L1c: Basic Processing

2018 IEEE SPS Summer School on Light Field Data Representation, Interpretation, and Compression

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Outline

Lecture 1a: Introduction to Light Fields

Lecture 1b: Cameras, Sampling, & Calibration

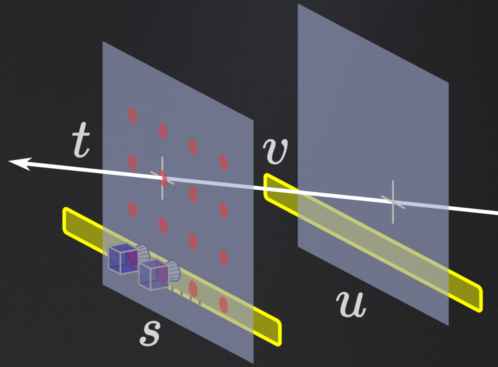
Lecture 1c: Basic Processing

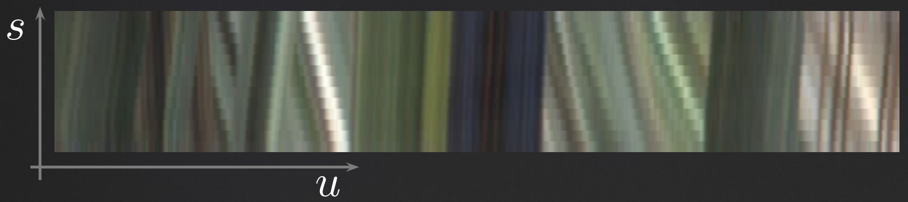
- EPI image analysis in the spatial domain
- Frequency-domain analysis

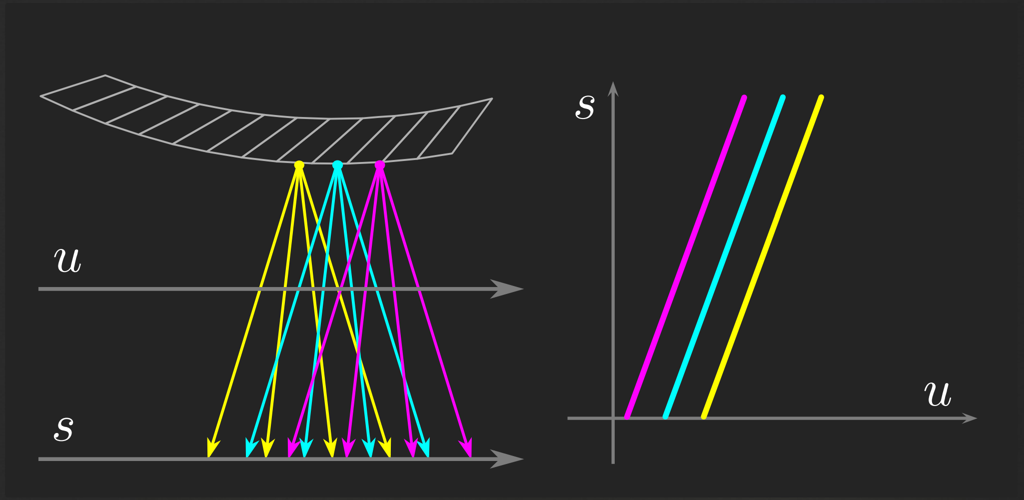
Hands-on: Writing a renderer, handling light fields in matlab

Epipolar Plane Images (EPIs)

EPIs



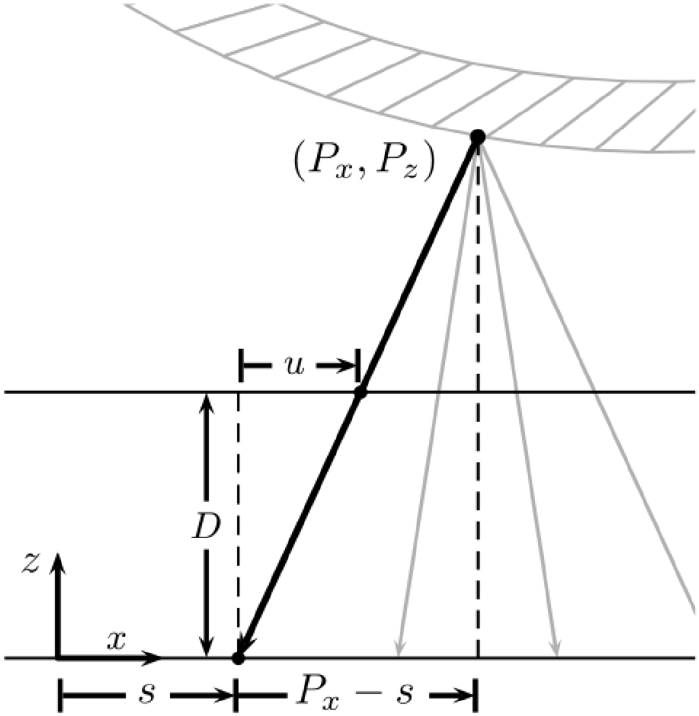




Animation: panning left/right

$$\mathcal{L}(s, t, u, v) = \mathcal{L}(s + \Delta s, t + \Delta t, u - m\Delta s, v - m\Delta t)$$

The Point/Plane Correspondence



Point-plane correspondence *(no occlusion)*:

Relative:

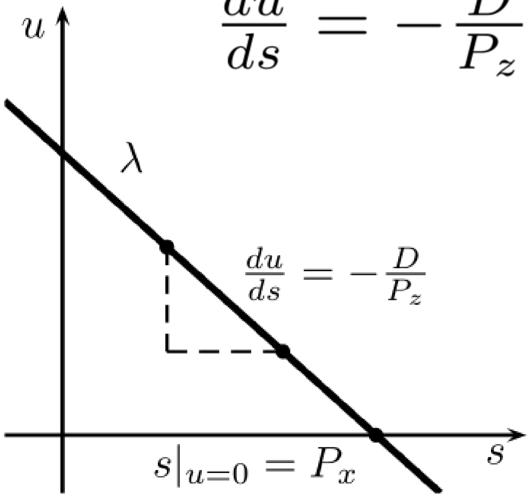
$$\begin{bmatrix} u \\ v \end{bmatrix} = \left(\frac{D}{P_z}\right) \begin{bmatrix} P_x - s \\ P_y - t \end{bmatrix}$$

$$\frac{du}{ds} = -\frac{D}{P_z}$$

Absolute:

$$\begin{bmatrix} U \\ V \end{bmatrix} = \begin{bmatrix} u \\ v \end{bmatrix} + \begin{bmatrix} s \\ t \end{bmatrix}$$

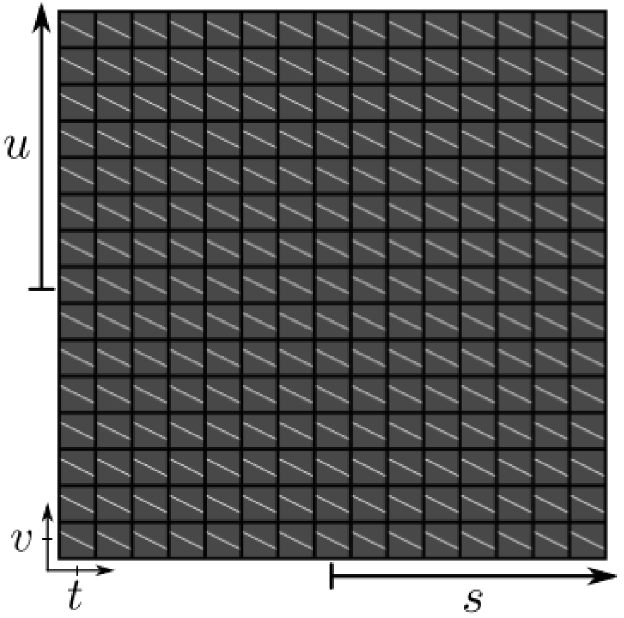
$$\frac{dU}{ds} = 1 - \frac{D}{P_z}$$



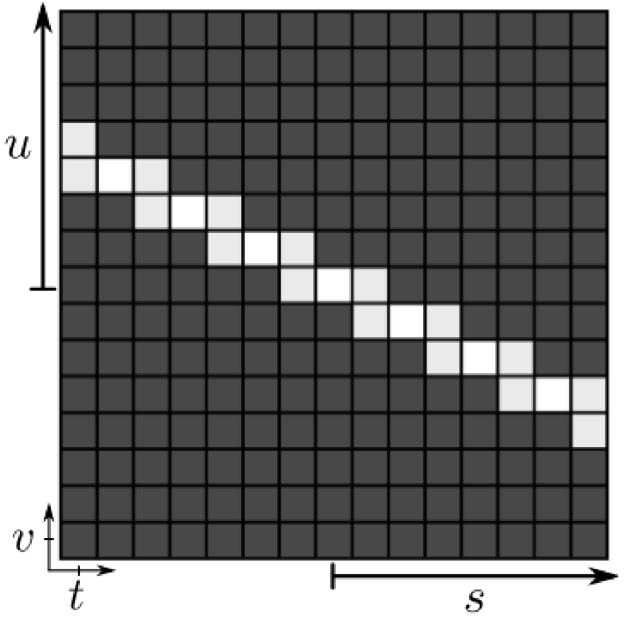
Naming Linear Subspaces in 2-, 3-, and 4-D

Domain:	1D	2D	3D	4D
# Linear Equations: 1	Point	Line	Plane	Hyperplane
2		Point	Line	Plane
3			Point	Line
4				Point

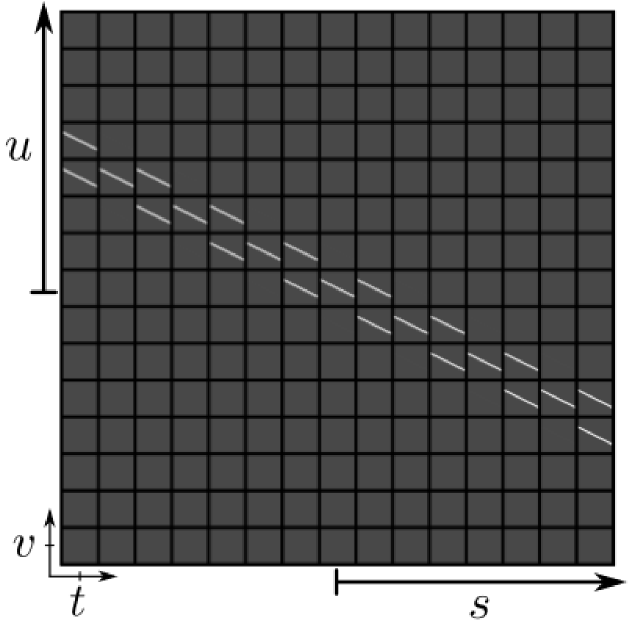
Visualizing LF Hyperplane Intersection



(a)



(b)



Hyperplane

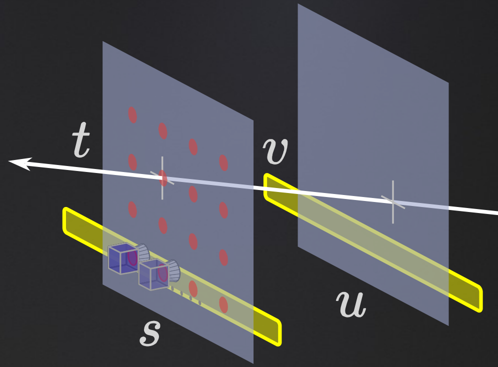
$t = m\,v + t_0$

Hyperplane

$s = m\,u + s_0$

Plane in 4D

Depth from Slope



$\mathcal{L}_s = \mathcal{L}(\, s+\delta, t, u, v\,) - \mathcal{L}(\, s, t, u, v\,)$

$\mathcal{L}_u = \mathcal{L}(\, s, t, u+\delta, v\,) - \mathcal{L}(\, s, t, u, v\,)$

$P_z = D \,/\, (1 - \mathcal{L}_s \,/\, \mathcal{L}_u)$

$$\begin{bmatrix} s \\ t \\ U \\ V \\ 1 \end{bmatrix} = \begin{bmatrix} h_{1,1} & 0 & h_{1,3} & 0 & h_{1,5} \\ 0 & h_{2,2} & 0 & h_{2,4} & h_{2,5} \\ h_{3,1} & 0 & h_{3,3} & 0 & h_{3,5} \\ 0 & h_{4,2} & 0 & h_{4,4} & h_{4,5} \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i \\ j \\ k \\ l \\ 1 \end{bmatrix}$$

… But we have a sampled light field in *i,j,k,l*

Use intrinsic matrix to convert

$$\frac{\mathrm{d}u}{\mathrm{d}s} = \frac{H_{3,1} + H_{3,3}\,\mathrm{d}k/\mathrm{d}i}{H_{1,1} + H_{1,3}\,\mathrm{d}k/\mathrm{d}i}$$

Combining Estimates

4D pointwise slope estimates are noisy

Weight by gradient strength and sum in neighbourhoods:

$$h = \frac{\sum_P L_s^2 \frac{L_u}{L_s}}{\sum_P L_s^2} = \frac{\sum_P L_s L_u}{\sum_P L_s^2}$$

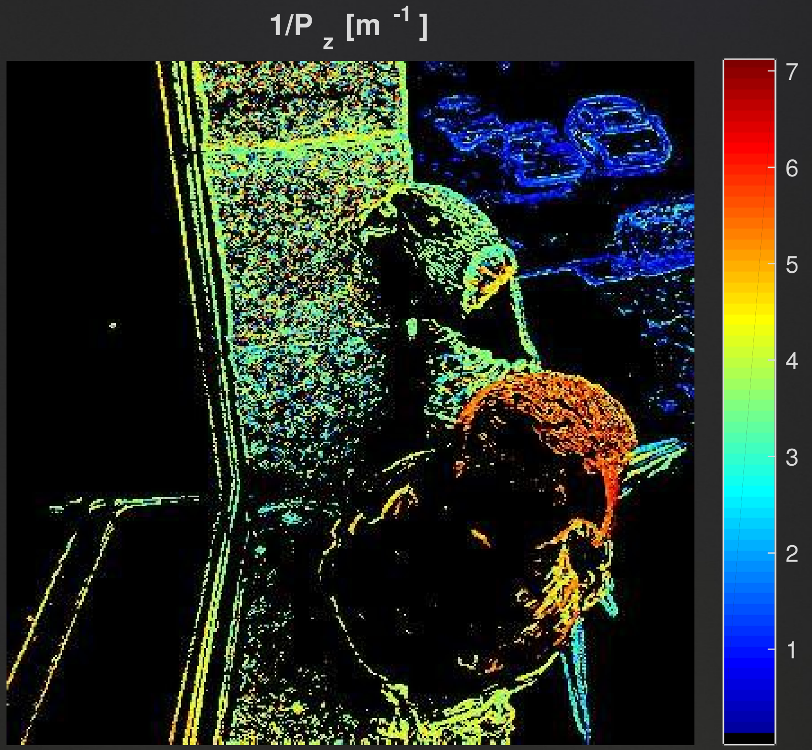
[Adelson and Wang 1992]

Slopes are "view independent" – looks Lambertian, can also filter accordingly

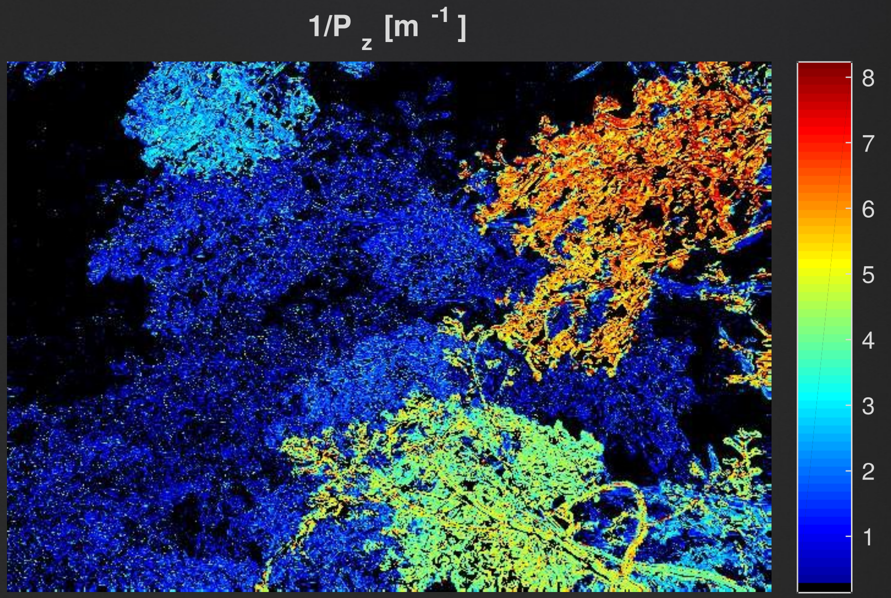
For some applications simply ignore regions of low gradient strength

When required, "fill in the blanks"

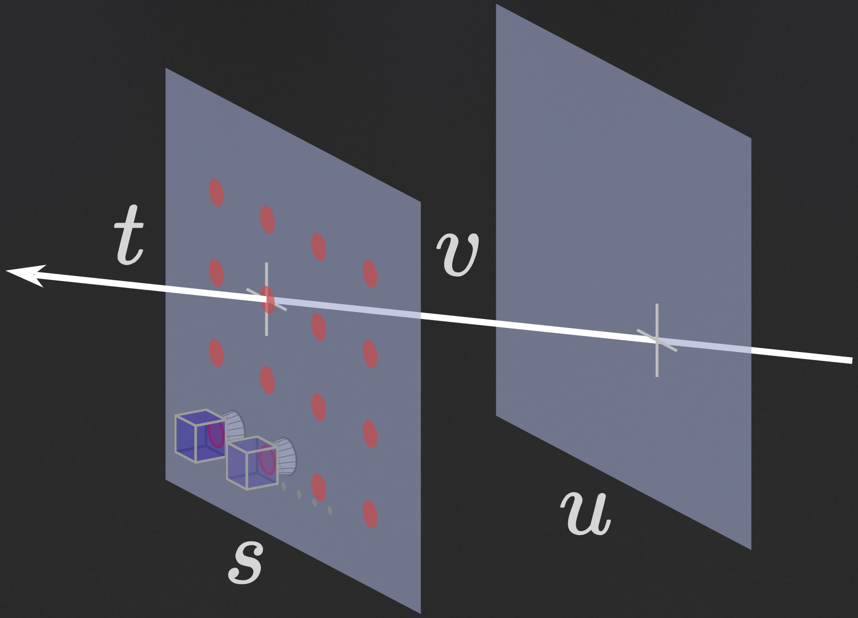
Depth Estimation



Depth Estimation



Focus

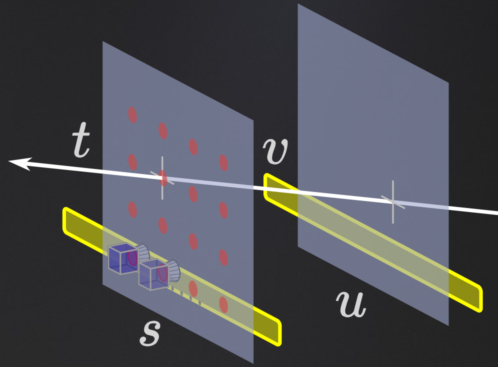


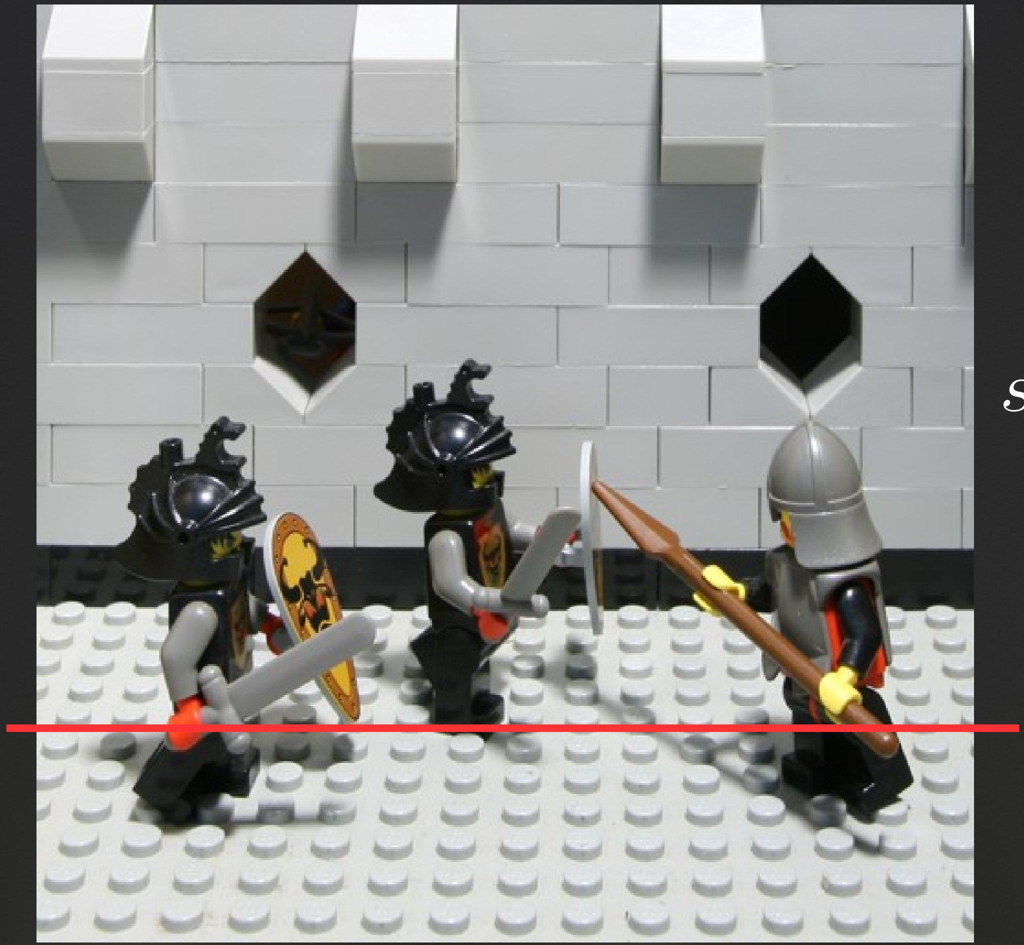
Exercise:

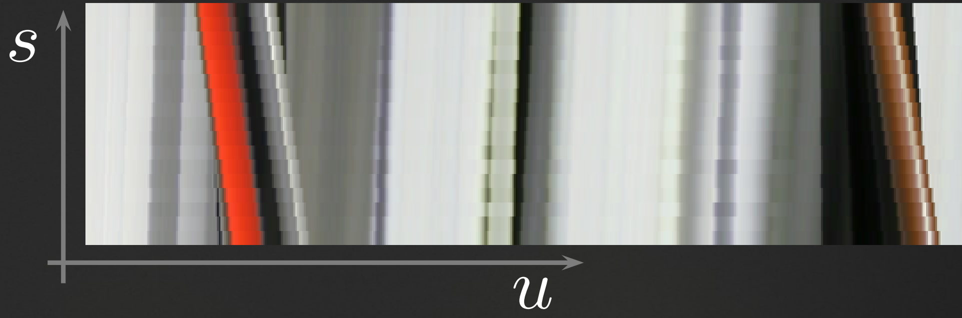
Write out what a single large, square aperture covering s,t sees

(Don't over-think it)

Focus: Shift and Add

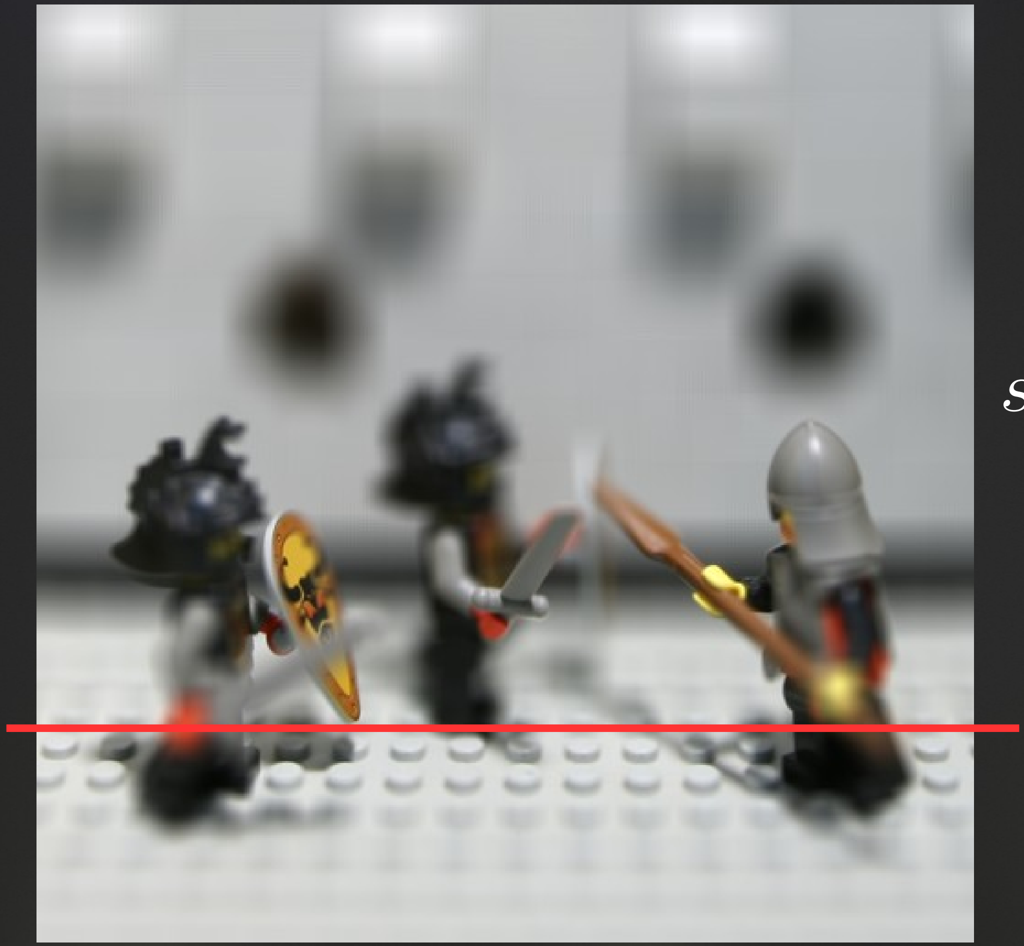


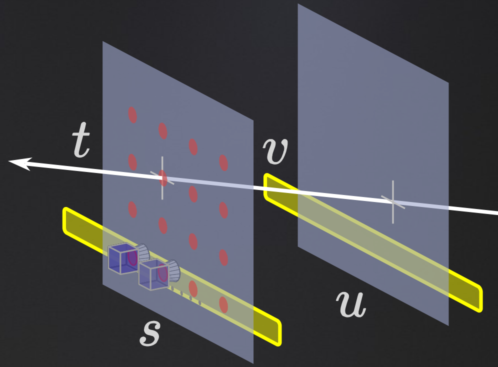


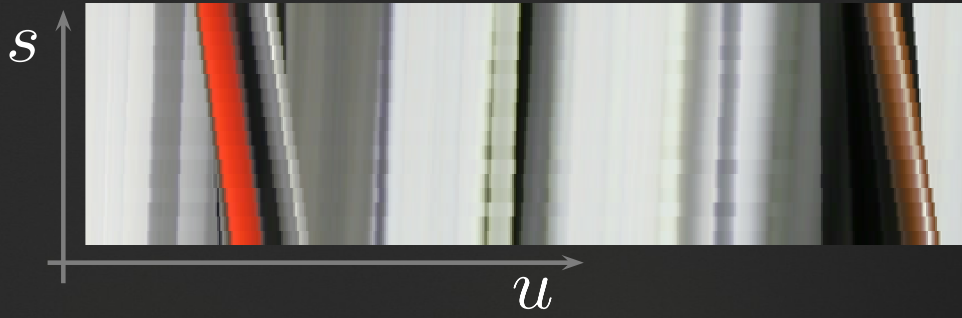


[LF c/o Stanford]

Focus: Shift and Add

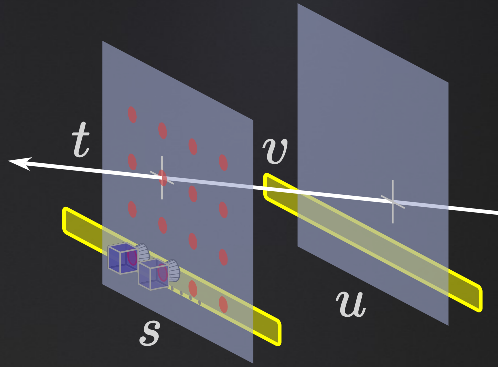


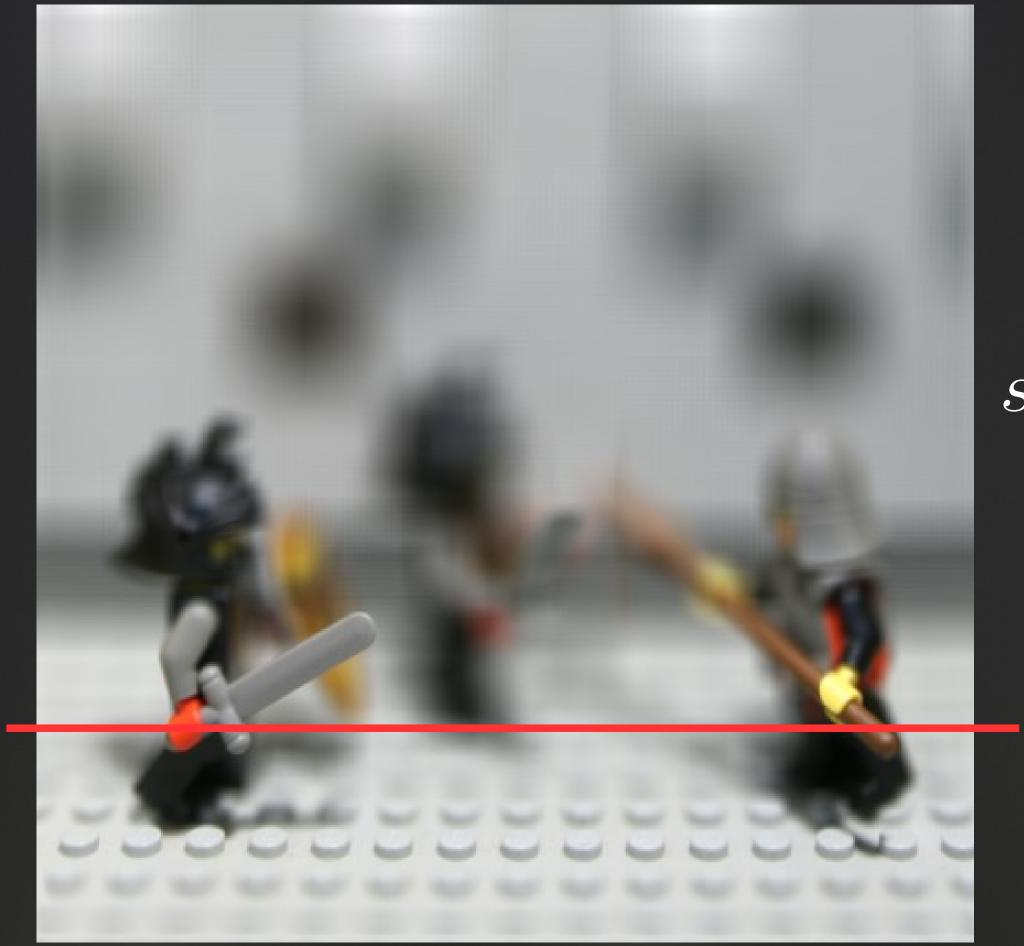




[LF c/o Stanford]

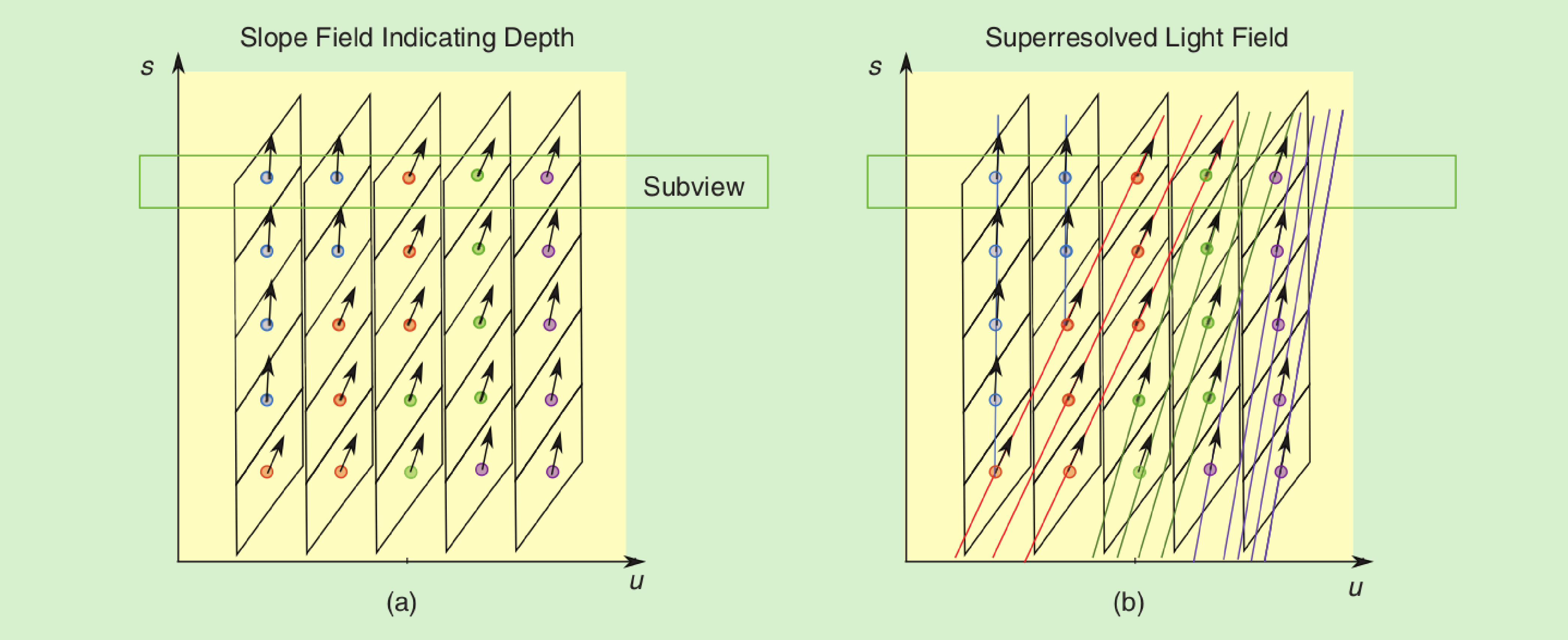
Focus: Shift and Add





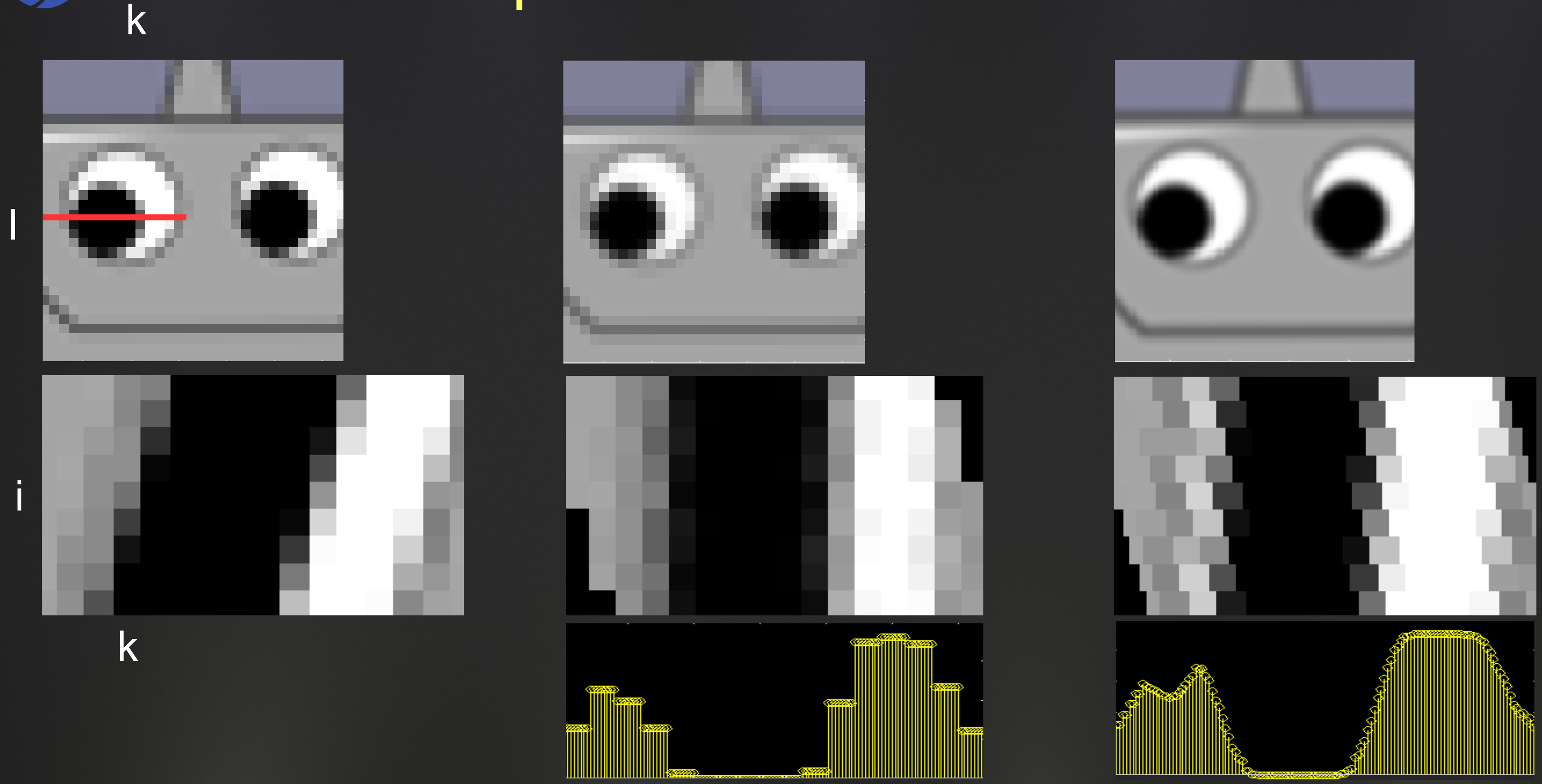
[LF c/o Stanford]

Linear Super-Resolution



[Image c/o Ihrke et al 2016]

Linear Super-Resolution: Shift and Add



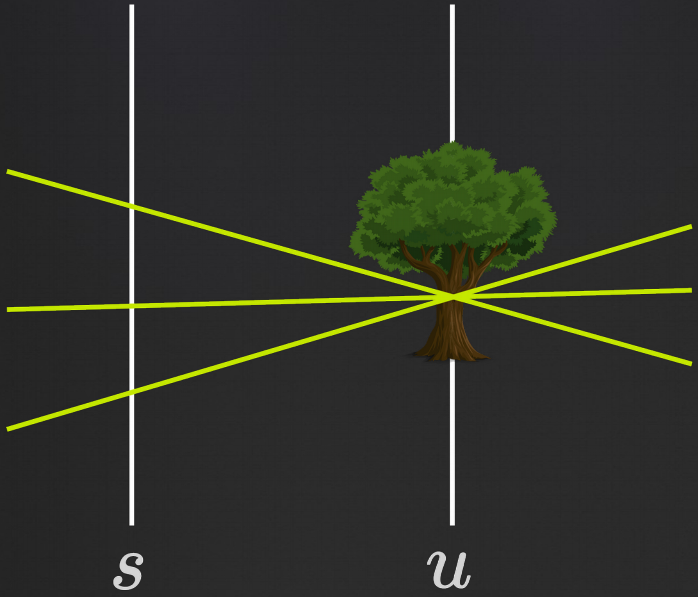
Input in k,l and EPI

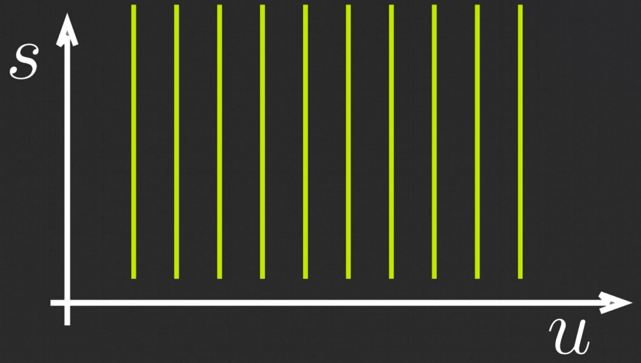
Skewed, summed

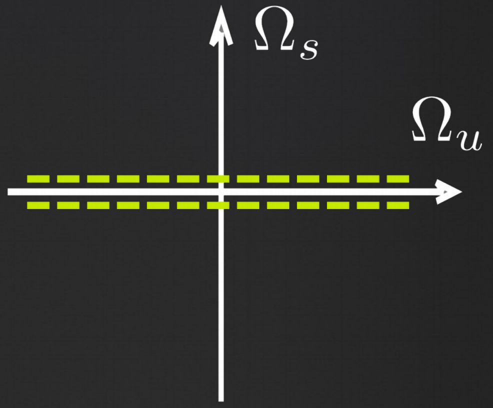
Upsampled, skewed, summed

Frequency-Domain Analysis

Lambertian Scene in Freq Domain



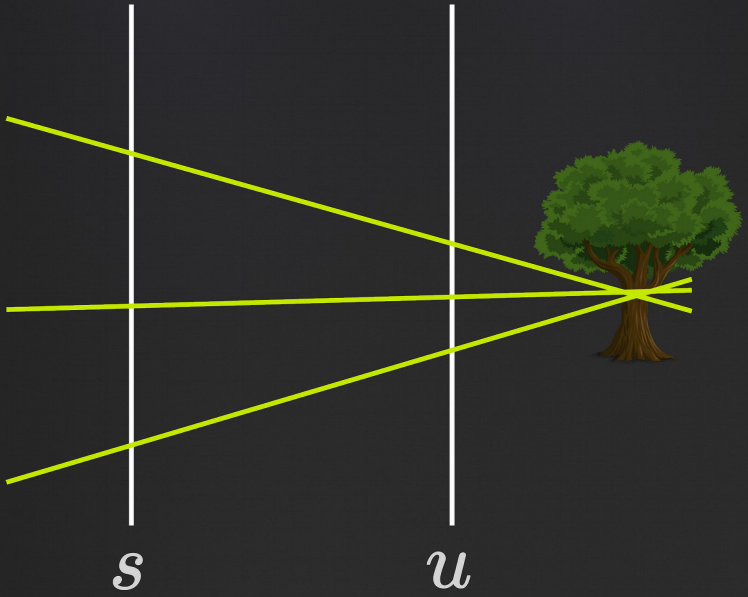


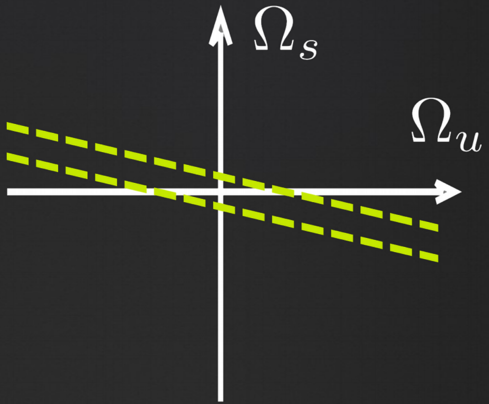


$$L_{freq}(\boldsymbol{\Omega}) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} L_{cont}(s,t,u,v)\,\mathrm{e}^{-j(\Omega_s s+\Omega_t t+\Omega_u u+\Omega_v v)}\,dvdudtds$$

$$= \delta(\Omega_s)\delta(\Omega_t)\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} L(\Omega_s,\Omega_t,u,v)\mathrm{e}^{-j(\Omega_u u+\Omega_v v)}dvdu\,.$$

Lambertian Scene in Freq Domain





$$L'_{cont}(s,t,u,v) = L_{cont}(\boldsymbol{R}[s,t,u,v]^{\mathrm{T}}),$$

$$L'_{freq}(\boldsymbol{\Omega}) = L_{freq}(\boldsymbol{R}\boldsymbol{\Omega}^{T}),$$

Point-plane correspondence *(no occlusion)*:

Relative:

$$\begin{bmatrix} u \\ v \end{bmatrix} = \left(\tfrac{D}{P_z}\right) \begin{bmatrix} P_x - s \\ P_y - t \end{bmatrix}$$

$$\frac{du}{ds} = -\frac{D}{P_z}$$

Absolute:

$$\begin{bmatrix} U \\ V \end{bmatrix} = \begin{bmatrix} u \\ v \end{bmatrix} + \begin{bmatrix} s \\ t \end{bmatrix}$$

$$\frac{dU}{ds} = 1 - \frac{D}{P_z}$$

Frequency-domain ROS *(Lambertian scene)*:

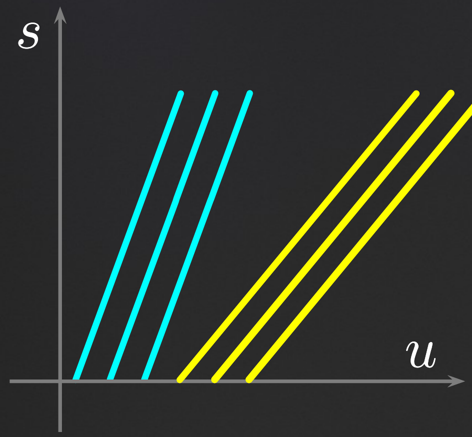
Single depth→Frequency plane

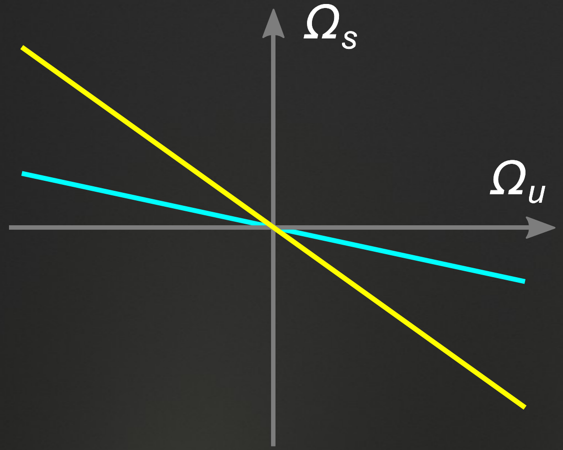
$$\Omega_s / \Omega_u = \Omega_t / \Omega_v =$$

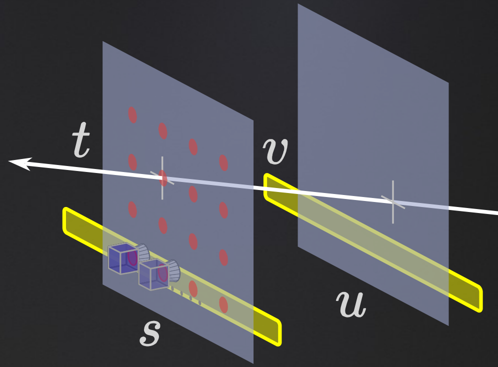
D / P_z

D / P_z -1

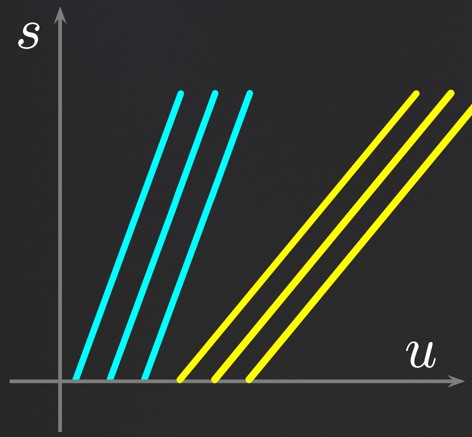
Example: Focus

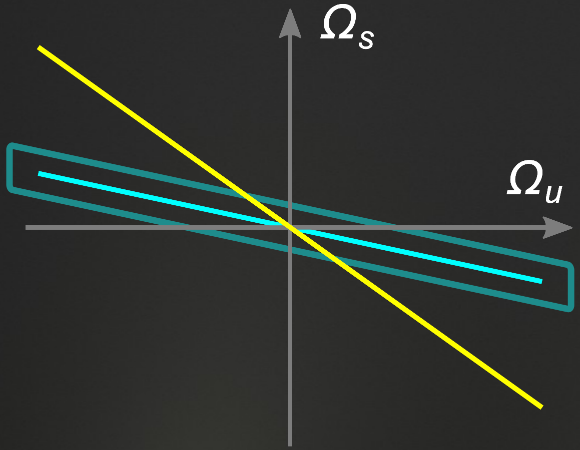


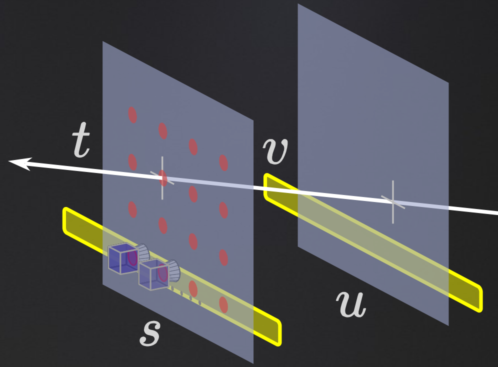




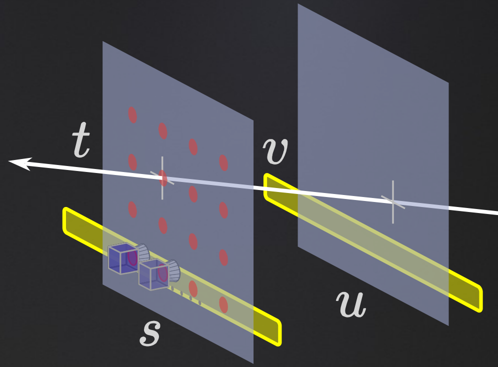
Example: Focus

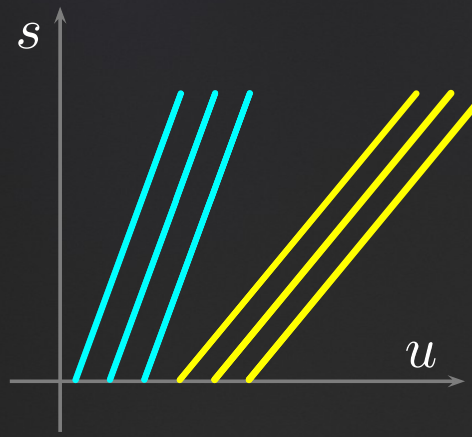


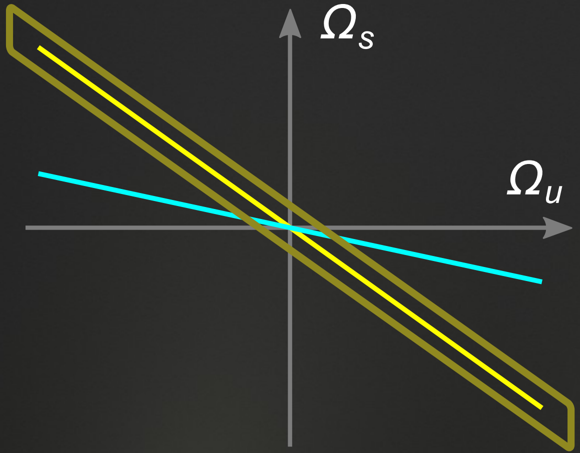




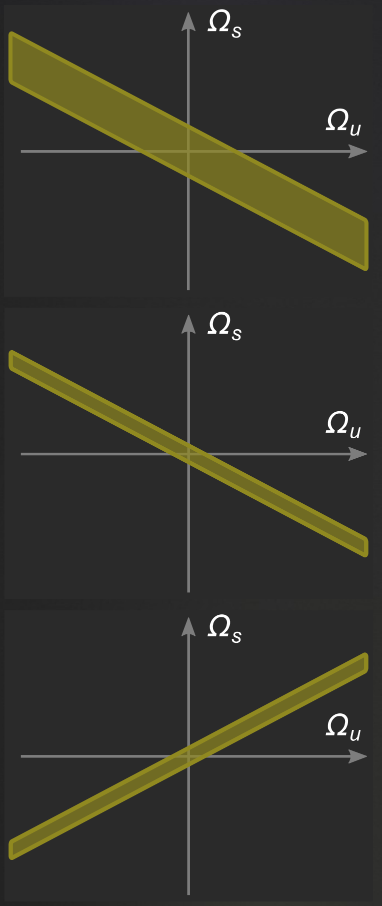
Example: Focus

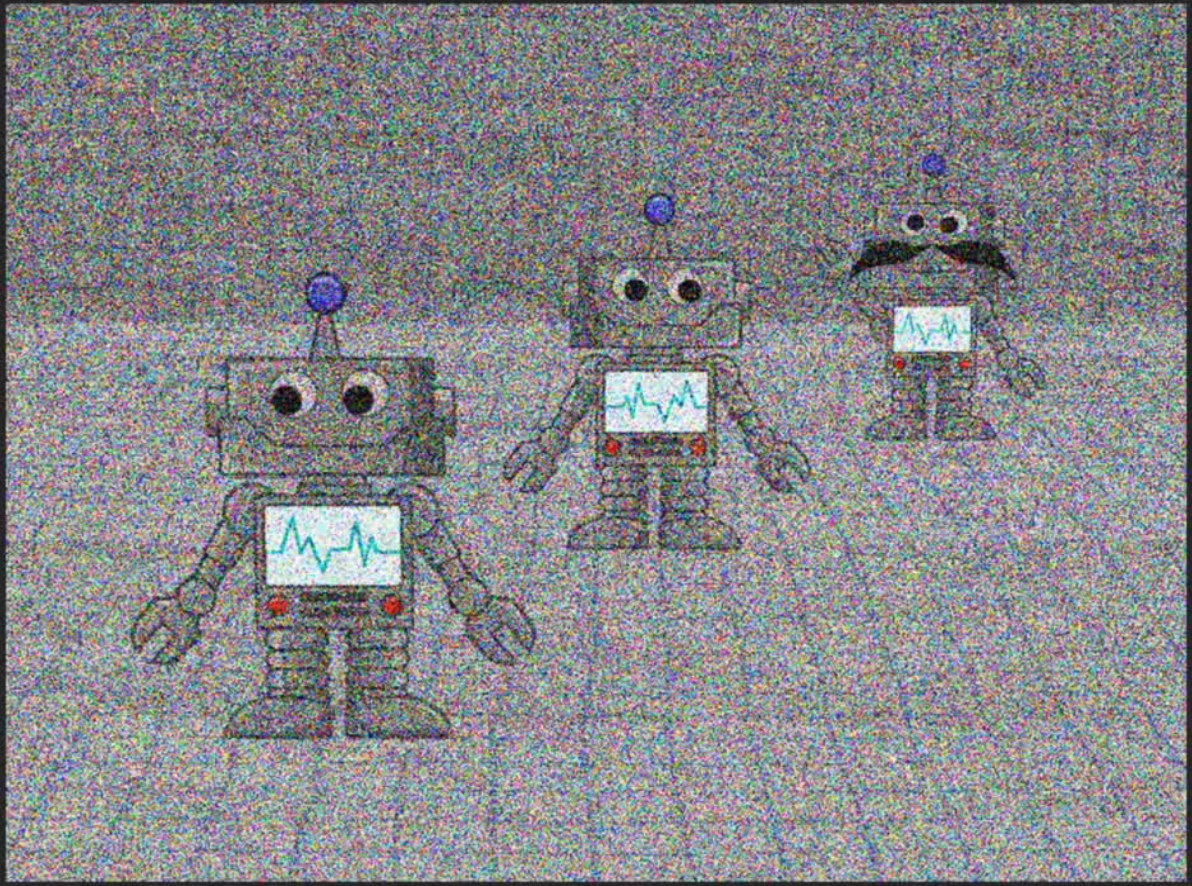


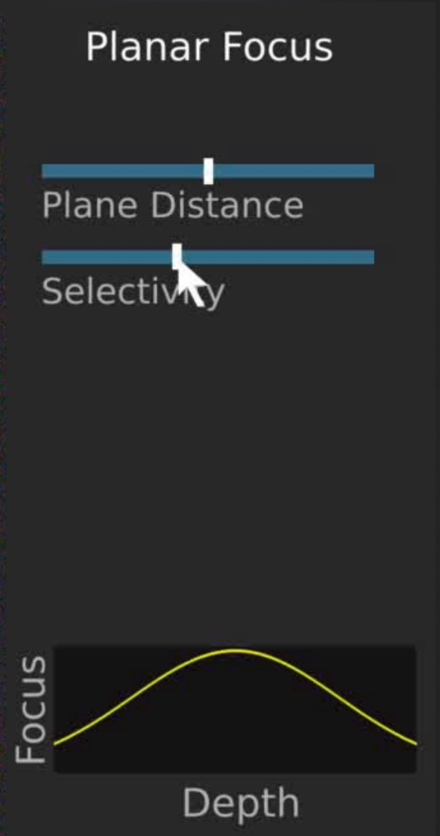




Focus as a Noise Filter







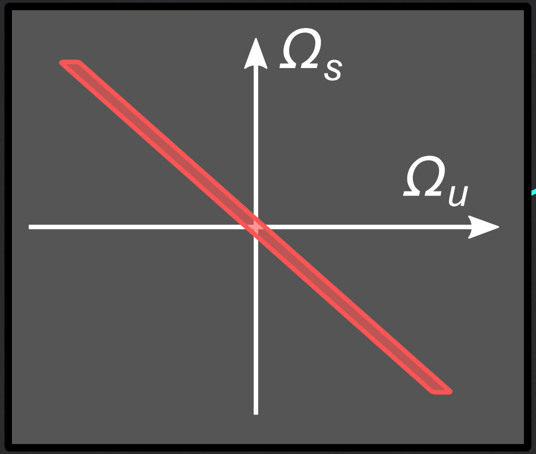
Animation: adjusting slope/bandwidth for filtering noise

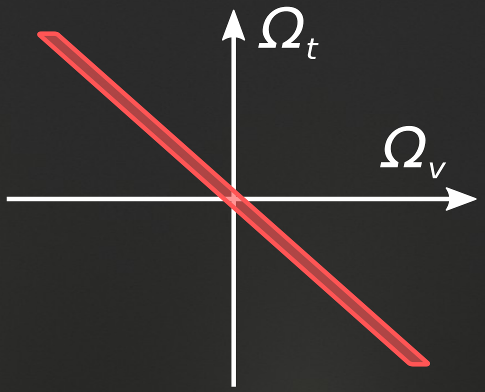
4D Visualization of Freq Domain

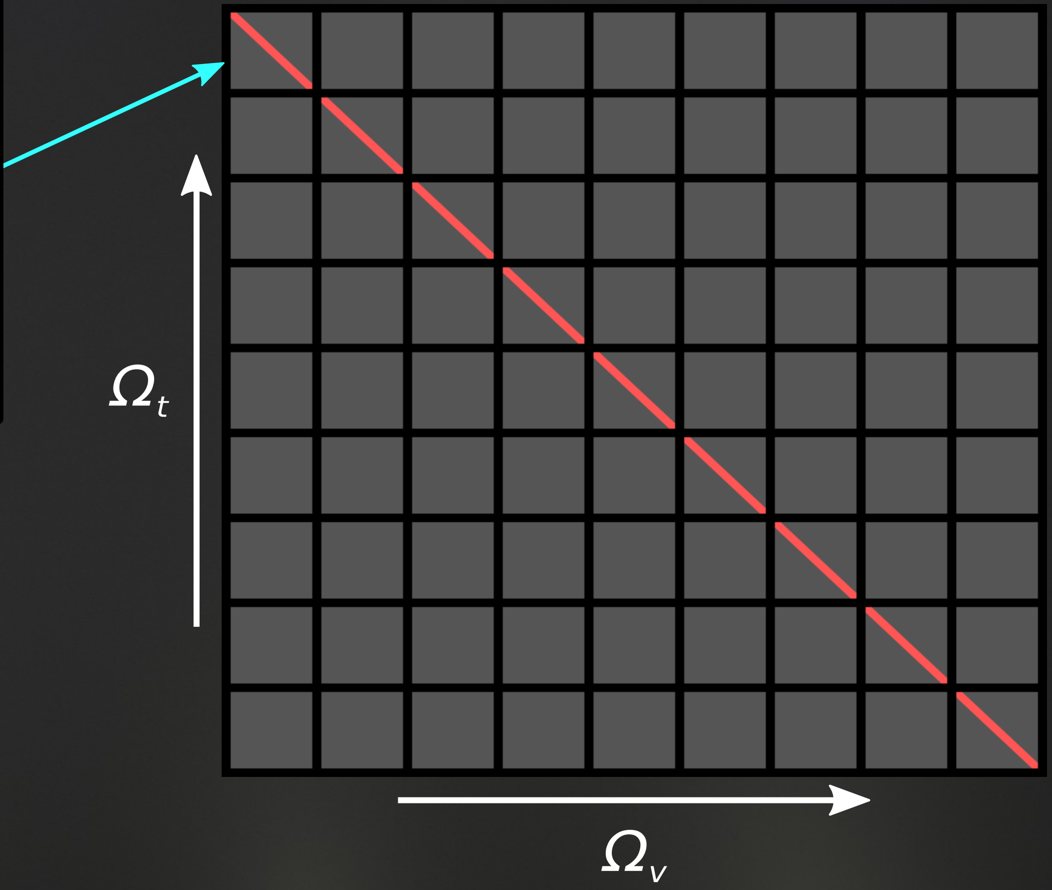
$$\frac{\Omega_s}{\Omega_u} = m$$

$$\frac{\Omega_t}{\Omega_v} = \frac{\Omega_s}{\Omega_u}$$

$$\frac{\Omega_t}{\Omega_v} = m$$





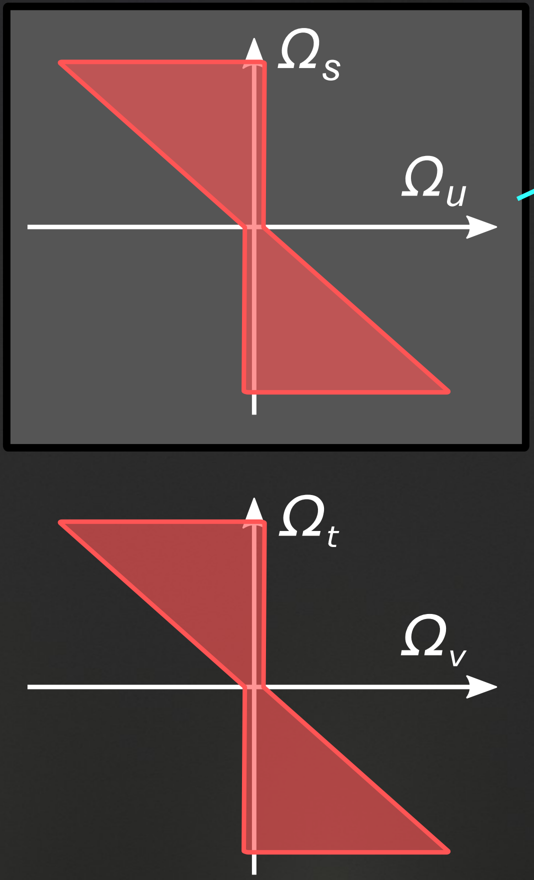


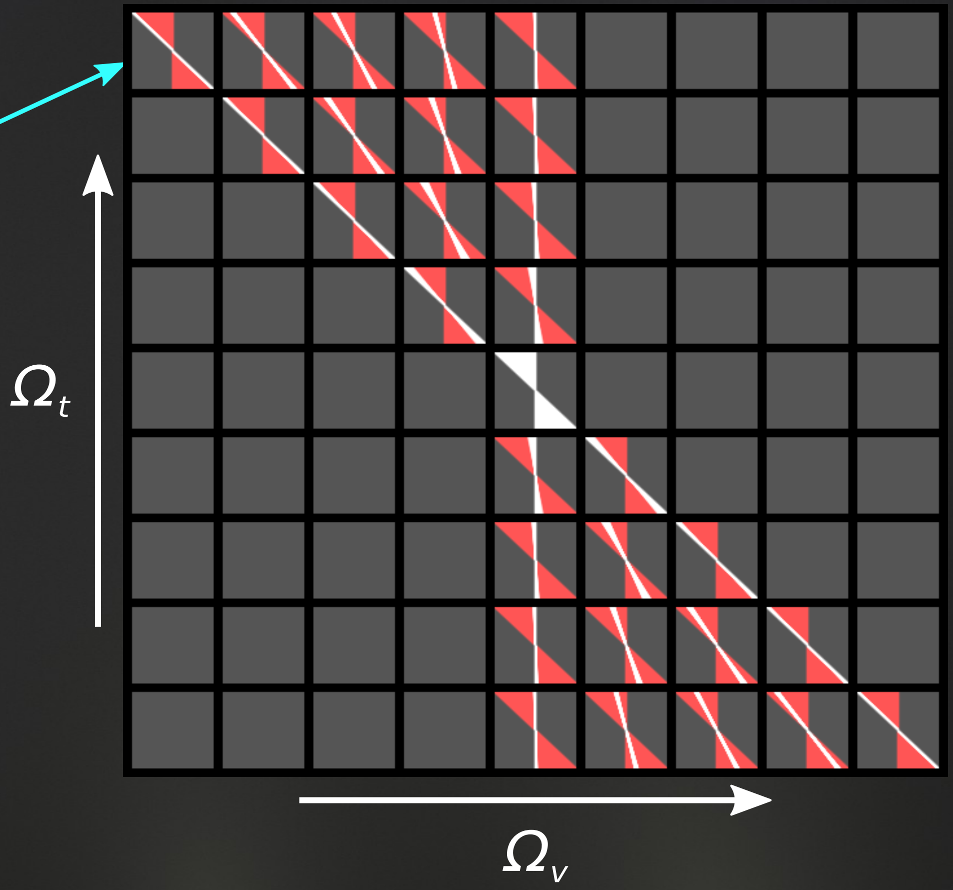
Dual-Fan and Hyperfan

$$m_1 < \frac{\Omega_s}{\Omega_u} < m_2$$

$$\frac{\Omega_t}{\Omega_v} = \frac{\Omega_s}{\Omega_u}$$

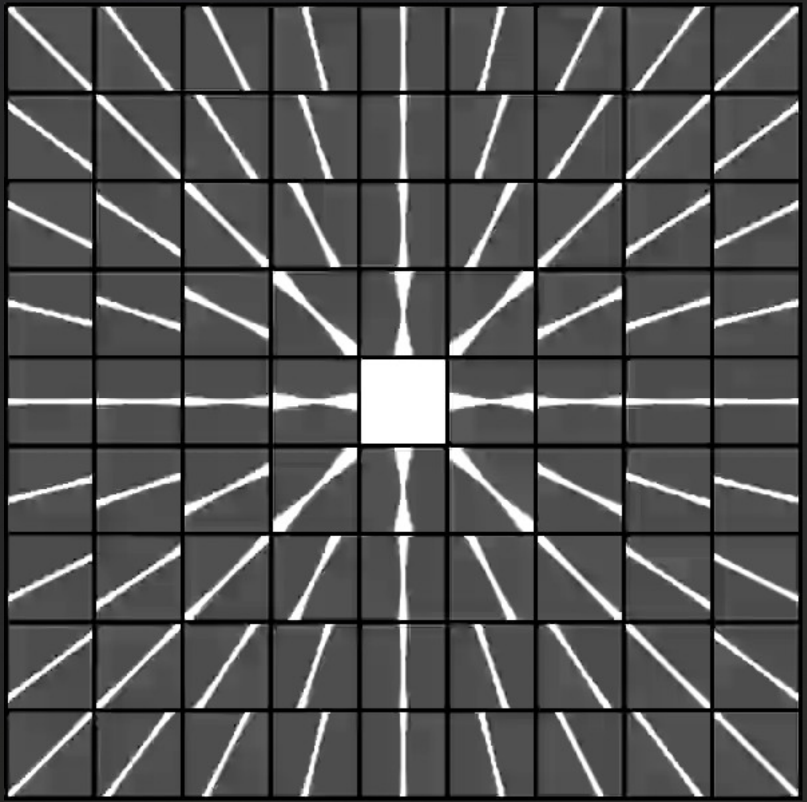
$$m_1 < \frac{\Omega_t}{\Omega_v} < m_2$$



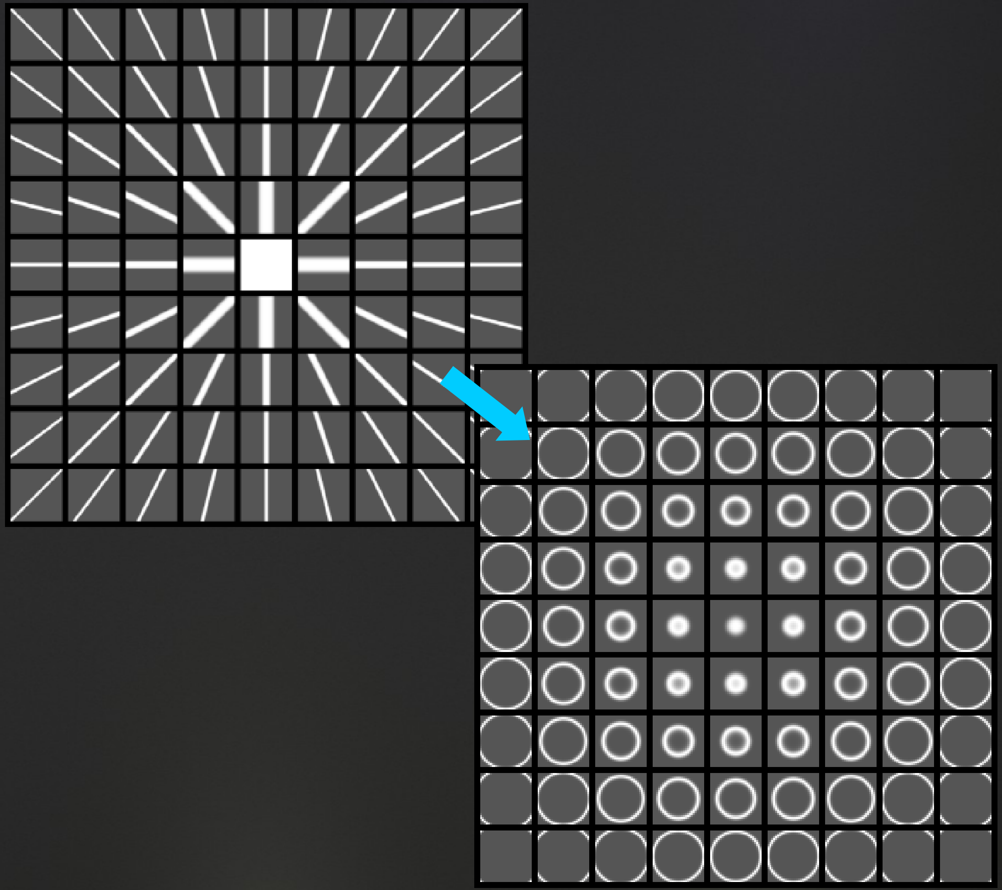


Red: Dual-fan; White: Hyperfan (Hypercone intersected w/fan)

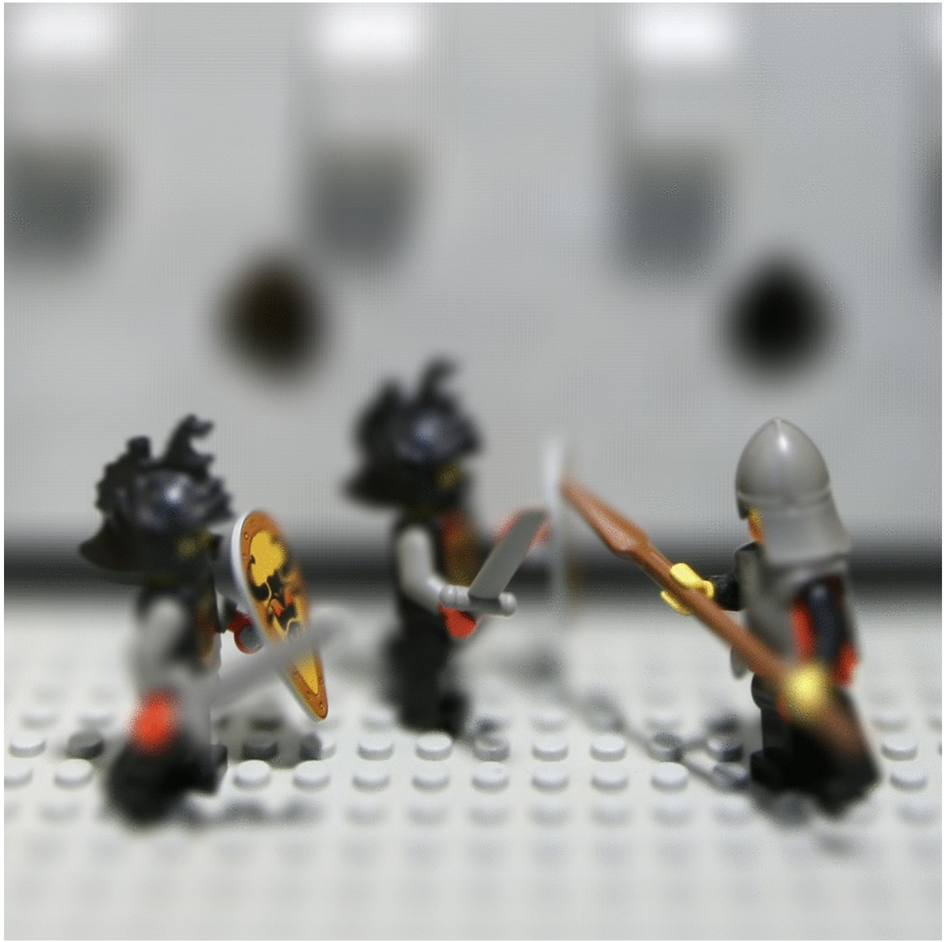
“Dimensionality Gap” = Hypercone



Animation: rotating the hypercone



Hyperfan (Dimensionality Gap) Filter

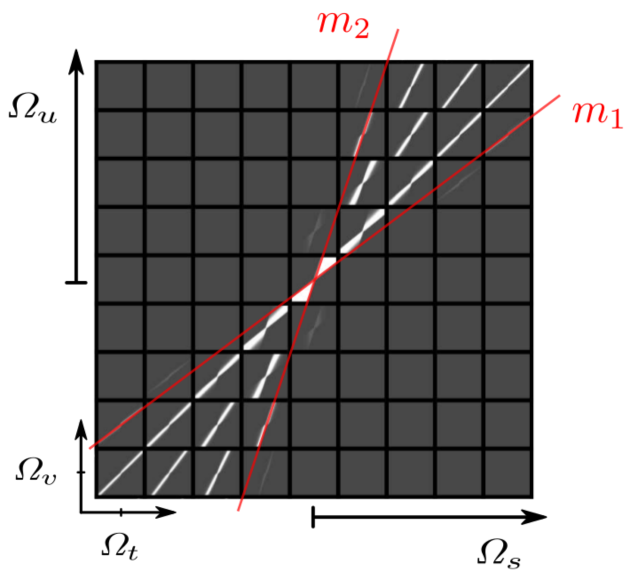


Animation: volumetric focus

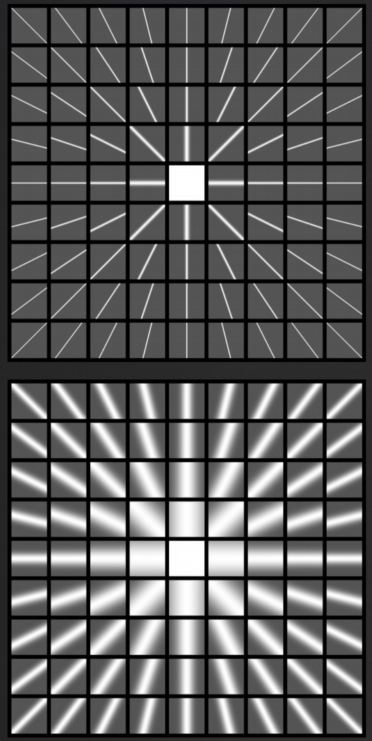
Depth range → Frequency hyperfan

2D Fan 2D Fan	$m_1 < \begin{matrix} \Omega_s / \Omega_u \\ \Omega_t / \Omega_v \end{matrix} < m_2$
Hypercone	$\Omega_s / \Omega_u = \Omega_t / \Omega_v$

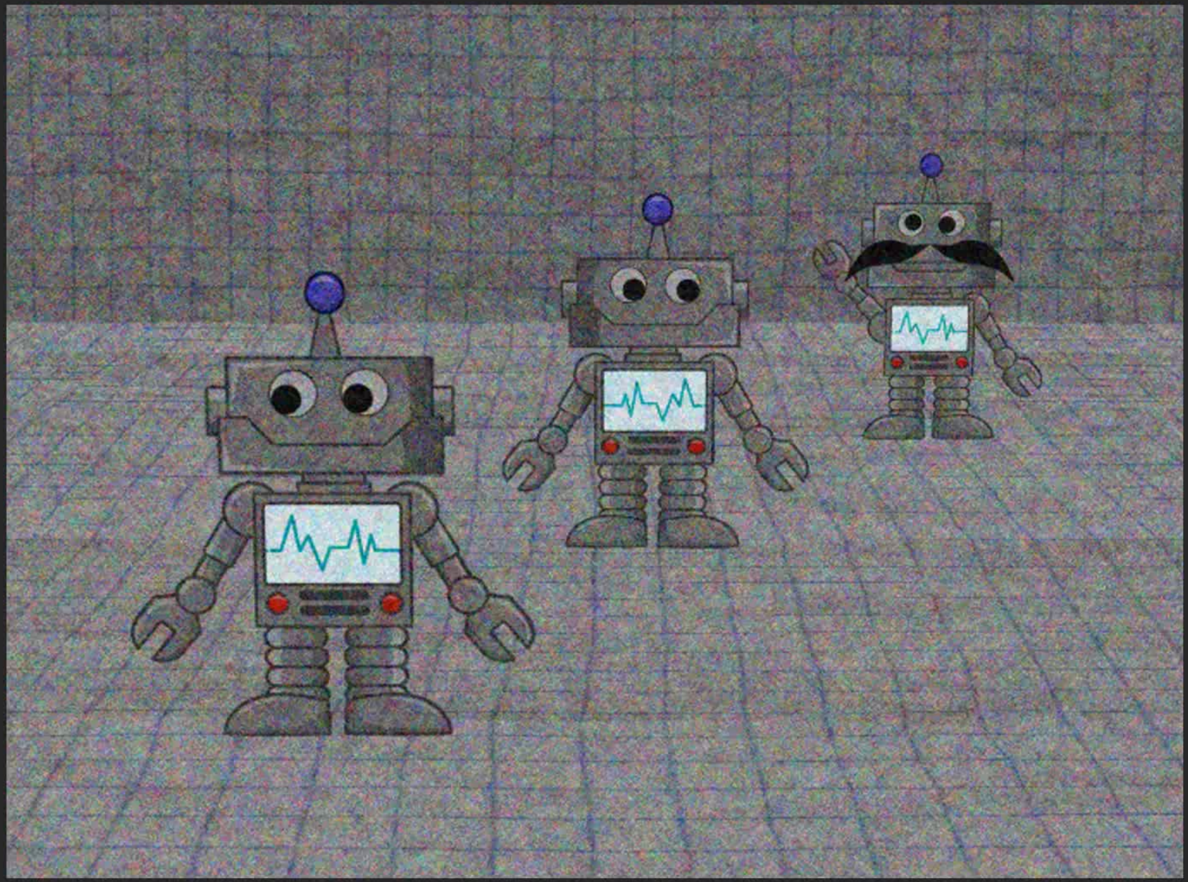
4D Hyperfan

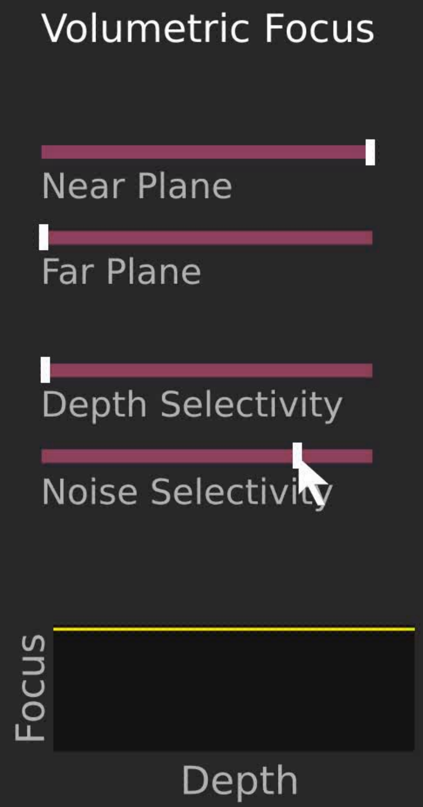


Hyperfan Noise Selectivity



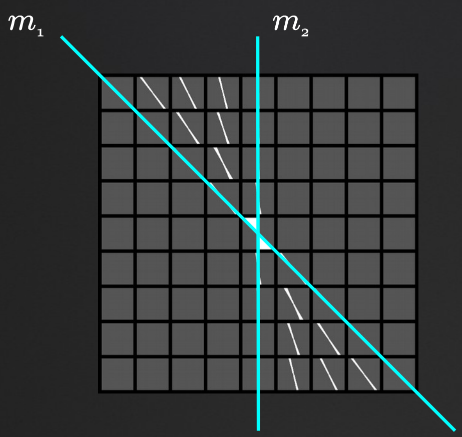
Noise selectivity



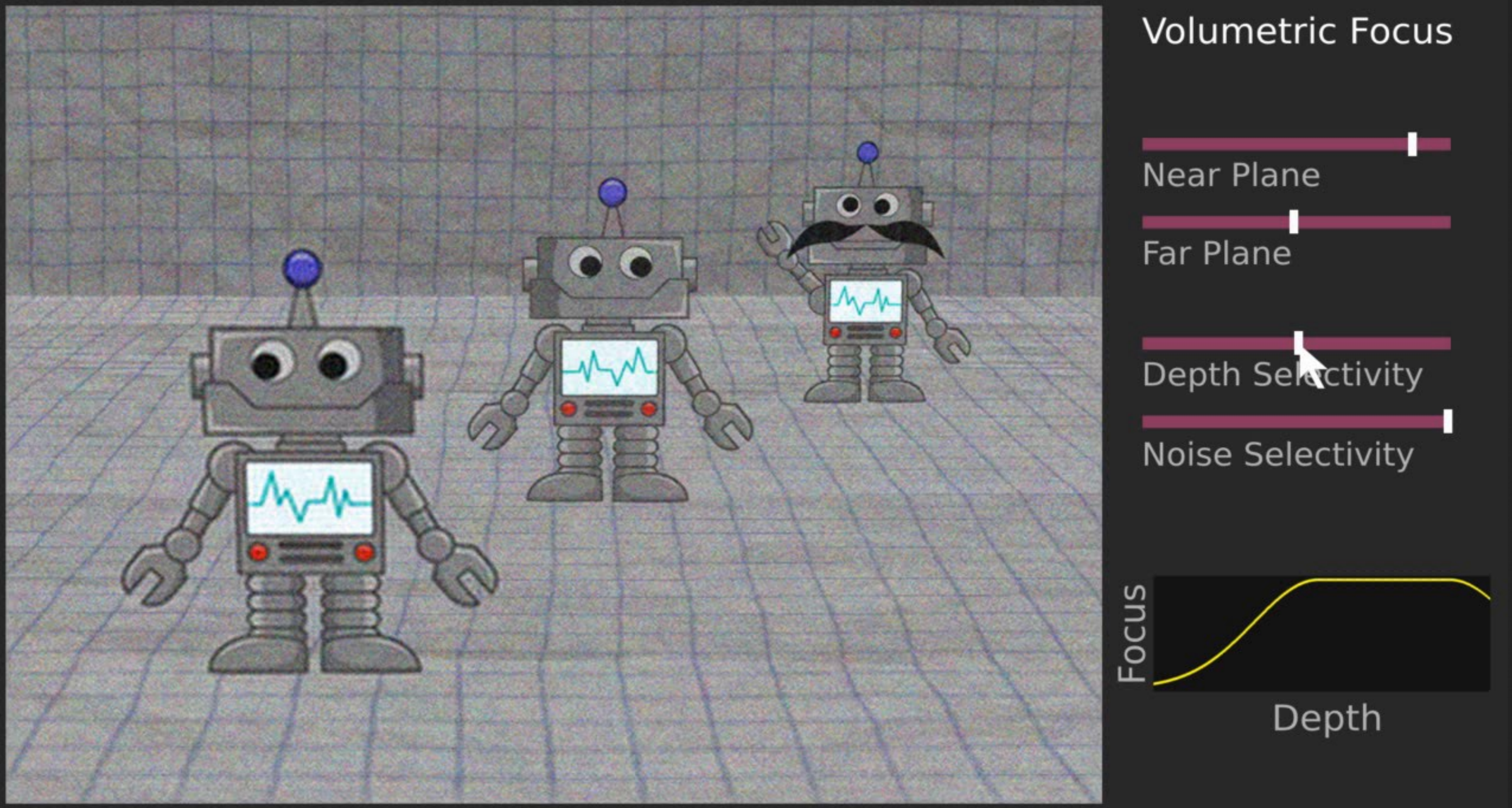


Animation: adjusting hypercone gain

Hyperfan Depth Selectivity

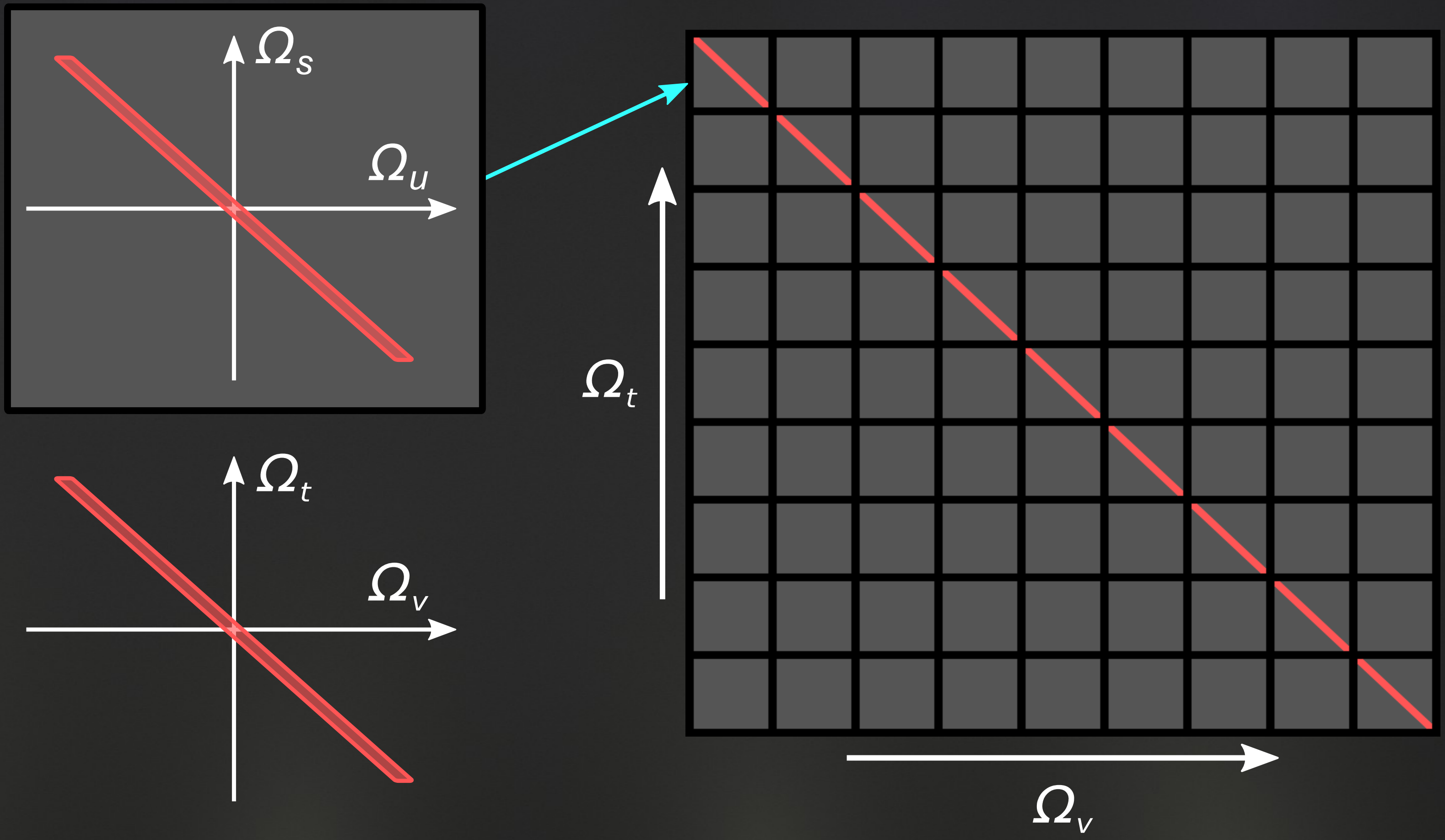


Depth range
&
Selectivity

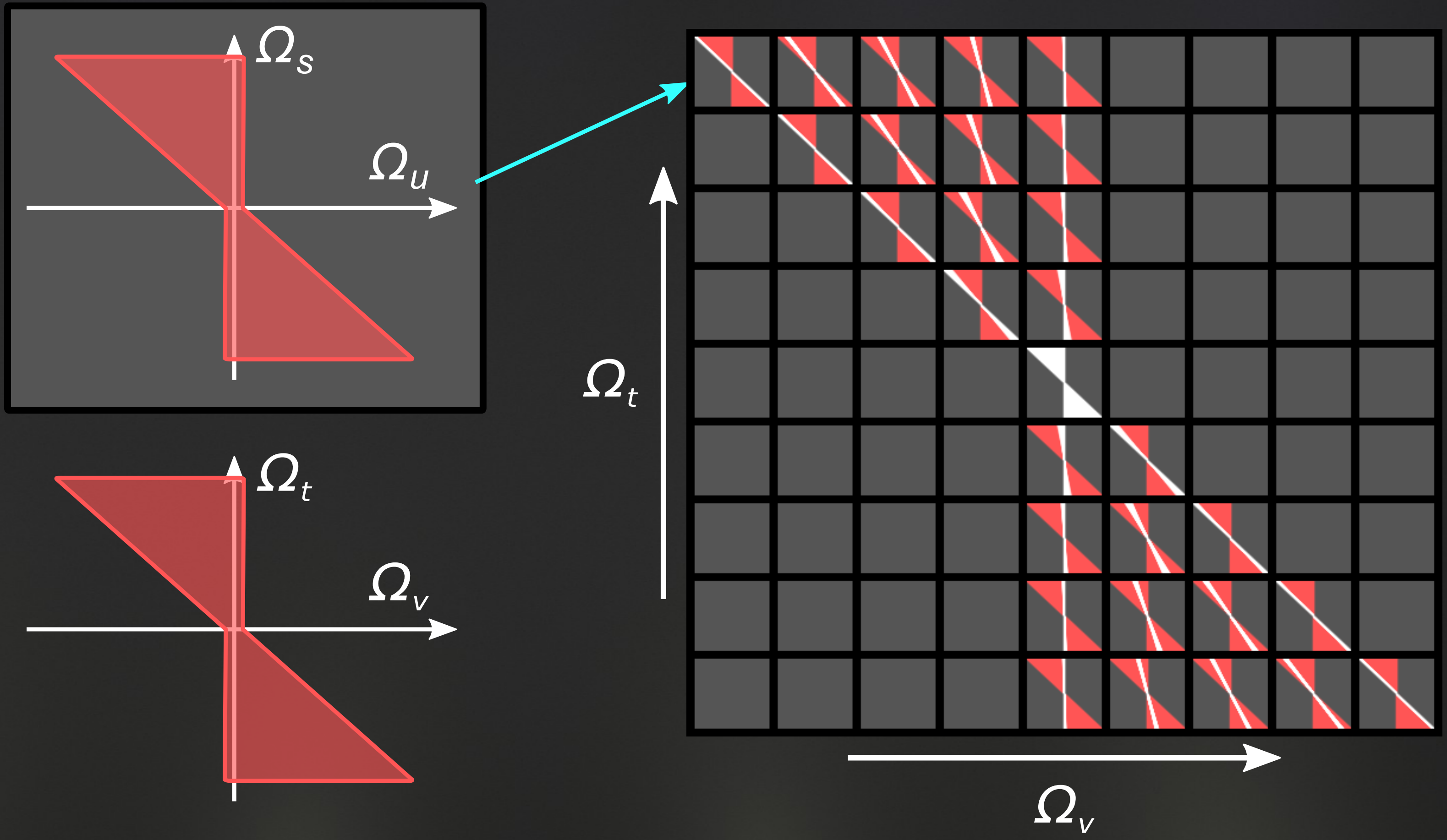


Animation: adjusting depth limits on volumetric focus

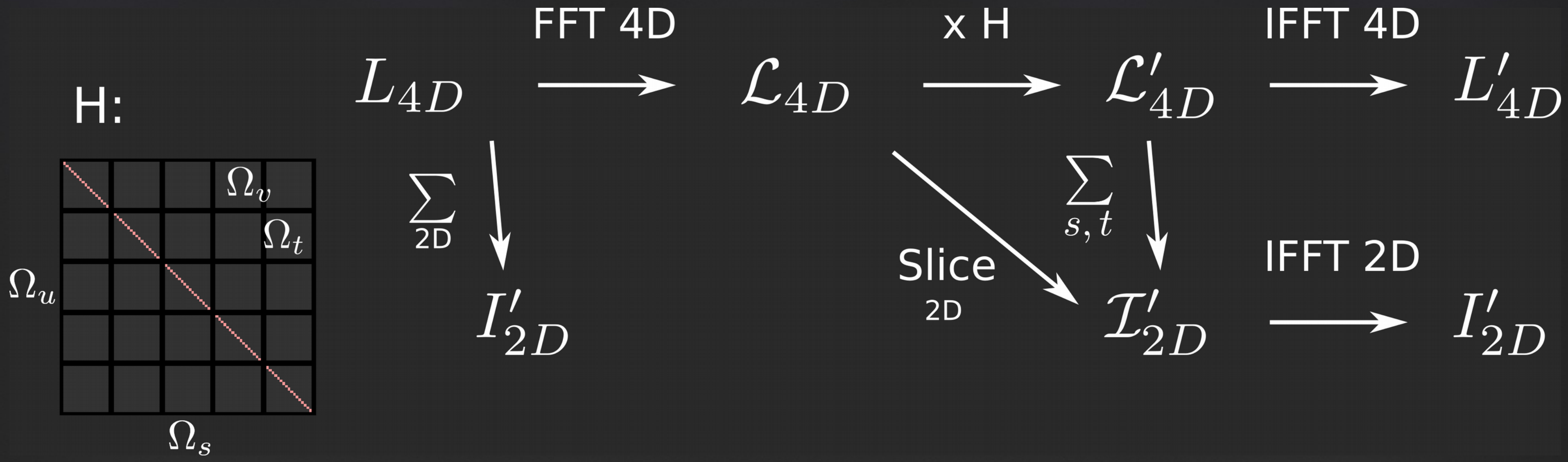
Separability: Plane Separates into 2D filters



… hyperfan does not



Fourier-Slice Theorem

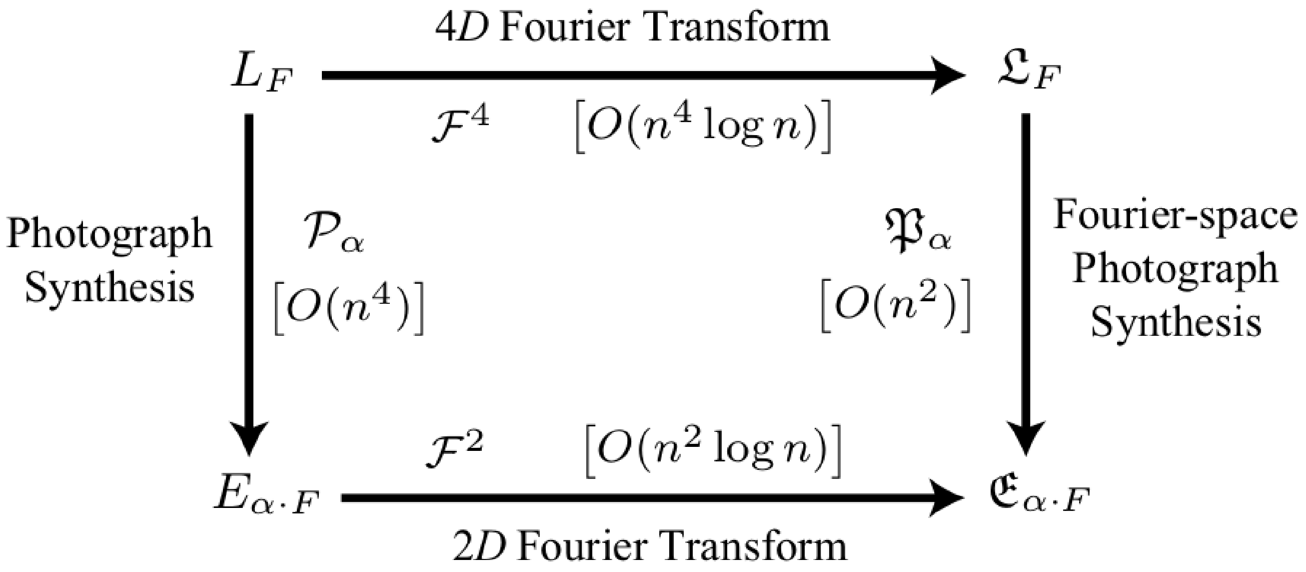


$$L_{freq}(\boldsymbol{\Omega}) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} L_{cont}(s,t,u,v)\, e^{-j(\Omega_s s+\Omega_t t+\Omega_u u+\Omega_v v)}\, dv\,du\,dt\,ds$$

$$= \delta(\Omega_s)\delta(\Omega_t)\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} L(\Omega_s,\Omega_t,u,v)\, e^{-j(\Omega_u u+\Omega_v v)}\, dv\,du\ .$$

Fourier-Slice Theorem

Shift-sum



Slice

[Ng 2005]

References

Much of the introductory content in these talks is written up in
Dansereau “Plenoptic Signal Processing for Robust Vision in Field Robotics”, 2014
with extensive citations to the source works.

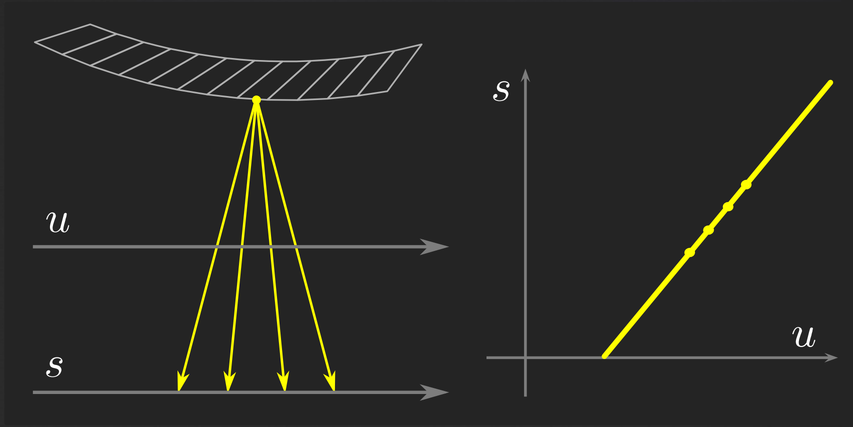
Another useful review with extensive citations to relevant work is:
Ihrke et al "Principles of Light Field Imaging", 2016

A few key works:

Ng et al “Light field photography with a hand-held plenoptic camera”, 2005
Ng “Fourier slice photography”, 2005
Levoy and Hanrahan “Light field rendering”, 1996
Gortler et al “The Lumigraph”, 1996
Adelson and Bergen “The plenoptic function and the elements of early vision”, 1991

Points (and Planes) To Ponder

Domain:		1D	2D	3D	4D
# Linear Equations:	1	Point	Line	Plane	Hyperplane
	2		Point	Line	Plane
	3			Point	Line
	4				Point



In 4D, what's the intersection of two planes? Are there exceptions?

The point-plane correspondence maps a 3D geometric point to a 4D LF plane.
A 4D LF point corresponds to a ray in 3D geometric space.
Use these to interpret the intersection of two 4D planes in 3D geometric space.