



Fast 3D velocity updates using the pre-stack exploding-reflector model

Claudio Guerra and Biondo Biondi

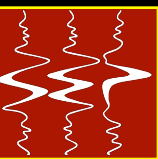
**SEP 140, pp 1-10
May 2010**



Fast 3D velocity updates using image-space generalized sources

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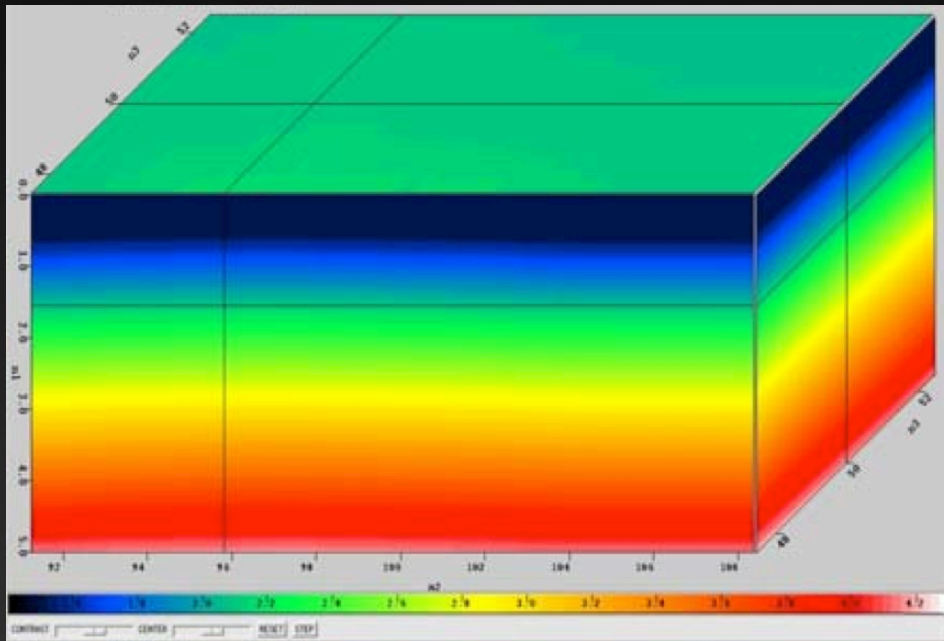
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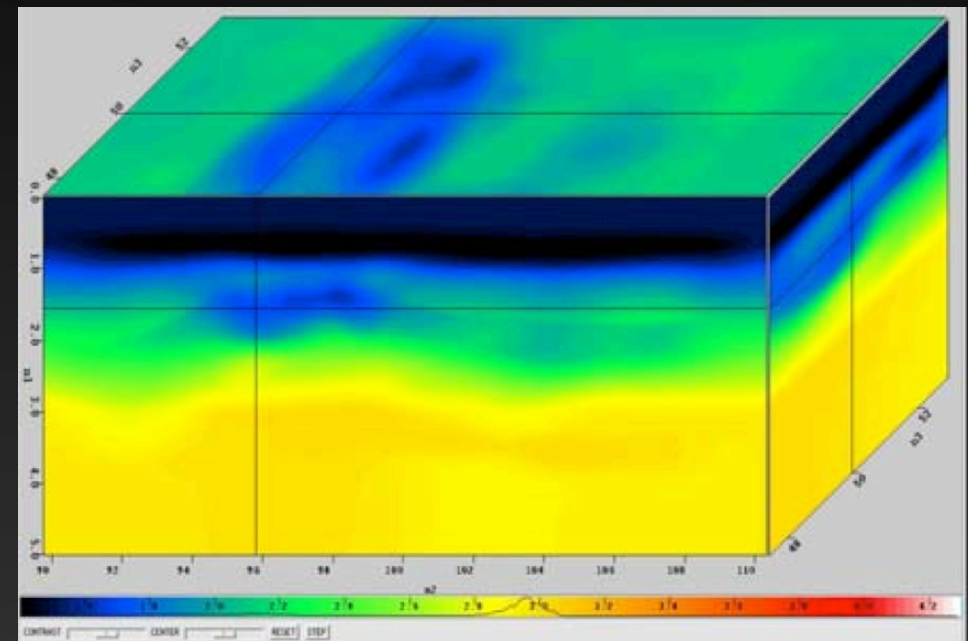
- **Image-space wave-equation tomography is theoretically more robust than ray-based methods in complex geology**



- **Image-space wave-equation tomography has rarely been applied in 3D**

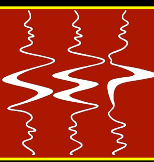


Initial velocity



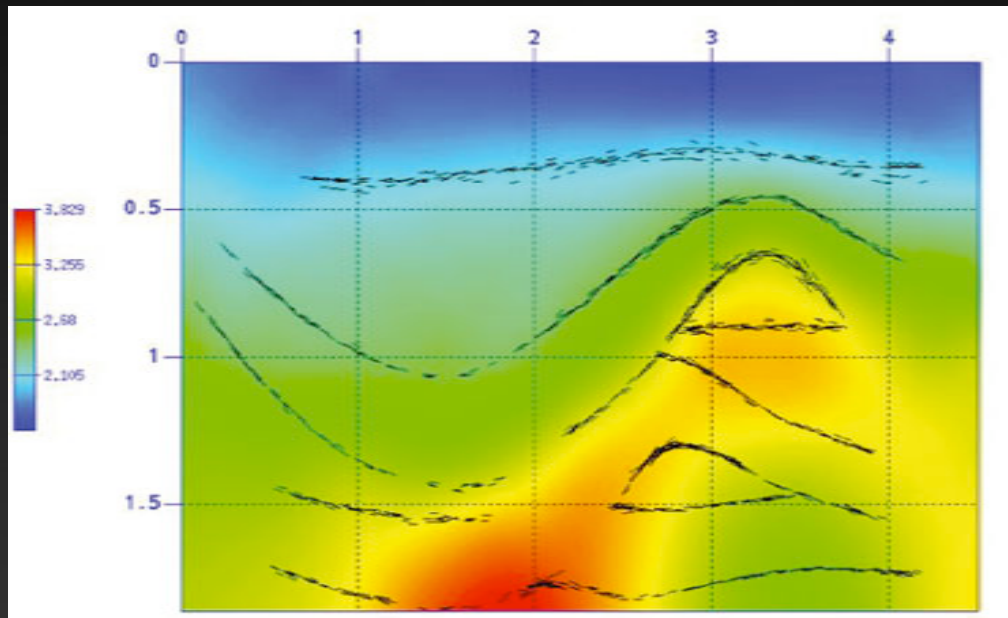
Final velocity

Fei et al., 2009



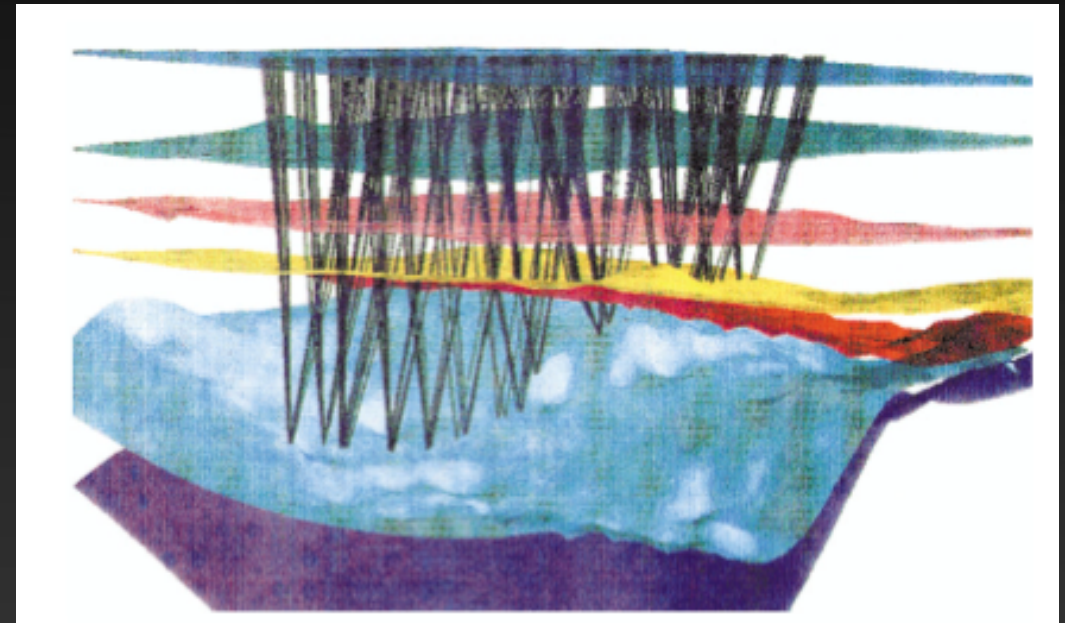
- **Higher cost and lower flexibility than ray-based methods**

Grid-based



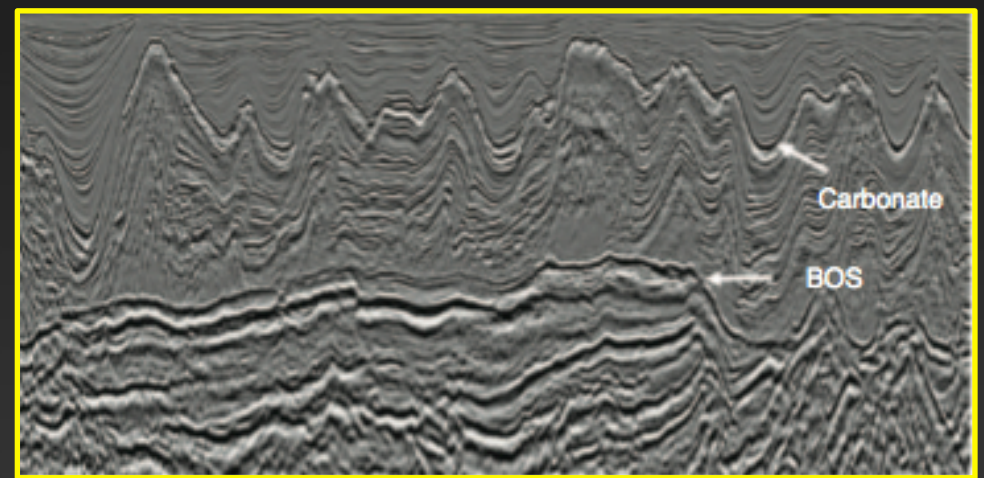
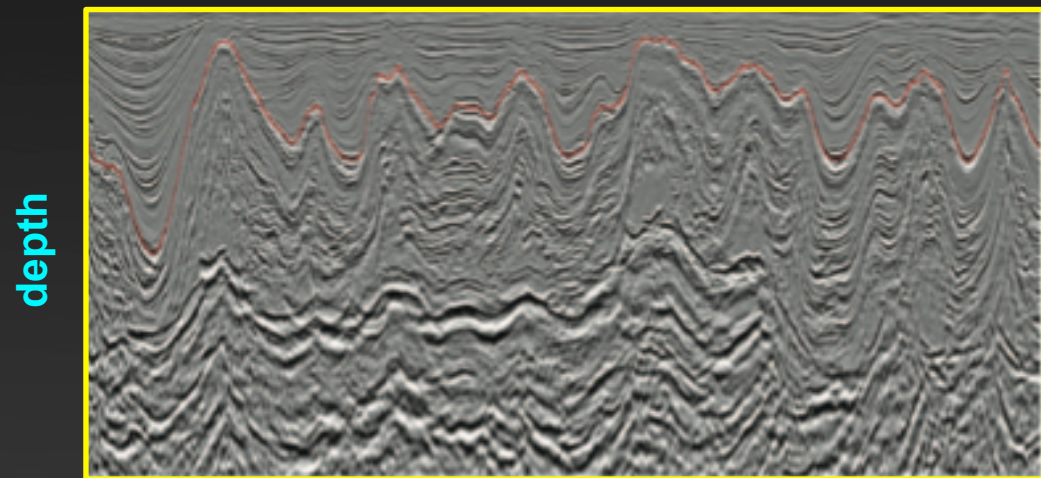
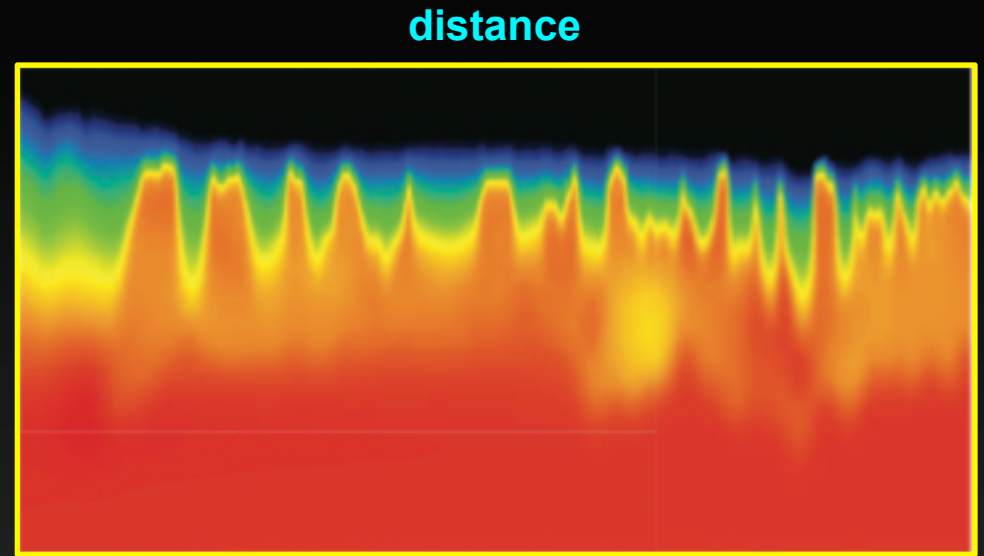
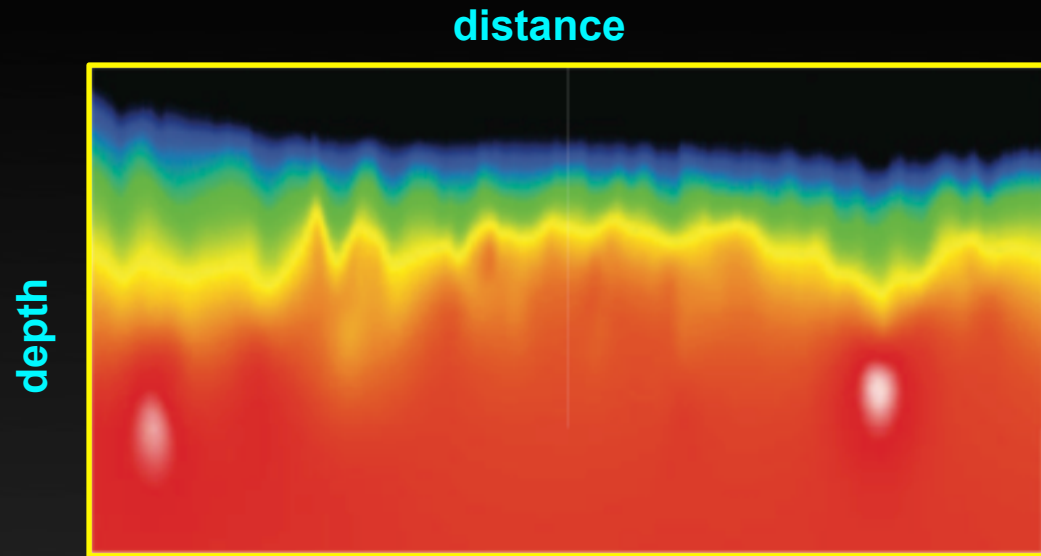
www.sintef.no

Horizon-based

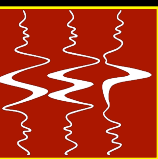


Jones et al., 1998

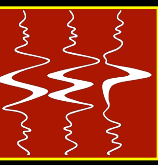
Motivation



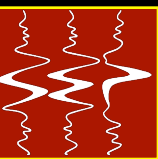
Wang et al., 2008



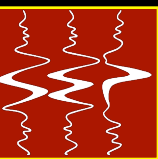
- **Reduce cost, improve flexibility and keep robustness**



- **Accelerate 3D image-space wave-equation tomography (ISWET)**



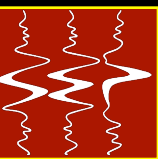
- **Accelerate 3D image-space wave-equation tomography (ISWET)**
 - Decreasing data size



- **Accelerate 3D image-space wave-equation tomography (ISWET)**
 - Decreasing data size
 - Solving in a target-oriented manner



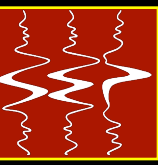
- **Accelerate 3D image-space wave-equation tomography (ISWET)**
 - Decreasing data size
 - Solving in a target-oriented manner
- **Incorporate strategies from ray-based methods into ISWET**



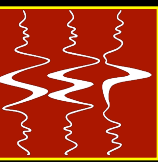
- **Accelerate 3D image-space wave-equation tomography (ISWET)**
 - Decreasing data size
 - Solving in a target-oriented manner
- **Incorporate strategies from ray-based methods into ISWET**
 - Using the image-space generalized wavefields



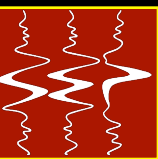
- **Generalized-source domain**
- **Pre-stack exploding-reflector model**
- **Image-space phase-encoded wavefields**
- **MVA in the image-space generalized-source domain**
- **Conclusions**



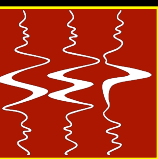
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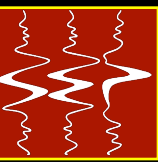
- **Wavefields are combined using the linearity of wavefield propagation**



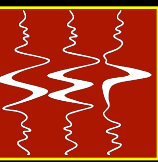
- **Wavefields are combined using the linearity of wavefield propagation**
- **Seismic acquisition**
 - **Simultaneous-sources**



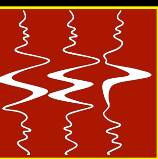
- **Wavefields are combined using the linearity of wavefield propagation**
- **Seismic acquisition**
 - **Simultaneous-sources**
- **Seismic processing**
 - **plane-wave encoding (Whitmore, 1995)**
 - **random-phase encoding (Romero et al., 2000)**
 - **controlled illumination (Rietveld et al., 1992)**



- **Combination of wavefields using the linearity of wavefield propagation**
- **Use of a smaller number of experiments while keeping the image quality**

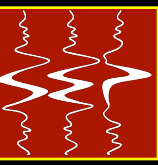


- **Combination of wavefields using the linearity of wavefield propagation**
- **Use of a smaller number of experiments while keeping the sensitive information**



- **Data-space generalized sources**
 - plane-wave encoding, random-phase encoding, controlled illumination

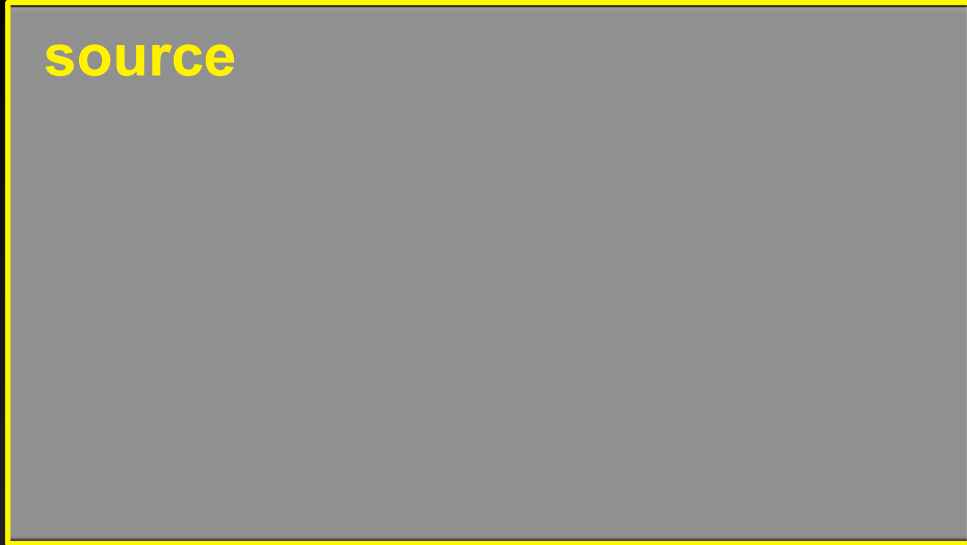
Data-space: 0° plane wave



distance

source

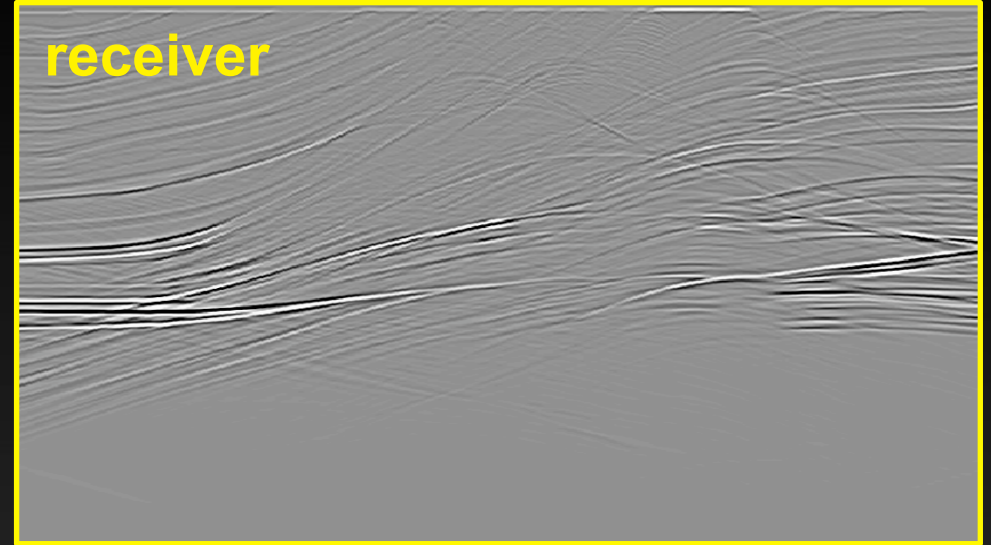
time



distance

receiver

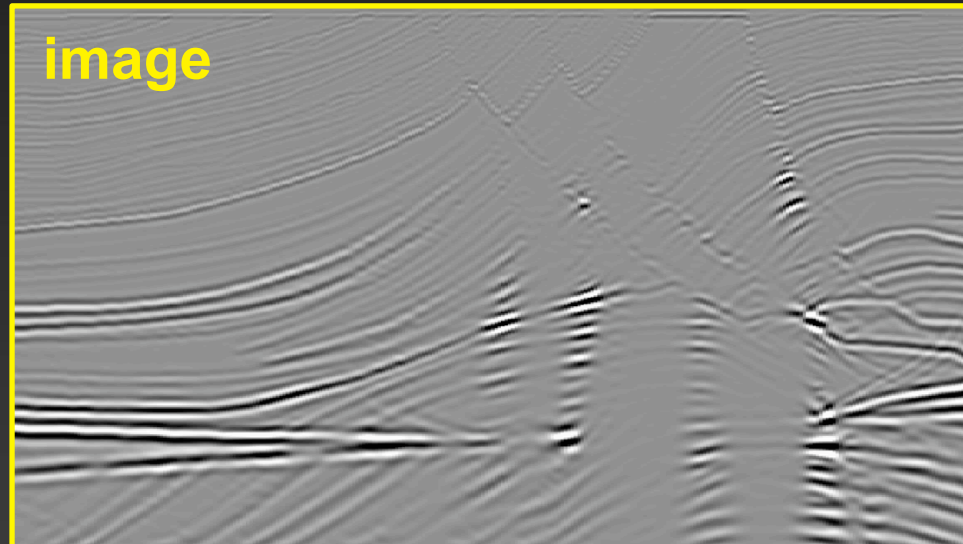
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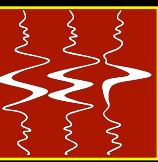


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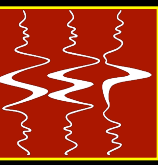
image

depth

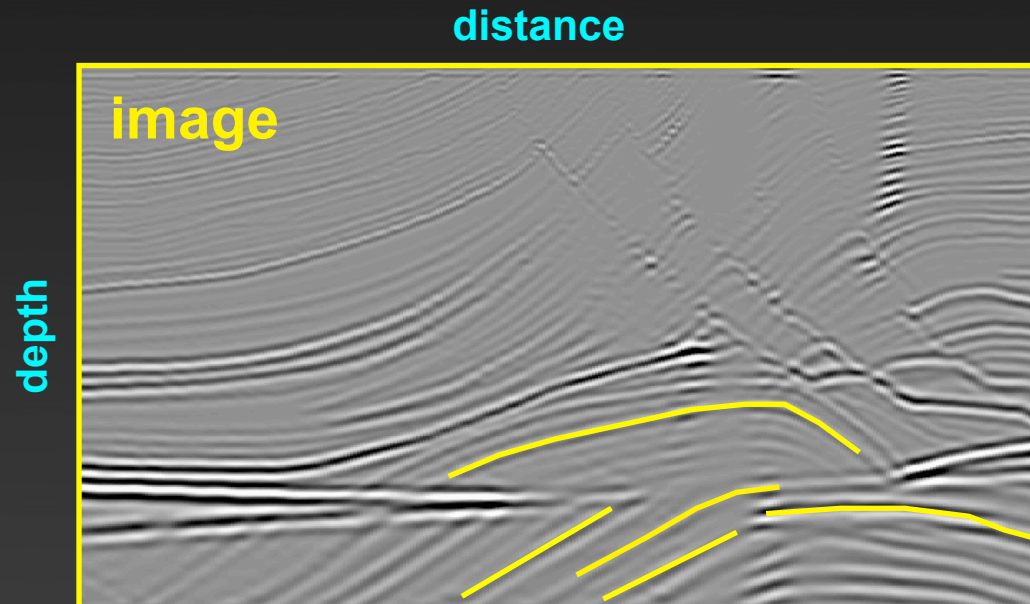




- **Data-space generalized sources**
- **Image-space generalized sources**
 - **Pre-stack exploding-reflector modeling (PERM) (Biondi, 2006)**
 - **Image-space phase-encoded wavefields (ISPEW) (Guerra and Biondi, 2008)**



– Models wavefields from selected reflectors

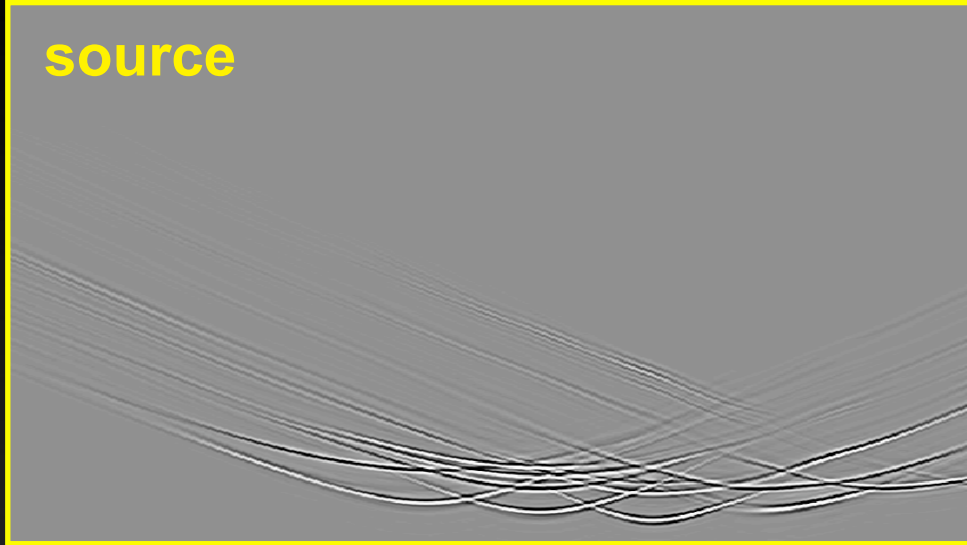




distance

source

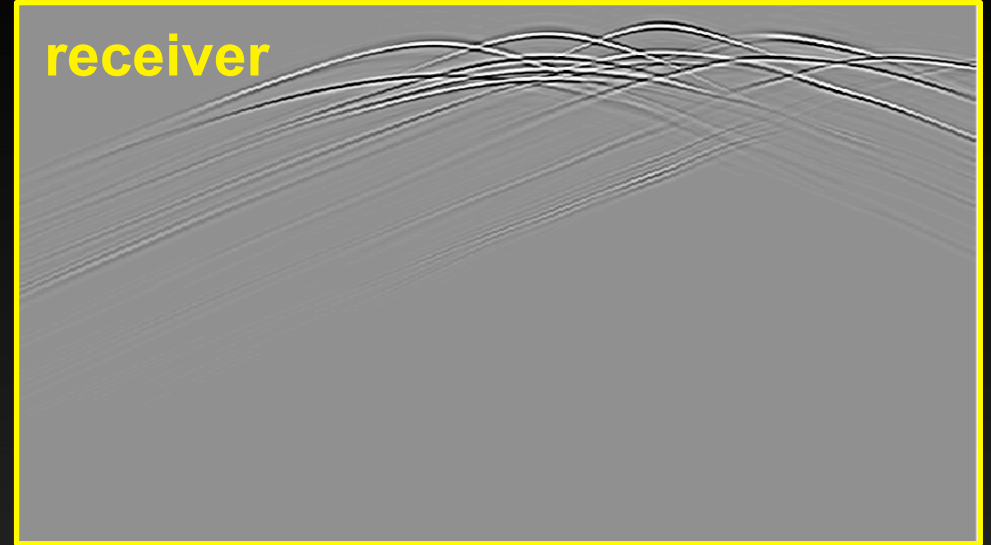
time



distance

receiver

time



distance

image

depth

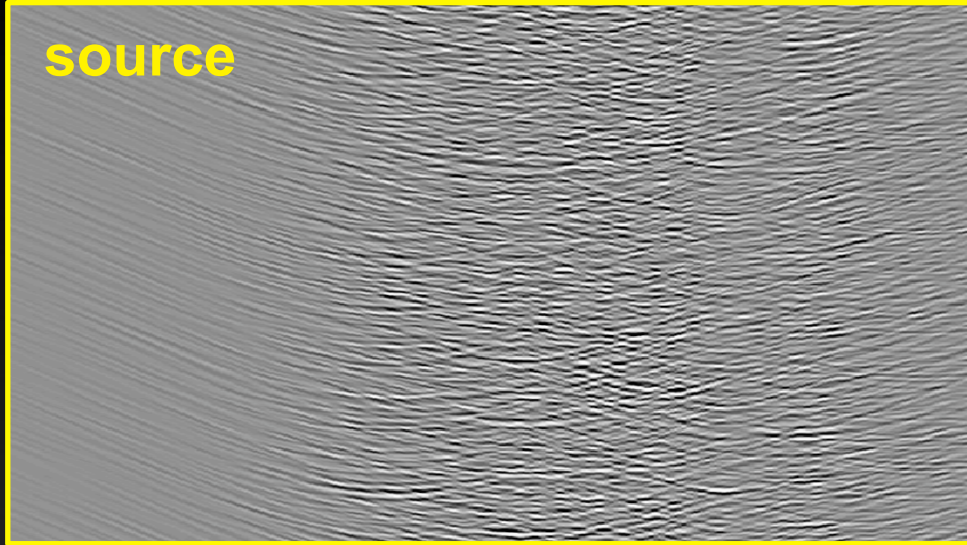




distance

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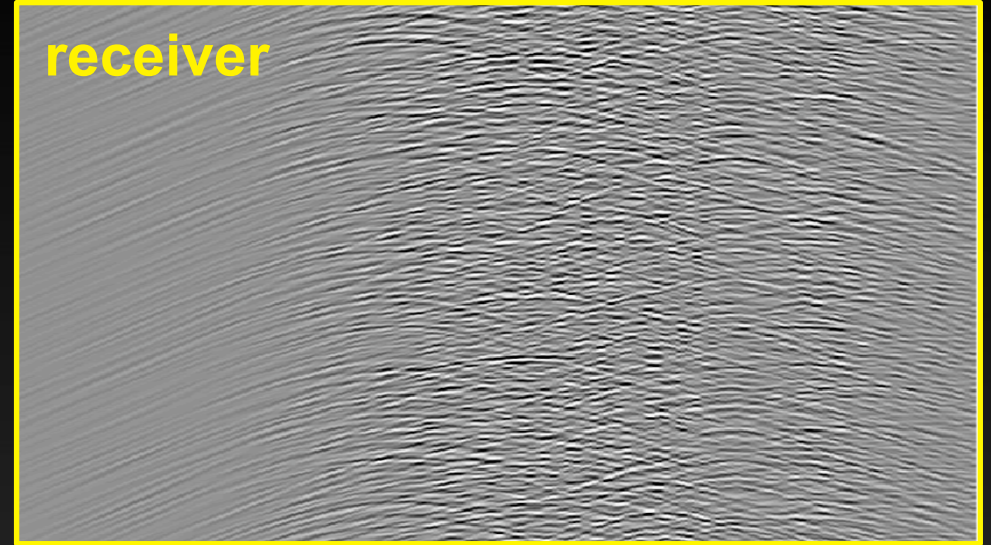
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distance

receiver

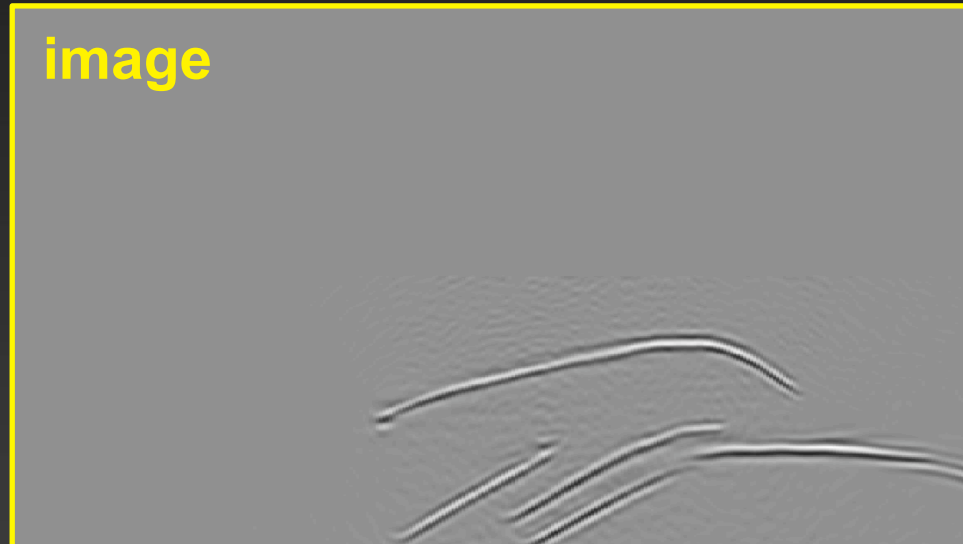
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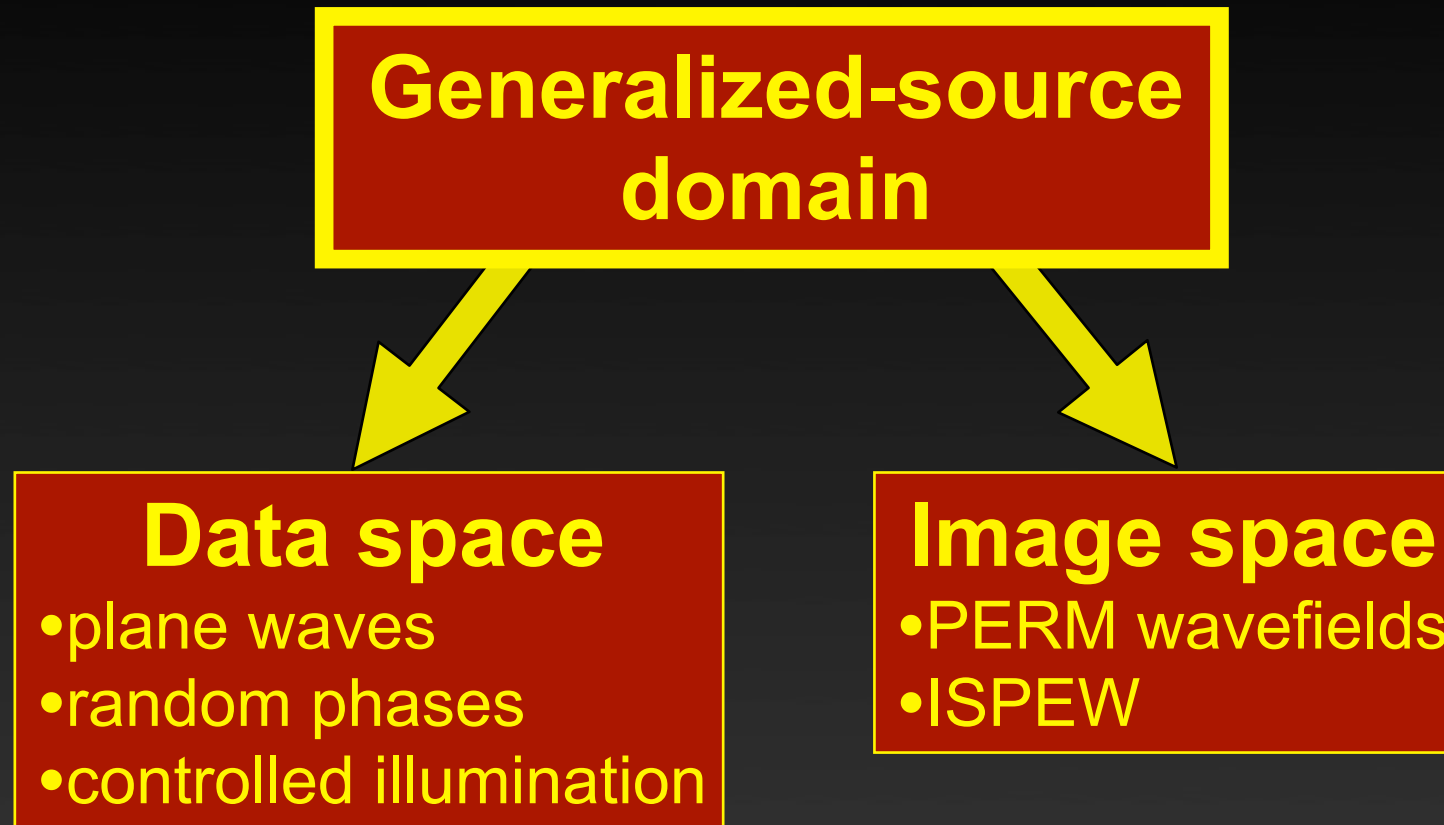
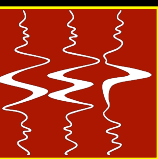


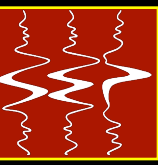
distance

image

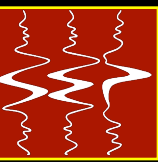
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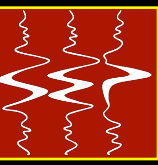


- Generalized-source domain
- **Pre-stack exploding reflector model**
- Image-space phase-encoded wavefields
- MVA in the image-space generalized-source domain
- Conclusions



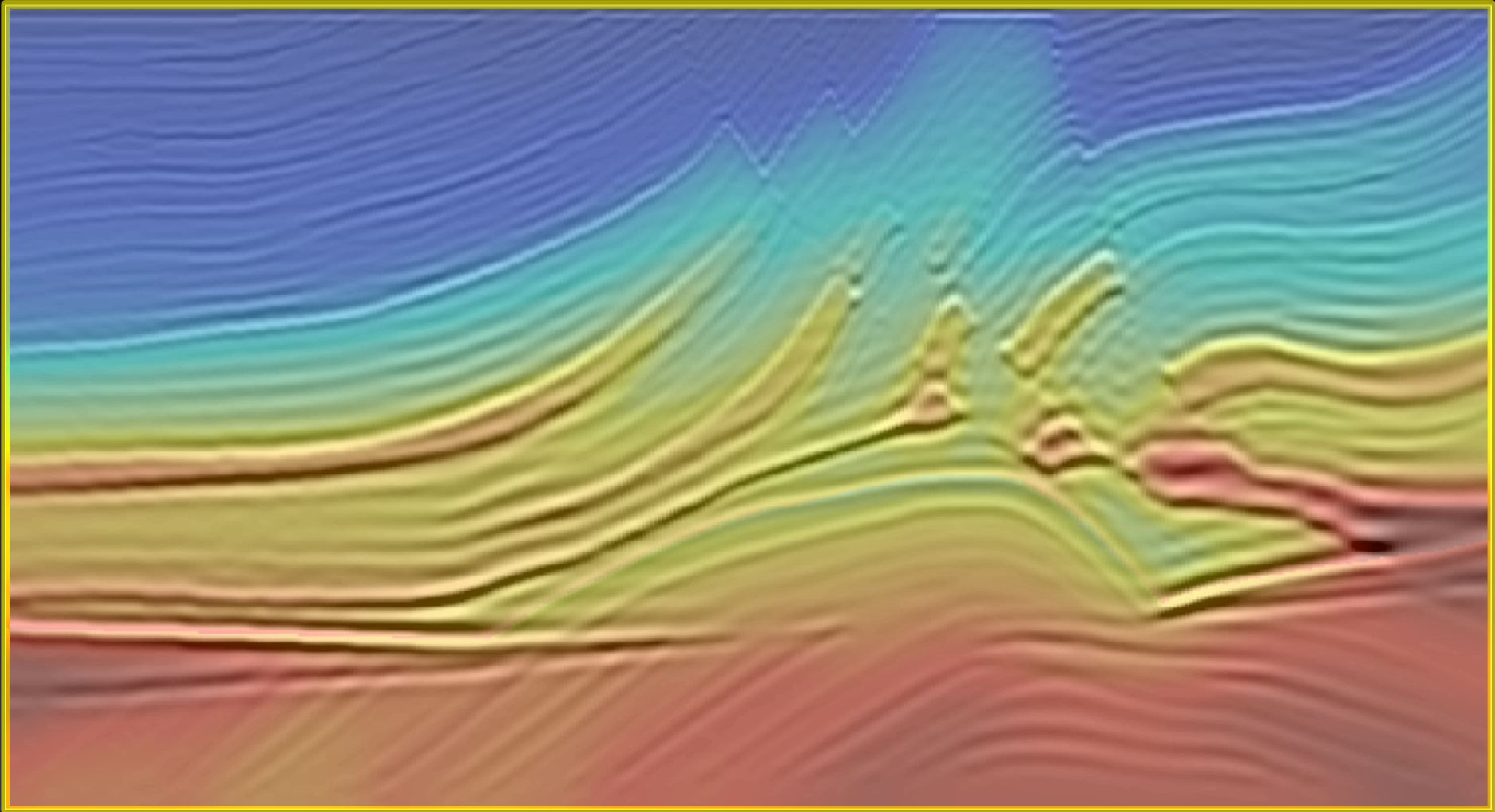
- **The exploding-reflector model synthesizes zero-offset data, assuming focused reflectors at zero-subsurface-offset**

Exploding reflectors

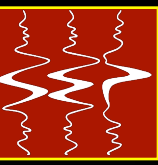


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depth

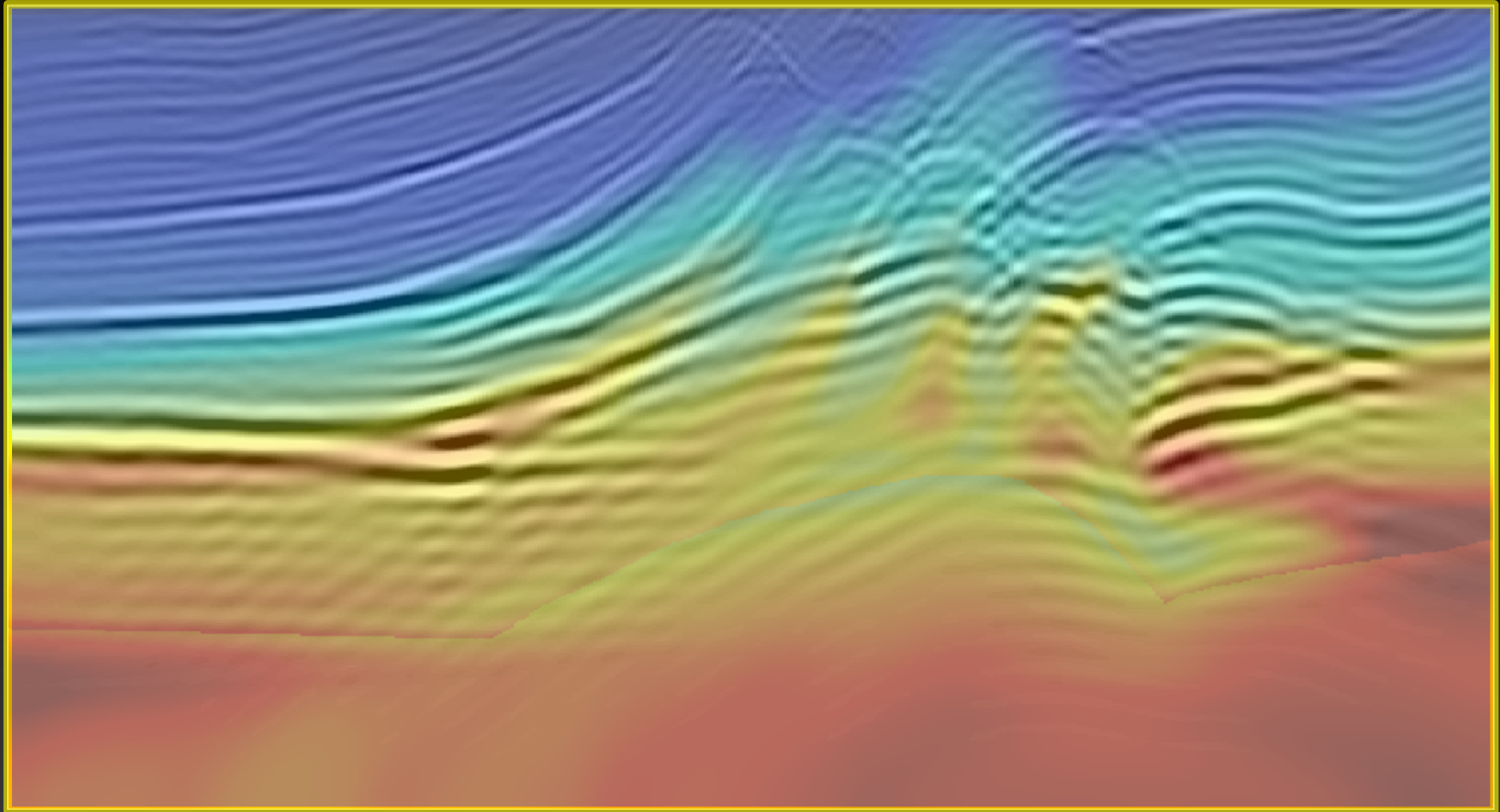


Exploding reflectors

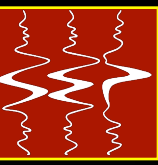


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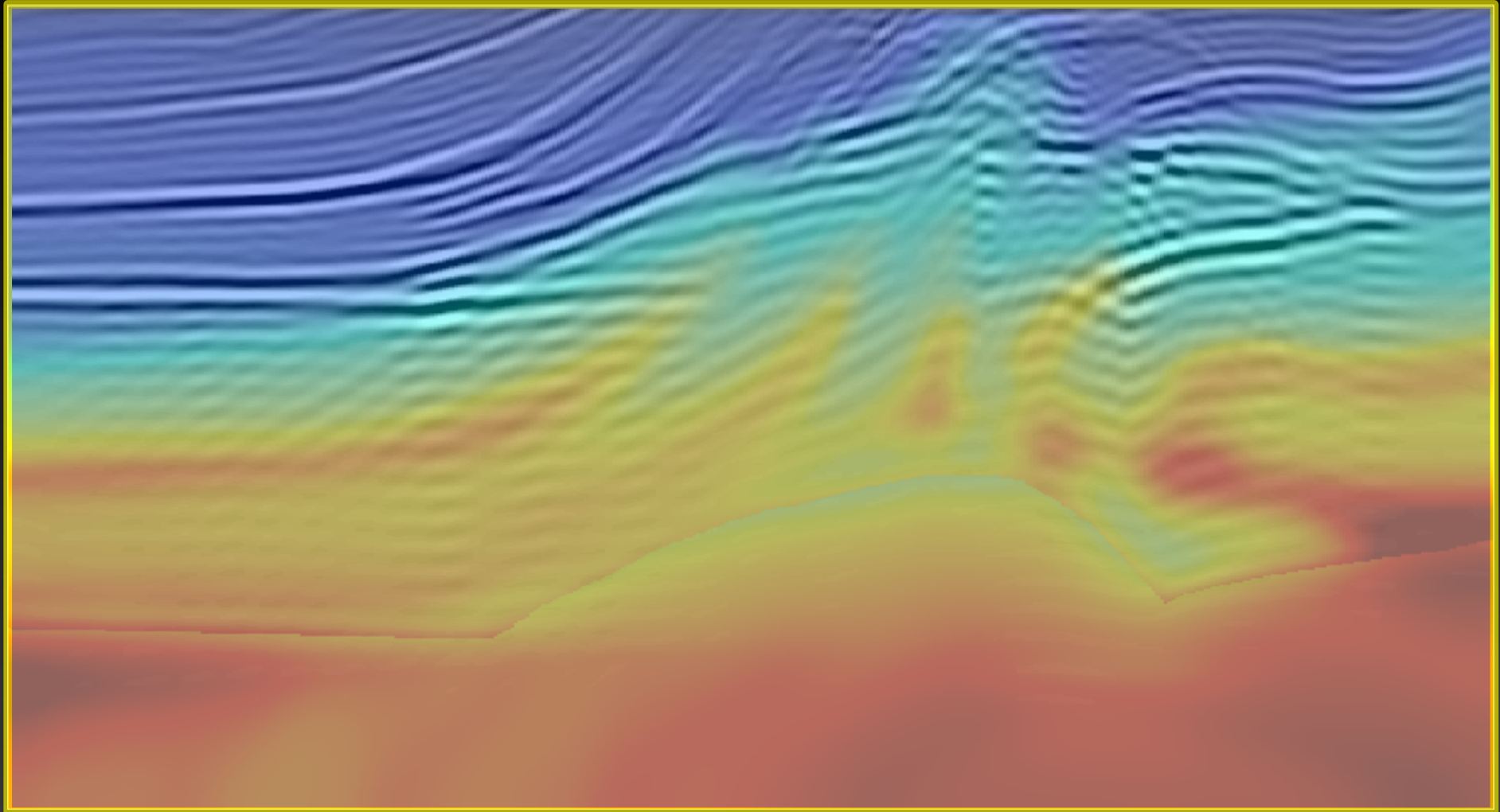


Exploding reflectors

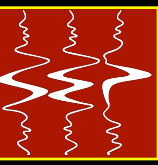


distance

depth

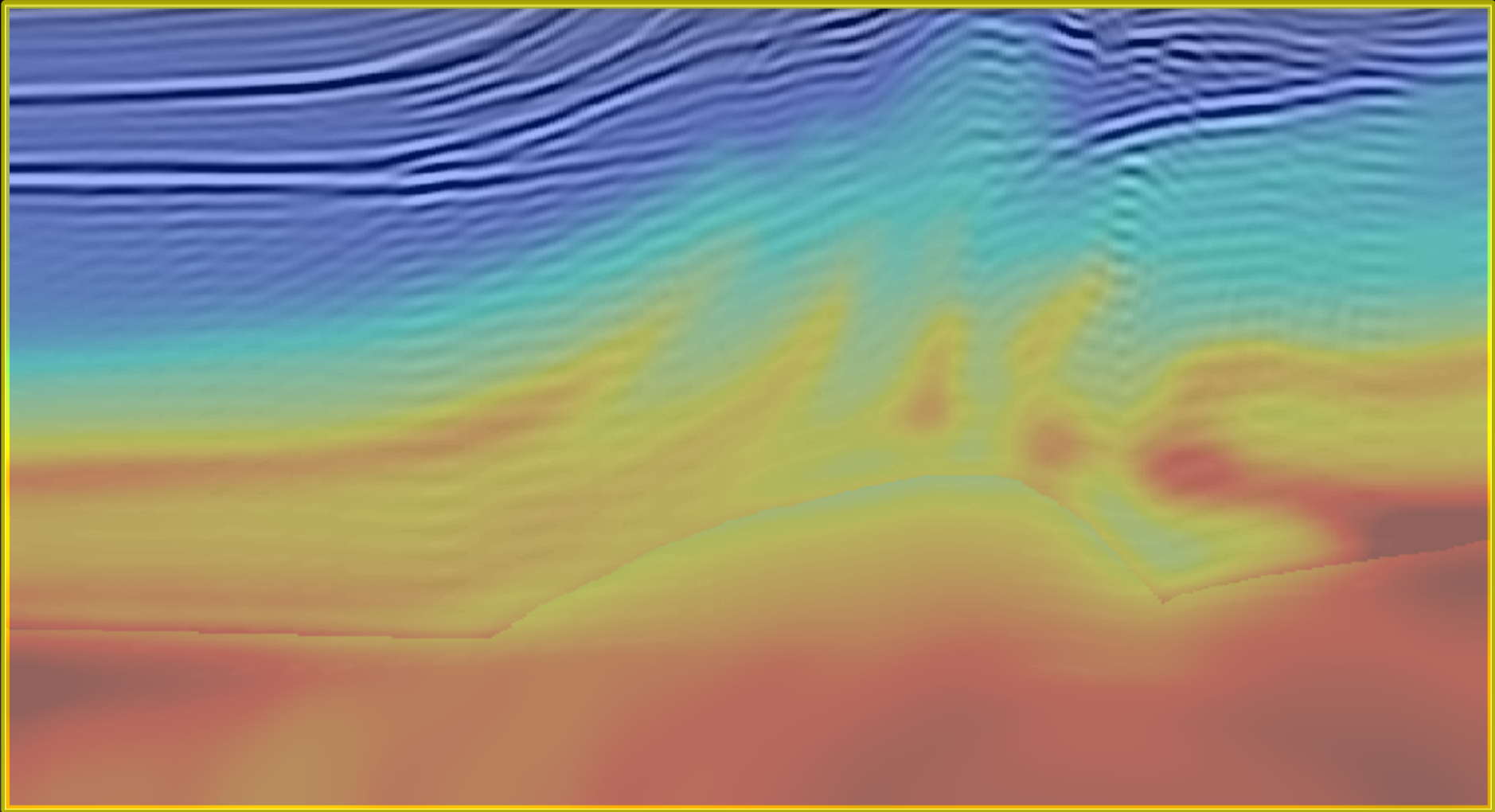


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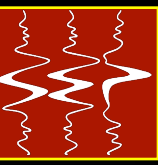


distance

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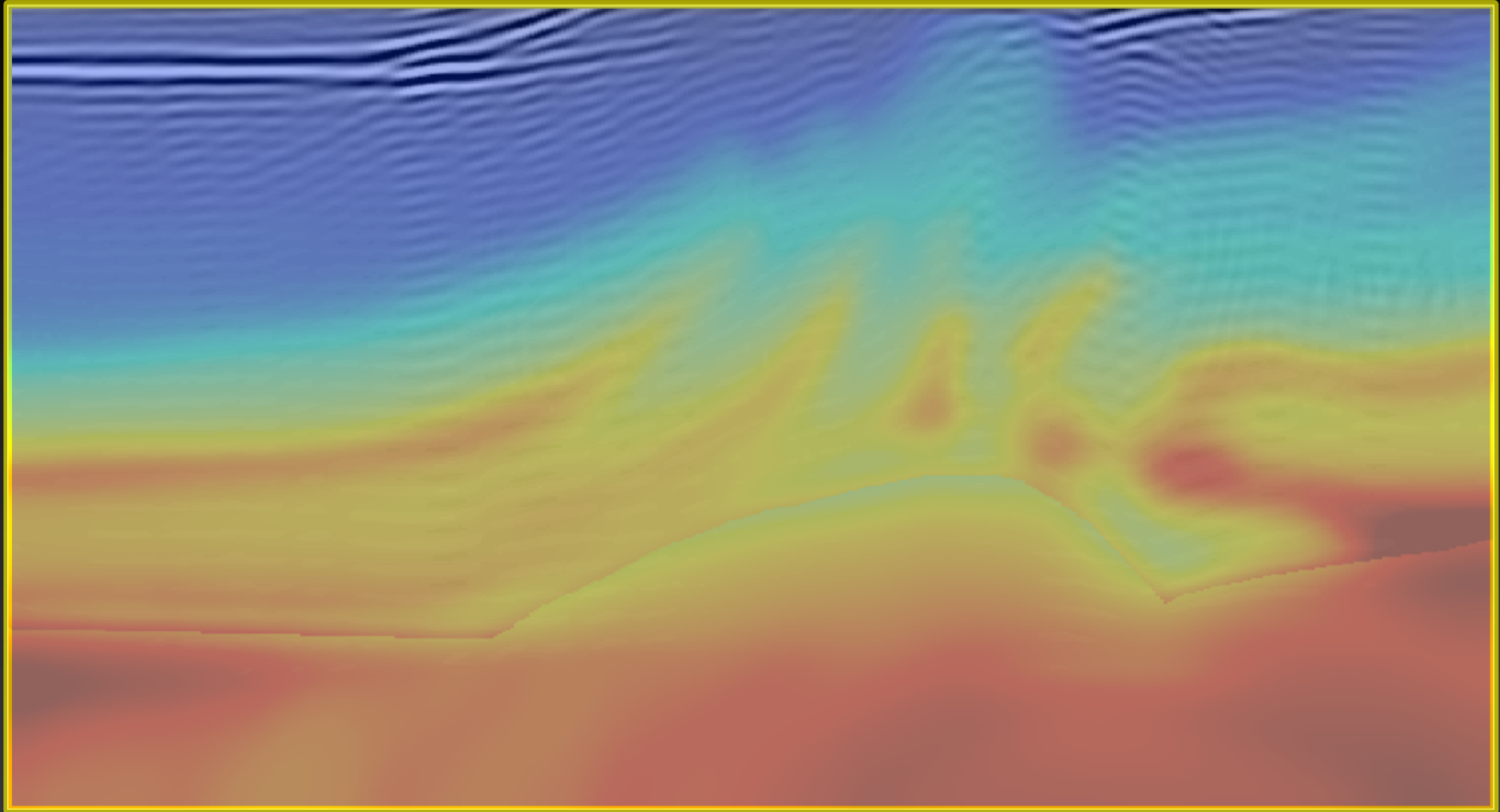


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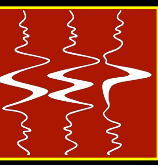


distance

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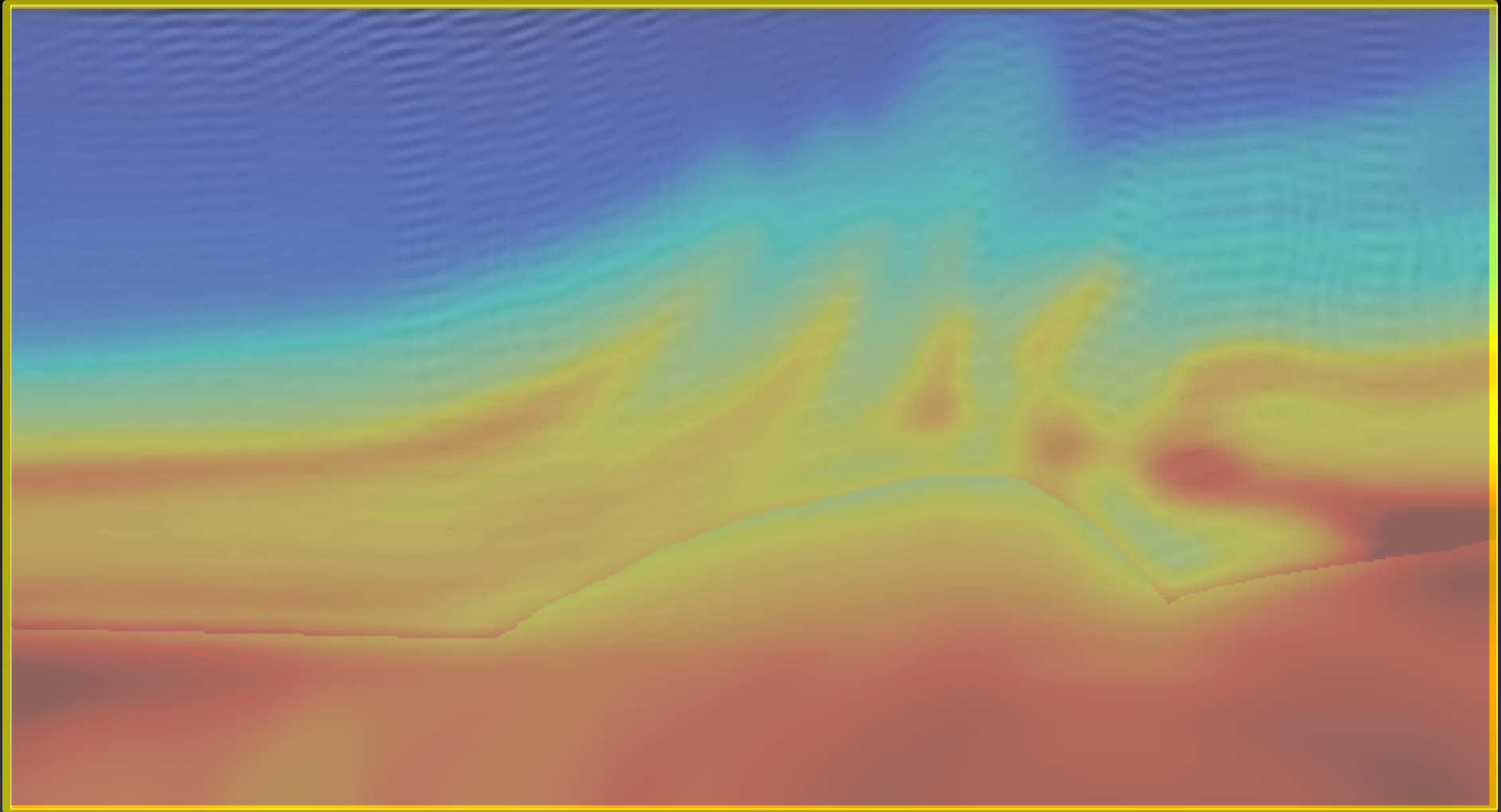


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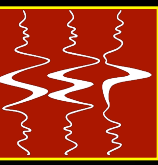


distance

depth

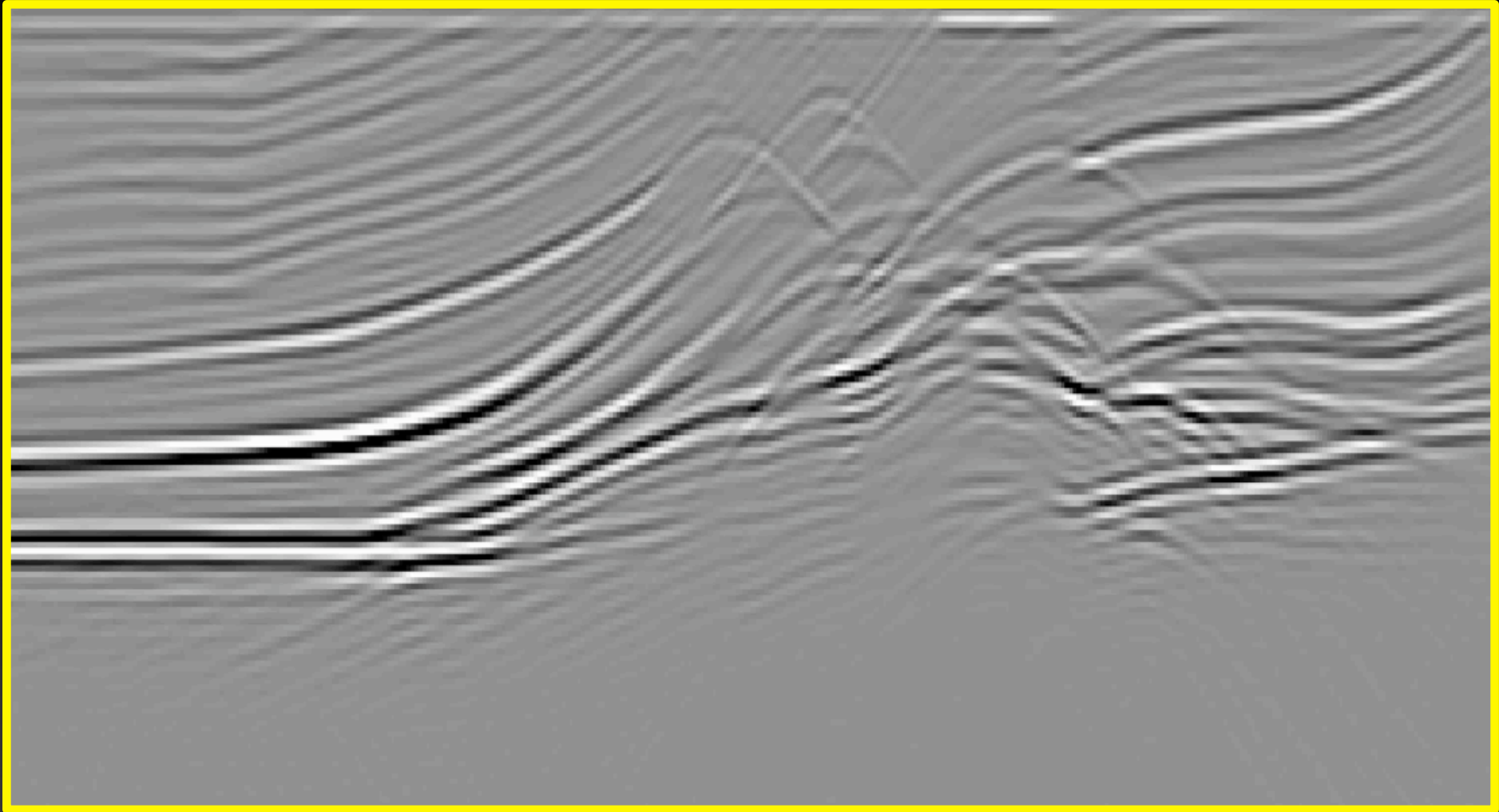


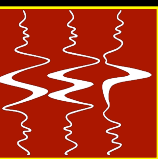
Exploding reflectors



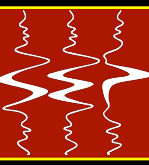
distance

time





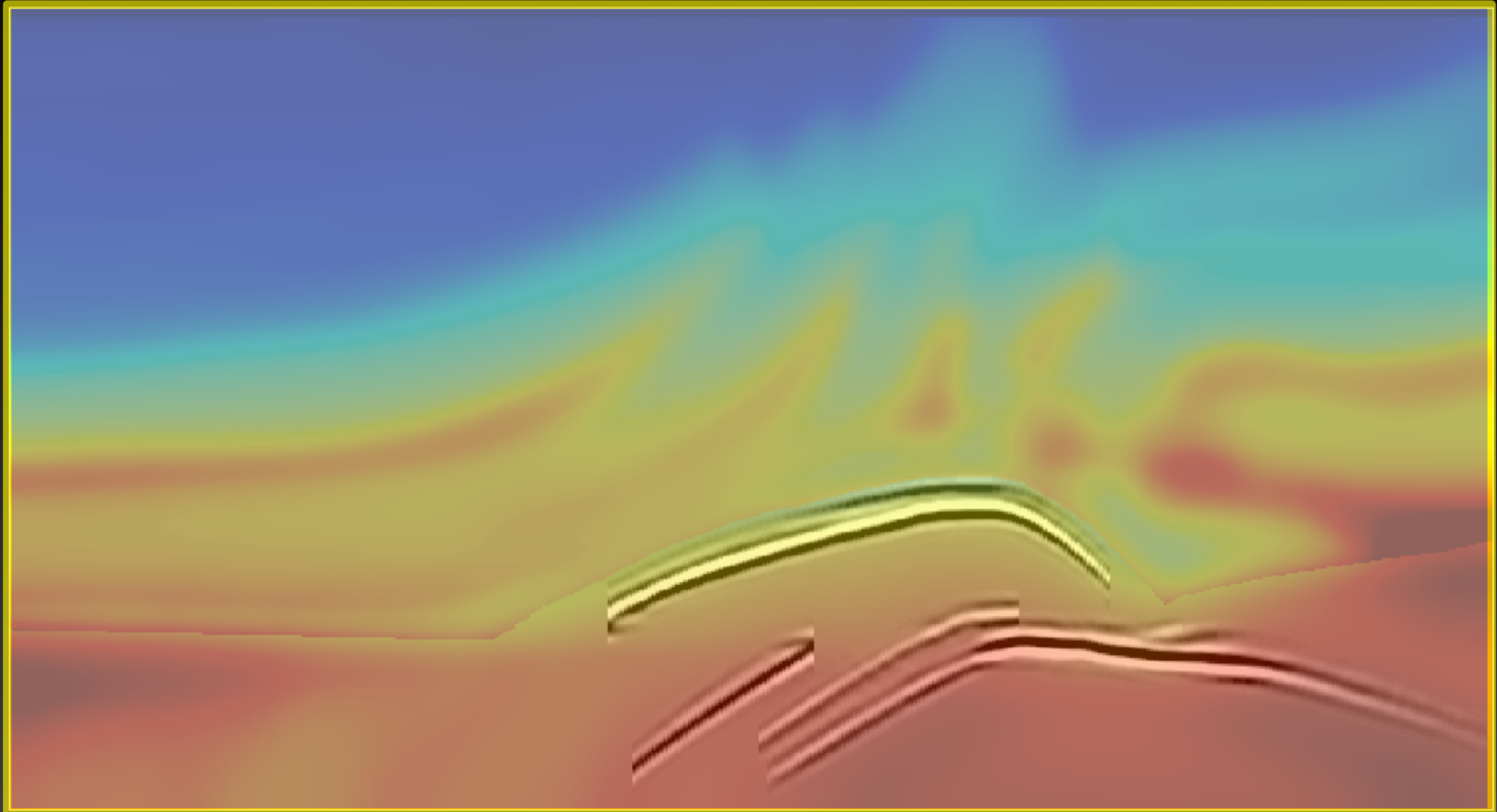
- **Generalizes the exploding-reflector model**
 - **considers energy at nonzero-subsurface offsets**

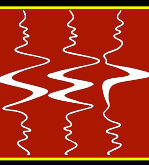


- **Synthesizes source and receiver wavefields**

distance

depth

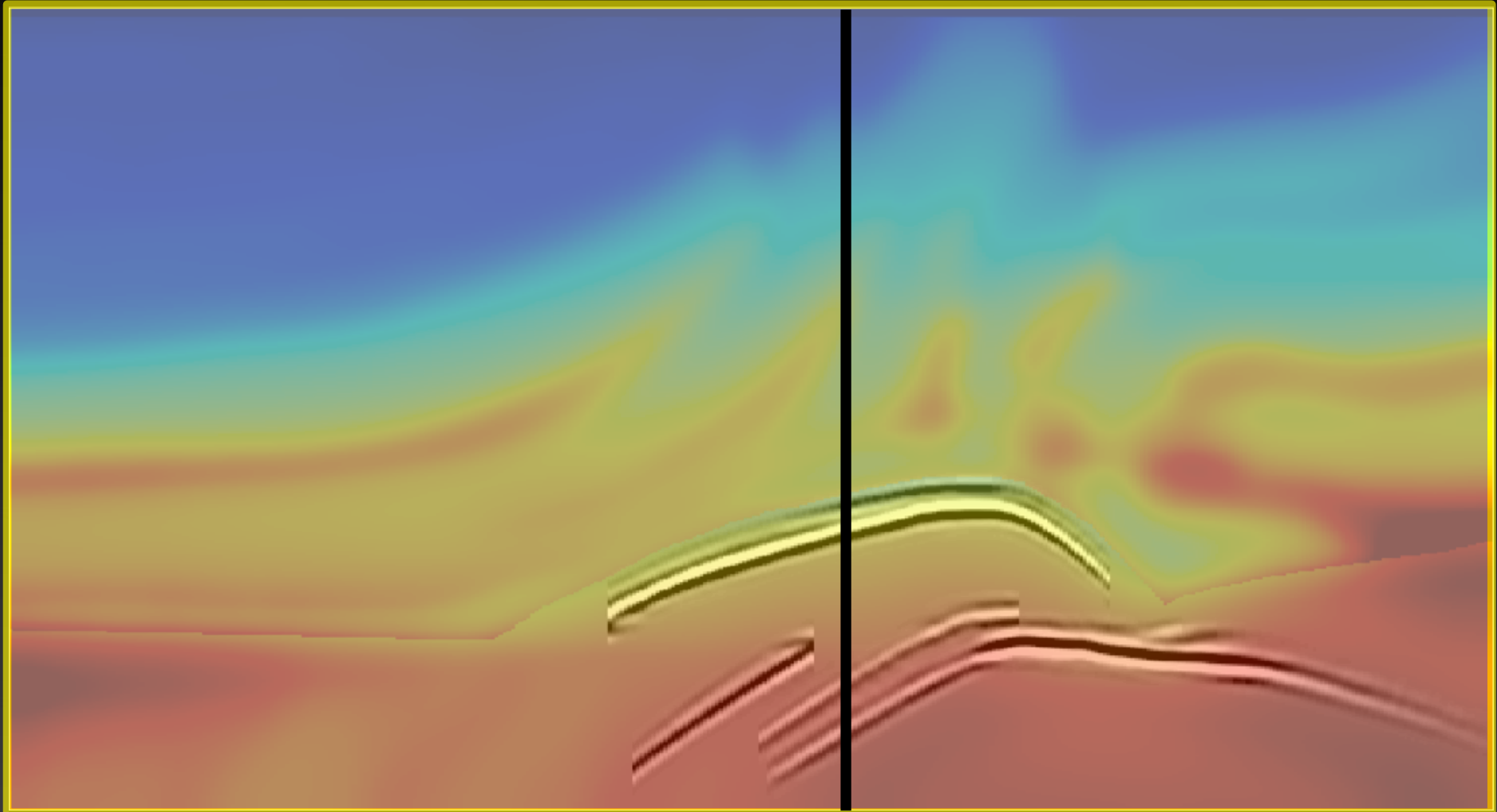




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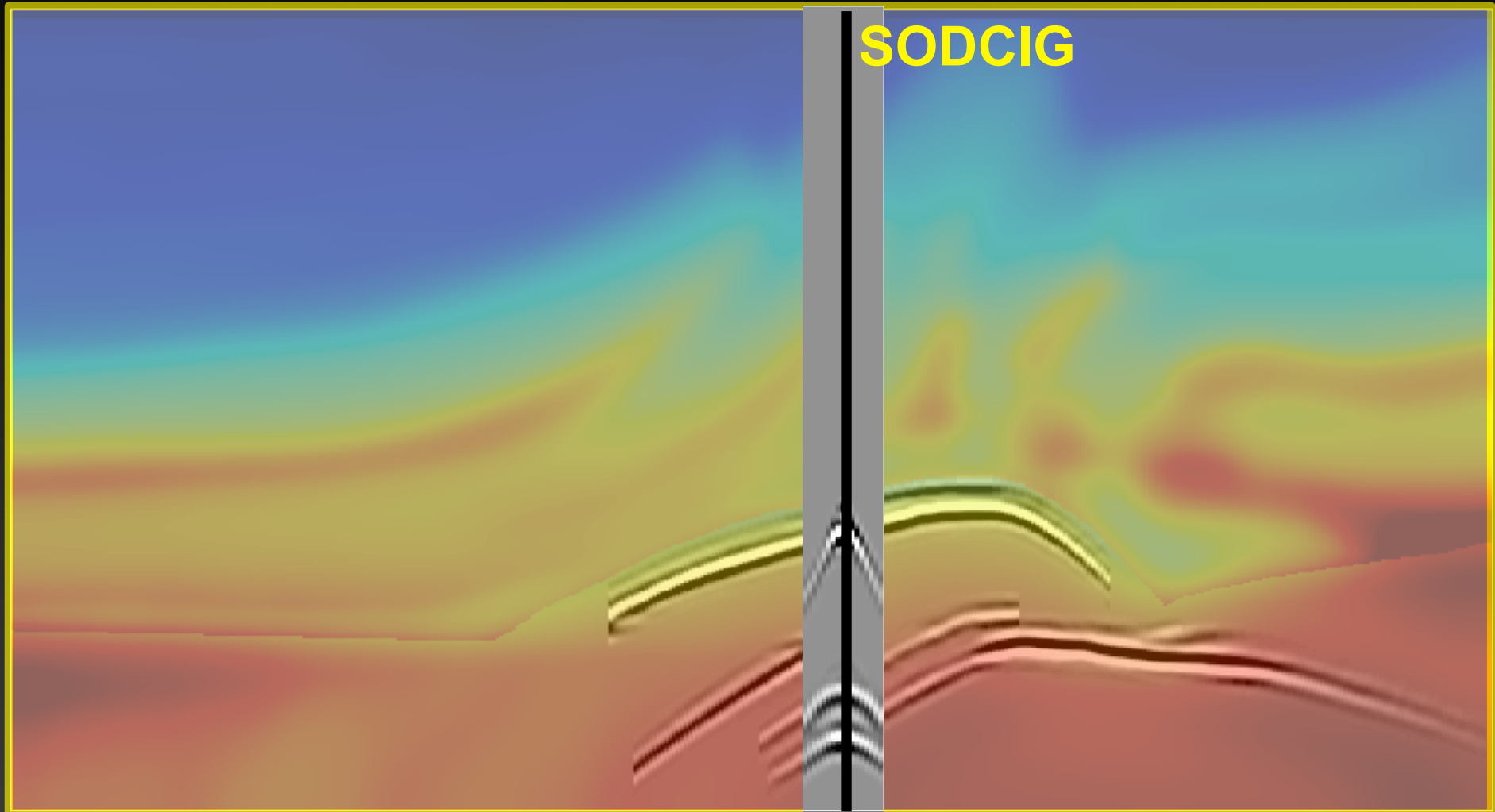


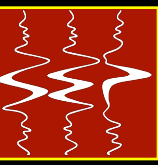


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distance

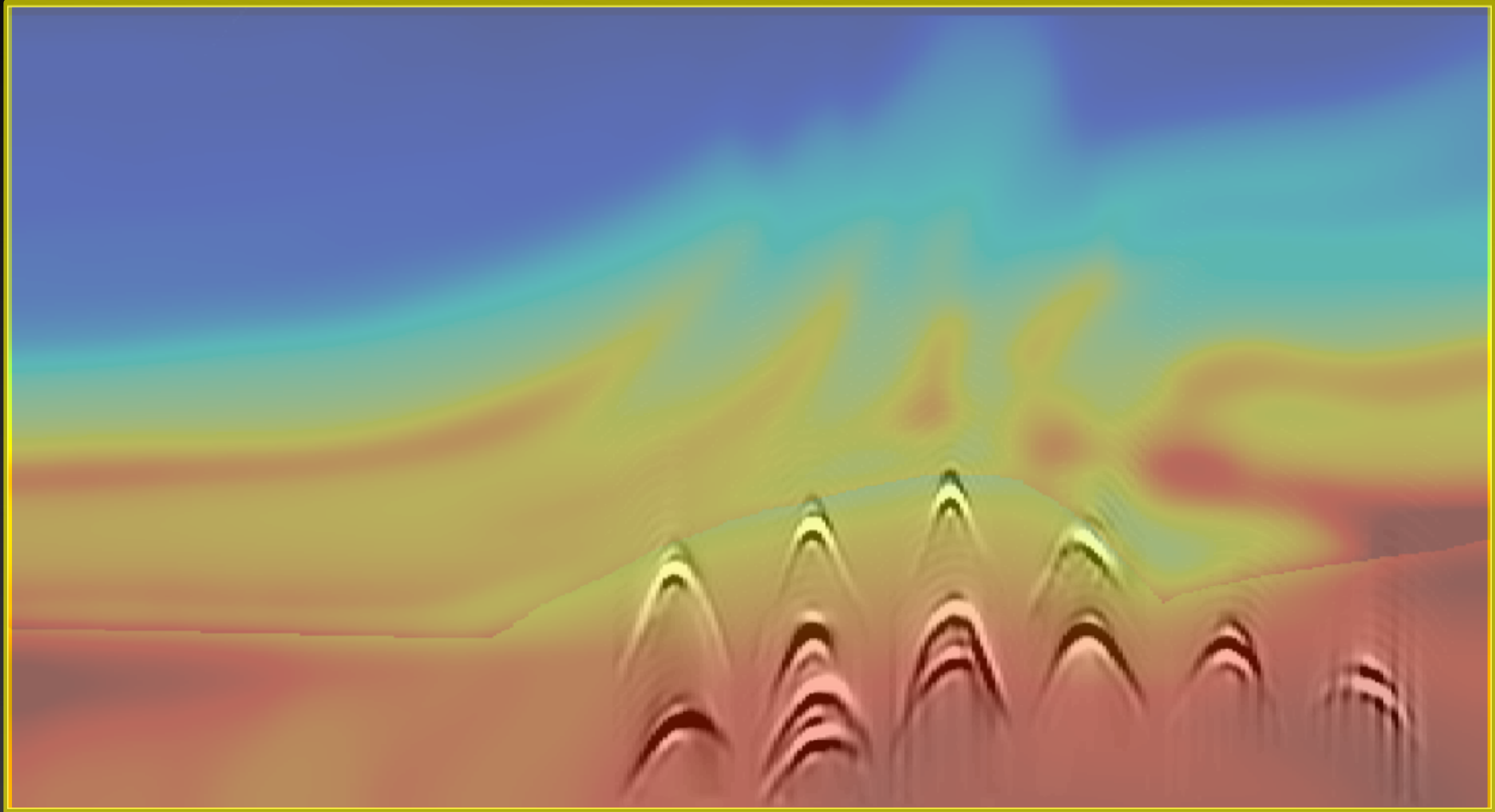
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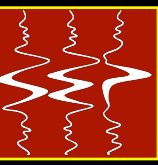




distance

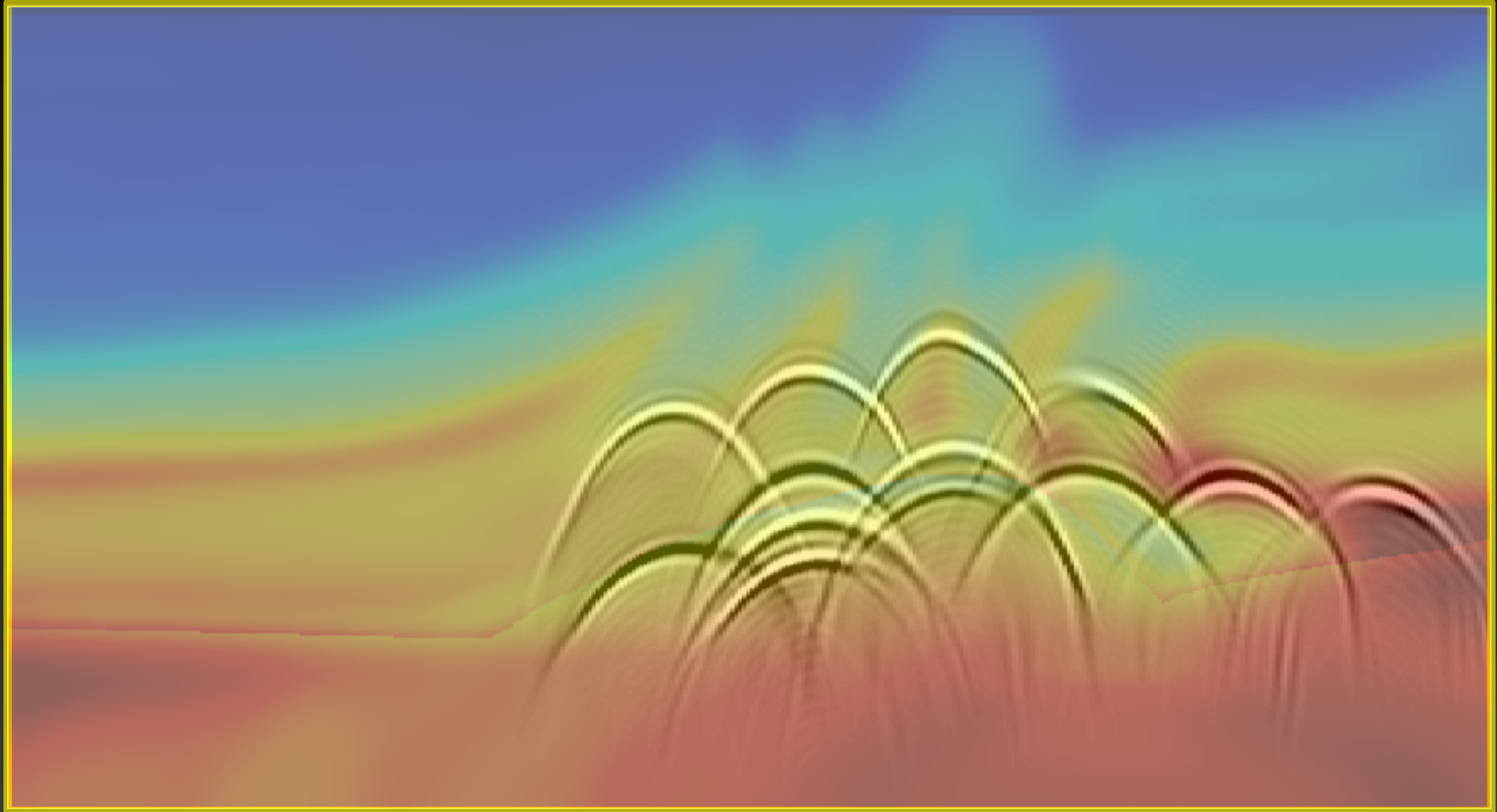
depth

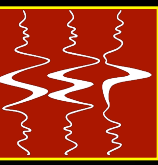




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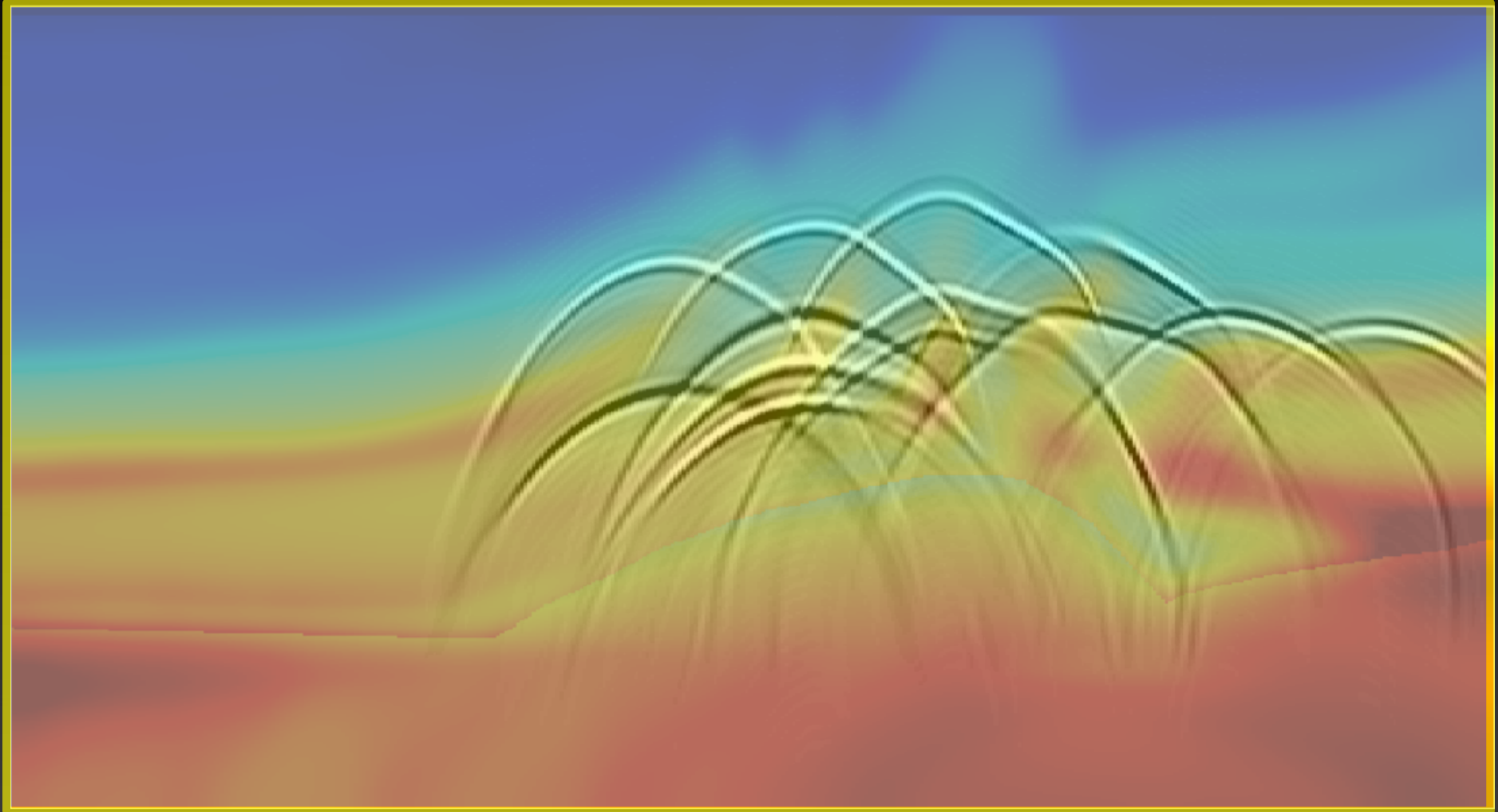
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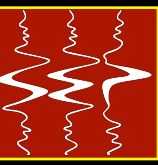




distance

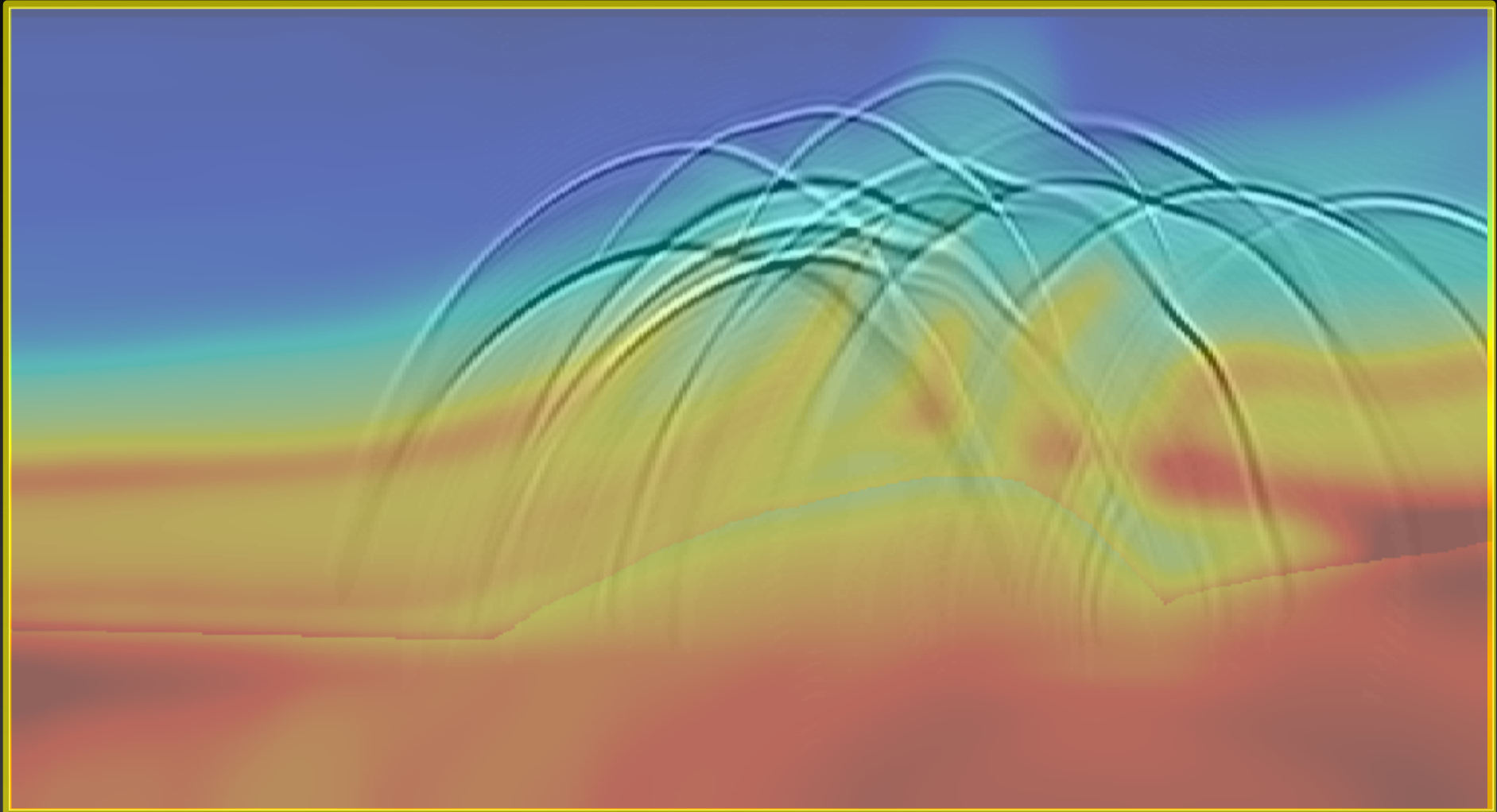
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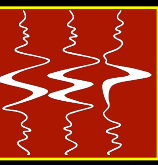




distance

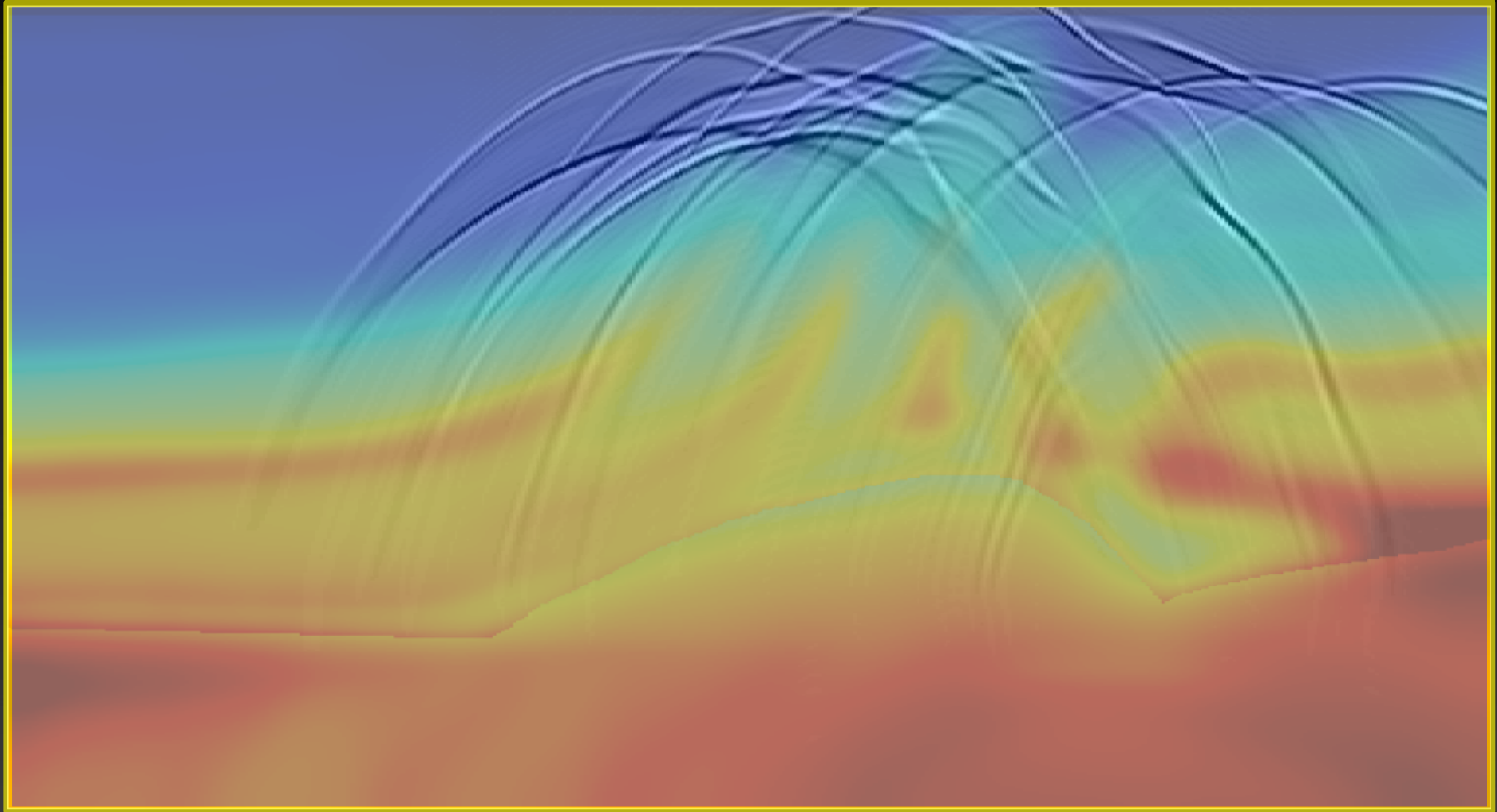
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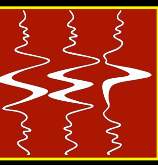




distance

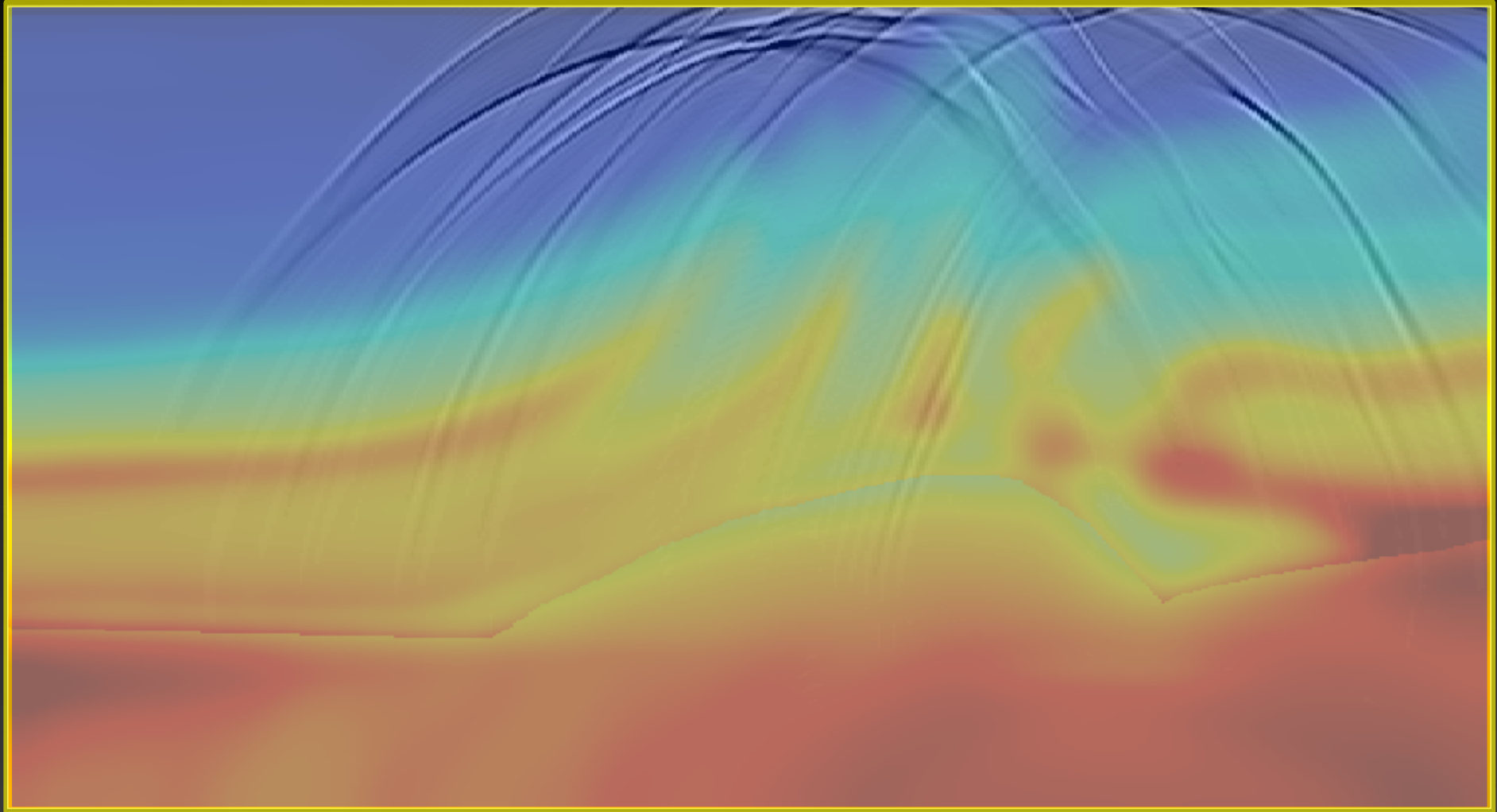
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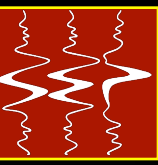




distance

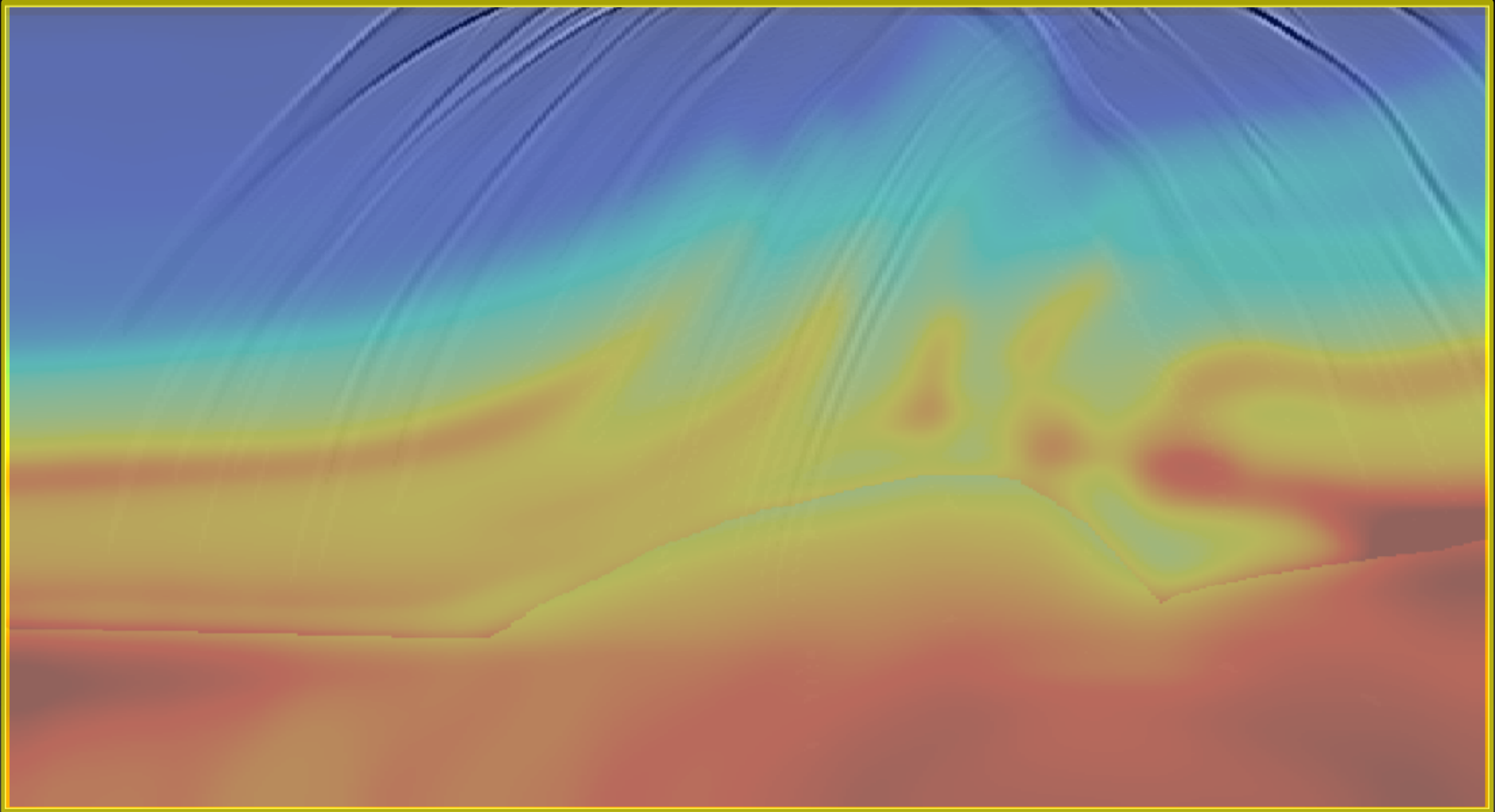
depth





distance

depth

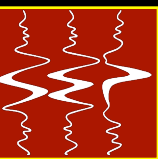




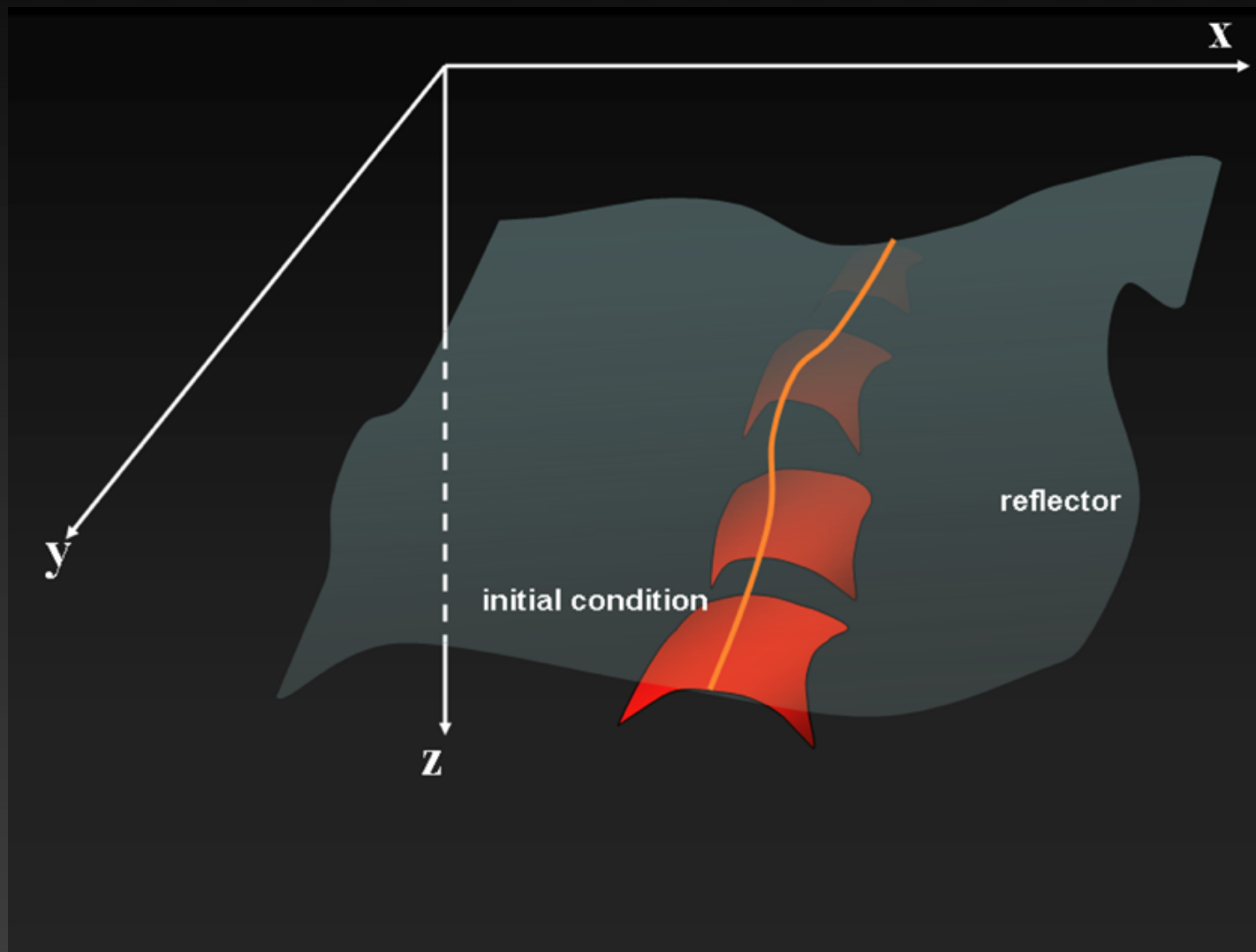
- **Can be used in a target-oriented manner**
distance

depth



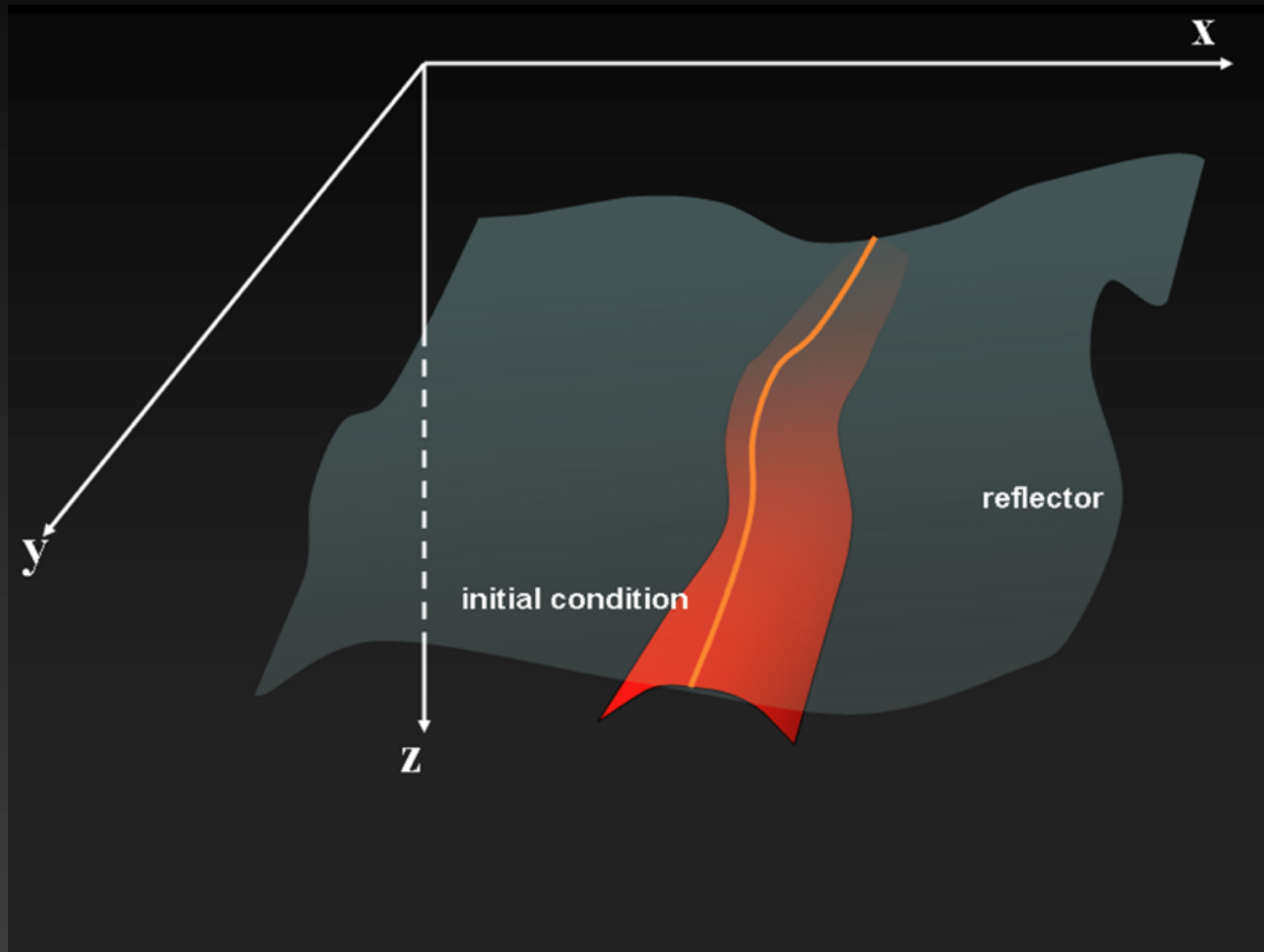


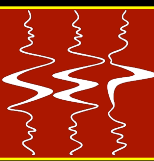
- In 3D, several hundreds to few thousands of PERM wavefields





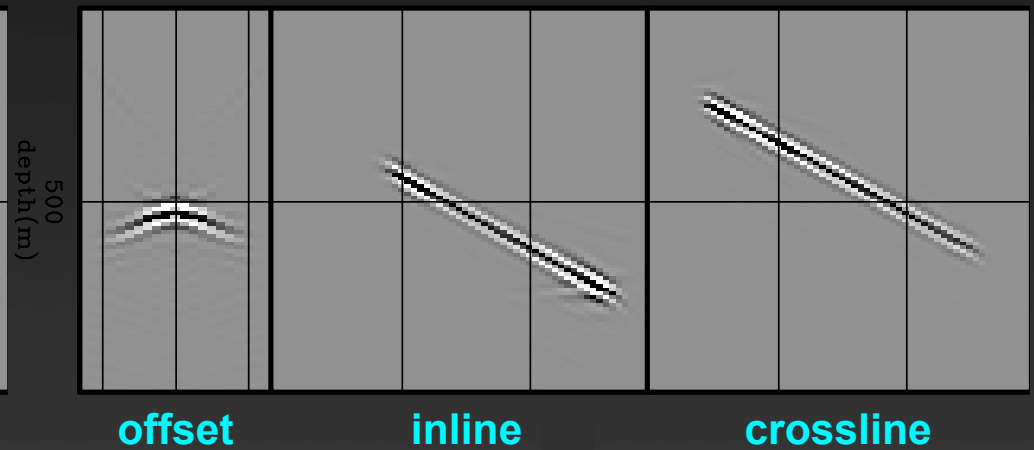
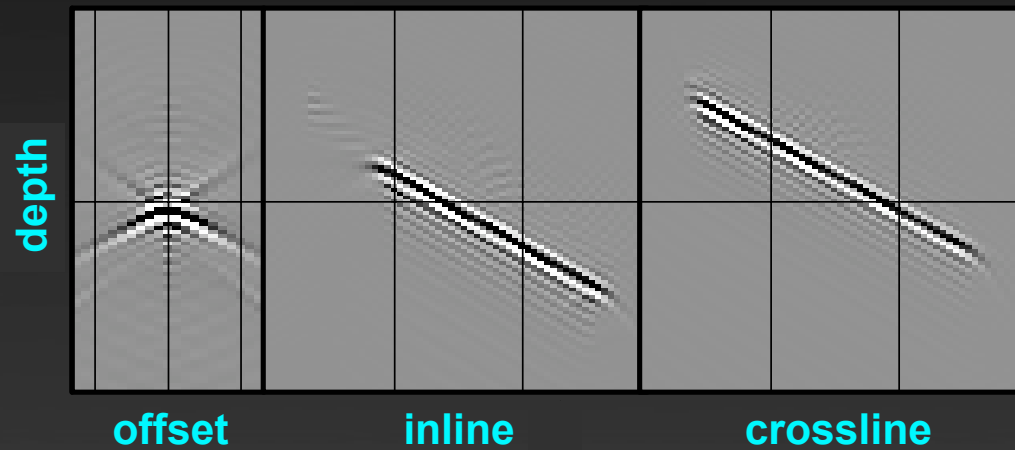
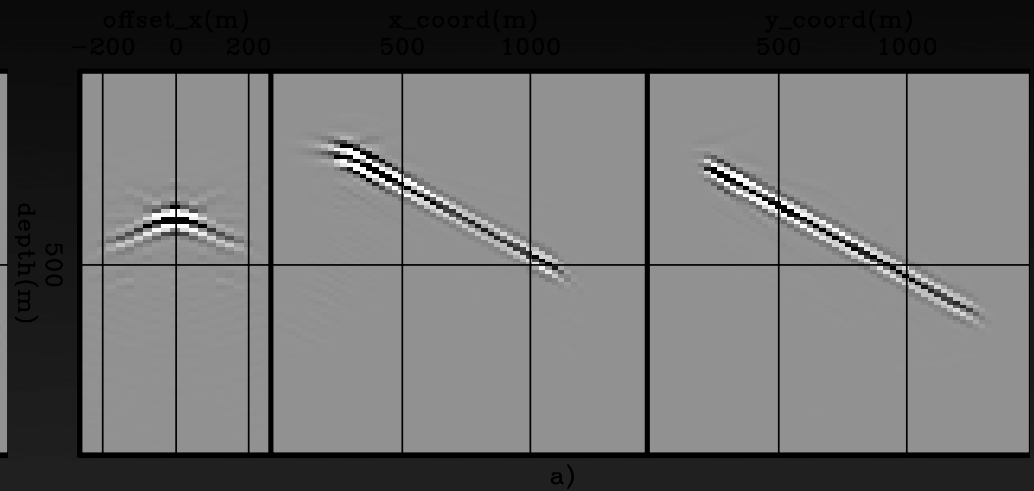
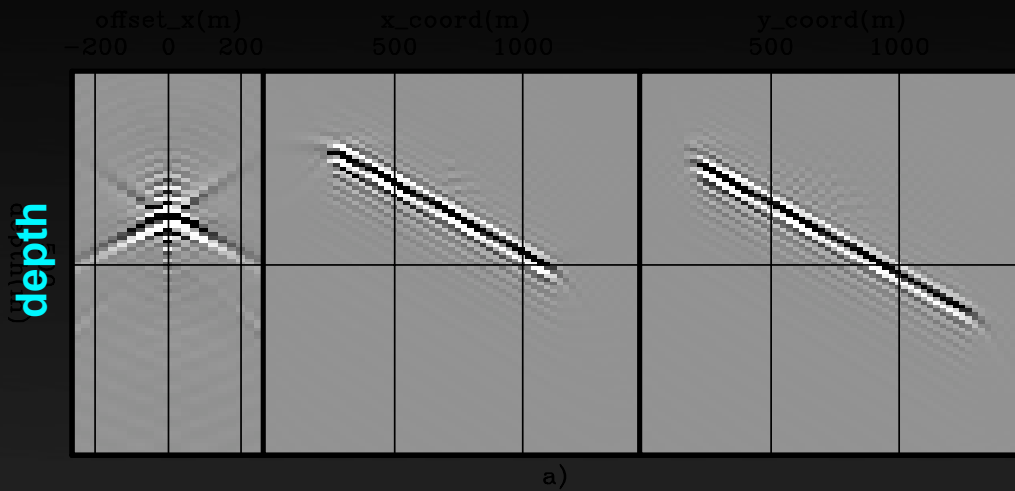
- **Inline PERM and crossline exploding-reflector modeling**
- **Few tens of PERM wavefields**

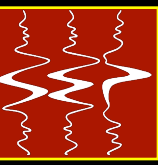




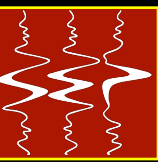
CAM

PERM

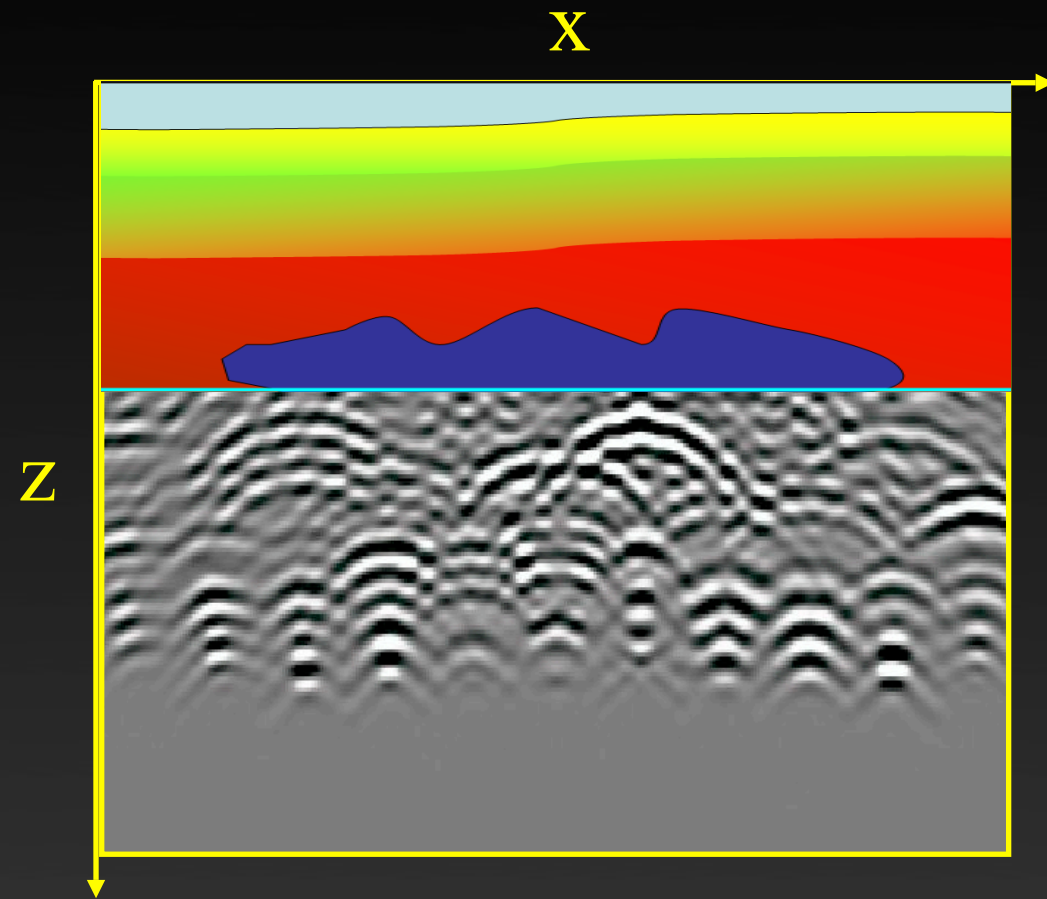
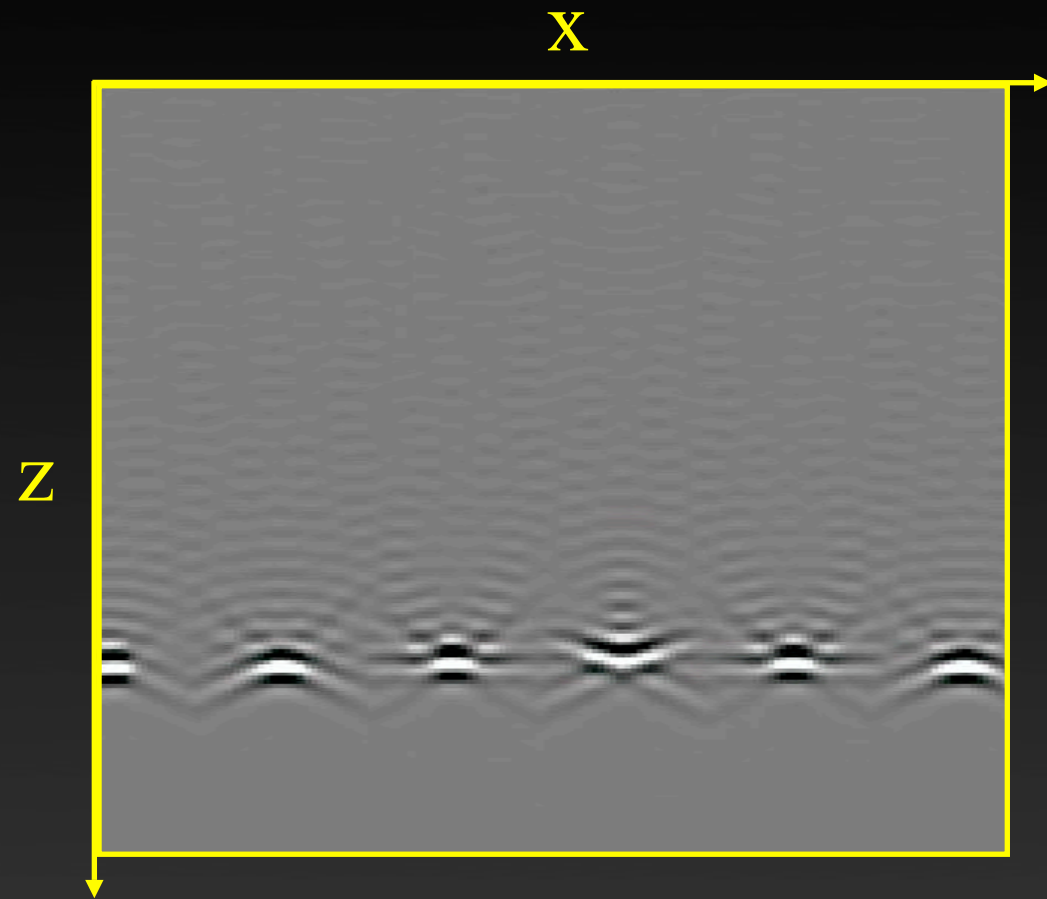


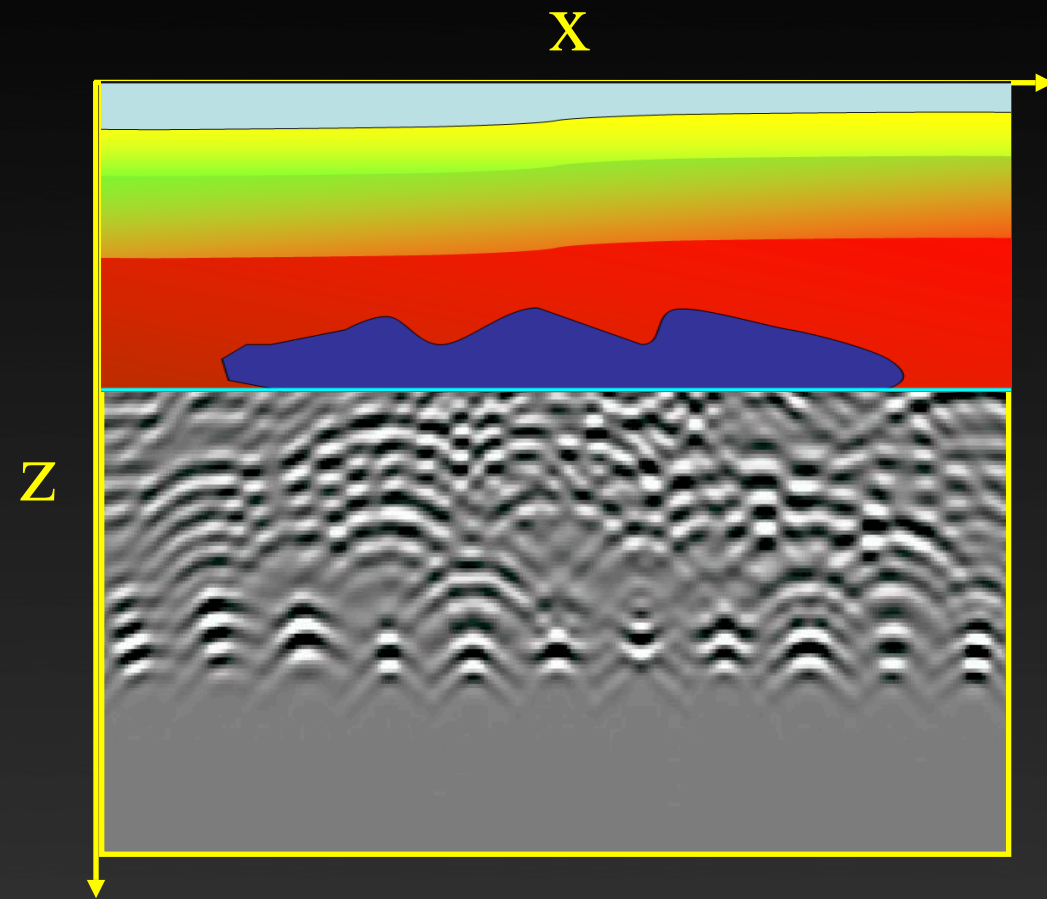
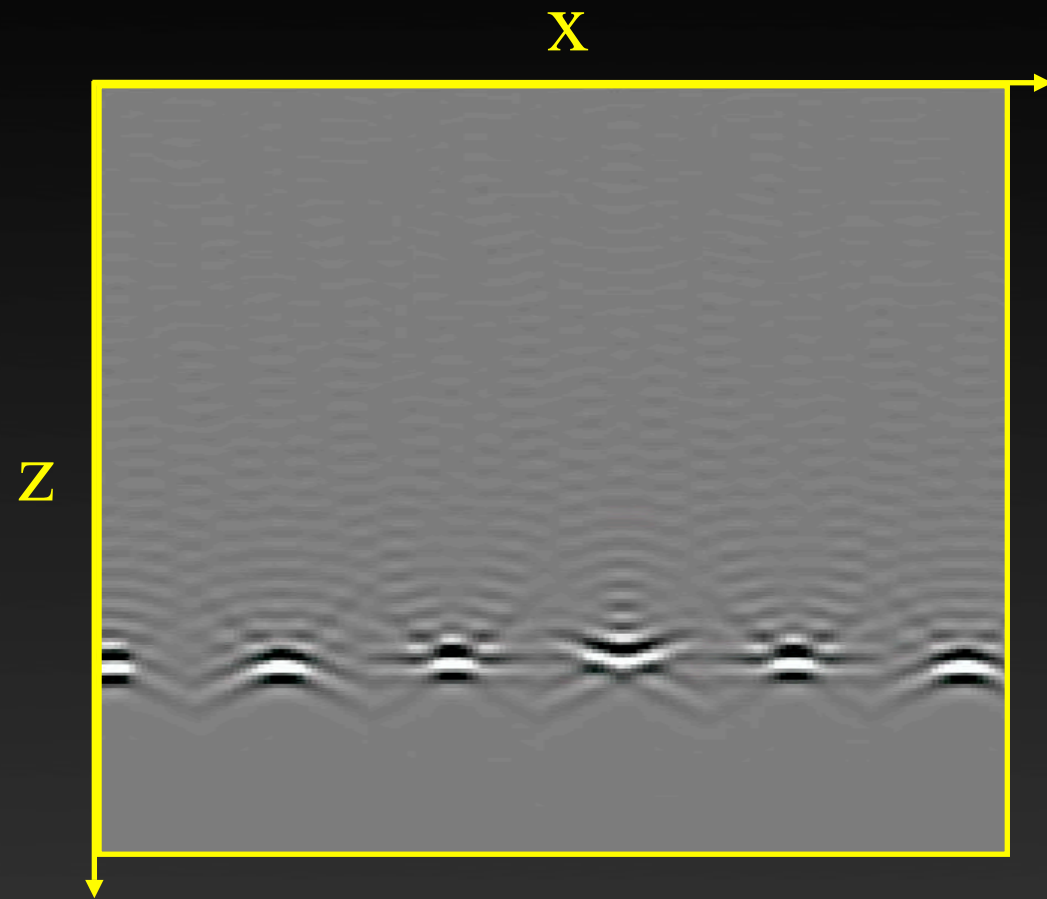


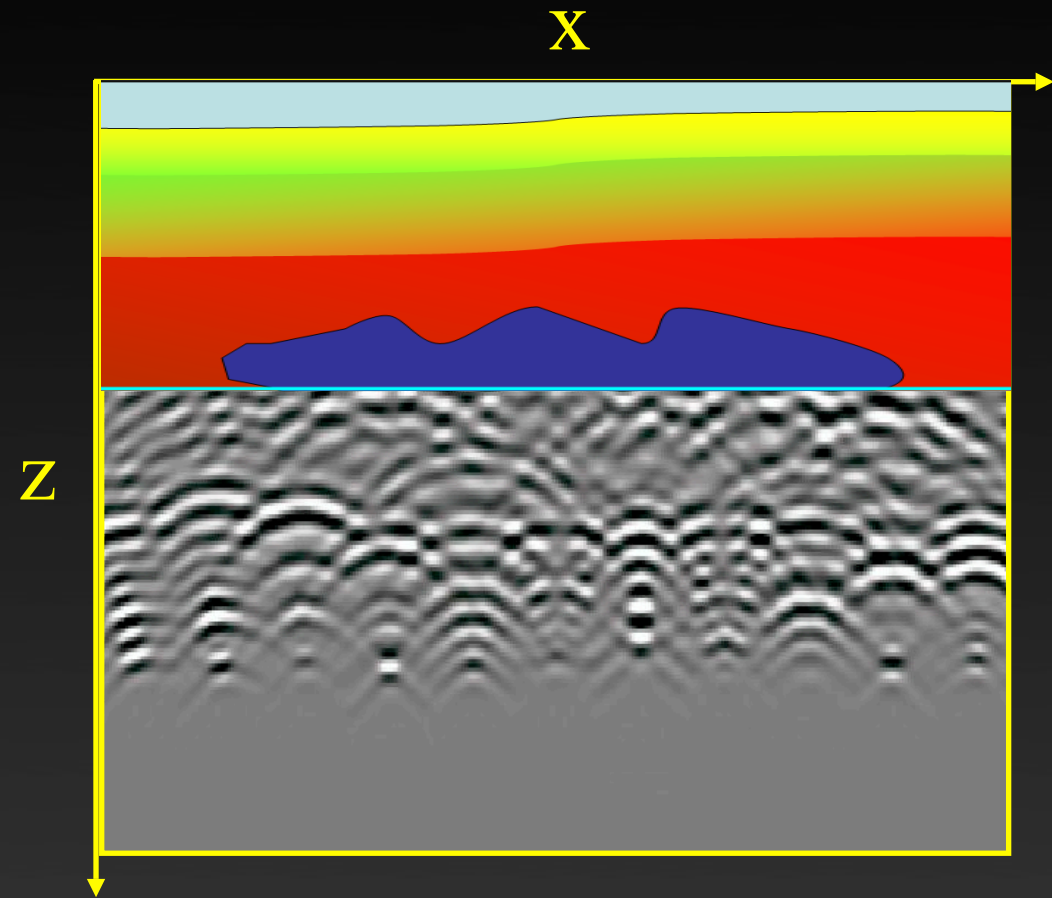
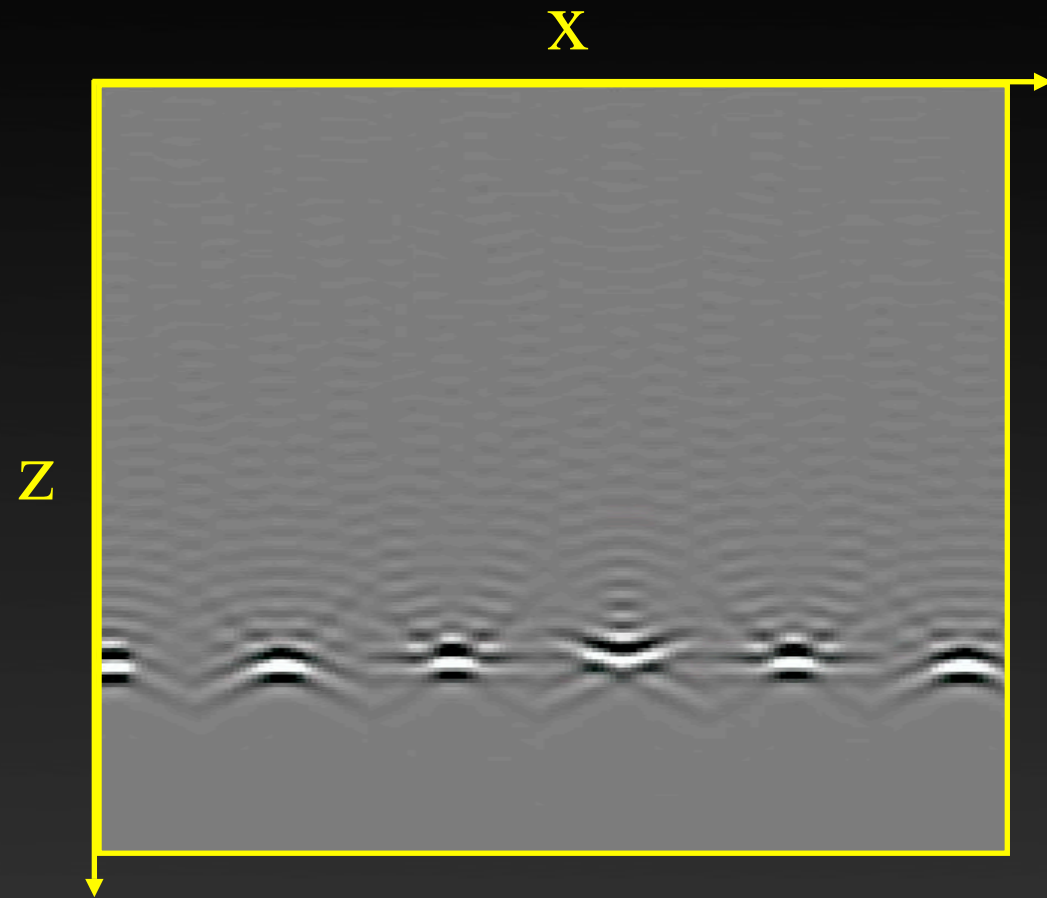
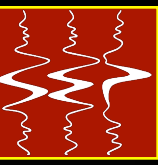
- Generalized-source domain
- Pre-stack exploding reflector model
- **Image-space phase-encoded wavefields**
- MVA in the image-space generalized-source domain
- Conclusions

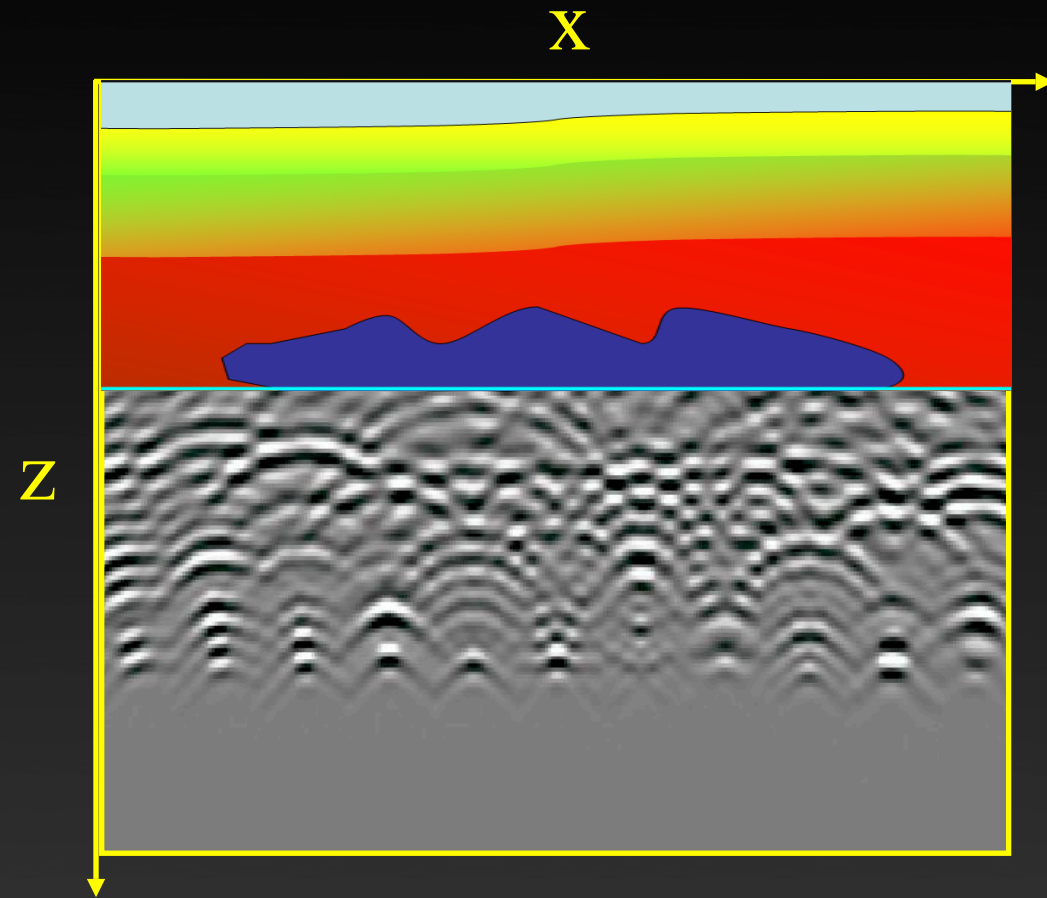
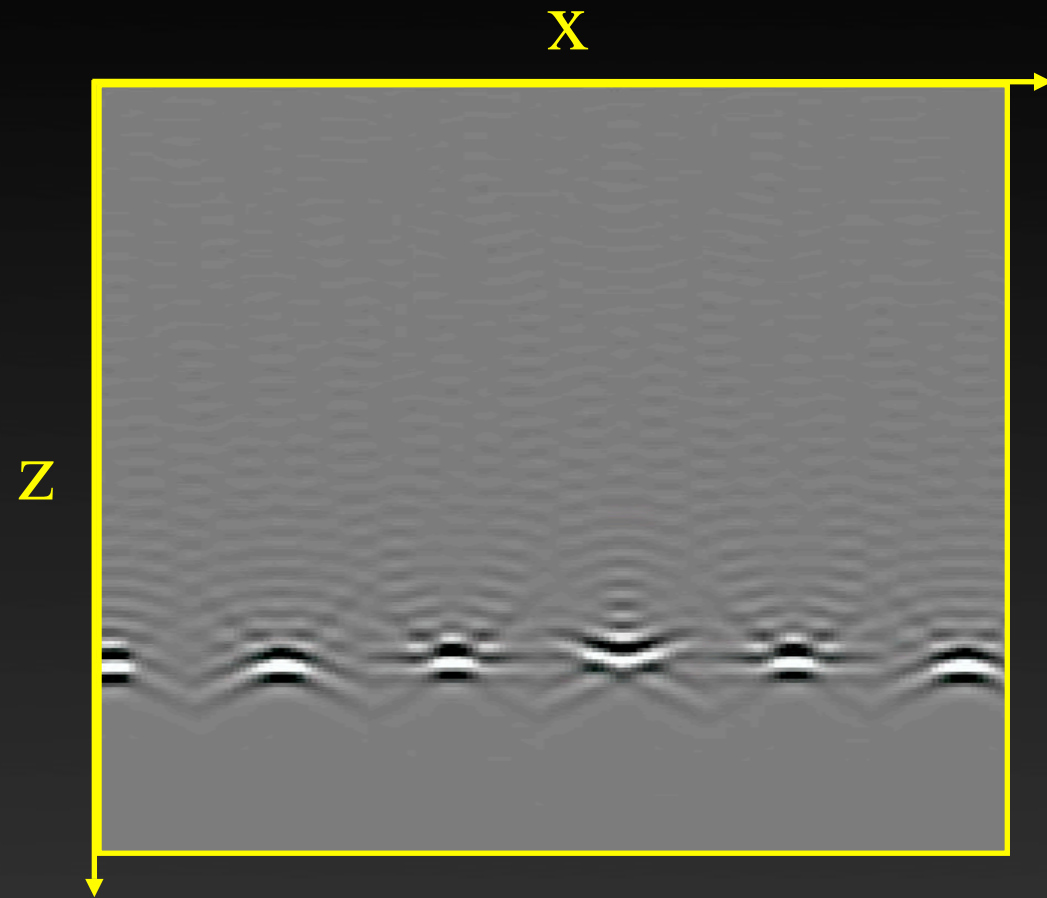
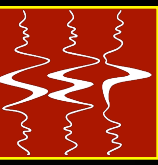


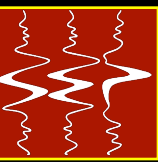
- **Further data reduction by phase encoding the modeling experiments**



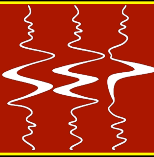








- Generalized-source domain
- Pre-stack exploding reflector model
- Image-space phase-encoded wavefields
- **MVA in the image-space generalized-source domain**
- Conclusions



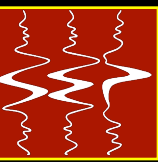
- **Small number of wavefields**



- **Small number of wavefields**
- **Wavefields are initiated from selected reflectors**



- **Small number of wavefields**
- **Wavefields are initiated from selected reflectors**
 - **Naturally incorporates a horizon-based tomography strategy into wave-extrapolation methods**



- **Small number of wavefields**
- **Wavefields are initiated from selected reflectors**
- **Easily solved in a target-oriented way**

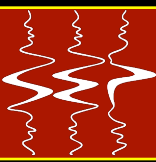


$$J(s) = \frac{1}{2} \left\| \Delta \tilde{I}(s) \right\|_2 = \frac{1}{2} \left\| \tilde{I}(s) - \mathbf{M} \tilde{I}(s) \right\|_2$$

$\tilde{I}(s)$ = current seismic image

\mathbf{M} = focusing operator

$\Delta \tilde{I}(s)$ = perturbed image



$$J(s) = \frac{1}{2} \left\| \Delta \tilde{I}(s) \right\|_2 = \frac{1}{2} \left\| \tilde{I}(s) - \mathbf{M} \tilde{I}(s) \right\|_2$$

$$\text{DSO} : \mathbf{M} = \mathbf{1} - \mathbf{O}$$

$\tilde{I}(s)$ = current seismic image

\mathbf{M} = focusing operator

$\Delta \tilde{I}(s)$ = perturbed image

\mathbf{O} = DSO operator



$$J(s) = \frac{1}{2} \left\| \Delta \tilde{I}(s) \right\|_2 = \frac{1}{2} \left\| \tilde{I}(s) - \mathbf{M} \tilde{I}(s) \right\|_2$$

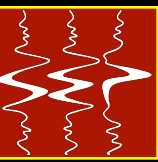
$$\nabla J = \left(\frac{\partial \tilde{I}}{\partial s} \right)' \mathbf{O}' \mathbf{O} \tilde{I} \Big|_{s=s_0}$$

$\tilde{I}(s)$ = current seismic image

\mathbf{M} = focusing operator

$\Delta \tilde{I}(s)$ = perturbed image

s_0 = current velocity



- **North Sea 3D dataset**
 - 12 x 4 km

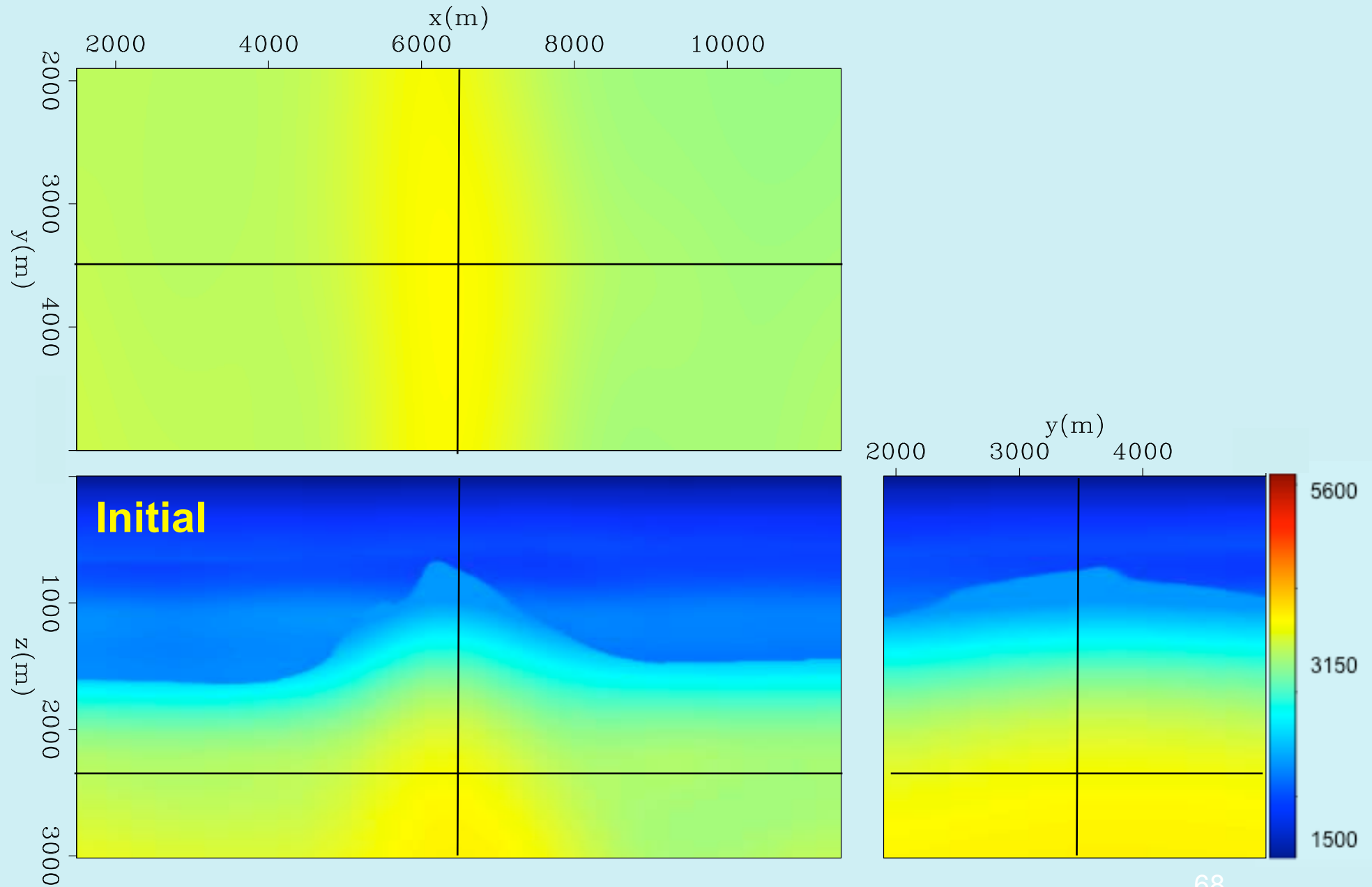


- **North Sea 3D dataset**
 - 12 x 4 km
- **AMO data with 3600 m maximum offset**
 - CAM images as the initial conditions
 - 20 ISPEW
 - Target region: 600 - 3200 m depth range

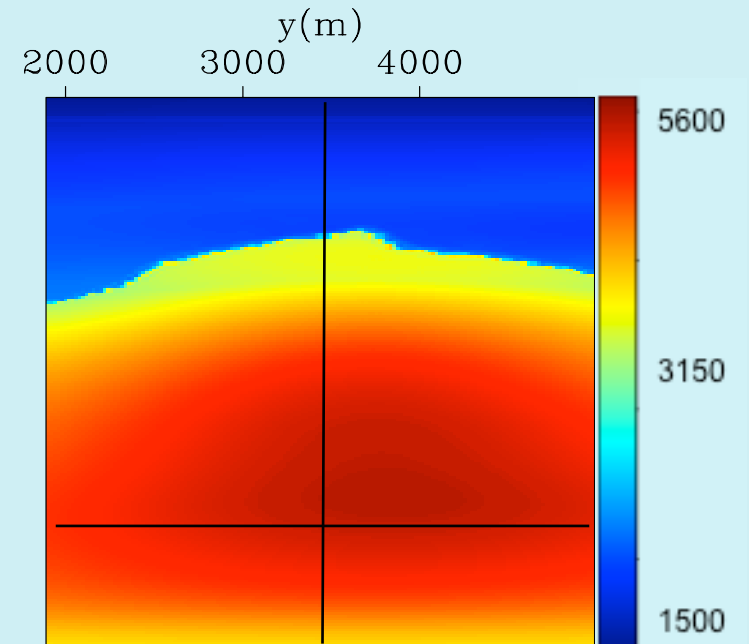
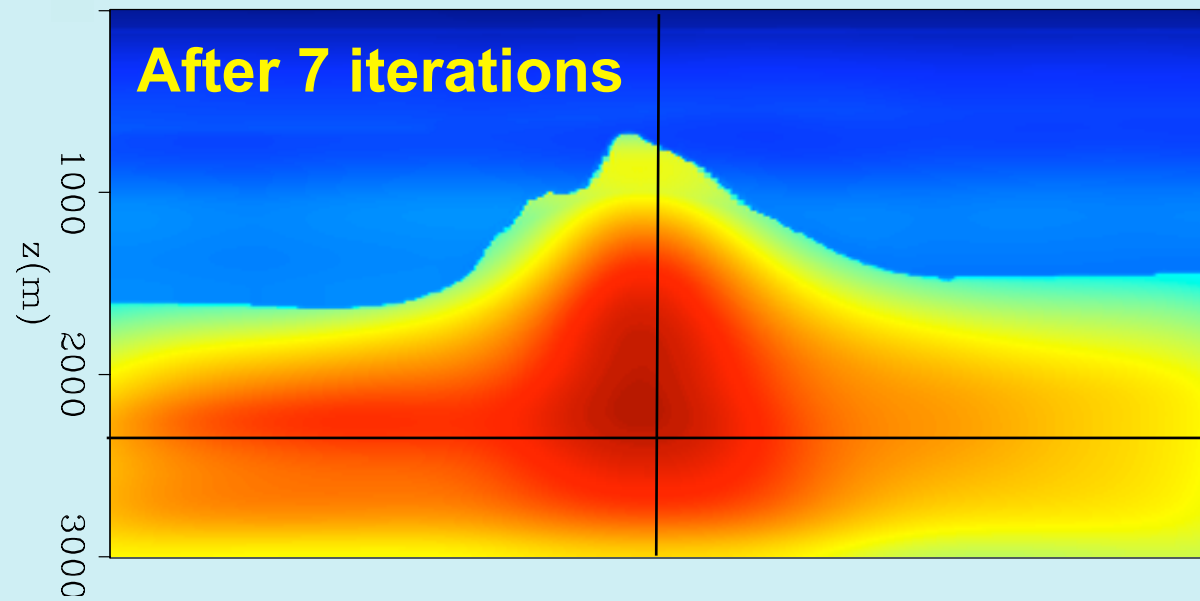
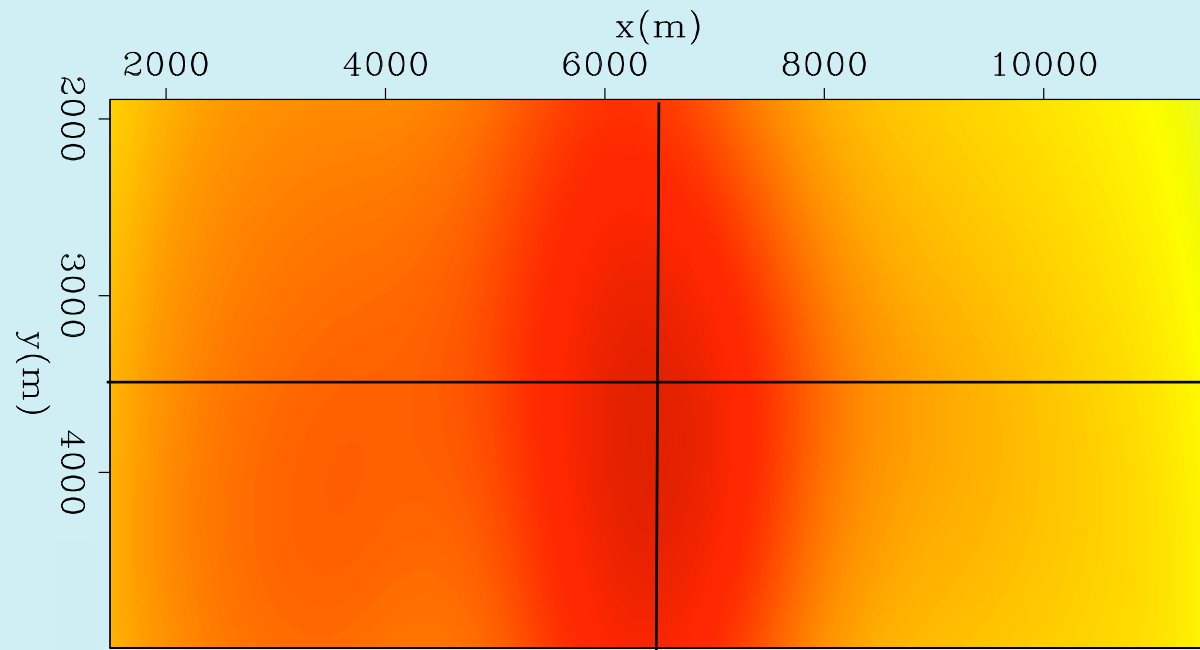


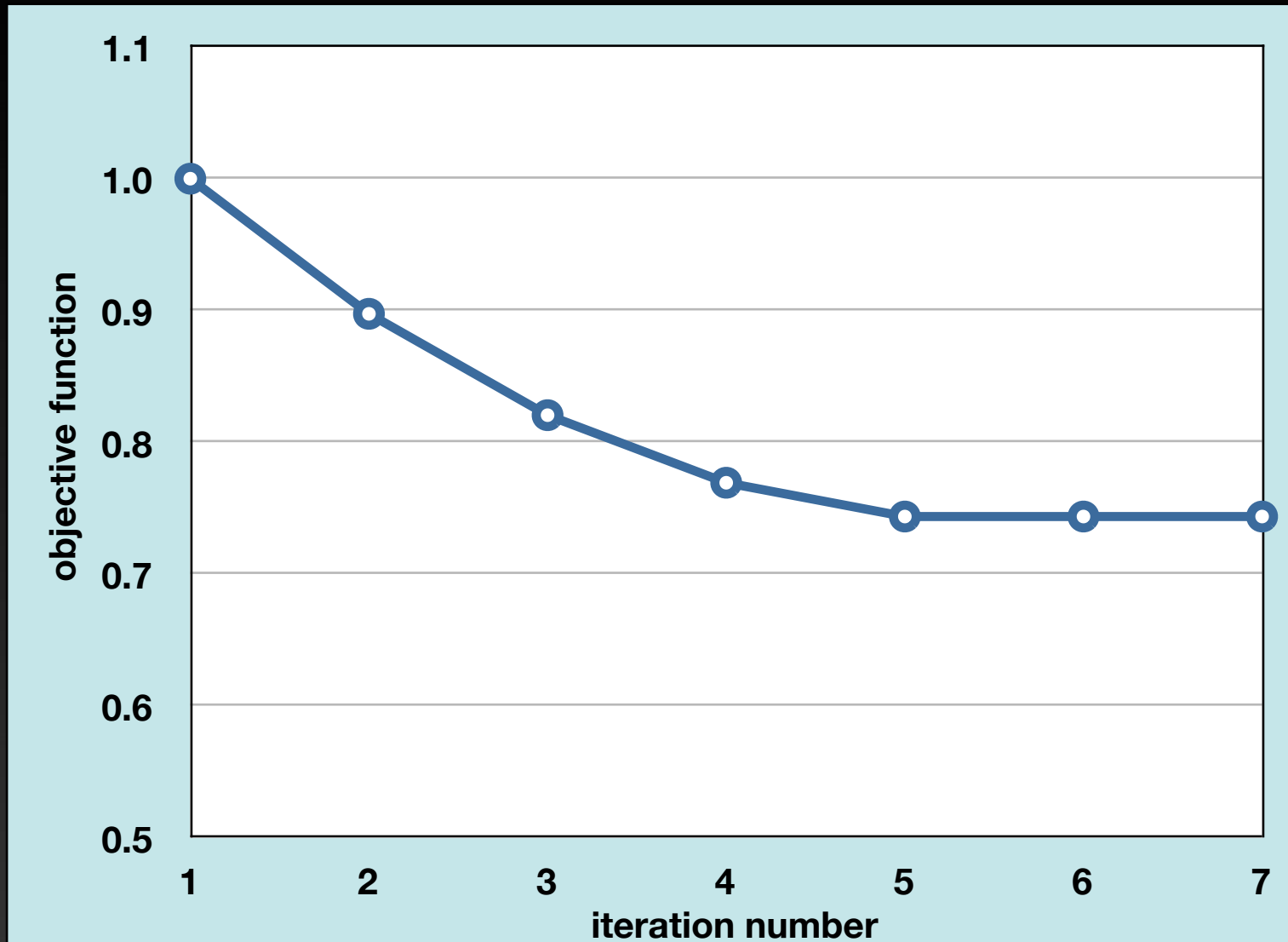
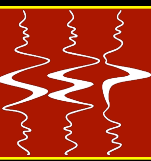
- **North Sea 3D dataset**
 - 12 x 4 km
- **AMO data with 3600 m maximum offset**
 - CAM images as the initial conditions
 - 20 ISPEW
 - Target region: 600 - 3200 m depth range
- **CEES: 20 Dual Nehalem 5520, 24Gb RAM**
 - Perturbed image: 20 min
 - Gradient: 40 min

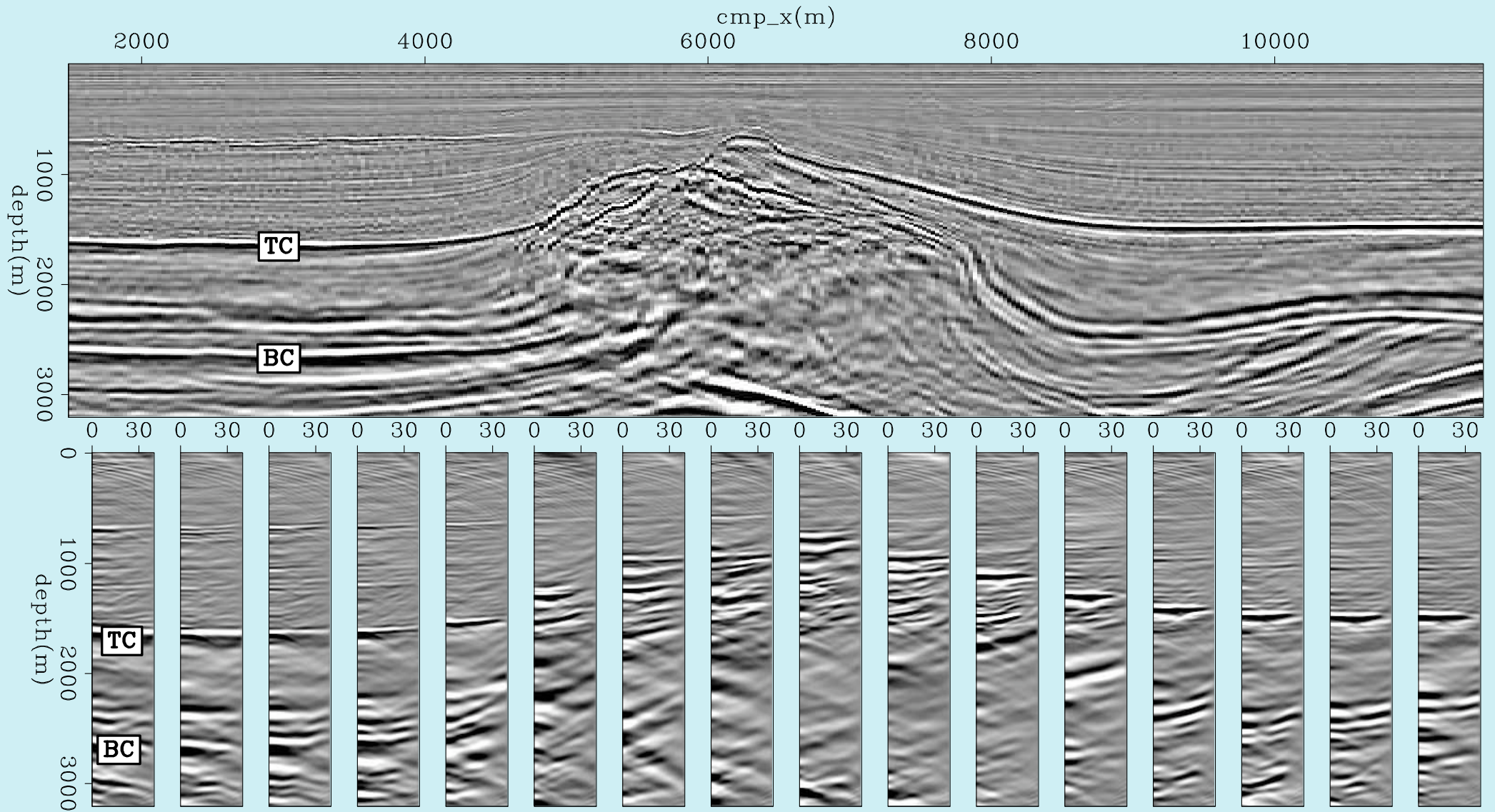
MVA: ISPEW



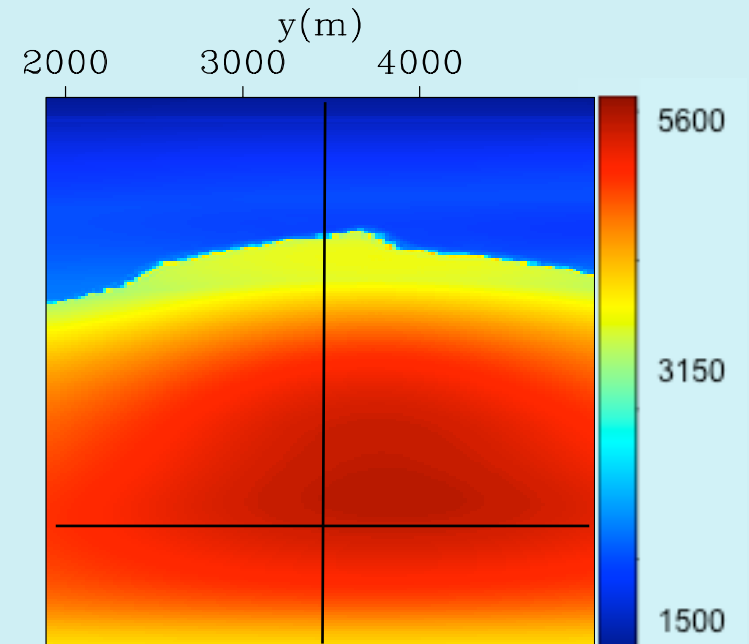
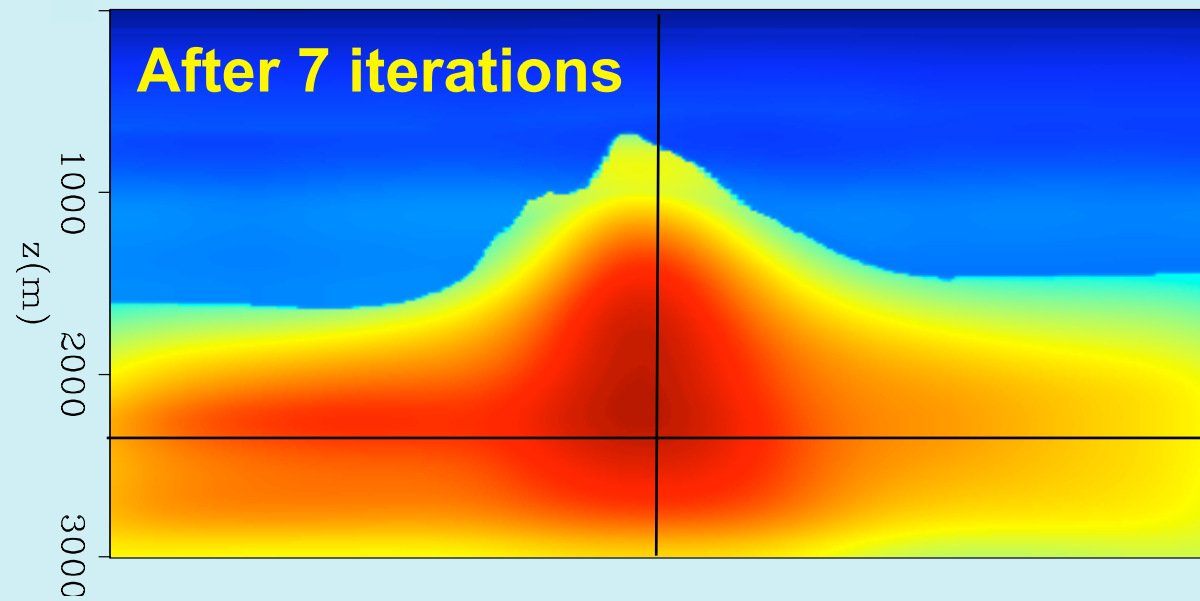
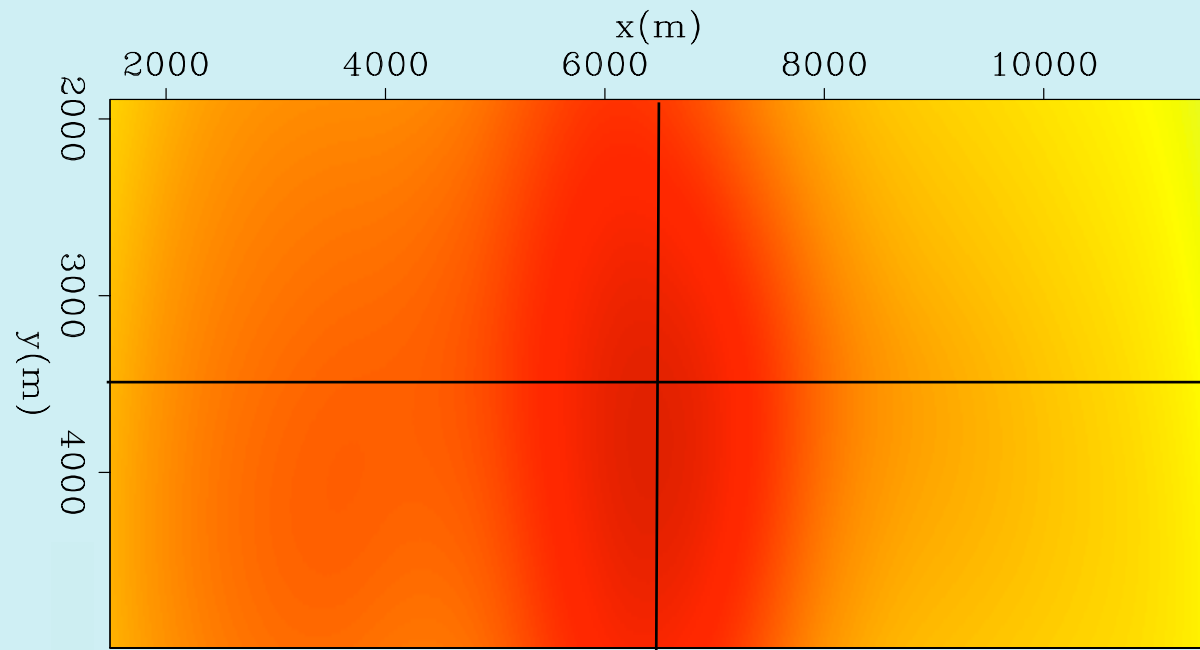
MVA: ISPEW



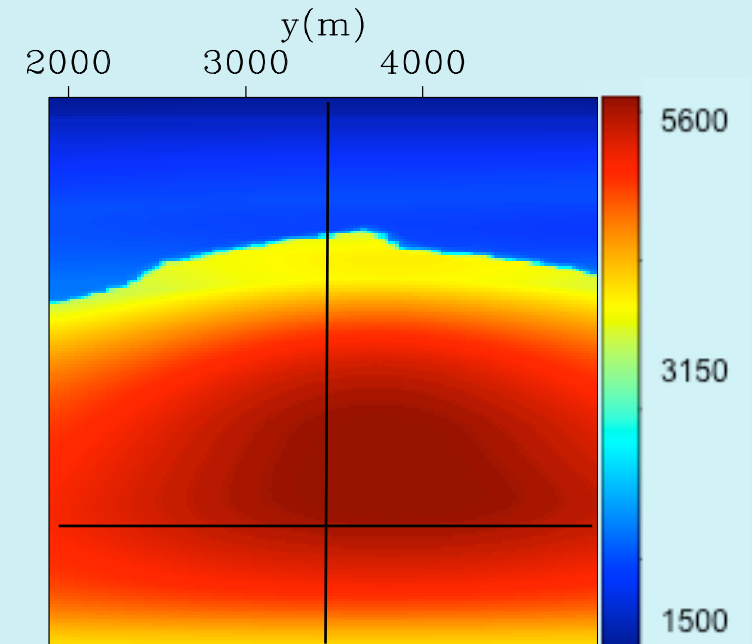
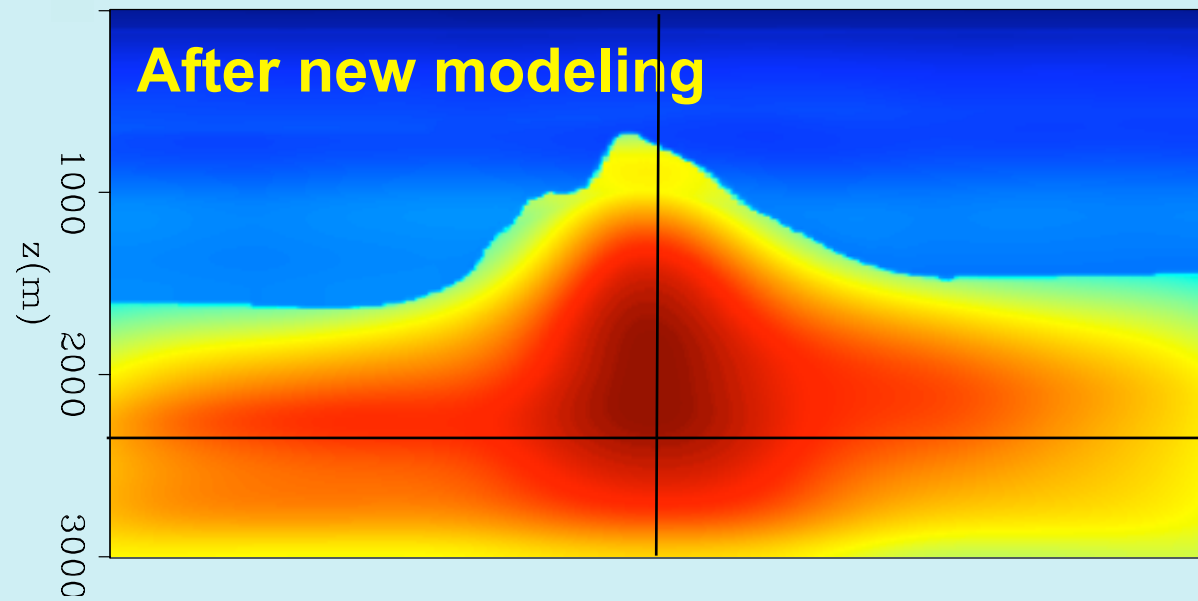
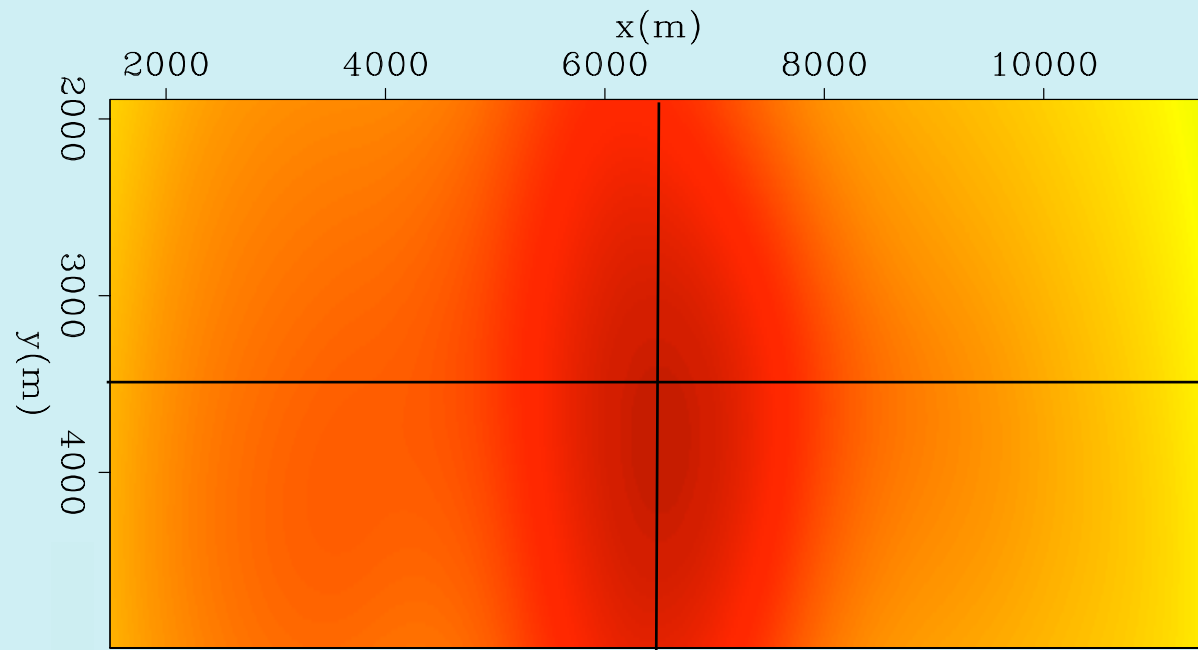




MVA: ISPEW

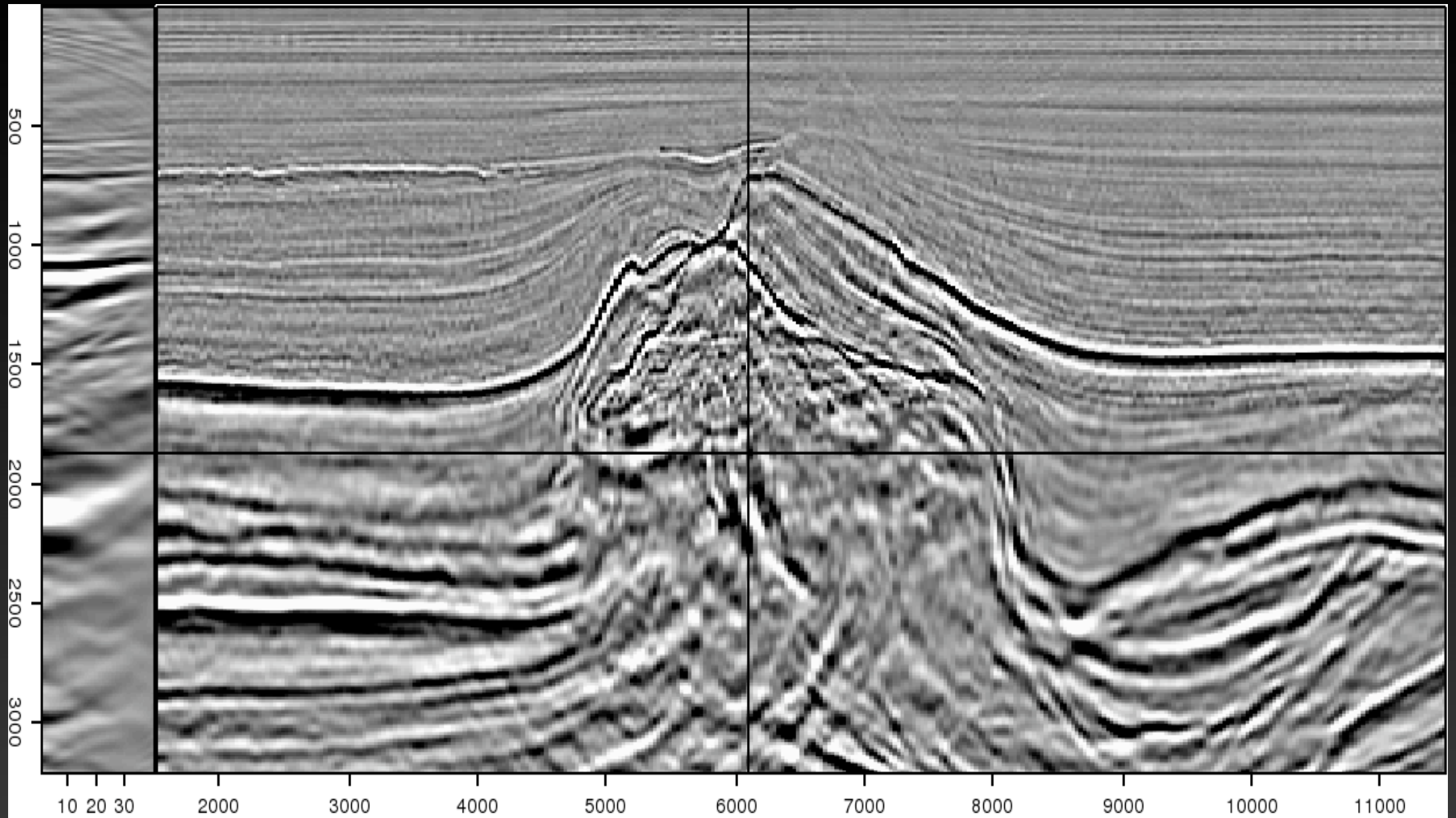
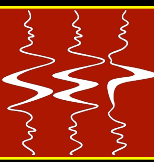


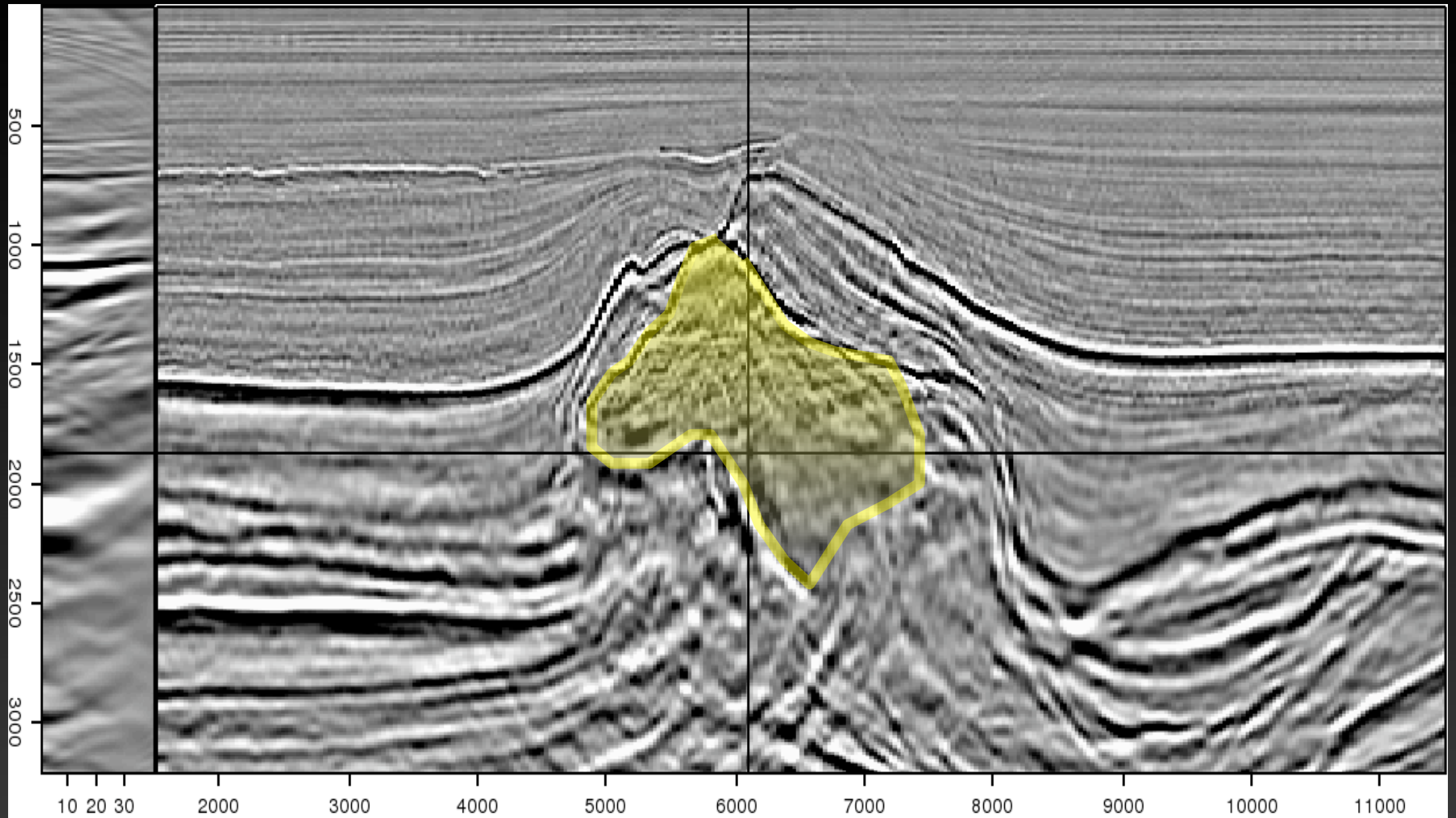
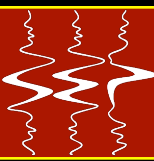
MVA: ISPEW

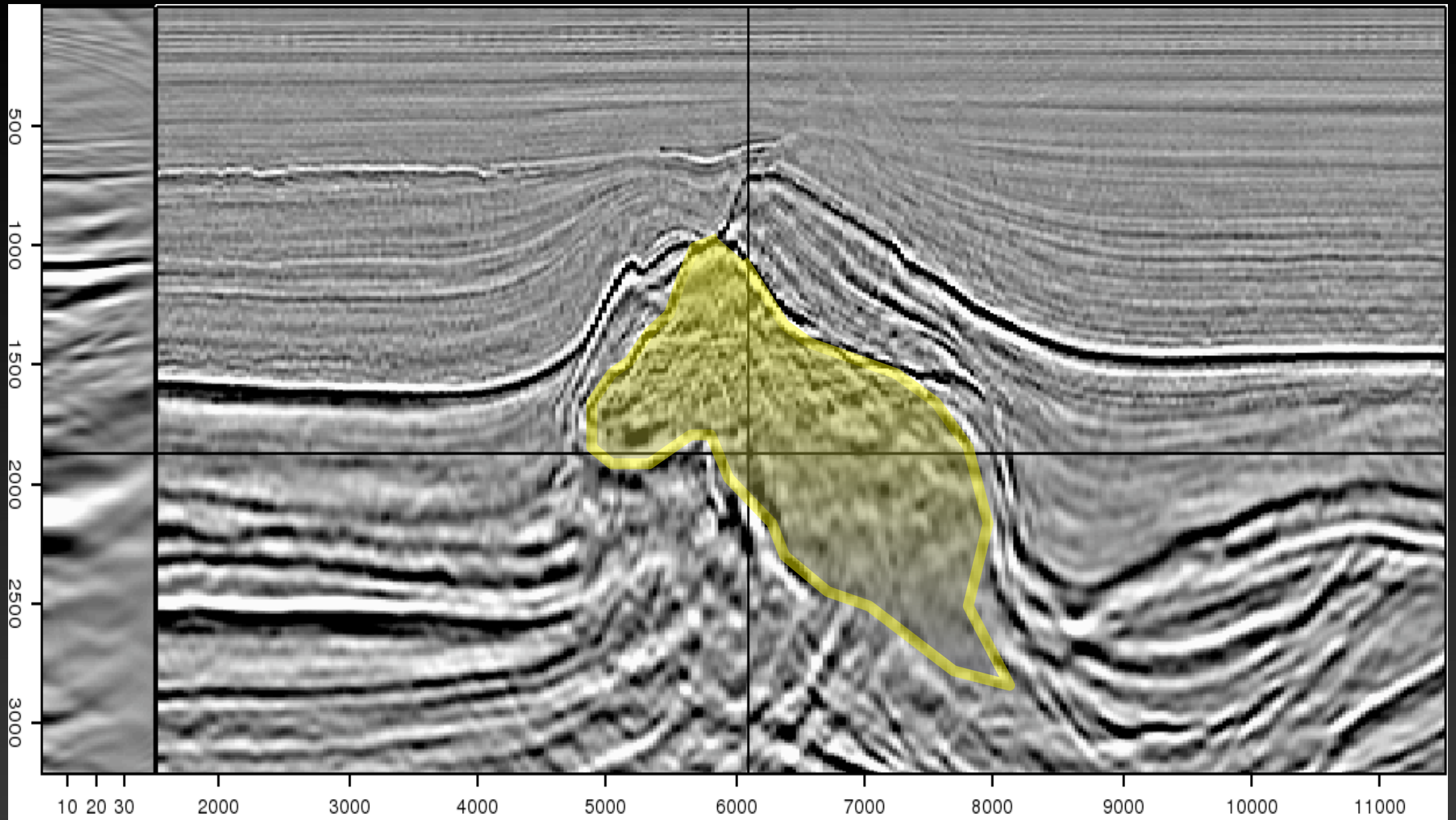
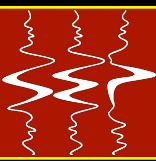




- **Salt flooding**
- **Interpretation of the base of salt**
- **Sub-salt velocity definition**

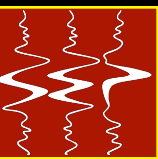








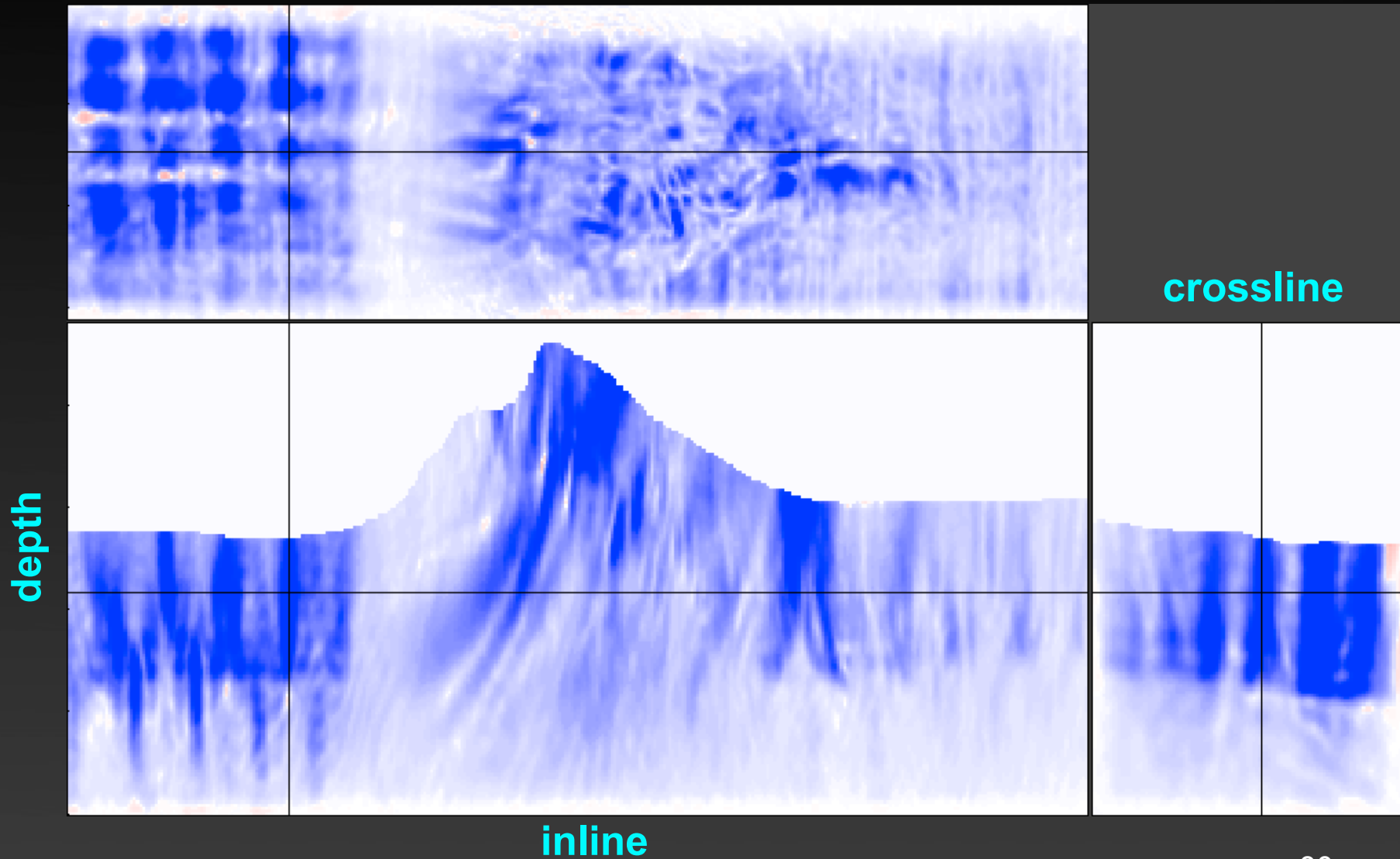
- **Image-space generalized wavefields accelerate MVA**
 - **data size**
 - **target-oriented**

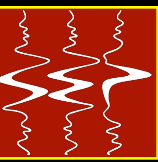


- **Image-space generalized wavefields accelerate MVA**
- **Image-space generalized wavefields naturally incorporate a horizon-based strategy**
 - **A grid-based strategy can be potentially used**



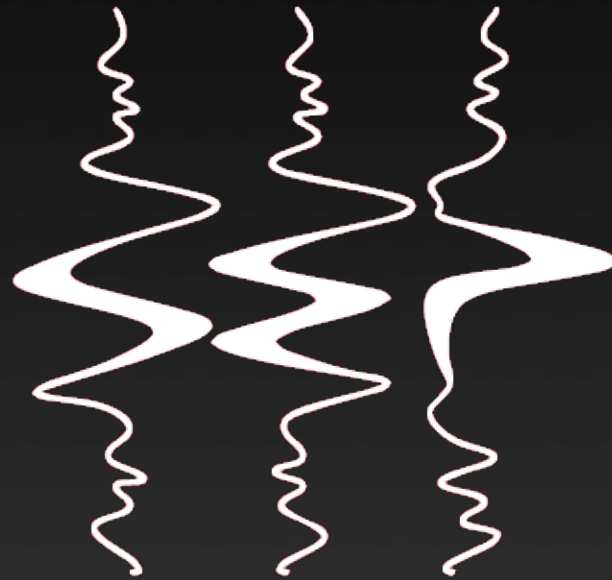
- **Grid-tomography strategy**





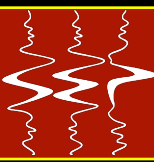
- Pierre Jousselin, from Total, for discussing about velocity model building in the North Sea
- Bob Clapp for continuously improving SEP's visualization/interpretation capability
- Dennis Michael, from CEES, for his continuous support
- TotalFinaElf for providing the North Sea dataset

Thanks



STANFORD
EXPLORATION PROJECT

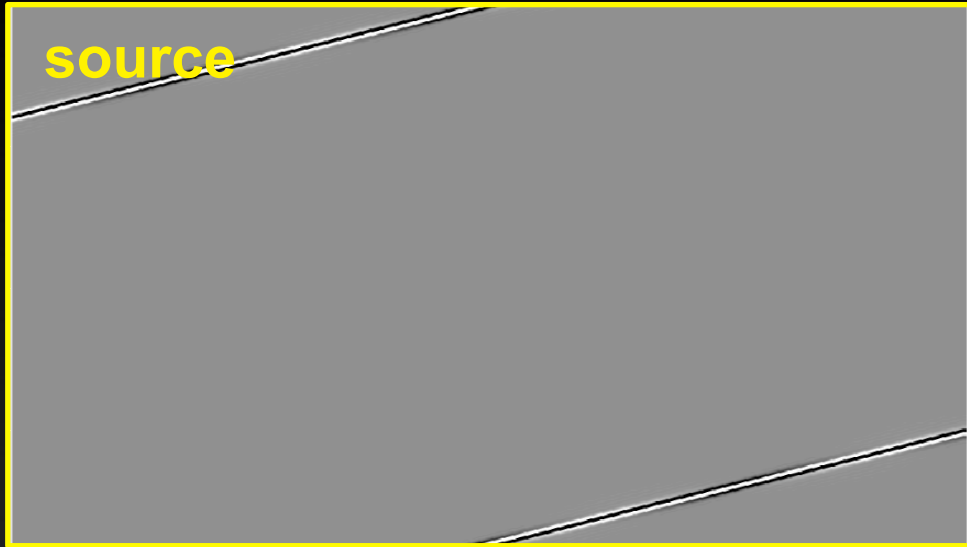
Data-space: plane waves



distance

source

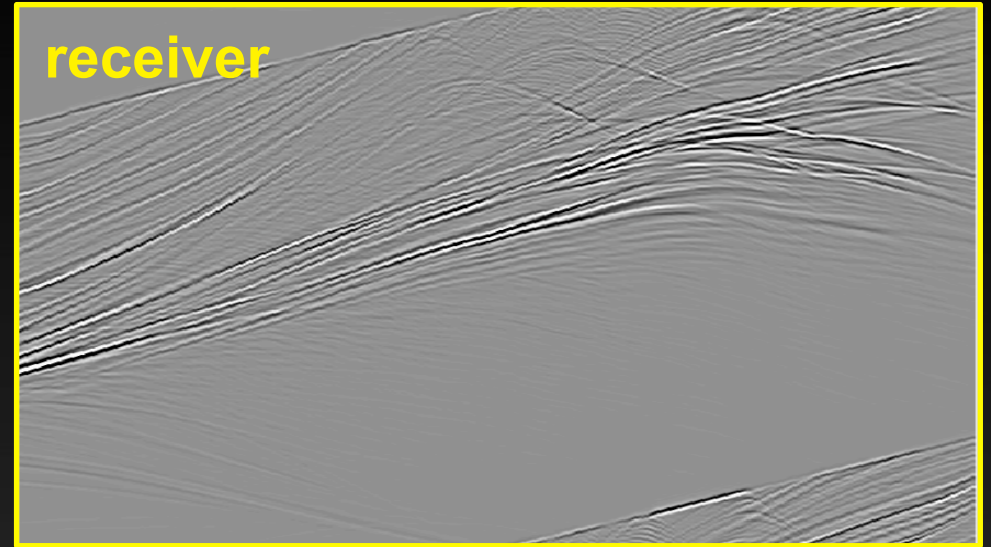
time



distance

receiver

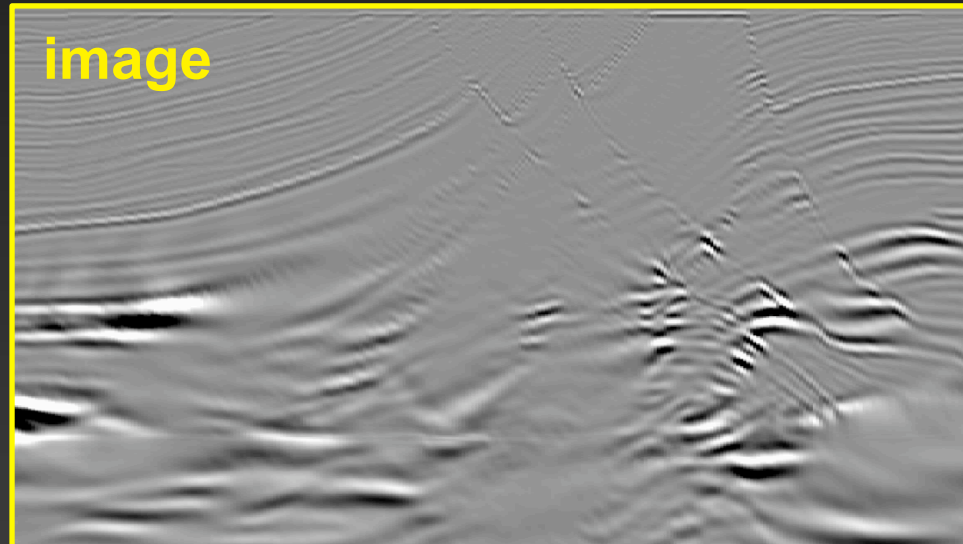
time



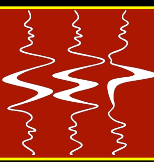
distance

image

depth



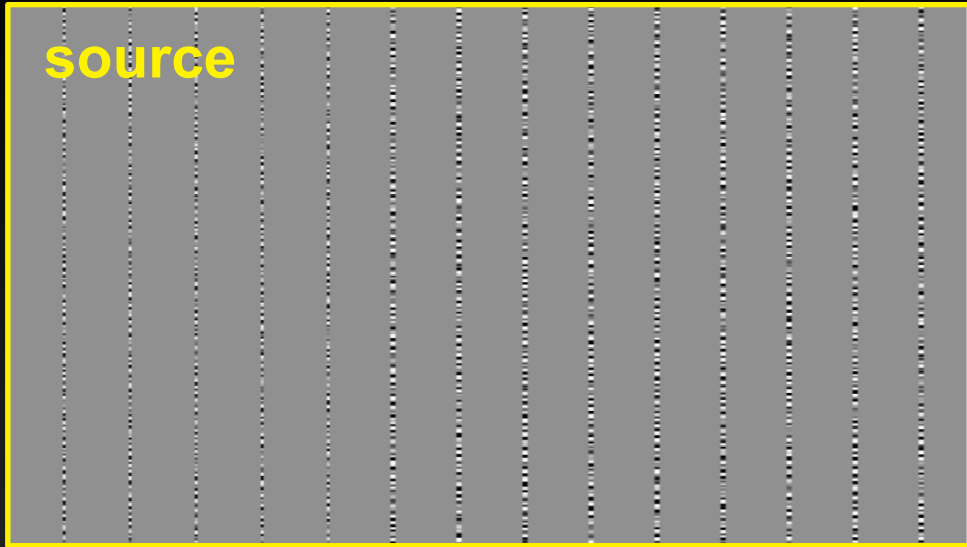
Data-space: random phases



distance

source

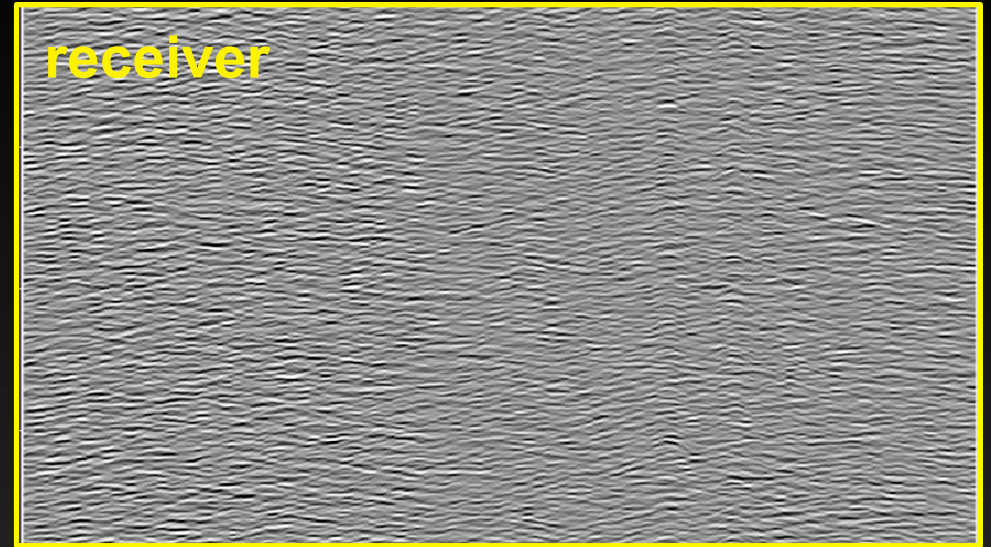
time



distance

receiver

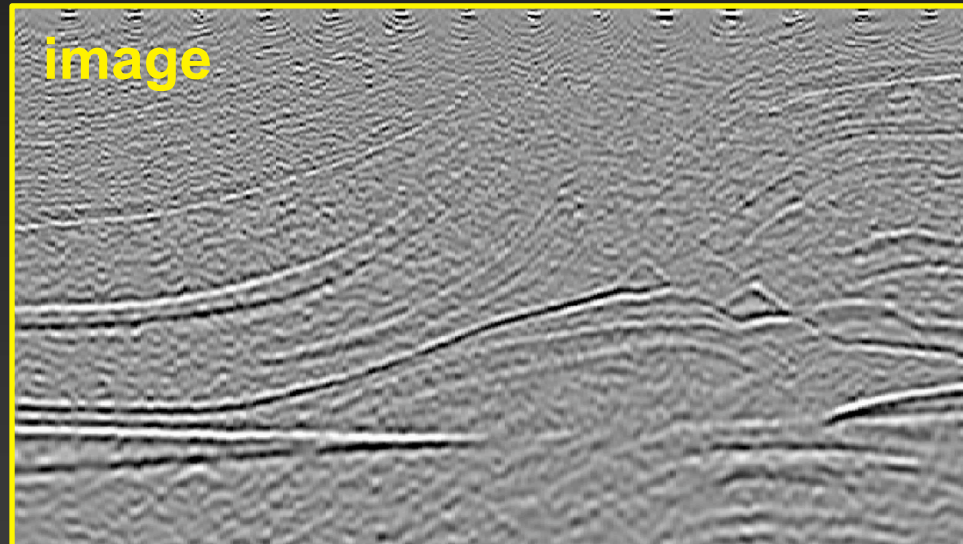
time



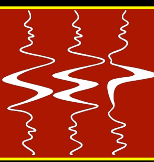
distance

image

depth



Data-space: controlled illumination



distance

source

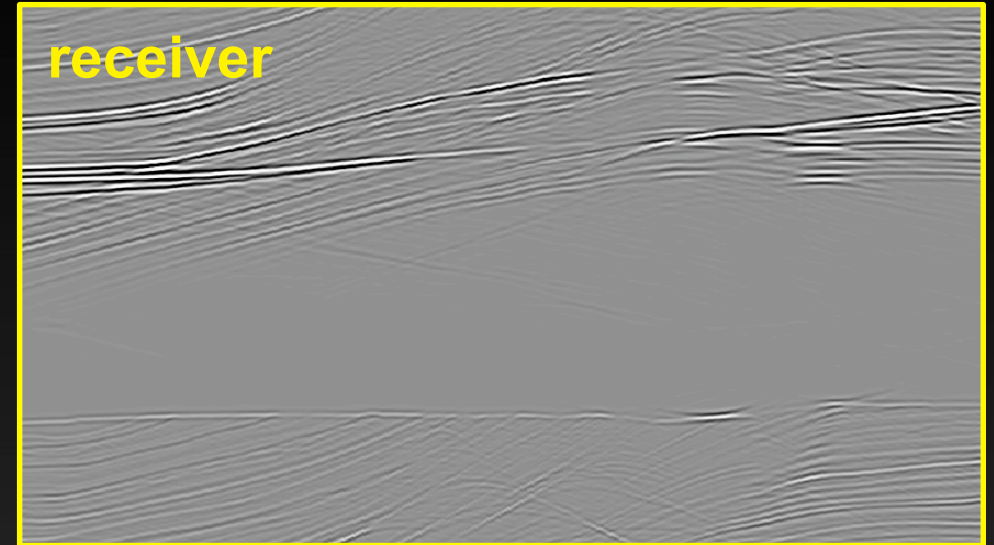
time



distance

receiver

time



distance

image

depth

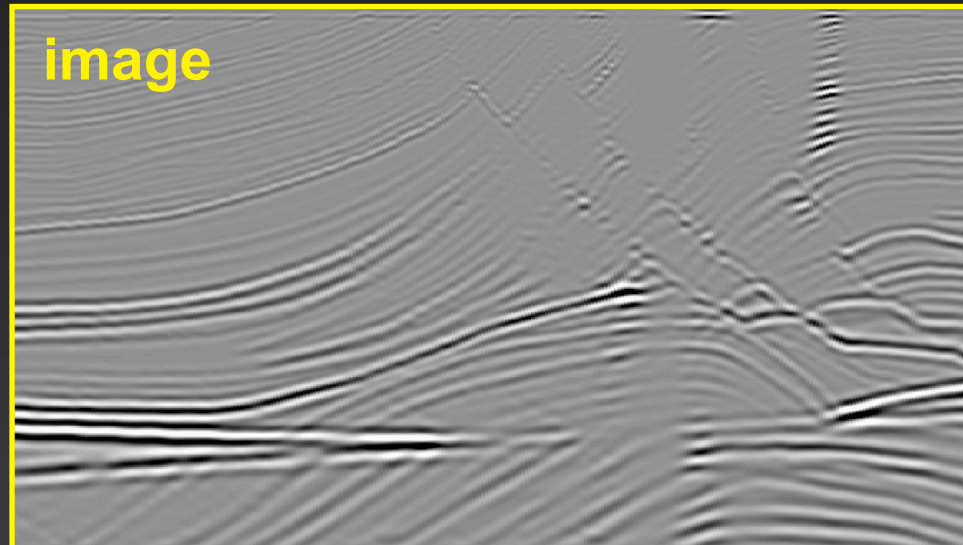


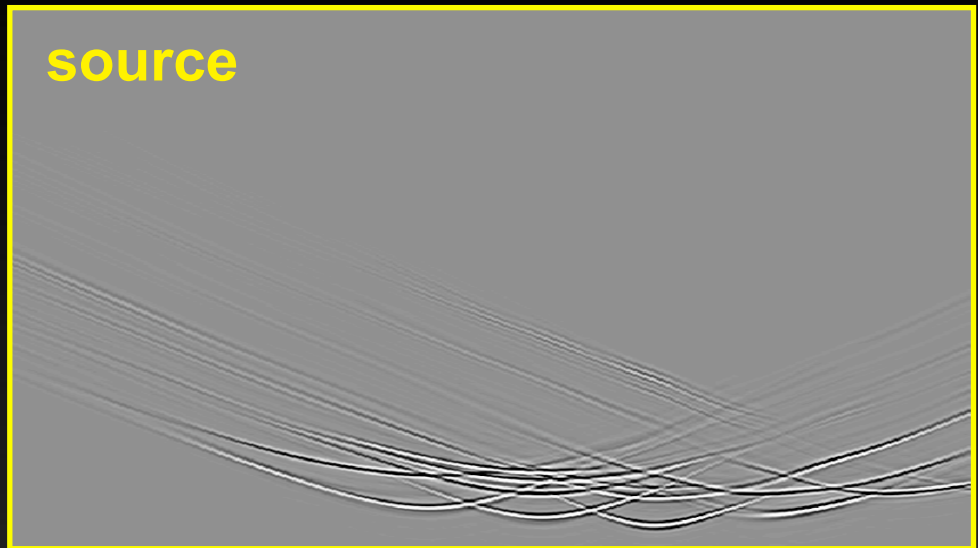
Image-space: prestack-exploding reflector



distance

source

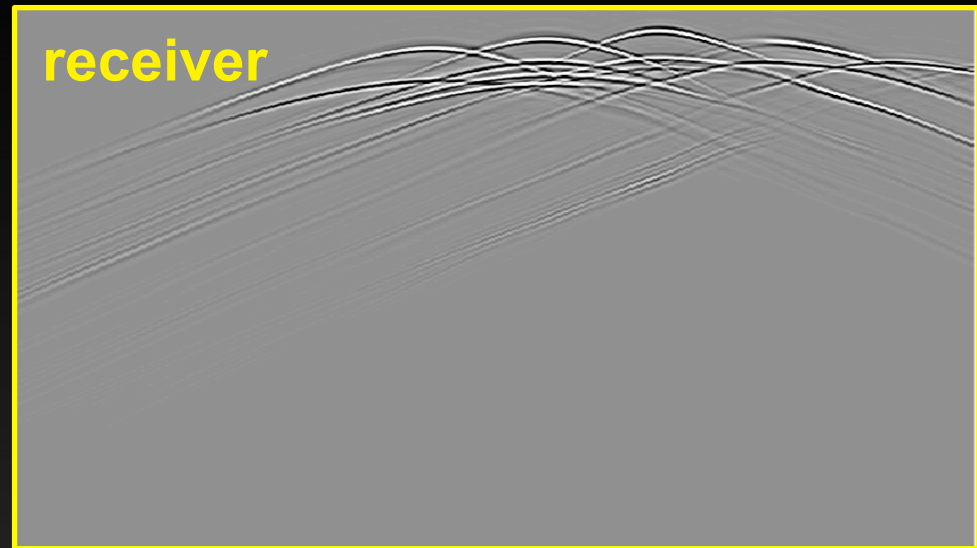
time



distance

receiver

time



distance

image

depth

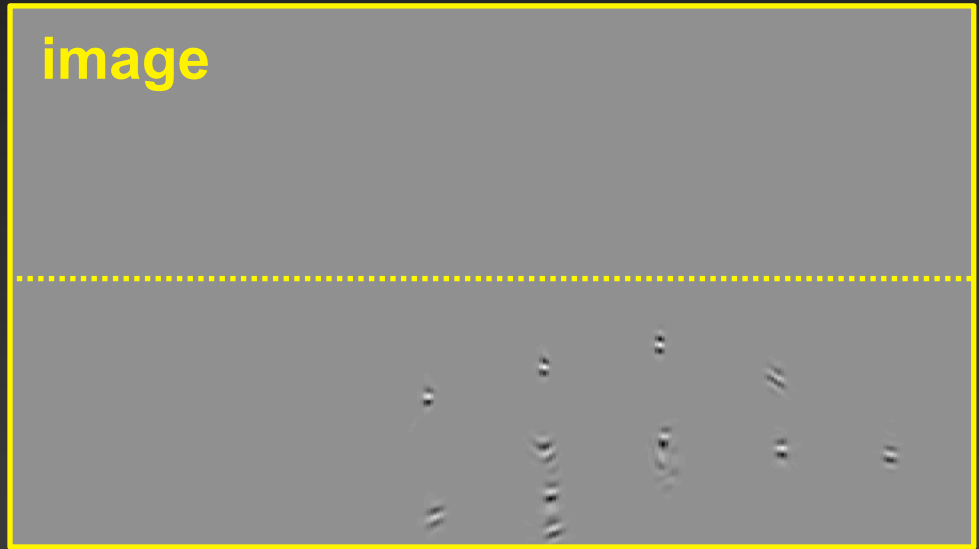
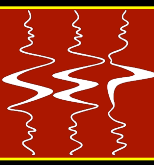


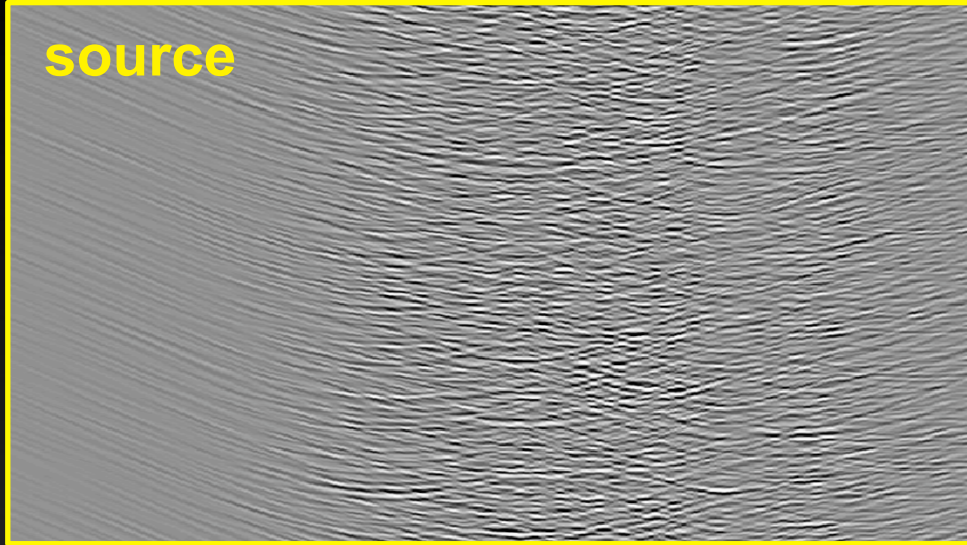
Image-space: random phases (ISPEW)



distance

source

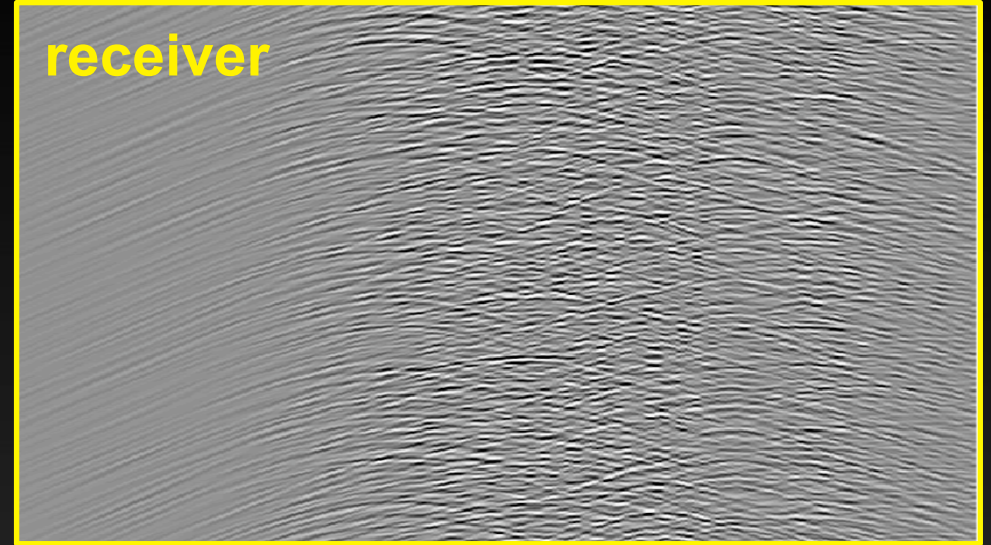
time



distance

receiver

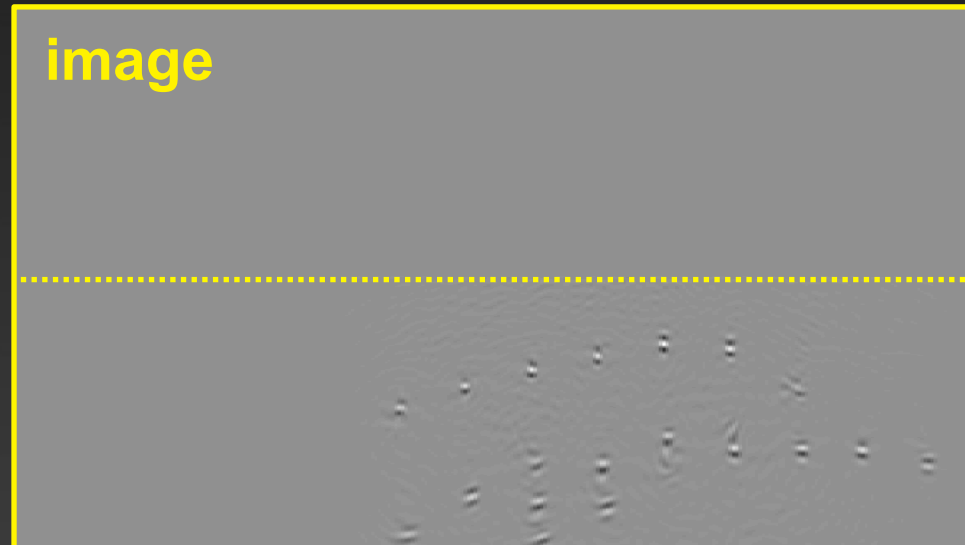
time

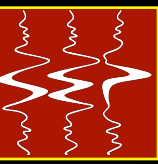


distance

image

depth





Source wavefield

$$\begin{cases} \left(\frac{\partial}{\partial z} - i\Lambda \right) \tilde{P}_d(\mathbf{x}, \mathbf{r}_m, \omega) & = \tilde{I}_d(\mathbf{x}, \mathbf{h}, \mathbf{r}_m, \omega) \\ \tilde{P}_d(x, y, z = z_{\max}, \mathbf{r}_m, \omega) & = 0 \end{cases}$$

Receiver wavefield

$$\begin{cases} \left(\frac{\partial}{\partial z} + i\Lambda \right) \tilde{P}_u(\mathbf{x}, \mathbf{r}_m, \omega) & = \tilde{I}_u(\mathbf{x}, \mathbf{h}, \mathbf{r}_m, \omega) \\ \tilde{P}_u(x, y, z = z_{\max}, \mathbf{r}_m, \omega) & = 0 \end{cases}$$

Λ = SSR operator

\tilde{P}_d = phase encoded source wavefield

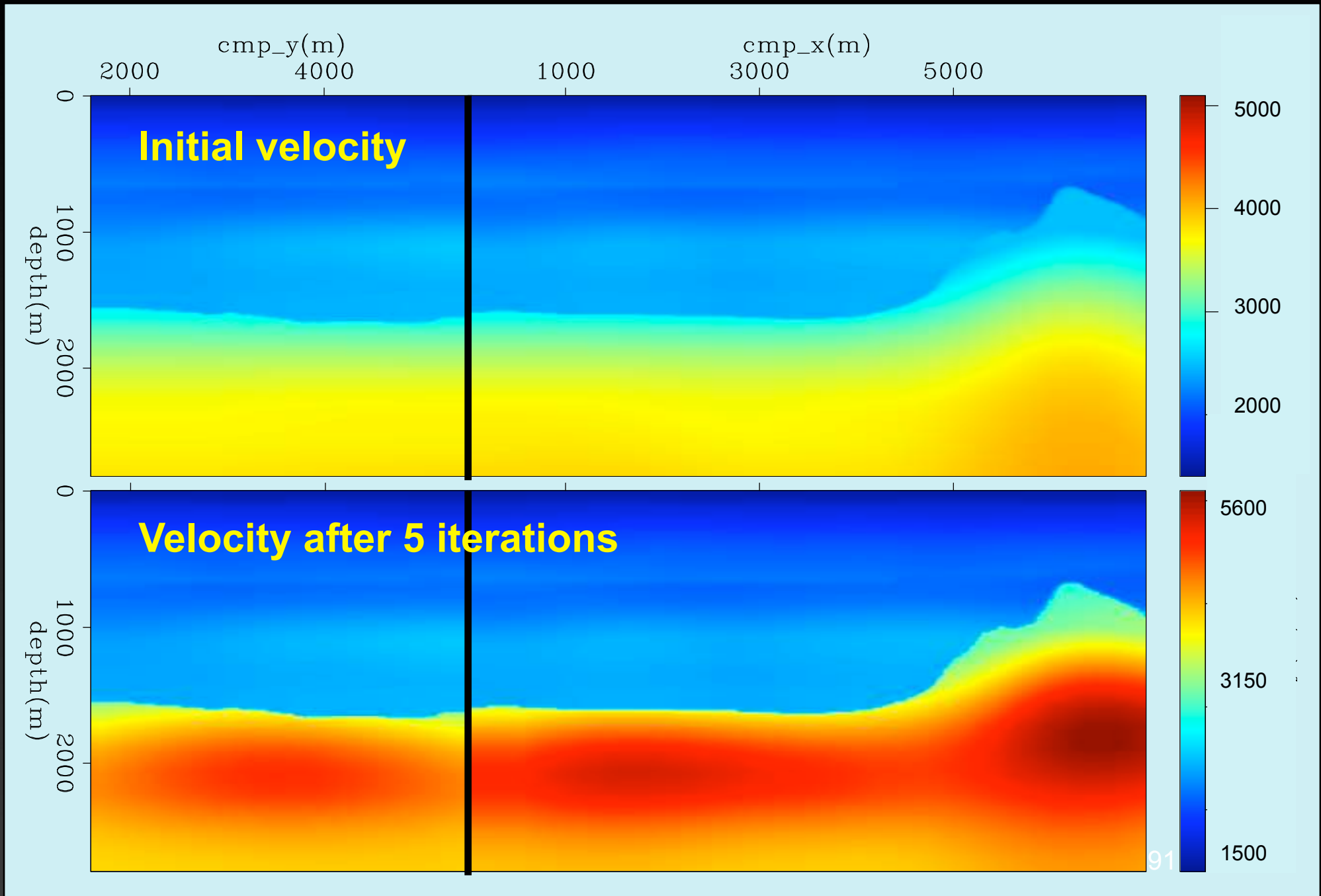
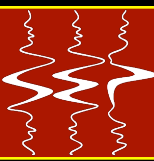
\tilde{I}_d = source wavefield initial condition

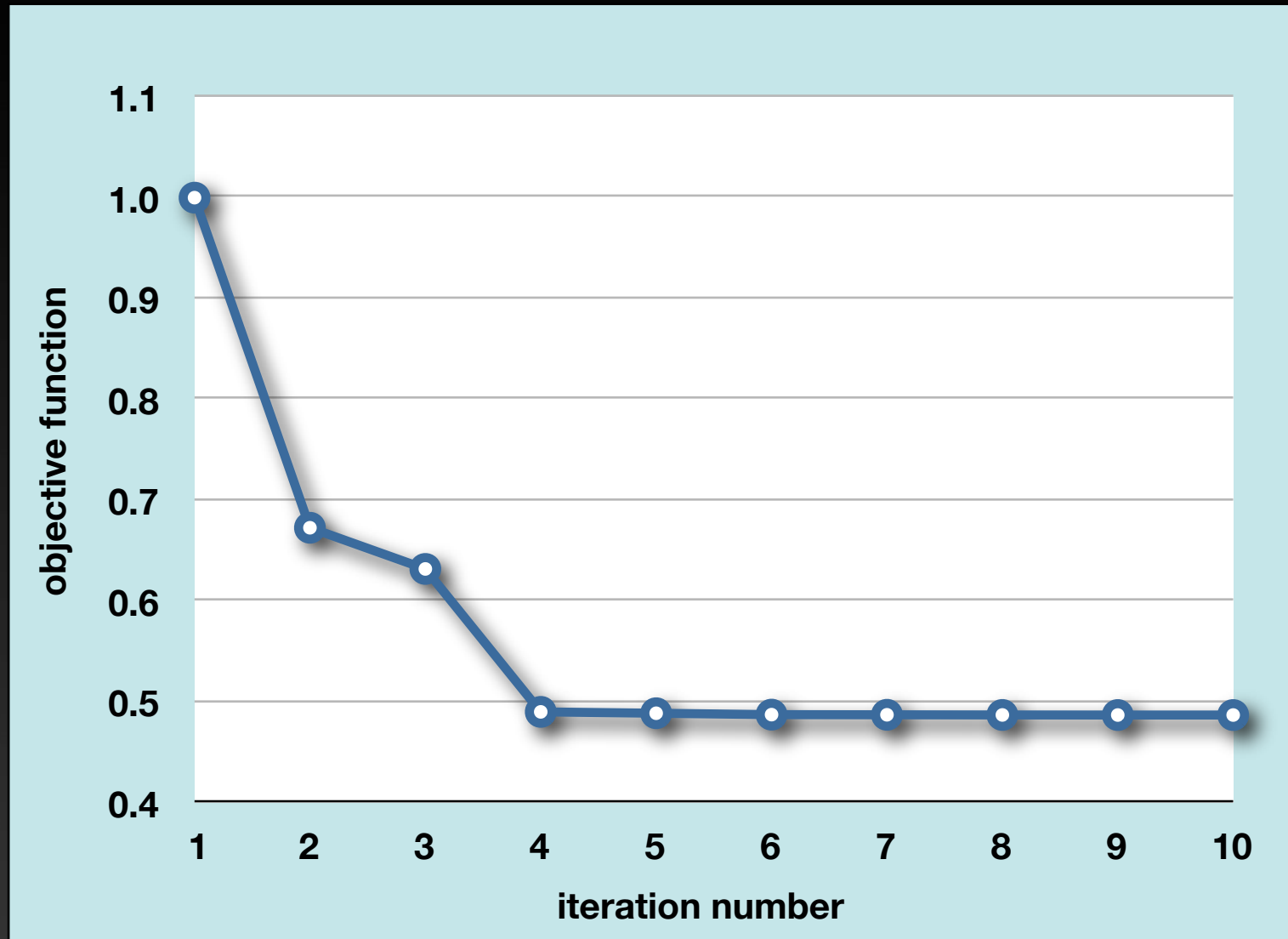
\mathbf{r}_m = index of random realizations

\tilde{P}_u = phase encoded receiver wavefield

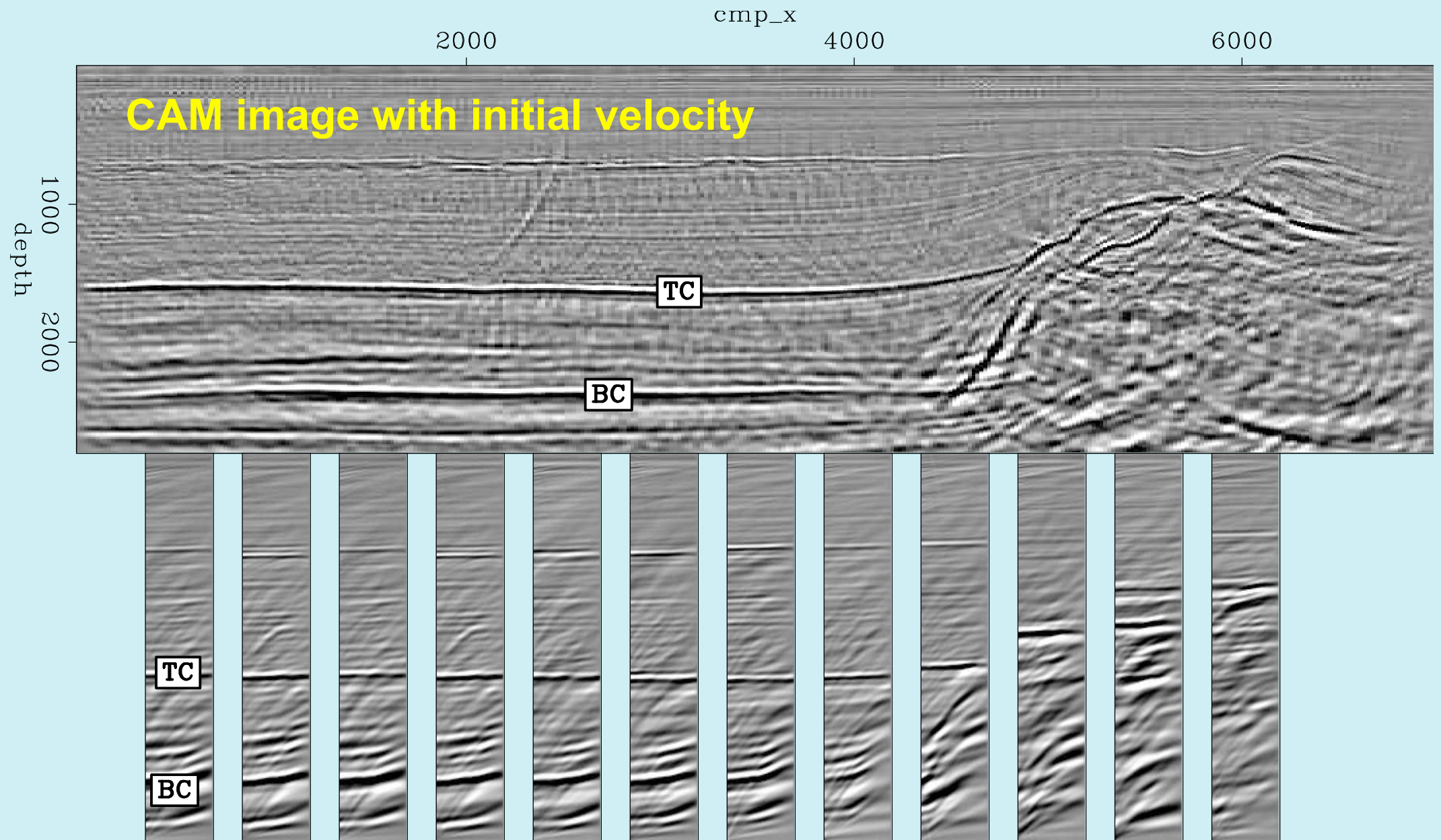
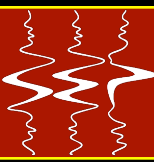
\tilde{I}_u = receiver wavefield initial condition

MVA: PERM wavefields

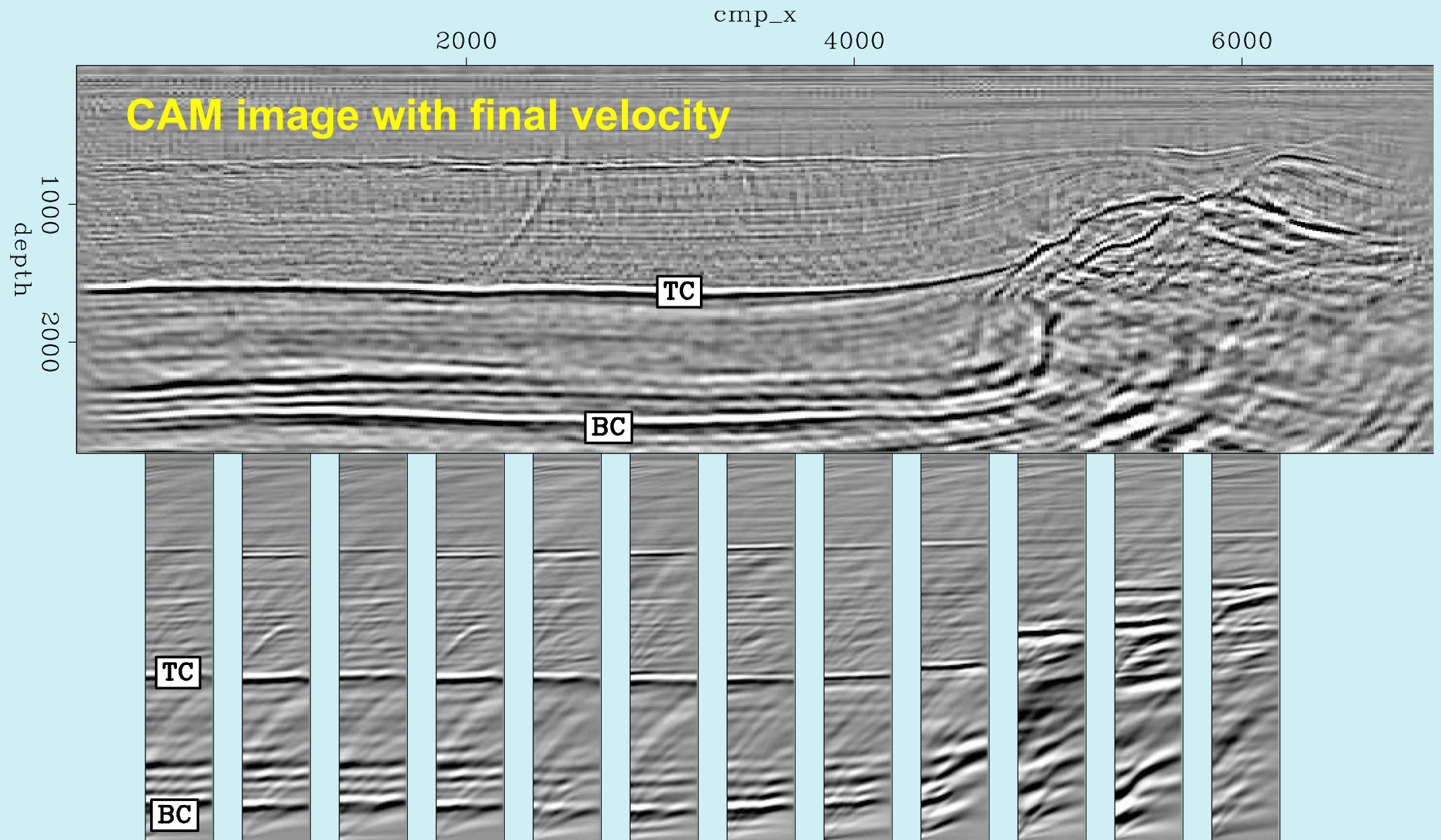
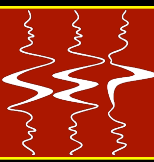




MVA: PERM wavefields



MVA: PERM wavefields



MVA: PERM wavefields

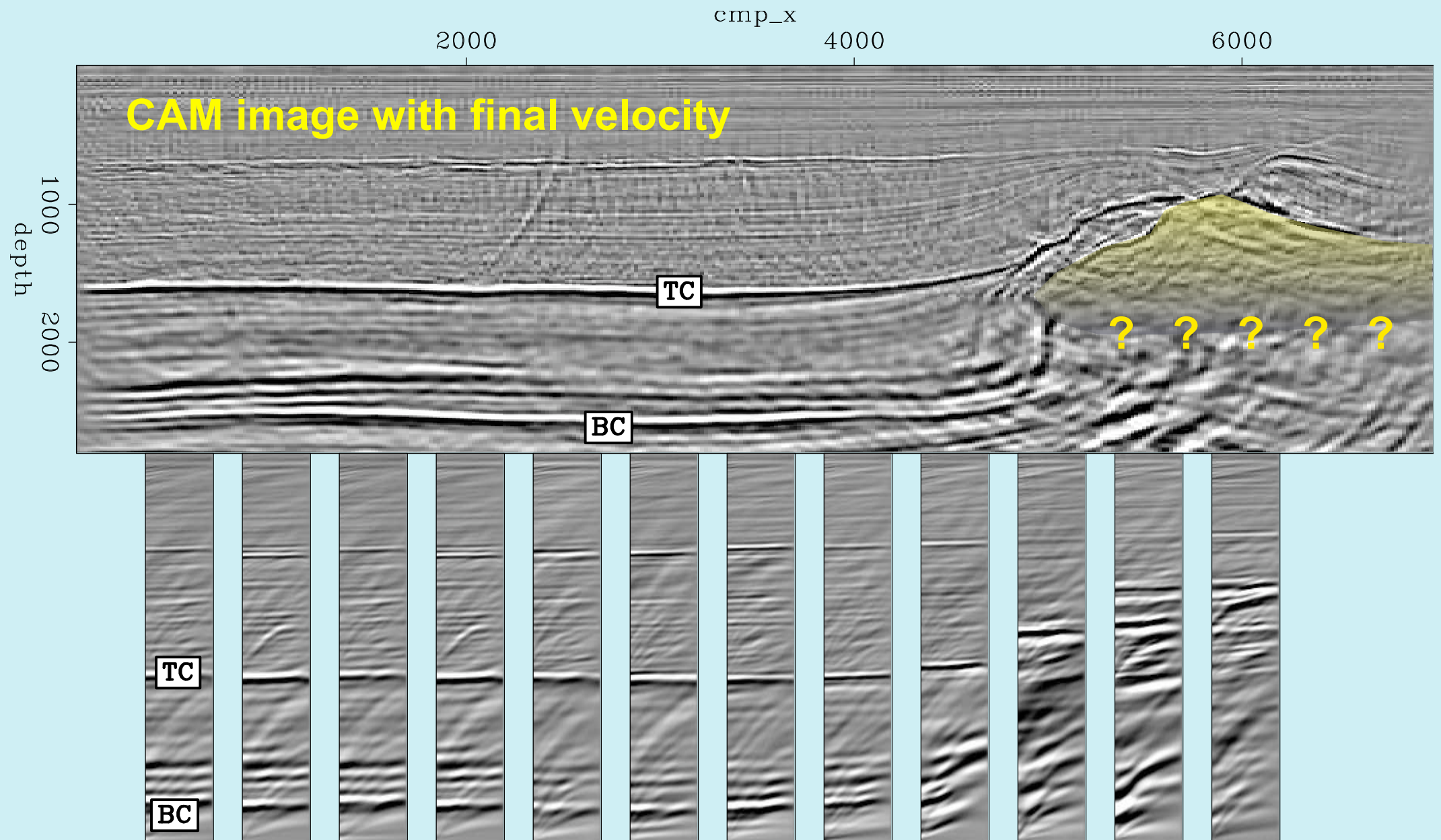


Image-space phase-encoded wavefields

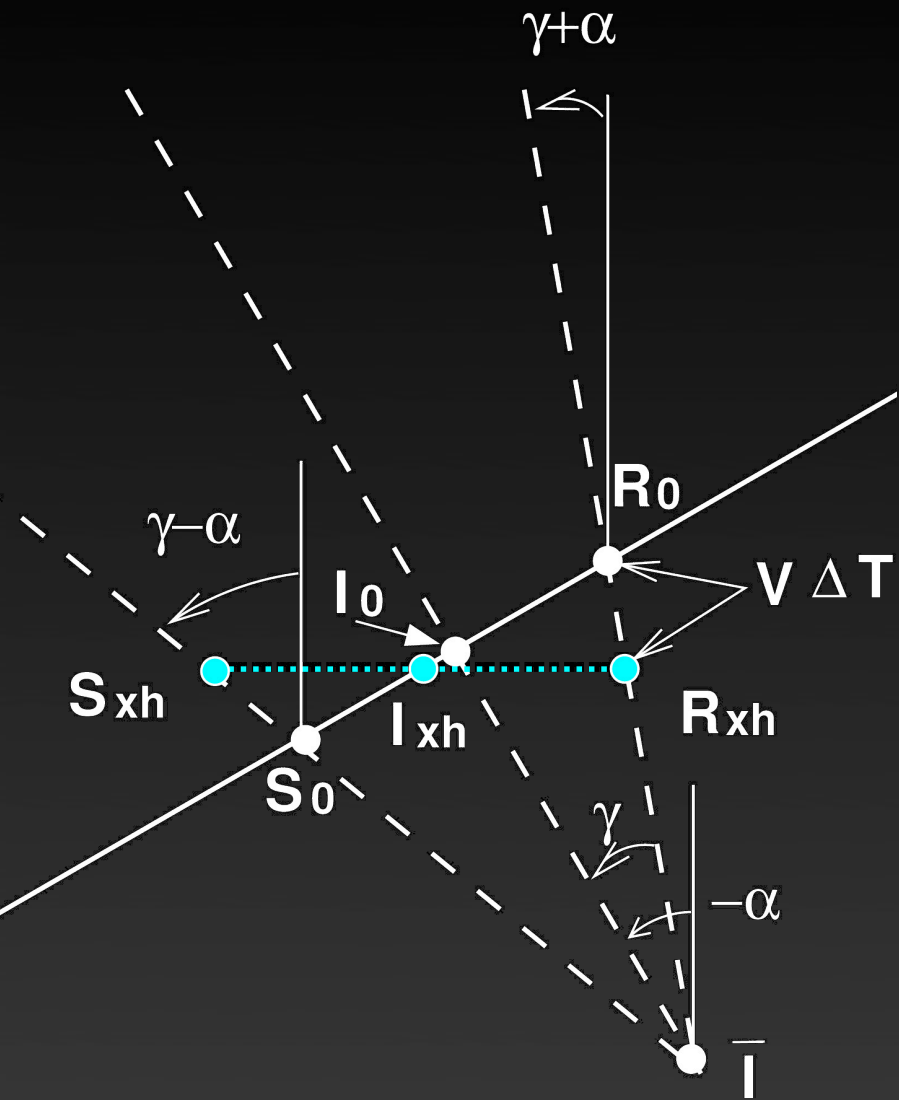
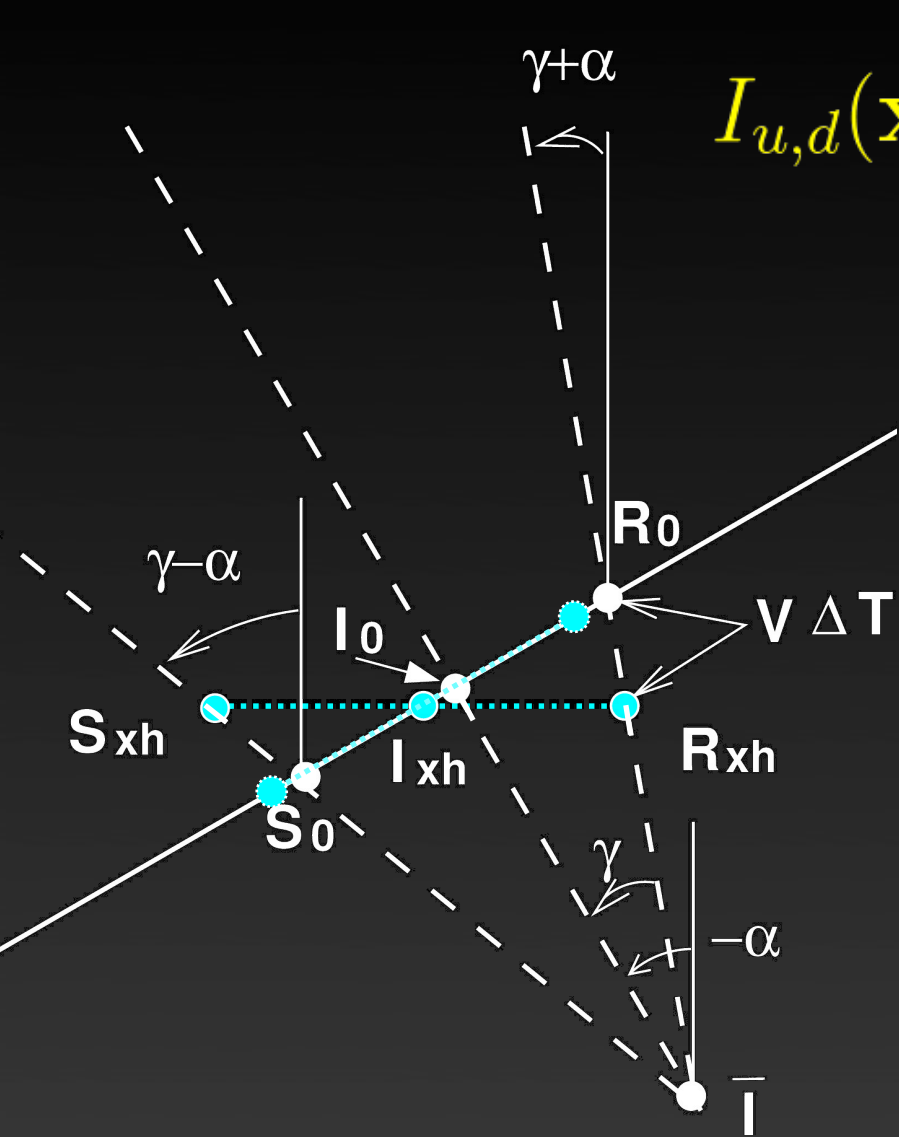


Image-space phase-encoded wavefields



$$I_{u,d}(\mathbf{x}, \mathbf{h}) = \iiint_{\alpha\gamma x'} \rho I(\mathbf{x}, \mathbf{h}; x') dx' d\gamma d\alpha \Big|_{\zeta}$$

$$\zeta(\alpha, \gamma, h, x') = z - htg(\gamma) - x'tg(\alpha) \pm htg(\gamma \pm \alpha)$$

Image-space WETom with ISPEW

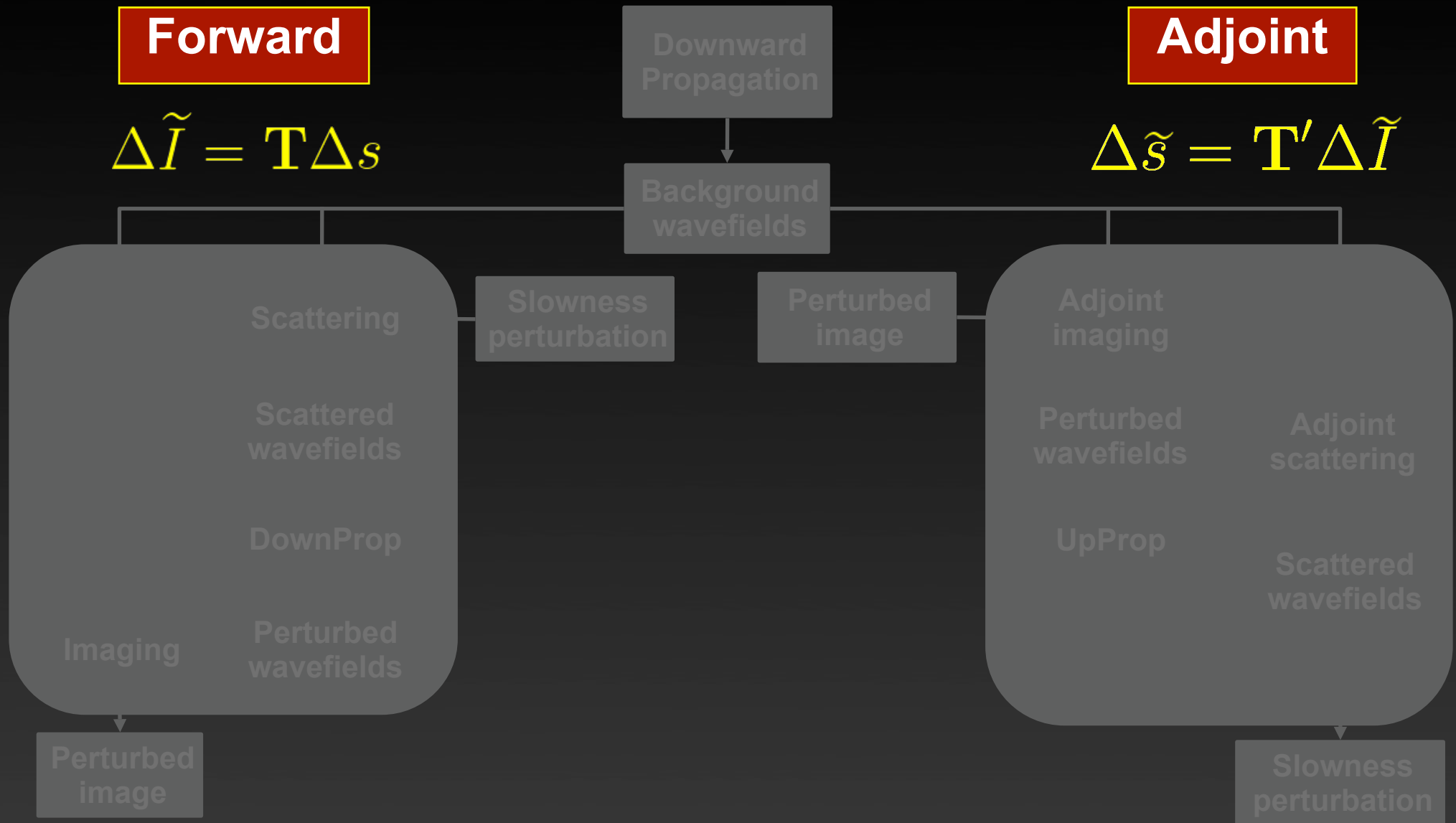


Image-space WETom with ISPEW

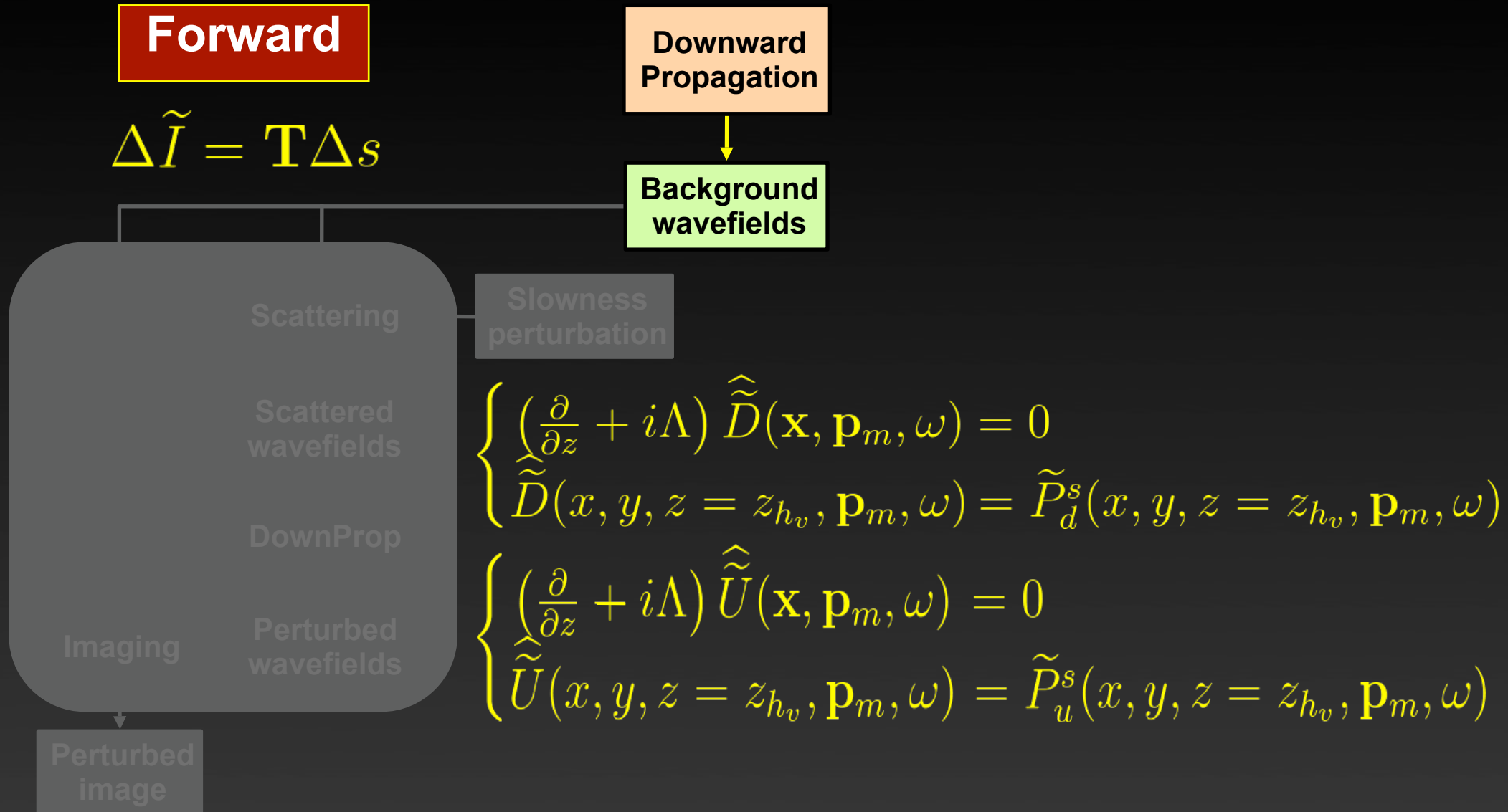
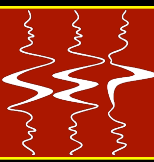


Image-space WETom with ISPEW

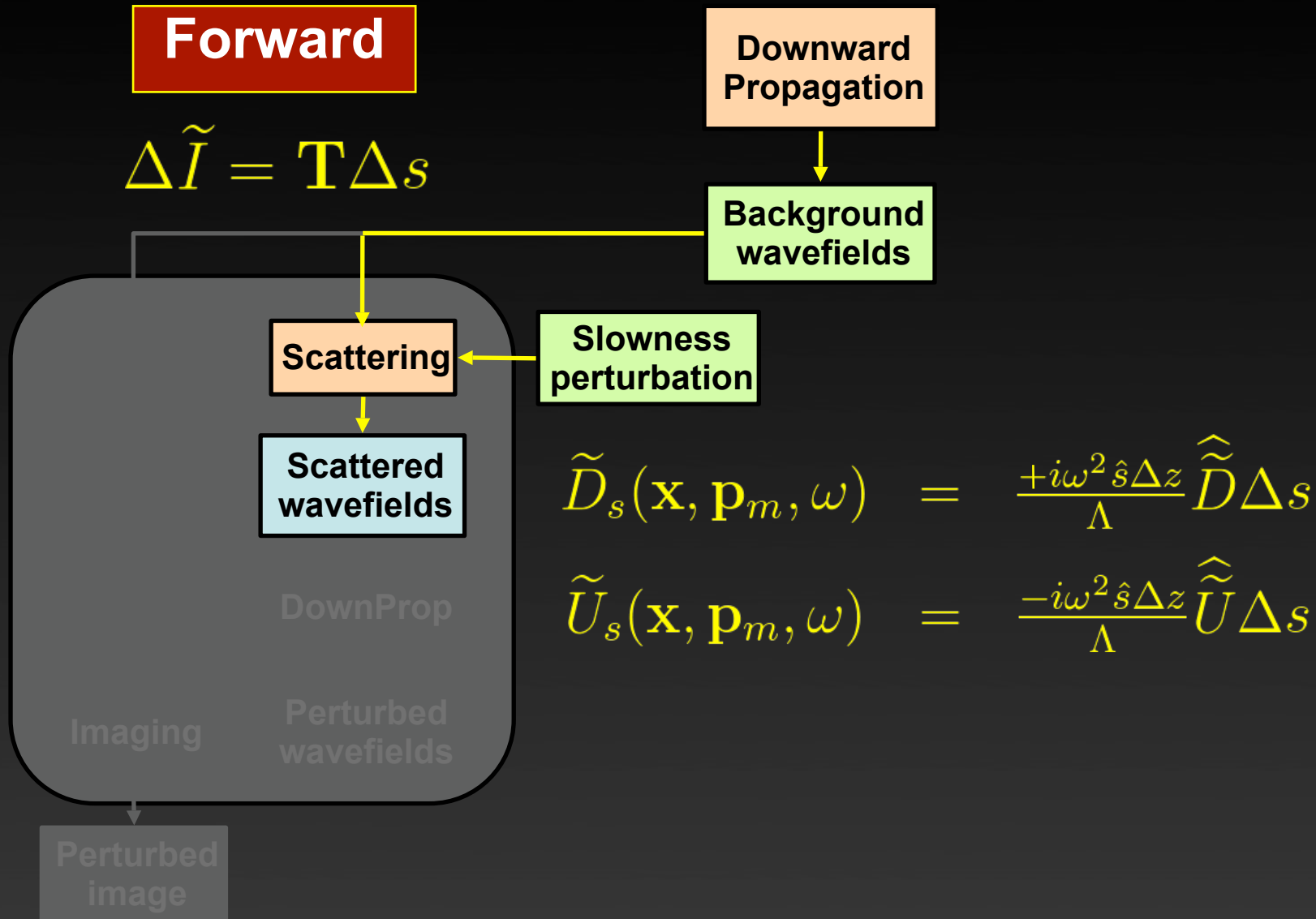
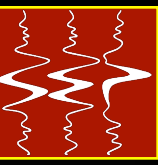


Image-space WETom with ISPEW

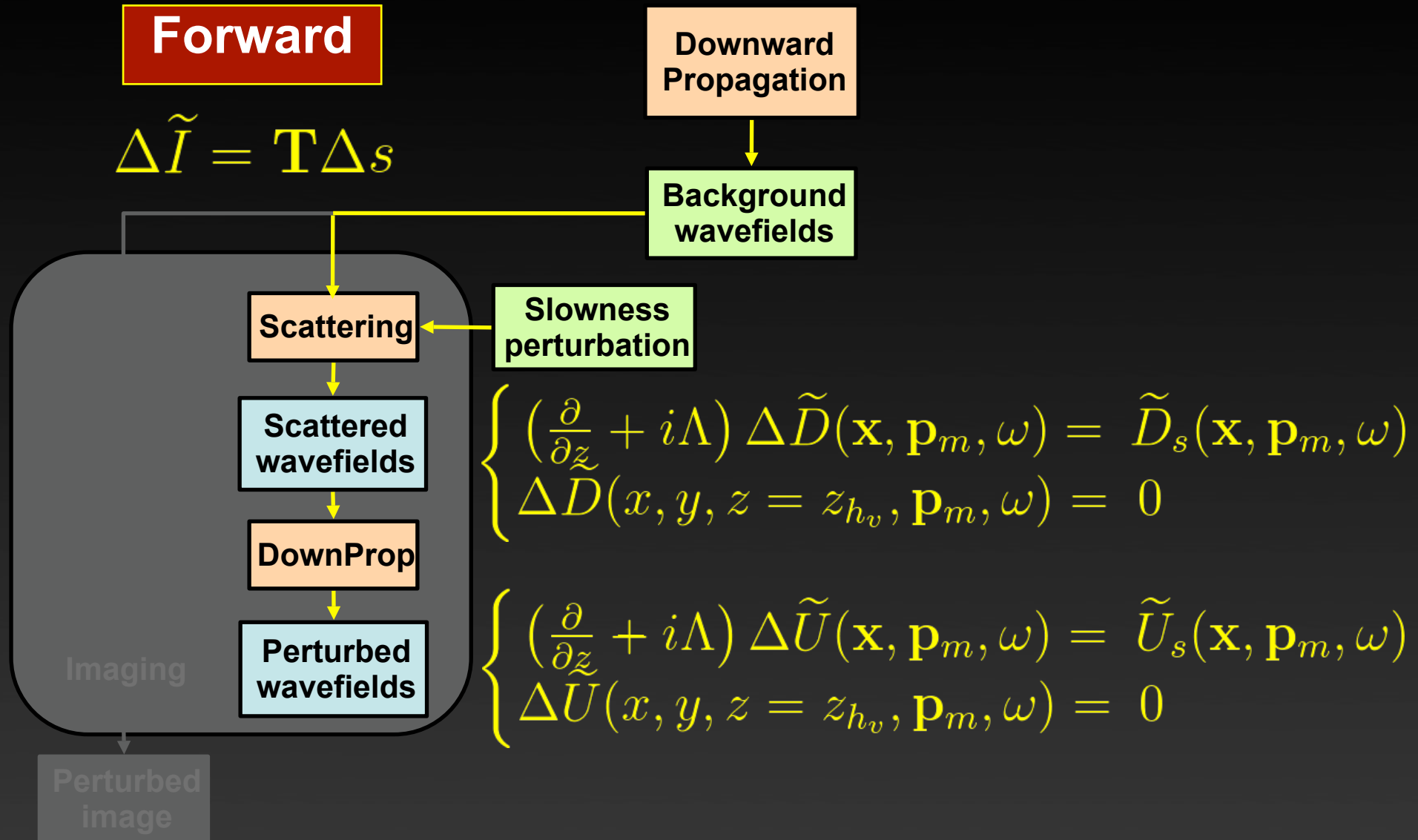


Image-space WETom with ISPEW

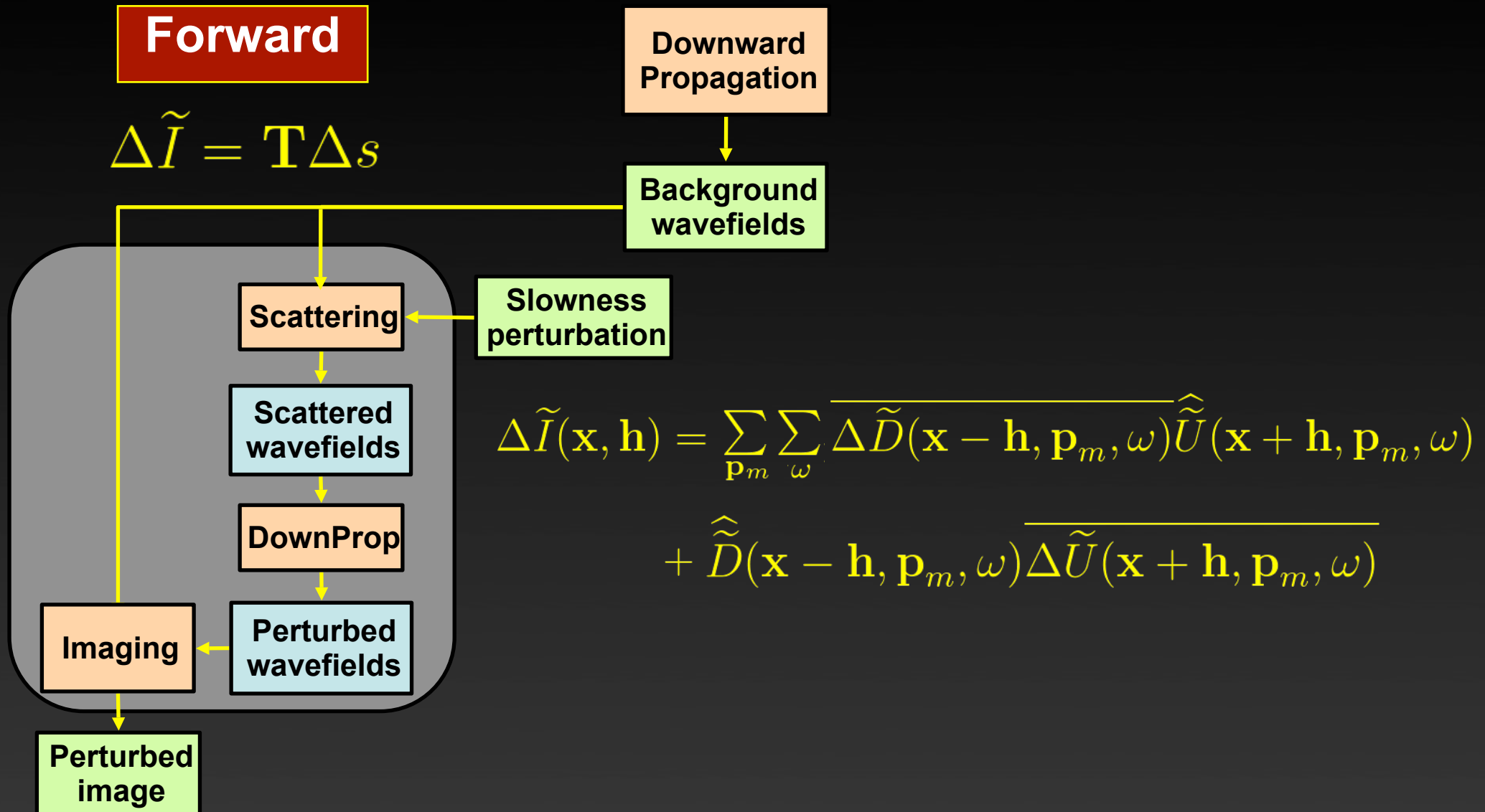


Image-space WETom with ISPEW

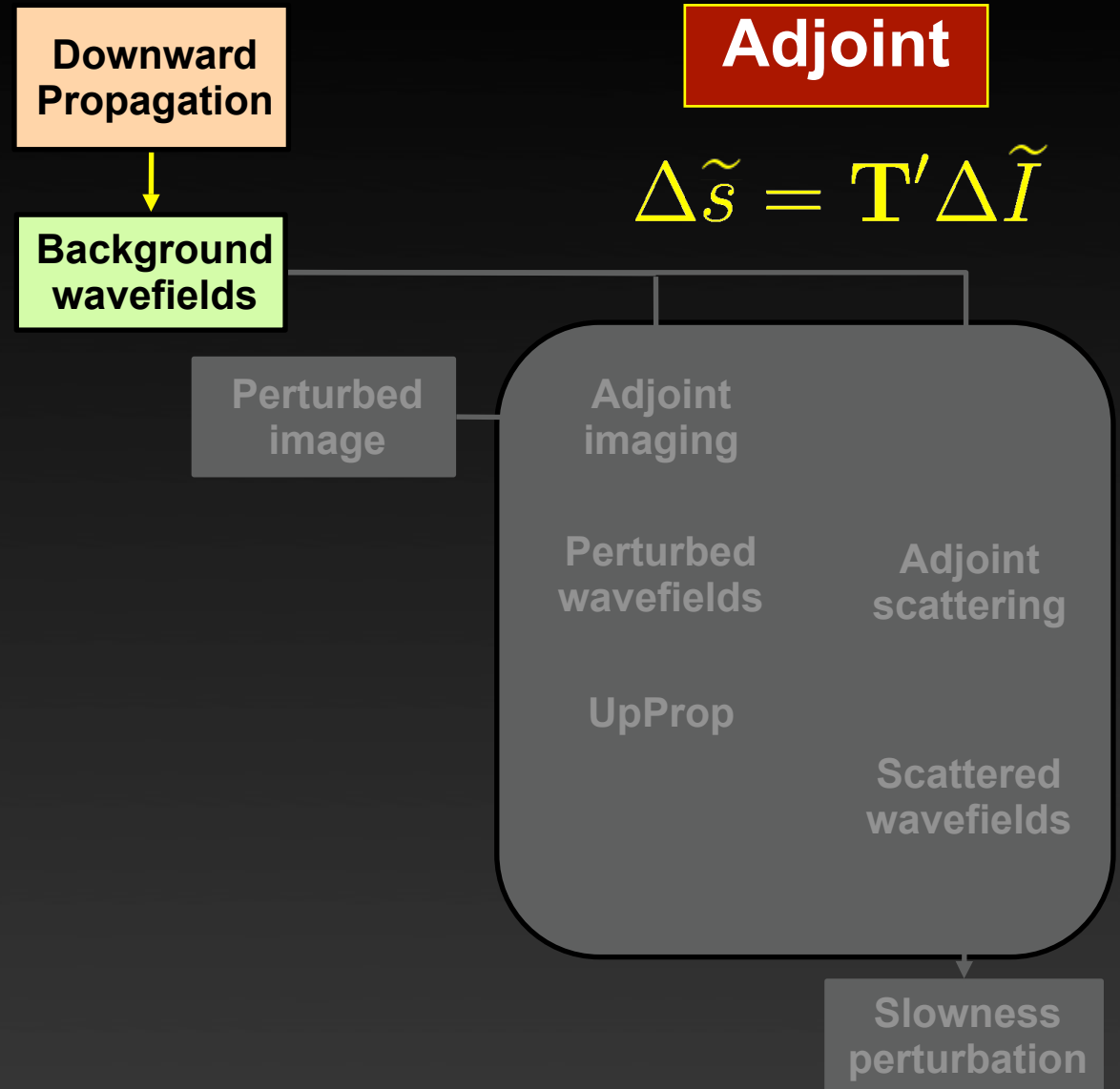


Image-space WETom with ISPEW

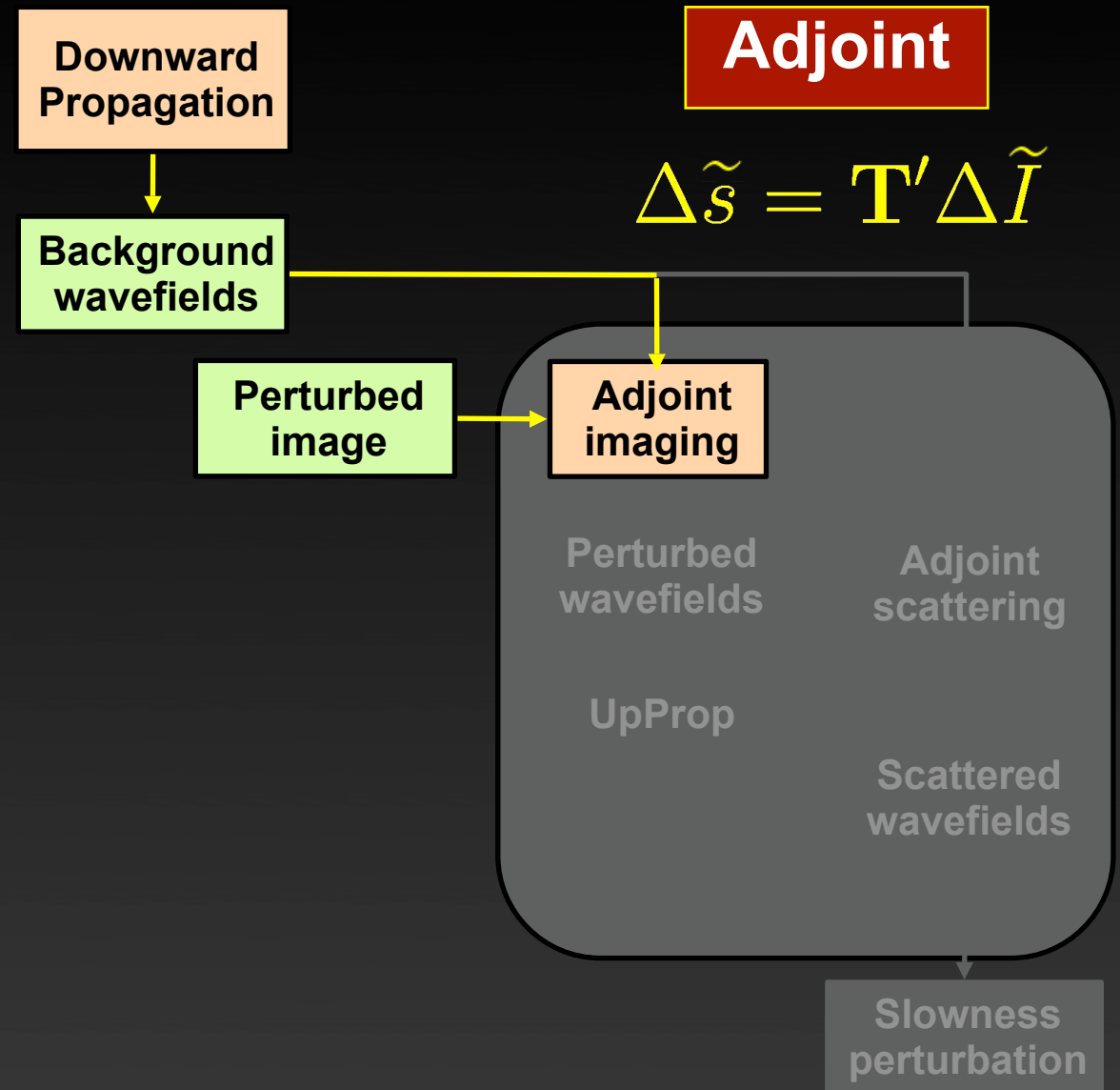


Image-space WETom with ISPEW

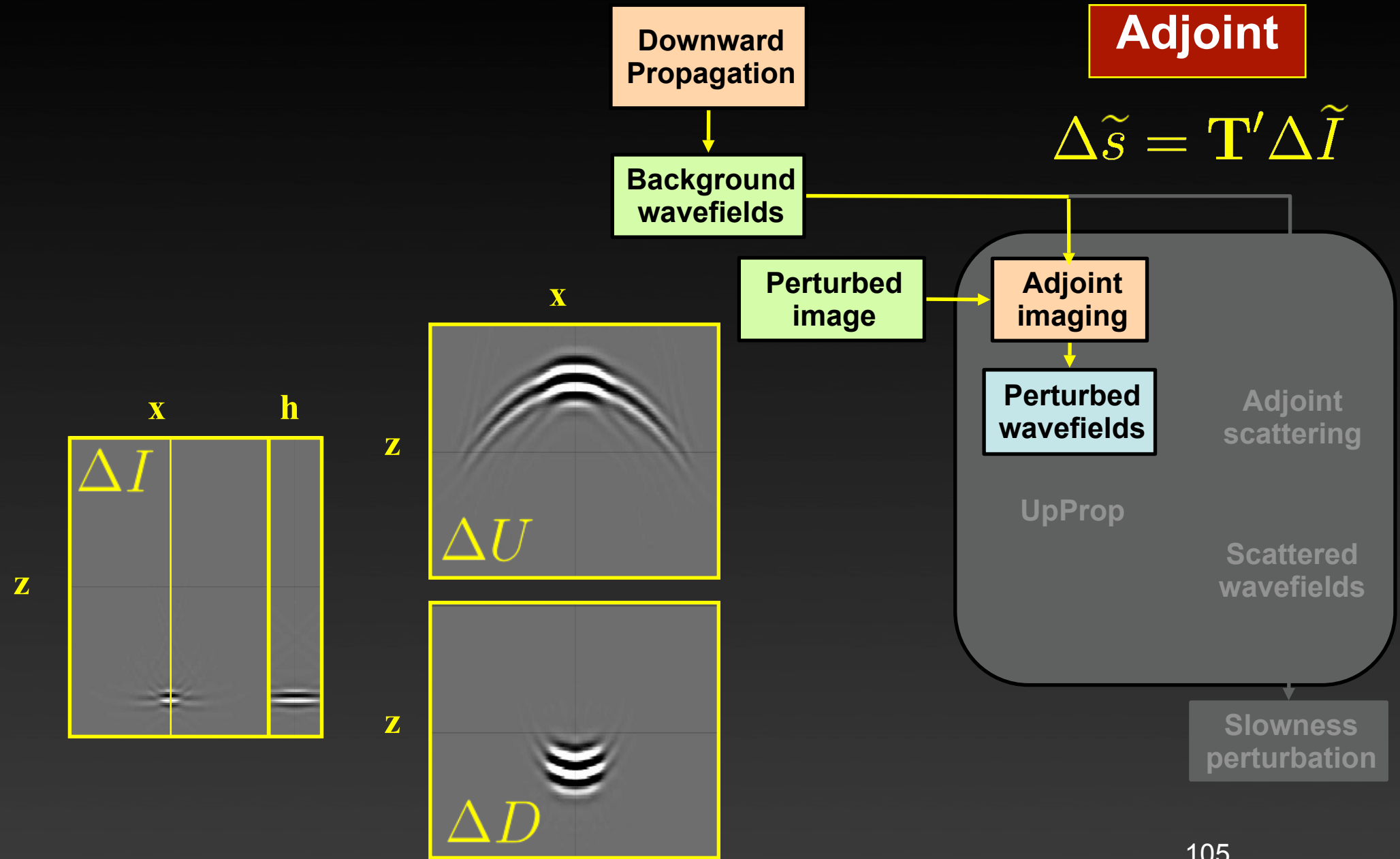
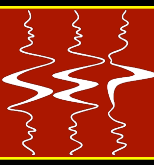


Image-space WETom with ISPEW

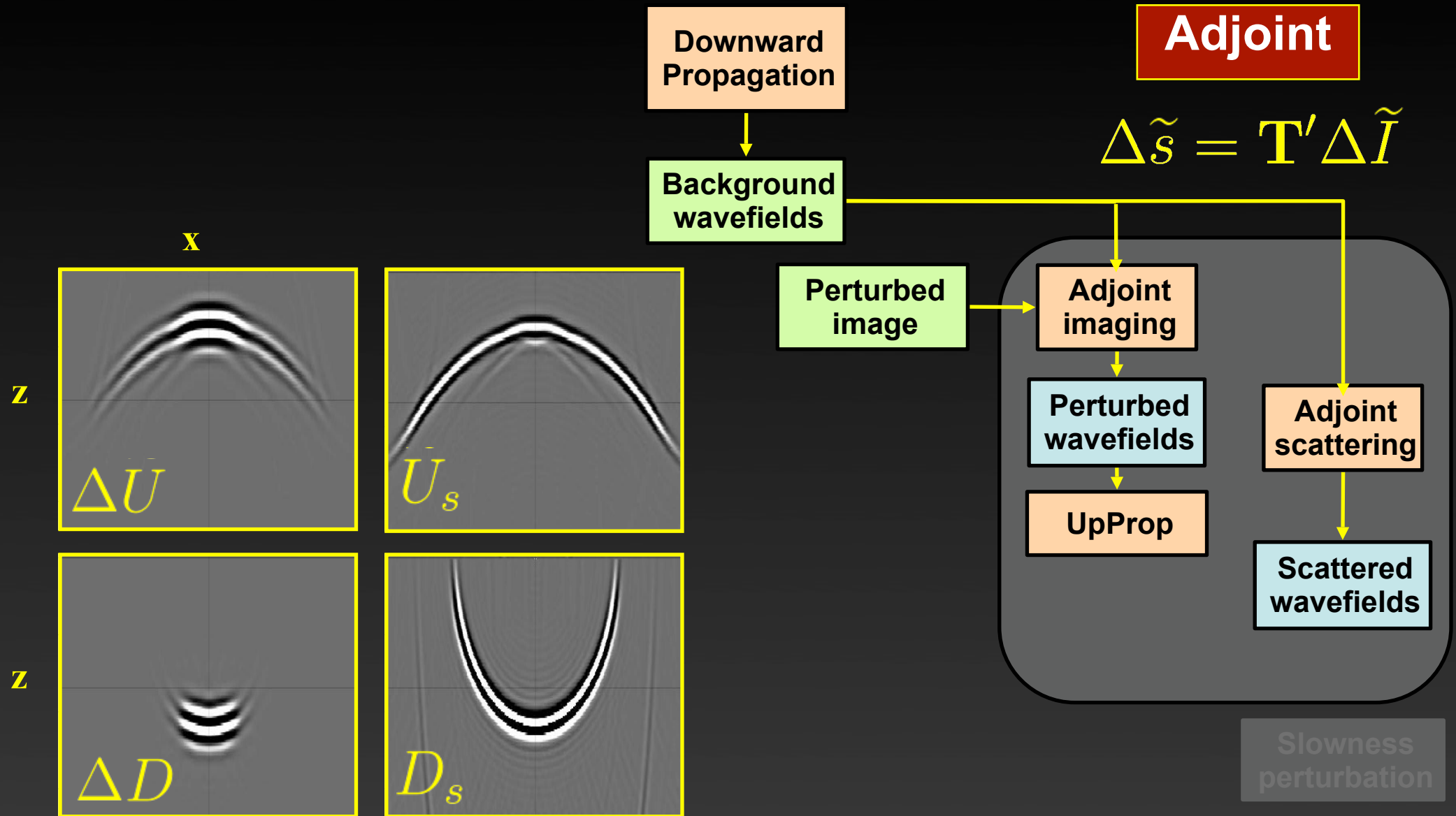


Image-space WETom with ISPEW

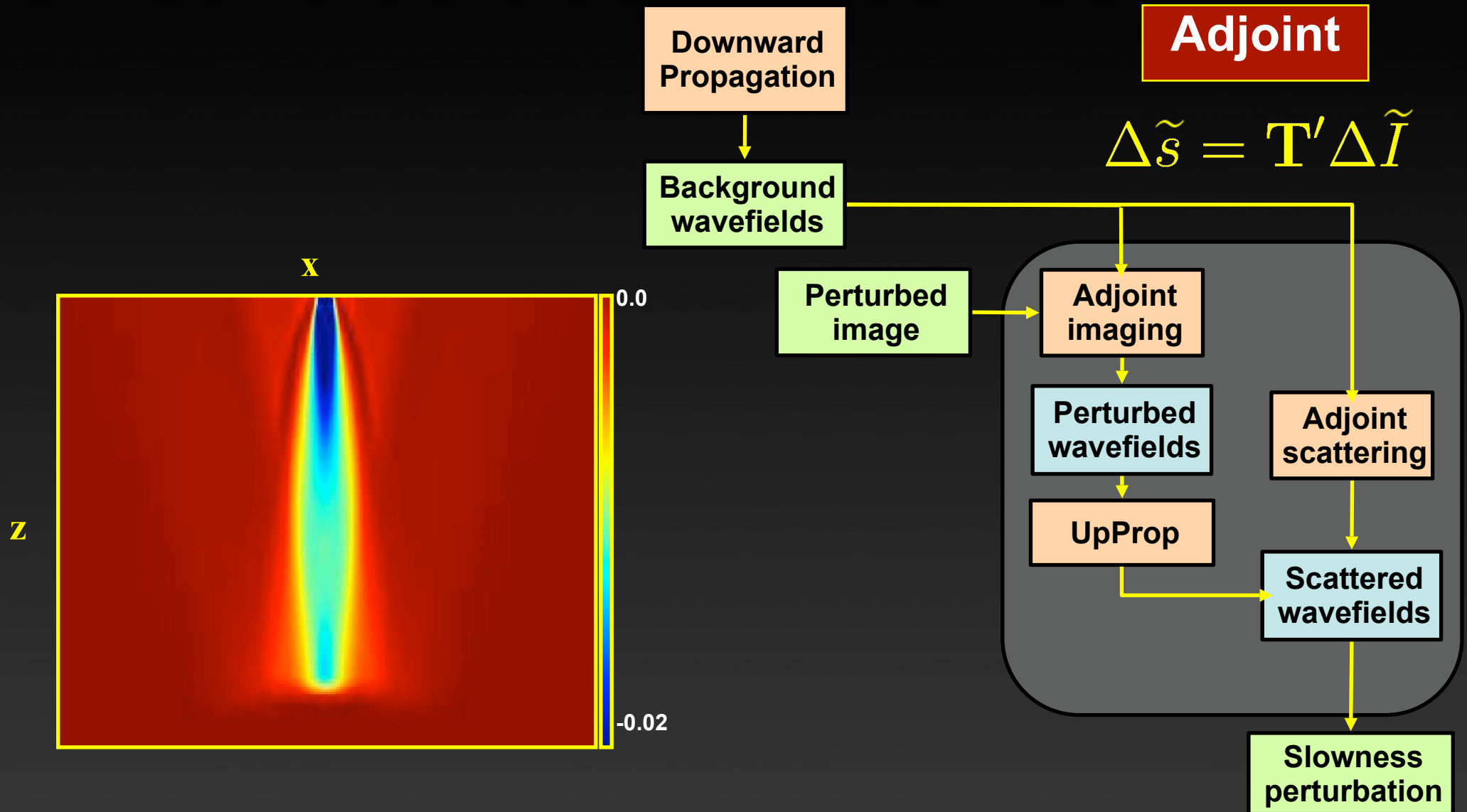
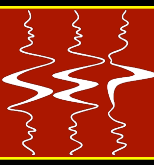


Image-space WETom with ISPEW

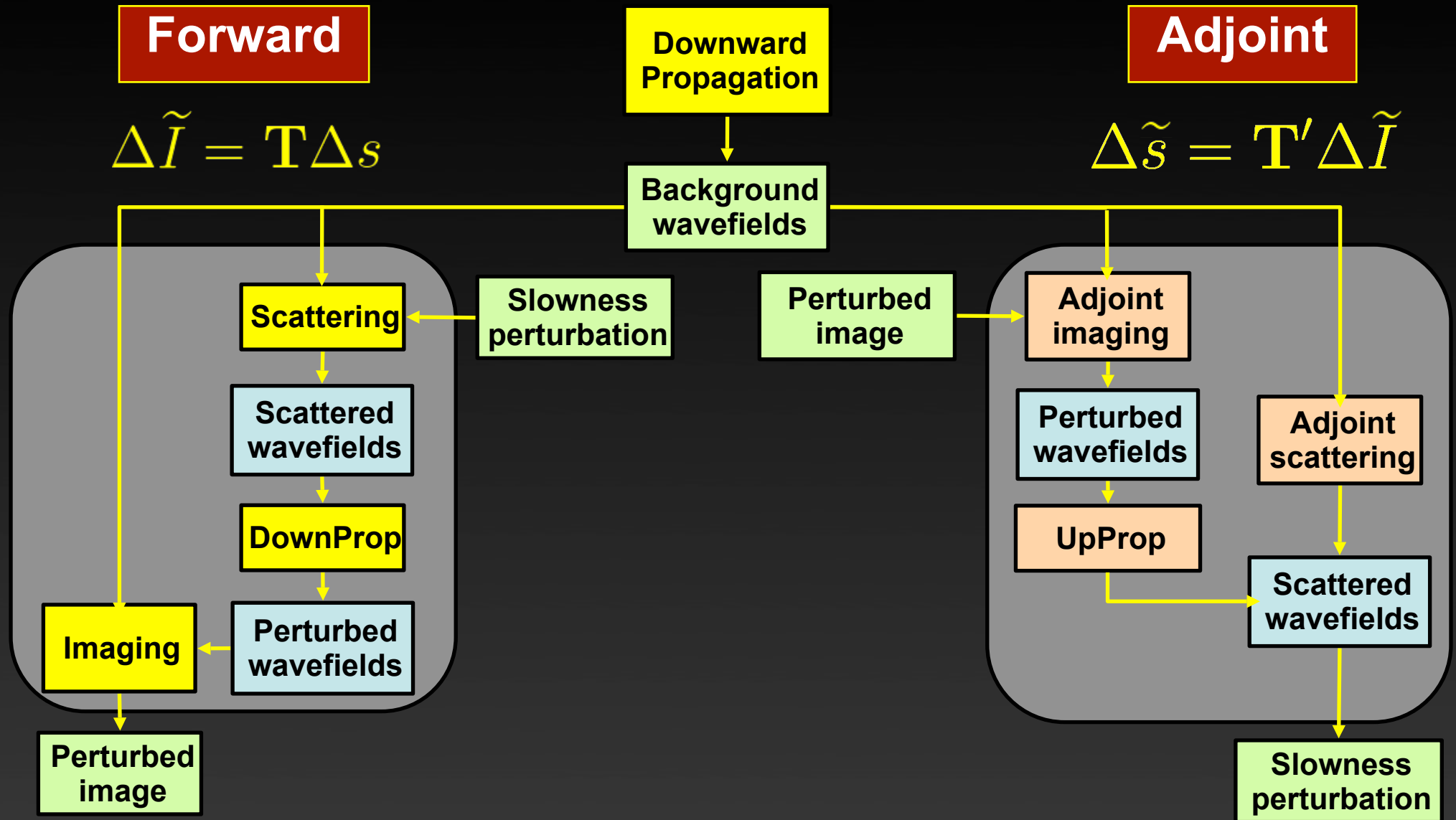
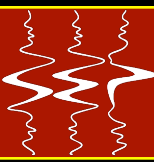


Image-space WETom – velocity optimization

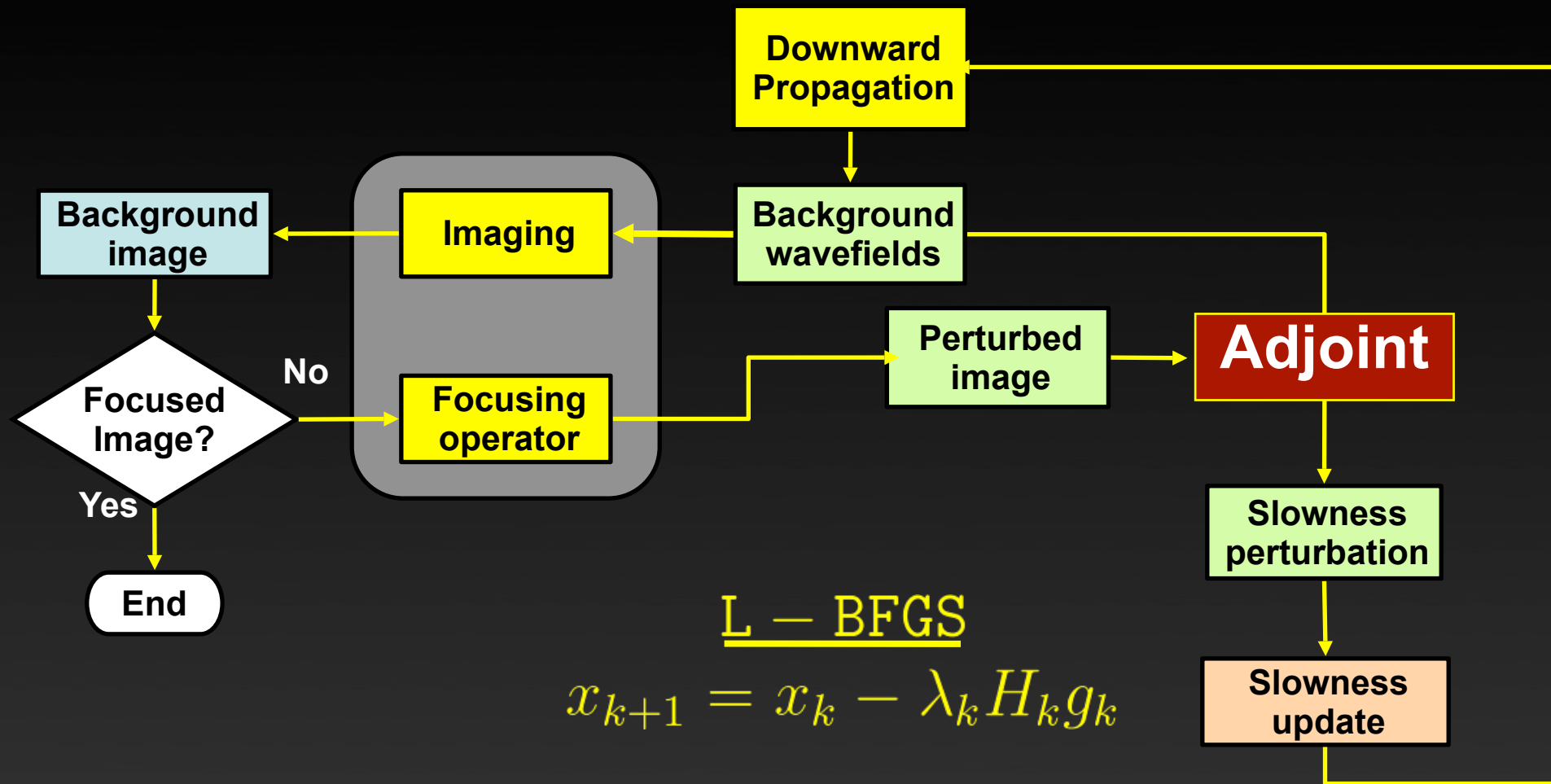
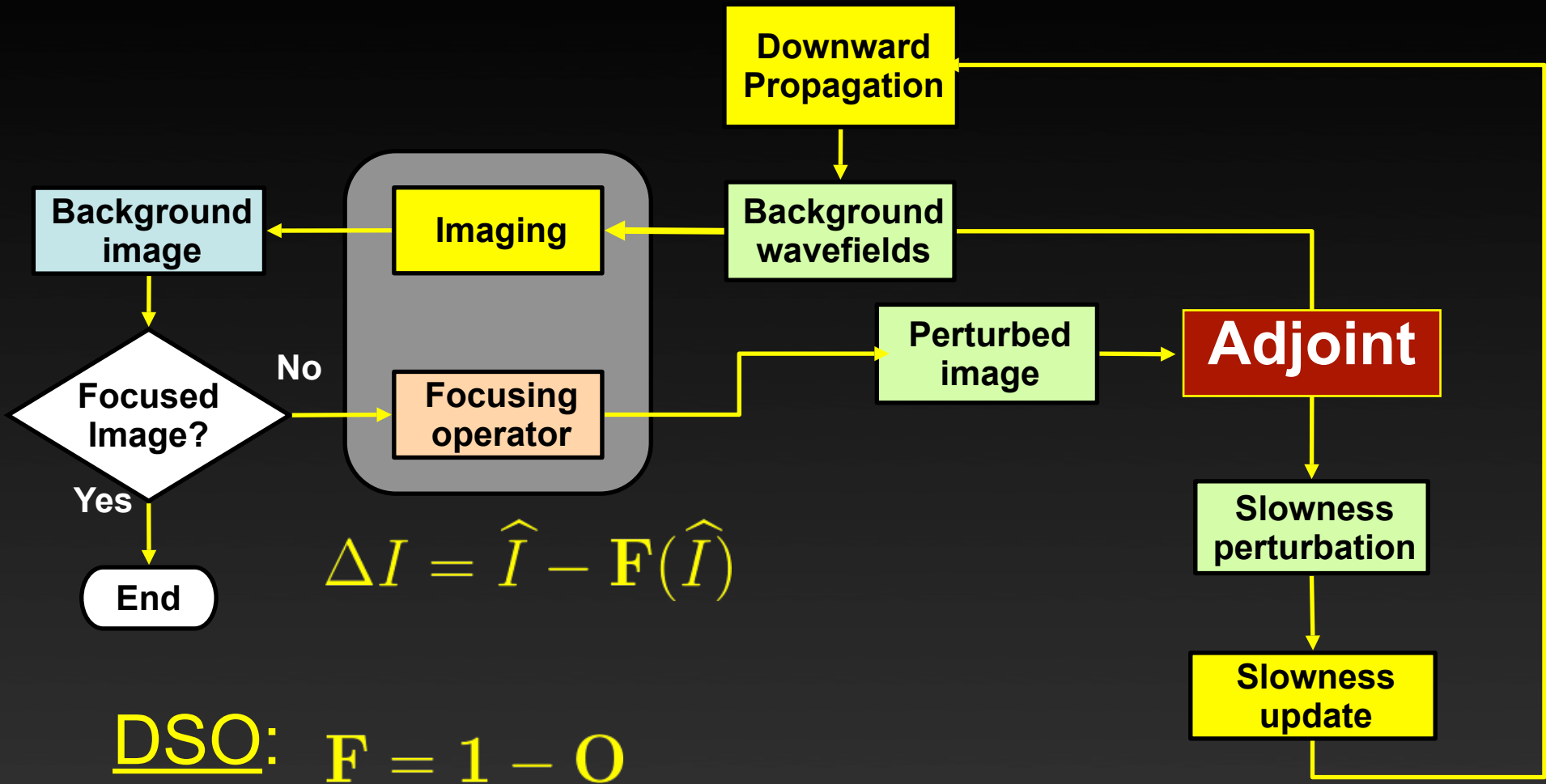
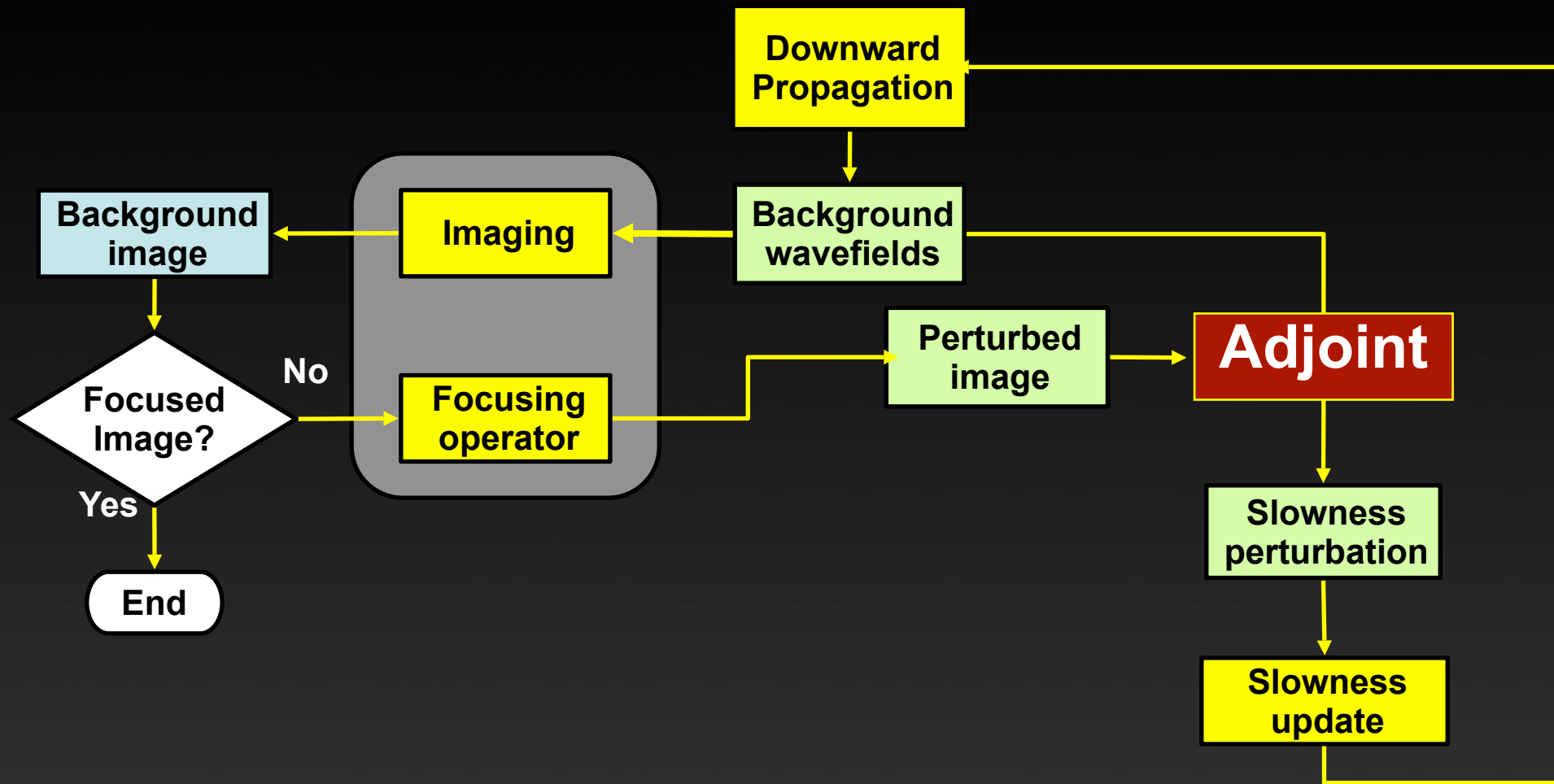


Image-space WETom – velocity optimization



DSO: $\mathbf{F} = \mathbf{1} - \mathbf{O}$
 $\Delta I = |h| \hat{I}$

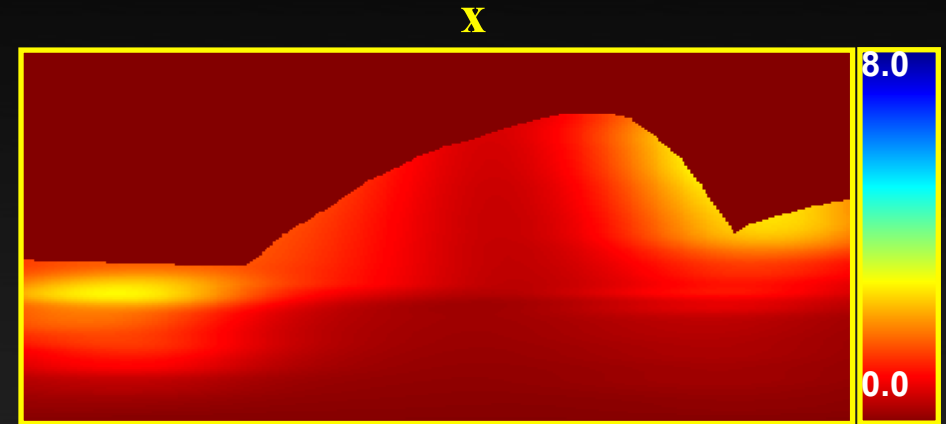
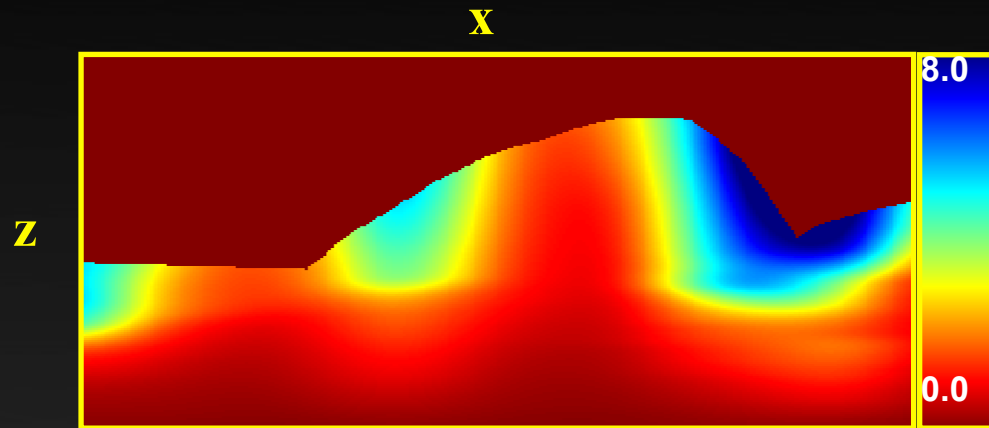
Image-space WETom – optimization



Numerical example – slowness perturbation

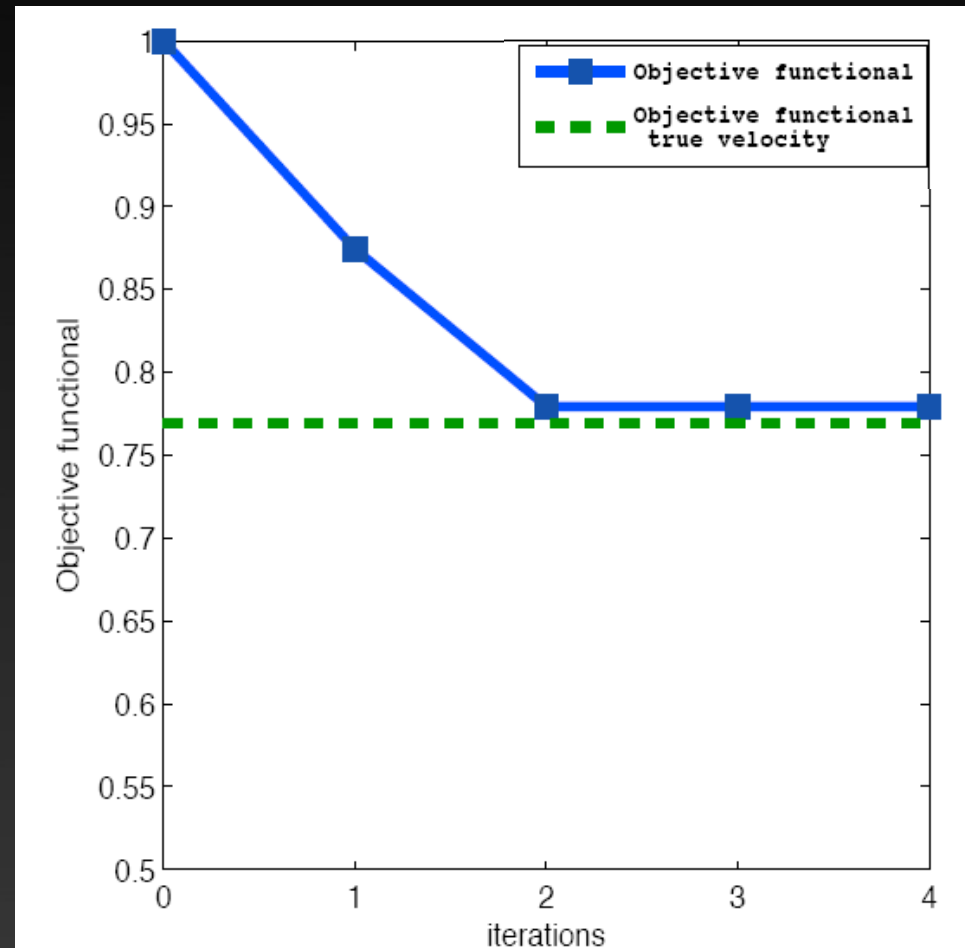
Initial gradient

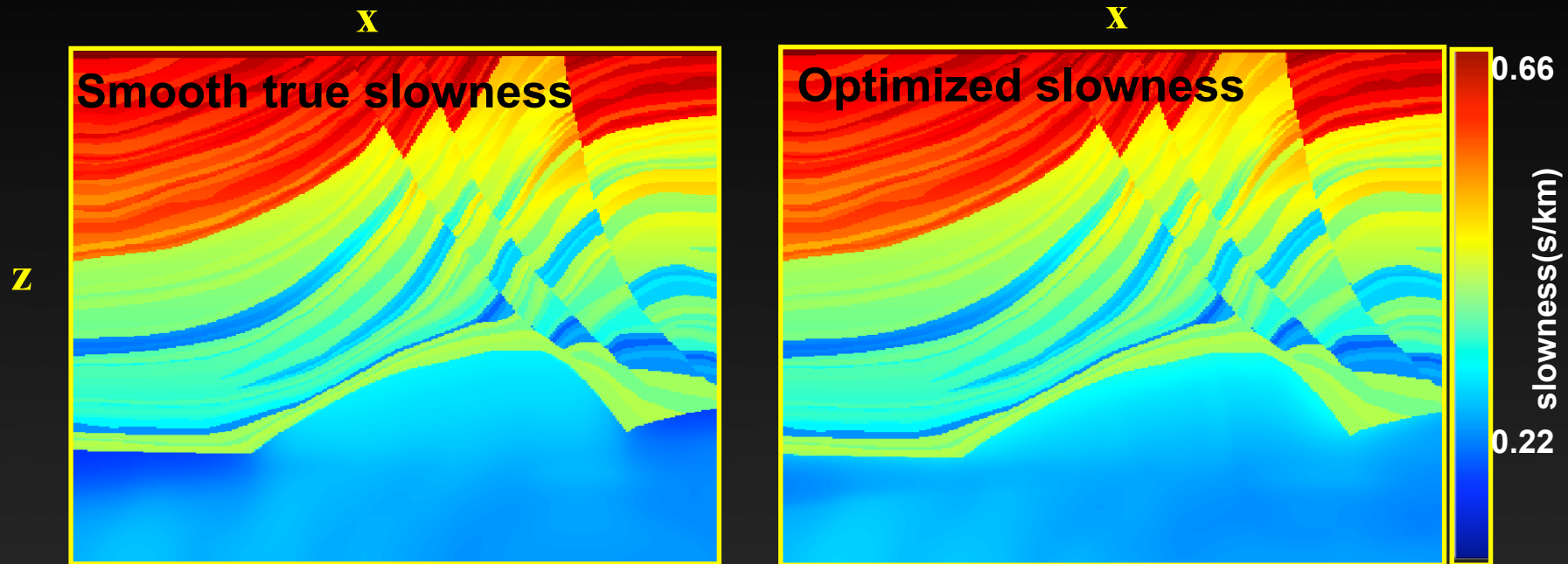
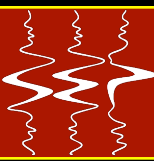
Final gradient



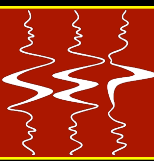
Numerical example – slowness perturbation

11 ISPEW

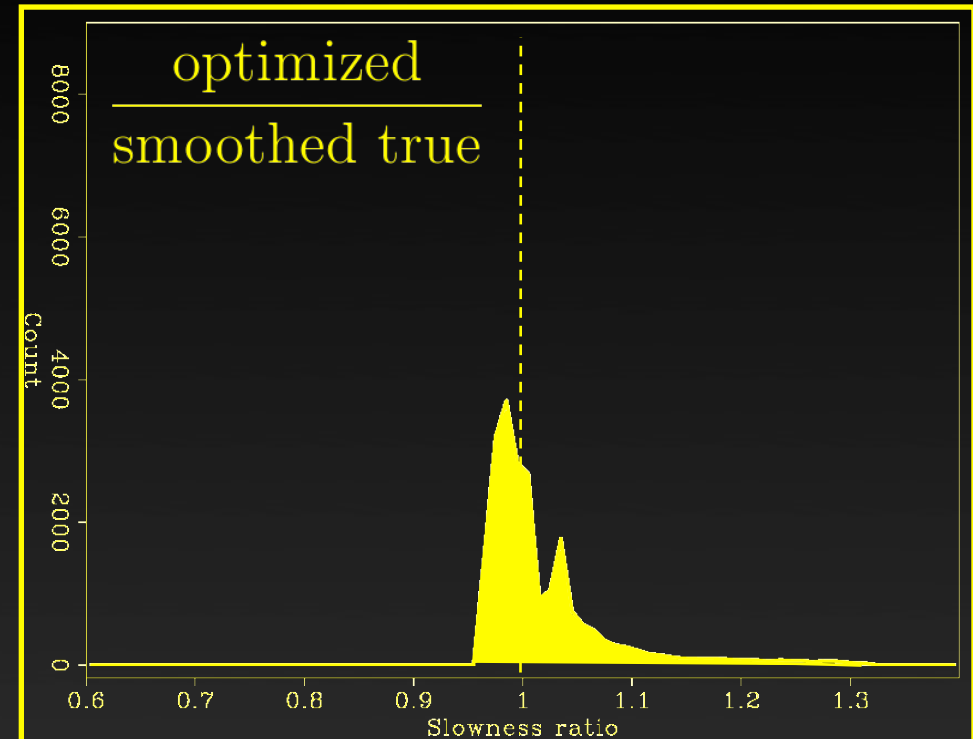
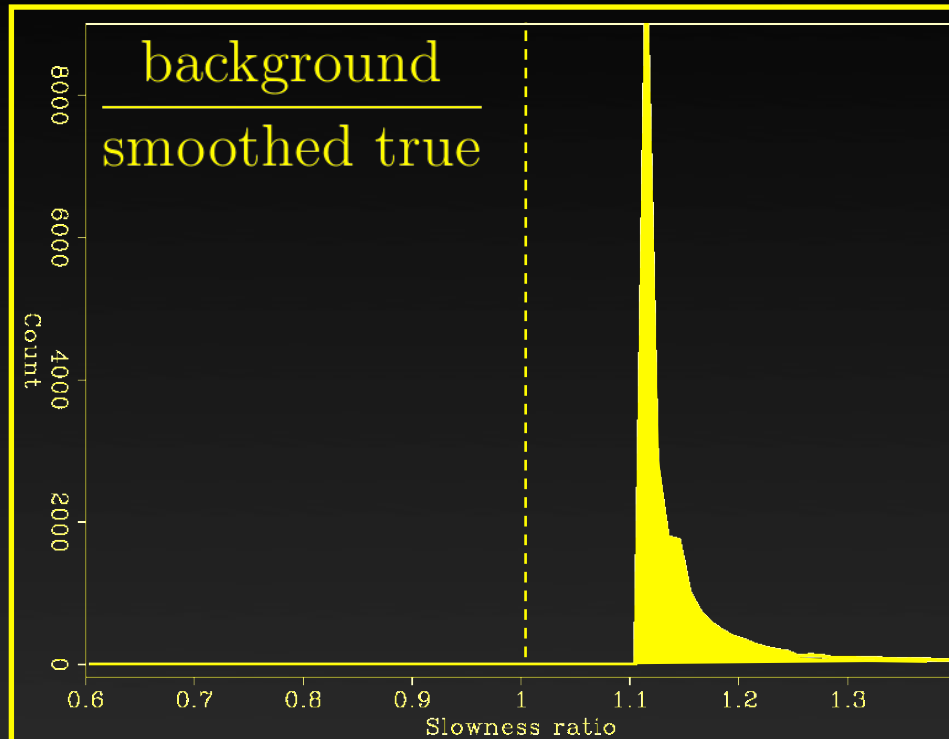




nonlinear iterations **20X faster** than
the conventional shot-profile scheme

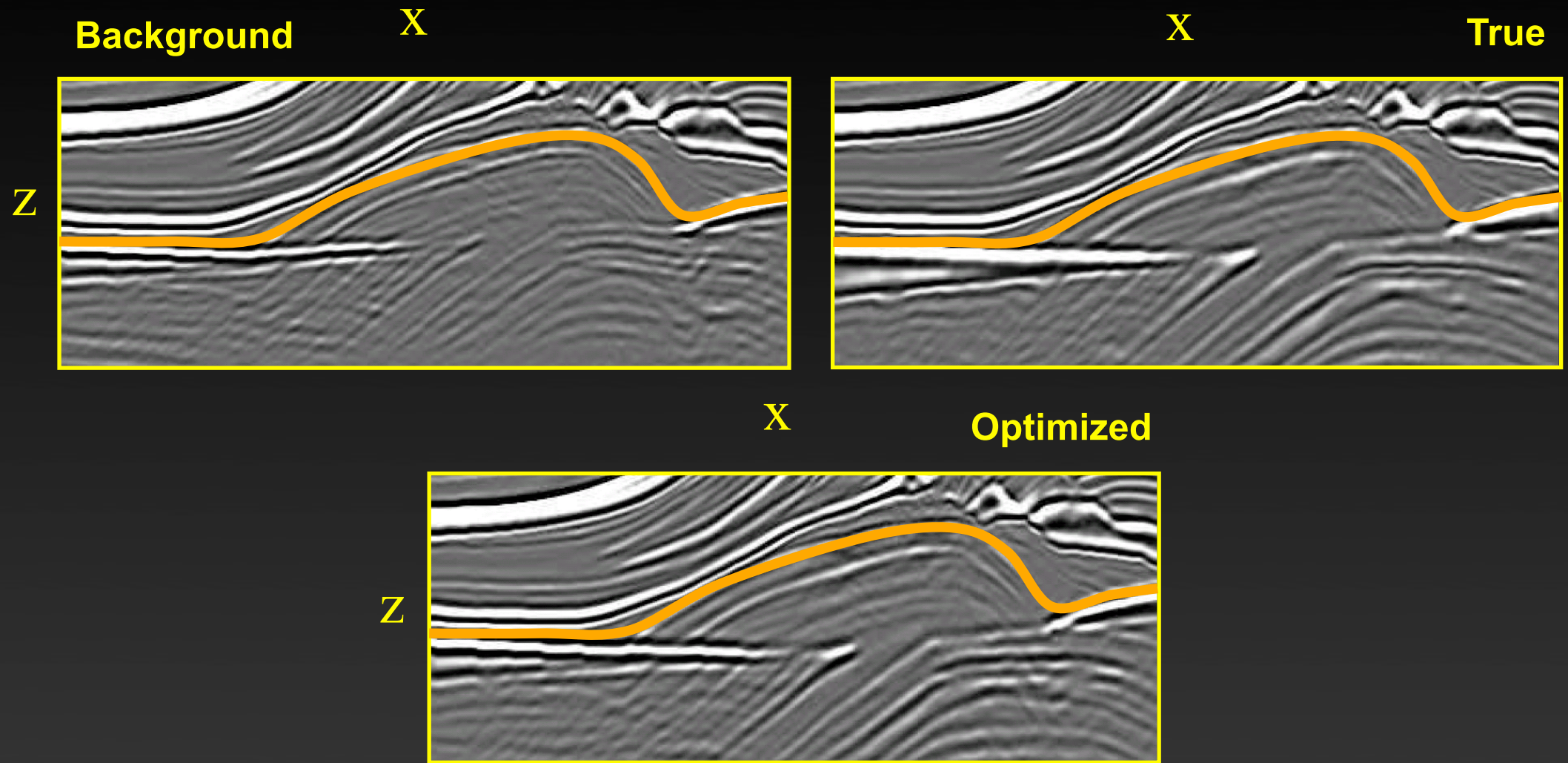
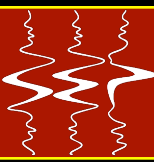


- Histograms

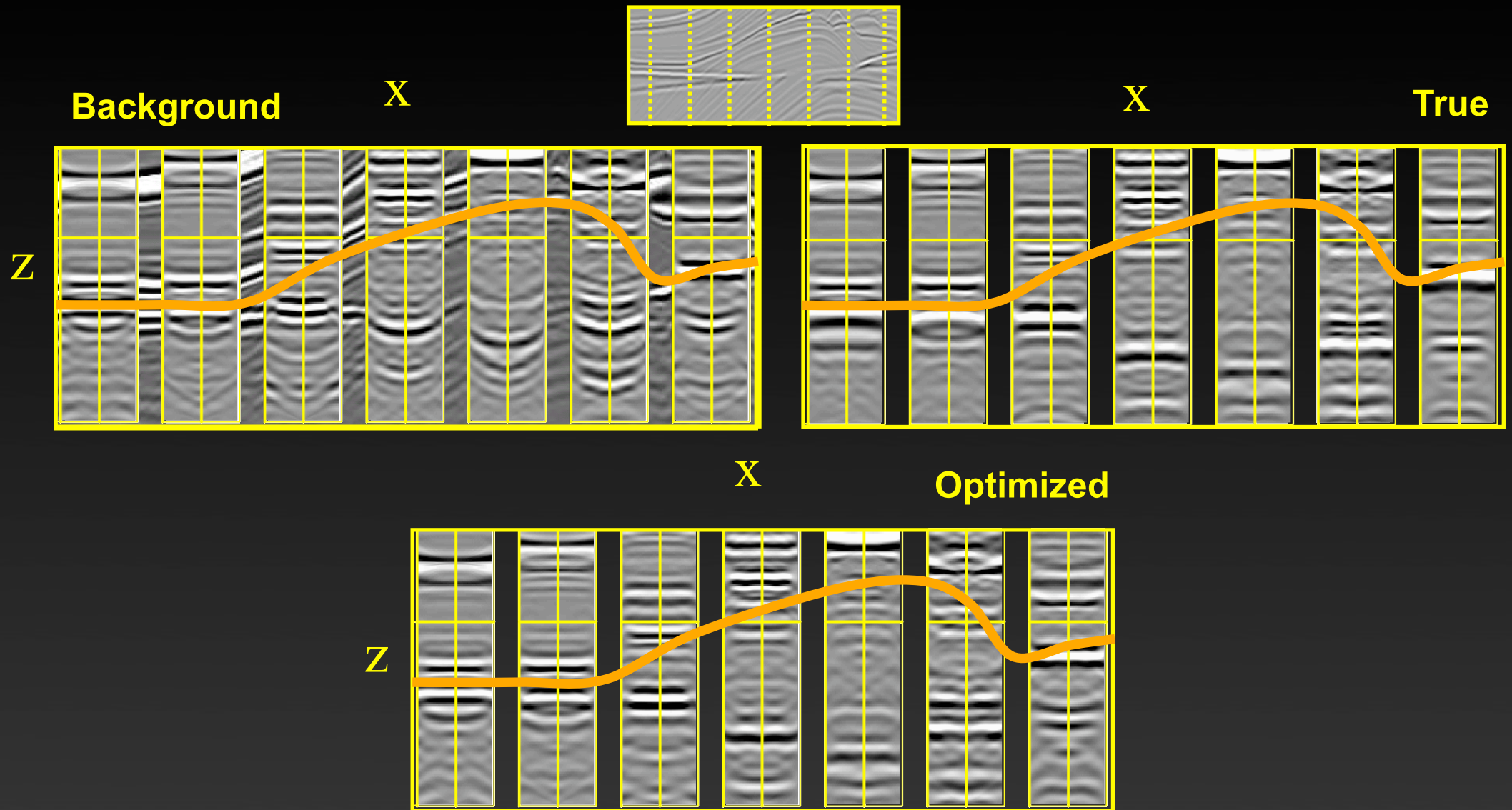


nonlinear iterations **20X faster** than
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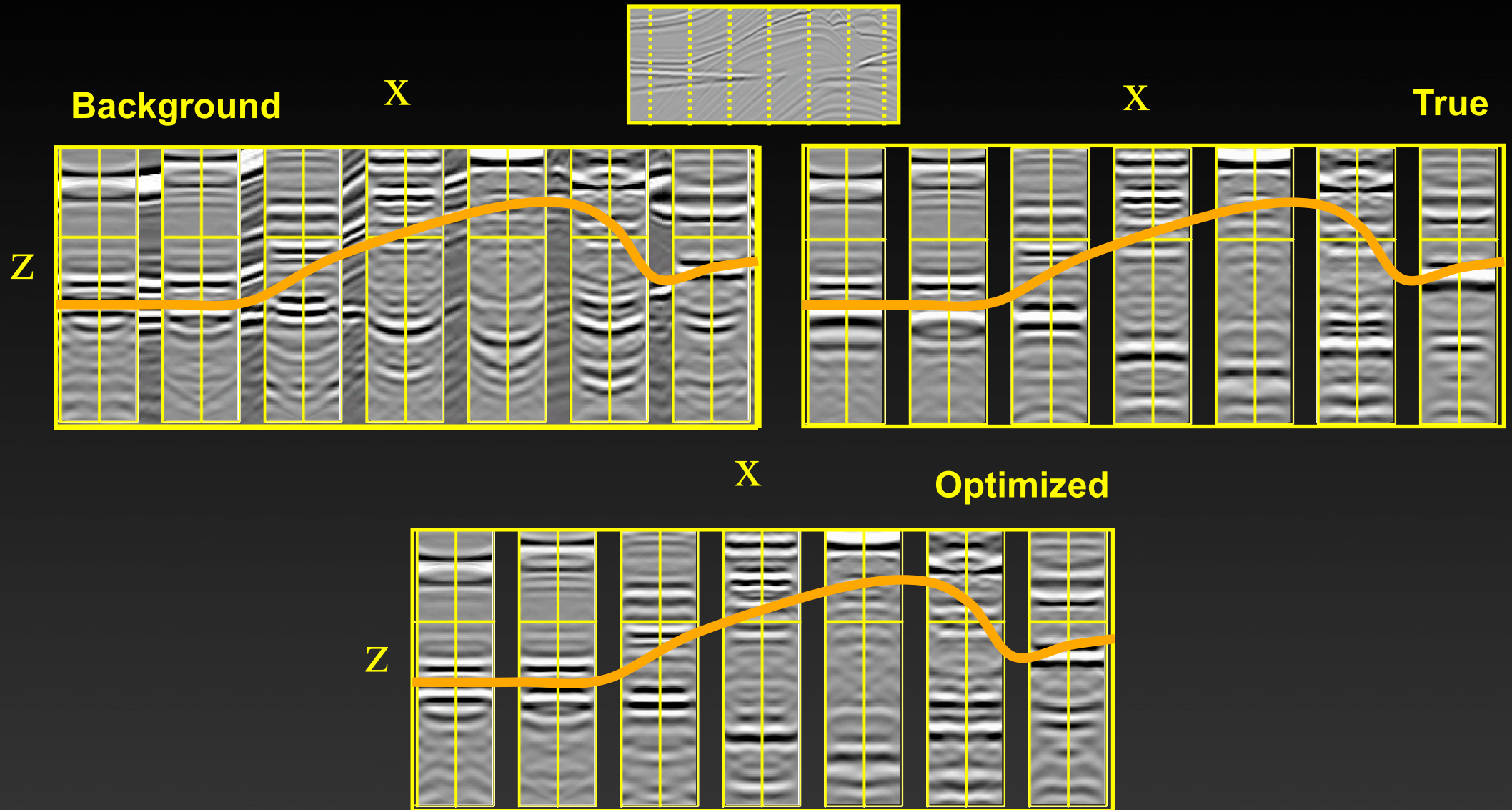
Numerical example - Images



Numerical example

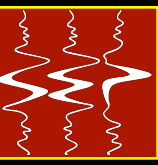


Numerical example

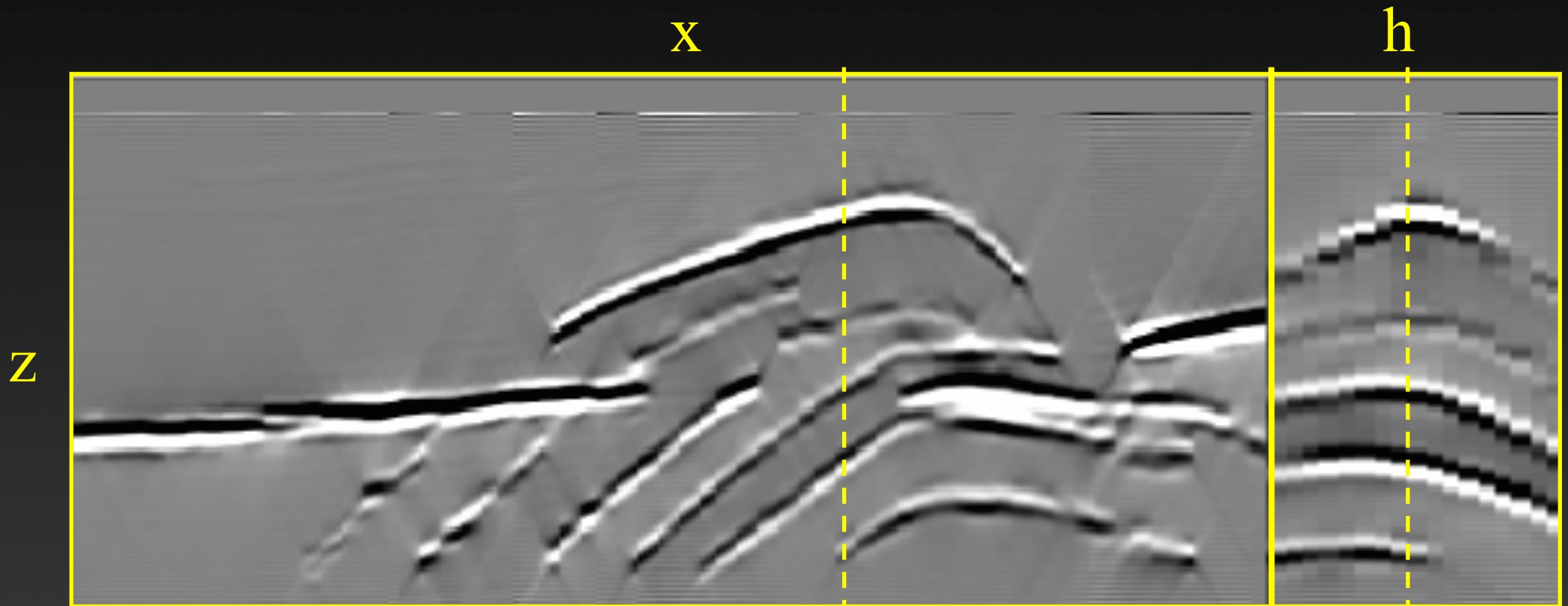


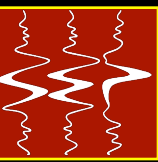
20X faster

Numerical example -



- Image-space phase-encoded wavefields
 - 12 reflectors





Source wavefield initial condition

$$\begin{aligned}\tilde{I}_d(\mathbf{x}, \mathbf{h}, \mathbf{r}_m, \omega) &= \sum_{x_m} \sum_{y_m} I_d(\mathbf{x}, \mathbf{h}; x_m, y_m) \\ &\quad \times \beta(\mathbf{x}, \mathbf{h}, \mathbf{r}_m, \omega; x_m, y_m)\end{aligned}$$

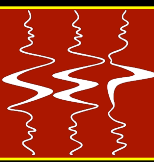
Receiver wavefield initial condition

$$\begin{aligned}\tilde{I}_u(\mathbf{x}, \mathbf{h}, \mathbf{r}_m, \omega) &= \sum_{x_m} \sum_{y_m} I_u(\mathbf{x}, \mathbf{h}; x_m, y_m) \\ &\quad \times \beta(\mathbf{x}, \mathbf{h}, \mathbf{r}_m, \omega; x_m, y_m)\end{aligned}$$

I_d, I_u = rotated images according to the apparent geological dip

$$\beta = e^{i\gamma}$$

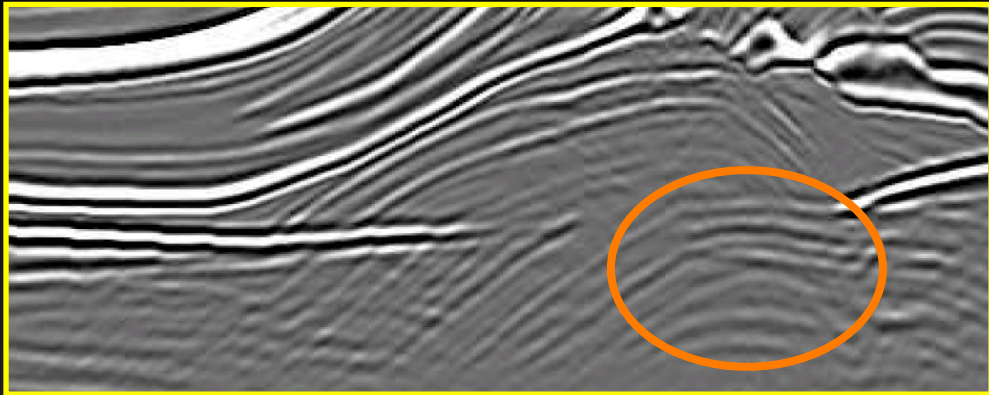
γ = random phases



Initial

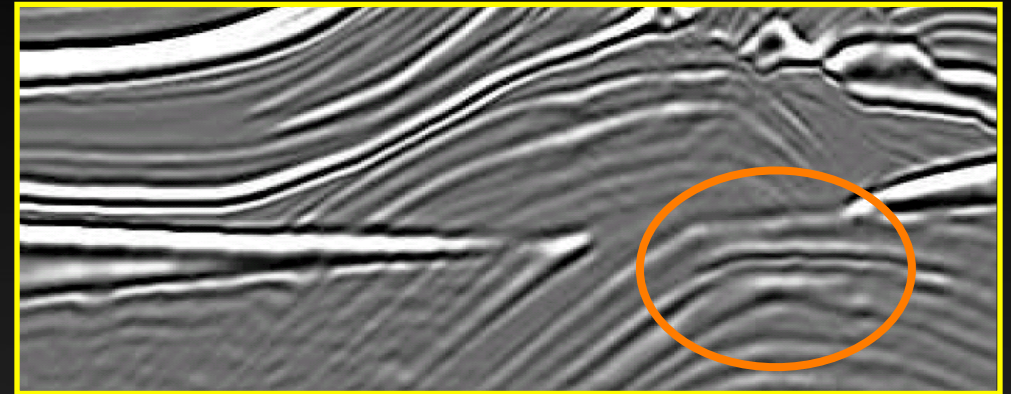
x

z



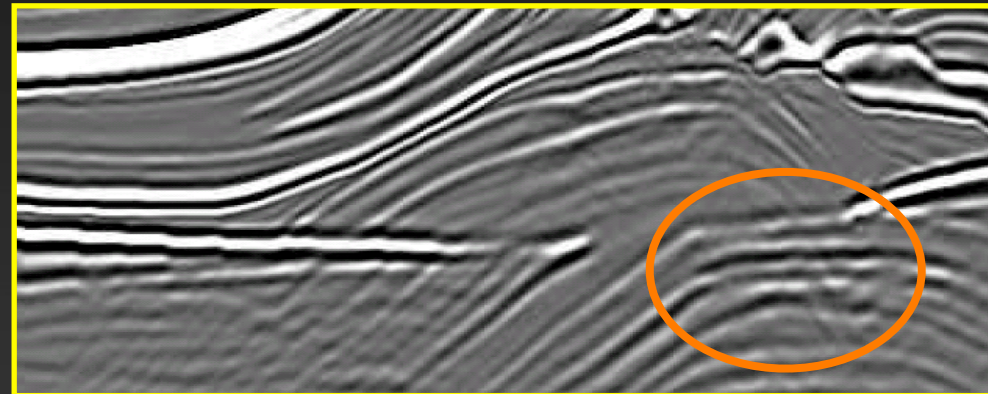
True

x



Optimized

z



20x faster