augmented reality
[erweiterte realität]

Bauhaus-Universität
Weimar

Projectors for Graphics

-Course-

Visually Augmenting the
Real World with Projectors

Oliver Bimber

Theatres

Karl May Festival Elspe, 2006

Theatres

Karl May Festival Elspe, 2006

Advertisement

Moritz Immobilien Leinefelde, 2007

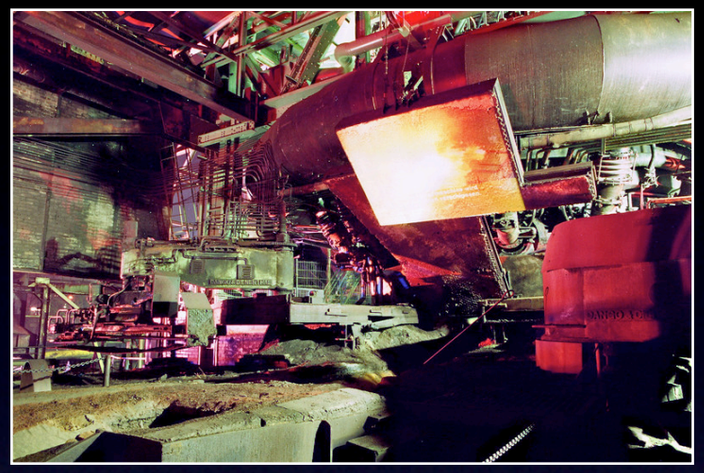
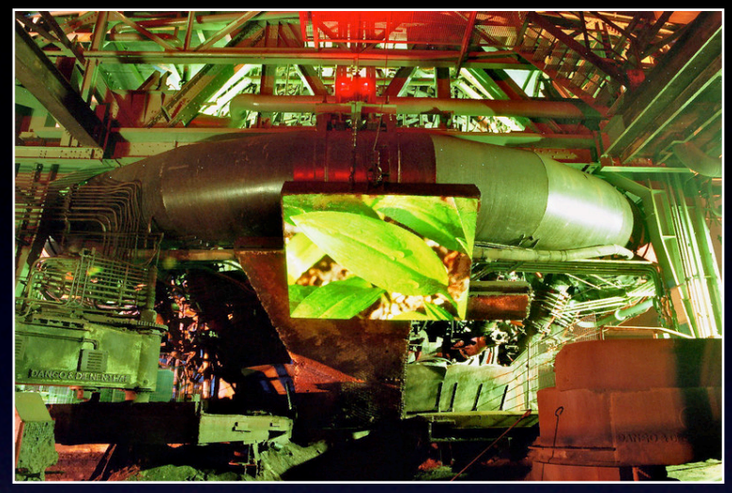
Advertisement

Moritz Immobilien Leinefelde, 2007

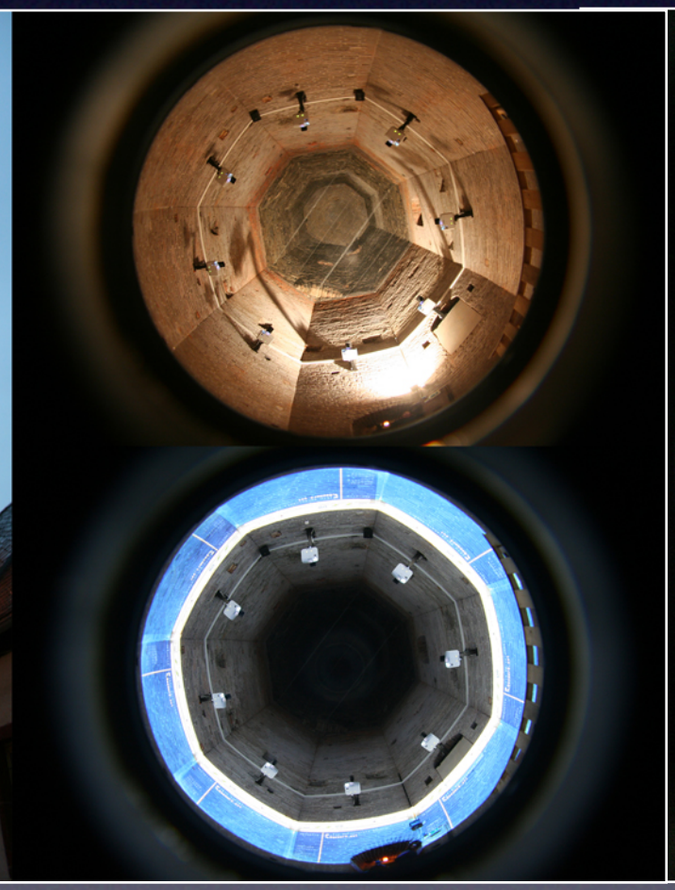
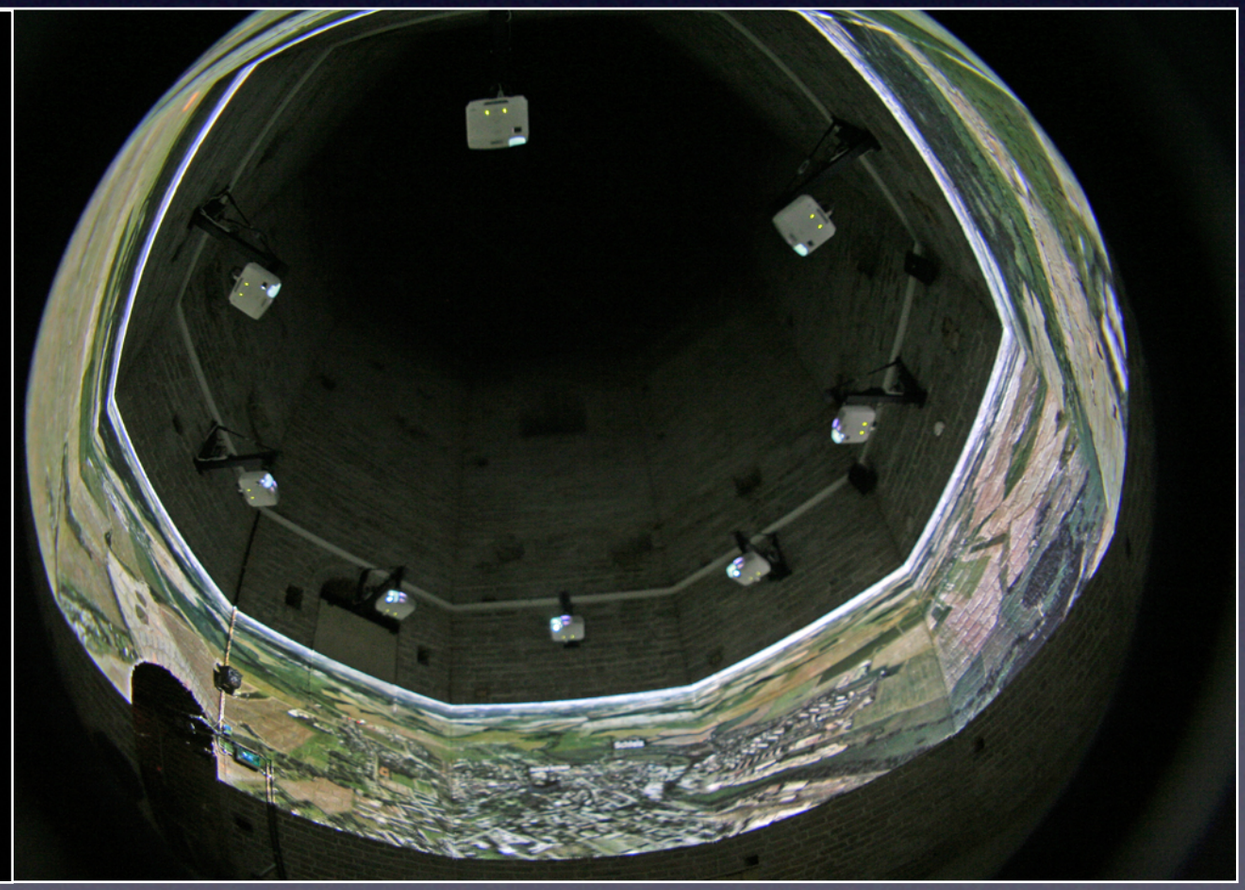
Advertisement

World of Events, 2007

Historic Sites

Henrichshütte Hattingen, 2007

Osterburg Weida, 2007

Historic Sites

Dechen Cave Iserlohn, 2007

Public Viewing

Castle Klaffenbach, Chemnitz, 2007

Public Viewing

Castle Klaffenbach, Chemnitz, 2007

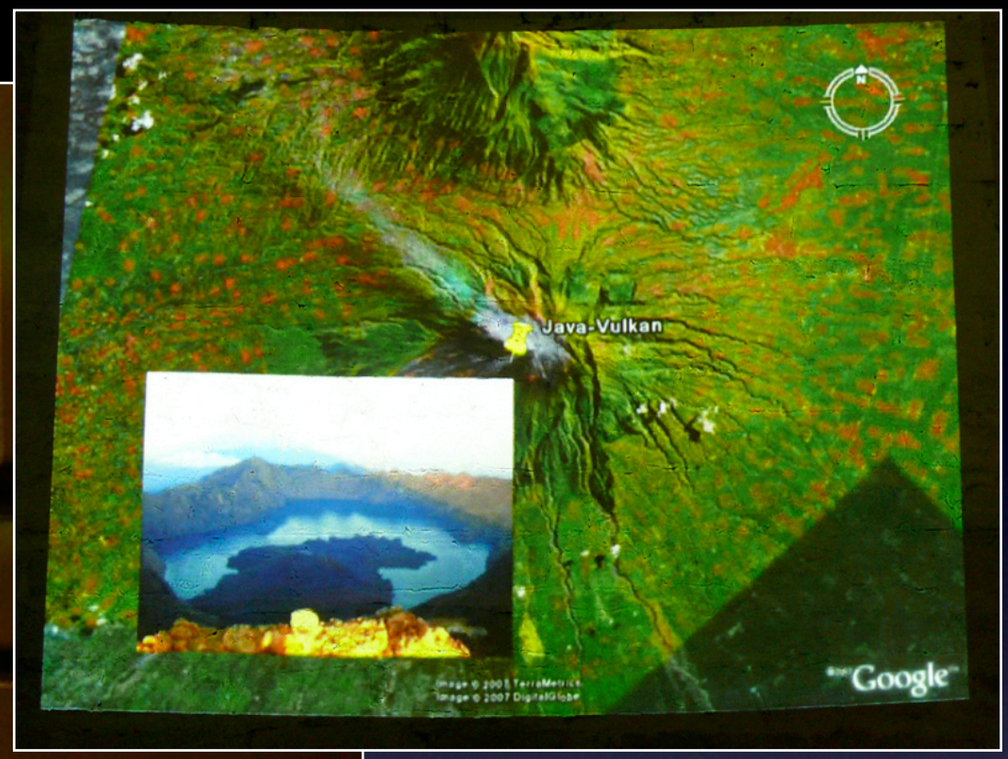
Festivals

Abbey Neumünster, Luxembourg, 2007

Festivals

Abbey Neumünster, Luxembourg, 2007

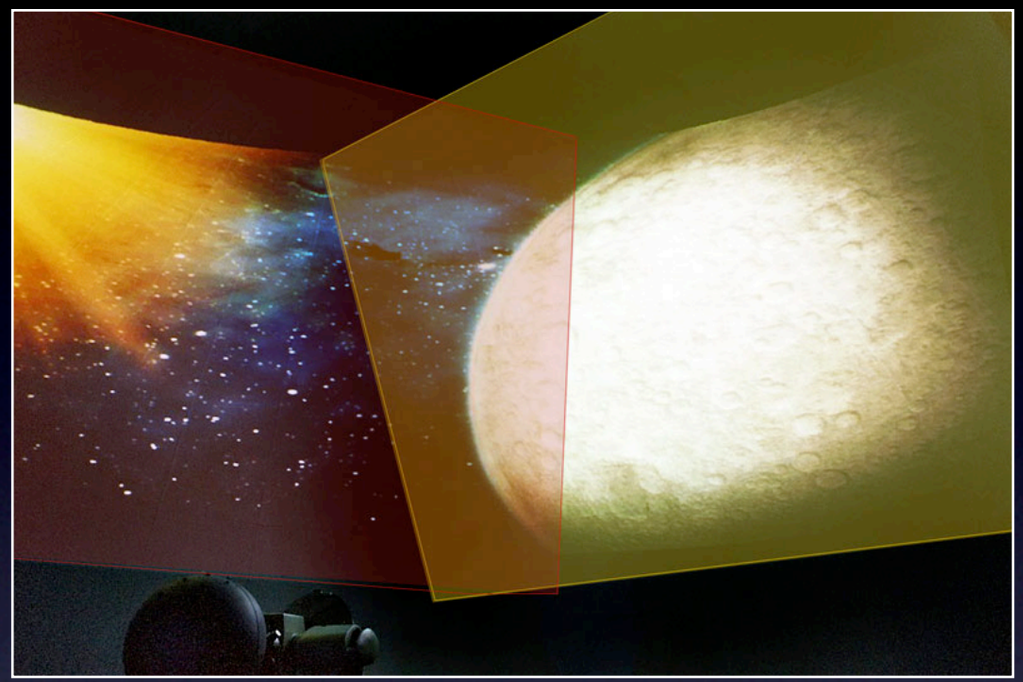
Museums

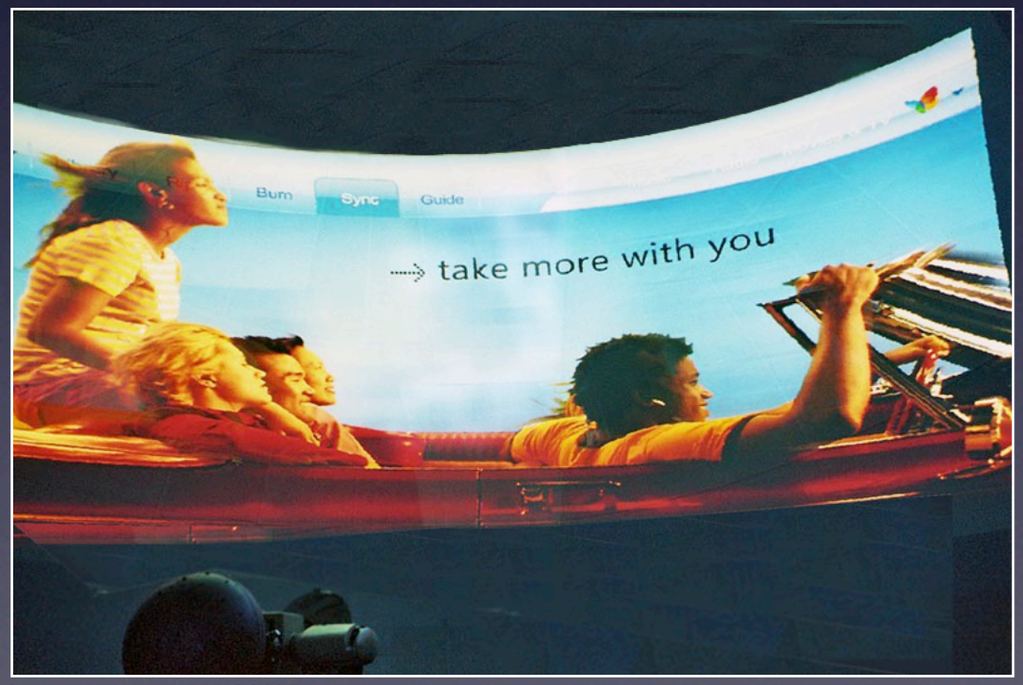


Watermuseum Aquarius Mülheim, 2007

Senckenbergmuseum Frankfurt, 2006

Immersive Visualization





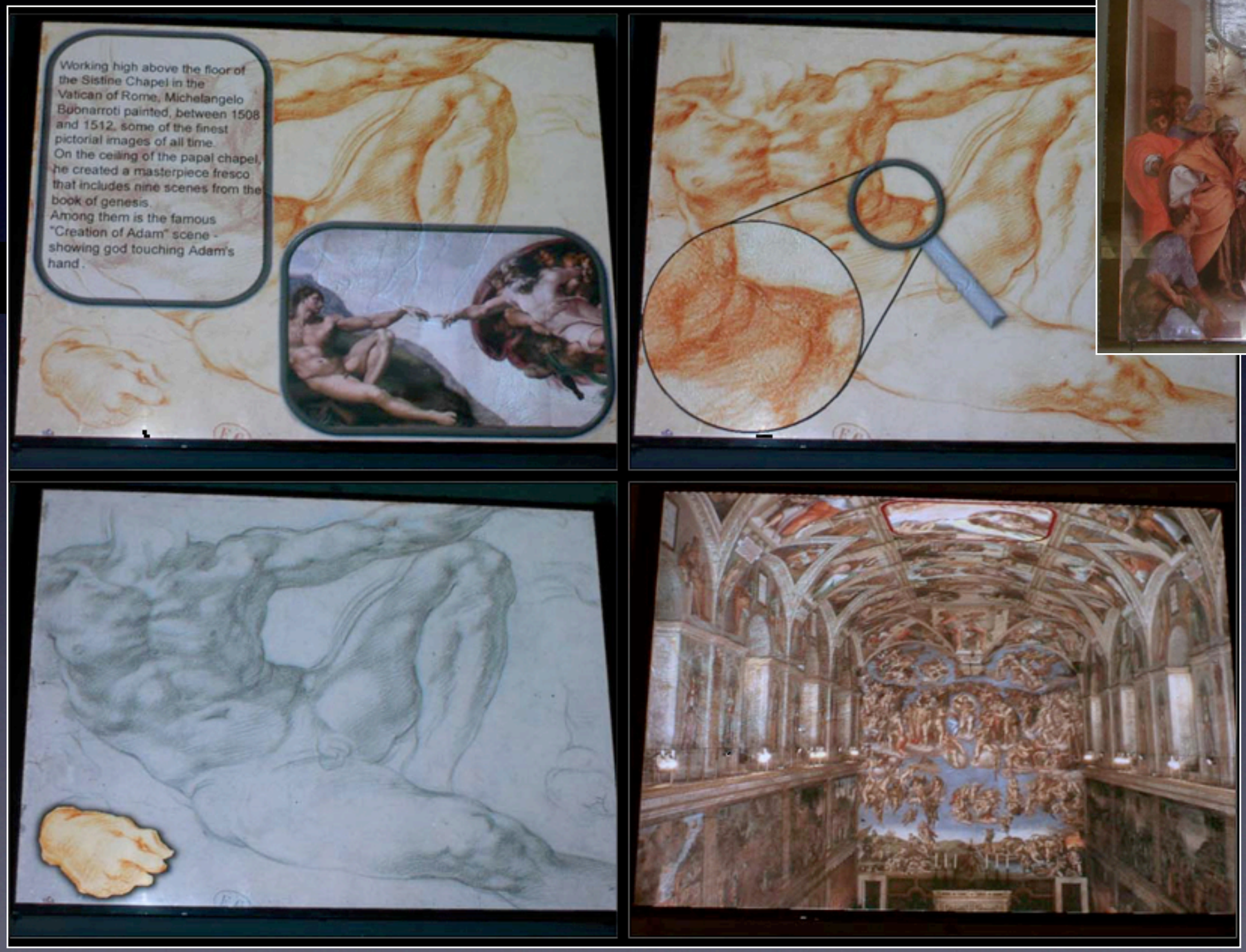
Sternwarte Düsseldorf, 2007

Vehicles

Airbus/EADS, 2006

Superimposing Paintings...

Bimber et al, IEEE Multimedia, 2005



augmented reality [erweiterte realität]

Holografiezentrum Bamberg

DaimlerChrysler

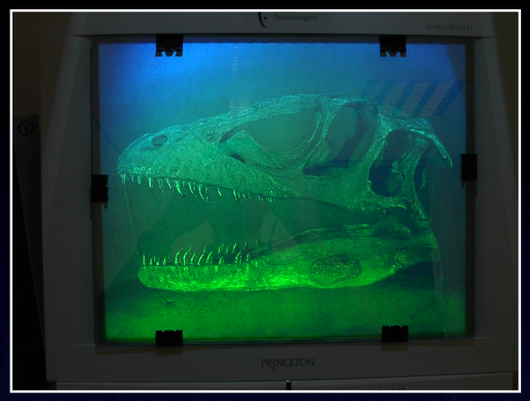
Deutsche Forschungsgemeinschaft DFG

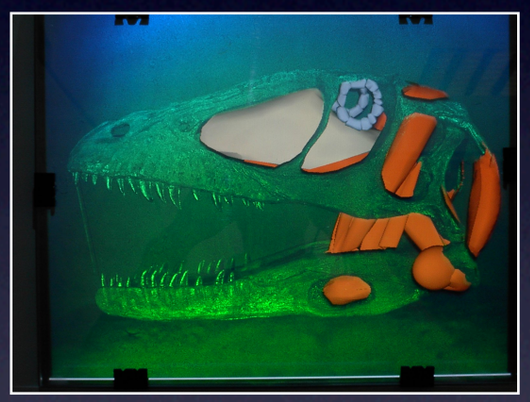
Brown University

Bonn

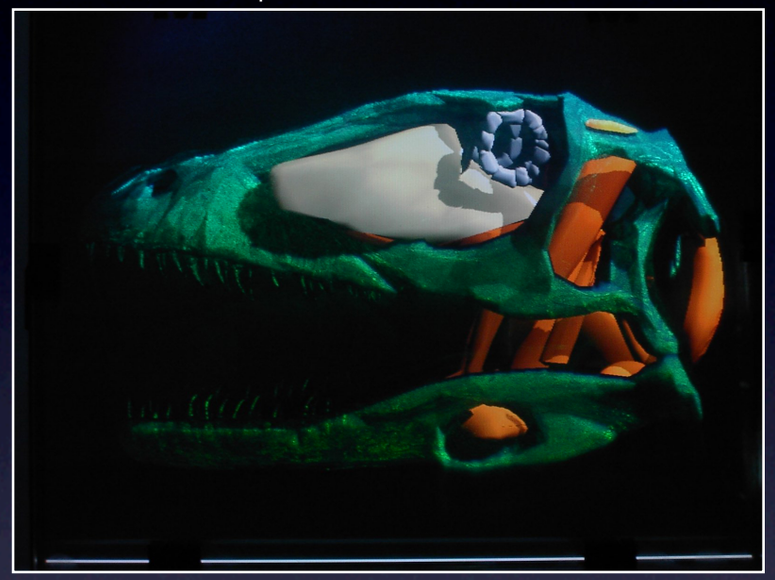
Bauhaus-Universität Weimar

...and Holograms

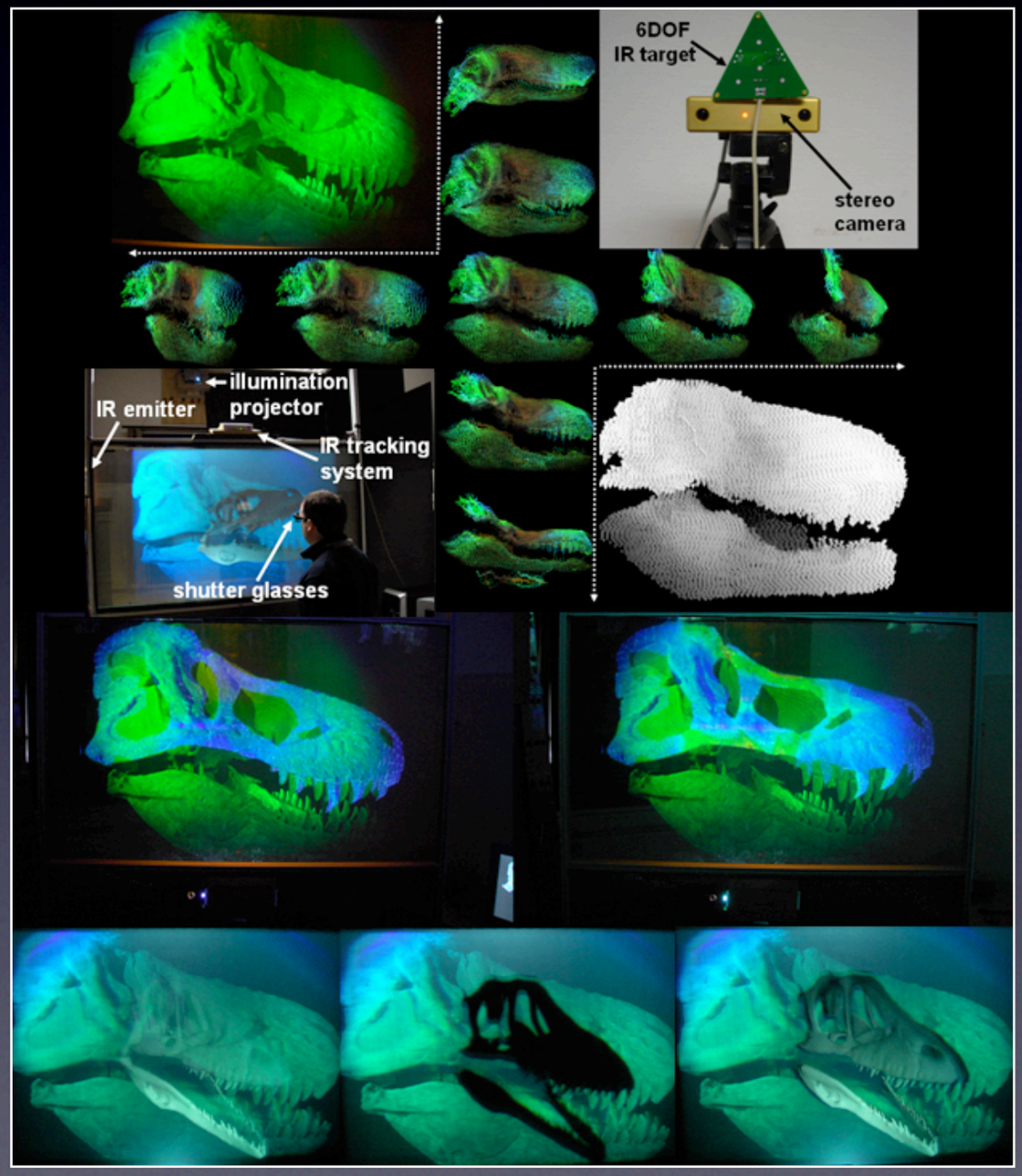




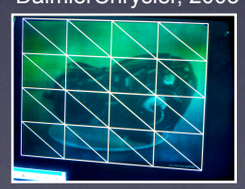
Bimber et al, IEEE Computer 2005

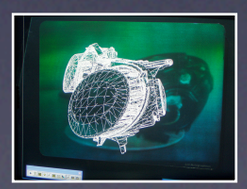


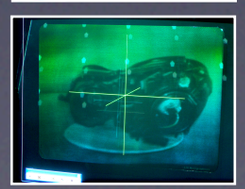
London Museum of Natural History, 2005

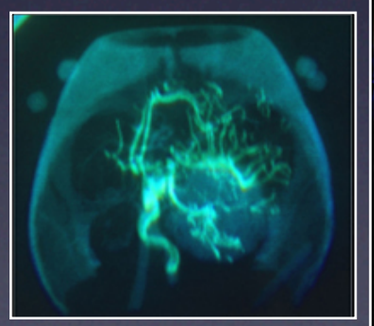


DaimlerChrysler, 2005

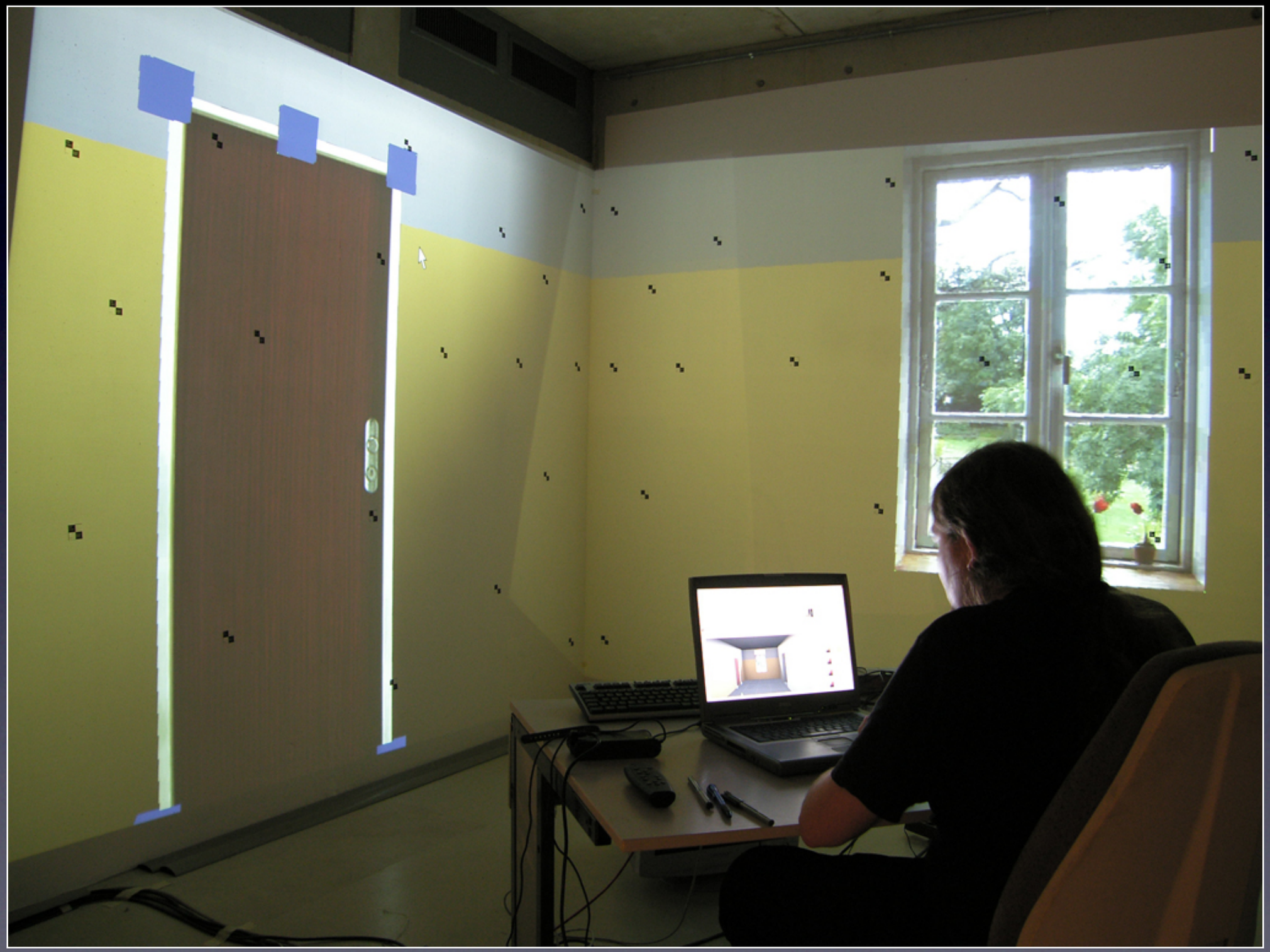








Architectural Visualization

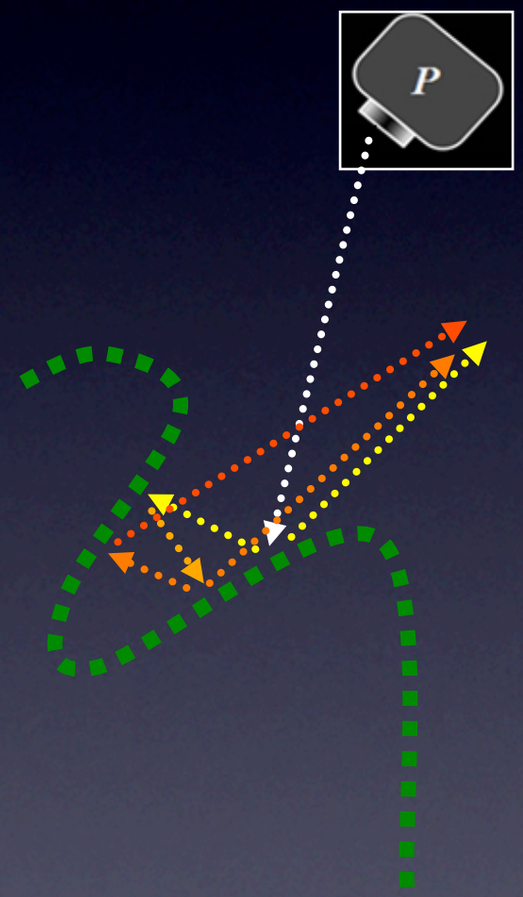


3D Games

What's The Problem?

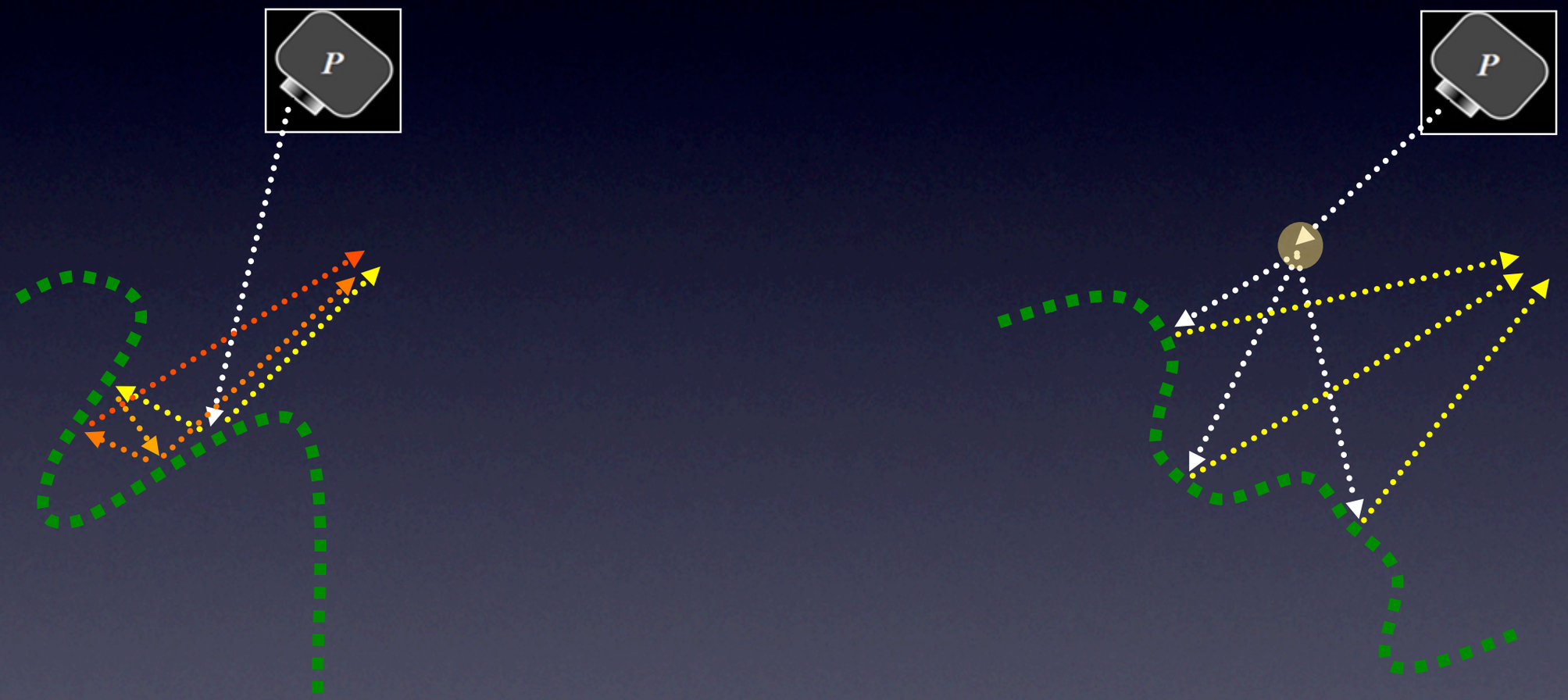
Inverting the Light-Transport

Inverting the Light-Transport

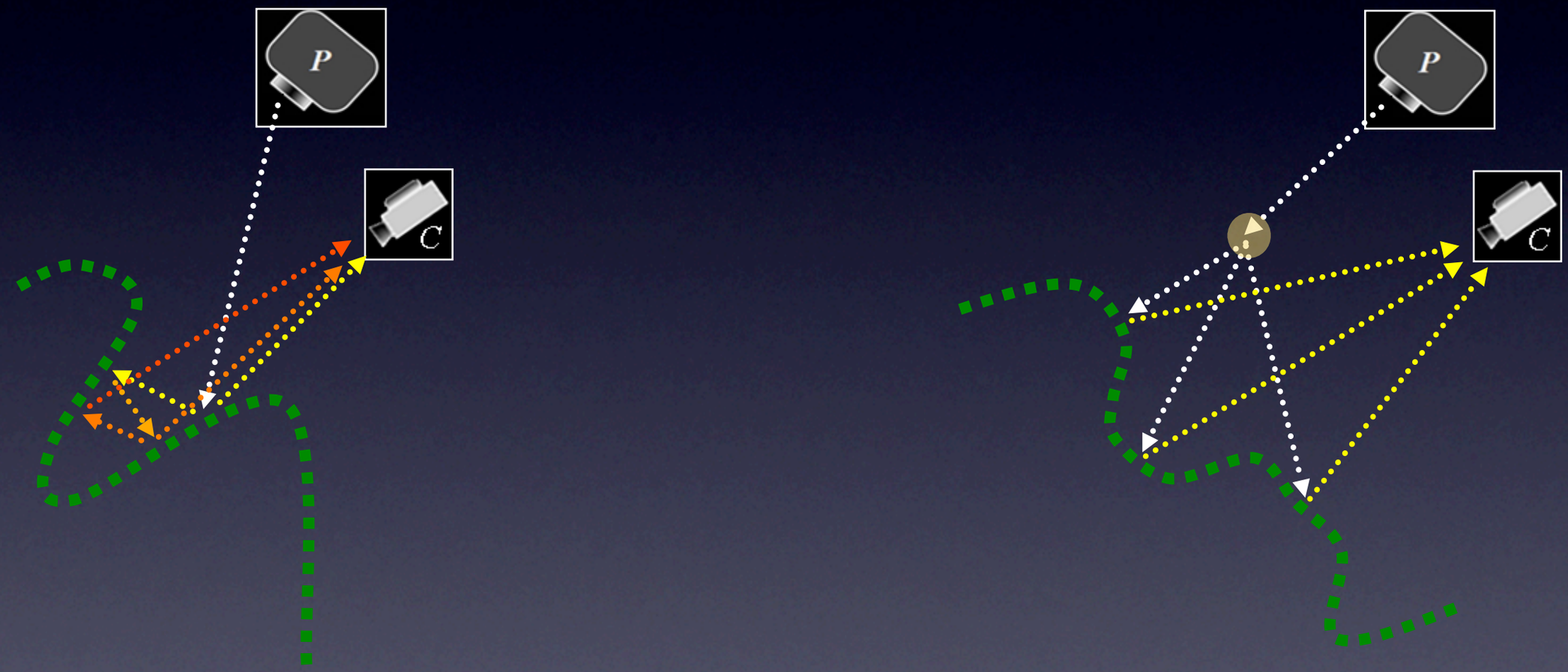


Inverting the Light-Transport

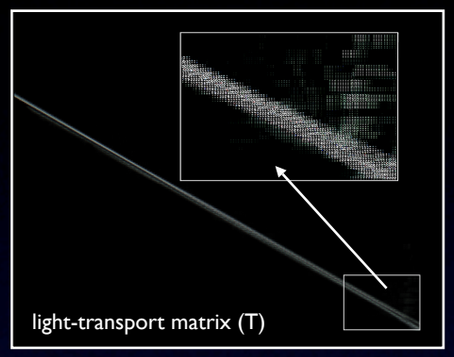
Inverting the Light-Transport

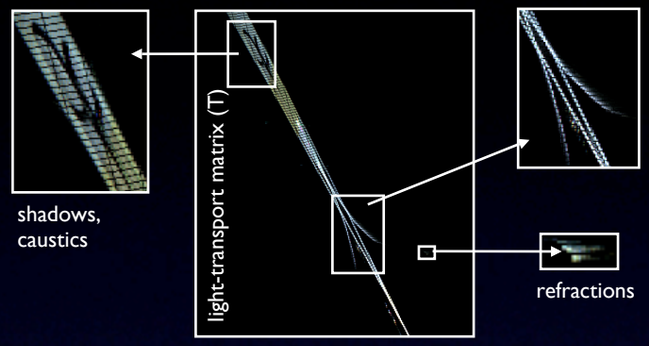


Inverting the Light-Transport

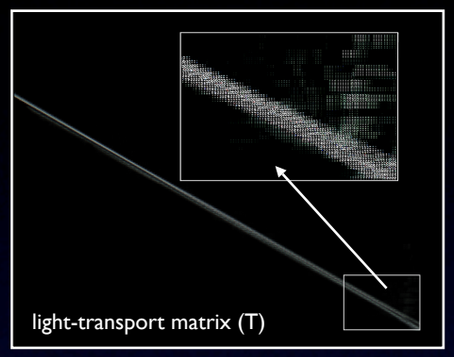


Inverting the Light-Transport

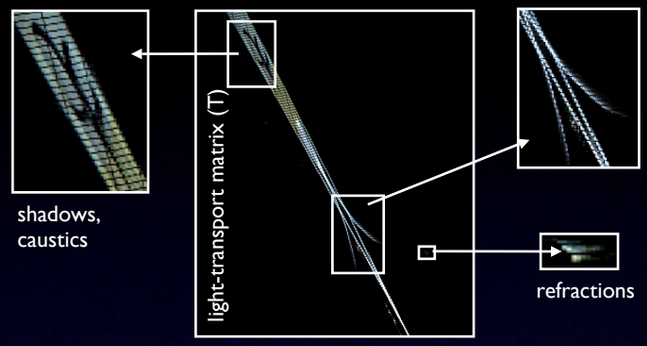


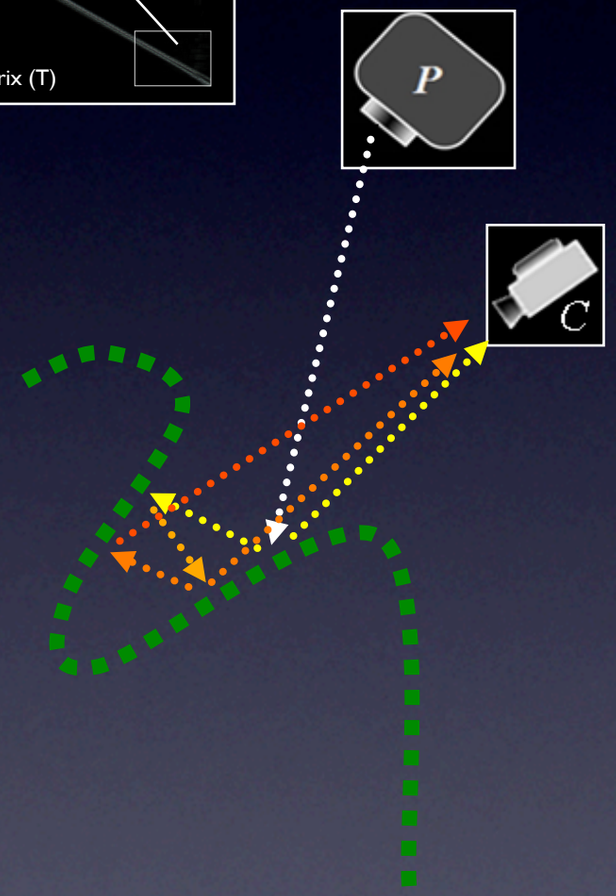


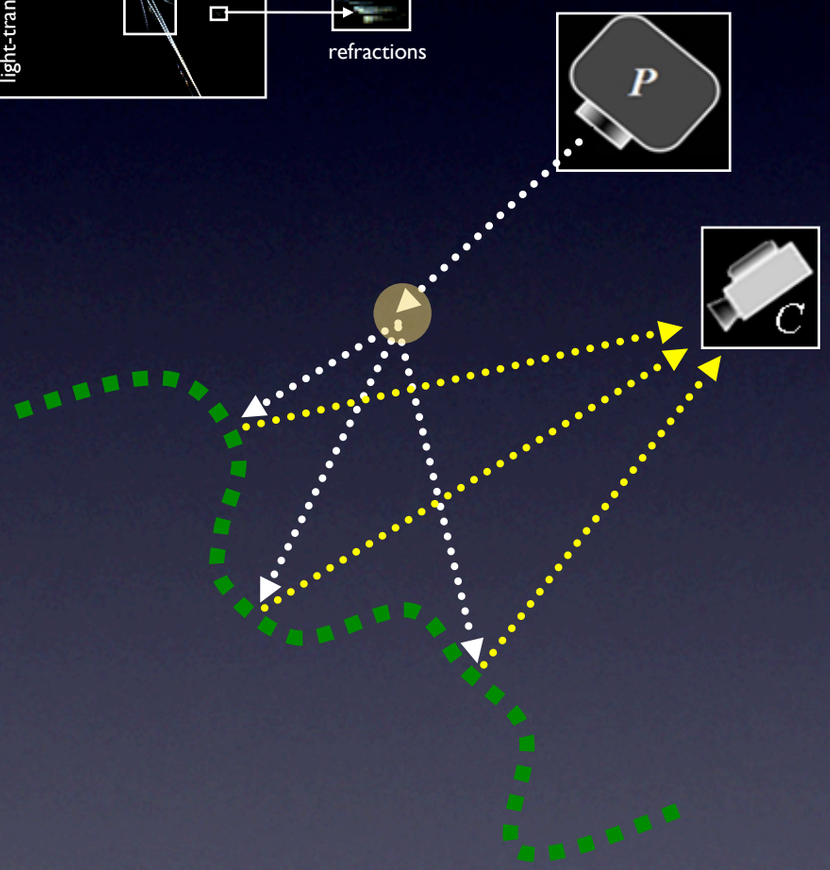
Inverting the Light-Transport



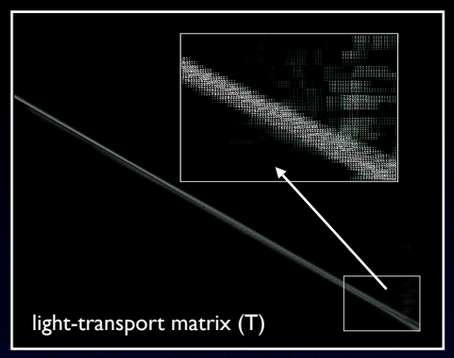
c=Tp



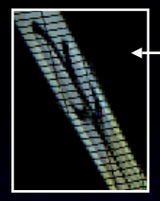


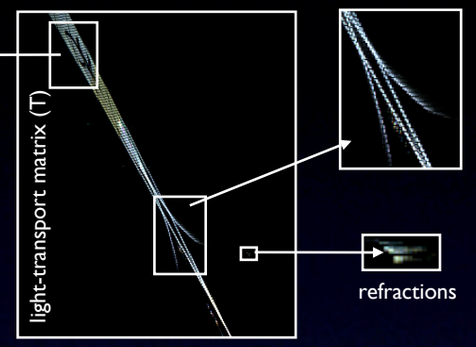


Inverting the Light-Transport

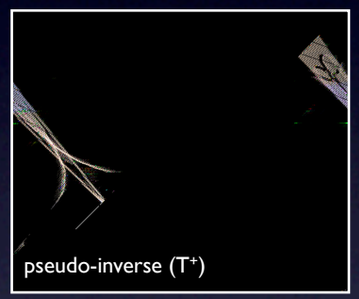


$c=Tp \longrightarrow p=T^{-1}c$

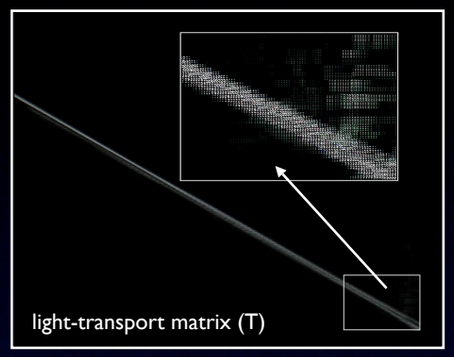




Wetzstein and Bimber, Pacific Graphics 2007



Inverting the Light-Transport



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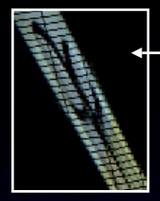
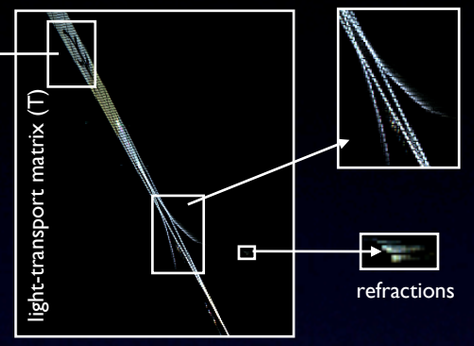
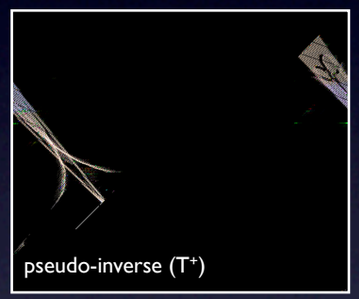
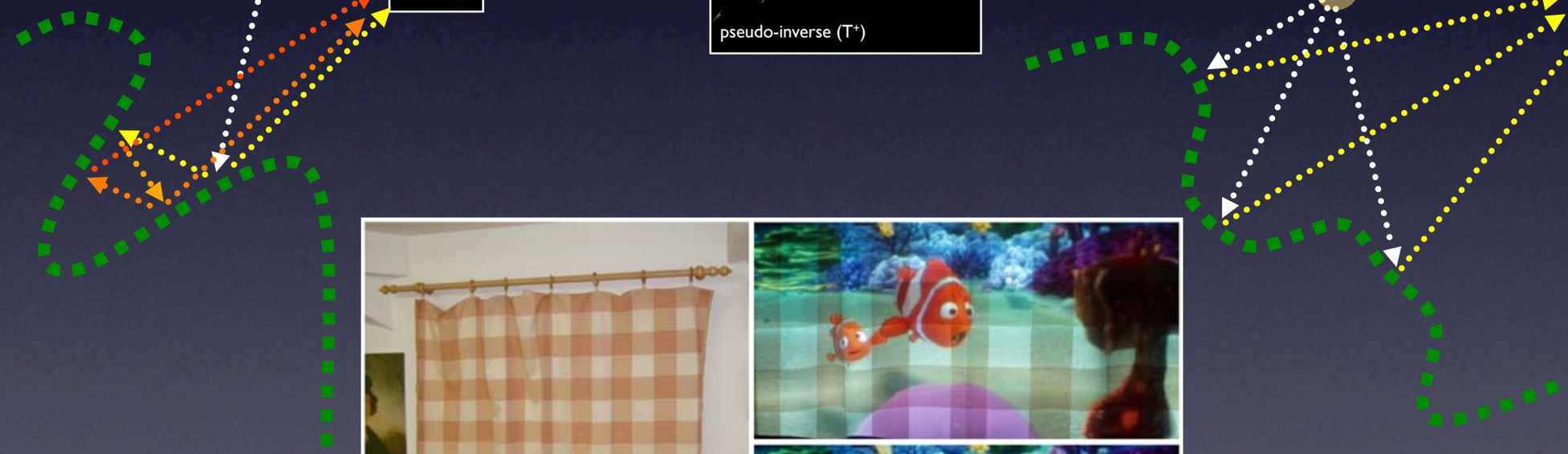

shadows, caustics



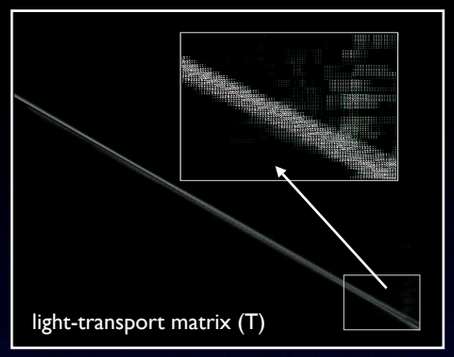
Wetzstein and Bimber, Pacific Graphics 2007





local diffuse reflections and geometry

Inverting the Light-Transport



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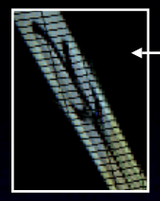
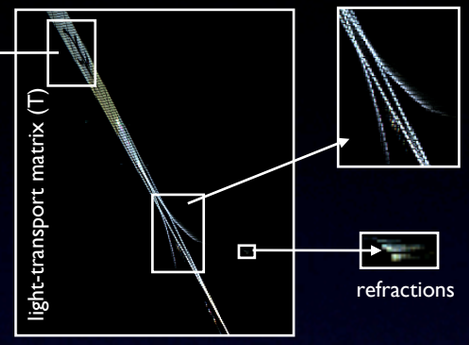
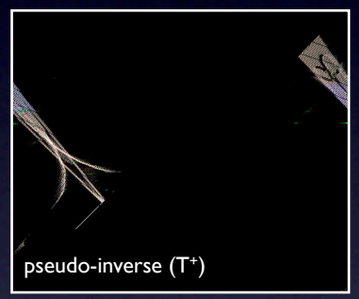
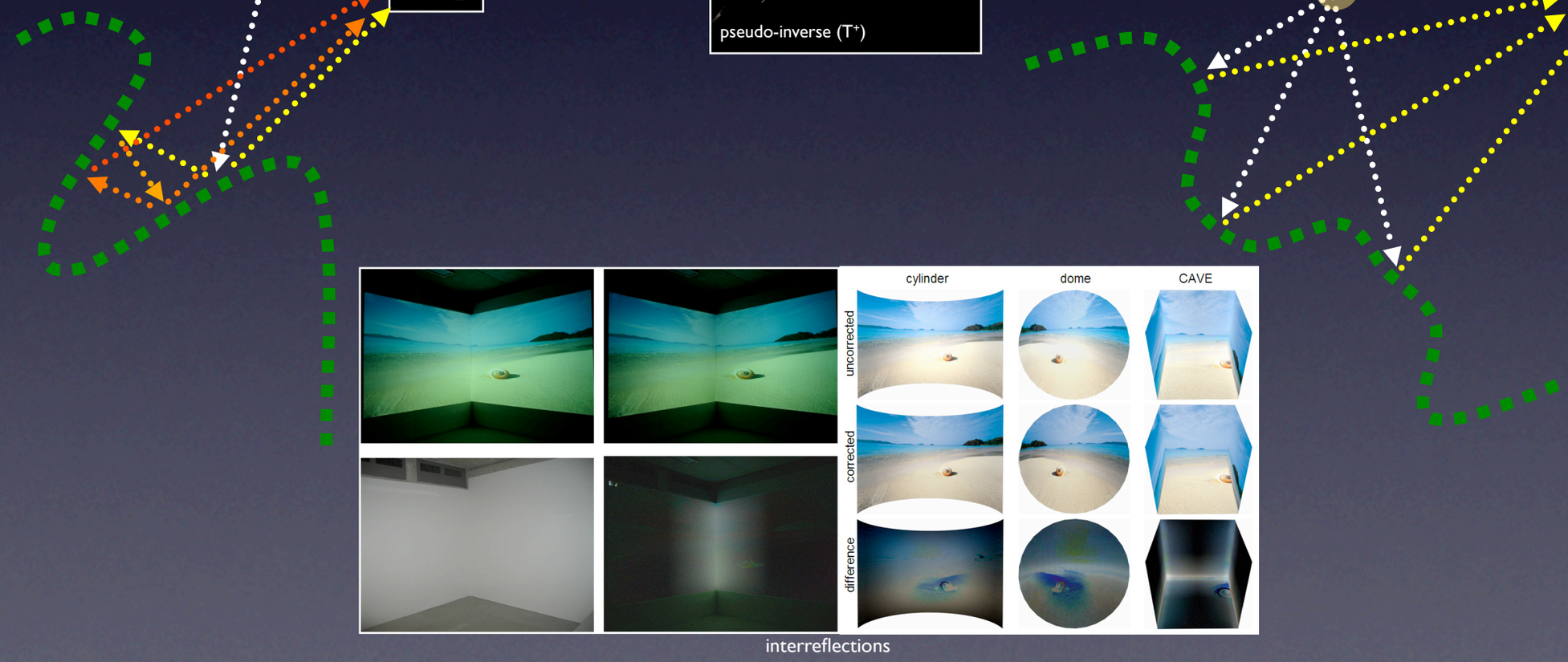

shadows, caustics



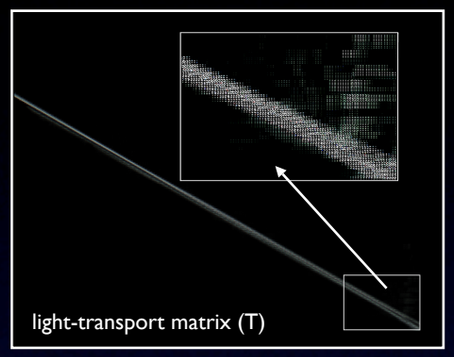
Wetzstein and Bimber, Pacific Graphics 2007





interreflections

Inverting the Light-Transport



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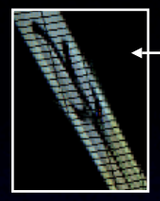
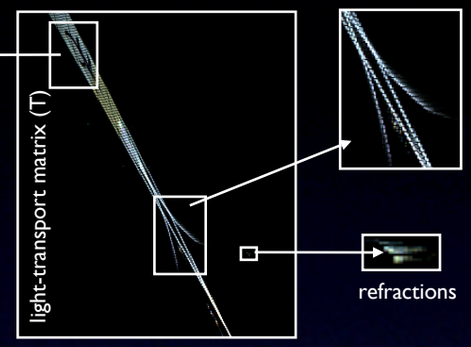
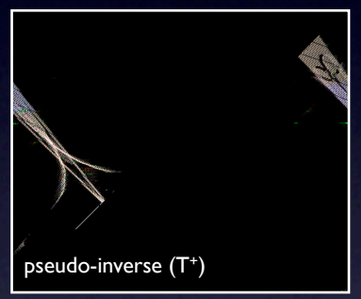
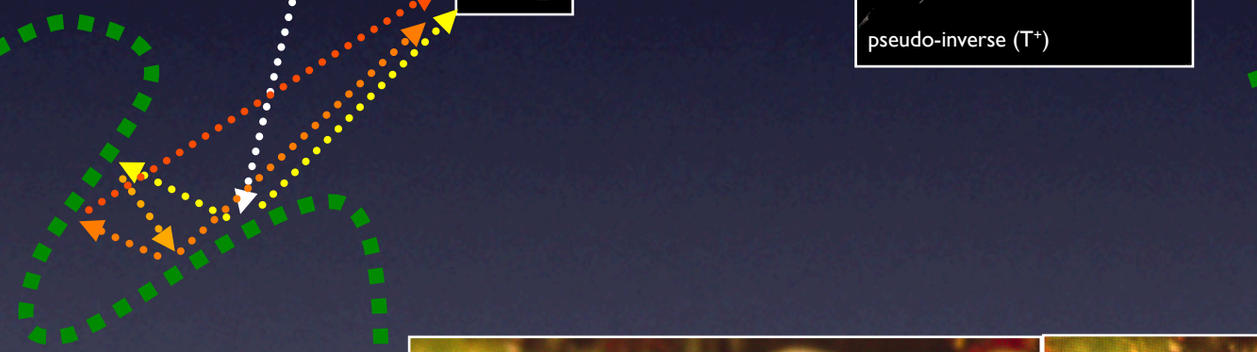




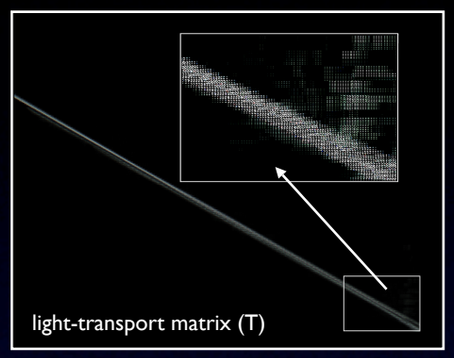
Wetzstein and Bimber, Pacific Graphics 2007





regional defocs / depth of field

Inverting the Light-Transport



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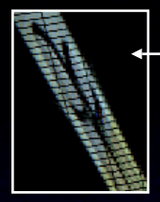
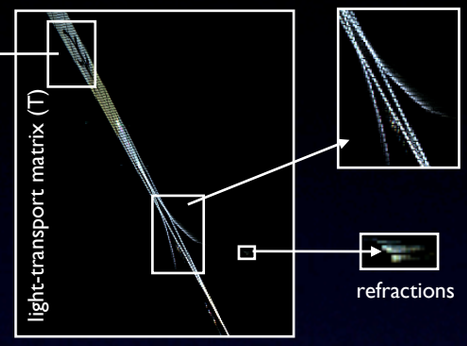
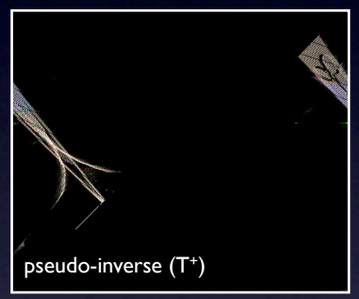
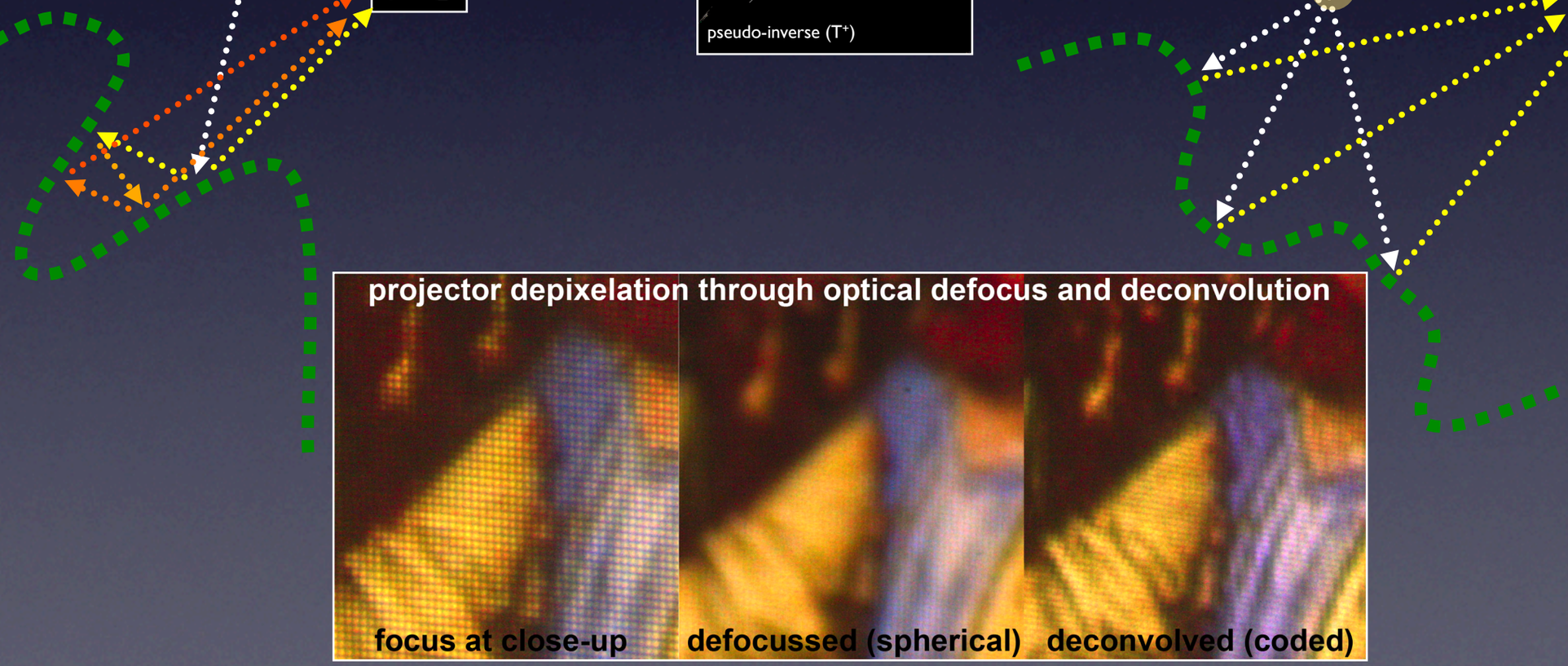

shadows, caustics



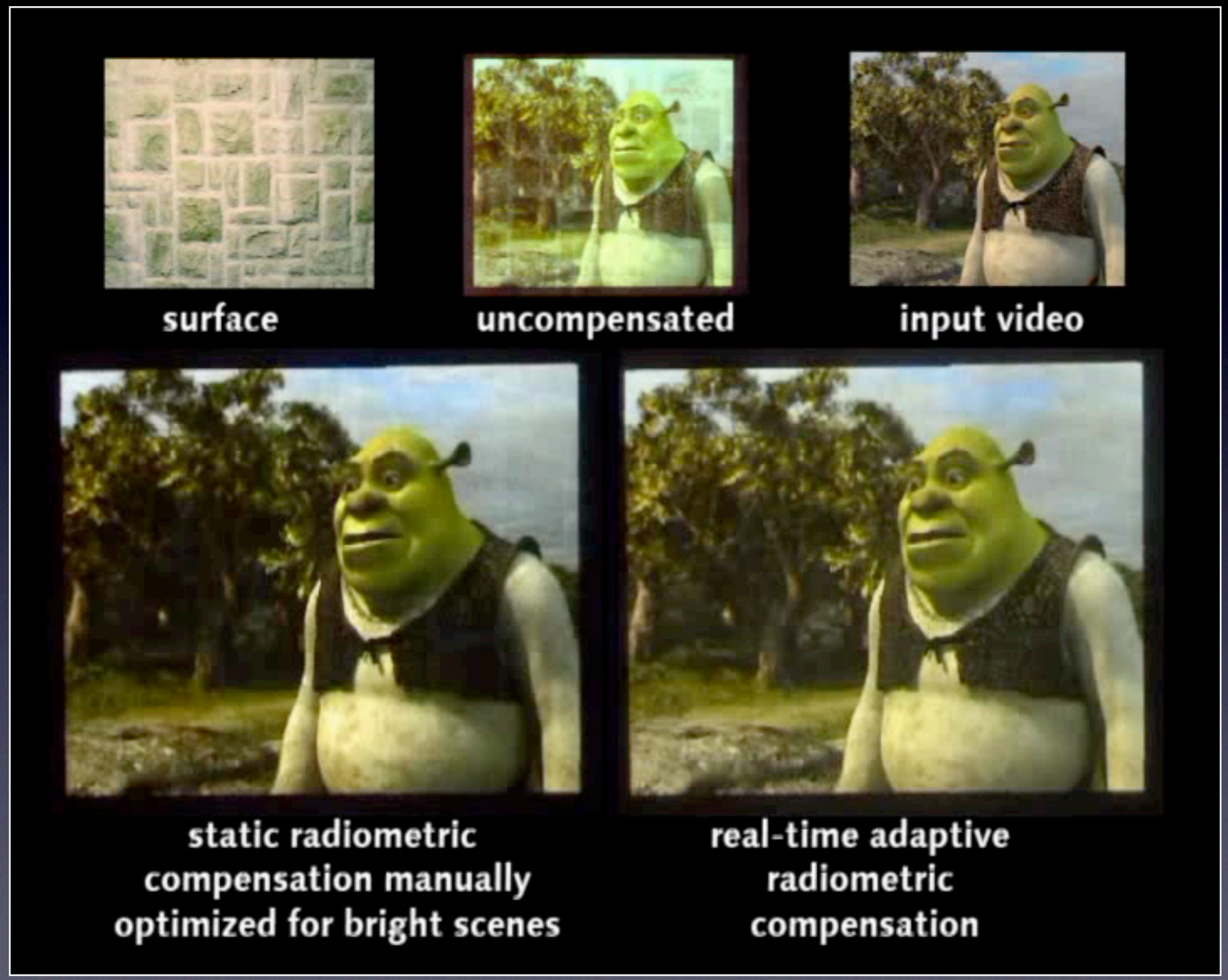
Wetzstein and Bimber, Pacific Graphics 2007





pixelation

Considering Human Visual Perception



Grundhöfer and Bimber, IEEE TVCG 2008

Geometry

Geometric Registration

without correction

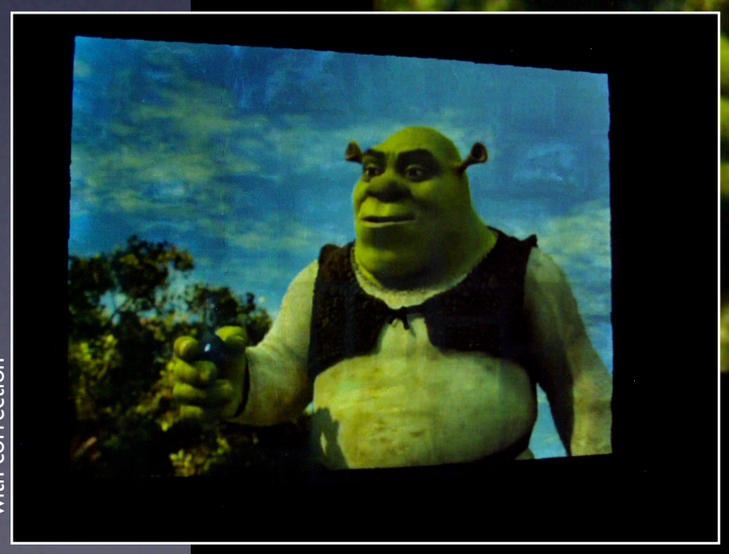
with correction

radiometric compensation

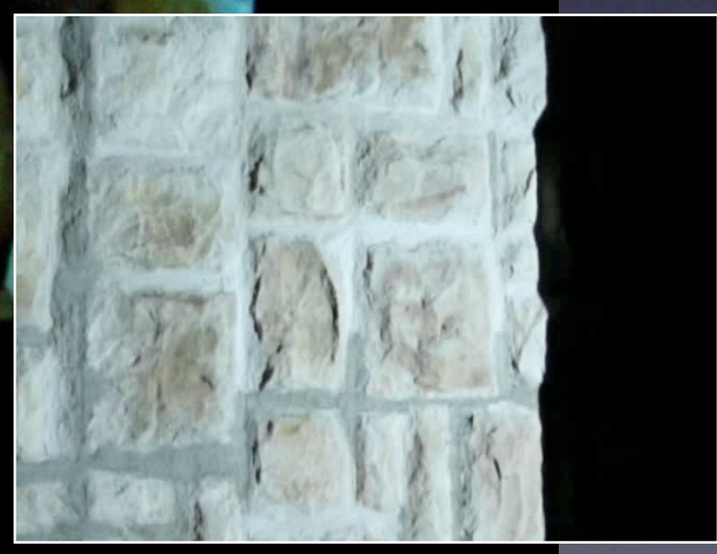
Geometric Registration

without correction

misaligned projection

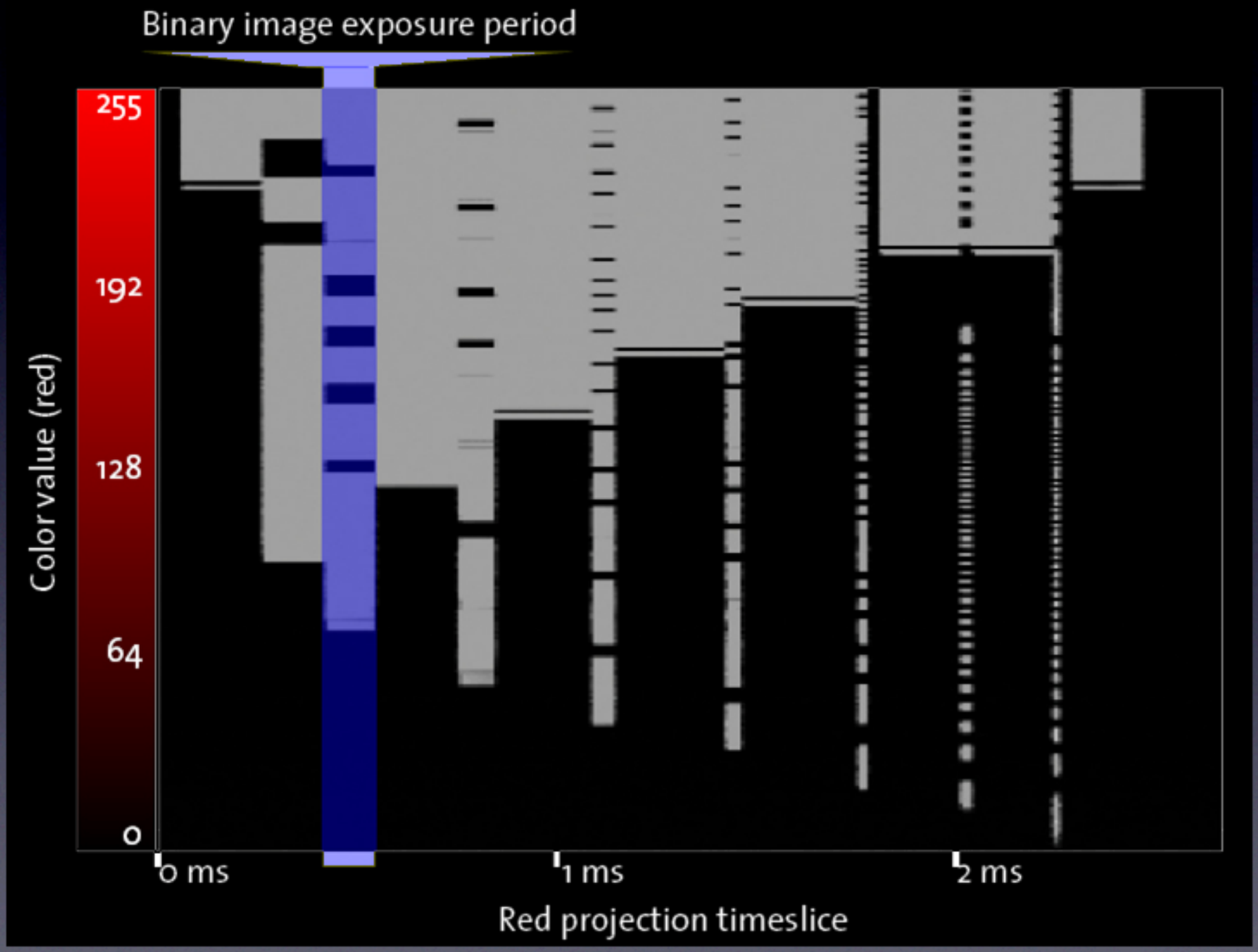


with correction



Imperceptible Online Calibration

Cotting et al., ISMAR 2004 (spatial coding)



Imperceptible Online Calibration

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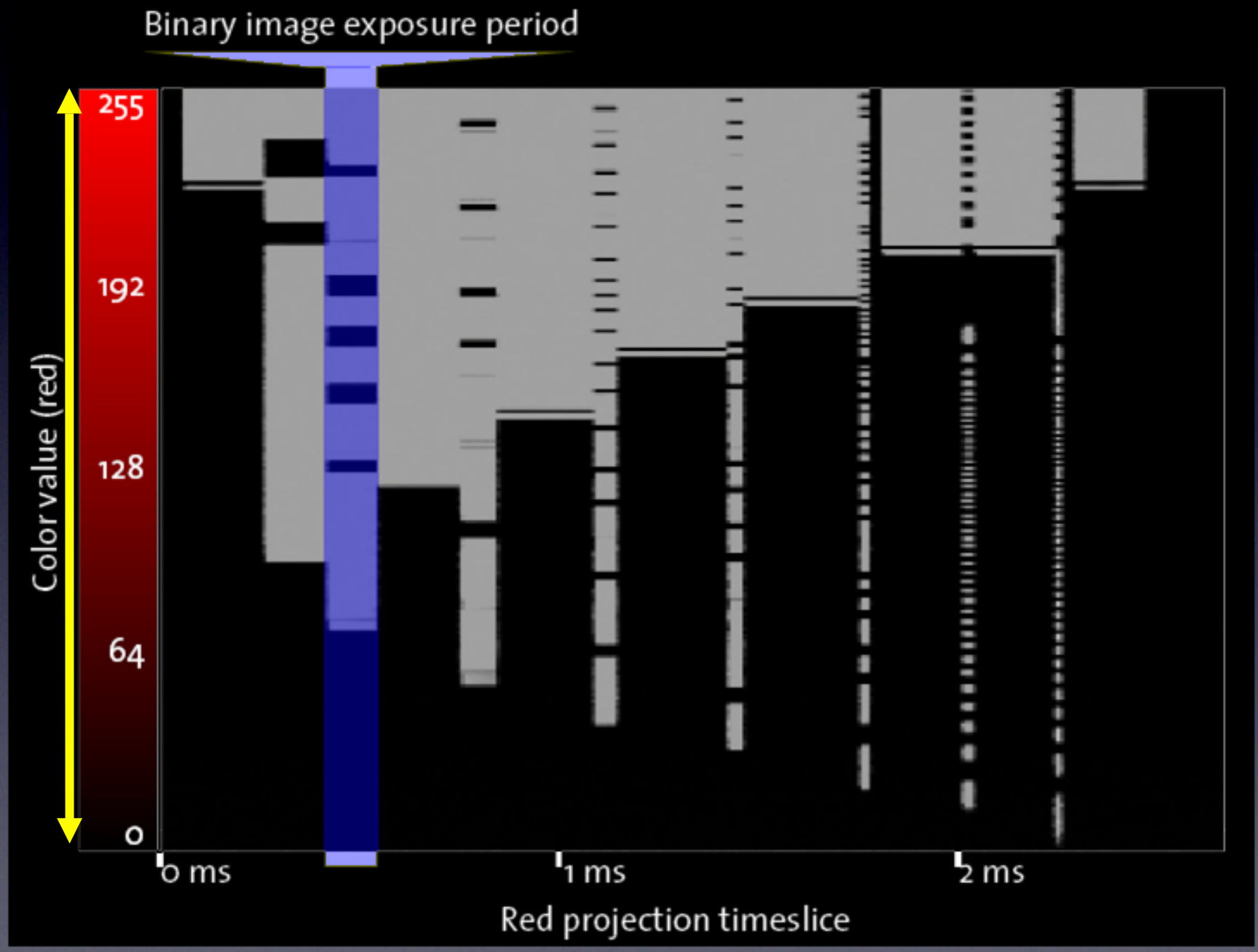

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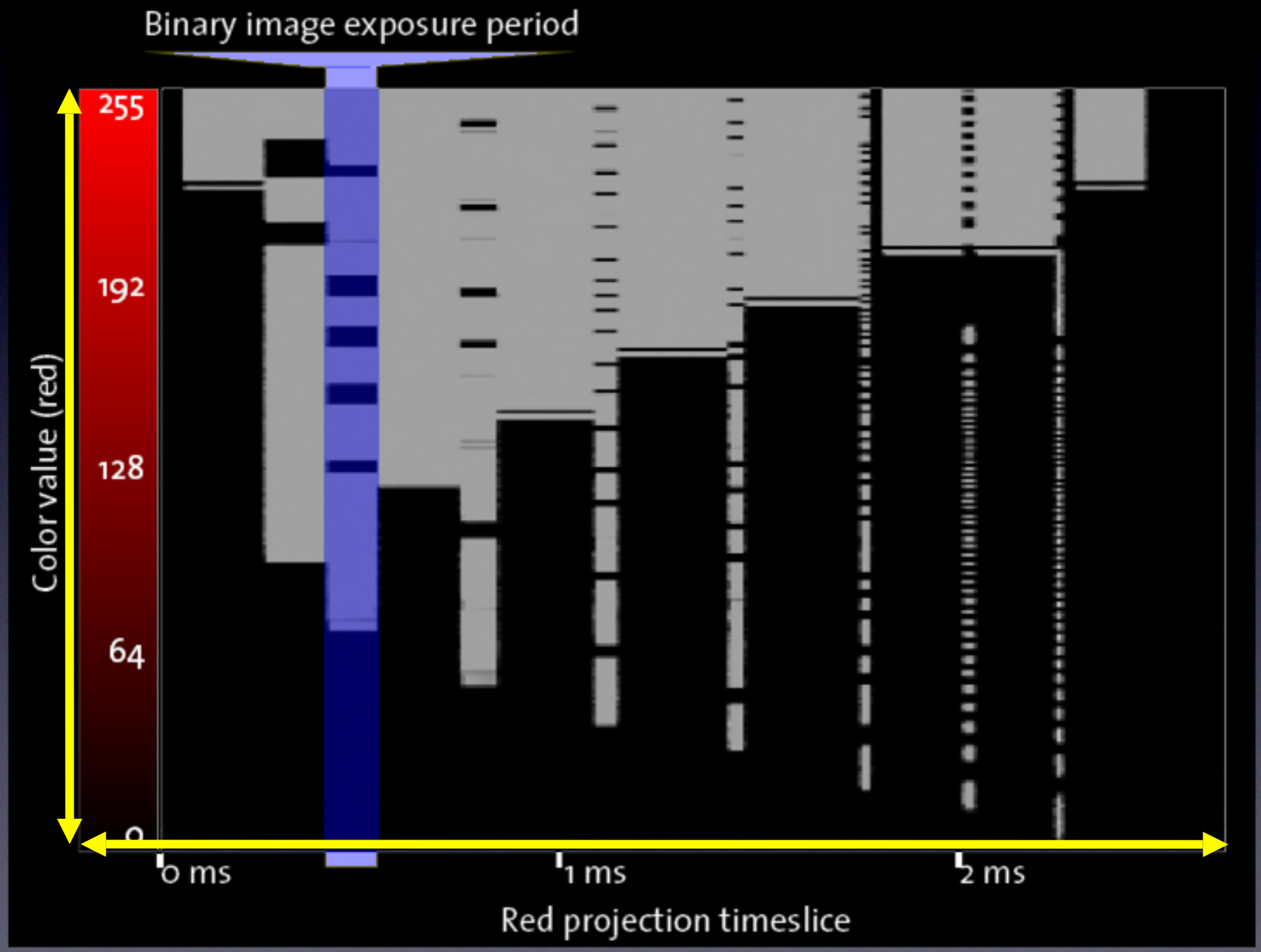
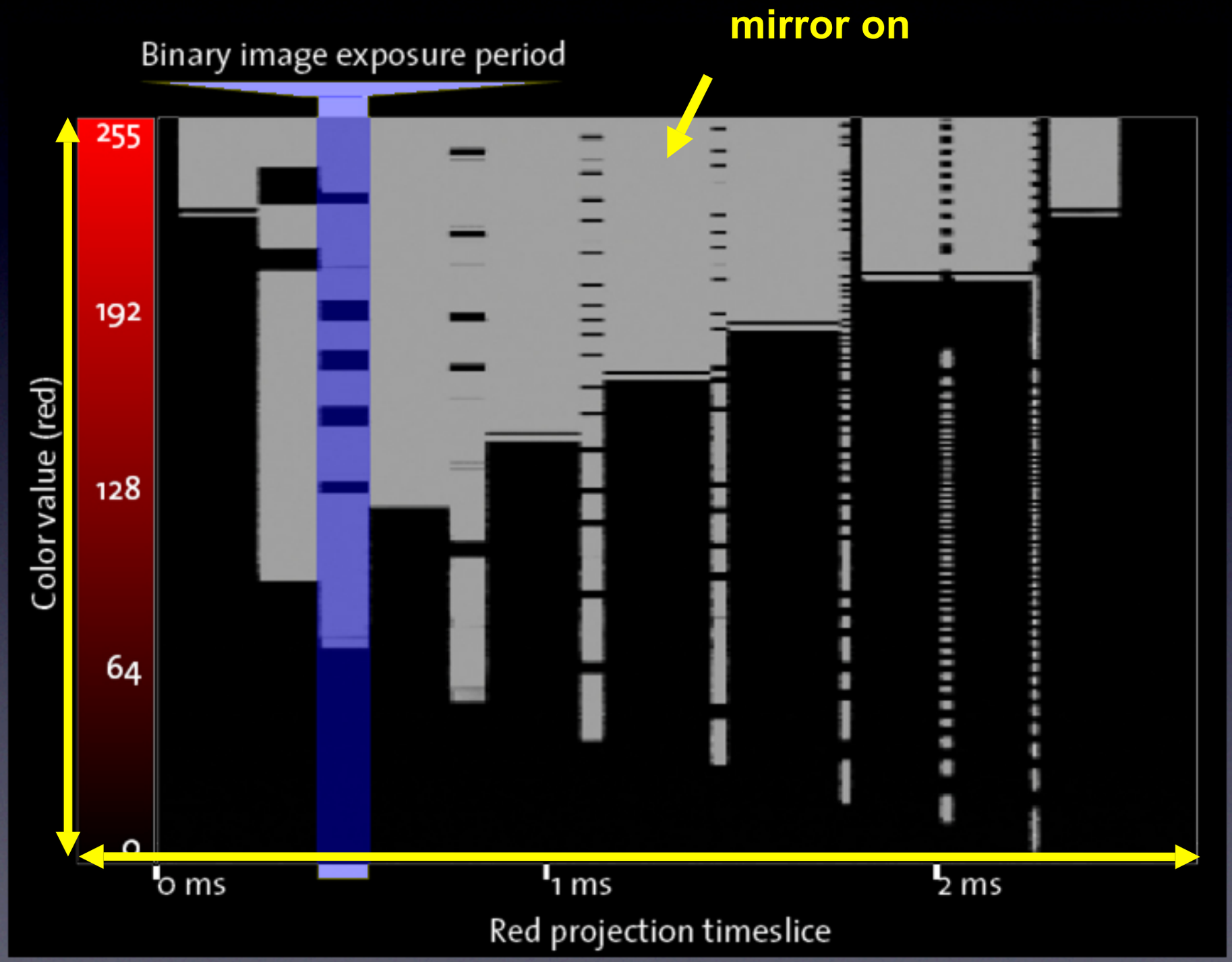


Imperceptible Online Calibration

Cotting et al., ISMAR 2004 (spatial coding)



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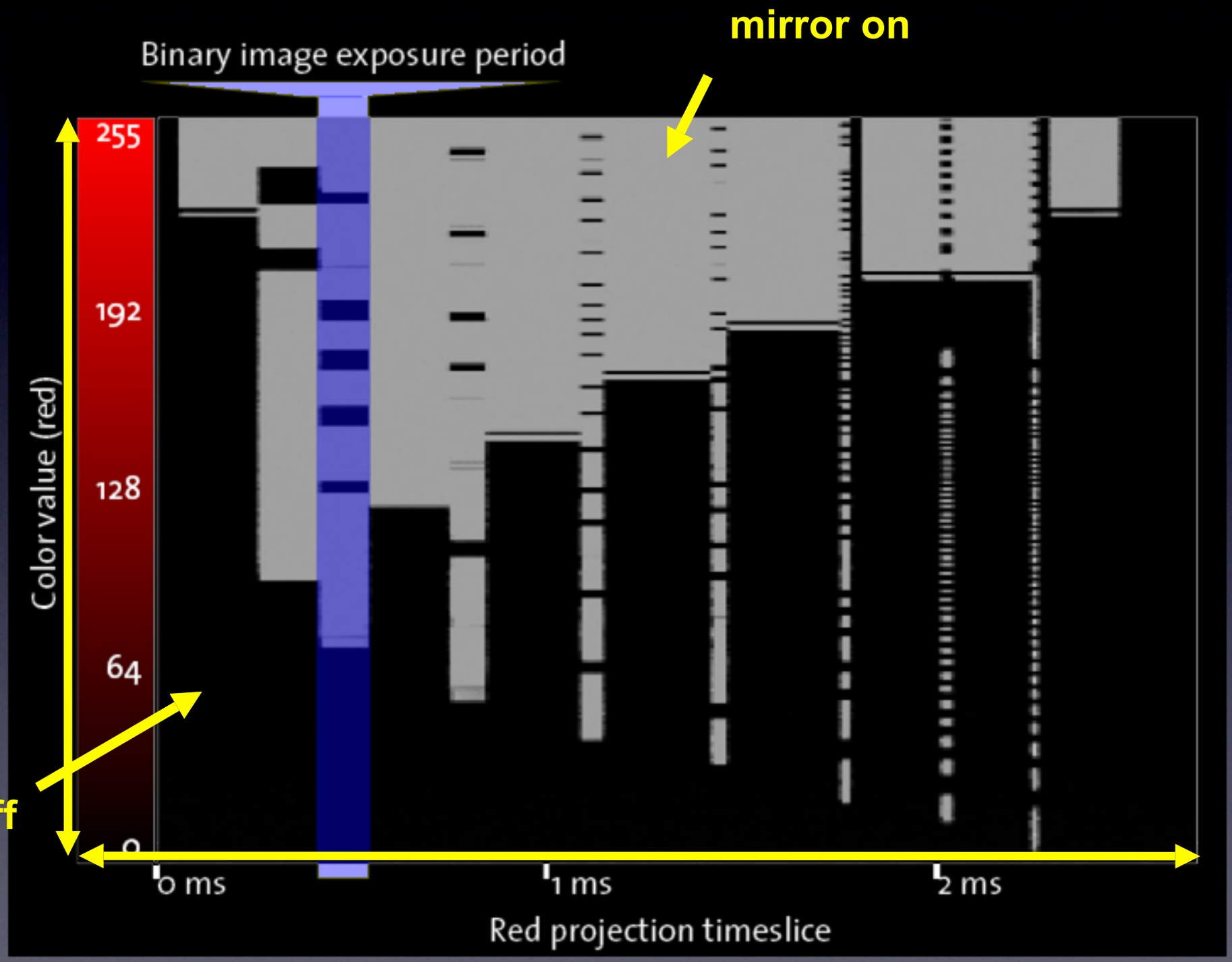

Imperceptible Online Calibration

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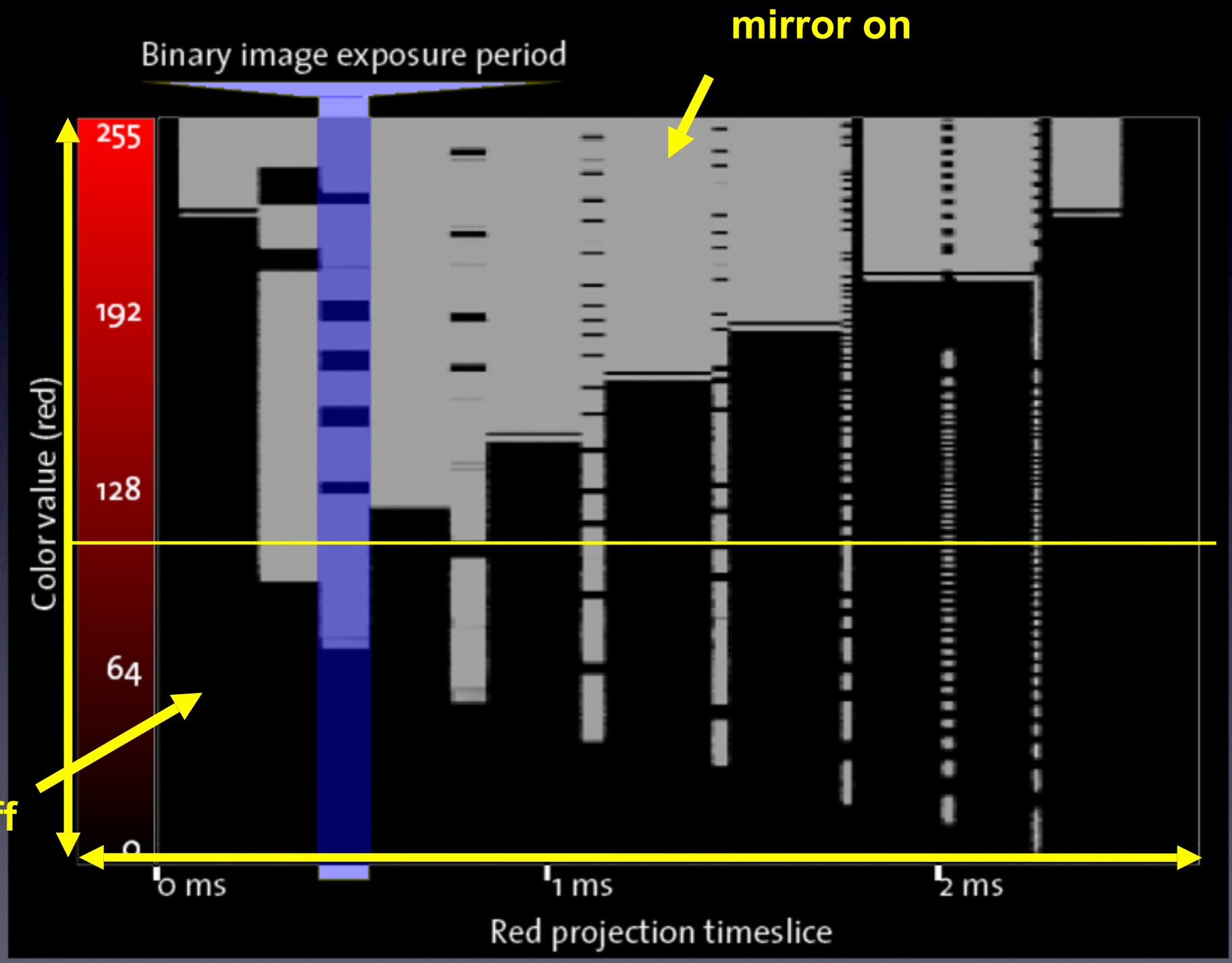

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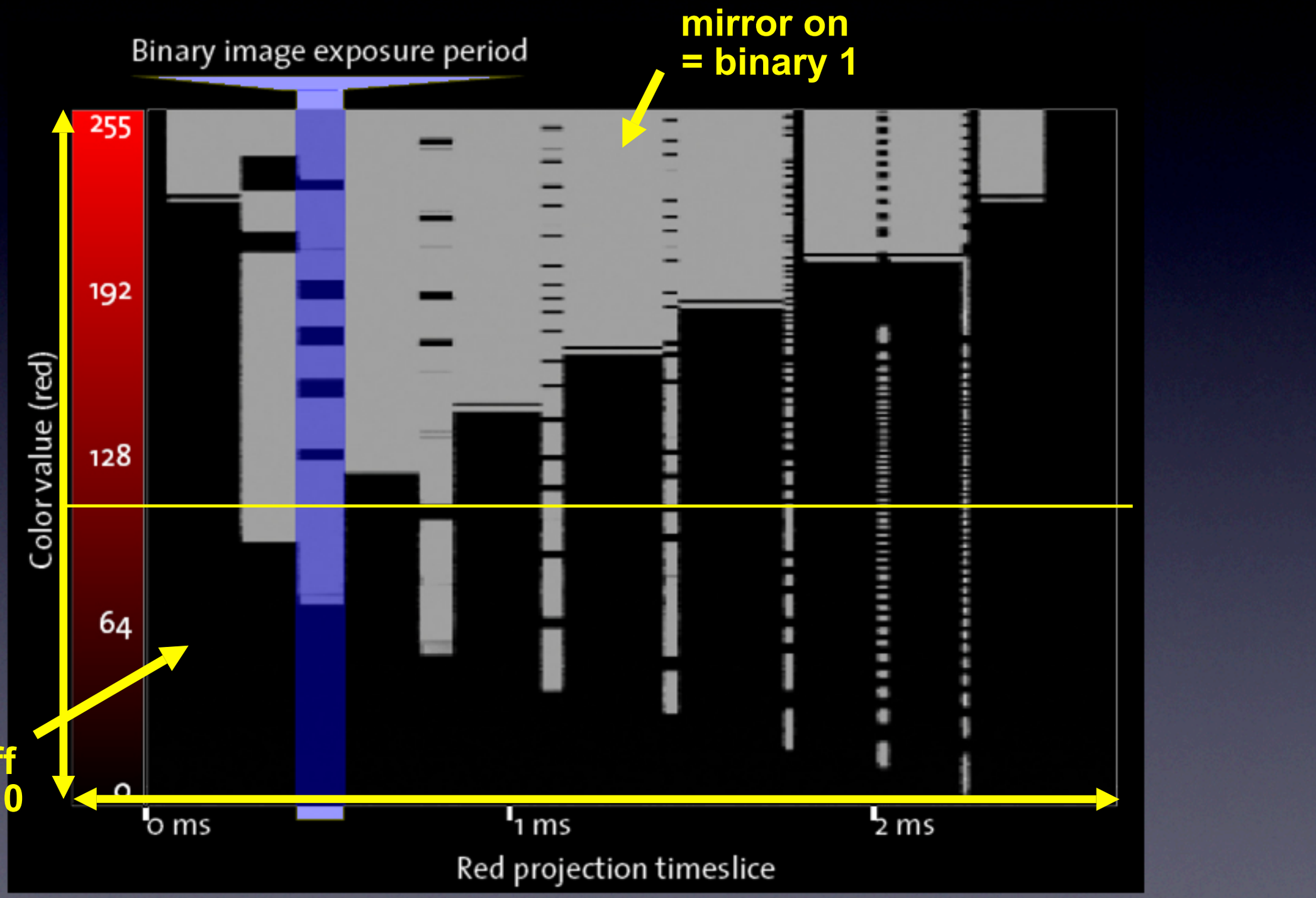

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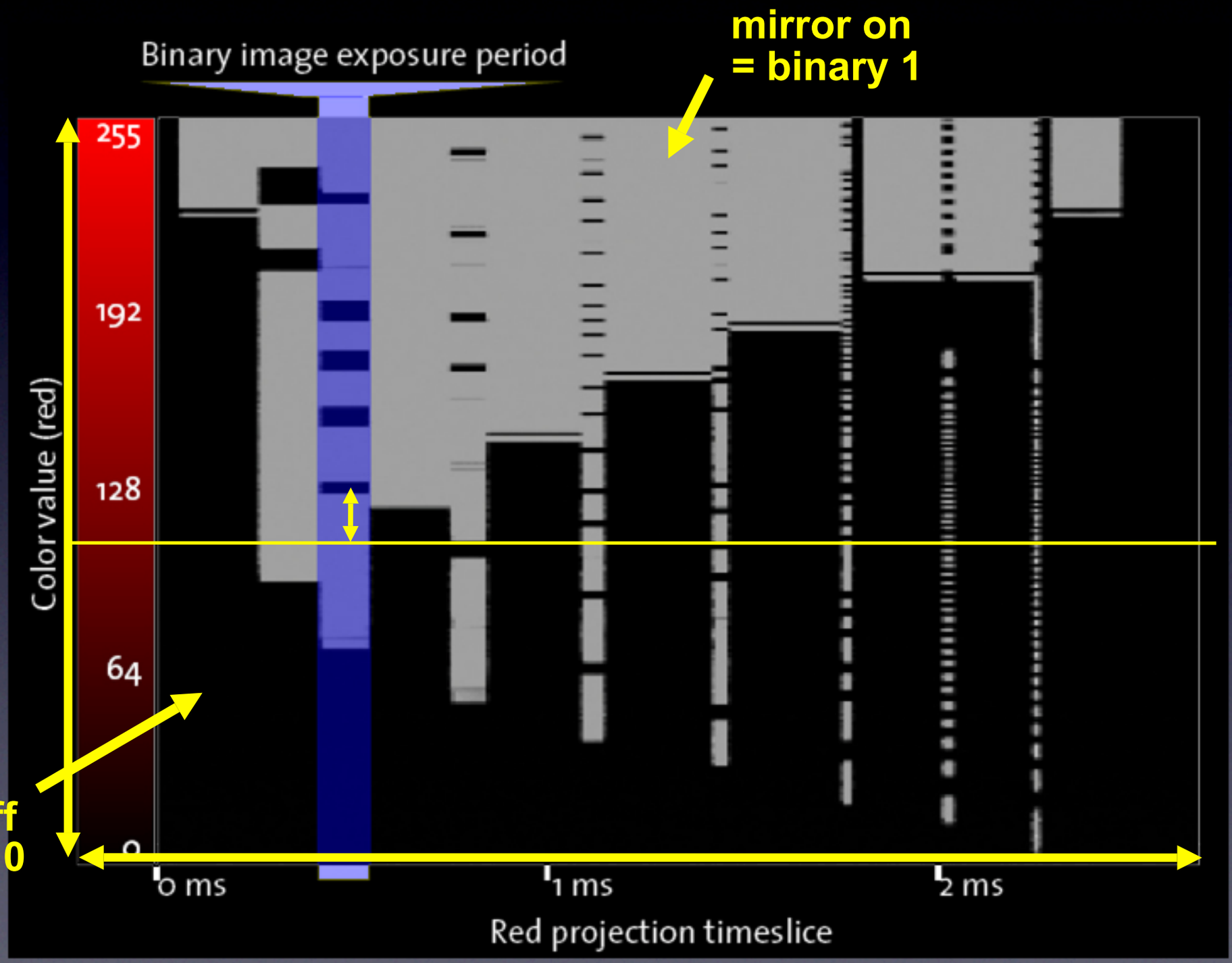

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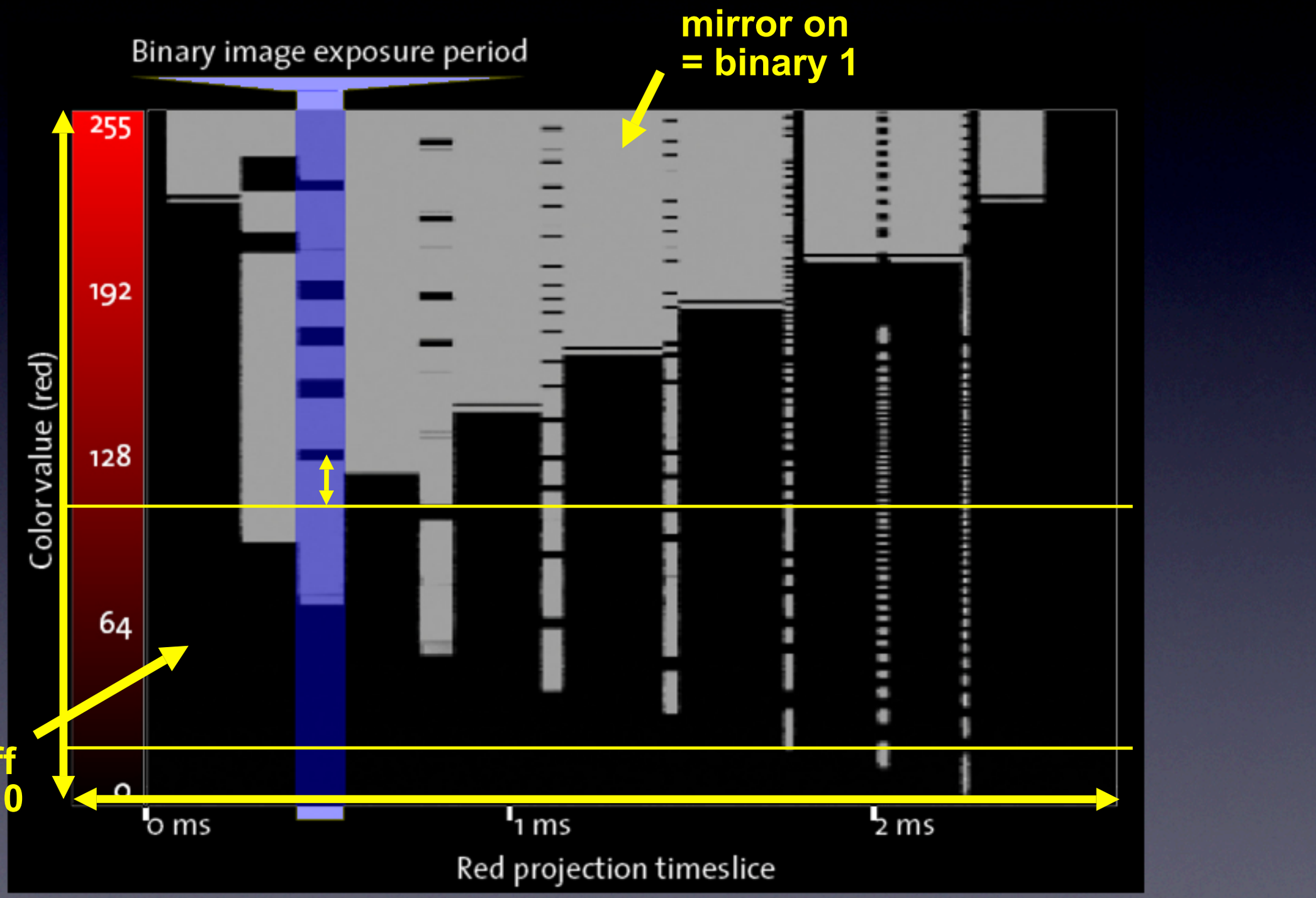

Imperceptible Online Calibration

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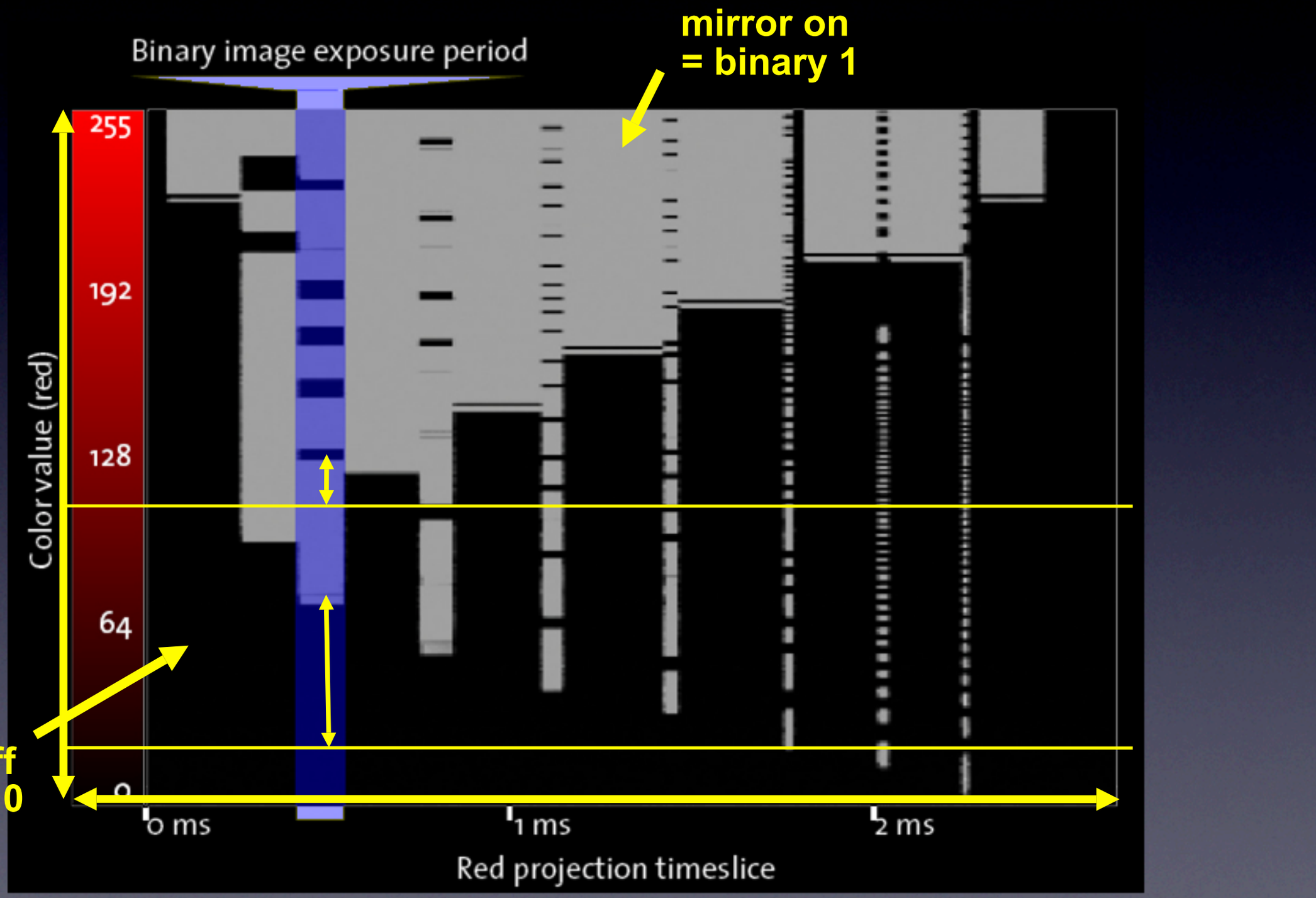
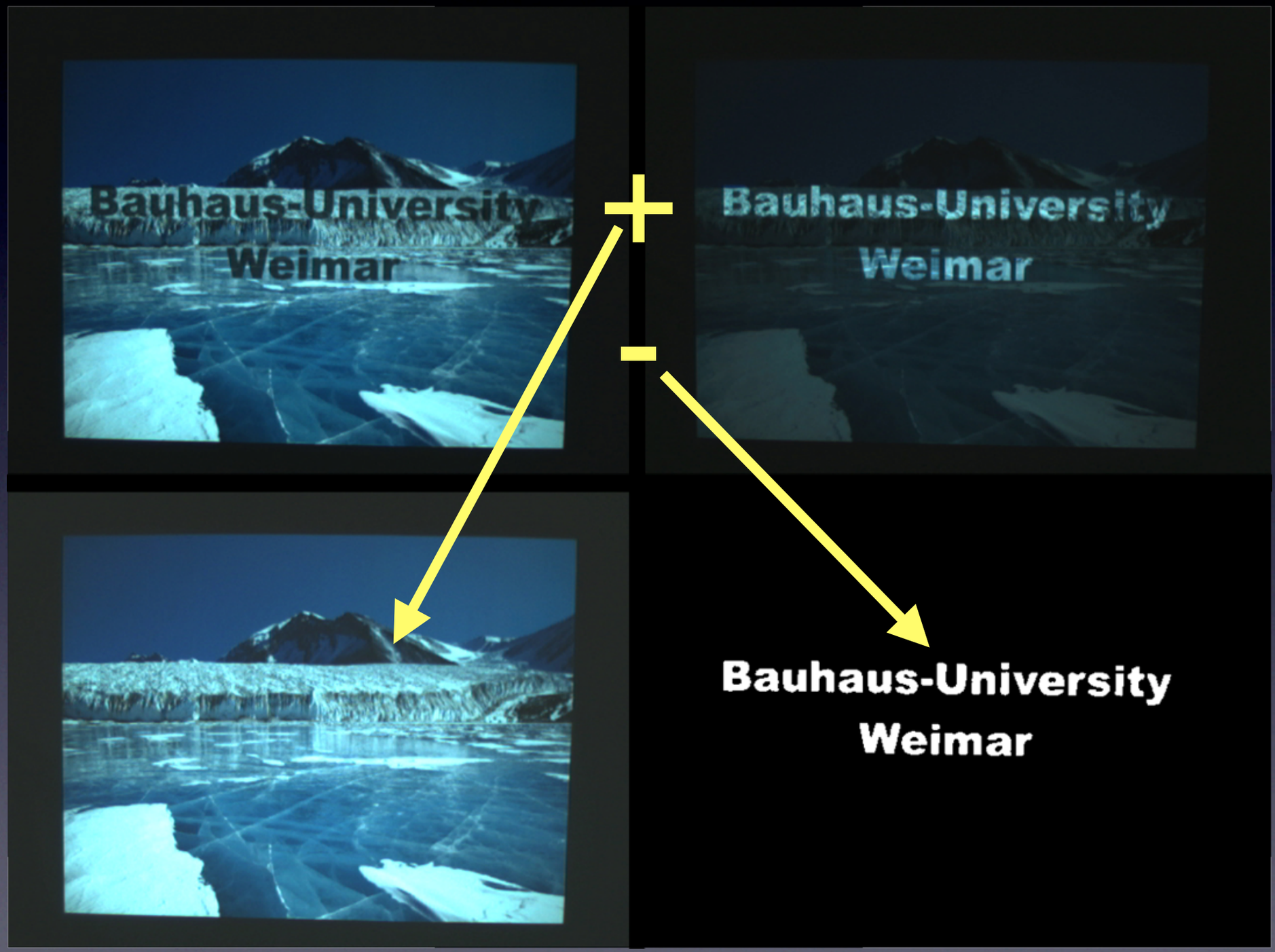


Imperceptible Online Calibration

Raskar et al, Siggraph'98
(temporal coding of binary information)



Imperceptible Online Calibration

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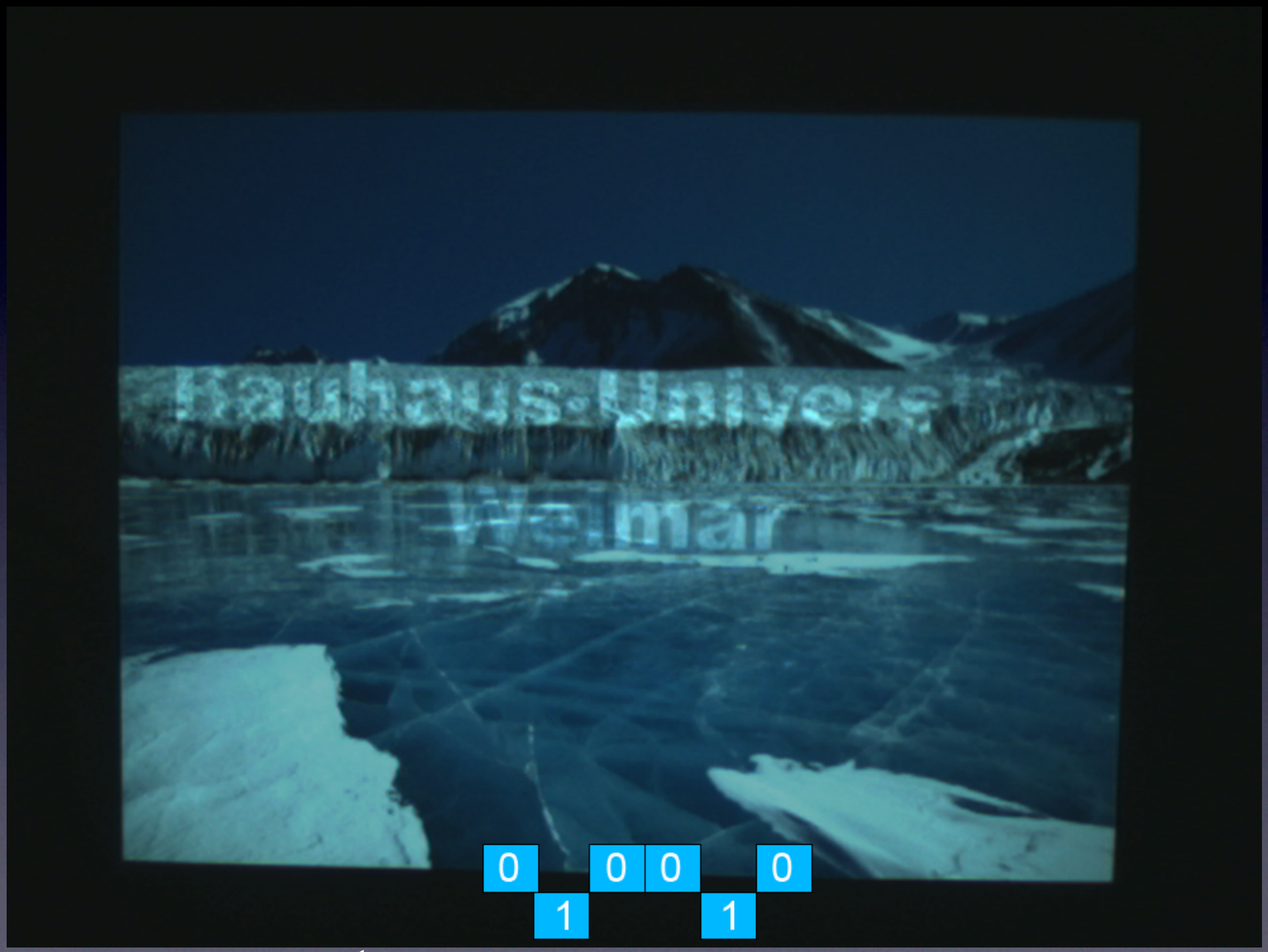
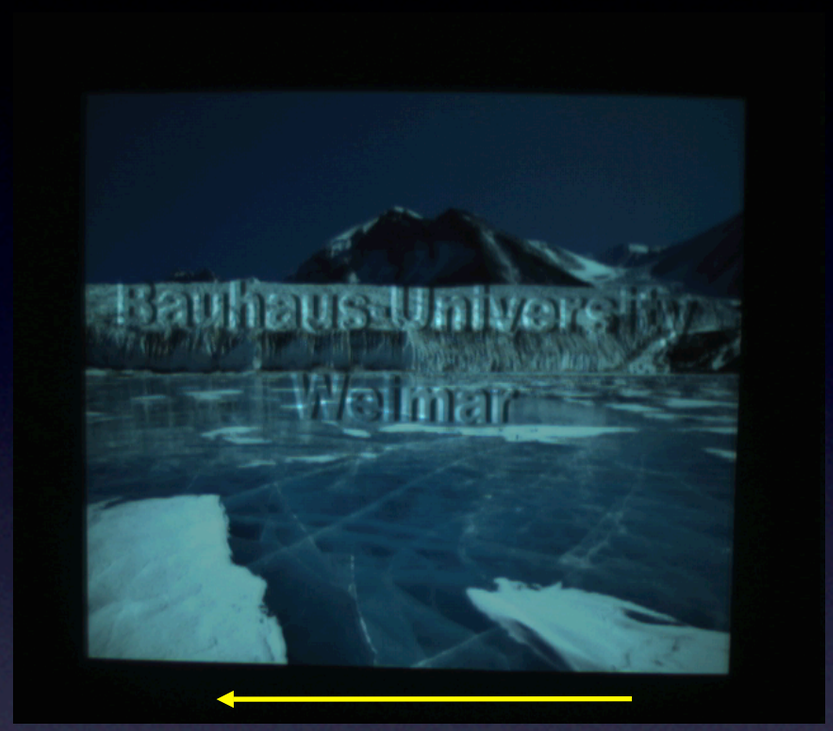
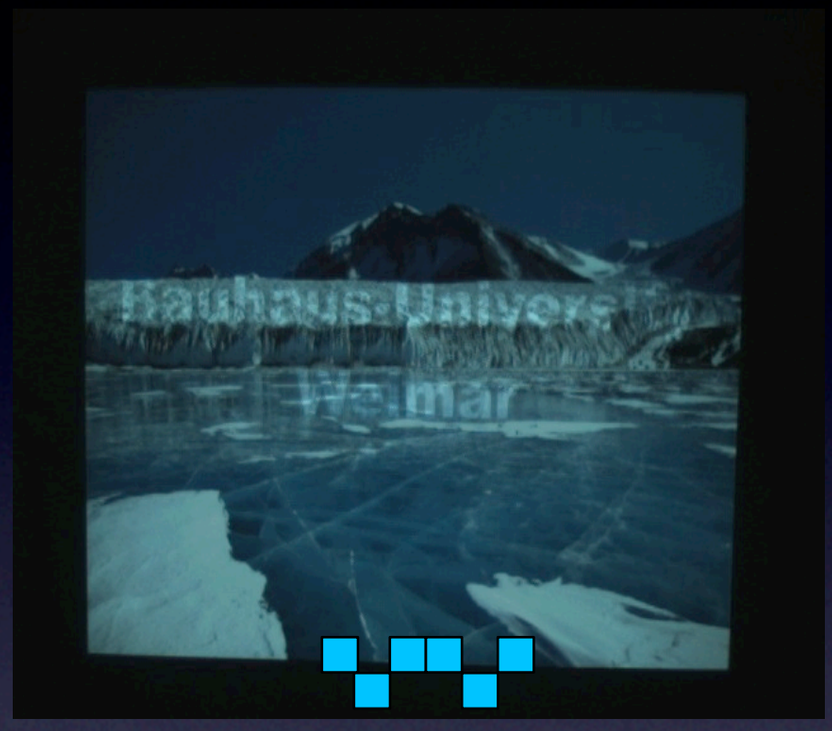


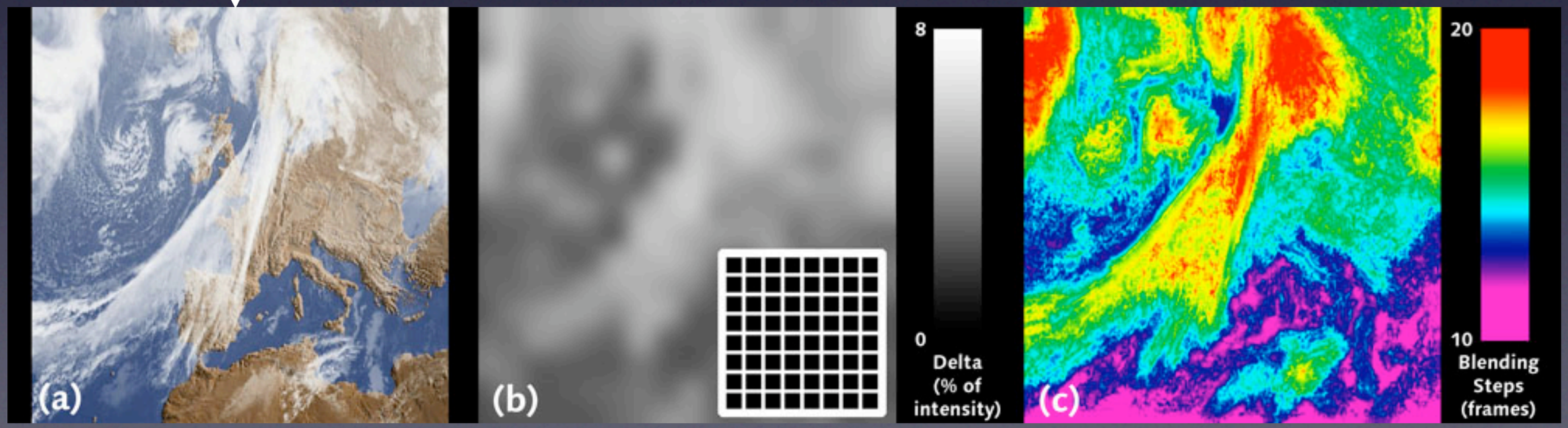
Adaptive Temporal Coded Projection

Grundhöfer, Seeger, Häntsch, Bimber, ISMAR'07

deriving local coding contrast from contrast sensitivity parameters (local spatial *F* and *L*) in code and display images







Adaptive Temporal Coded Projection

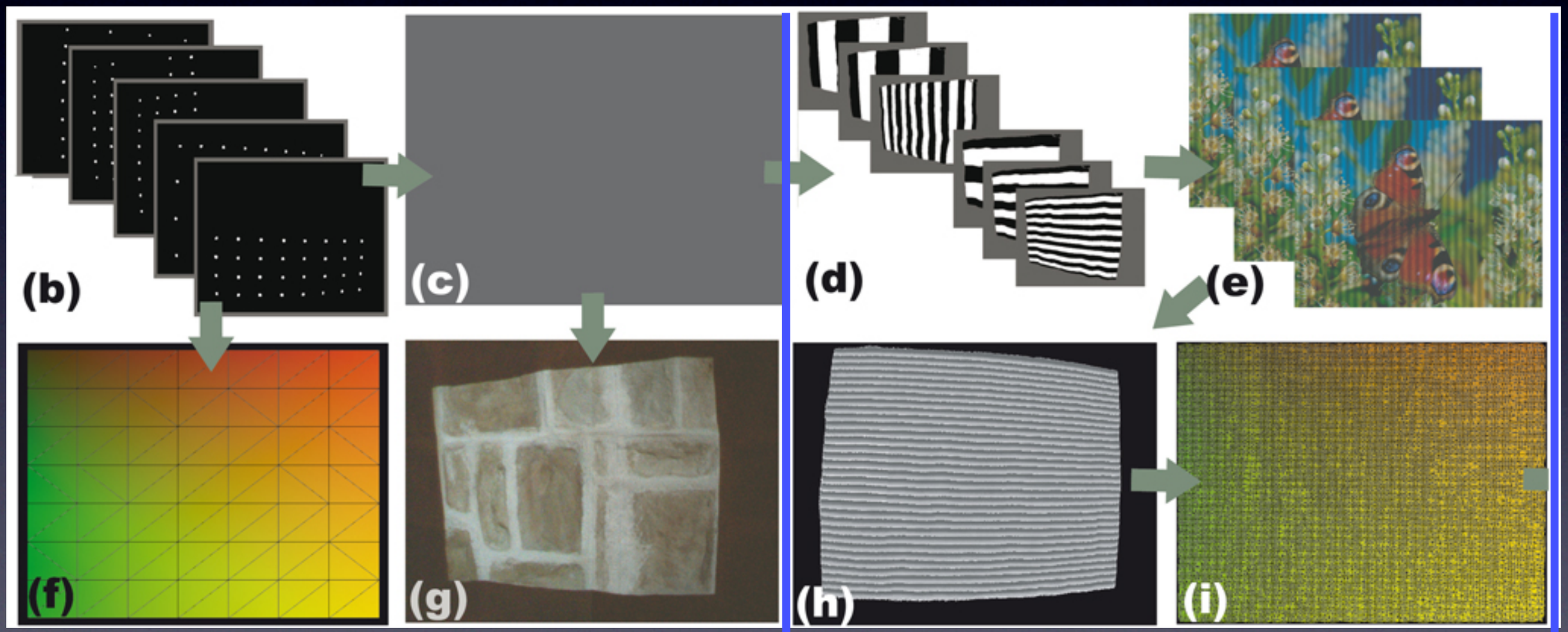
Zollmann and Bimber, Eurographics 2007

binary points (quick geometry)

flat image (reflectance)

binary Gray code (surface discontinuities)

phase shifted cosine (precise geometry)



rough calibration (1.7 seconds)

pixel-precise calibration (6.4 seconds)

Adaptive Temporal Coded Projection

Zollmann and Bimber, Eurographics 2007

projection

camera image

Intensity and Color

Radiometric Compensation

- Local reflectance parameters of surface are measured with camera under structured projection as part of the calibration process
- Different basic methods exist for compensation: considering color mixing between camera and projector, multiple projectors, or real-time correction via closed feedback loop
- Some methods consider environment light, too
- Compensation can be done in real-time, if implemented on GPU
- These techniques can only compensate local diffuse reflections

color mixing

red in red | green in red | blue in red

$$V = \text{(per pixel)} \begin{bmatrix} V_{RR} & V_{RG} & V_{RB} \\ V_{GR} & V_{GG} & V_{GB} \\ V_{BR} & V_{BG} & V_{BB} \end{bmatrix}$$

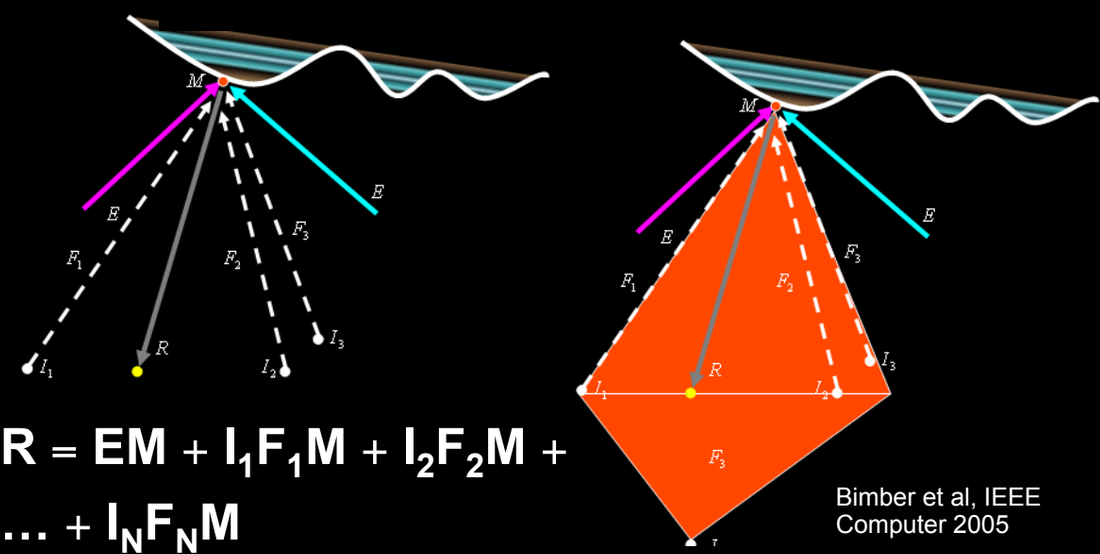
Nayar et al, ProCams, 2003

Yoshida et al, VSMM, 2003 (3x4 color mixing matrix)

Grossberg et al, CVPR, 2004

R=V*I

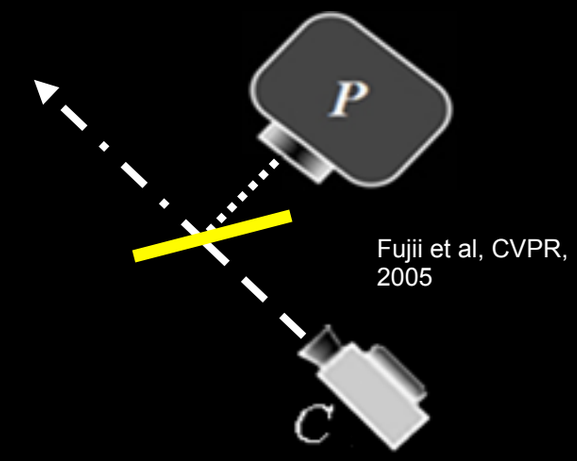
multiple projectors



$$R = EM + I_1F_1M + I_2F_2M + \ldots + I_NF_NM$$

Bimber et al, IEEE Computer 2005

real-time

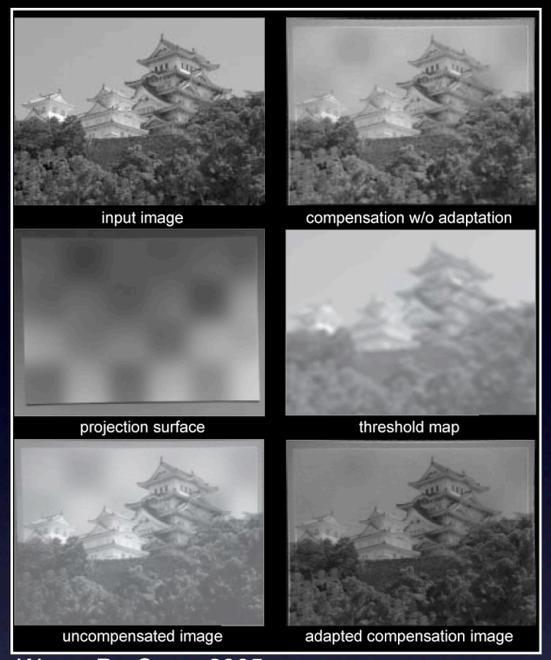


Fujii et al, CVPR, 2005

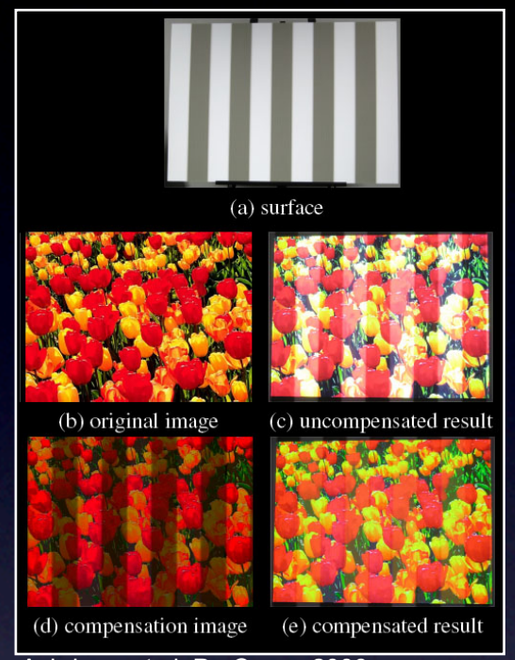
$$R_t=M_t/M_0*(E_t*M_0+V_0*I_t)$$

Adaptive Radiometric Compensation

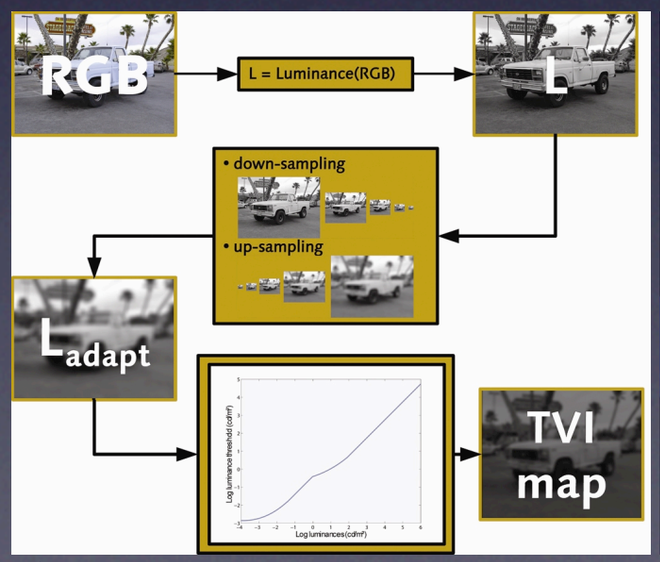
- Consider human visual perception (eg. local contrast perception)
- Adapt parameters for radiometric compensation spatially (different image regions) and temporally (for each frame)
- Achieve much better results than static techniques
- Require more processing

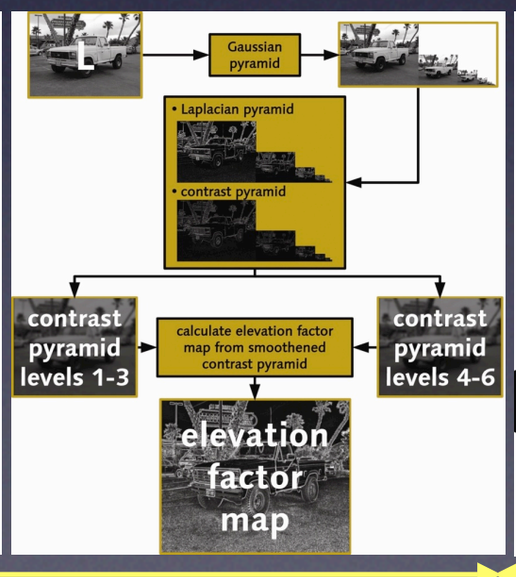


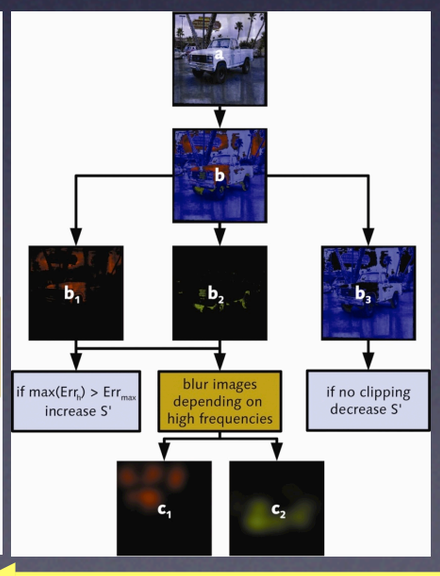
Wang, ProCams 2005
(only gray scale)

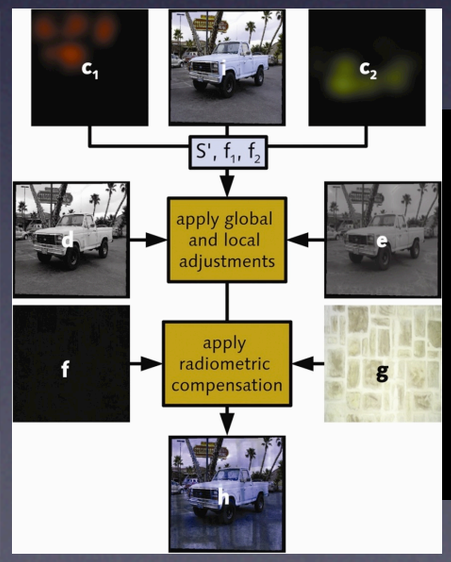


Ashdown et al, ProCams, 2006
(only static)

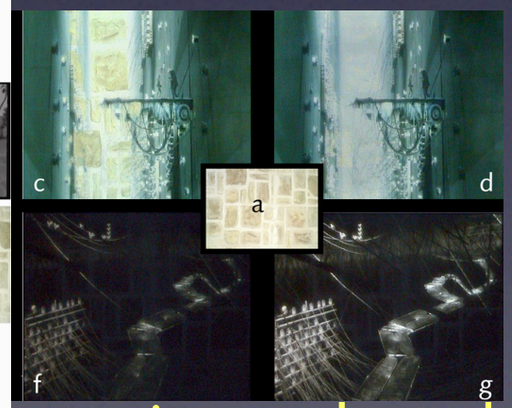








Grundhöfer and Bimber, IEEE TVCG 2008 (color and realtime)



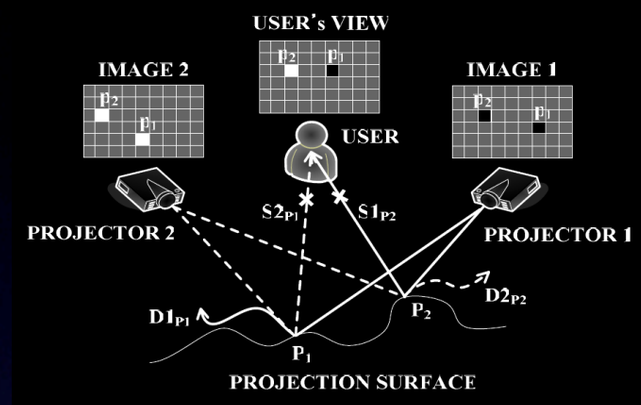
static adapted

analysis synthesis

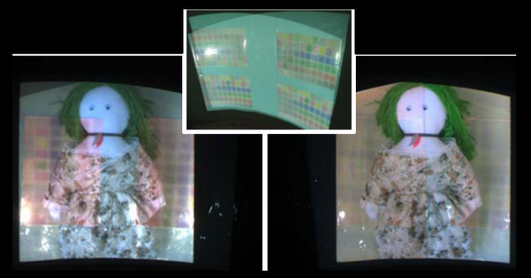
Specular and Global Effects

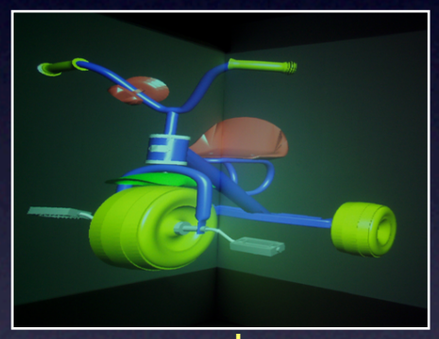
- Specular highights and shadows can be compensated with multiple projectors (highlights are view dependent!)
- Scattering can be compensated in real-time through reverse radiosity techniques
- In theory, all measurable light modulations can be compensated by measuring and inverting the light transport (ie., comuting the inverse light transport matrix)- but this is not practical due to performance (only scanning, compensation is in real-time) and quality reasons

specular highlights

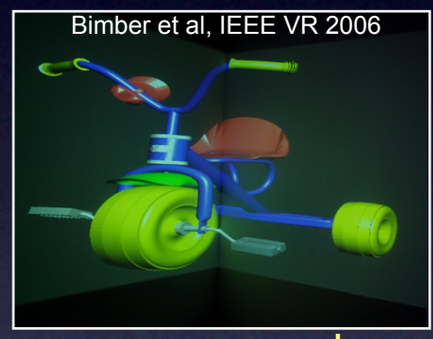


Park et al, PCM, 2005





normal



Bimber et al, IEEE VR 2006

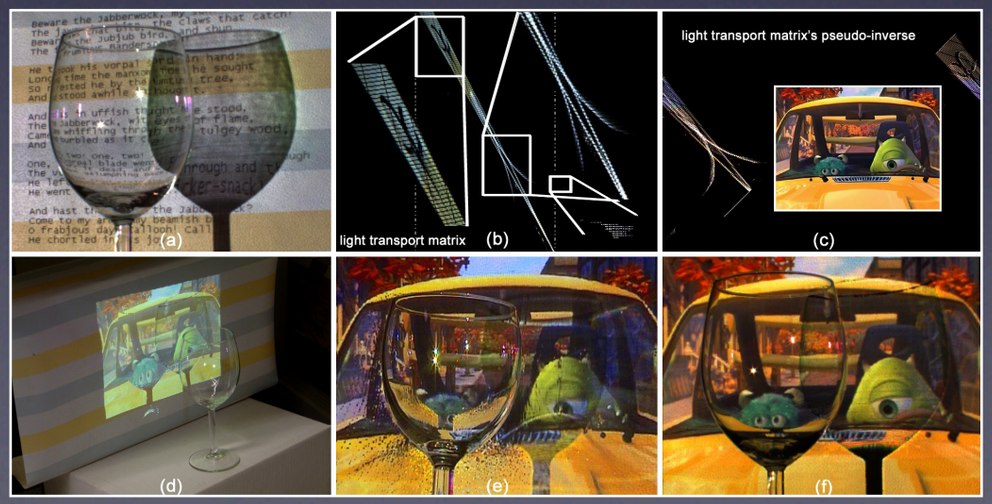
compensated

corrected scattering and color bleeding

related:
Seitz et al., ICCV 2005
Bimber et al., IEEE VR + Tech Rep. BUW, 2006
Mukaigawa et al., VRST 2006
Habe et al, ProCams 2007

scattering and interreflections

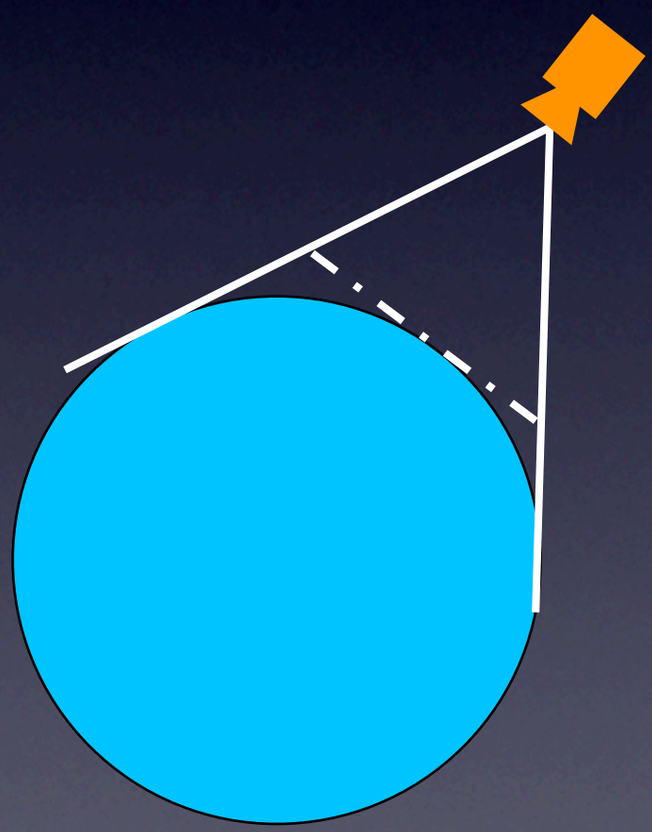
refraction, caustics, shadows, scattering, interreflactions, defocus, etc. (inverse light transport)



Wetzstein and Bimber, Pacific Graphics 2007

Defocus

Multi-Focal Projection



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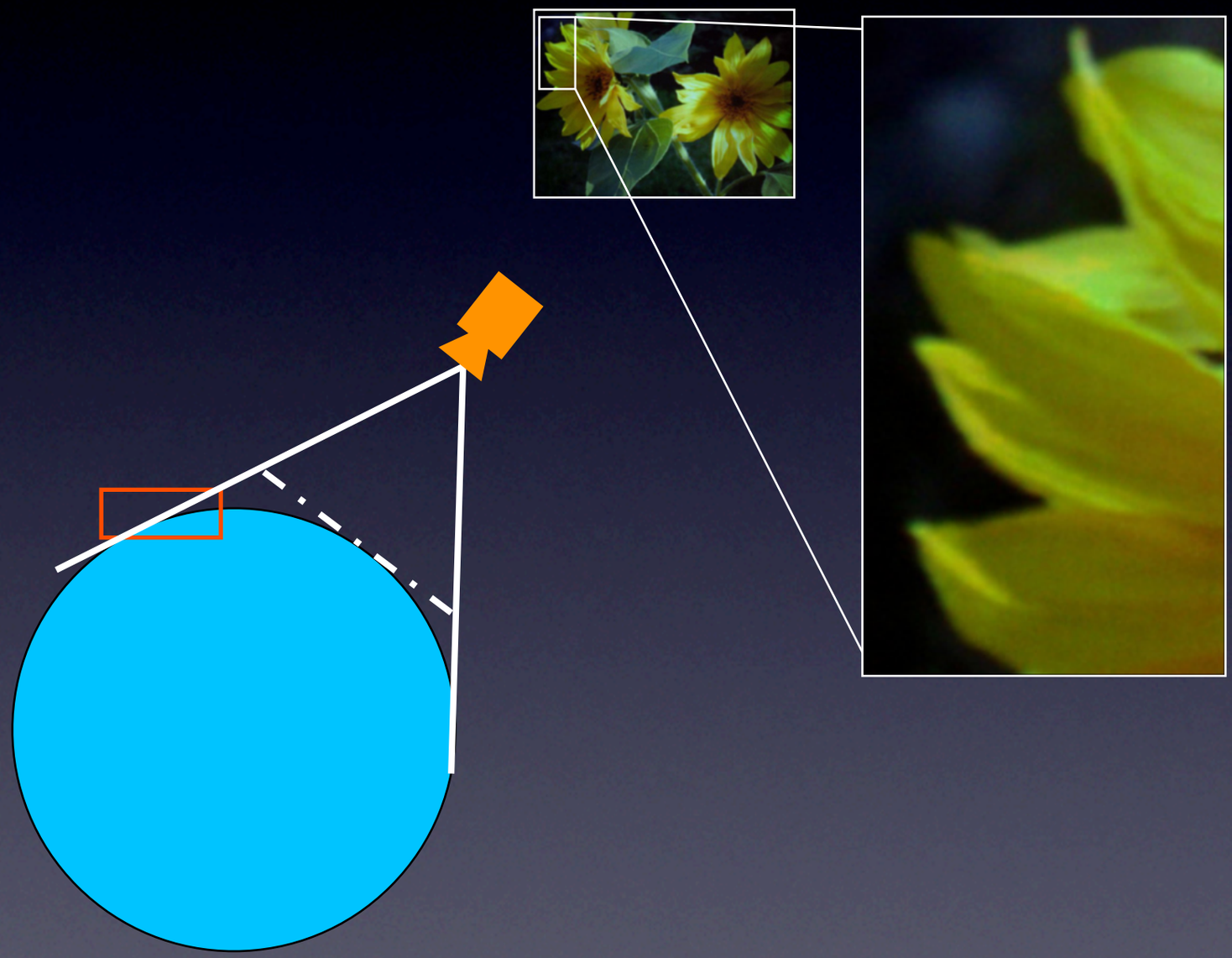
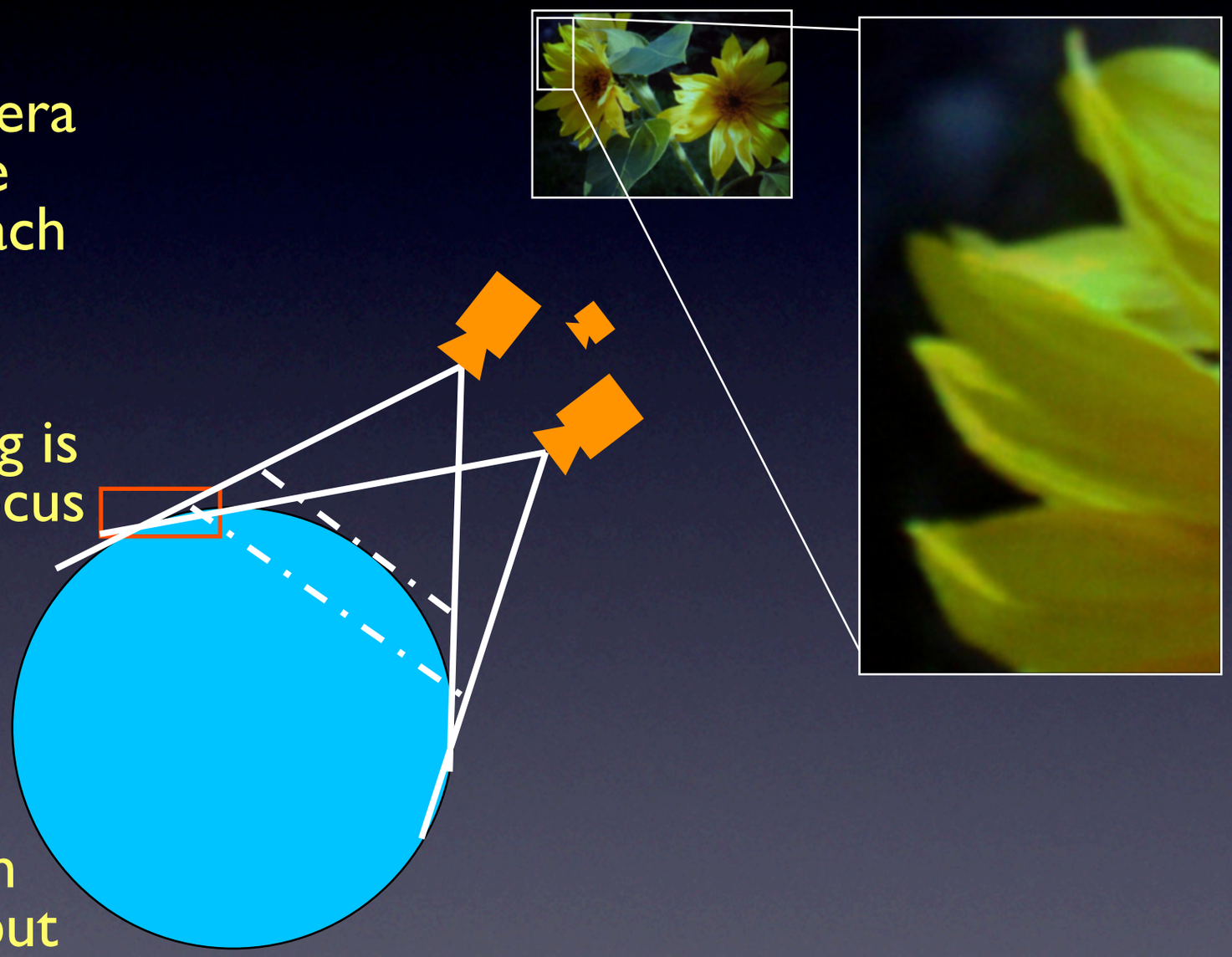


Multi-Focal Projection

- Multiple projectors with overlapping images and different focal planes
- Structured light and camera feedback delivers relative defocus of all pixels of each projector
- Projector-individual pixel contribution and blending is computed based on defocus
- Offline calibration and realtime correction on all surfaces (geometric complex and colored)
- Depth of field scales with number of projectors - but multiple projectors are required



Bimber et al, IEEE TVCG 2006

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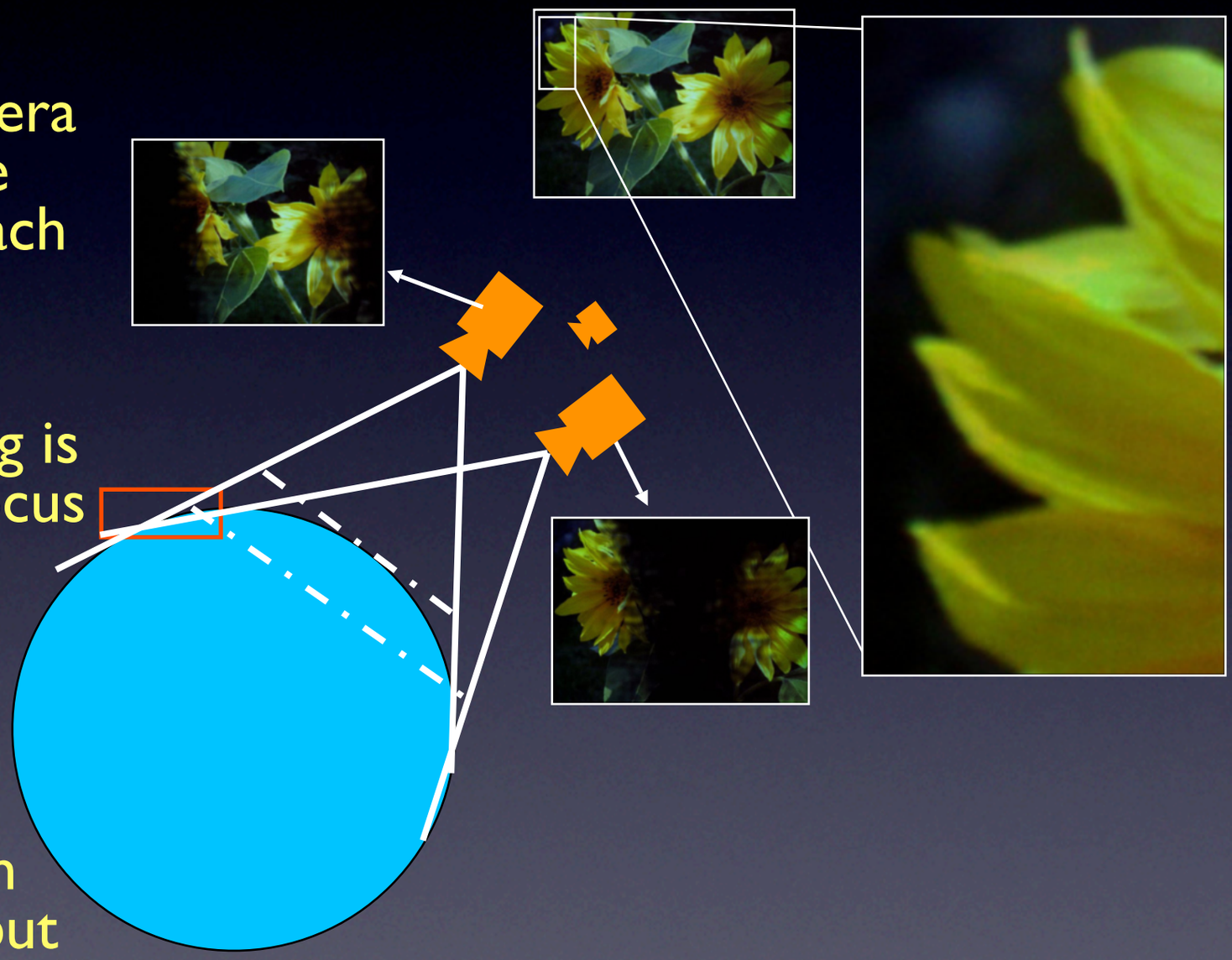

Bimber et al, IEEE TVCG 2006

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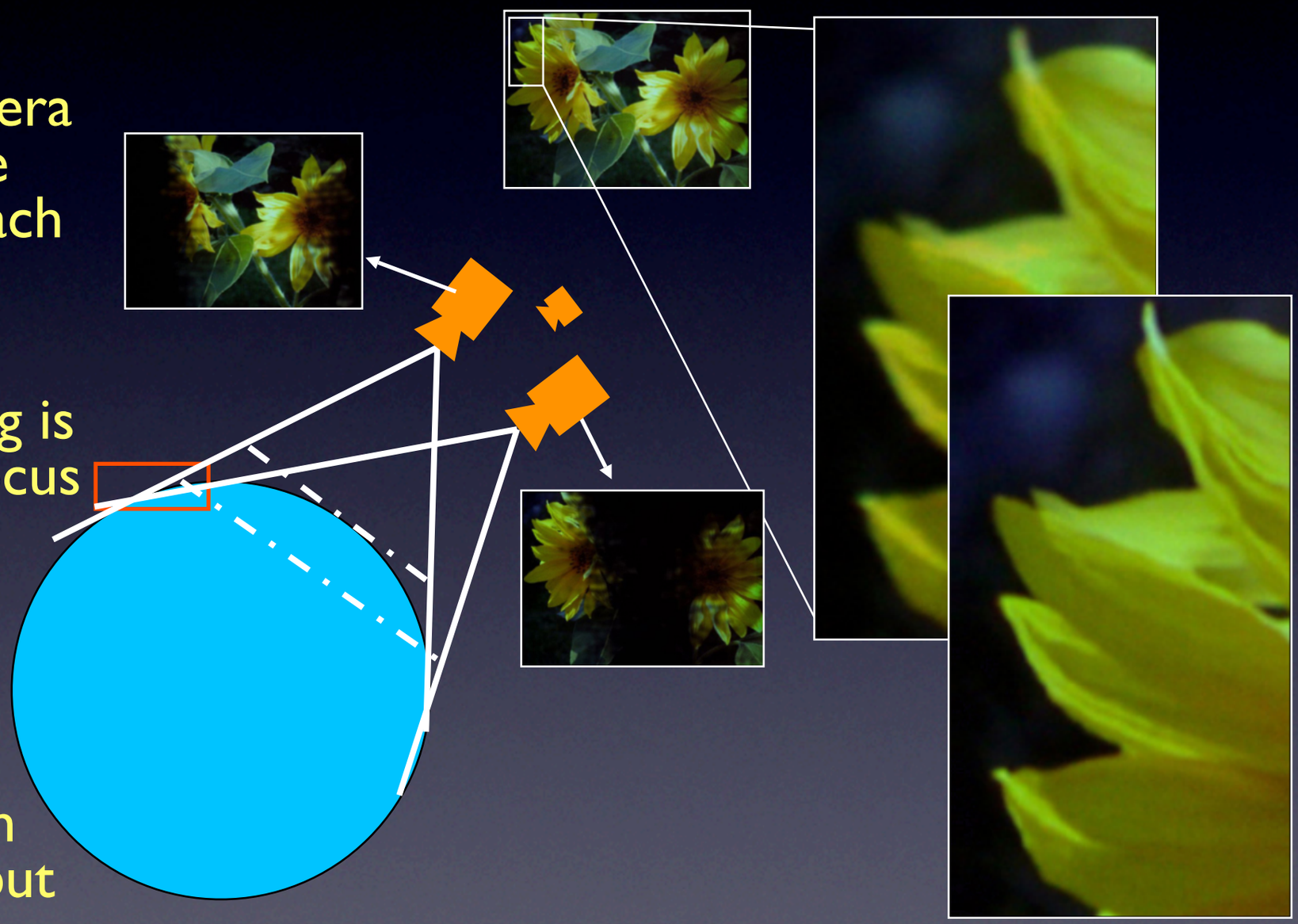


Bimber et al, IEEE TVCG 2006

Inverse Filtering / Deconvolution

Defocus as a convolution:

image * kernel / aperture = result

Inverse Filtering / Deconvolution

Defocus as a convolution:

image kernel / aperture result

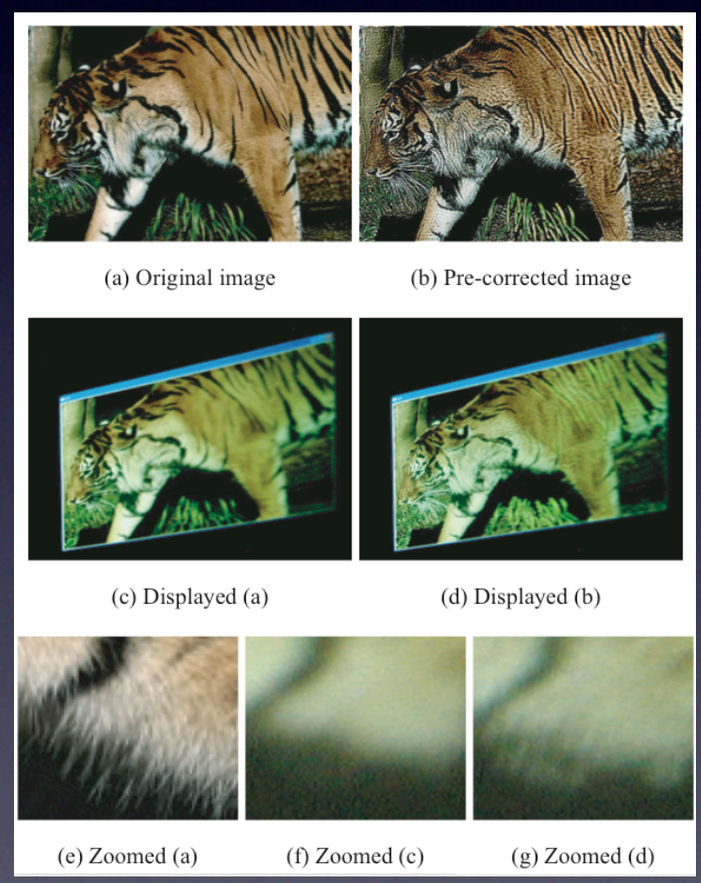
Defocus compensation as deconvolution:

Inverse Filtering / Deconvolution

- Estimating blur scales / point spread function
  - using test pattern / structured light
  - comparing blurred original with camera-captured original
- Calculating compensation images for each scale
  - division in frequency domain
  - optimization in spatial domain
- Combine final compensation image from that images / image portions using linear interpolation

Brown, M. S., Song. P., and Cham. T.-J.
2006. Image Pre-Conditioning for Out-of-Focus Projector Blur,
In Proc. of IEEE Conference of CVPR, vol. II, 1956-1963.

Zhang, L., and Nayar, S. K.
2006. Projector Defocus Analysis for Scene Capture and Image Display.
ACM Trans. Graph. (Siggraph) 25, 3, 907-915.



Oyamada, Y., and Saito, H.
2007. Focal Pre-Correction of Projected Image for Deblurring Screen Image.
In Proc. of IEEE ProCams,

Ringing Artifacts

$$\hat{\mathrm{I}} = \frac{\hat{\mathrm{I}'}}{\hat{\mathrm{K}}_s}$$

⟵ division by possibly very small values!

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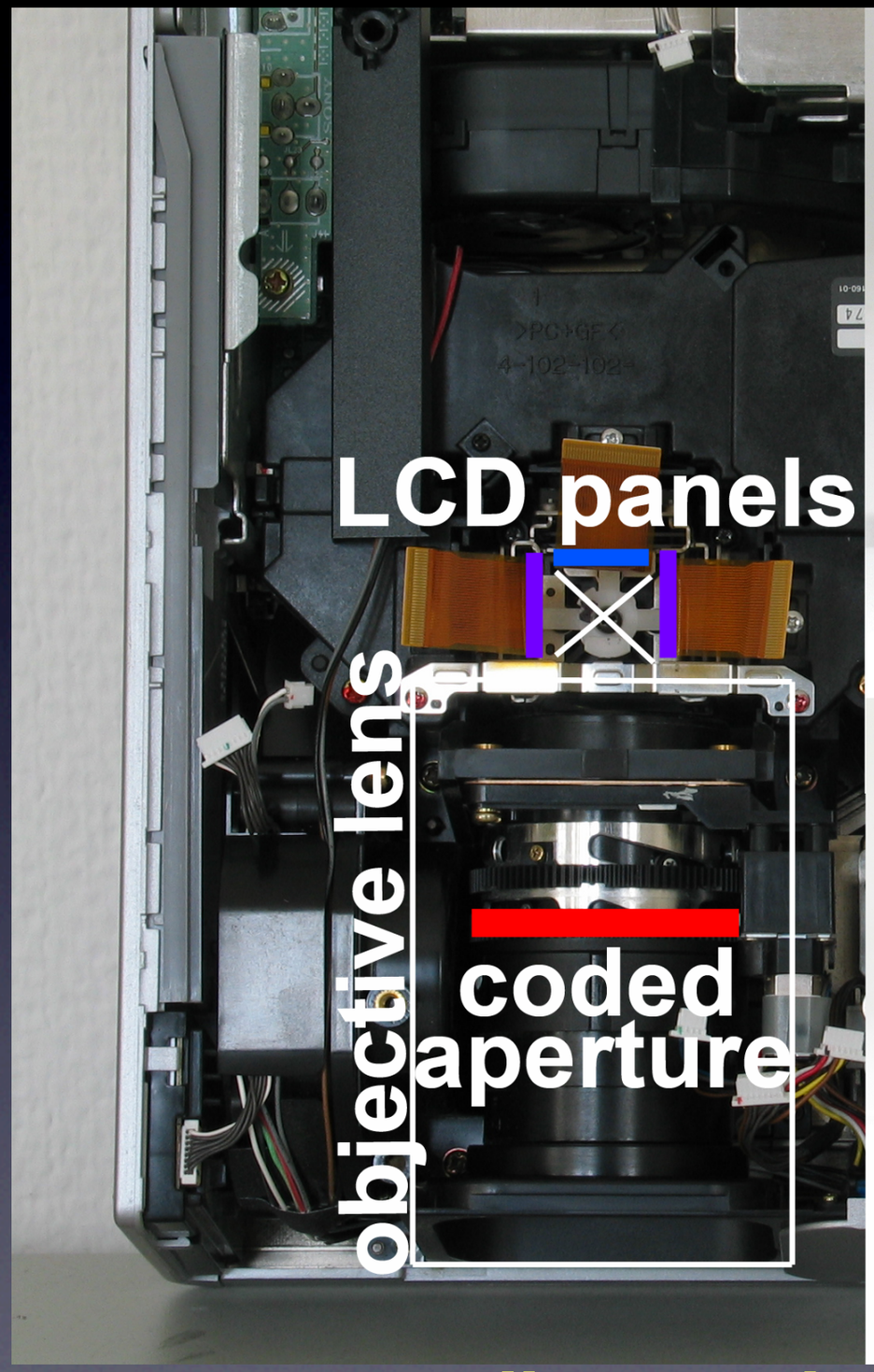
Coded Aperture Projection



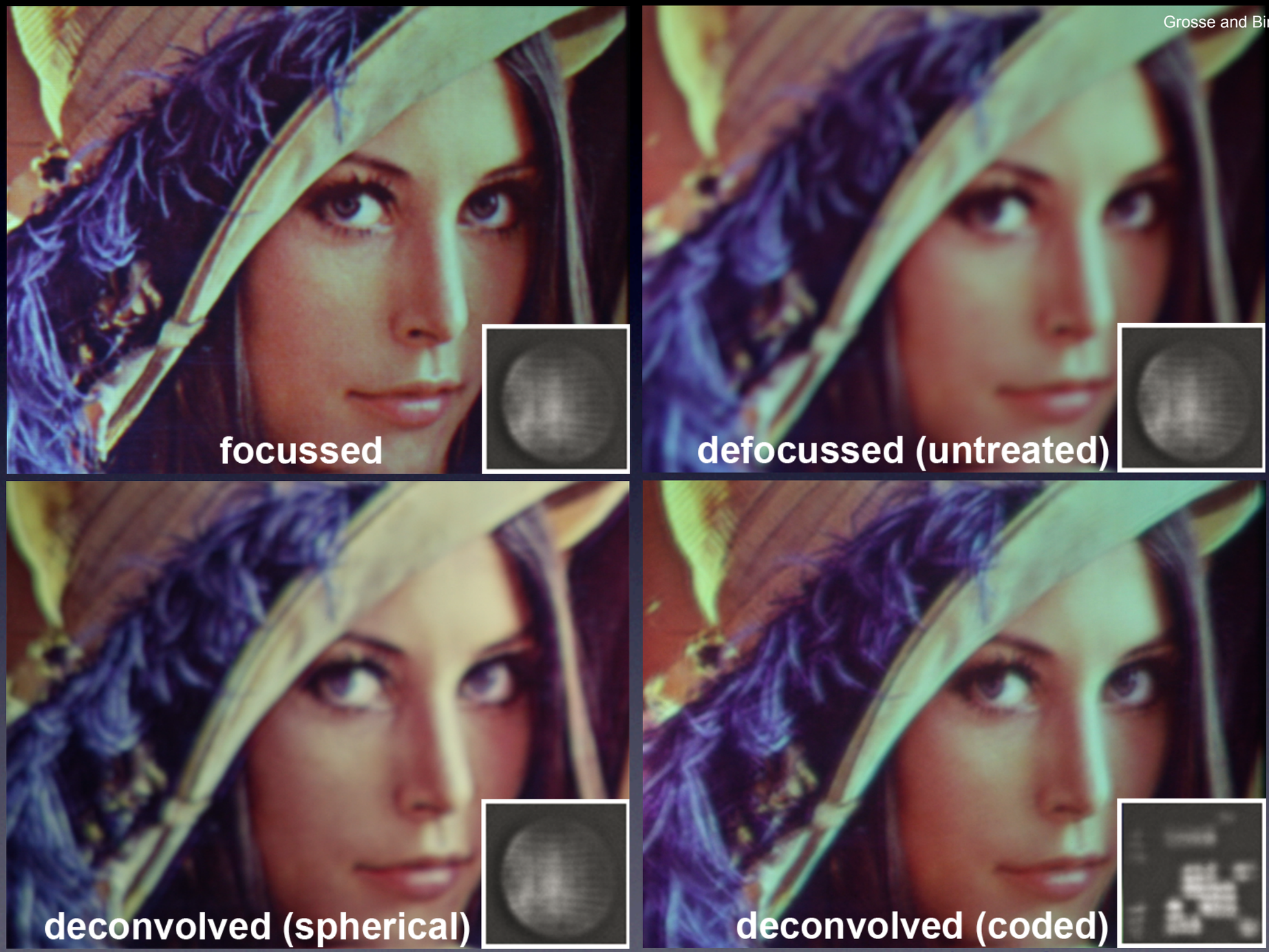
Grosse and Bimber, EDT/IPT 2008

see talk on wednesday, 1:45pm in 406AB

Grosse and Bimber, EDT/IPT 2008

Coded vs. Spherical Apertures

Grosse and Bimber, EDT/IPT 2008



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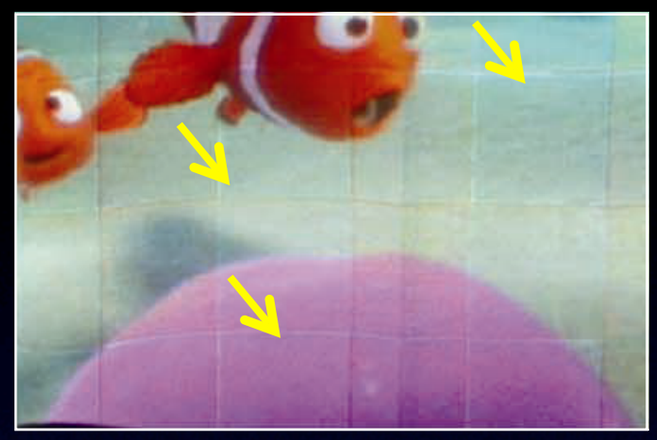
Grosse and Bimber, EDT/IPT 2008

Limitations and Solutions

Limitations and Solutions

- Current technical limitations: resolution, contrast/dynamic range, speed
- These are mainly limitations for projectors (not so much for cameras)
- Approaches to solve them: super-resolution projection, high-dynamic range projection, high-speed projection
- Super-resolution: single projector (wobbulation) or multipe projectors



cam

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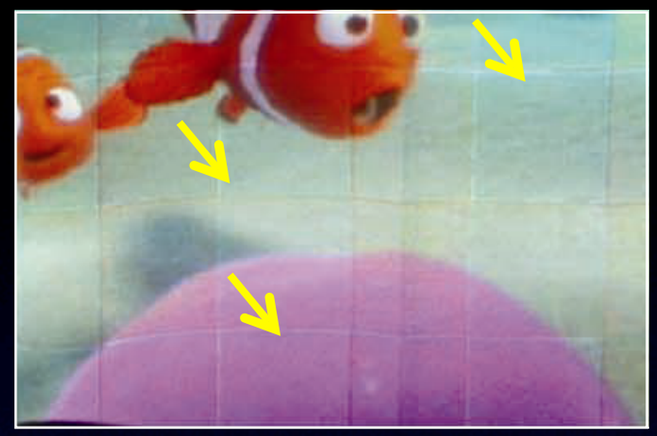
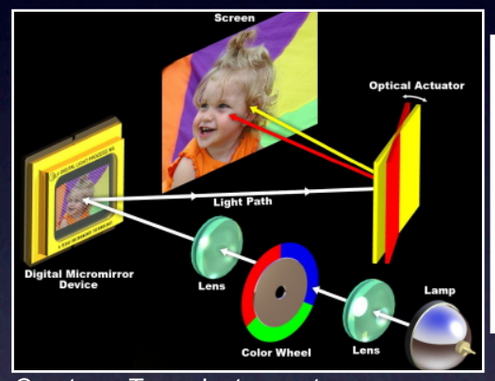
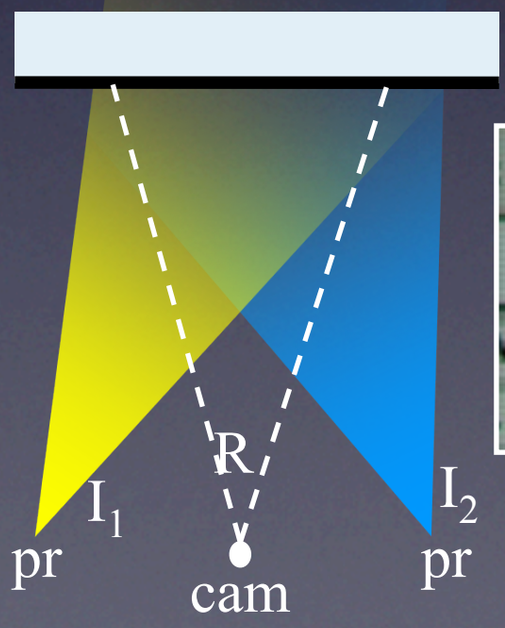


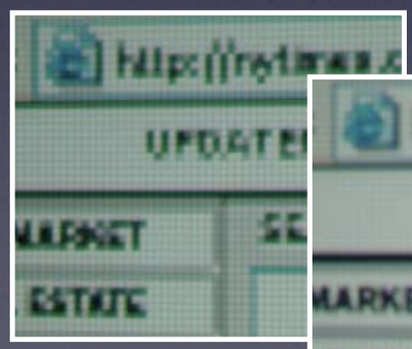


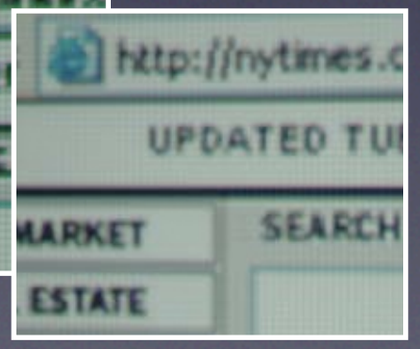
Courtesy: Texas Instruments (SmoothPicture)

Allen, et al., SID, 2005



Damera-Venkata, et al., ProCams, 2007





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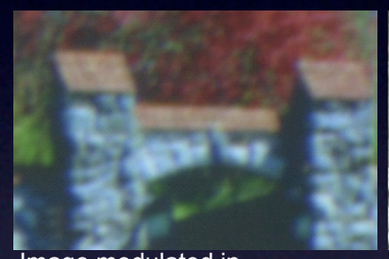
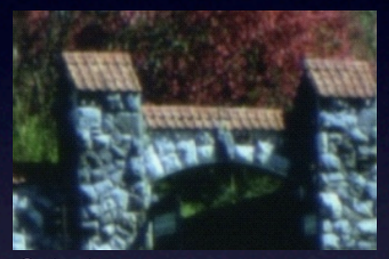


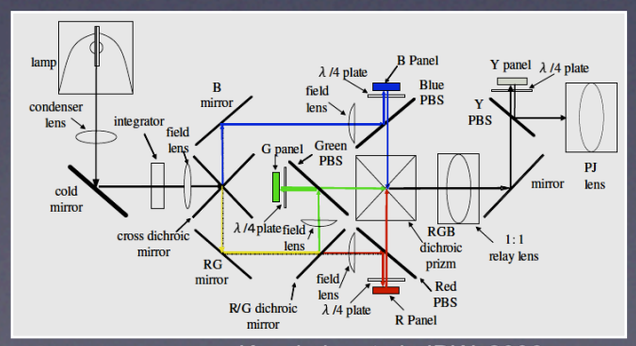
Image modulated in chrominance (low resolution)

Image modulated in luminance (high resolution)

→



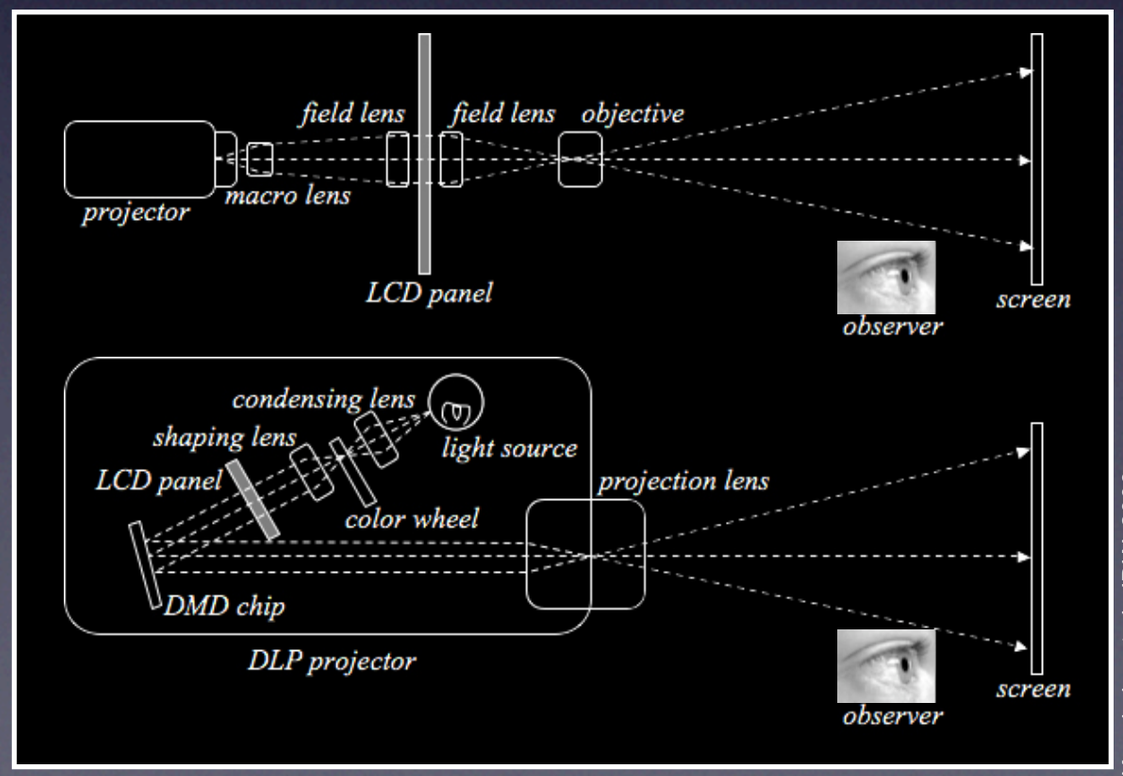
Output image



Kusakabe et al., IDW, 2006

contrast 1:2,500,000

Courtesy: Carl Zeis AG

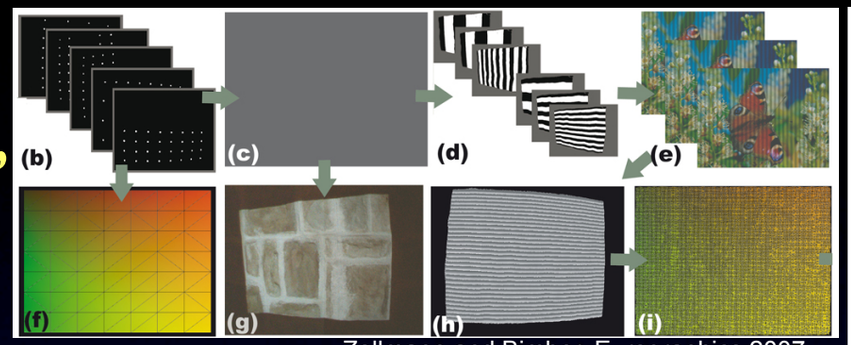


Palovych et al., SPIE, 2005
Damberg et al., SID, 2007

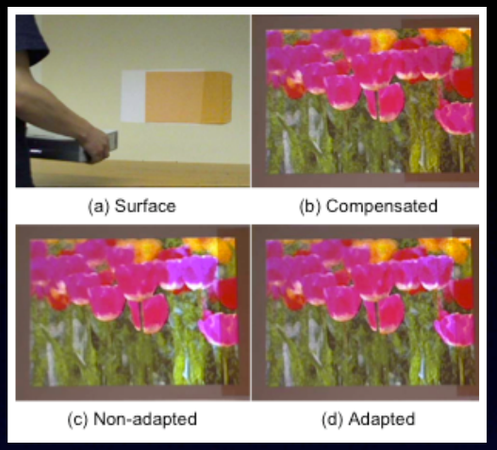
Kusakabe et al., IDW, 2006
Damberg et al., SID, 2007
see also Siggraph'07 Etech

Limitations and Solutions

- Current technical limitations: resolution, contrast/dynamic range, speed
- These are mainly limitations for projectors (not so much for cameras)
- Approaches to solve them: super-resolution projection, high-dynamic range projection, high-speed projection
- Super-resolution: single projector (wobbulation) or multipe projectors
- HDR: modulating image path or illumination path on a transmissive (LCD) or reflective (DLP/LCoS) basis
- High-Speed: fast DMDs and GLVs are very promising - this will allow fast transmisstion of data between projector and camera



Zollmann and Bimber, Eurographics 2007



Fujii et al, CVPR, 2005

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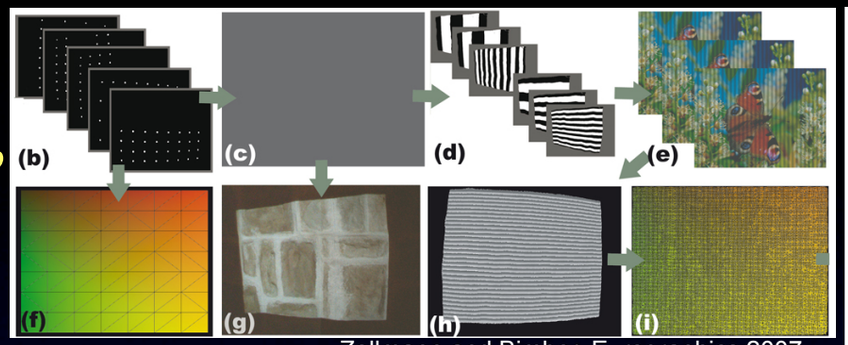

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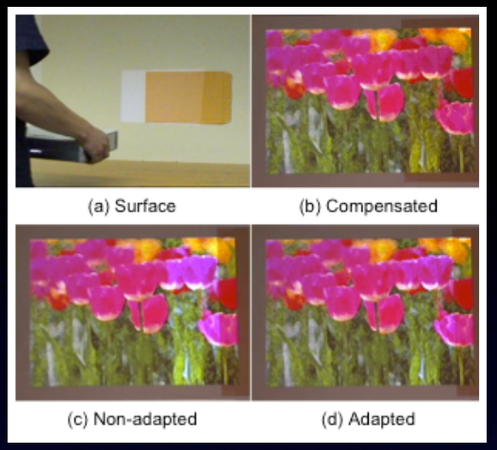
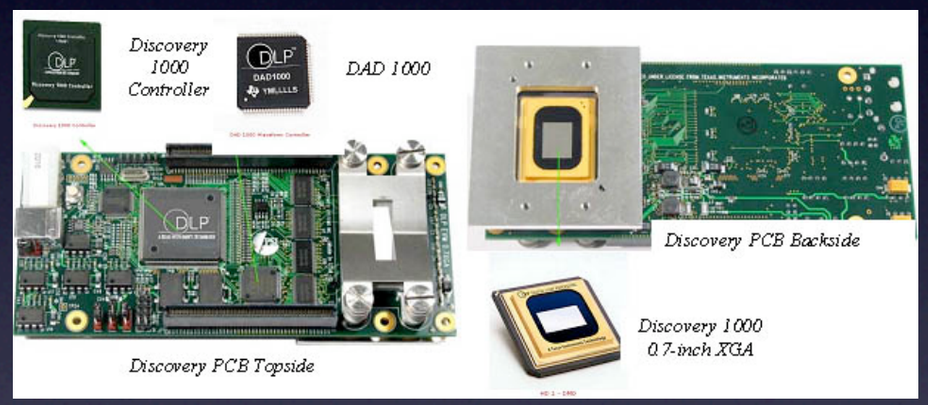
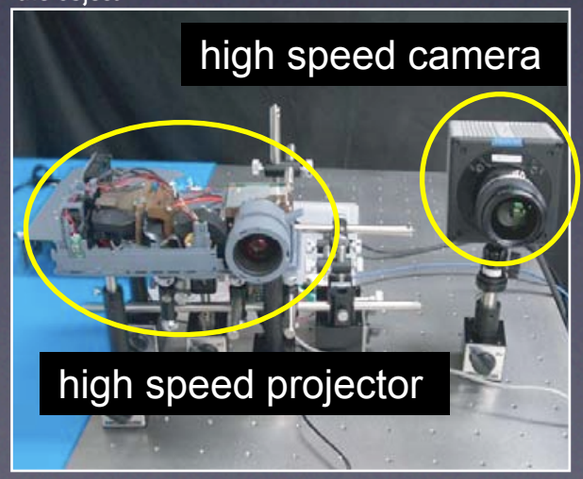


Fujii et al, CVPR, 2005

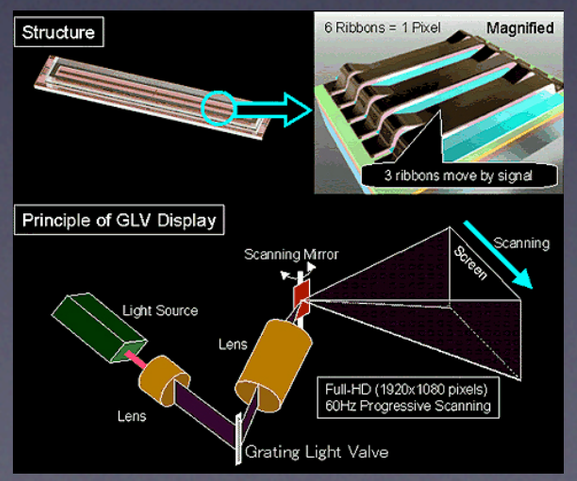


DMD Discovery Board, Courtesy: Texas Instruments

McDowall et al., EDT'05, Takei et al., IROS'07
3,000 Hz shape measurement with tracking of the object



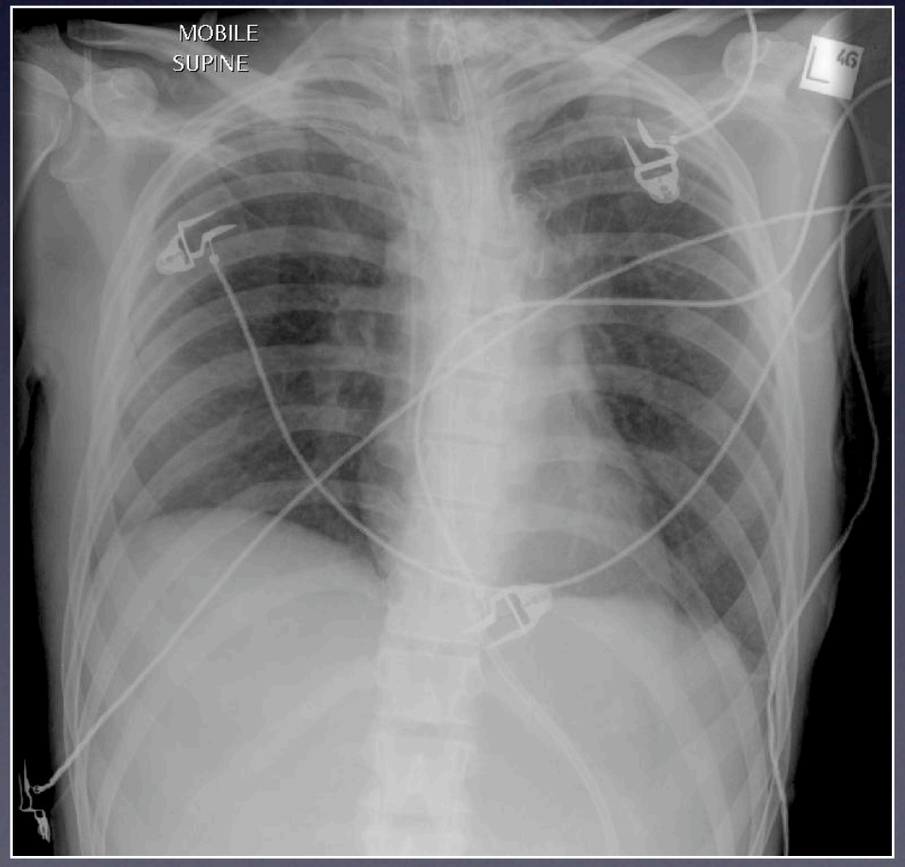
Grating Light Valve (GLV) about 1000 times fatser than DMD

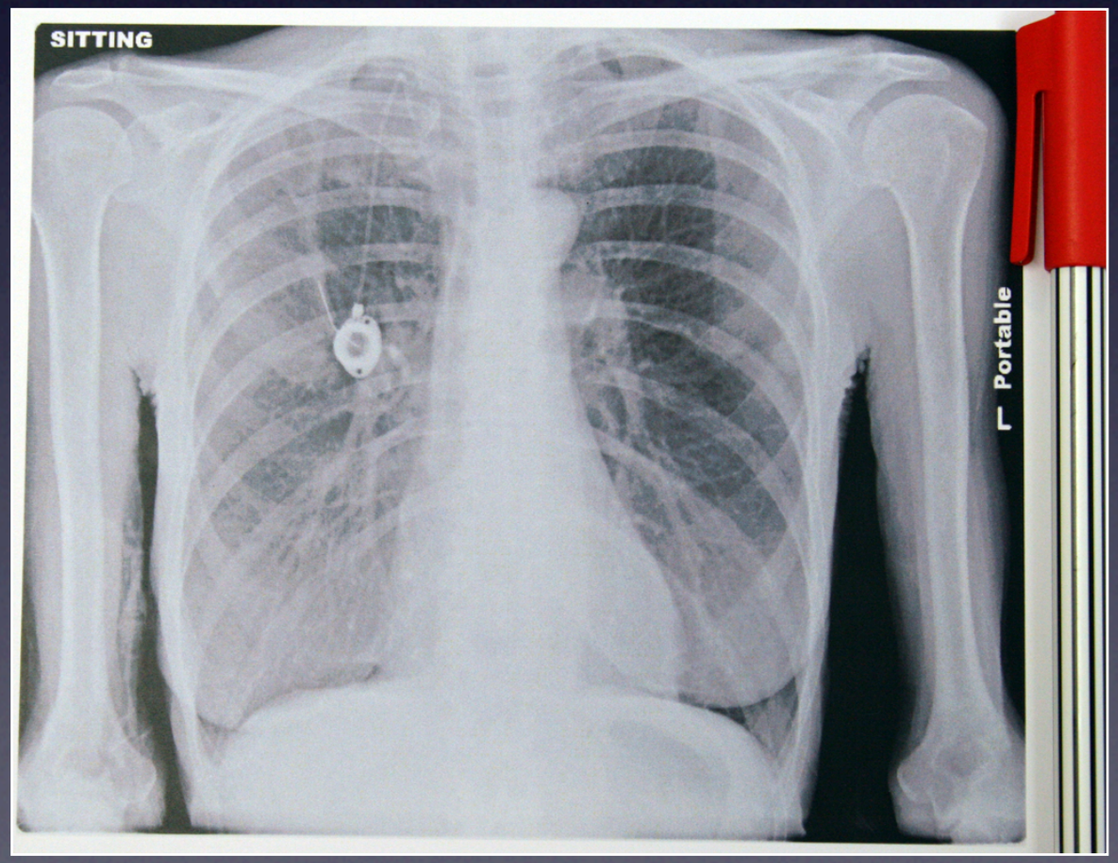


Beyond Projecting Images (Two Recent Examples)

High Dynamic Range Visualization

- Medical images/displays
  - negative film / X-ray film / laser film: 10^3-10^4:1 (1,000-10,000:1), light box: 2,000 cd/m^2 (currently still highest image quality)
  - medical monitors: 700-1,000:1, 700-1,000 cd/m^2 (support dynamic visualizations)
  - paper prints: <100:1, <100 cd/m^2 (no diagnostics image quality)



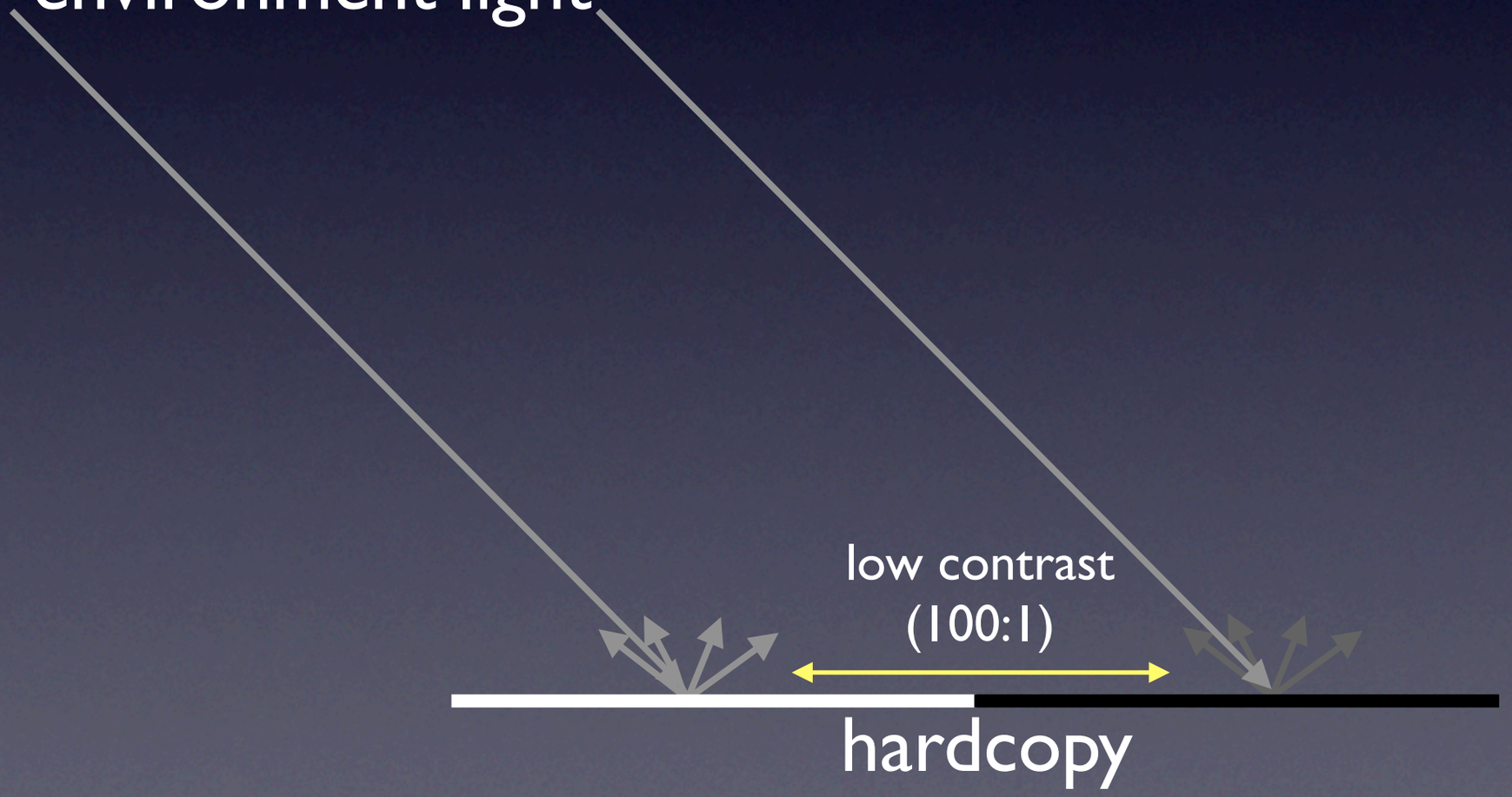


Superimposing Dynamic Range

hardcopy

see demo in hall H

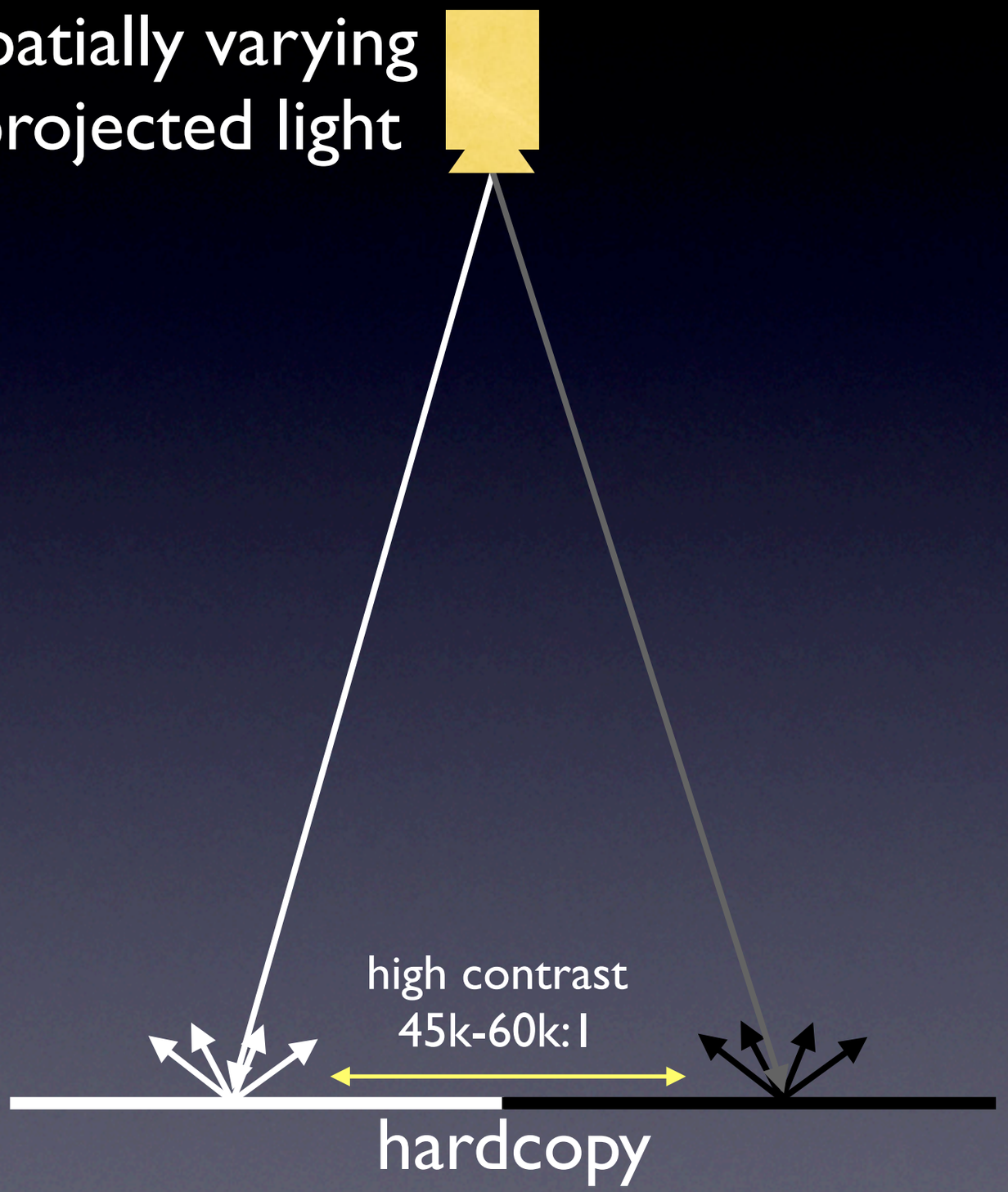
Superimposing Dynamic Range



see demo in hall H

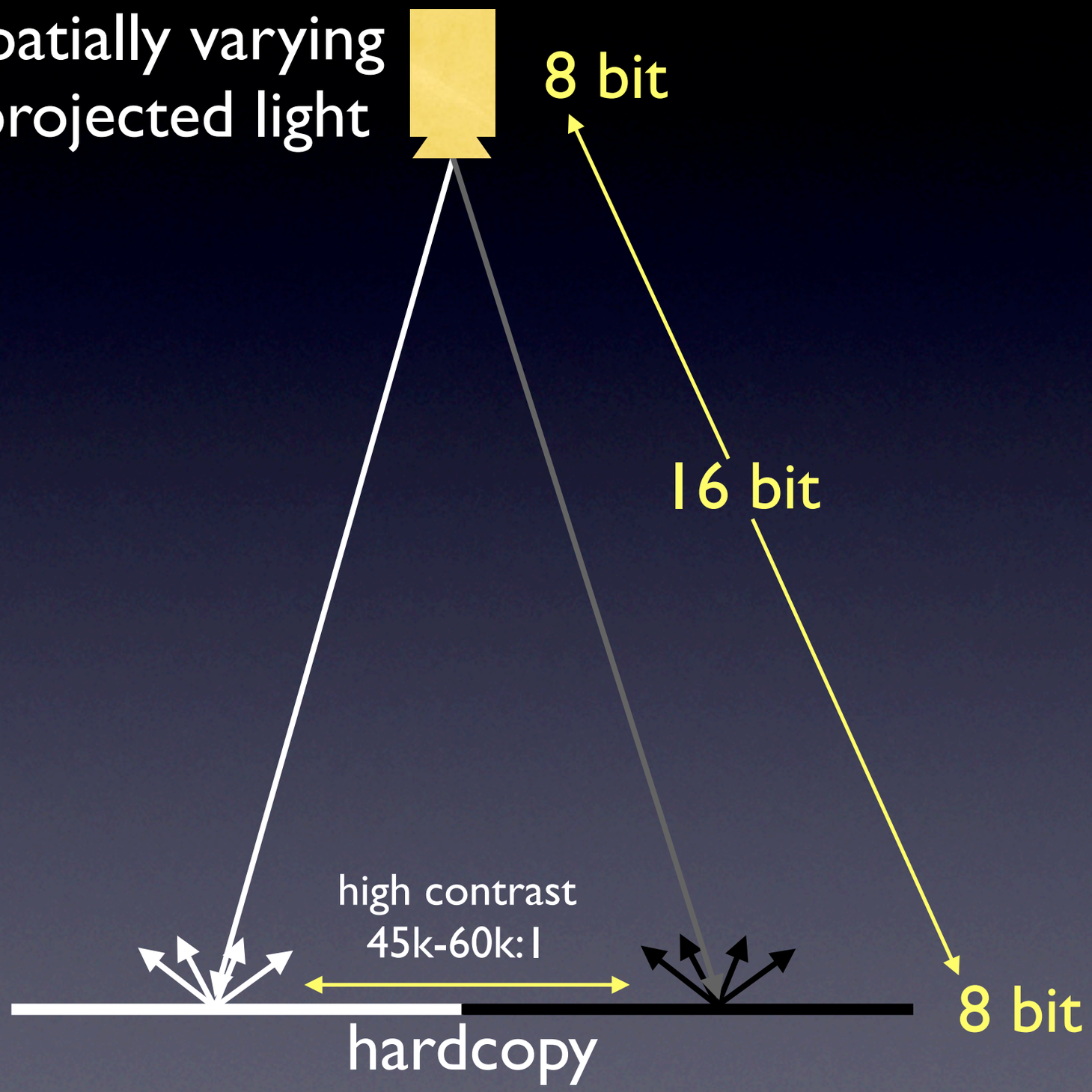
Superimposing Dynamic Range

spatially varying projected light



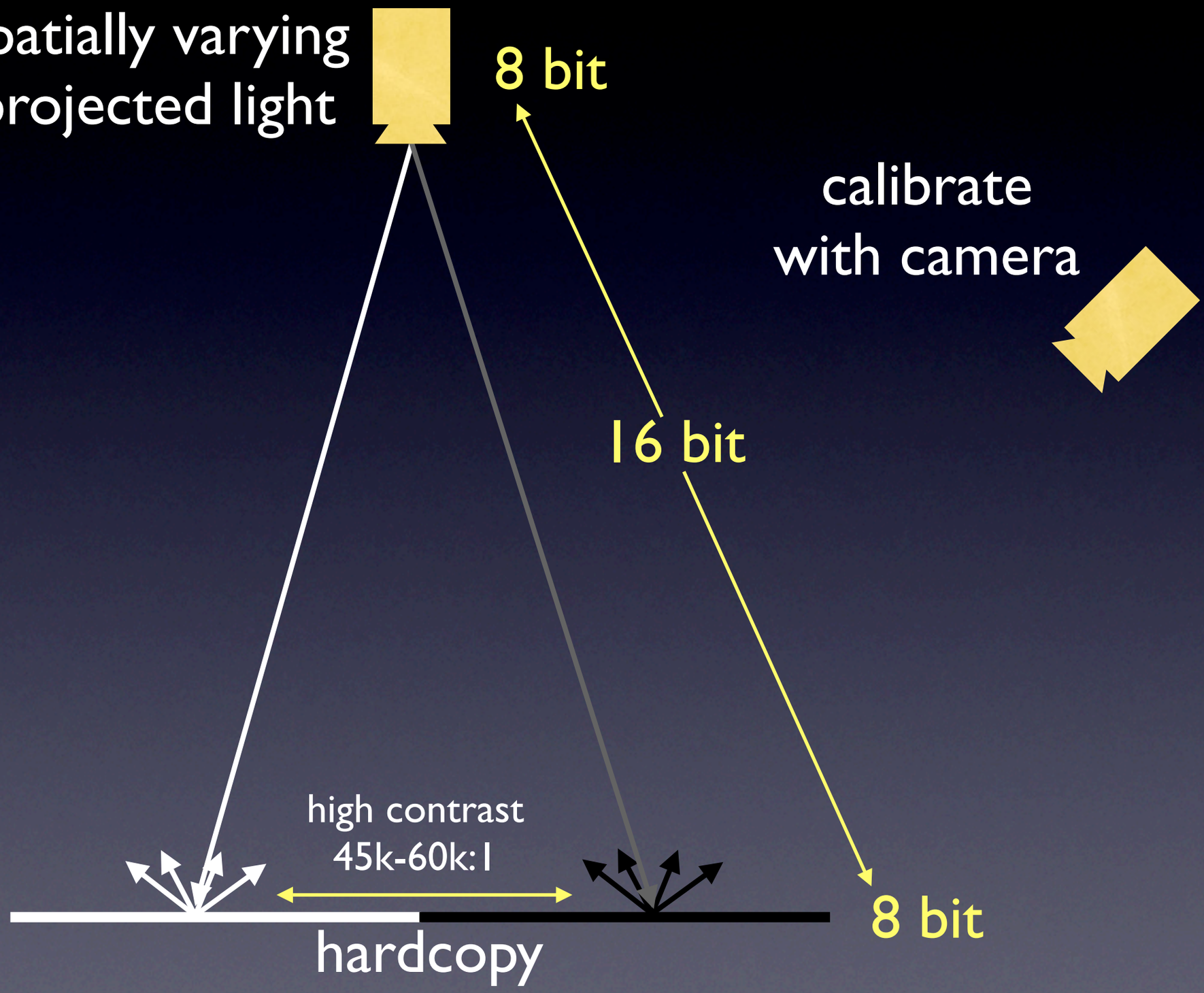
see demo in hall H

Superimposing Dynamic Range



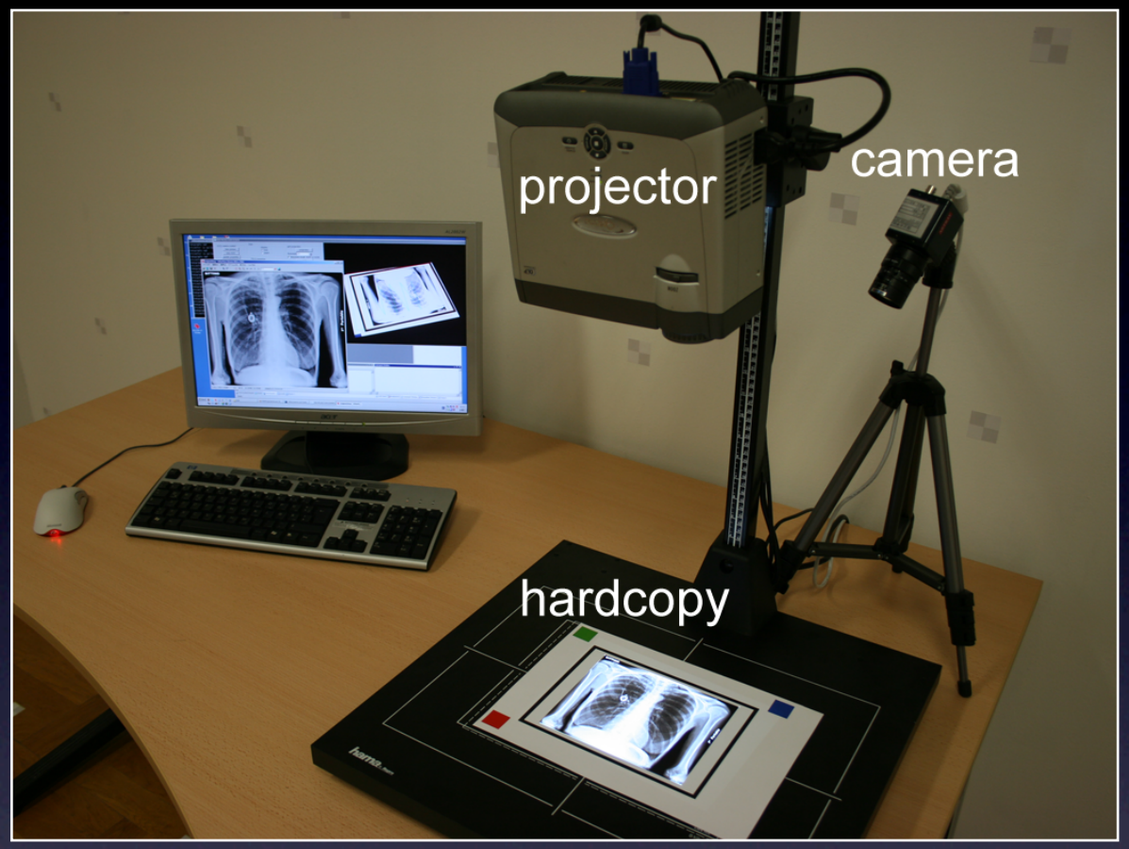
see demo in hall H

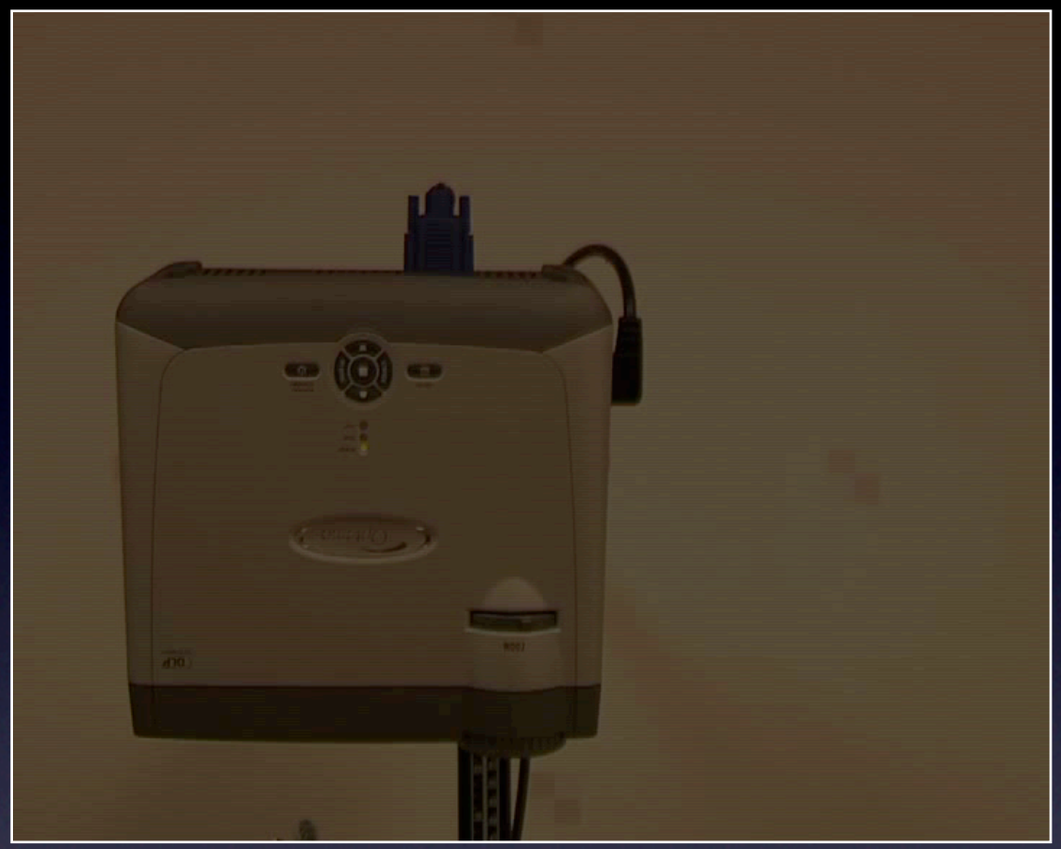
Superimposing Dynamic Range



see demo in hall H

Prototype

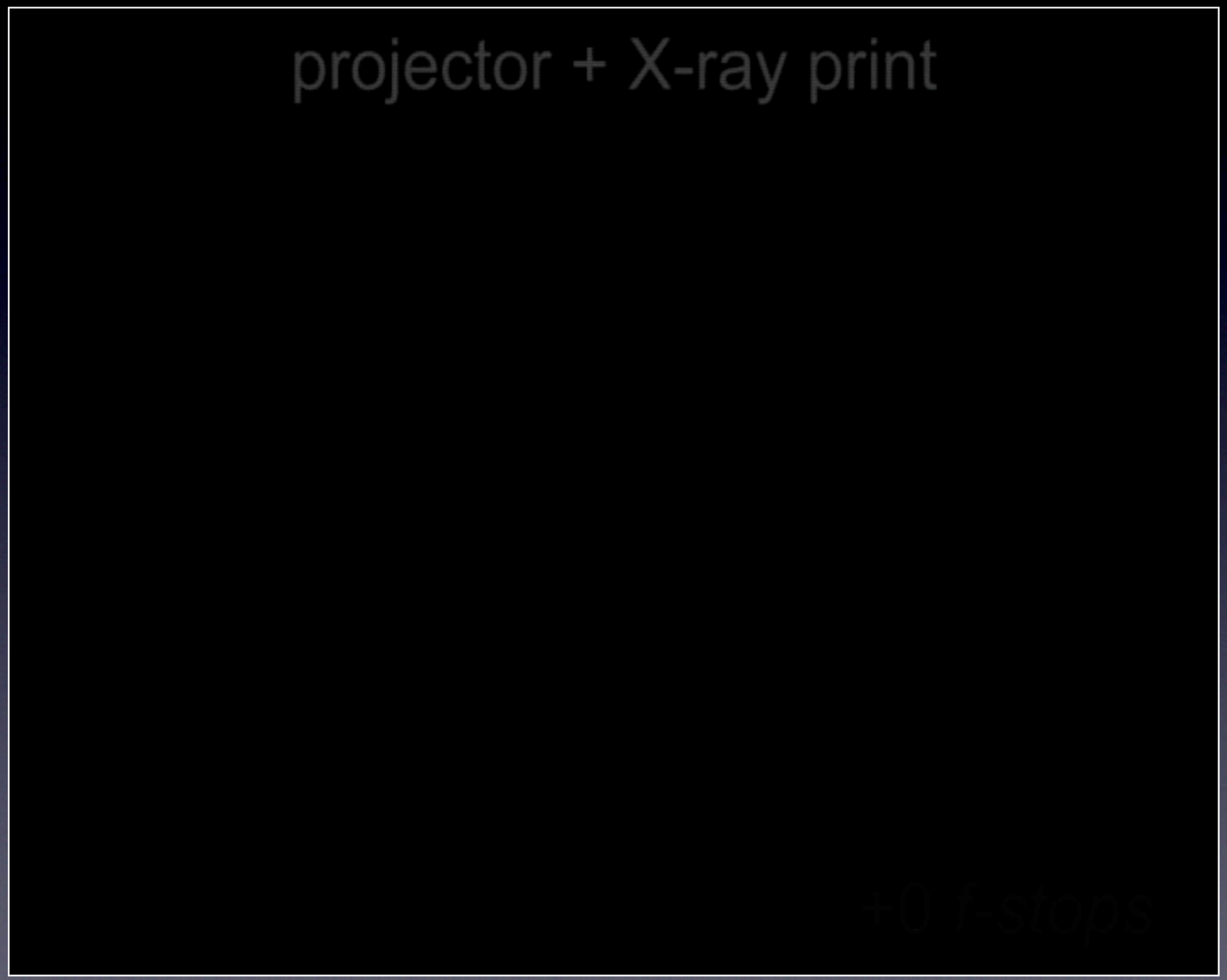




- Current image quality (all values are measured)
  - contrast: >45,000 - 60,000:1, peak luminance: >2,750 cd/m^2
  - tonal resolution: >620 perceptually distinguishable tonal values
  - color space extension: > x1.4 (regular projection) or > x3.3 (regular hardcopy print)
  - spatial resolution: several thousand DPI (considereing gray scales: 150 lpi)
  - contrast frequency: up to 7 cpd
  - registration precision: 0.3 mm

see demo in hall H

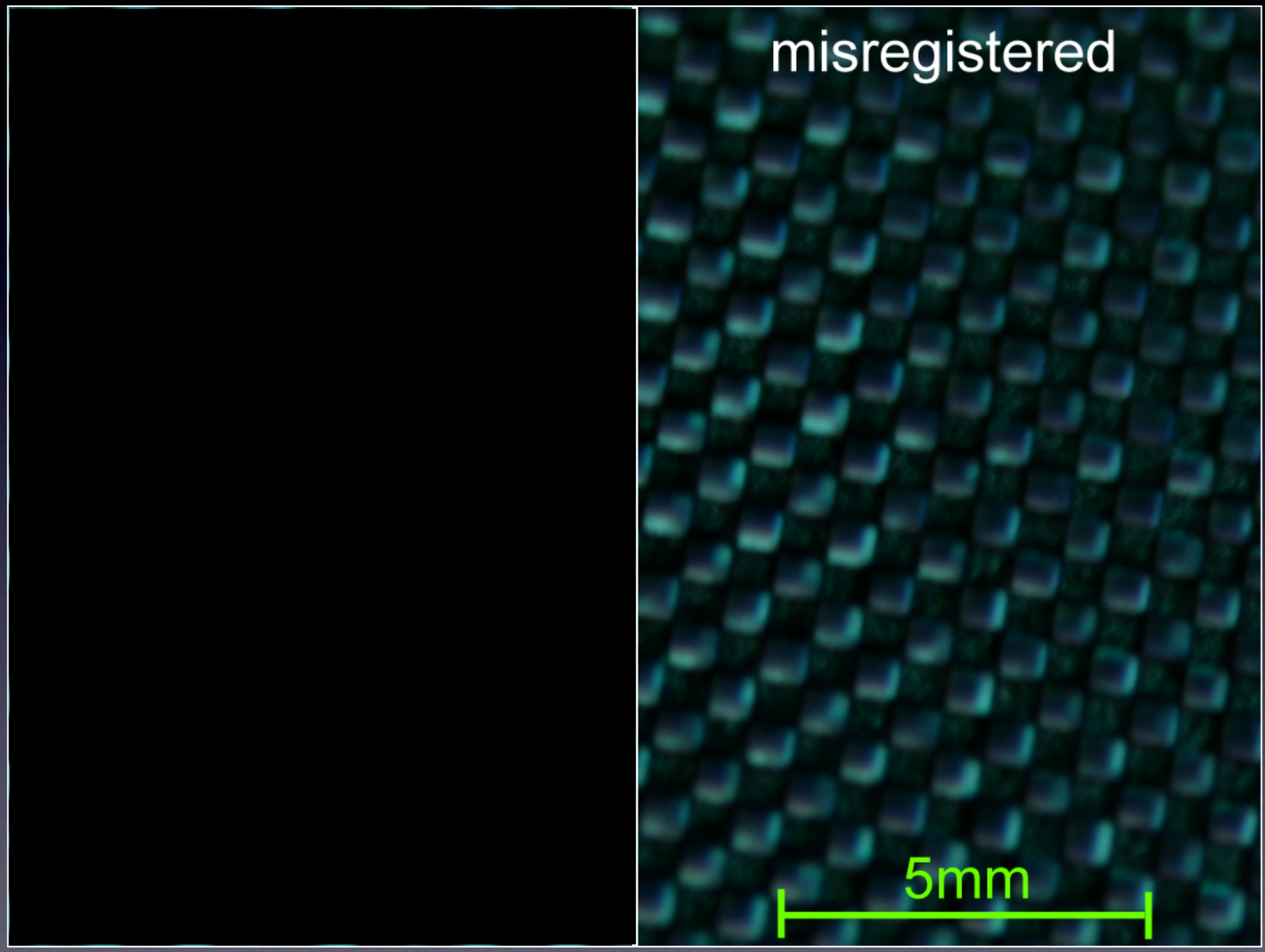
Example



thanks to National Cancer Institute, NCI

see demo in hall H

Geometric Registration



see demo in hall H

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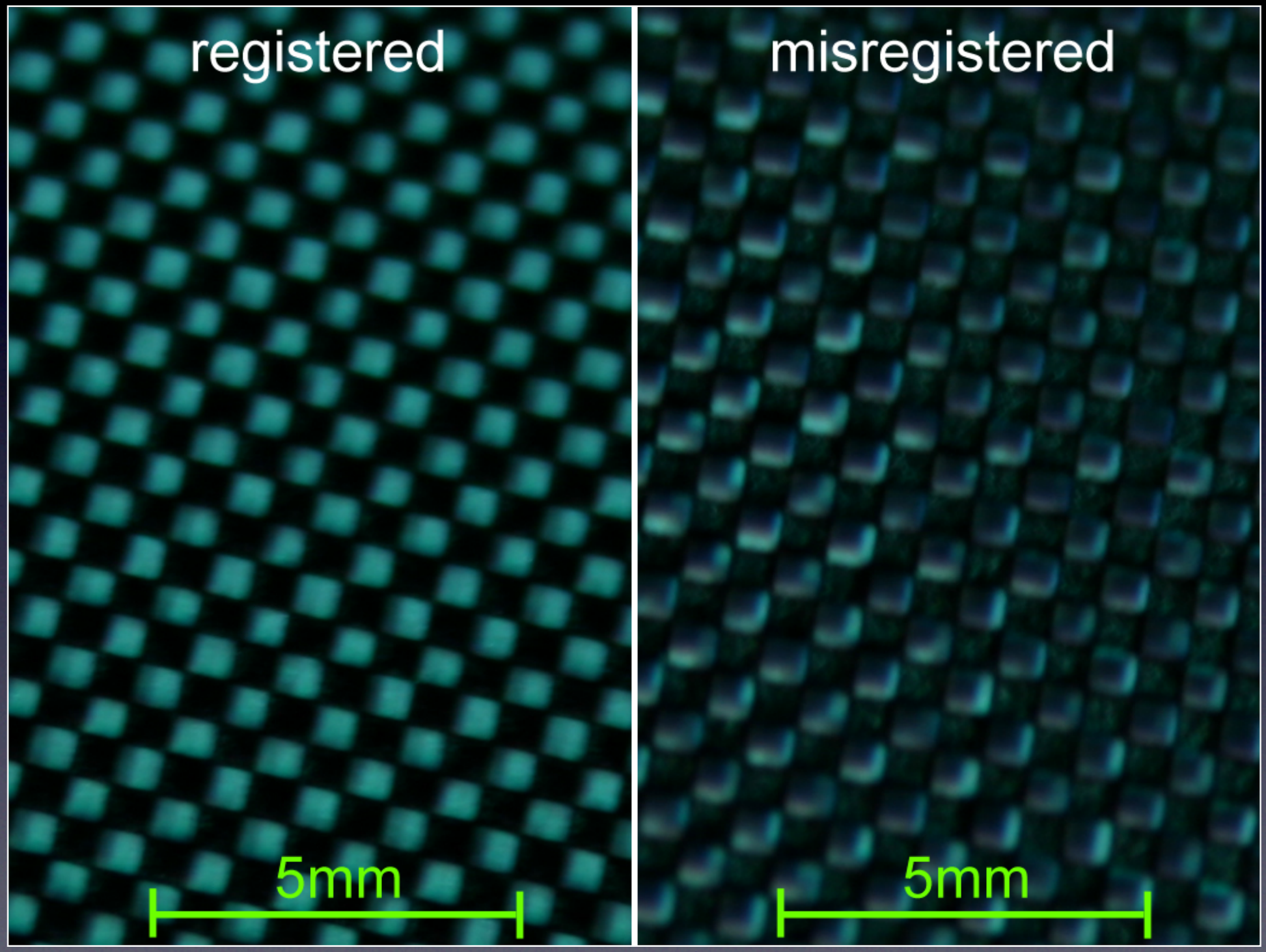
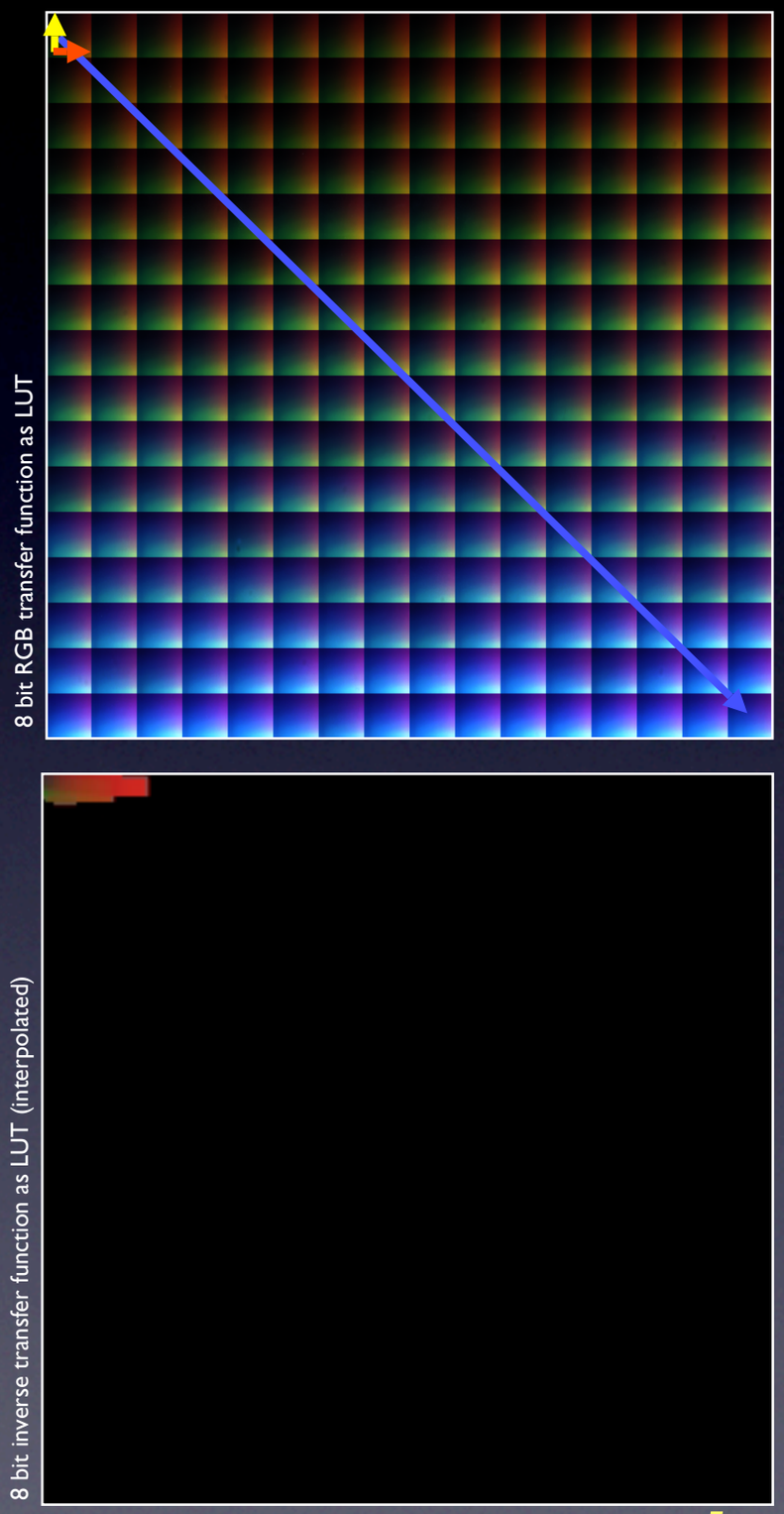


see demo in hall H

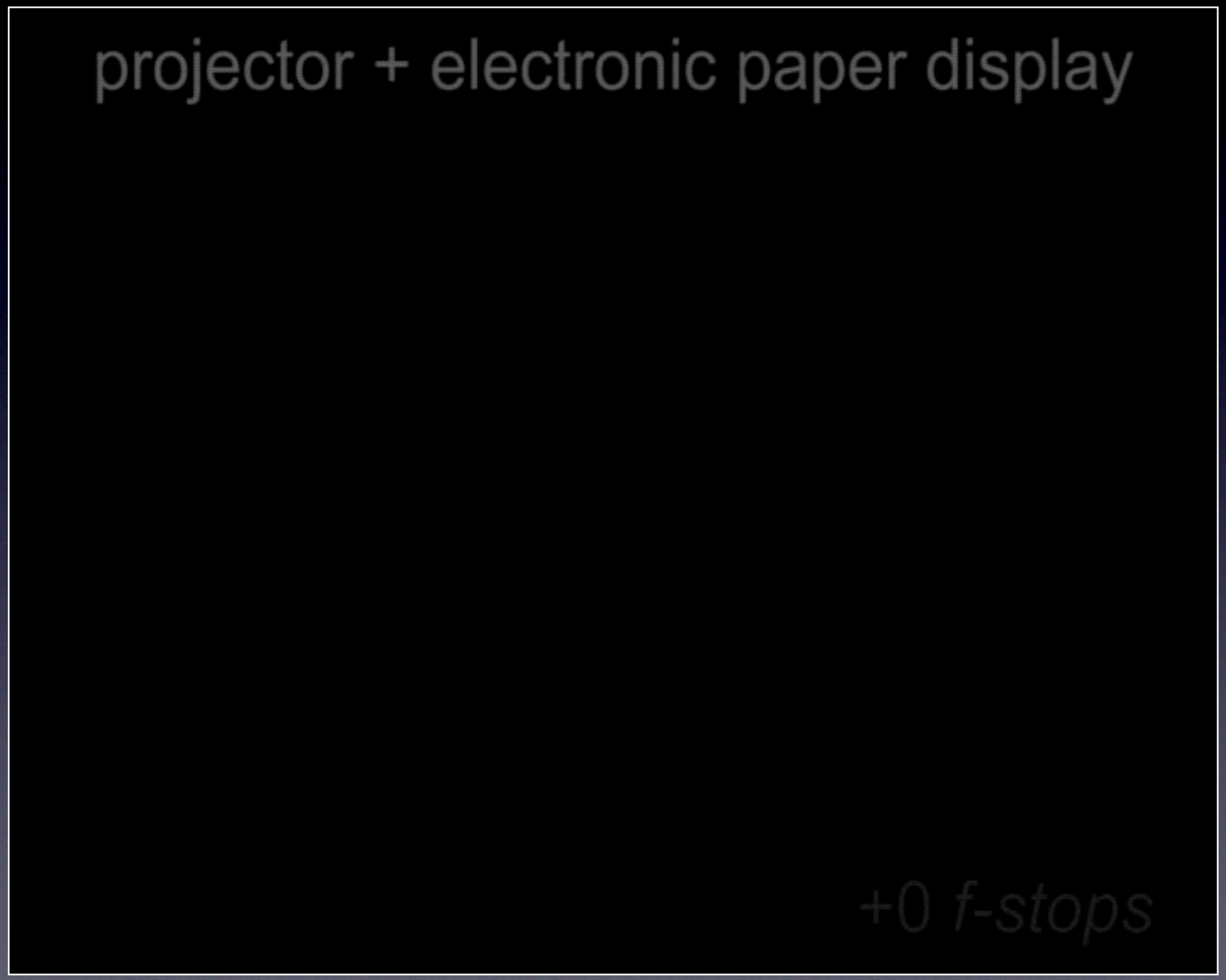
Photometric Calibration



see demo in hall H

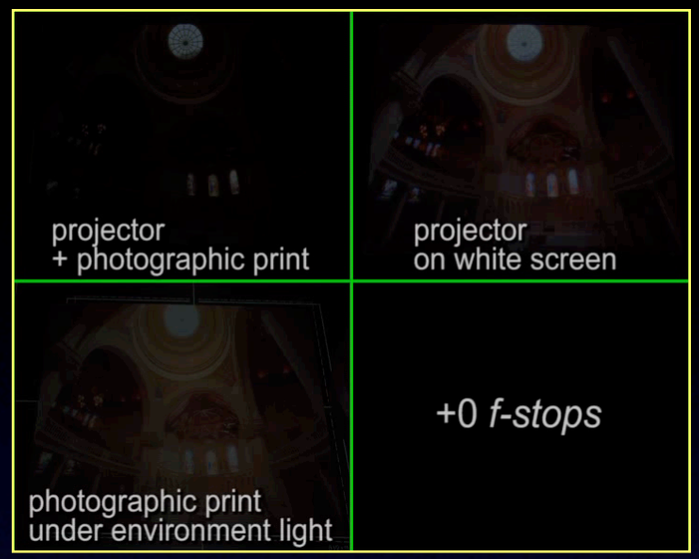
Interactive Displays

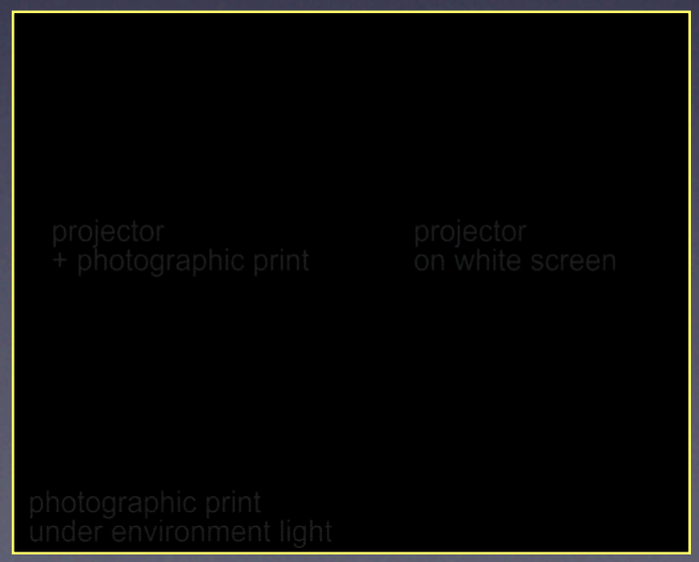
projector + electronic paper display



see demo in hall H

Chrominance





see demo in hall H

Digital Video Composition

- Most important issues
  - keying of opaque foreground objects via difference keying (eg., chromakeying or luma keying)
  - keying of transparent foreground objects (eg., environment matting)
  - camera tracking for perspective effects
  - special composition effects (eg., occlusion, shadows, refraction, reflection, etc.)
  - moderator information
- In real environments
  - install physical bluescreens (temporally)
  - re-record in studio

Courtesy: ORAD

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Courtesy: ORAD

augmented reality [erweiterte realität]

mdr

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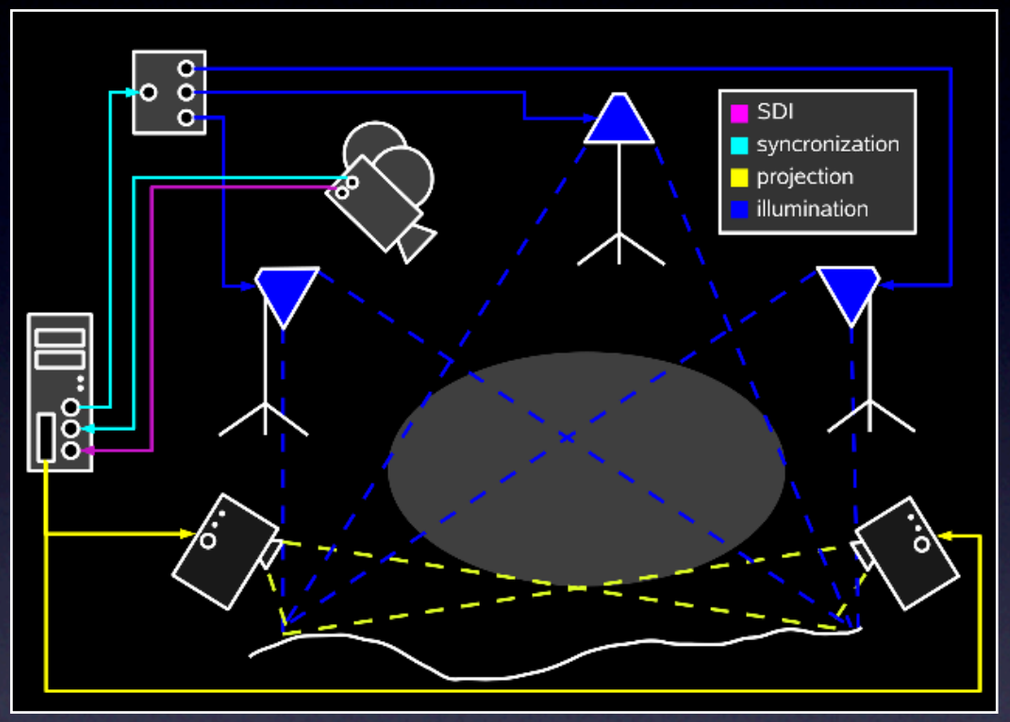
Bauhaus-Universität Weimar

VirtualStudio2Go

high-speed LED illumination

synchronized HD camera

high-speed LED illumination



conventional video projectors

conventional video projectors

see talk today, 3:45pm in 502A

augmented reality [erweiterte realität]

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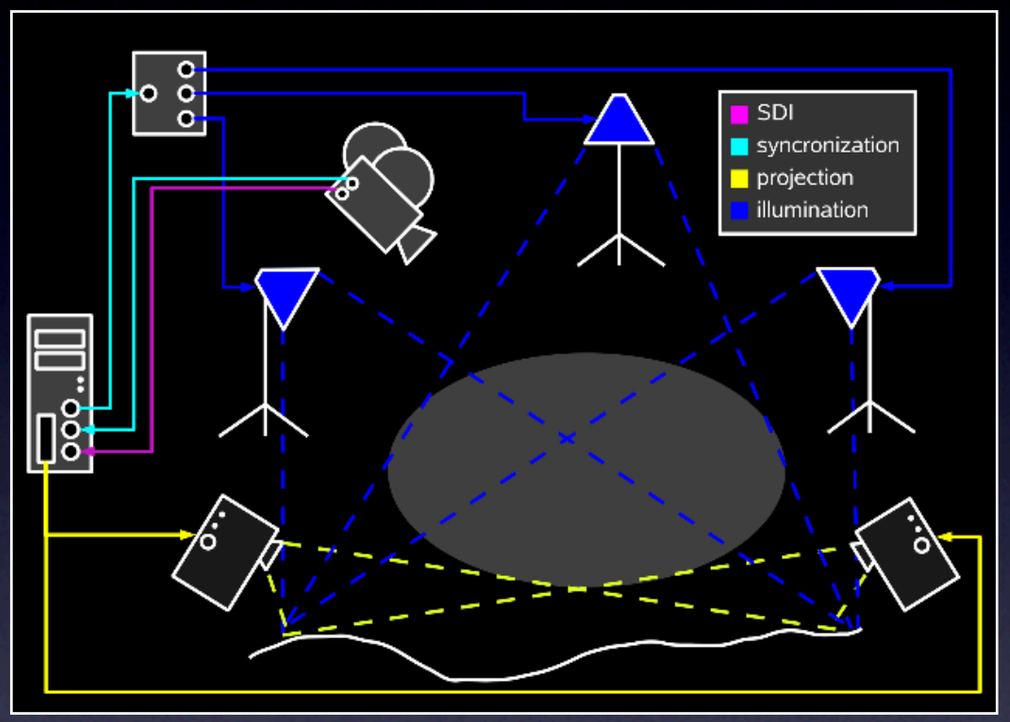

conventional video projectors

conventional video projectors

720p at 59.94Hz

see talk today, 3:45pm in 502A

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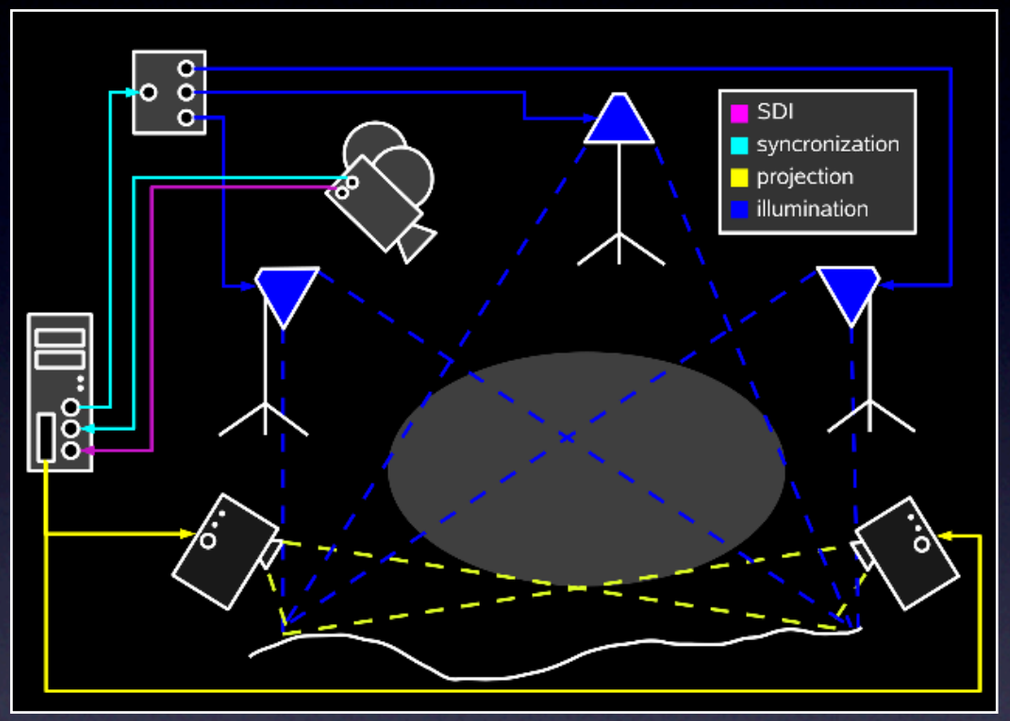

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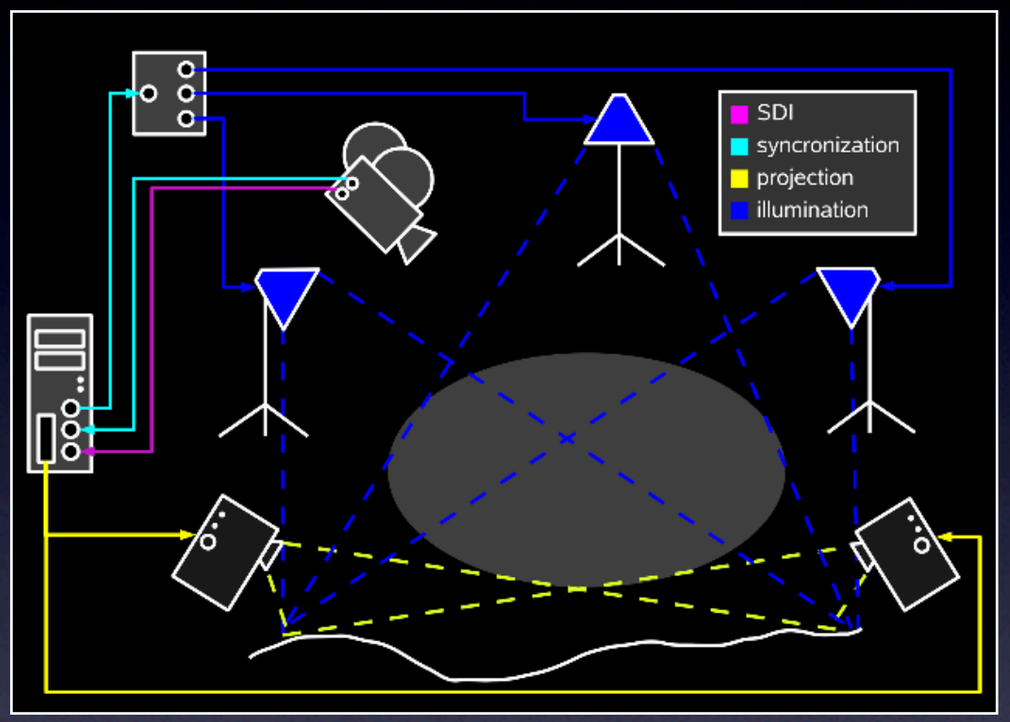

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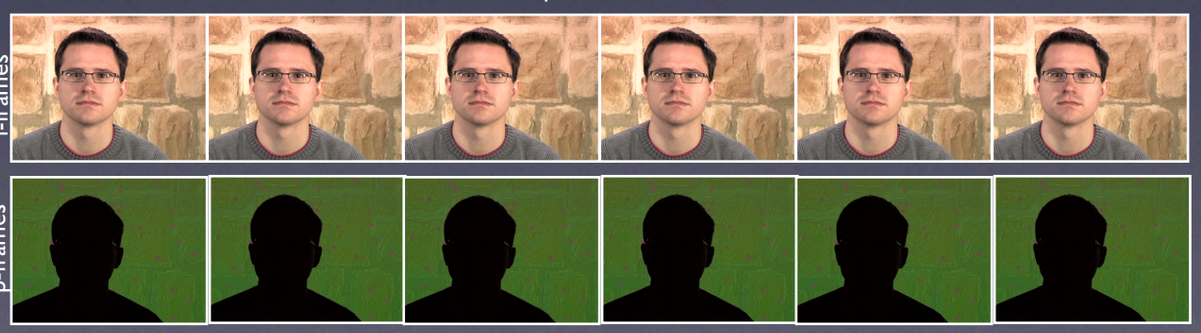

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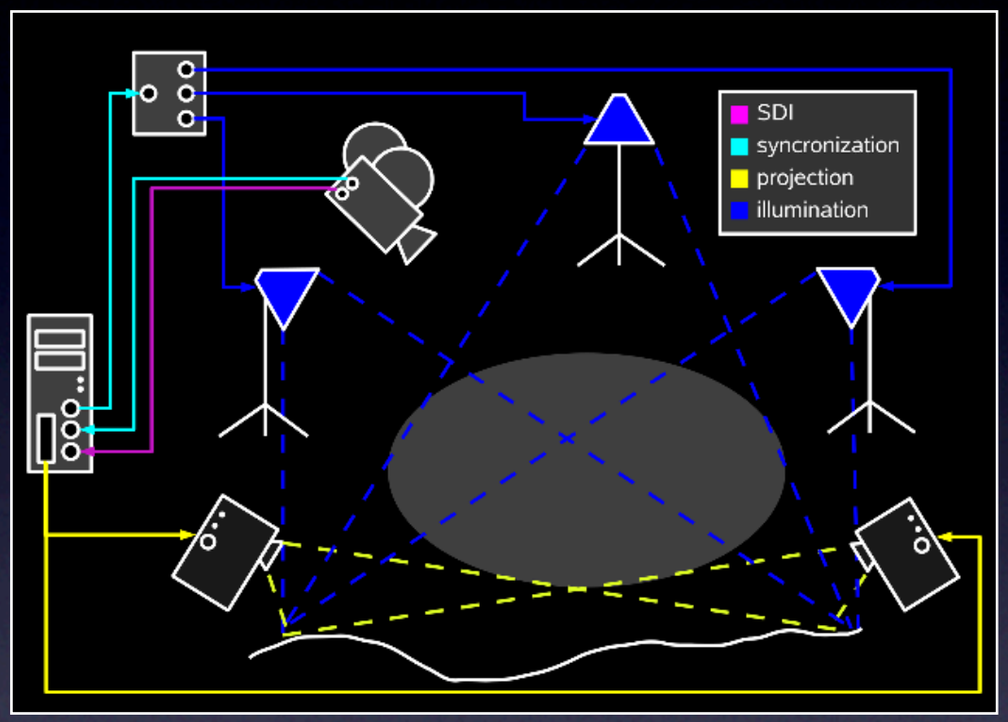

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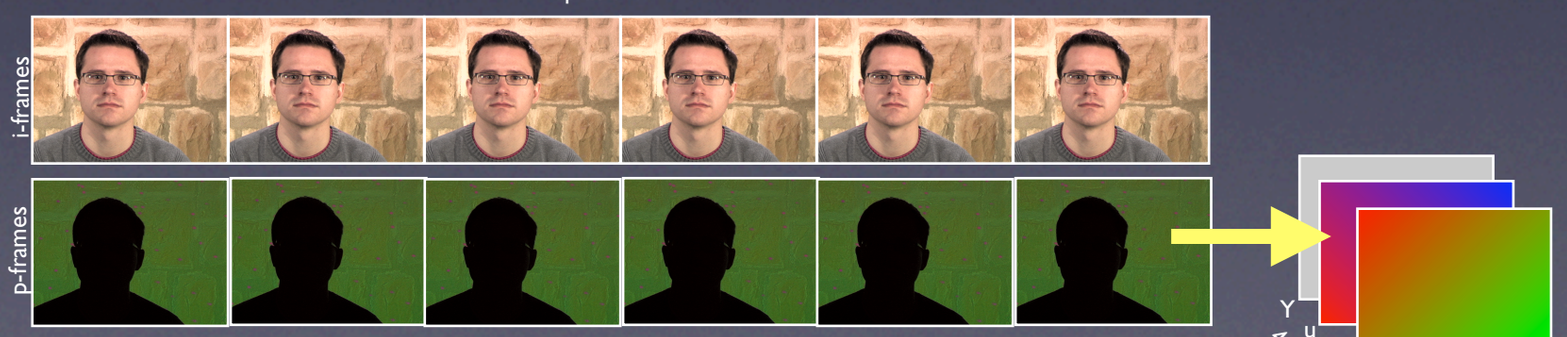

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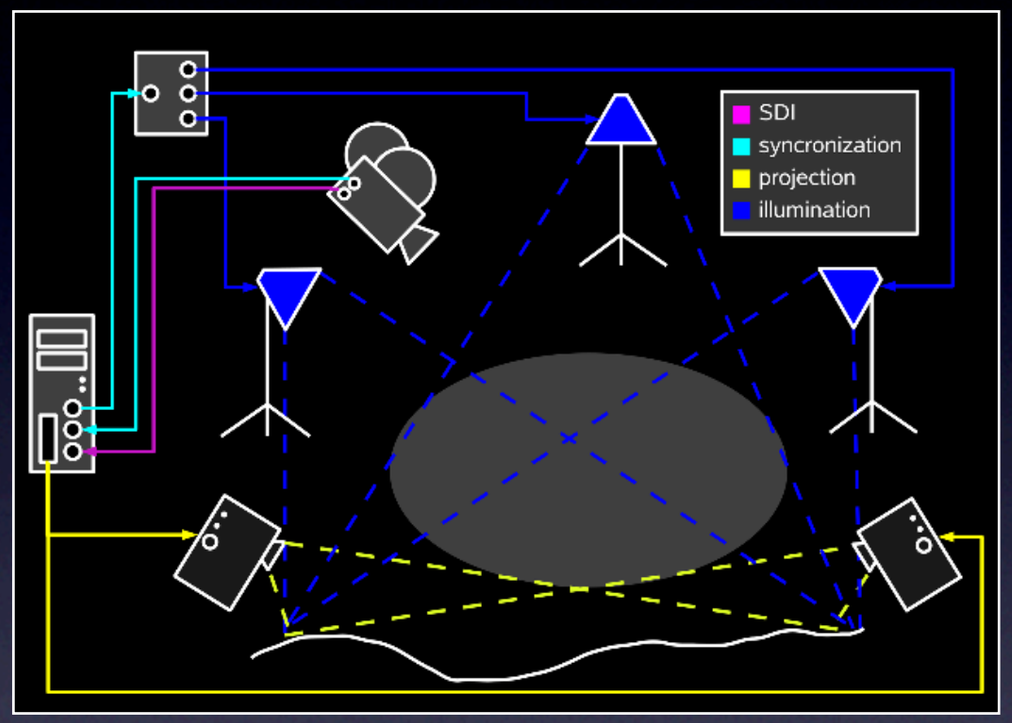

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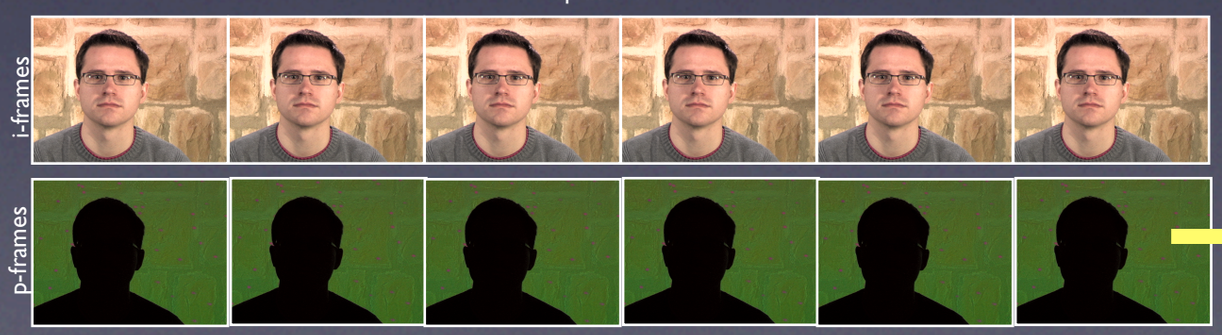

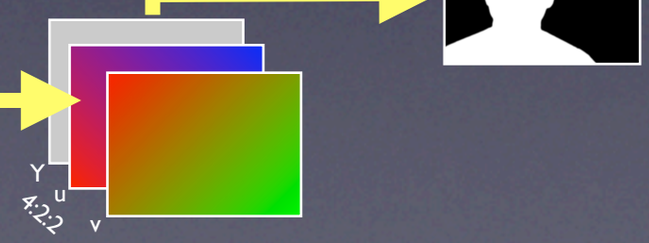

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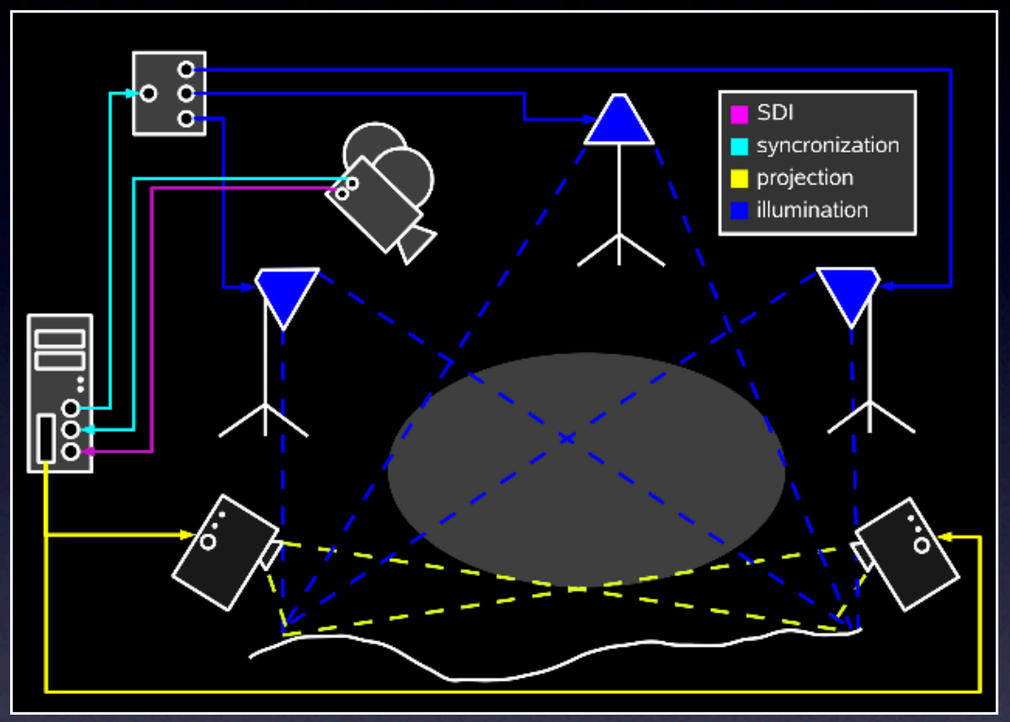

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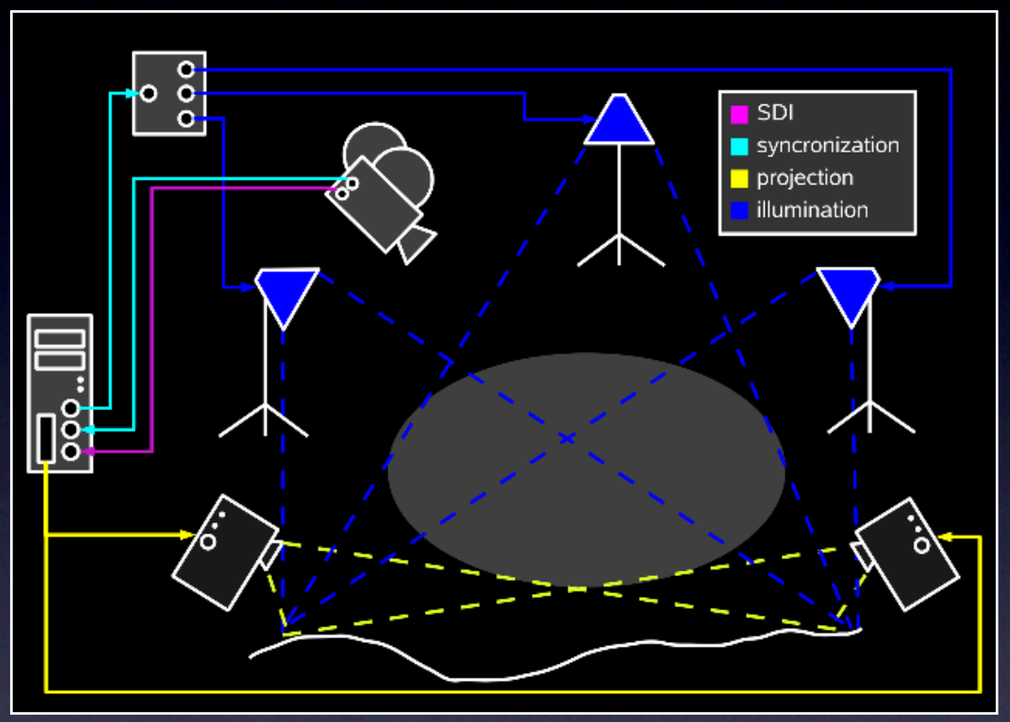

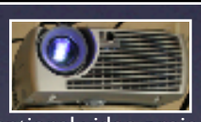

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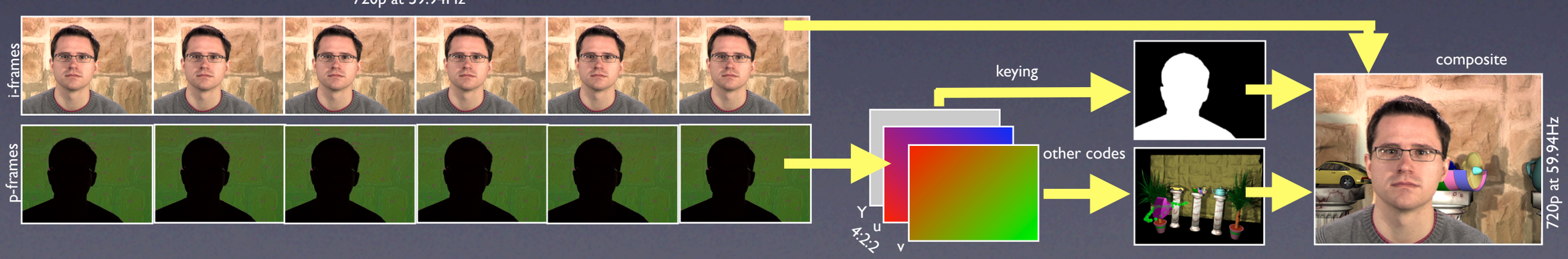
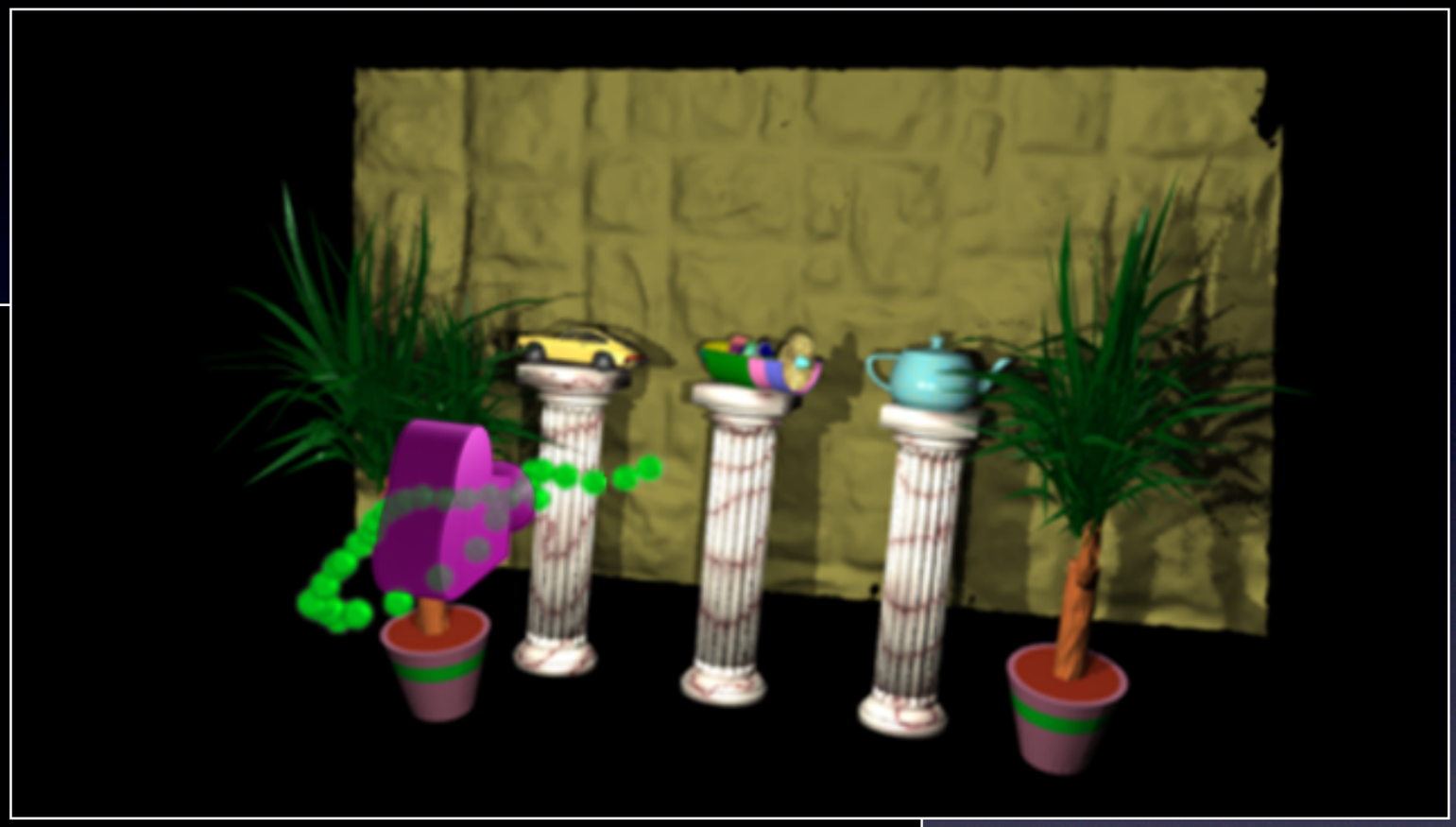


see talk today, 3:45pm in 502A

Scene Reconstruction and Tracking...

i-frames

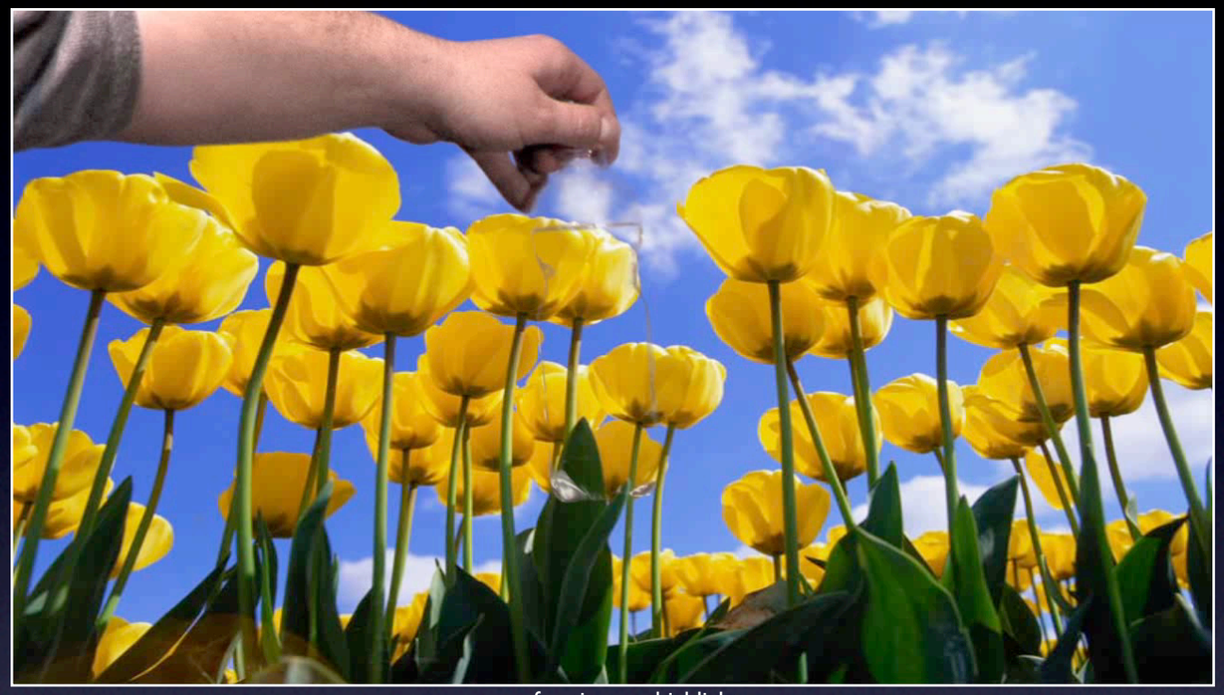
camera path, scene geometry, and composit effects



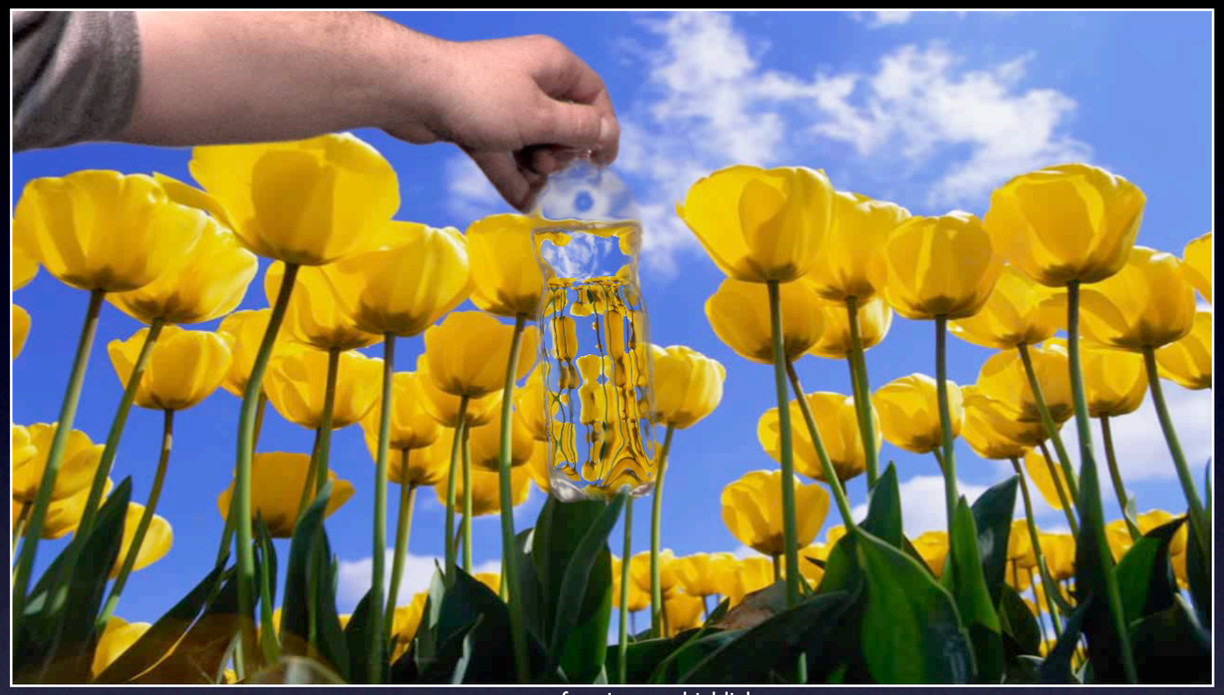
final composit

see talk today, 3:45pm in 502A

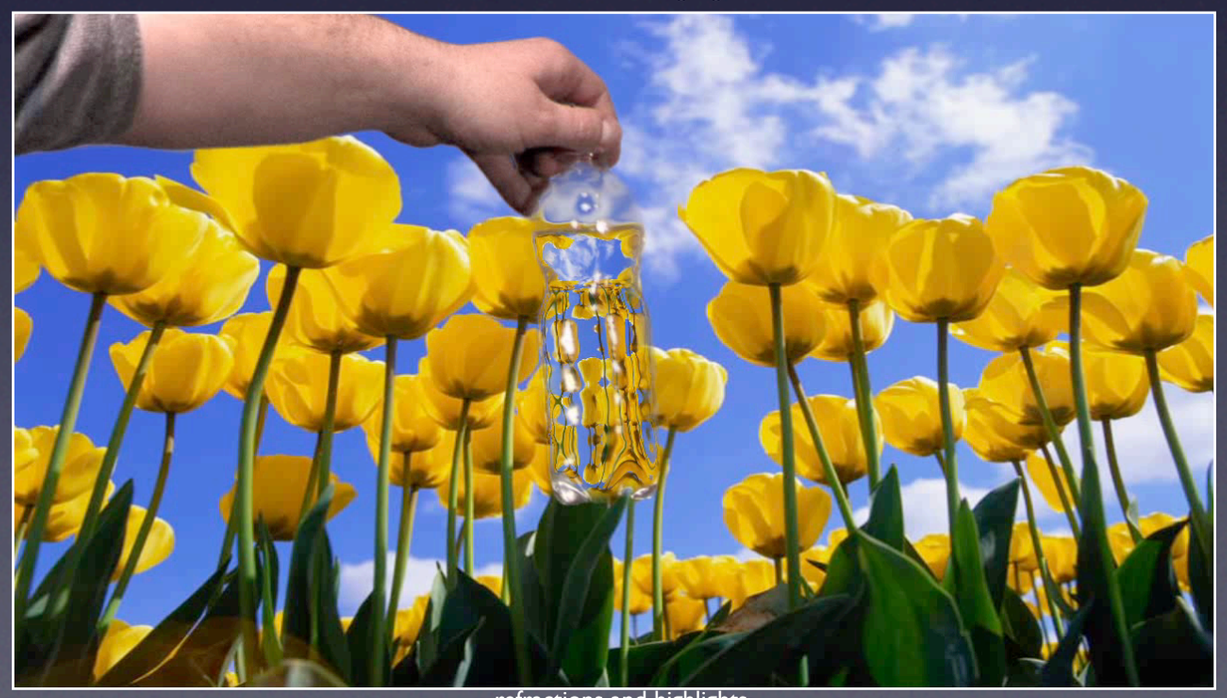
...Keying and Environment Matting...



no refraction, no highlights



refraction, no highlights



refractions and highlights

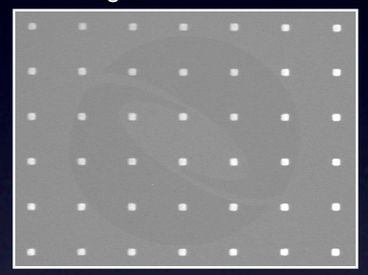
steps

see talk today, 3:45pm in 502A

...Modertor Information...

example

tracking features in u channel

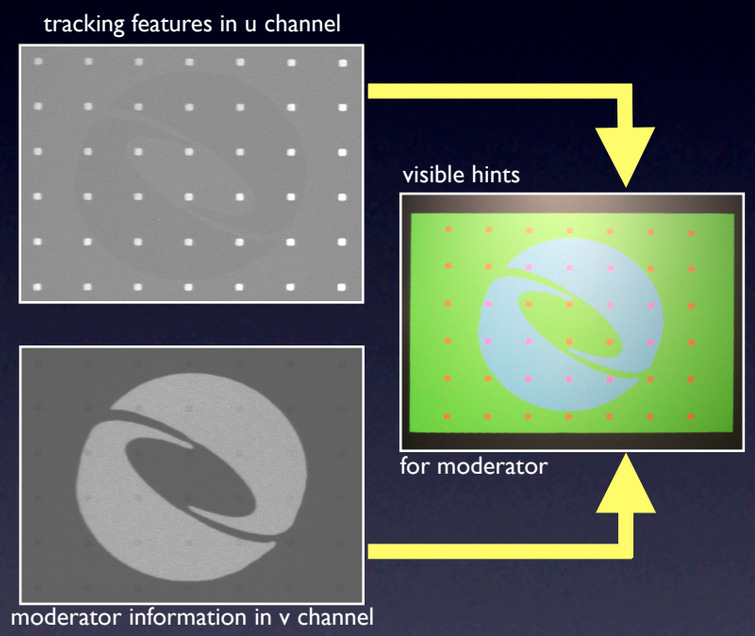


moderator information in v channel

see talk today, 3:45pm in 502A

...Modertor Information...

example



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augmented reality [erweiterte realität]

mdr

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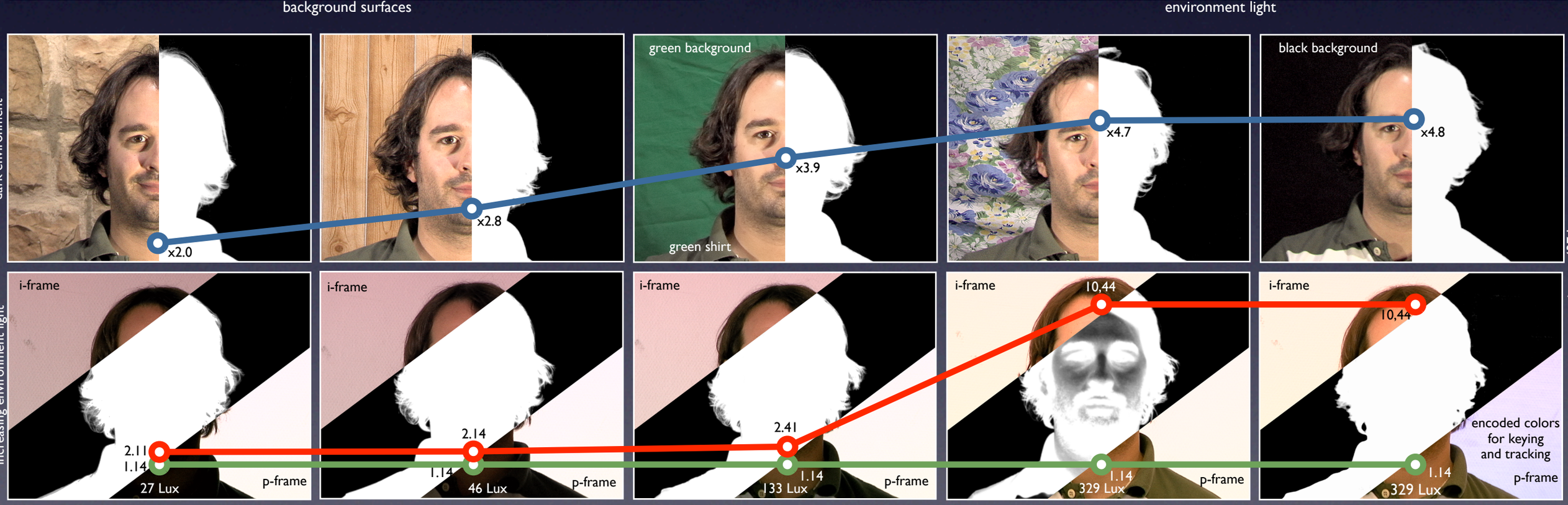
...In Real Environments

background surfaces

environment light



average increase of displacement error of captured environment matte after modulating with the background surface (unmodulated original environment matte = x1.0)

average noise radius of feature centers on camera's image plane (in pixels) for tracking features computed from modulated and interfered u,v ramps

average noise radius of feature centers on camera's image plane (in pixels) for directly encoded features

see talk today, 3:45pm in 502A

Thank You!

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