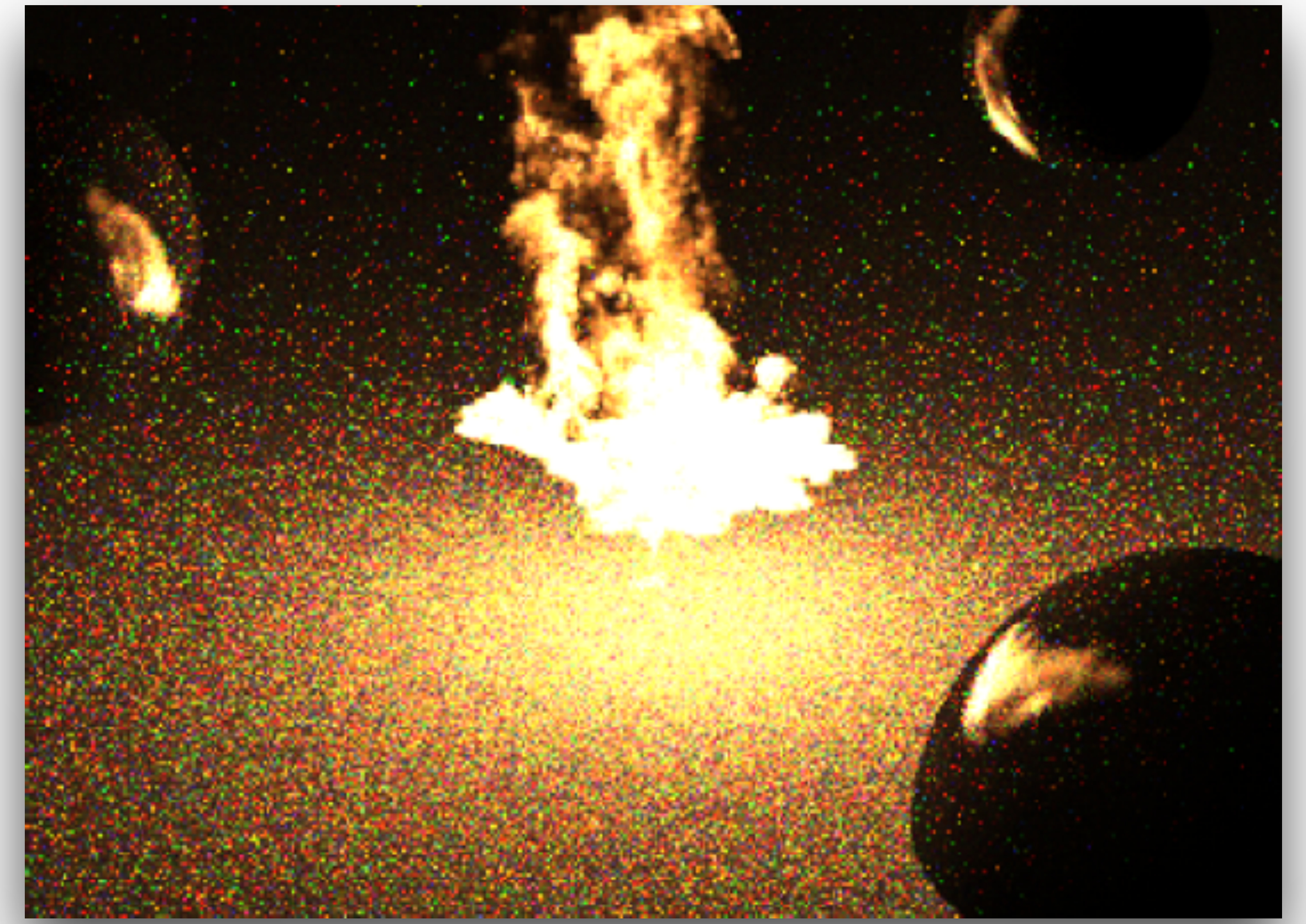
Next Event Estimation

- Line integration does not work well with NEE

Point + NEE



Line + NEE



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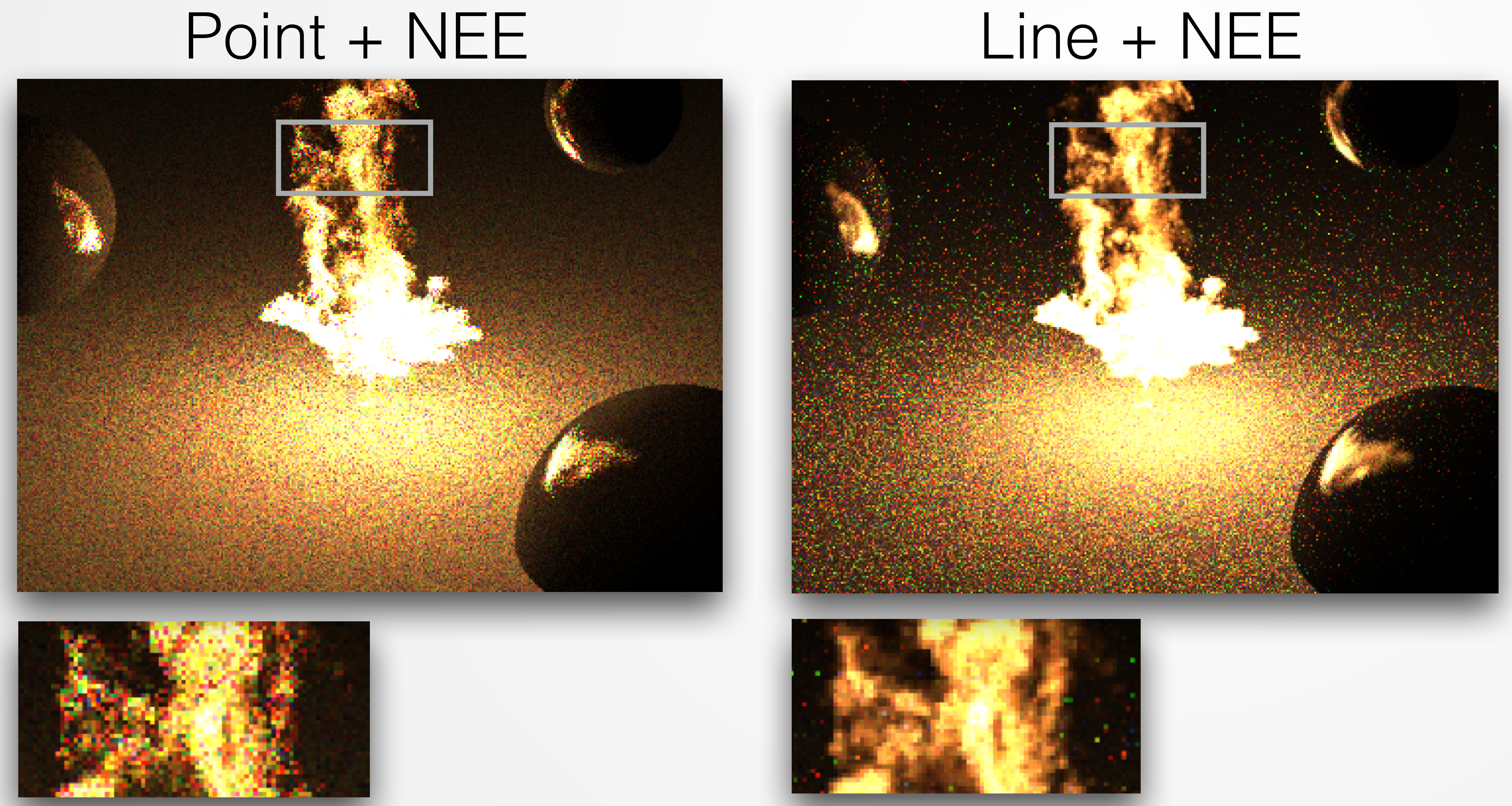

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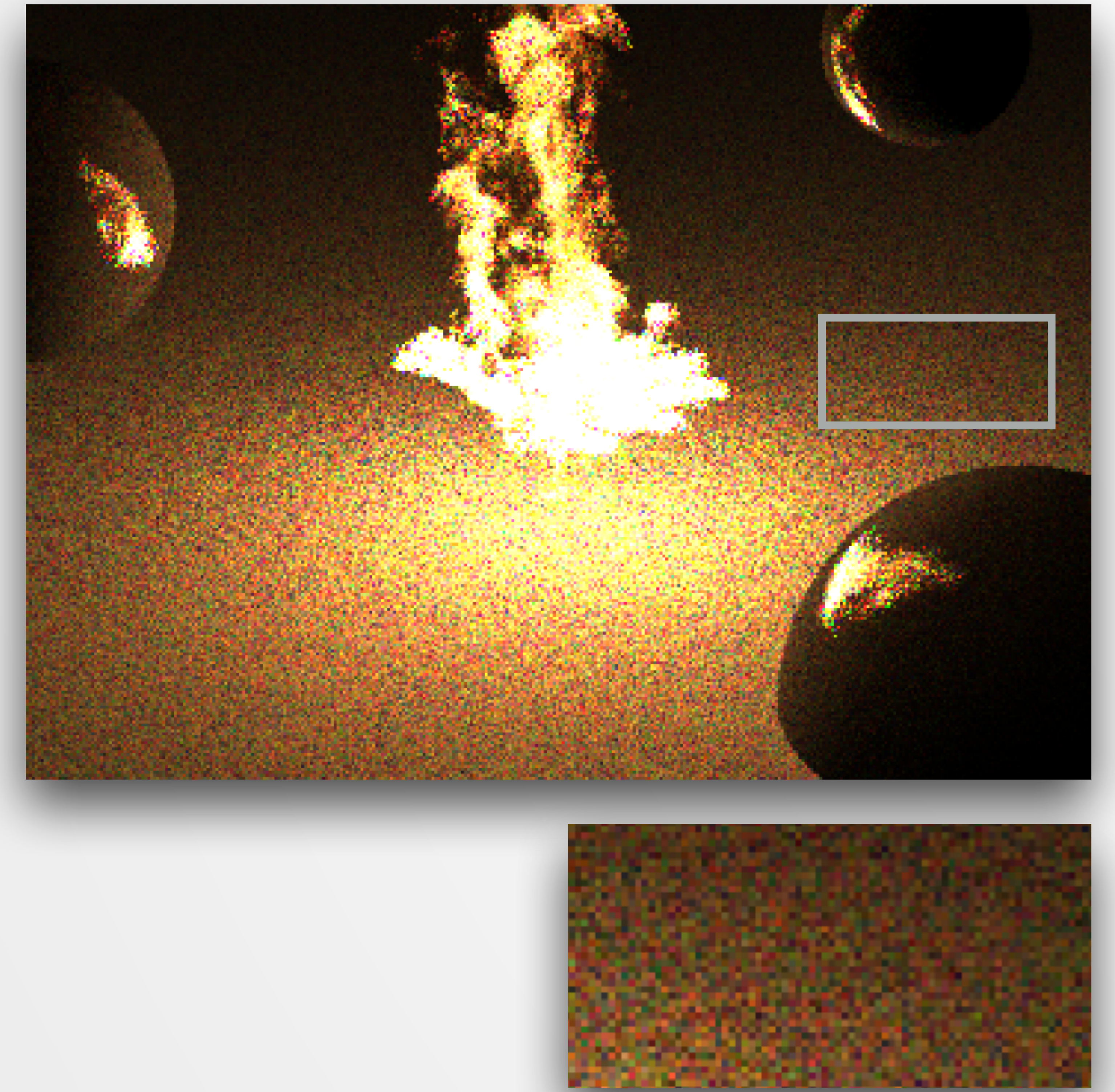
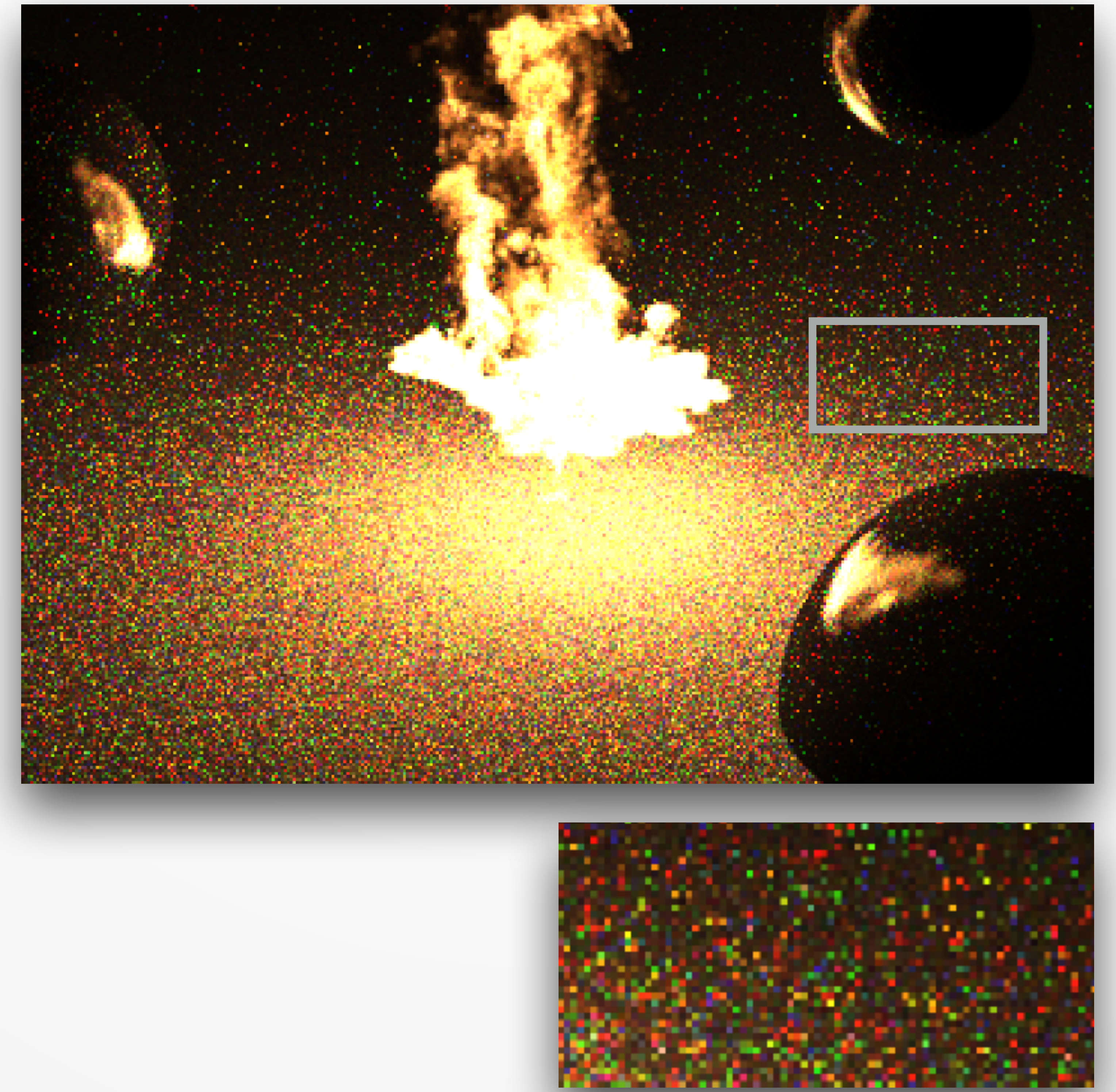


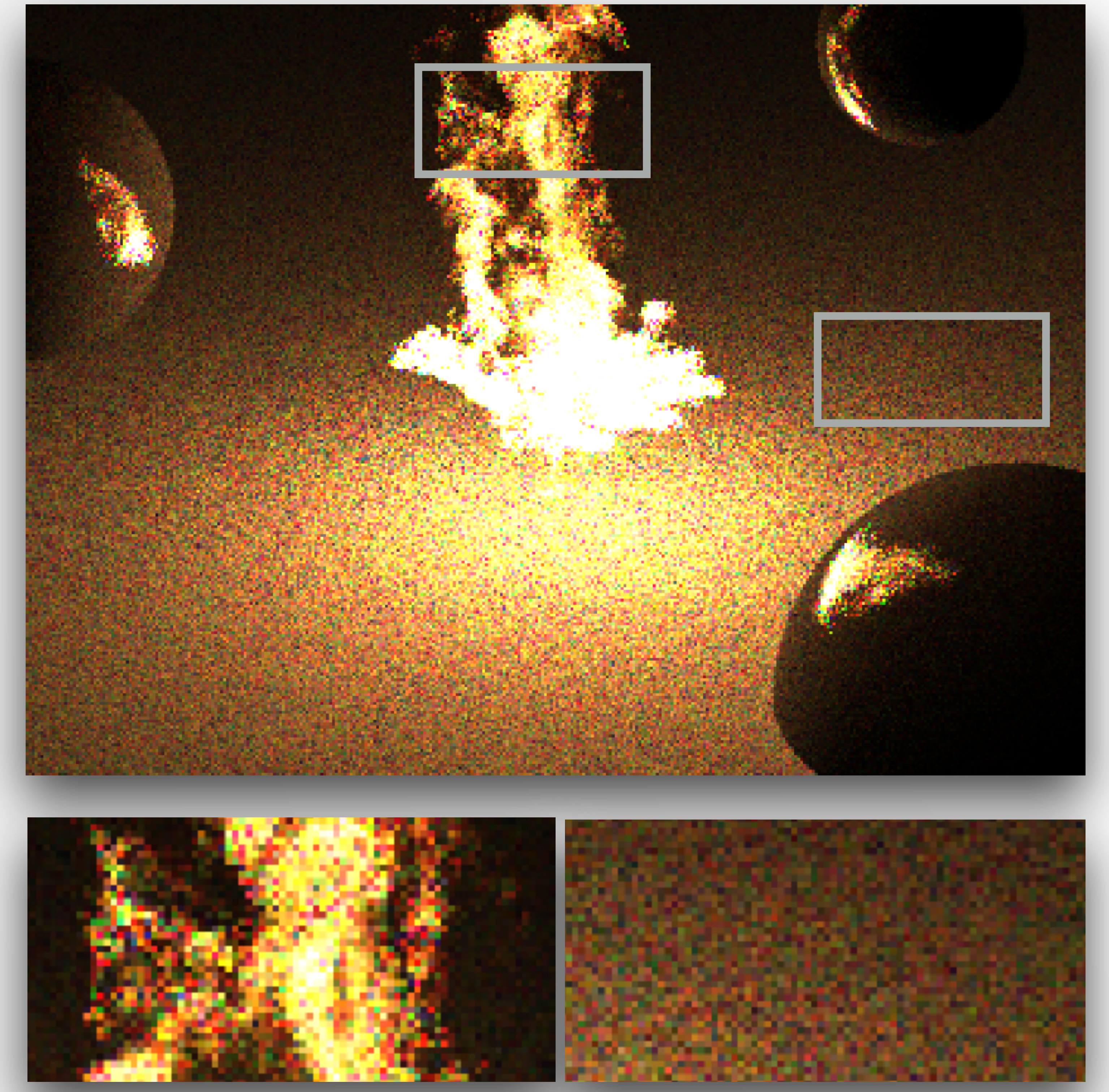
Line + NEE



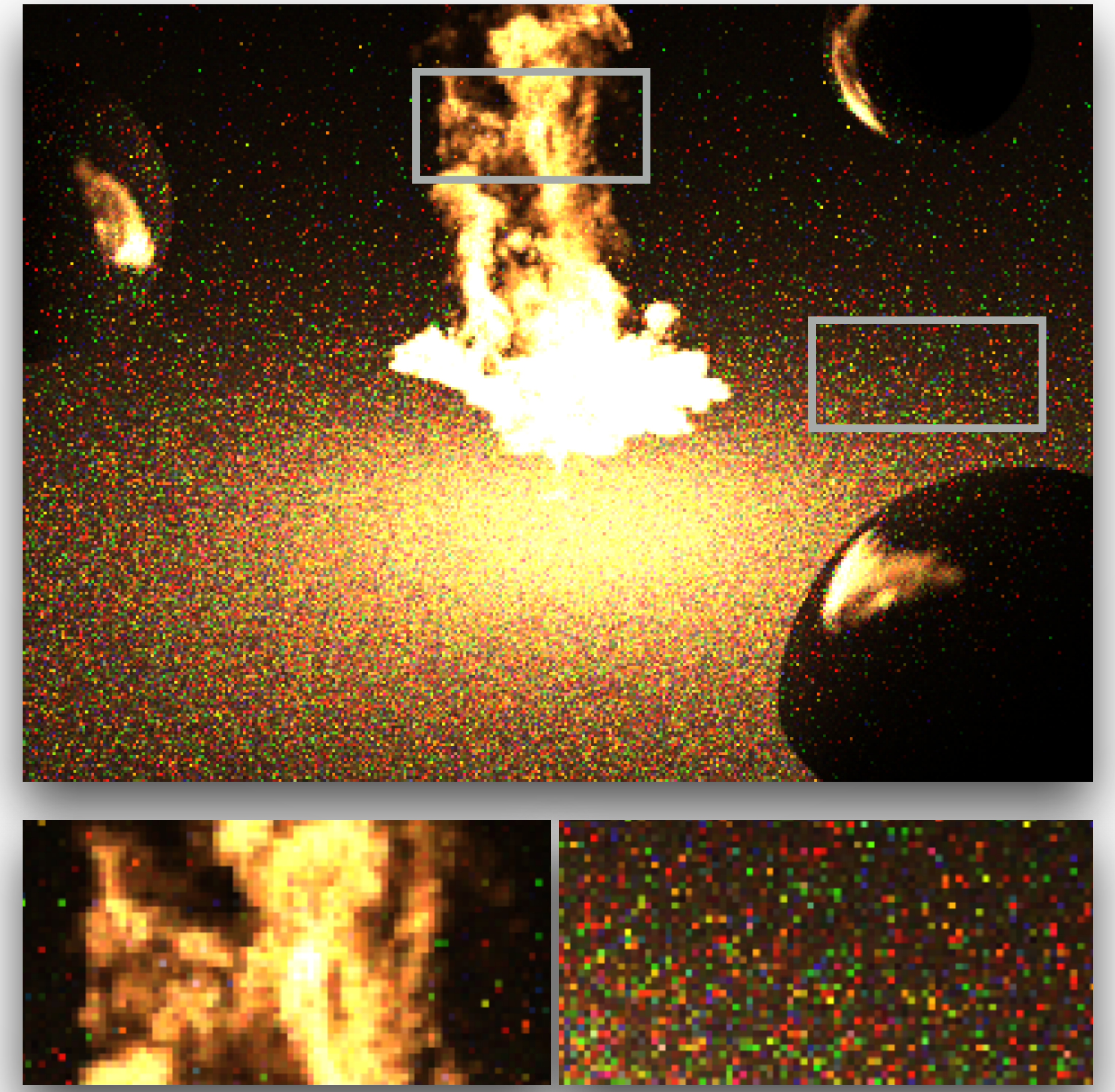
Next Event Estimation

- Line integration does not work well with NEE
- Idea: modify NEE to be able to create no-collision paths

Point + NEE



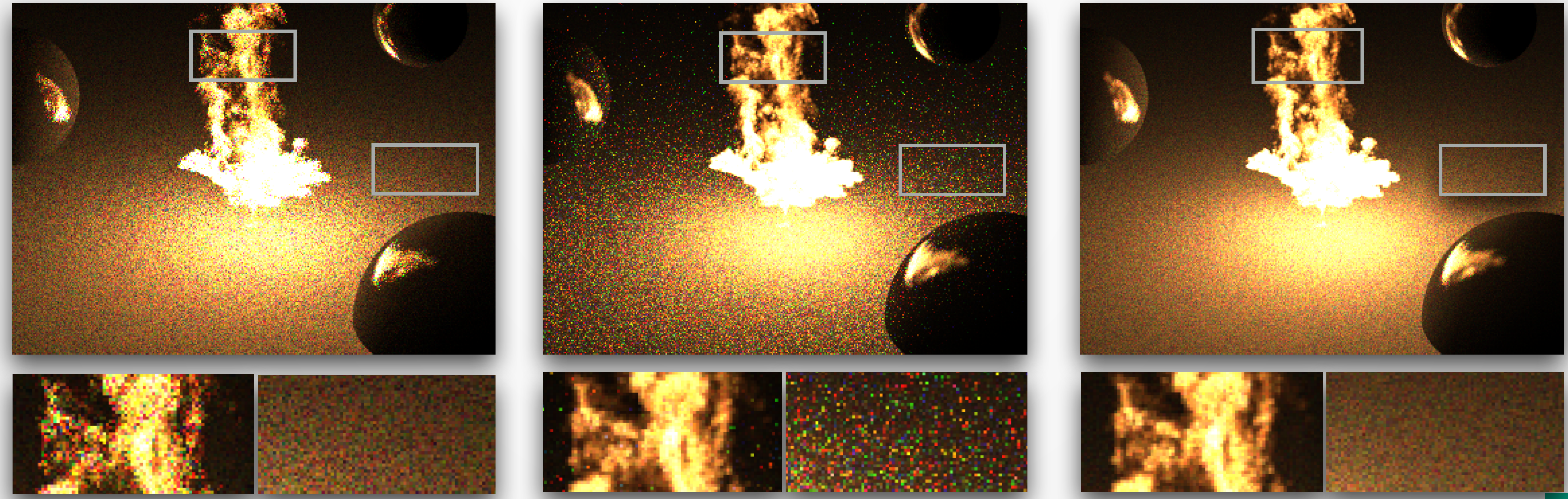
Line + NEE



Next Event Estimation

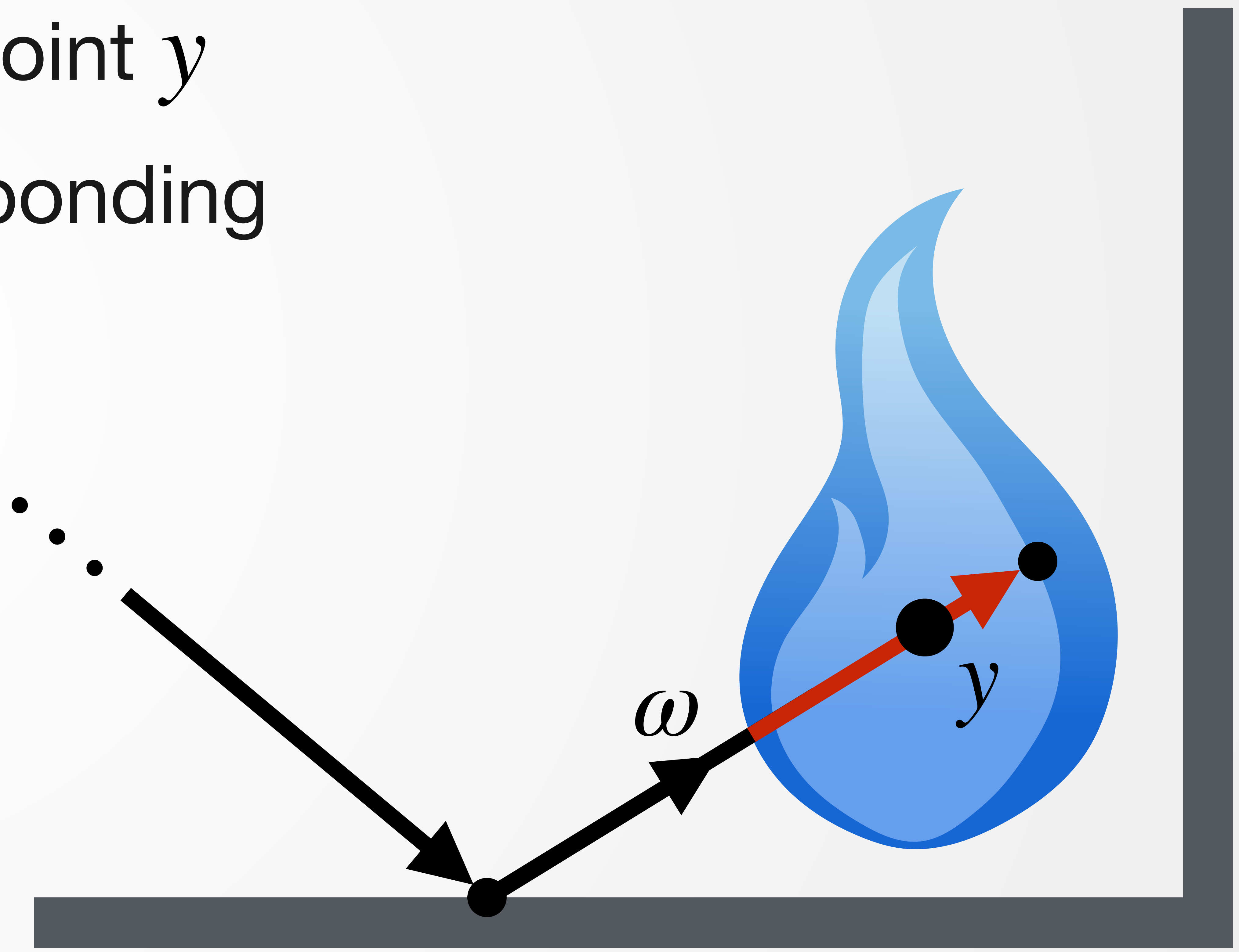
- Line integration does not work well with NEE
- Idea: modify NEE to be able to create no-collision paths

Point + NEE | Line + NEE | Line + FNEE



Forward Next Event Estimation

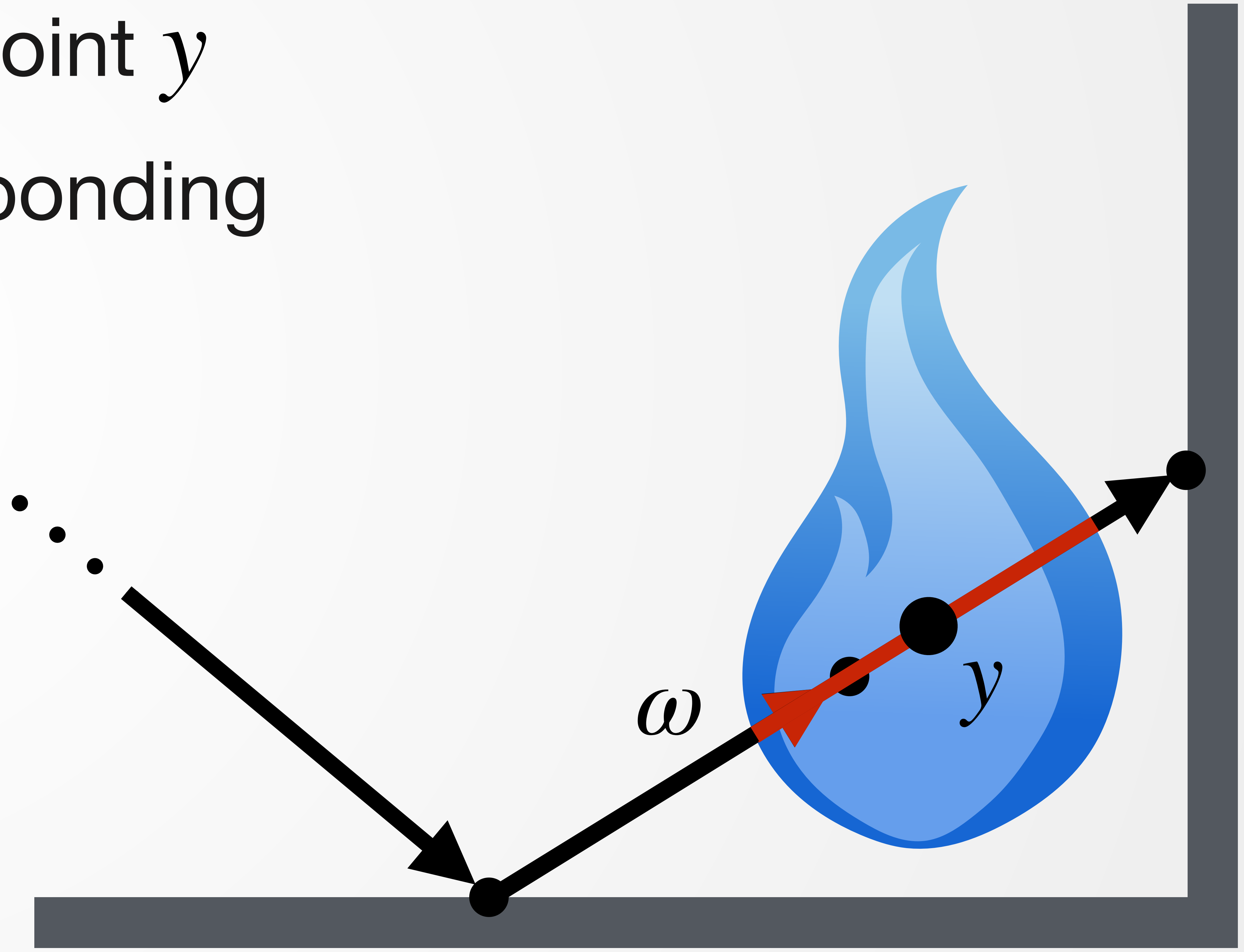
- Combine forward and NEE sampling by
  - first: importance sampling of an emissive point y
  - then: transmittance sampling in the corresponding direction ω
- Advantages



forward next event estimation

Forward Next Event Estimation

- Combine forward and NEE sampling by
  - first: importance sampling of an emissive point y
  - then: transmittance sampling in the corresponding direction ω
- Advantages
  - Allows no-collision paths
  - Shorter segments in dense volumes



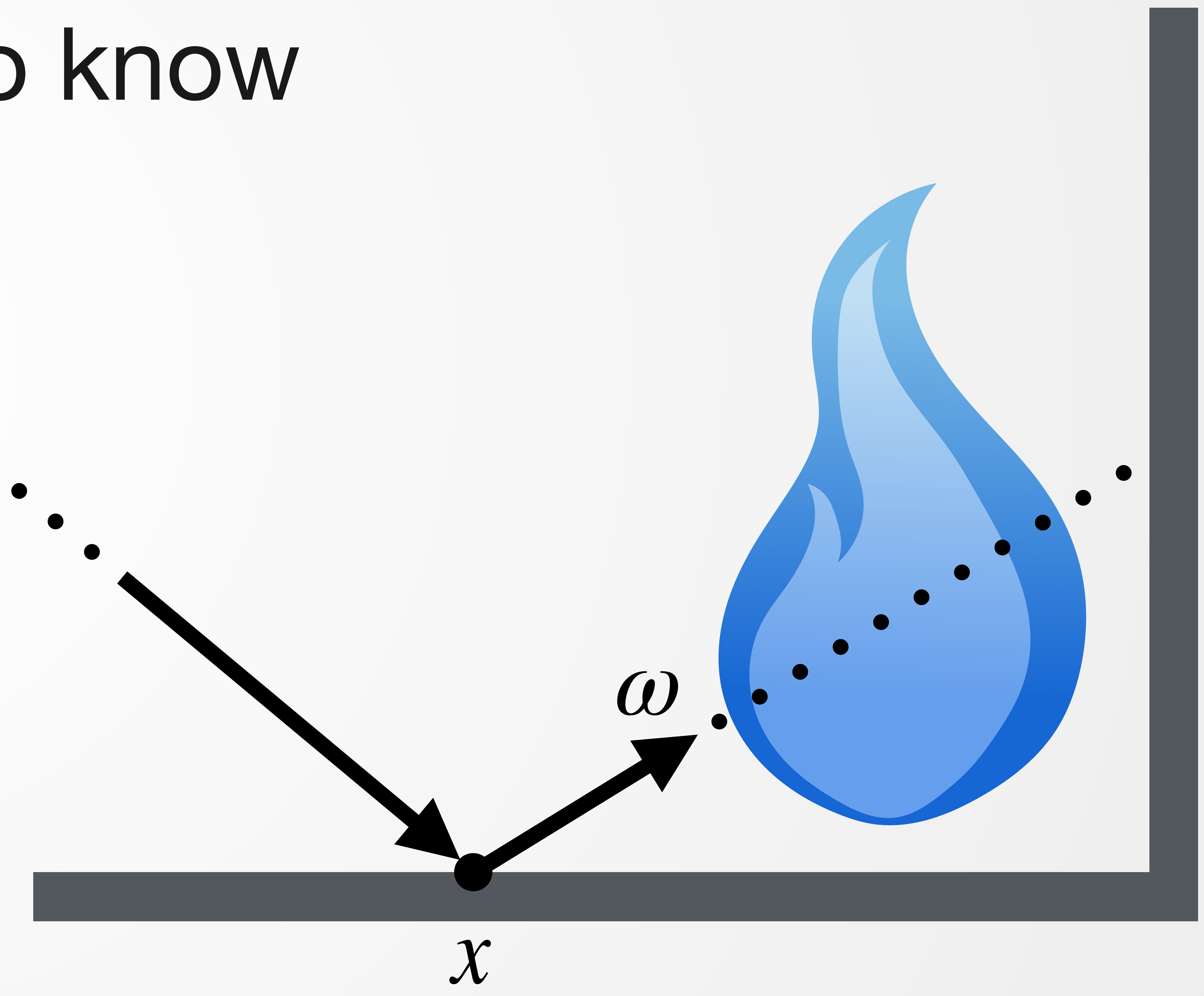
forward next event estimation

Forward Next Event Estimation

- Problem: Multiple points correspond to the same direction
- For the final path PDF we need to know

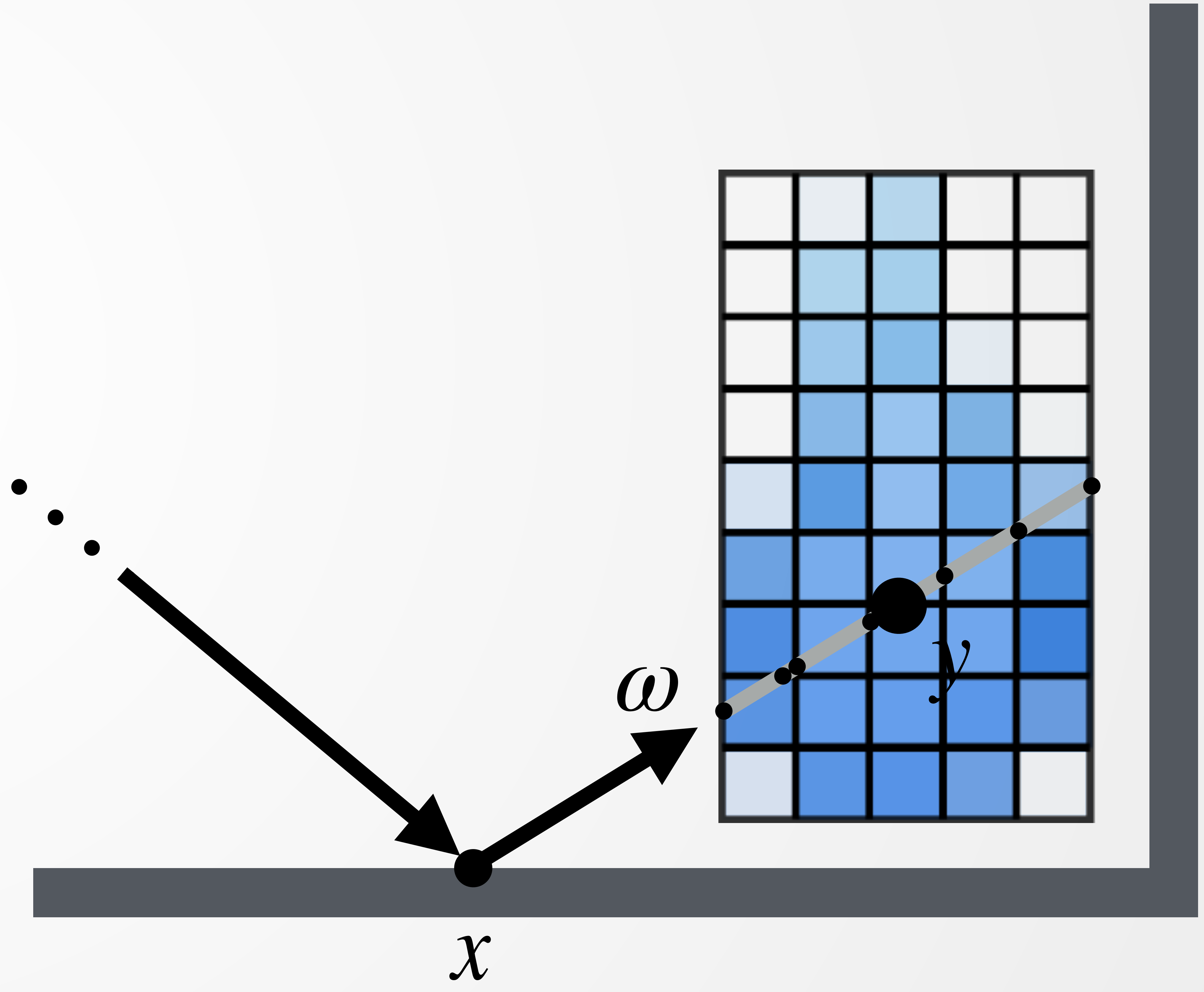
$$p_\sigma(\omega) = \int_0^\infty p_V(x + \omega t)\, t^2\, dt$$

- Too expensive to evaluate all the time



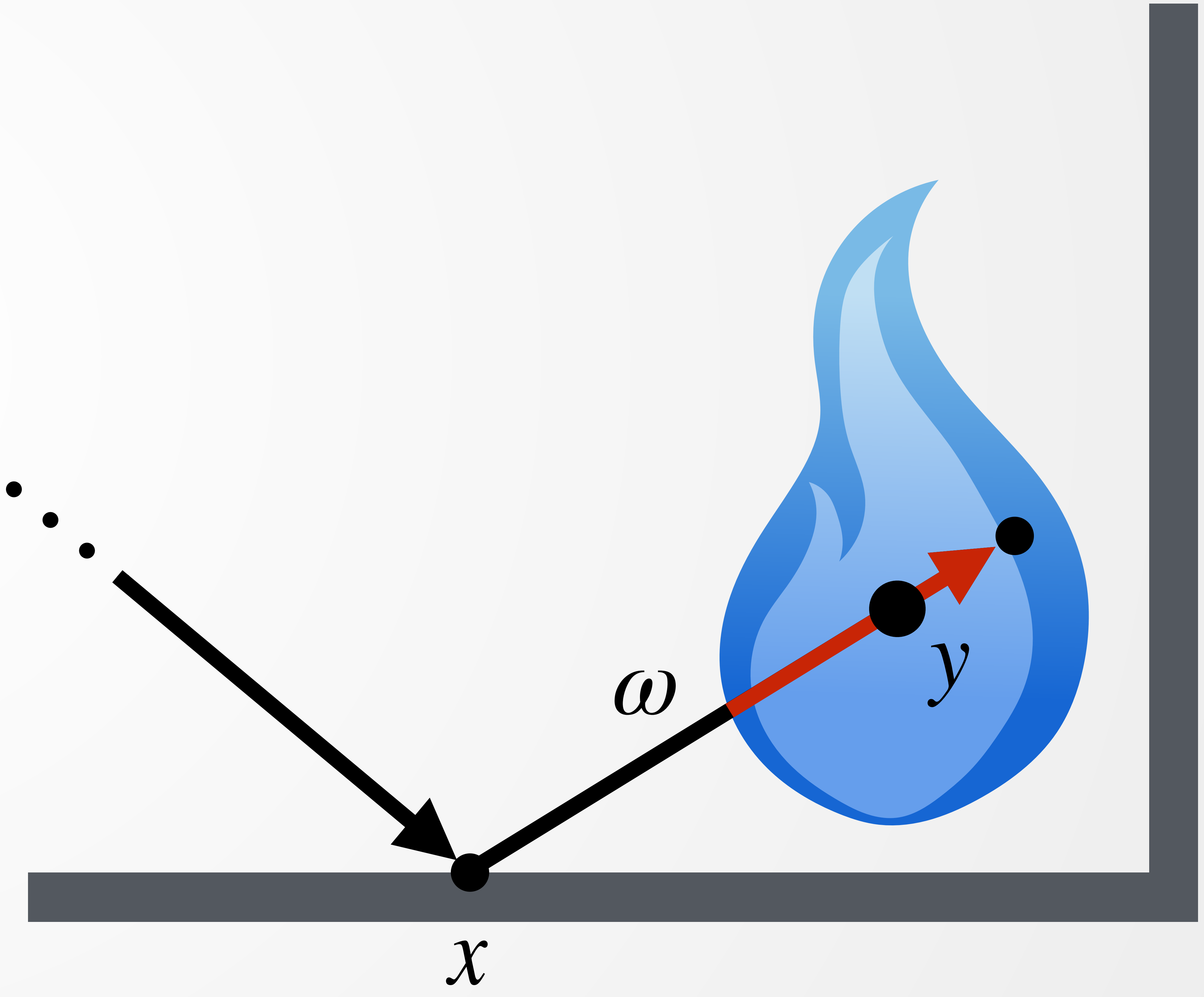
Forward Next Event Estimation

- Solution: Low resolution volume for
  - Initial point sampling
  - PDF integration



Forward Next Event Estimation

- Solution: Low resolution volume for
  - Initial point sampling
  - PDF integration
- On original resolution
  - Free path sampling
  - Line integration



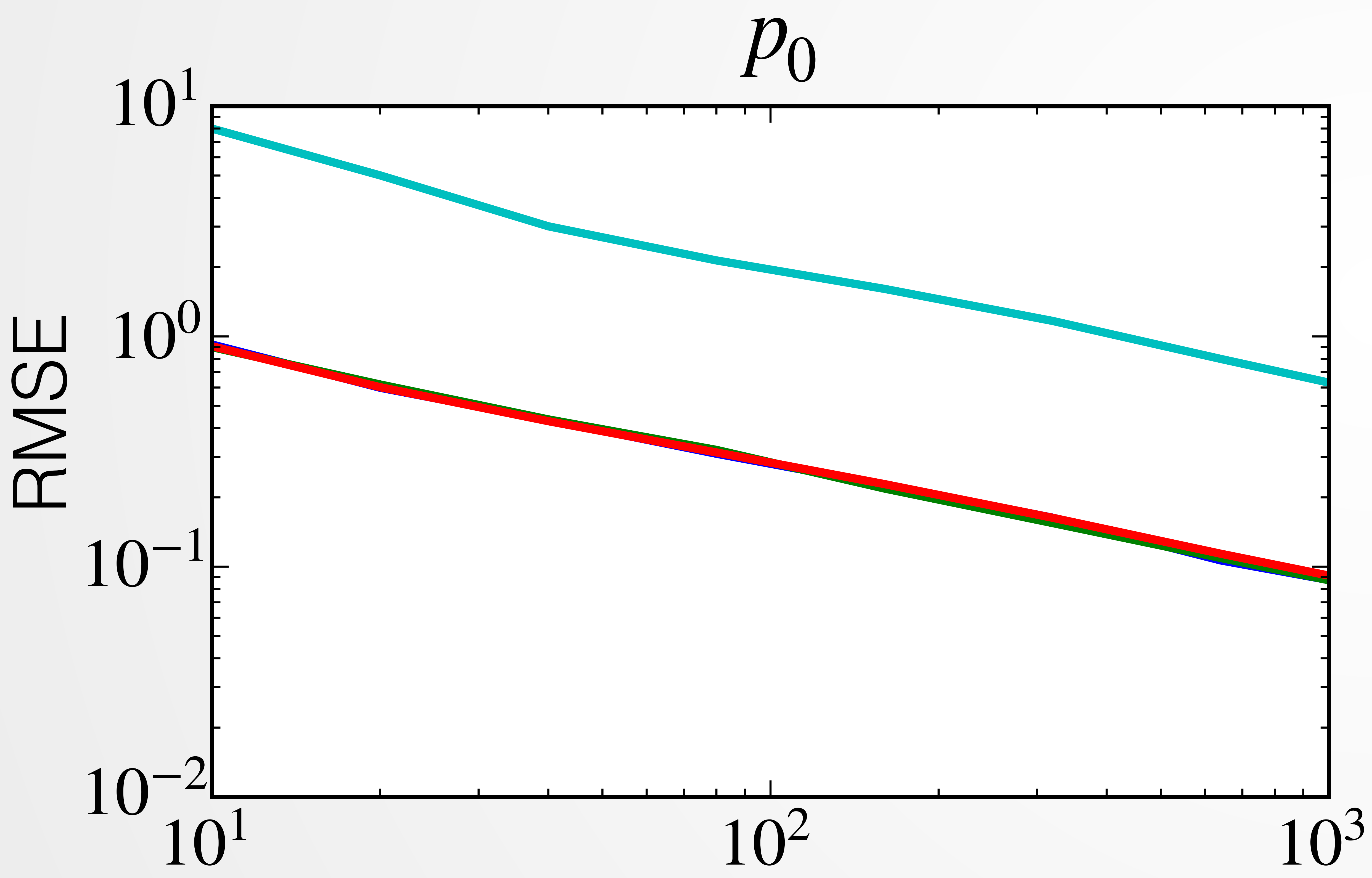
FNEE Test

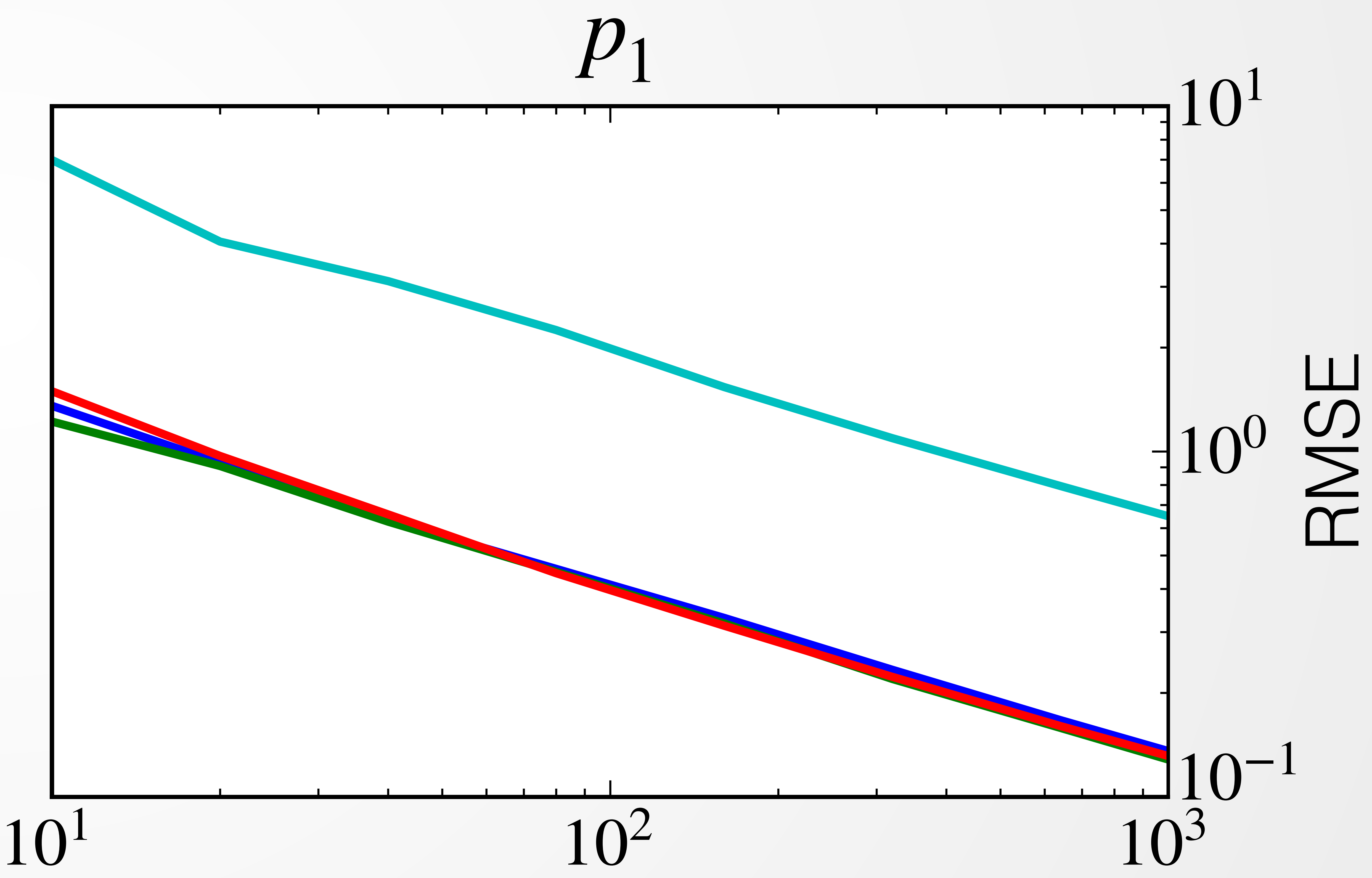
- Irradiance computed for two points
- RMSE comparison of
  - NEE with point integration
  - FNEE with line integration for 4096^3, 512^3, 64^3

FNEE Test

- NEE
- FNEE 4096^3
- FNEE 512^3
- FNEE 64^3

- Equal-sample RMSE

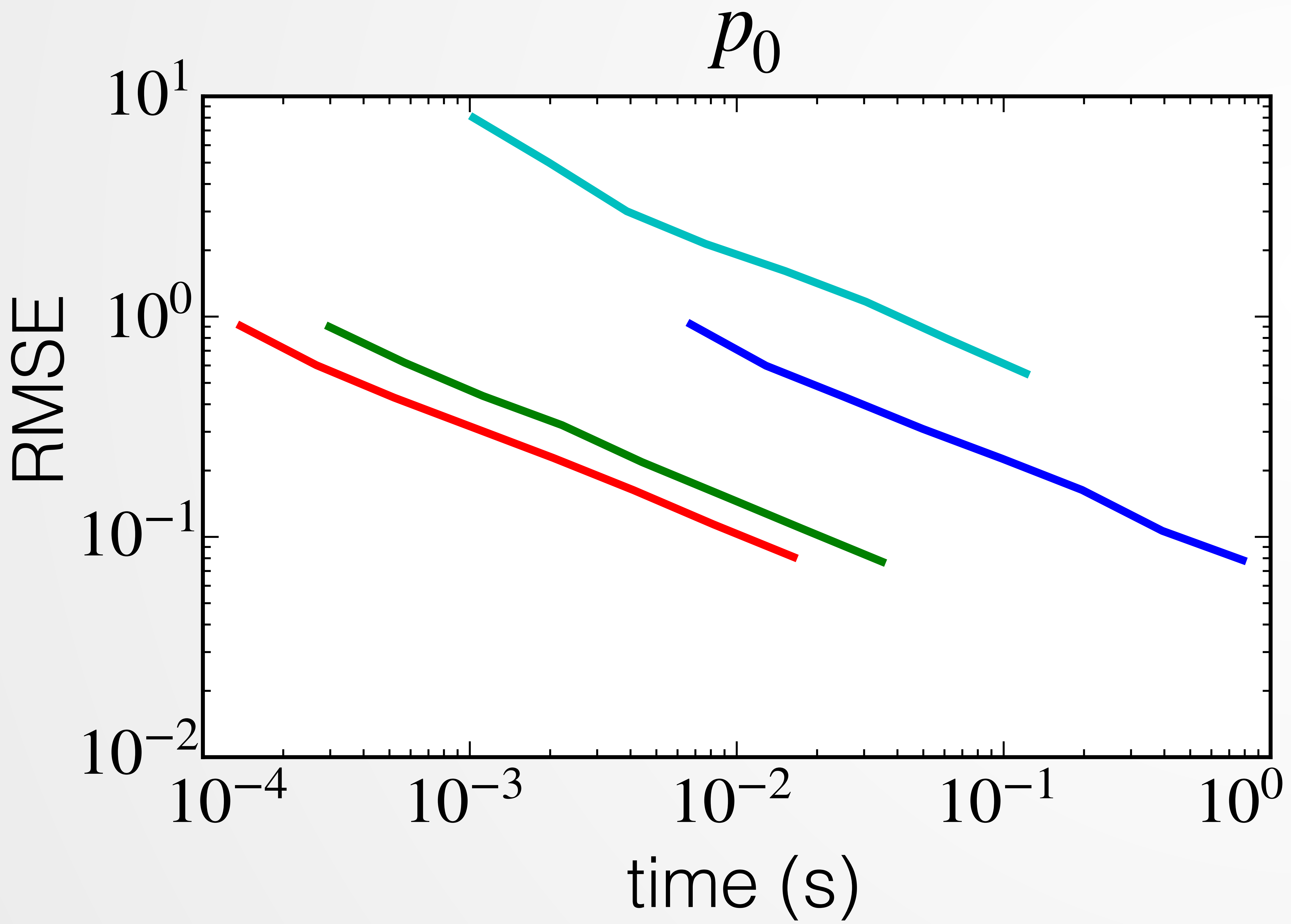


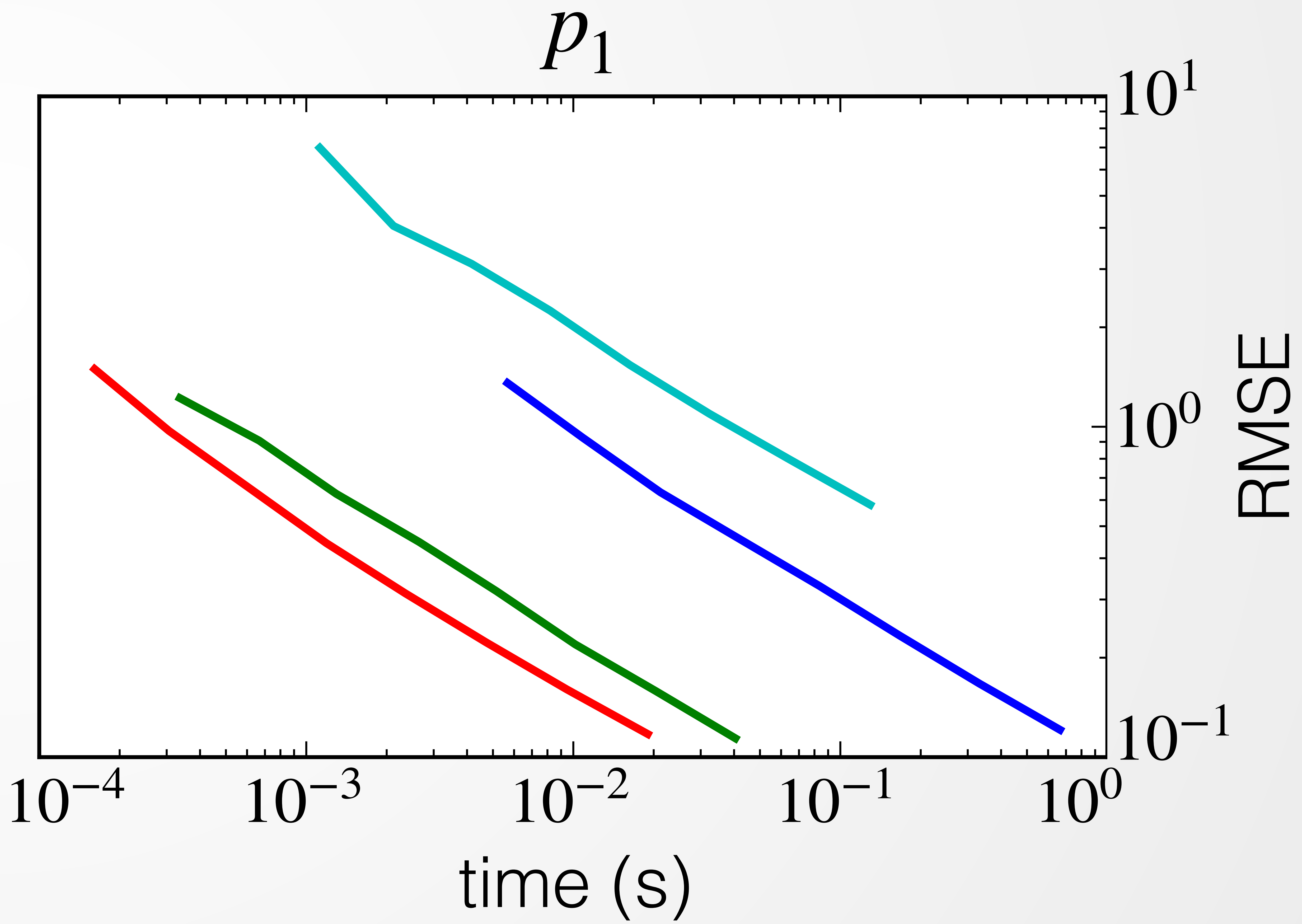


FNEE Test

- NEE
- FNEE 4096^3
- FNEE 512^3
- FNEE 64^3

- Equal-time RMSE

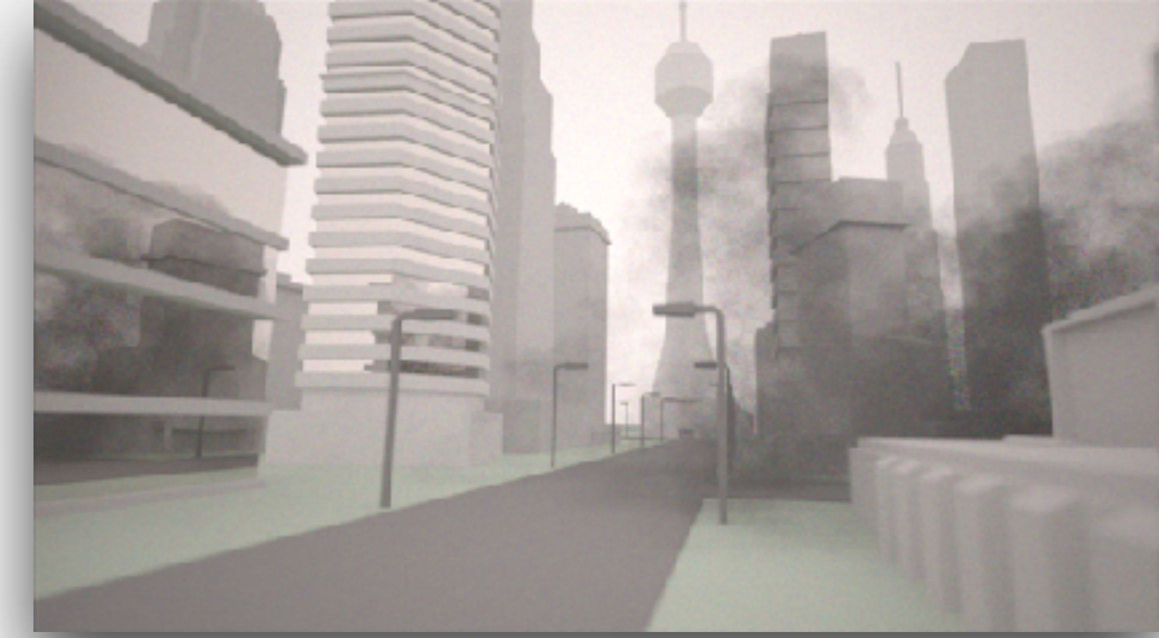




Results

Results

- Explosion (thin) - equal time - 10min



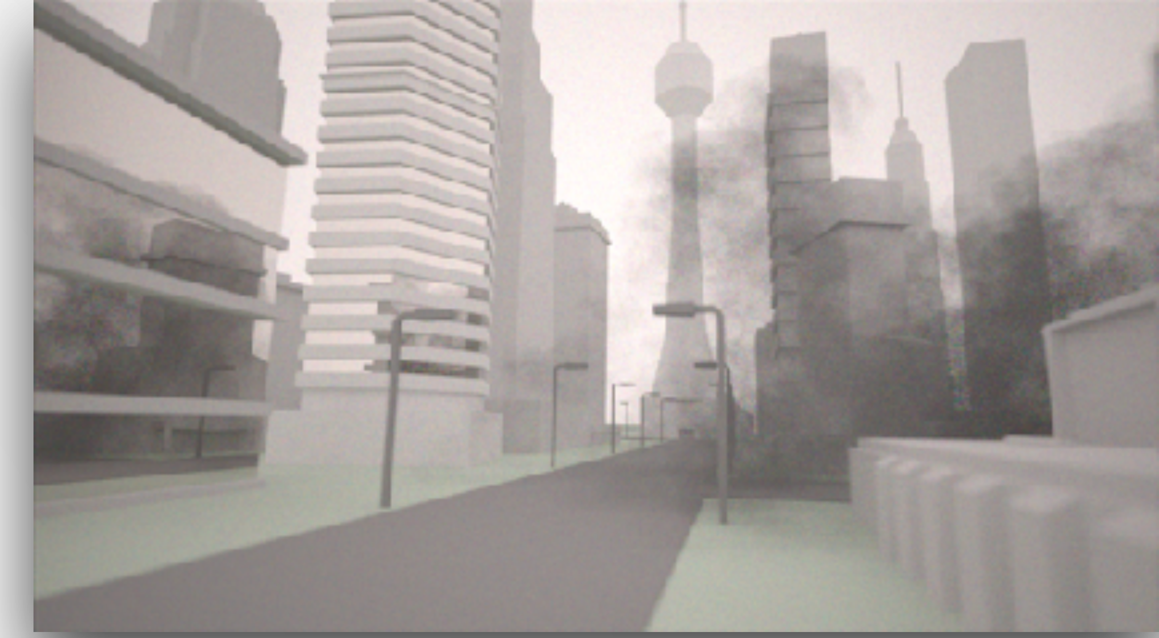
Density

FNEE - RMSE 0.748 - 48spp

NEE - RMSE 0.983 - 43spp

Results

- Explosion (thin) - equal time - 10min



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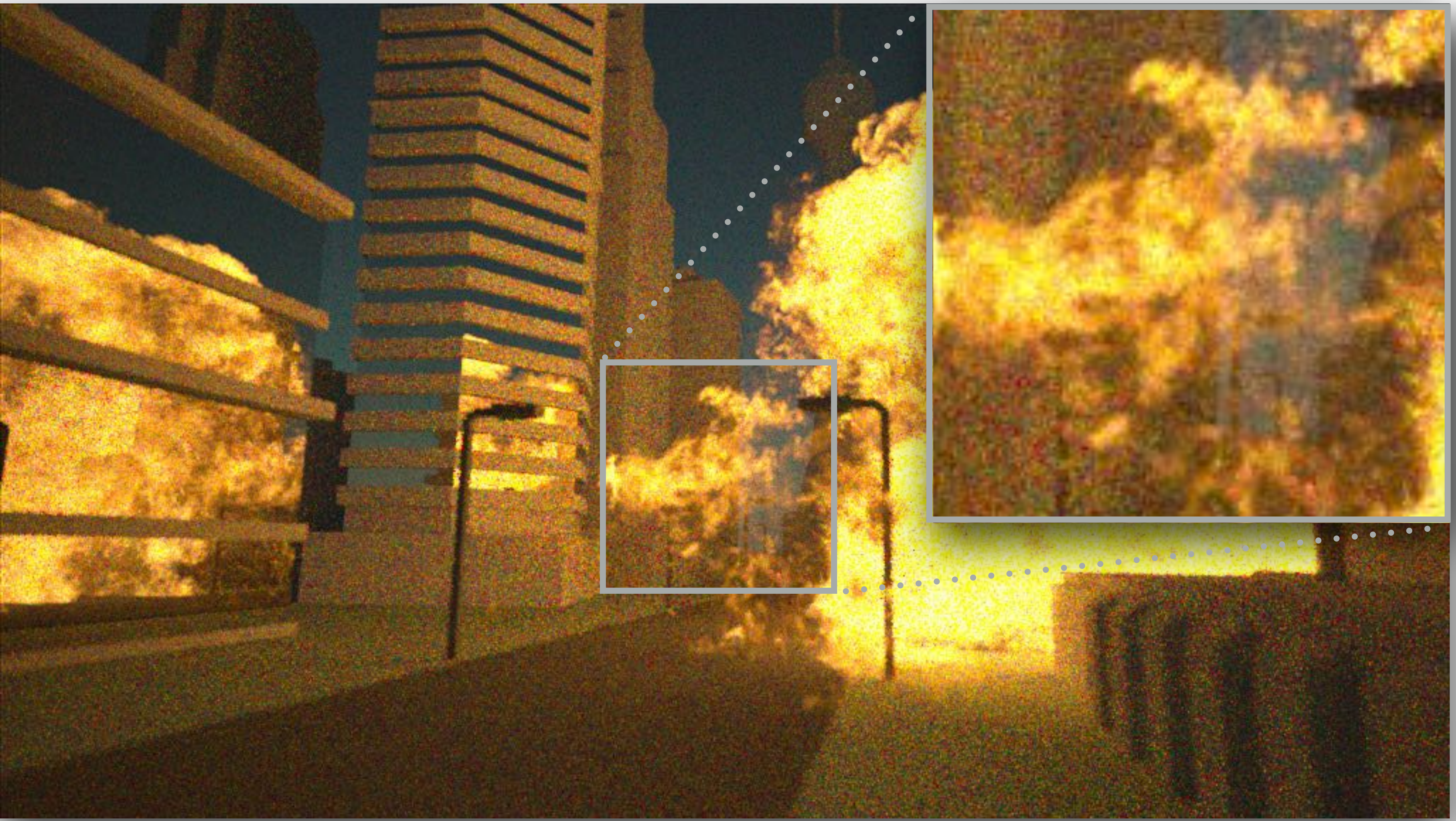
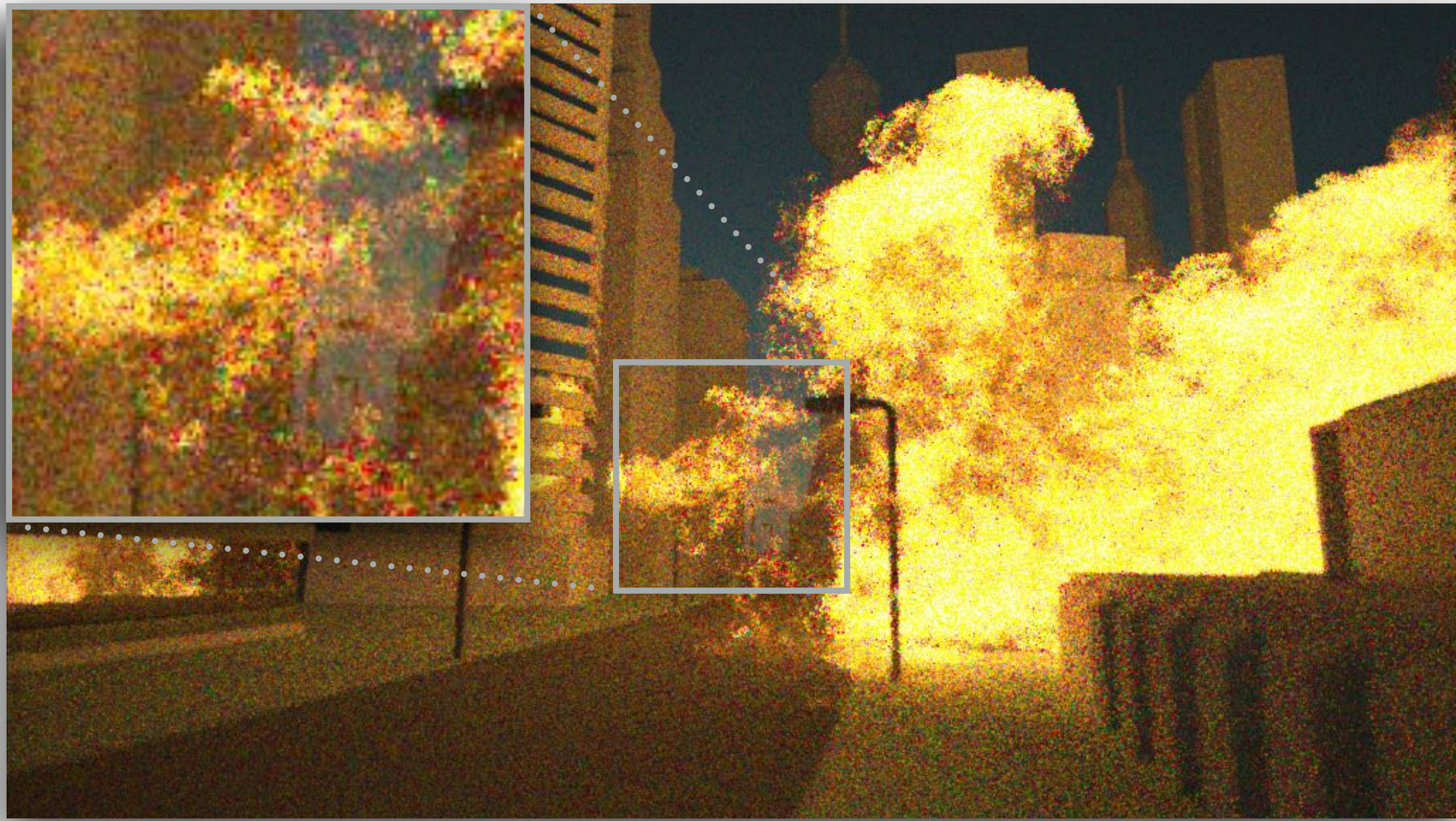
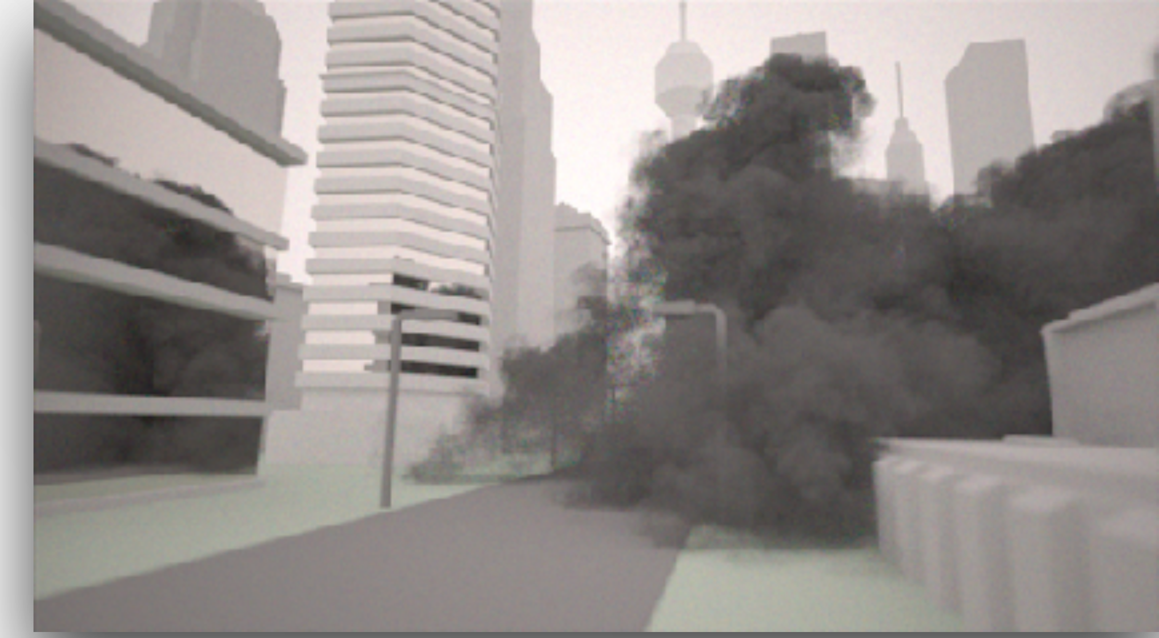


FNEE - RMSE 0.748 - 48spp

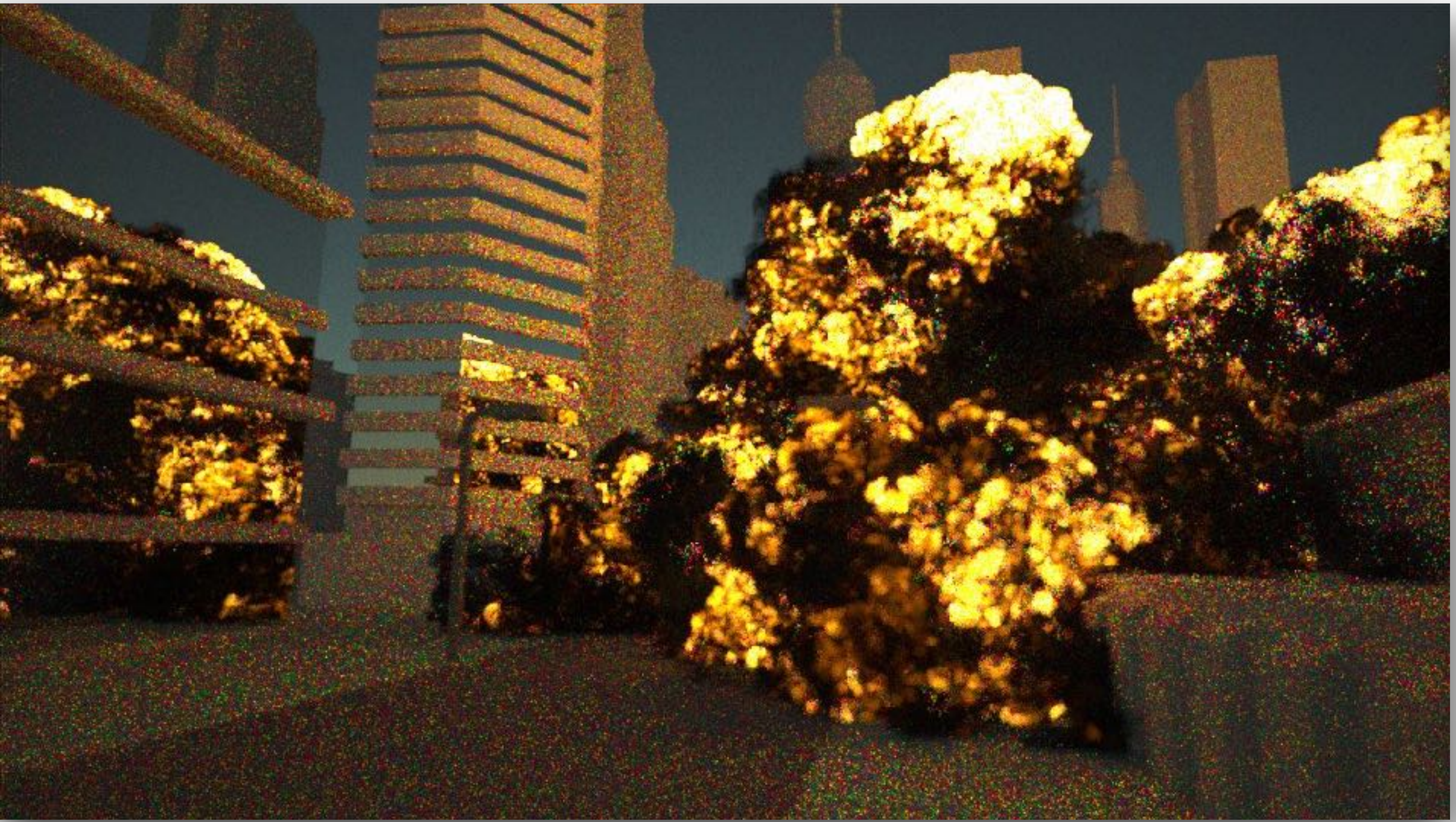


NEE - RMSE 0.983 - 43spp

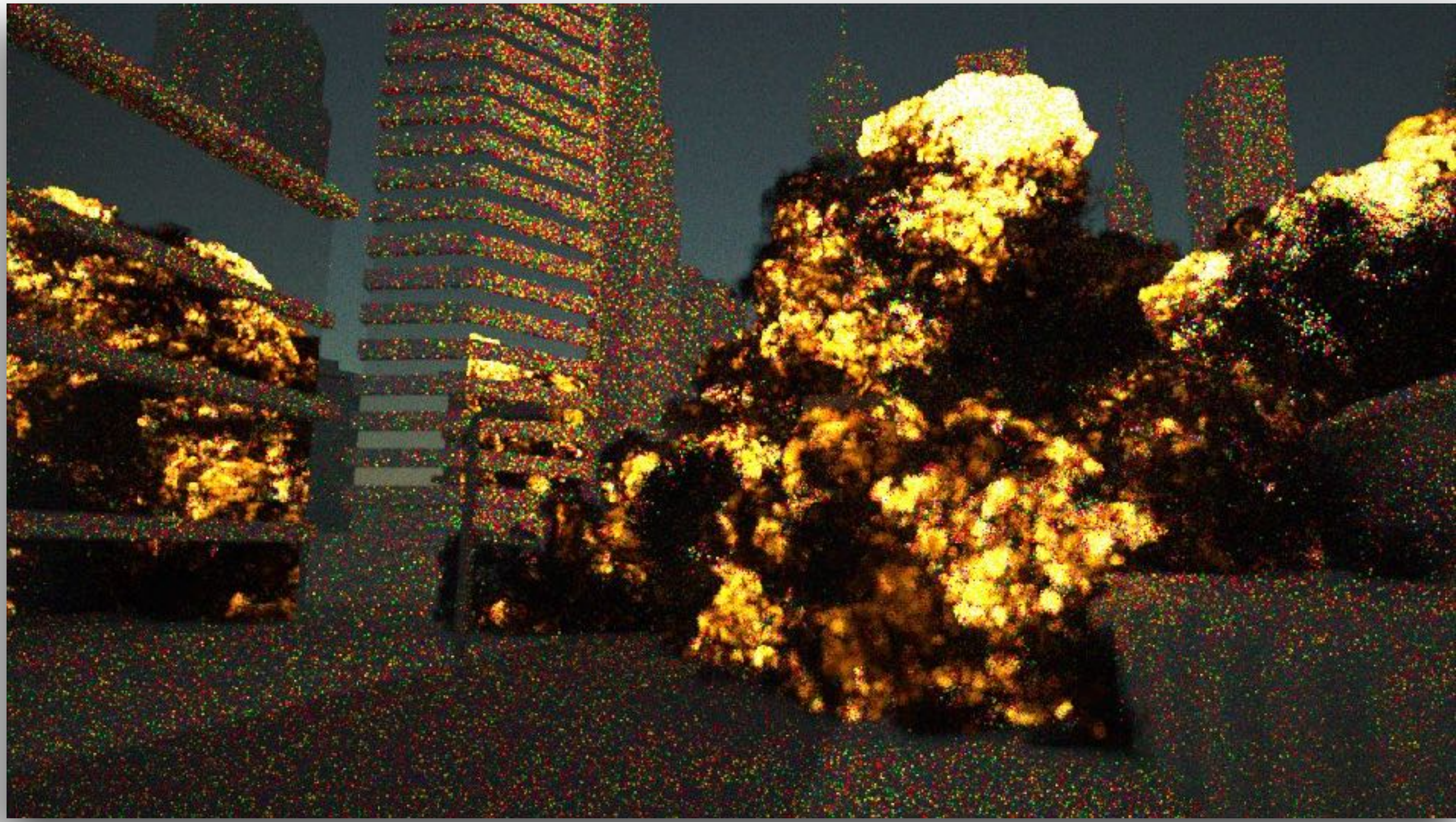
Results



- Explosion (dense) - equal time - 30min

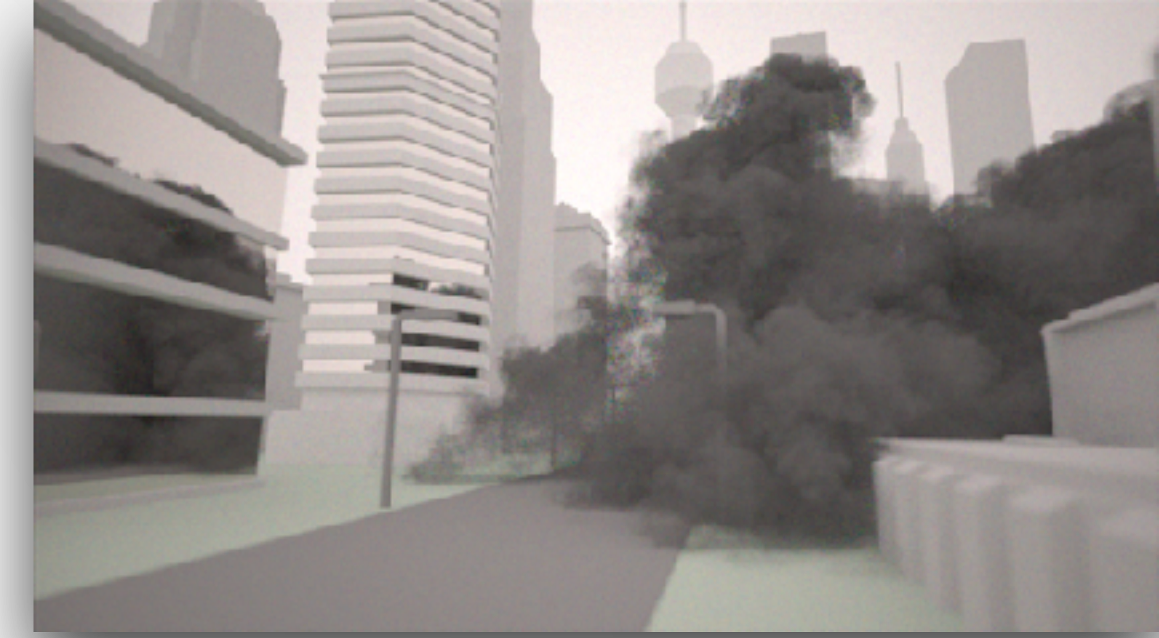


FNEE - RMSE 0.572 - 196spp

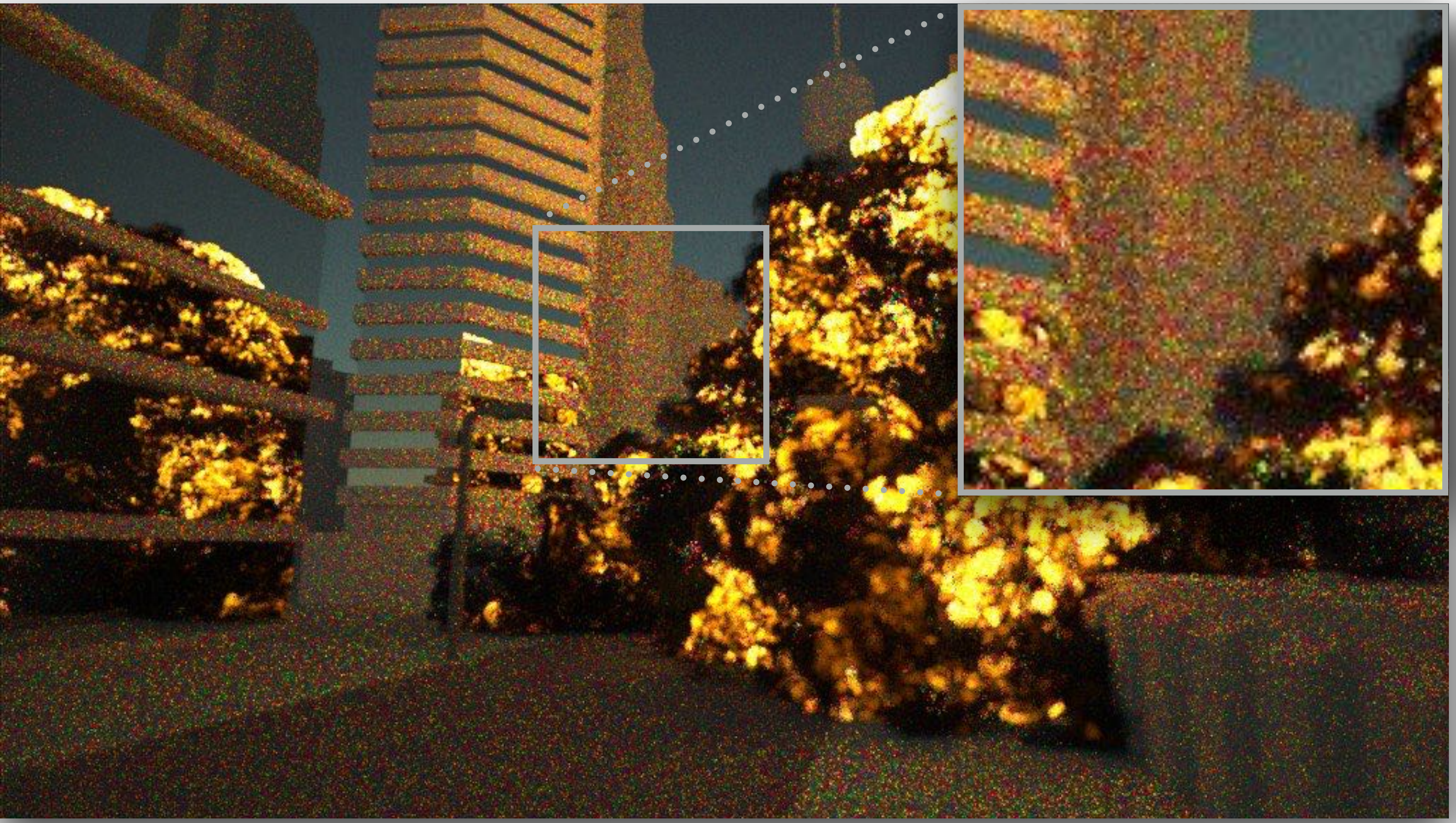


NEE - RMSE 0.892 - 73spp

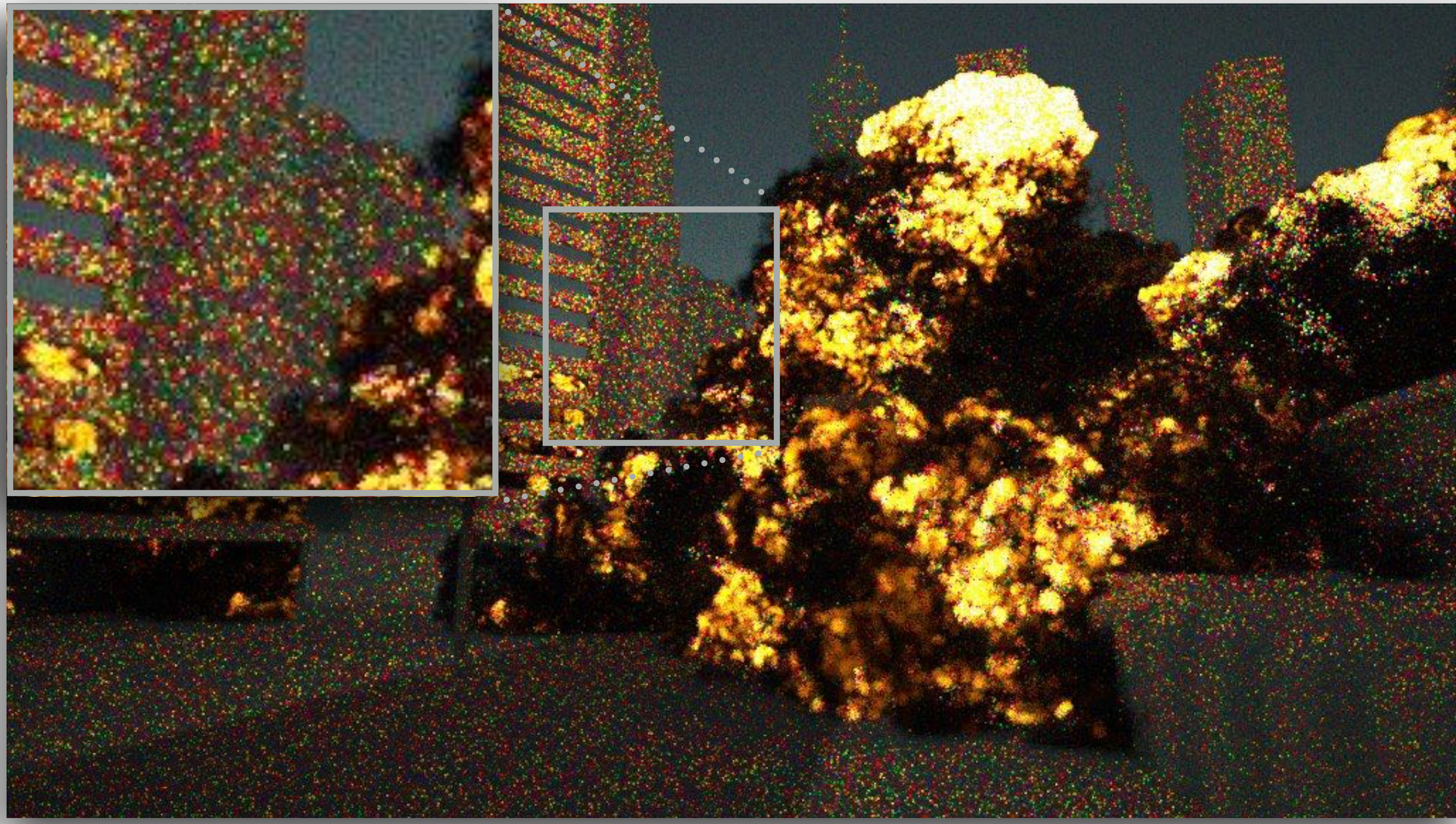
Results



- Explosion (dense) - equal time - 30min

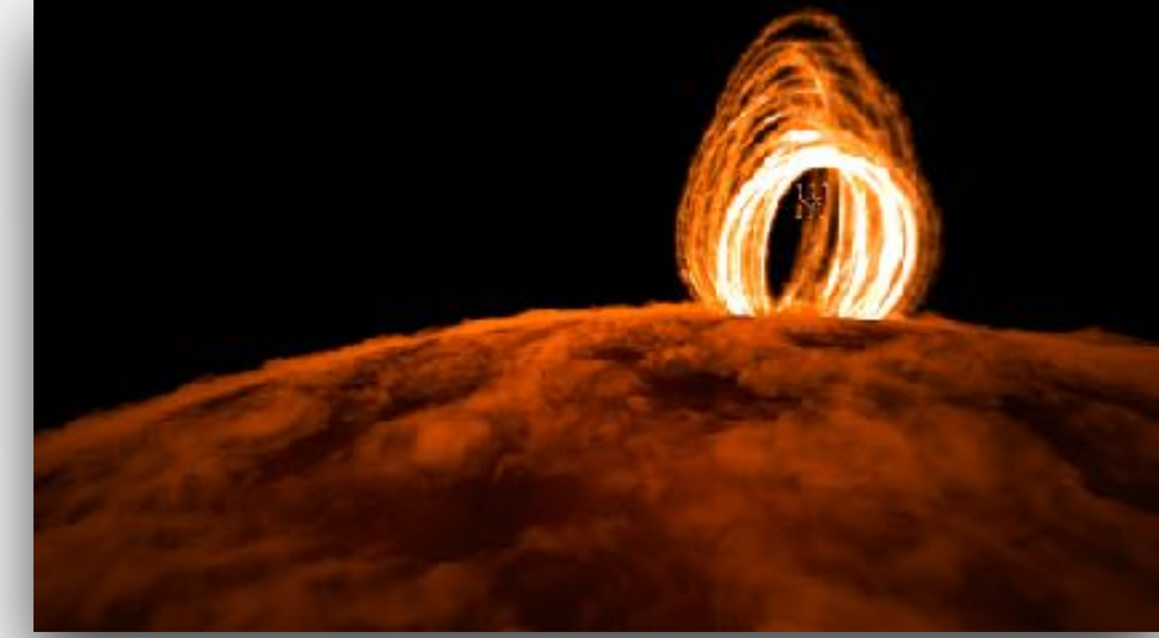


FNEE - RMSE 0.572 - 196spp



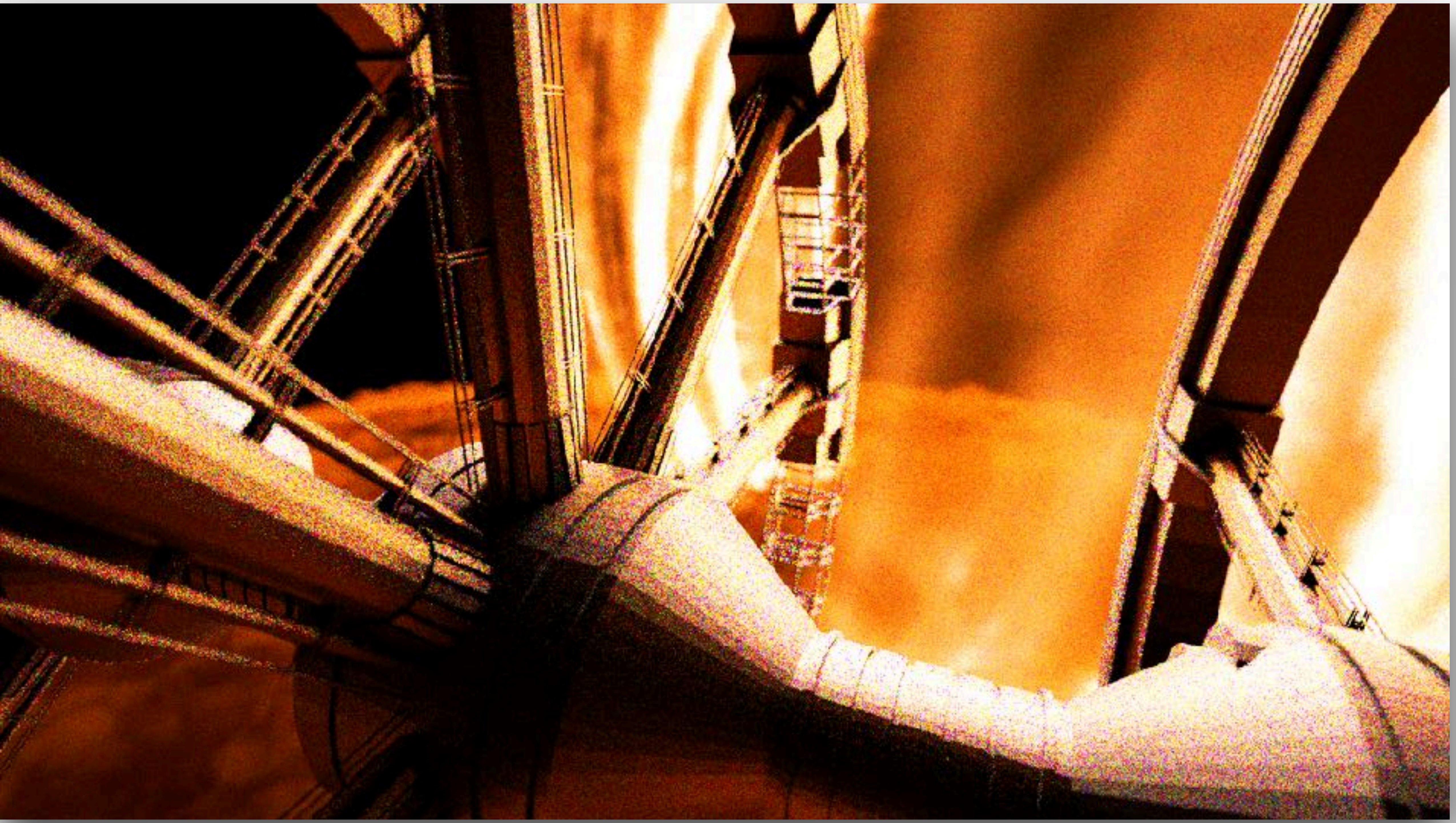
NEE - RMSE 0.892 - 73spp

Results

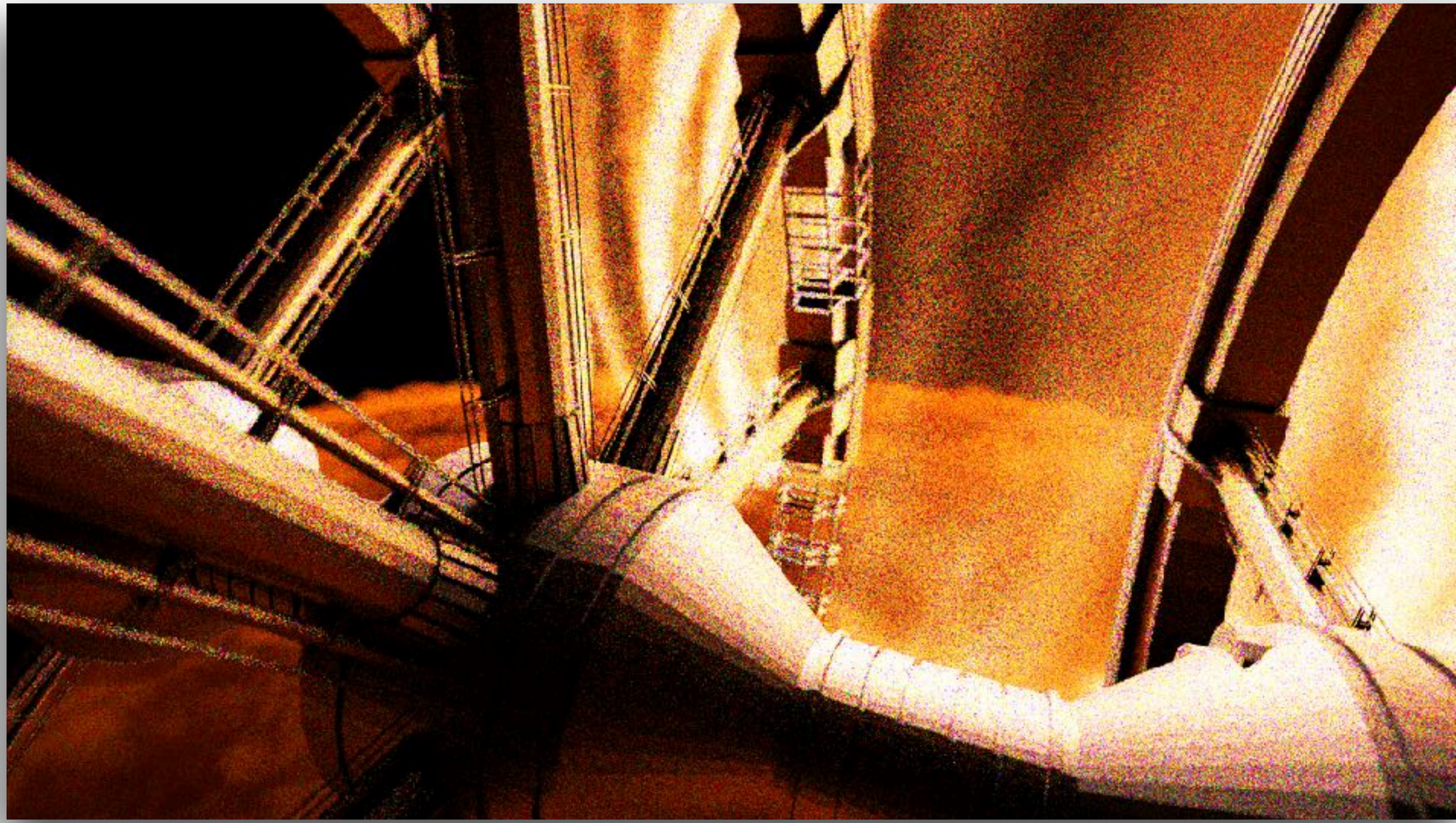


Overview

- Solar flare (30GB) - equal sample - 128spp



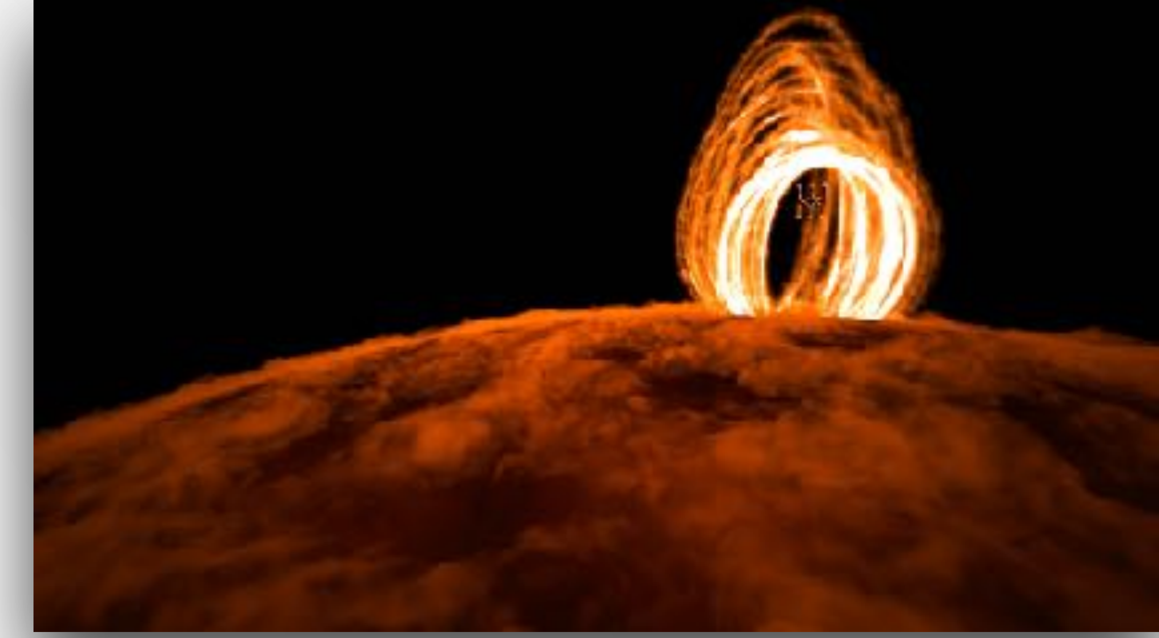
FNEE - RMSE 36.7 - 11.2 core hours



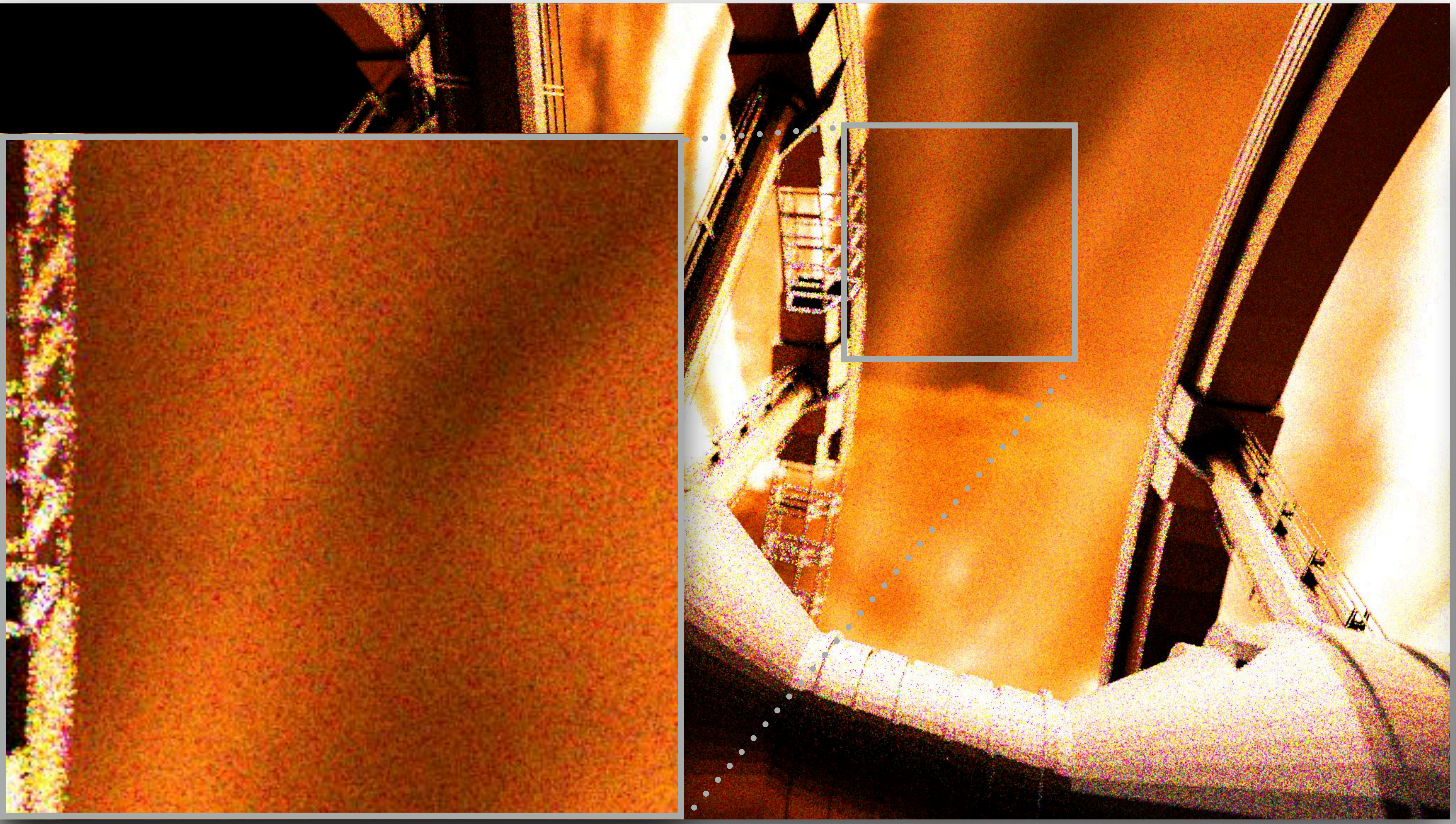
NEE - RMSE 52.6 - 7.5 core hours

Results

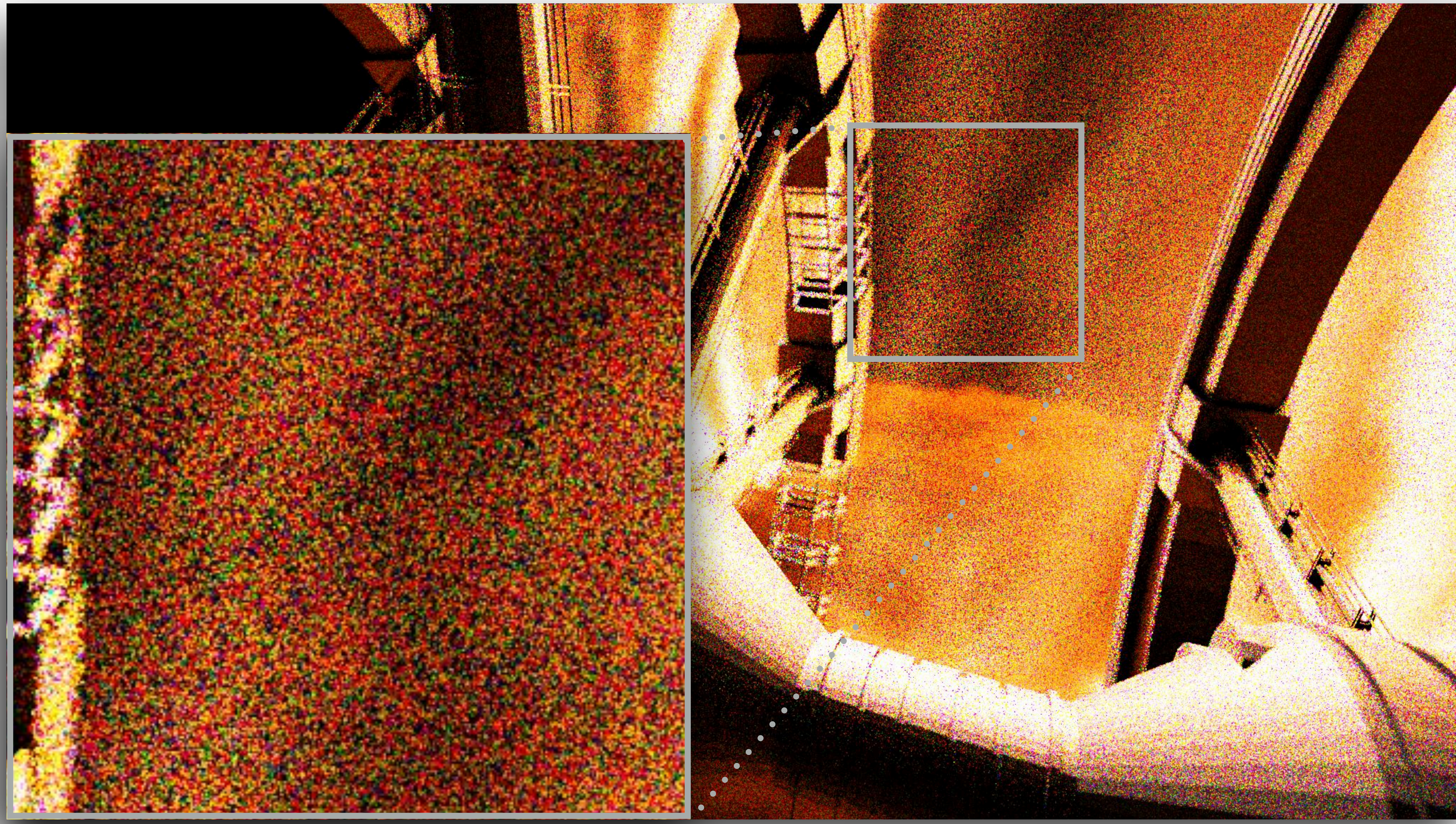
- Solar flare (30GB) - equal sample - 128spp



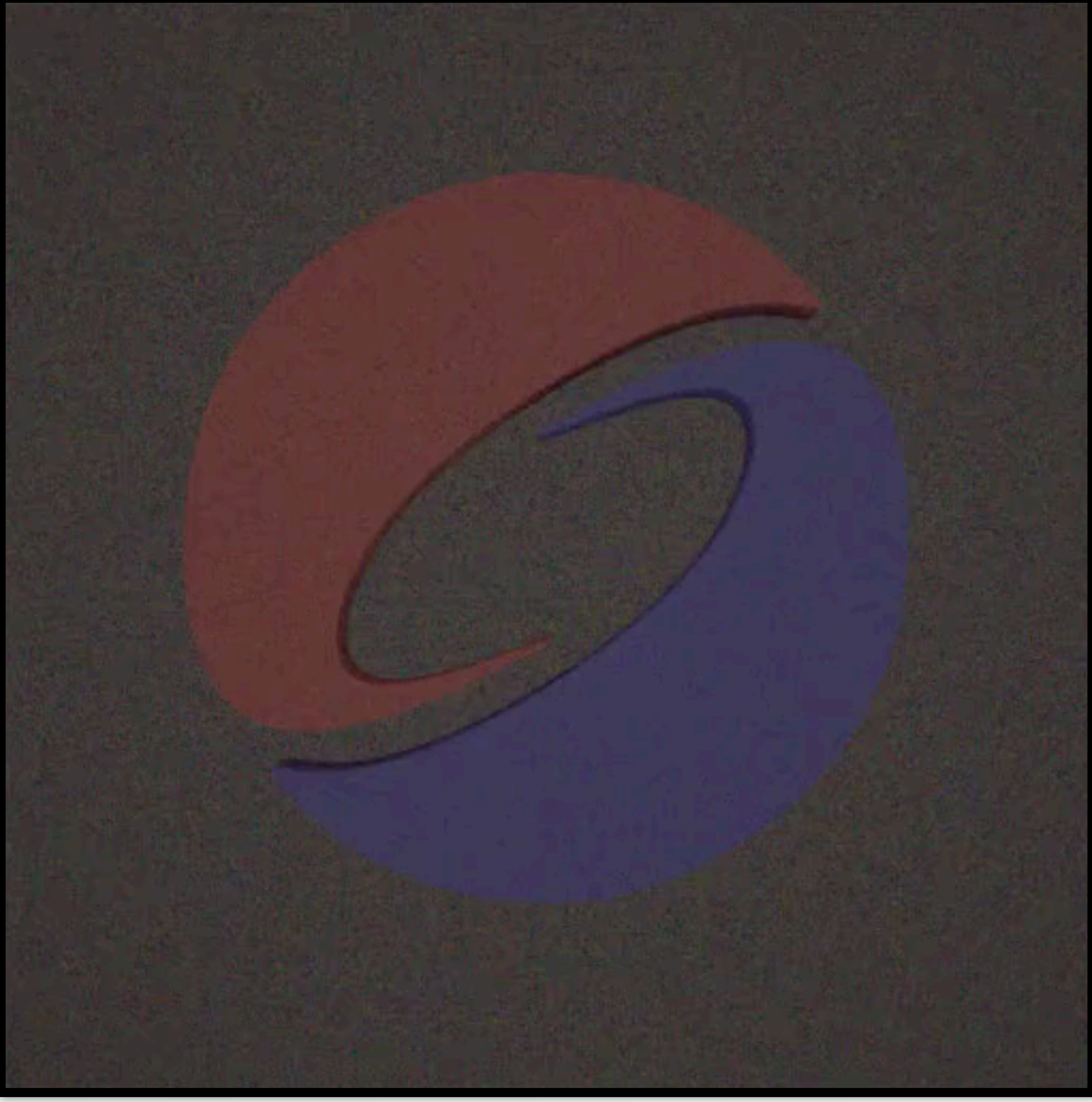
Overview



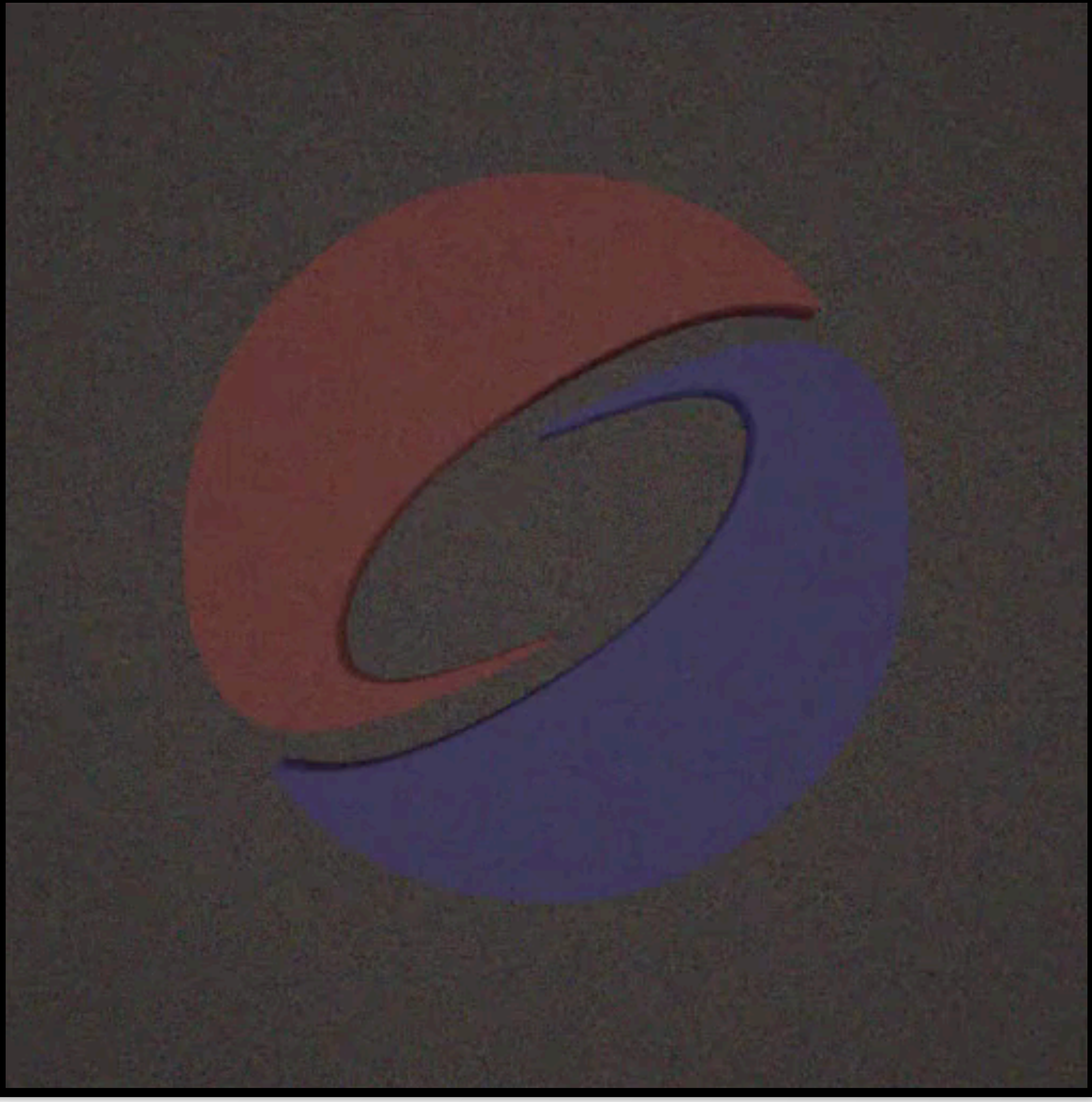
FNEE - RMSE 36.7 - 11.2 core hours



NEE - RMSE 52.6 - 7.5 core hours
RMSE 36.7 ~ 15 core hours

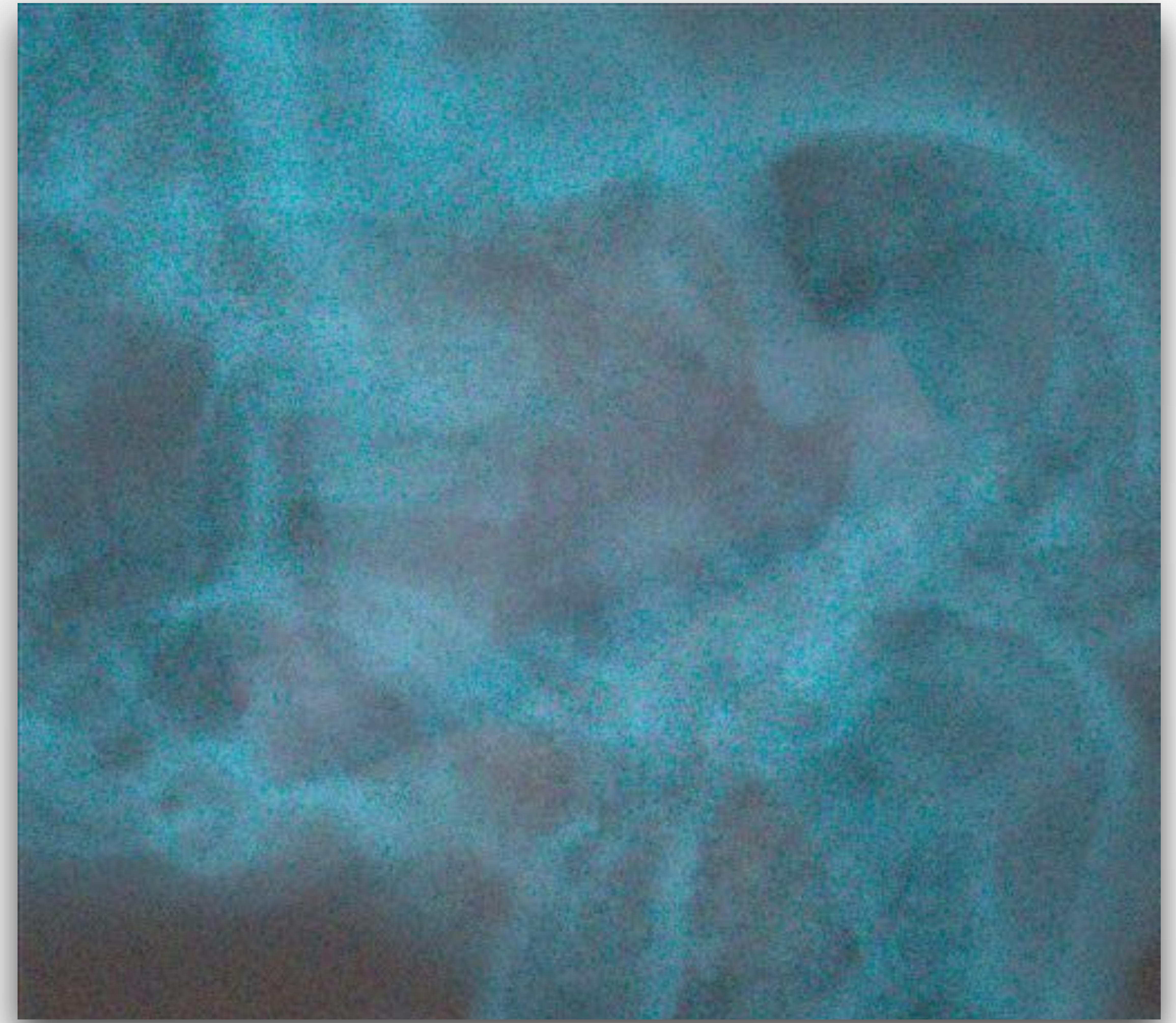


FNEE

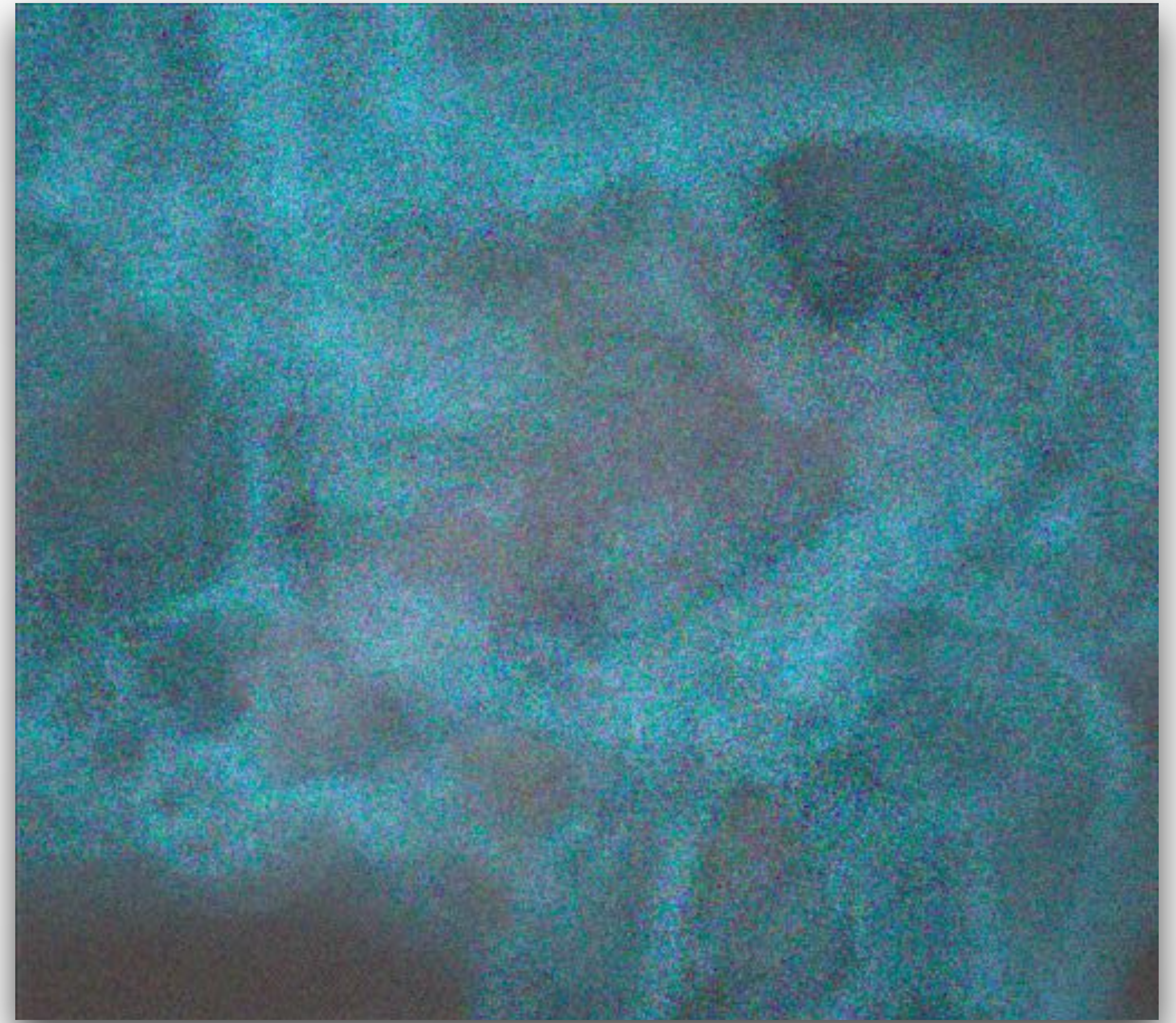


NEE

Results - Equal Time 10min



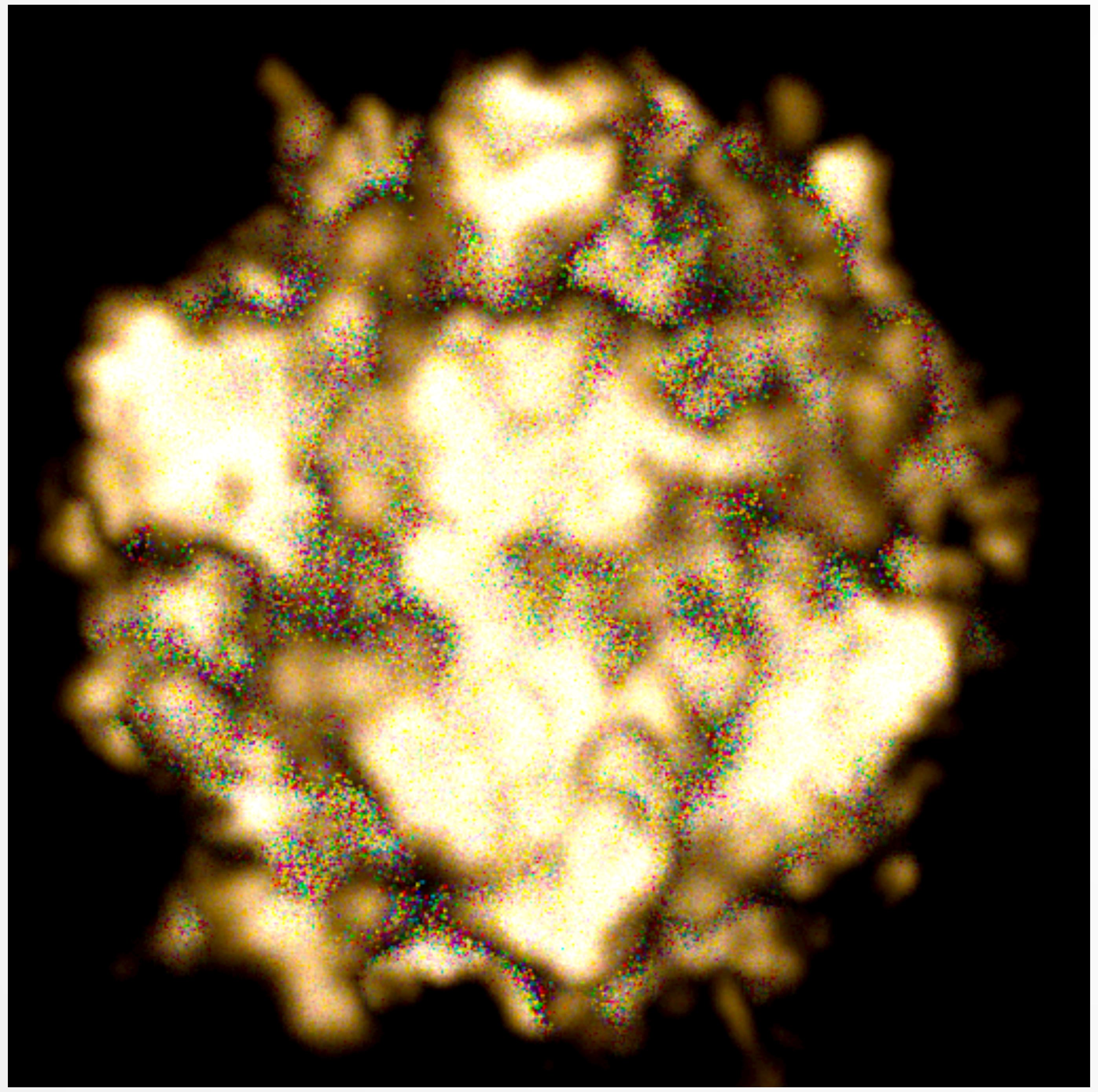
FNEE - RMSE 0.05 - 134spp



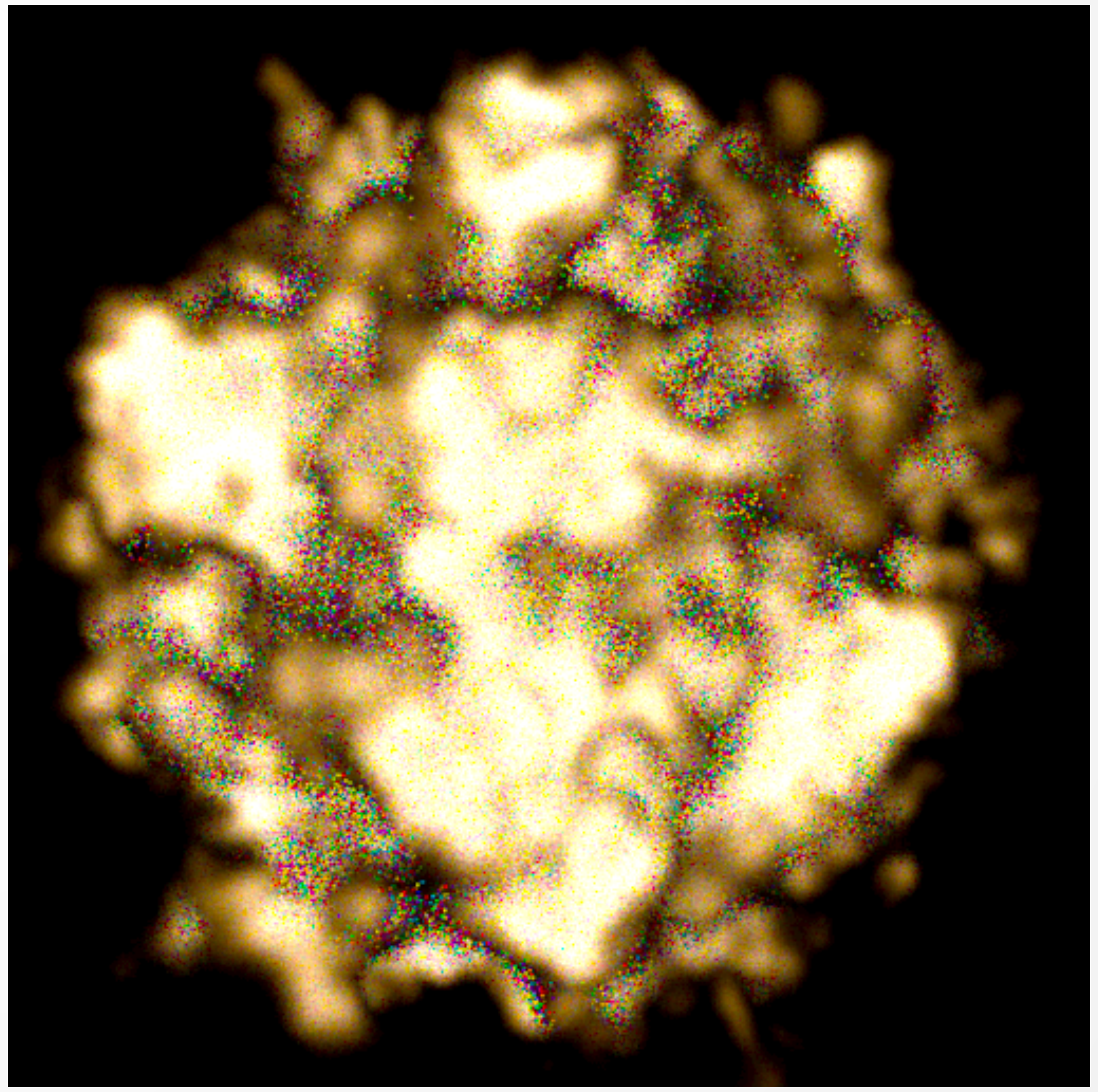
NEE - RMSE 0.11 - 174spp

Limitations and Future Work

- Line integration does not improve forward sampling for dense volumes



line integration



point integration

Limitations and Future Work

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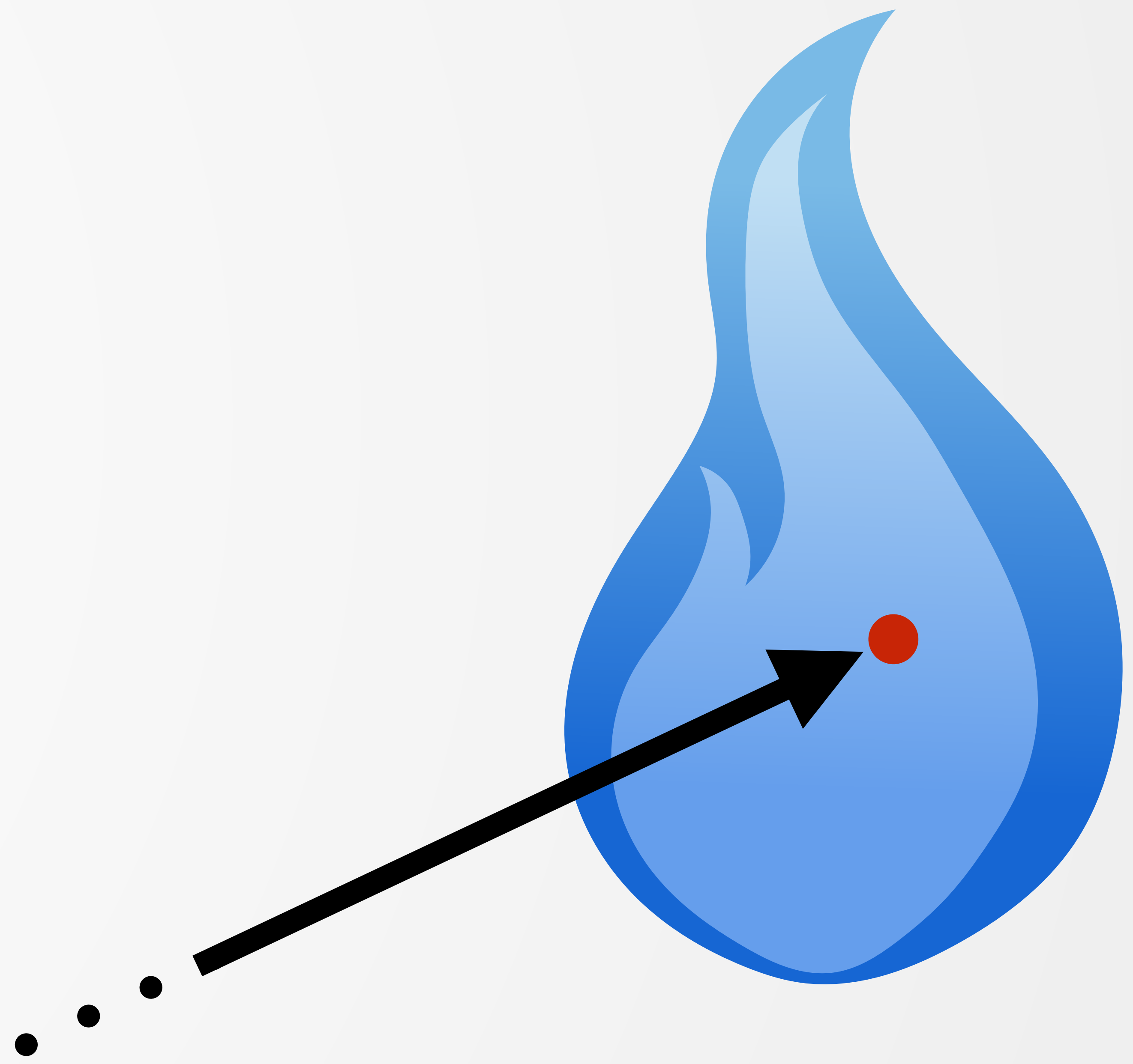
- Line integration does not improve forward sampling for dense volumes
- Extension to more rendering algorithms
- Combination with delta/residual tracking

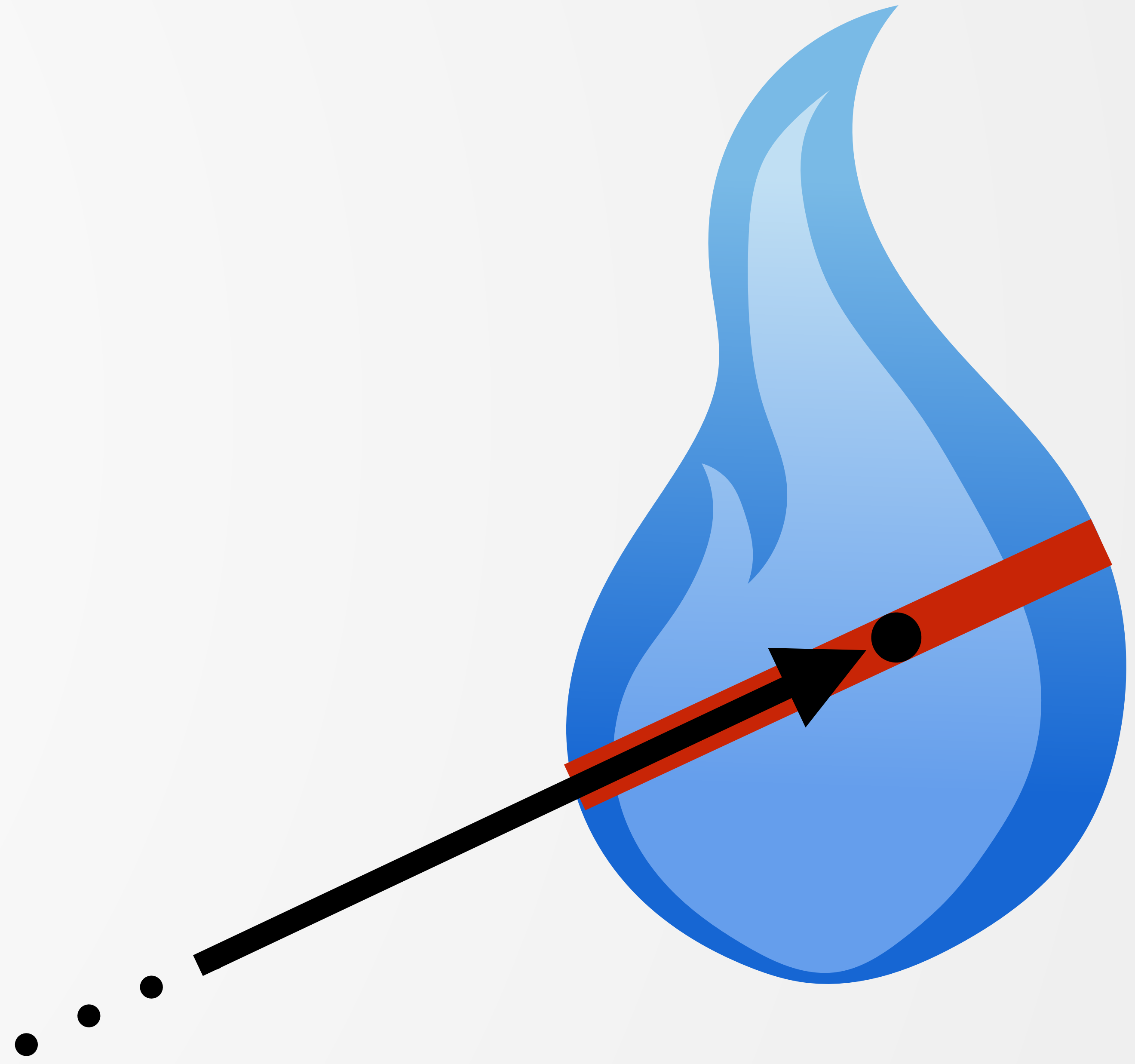
Conclusion

	dense	thin	MIS of forward & NEE
point integration	✓	✗	
deterministic			
line integration + NEE			
line integration + FNEE			



Conclusion

	dense	thin	MIS of forward & NEE
point integration	✓	✗	
deterministic	✗	✓	
line integration + NEE			
line integration + FNEE			



Conclusion

	dense	thin	MIS of forward & NEE
point integration	✓	✗	
deterministic	✗	✓	
line integration + NEE	✓	✓	
line integration + FNEE			

Conclusion

	dense	thin	MIS of forward & NEE
point integration	✓	✗	✓
deterministic	✗	✓	✗
line integration + NEE	✓	✓	✗
line integration + FNEE			

Conclusion

	dense	thin	MIS of forward & NEE
point integration	✓	✗	✓
deterministic	✗	✓	✗
line integration + NEE	✓	✓	✗
line integration + FNEE	✓	✓	✓

Acknowledgements

- Many thanks to Luca Fascione, Tomas Davidovic and Marc Droske

Thank You for your Attention!

Backup / Trash

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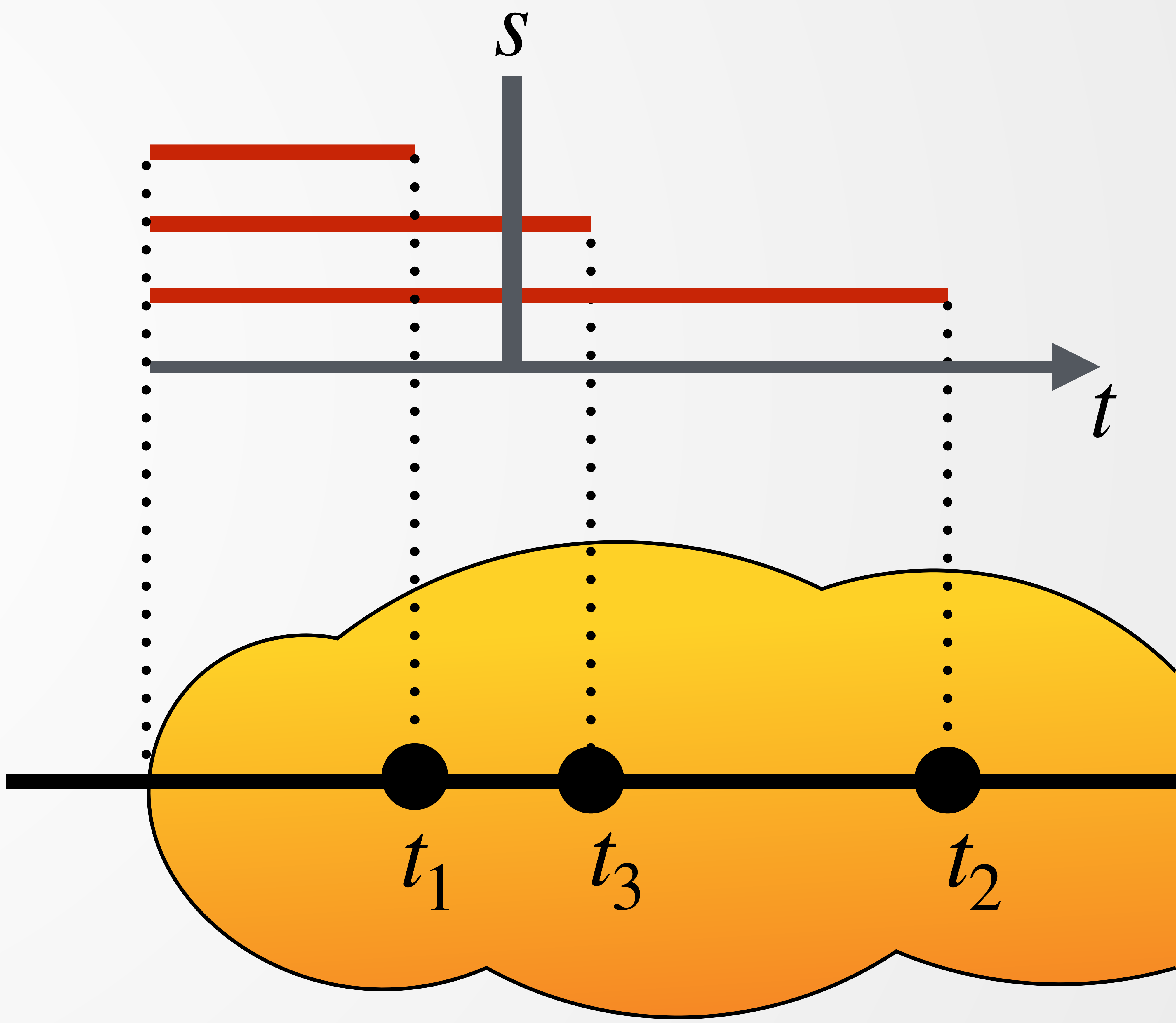
Weight Function

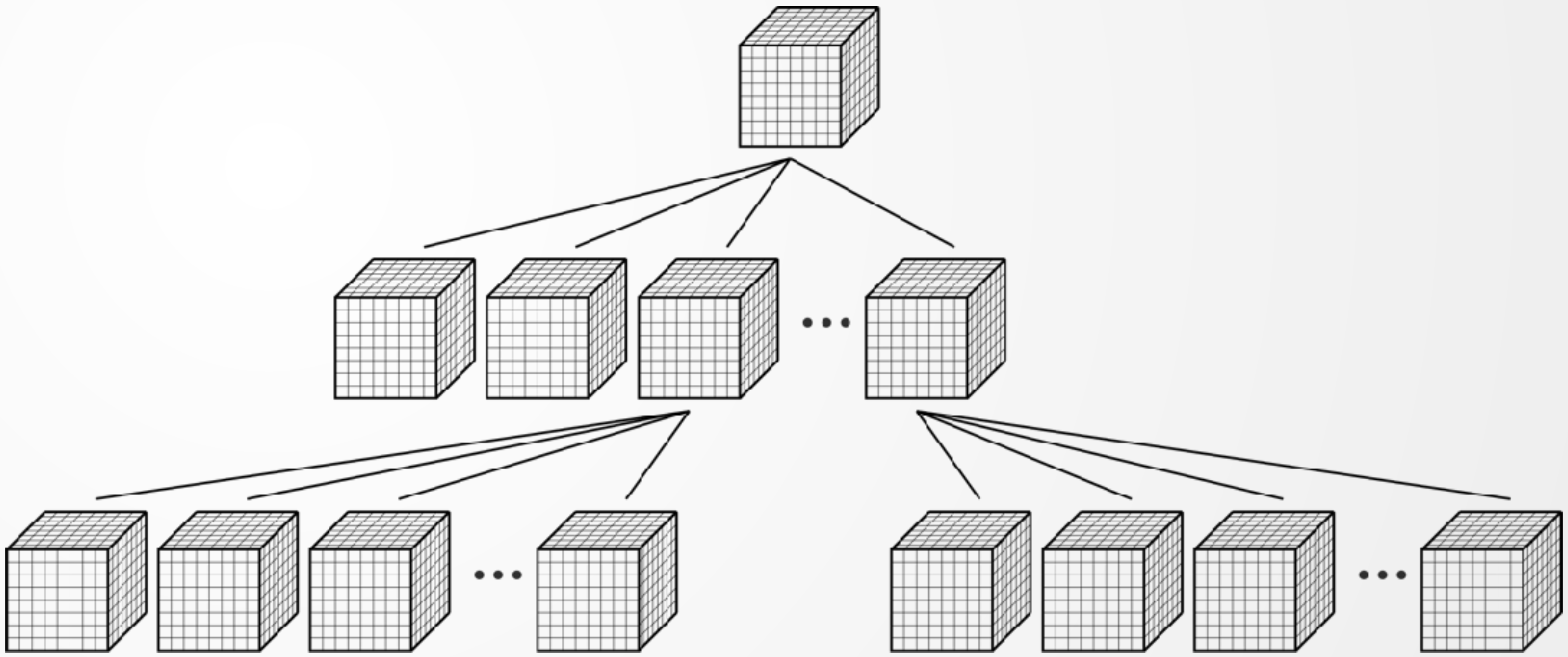
- If we use transmittance sampling

$$\int_0^\infty \tau(t)\, L_e(t)\, dt \approx \frac{1}{N} \sum_{i=1}^{N} \int_0^{t_i} L_e(s)\, ds$$



Volume Representation

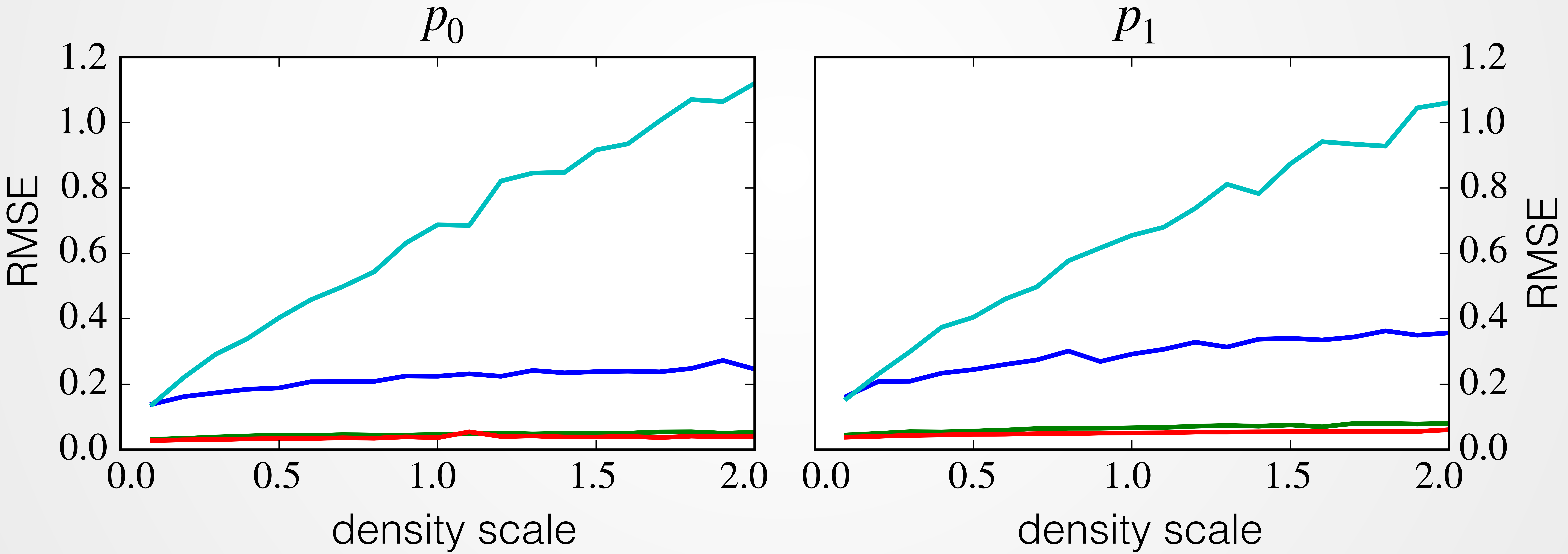
- Multiresolution Grid
- Density and temperature per voxel
- FNEE always at 64^3



FNEE Test

- NEE
- **FNEE** 4096^3
- **FNEE** 512^3
- **FNEE** 64^3

- Equal-time RMSE different densities



Results - Equal Time 15min

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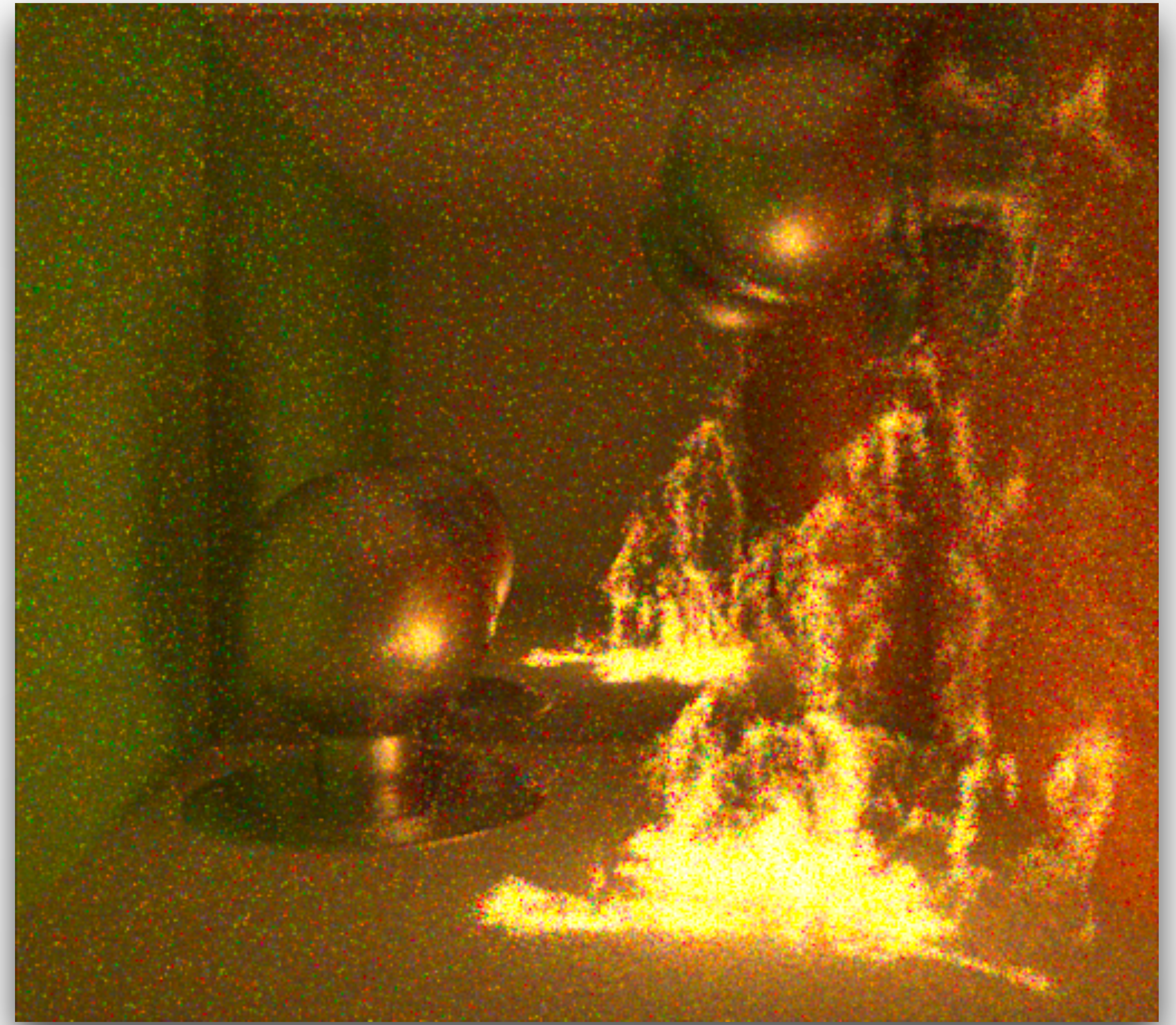
FNEE - RMSE 0.13 - 47spp



NEE - RMSE 0.21 - 70spp

Conclusion

- Line Integration robustly improves efficiency for thin emissive media
- FNEE allows MIS and samples transmittance which is beneficial for dense emissive media
- Together Line Integration and FNEE can efficiently render a very wide range of emissive heterogeneous media