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- Part III: Beyond seismic interferometry

Part III: Beyond seismic interferometry

Kees Wapenaar, Jan Thorbecke, Joost van der Neut, Evert Slob,
Filippo Broggini, Jyoti Behura, Satyan Singh, Roel Snieder
and Ivan Vasconcelos

Also available as E-lecture:

https://youtu.be/DrpagMsK09M

- Introduction
- Green’s functions and focusing functions
- 3-D Marchenko equations
- Iterative solution
- Green’s function retrieval
- Marchenko imaging
- Issues for discussion

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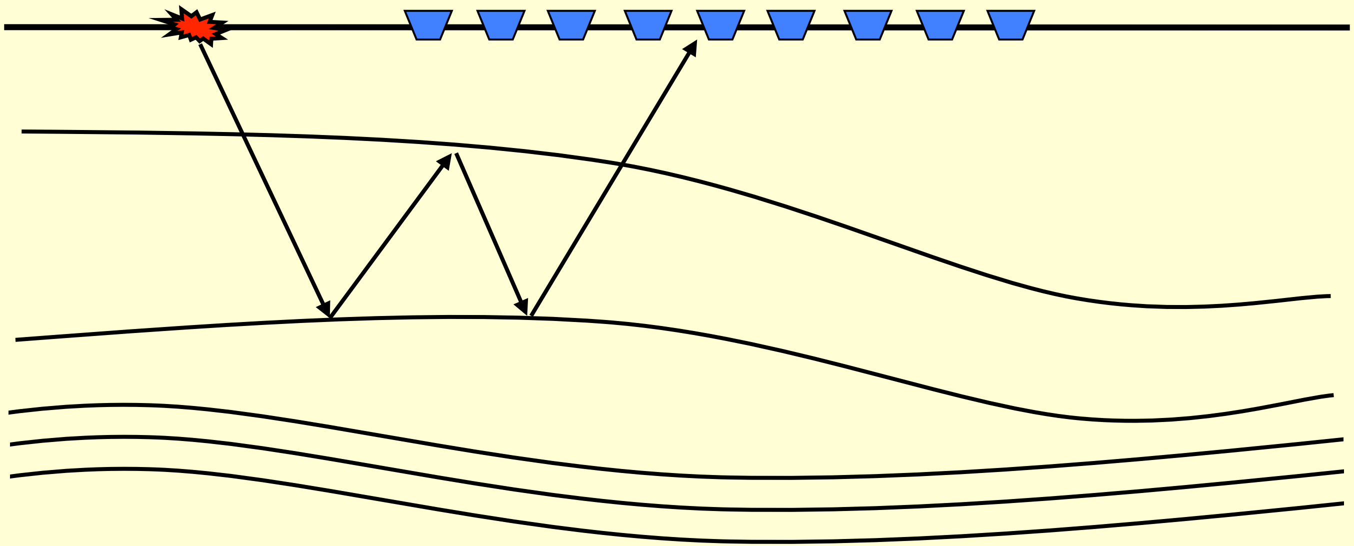
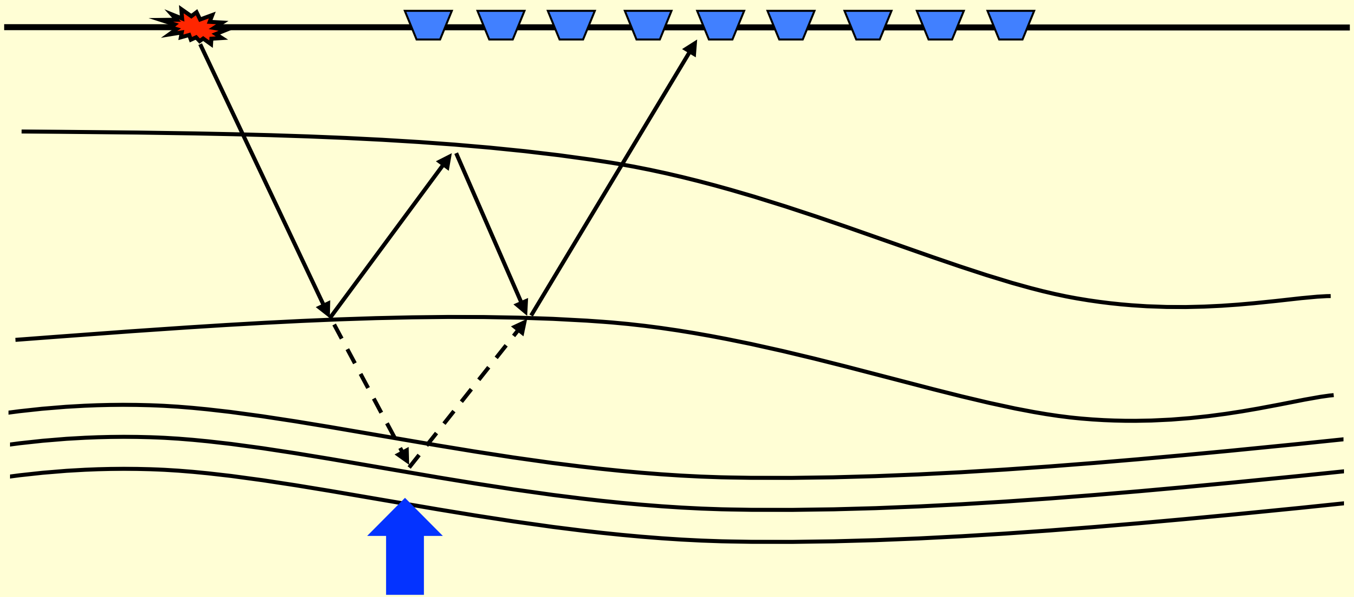
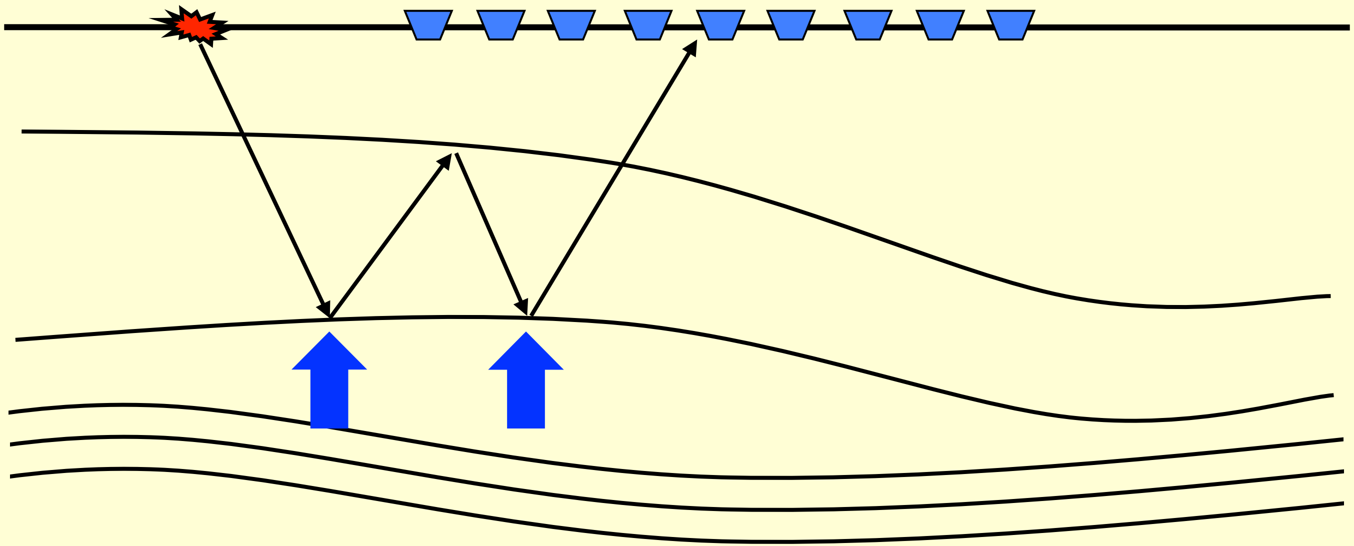


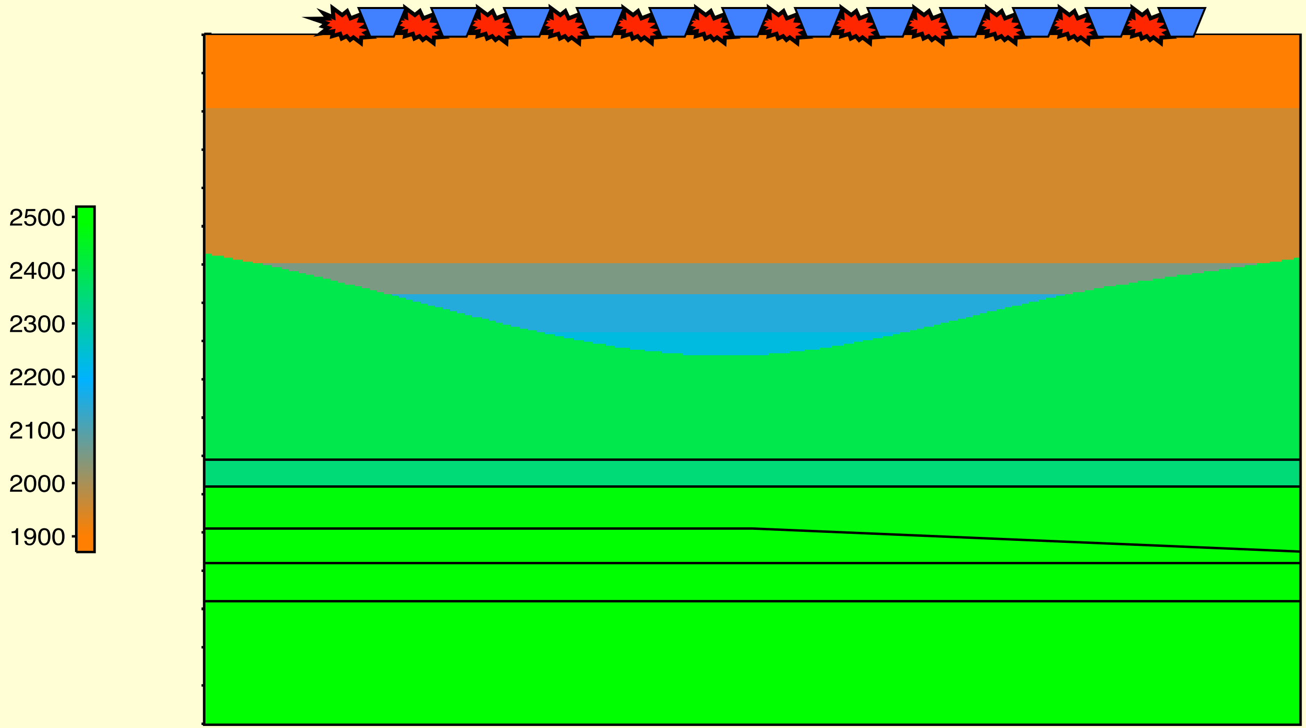
Internal multiples



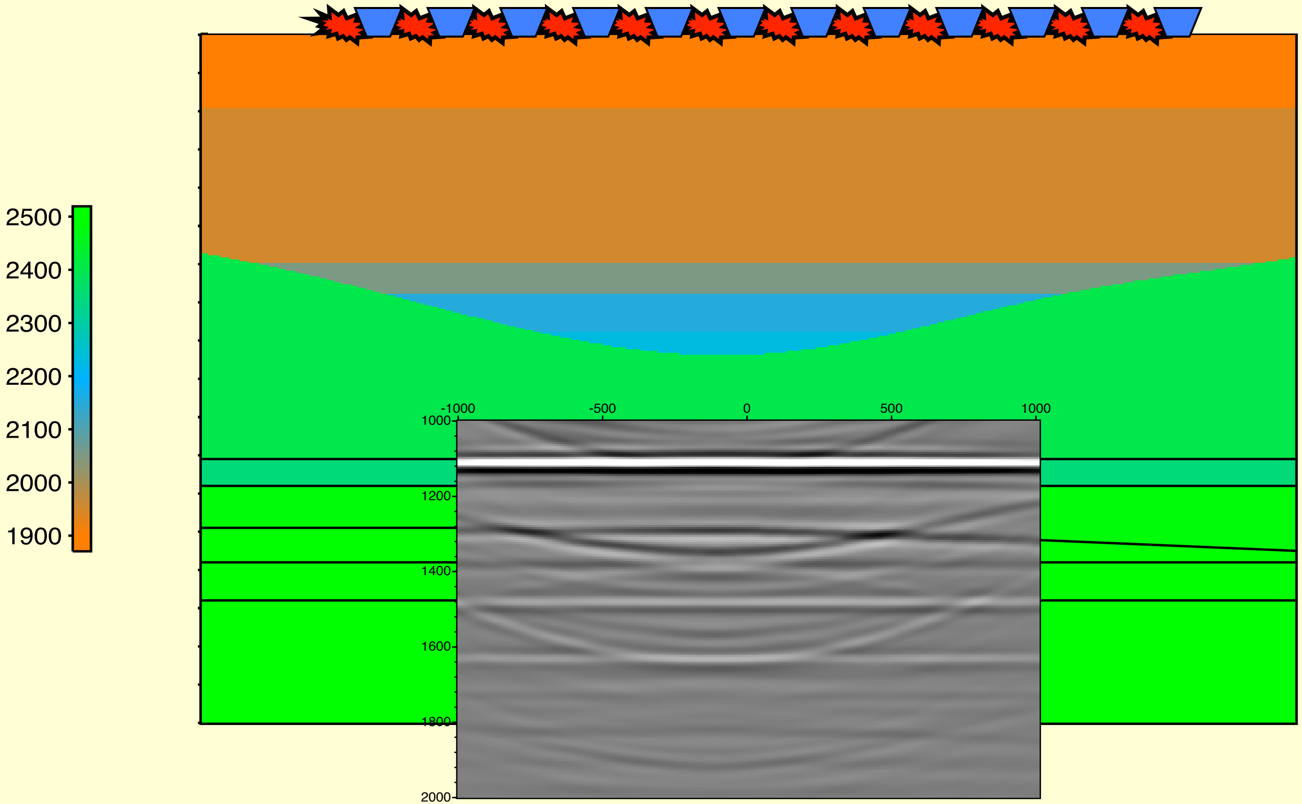
False images from internal multiples



Improved illumination with internal multiples



2500
2400
2300
2200
2100
2000
1900



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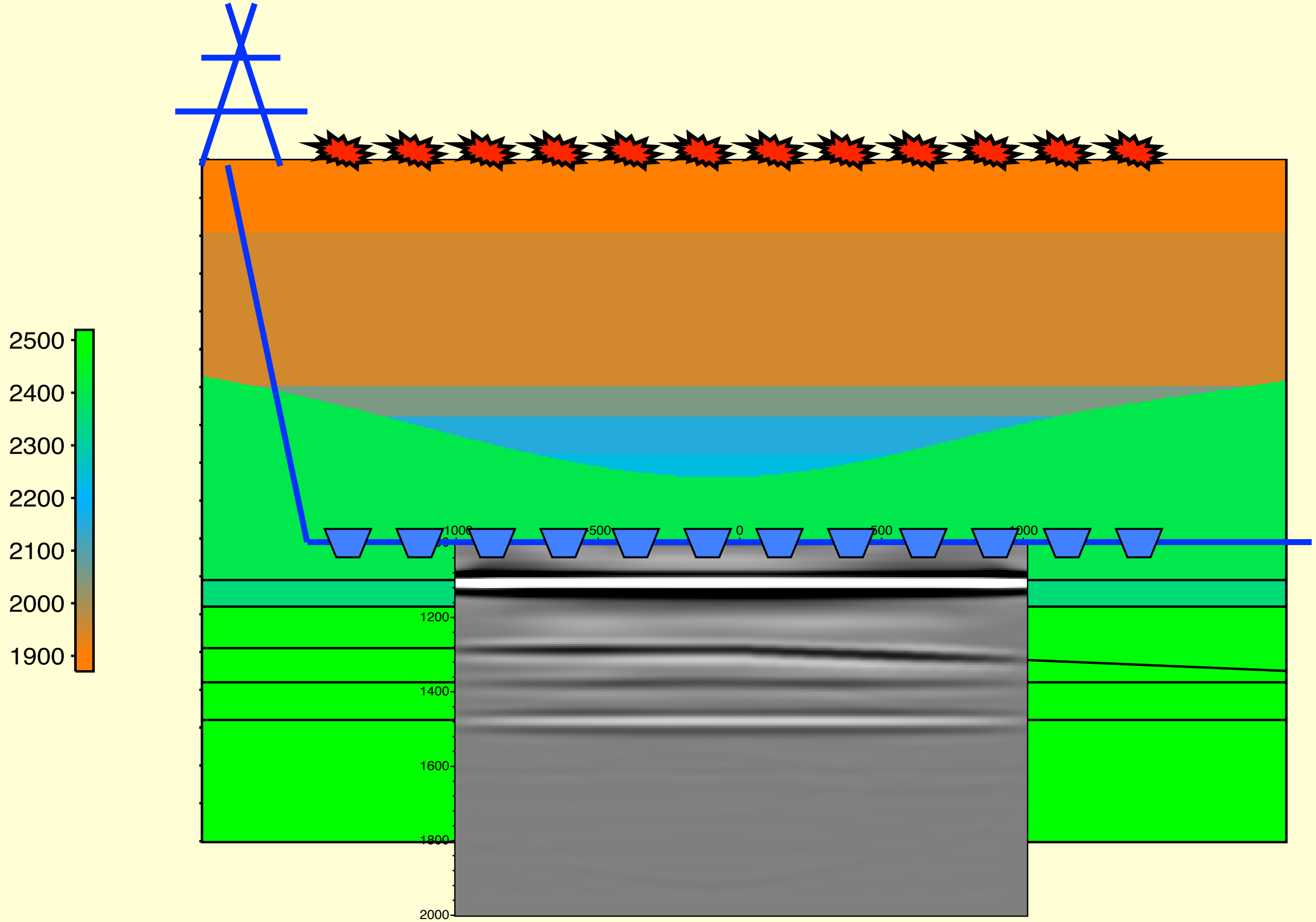
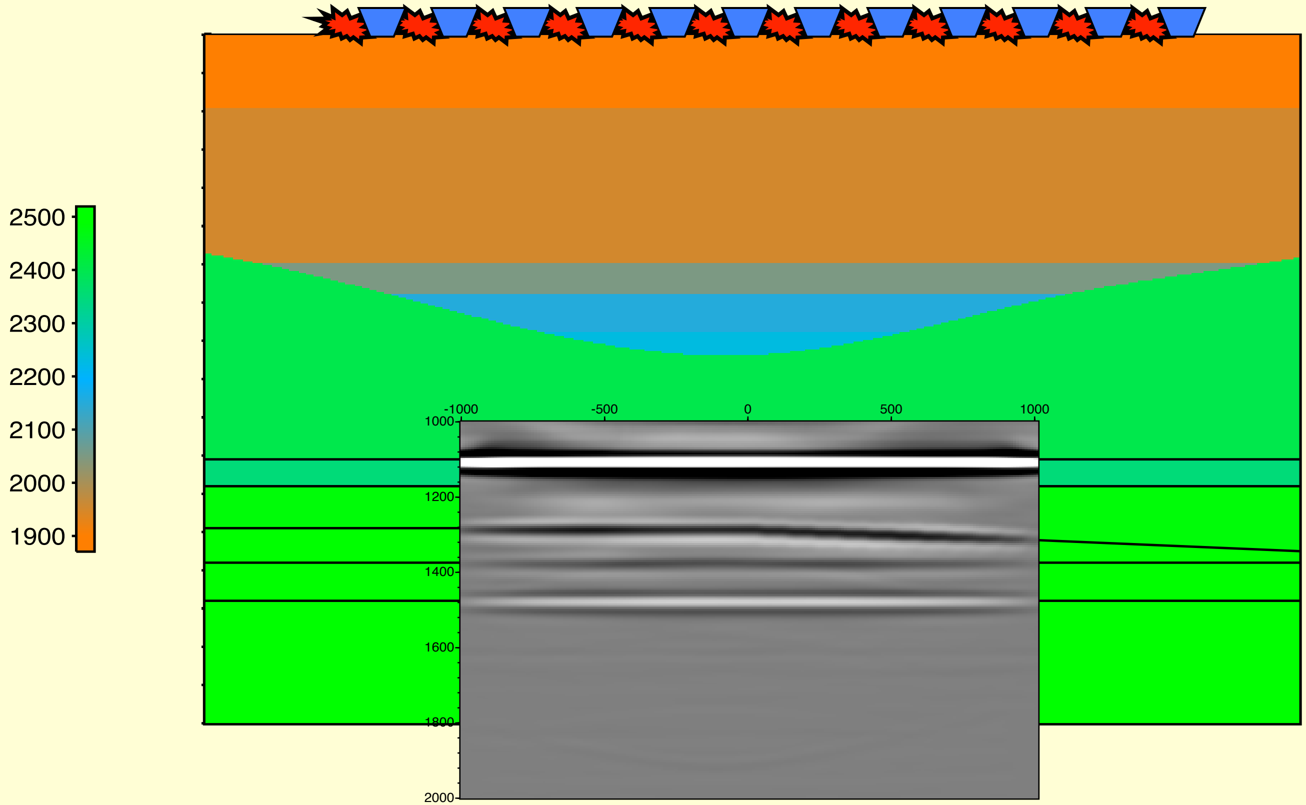
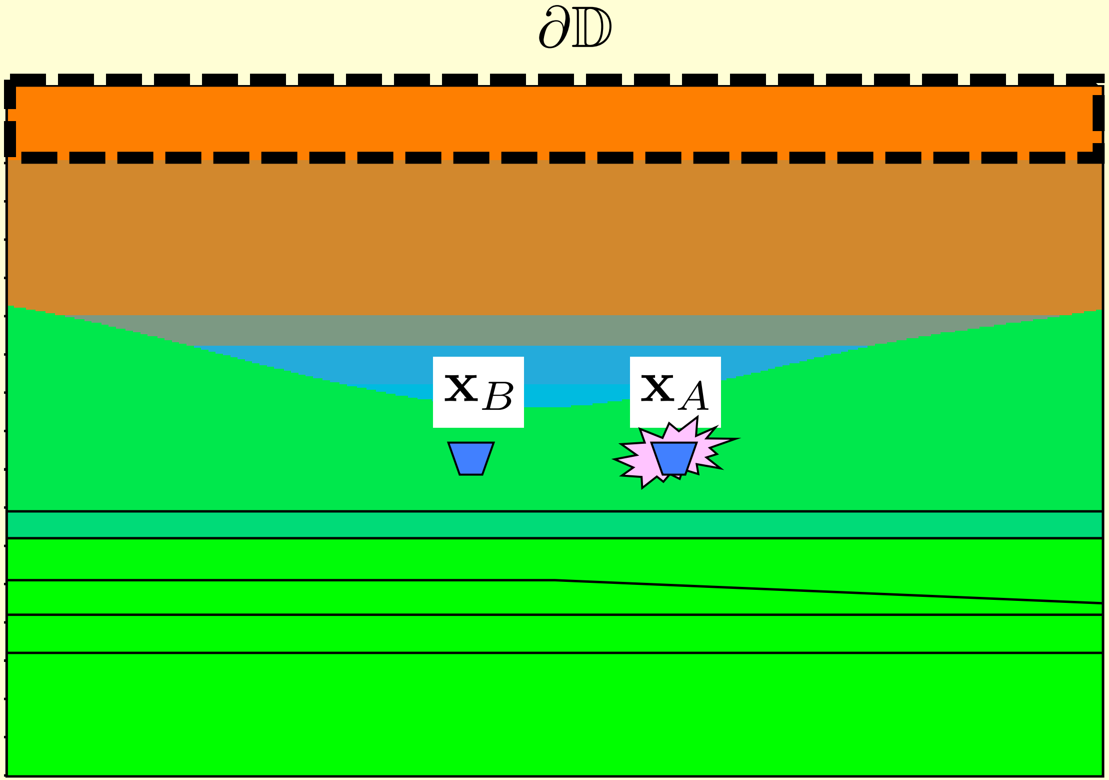


Solution 1: receivers in a borehole



Solution 2: Marchenko imaging



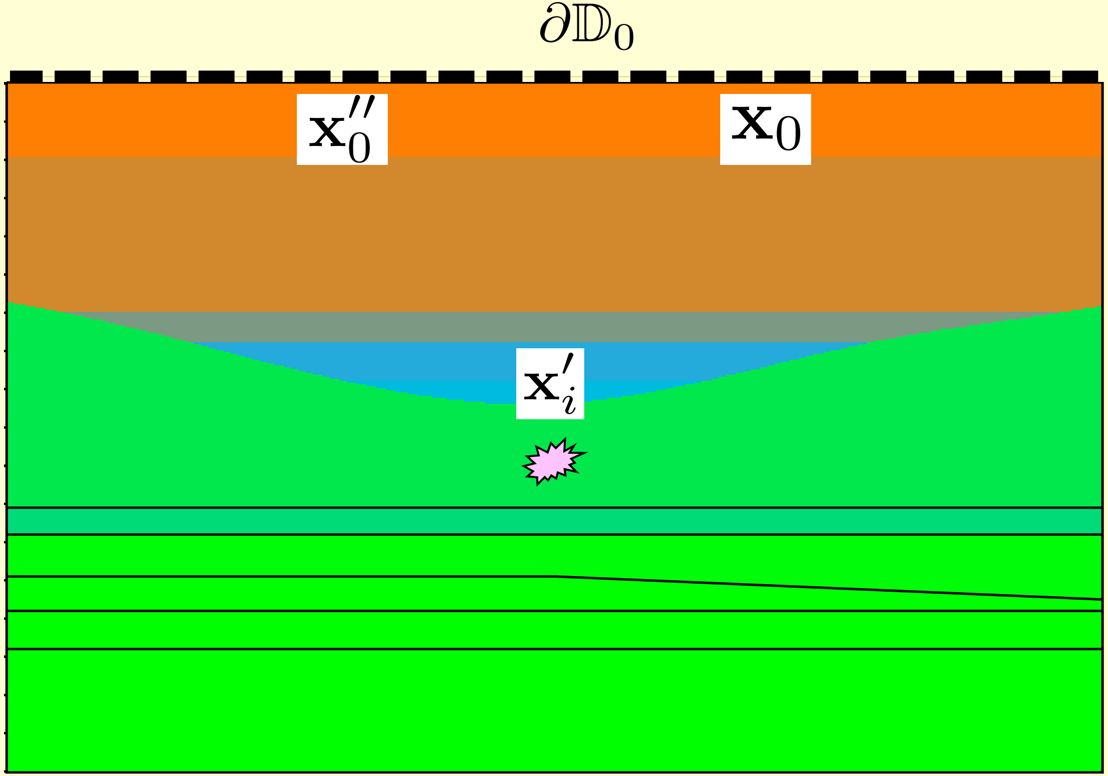
Interferometric Green's function representation:

Sources at $\partial\mathbb{D}$, *enclosing* the medium

Receivers *inside* the medium, at VS position

$$G(\mathbf{x}_B,\mathbf{x}_A,t)+G(\mathbf{x}_B,\mathbf{x}_A,-t)\approx\int_{\partial\mathbb{D}}\mathrm{d}\mathbf{x}\int G(\mathbf{x}_B,\mathbf{x},t+t')G(\mathbf{x}_A,\mathbf{x},t')\mathrm{d}t'$$

(Phys. Rev. Lett., 2004)



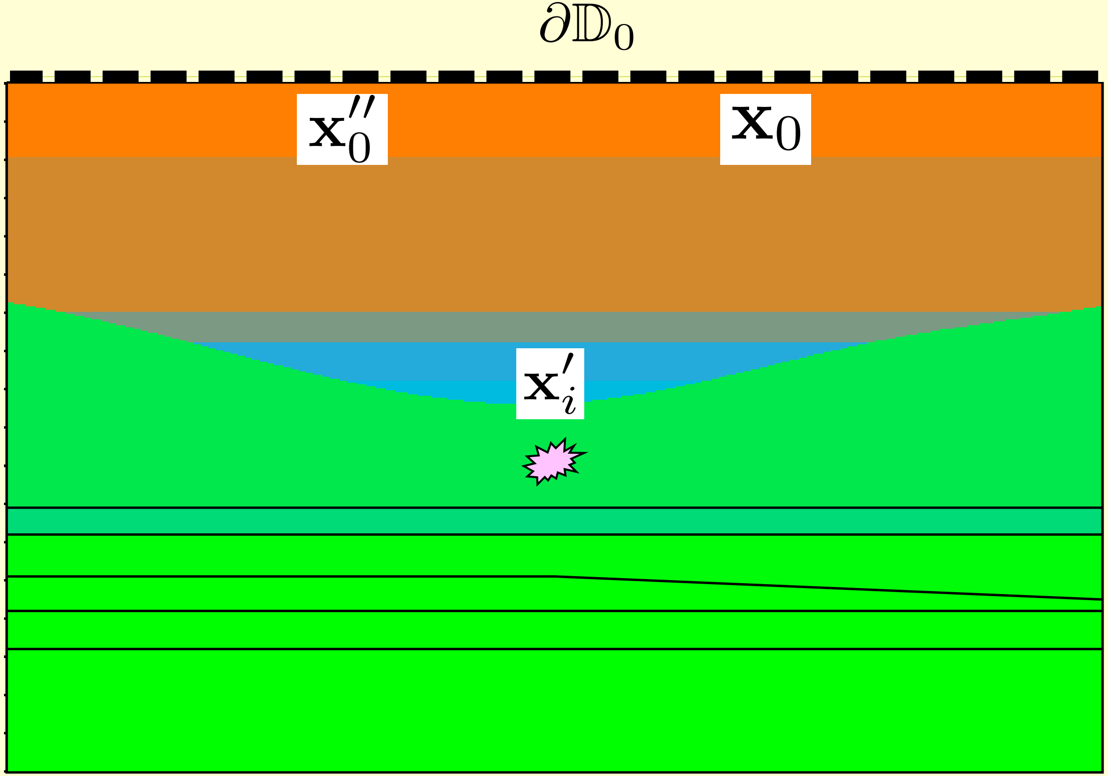
Single-sided Green's function representation:

Sources *and* receivers at $\partial\mathbb{D}_0$, at *one side* of the medium

No receiver at VS!

$$G(\mathbf{x}_0'', \mathbf{x}_i', t) = f_2(\mathbf{x}_i', \mathbf{x}_0'', -t) + \int_{\partial\mathbb{D}_0} \mathrm{d}\mathbf{x}_0 \int_{-\infty}^{t} R(\mathbf{x}_0'', \mathbf{x}_0, t - t') f_2(\mathbf{x}_i', \mathbf{x}_0, t') \mathrm{d}t'$$

(Phys. Rev. Lett., 2013)



Assumption:
Lossless medium

Approximation:
Evanescent field
not included

$$G(\mathbf{x}_0'', \mathbf{x}_i', t) = f_2(\mathbf{x}_i', \mathbf{x}_0'', -t) + \int_{\partial\mathbb{D}_0} \mathrm{d}\mathbf{x}_0 \int_{-\infty}^{t} R(\mathbf{x}_0'', \mathbf{x}_0, t - t') f_2(\mathbf{x}_i', \mathbf{x}_0, t') \mathrm{d}t'$$

(Phys. Rev. Lett., 2013)

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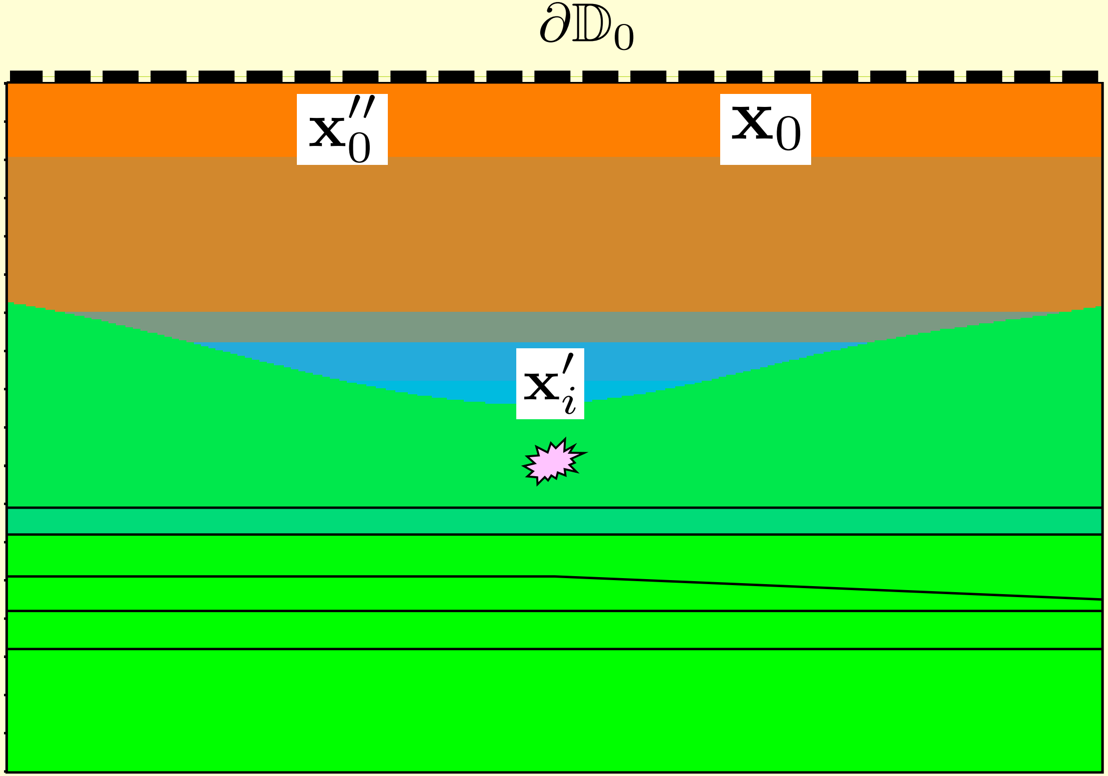
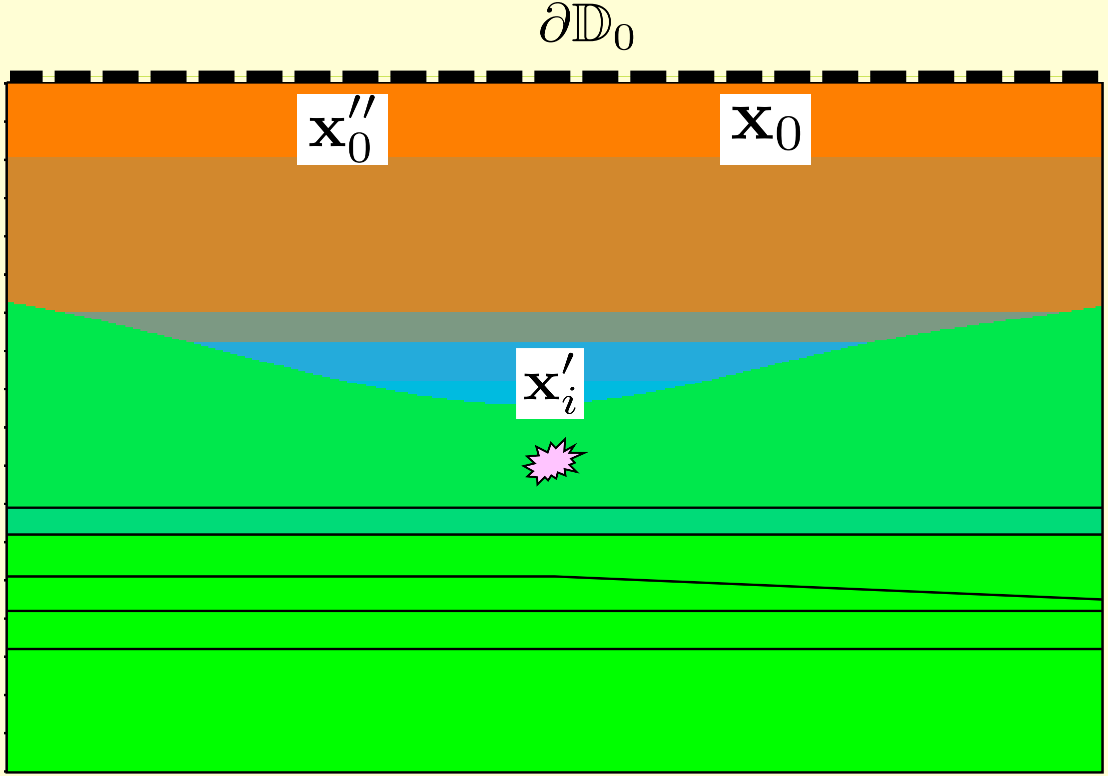


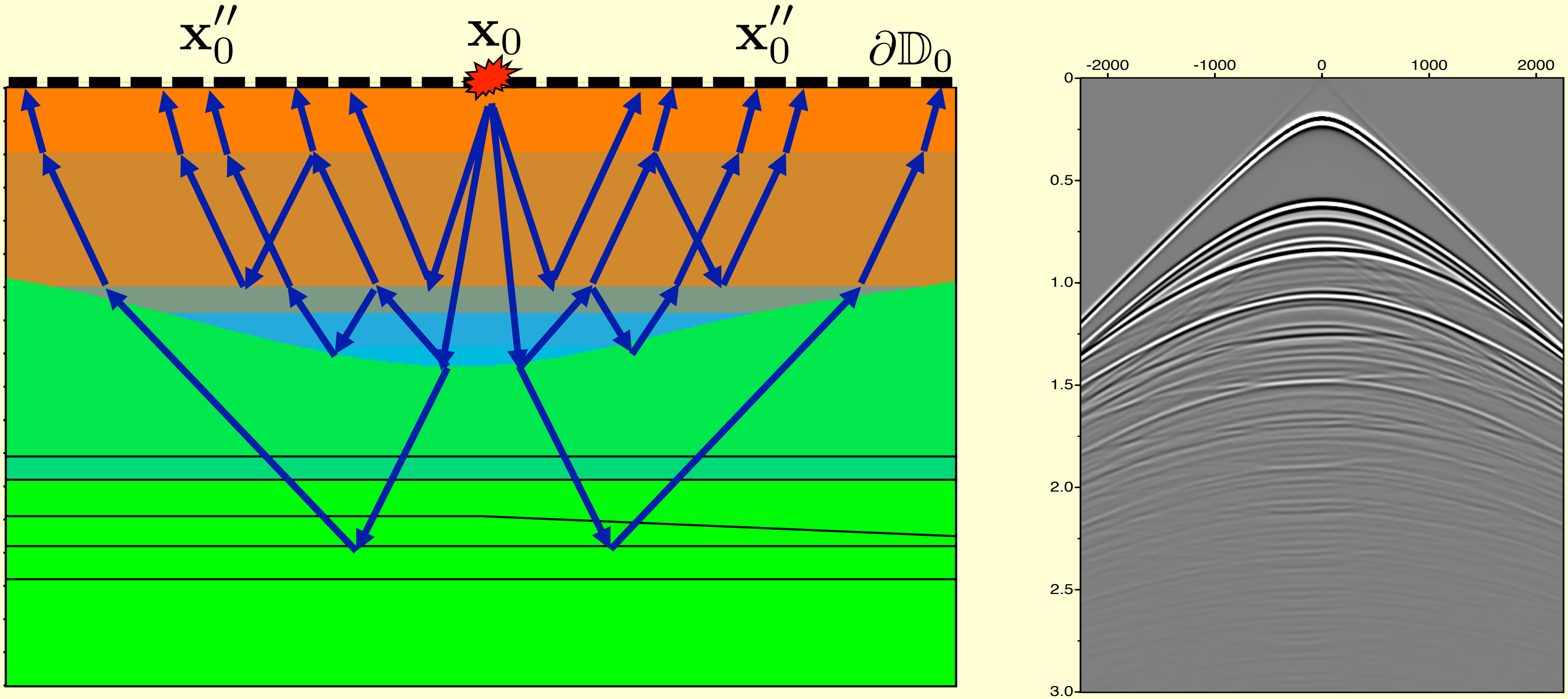
Single-sided Green's function representation

$$G(\mathbf{x}_0'', \mathbf{x}_i', t) - f_2(\mathbf{x}_i', \mathbf{x}_0'', -t) = \int_{\partial\mathbb{D}_0} \mathrm{d}\mathbf{x}_0 \int_{-\infty}^{t} R(\mathbf{x}_0'', \mathbf{x}_0, t - t') f_2(\mathbf{x}_i', \mathbf{x}_0, t') \mathrm{d}t'$$

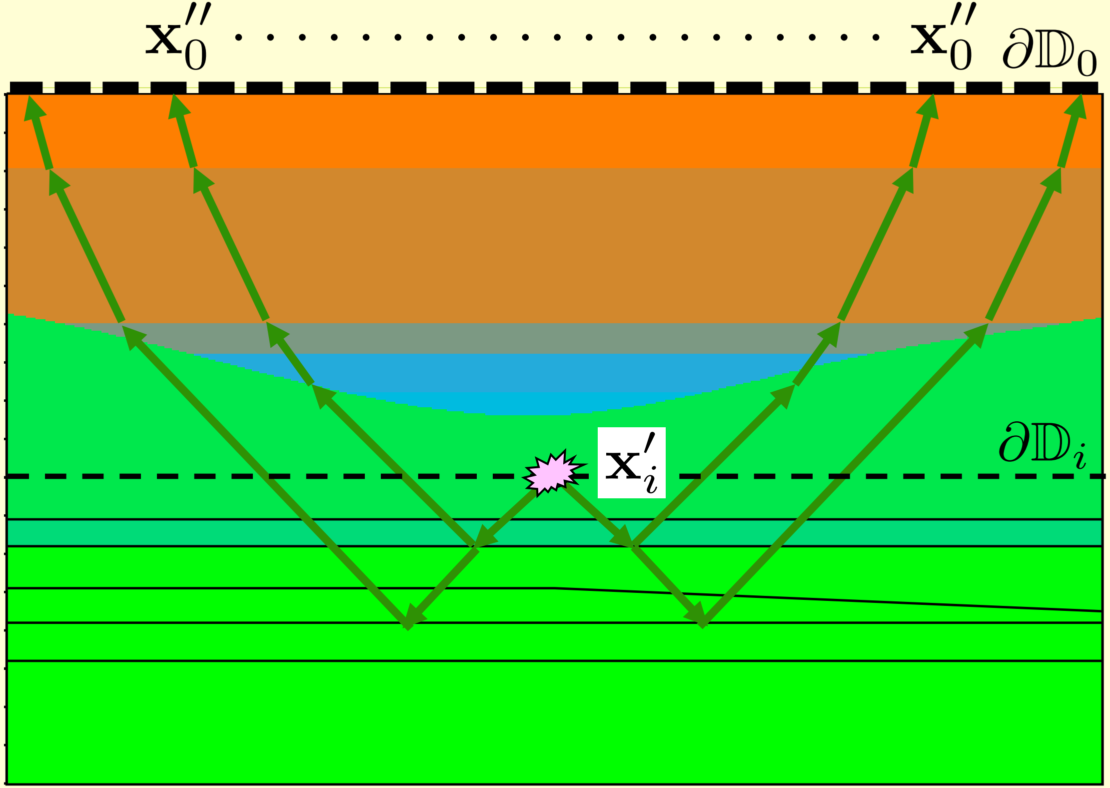


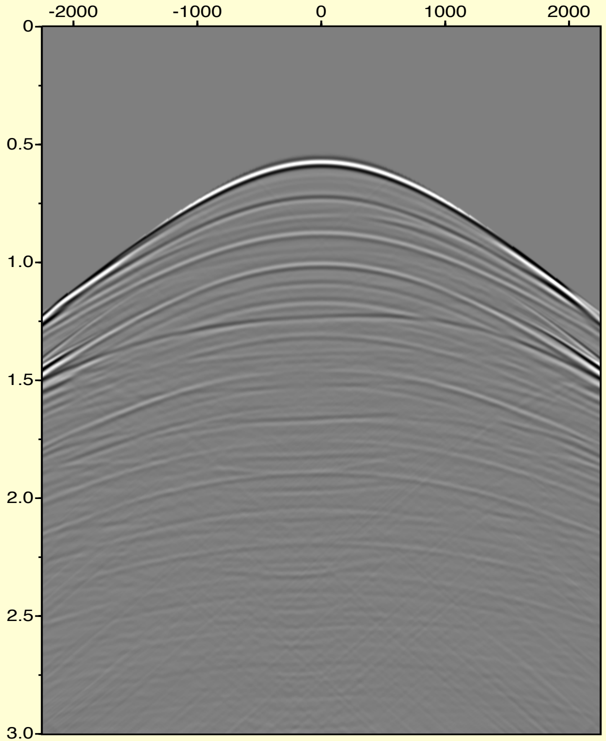
Decomposed
Single-sided
Green's function
representations

$$G^{-,+}(\mathbf{x}_0'', \mathbf{x}_i', t) + f_1^-(\mathbf{x}_0'', \mathbf{x}_i', t) = \int_{\partial\mathbb{D}_0} \mathrm{d}\mathbf{x}_0 \int_{-\infty}^{t} R(\mathbf{x}_0'', \mathbf{x}_0, t-t') f_1^+(\mathbf{x}_0, \mathbf{x}_i', t')\mathrm{d}t'$$

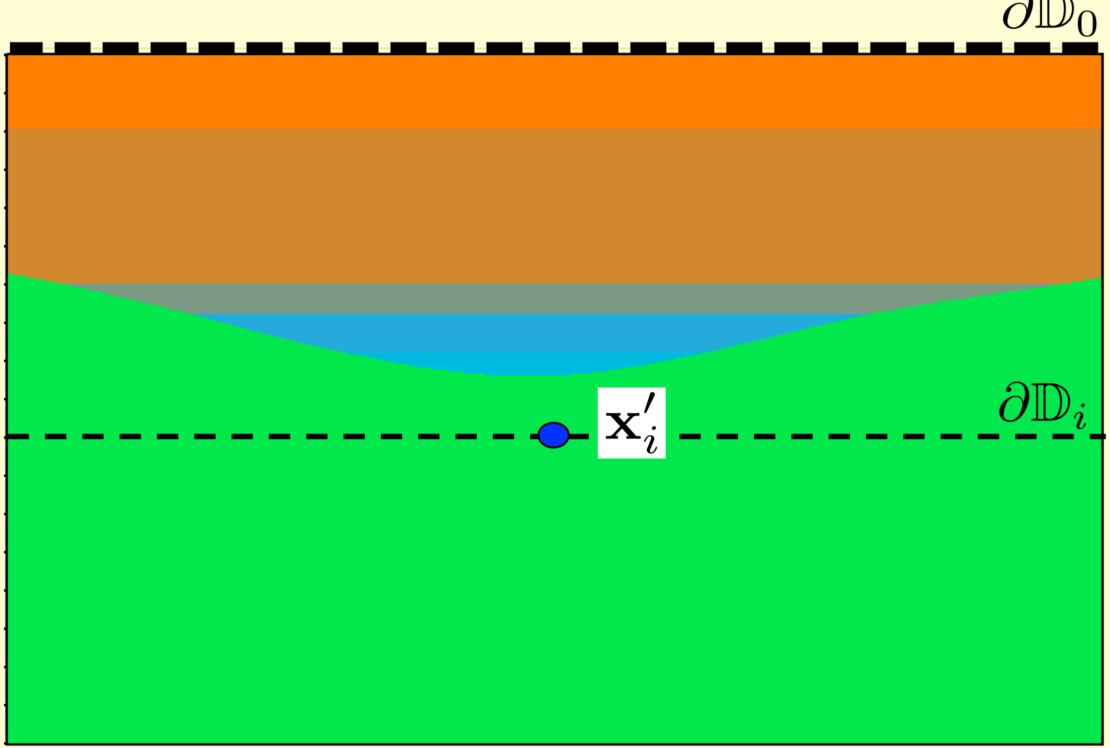


$$G^{-,+}(\mathbf{x}_0'', \mathbf{x}_i', t) + f_1^-(\mathbf{x}_0'', \mathbf{x}_i', t) = \int_{\partial\mathbb{D}_0} \mathrm{d}\mathbf{x}_0 \int_{-\infty}^{t} R(\mathbf{x}_0'', \mathbf{x}_0, t - t') f_1^+(\mathbf{x}_0, \mathbf{x}_i', t') \mathrm{d}t'$$

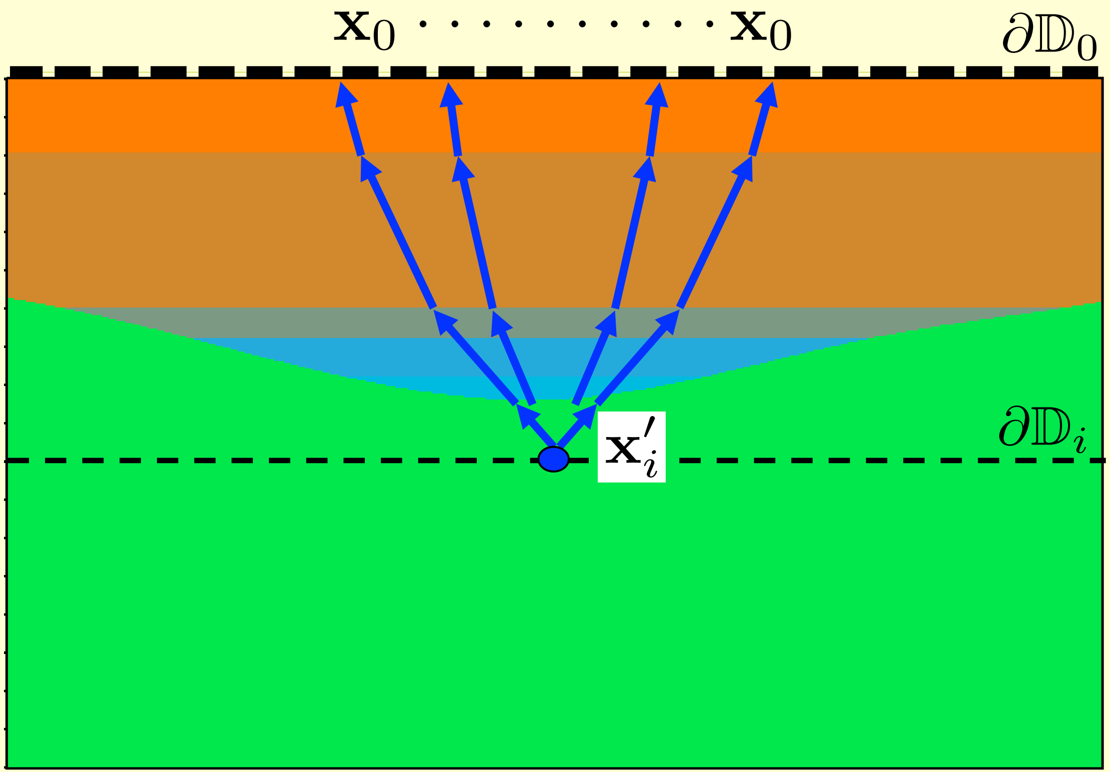


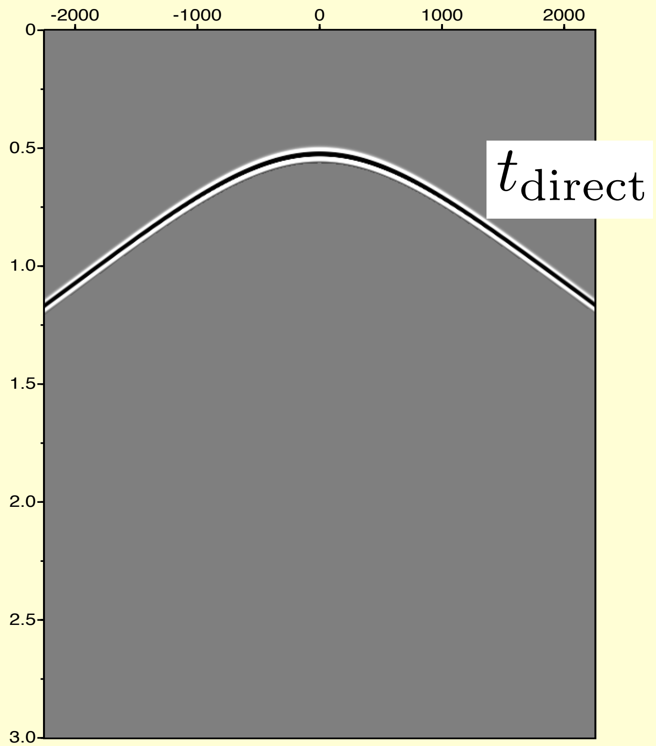


$$G^{-,+}(\mathbf{x}_0'',\mathbf{x}_i',t)+f_1^{-}(\mathbf{x}_0'',\mathbf{x}_i',t)=\int_{\partial\mathbb{D}_0}\mathrm{d}\mathbf{x}_0\int_{-\infty}^{t}R(\mathbf{x}_0'',\mathbf{x}_0,t-t')f_1^{+}(\mathbf{x}_0,\mathbf{x}_i',t')\mathrm{d}t'$$

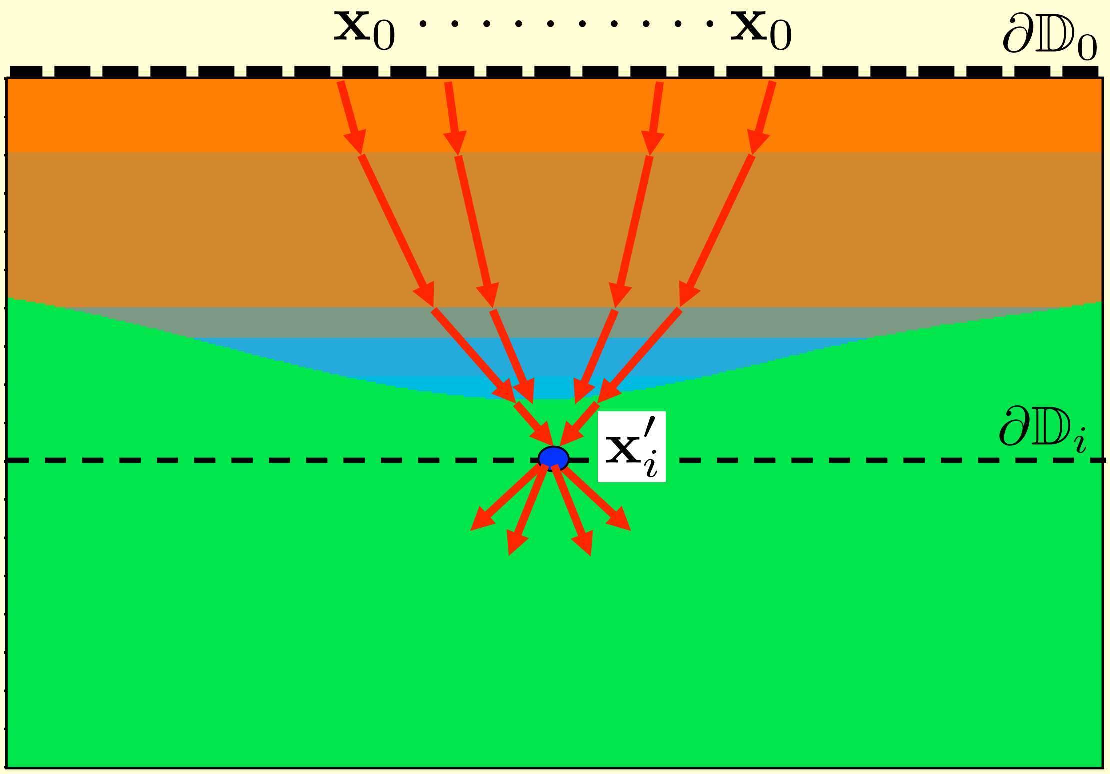


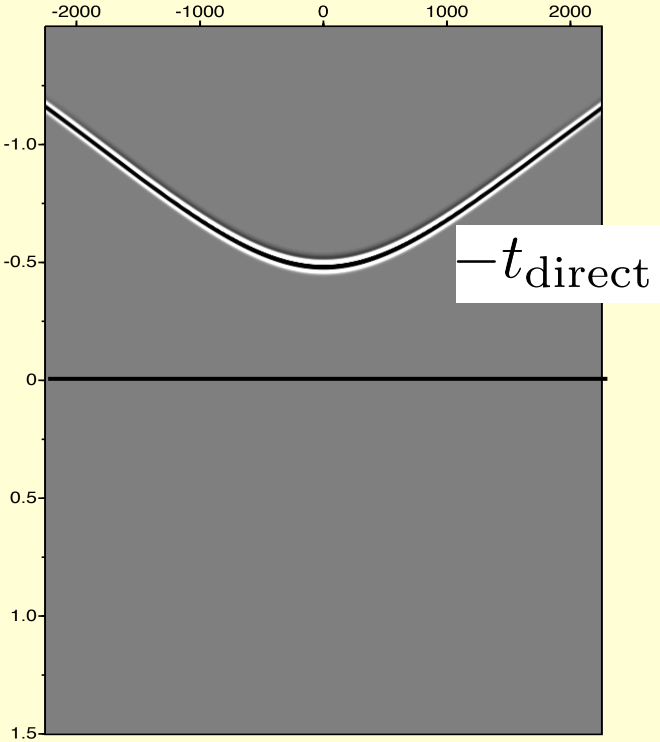
$\partial\mathbb{D}_0$
$\mathbf{x}'_i$
$\partial\mathbb{D}_i$



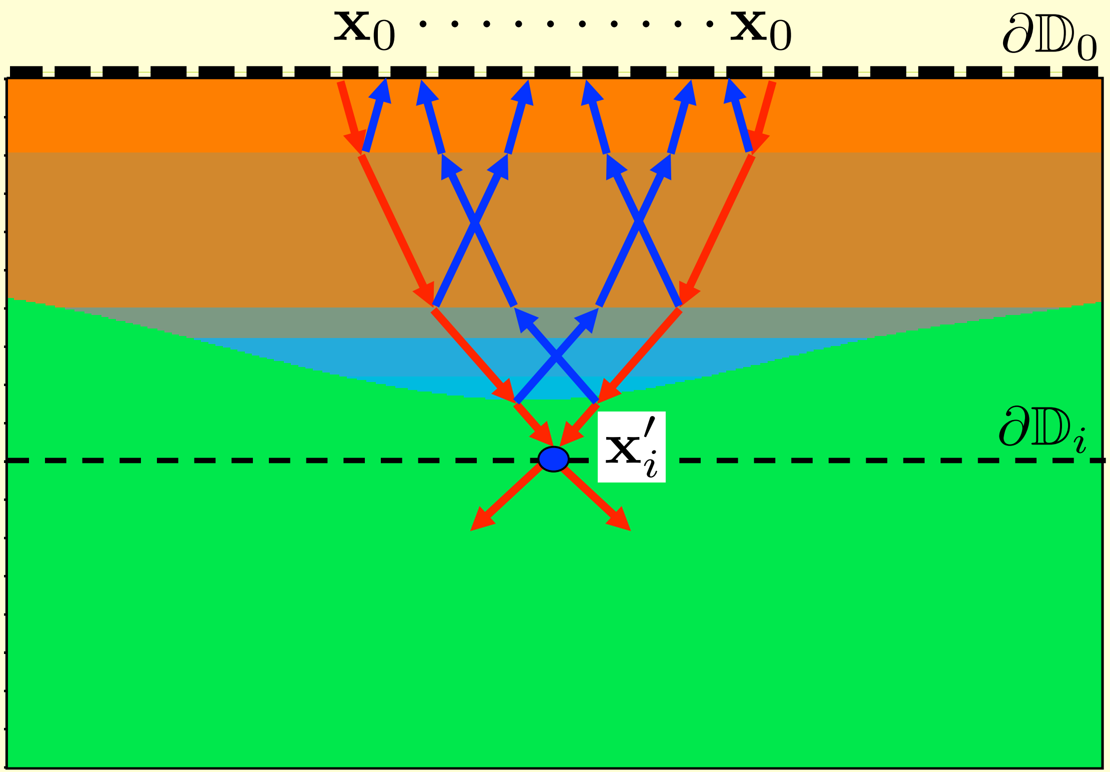


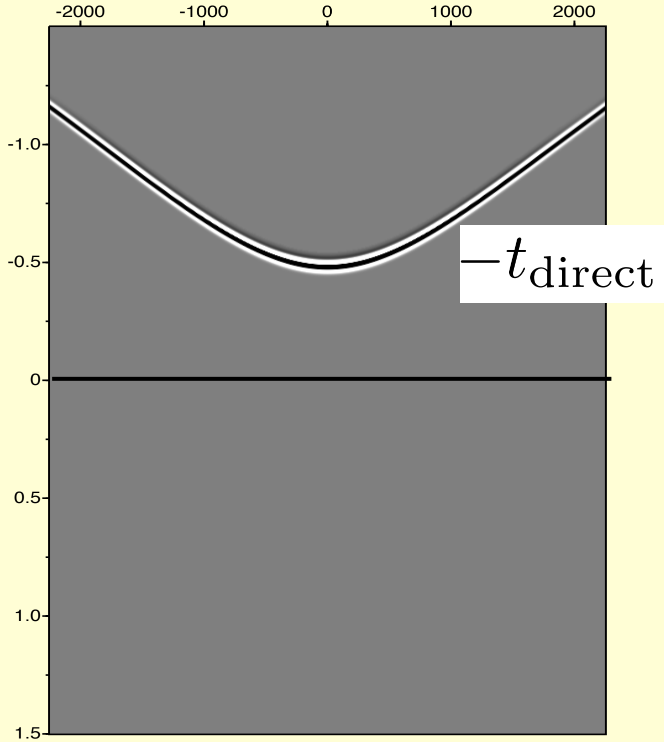
$$G_{\mathrm{d}}(\mathbf{x}_0, \mathbf{x}_i', t)$$



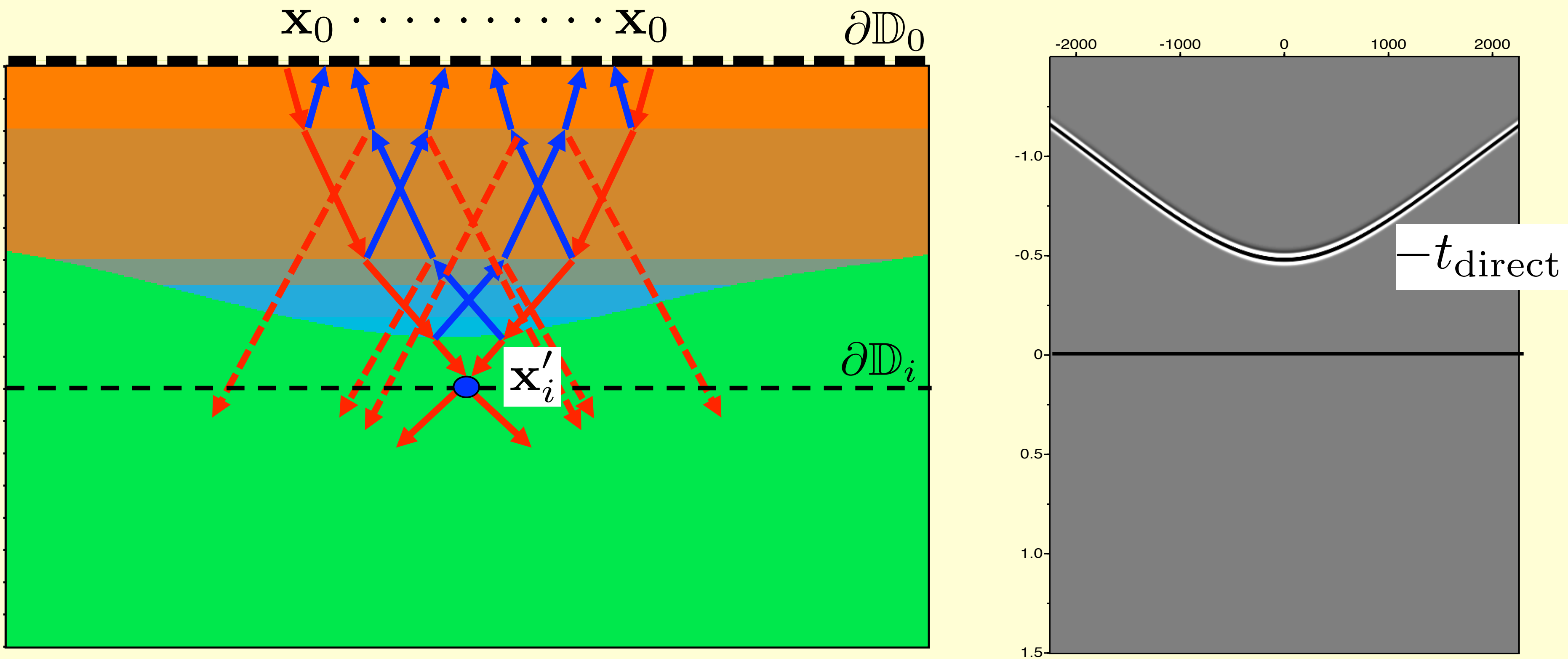


$$f_1^+(\mathbf{x}_0, \mathbf{x}'_i, t)$$

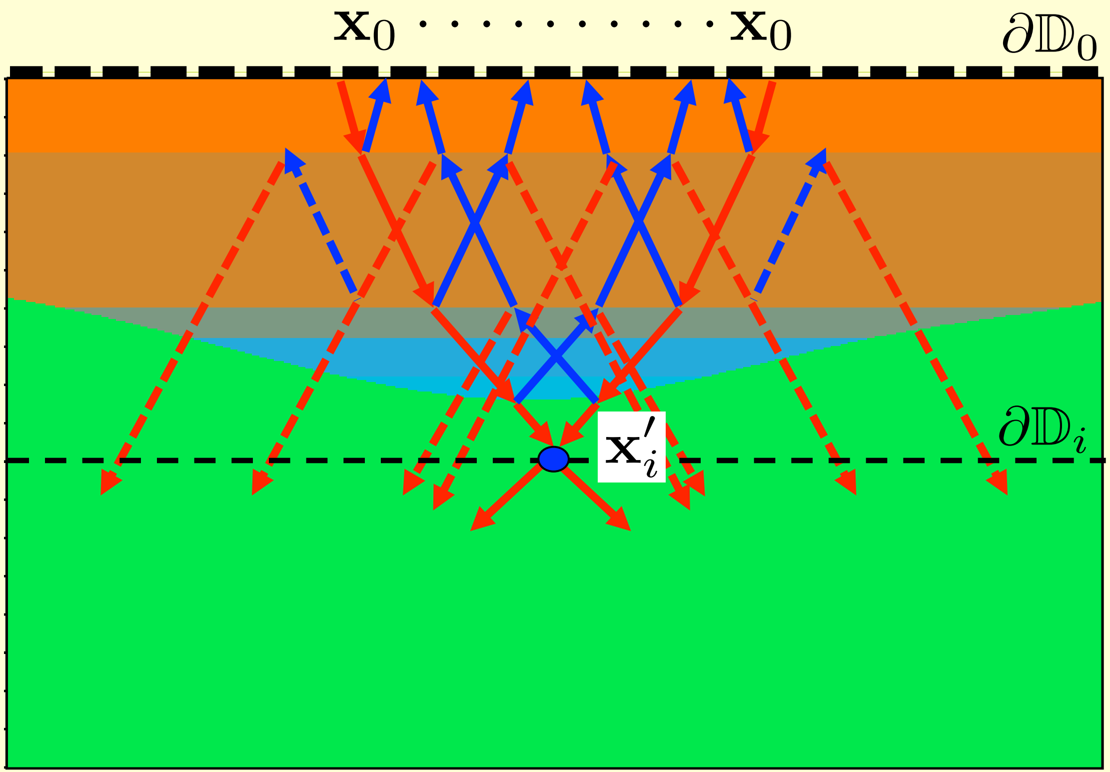


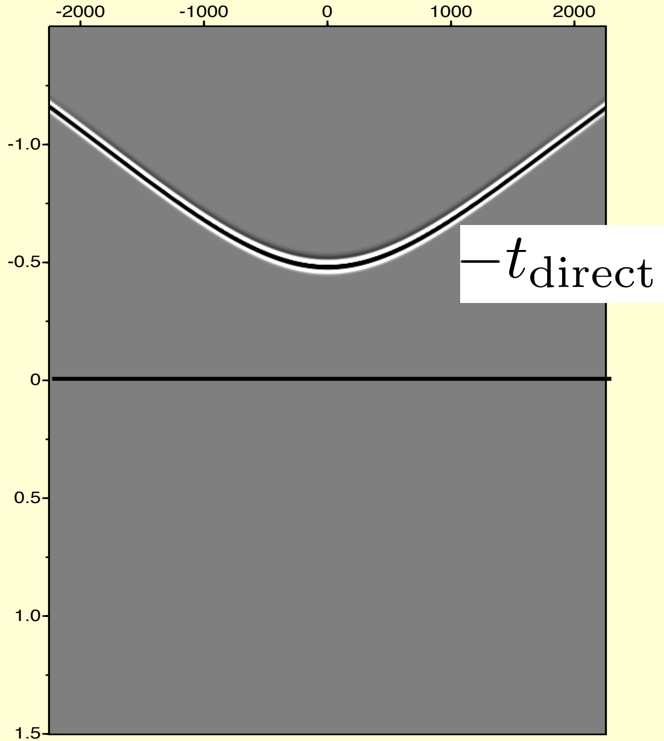


$$f_1^+(\mathbf{x}_0, \mathbf{x}'_i, t)$$

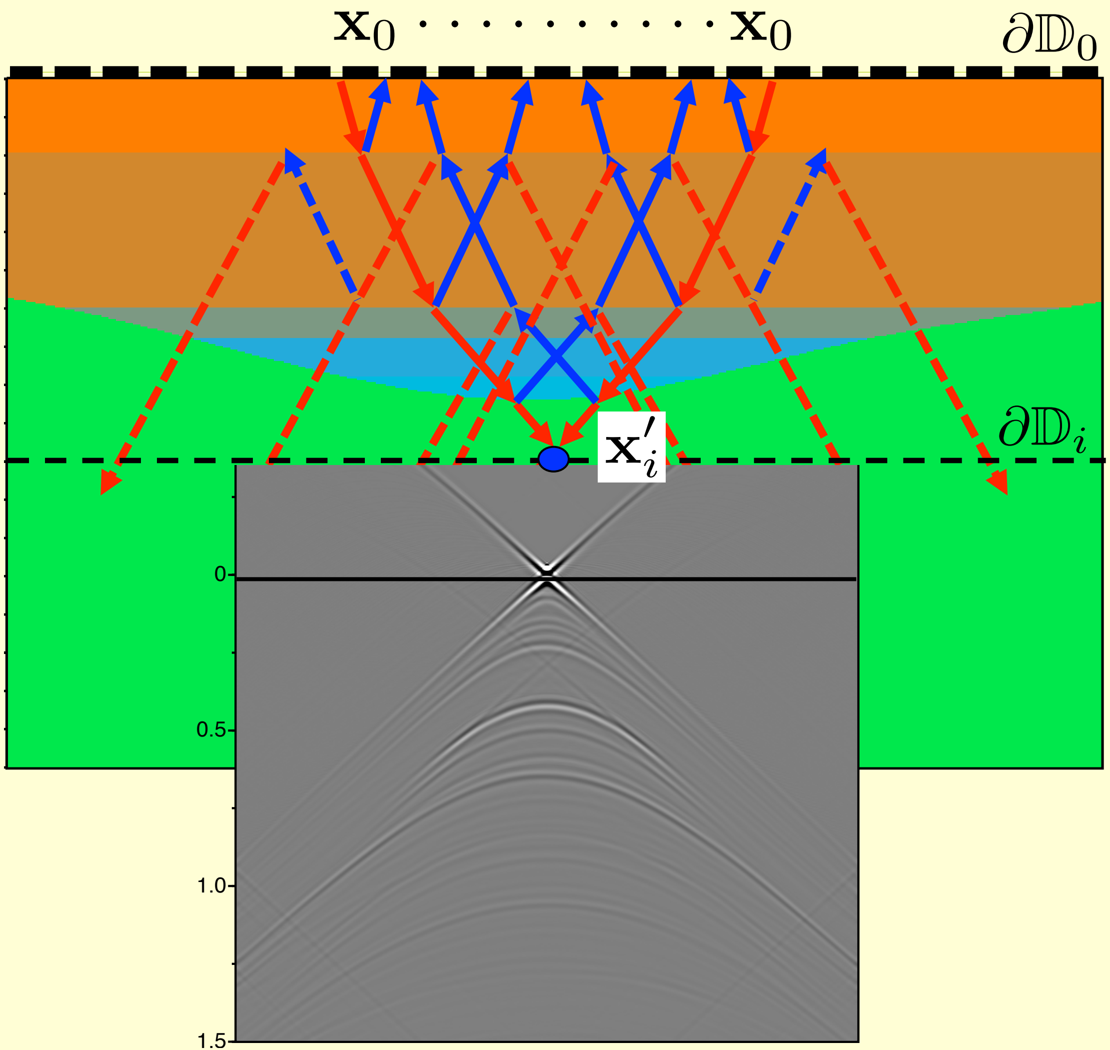


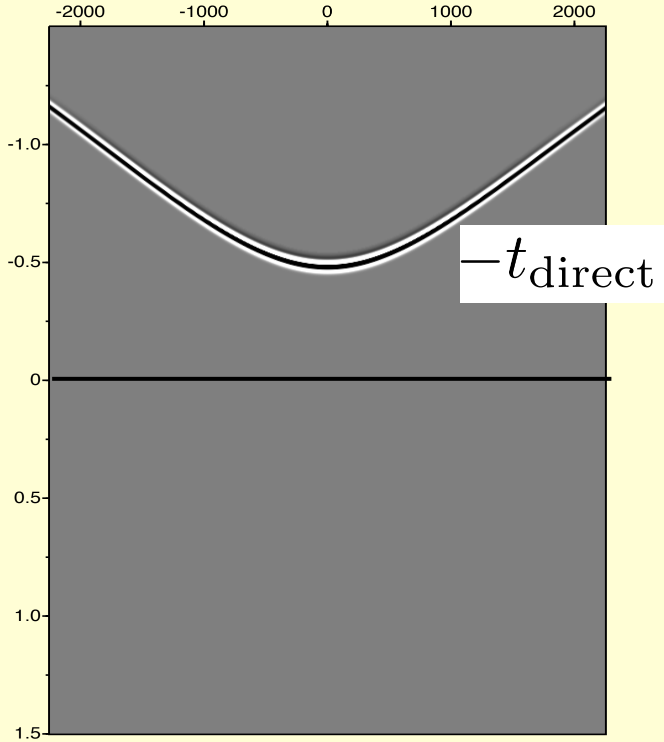
$f_1^+(\mathbf{x}_0, \mathbf{x}_i', t)$





$f_1^+(\mathbf{x}_0, \mathbf{x}_i', t)$





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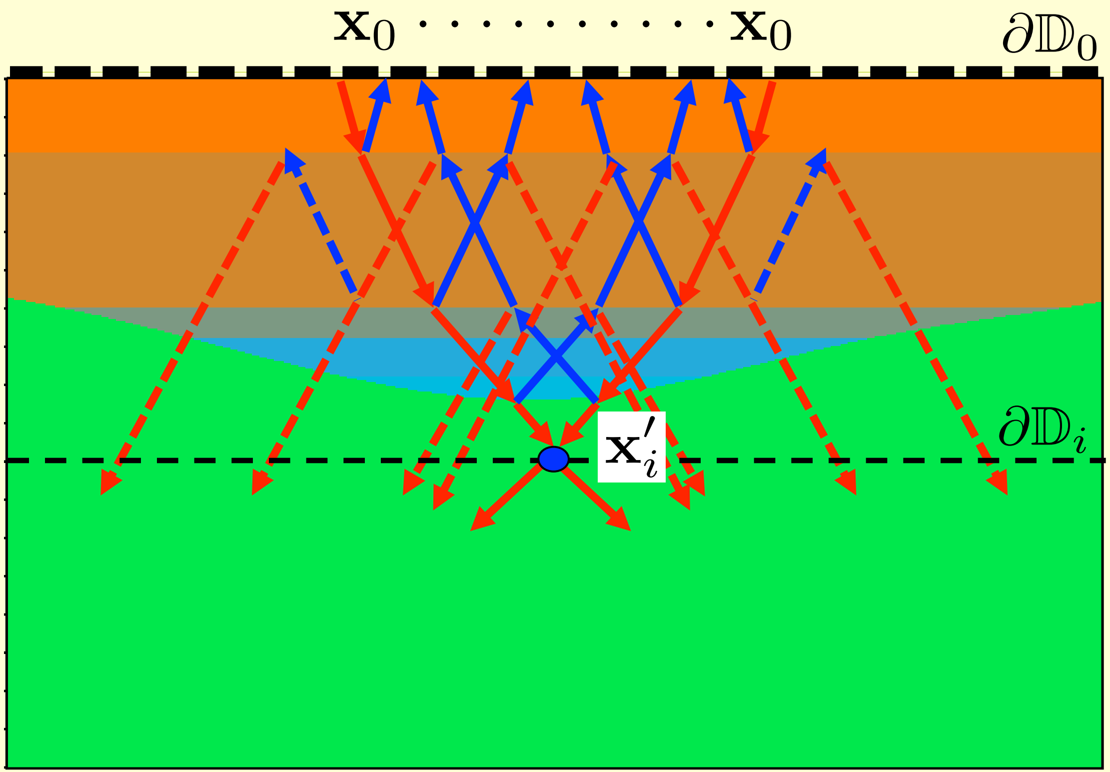
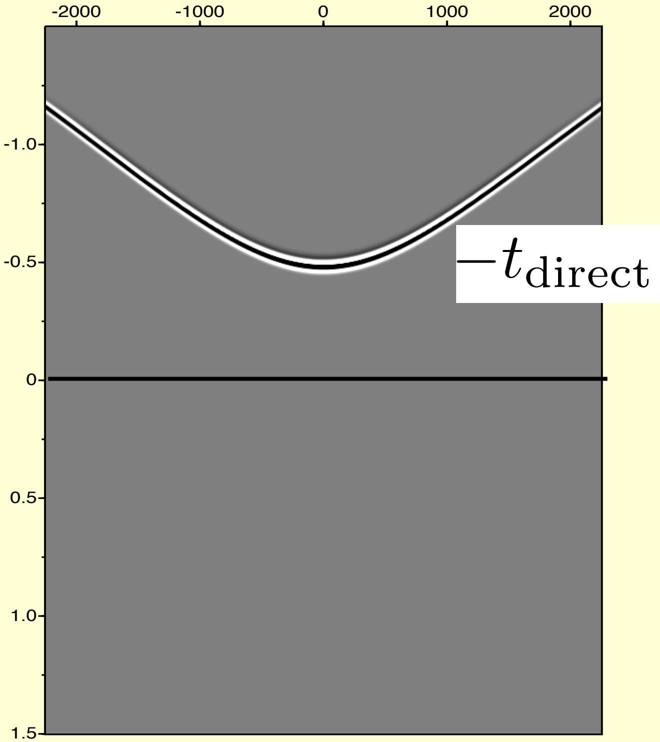
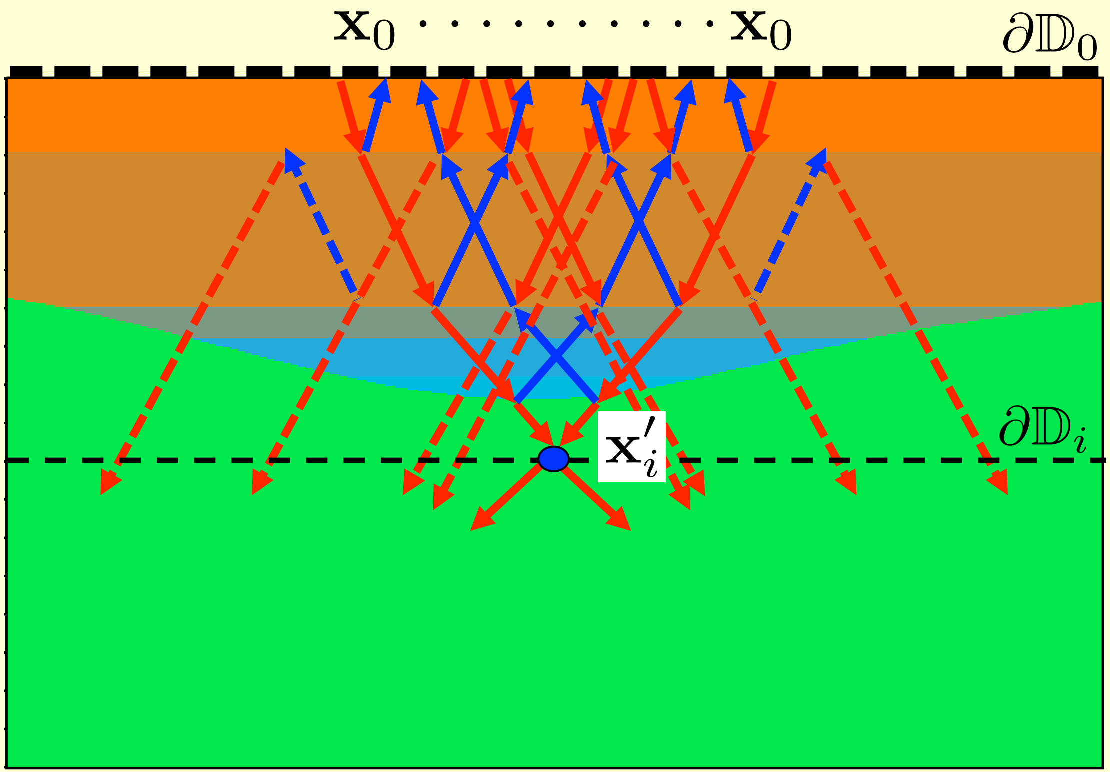
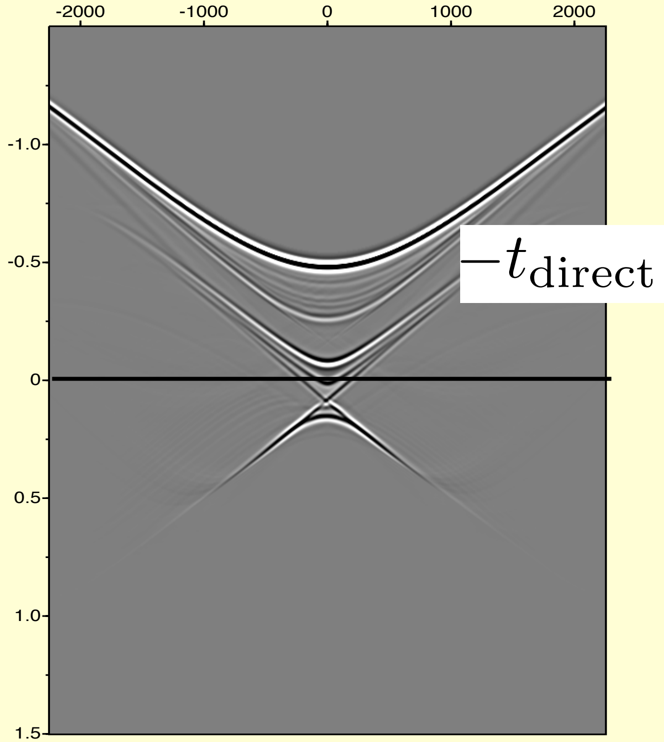


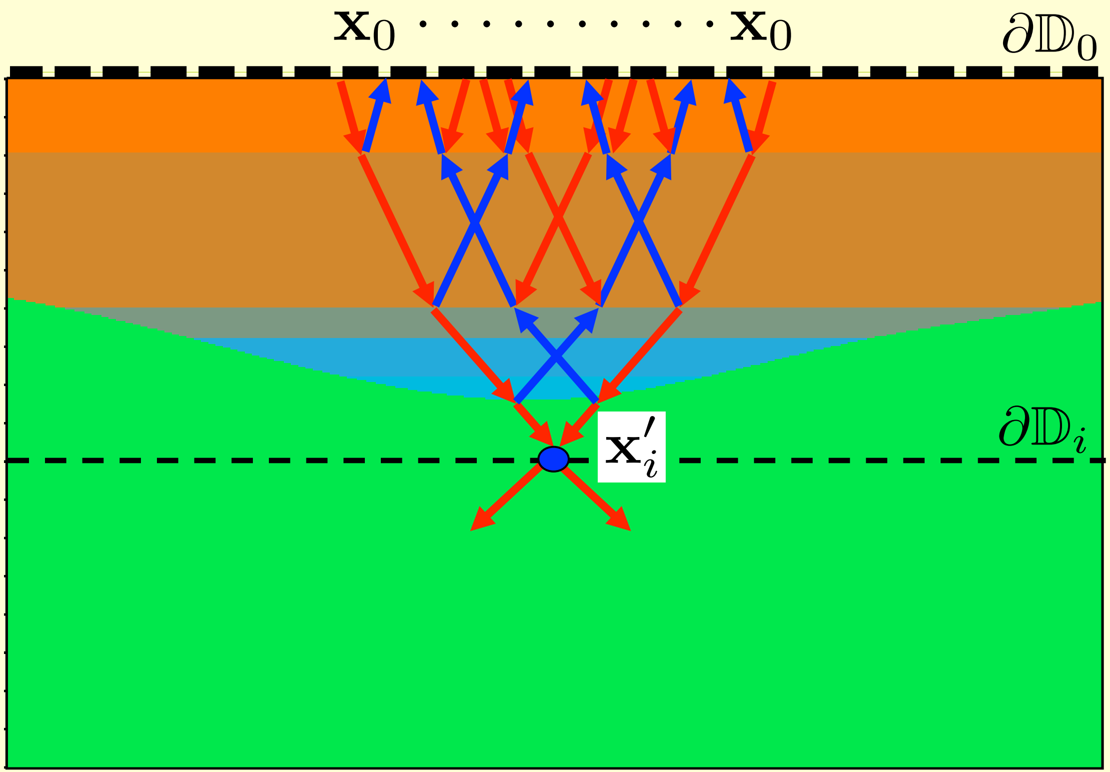


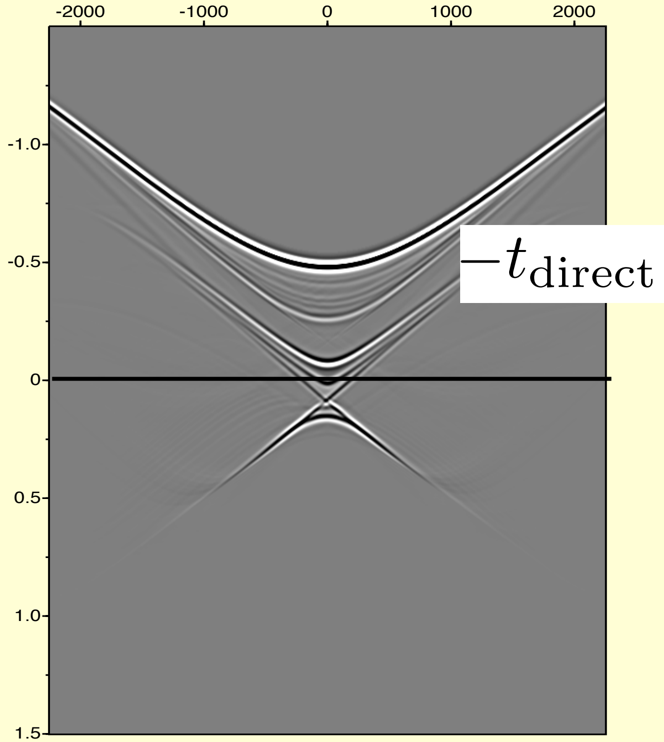
$f_1^+(\mathbf{x}_0, \mathbf{x}'_i, t)$



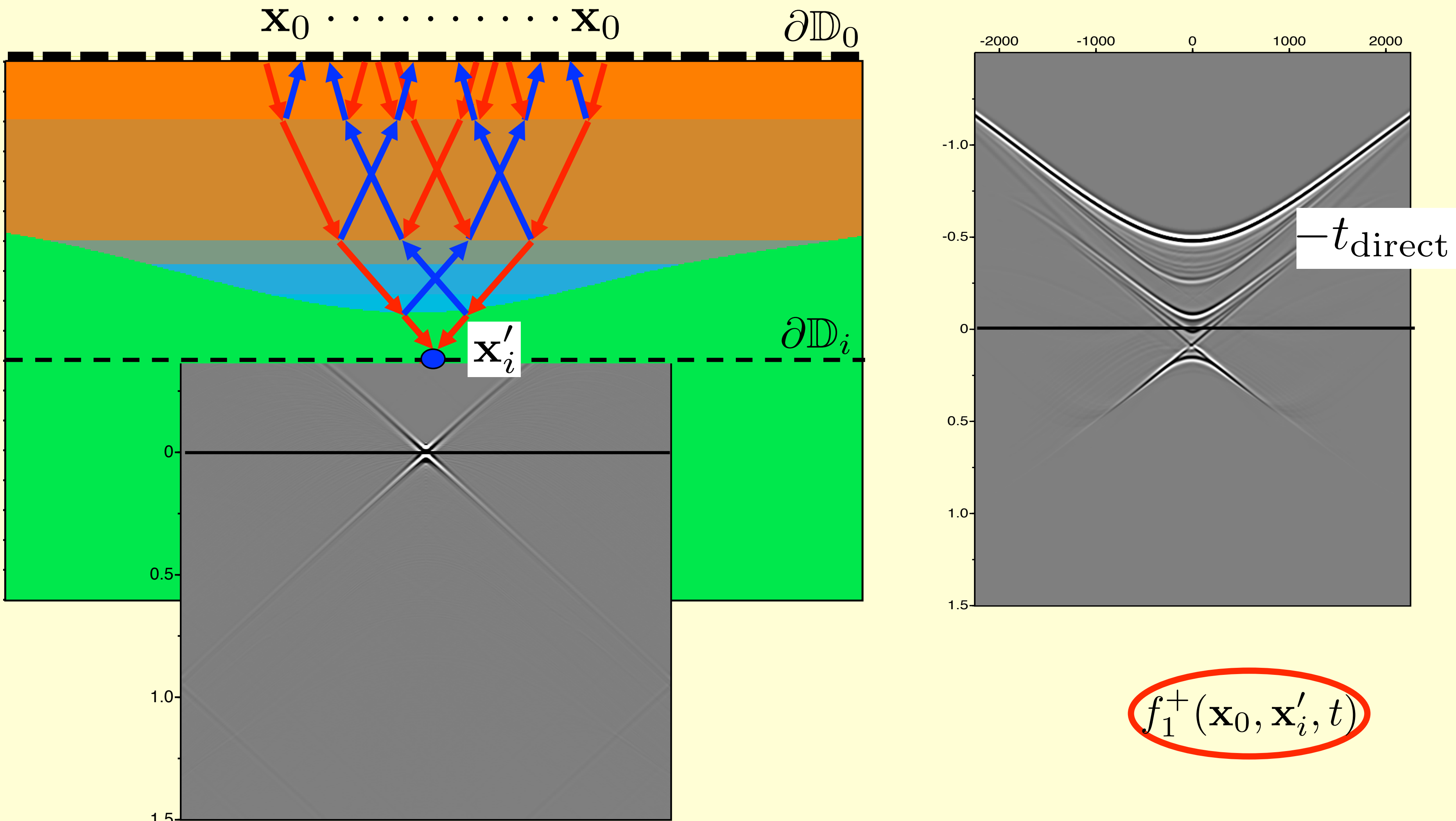


$f_1^+(\mathbf{x}_0, \mathbf{x}_i', t)$

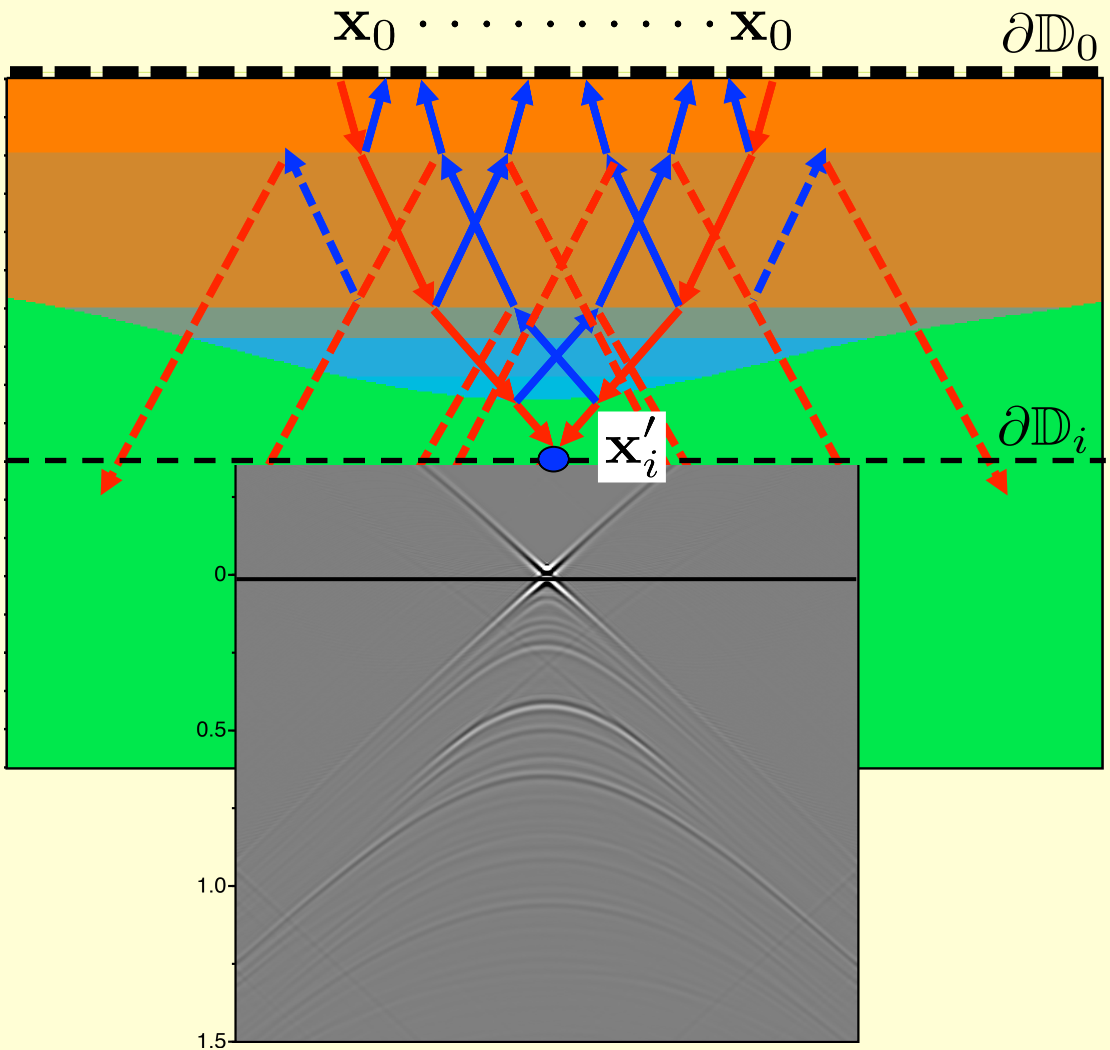


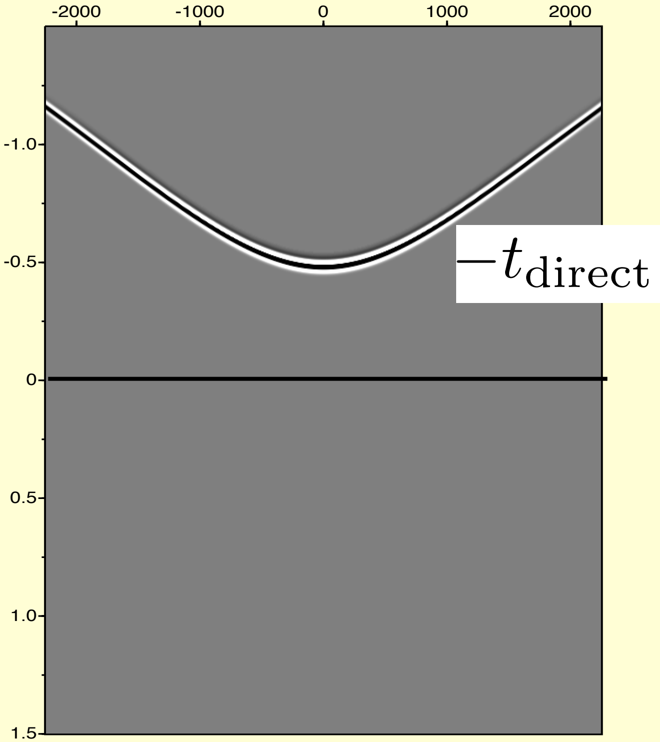


$f_1^+(\mathbf{x}_0, \mathbf{x}_i', t)$

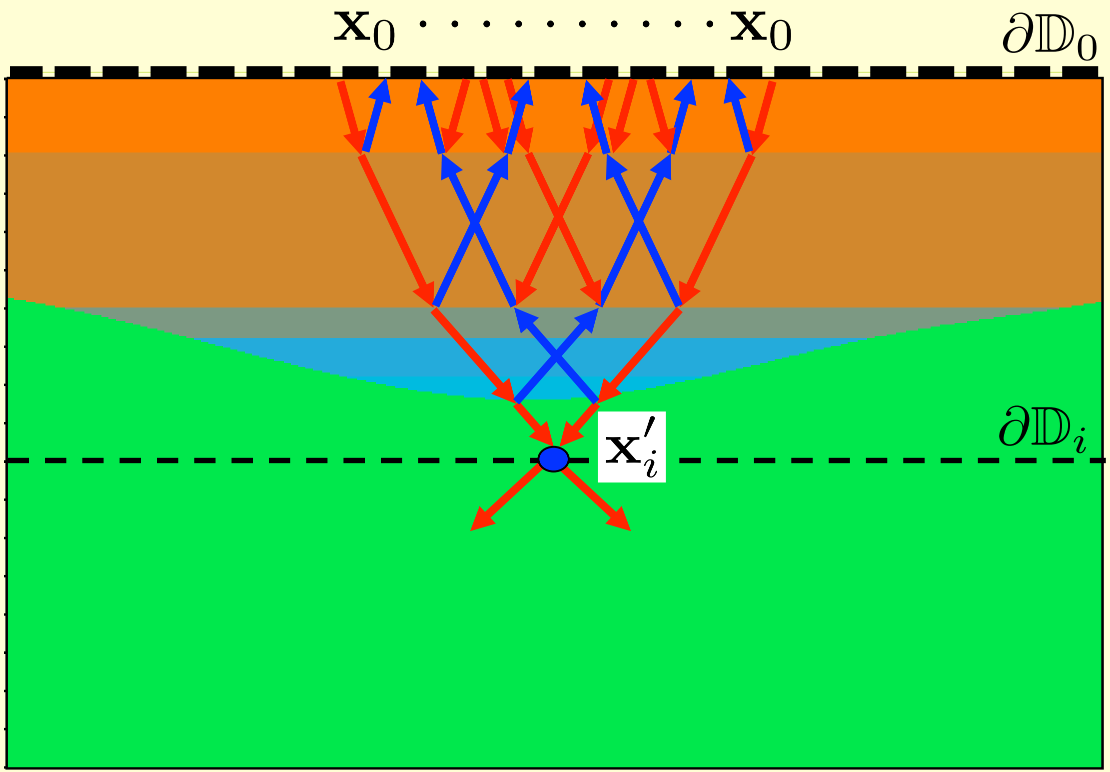


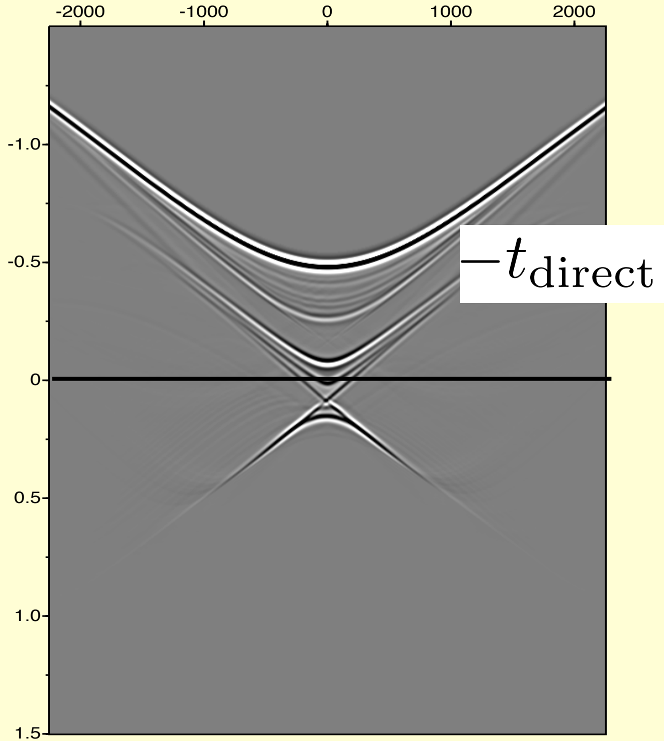
$\mathbf{x}_0 \cdots\cdots\cdots \mathbf{x}_0$
$\partial\mathbb{D}_0$
$\partial\mathbb{D}_i$
$\mathbf{x}_i'$
0
0.5
1.0
1.5
-2000
-1000
0
1000
2000
-1.0
-0.5
0
0.5
1.0
1.5
$-t_{\text{direct}}$
$f_1^+(\mathbf{x}_0, \mathbf{x}_i', t)$



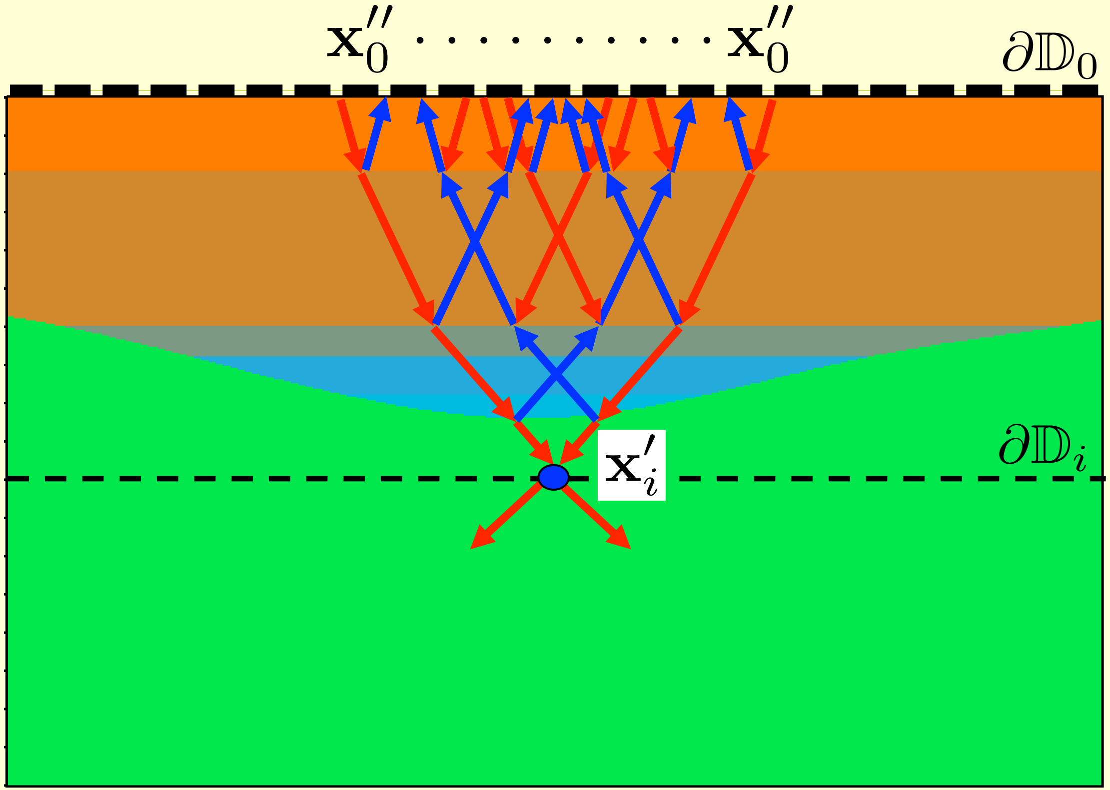


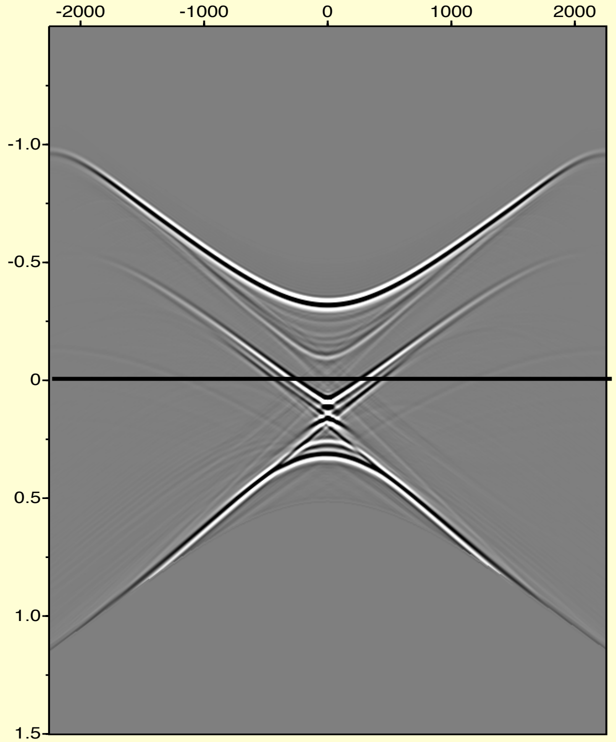
$f_1^+(\mathbf{x}_0, \mathbf{x}'_i, t)$



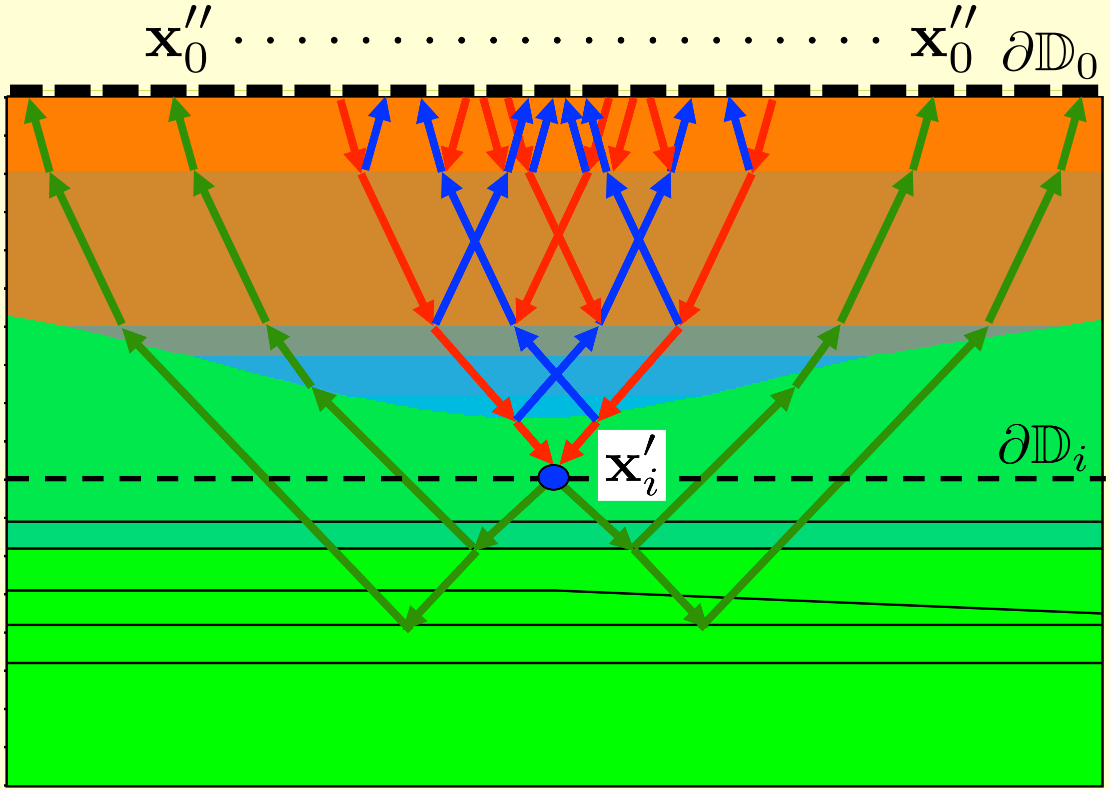


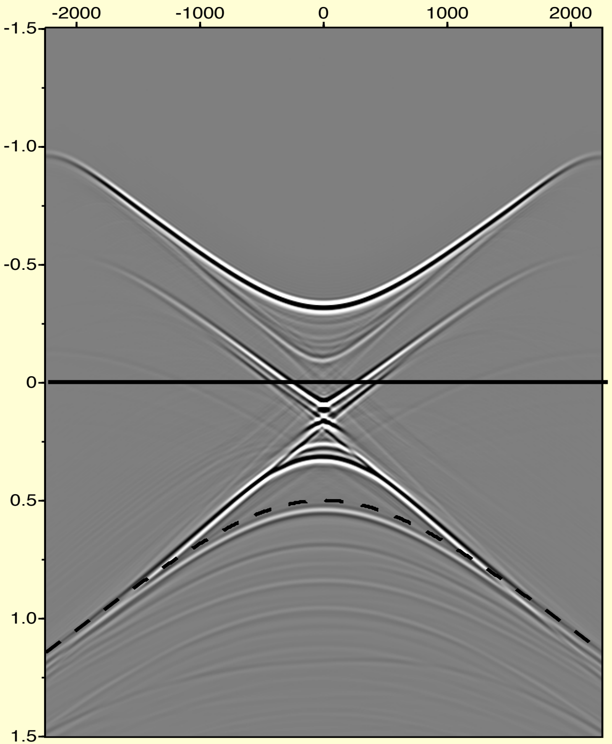
$f_1^+(\mathbf{x}_0, \mathbf{x}'_i, t)$



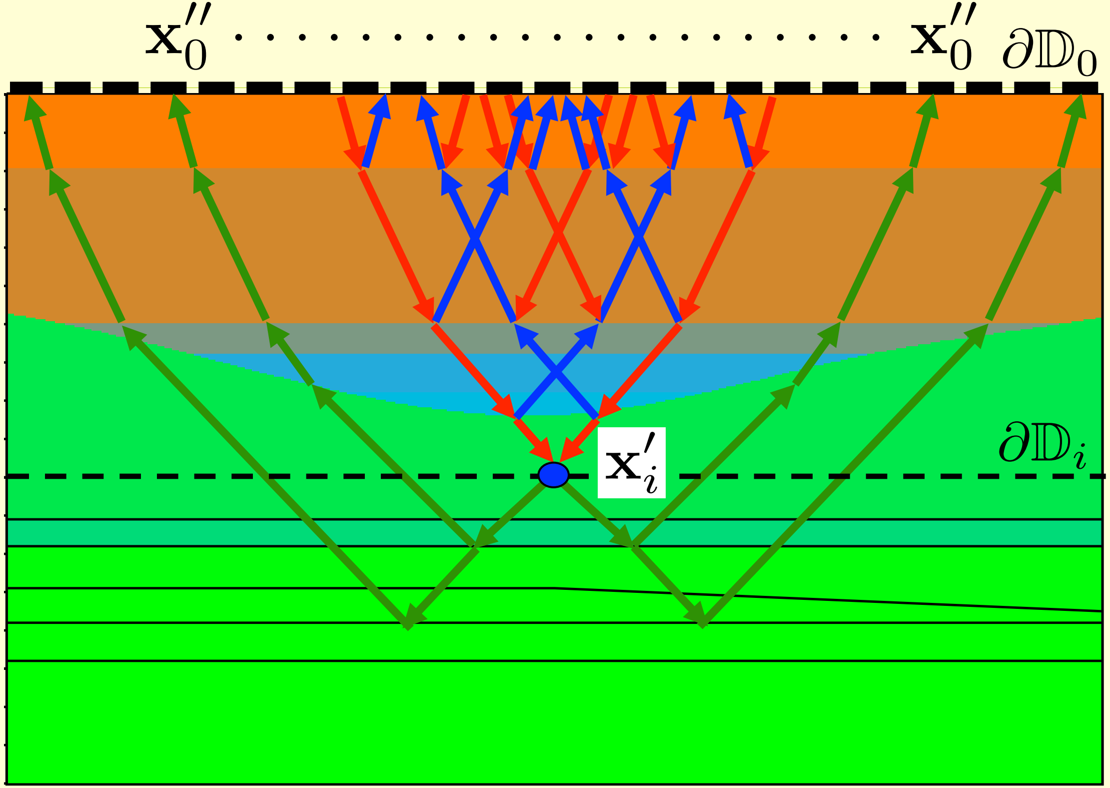


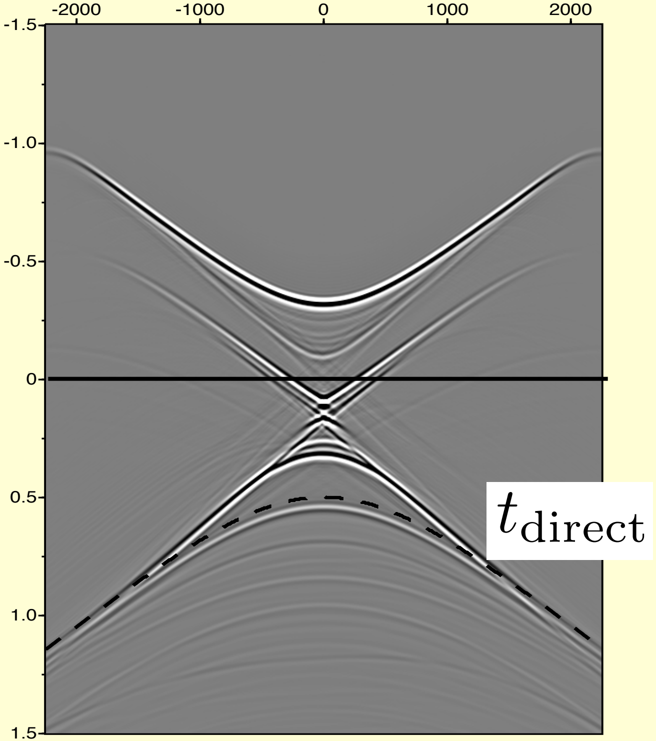
$$f_1^-(\mathbf{x}_0'', \mathbf{x}_i', t) = \int_{\partial\mathbb{D}_0} \mathrm{d}\mathbf{x}_0 \int_{-\infty}^{t} R(\mathbf{x}_0'', \mathbf{x}_0, t-t') f_1^+(\mathbf{x}_0, \mathbf{x}_i', t') \mathrm{d}t'$$



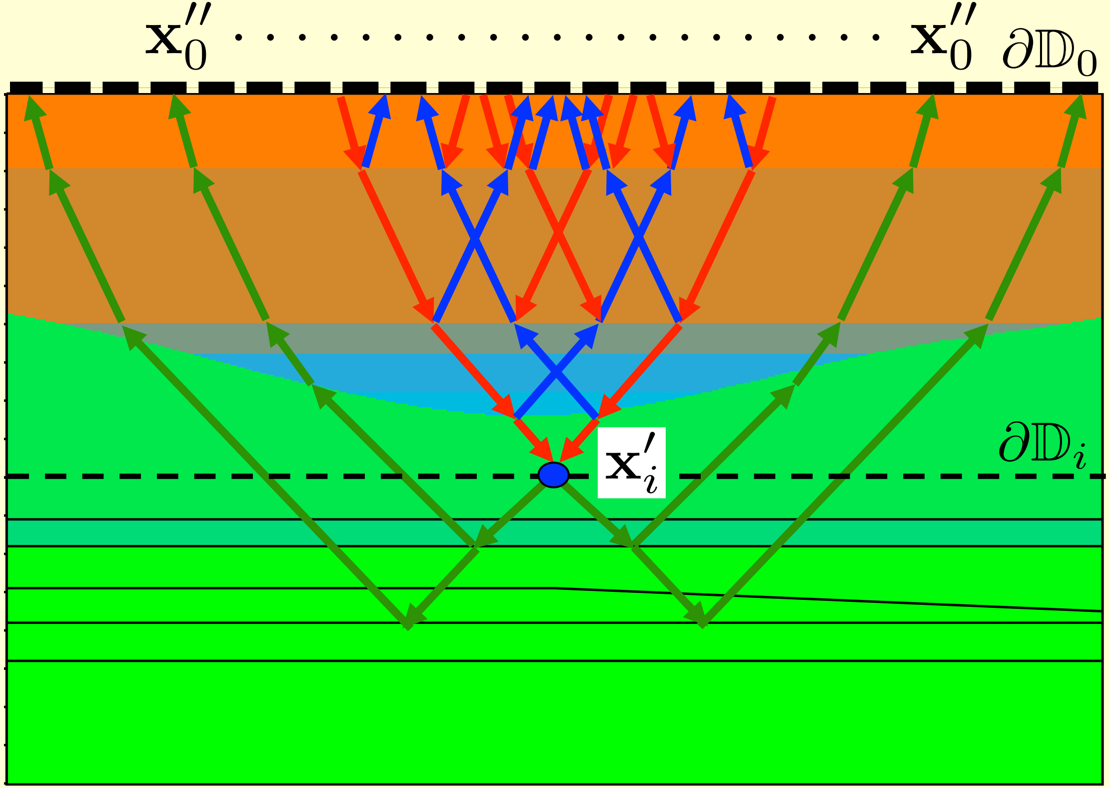


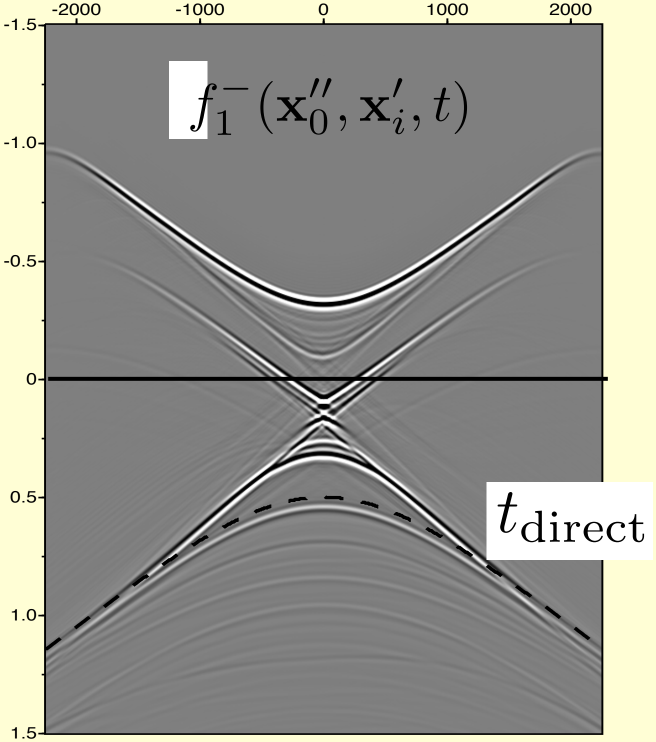
$$G^{-,+}(\mathbf{x}_0'', \mathbf{x}_i', t) + f_1^{-}(\mathbf{x}_0'', \mathbf{x}_i', t) = \int_{\partial\mathbb{D}_0} \mathrm{d}\mathbf{x}_0 \int_{-\infty}^{t} R(\mathbf{x}_0'', \mathbf{x}_0, t - t') f_1^{+}(\mathbf{x}_0, \mathbf{x}_i', t') \mathrm{d}t'$$



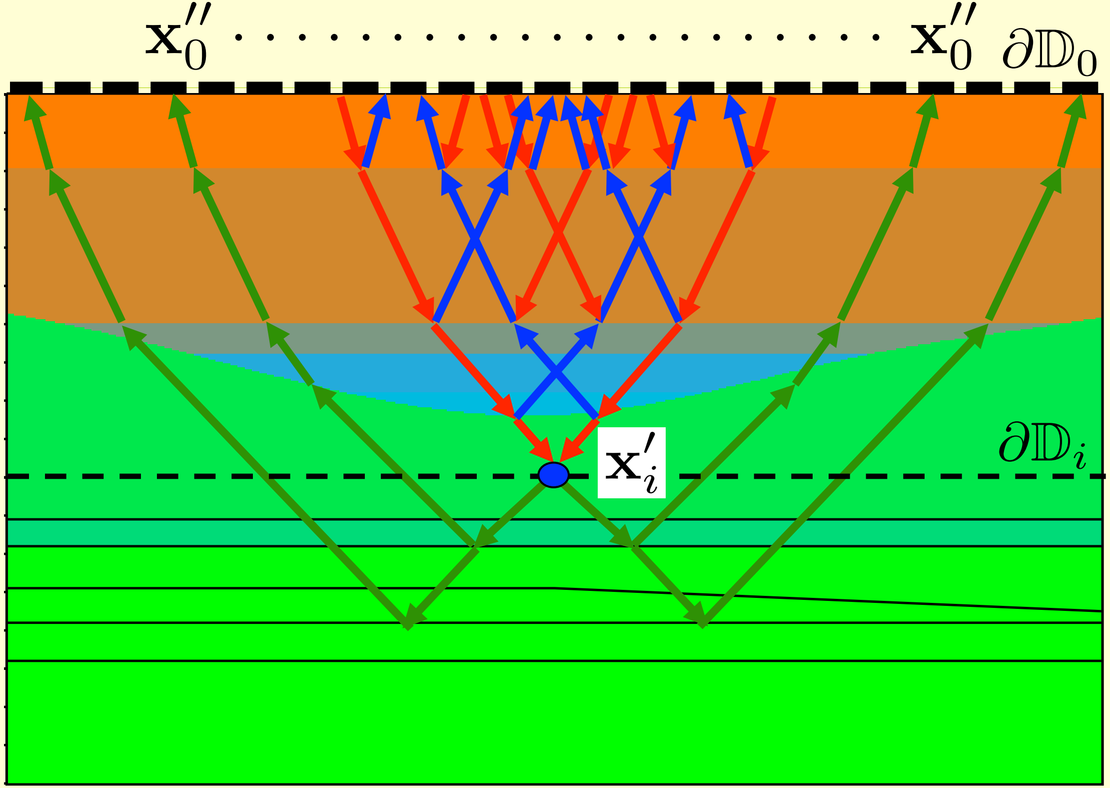


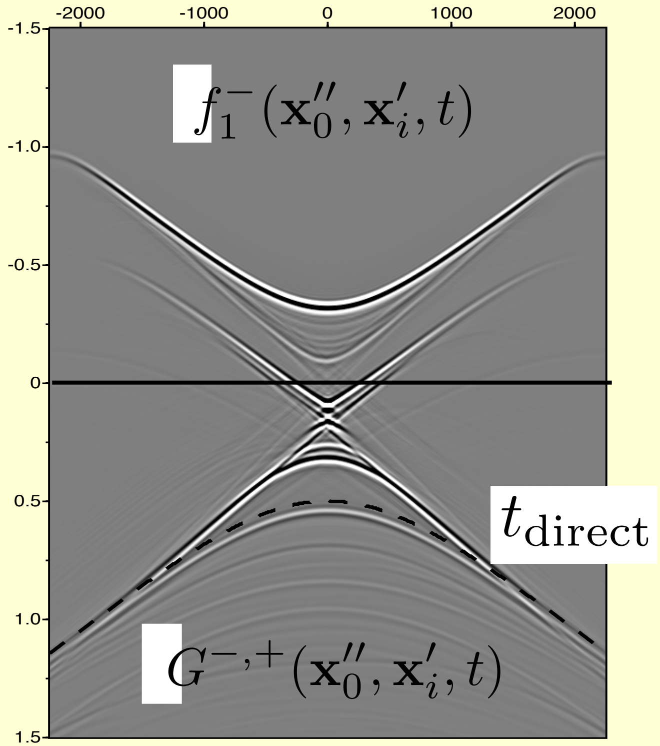
$$G^{-,+}(\mathbf{x}_0'',\mathbf{x}_i',t)+f_1^-(\mathbf{x}_0'',\mathbf{x}_i',t)=\int_{\partial\mathbb{D}_0}\mathrm{d}\mathbf{x}_0\int_{-\infty}^{t}R(\mathbf{x}_0'',\mathbf{x}_0,t-t')f_1^+(\mathbf{x}_0,\mathbf{x}_i',t')\mathrm{d}t'$$



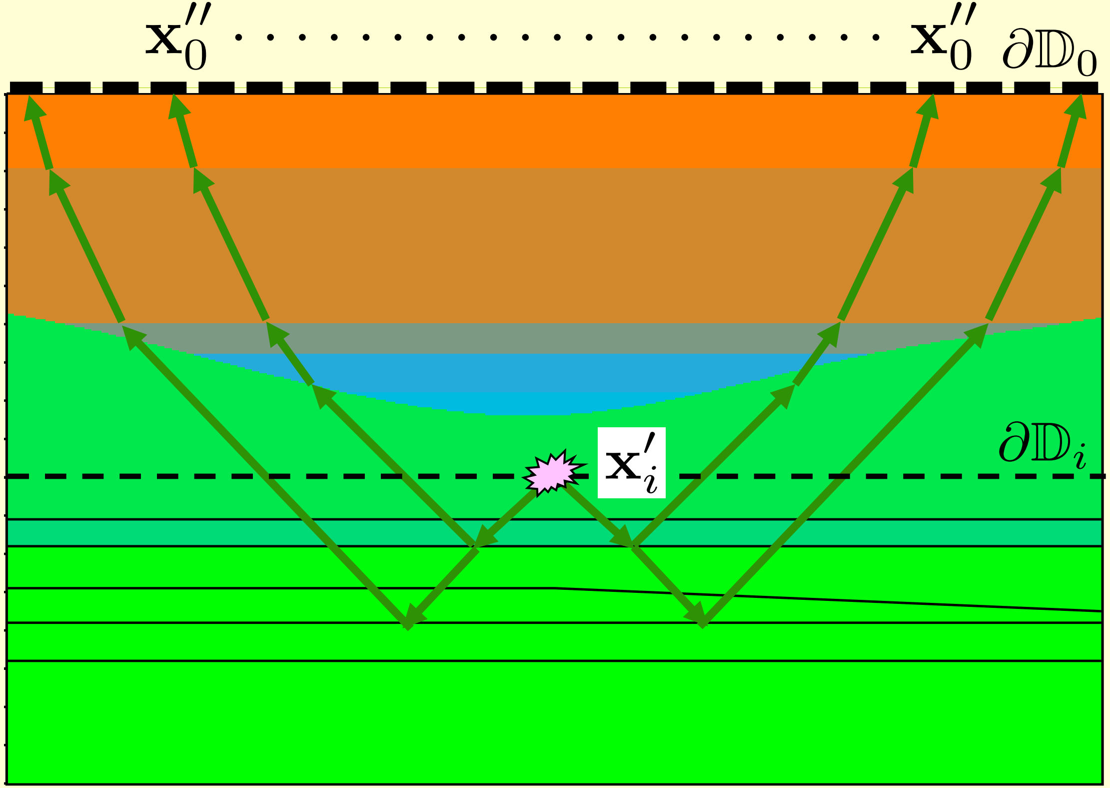


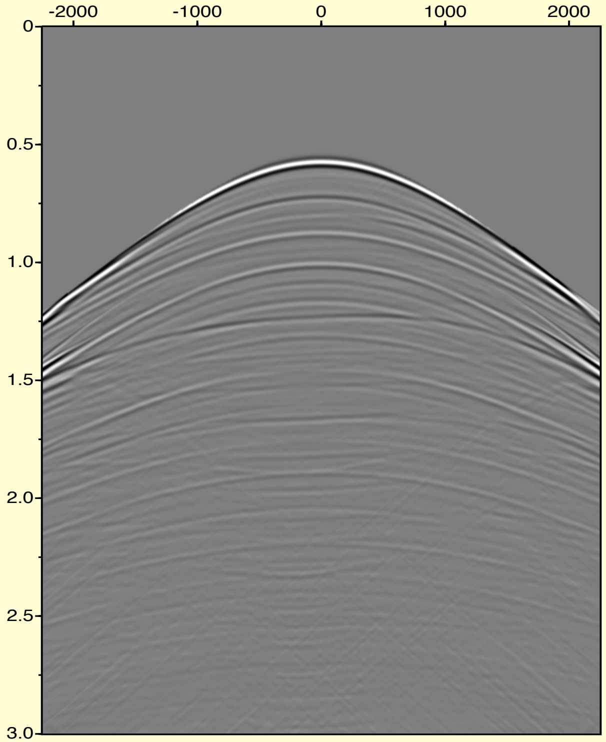
$$G^{-,+}(\mathbf{x}_0'', \mathbf{x}_i', t) + f_1^-(\mathbf{x}_0'', \mathbf{x}_i', t) = \int_{\partial\mathbb{D}_0} \mathrm{d}\mathbf{x}_0 \int_{-\infty}^{t} R(\mathbf{x}_0'', \mathbf{x}_0, t - t') f_1^+(\mathbf{x}_0, \mathbf{x}_i', t') \mathrm{d}t'$$



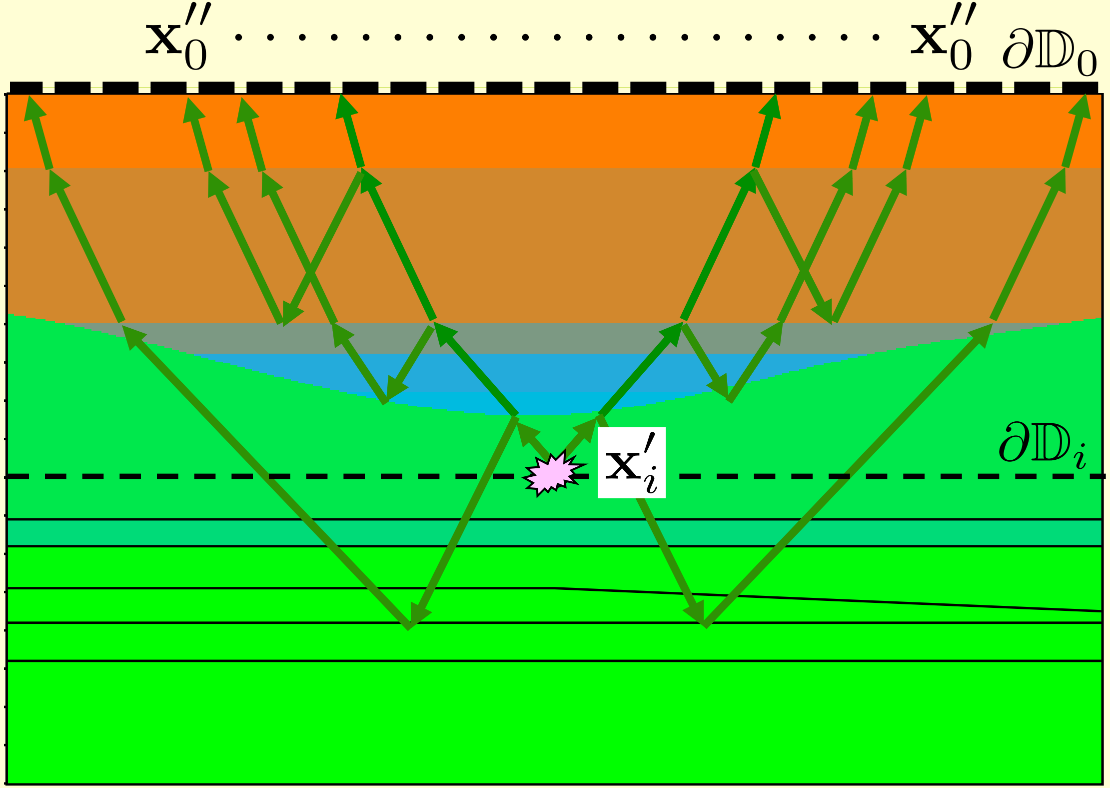


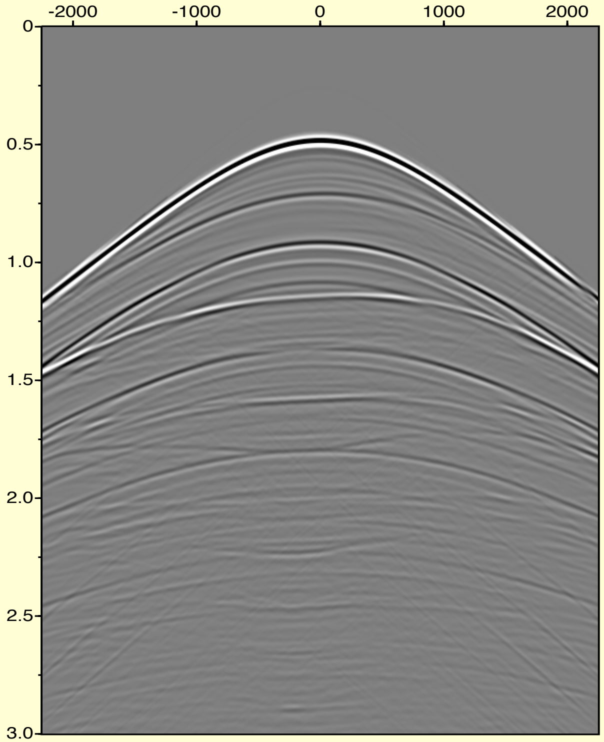
$$G^{-,+}(\mathbf{x}_0'', \mathbf{x}_i', t) + f_1^-(\mathbf{x}_0'', \mathbf{x}_i', t) = \int_{\partial\mathbb{D}_0} \mathrm{d}\mathbf{x}_0 \int_{-\infty}^{t} R(\mathbf{x}_0'', \mathbf{x}_0, t - t') f_1^+(\mathbf{x}_0, \mathbf{x}_i', t') \mathrm{d}t'$$





$$G^{-,+}(\mathbf{x}_0'', \mathbf{x}_i', t) + f_1^-(\mathbf{x}_0'', \mathbf{x}_i', t) = \int_{\partial\mathbb{D}_0} \mathrm{d}\mathbf{x}_0 \int_{-\infty}^{t} R(\mathbf{x}_0'', \mathbf{x}_0, t - t') f_1^+(\mathbf{x}_0, \mathbf{x}_i', t')\mathrm{d}t'$$





$$G^{-,-}(\mathbf{x}_0'',\mathbf{x}_i',t)+f_1^{+}(\mathbf{x}_0'',\mathbf{x}_i',-t)=\int_{\partial\mathbb{D}_0}\mathrm{d}\mathbf{x}_0\int_{-\infty}^{t}R(\mathbf{x}_0'',\mathbf{x}_0,t-t')f_1^{-}(\mathbf{x}_0,\mathbf{x}_i',-t')\mathrm{d}t'$$

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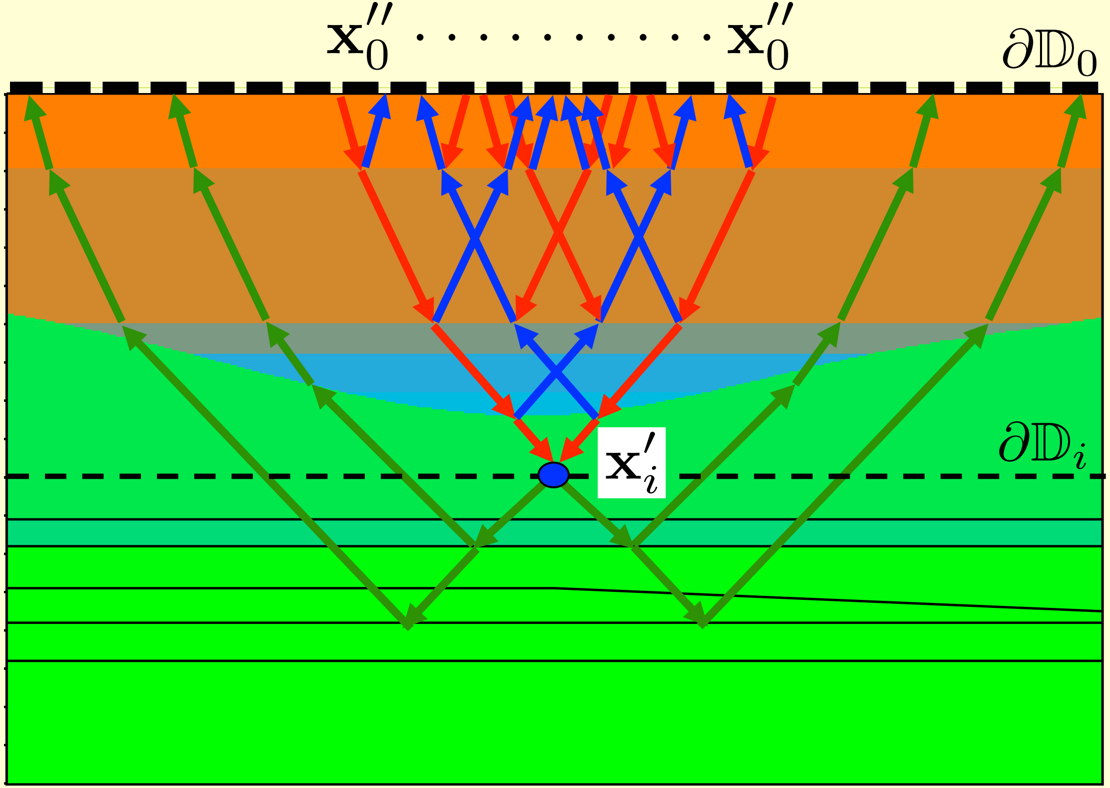
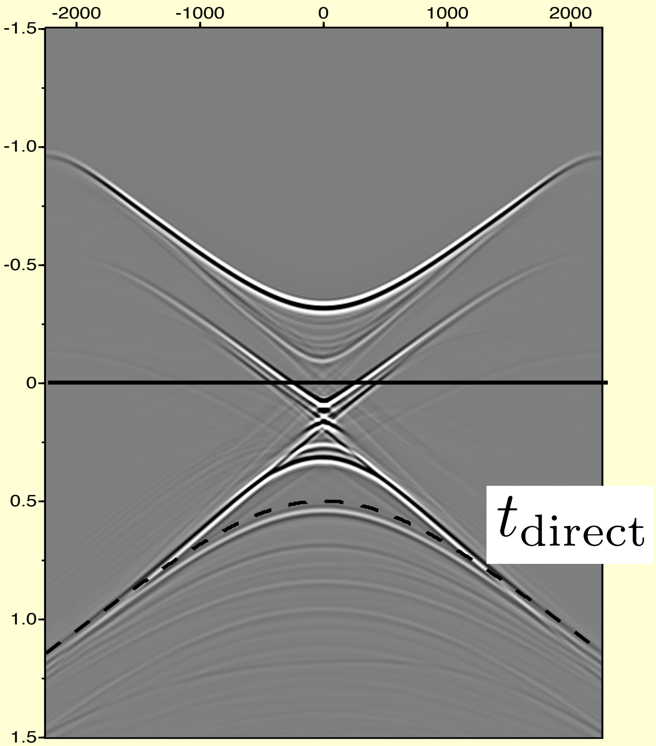
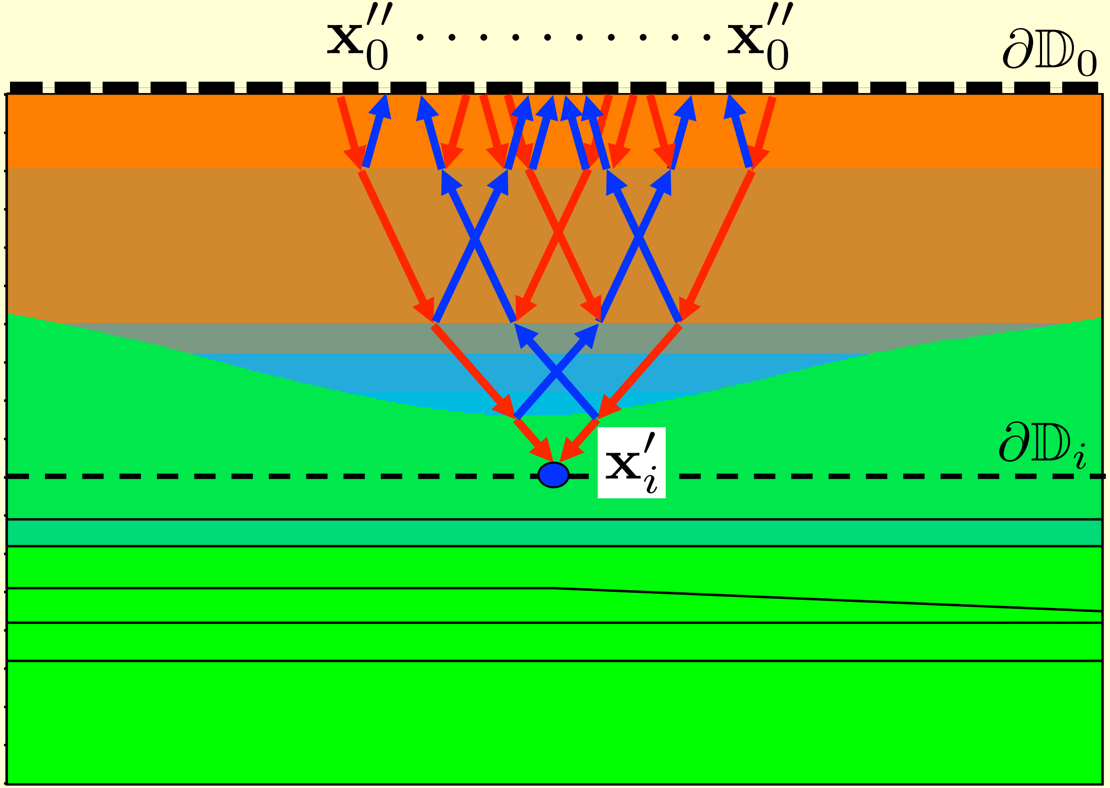
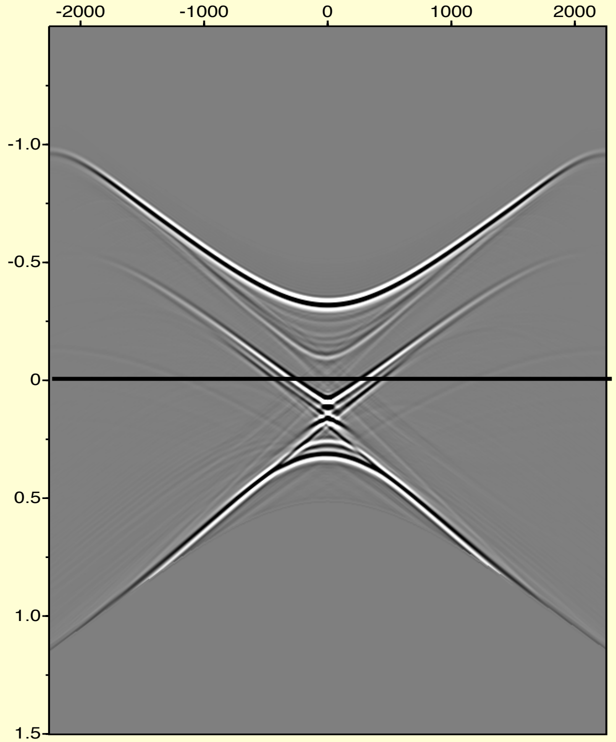


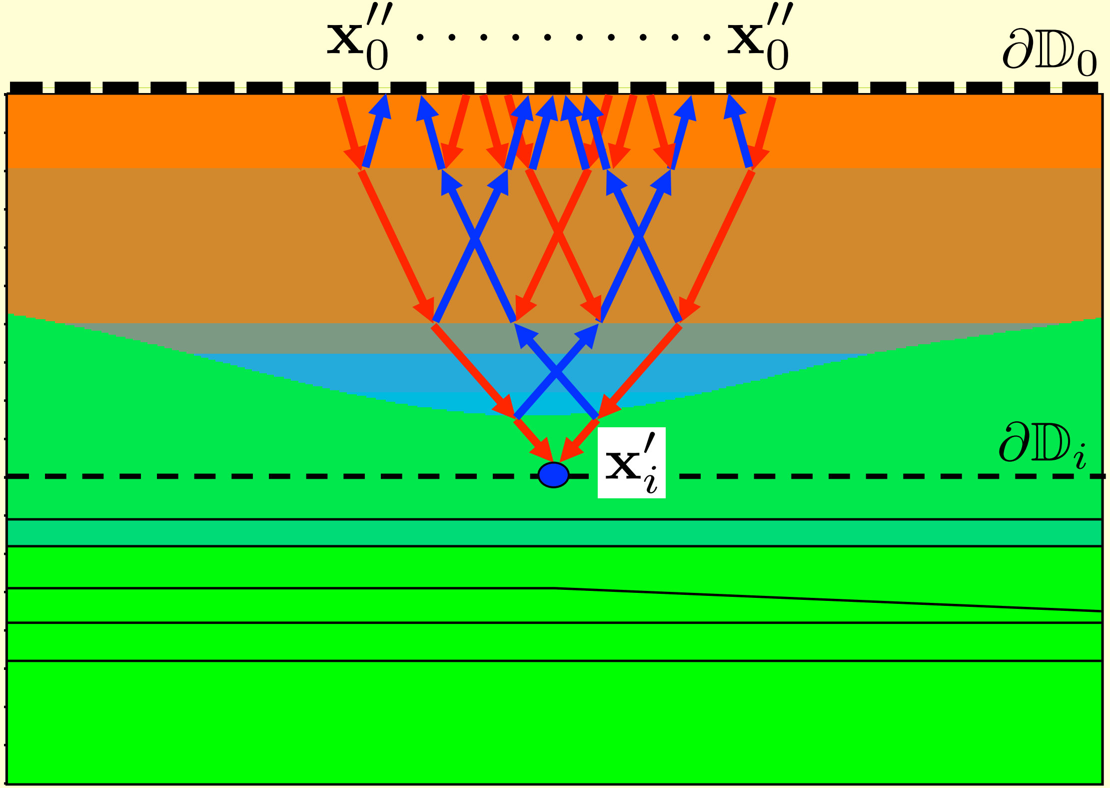


$$G^{-,+}(\mathbf{x}_0'',\mathbf{x}_i',t)+f_1^{-}(\mathbf{x}_0'',\mathbf{x}_i',t)=\int_{\partial\mathbb{D}_0}\mathrm{d}\mathbf{x}_0\int_{-\infty}^{t}R(\mathbf{x}_0'',\mathbf{x}_0,t-t')f_1^{+}(\mathbf{x}_0,\mathbf{x}_i',t')\mathrm{d}t'$$



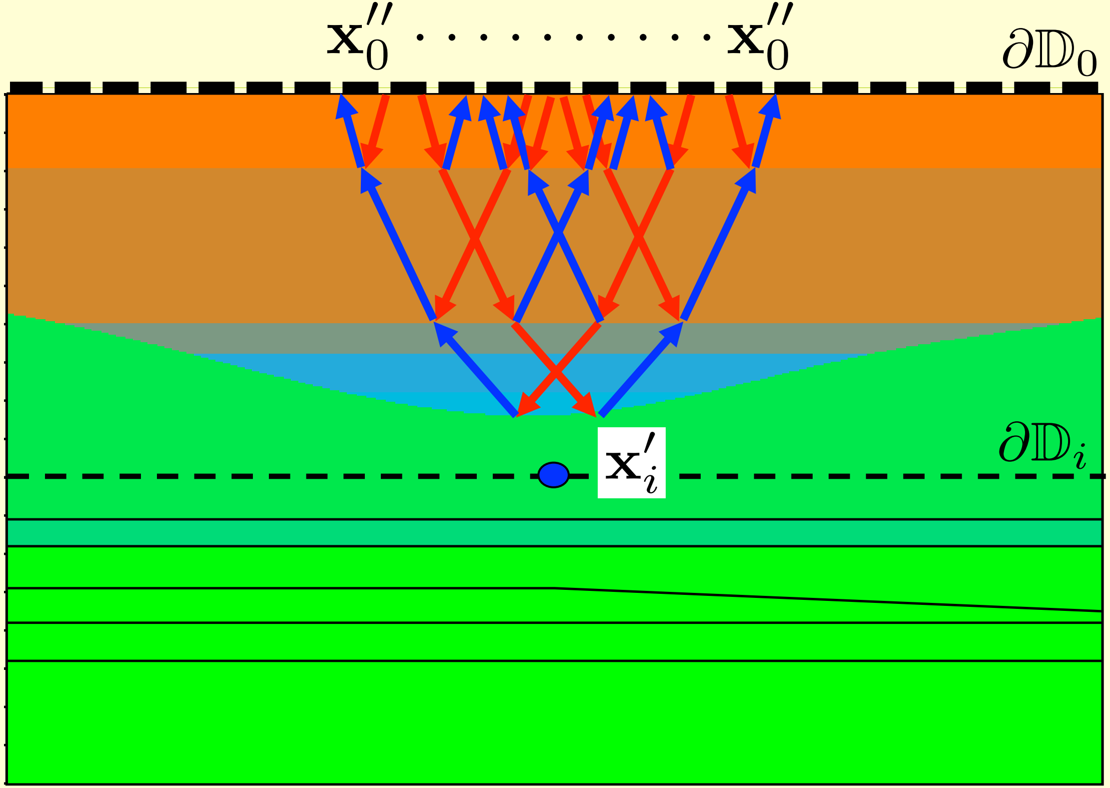


$$t < t_{\text{direct}} : \qquad f_1^-(\mathbf{x}_0'', \mathbf{x}_i', t) = \int_{\partial\mathbb{D}_0} \mathrm{d}\mathbf{x}_0 \int_{-\infty}^{t} R(\mathbf{x}_0'', \mathbf{x}_0, t - t') f_1^+(\mathbf{x}_0, \mathbf{x}_i', t') \mathrm{d}t'$$



Measured reflection data

$$t < t_{\rm direct}: \qquad f_1^-(\mathbf{x}_0'', \mathbf{x}_i', t) = \int_{\partial\mathbb{D}_0} {\rm d}\mathbf{x}_0 \int_{-\infty}^{t} R(\mathbf{x}_0'', \mathbf{x}_0, t-t') f_1^+(\mathbf{x}_0, \mathbf{x}_i', t') {\rm d}t'$$



Measured reflection data

$$t < t_{\text{direct}}: \quad f_1^+(\mathbf{x}_0'', \mathbf{x}_i', -t) = \int_{\partial\mathbb{D}_0} \mathrm{d}\mathbf{x}_0 \int_{-\infty}^{t} R(\mathbf{x}_0'', \mathbf{x}_0, t - t') f_1^-(\mathbf{x}_0, \mathbf{x}_i', -t') \mathrm{d}t'$$

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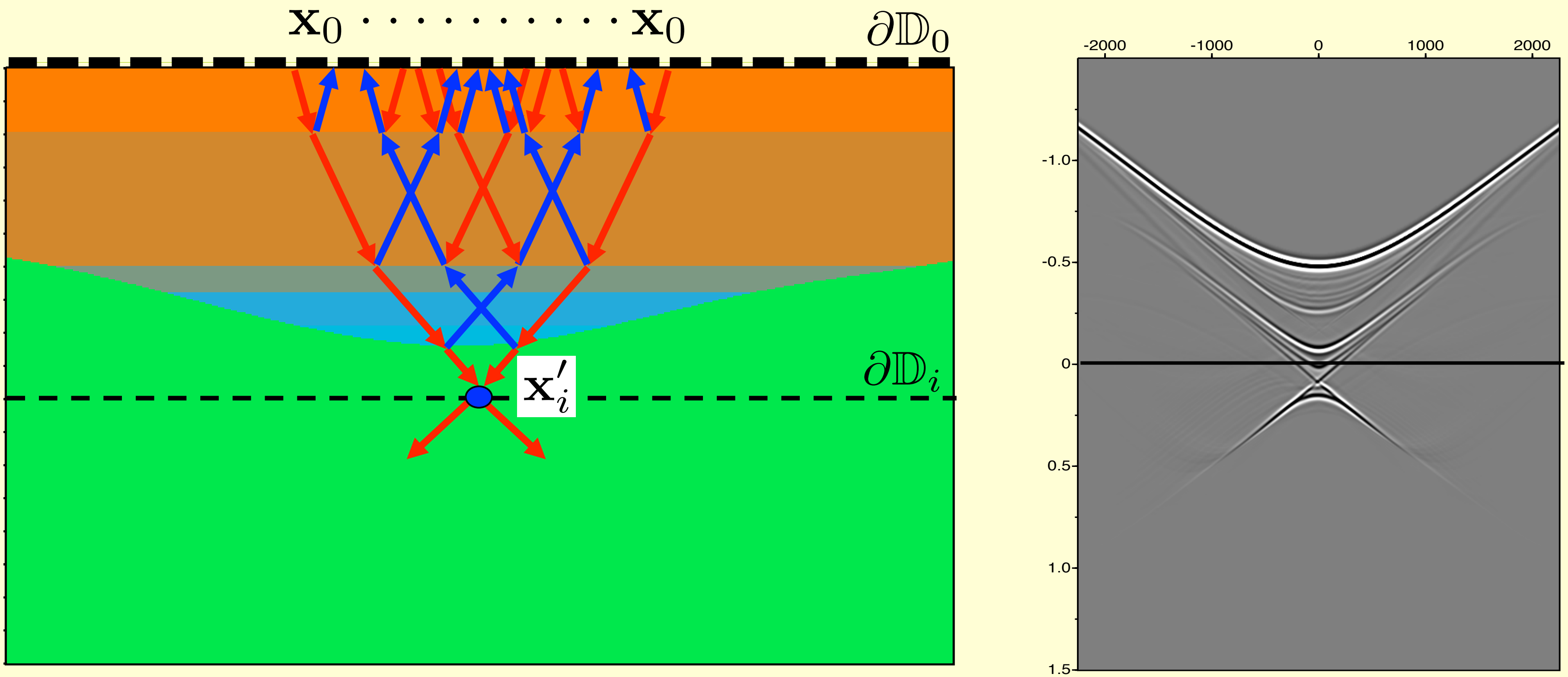
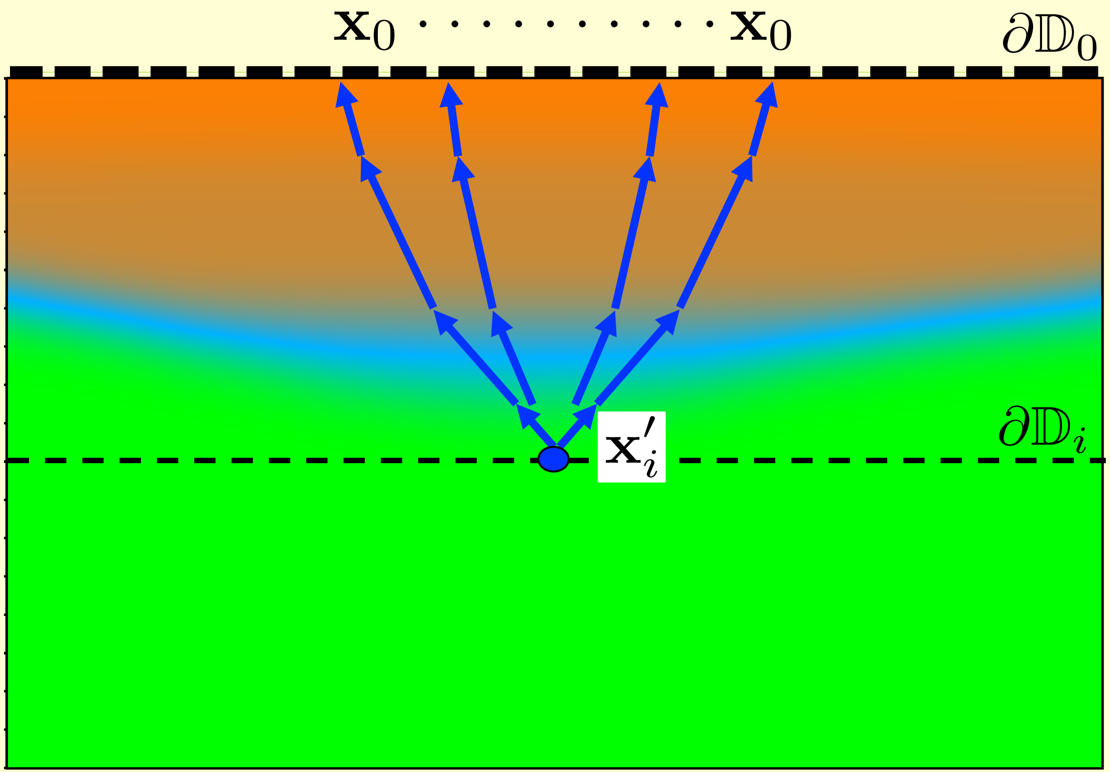
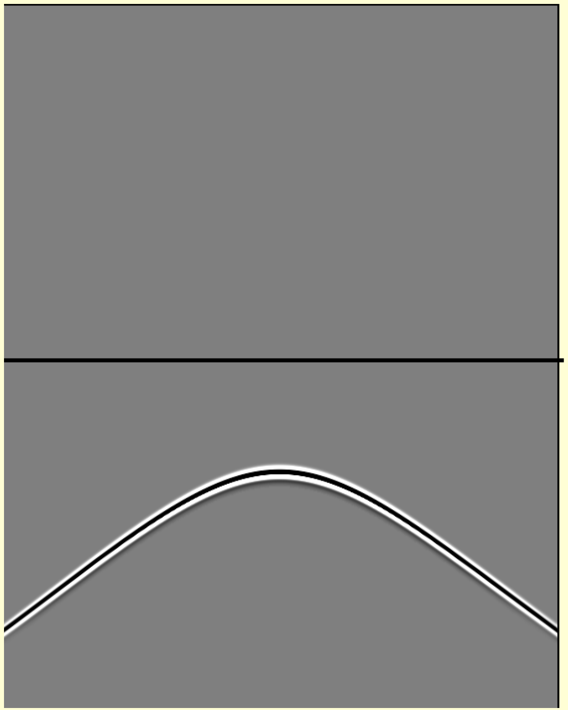


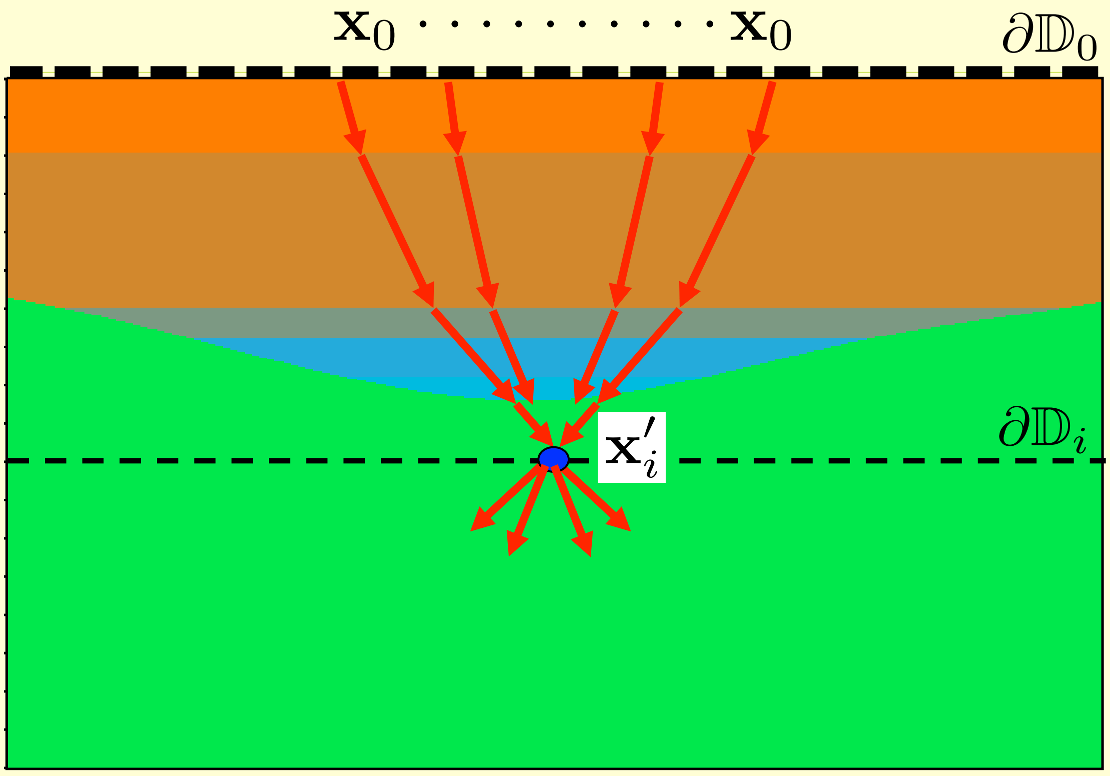
Ansatz: $f_1^+(\mathbf{x}_0,\mathbf{x}'_i,t) \approx \underbrace{G_\mathrm{d}(\mathbf{x}_0,\mathbf{x}'_i,-t)}_{\text{Direct}} + \underbrace{M^+(\mathbf{x}_0,\mathbf{x}'_i,t)}_{\text{Coda}}$

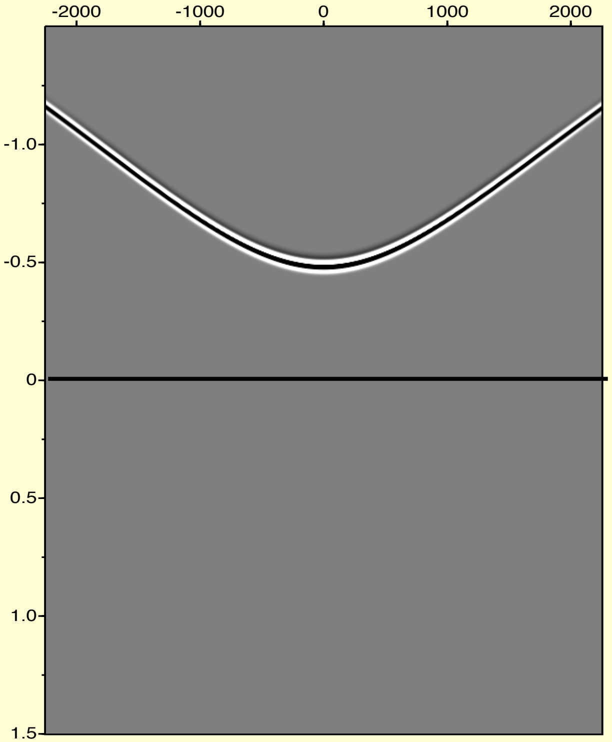


Smooth model



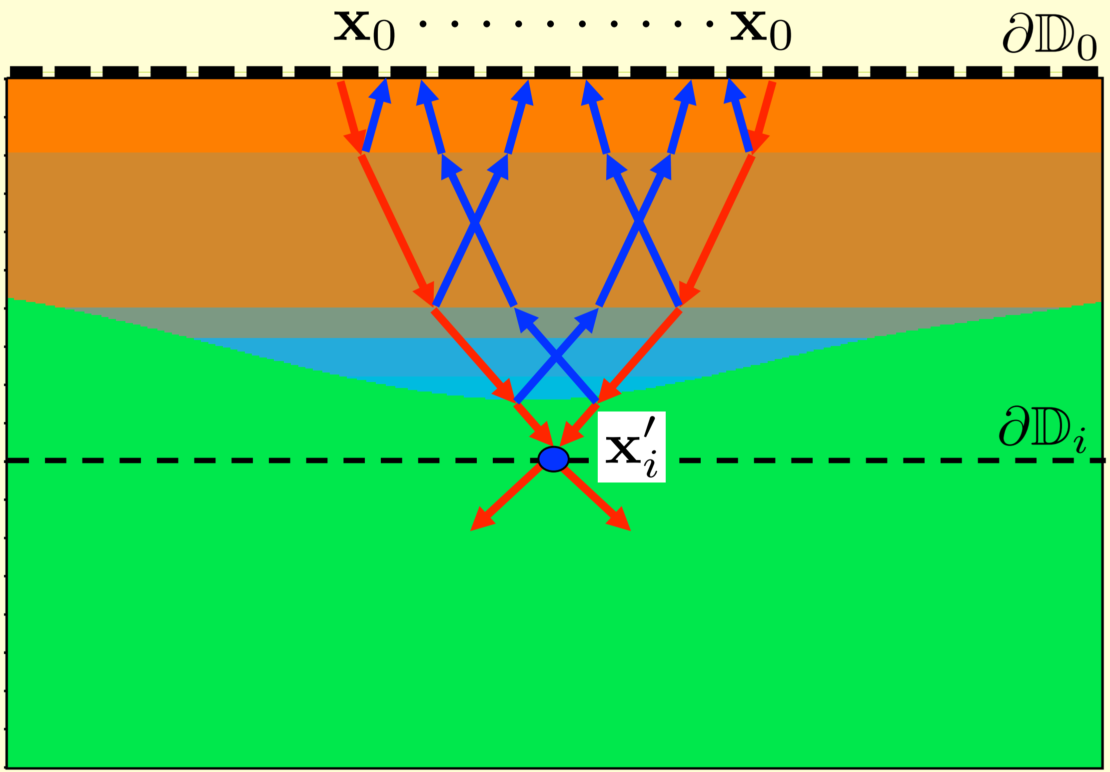
$$G_{\mathrm{d}}(\mathbf{x}_0, \mathbf{x}_i', t)$$

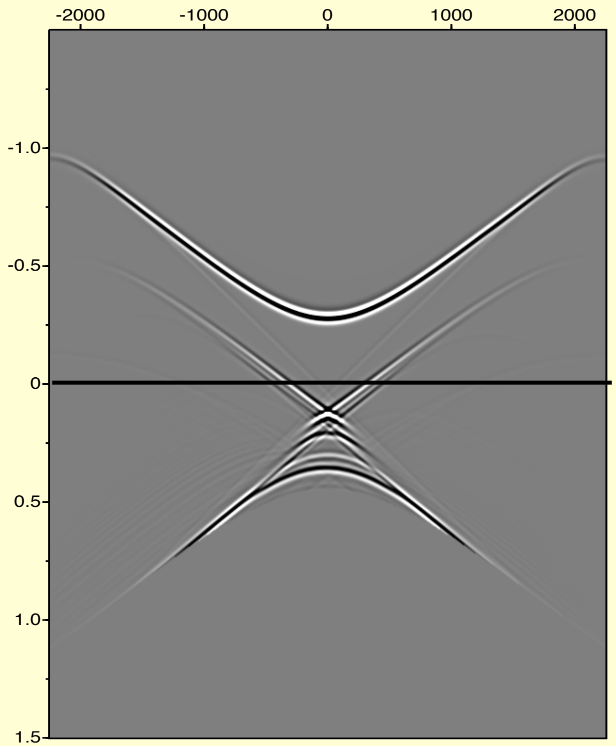




$$f^{+}_{1,0}(\mathbf{x}_0, \mathbf{x}'_i, t)$$

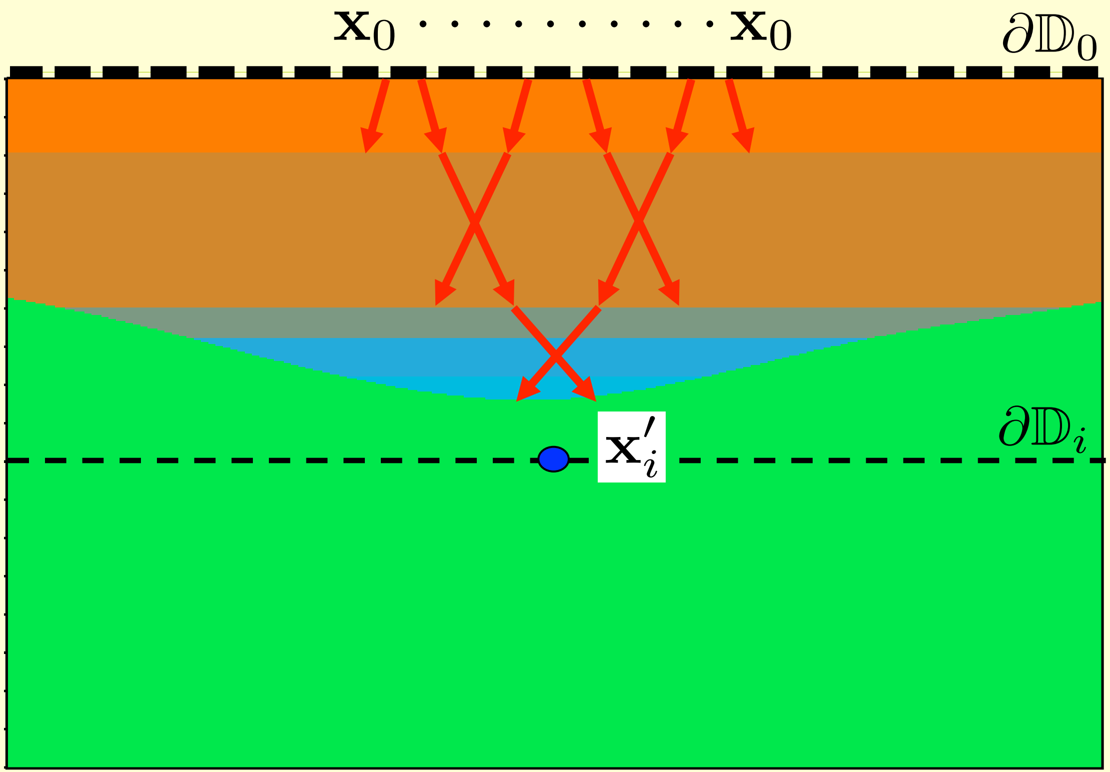
$$\approx G_{\mathrm{d}}(\mathbf{x}_0, \mathbf{x}'_i, -t)$$

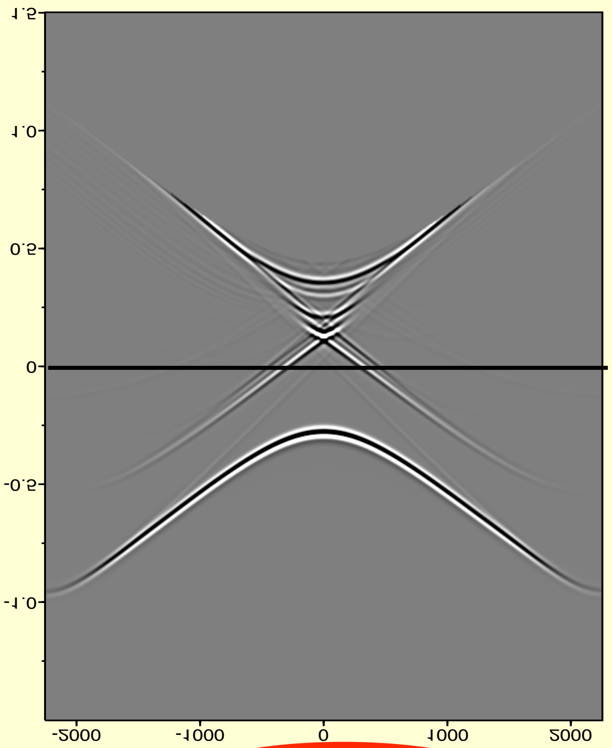




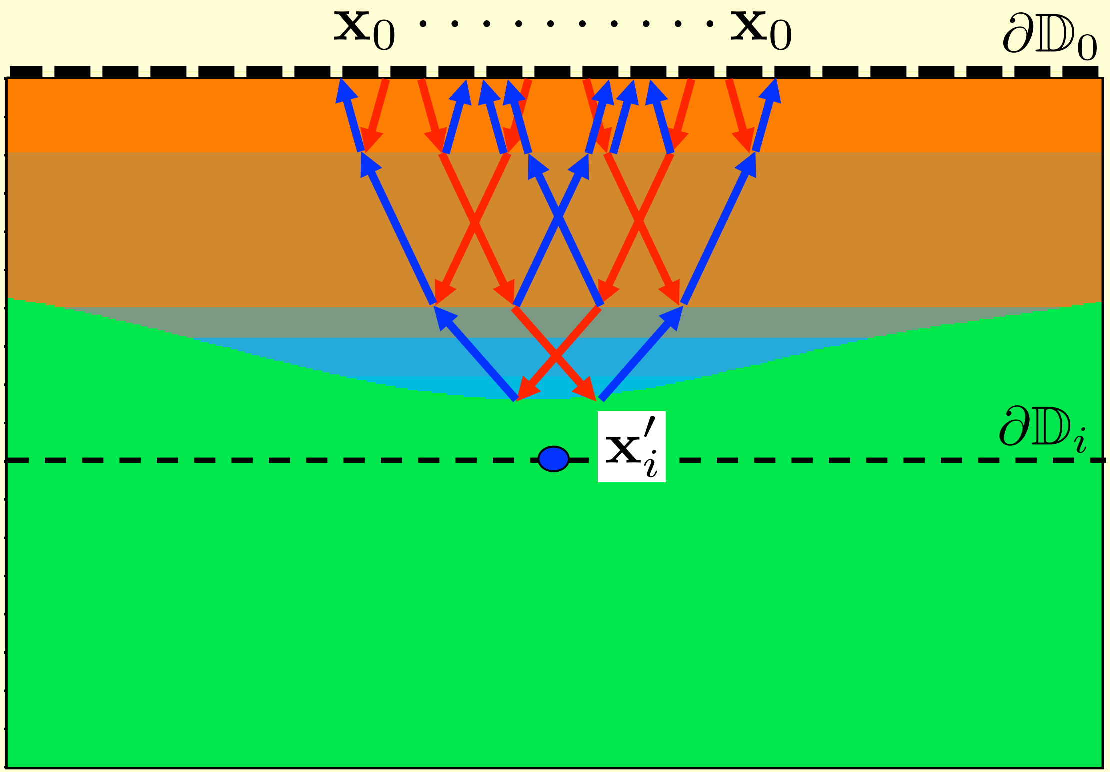
$$t < t_{\rm direct}: \quad f_{1,0}^{-}(\mathbf{x}_0'', \mathbf{x}_i', t) = \int_{\partial\mathbb{D}_0} \mathrm{d}\mathbf{x}_0 \int_{-\infty}^{t} R(\mathbf{x}_0'', \mathbf{x}_0, t - t') f_{1,0}^{+}(\mathbf{x}_0, \mathbf{x}_i', t') \mathrm{d}t'$$

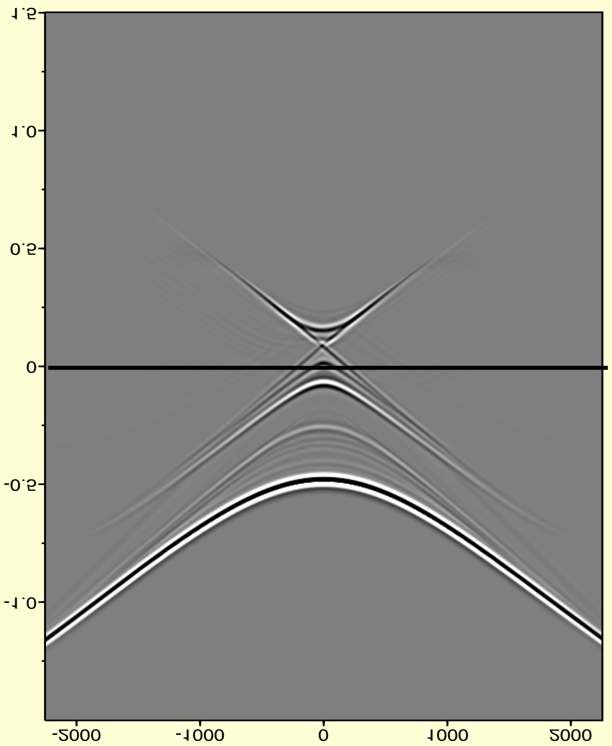
Reflection data



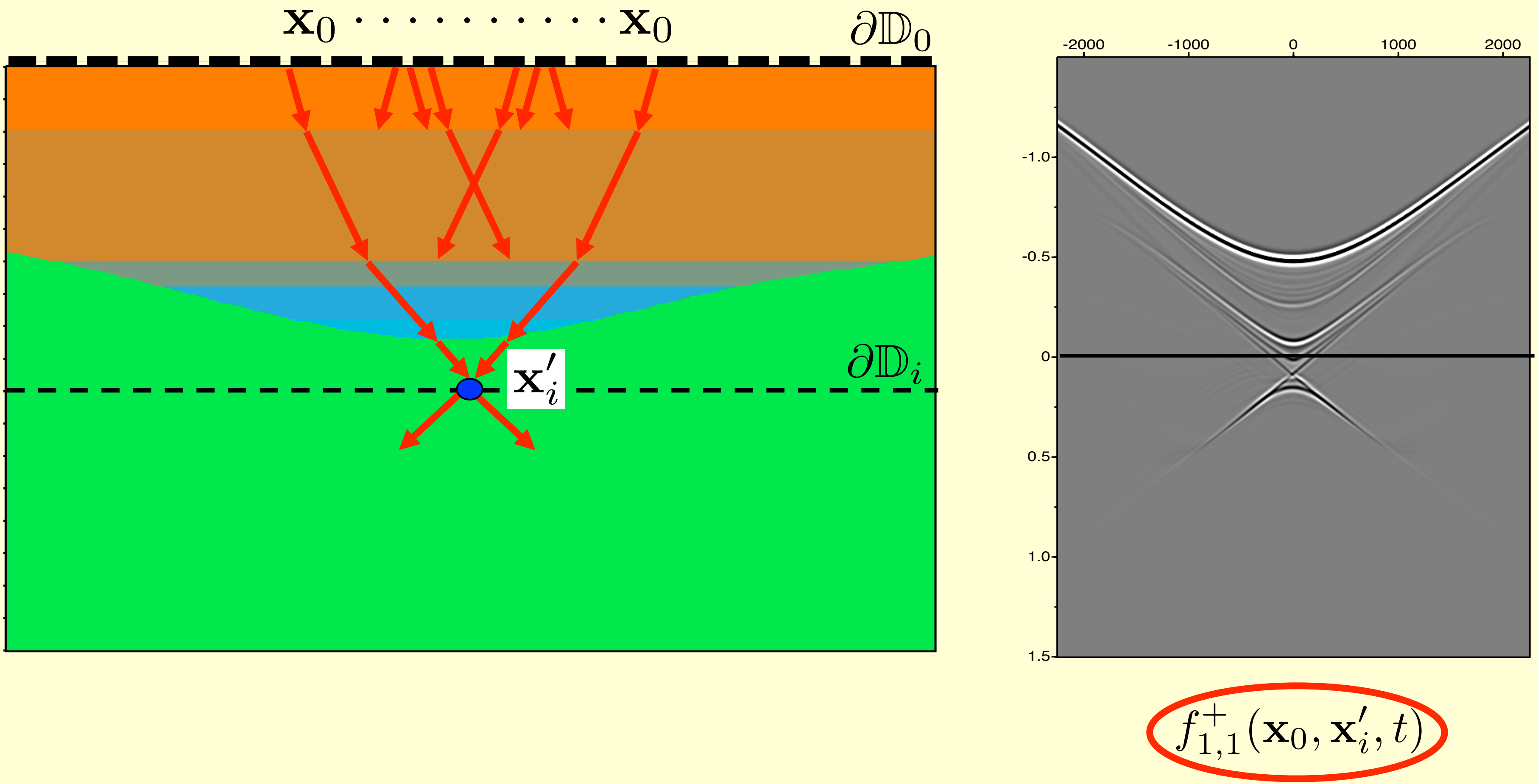


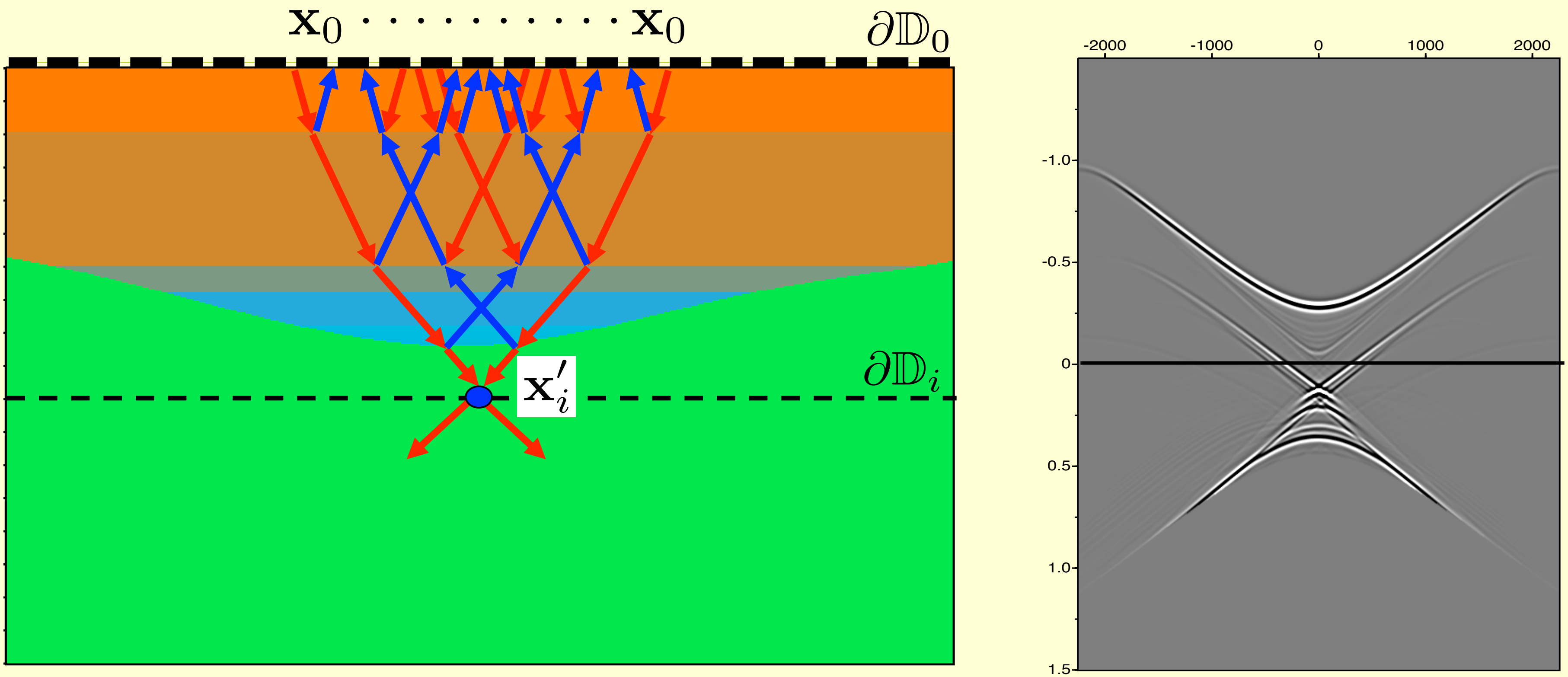
$$f^-_{1,0}(\mathbf{x}_0, \mathbf{x}_i', -t)$$



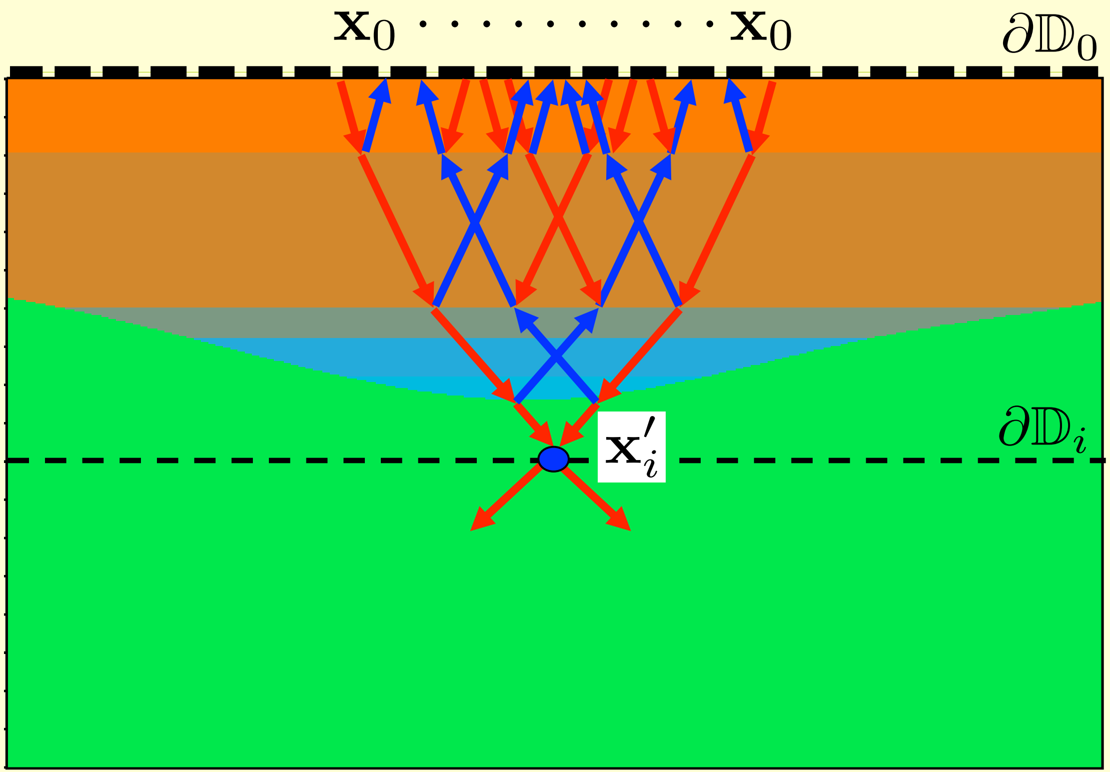


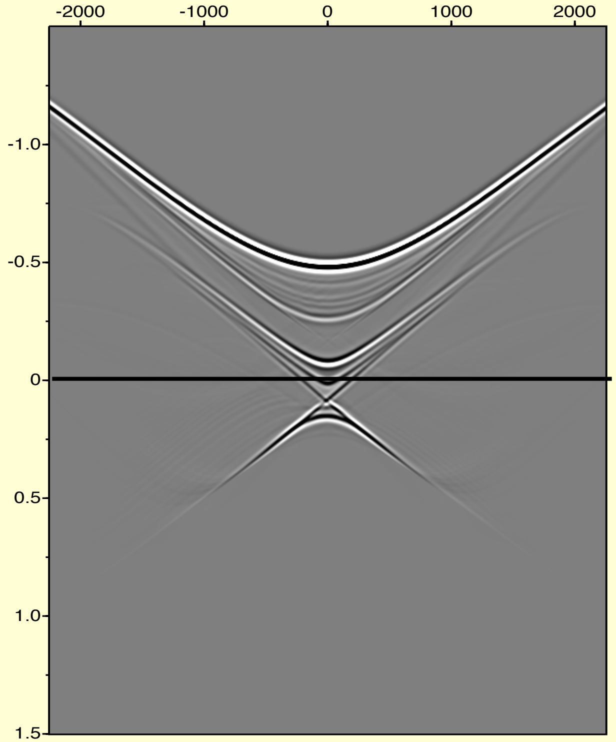
$f^+_{1,1}(\mathbf{x}_0, \mathbf{x}'_i, -t)$


$\mathbf{x}_0 \cdots\cdots\cdots \mathbf{x}_0$
$\partial\mathbb{D}_0$
$\mathbf{x}_i'$
$\partial\mathbb{D}_i$
-2000
-1000
0
1000
2000
-1.0
-0.5
0
0.5
1.0
1.5
$f_{1,1}^{+}(\mathbf{x}_0, \mathbf{x}_i', t)$

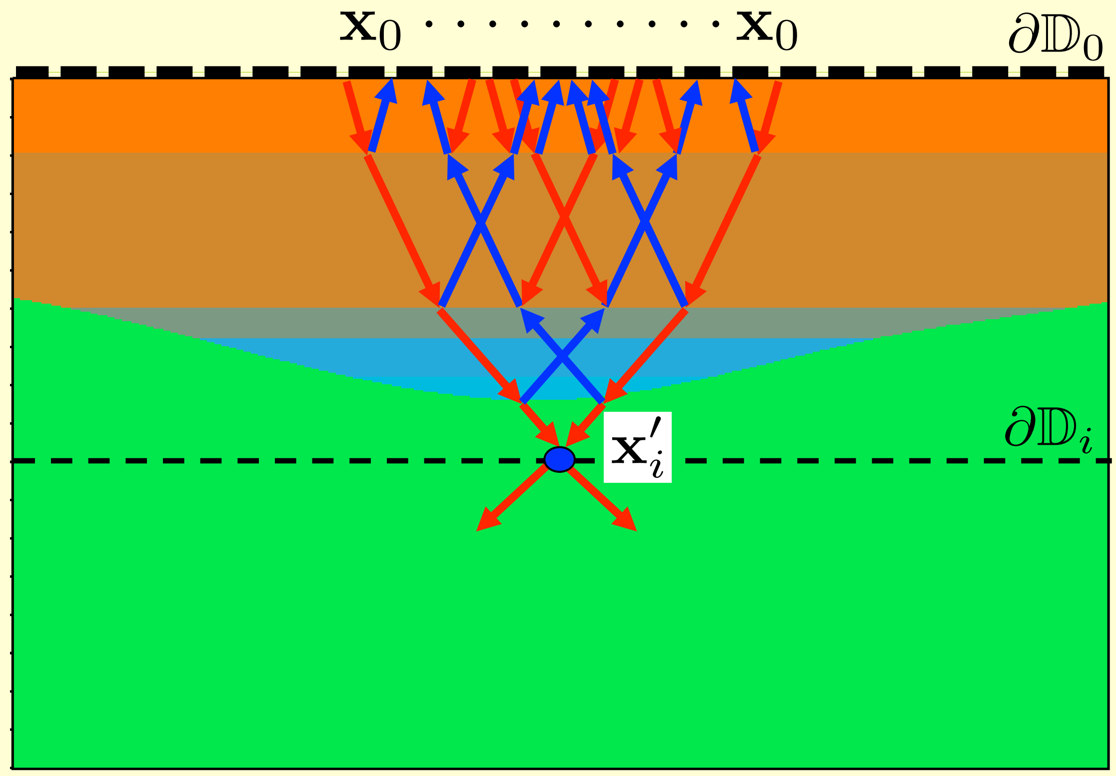


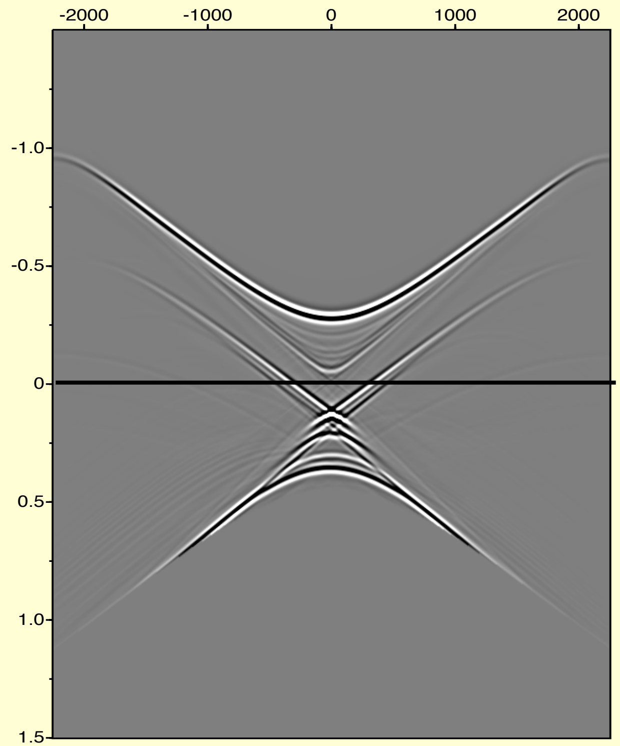
$f^-_{1,1}(\mathbf{x}_0,\mathbf{x}'_i,t)$





$f^+_{1,4}(\mathbf{x}_0, \mathbf{x}'_i, t)$





$f^-_{1,4}(\mathbf{x}_0, \mathbf{x}_i', t)$

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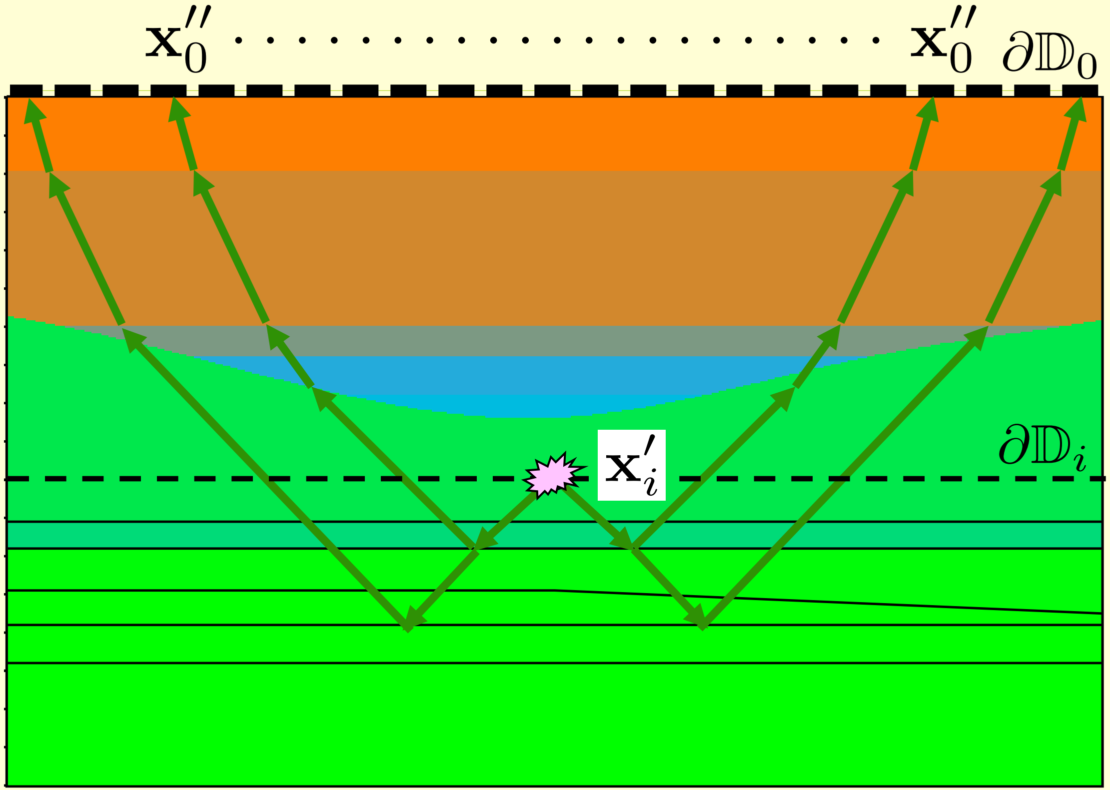
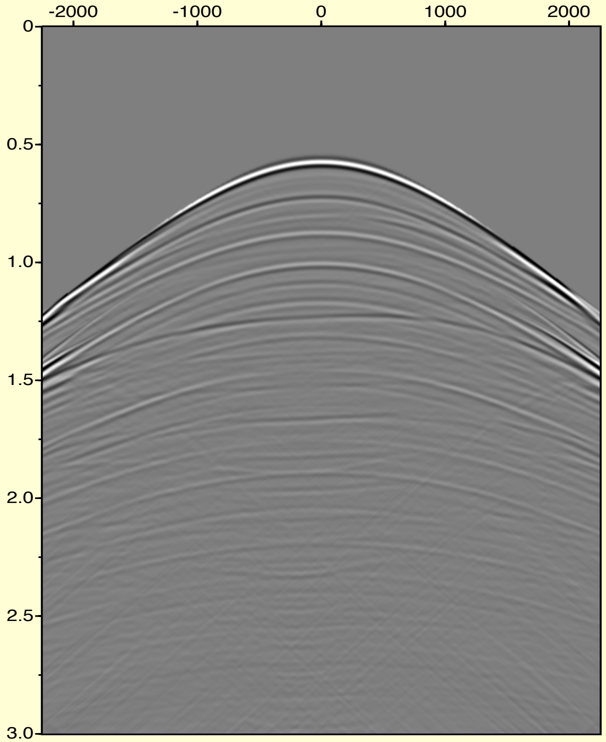
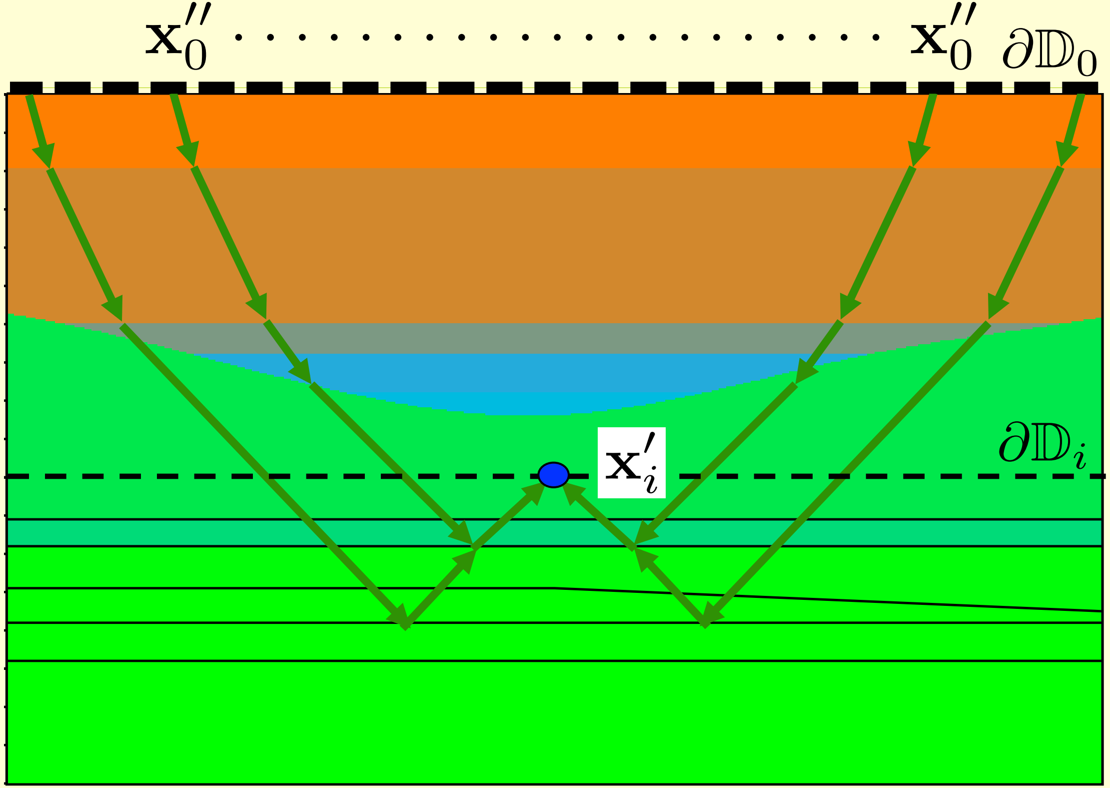
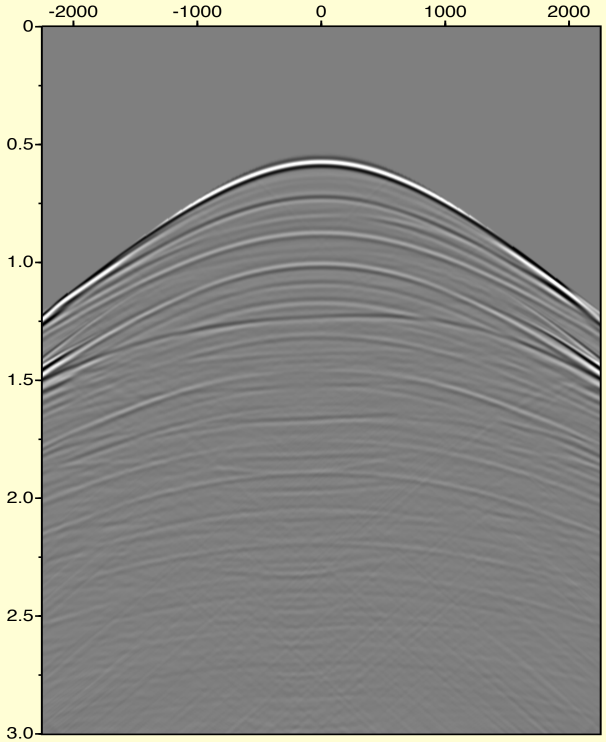


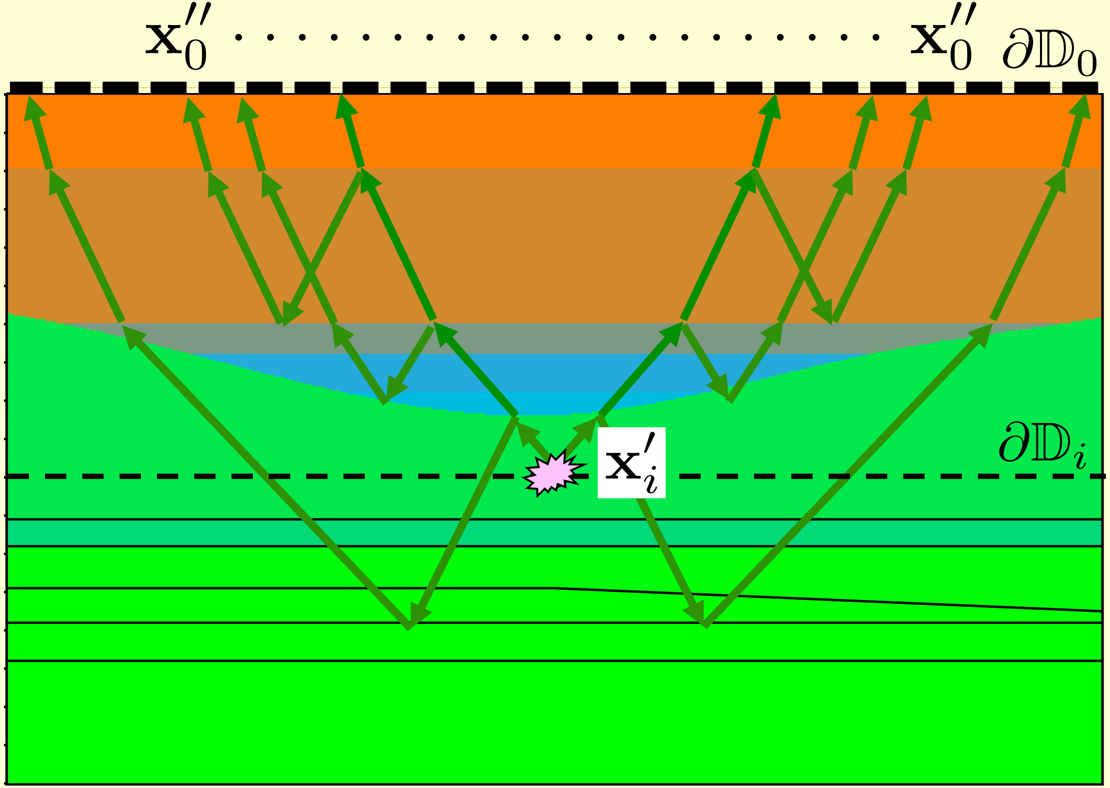


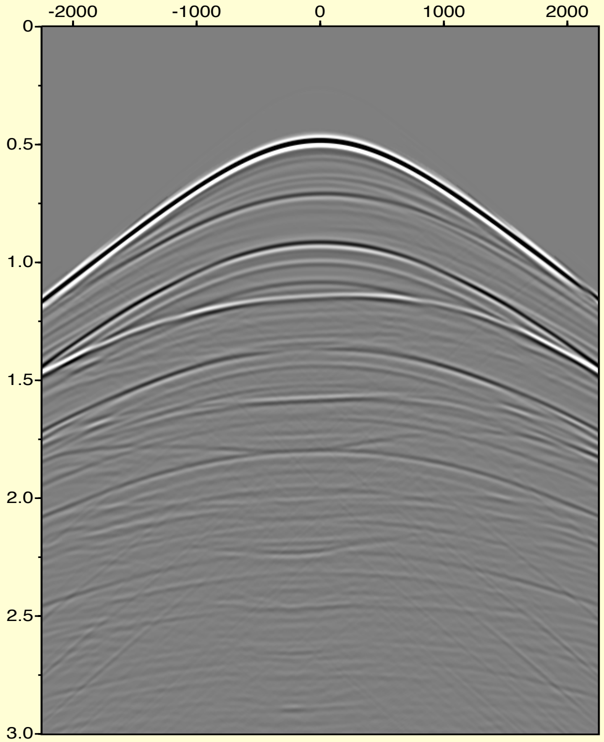
$$G^{-,+}(\mathbf{x}_0'', \mathbf{x}_i', t) + f_1^-(\mathbf{x}_0'', \mathbf{x}_i', t) = \int_{\partial\mathbb{D}_0} \mathrm{d}\mathbf{x}_0 \int_{-\infty}^{t} R(\mathbf{x}_0'', \mathbf{x}_0, t - t') f_1^+(\mathbf{x}_0, \mathbf{x}_i', t')\mathrm{d}t'$$



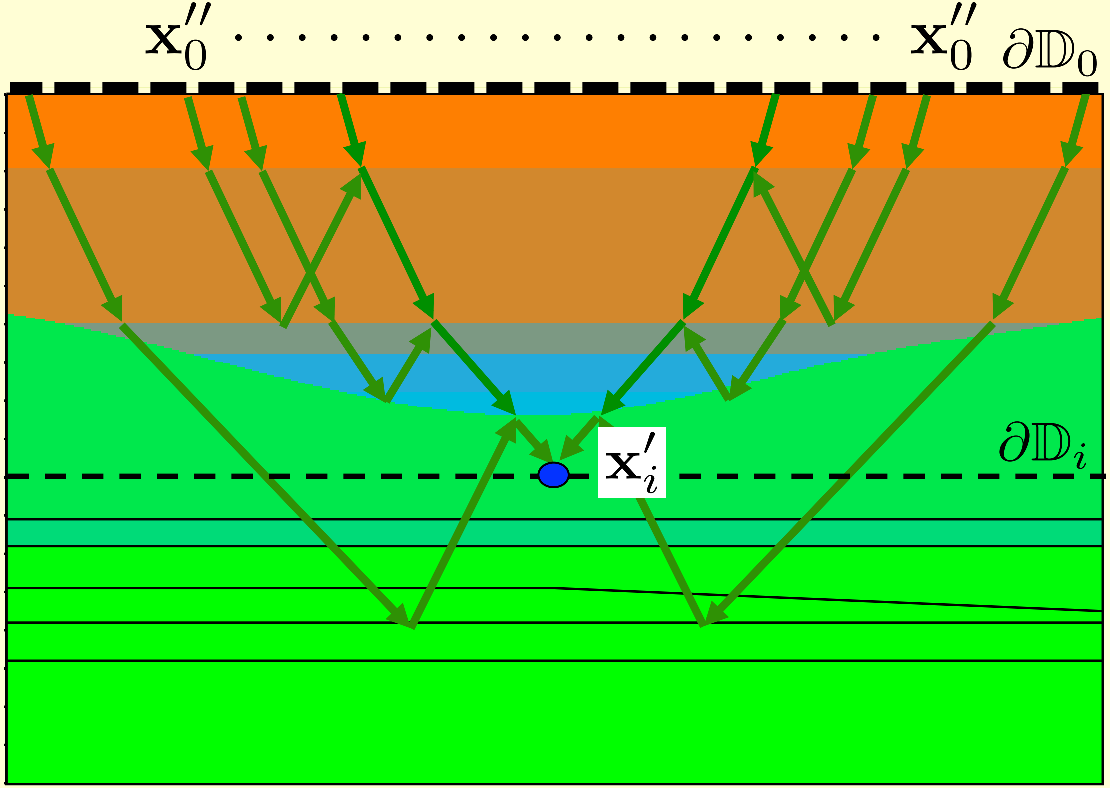


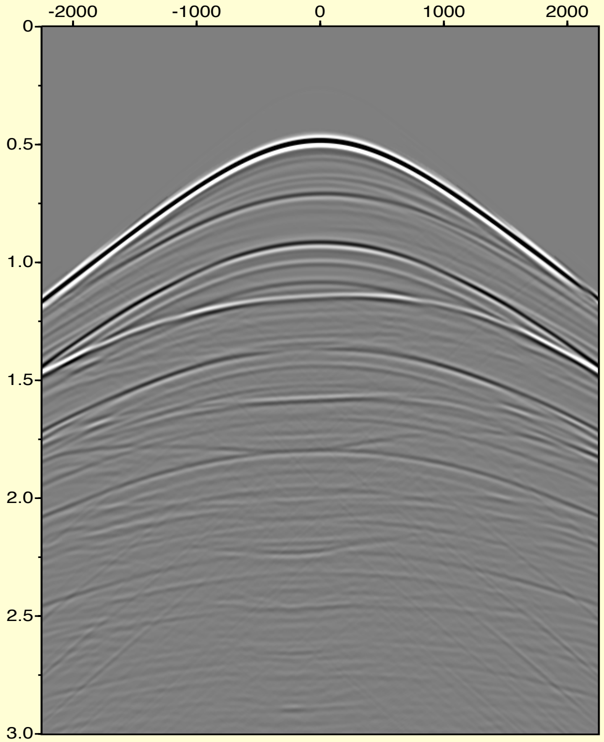
$$G^{-,+}(\mathbf{x}_i', \mathbf{x}_0'', t) + f_1^-(\mathbf{x}_0'', \mathbf{x}_i', t) = \int_{\partial\mathbb{D}_0} \mathrm{d}\mathbf{x}_0 \int_{-\infty}^{t} R(\mathbf{x}_0'', \mathbf{x}_0, t - t') f_1^+(\mathbf{x}_0, \mathbf{x}_i', t')\mathrm{d}t'$$



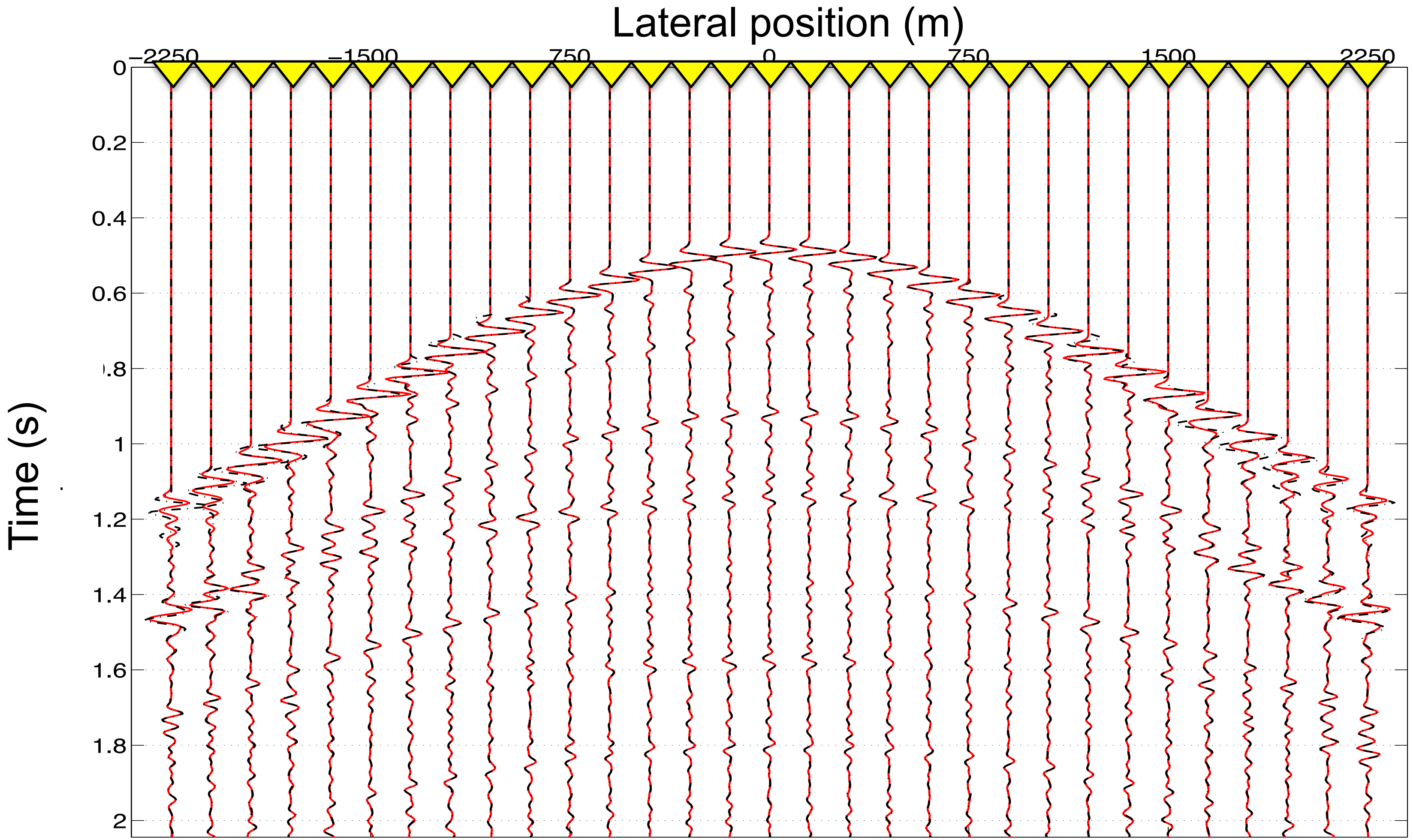


$$-G^{-,-}(\mathbf{x}_0'',\mathbf{x}_i',t)+f_1^+(\mathbf{x}_0'',\mathbf{x}_i',-t)=\int_{\partial\mathbb{D}_0}\mathrm{d}\mathbf{x}_0\int_{-\infty}^{t}R(\mathbf{x}_0'',\mathbf{x}_0,t-t')f_1^-(\mathbf{x}_0,\mathbf{x}_i',-t')\mathrm{d}t'$$





$$-G^{+,+}(\mathbf{x}'_i,\mathbf{x}''_0,t)+f_1^+(\mathbf{x}''_0,\mathbf{x}'_i,-t)=\int_{\partial\mathbb{D}_0}\mathrm{d}\mathbf{x}_0\int_{-\infty}^{t}R(\mathbf{x}''_0,\mathbf{x}_0,t-t')f_1^-(\mathbf{x}_0,\mathbf{x}'_i,-t')\mathrm{d}t'$$



$$G^{+,+}(\mathbf{x}'_i, \mathbf{x}''_0, t) + G^{-,+}(\mathbf{x}'_i, \mathbf{x}''_0, t)$$

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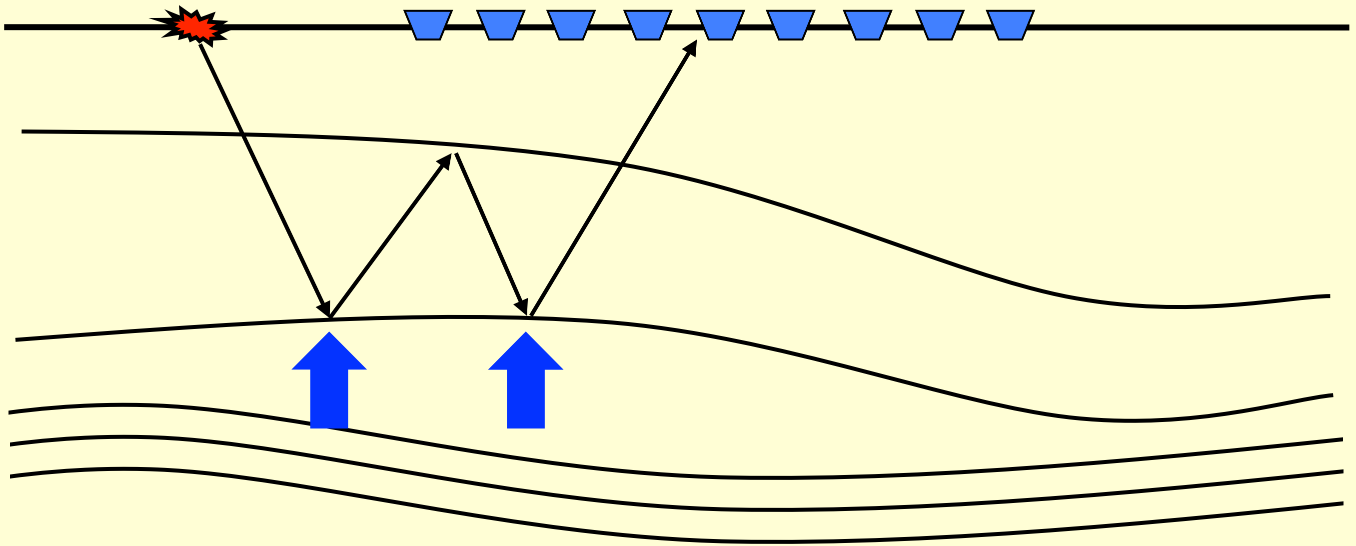
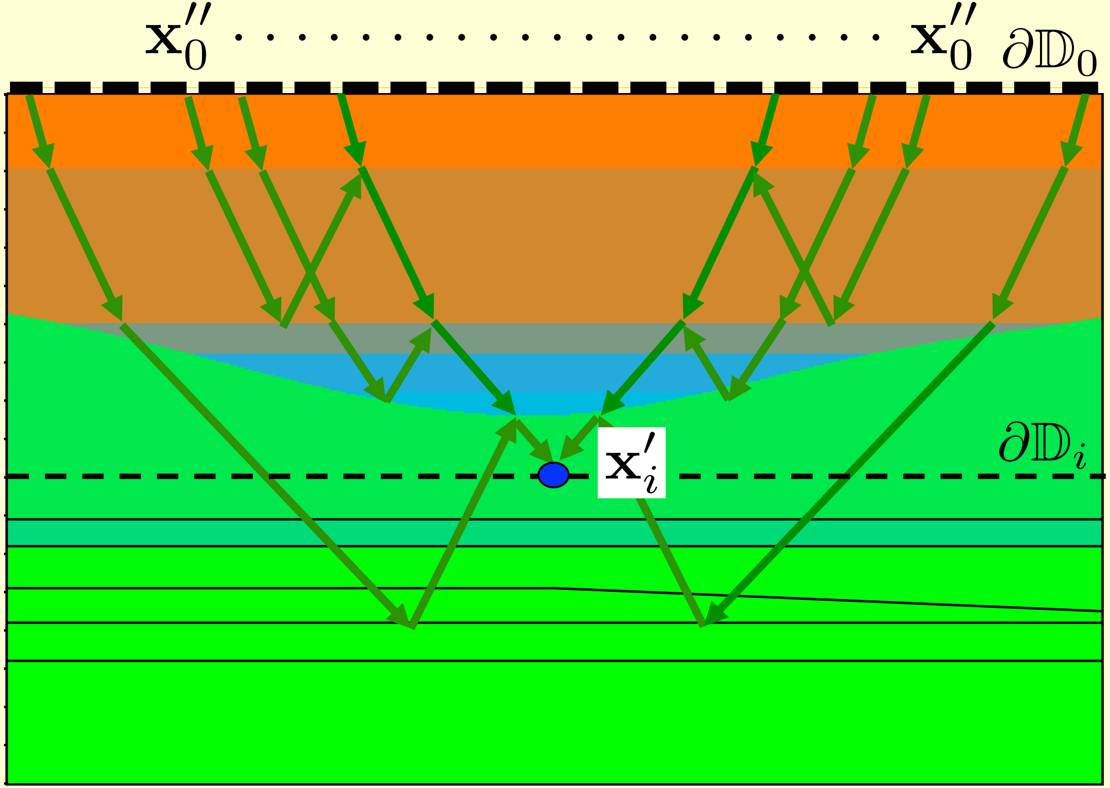
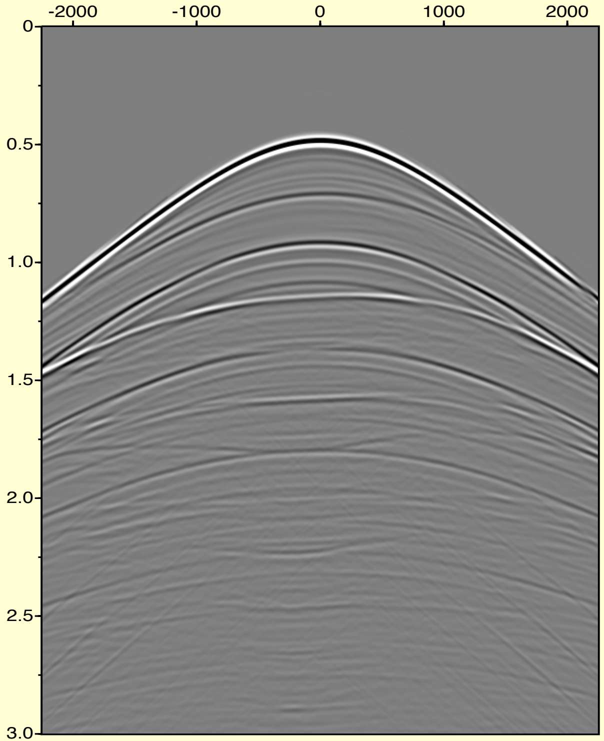
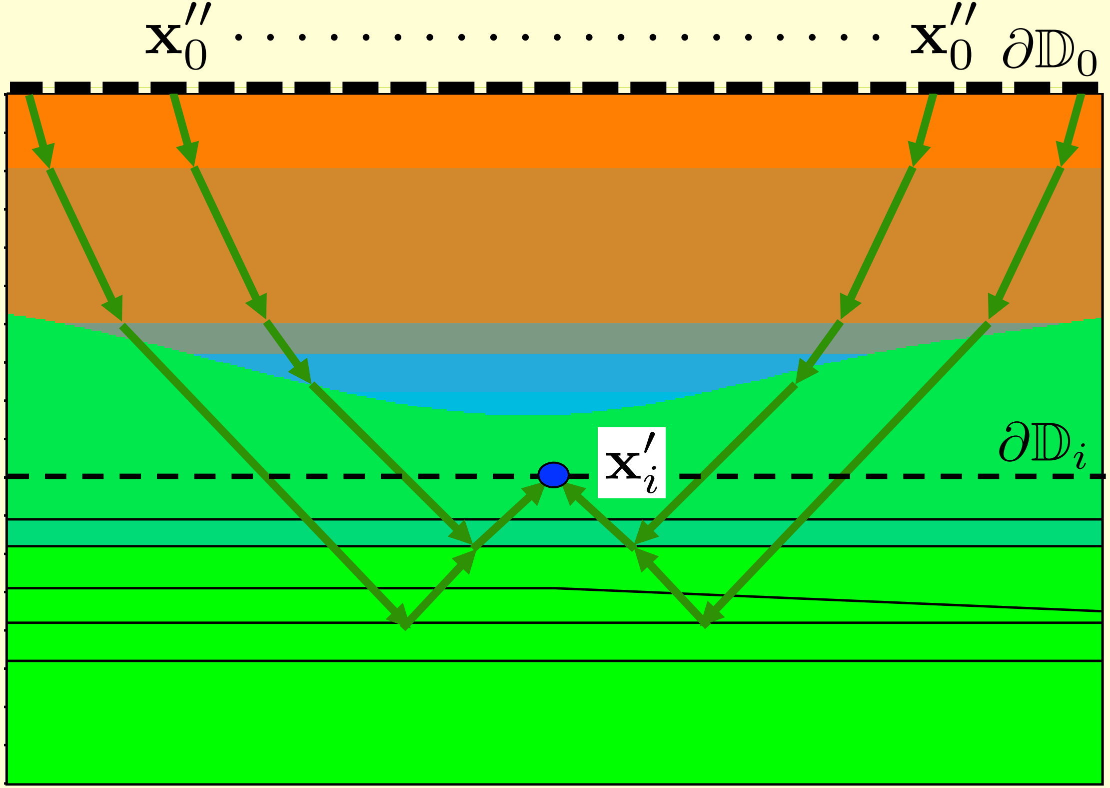


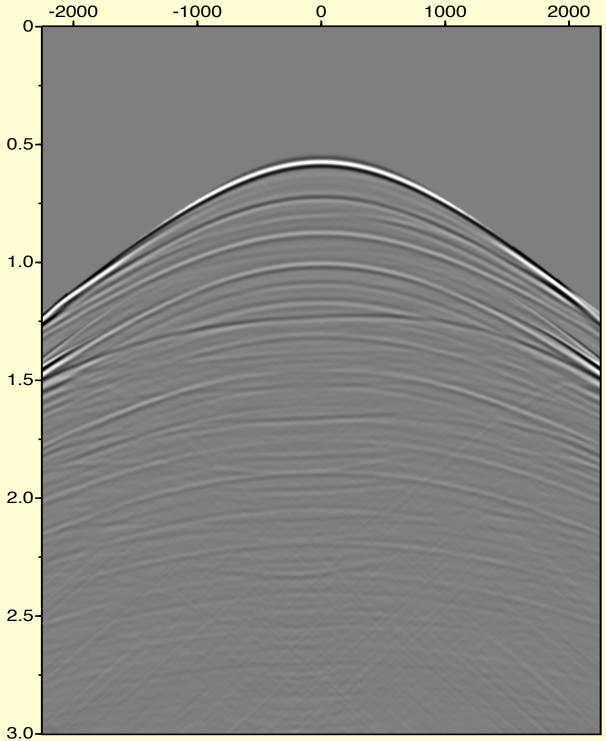
Improved illumination with internal multiples



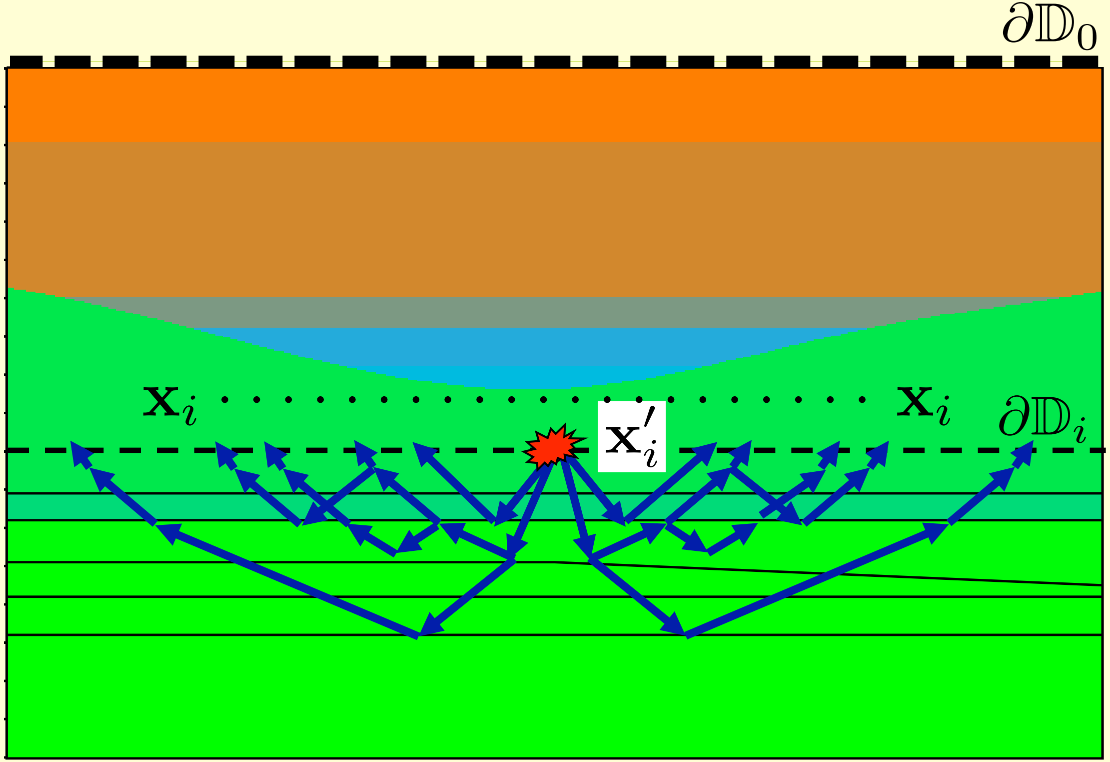


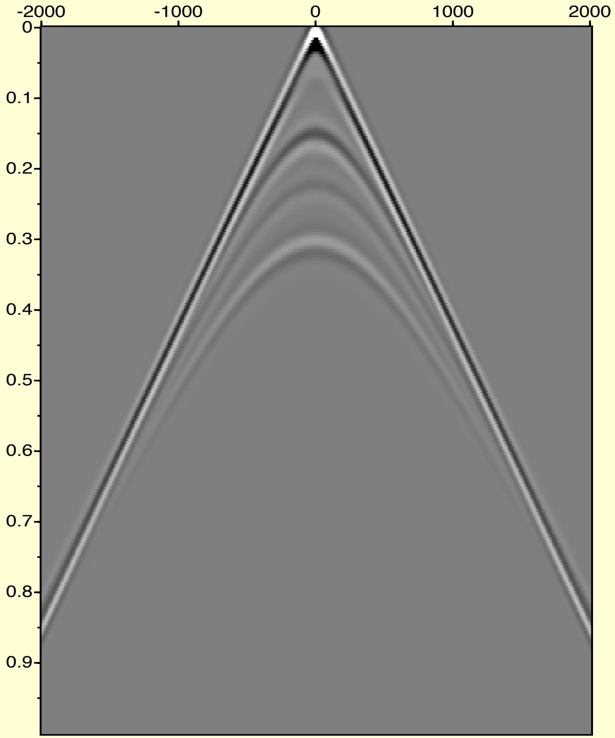
$$G^{-,+}(\mathbf{x}_i, \mathbf{x}_0'', t) = \int_{\partial\mathbb{D}_i} \mathrm{d}\mathbf{x}_i' \int_{-\infty}^{\infty} R(\mathbf{x}_i, \mathbf{x}_i', t') G^{+,+}(\mathbf{x}_i', \mathbf{x}_0'', t - t') \mathrm{d}t'$$



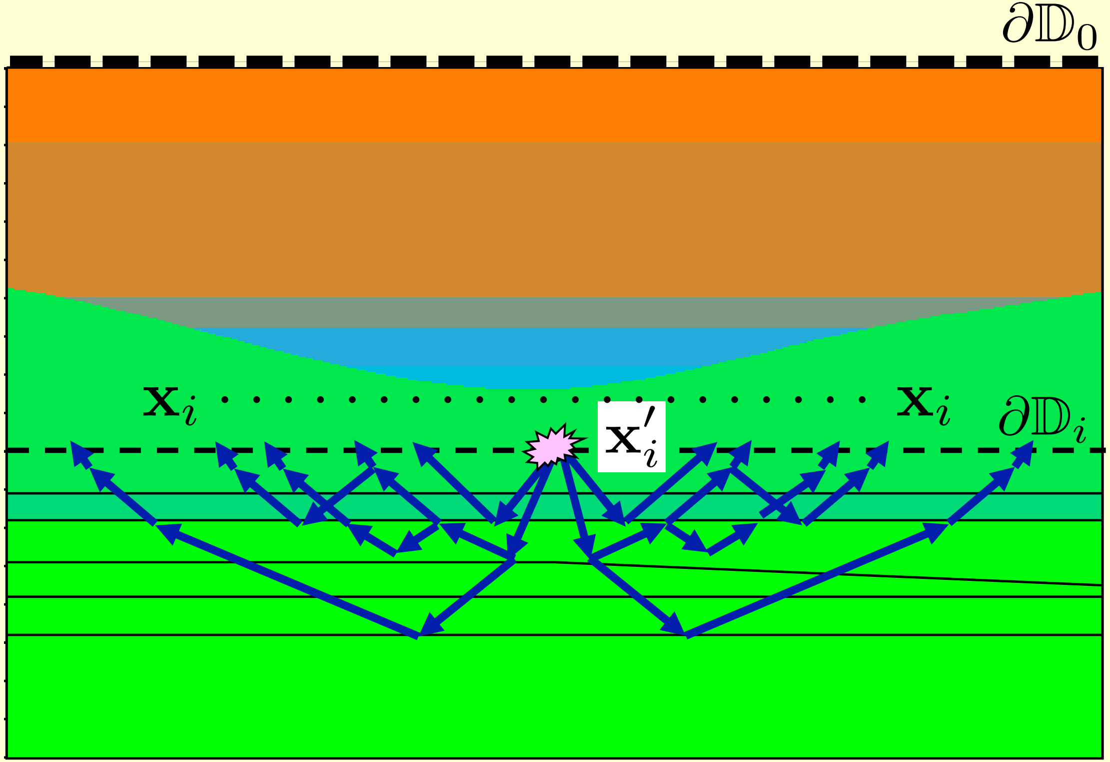


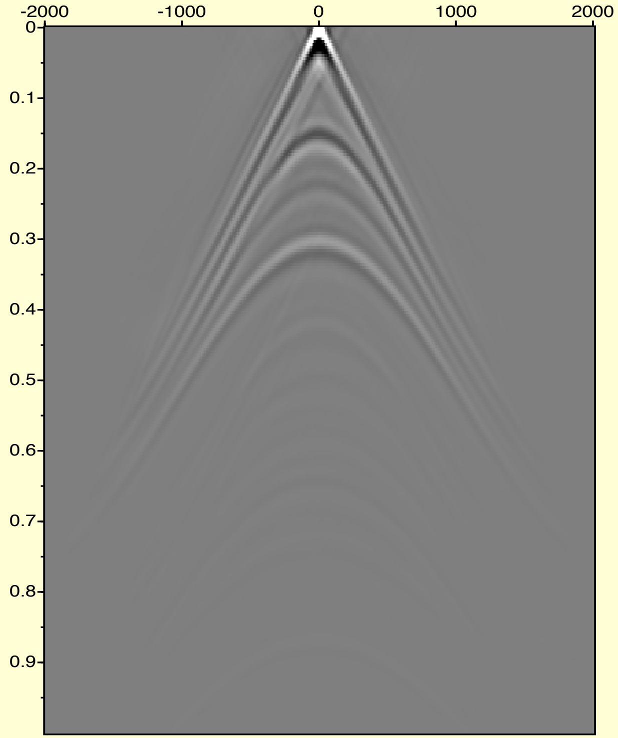
$$G^{-,+}(\mathbf{x}_i, \mathbf{x}_0'', t) = \int_{\partial\mathbb{D}_i} \mathrm{d}\mathbf{x}_i' \int_{-\infty}^{\infty} R(\mathbf{x}_i, \mathbf{x}_i', t') G^{+,+}(\mathbf{x}_i', \mathbf{x}_0'', t - t') \mathrm{d}t'$$



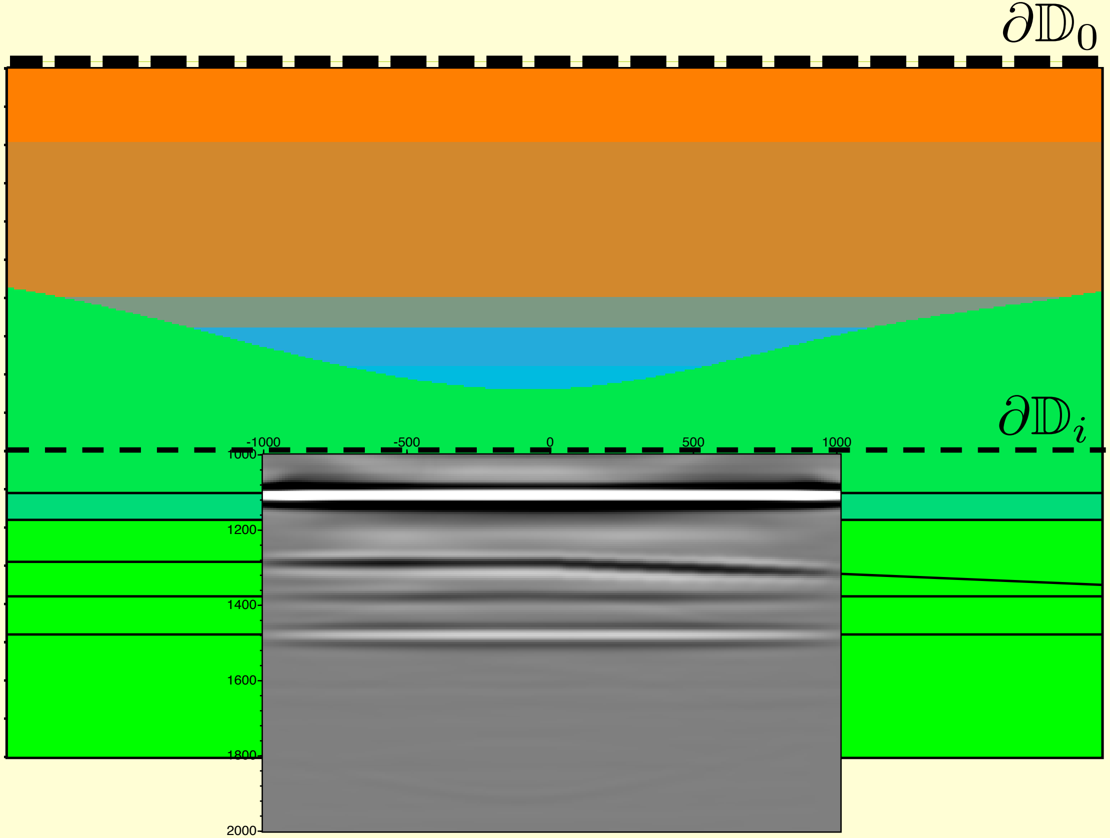


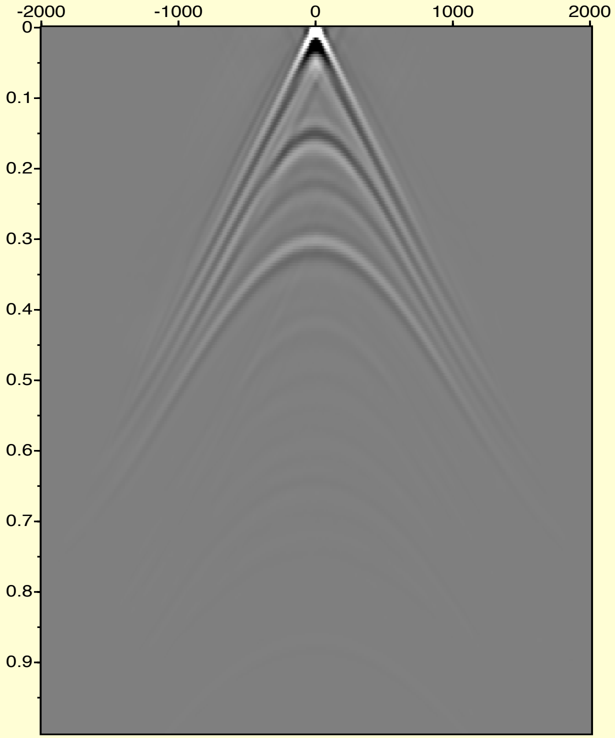
$$G^{-,+}(\mathbf{x}_i, \mathbf{x}''_0, t) = \int_{\partial\mathbb{D}_i} \mathrm{d}\mathbf{x}'_i \int_{-\infty}^{\infty} R(\mathbf{x}_i, \mathbf{x}'_i, t') G^{+,+}(\mathbf{x}'_i, \mathbf{x}''_0, t - t')\mathrm{d}t'$$



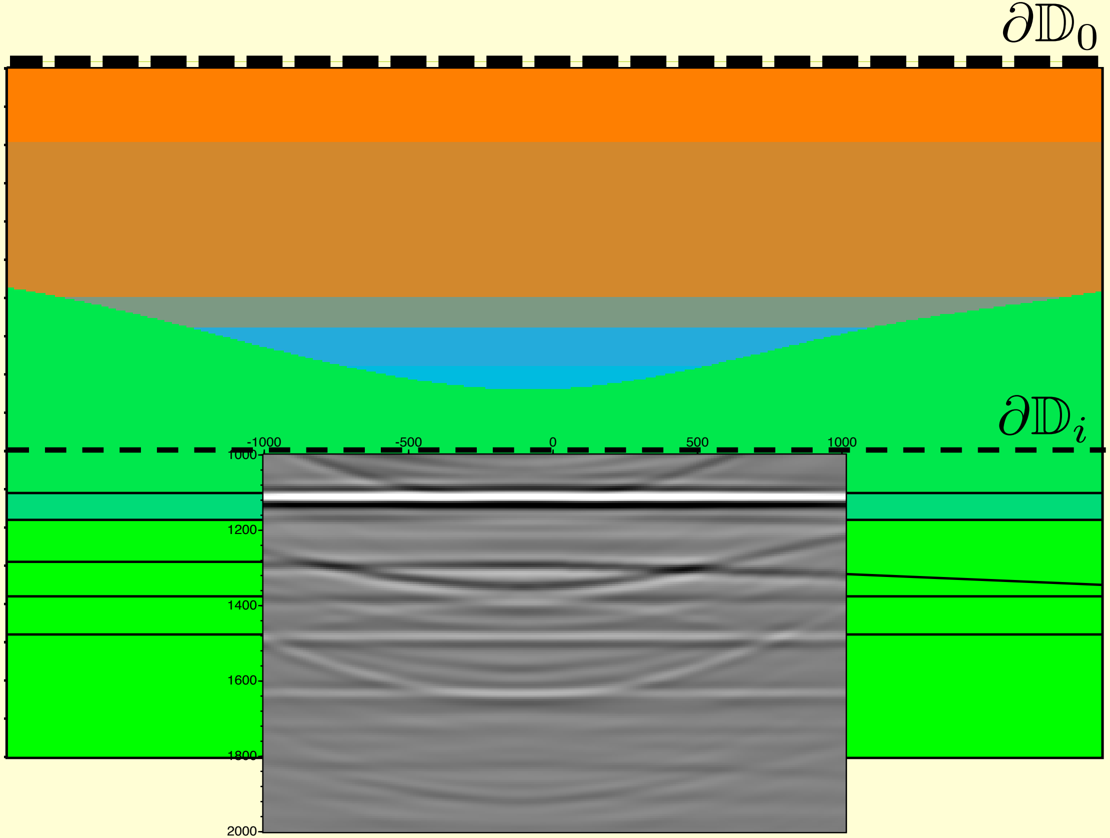


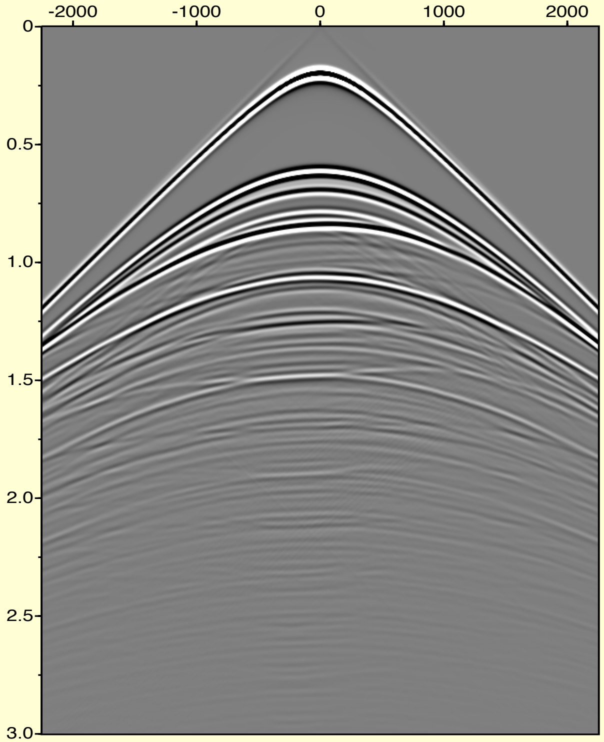
$$G^{-,+}(\mathbf{x}_i, \mathbf{x}_0'', t) = \int_{\partial\mathbb{D}_i} \mathrm{d}\mathbf{x}_i' \int_{-\infty}^{\infty} R(\mathbf{x}_i, \mathbf{x}_i', t') G^{+,+}(\mathbf{x}_i', \mathbf{x}_0'', t - t') \mathrm{d}t'$$





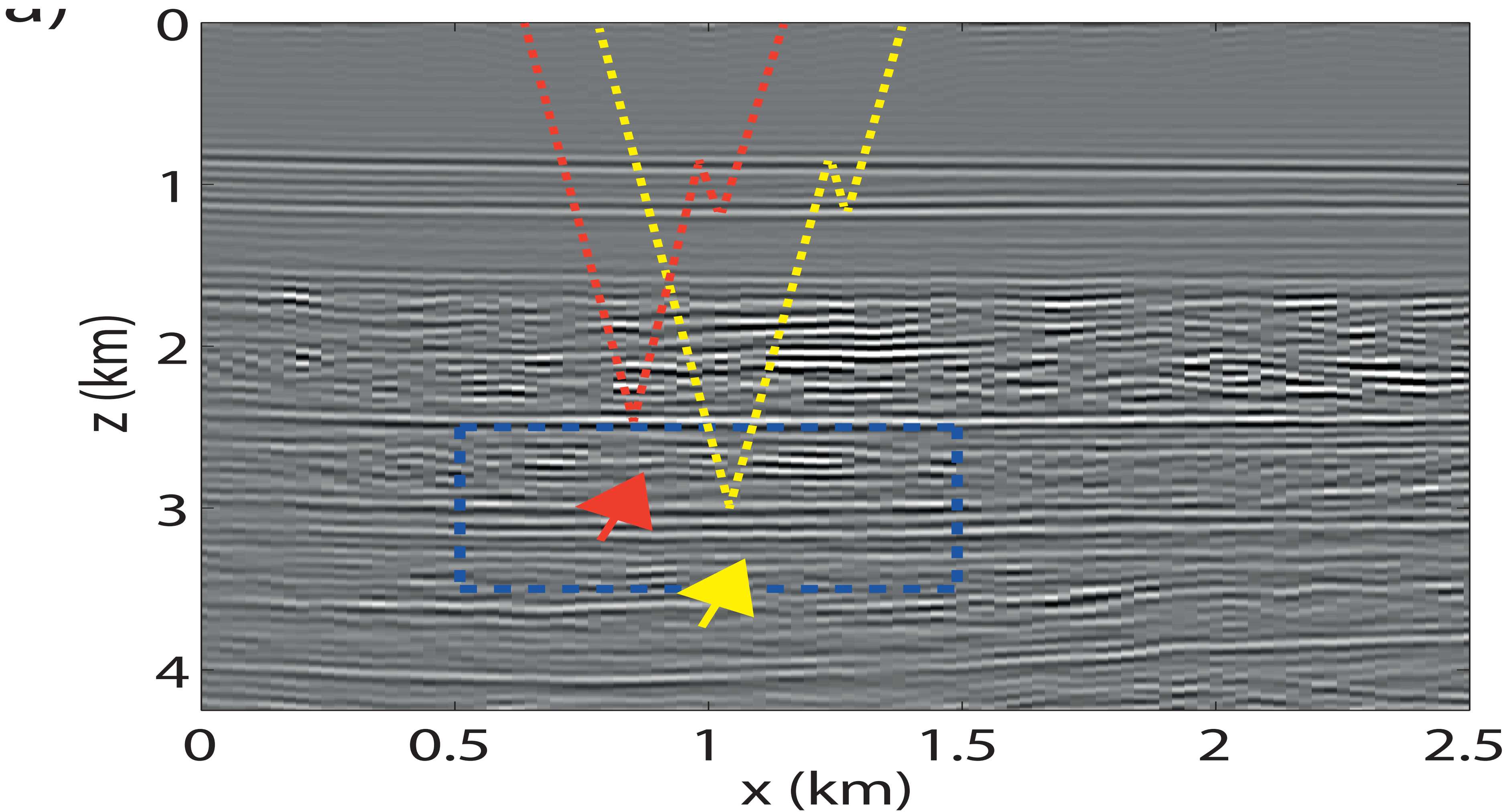
Marchenko imaging



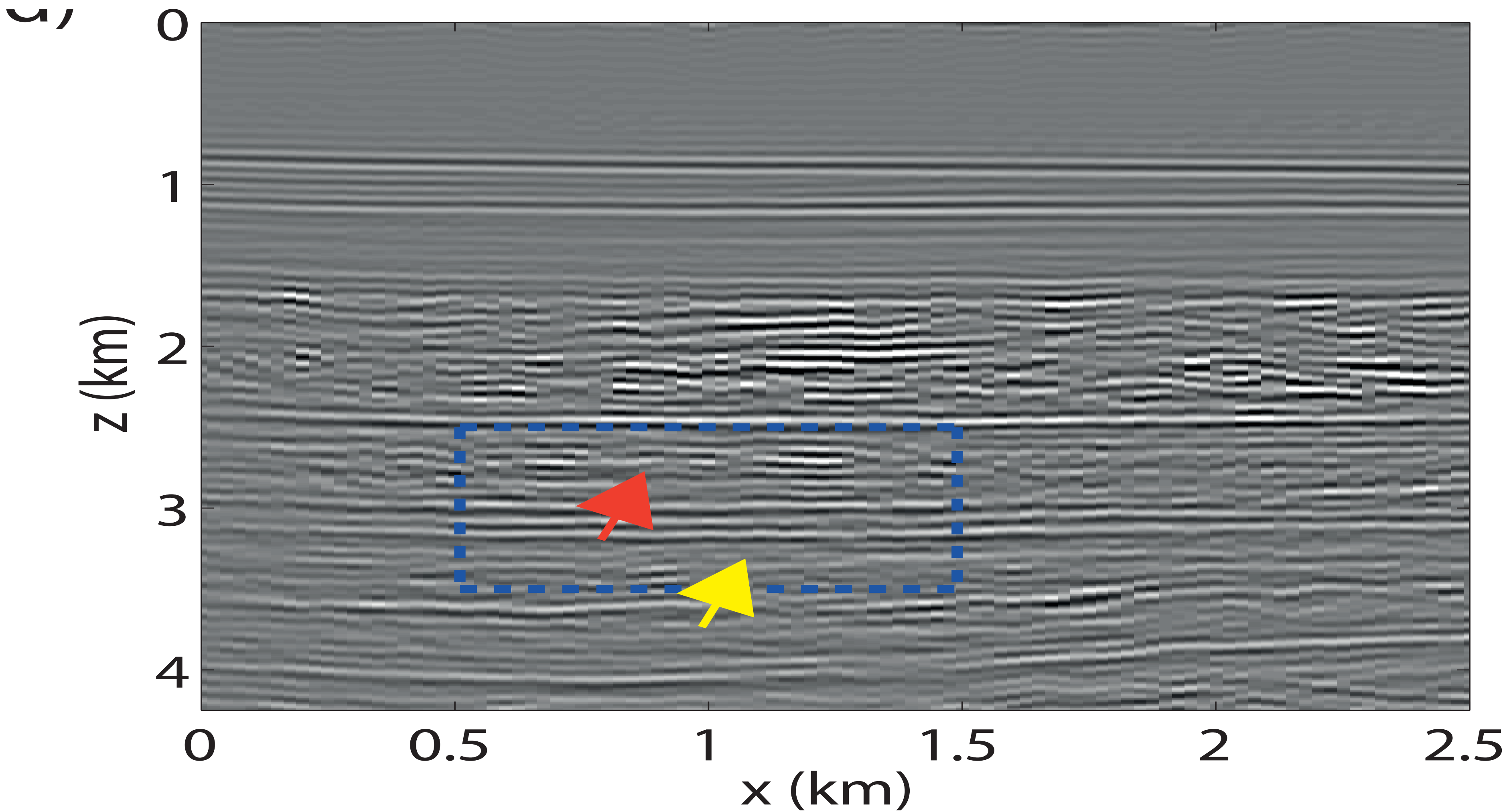


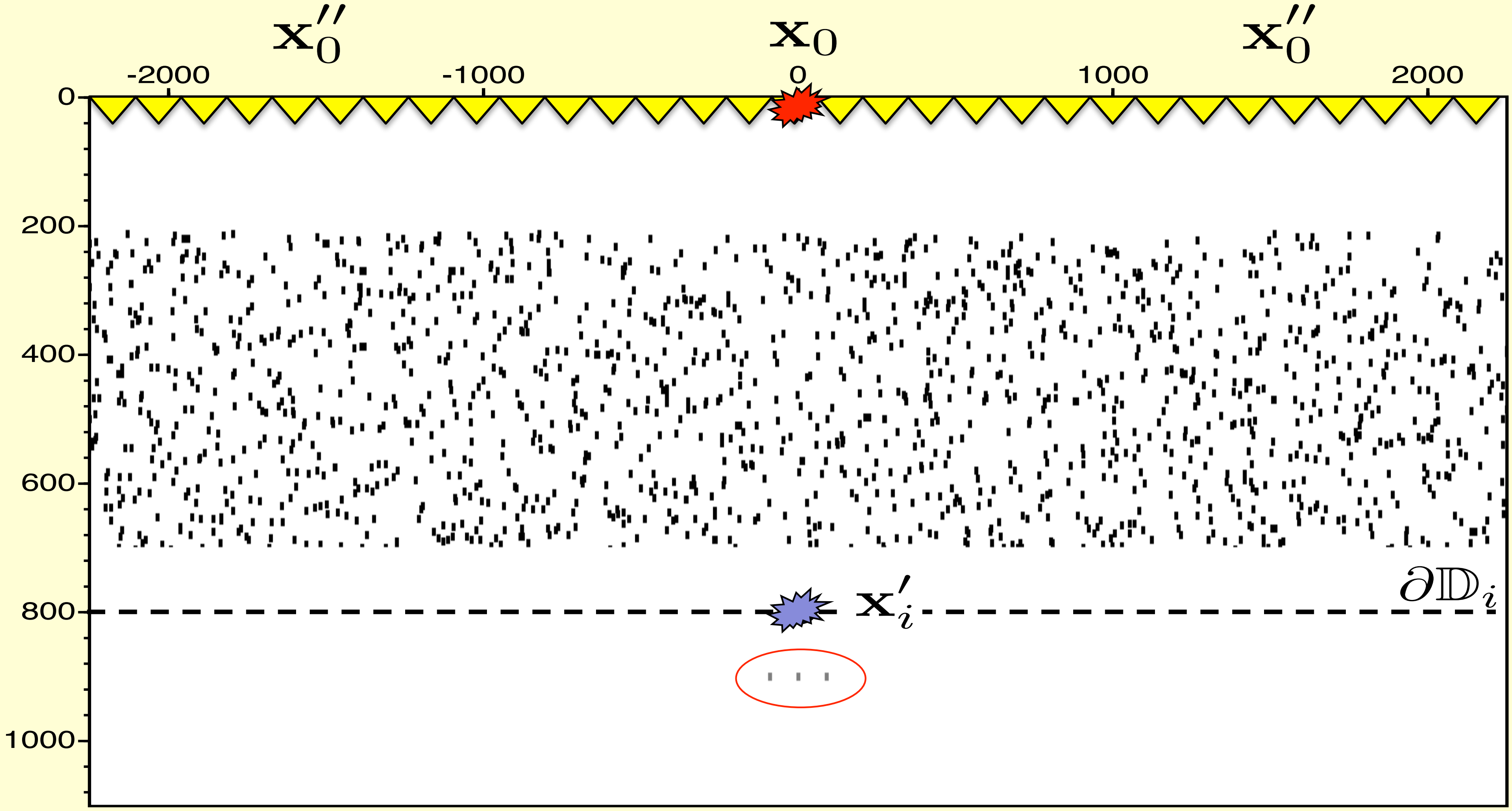
Standard imaging

Joost van der Neut et al., 2015

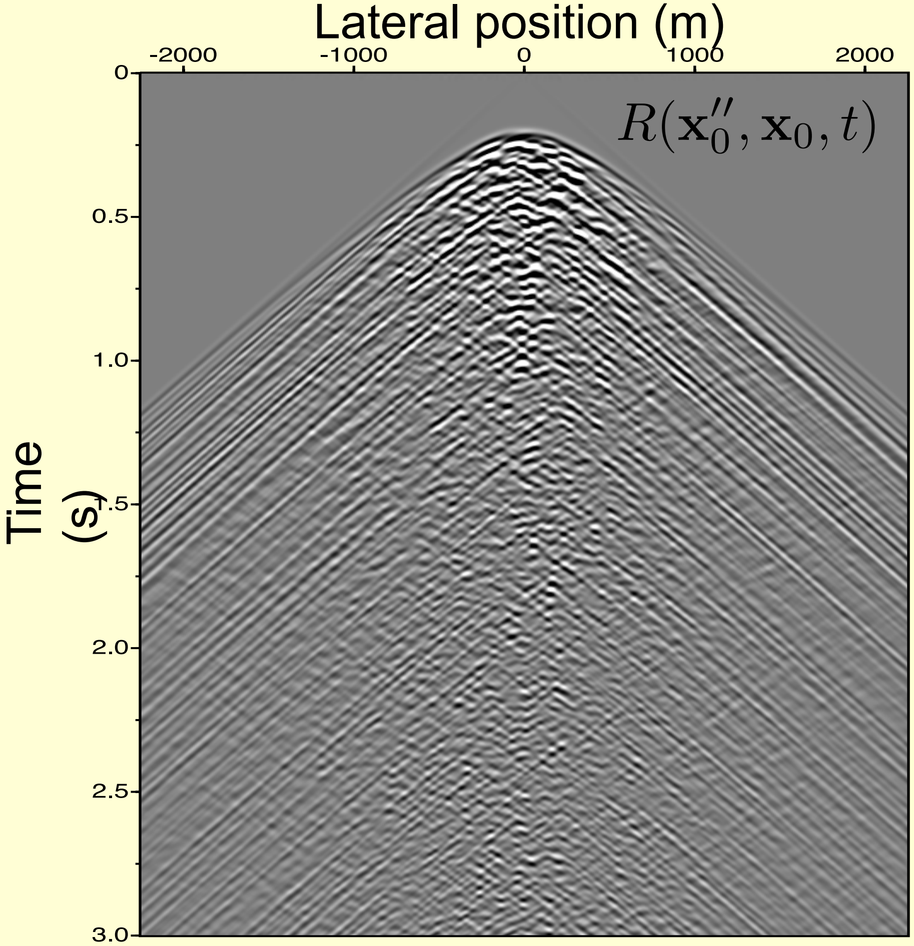


Joost van der Neut et al., 2015

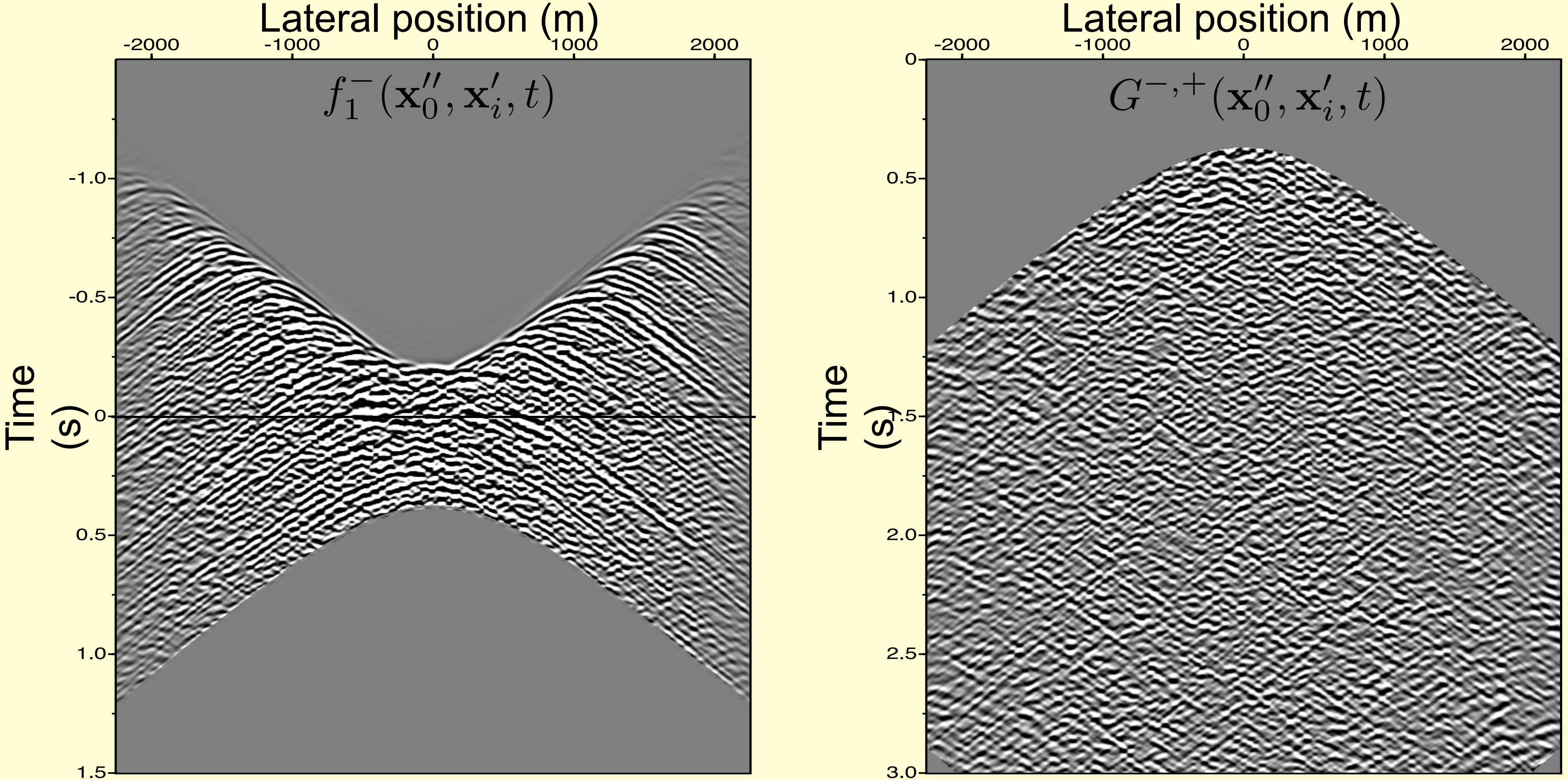




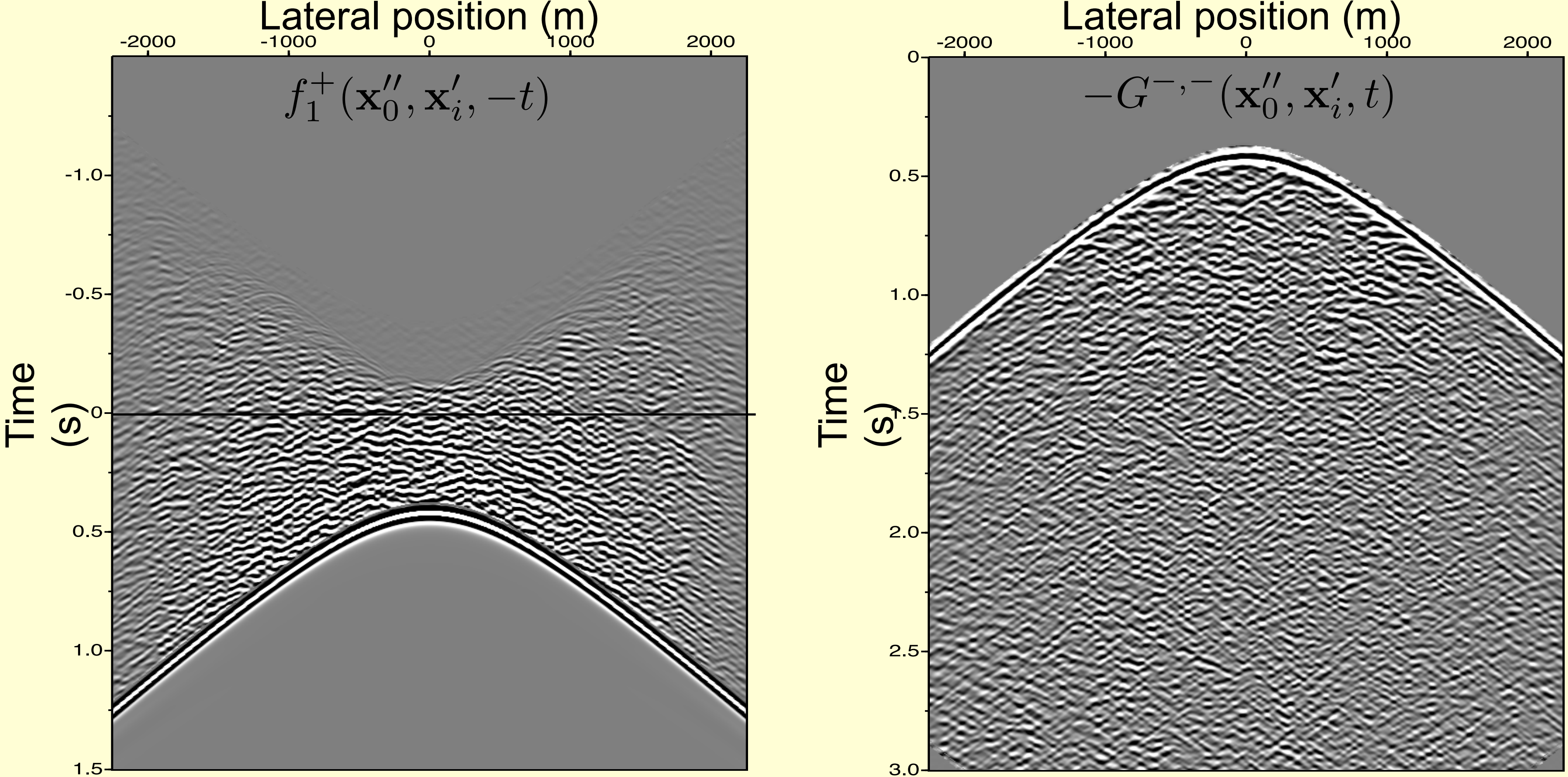
$\mathbf{x}_0''$
$\mathbf{x}_0$
$\mathbf{x}_0''$
-2000
-1000
0
1000
2000
0
200
400
600
800
1000
$\mathbf{x}_i'$
$\partial\mathbb{D}_i$



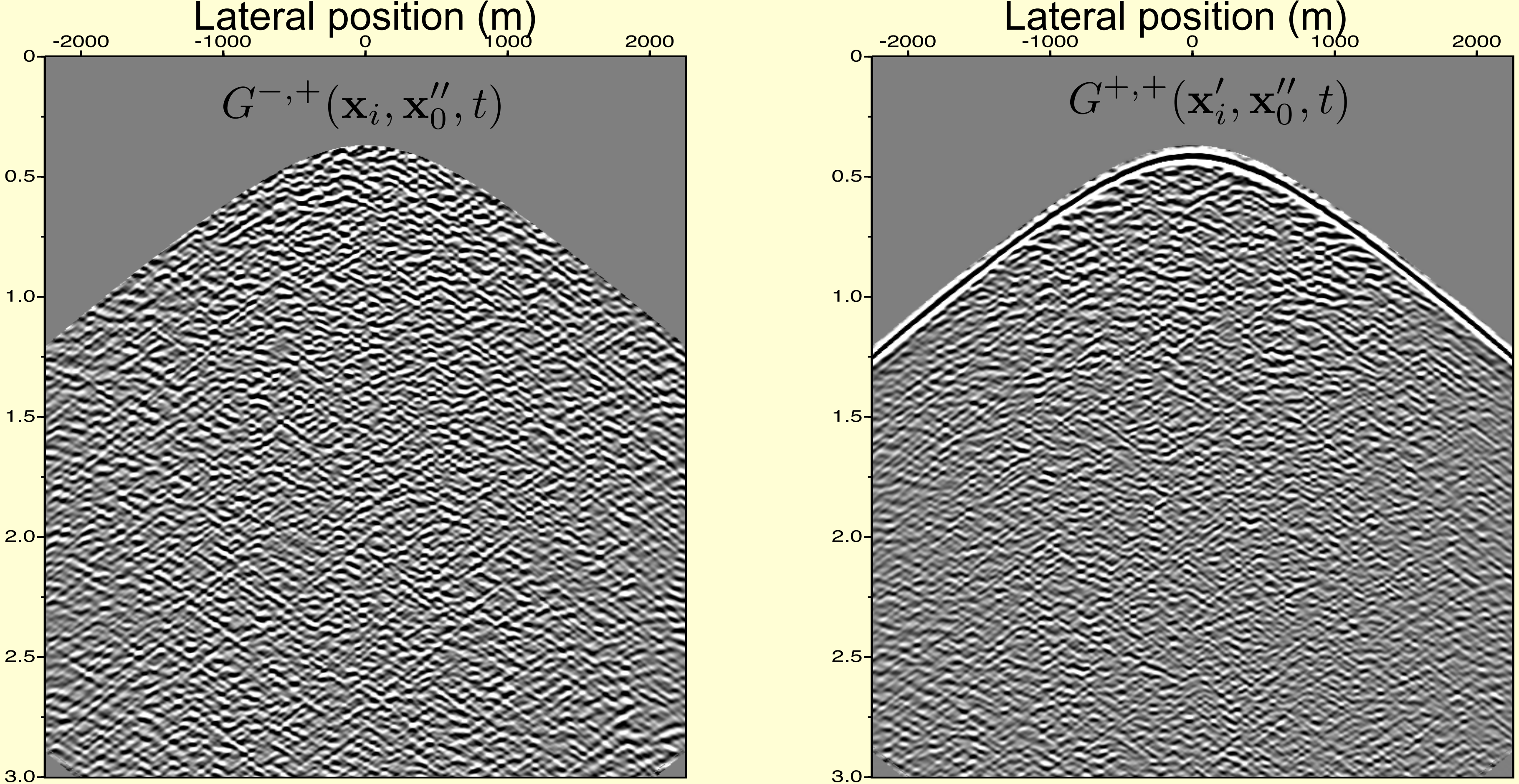
Lateral position (m)
-2000
-1000
0
1000
2000
$R(\mathbf{x}_0'', \mathbf{x}_0, t)$
Time (s)
0
0.5
1.0
1.5
2.0
2.5
3.0



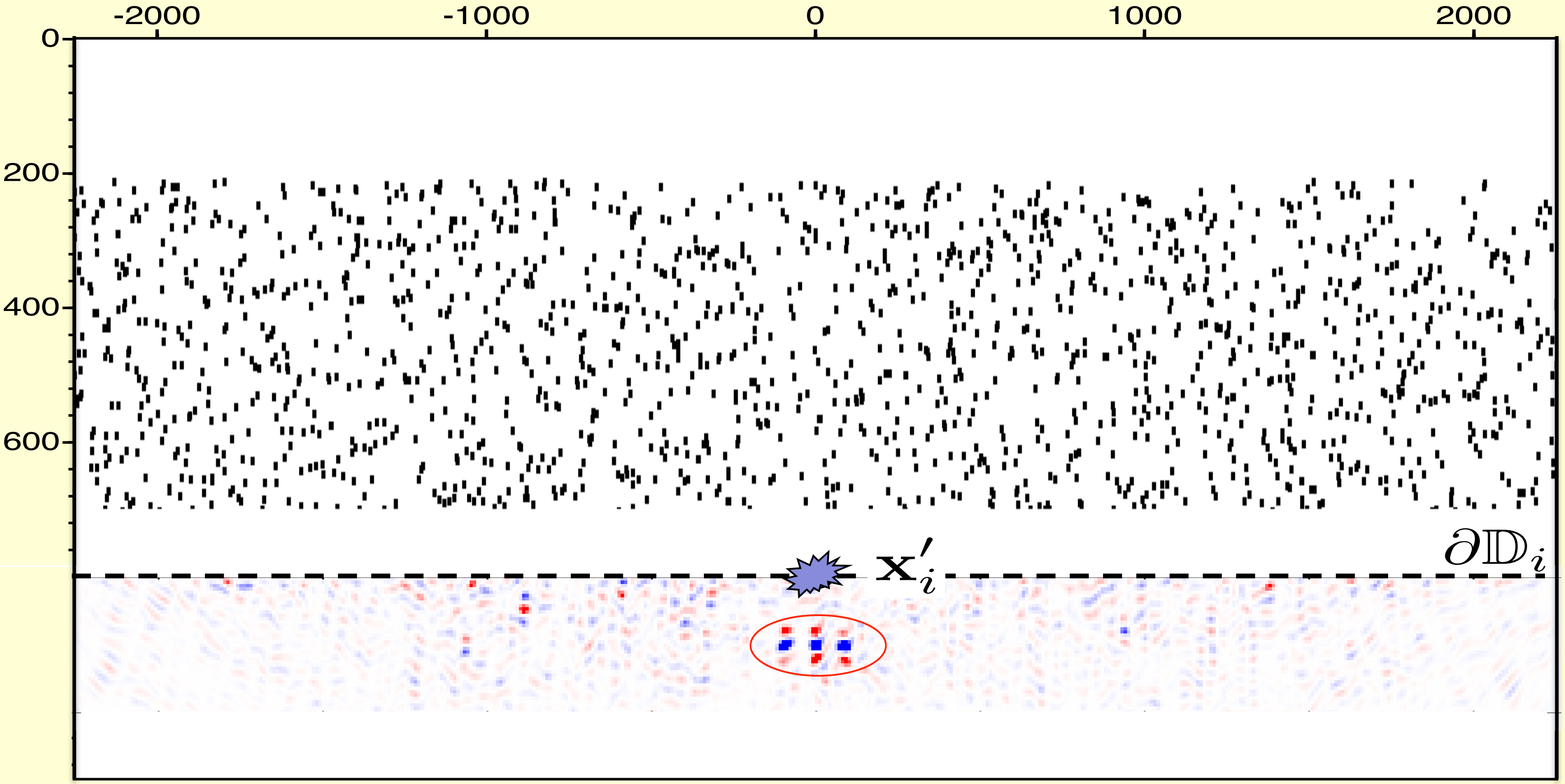
$$G^{-,+}(\mathbf{x}_0'', \mathbf{x}_i', t) + f_1^-(\mathbf{x}_0'', \mathbf{x}_i', t) = \int_{\partial\mathbb{D}_0} \mathrm{d}\mathbf{x}_0 \int_{-\infty}^{t} R(\mathbf{x}_0'', \mathbf{x}_0, t-t') f_1^+(\mathbf{x}_0, \mathbf{x}_i', t') \mathrm{d}t'$$



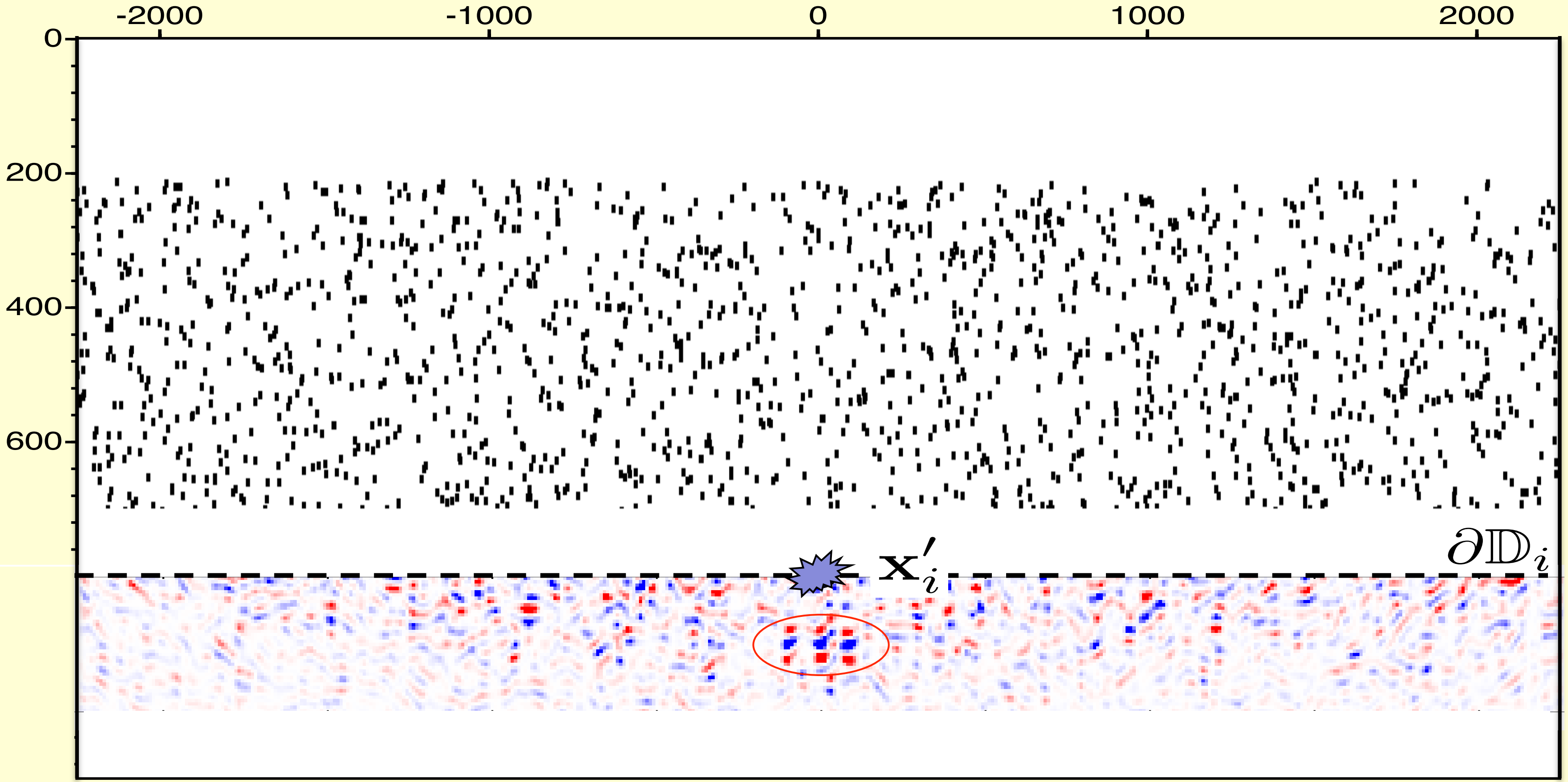
$$-G^{-,-}(\mathbf{x}_0'', \mathbf{x}_i', t) + f_1^+(\mathbf{x}_0'', \mathbf{x}_i', -t) = \int_{\partial \mathbb{D}_0} \mathrm{d}\mathbf{x}_0 \int_{-\infty}^{t} R(\mathbf{x}_0'', \mathbf{x}_0, t-t') f_1^-(\mathbf{x}_0, \mathbf{x}_i', -t') \mathrm{d}t'$$



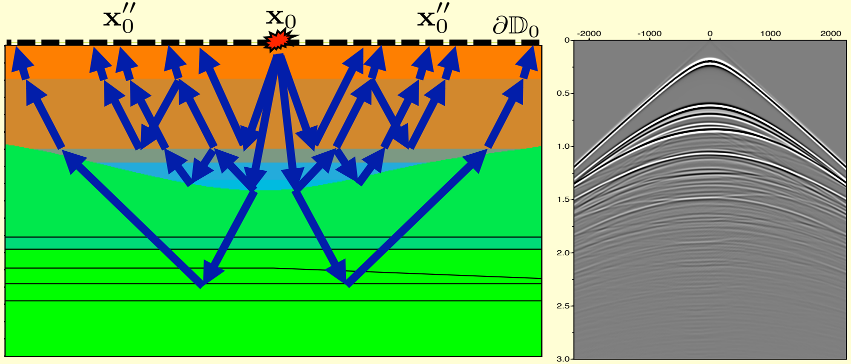
$$G^{-,+}(\mathbf{x}_i, \mathbf{x}''_0, t) = \int_{\partial \mathbb{D}_i} \mathrm{d}\mathbf{x}'_i \int_{-\infty}^{\infty} R(\mathbf{x}_i, \mathbf{x}'_i, t') G^{+,+}(\mathbf{x}'_i, \mathbf{x}''_0, t - t') \mathrm{d}t'$$



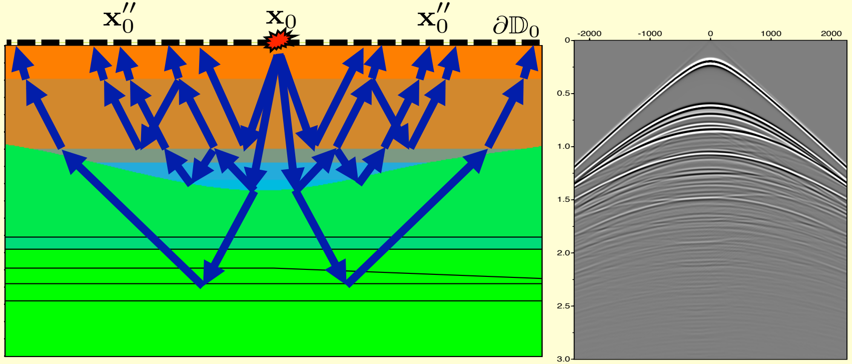
Marchenko imaging



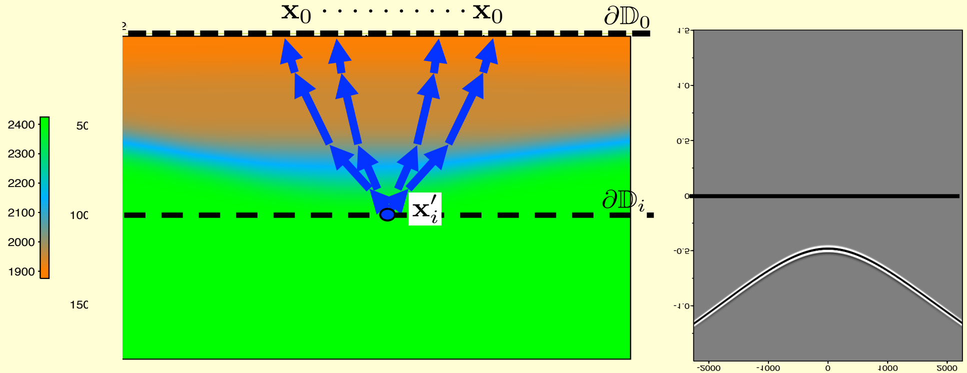
Standard imaging



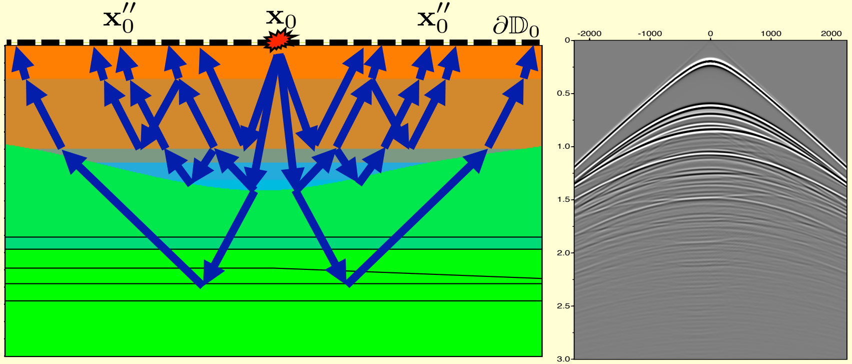
Reflection data



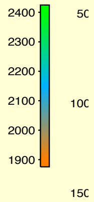
Reflection data

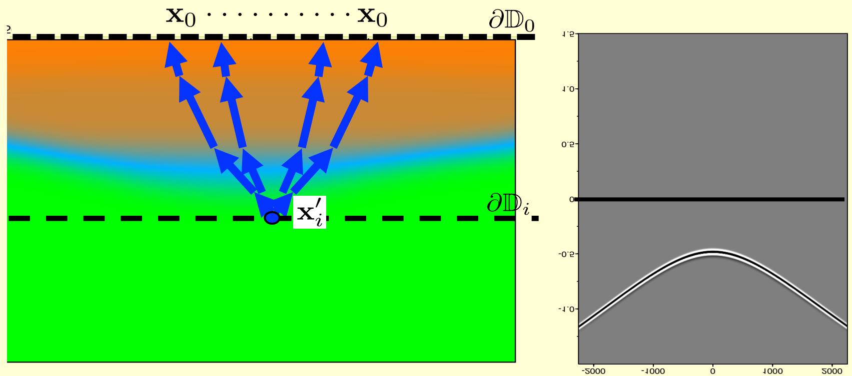


First arrivals

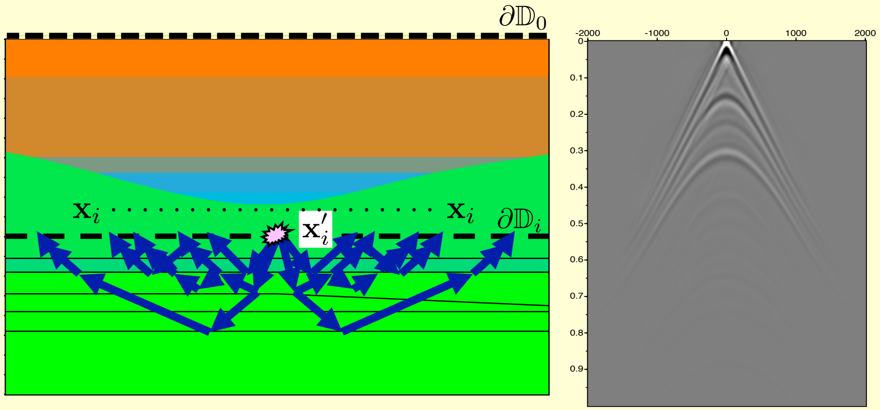


Reflection data

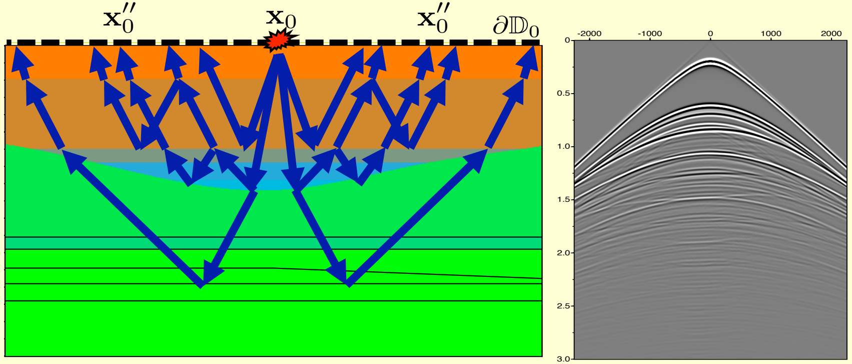


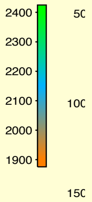


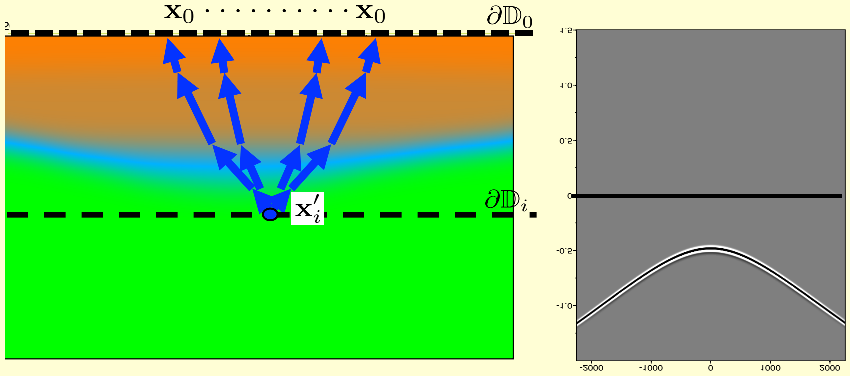
First arrivals



Data-driven redatuming, AVO analysis

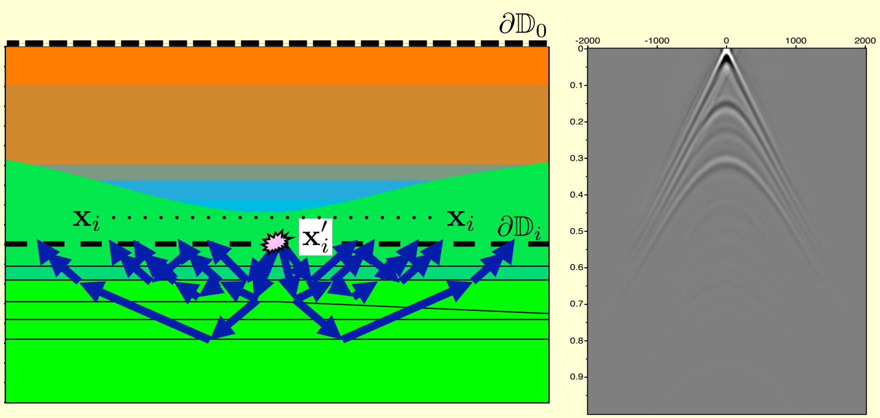


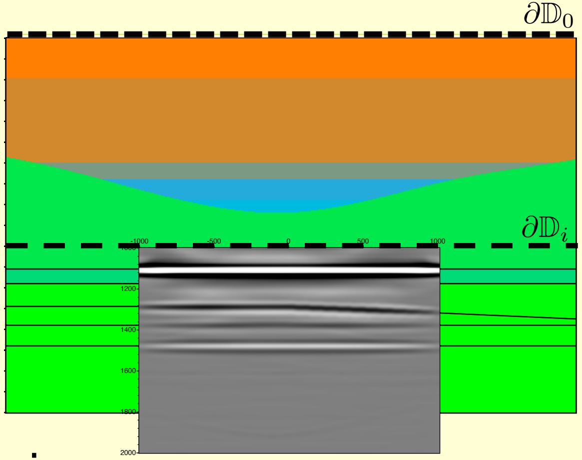




Reflection data

First arrivals





Data-driven redatuming, AVO analysis and imaging

- Introduction
- Green’s functions and focusing functions
- 3-D Marchenko equations
- Iterative solution
- Green’s function retrieval
- Marchenko imaging
- Issues for discussion

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- Non-recursive (target oriented)

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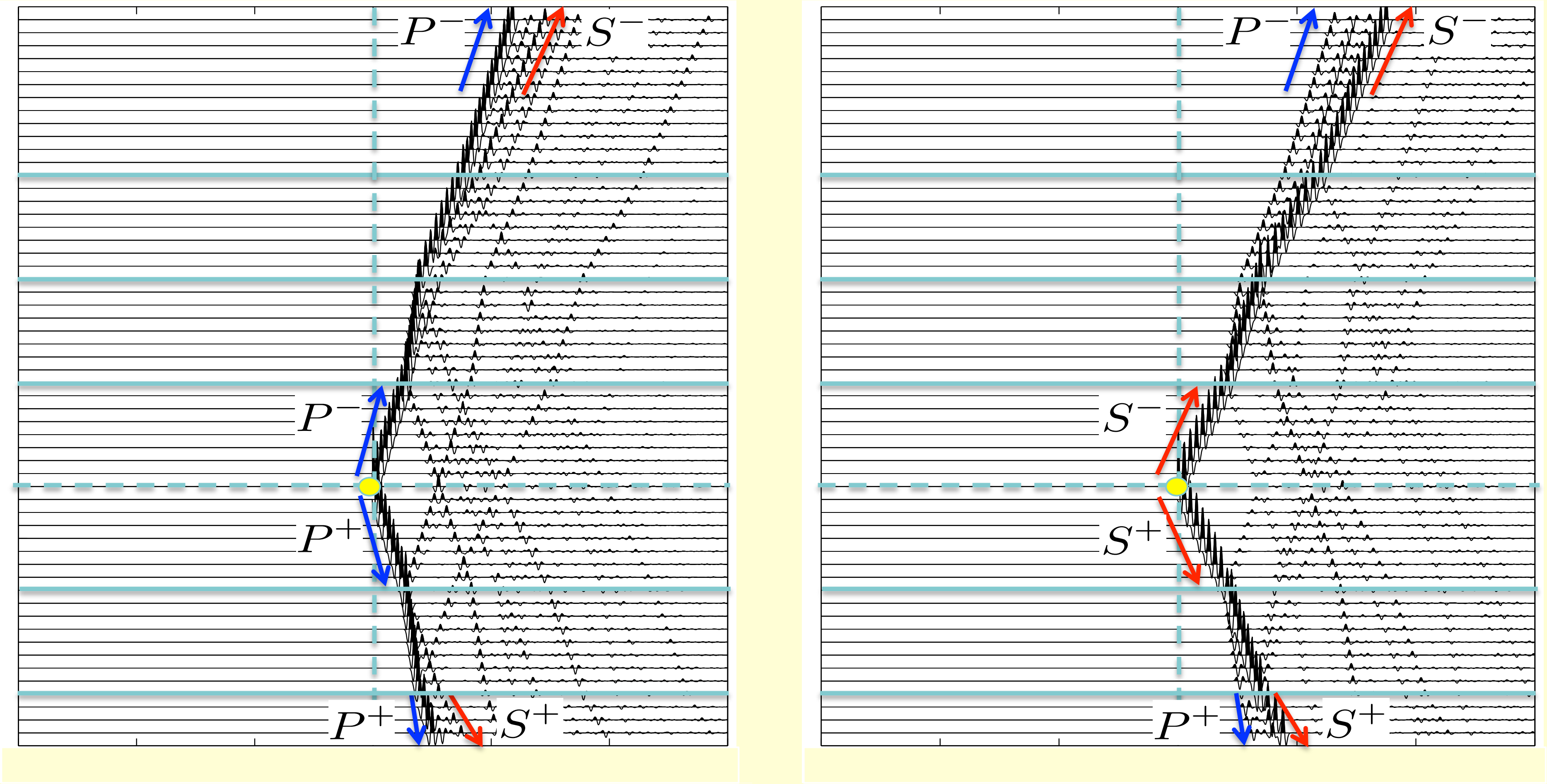
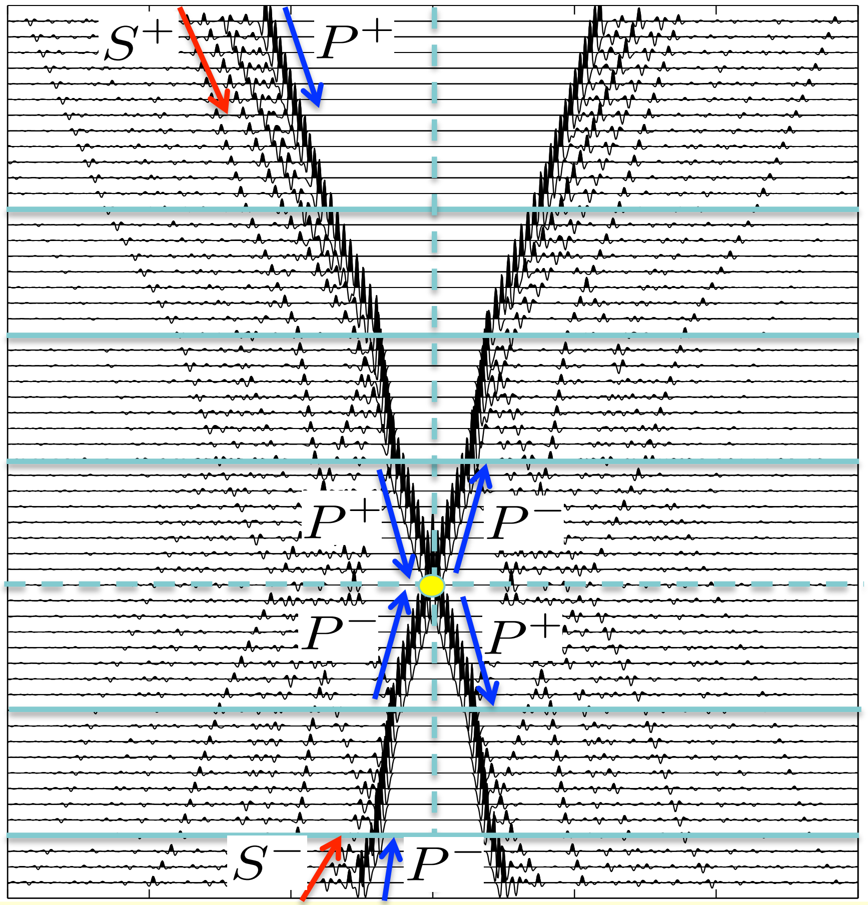
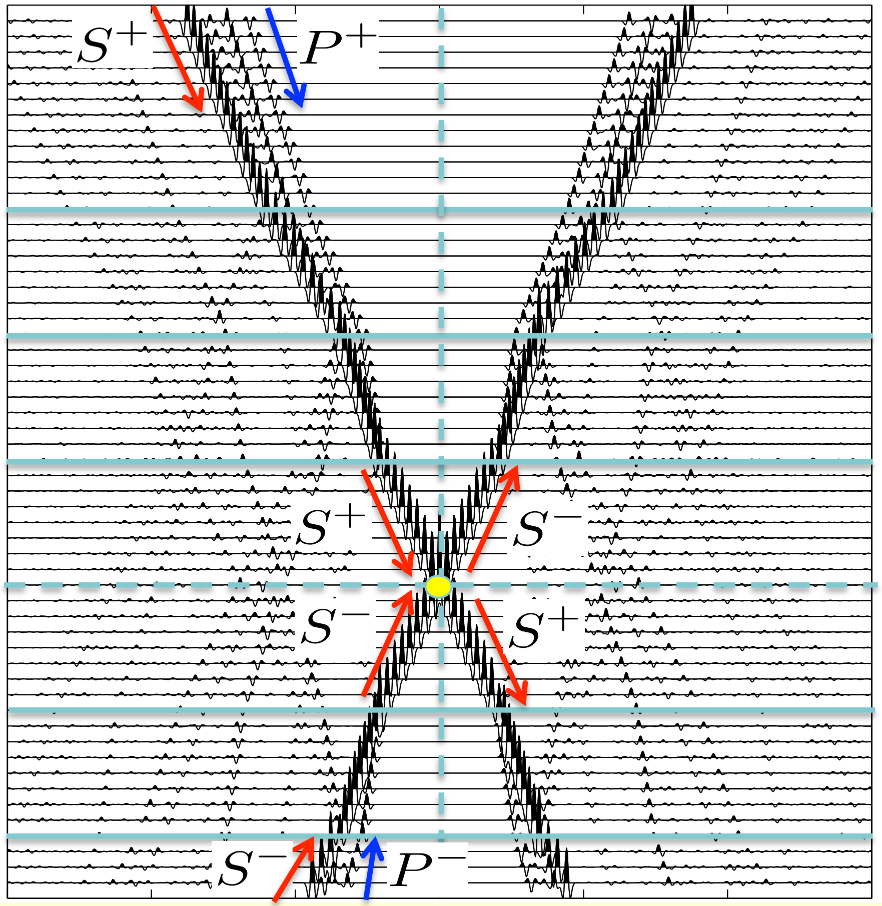
- Ambiguity direct arrival (refracted waves)
- Extension to elastodynamic waves

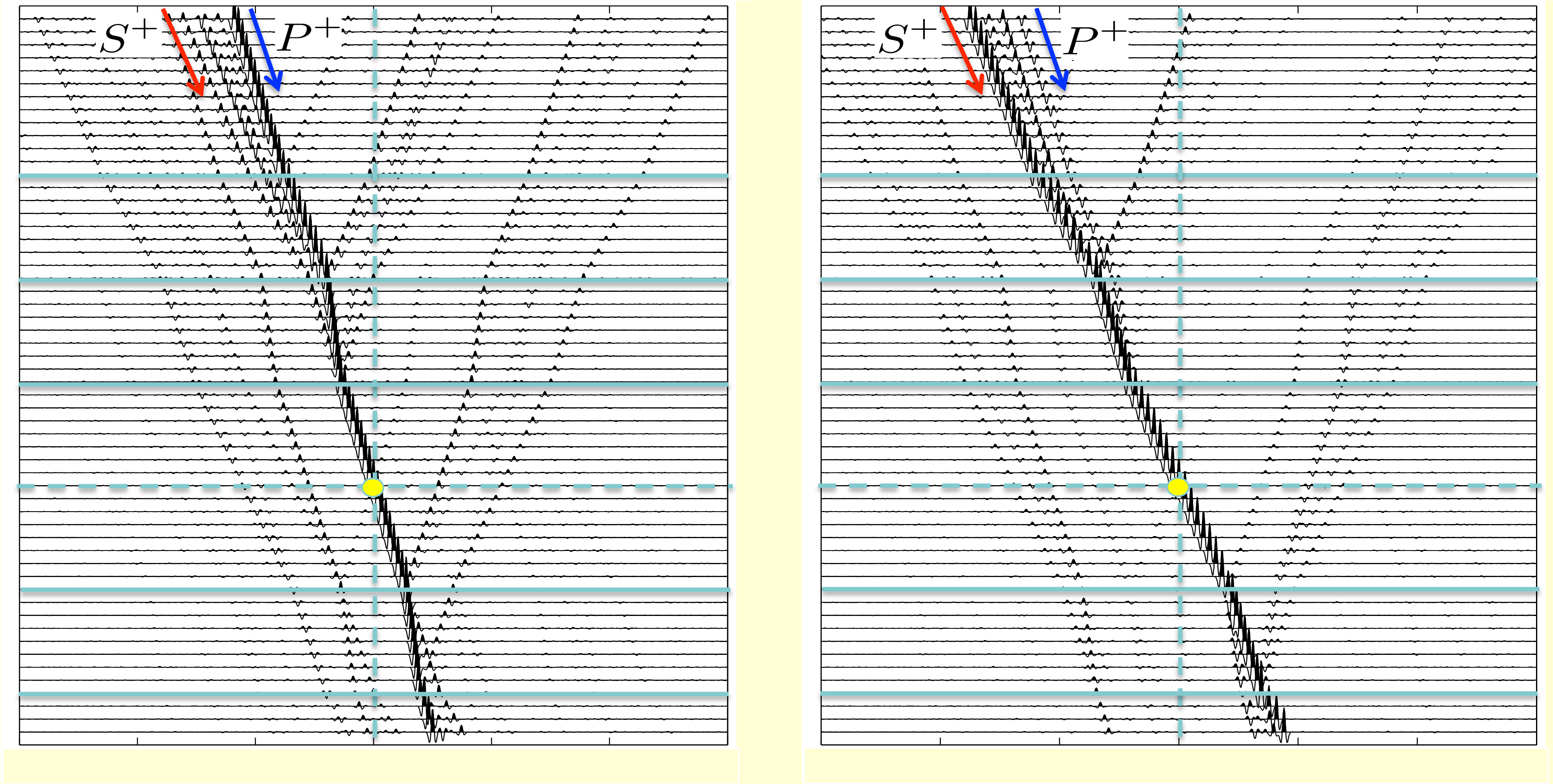


Elastodynamic Green's functions





Time-reversal, two-sided illumination



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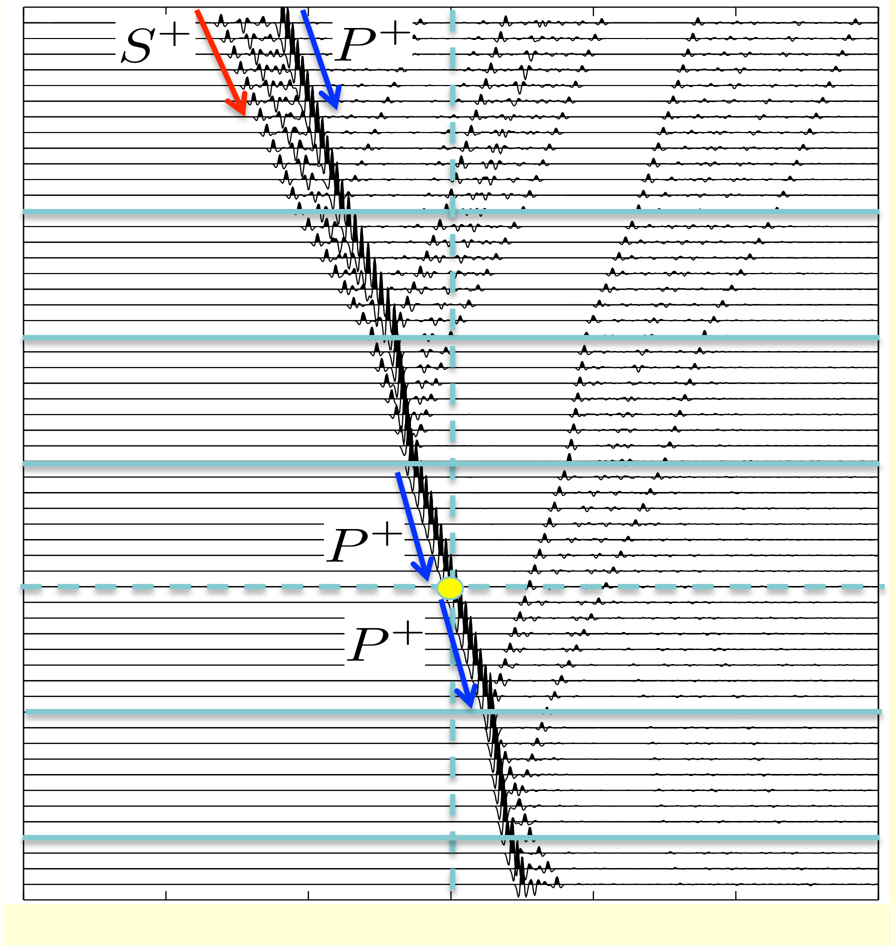
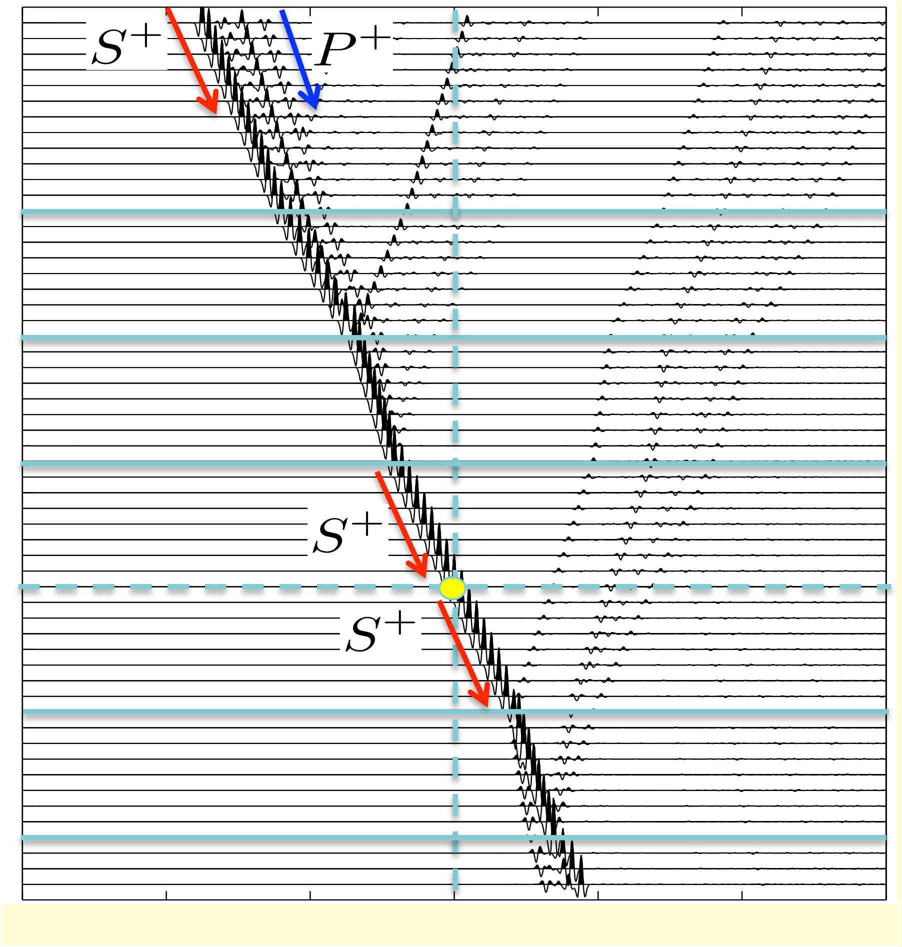
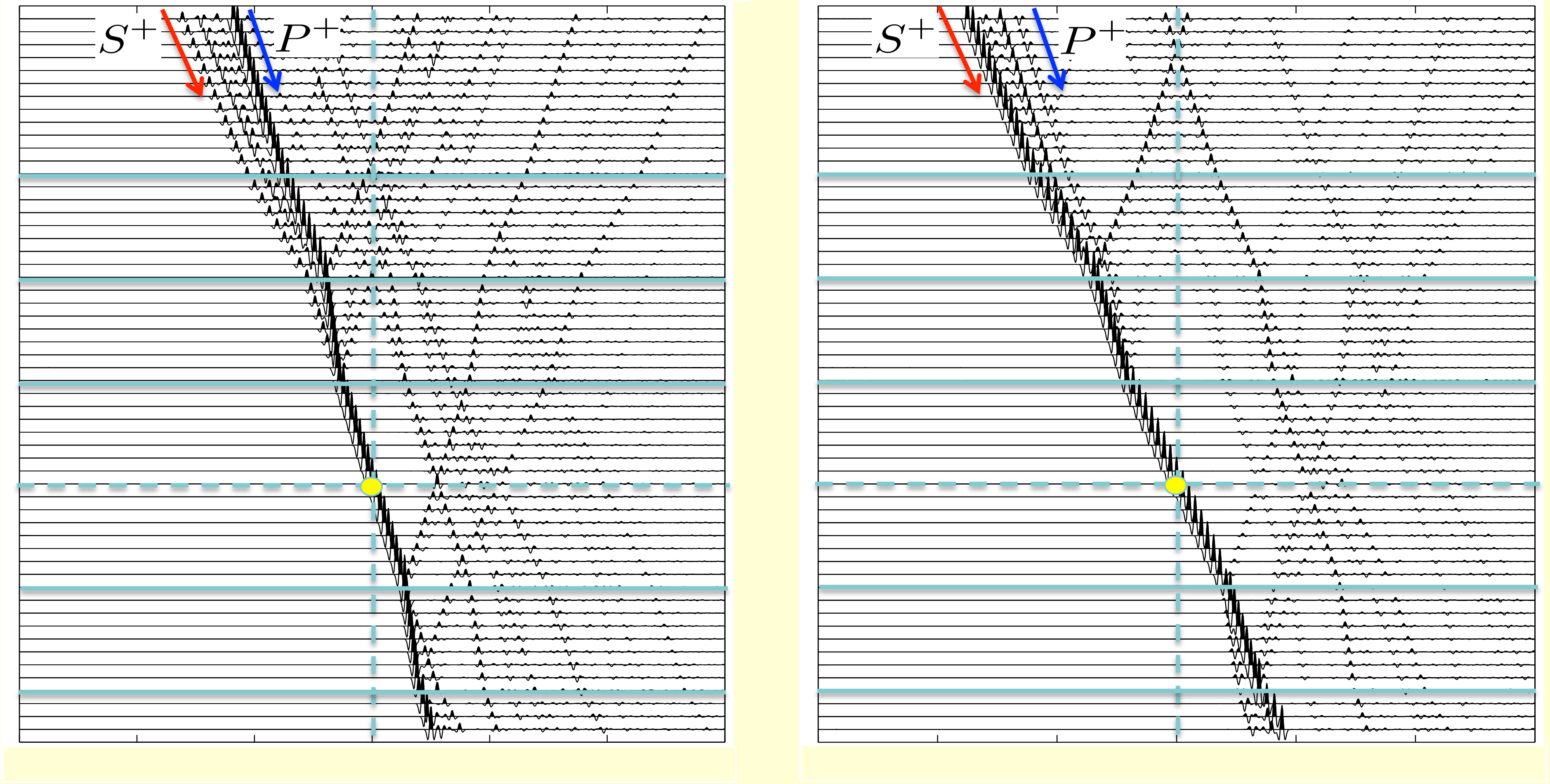
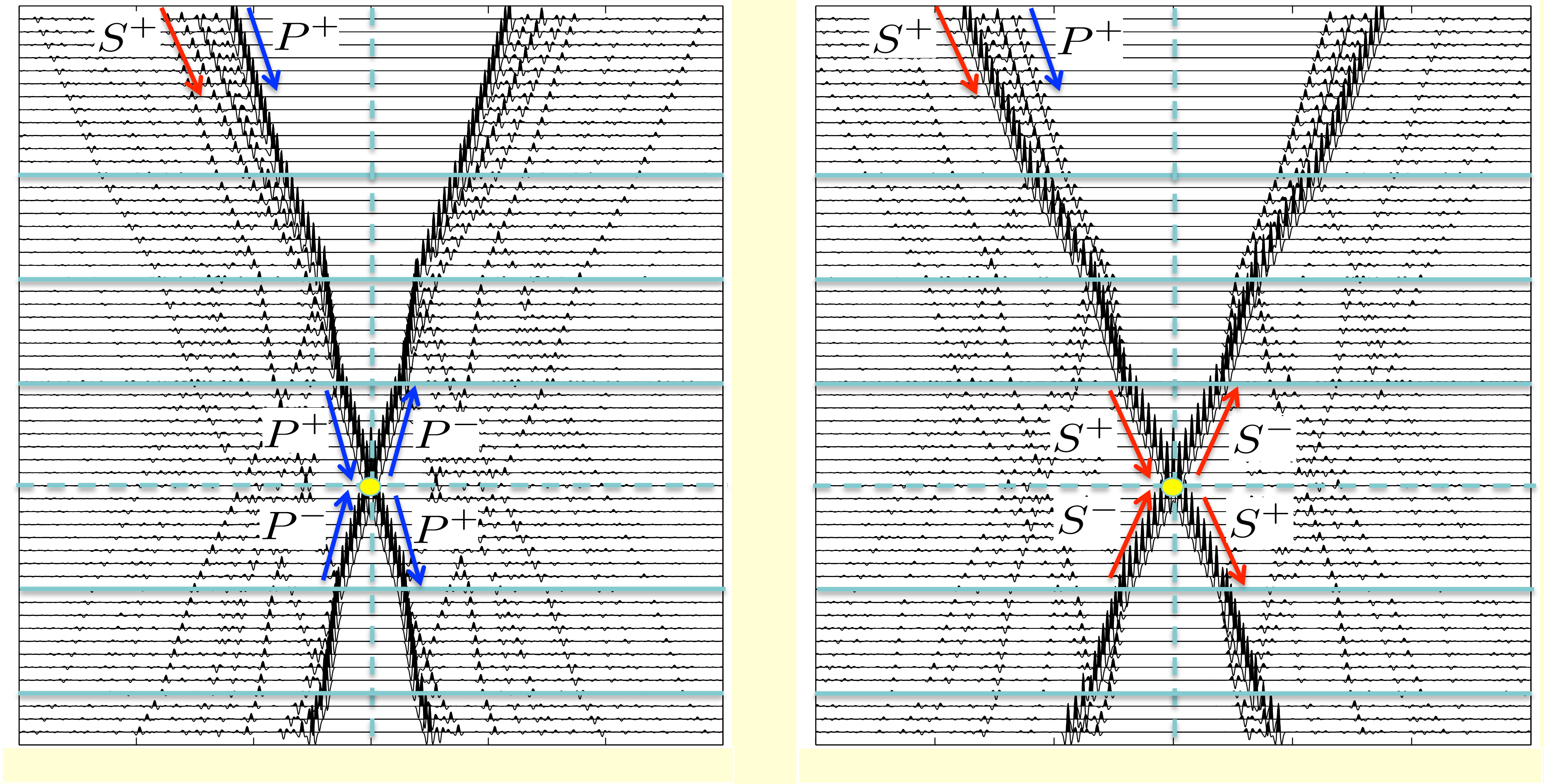




Marchenko, one-sided, $\mathbf{F}_1^+(z_0, z_A, t) \quad \cdot \mathbf{F}_1^-(z_0, z_A, -t)$



Marchenko, one-sided, $\mathbf{F}_1^+(z_0, z_A, t) - \mathbf{F}_1^-(z_0, z_A, -t)$



Marchenko, one-sided, plus its time-reversal