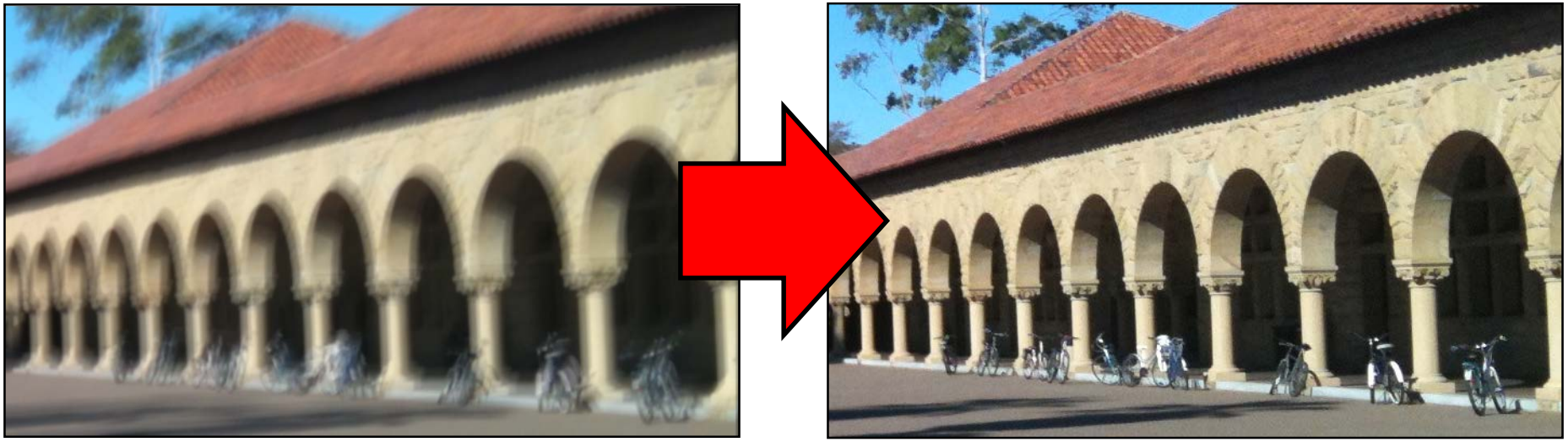
Blind Deblurring using Internal Patch Recurrence

Tomer Michaeli & Michal Irani

Weizmann Institute



Scale Invariance in Natural Images

Small patterns recur at different scales

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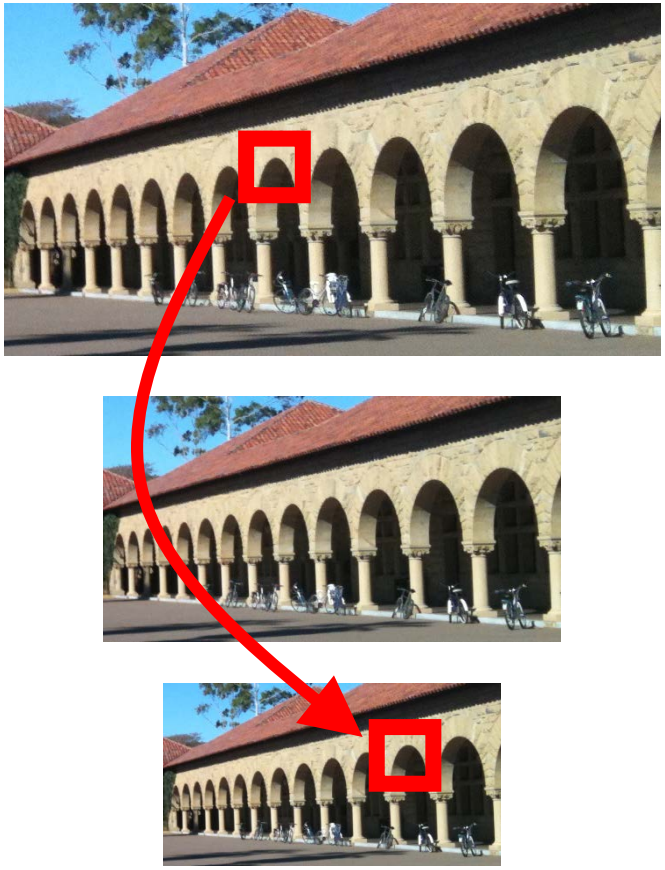

Scale Invariance in Natural Images

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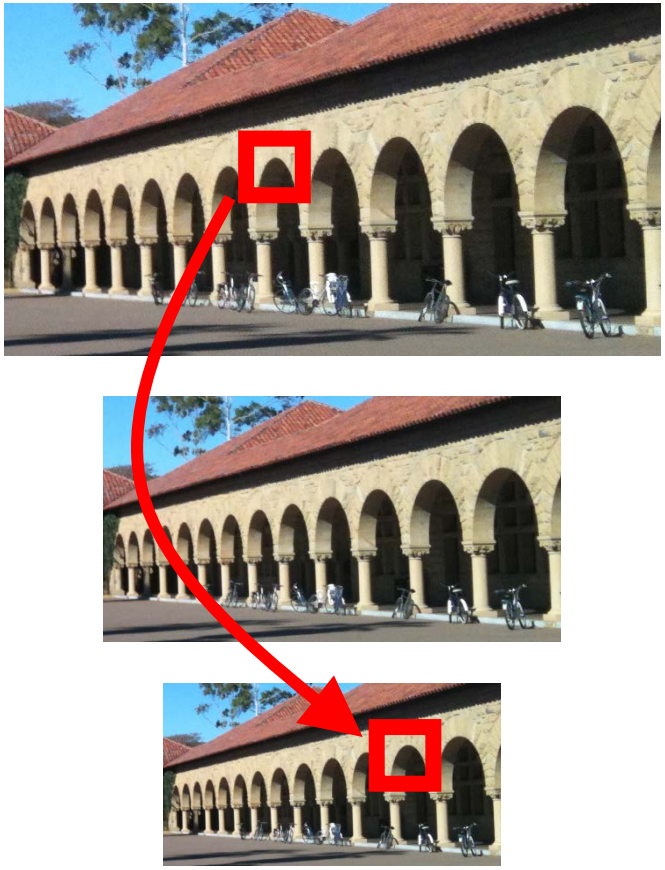


True for most patches in any natural image

[Glasner *et al.* `09]

Scale Invariance in Natural Images

Small patterns recur at different scales

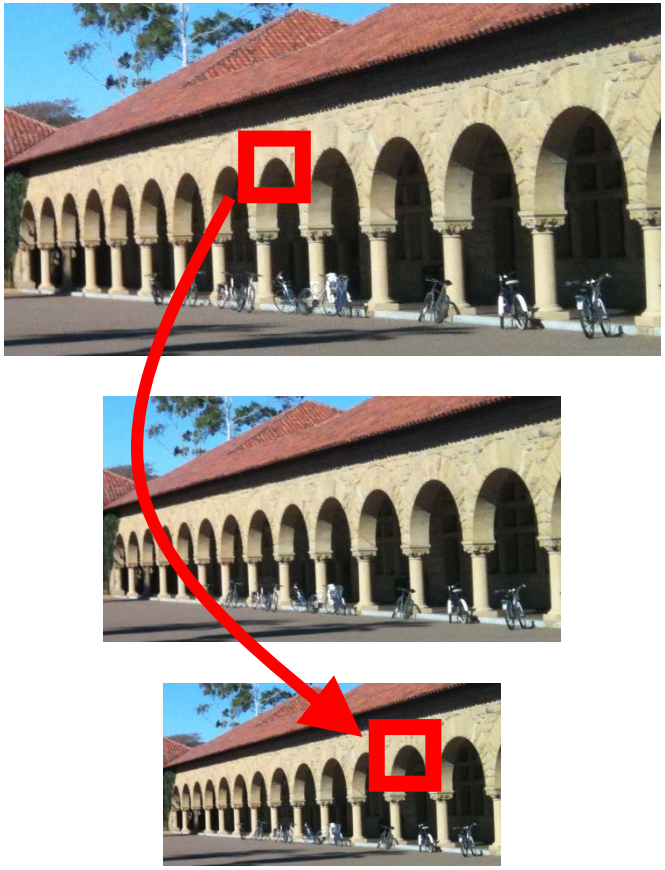
- **Fractal image compression**

  [Barnsley & Sloan `87], ...

- **Single image super-resolution**

  [Glasner *et al.* `09],

  [Freedman & Fattal `11], …



True for most patches in any natural image

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Scale Invariance in Natural Images

Small patterns recur at diff cales

- **Fractal image com n**

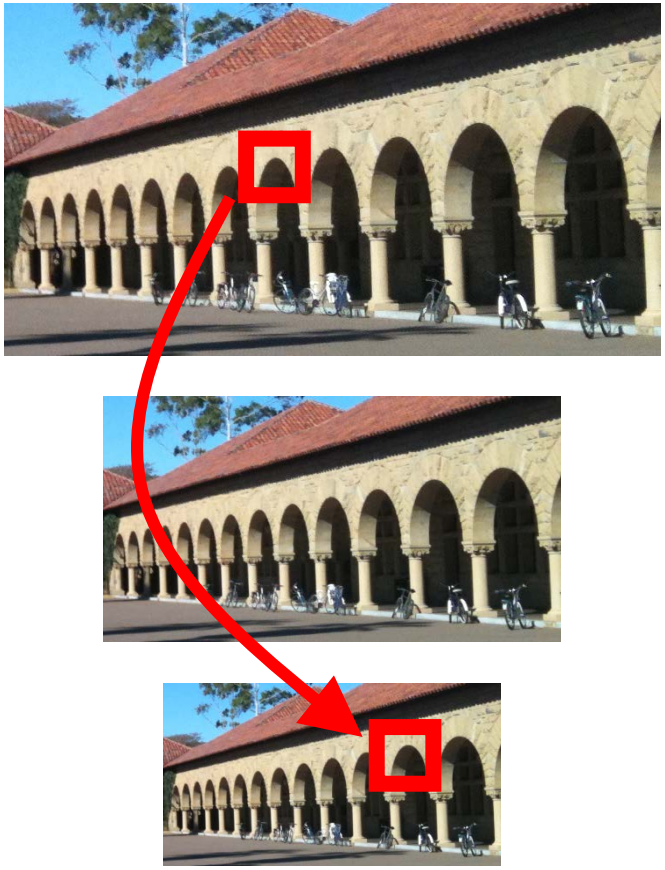
  [Barnsley & 87], ...

- **Single i uper-resolution**

  [*et al.* `09],

  eedman & Fattal `11], …

Ideal imaging conditions

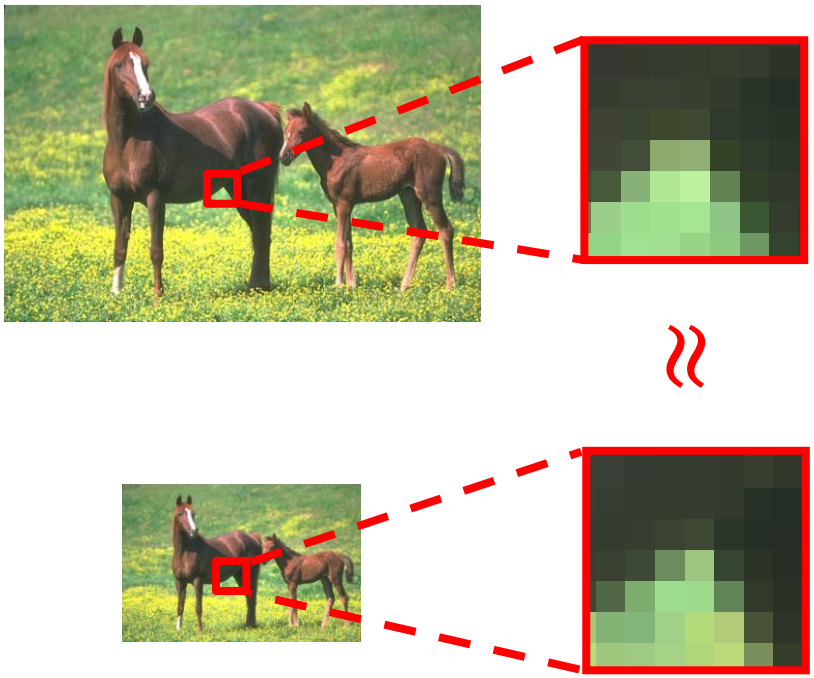


True for most patches in any natural image

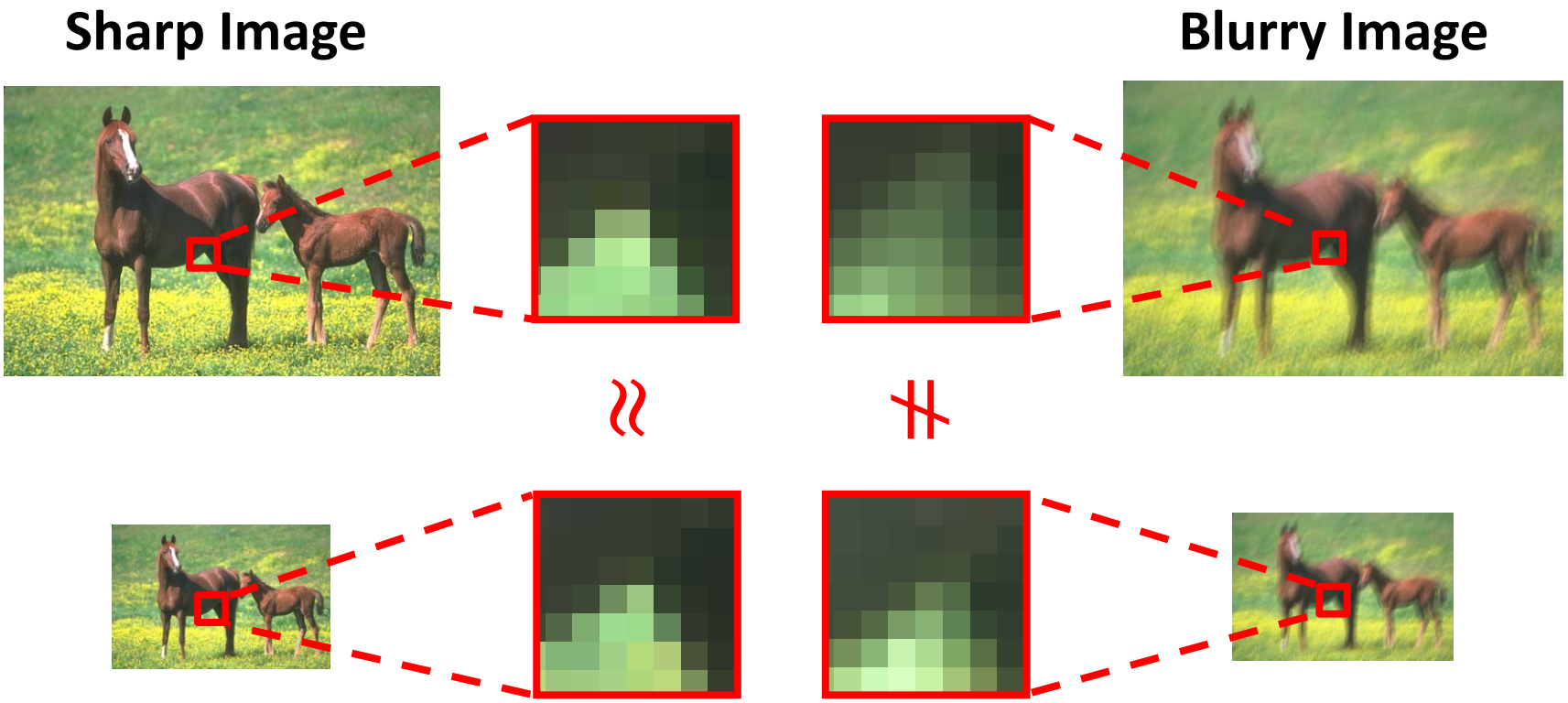
[Glasner *et al.* `09]

Scale Invariance in Natural Images

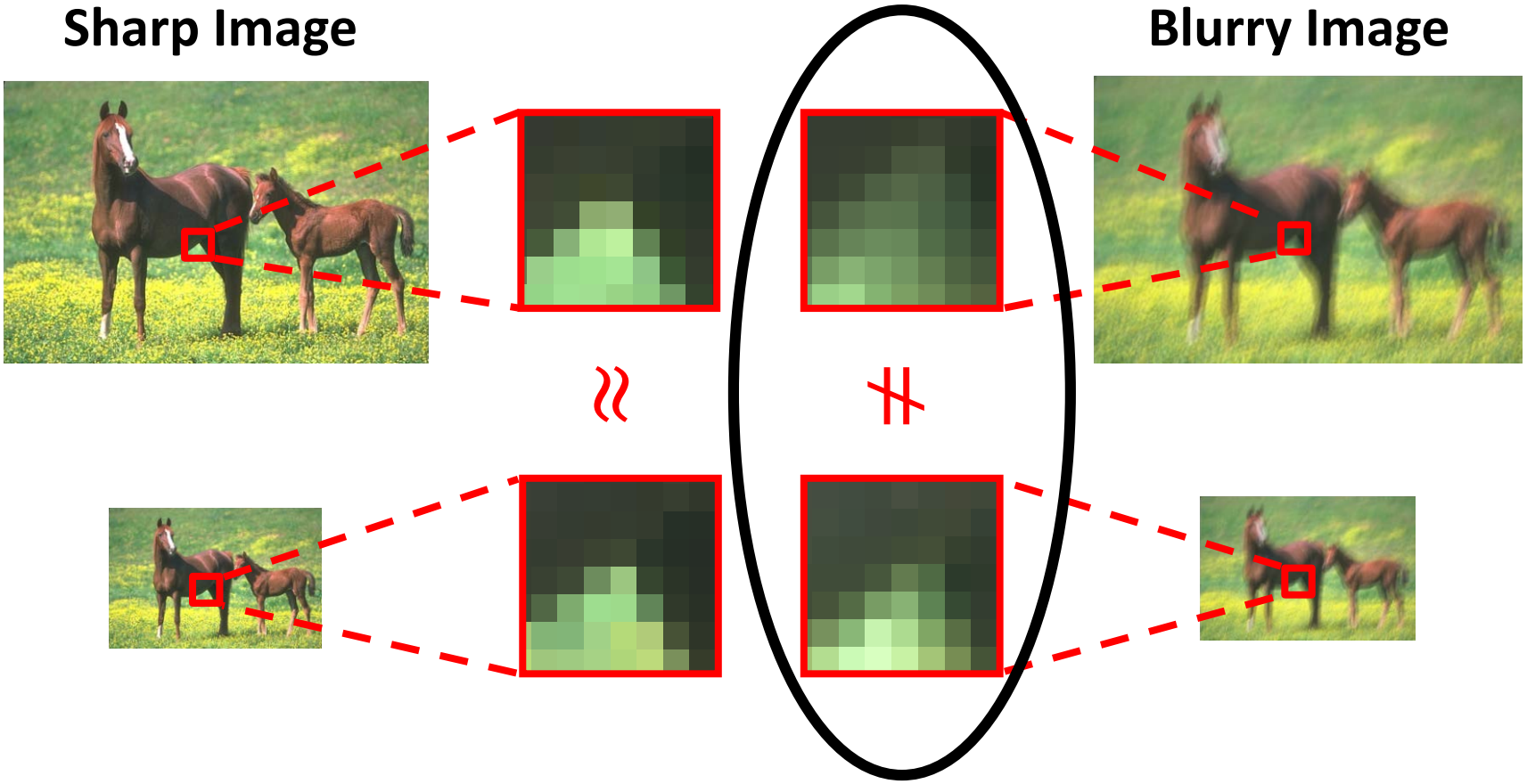
Sharp Image



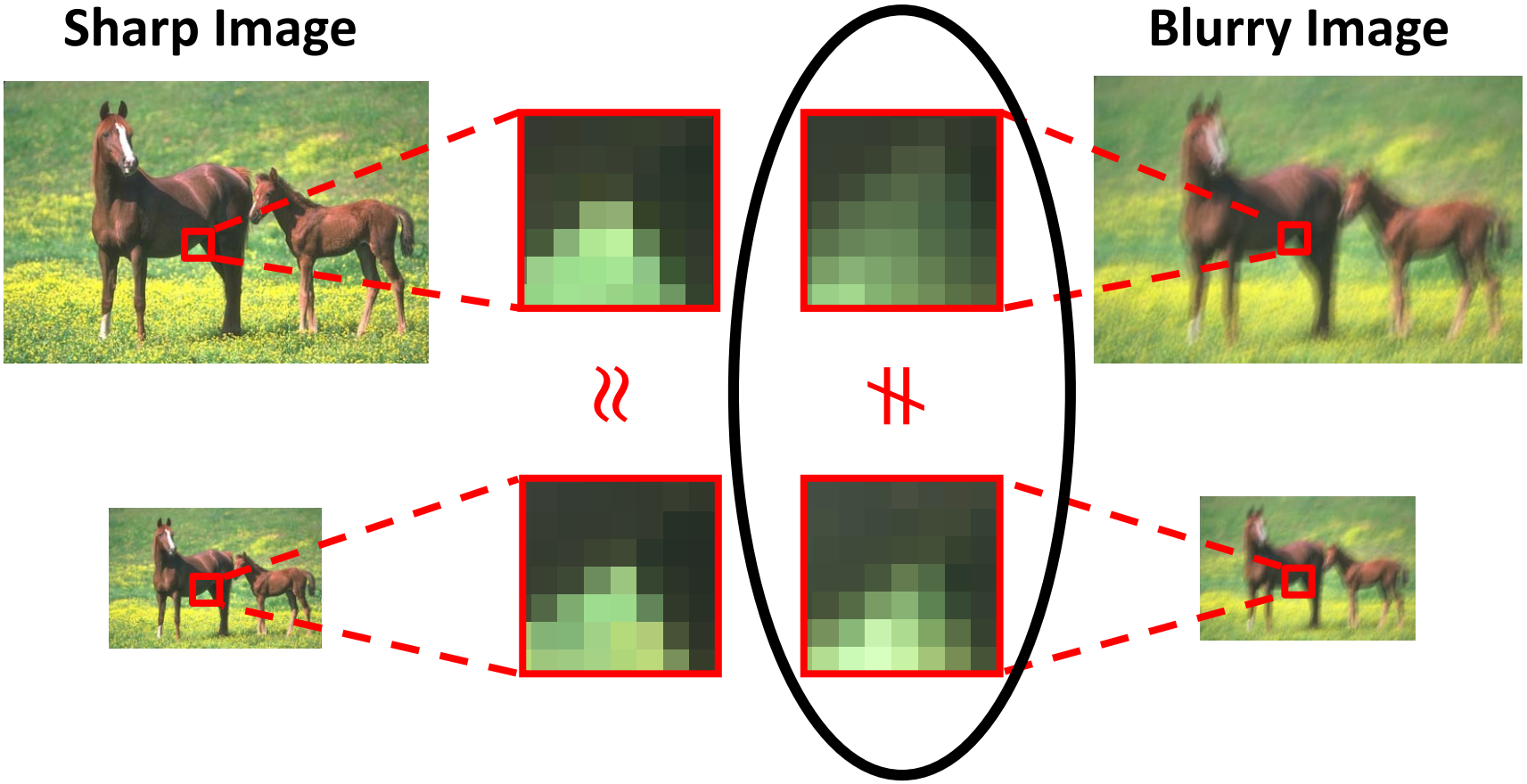
Scale Invariance in Natural Images



Scale Invariance in Natural Images

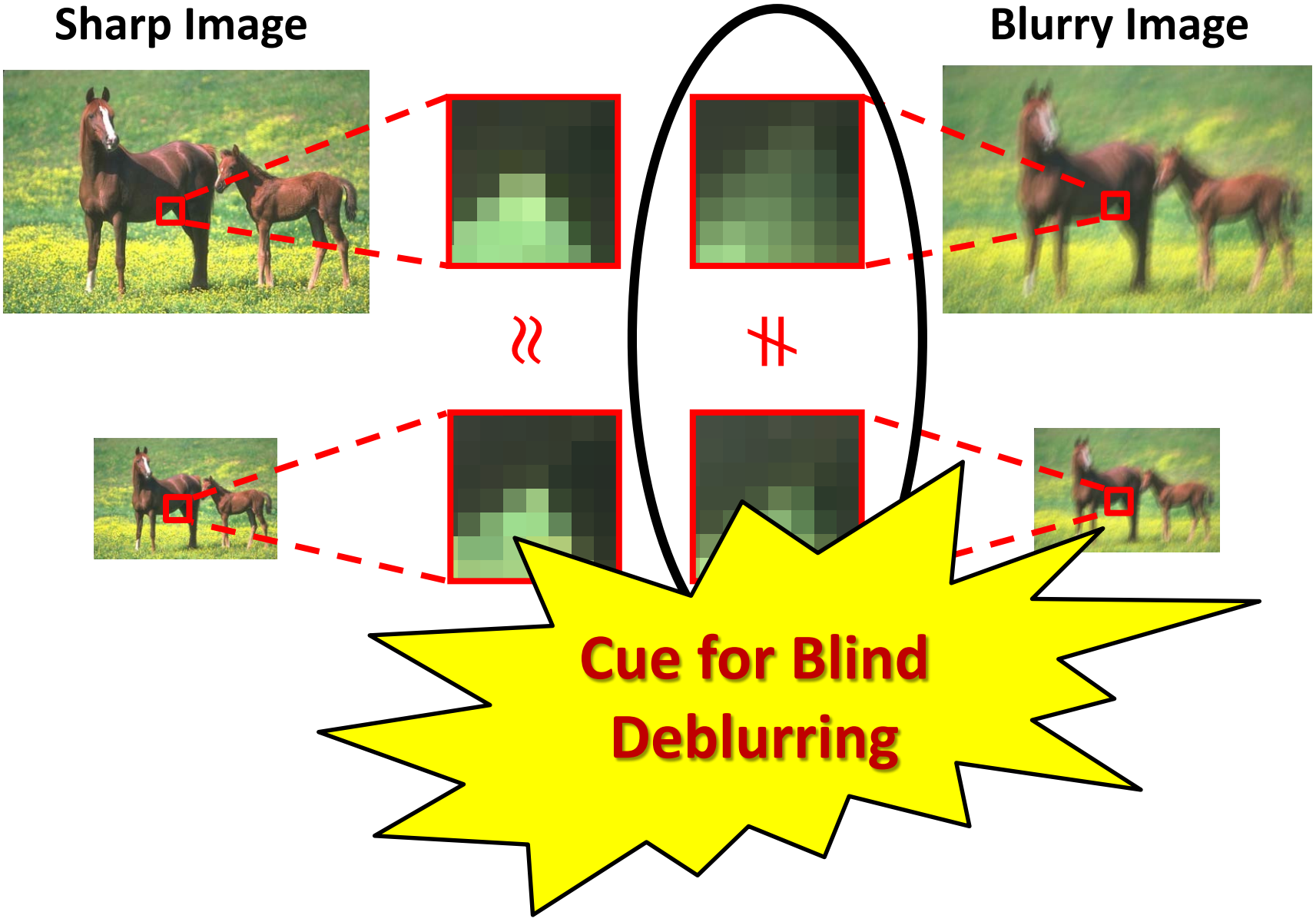


Scale Invariance in Natural Images



Deviations from patch recurrence
➔information on the blur

Scale Invariance in Natural Images



Blind Deblurring

Blurry image y

Blind Deblurring

Blurry image y

Deblurring

Sharp image x

Blind Deblurring

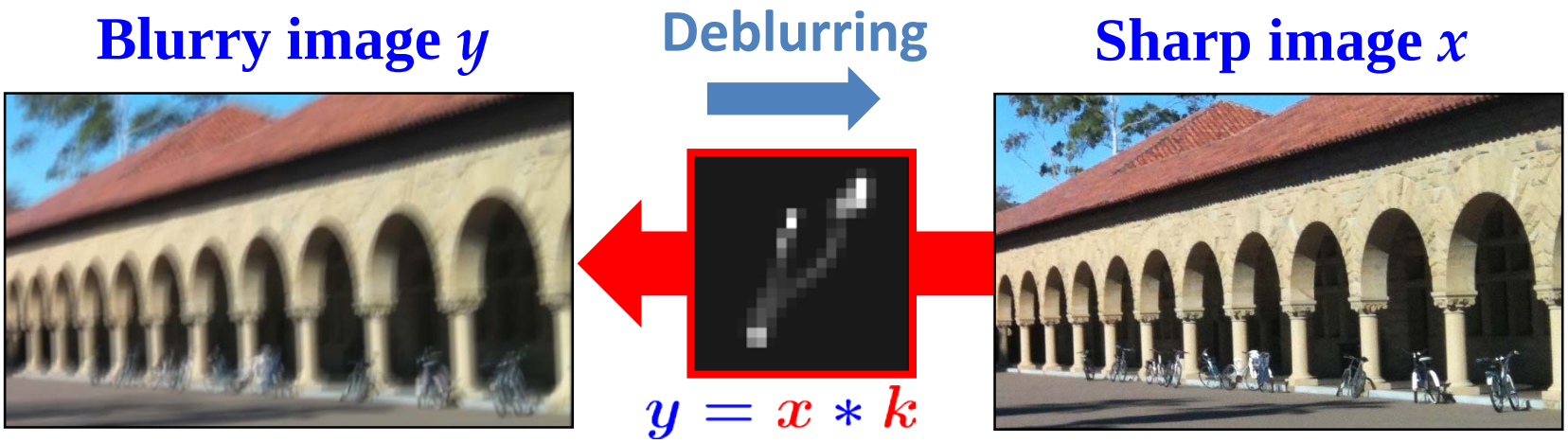
Blurry image y

Deblurring

Sharp image x

$$y = x * k$$

Blind Deblurring



Examples of previous priors:

- **Enhance/detect edges**

  [Xu & Jia `10], [Cho & Lee `09], [Cho *et al.* `11], …

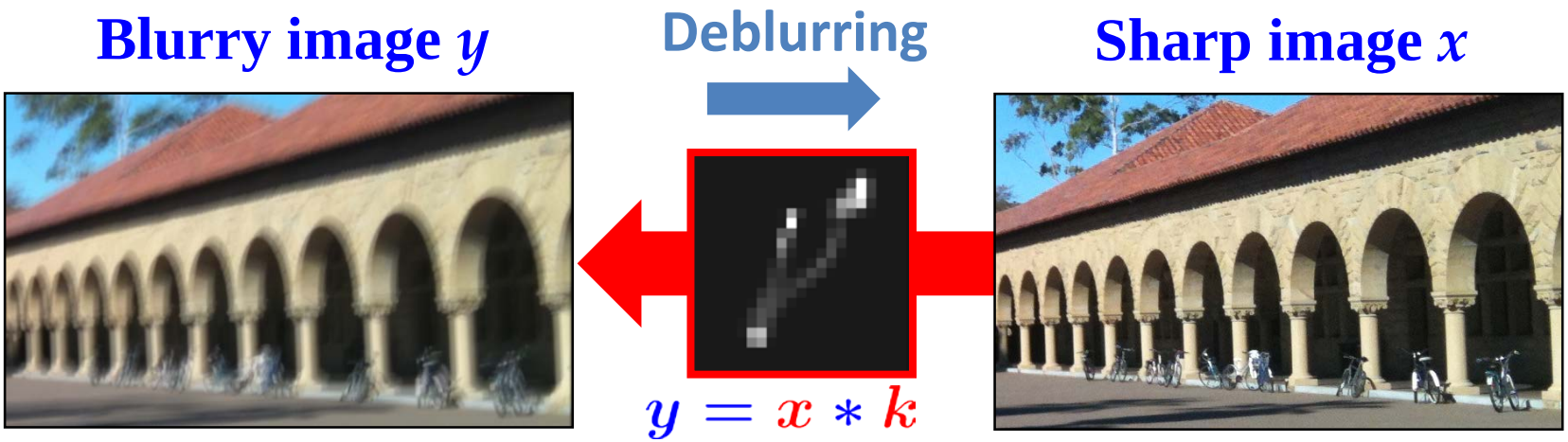
- **Sparse gradients**

  [Levin *et al.* `11], [Krishnan *et al.* `11], …

- **External patch prior**

  [Sun *et al.* `13]

Blind Deblurring



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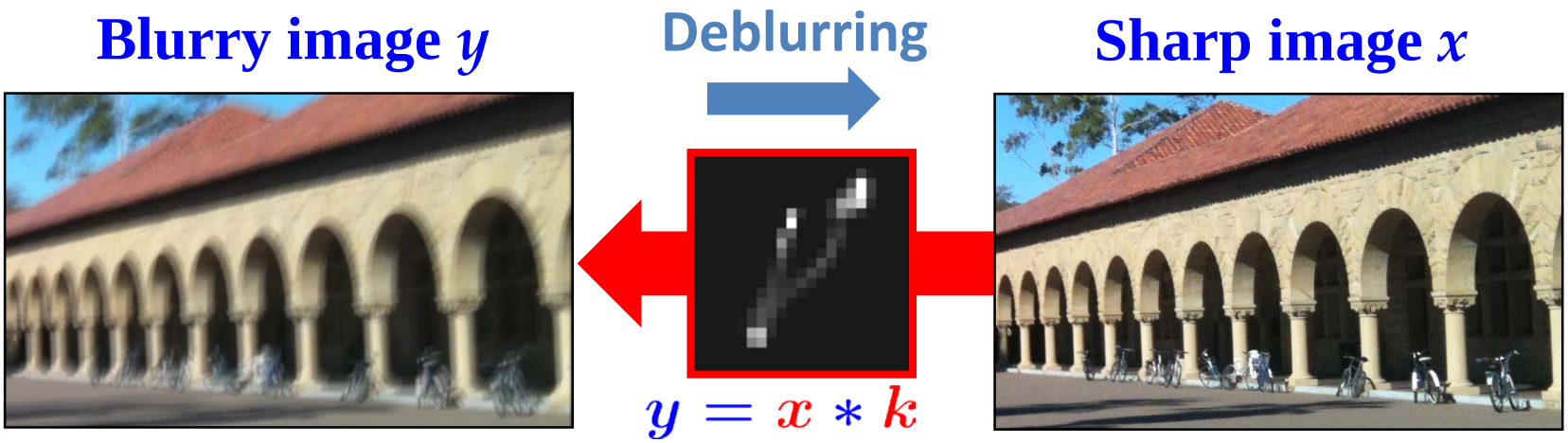
- **External patch prior**

  [Sun *et al.* `13]

Cross-Scale Recurrence → Strong Prior

Blind Deblurring

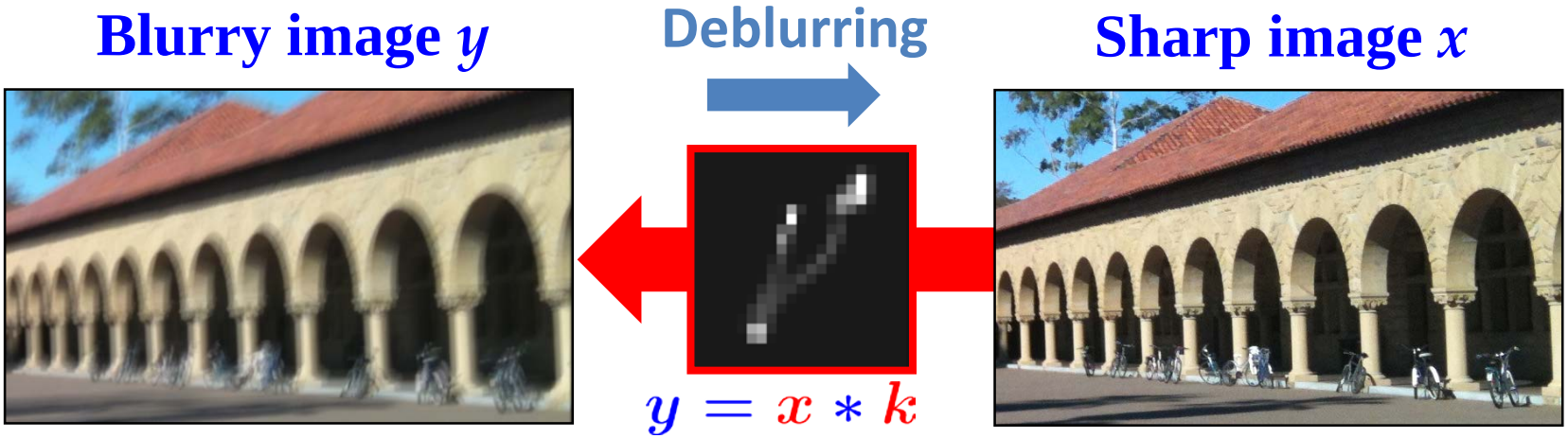


Blind Super Resolution

[Michaeli & Irani `13]

Cross-Scale Recurrence ➔ Strong Prior

Blind Deblurring

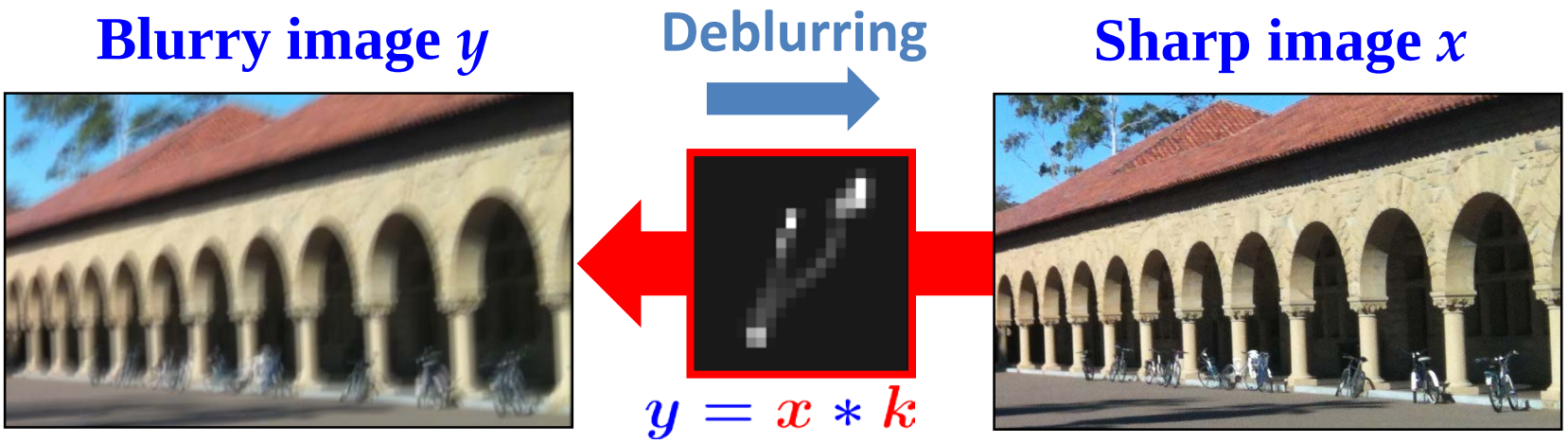


Blind Super Resolution ≠ Blind Deblurring

[Michaeli & Irani `13]

Cross-Scale Recurrence ➔ Strong Prior

Blind Deblurring



k = PSF

Blind Super Resolution ≠ Blind Deblurring

[Michaeli & Irani `13]

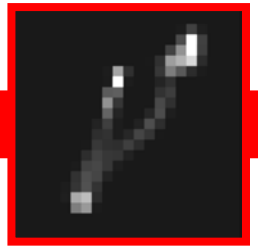
Cross-Scale Recurrence ➔ Strong Prior

Blind Deblurring

Blurry image y

Deblurring

Sharp image x



$$y = x * k$$

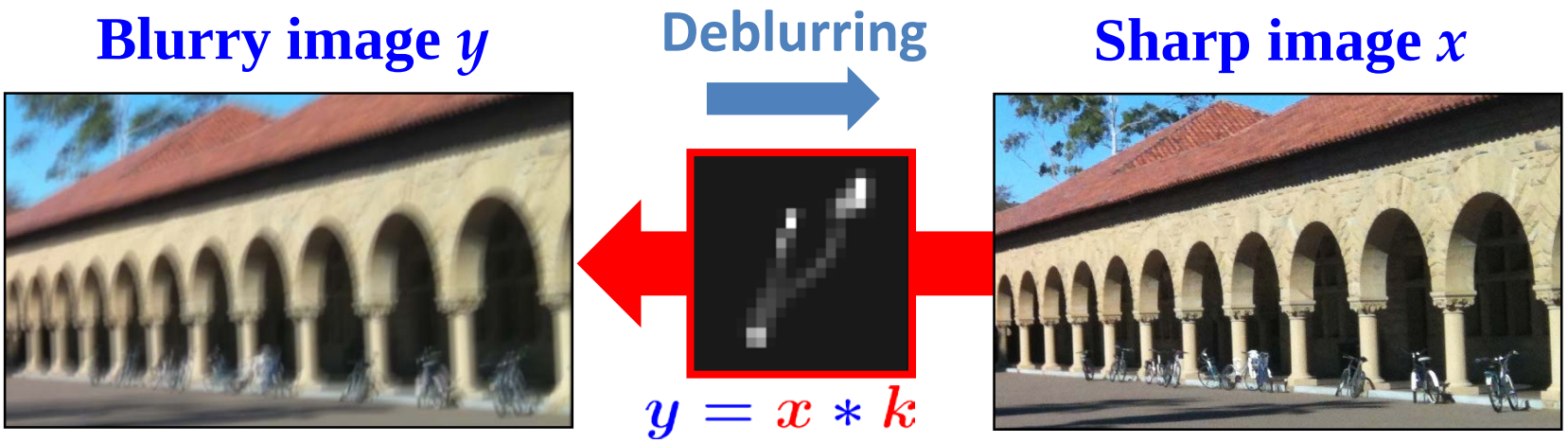
k ≠ PSF **k = PSF**

Blind Super Resolution ≠ Blind Deblurring

[Michaeli & Irani `13]

Cross-Scale Recurrence ➔ Strong Prior

Blind Deblurring



k ≠ PSF

k = PSF

Blind Super Resolution ≠ Blind Deblurring

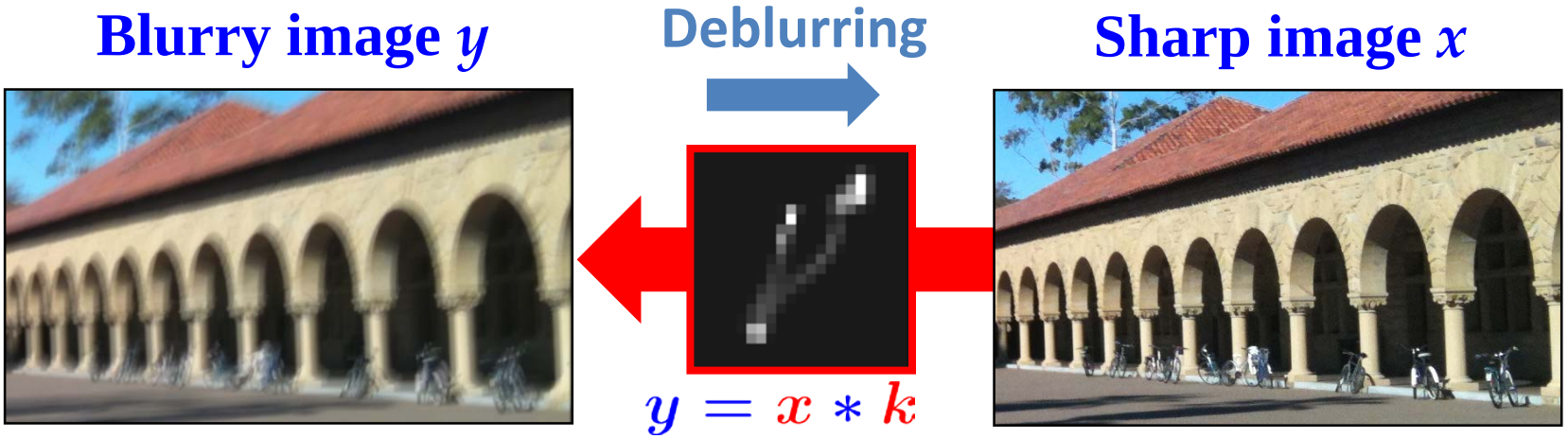
[Michaeli & Irani `13]

$$K(\omega) = \frac{\mathcal{PSF}(\omega)}{\mathcal{PSF}(\omega/\alpha)}$$

Zoom-in by α

Cross-Scale Recurrence ➔ Strong Prior

Blind Deblurring



k ≠ PSF

k = PSF

Blind Super Resolution ≠ Blind Deblurring

[Michaeli & Irani `13]

$$K(\omega) = \frac{\mathcal{PSF}(\omega)}{\mathcal{PSF}(\omega/\alpha)} = 1$$

Zoom-in by α

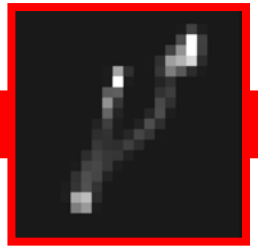
Cross-Scale Recurrence → Strong Prior

Blind Deblurring

Blurry image y

Deblurring

Sharp image x



$$y = x * k$$

k ≠ PSF **k = PSF**

Blind Super Resolution ≠ Blind Deblurring

[Michaeli & Irani `13]

$$K(\omega) = \frac{\mathcal{PSF}(\omega)}{\mathcal{PSF}(\omega/\alpha)} = 1$$

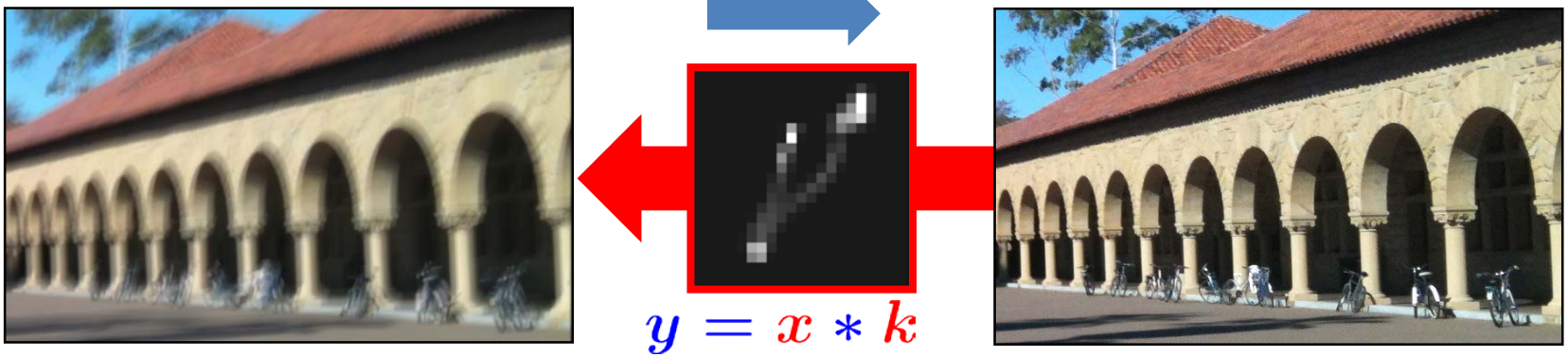
Zoom-in by α

$$k(\xi) = \delta(\xi)$$

Cross-Scale Recurrence ➔ Strong Prior

Blind Deblurring

Blurry image y | **Deblurring** | **Sharp image x**



k ≠ PSF **k = PSF**

Blind Super Resolution ≠ Blind Deblurring

[Michaeli & Irani `13]

$$K(\omega) = \frac{\mathcal{PSF}(\omega)}{\mathcal{PSF}(\omega/\alpha)} = 1$$

Zoom-in by α

$$k(\xi) = \delta(\xi)$$

Regardless of the PSF !!!

Cross-Scale Recurrence ➔ Strong Prior

Overview

Blurry image y

Deblurring

$$y = x * k$$

Sharp image x

Overview

Blurry image y

Deblurring

$$y = x * k$$

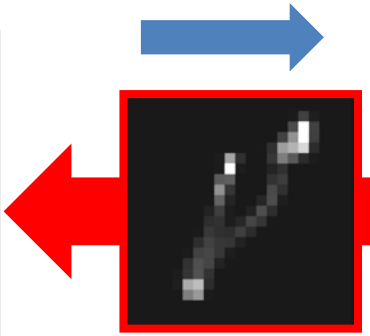
Sharp image x

Ideal camera (PSF=sinc)

Overview

Blurry image y

Deblurring

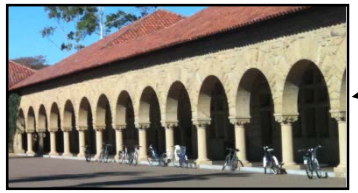


$$y = x * k$$

Sharp image x

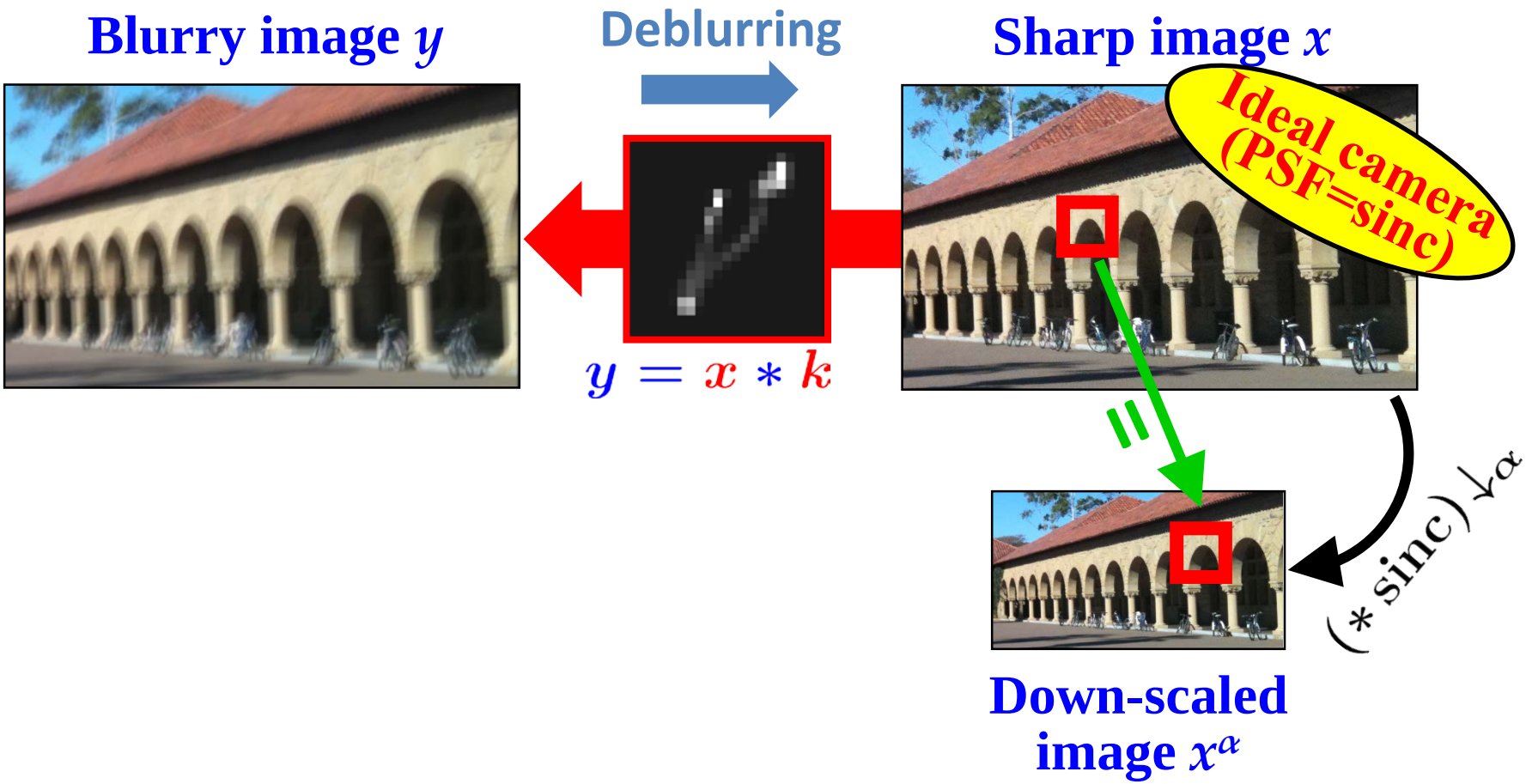
Ideal camera (PSF=sinc)

$(* \text{sinc}) \downarrow_\alpha$

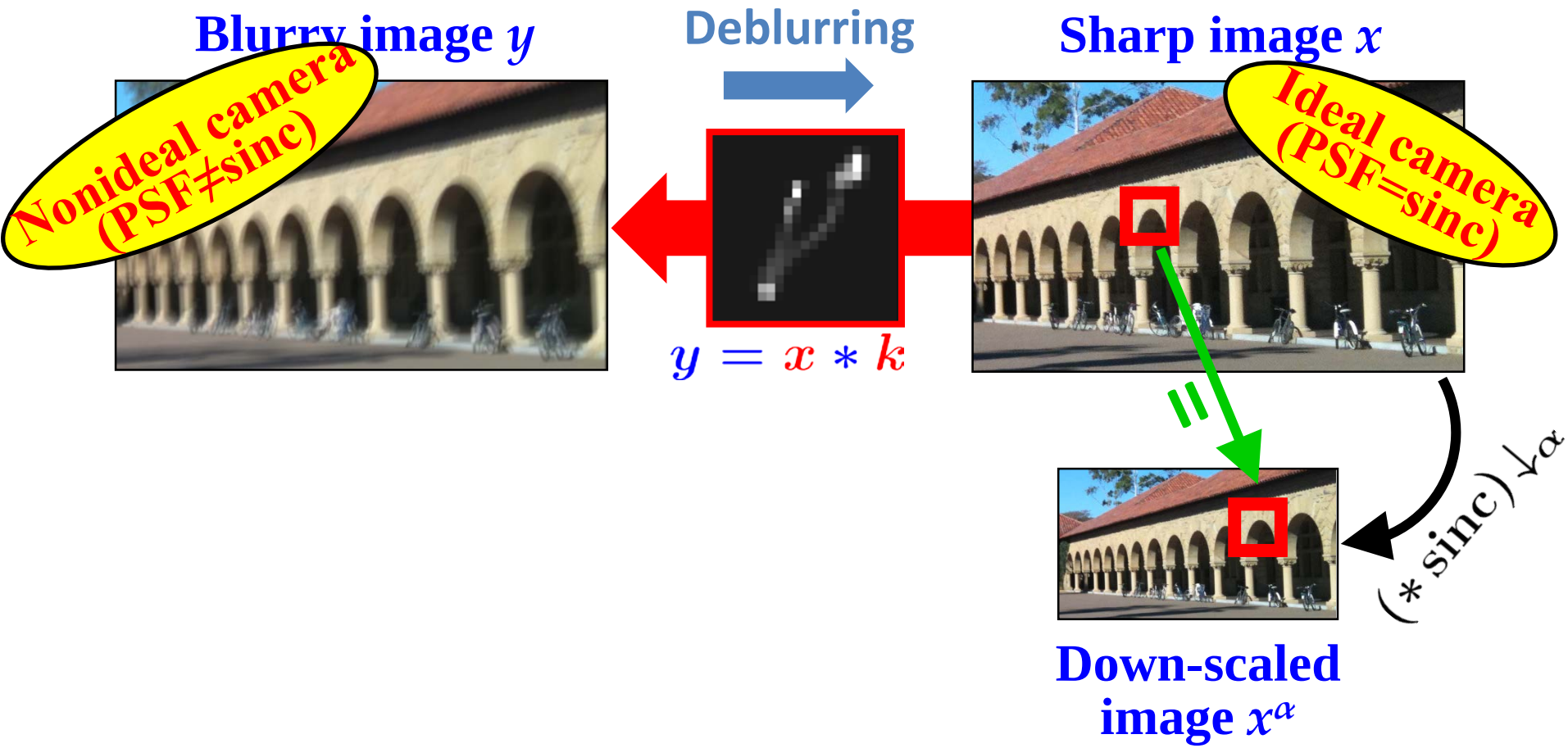


Down-scaled image x^α

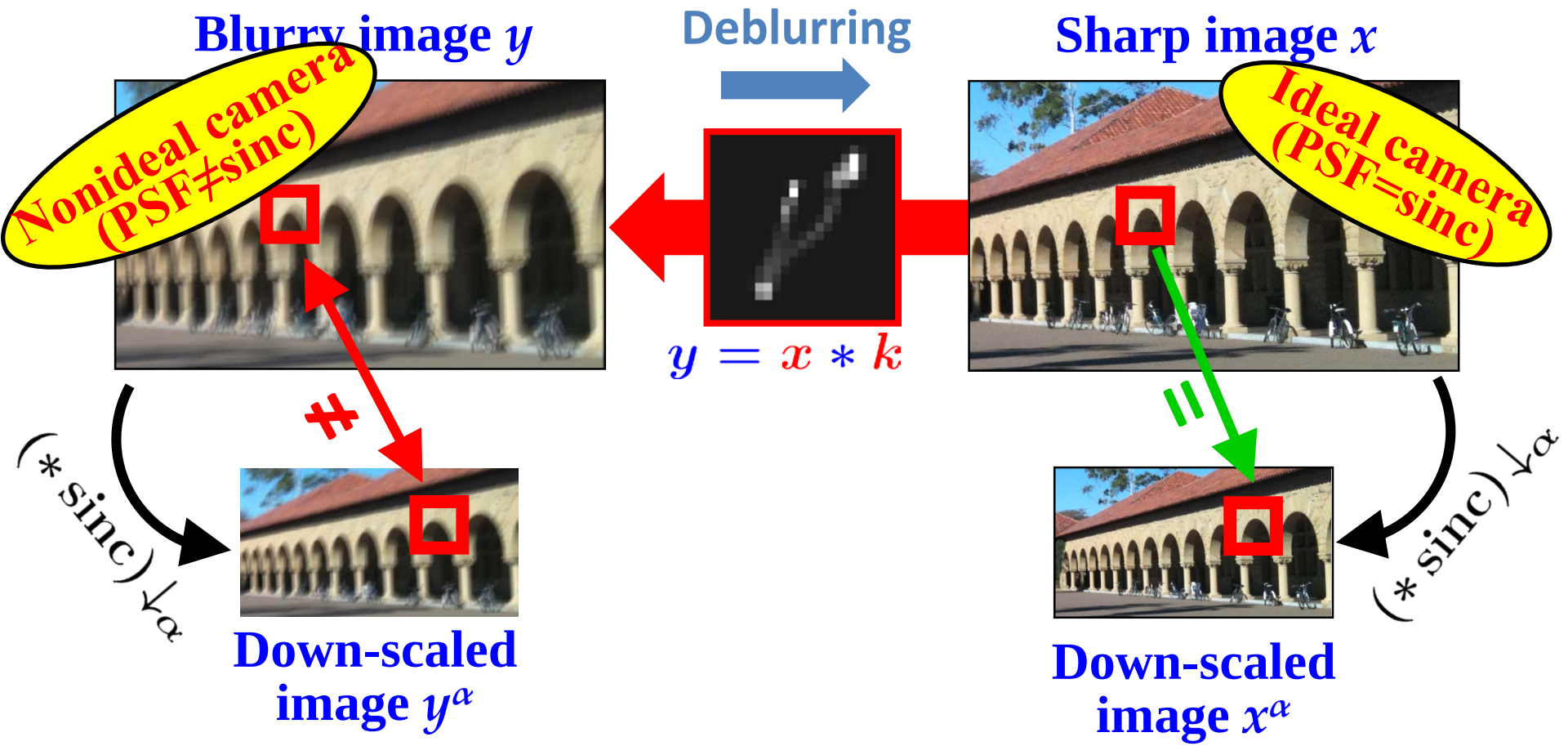
Overview


Blurry image y
Deblurring
Sharp image x
Ideal camera (PSF=sinc)
$y = x * k$
$(* \text{sinc}) \downarrow_\alpha$
Down-scaled image x^α

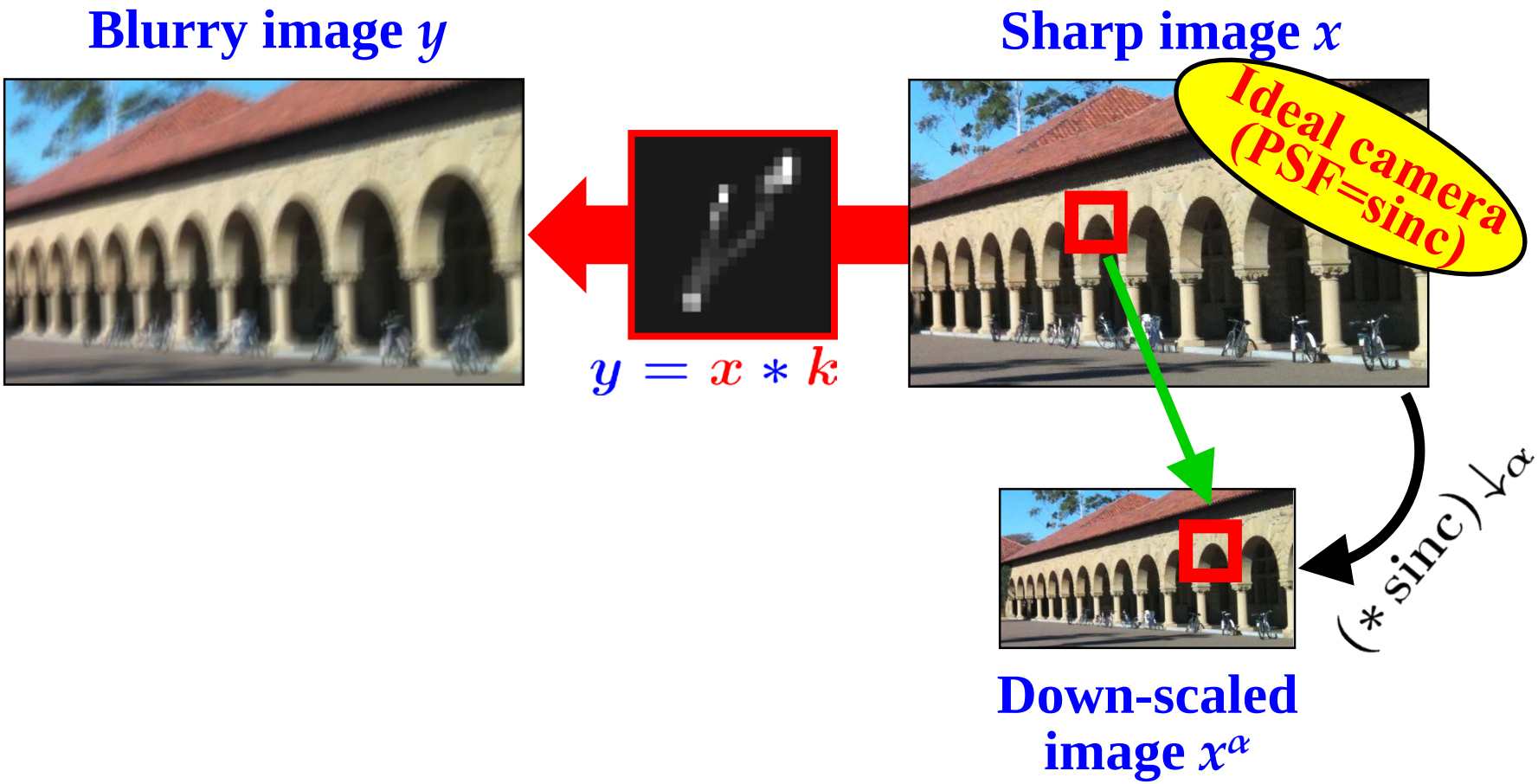
Overview


Blurry image y
Deblurring
Sharp image x
Nonideal camera (PSF≠sinc)
Ideal camera (PSF=sinc)
$y = x * k$
$(* \text{sinc}) \downarrow_\alpha$
Down-scaled image x^α

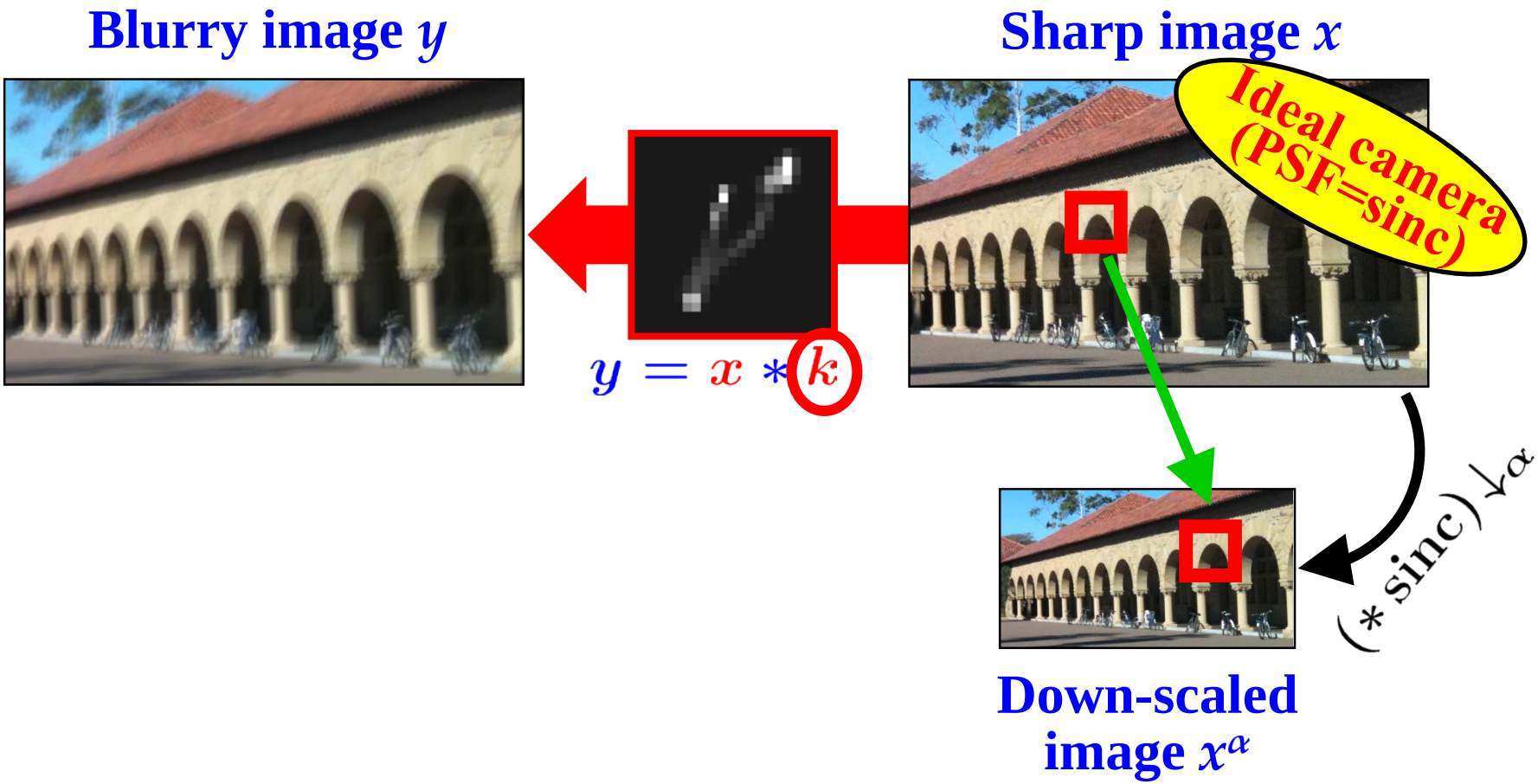
Overview


Blurry image y
Deblurring
Sharp image x
Nonideal camera (PSF≠sinc)
Ideal camera (PSF=sinc)
$y = x * k$
$\neq$
$=$
$(* \text{sinc})\downarrow_\alpha$
$(* \text{sinc})\downarrow_\alpha$
Down-scaled image y^α
Down-scaled image x^α

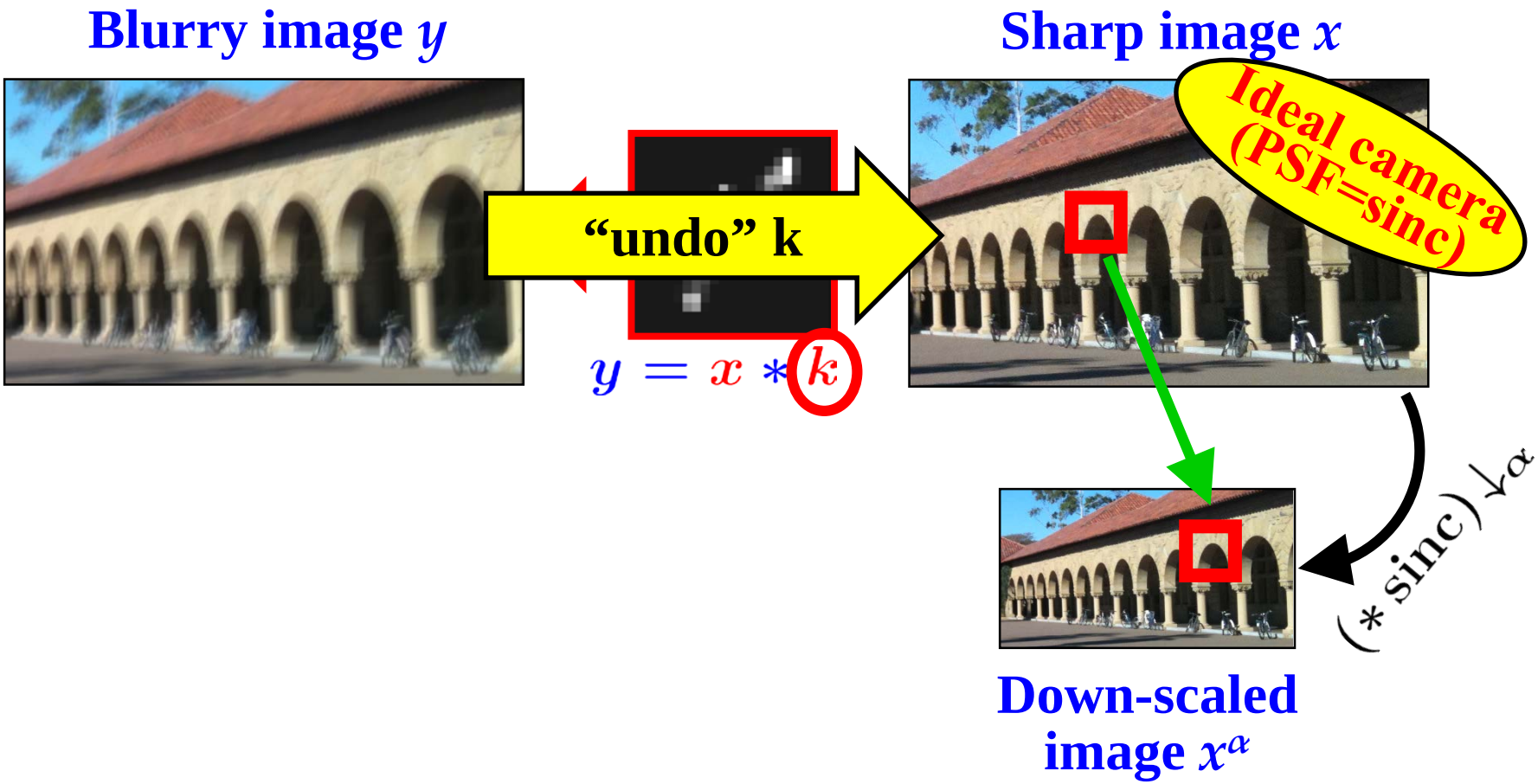
Overview


Blurry image y
Sharp image x
Ideal camera (PSF=sinc)
$y = x * k$
$(* \text{sinc}) \downarrow_\alpha$
Down-scaled image x^α

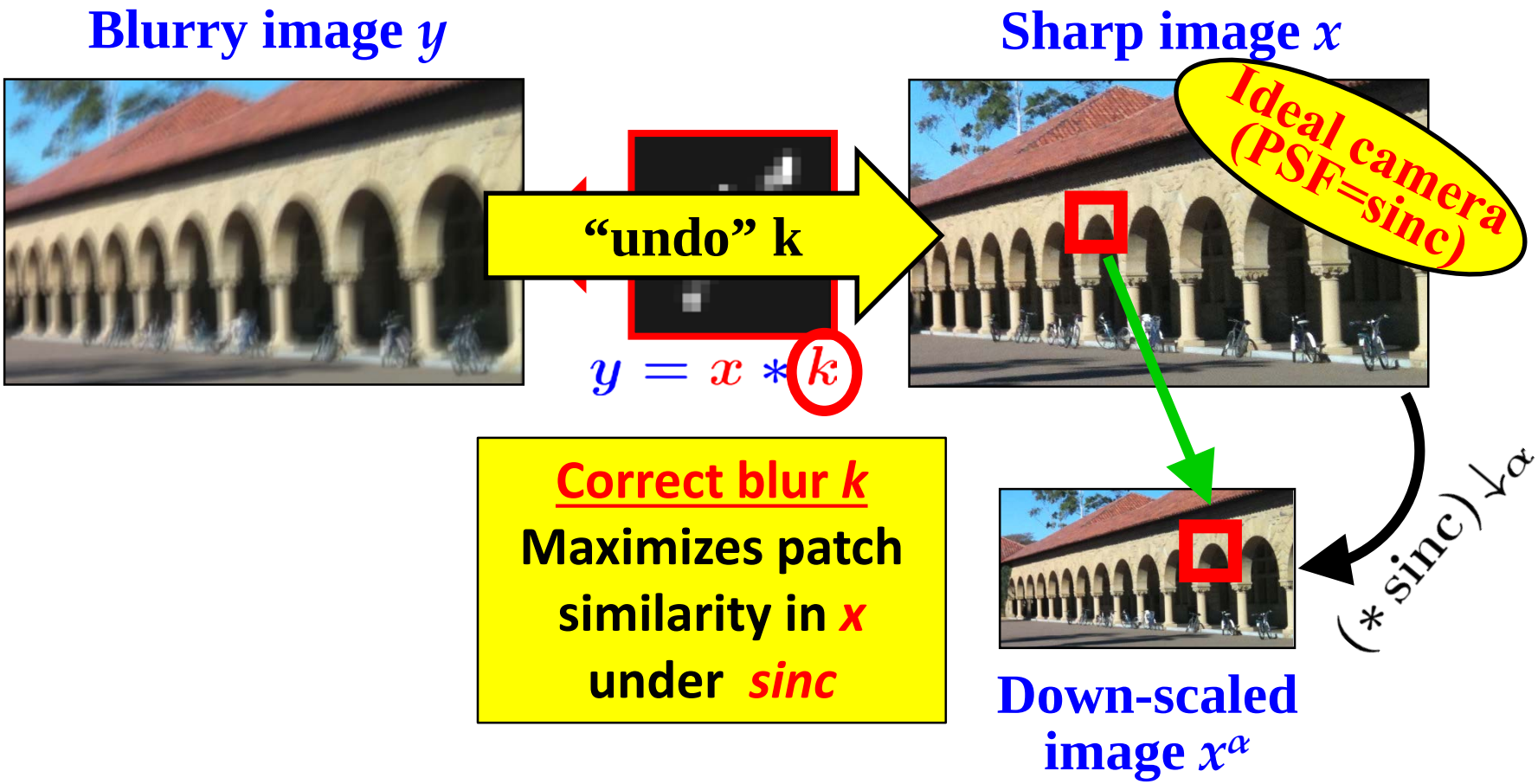
Overview


Blurry image y
Sharp image x
Ideal camera (PSF=sinc)
$y = x * k$
$(* \text{sinc}) \downarrow_\alpha$
Down-scaled image x^α

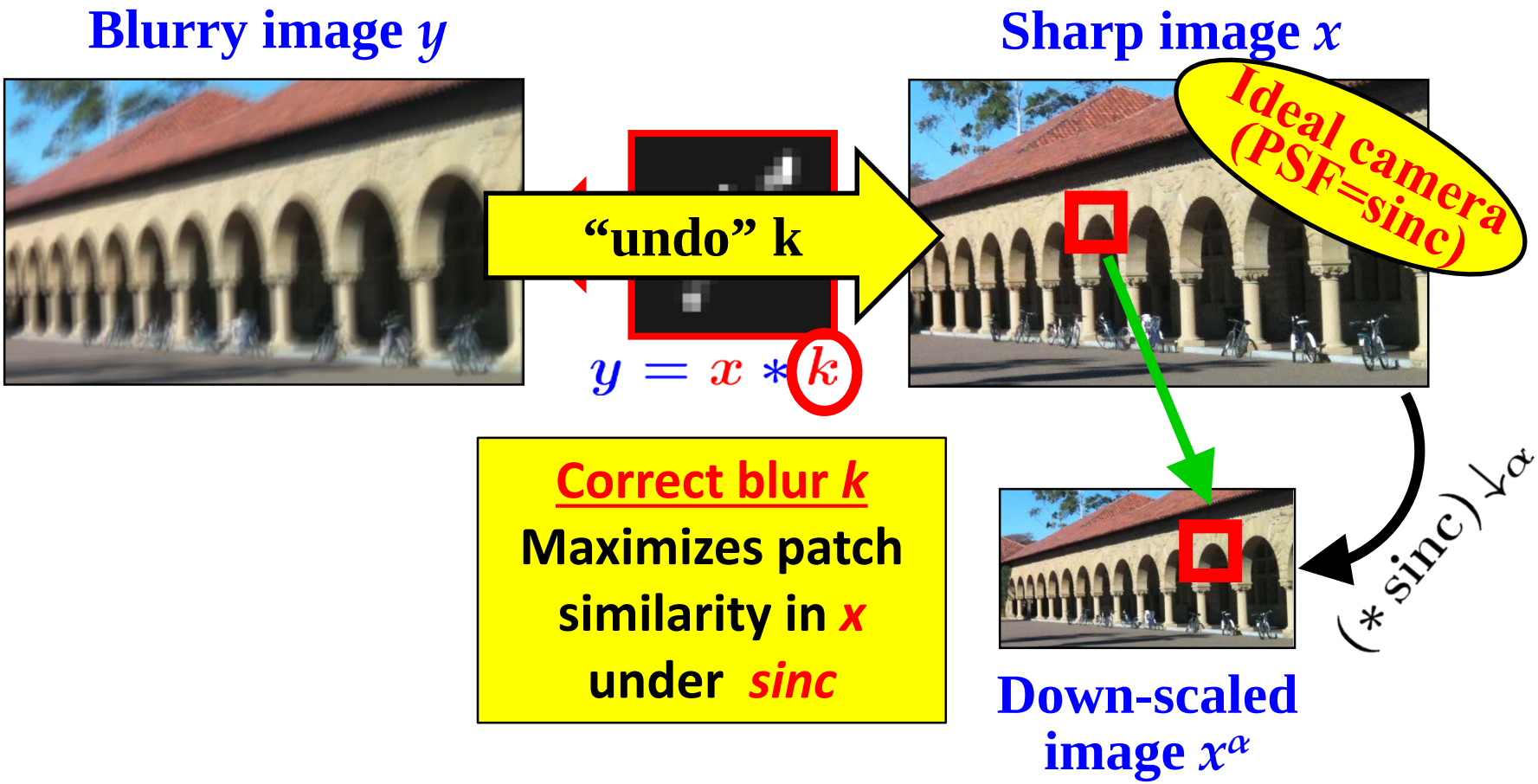
Overview


Blurry image y
Sharp image x
Ideal camera (PSF=sinc)
"undo" k
$y = x * k$
$(* \text{sinc}) \downarrow \alpha$
Down-scaled image x^{α}

Overview

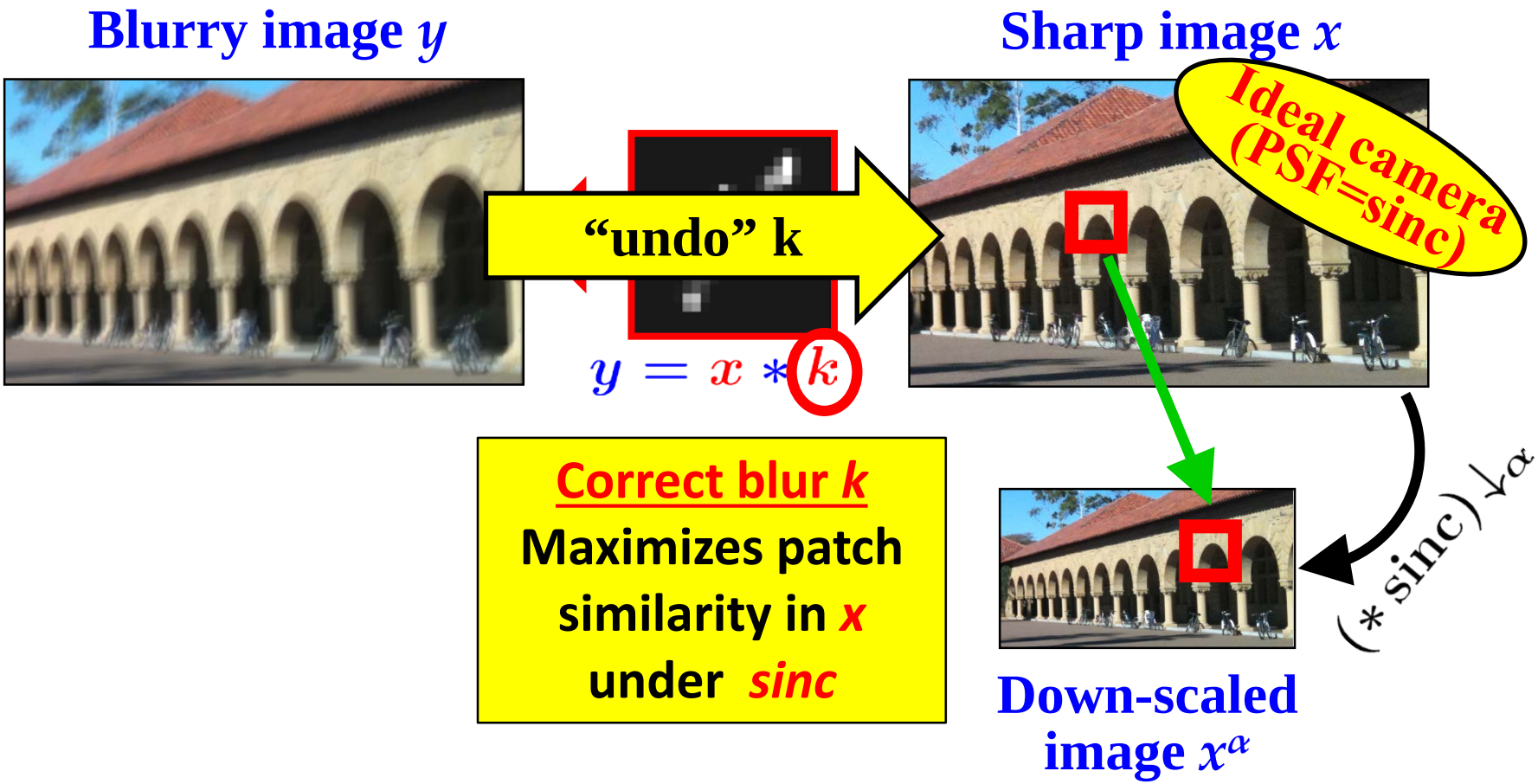

Blurry image y
Sharp image x
Ideal camera (PSF=sinc)
"undo" k
$y = x * k$
Correct blur *k*
Maximizes patch similarity in *x* under *sinc*
$(* \text{sinc}) \downarrow_\alpha$
Down-scaled image x^α

Overview



$$\arg\min_{x,k} \underbrace{\|y - k * x\|^2}_{\text{data term}} + \lambda \underbrace{\rho(x, x^\alpha)}_{\text{prior}}$$

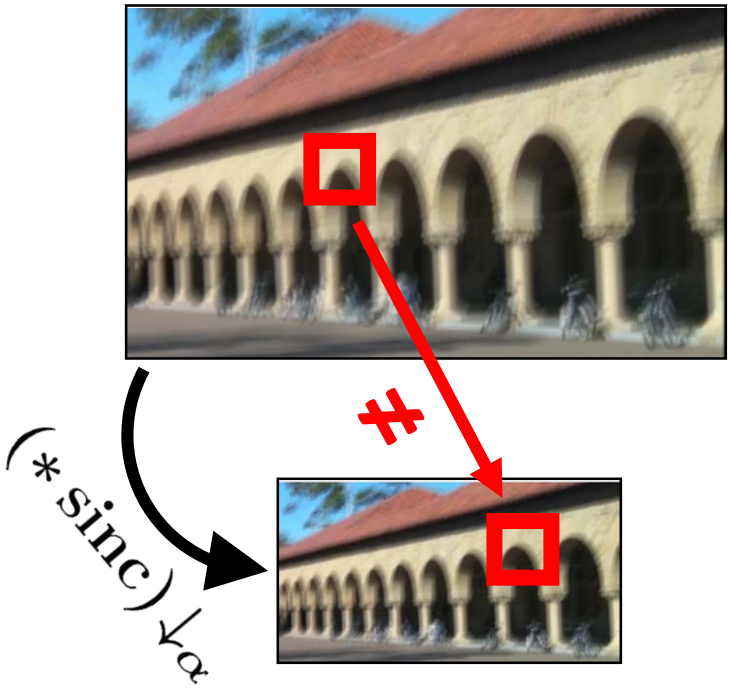
Overview



$$\arg\min_{x,k} \underbrace{\|y - k * x\|^2}_{\text{data term}} + \lambda \underbrace{\rho(x, x^{\alpha})}_{\text{prior}}$$

Overview

Blurry image y



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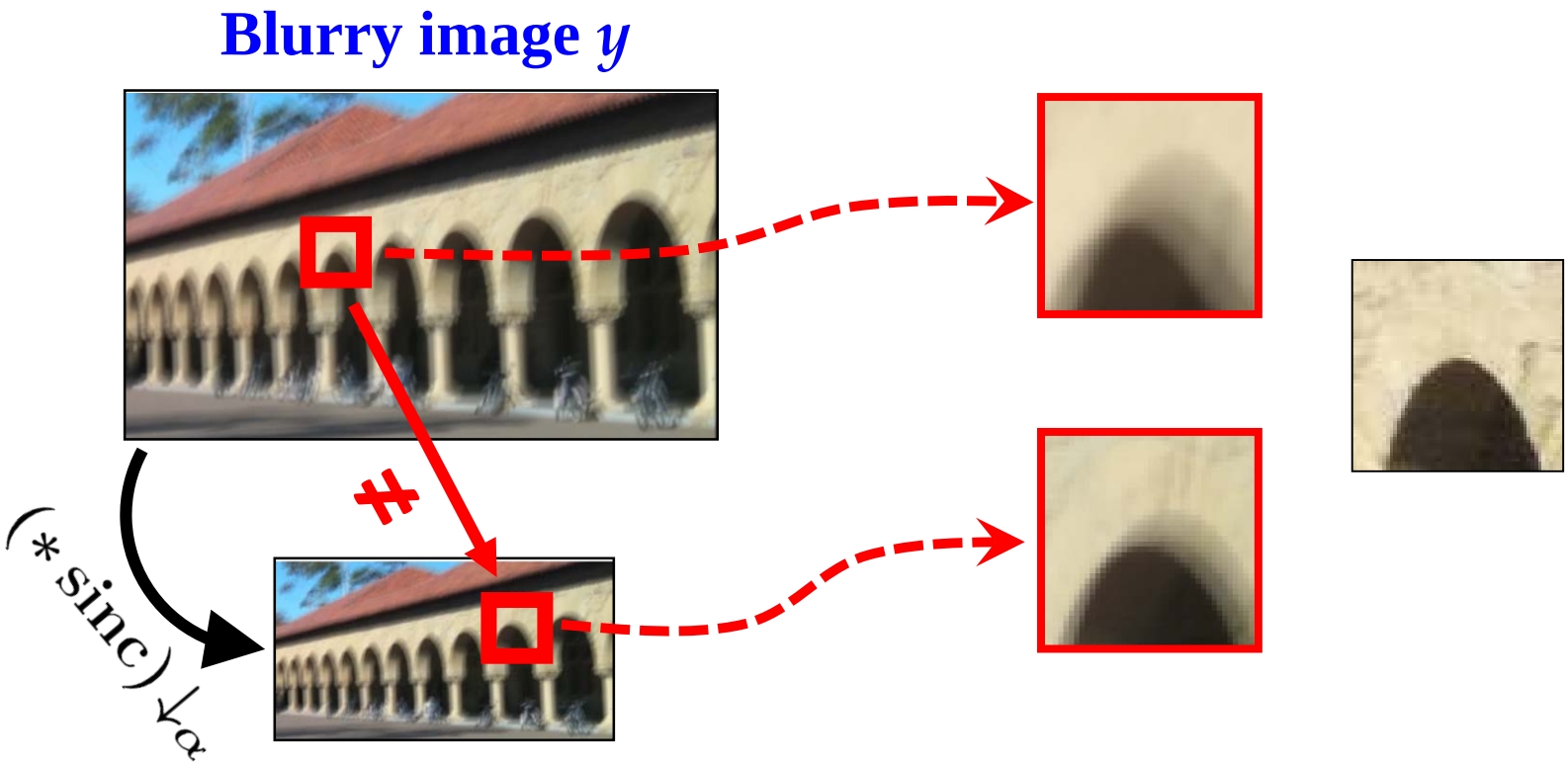
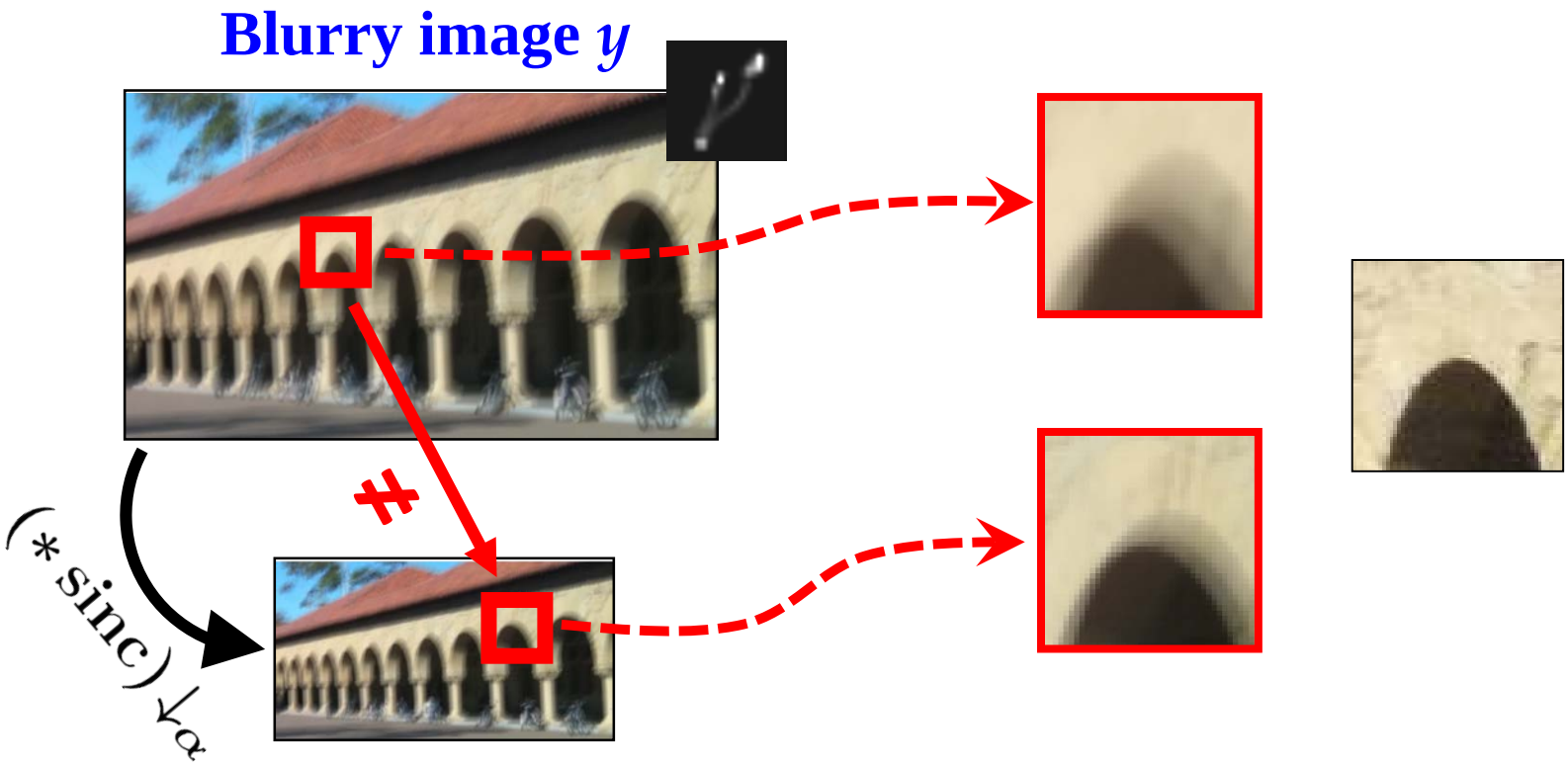
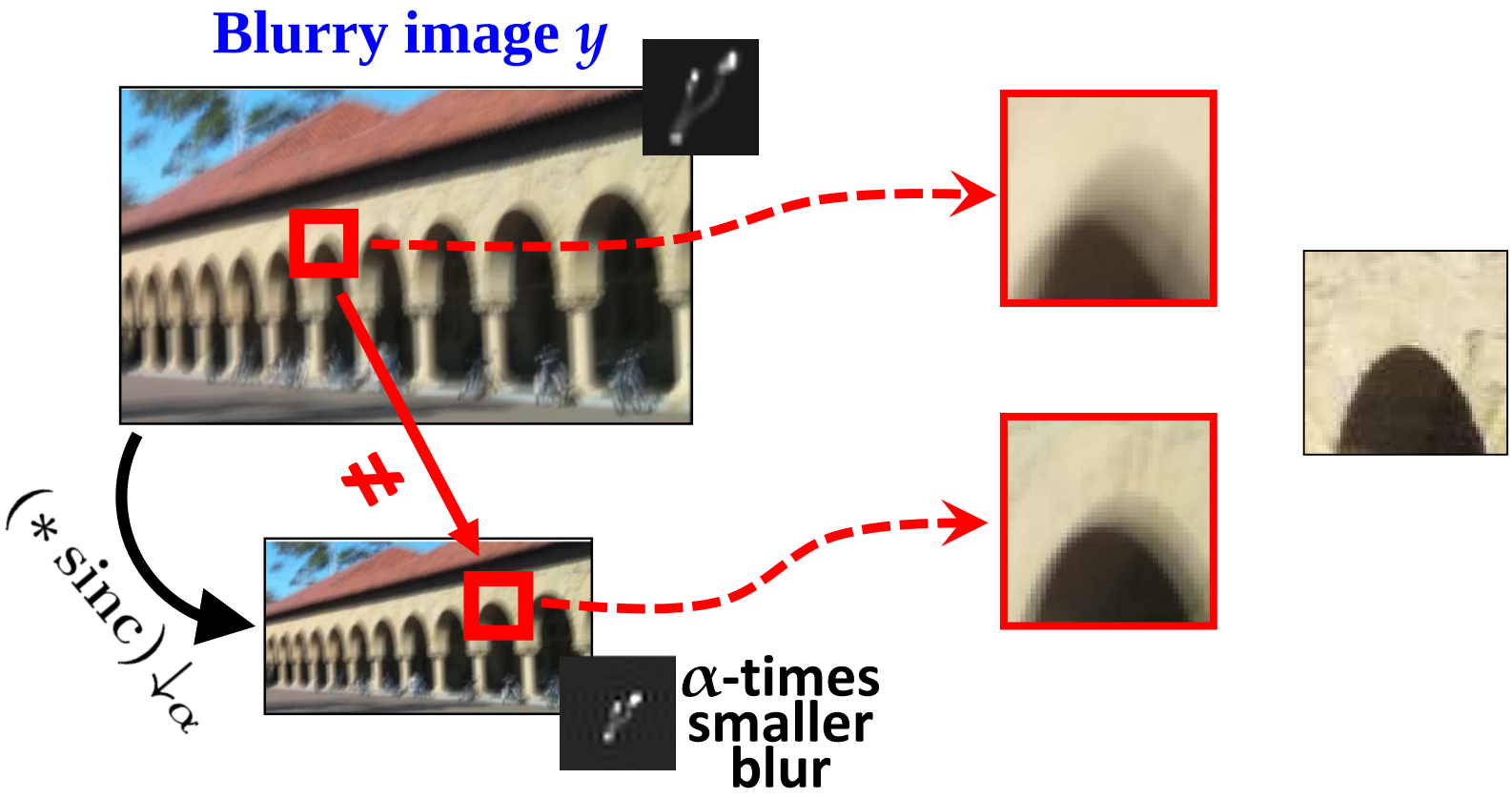


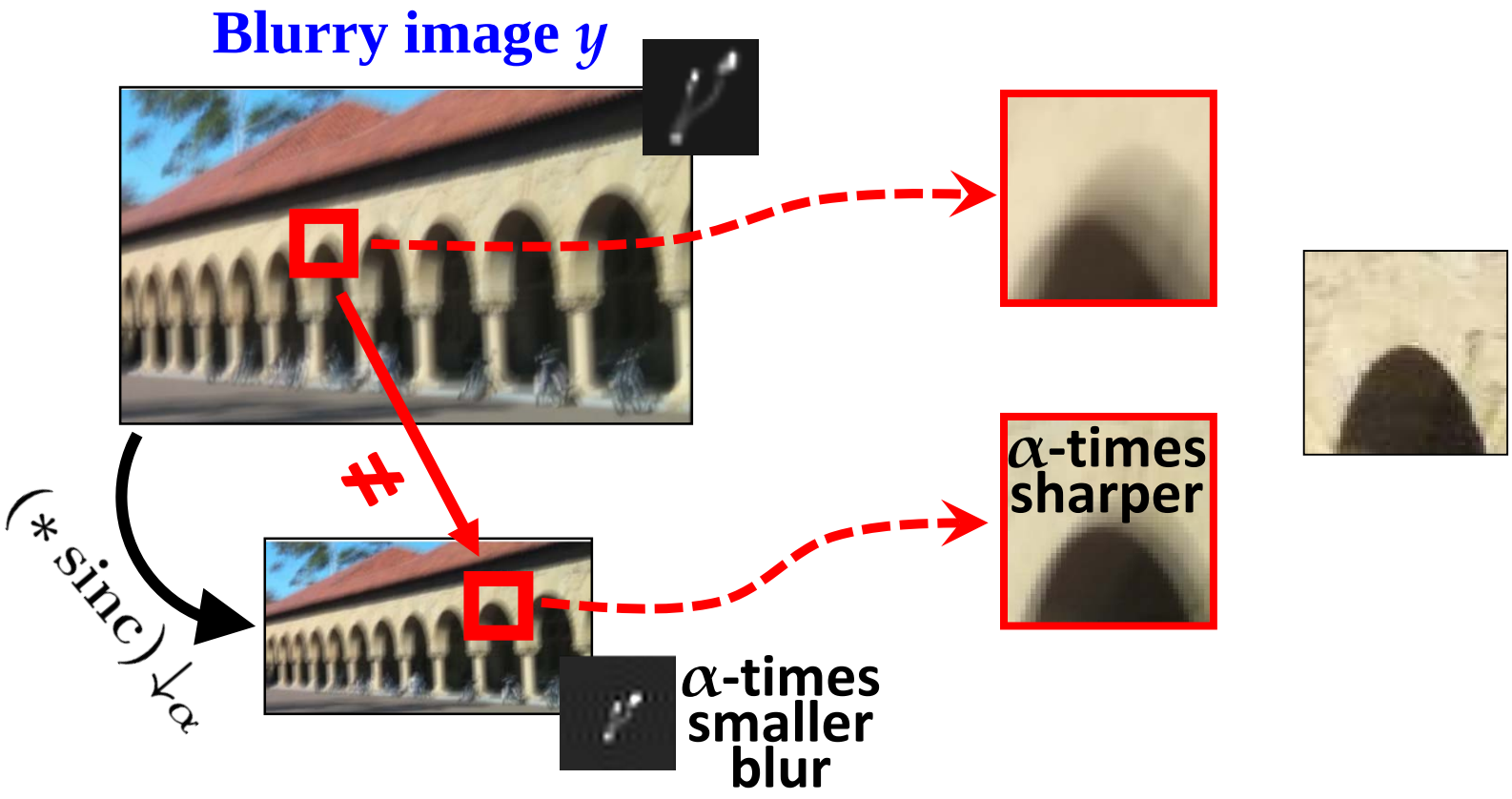
Overview



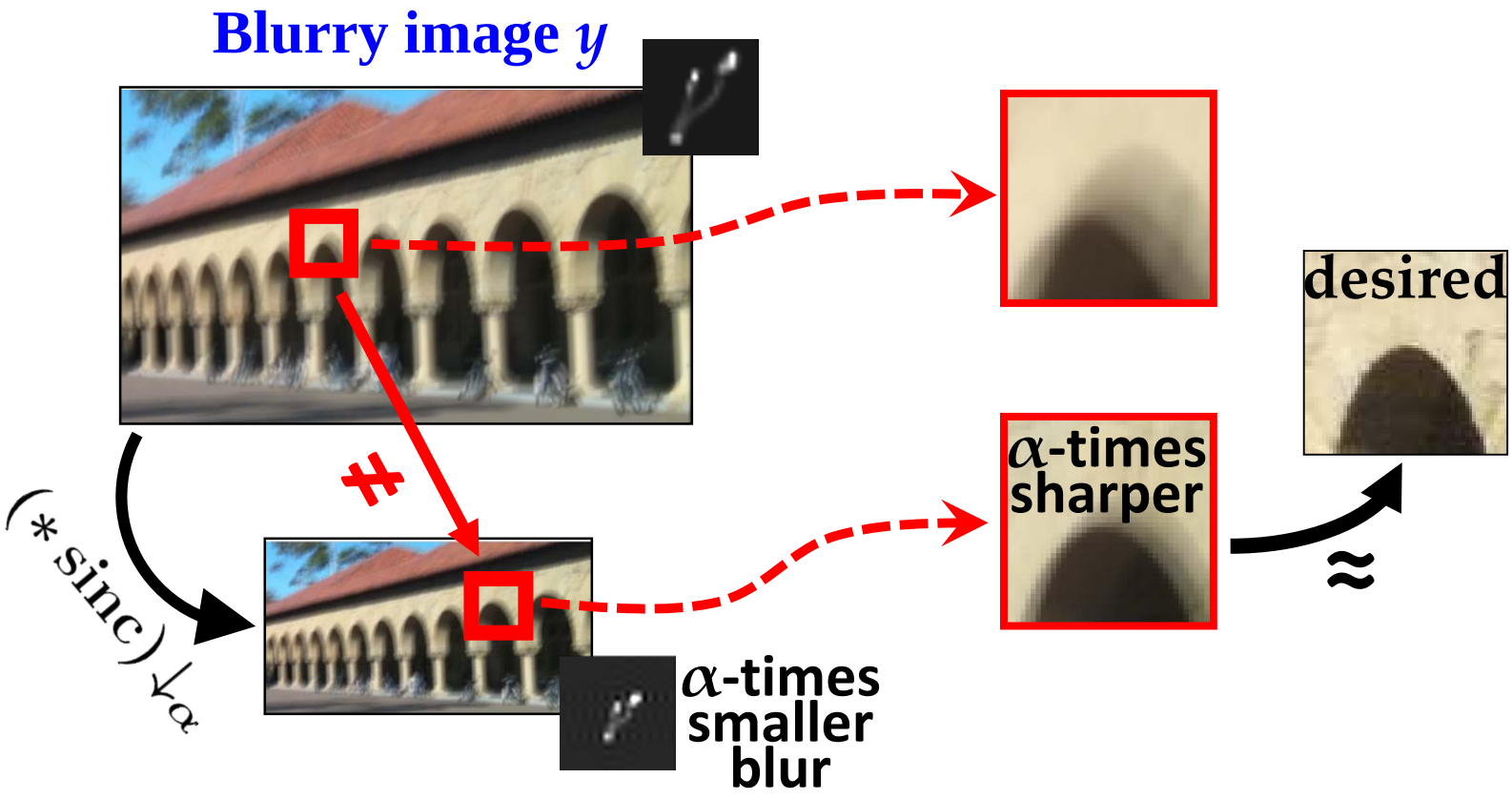
Overview


Blurry image y
$(* \text{sinc})\downarrow_\alpha$
$\neq$
α-times
smaller
blur

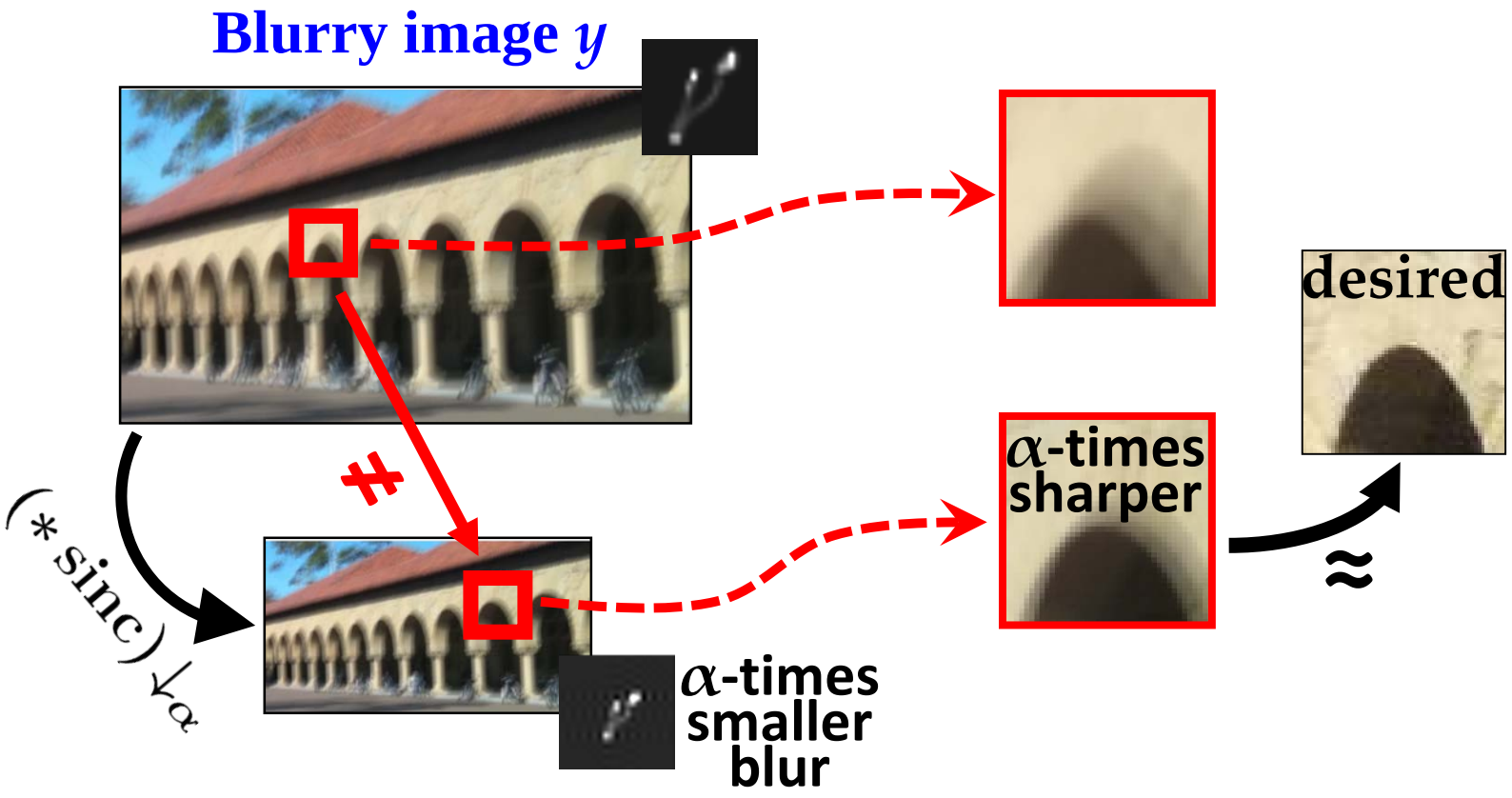
Overview


Blurry image y
$\neq$
$(* \text{sinc})\downarrow_\alpha$
α-times sharper
α-times smaller blur

Overview


Blurry image y
$(* \text{sinc})_{\downarrow\alpha}$
$\neq$
α-times smaller blur
α-times sharper
$\approx$
desired

Overview



The unknown sharp patches surface out in coarse scales of the blurry image!

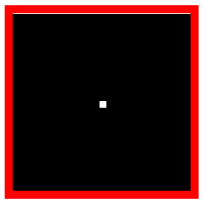
Algorithm

$$\arg\min_{x,k} \underbrace{\|y - k * x\|^2}_{\text{data term}} + \lambda \underbrace{\rho(x, x^{\alpha})}_{\text{prior}}$$

Algorithm

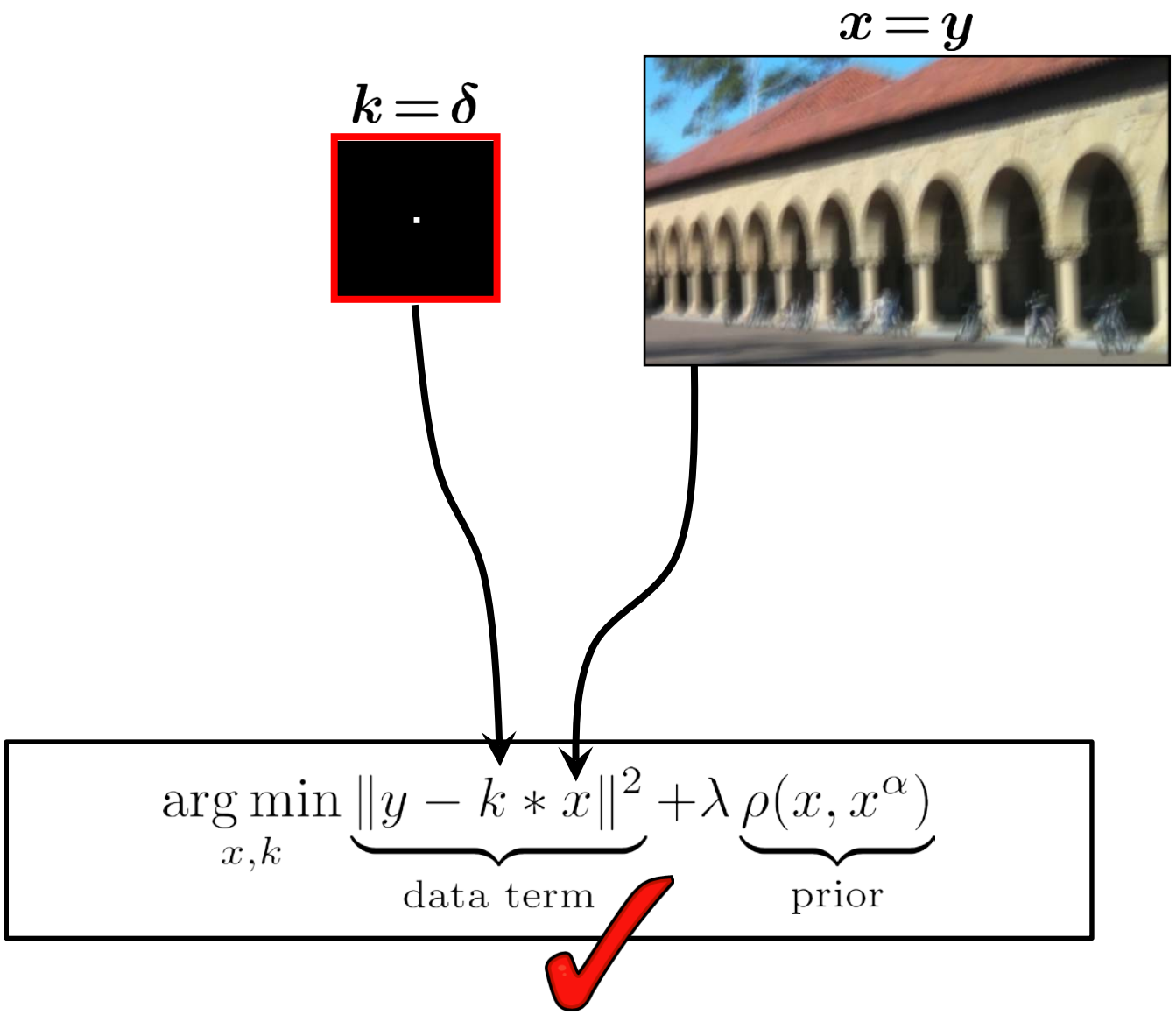
$x = y$

$k = \delta$



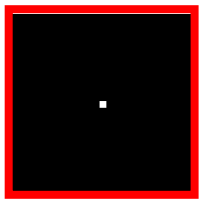
$$\arg\min_{x,k} \underbrace{\|y - k * x\|^2}_{\text{data term}} + \lambda \underbrace{\rho(x, x^{\alpha})}_{\text{prior}}$$

Algorithm


$x = y$
$k = \delta$
$\arg\min_{x,k} \underbrace{\|y - k * x\|^2}_{\text{data term}} + \lambda \underbrace{\rho(x, x^\alpha)}_{\text{prior}}$

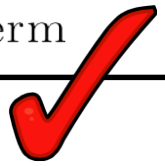
Algorithm

$k = \delta$

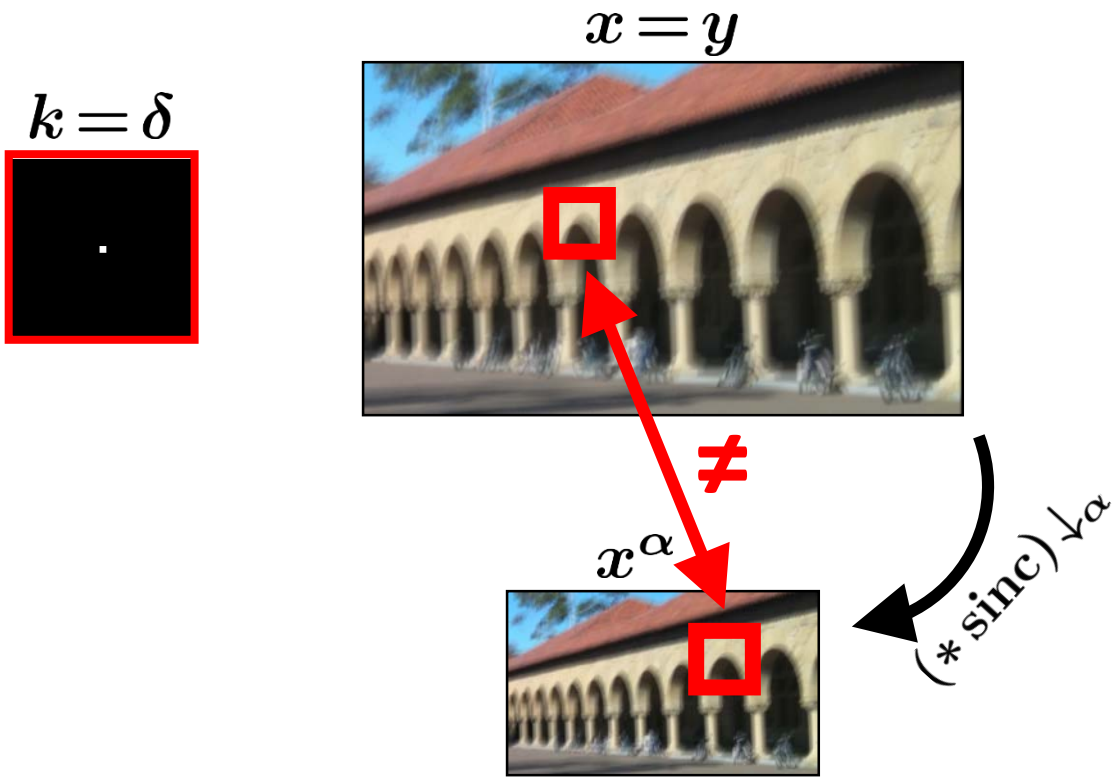


$x = y$

$$\arg\min_{x,k} \underbrace{\|y - k * x\|^2}_{\text{data term}} + \lambda \underbrace{\rho(x, x^\alpha)}_{\text{prior}}$$

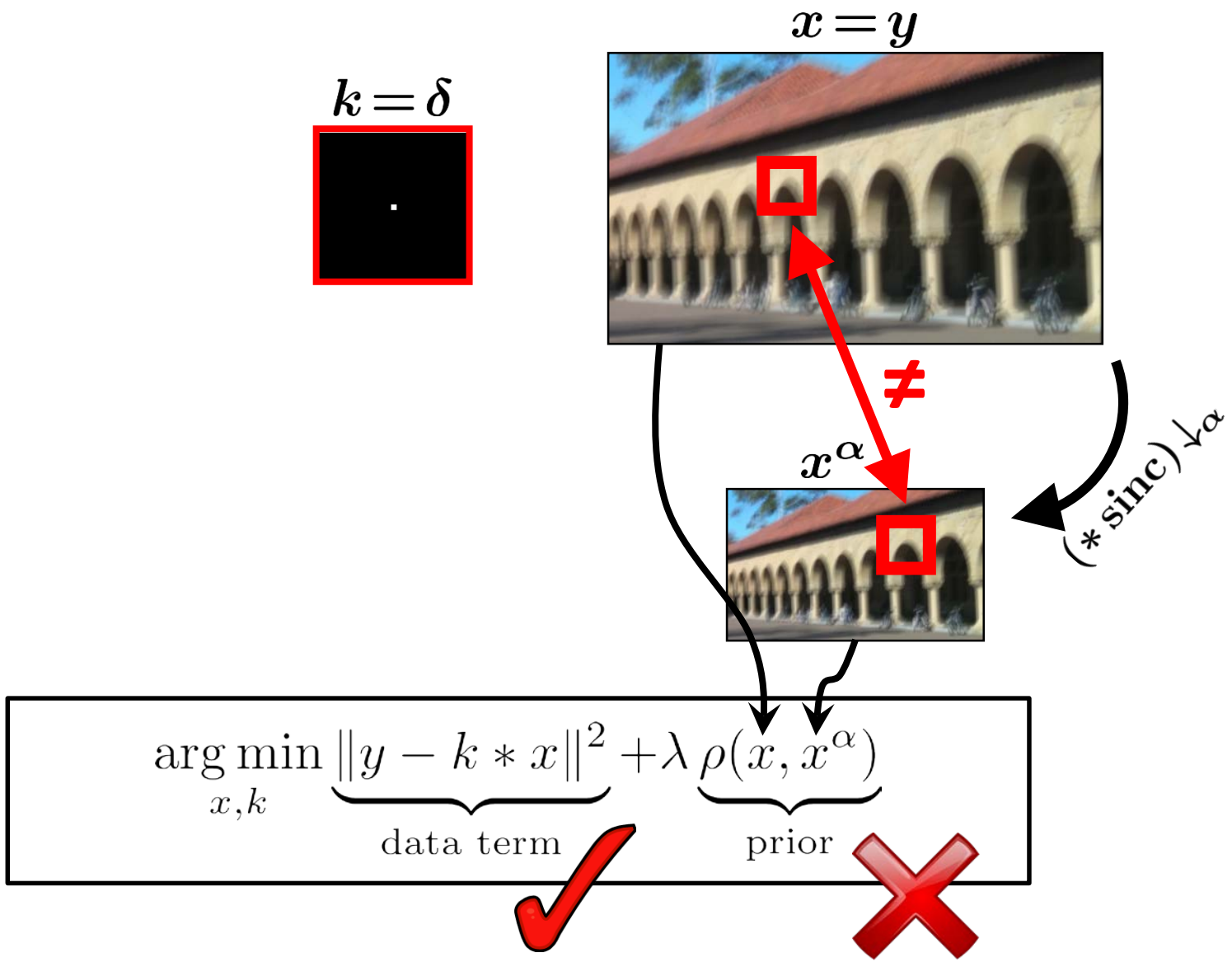


Algorithm



$$\arg\min_{x,k} \underbrace{\|y - k * x\|^2}_{\text{data term}} + \lambda \underbrace{\rho(x, x^\alpha)}_{\text{prior}}$$

Algorithm


$x = y$
$k = \delta$
$\neq$
x^α
$(* \, \mathrm{sinc}) \downarrow_\alpha$
$\arg\min_{x,k} \underbrace{\|y - k * x\|^2}_{\text{data term}} + \lambda \underbrace{\rho(x, x^\alpha)}_{\text{prior}}$

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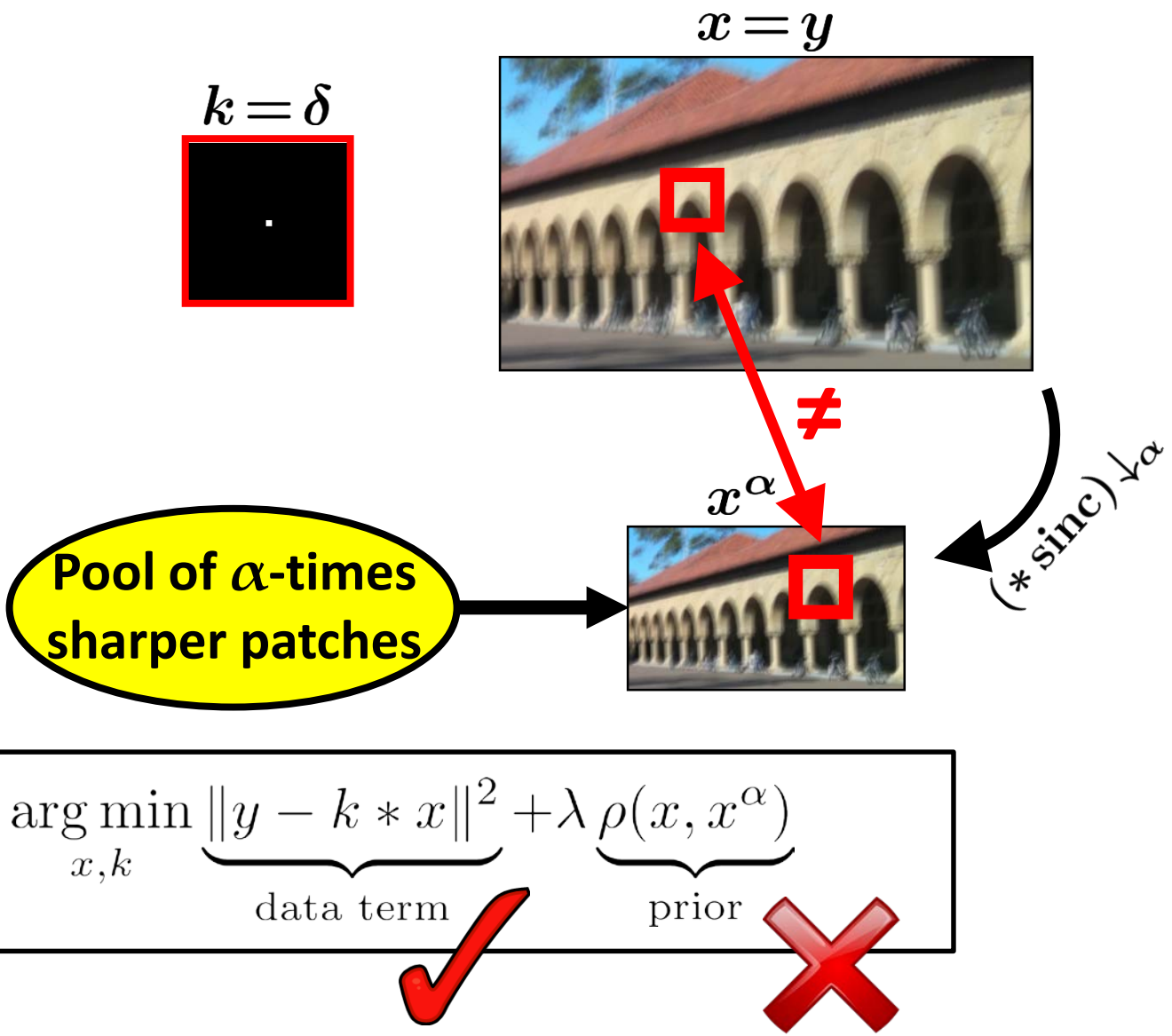
$x = y$
$k = \delta$
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x^α
$(* \text{ sinc})\downarrow_\alpha$
Pool of α-times sharper patches
$\arg\min_{x,k} \underbrace{\|y - k * x\|^2}_{\text{data term}} + \lambda \underbrace{\rho(x, x^\alpha)}_{\text{prior}}$

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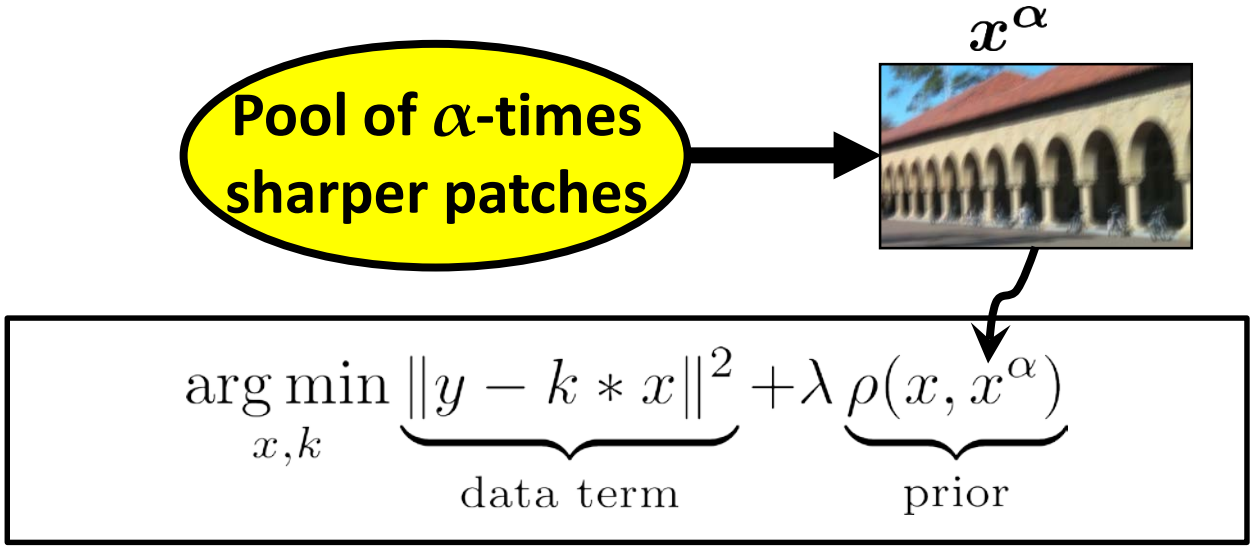
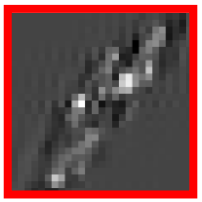

Pool of α-times sharper patches
x^{α}
$\arg\min_{x,k} \underbrace{\|y - k * x\|^2}_{\text{data term}} + \lambda \underbrace{\rho(x, x^{\alpha})}_{\text{prior}}$

Algorithm

k



x

Pool of α-times sharper patches

x^{α}

$$\arg\min_{x,k} \underbrace{\|y - k * x\|^2}_{\text{data term}} + \lambda \underbrace{\rho(x, x^{\alpha})}_{\text{prior}}$$

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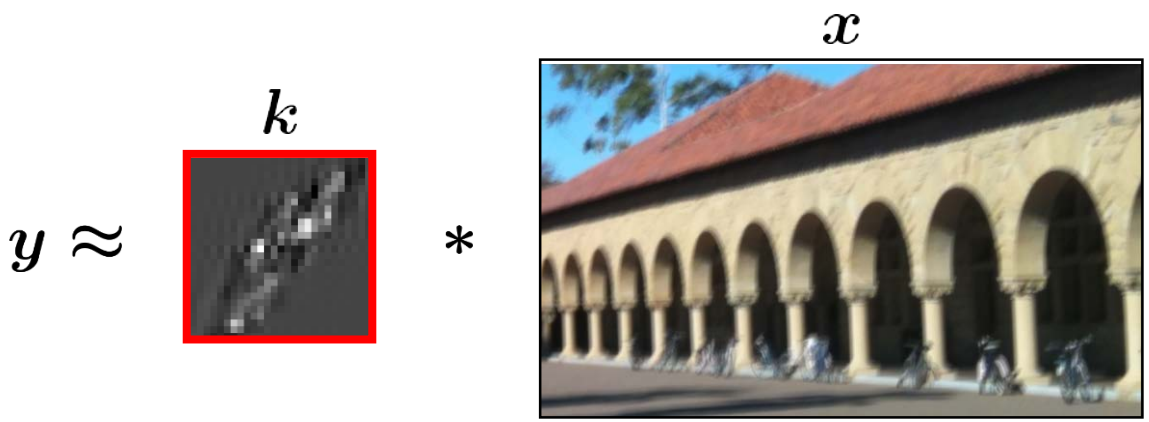
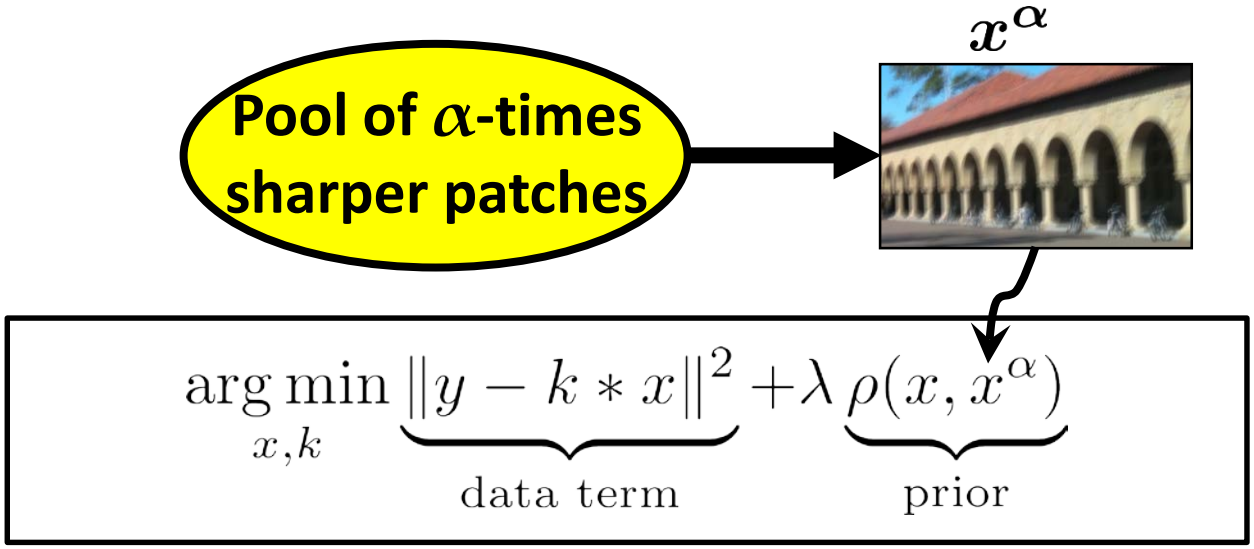
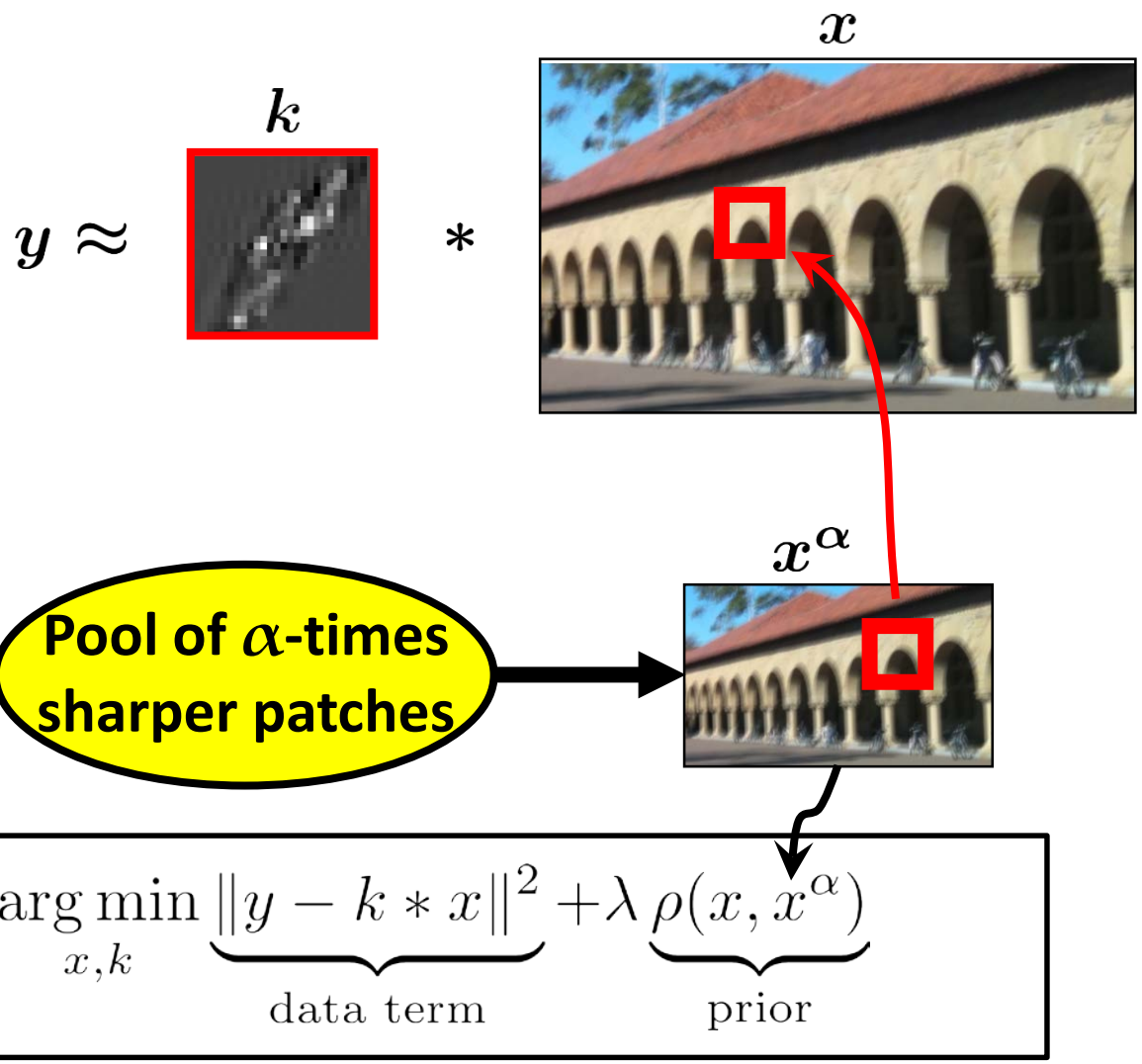

x
k
$y \approx$
$*$


x^α
Pool of α-times sharper patches
$\arg\min_{x,k} \underbrace{\|y - k * x\|^2}_{\text{data term}} + \lambda \underbrace{\rho(x, x^\alpha)}_{\text{prior}}$

Algorithm


x
k
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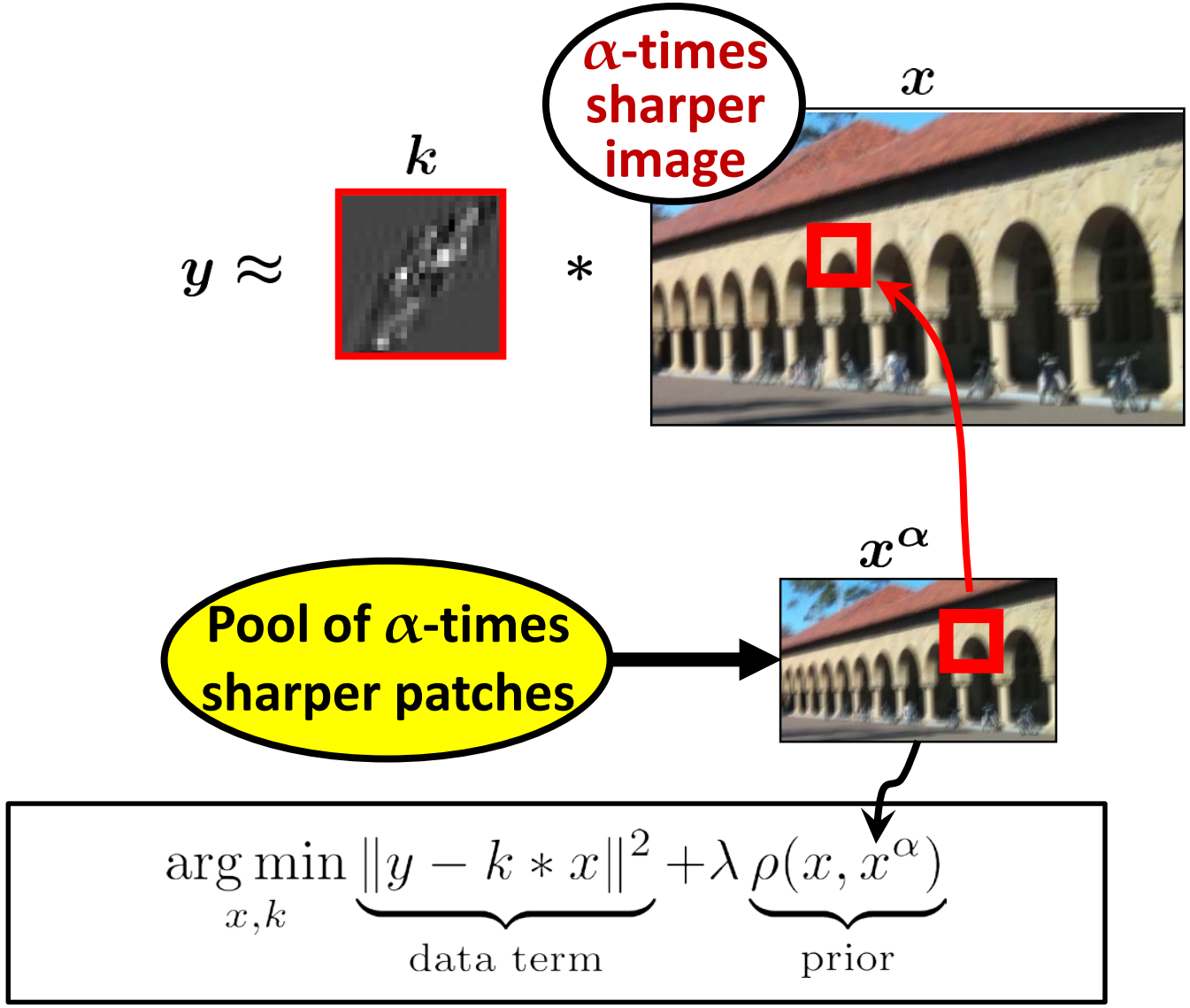
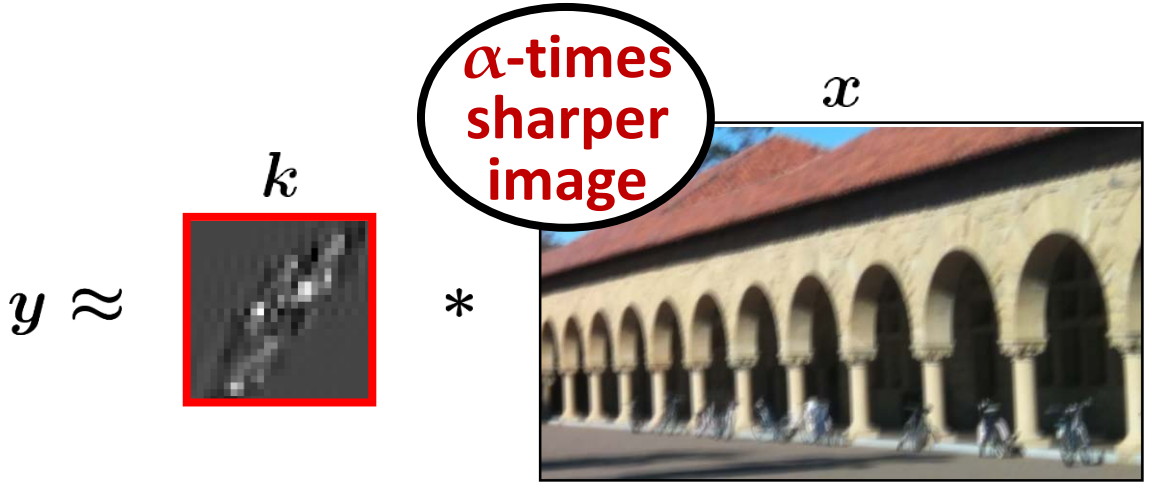

α-times sharper image
x
k
y ≈
*
x^α
Pool of α-times sharper patches
arg min_{x,k} ||y − k ∗ x||^2 + λ ρ(x, x^α)
data term
prior

Algorithm



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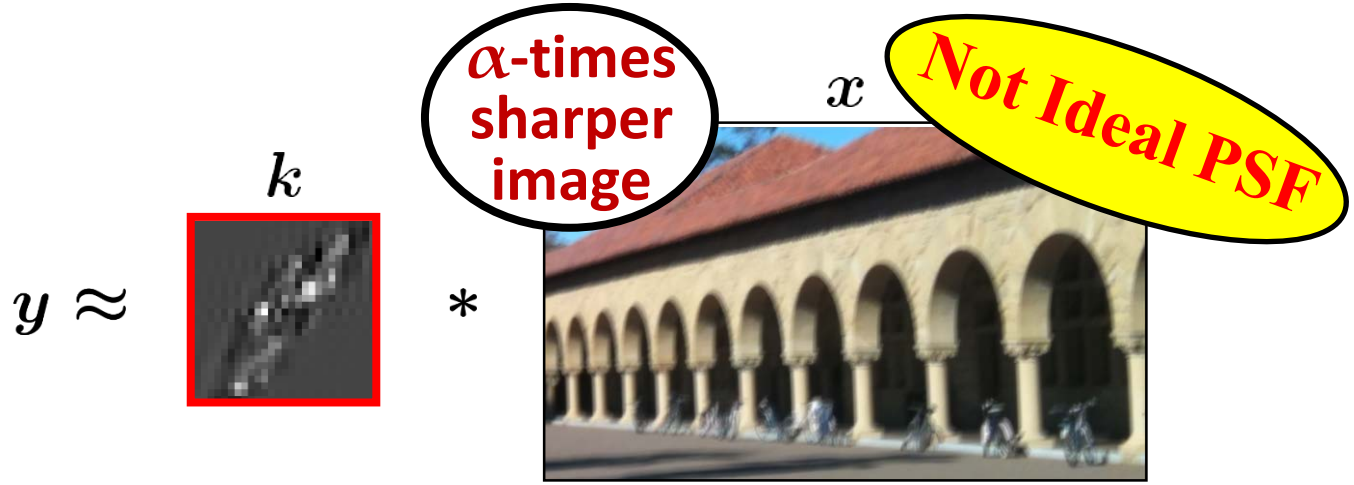

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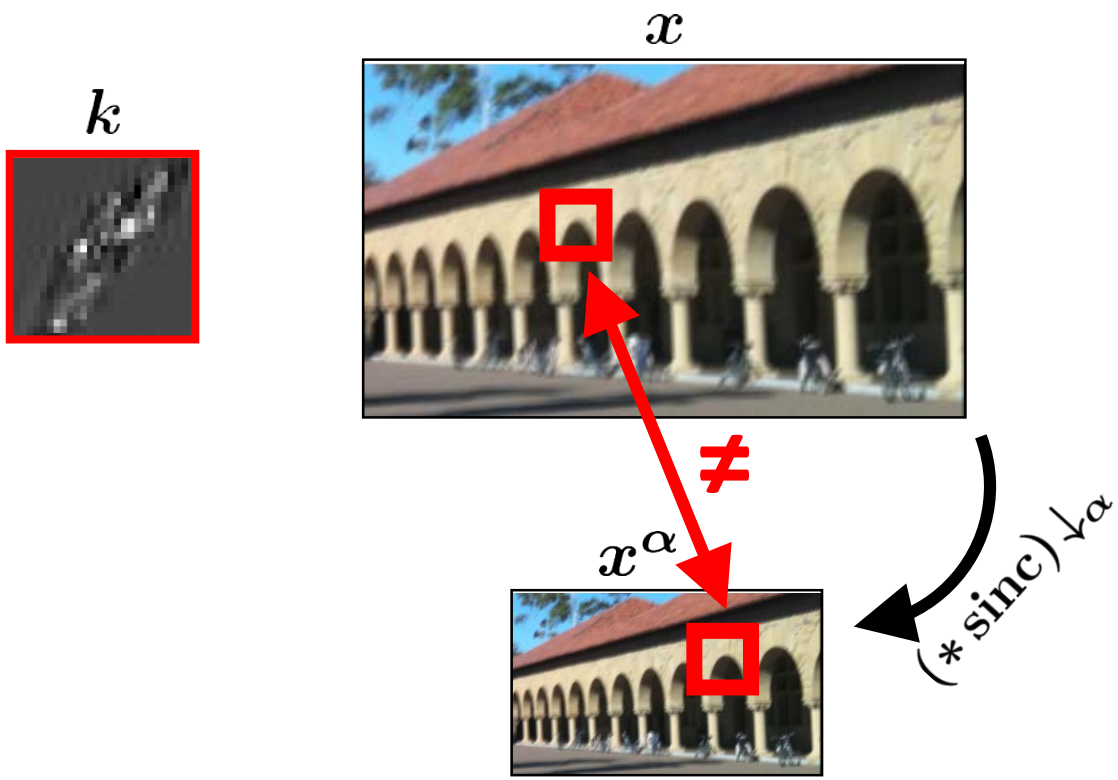

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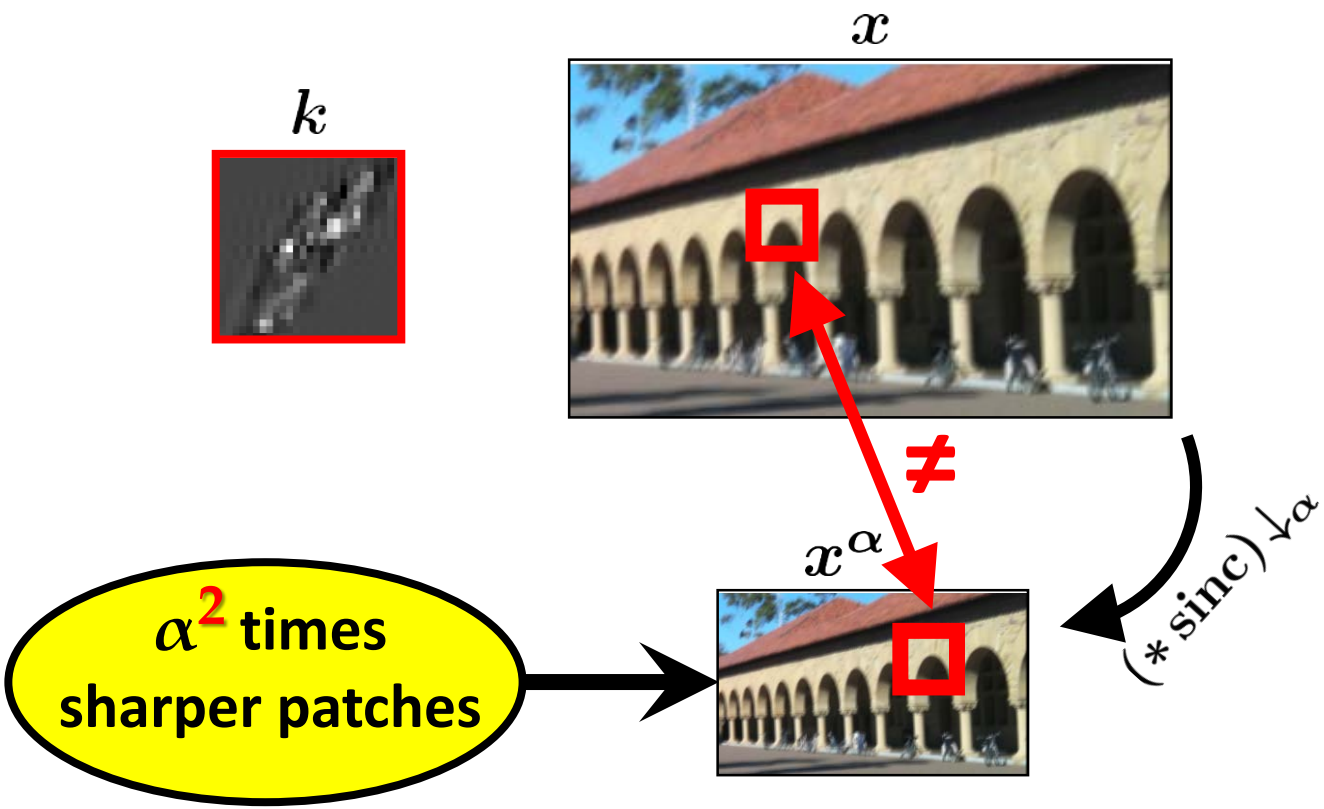

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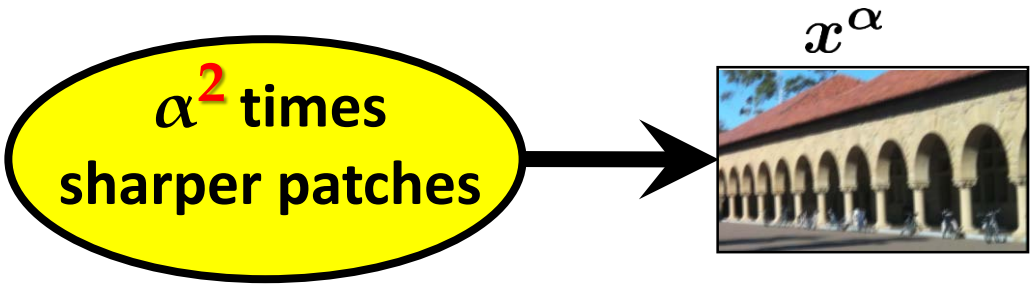

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Algorithm

$\boldsymbol{k}$

$\boldsymbol{x}$

$\boldsymbol{x^{\alpha}}$

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$y \approx$  $*$ 

k

x

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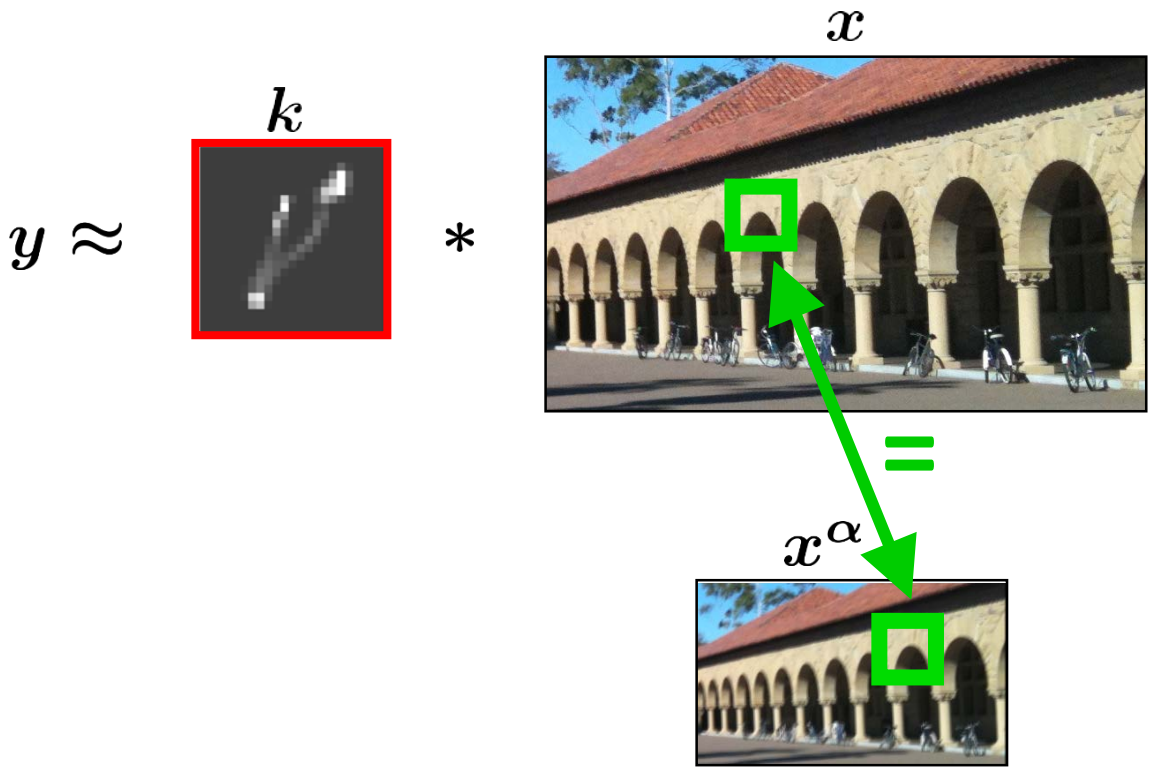

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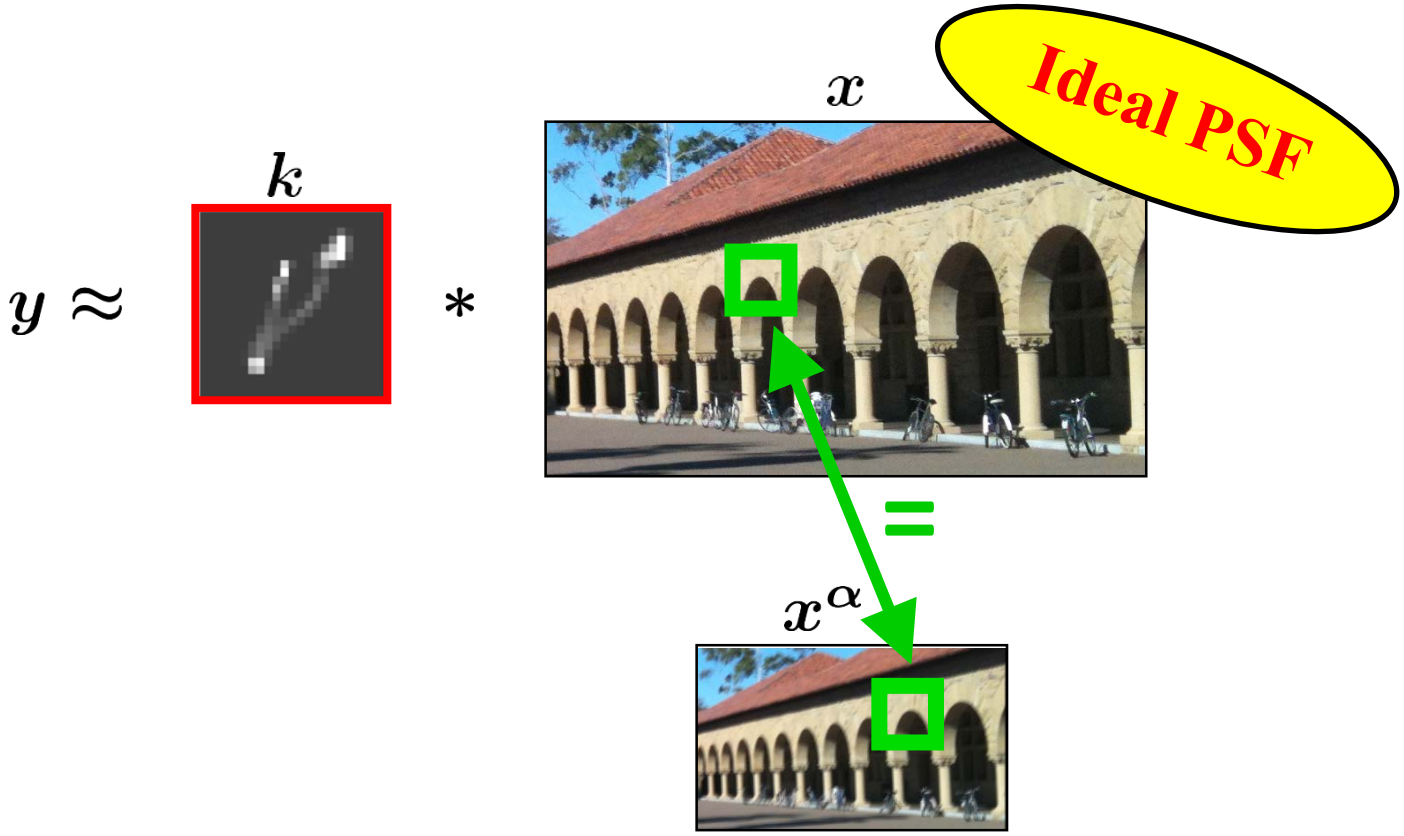

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   Minimize w.r.t x

3. **Kernel Update:**

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(80 sharp images x 8 blurs)

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Comparison to the state-of-the art:

[1] Sun, Cho, Wang, Hays – ICCP 2013
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Nonblind deblurring: Zoran & Weiss – ICCV 2011

Results

Relative error ***w.r.t.*** **ground-truth kernel** $\frac{ERR(Estimated\ kernel)}{ERR(GT\ kernel)}$

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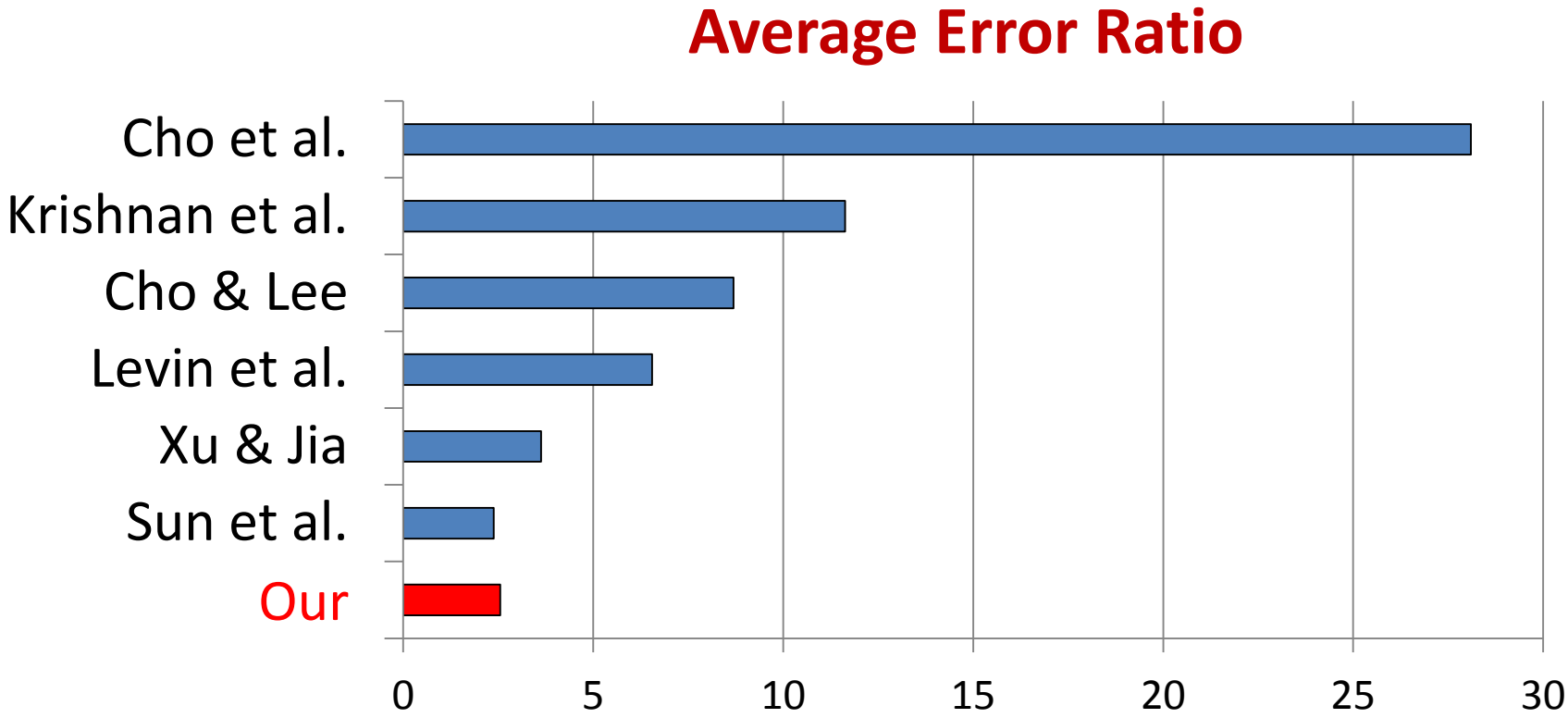

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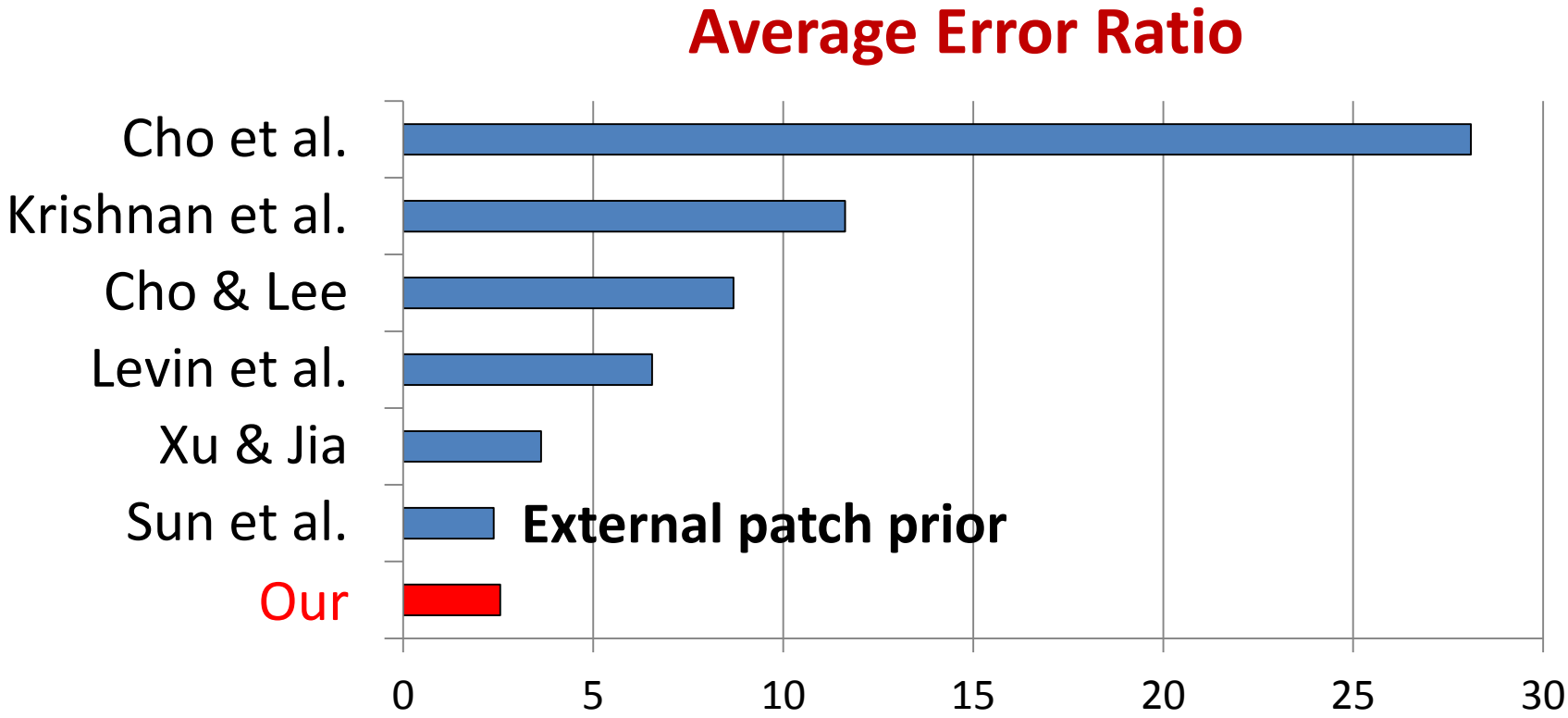

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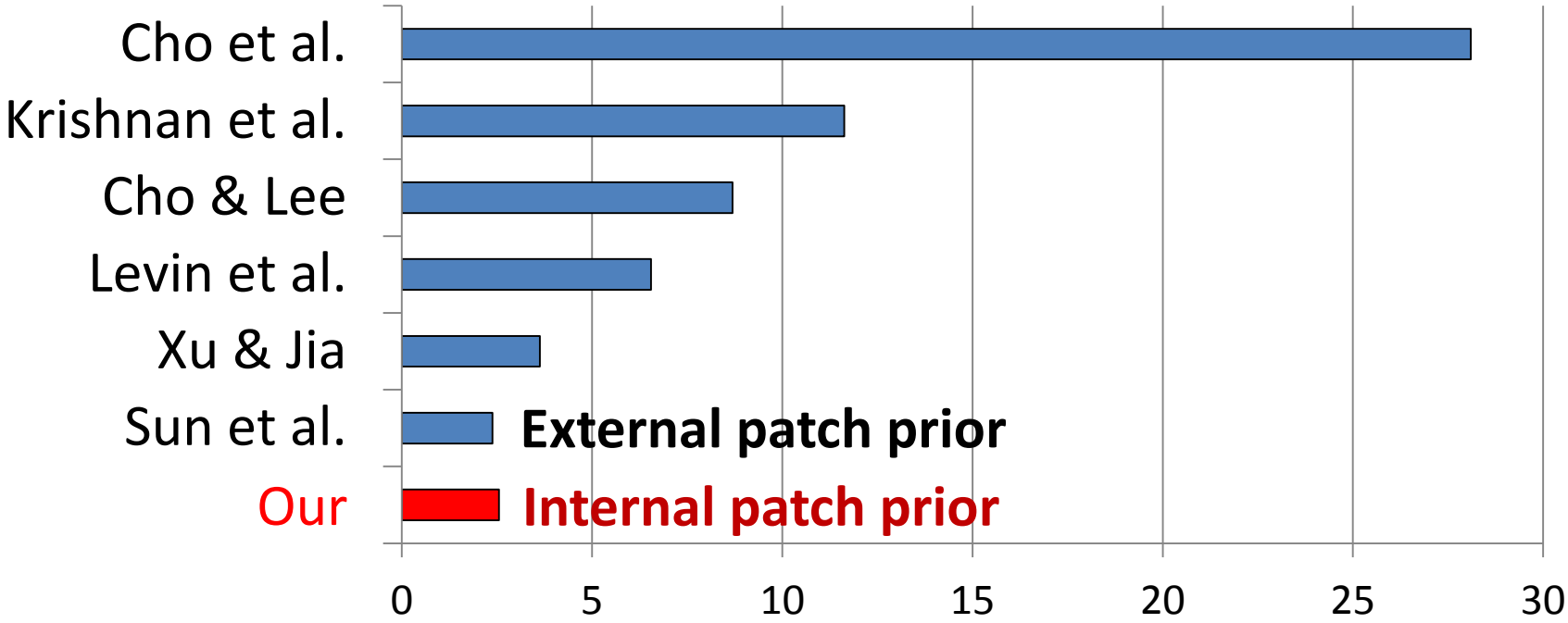
Average Error Ratio



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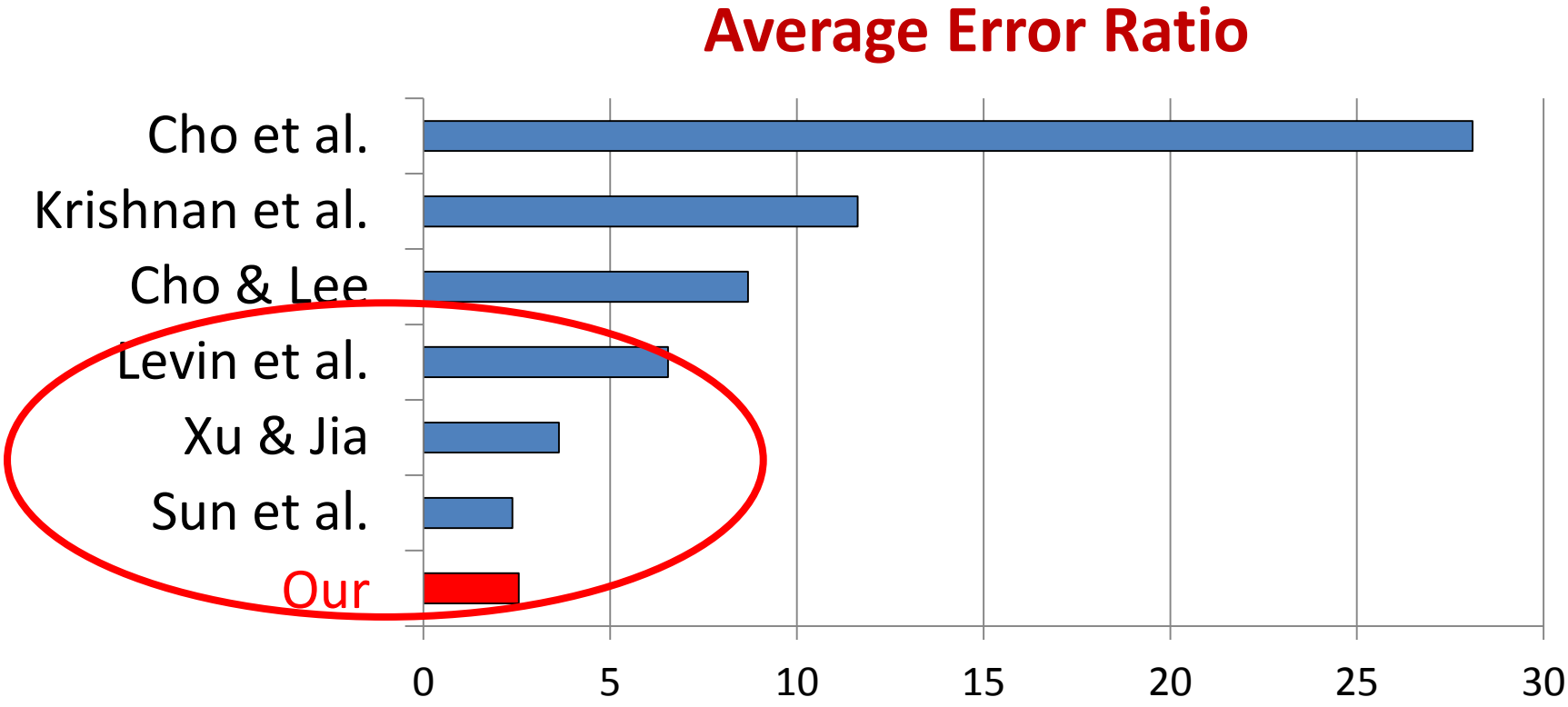
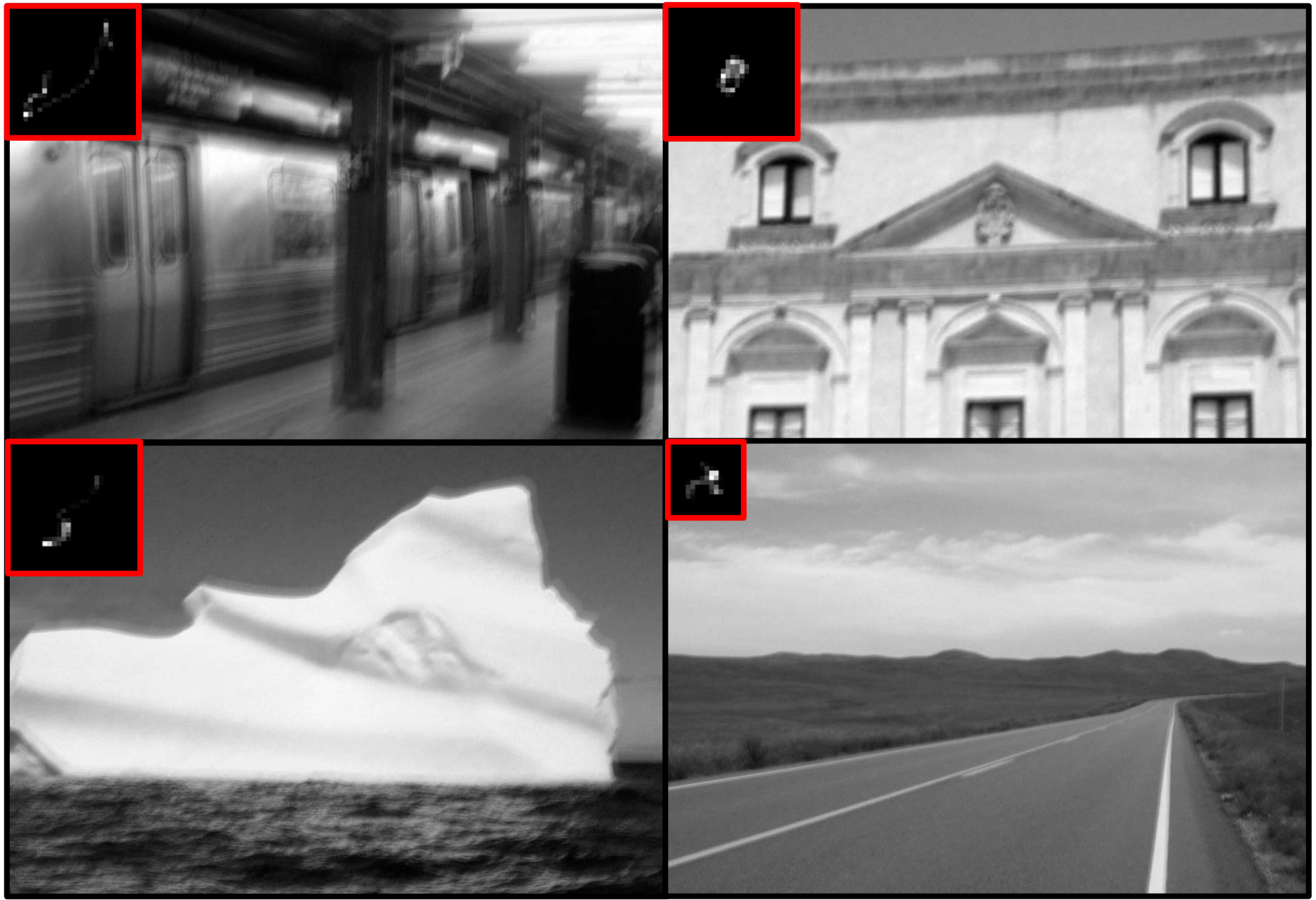


Blurry images



Our Method

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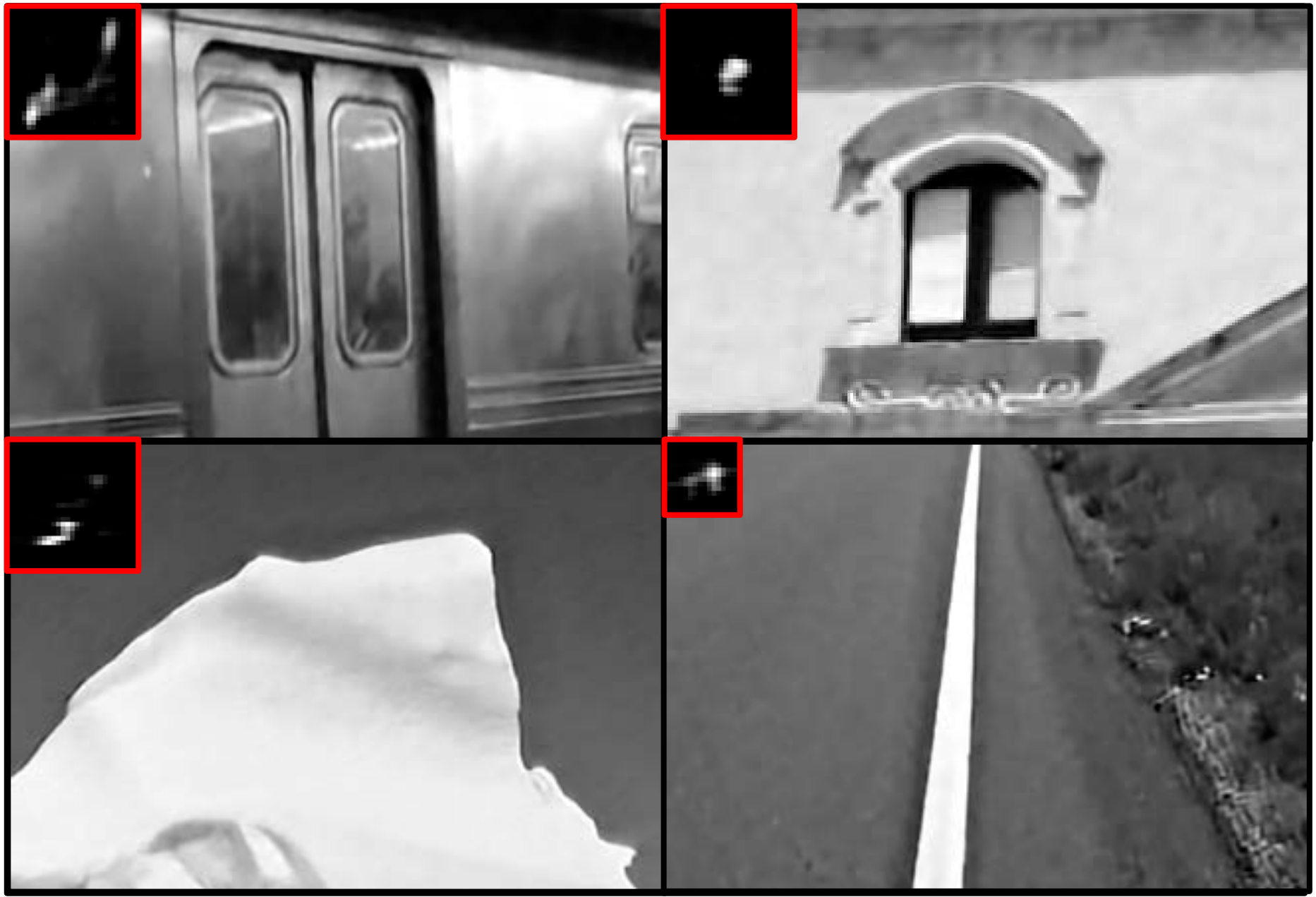
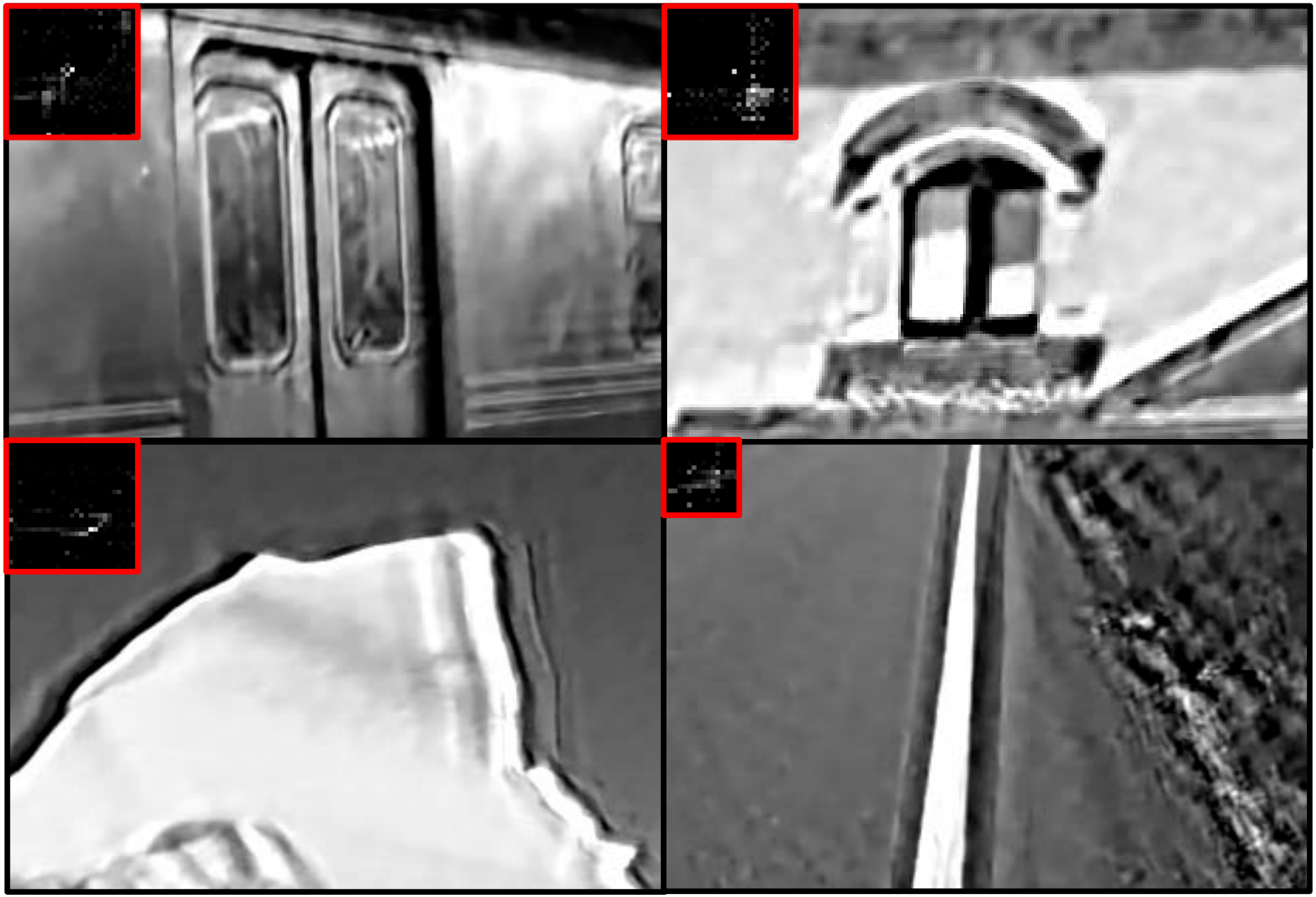


Levin *et al.*



Xu & Jia

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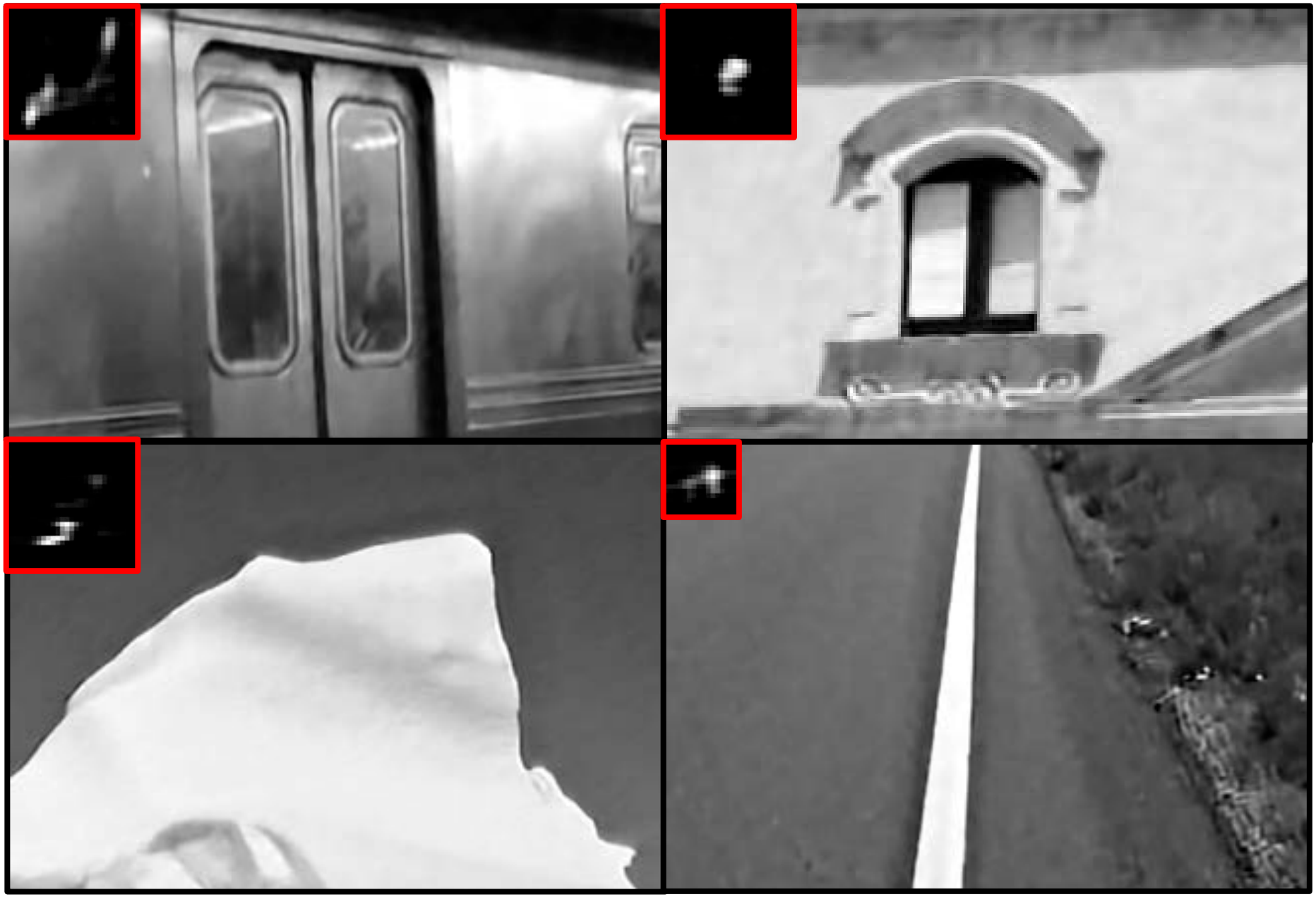

Robustness

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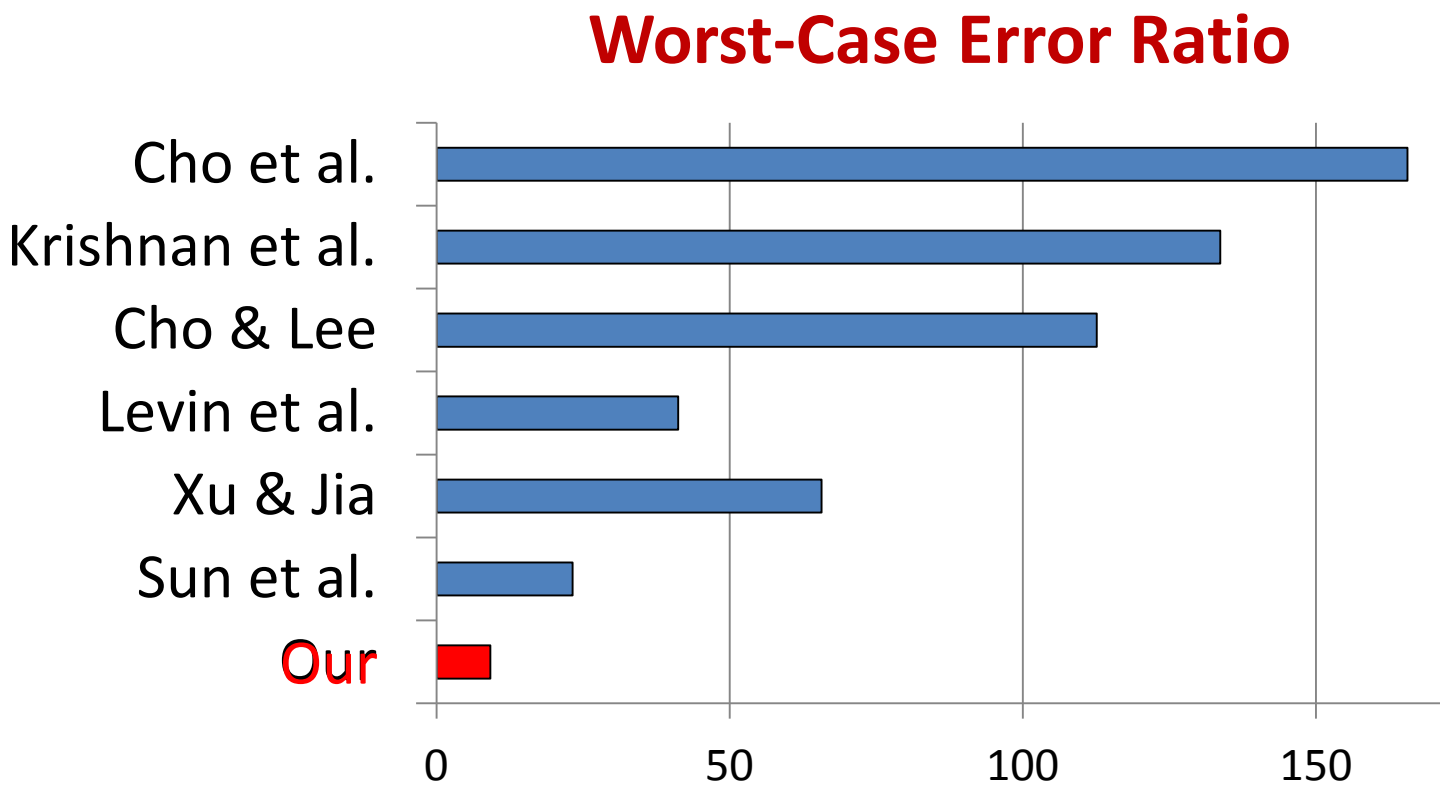
Worst-Case Error Ratio
Cho et al.
Krishnan et al.
Cho & Lee
Levin et al.
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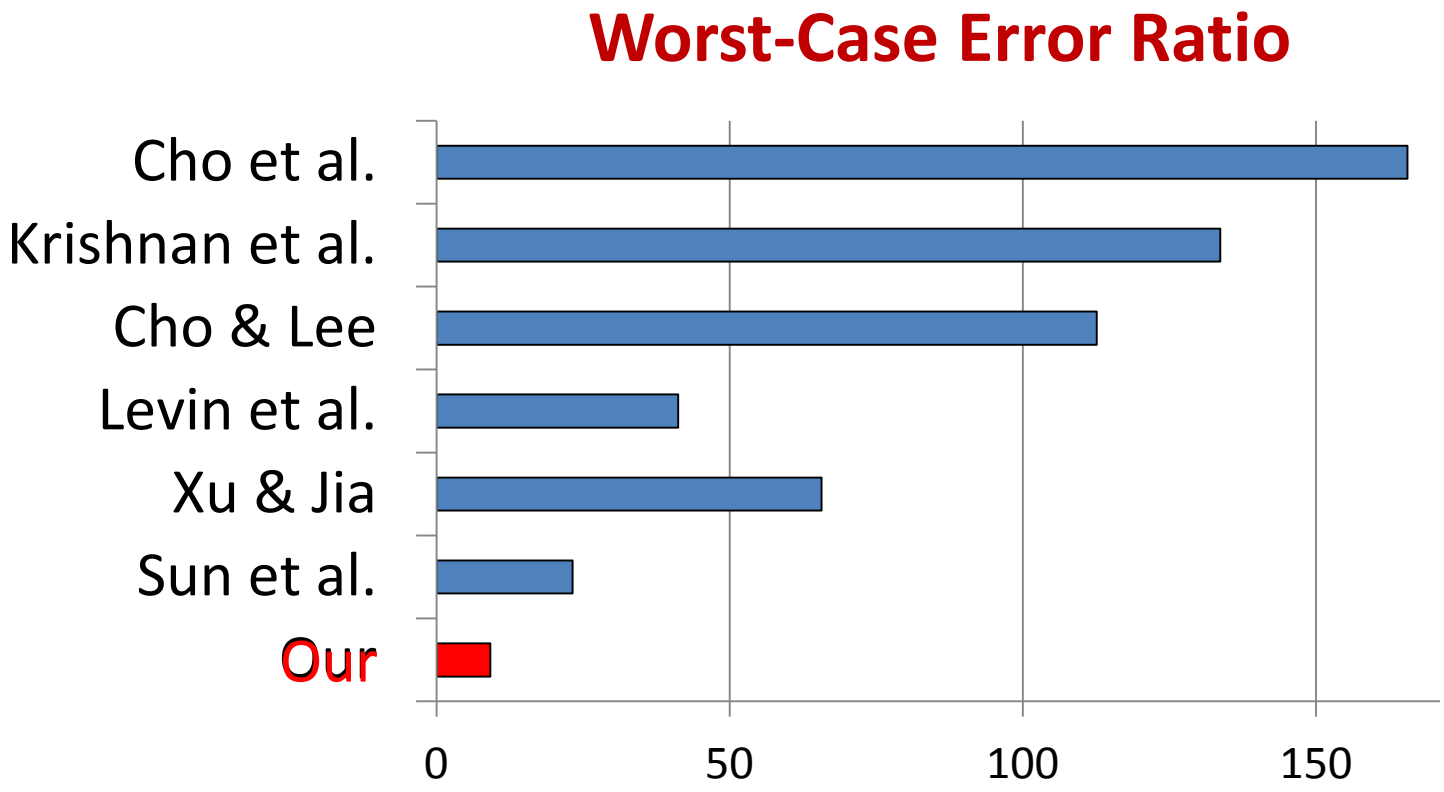
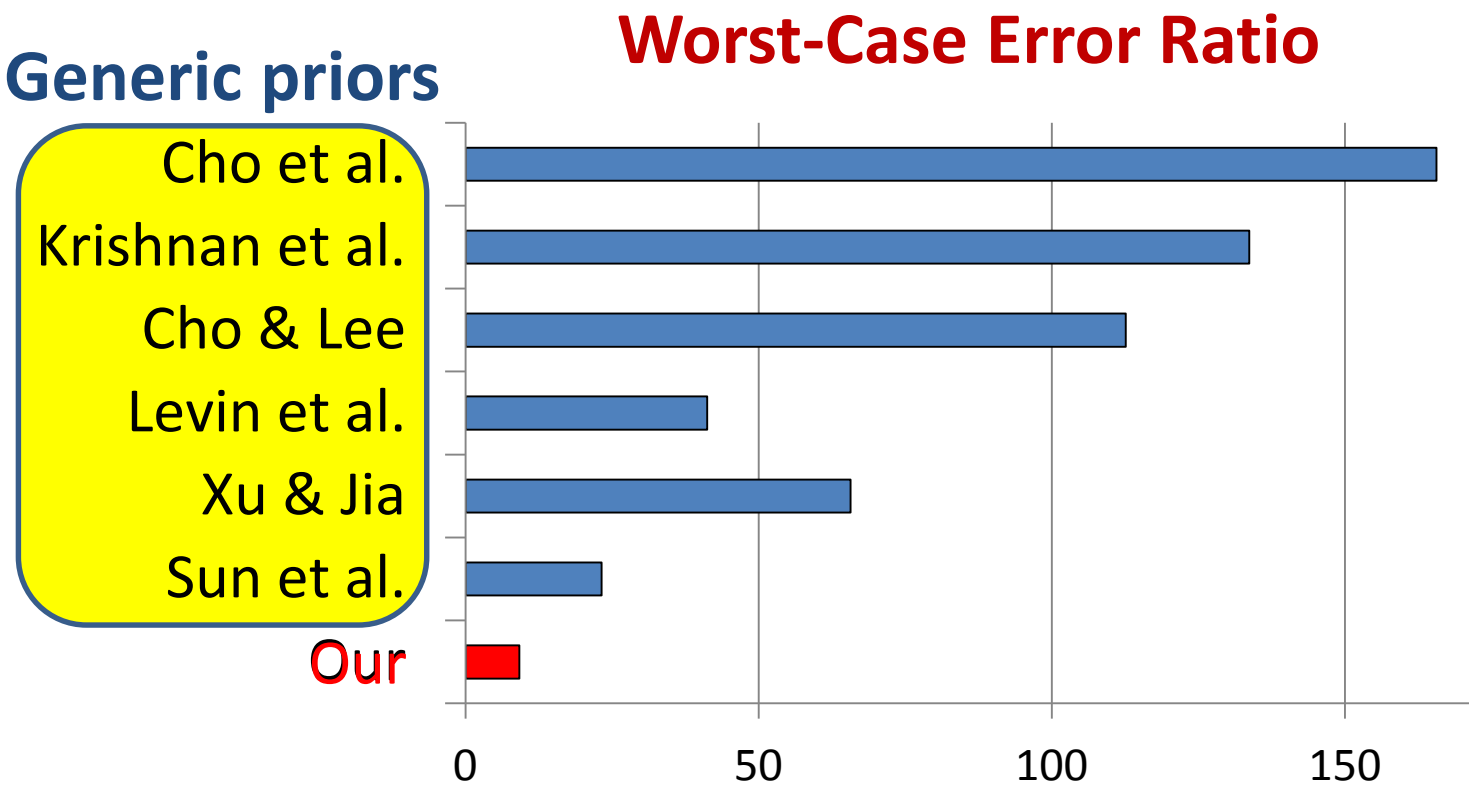
Sun et al.
Our
0
50
100
150

Robustness



Internal patch prior → An image-specific prior

Robustness



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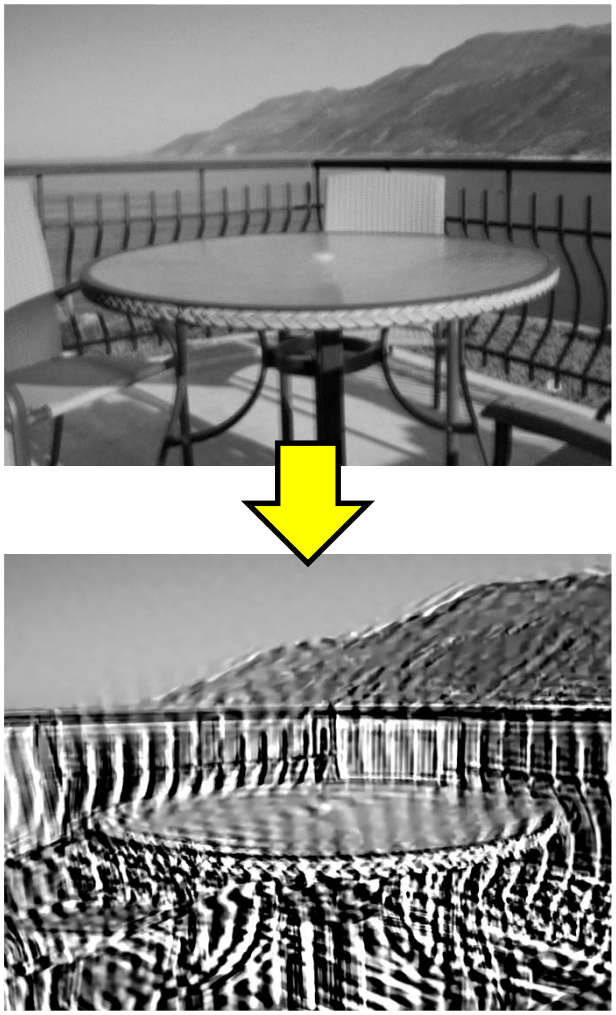
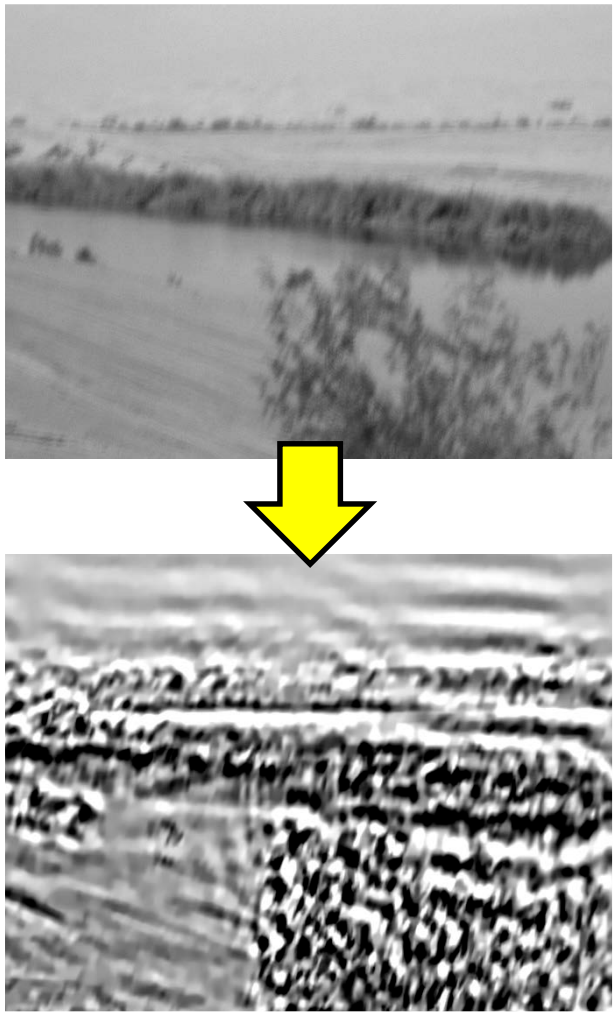
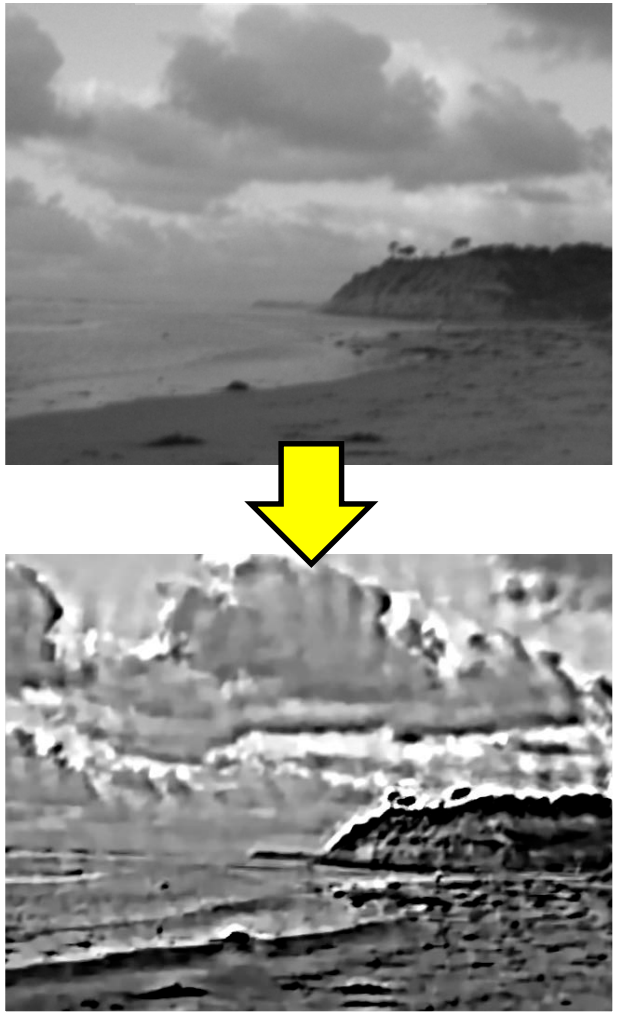
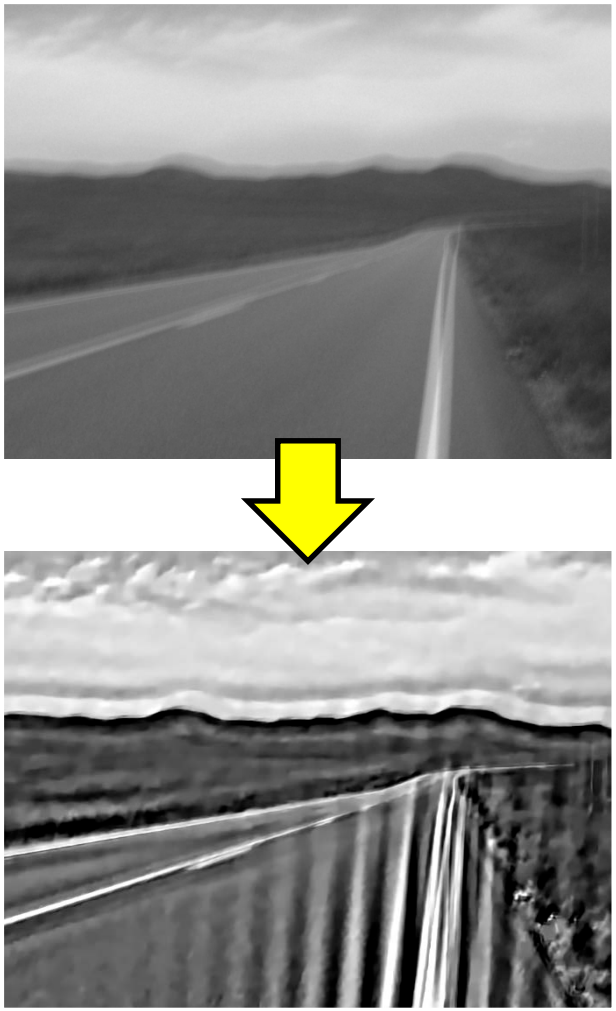
Worst Results

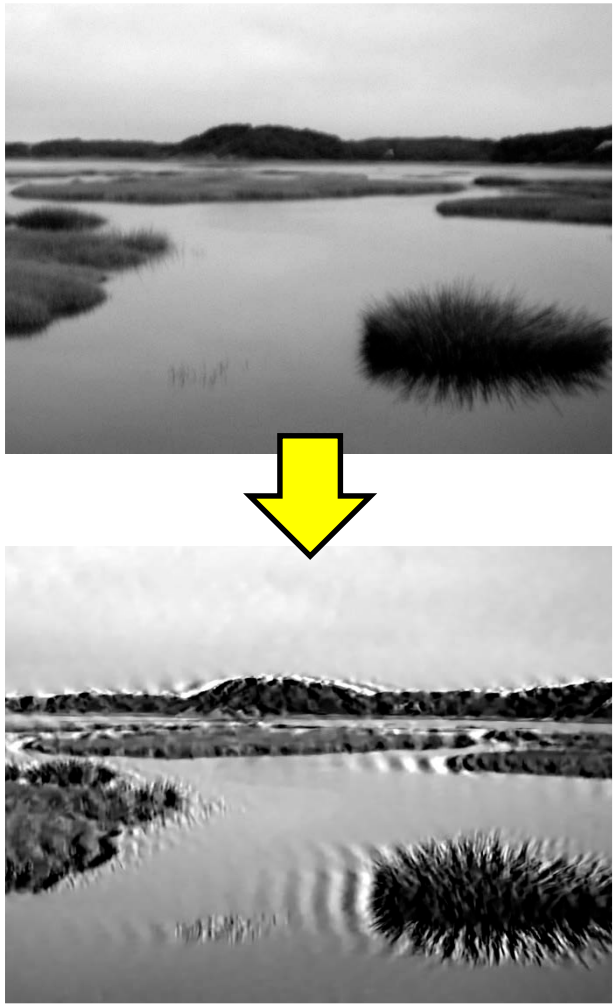
Cho *et al.*	Krishnan *et al.*	Cho & Lee
		

Worst Results

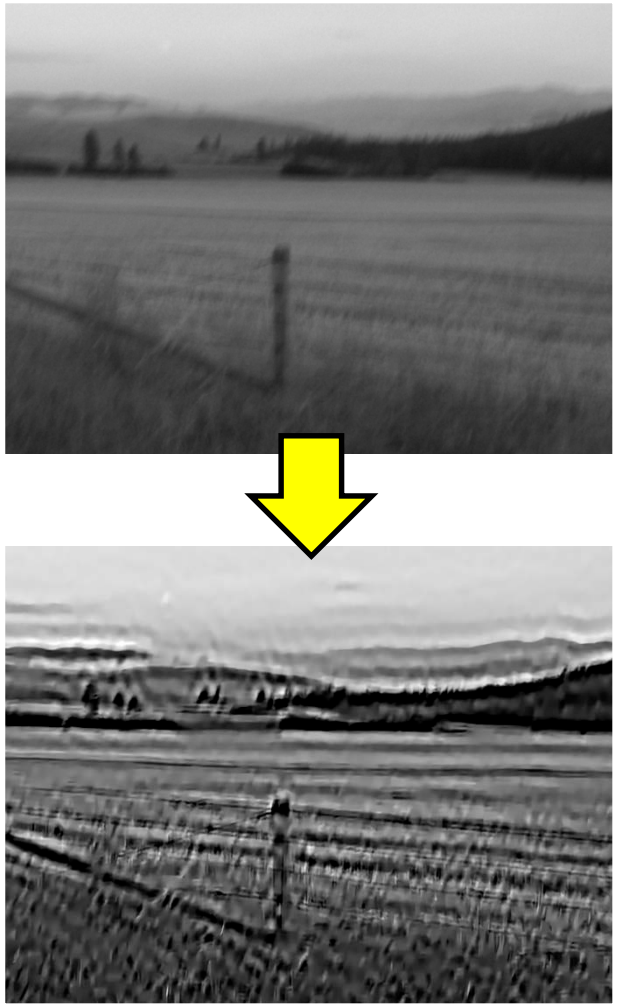
Xu & Jia



Levin *et al.*

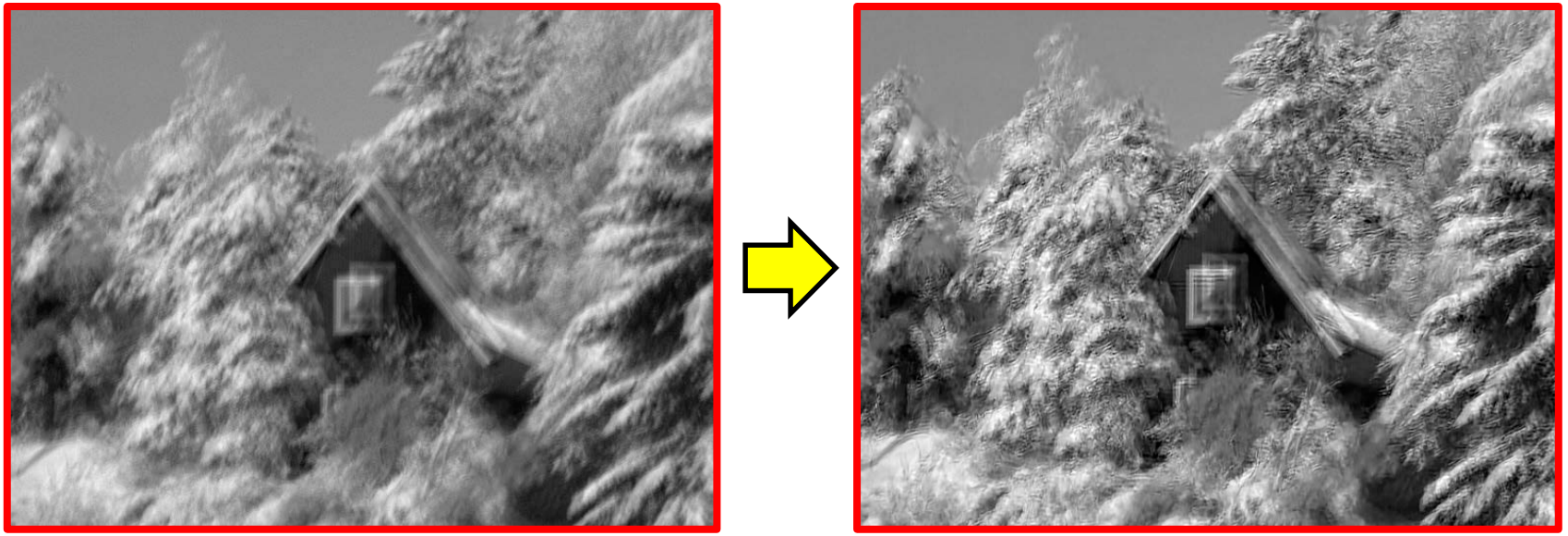


Sun *et al.*



Worst Results

Our



Summary

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  → cue for recovering the blur

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Thank You