Estimation of Q from surface-seismic reflection data in data space and image space

Yi Shen

SEP147 P113-126

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Why Q?

- **In reservoir characterization**:
  - Very sensitive to rock and fluid properties (saturation, porosity, permeability, etc.)

Why Q?

- **In seismic imaging**:
  - Enhances image quality/sharpness (include Q in deconvolution, stacking, migration, inverse Q filtering, etc.)

Why Q?

- **In seismic imaging**:
  - Corrects amplitude and phase of seismic data (AVO and anisotropy analysis)

Why Q?

- **In seismic imaging**:
  - Improve the accuracy of full waveform inversion

Why Q?

- **In seismic-acquisition design**
  - Helps determine how much signal may reach the target
  - Enables acquisition parameters to be optimized

Conventional ways of Q estimation

- Estimation of Q is based on
  - **Stacked traces**
  - **Ray theory**
  - **Time domain**

(Quan and Harris, 1997; Plessix, 2006; Rickett, 2006, 2007, etc)

Conventional ways of Q estimation

- Estimation of Q is based on
  - **Stacked traces**

    Pros: has optimum S/N ratio

(Quan and Harris, 1997; Plessix, 2006; Rickett, 2006, 2007, etc)

Conventional ways of Q estimation

- Estimation of Q is based on
  - **Stacked traces**

    Cons: has a distorted attenuation signature

    - path lengths
    - spectral distortions from NMO stretch
    - reflectivity-transmissivity effects

(Quan and Harris, 1997; Plessix, 2006; Rickett, 2006, 2007, etc)

Conventional ways of Q estimation

- Estimation of Q is based on
  - **Ray theory**

    Pros: is easily understood and implemented;
    has low computational cost

(Quan and Harris, 1997; Plessix, 2006; Rickett, 2006, 2007, etc)

Conventional ways of Q estimation

- Estimation of Q is based on
  - **Ray theory**

    Cons: can not handle complex structure

(Quan and Harris, 1997; Plessix, 2006; Rickett, 2006, 2007, etc)

Proposed method

- Estimation of Q is based on
  - **Q versus offset/angle analysis (QVO[1]/QVA)**
  - **Wave equation theory**
  - **Image domain**

[1]: Dasgupta, R. and R. A. Clark, 1998, Estimation of Q from surface seismic reflection data: Geophysics, 63, 2120–2128.

Proposed method

- Estimation of Q is based on
  - **Q versus offset/angle analysis (QVO[1]/QVA)**

  Pros: helps reduce attenuation signature distortion

[1]: Dasgupta, R. and R. A. Clark, 1998, Estimation of Q from surface seismic reflection data: Geophysics, 63, 2120–2128.

Proposed method

- Estimation of Q is based on
  - **Wave equation theory**
  - **Image domain**

    Pros: can handle the complex structure in the subsurface

Proposed method

- Estimation of Q is based on
  - **Wave equation theory**
  - **Image domain**

    Pros: has high S/N ratio

Theory

Two popular ways of estimating Q

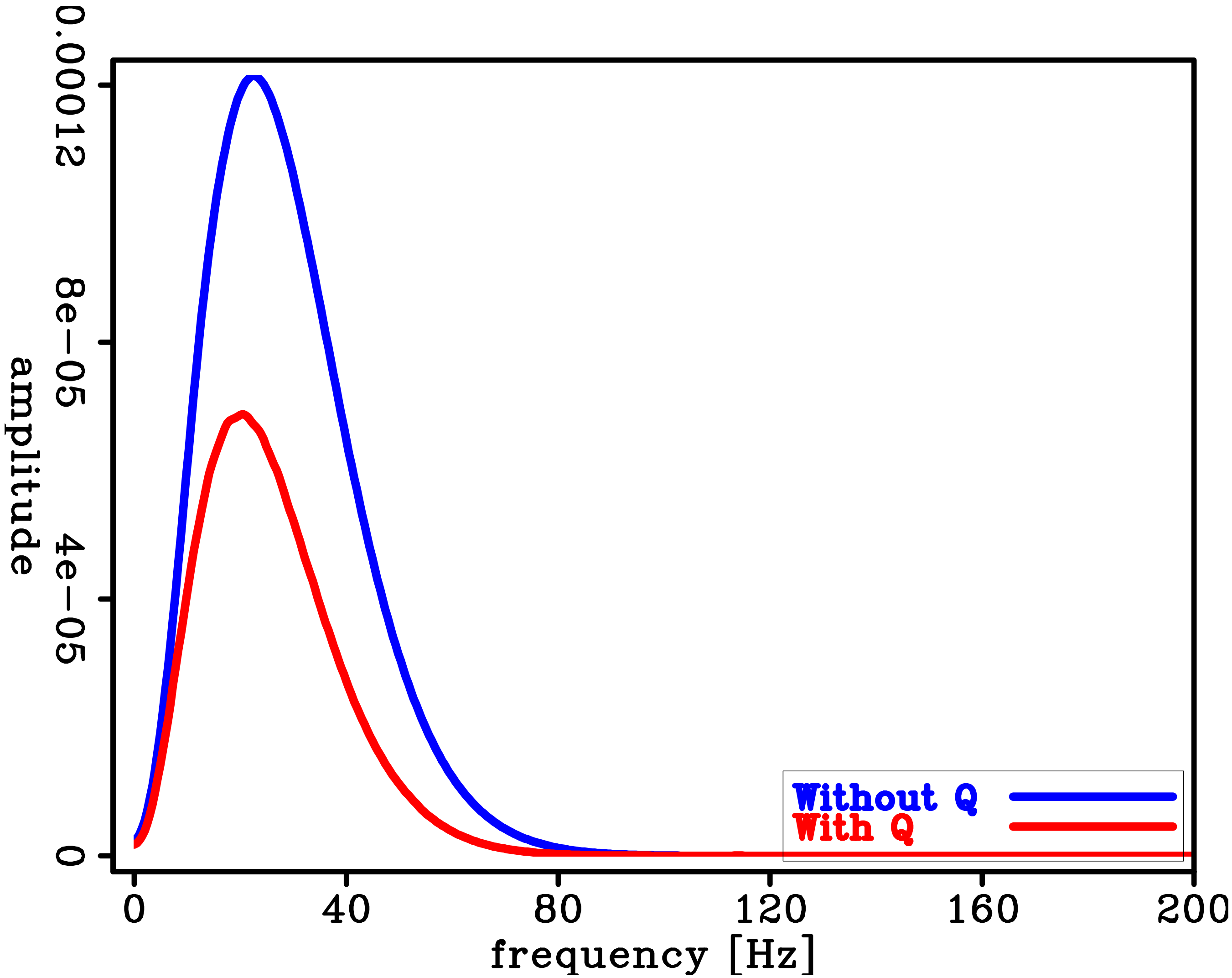
- **Central frequency shift**
- **Spectral ratio**

Theory

Two popular ways of estimating Q

- **Central frequency shift**
- Spectral ratio

Theory



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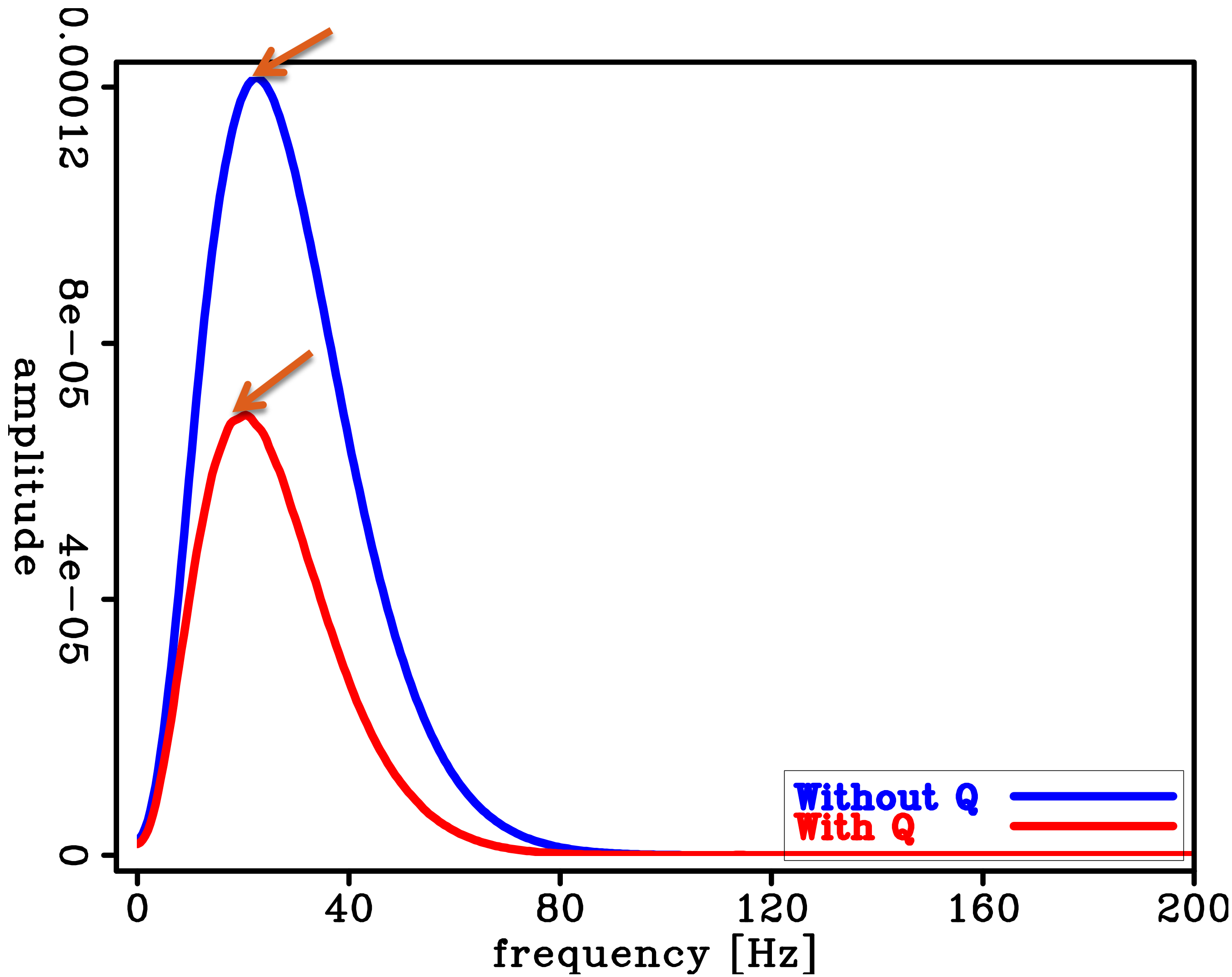
Theory



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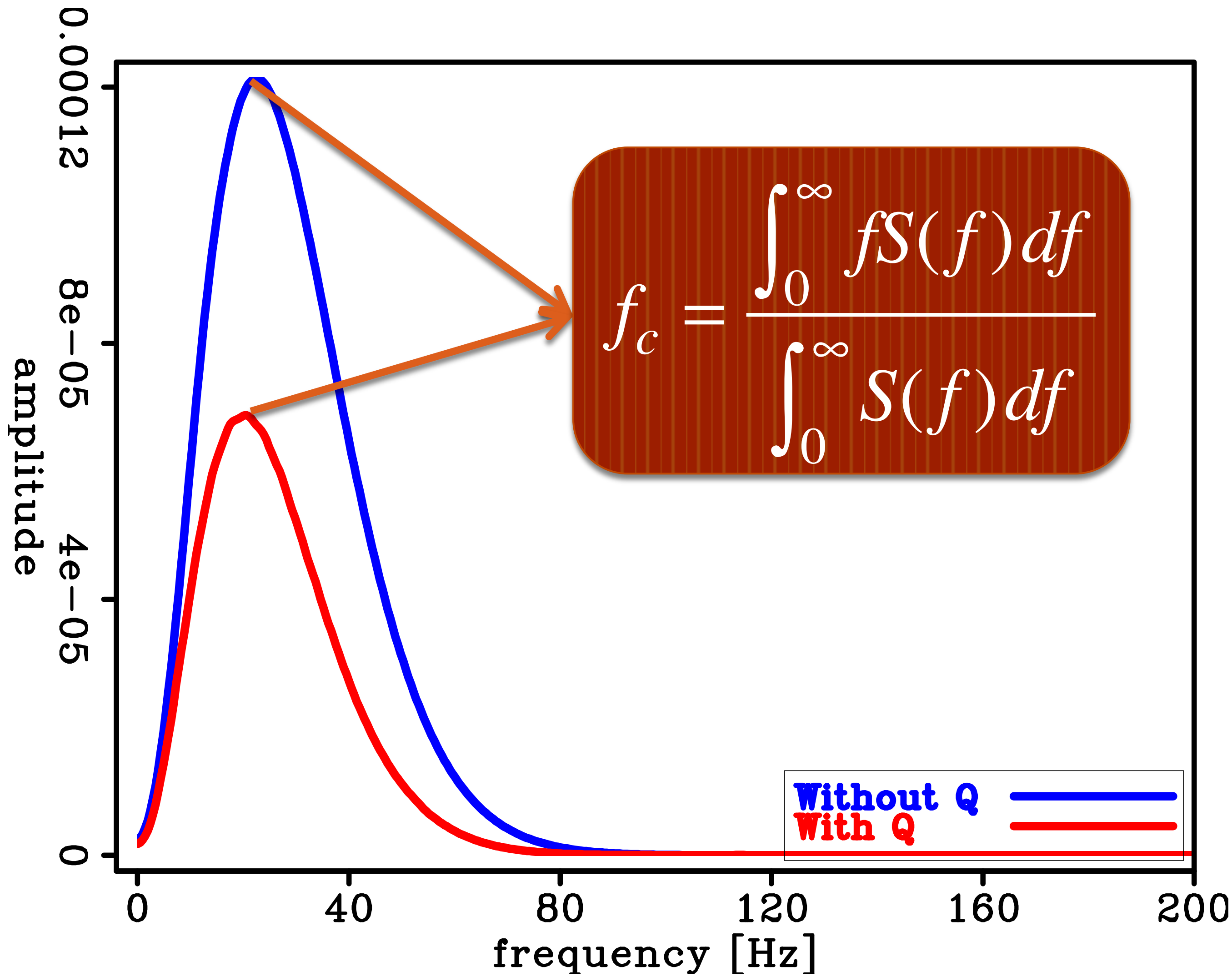
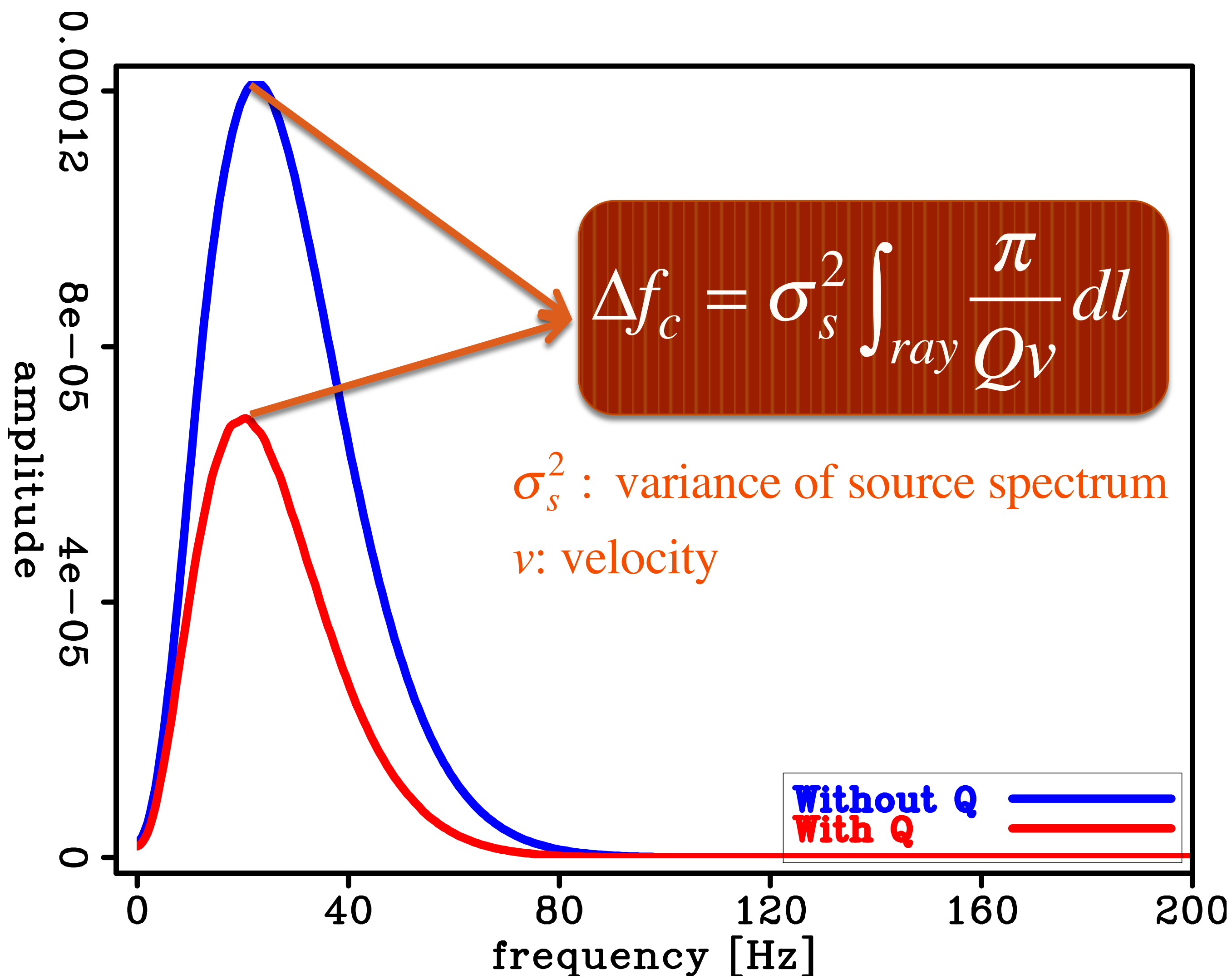
Theory


0.00012
8e−05
4e−05
0
amplitude
0
40
80
120
160
200
frequency [Hz]
Without Q
With Q
$f_c = \frac{\int_0^\infty f S(f)\,df}{\int_0^\infty S(f)\,df}$

Theory



$$\Delta f_c = \sigma_s^2 \int_{ray} \frac{\pi}{Qv} dl$$

σ_s^2 : variance of source spectrum

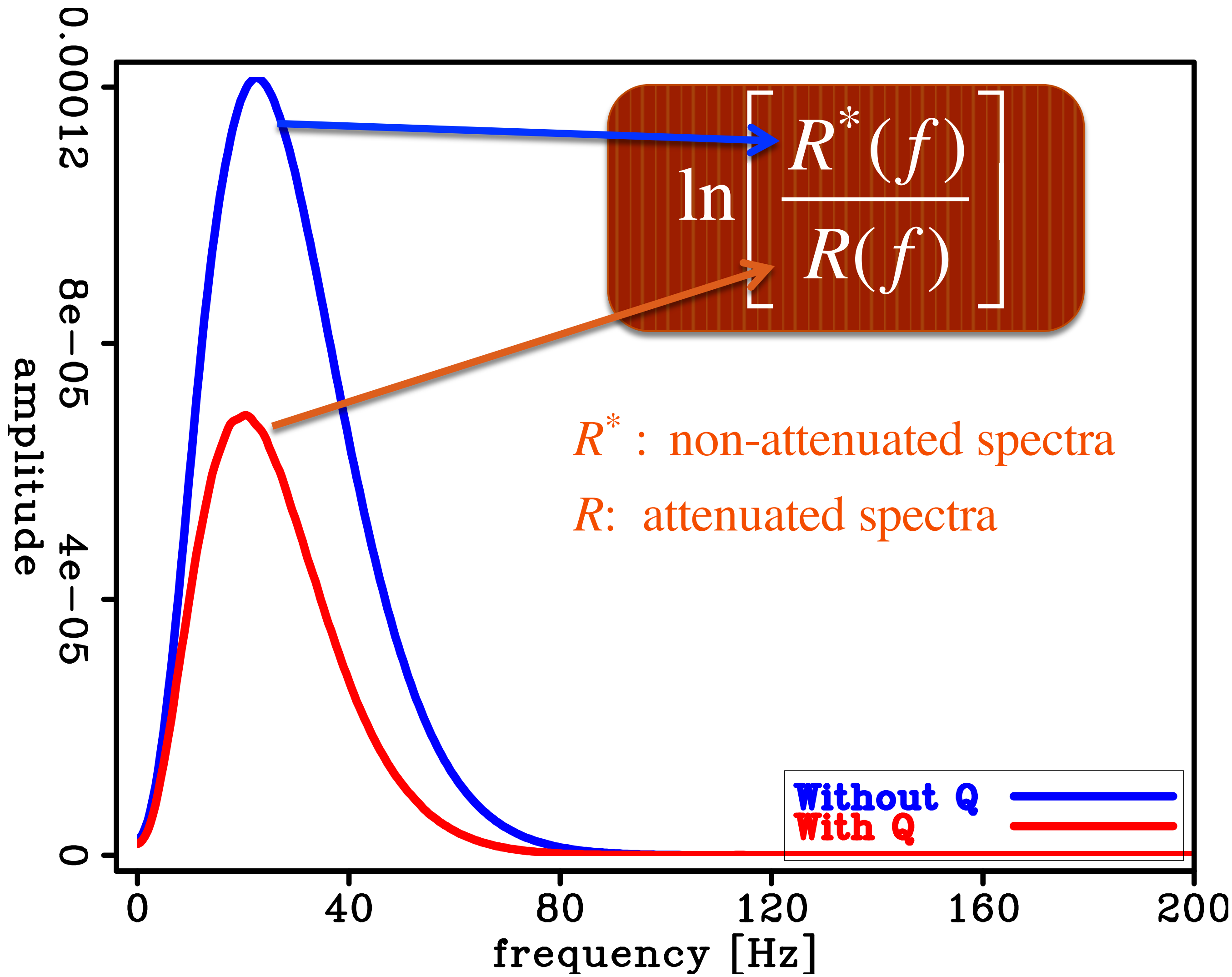
v: velocity

Theory

Two popular ways of estimating Q

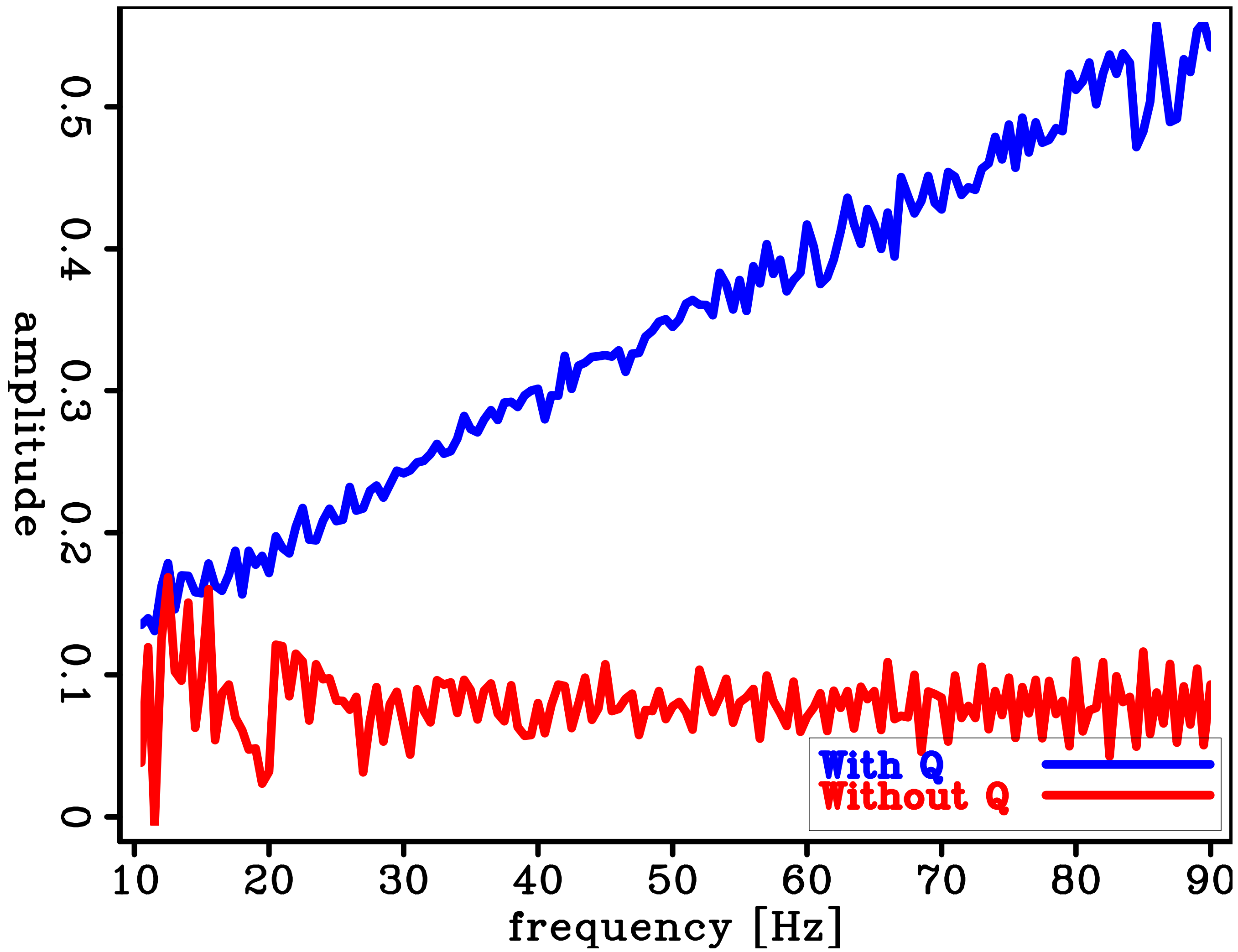
- Central frequency shift
- **Spectral ratio**

Theory



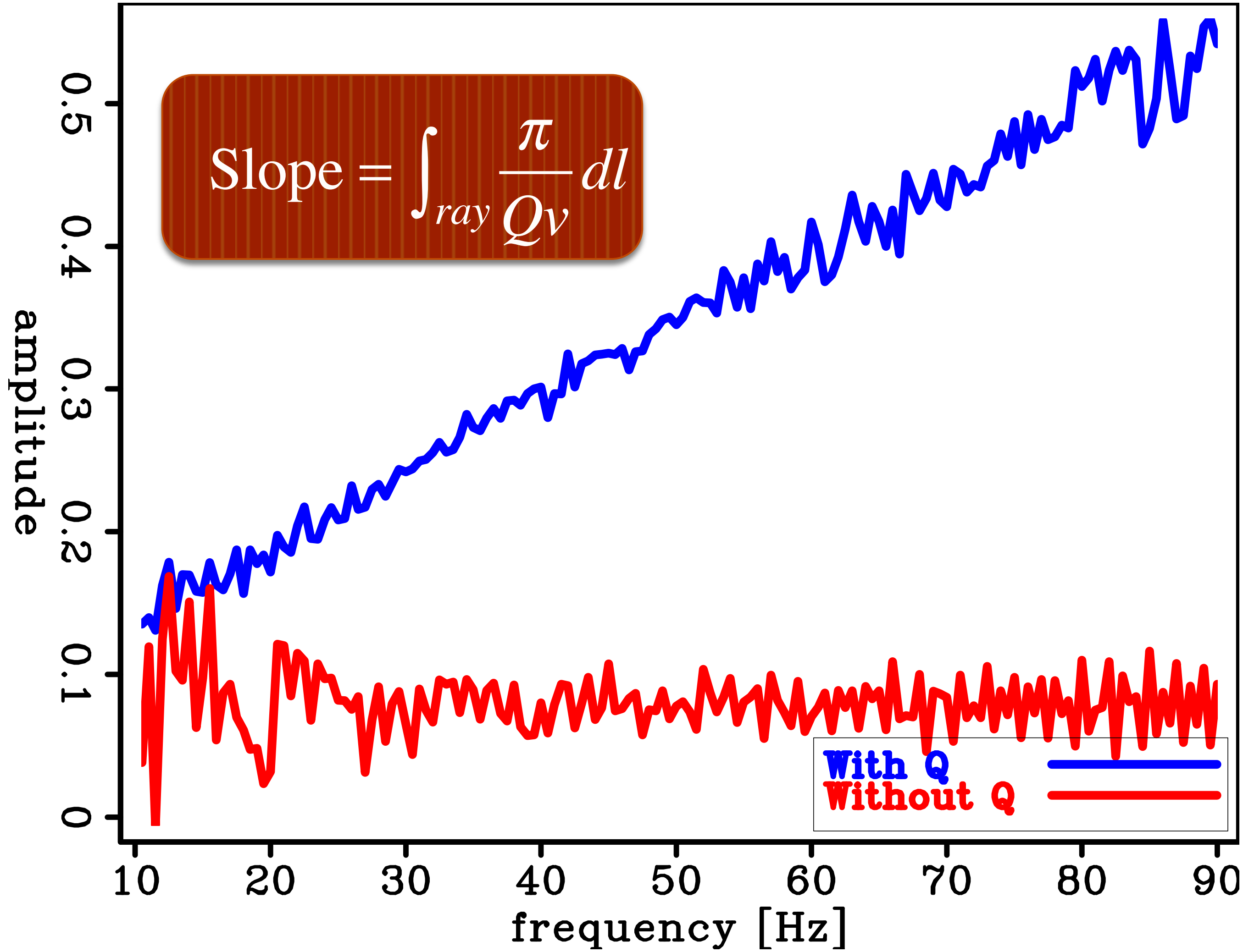
$\ln\left[\frac{R^*(f)}{R(f)}\right]$
R^* : non-attenuated spectra
R: attenuated spectra
Without Q
With Q
0.00012
8e−05
4e−05
0
amplitude
0
40
80
120
160
200
frequency [Hz]

Theory



amplitude
0
0.1
0.2
0.3
0.4
0.5
10
20
30
40
50
60
70
80
90
frequency [Hz]
With Q
Without Q

Theory



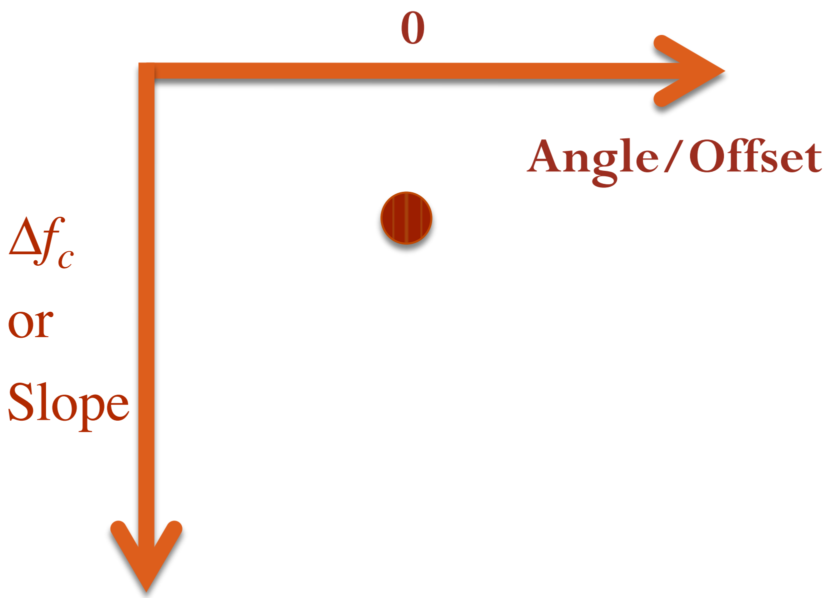
$$\text{Slope} = \int_{ray} \frac{\pi}{Qv} dl$$
amplitude
0
0.1
0.2
0.3
0.4
0.5
10
20
30
40
50
60
70
80
90
frequency [Hz]
With Q
Without Q

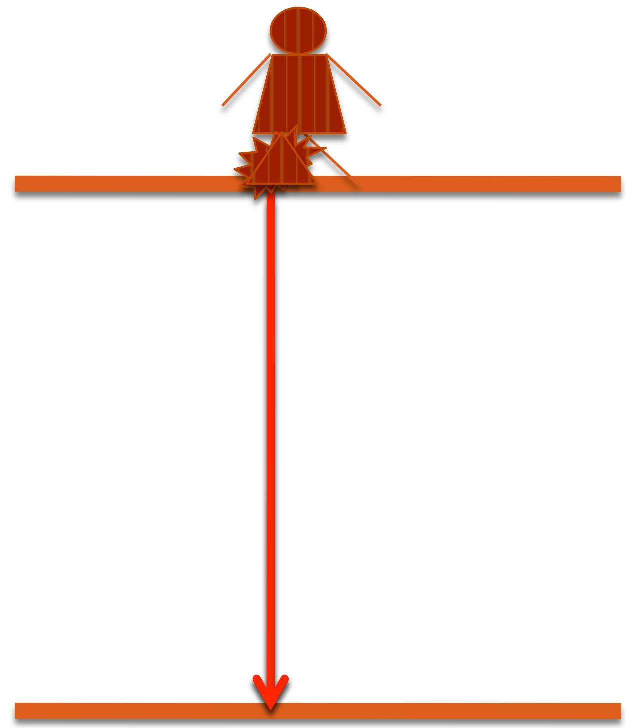
Theory

$$\Delta f_c \text{ \& Slope} \sim \int_{ray} \frac{\pi}{Qv}\, dl$$

Theory

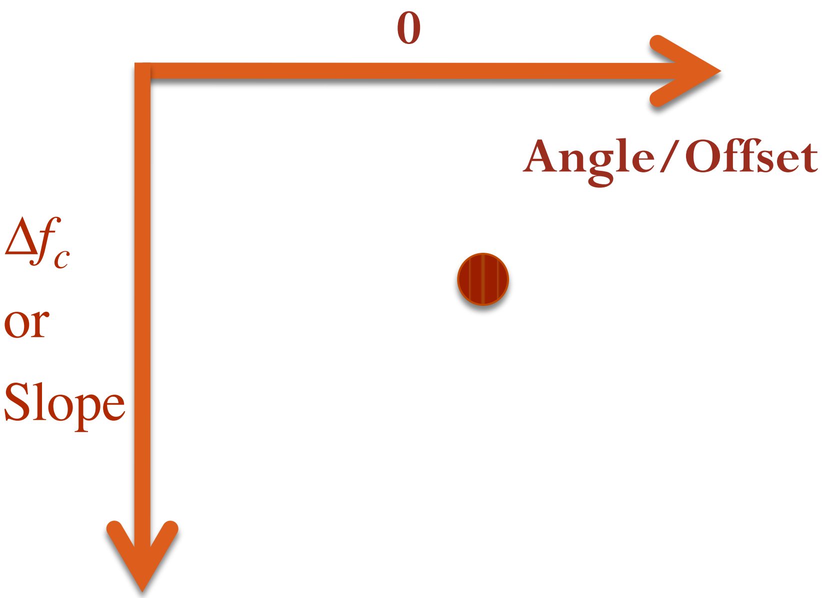
$$\Delta f_c \text{ \& Slope} \sim \int_{ray} \frac{\pi}{Qv} dl$$

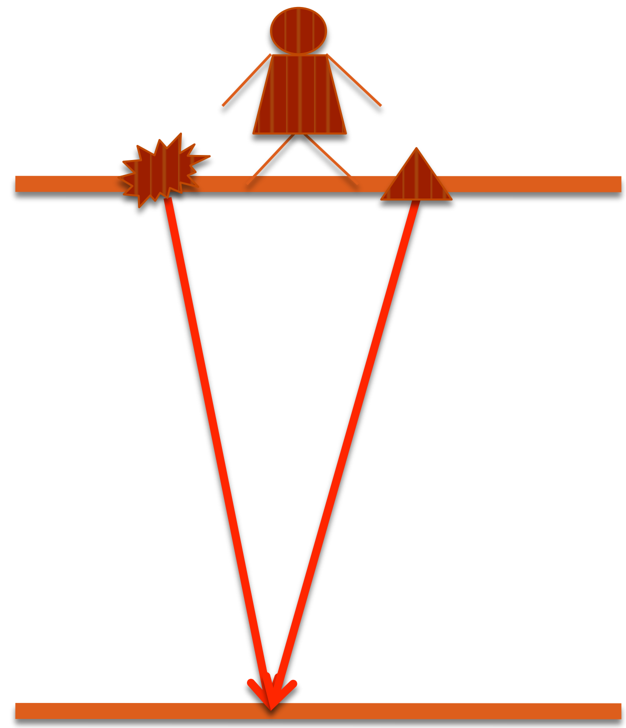




Theory

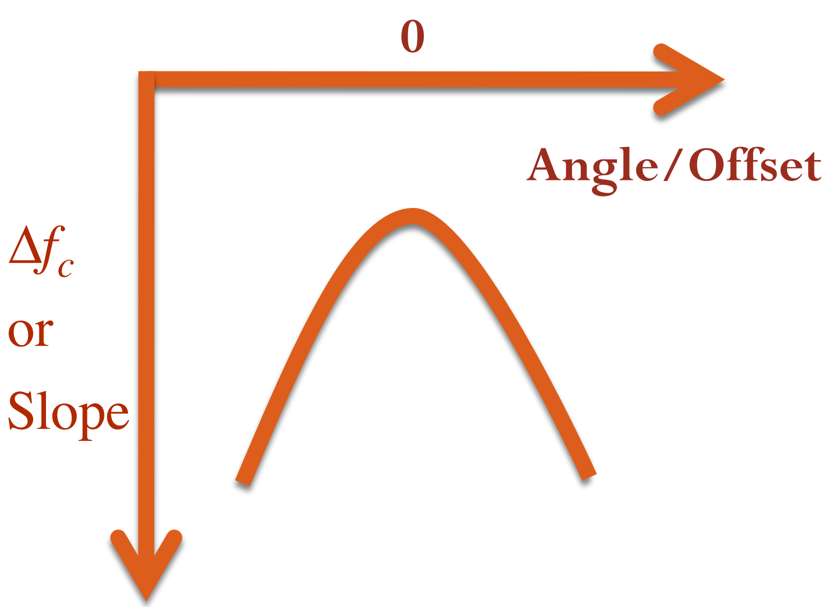
$$\Delta f_c \ \&\ \text{Slope} \sim \int_{ray} \frac{\pi}{Qv}\, dl$$





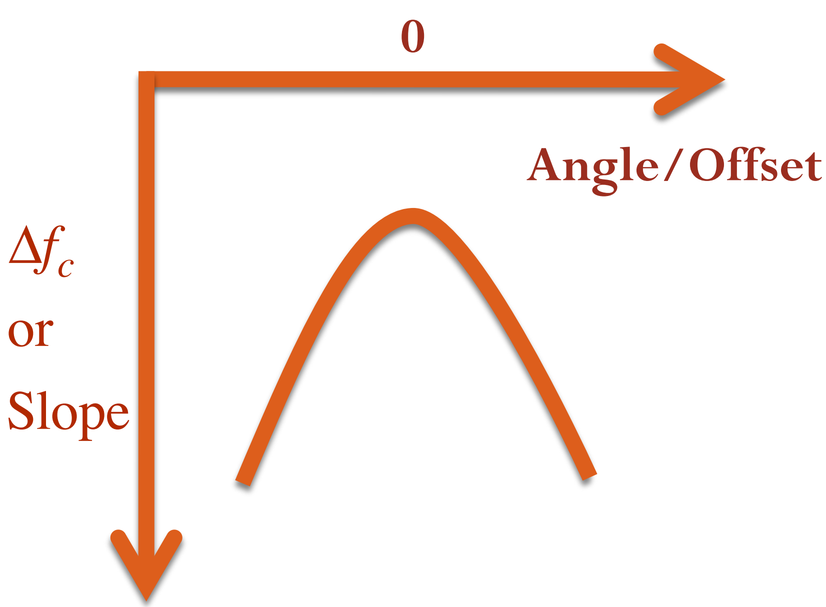
Theory

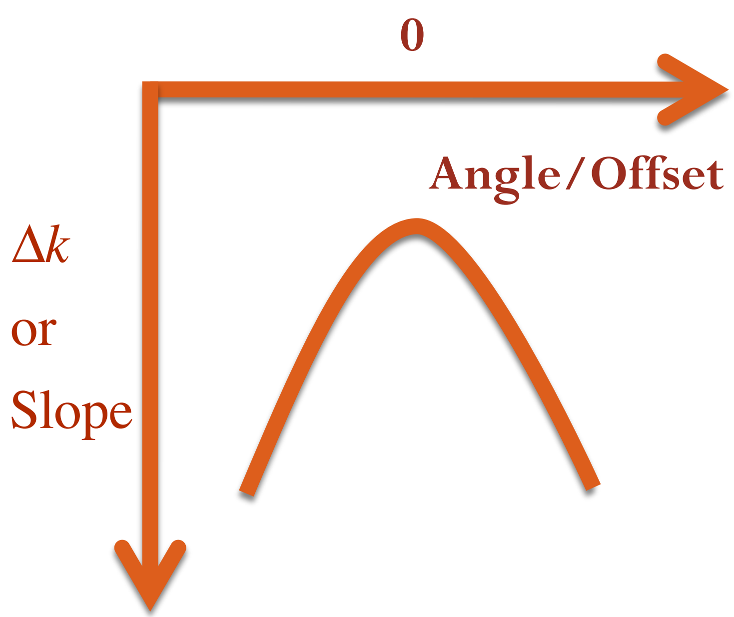
$$\Delta f_c \text{ \& Slope} \sim \int_{ray} \frac{\pi}{Qv} dl$$



Theory

- Time domain
- Image domain





Numerical test

- **Estimation of Q from data space**
  - Central frequency shift
- **Estimation of Q from image space**
  - Central frequency shift
  - Spectral ratio

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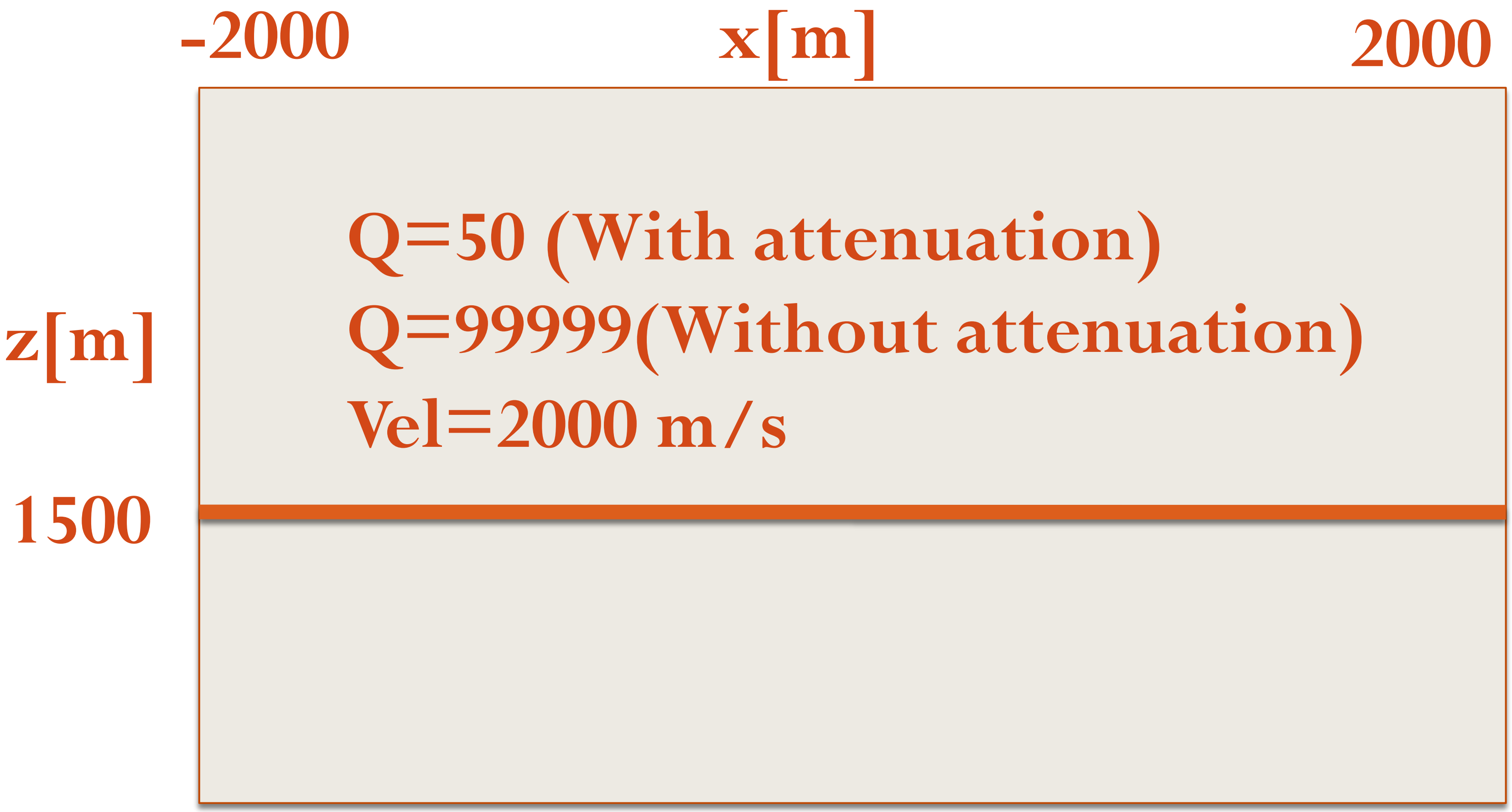
Incorporating Q in one-way wave equation

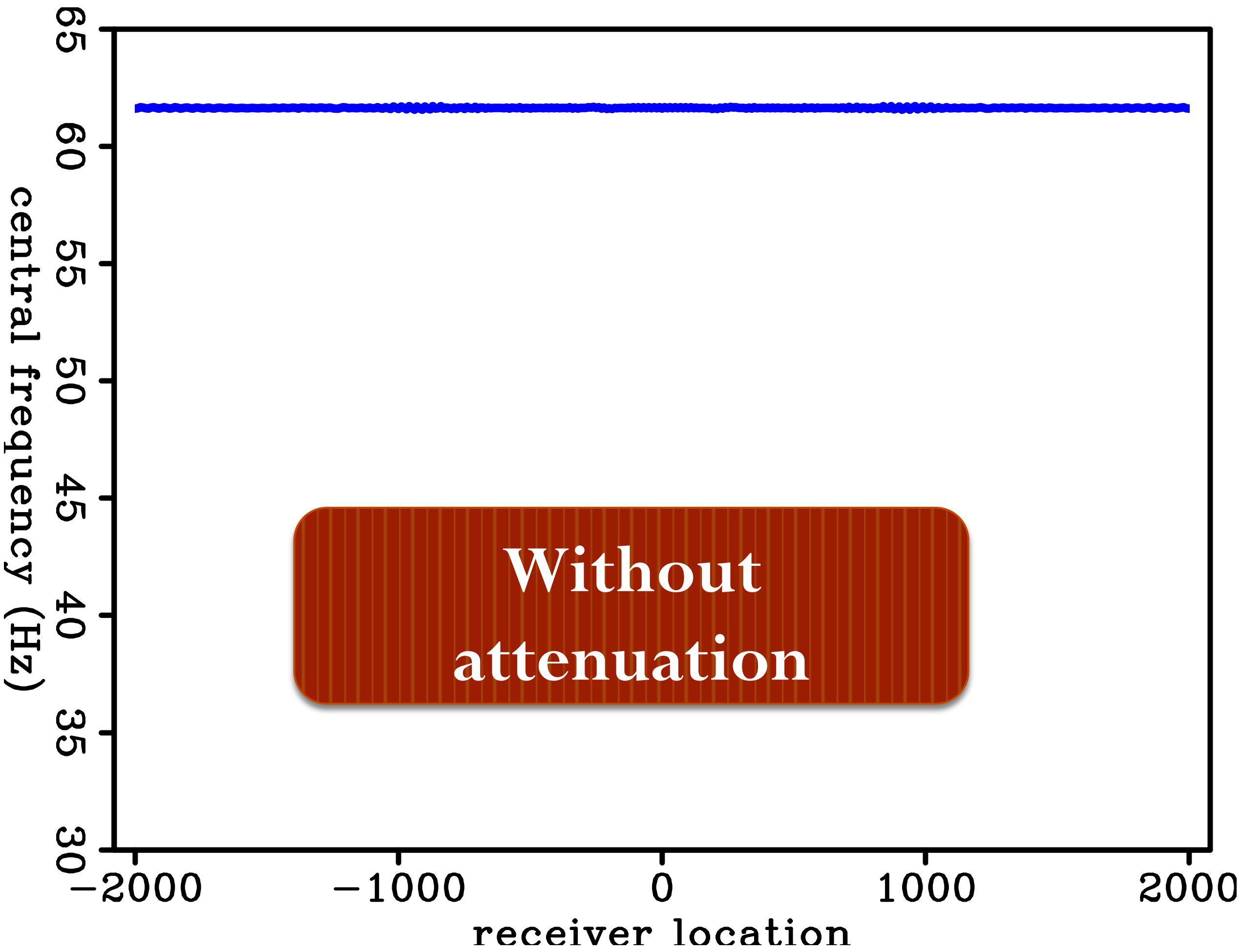
- Assume no dispersion

$$\tilde{v}(\omega) = v\left(1 + \frac{i}{2Q}\right)^{-1}$$

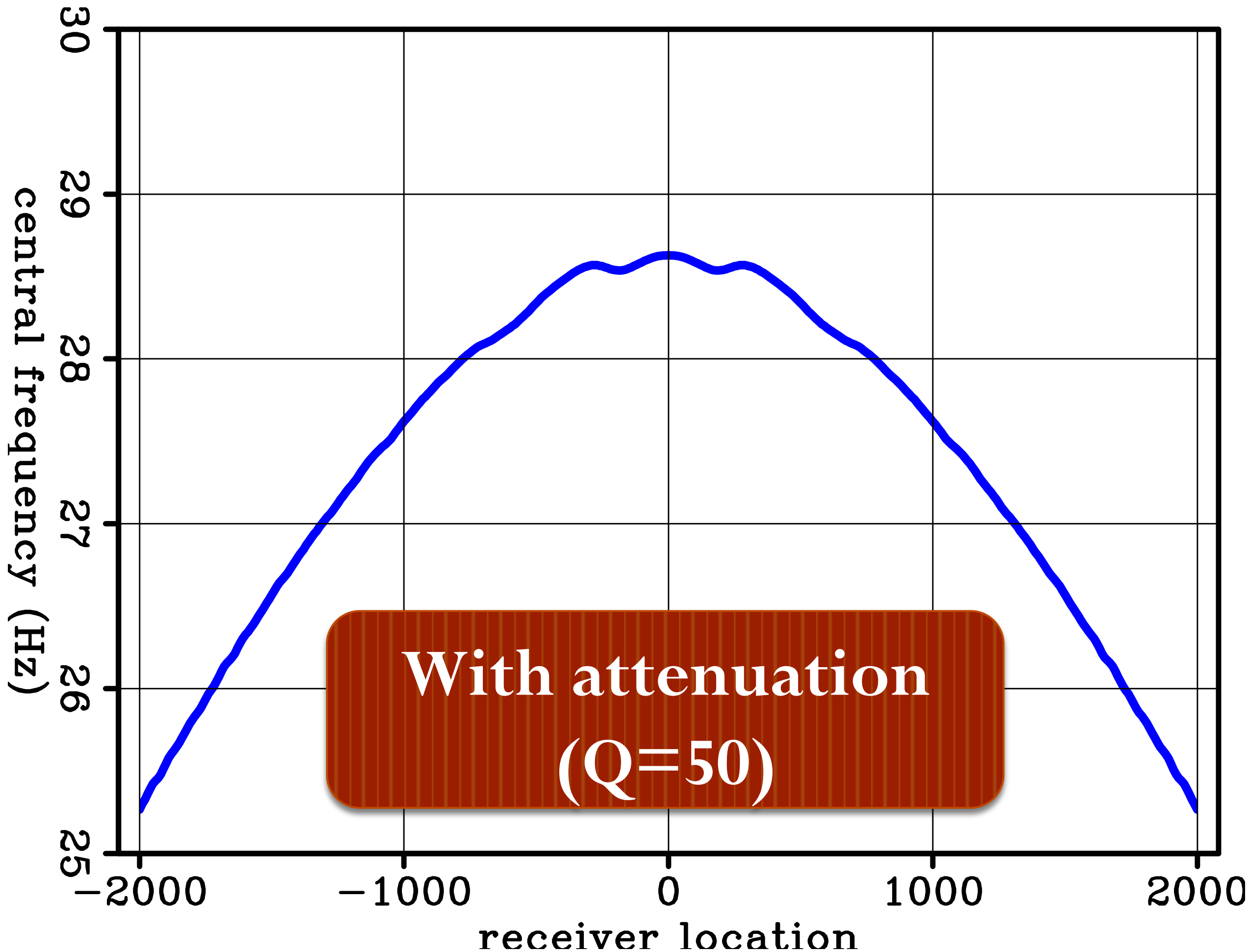
Model


-2000
x[m]
2000
z[m]
1500
Q=50 (With attenuation)
Q=99999(Without attenuation)
Vel=2000 m/s

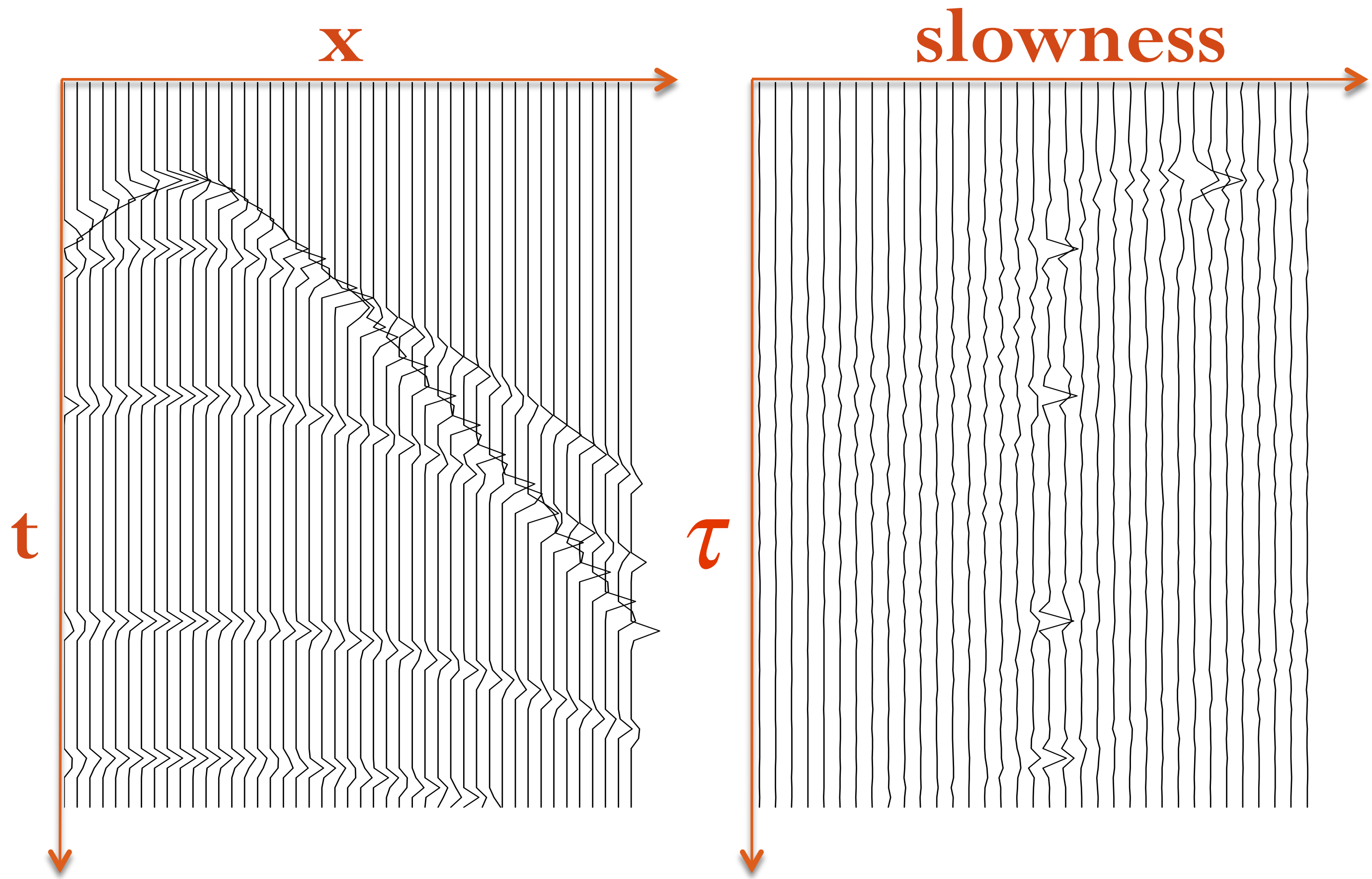
Central frequency



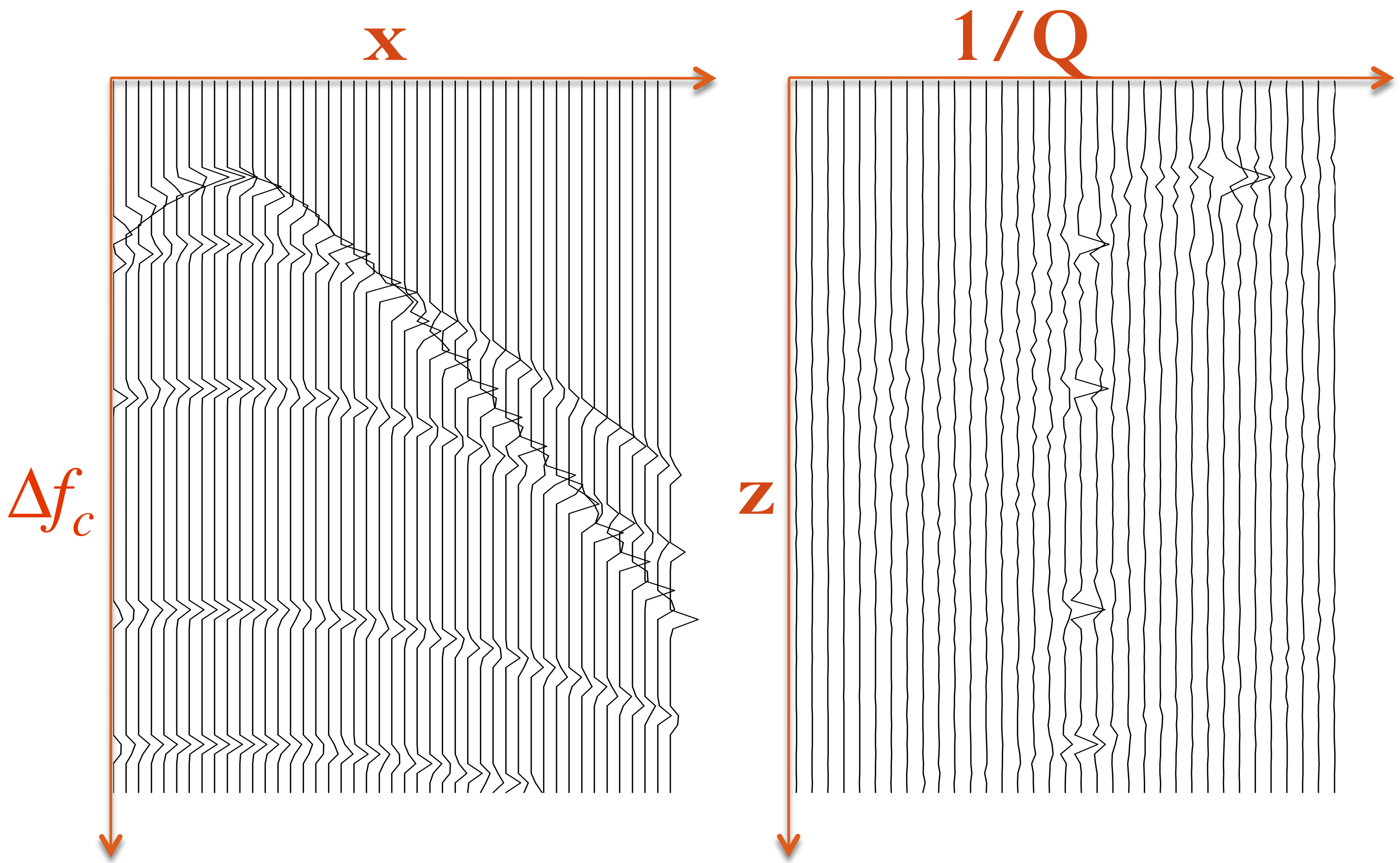
Central frequency



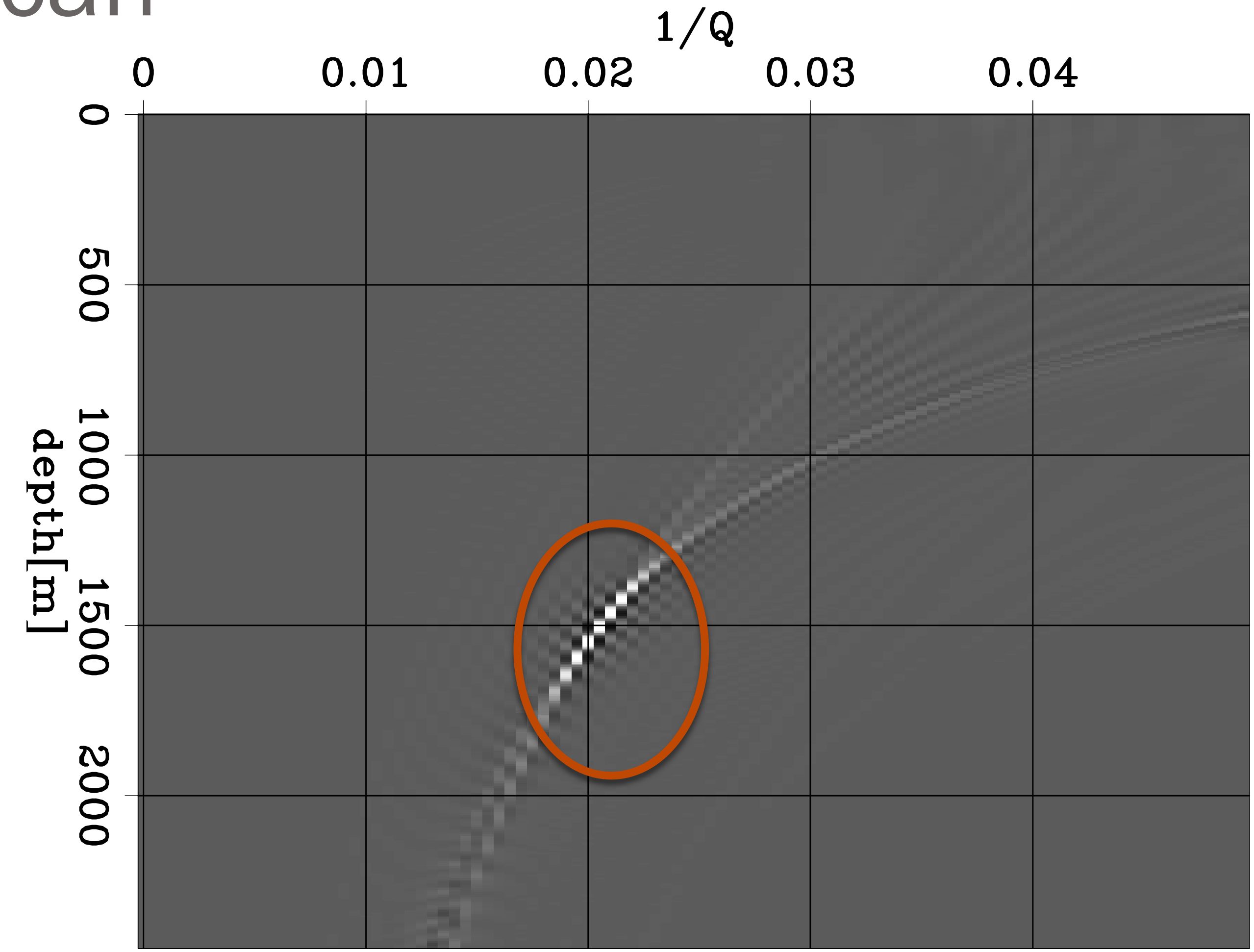
Velocity scan



Q scan



Q scan



Numerical test

- Estimation of Q from data space
  - Central frequency shift
- **Estimation of Q from image space**
  - Central frequency shift
  - Spectral ratio

Conventional migration

$$\mathbf{d} = \mathbf{F}\mathbf{m}$$

$$\mathbf{m} = \mathbf{F}^T \mathbf{d}$$

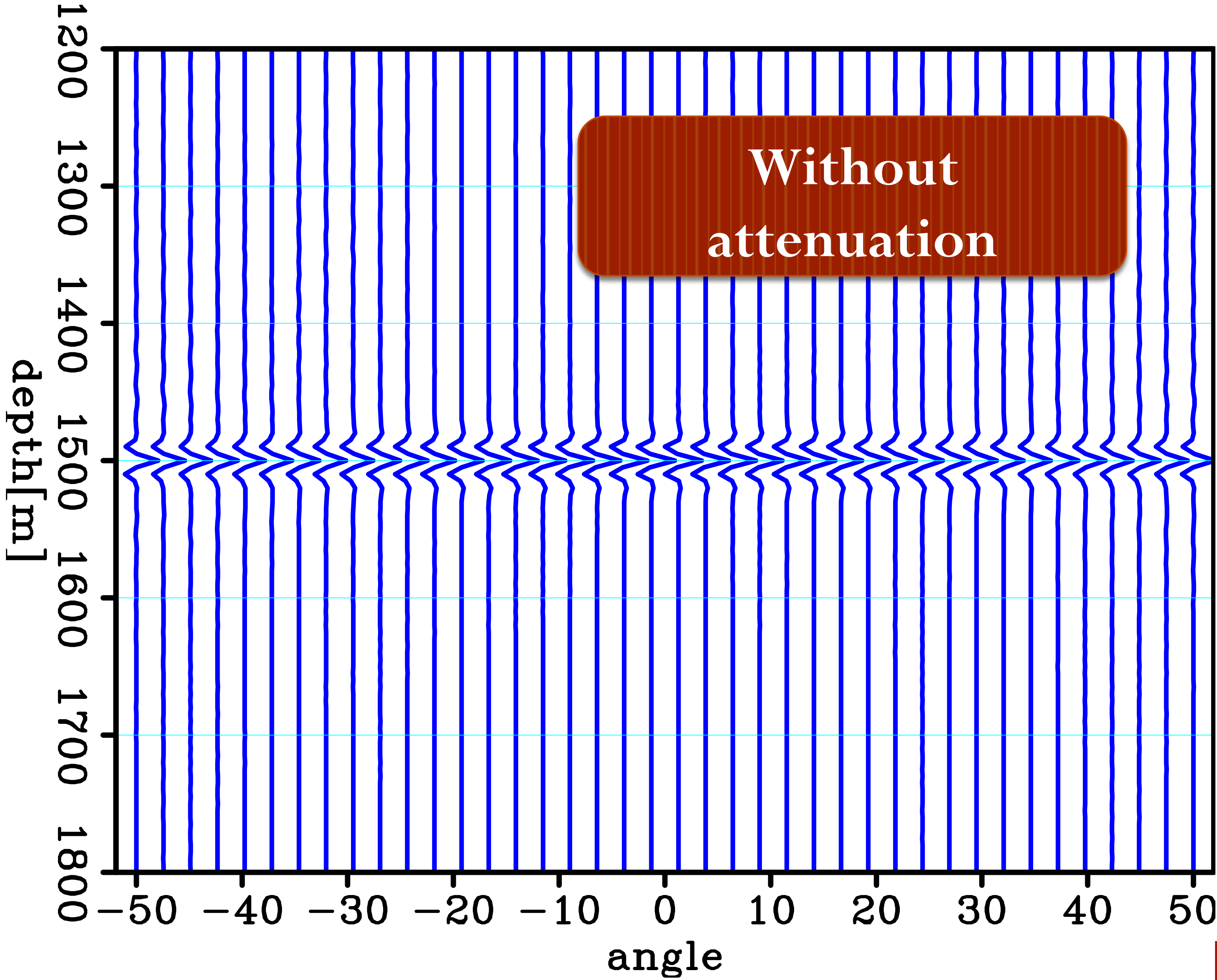
- **d** : data
- **m** : model
- **F** : forward modeling operator

Q compensation

$$\mathbf{d} = \mathbf{AFm}$$

$$\mathbf{m} = \mathbf{F}^{T}\mathbf{A}^{-1}\mathbf{d}$$

- **d** : data
- **m** : model
- **F** : forward modeling operator
- **A** : attenuation operator



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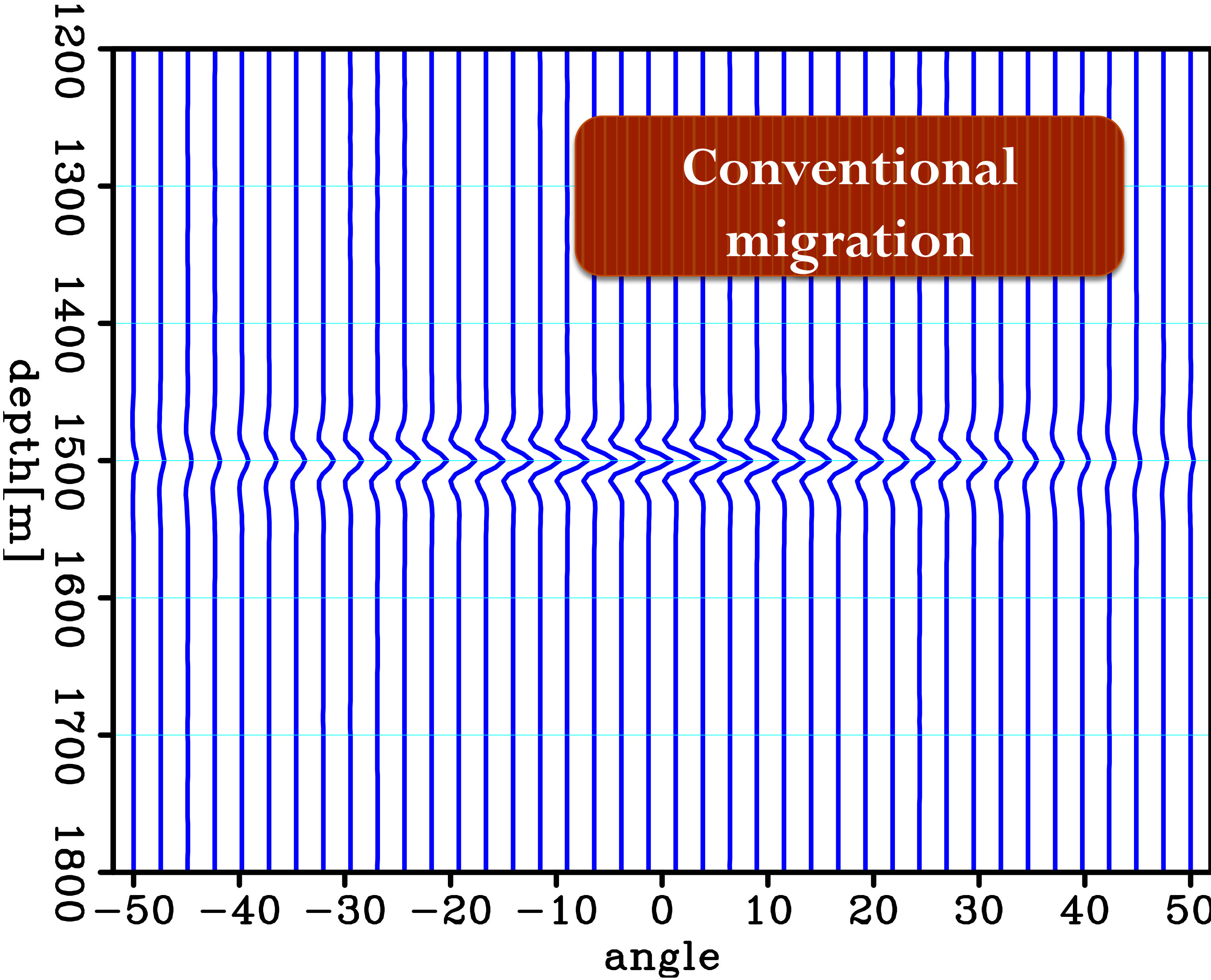
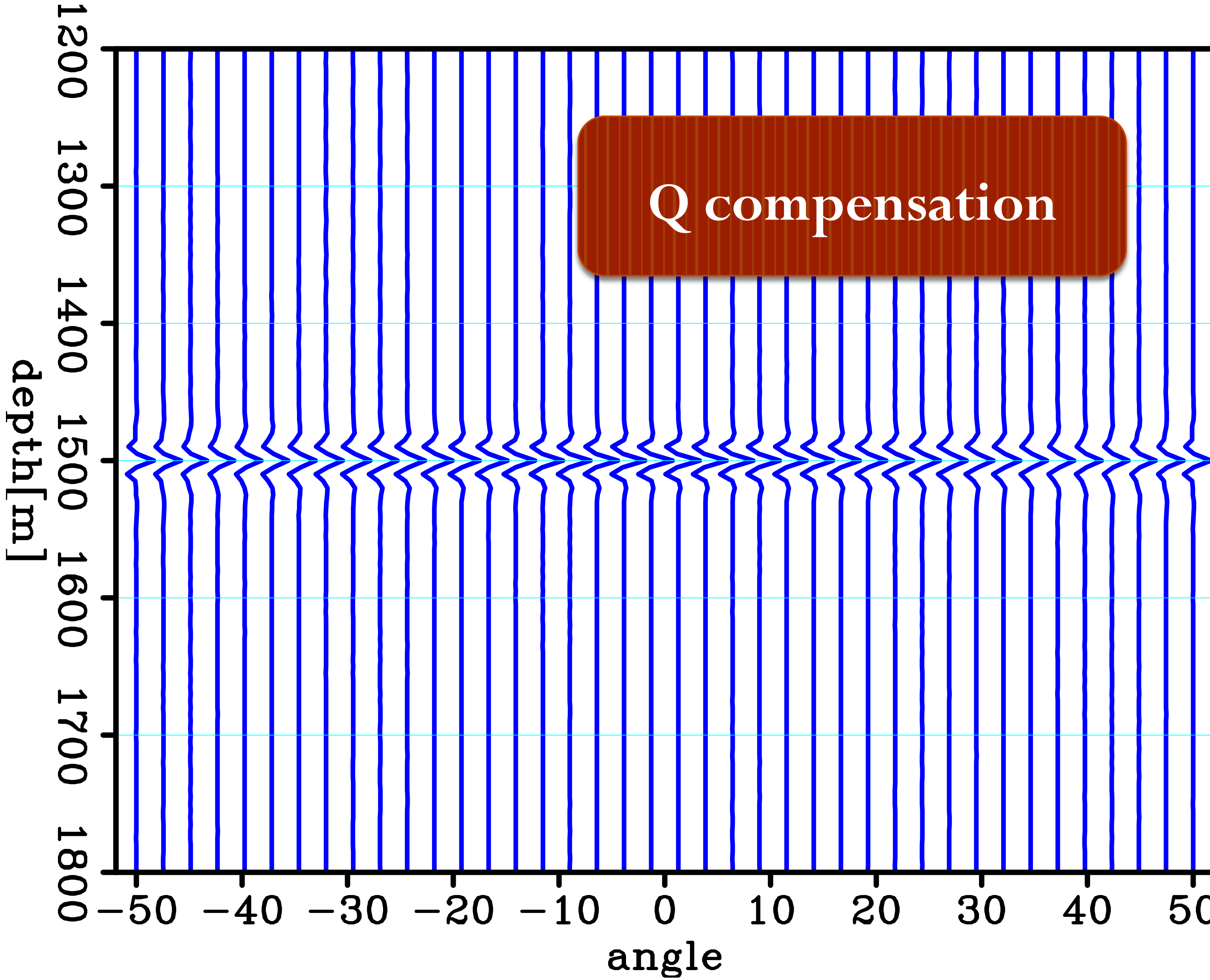

Conventional migration
depth[m]
1200
1300
1400
1500
1600
1700
1800
−50 −40 −30 −20 −10 0 10 20 30 40 50
angle



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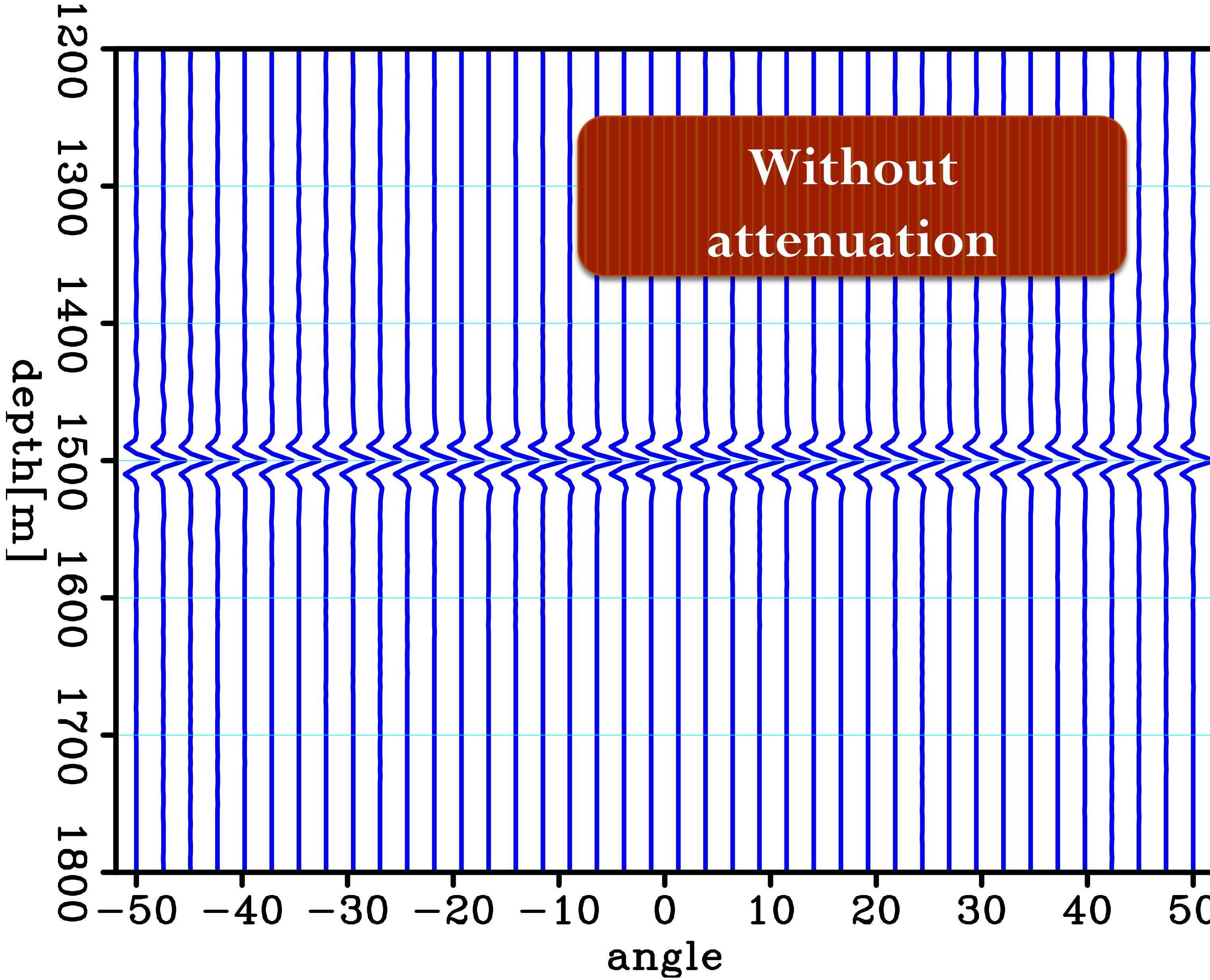

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Work flow

- First, take one common midpoint to compute the **image- wavenumber shift/slope** in its **angle-domain** common-image gathers after Q compensation.

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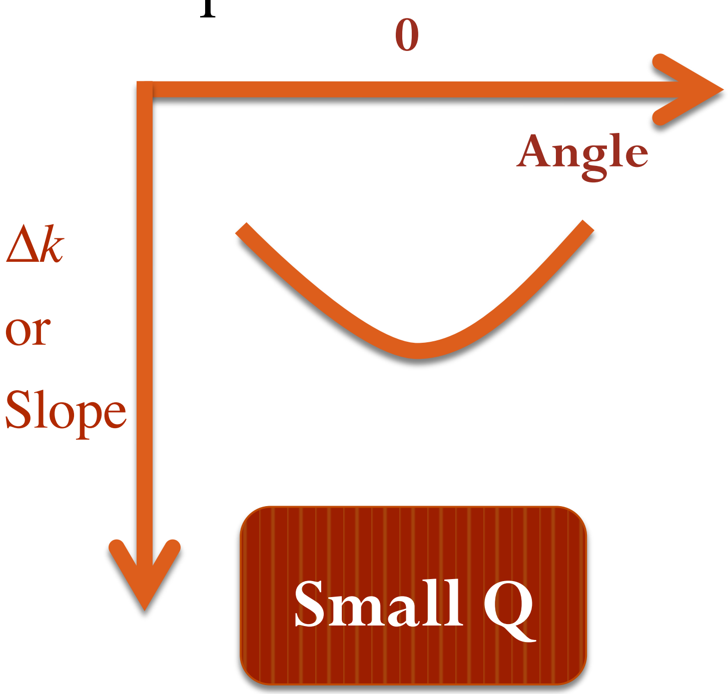
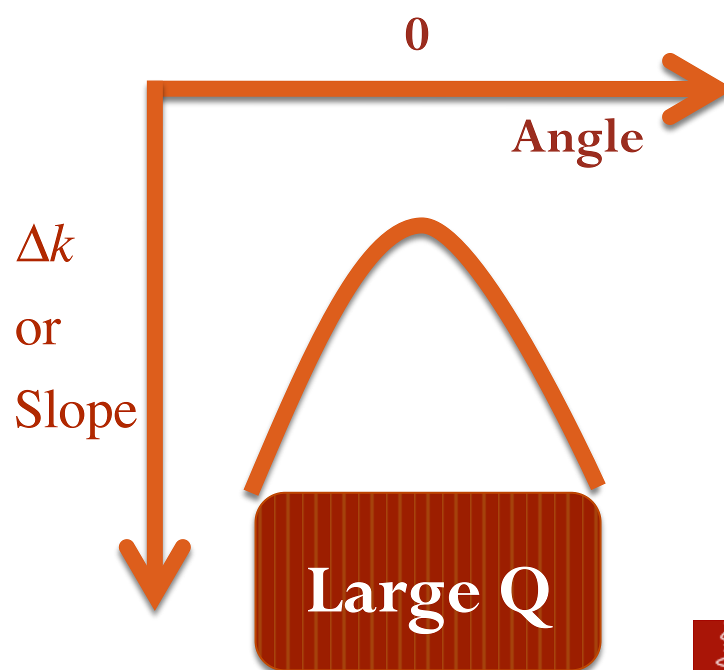




Work flow

- First, take one common midpoint to compute the **image- wavenumber shift/slope** in its **angle-domain** common-image gathers after Q compensation.

$$k_{\text{image}} = 4\pi f / v$$

f : frequency

v: velocity

Work flow

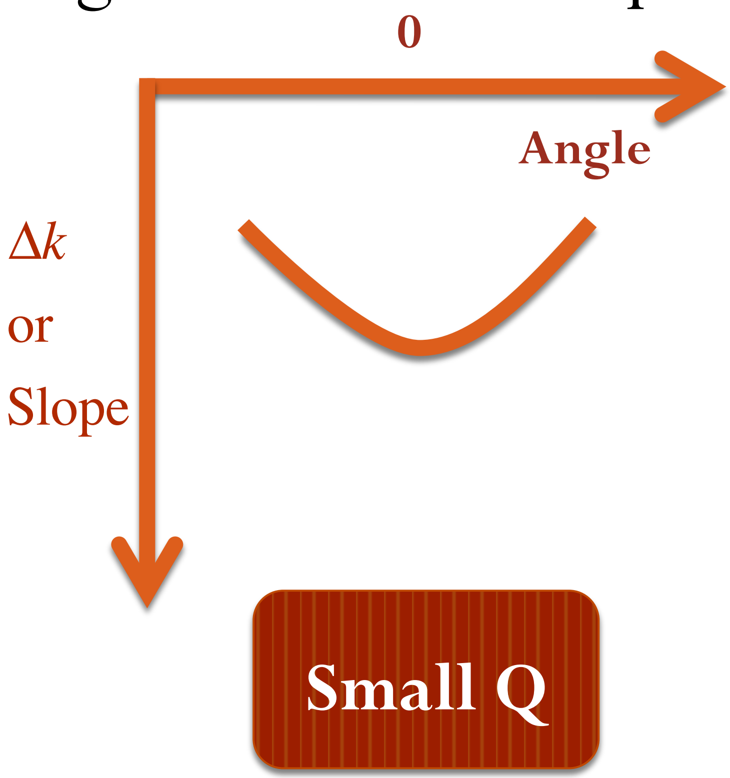
- Second**, an inverse shift correction** is applied to the gathers, **then compute the Q scan**

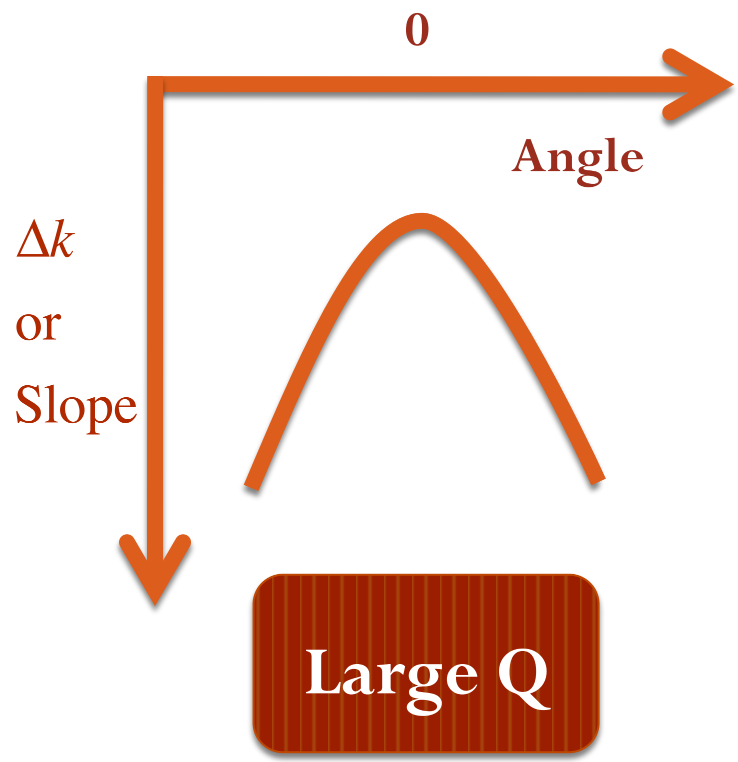
Work flow

- Second, ≈ **an inverse NMO** is applied to the gathers, then compute the Q scan

Work flow

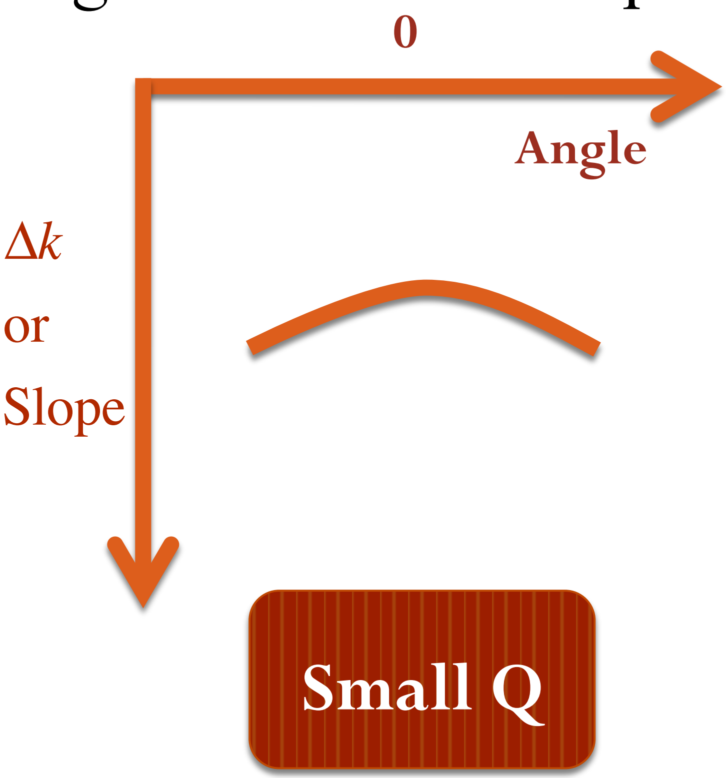
- Second, $\approx$ **an inverse NMO** is applied to the gathers, then compute the Q scan

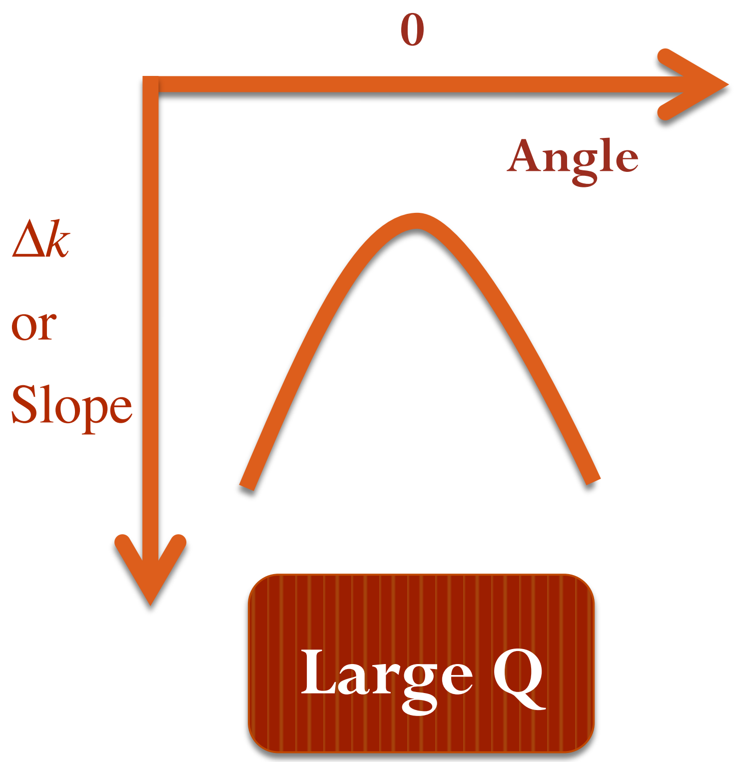




Work flow

- Second, ≈ **an inverse NMO** is applied to the gathers, then compute the Q scan





Work flow

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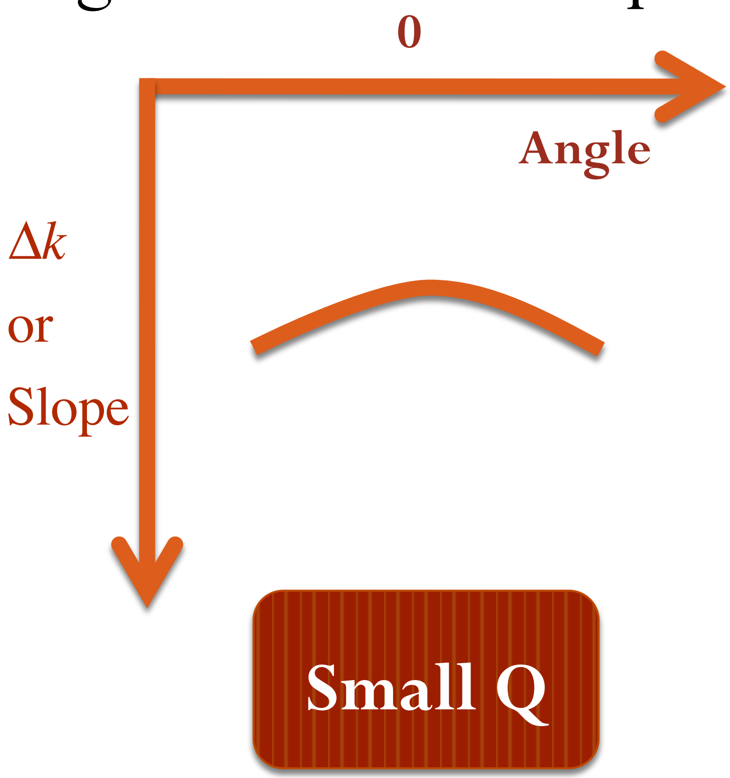
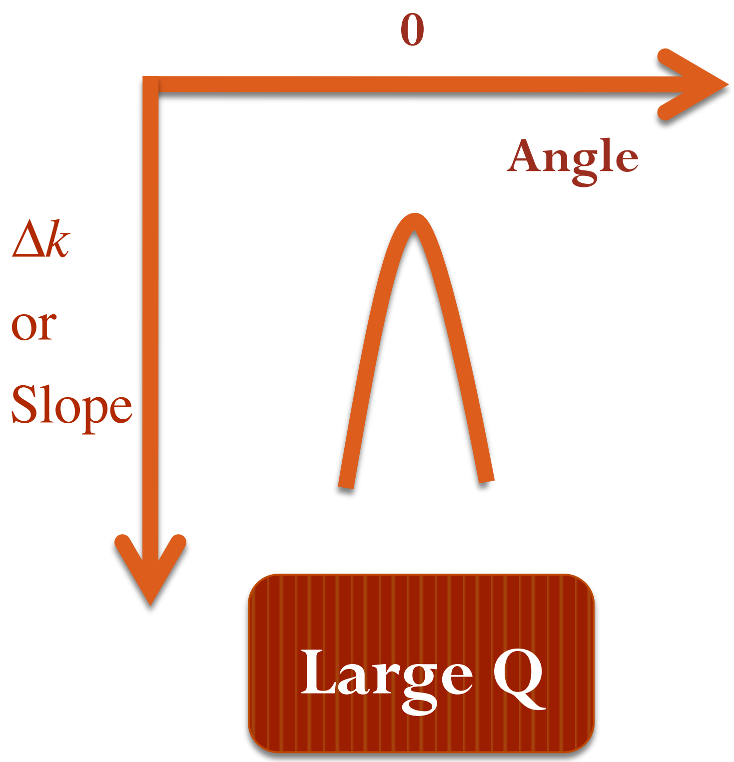
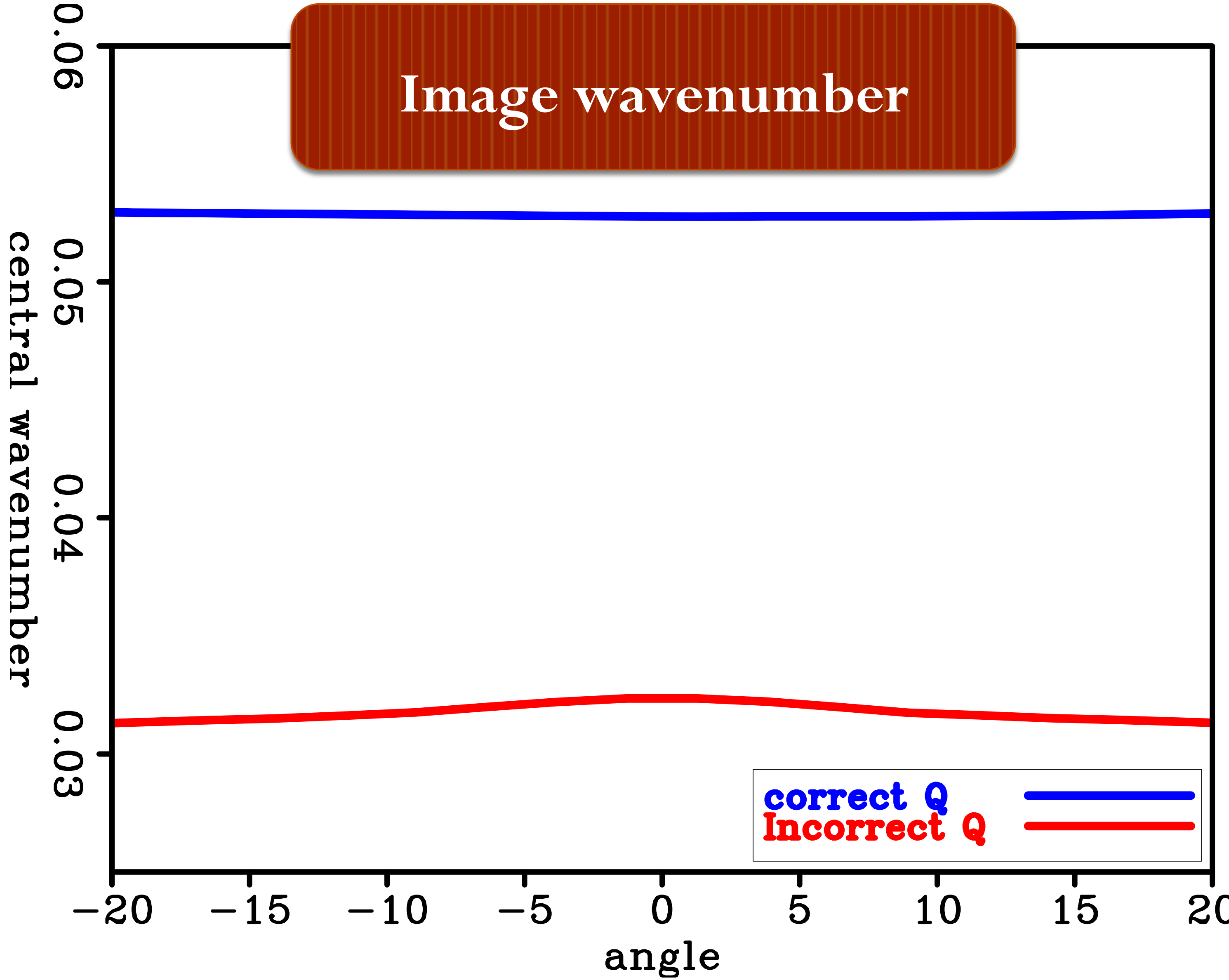


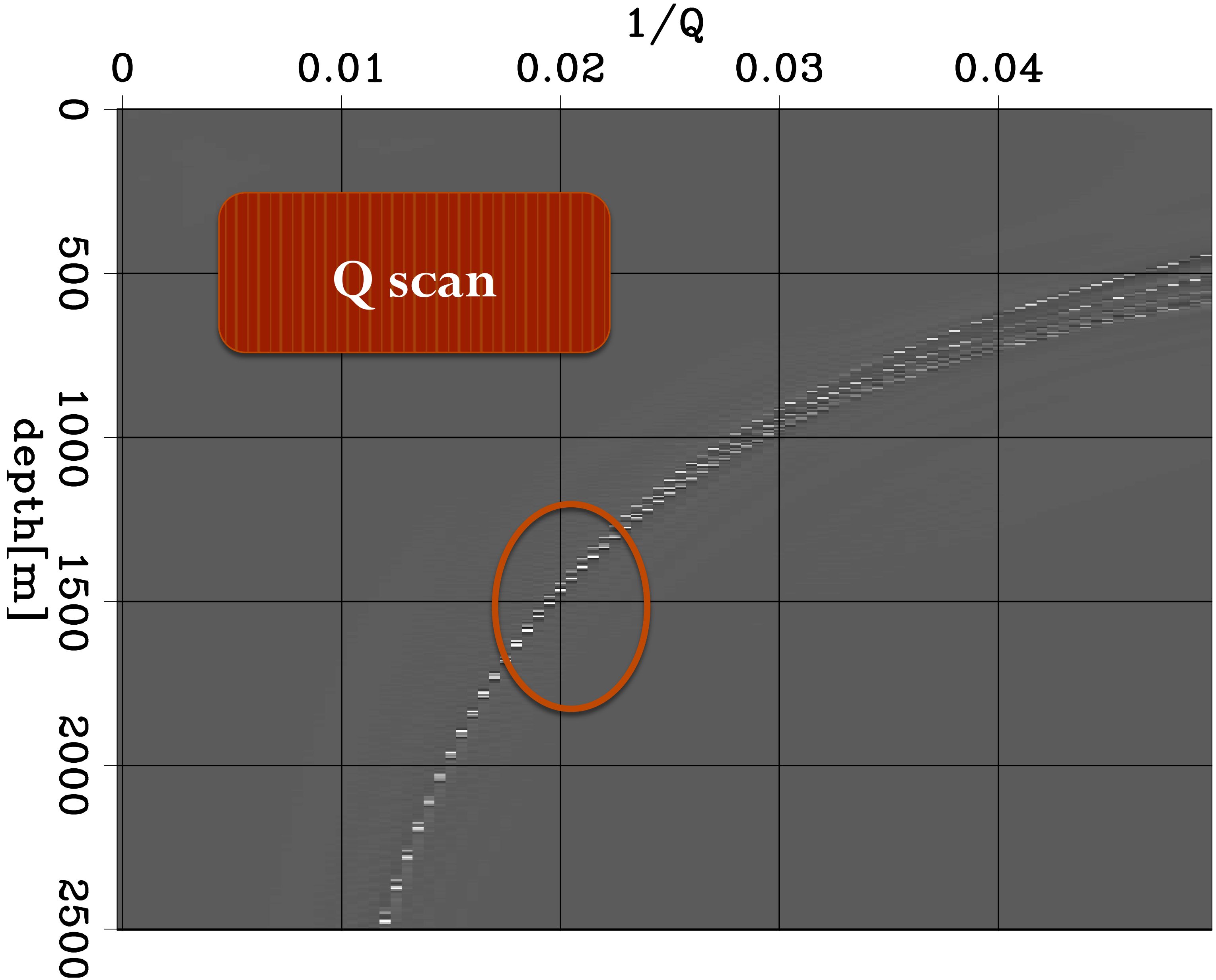


Numerical test

- Estimation of Q from data space
  - Central frequency shift
- **Estimation of Q from image space**
  - Central frequency shift
  - Spectral ratio

Image wavenumber




1/Q
0
0.01
0.02
0.03
0.04
0
500
1000
1500
2000
2500
depth[m]
Q scan

Numerical test

- Estimation of Q from data space
  - Central frequency shift
- **Estimation of Q from image space**
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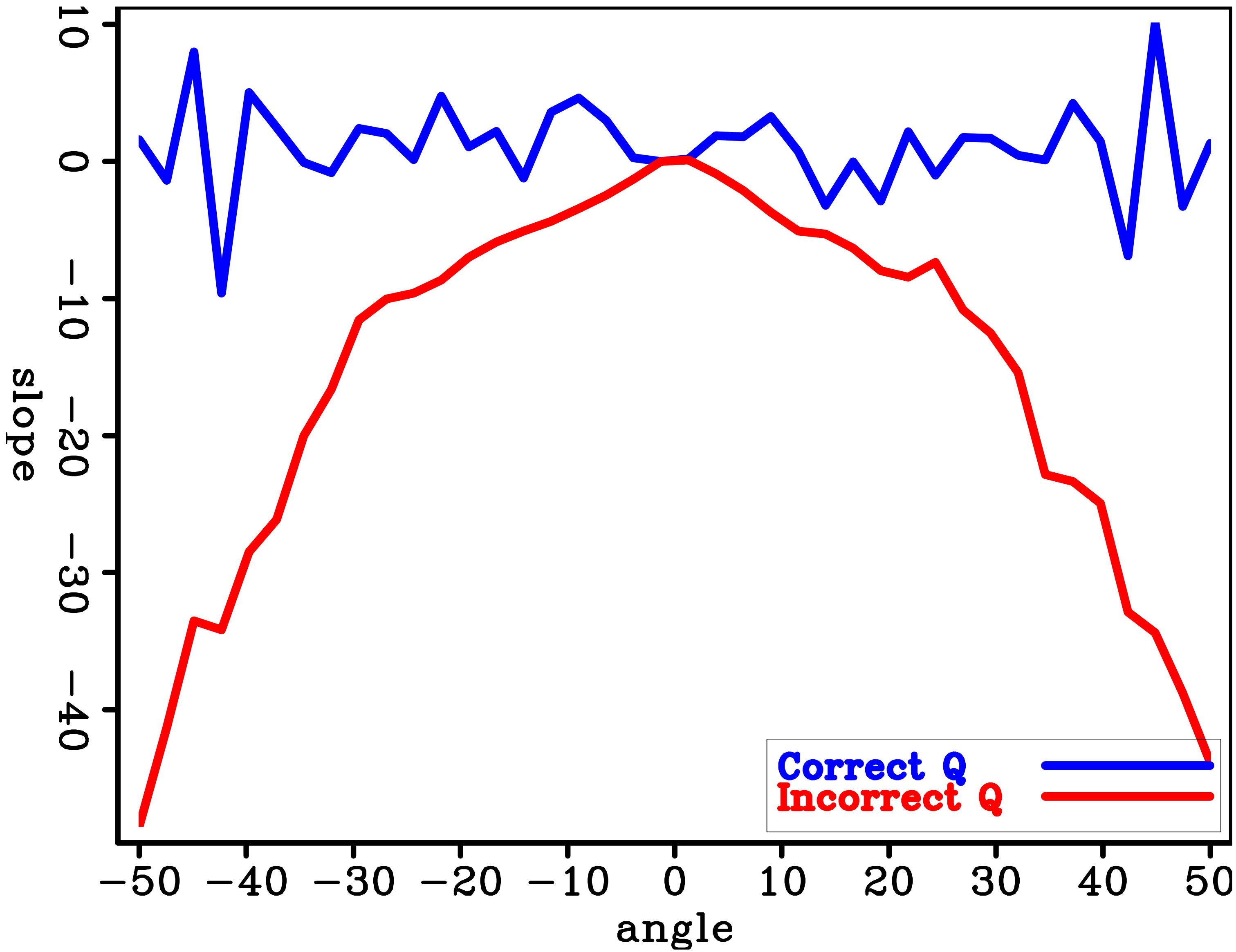
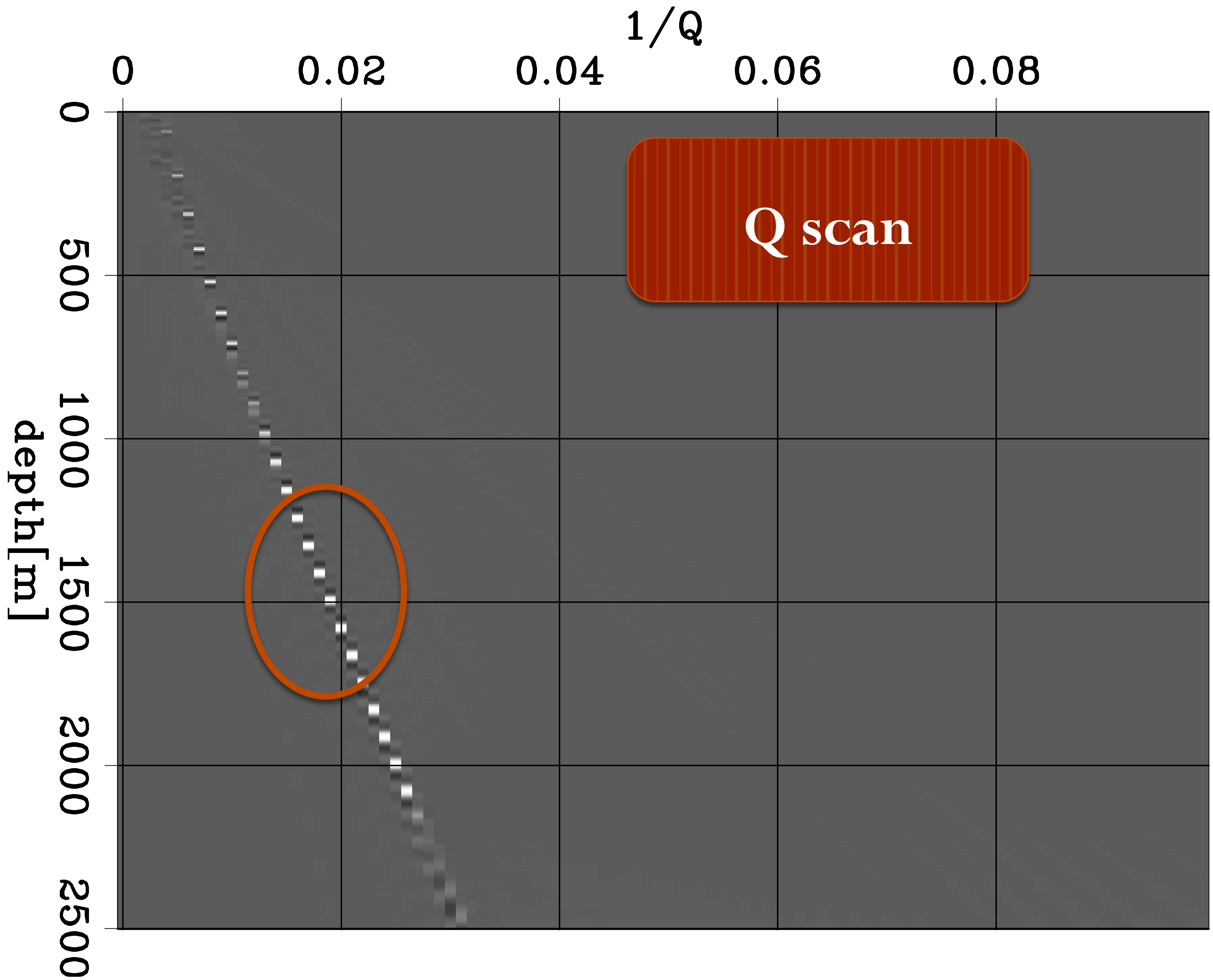
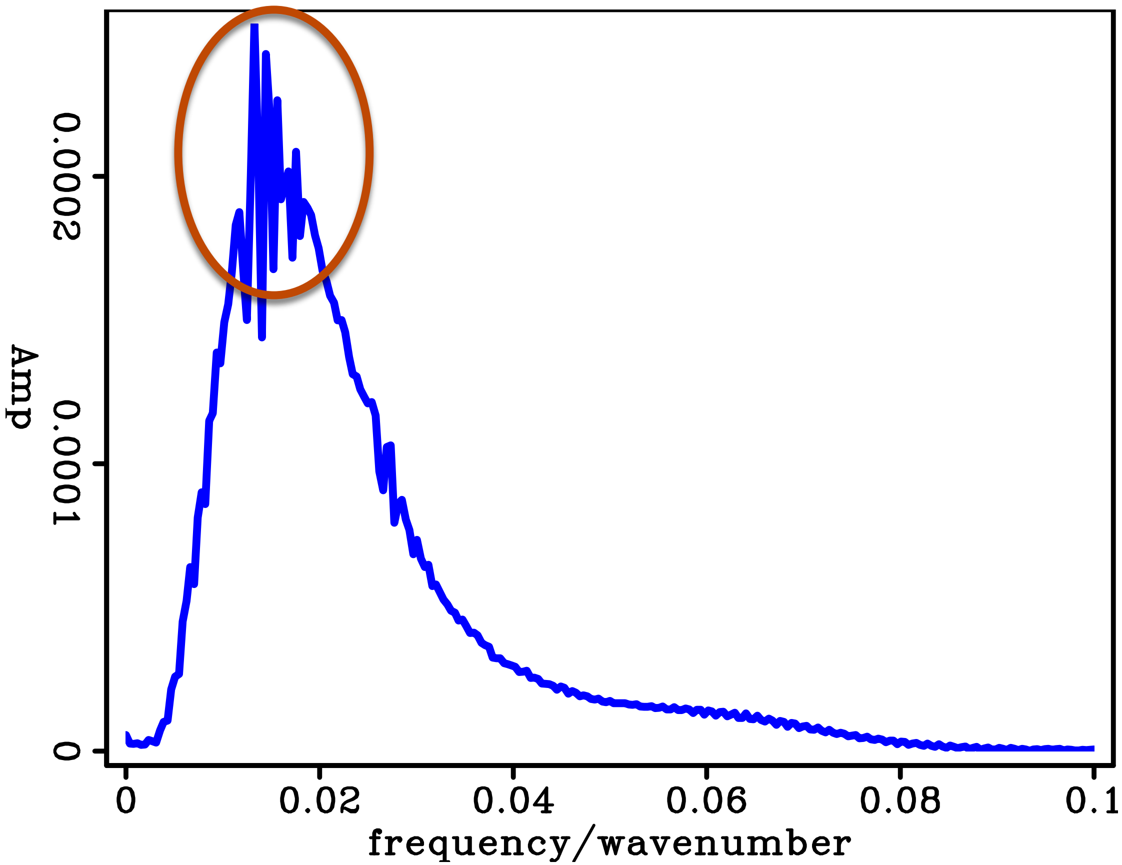


10
0
−10
−20
−30
−40
slope
−50
−40
−30
−20
−10
0
10
20
30
40
50
angle
Correct Q
Incorrect Q


1/Q
0
0.02
0.04
0.06
0.08
0
500
1000
1500
2000
2500
depth[m]
Q scan

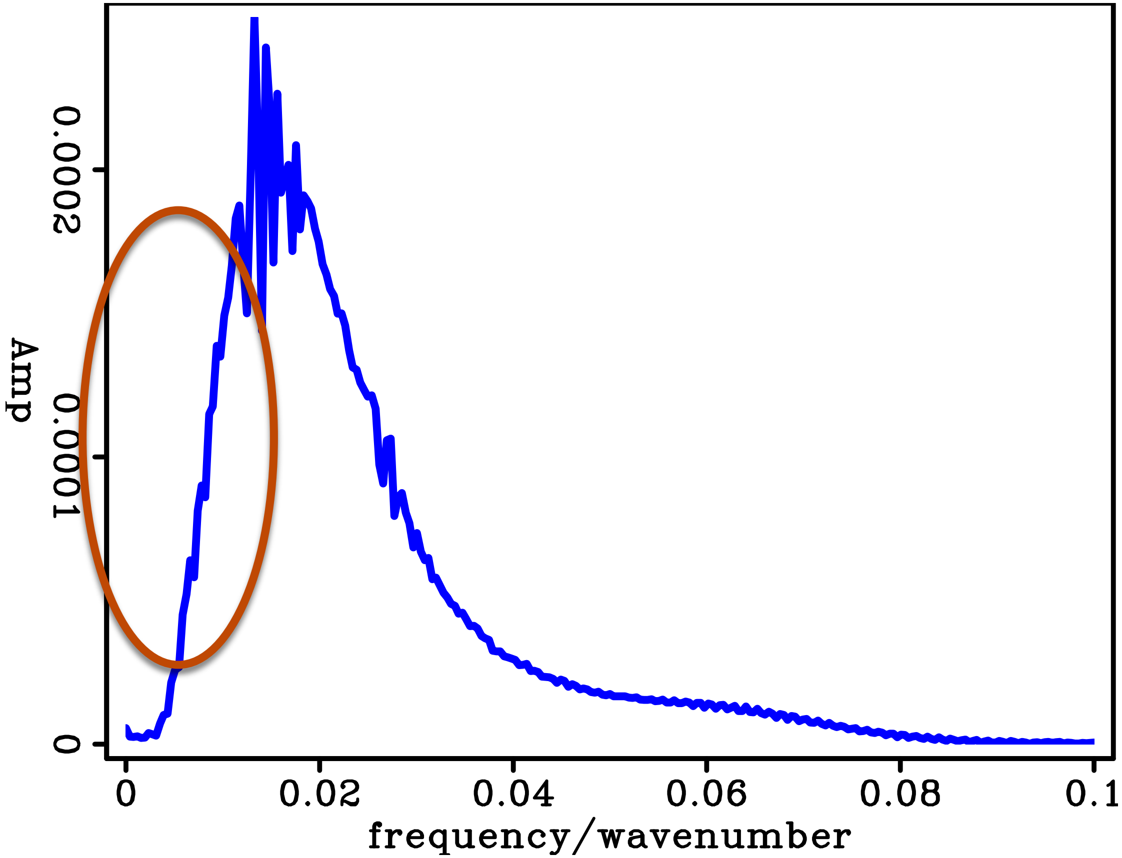
Spectral ratio vs. Central frequency shift

- Minimize the large error (e.g. abrupt jump)



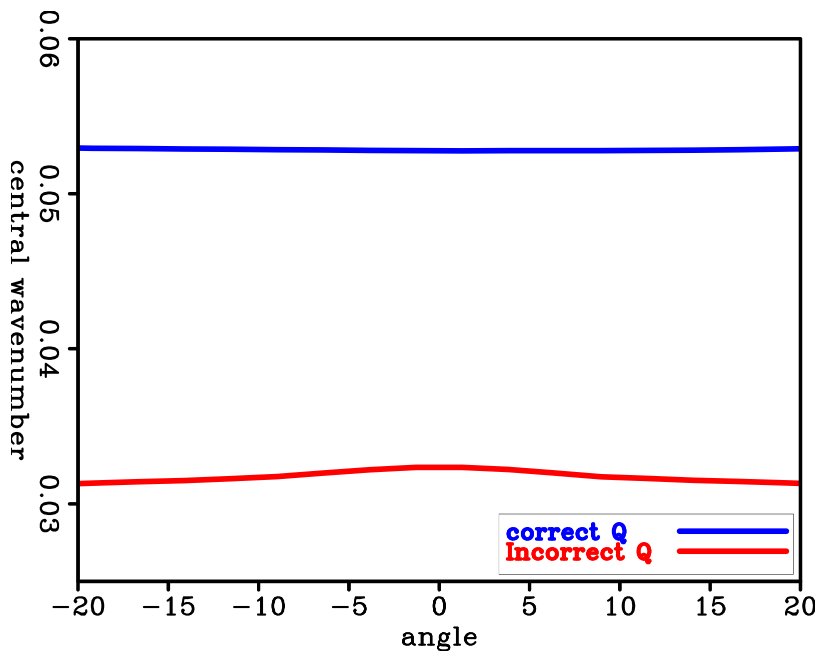
Spectral ratio vs. Central frequency shift

- Take the f/k band of interests

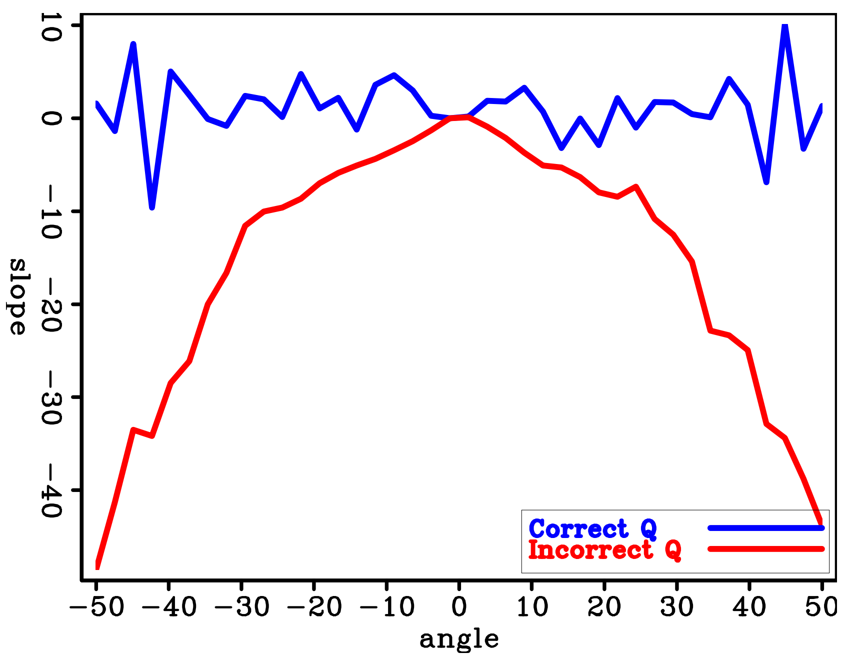


Spectral ratio vs. Central frequency shift

Central *k* shift

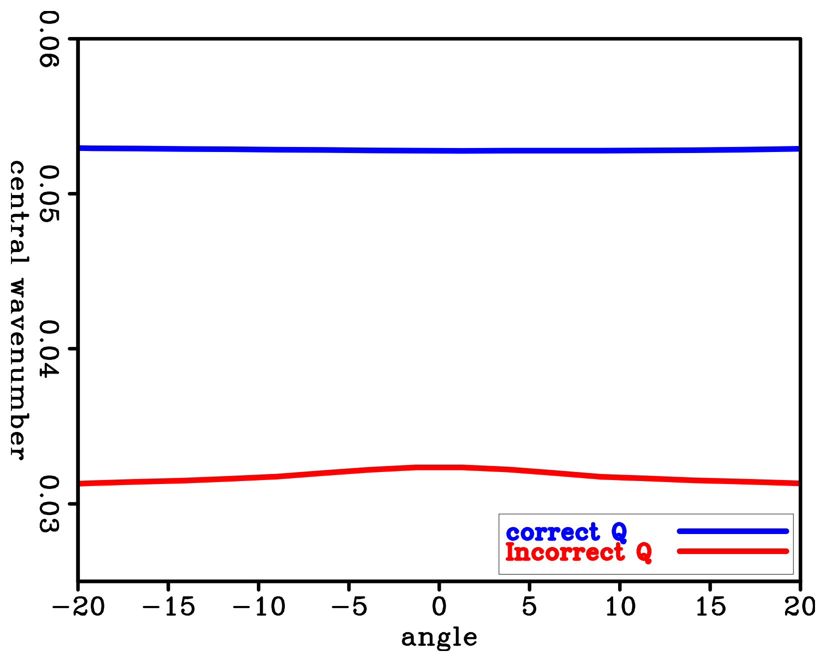


Spectral ratio

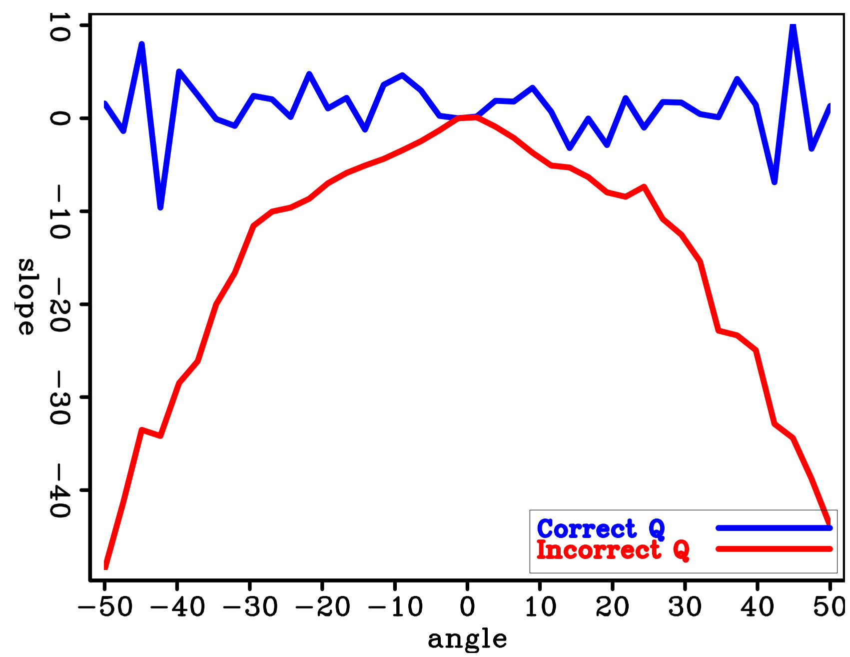


Spectral ratio vs. Central frequency shift

Central *k* shift

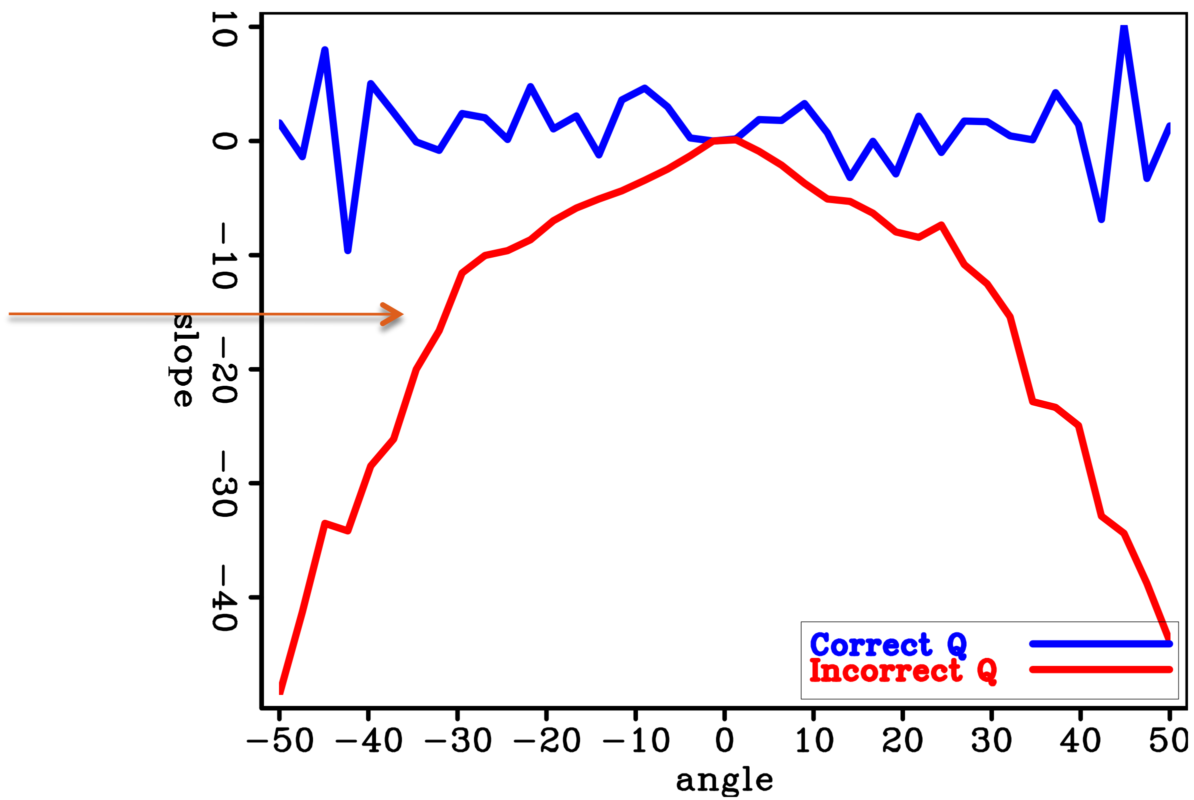


Spectral ratio



Future Work

- Wave-equation migration Q analysis (WEMQA)



Conclusion

- Analyzed Q versus offset (QVO) or Q versus angle (QVA) in both data domain and image domain
  - Well estimated Q
  - Spectral ratio method has advantage over central *f/k* shift method in image domain
  - WEMQA is needed for more complex model

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Acknowledgements

- Thanks to **Biondo Biondi**, **Robert Clapp and Dave Nichols** of Stanford for discussions and suggestions.

Thank You

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Outline

- The importance of estimation of Q
- Proposed method
- Numerical tests
- Future work
- Conclusion

Conventional ways of Q estimation

(Quan and Harris, 1997; Plessix, 2006; Rickett, 2006, 2007, etc)

- Estimation of Q based on
  - **Stacked traces**

    Cons: need the reference/source information
  - **Ray theory**
  - **Time domain**

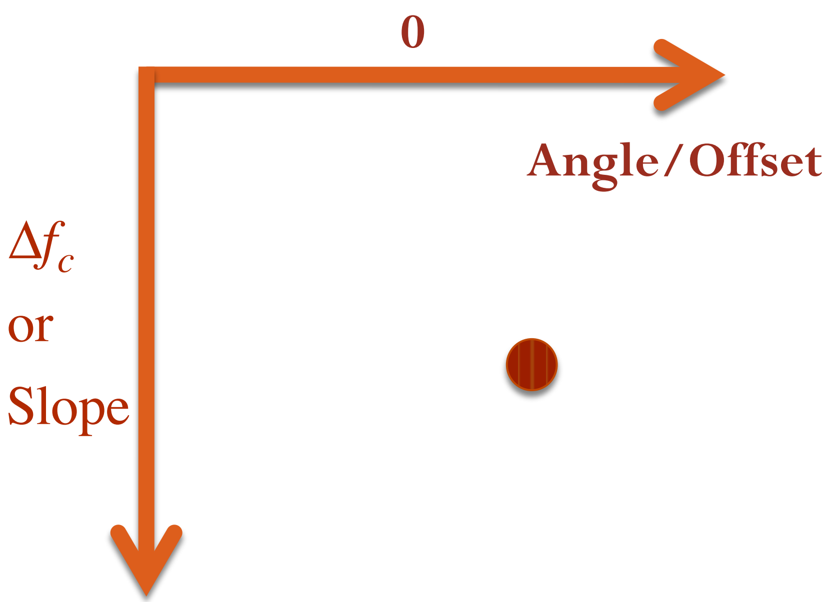
Proposed method

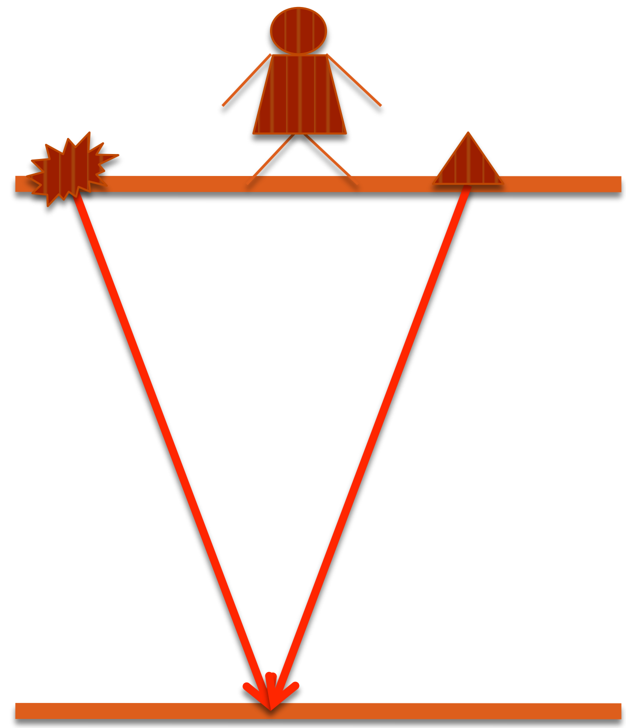
- Estimation of Q is based on
  - **Q versus offset analysis**

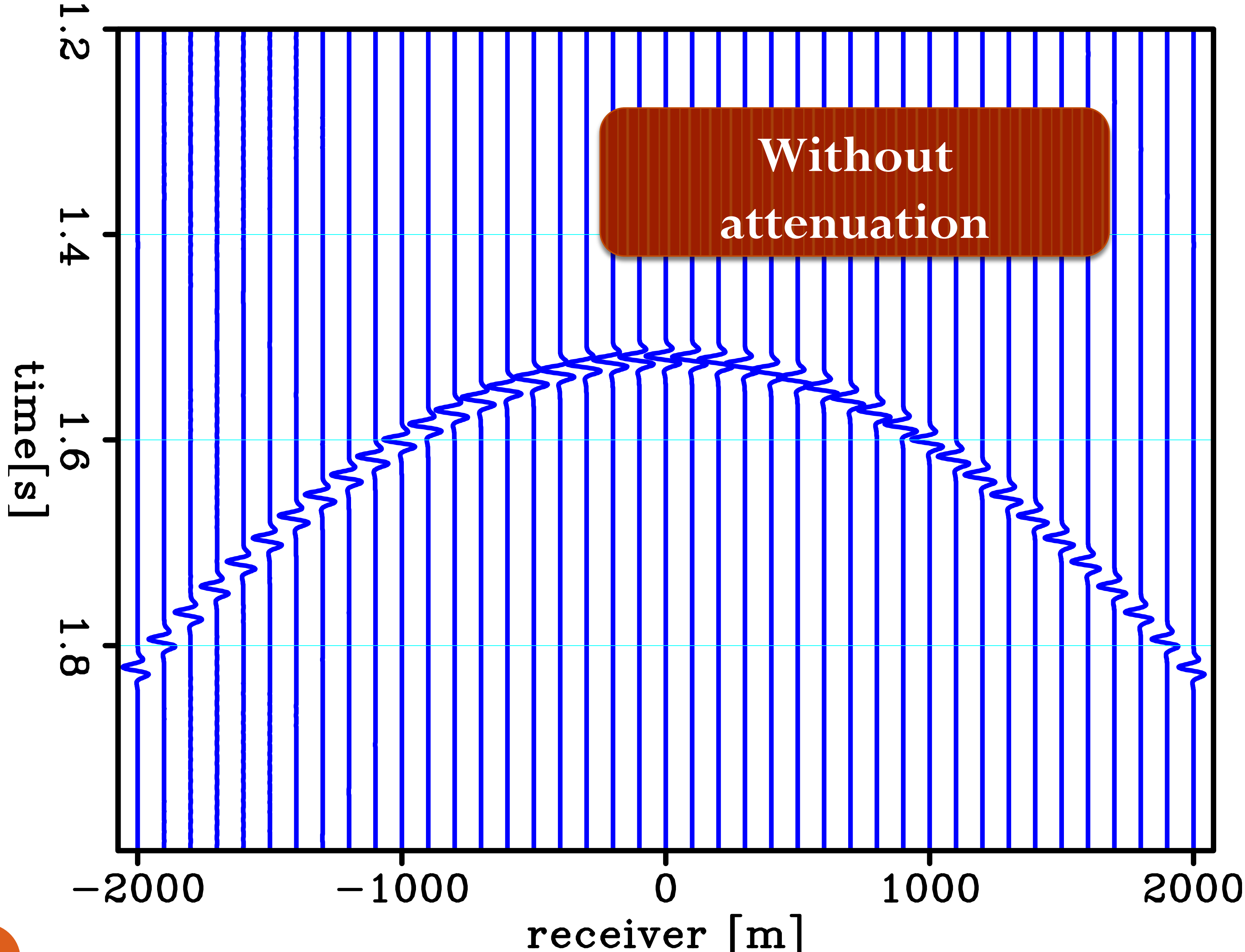
    Pros: need no reference/source information
  - **Wave equation theory**
  - **Image domain**

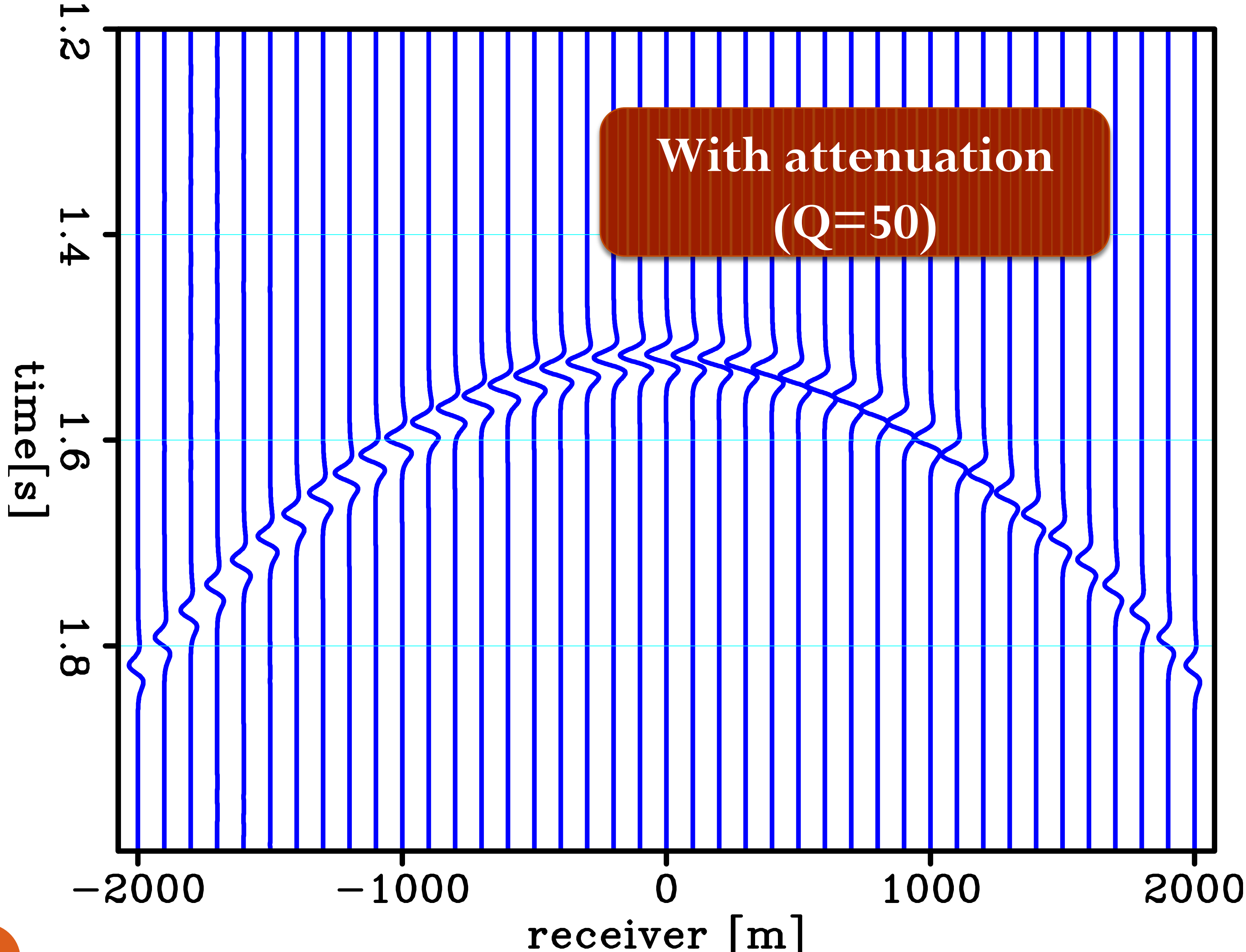
Theory

$$\Delta f_c \text{ \& Slope} \sim \int_{ray} \frac{\pi}{Qv} dl$$



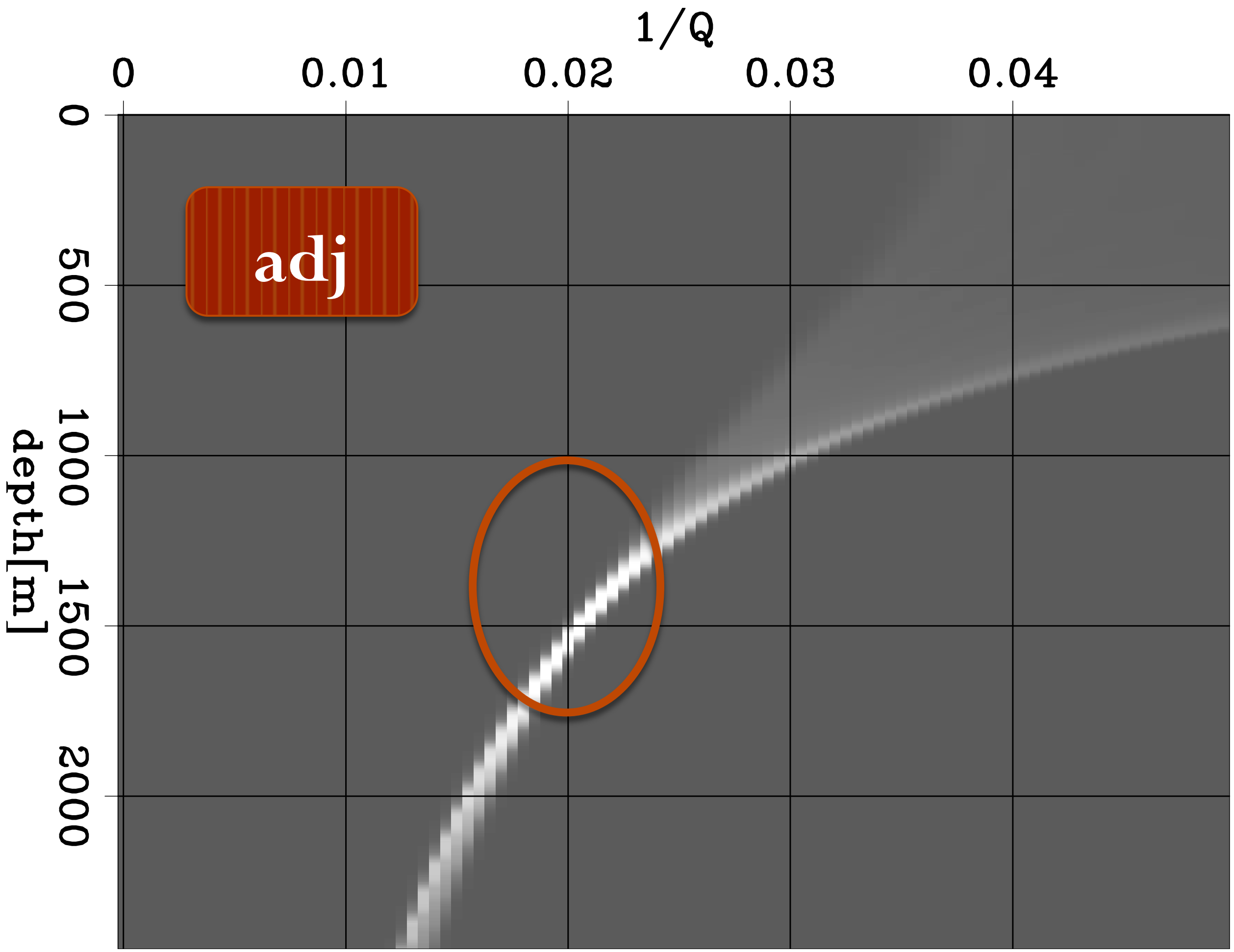



Without attenuation
1.2
1.4
1.6
1.8
time[s]
−2000
−1000
0
1000
2000
receiver [m]



With attenuation (Q=50)
1.2
1.4
1.6
1.8
time[s]
−2000
−1000
0
1000
2000
receiver [m]

Q spectra



Q migration

$$\mathbf{d} = \mathbf{A}\mathbf{F}\mathbf{m}$$

$$\mathbf{m} = \mathbf{F}^T \mathbf{A}^T \mathbf{d}$$

- **d** : data
- **m** : model
- **F** : downward continuation operator
- **A** : attenuation operator

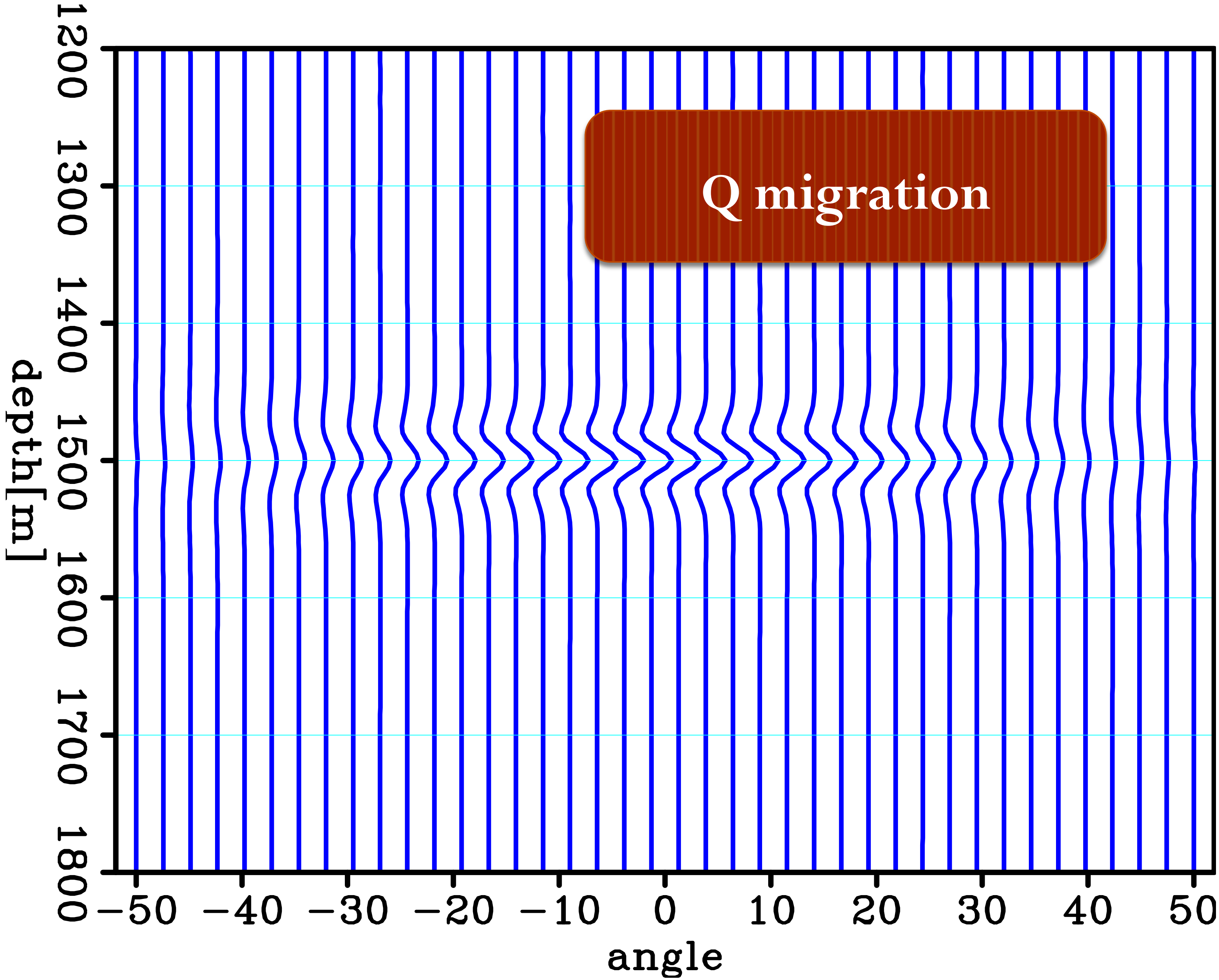
Q migration

$$\mathbf{d} = \mathbf{AFm}$$

$$\mathbf{m} = \mathbf{F}^T \mathbf{A}^T \mathbf{d}$$

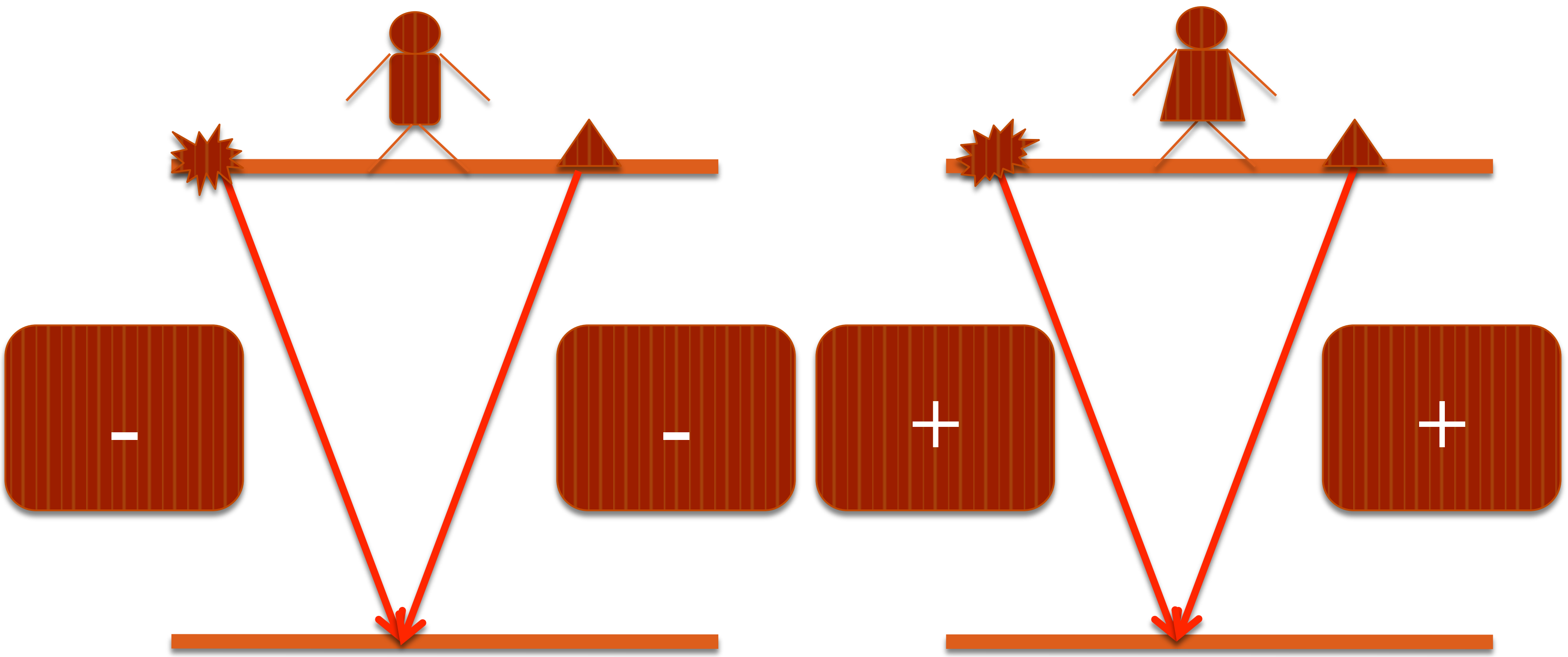
Further decay

- $\mathbf{d}$: data
- $\mathbf{m}$: model
- $\mathbf{F}$: downward continuation operator
- $\mathbf{A}$: attenuation operator


Q migration
1200
1300
1400
1500
1600
1700
1800
depth[m]
−50 −40 −30 −20 −10 0 10 20 30 40 50
angle

Amplitude

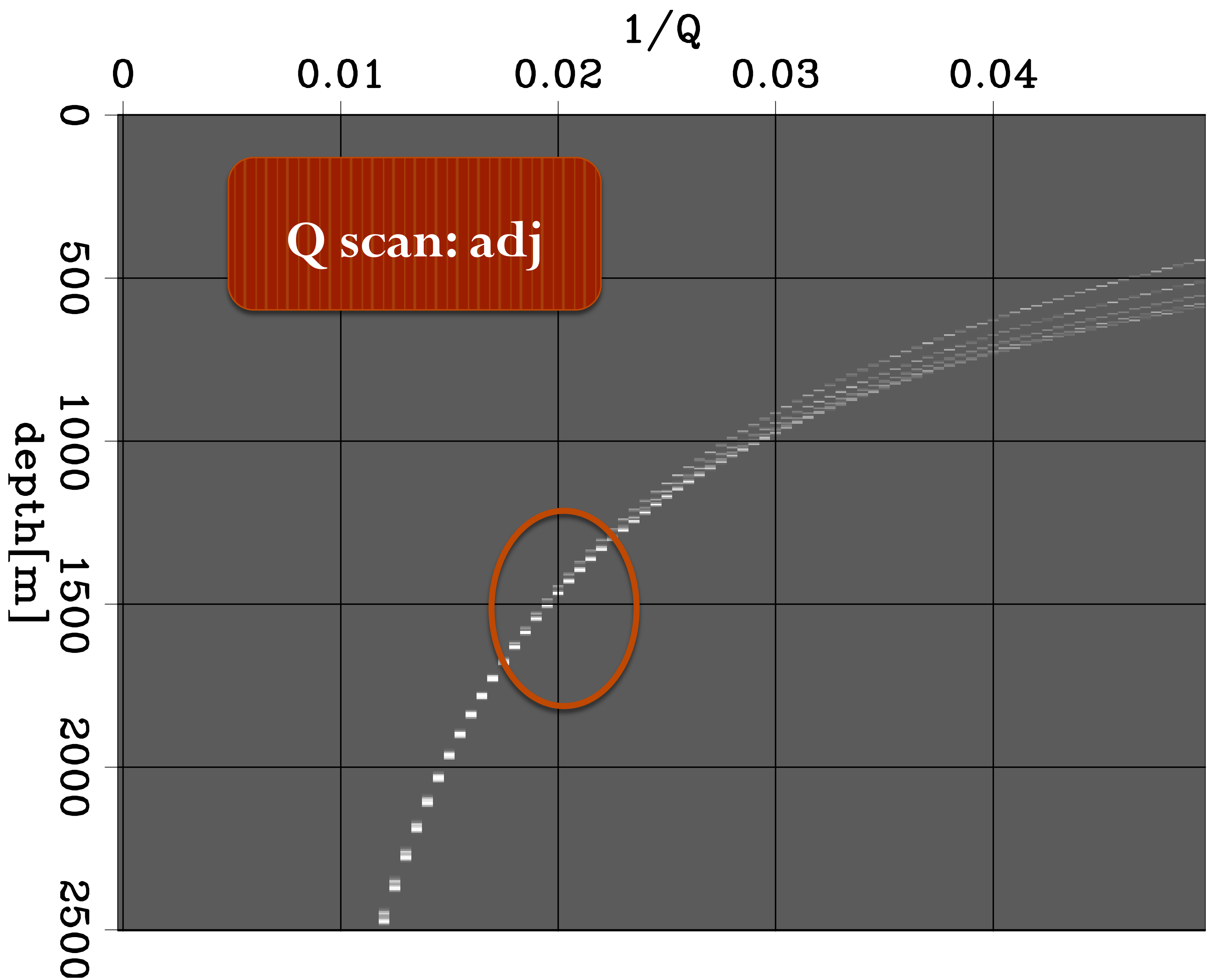
- migration
- Compensation



Work flow

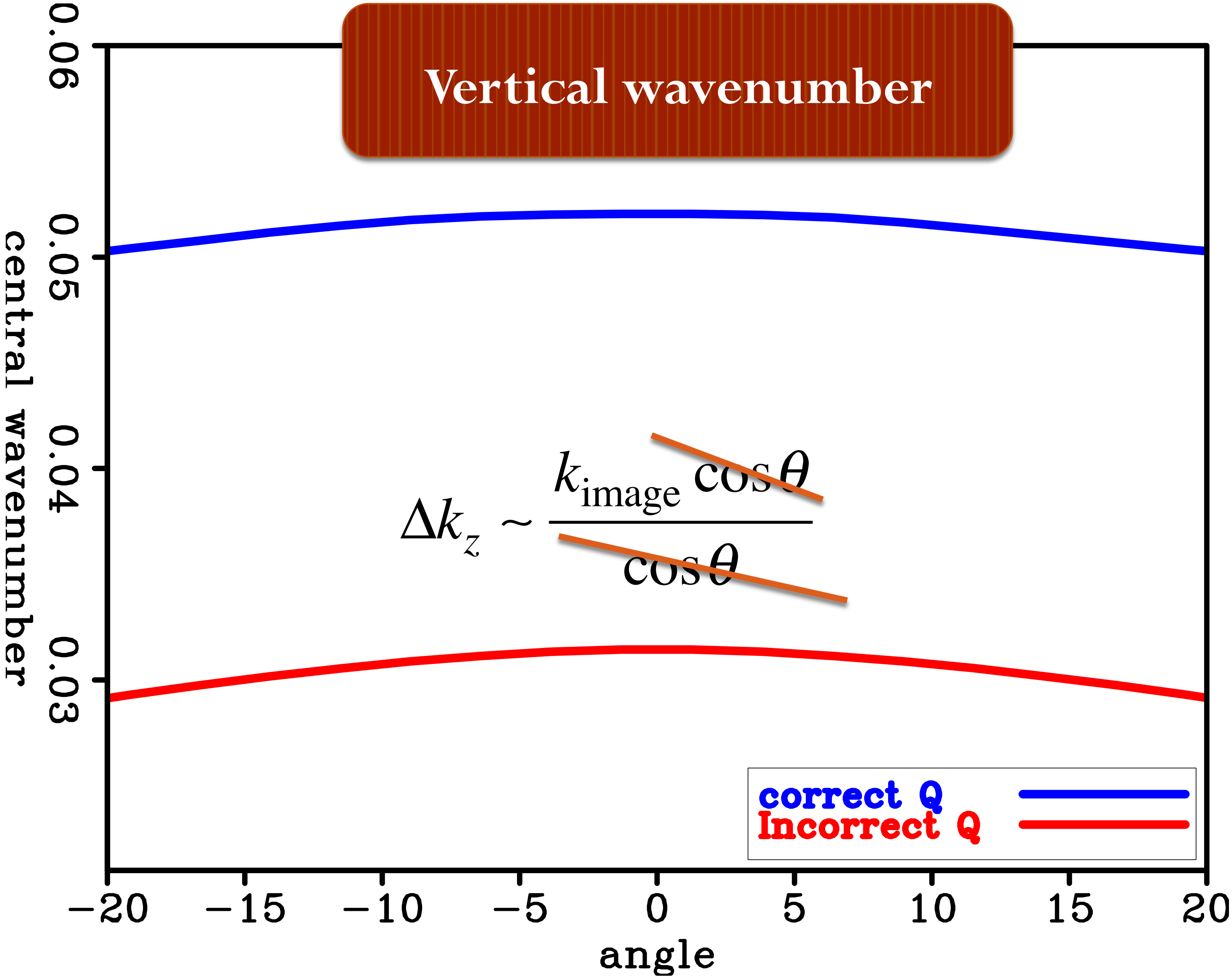
- First, take one common midpoint to compute the **image- wavenumber shift/slope** in its **angle-domain** common-image gathers after Q compensation.

$$k_{\text{image}} = 4\pi f / v = k_z / \cos\theta$$

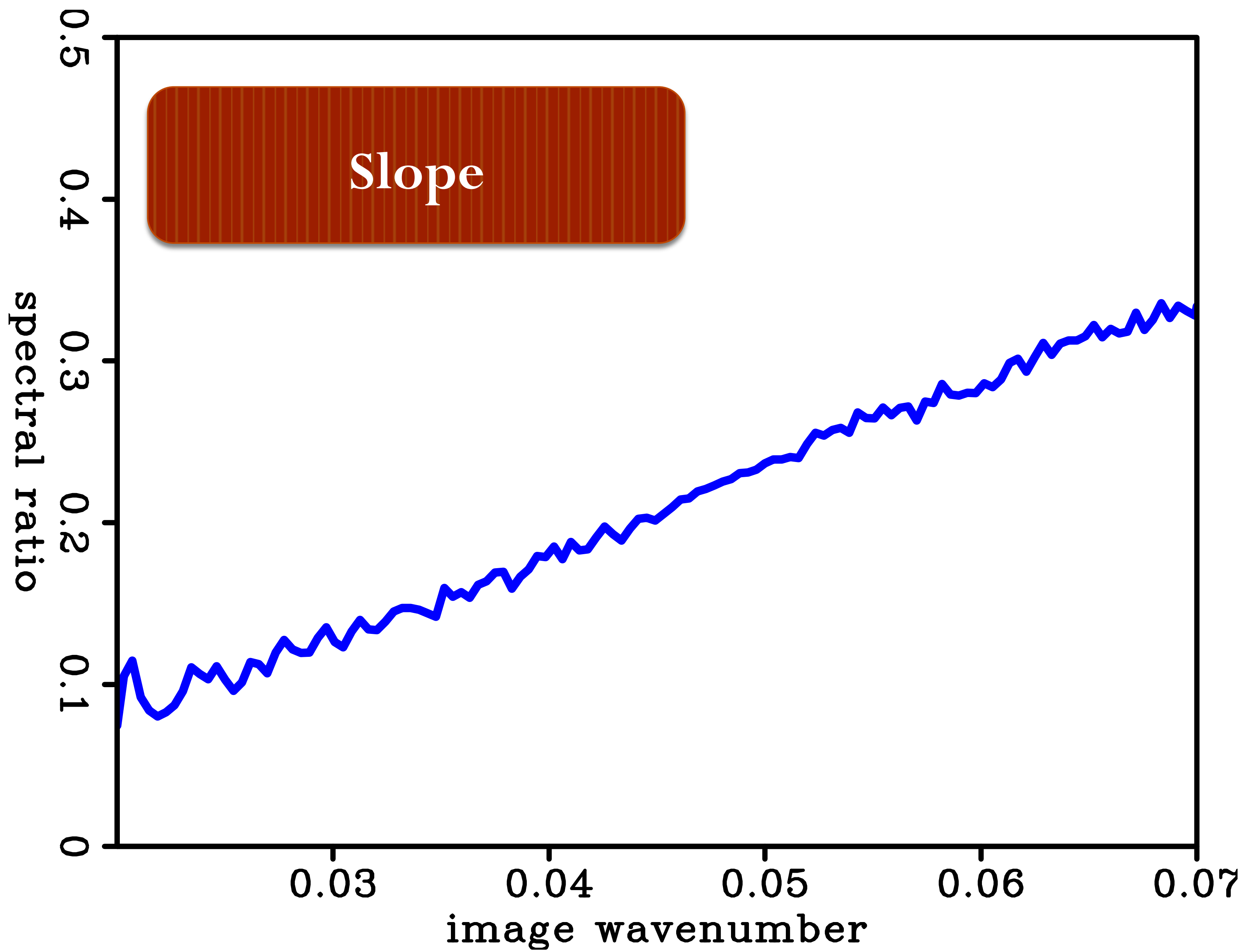


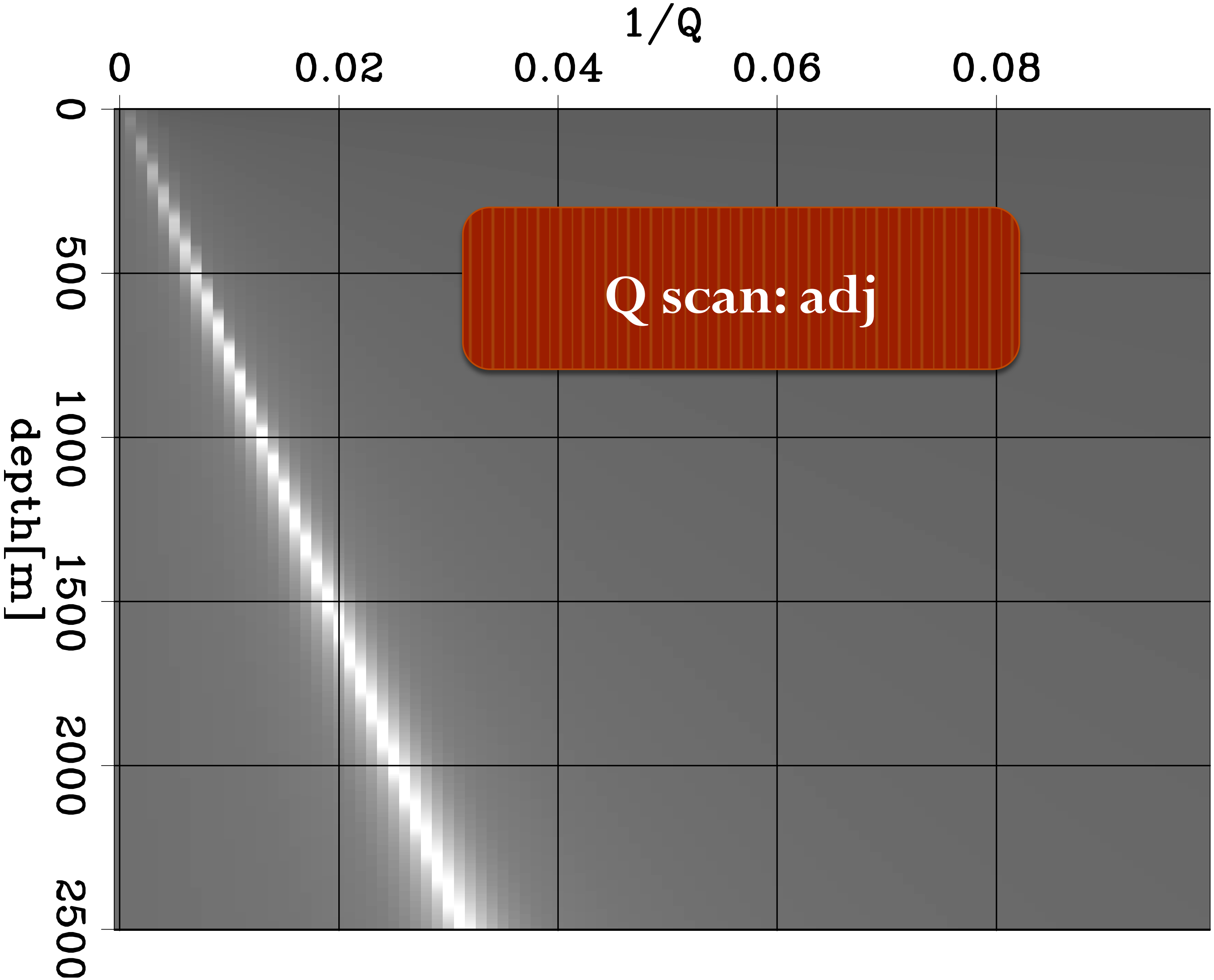
1/Q
0
0.01
0.02
0.03
0.04
0
500
1000
1500
2000
2500
depth[m]
Q scan: adj

Vertical wavenumber



$$\Delta k_z \sim \frac{k_{\text{image}} \cos\theta}{\cos\theta}$$


Slope
spectral ratio
0.5
0.4
0.3
0.2
0.1
0
0.03
0.04
0.05
0.06
0.07
image wavenumber



1/Q
0
0.02
0.04
0.06
0.08
0
500
1000
1500
2000
2500
depth[m]
Q scan: adj