Cosmic magnetism revealed through Faraday rotation

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L'institut Canadien d'astrophysique théorique

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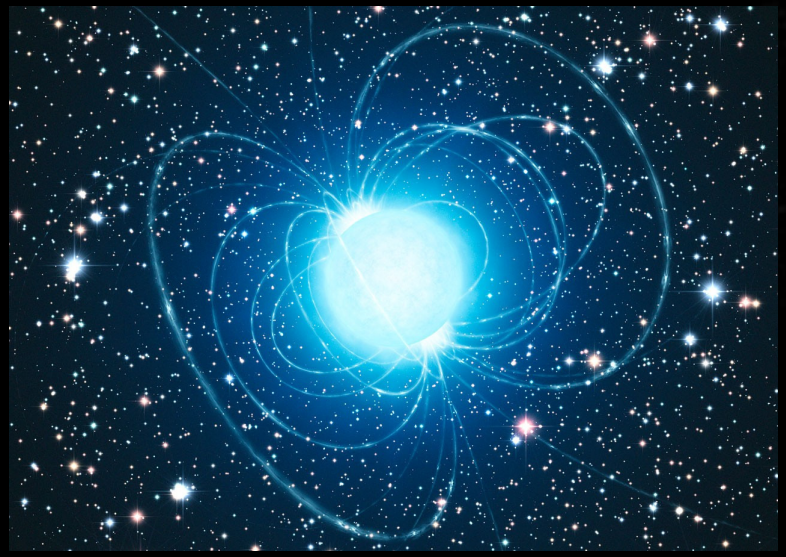
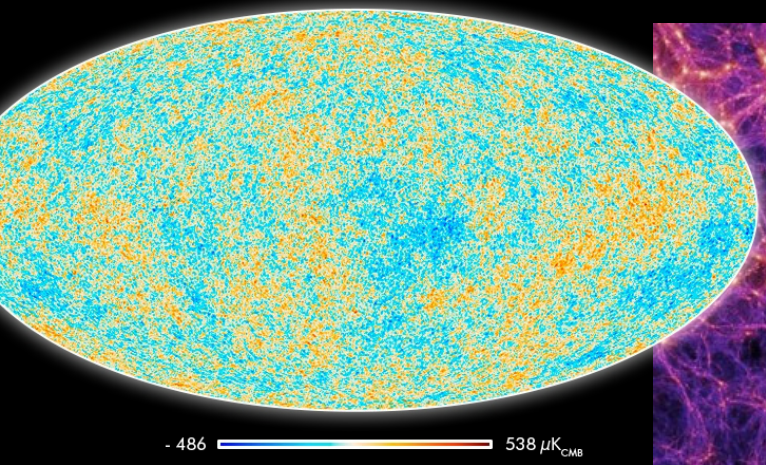
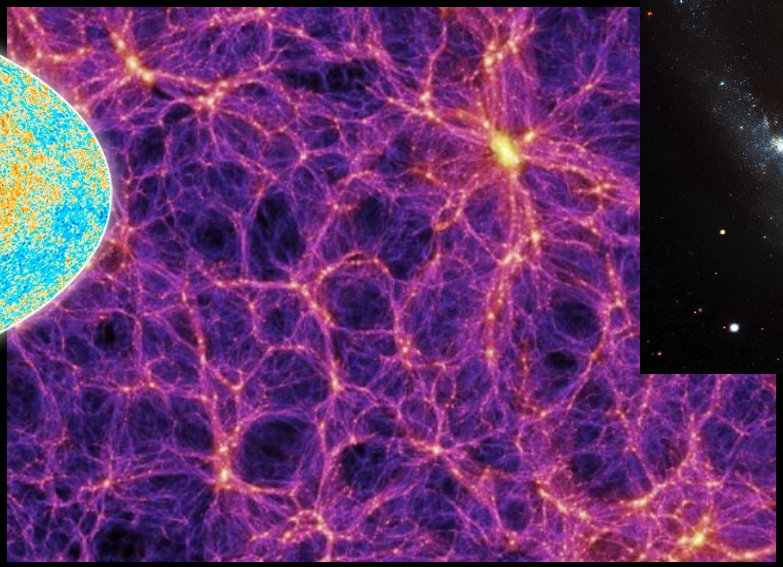
and others

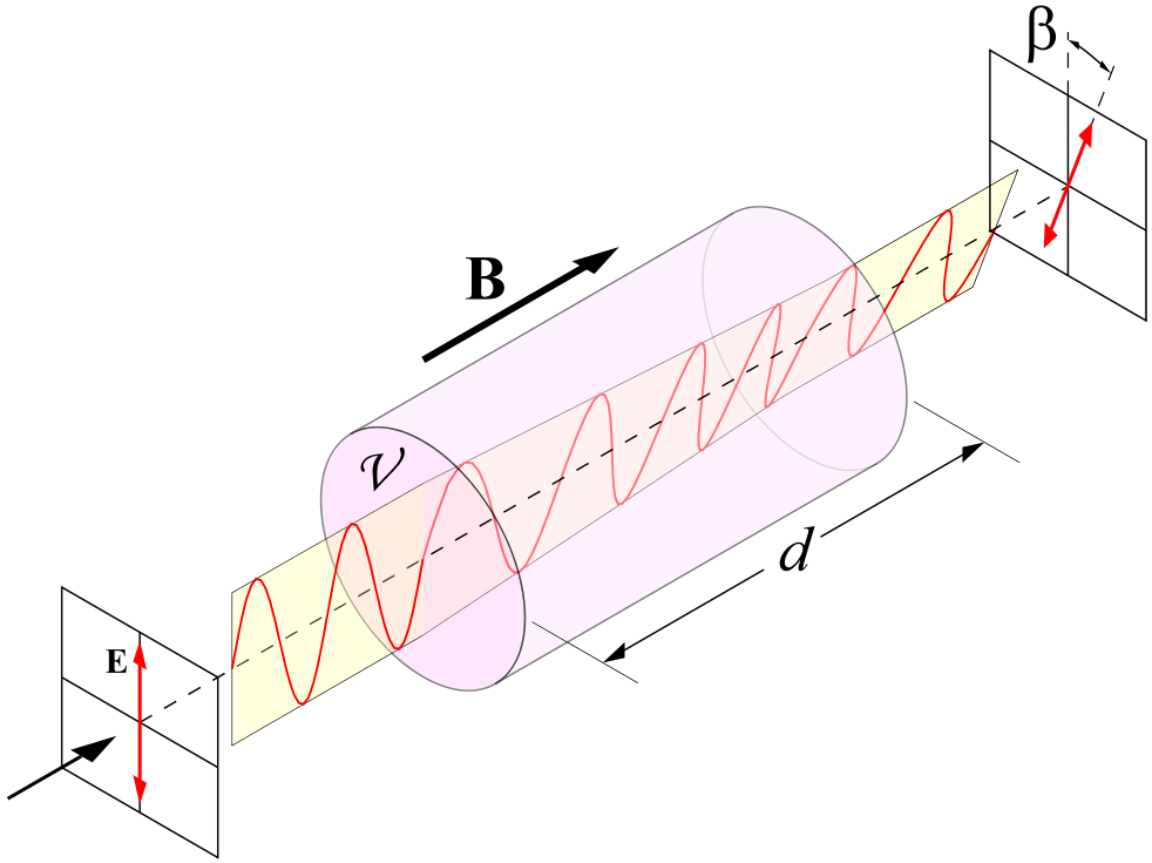
Western University, 2015-12-03




- 486
538 μK_{CMB}



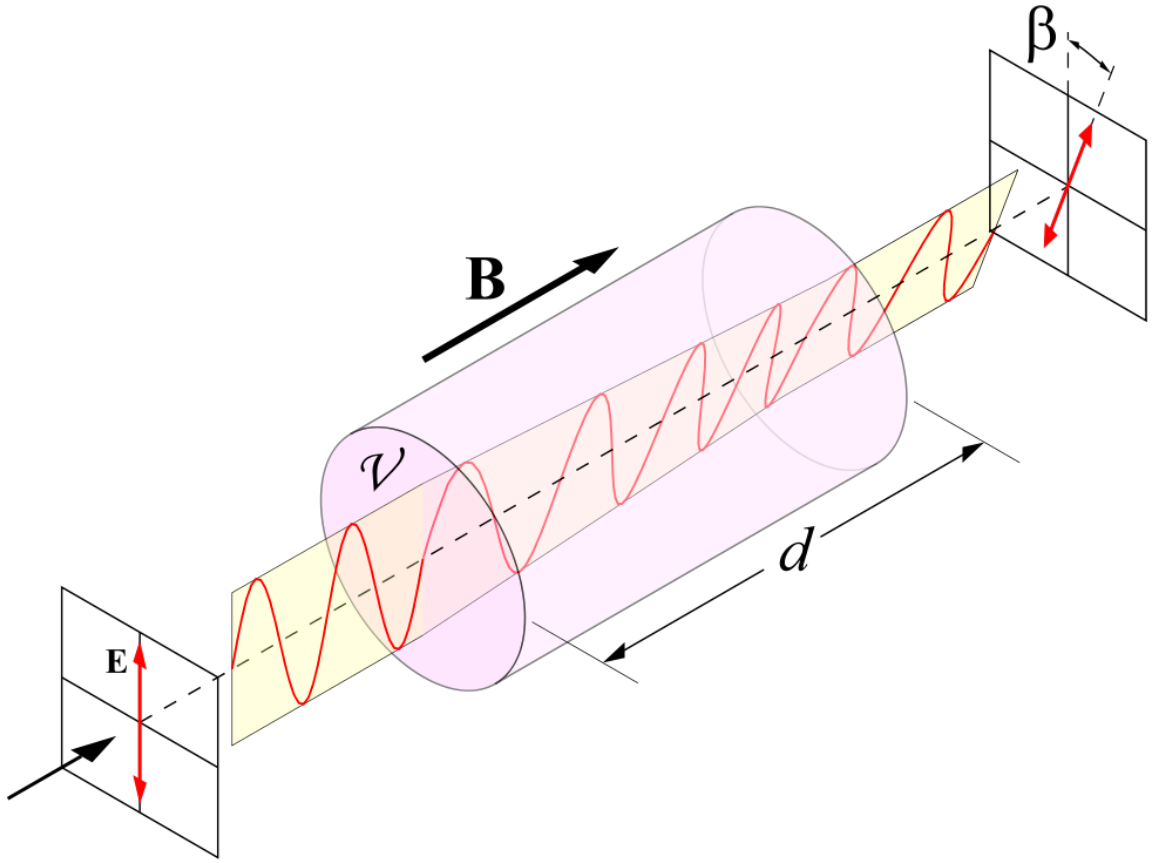
Faraday rotation



$$\mathrm{d}\beta \propto \lambda^2 n_\mathrm{e} B_r \,\mathrm{d}r$$

$$\Rightarrow \quad \beta \propto \lambda^2 \int_{r_\mathrm{source}}^{0} (1+z)^{-2}\; n_\mathrm{e} B_r \,\mathrm{d}r$$

Faraday rotation

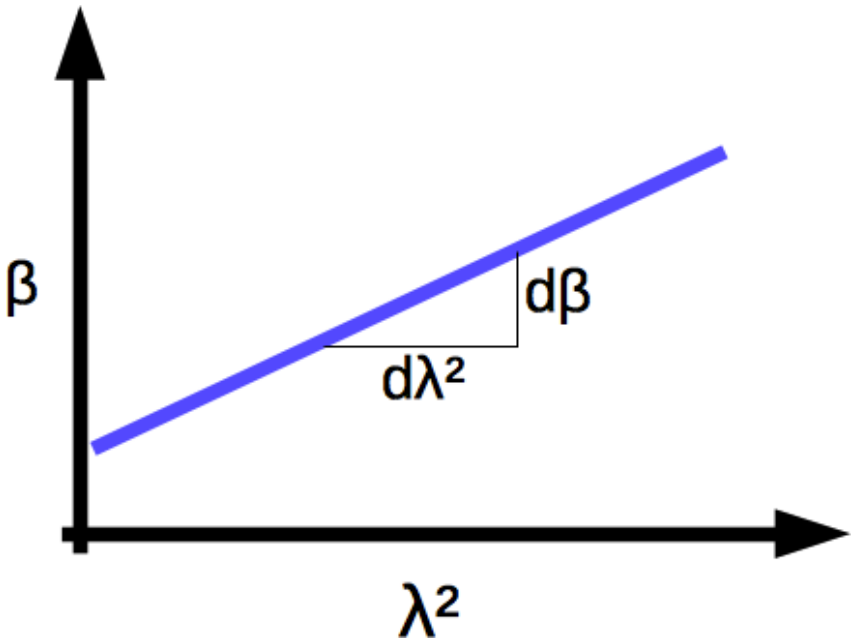


Faraday depth: $\phi \propto \int_{r_{\rm source}}^{0} (1+z)^{-2}\, n_{\rm e}\, B_r\, {\rm d}r$

$$\beta = \phi\lambda^2$$

Faraday rotation

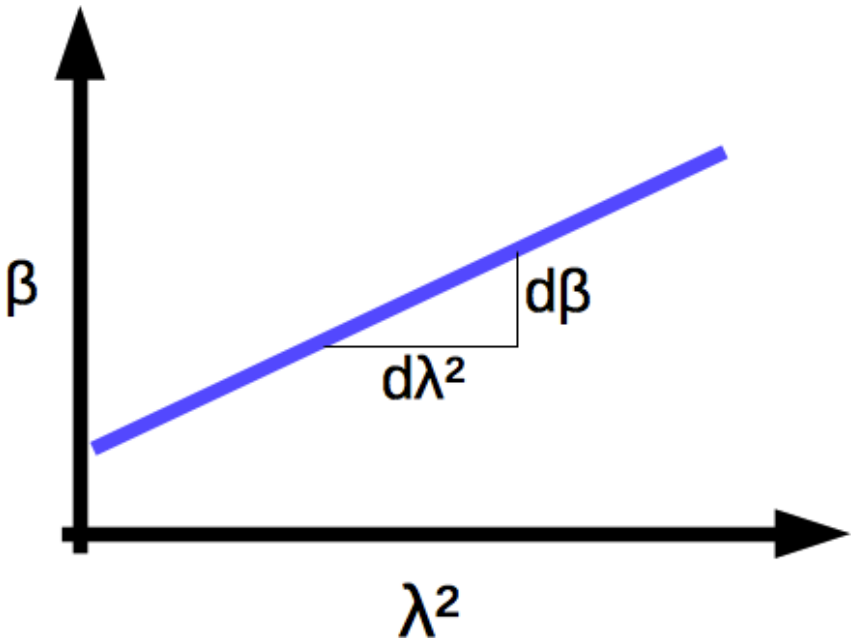
if B-fields in front of emission:



$$\phi = \mathrm{RM} = \frac{\mathrm{d}\beta}{\mathrm{d}\lambda^2}$$

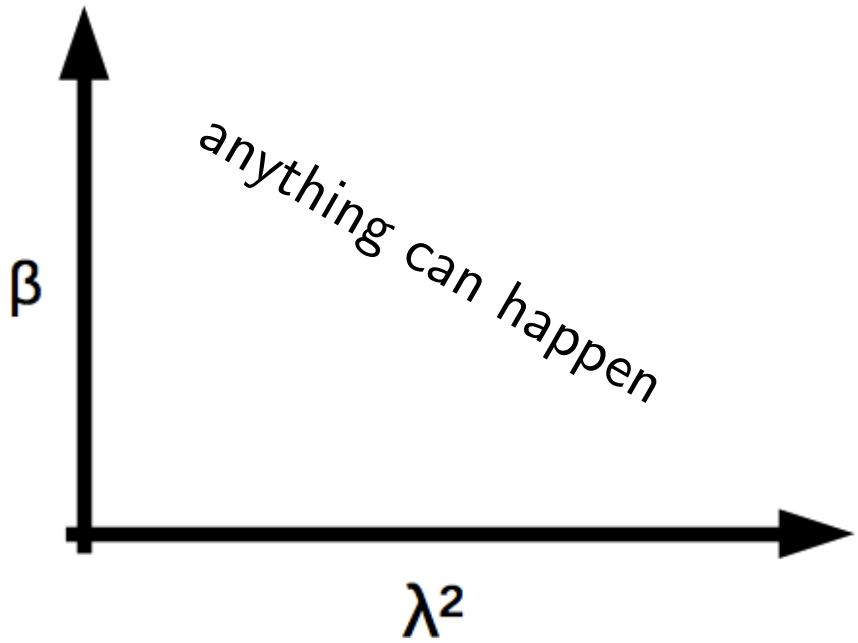
Faraday rotation

if B-fields in front of emission:

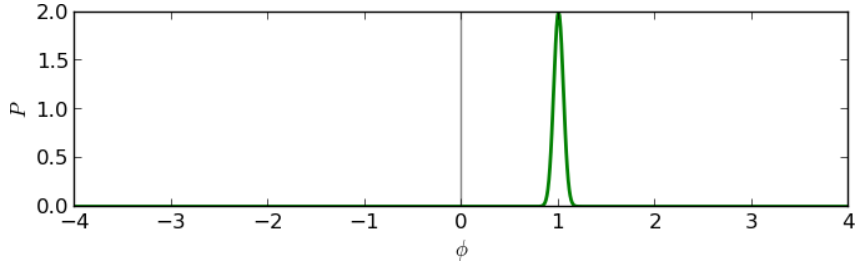


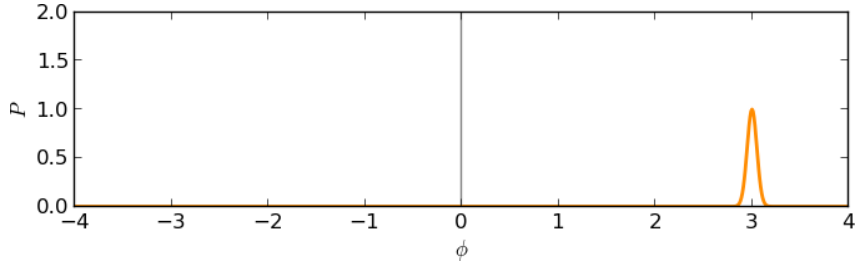
$$\phi = \mathrm{RM} = \frac{\mathrm{d}\beta}{\mathrm{d}\lambda^2}$$

if B-fields and emission mixed:



Use $Q(\lambda)$, $U(\lambda)$, $I(\lambda)$, RM synthesis,...


P
ϕ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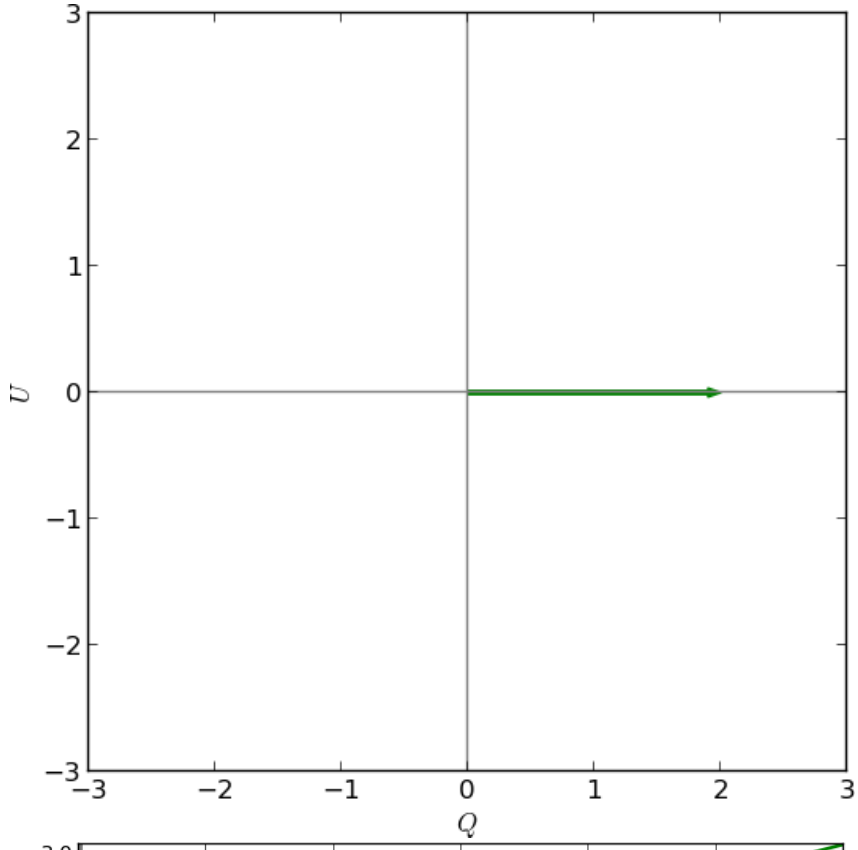
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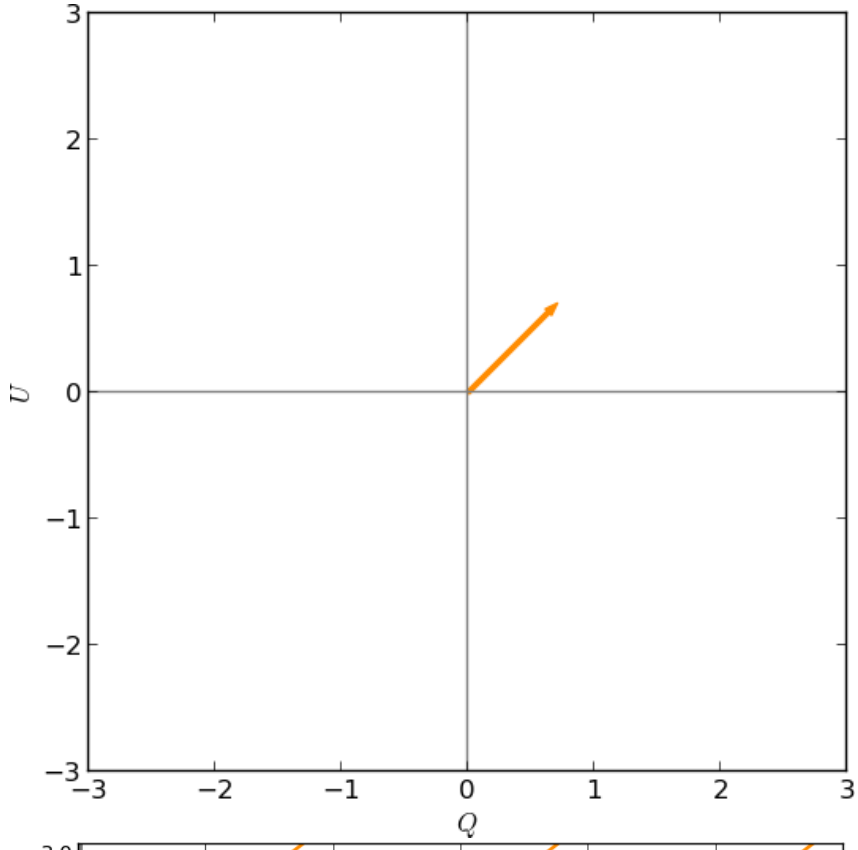
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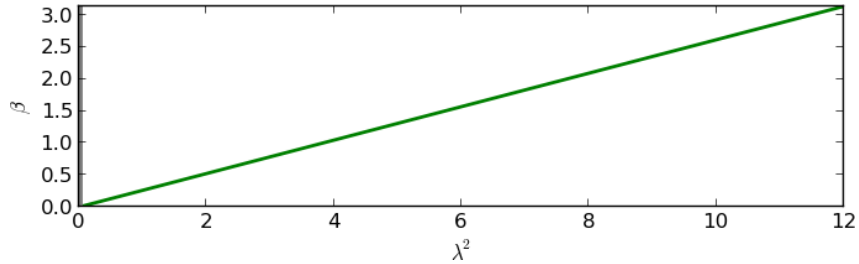
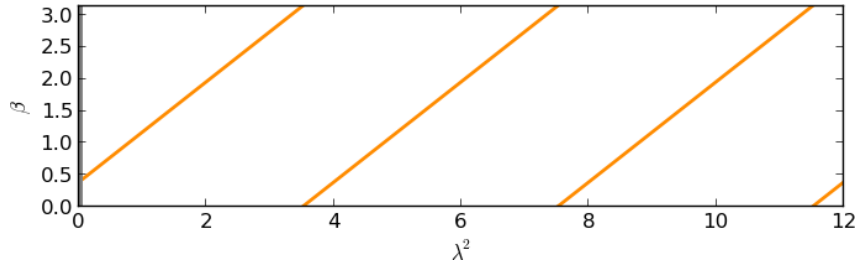
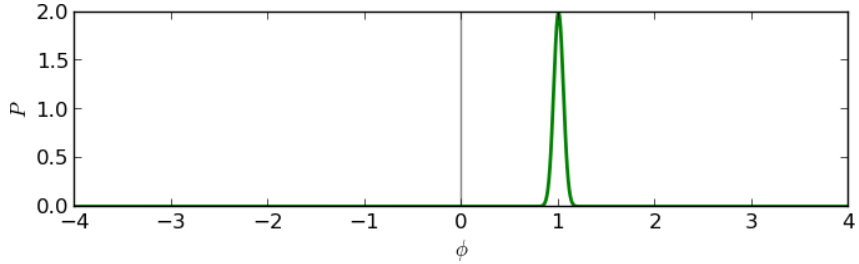

β
λ²


β
λ²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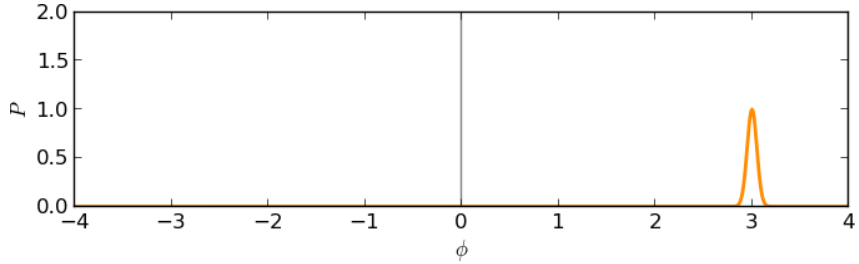
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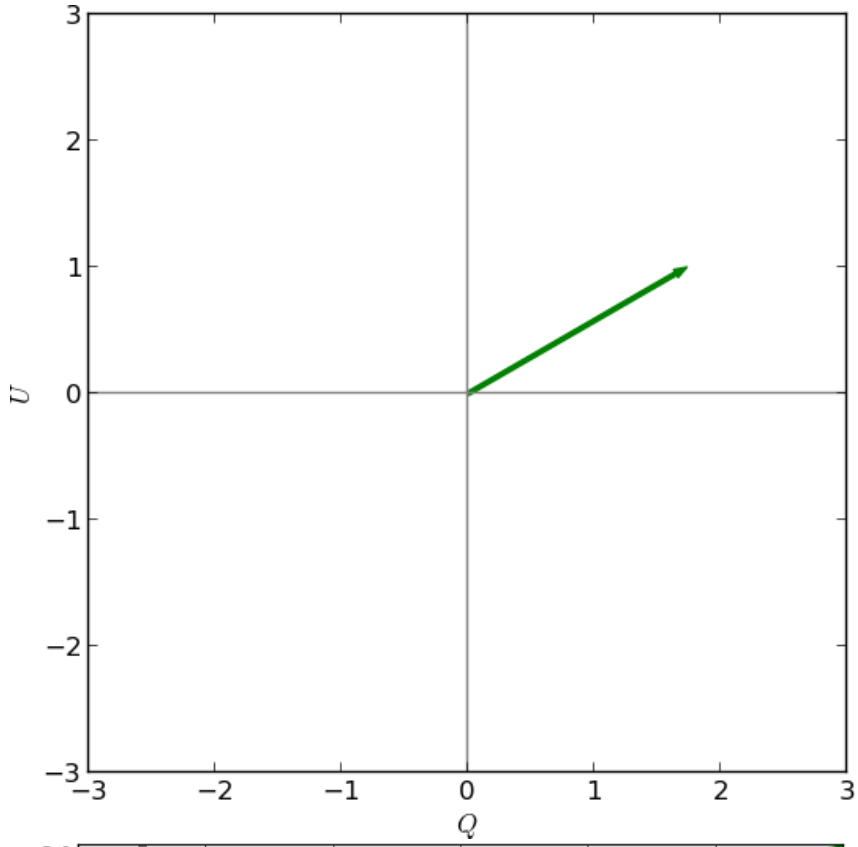
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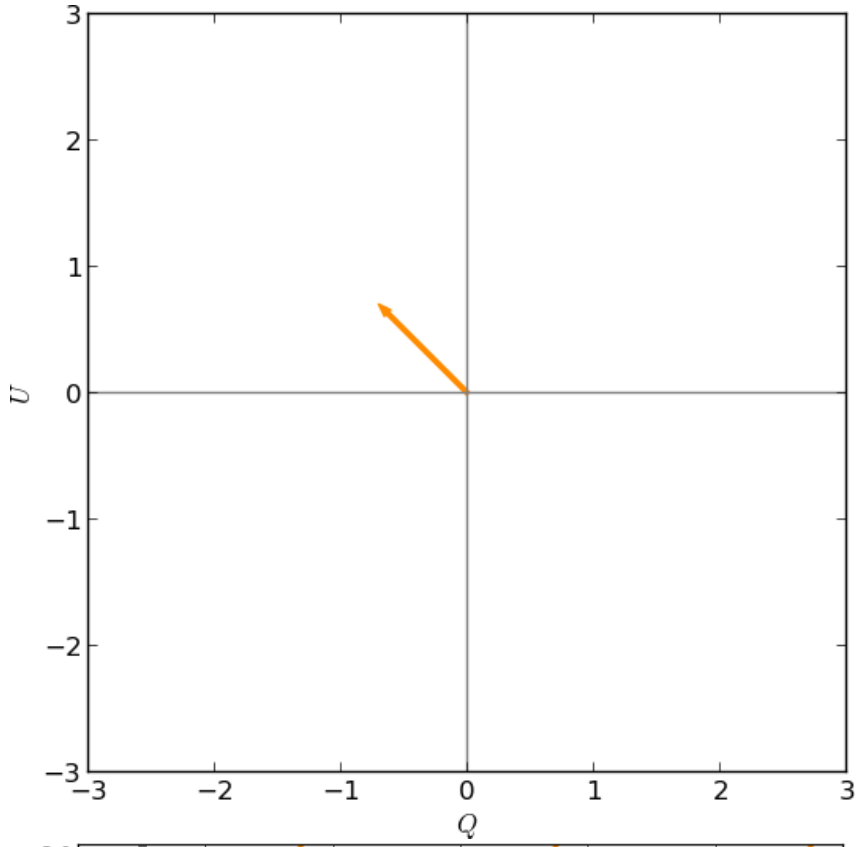
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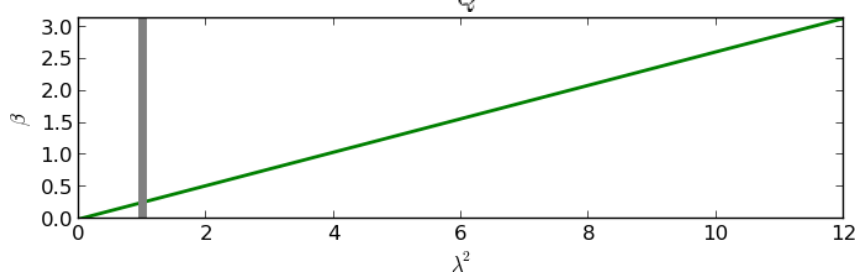
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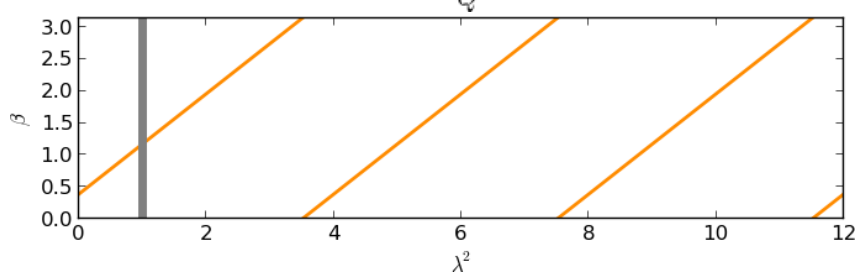
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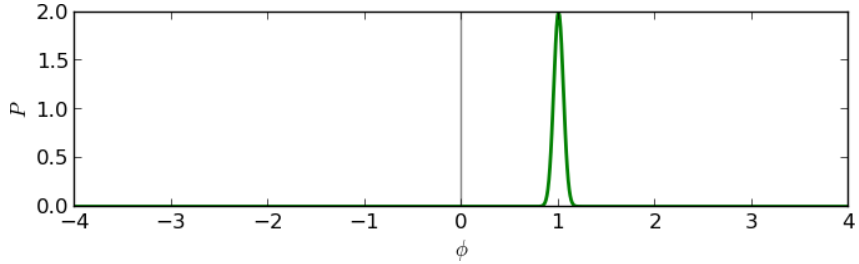
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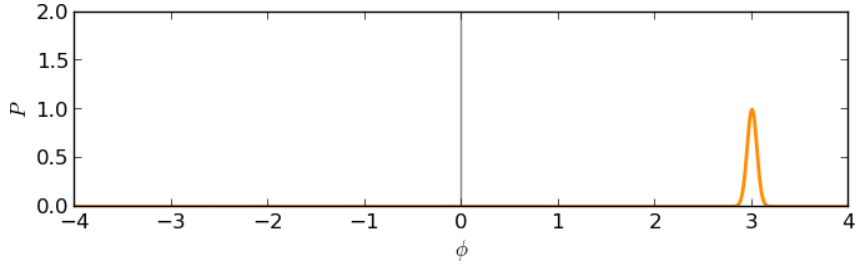
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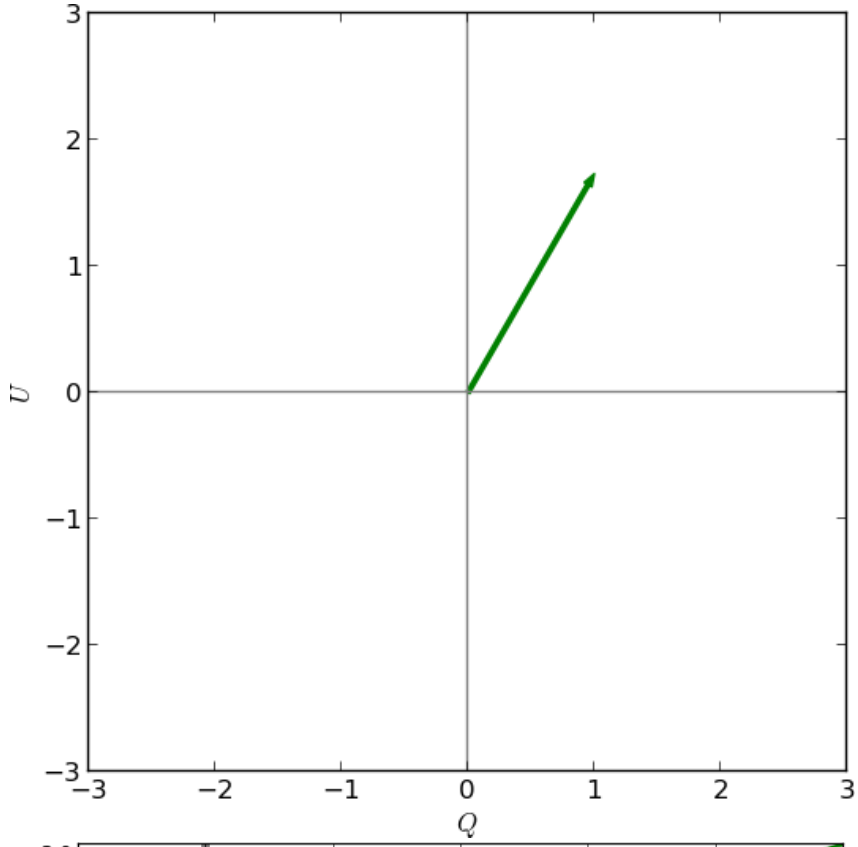
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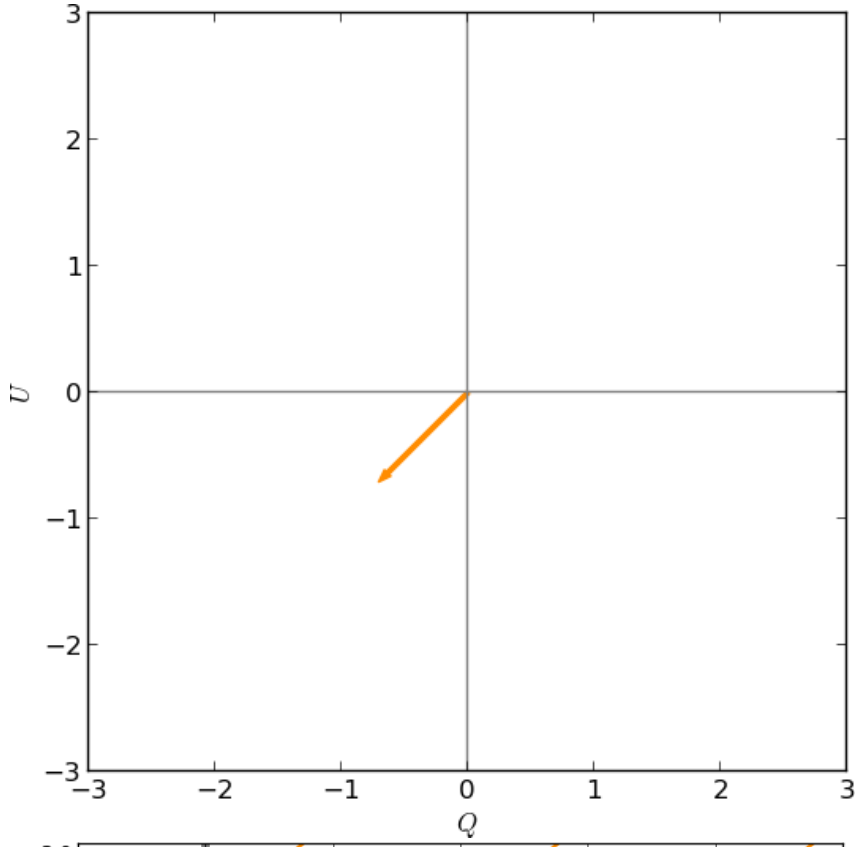
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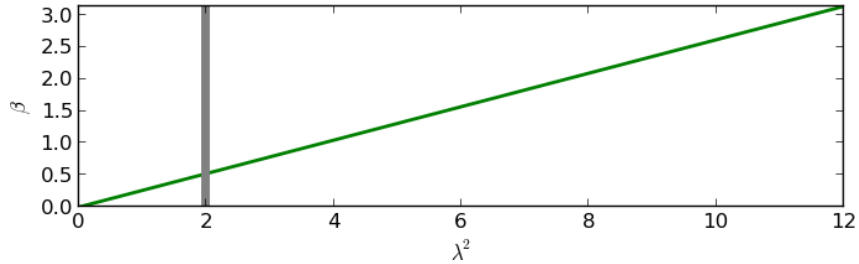
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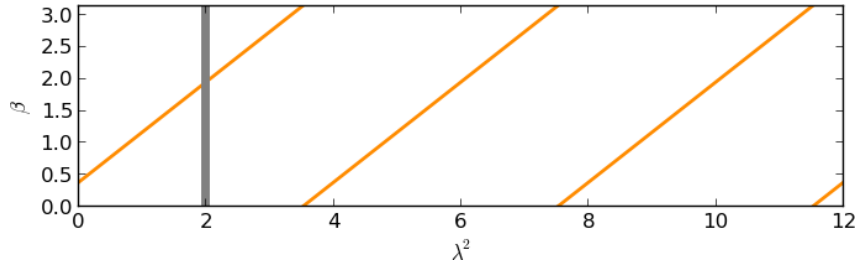
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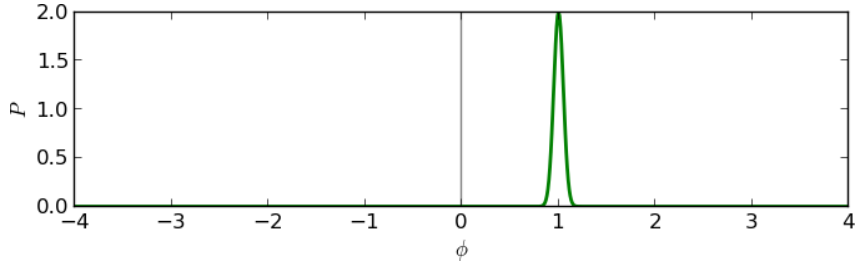
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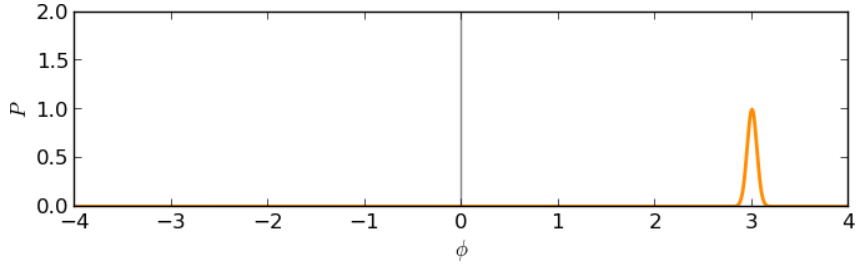
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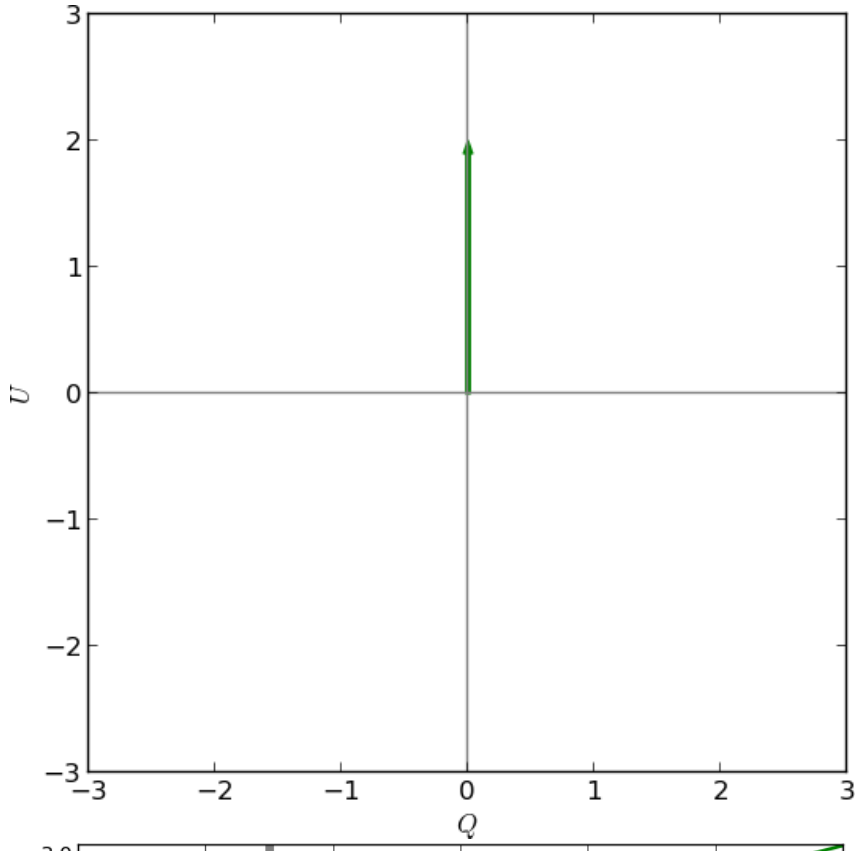
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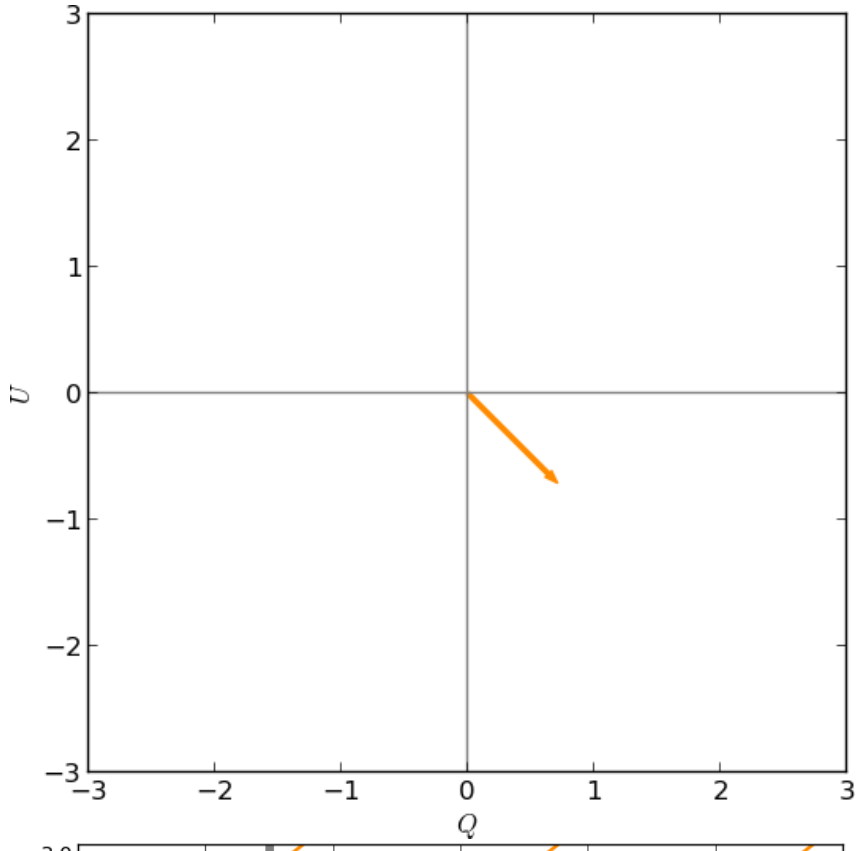
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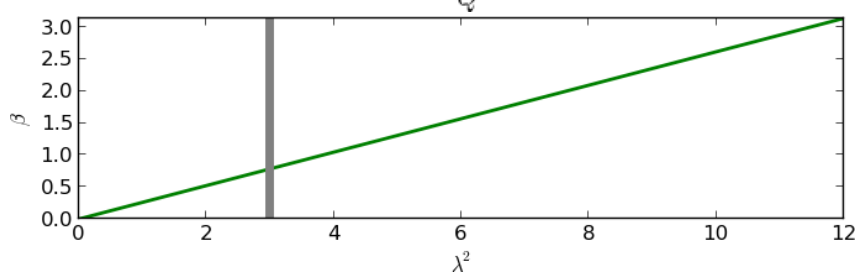
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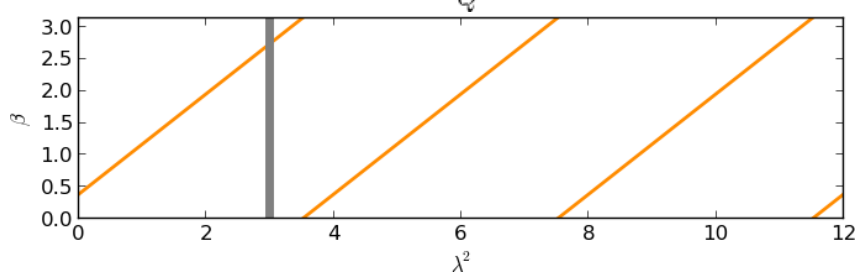
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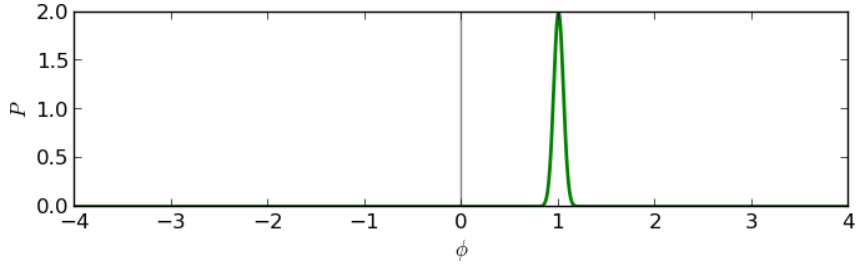
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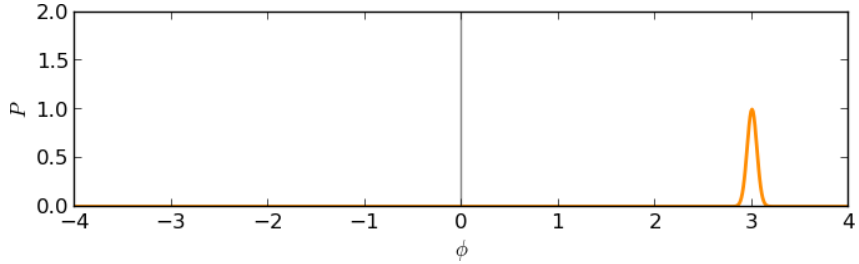
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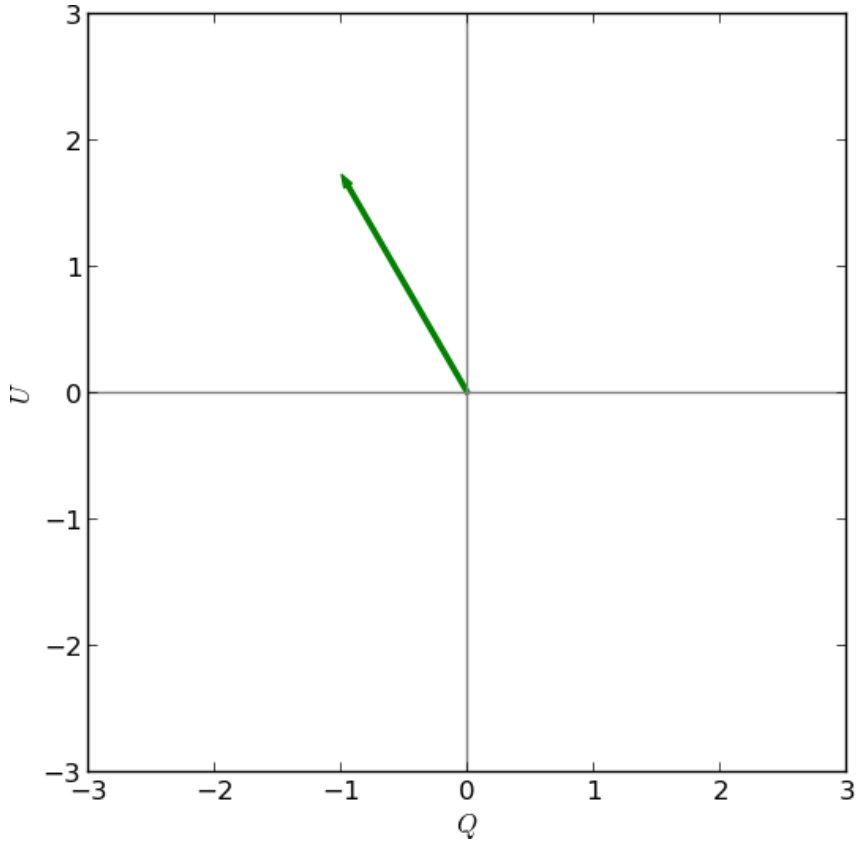
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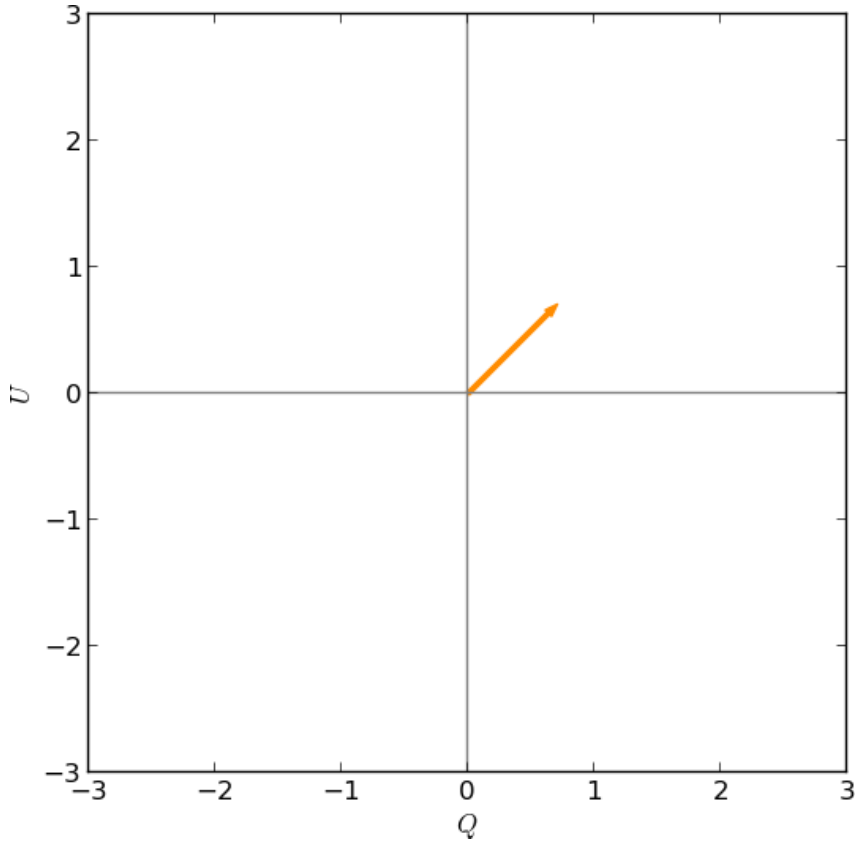
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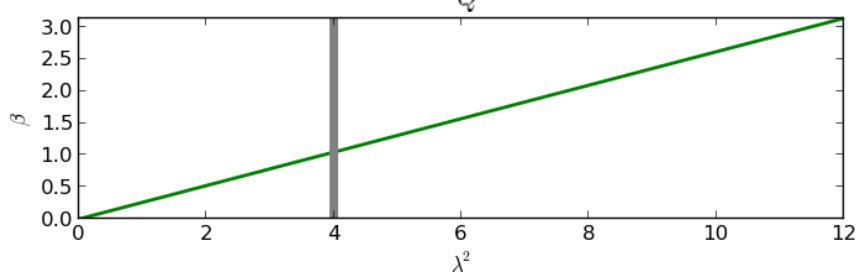
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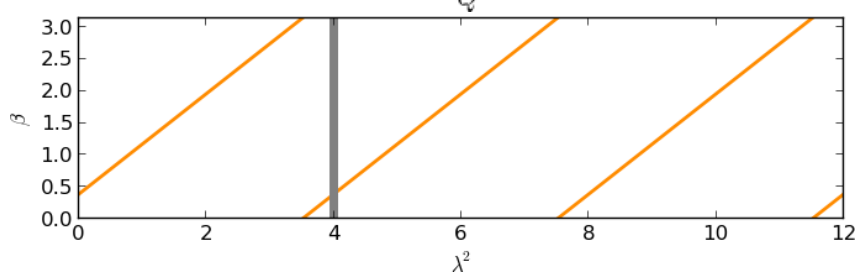
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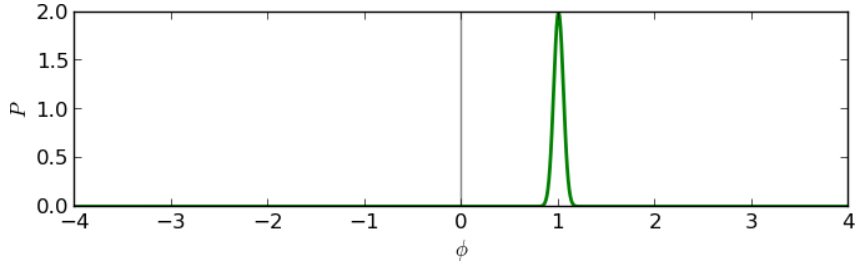
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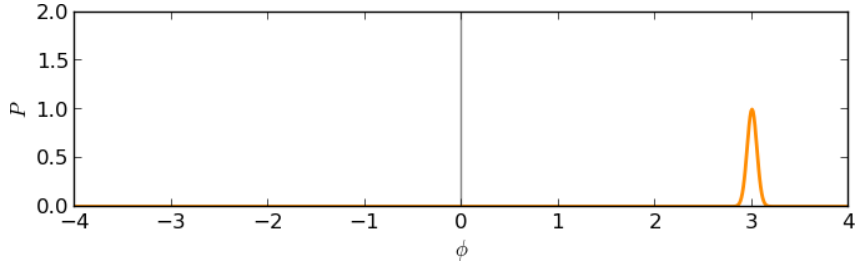
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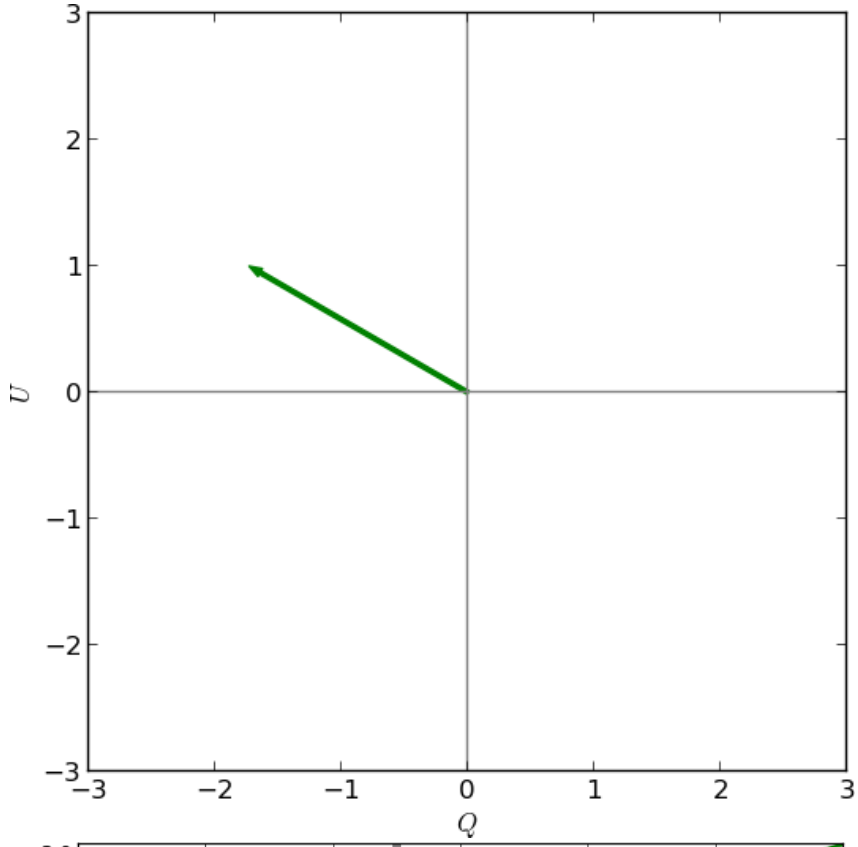
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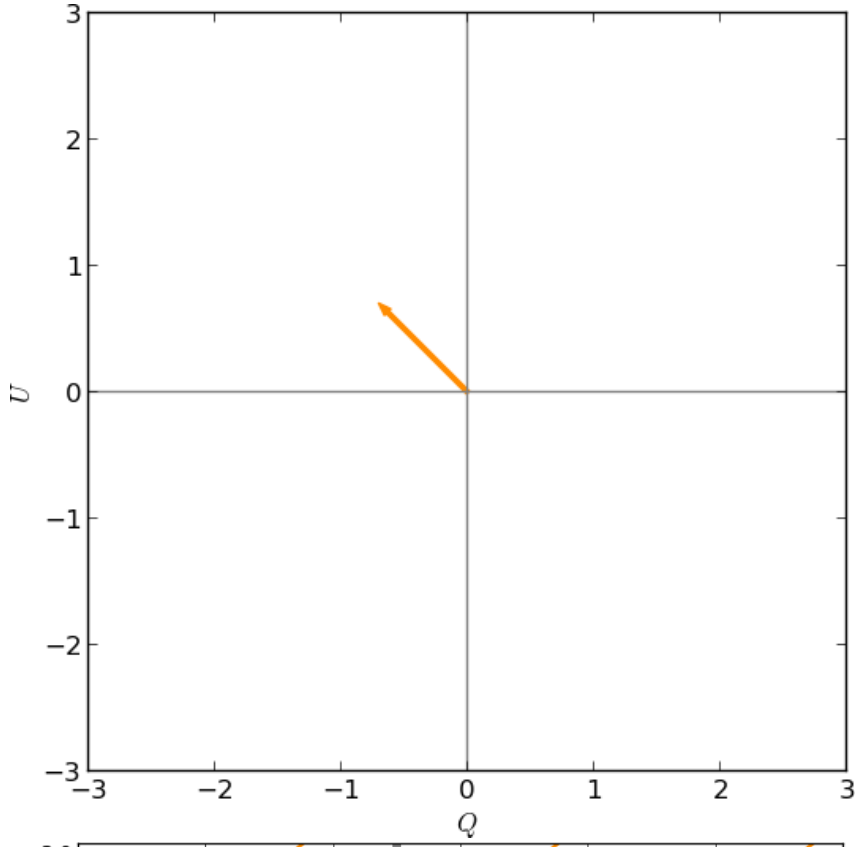
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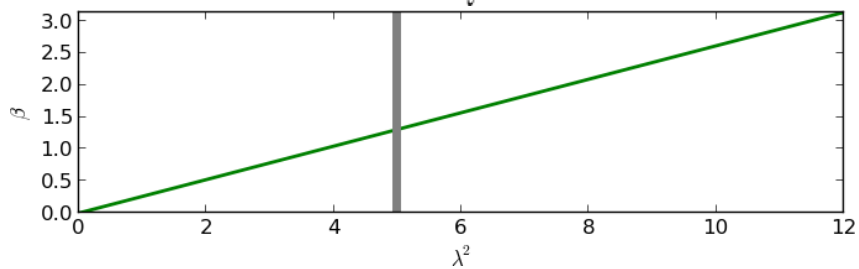
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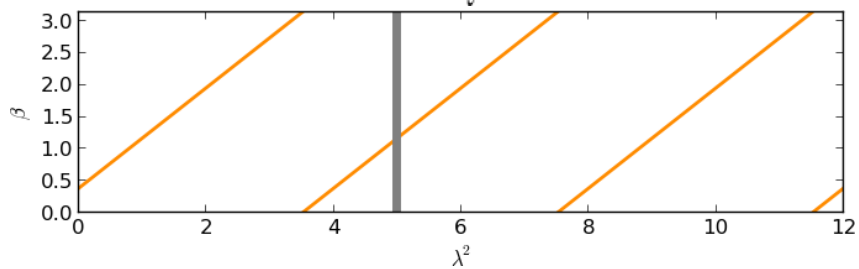
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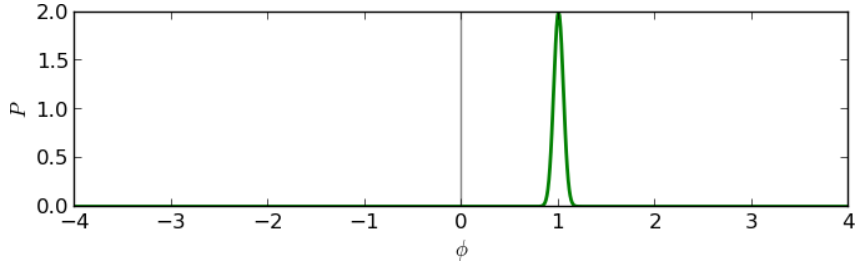
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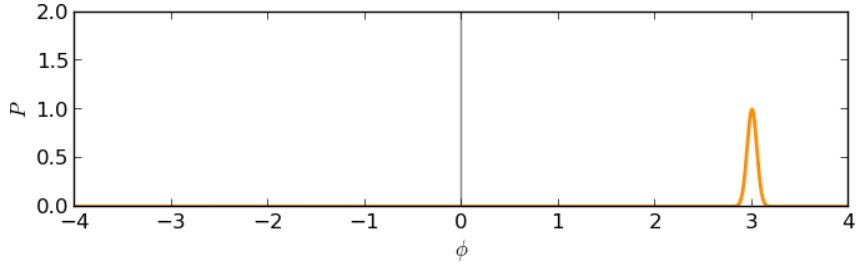
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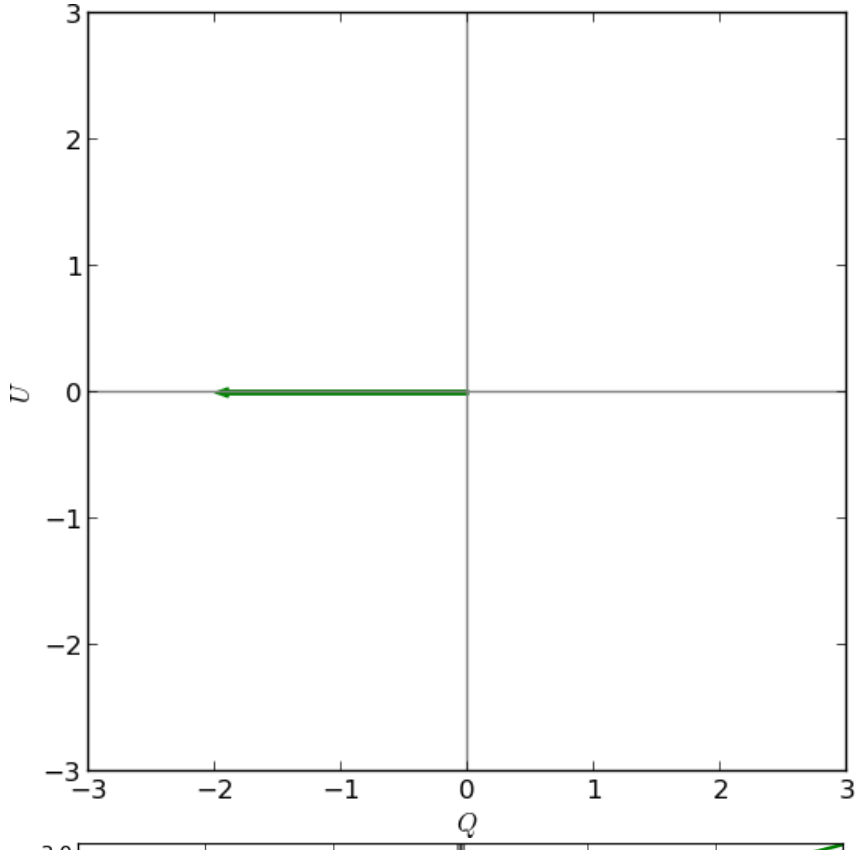
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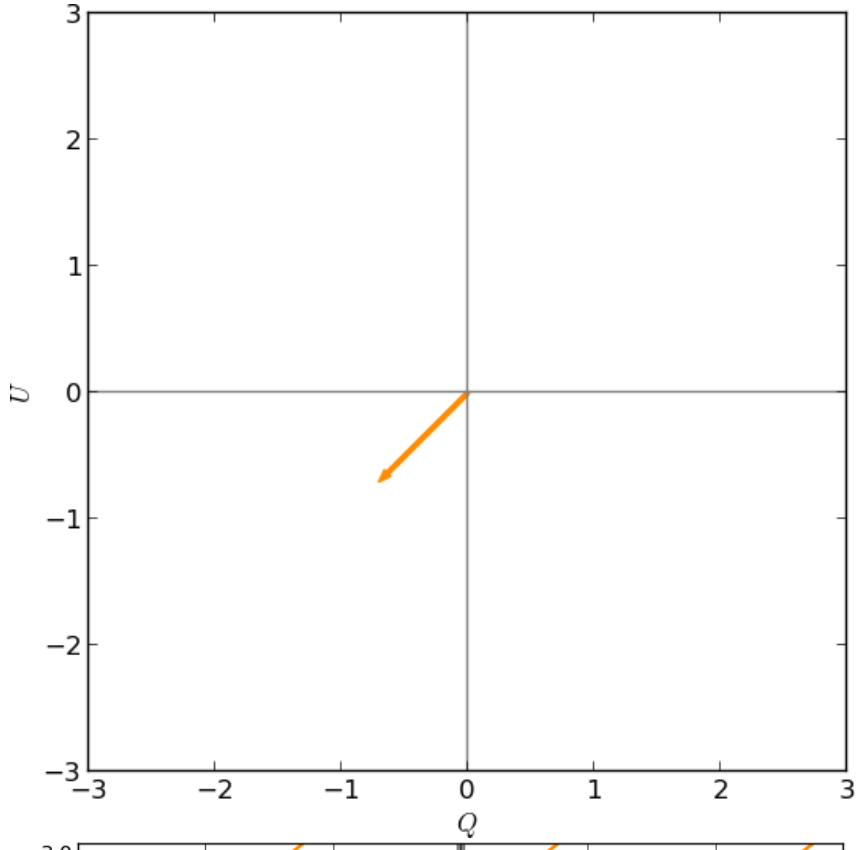
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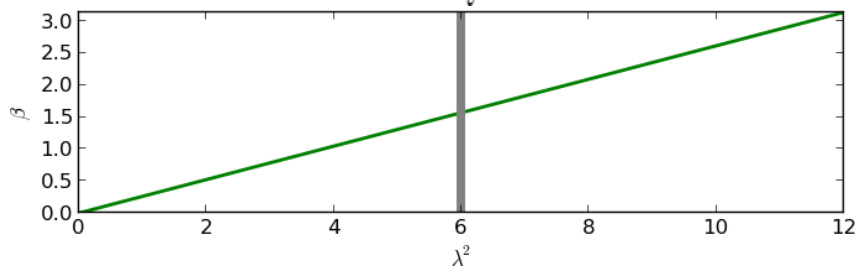
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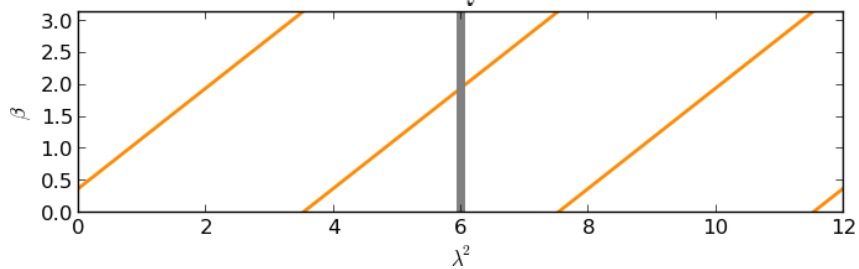
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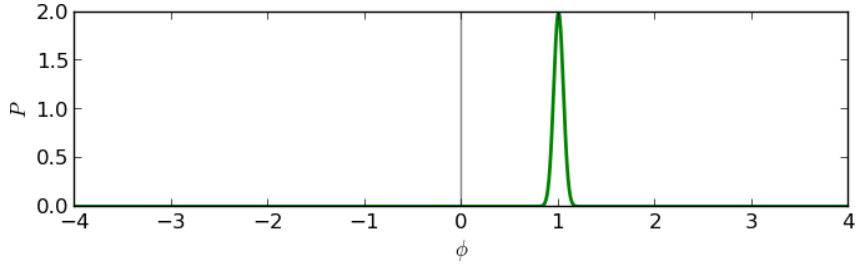
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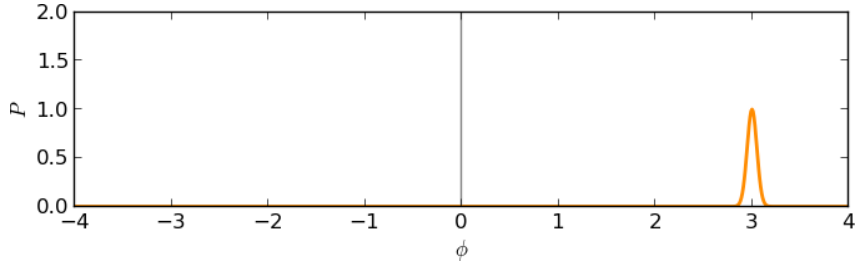
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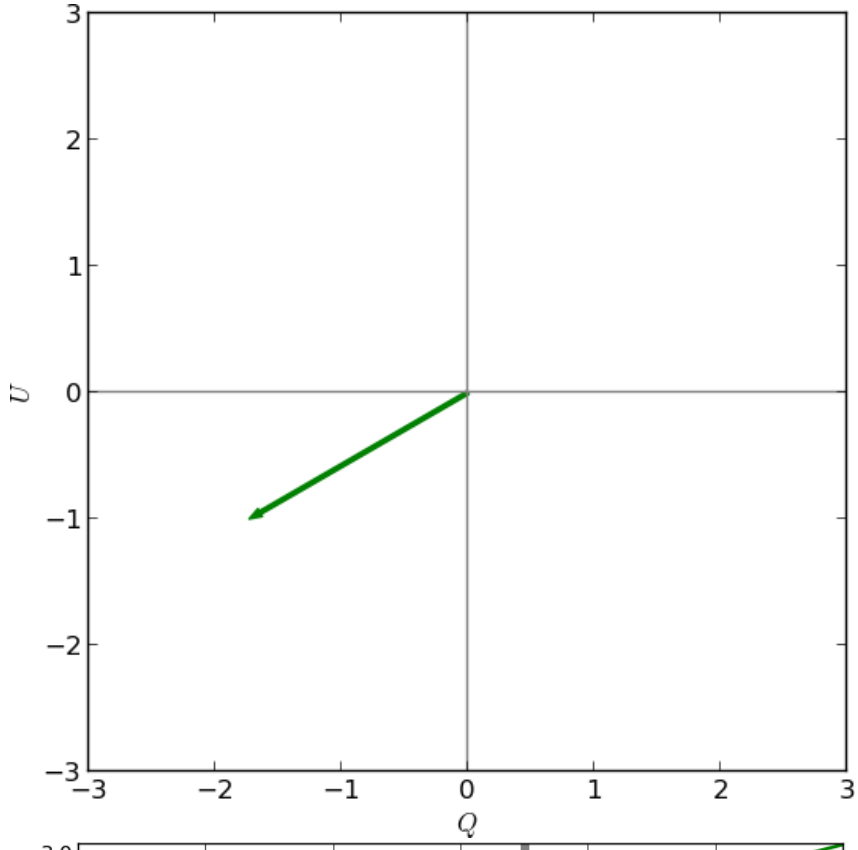
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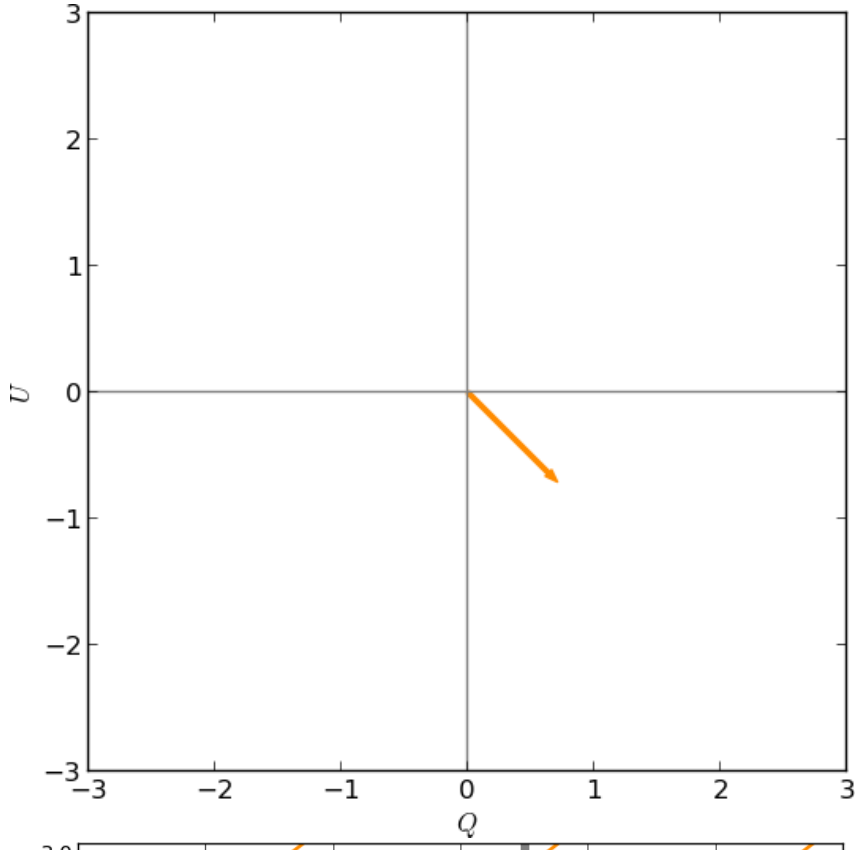
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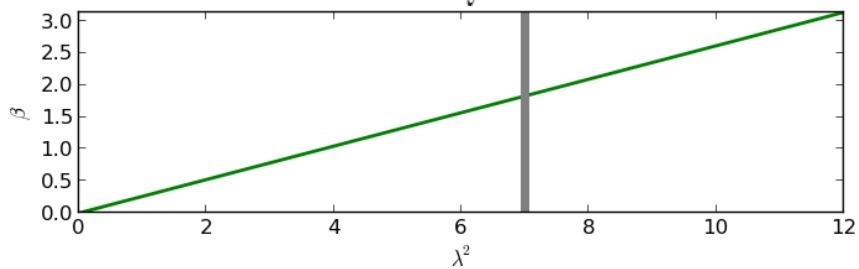
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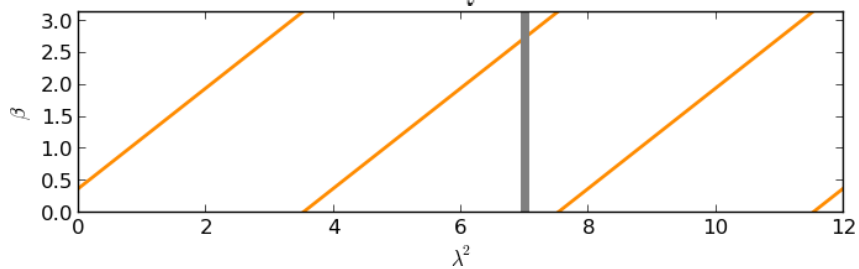
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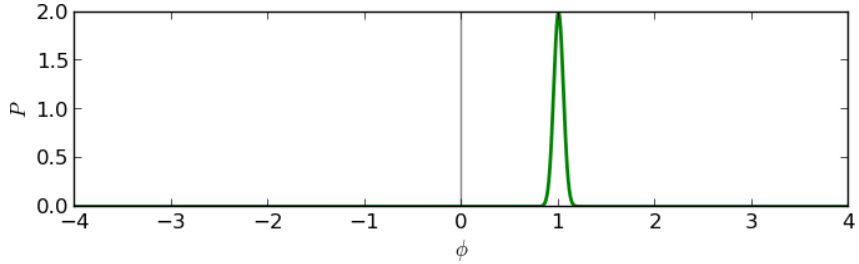
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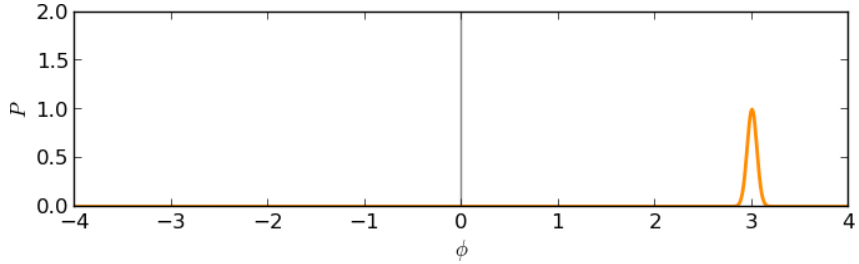
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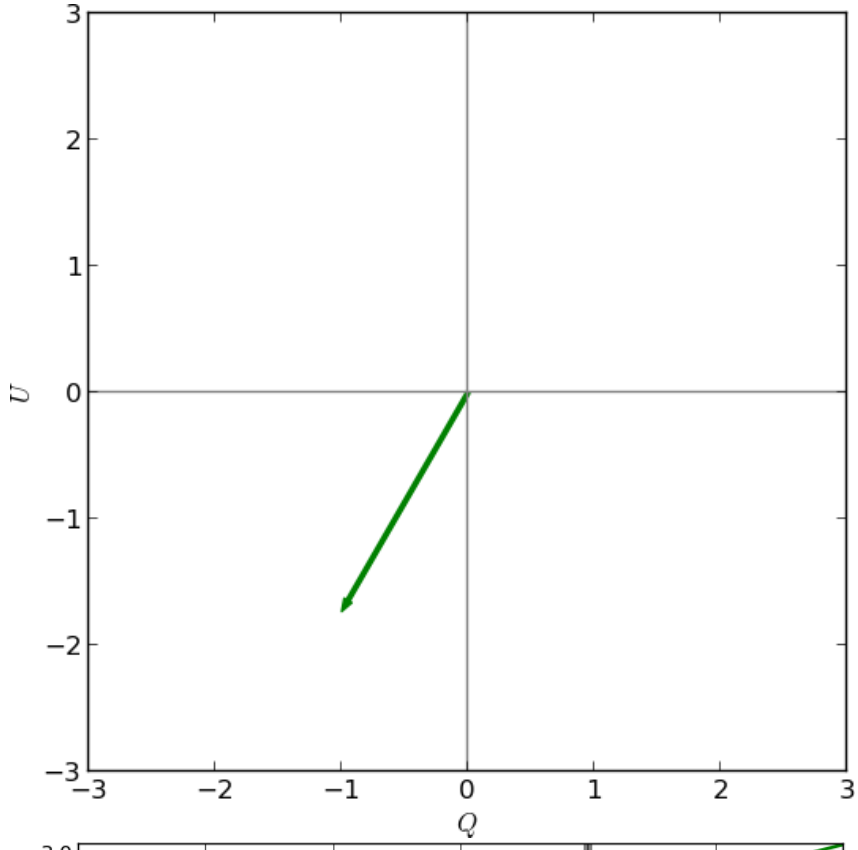
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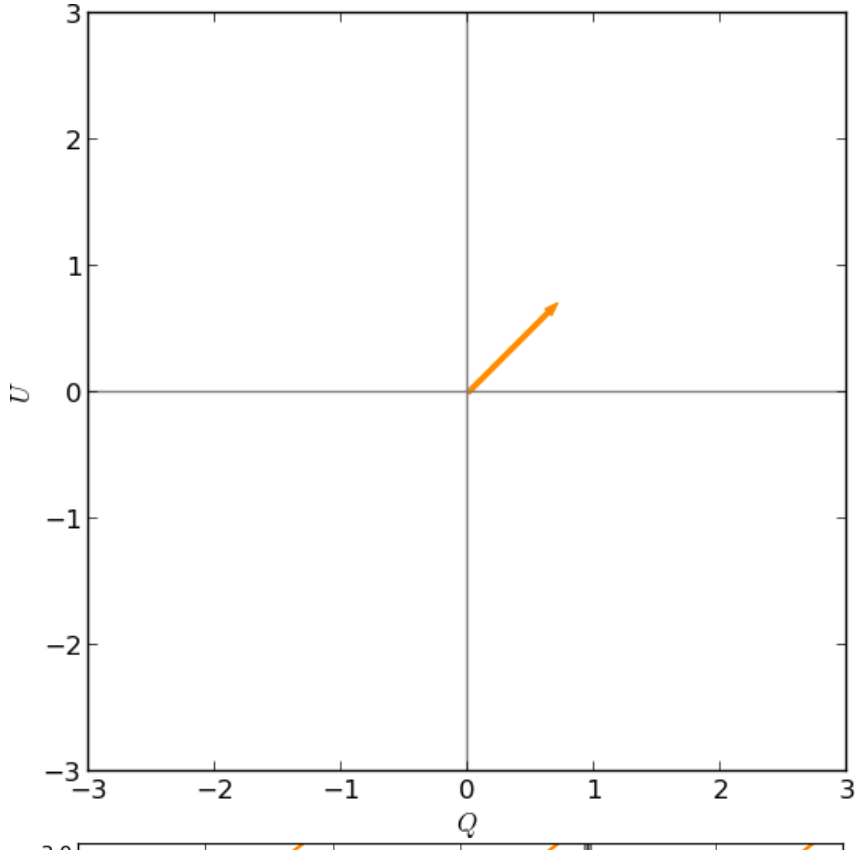
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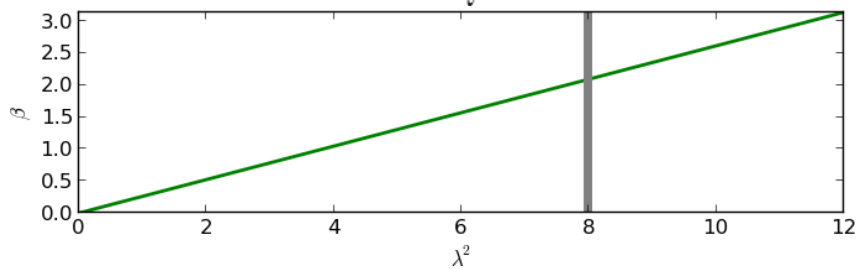
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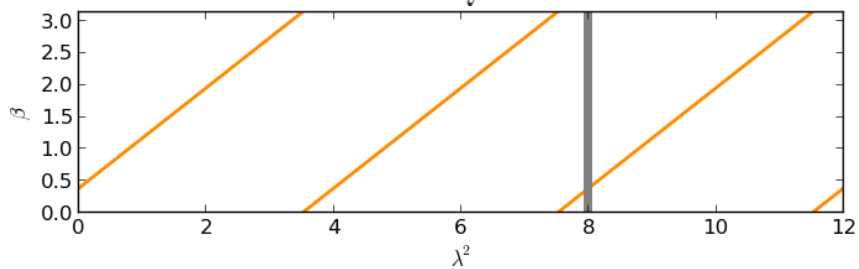
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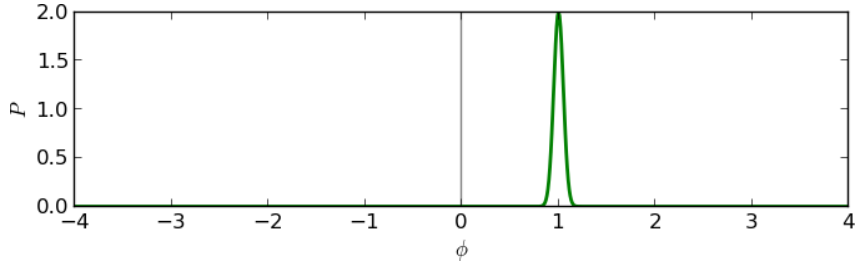
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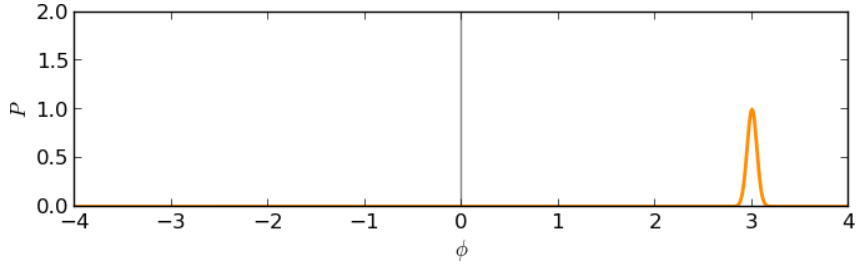
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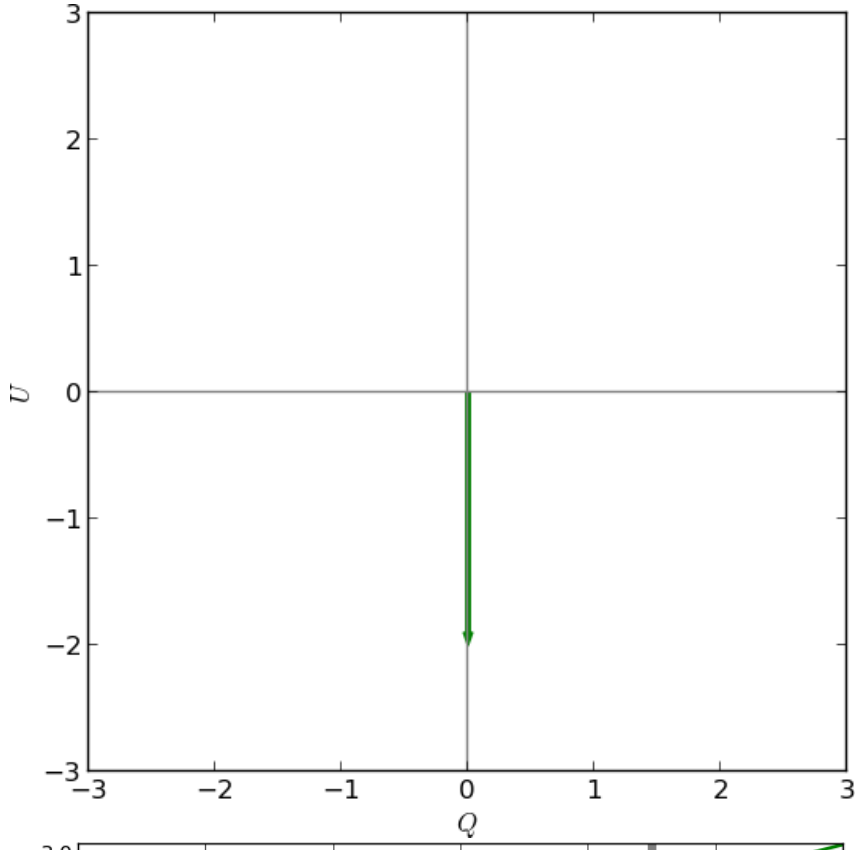
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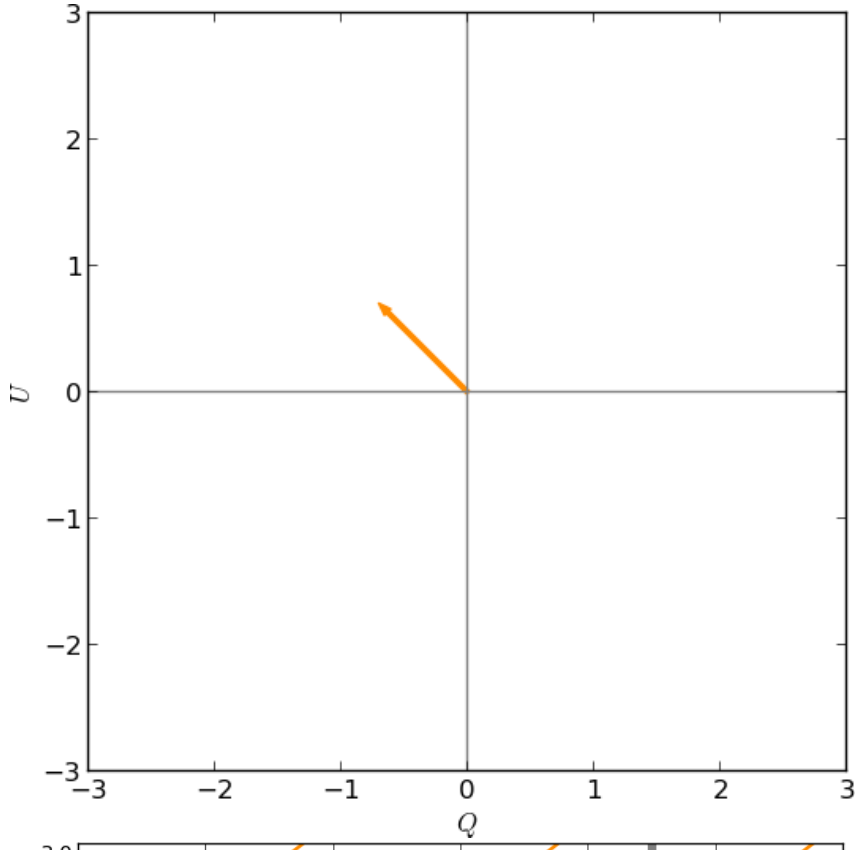
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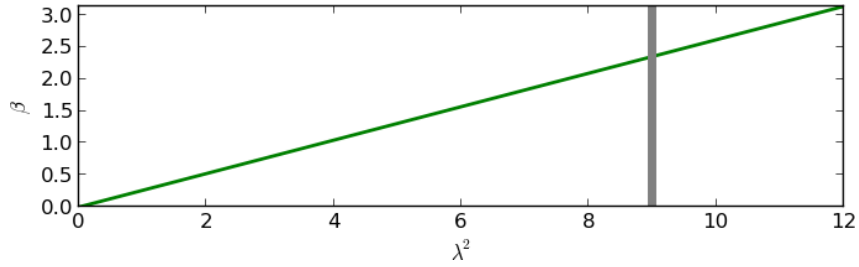
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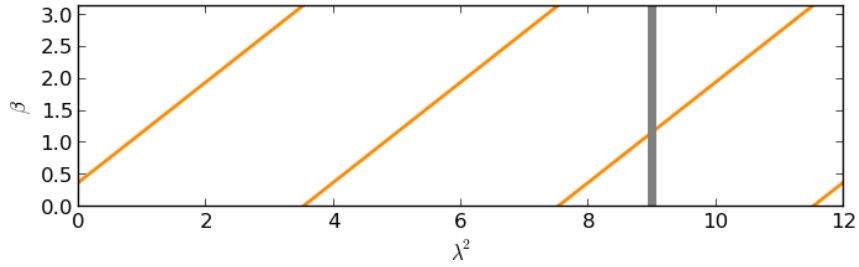
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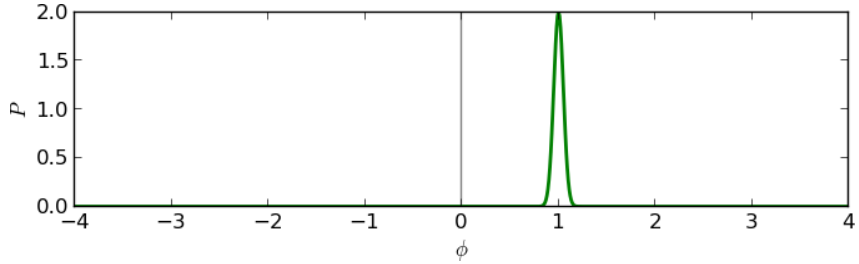
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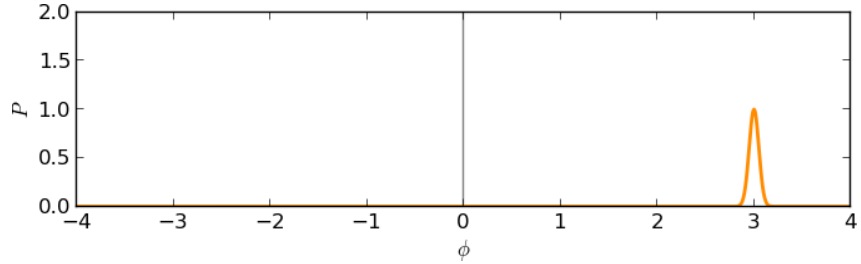
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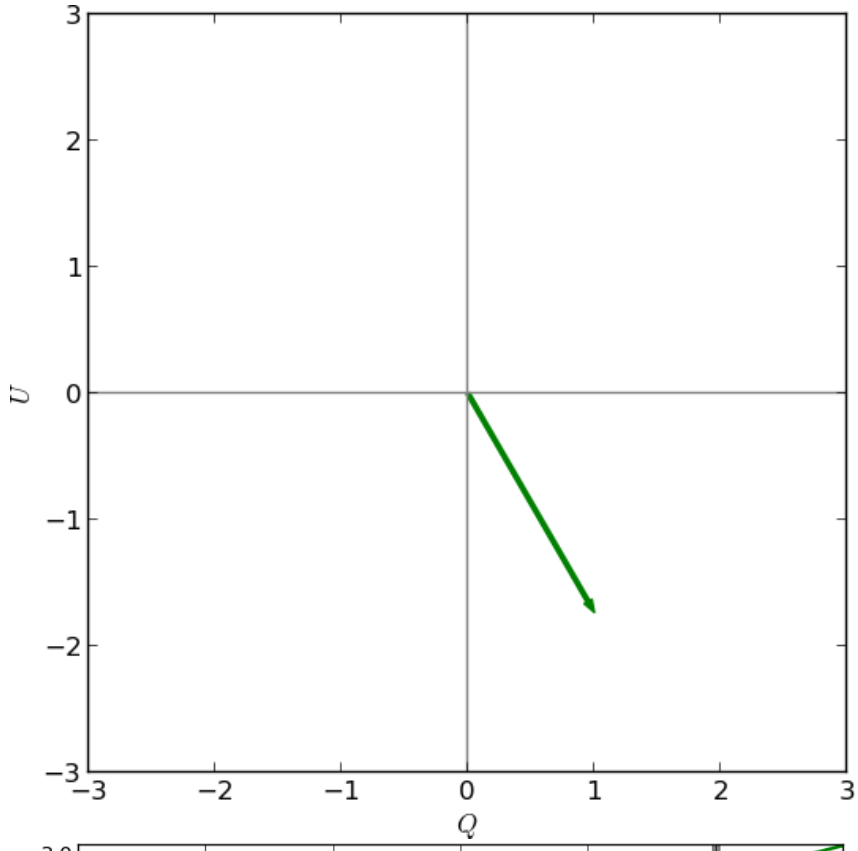
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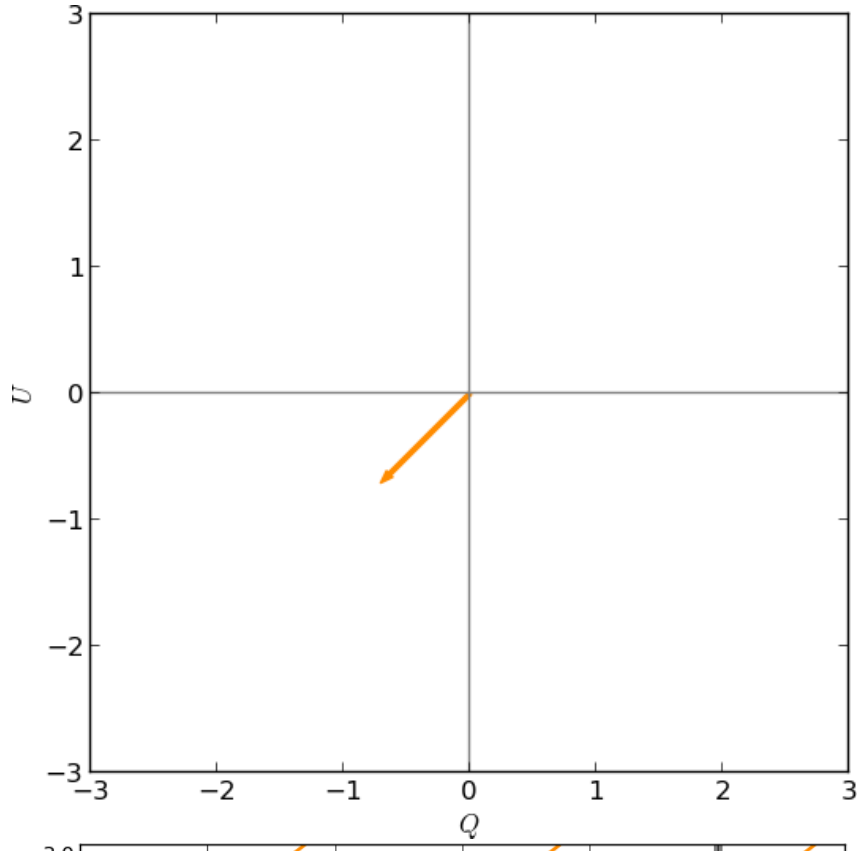
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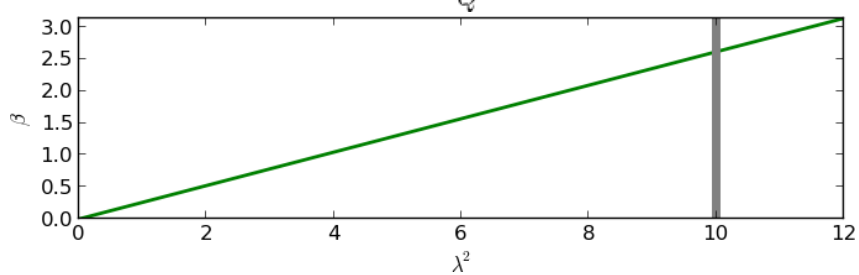
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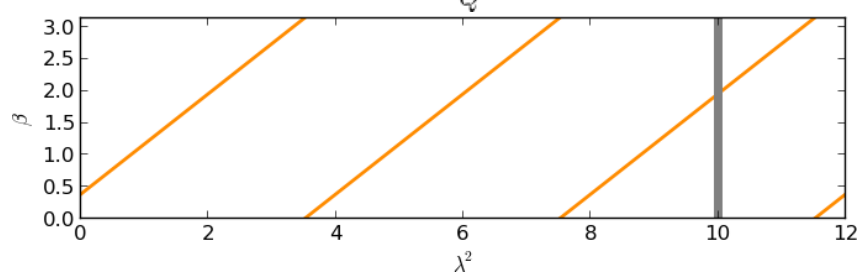
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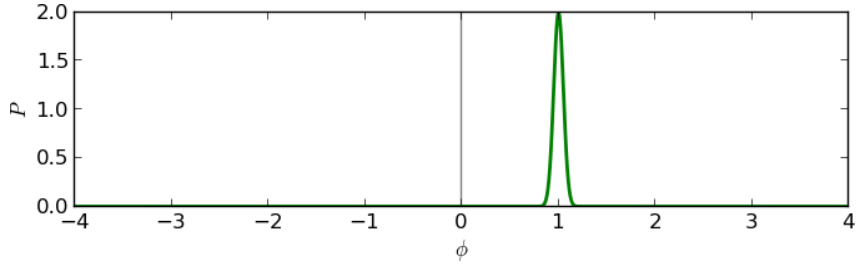
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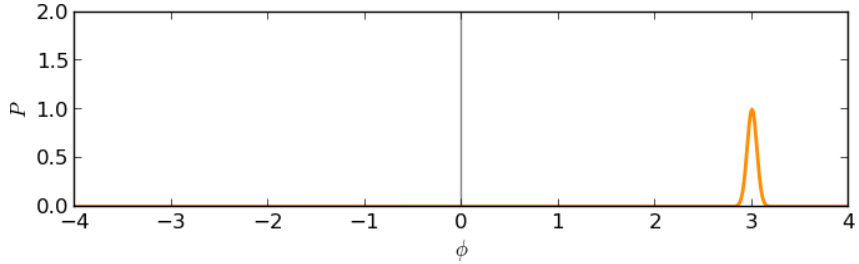
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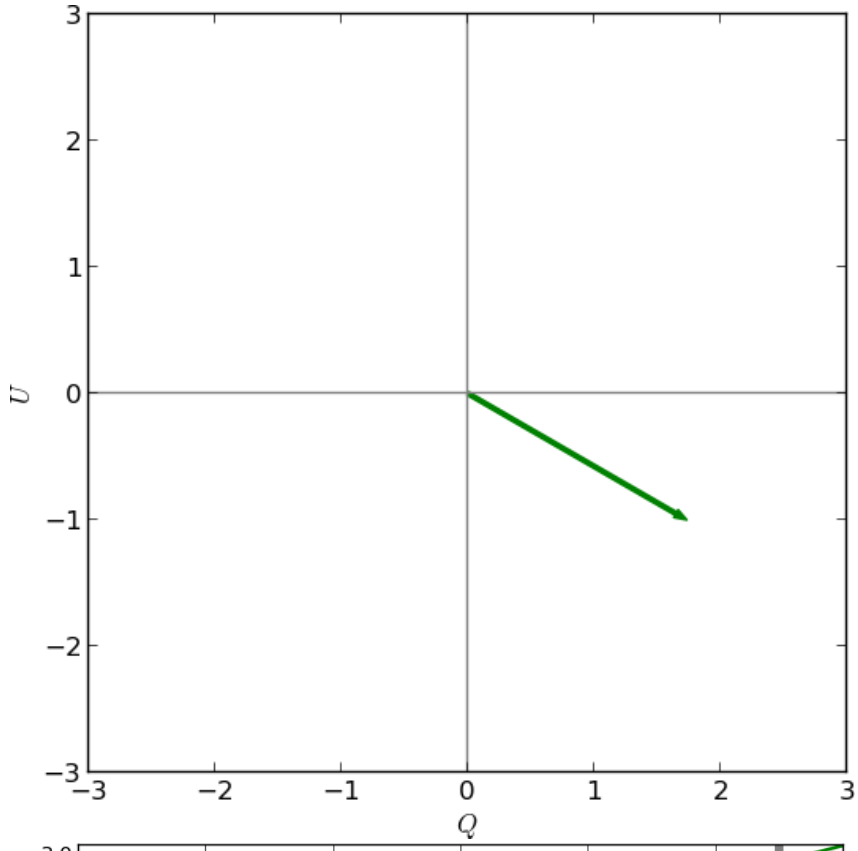
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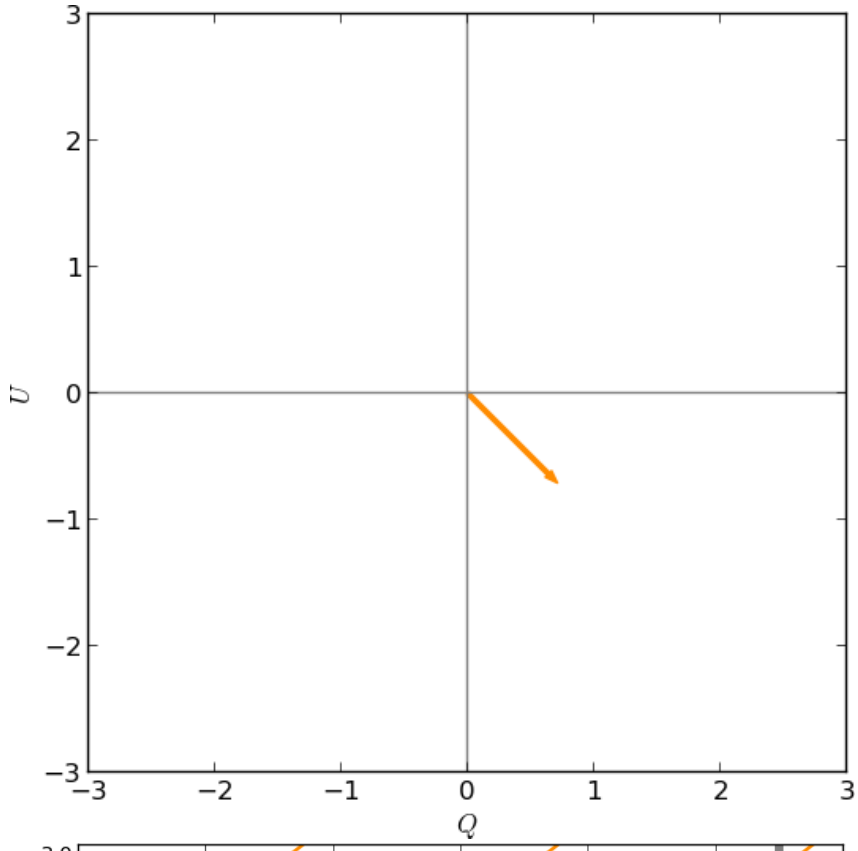
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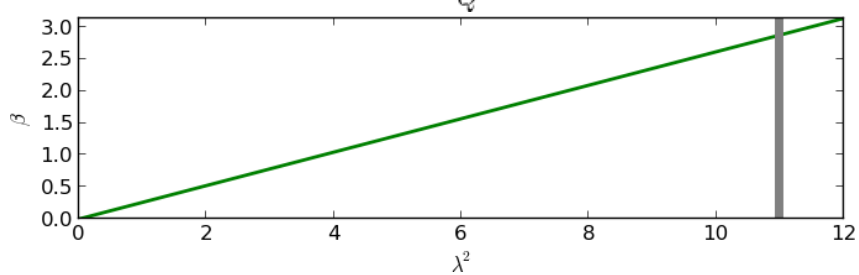
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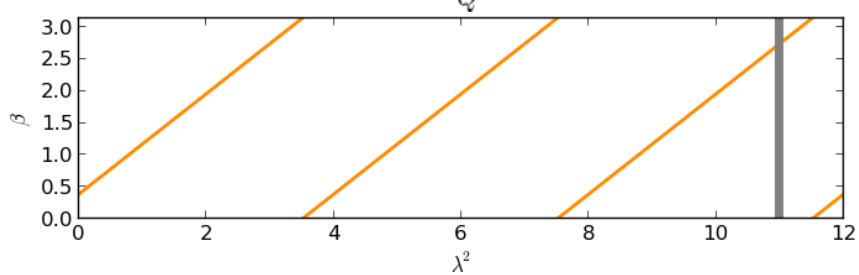
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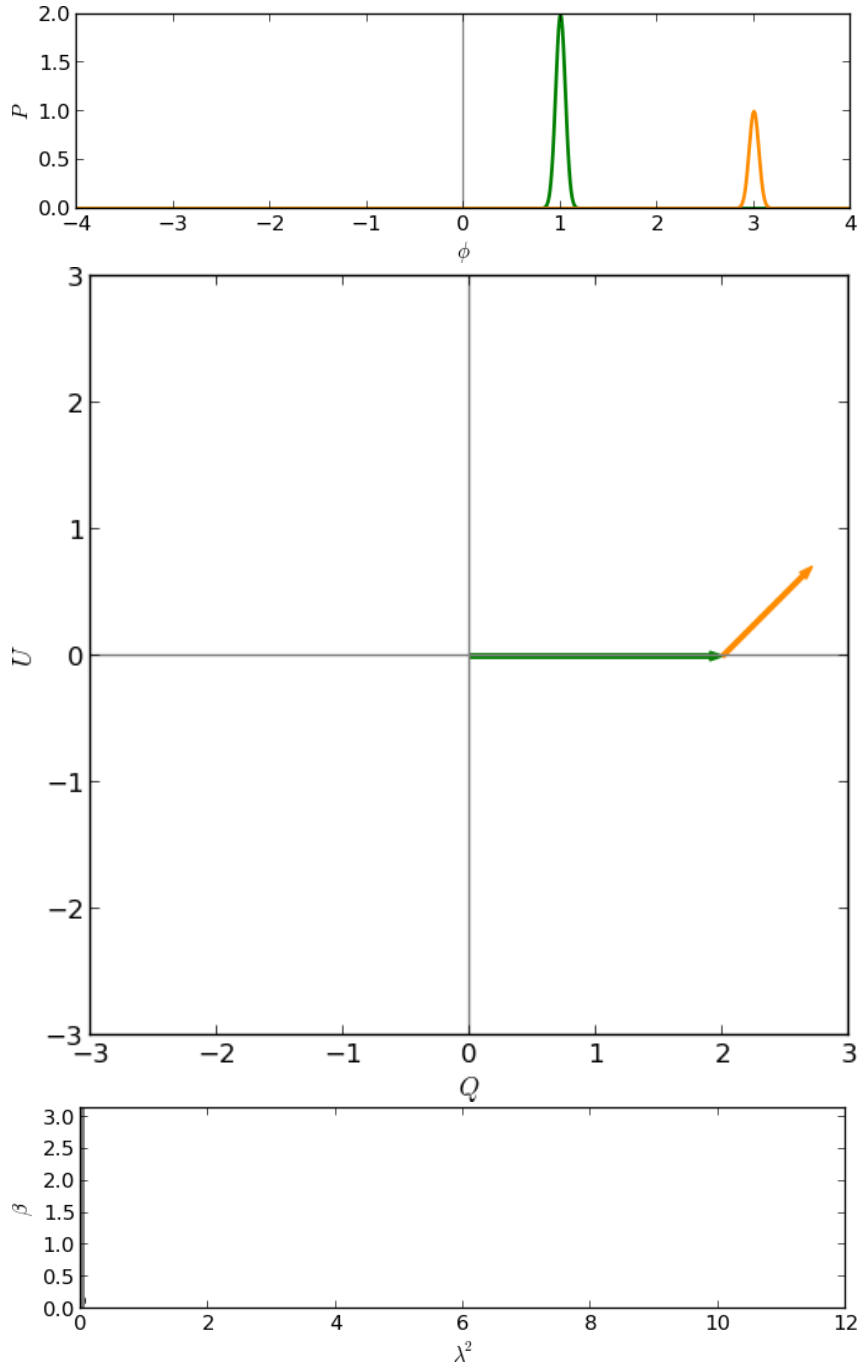
λ²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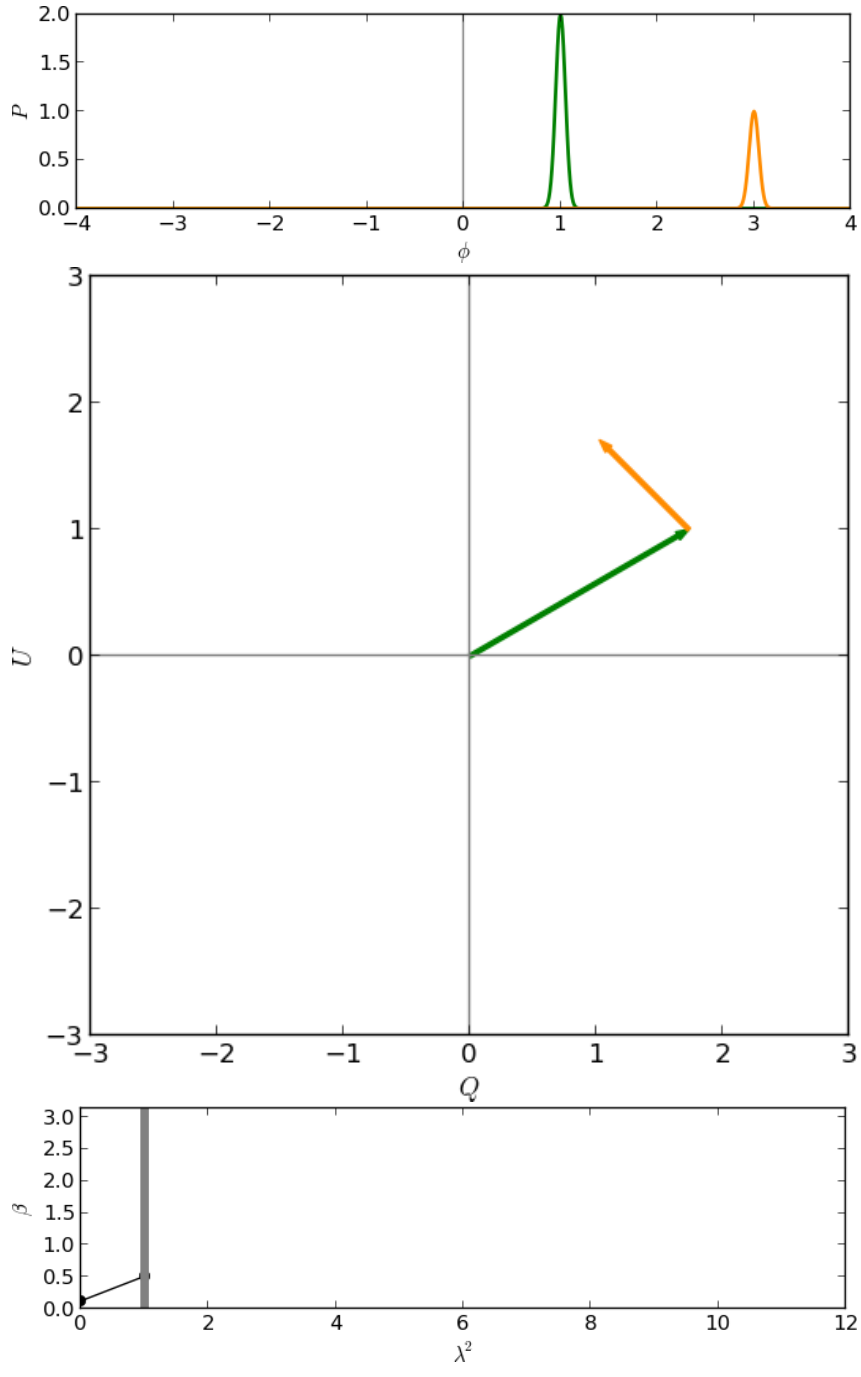
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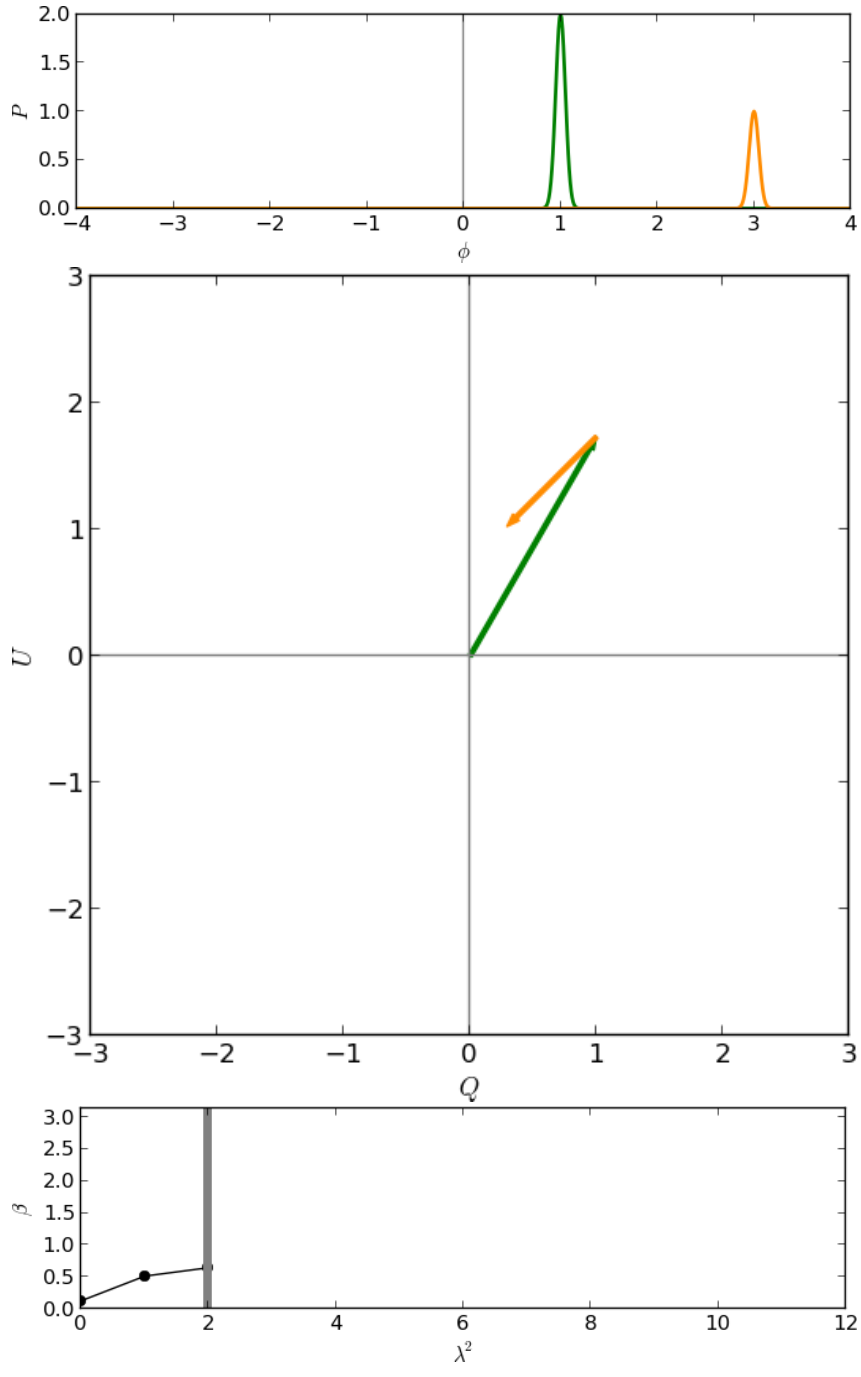
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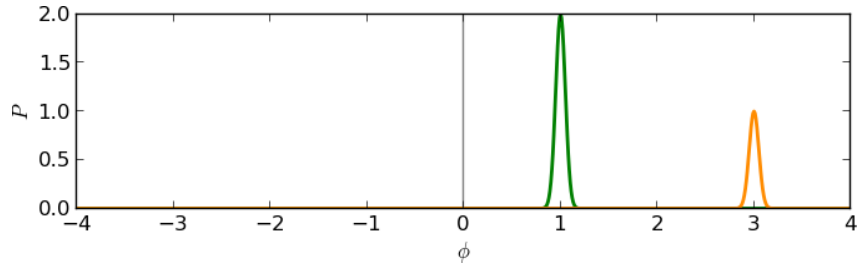
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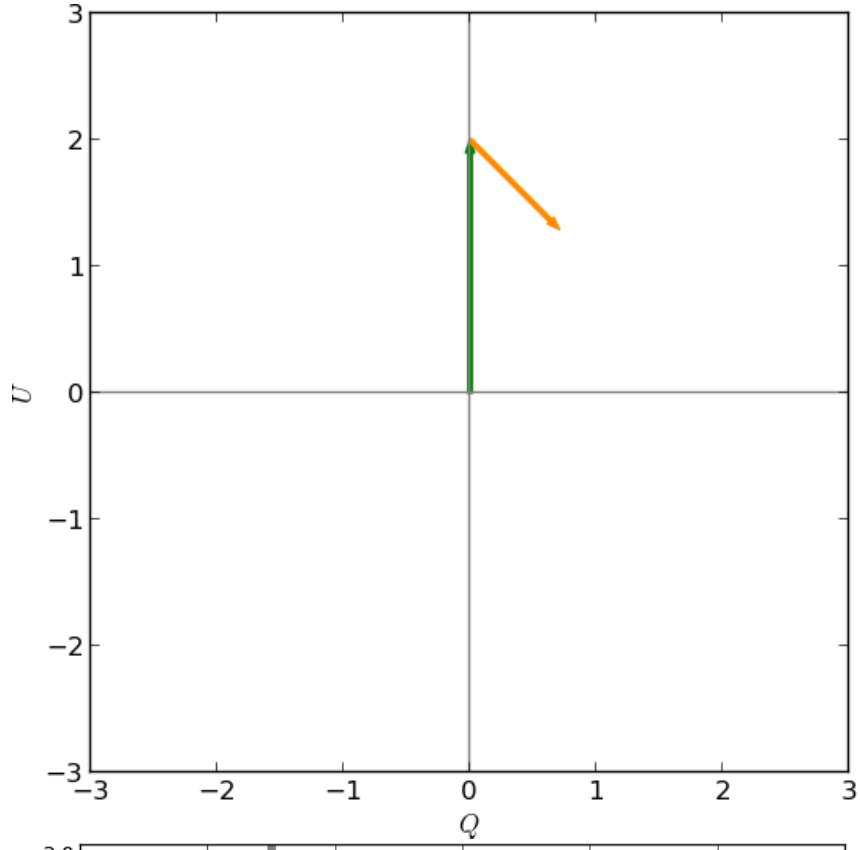
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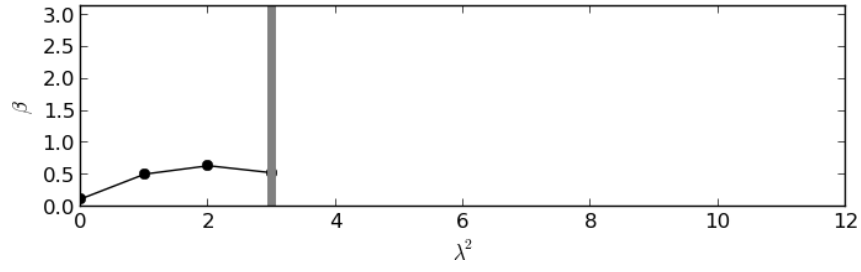
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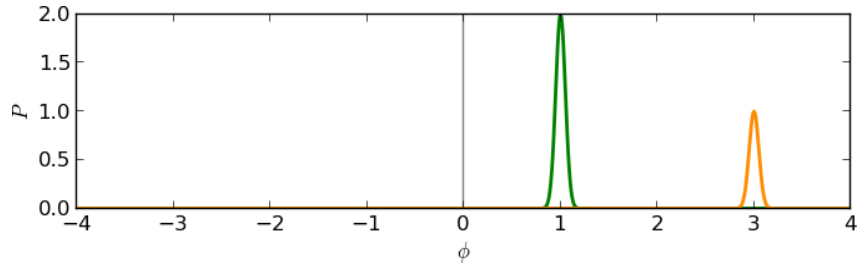
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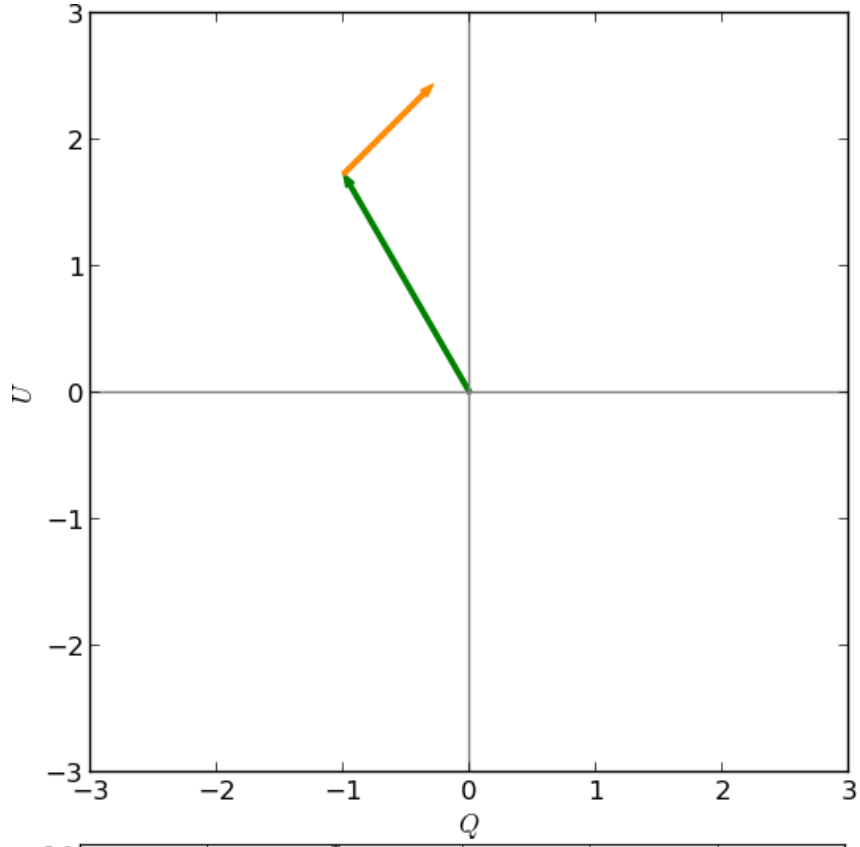
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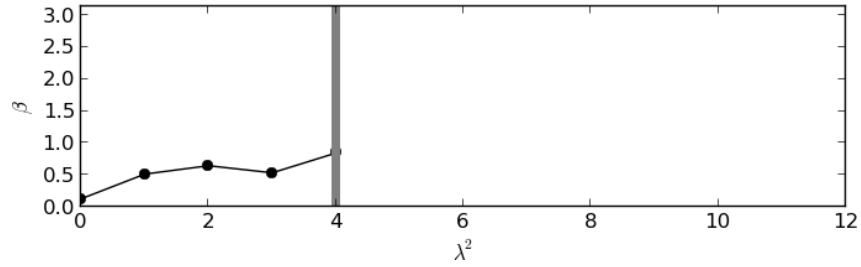
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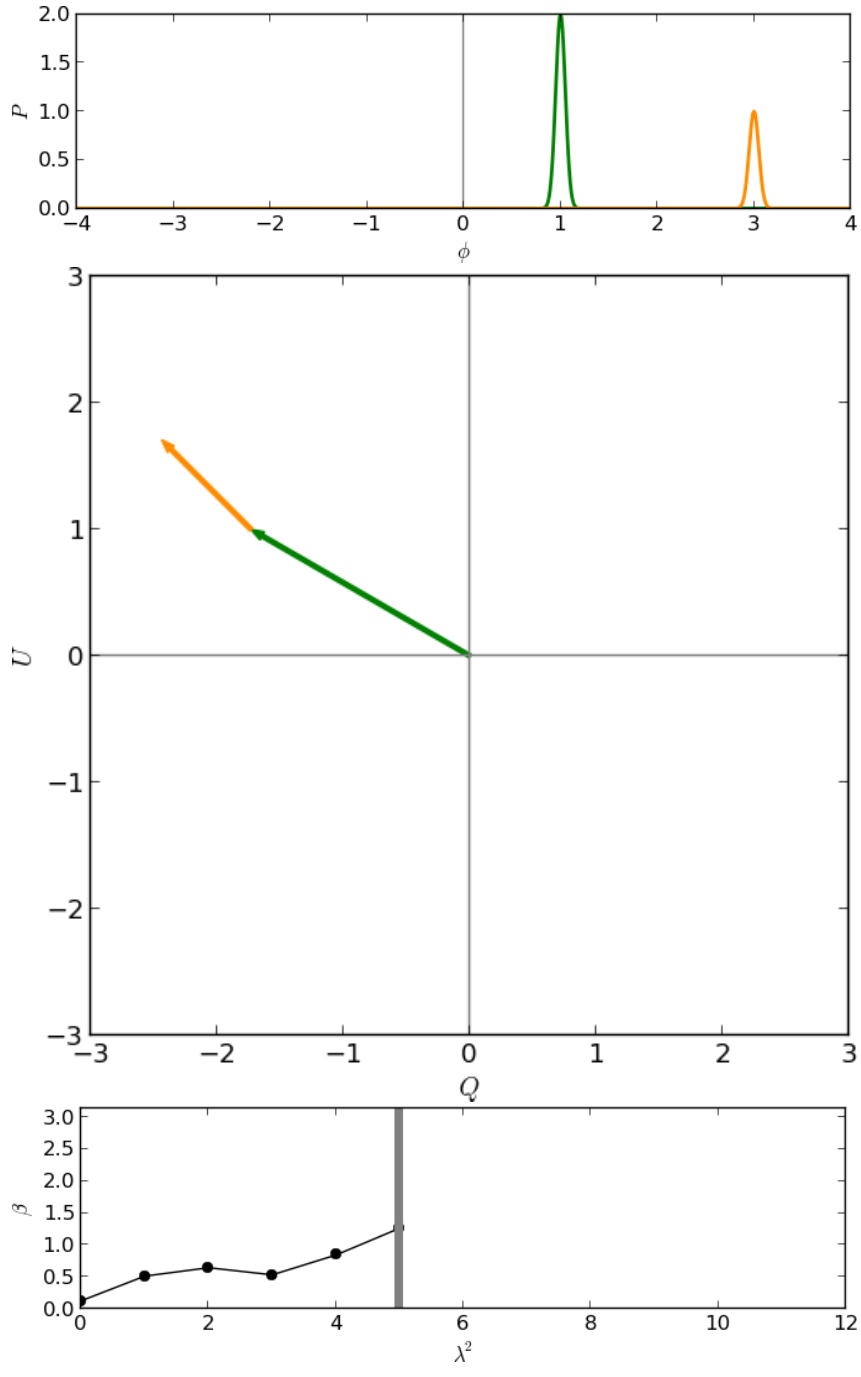
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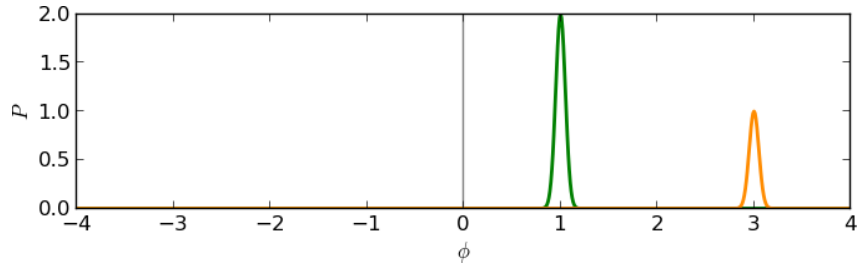
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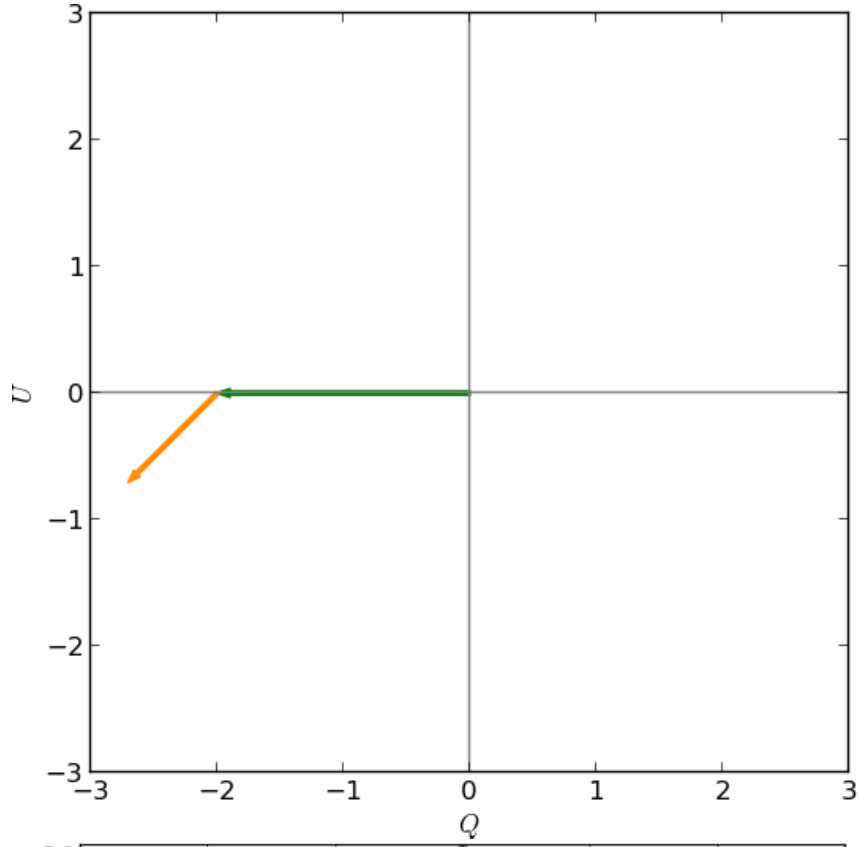
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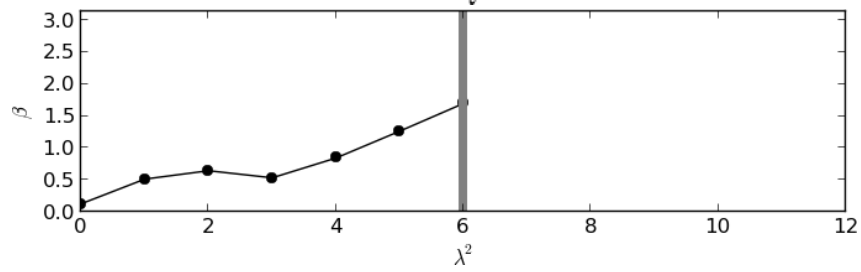
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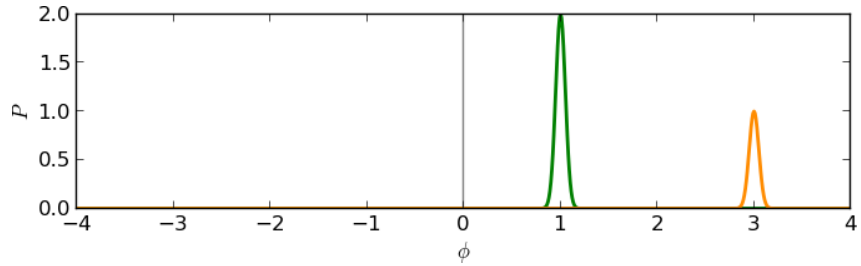
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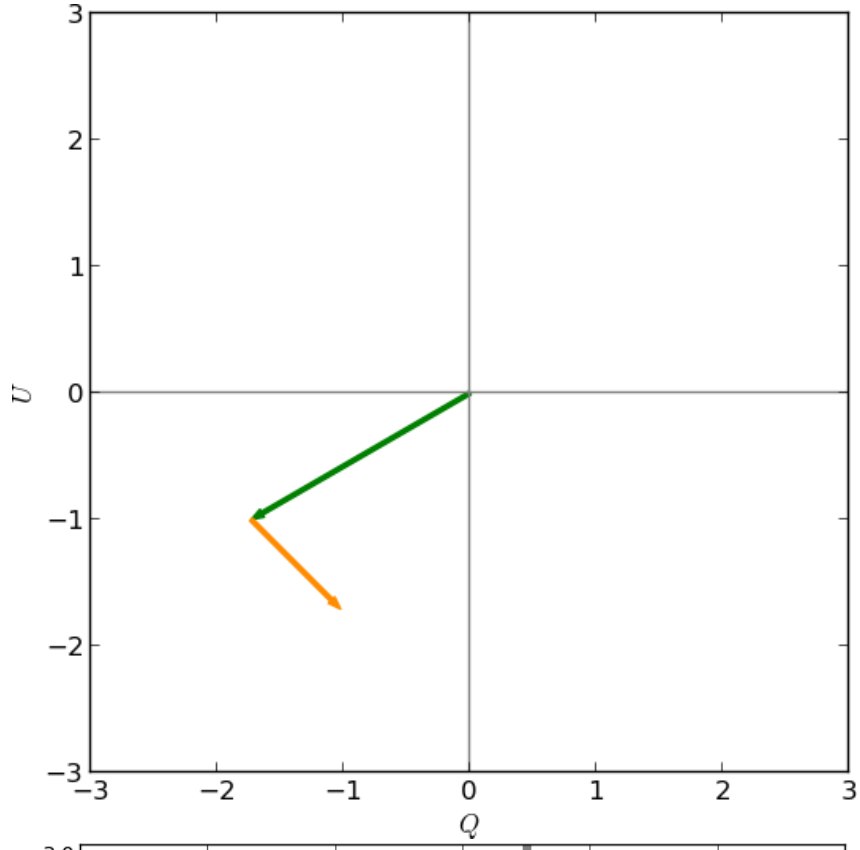
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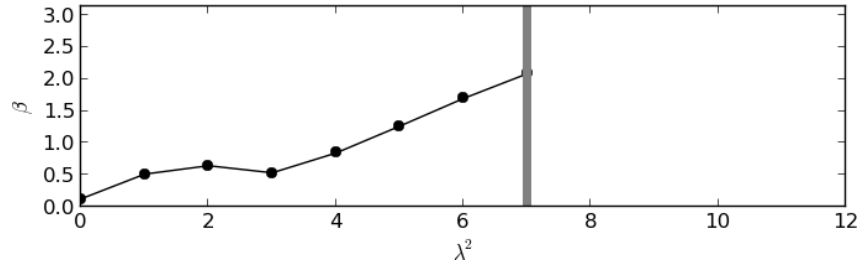
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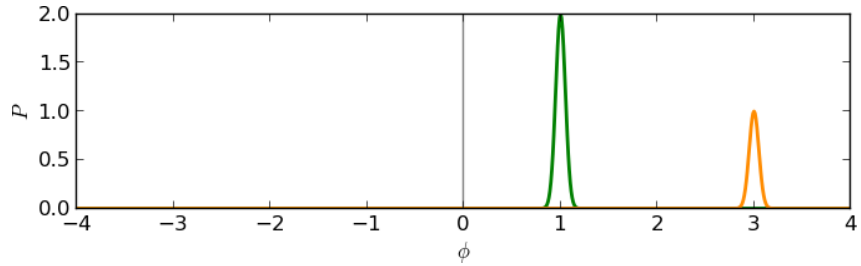
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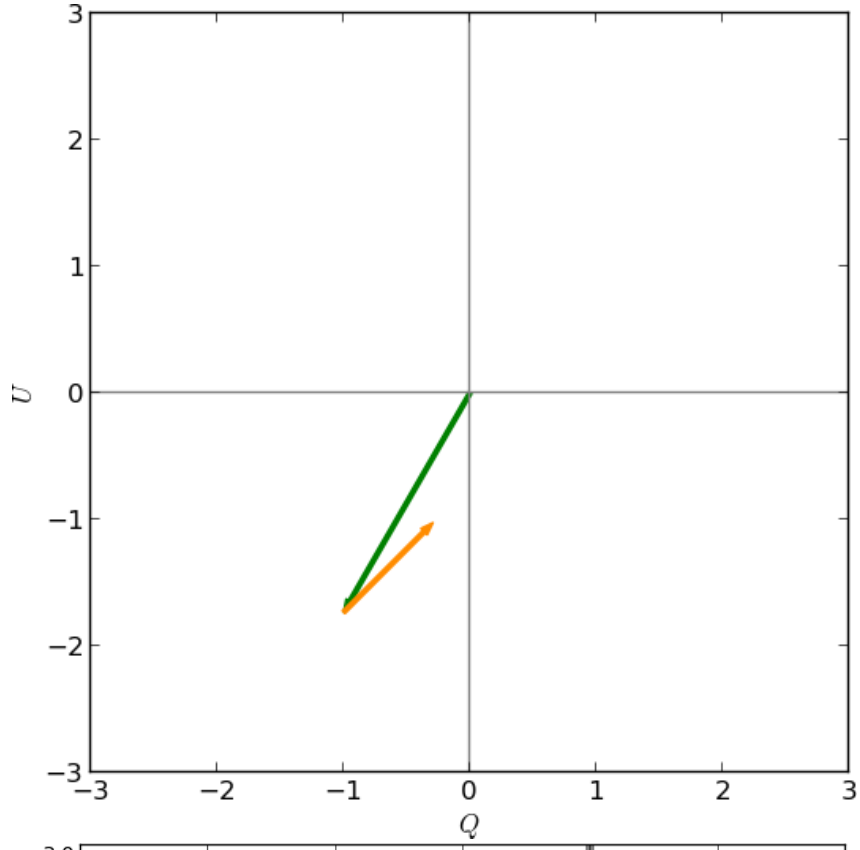
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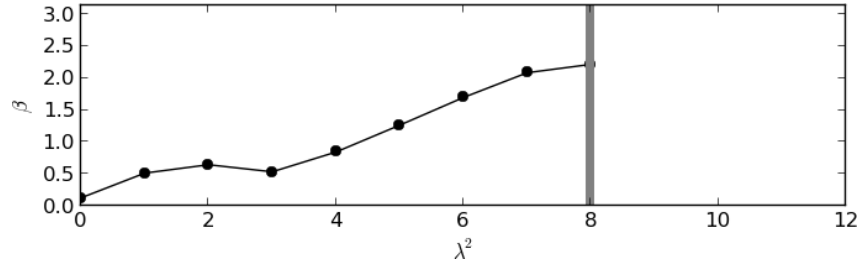
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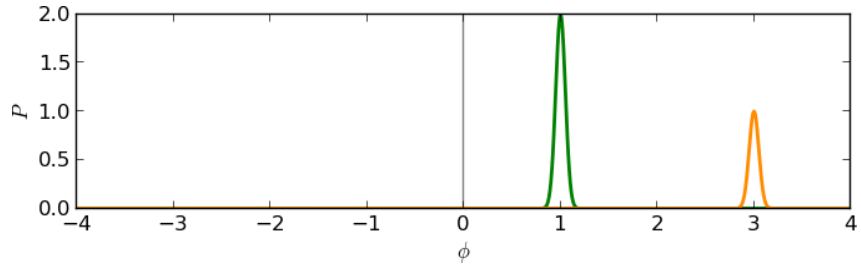
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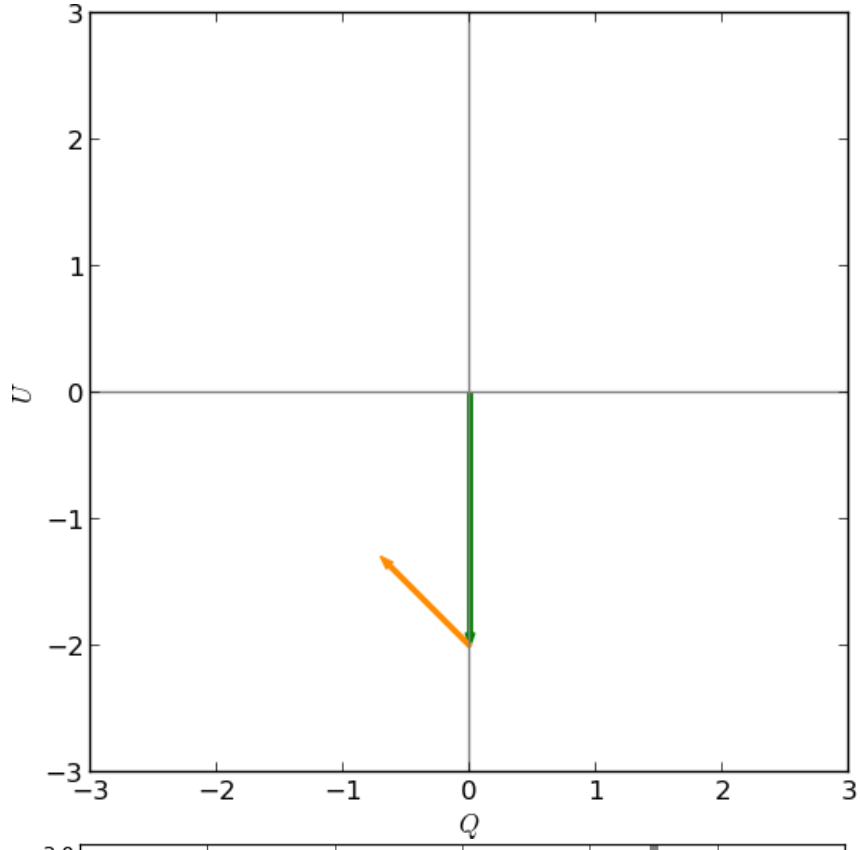
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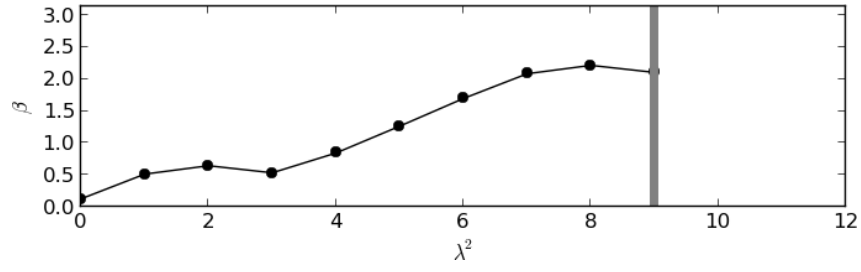
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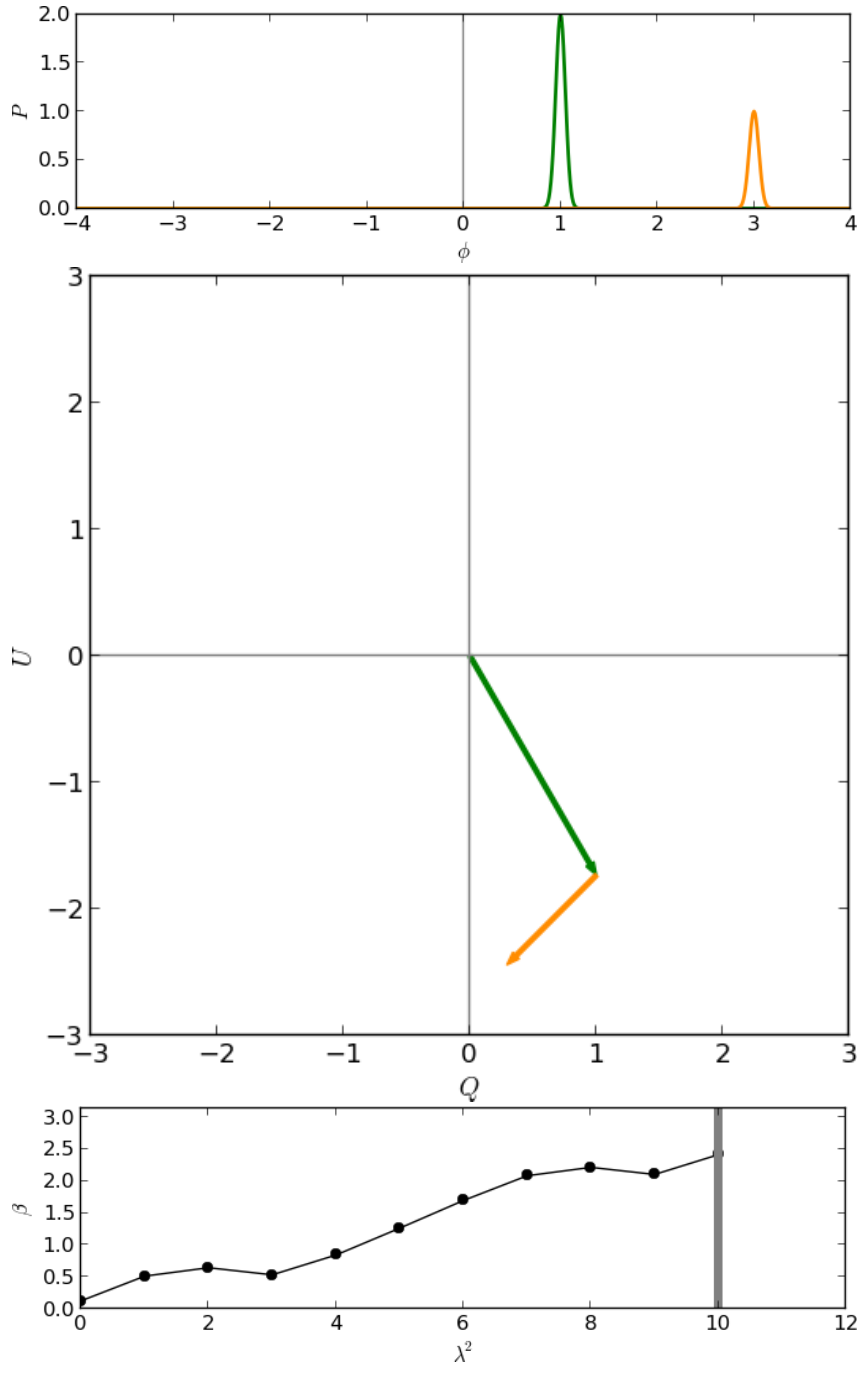
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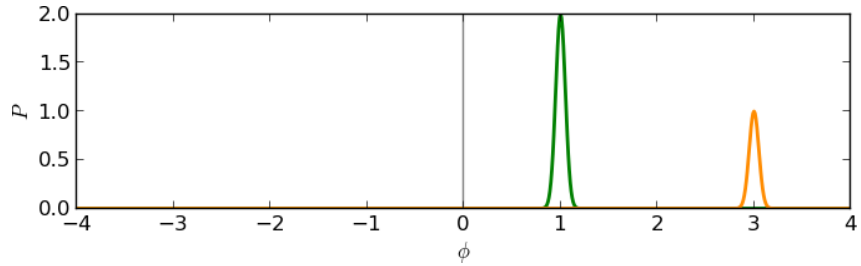
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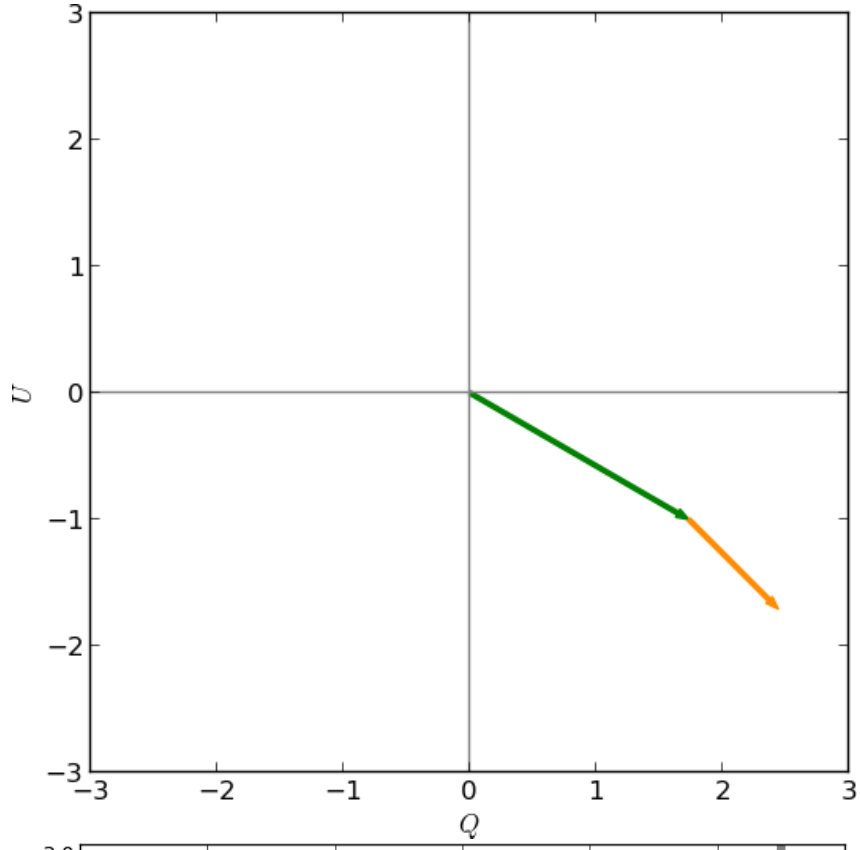
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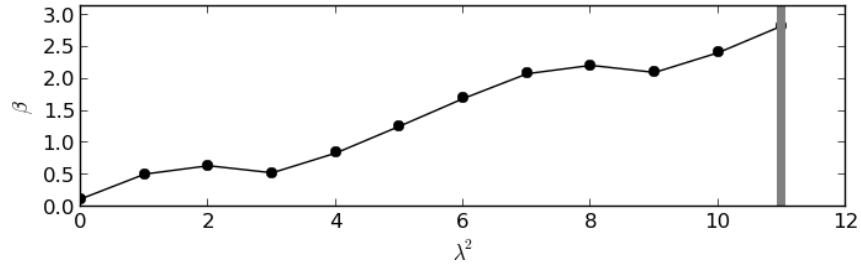
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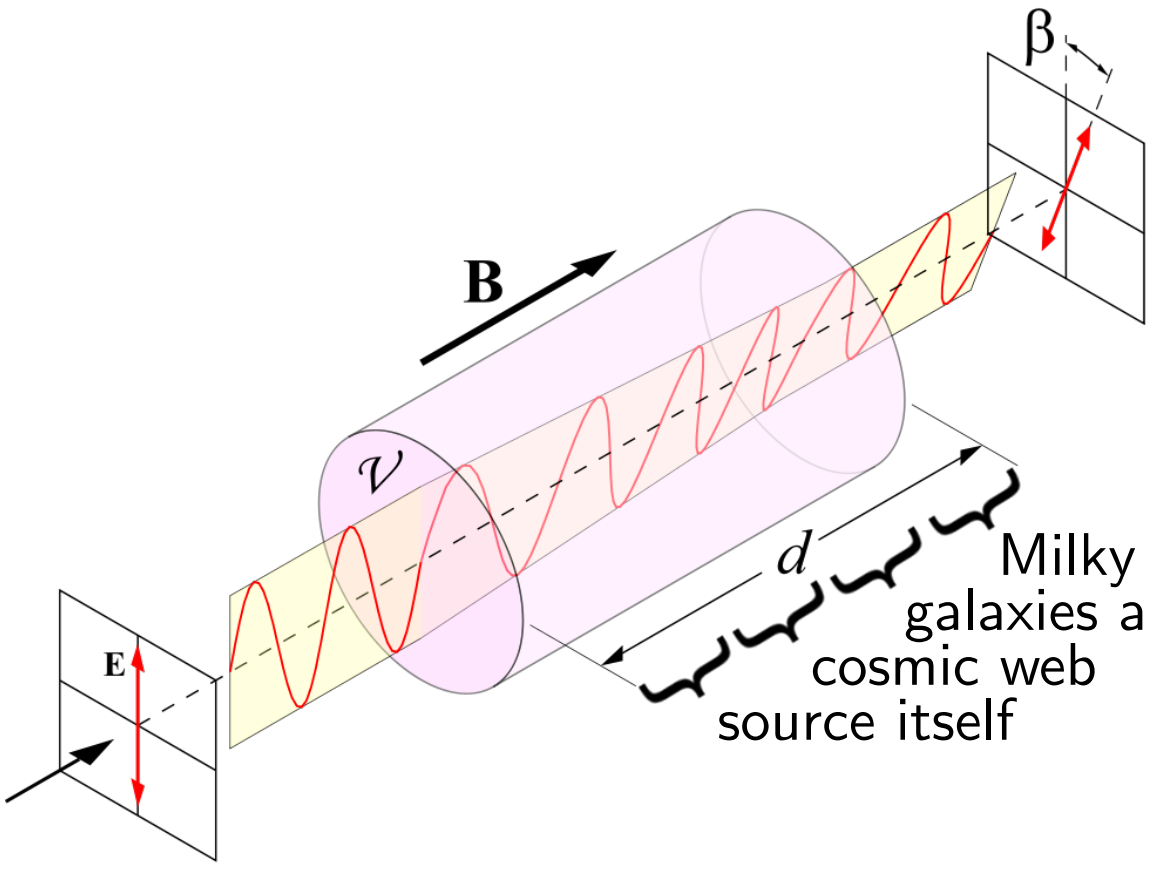
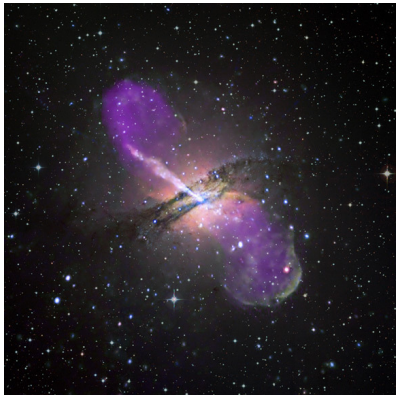
Faraday rotation

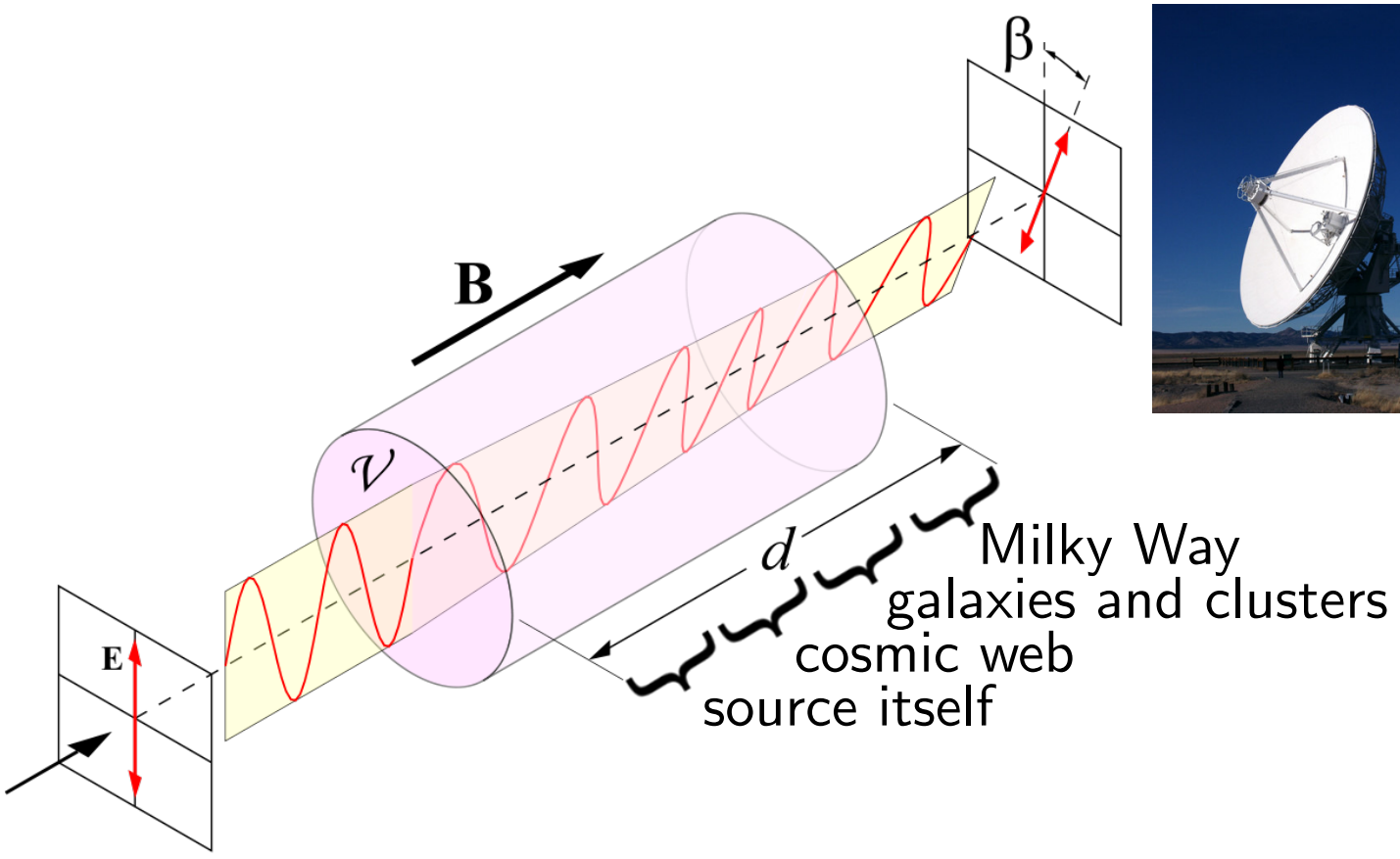


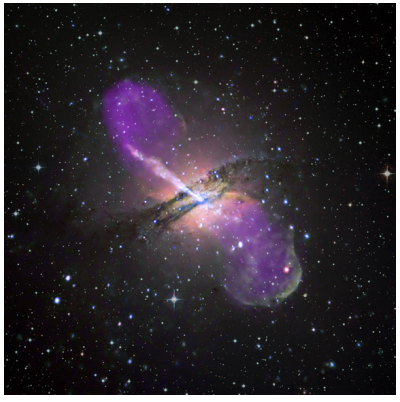


Faraday depth: $\phi \propto \int_{r_{\mathrm{source}}}^{0} (1+z)^{-2}\, n_{\mathrm{e}}\, B_r\, \mathrm{d}r$

$$\beta = \phi\lambda^2$$

Faraday rotation

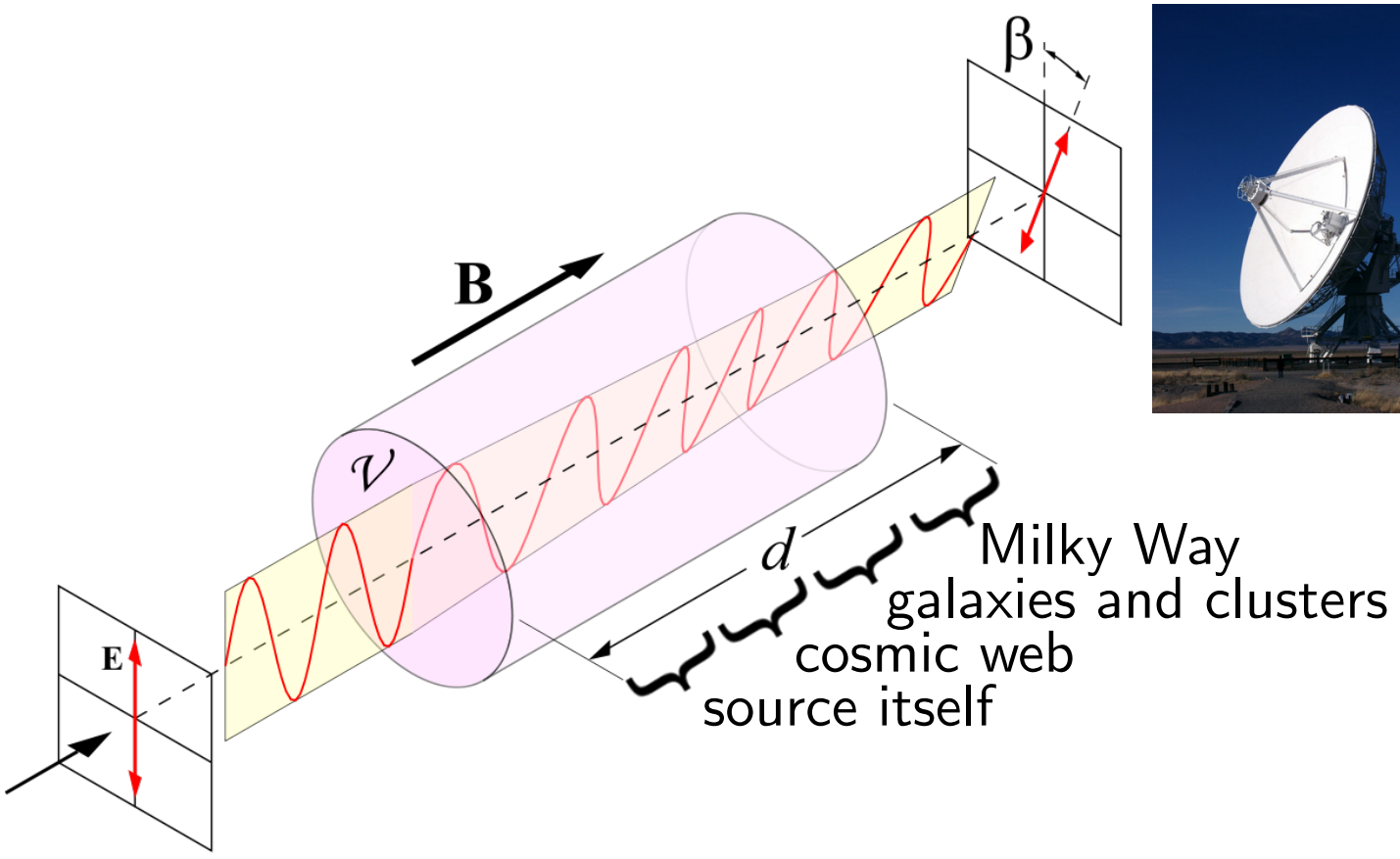


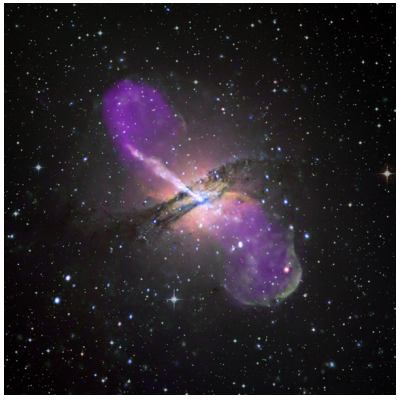


Faraday depth: $\phi \propto \int_{r_{\rm source}}^{0} (1+z)^{-2}\, n_{\rm e}\, B_r\, {\rm d}r$

$$\phi = \phi_{\rm MW} + \phi_{\rm other\ galaxies} + \phi_{\rm clusters} + \phi_{\rm filaments} + \phi_{\rm sheets} + \phi_{\rm voids} + \phi_{\rm source}$$

Faraday rotation

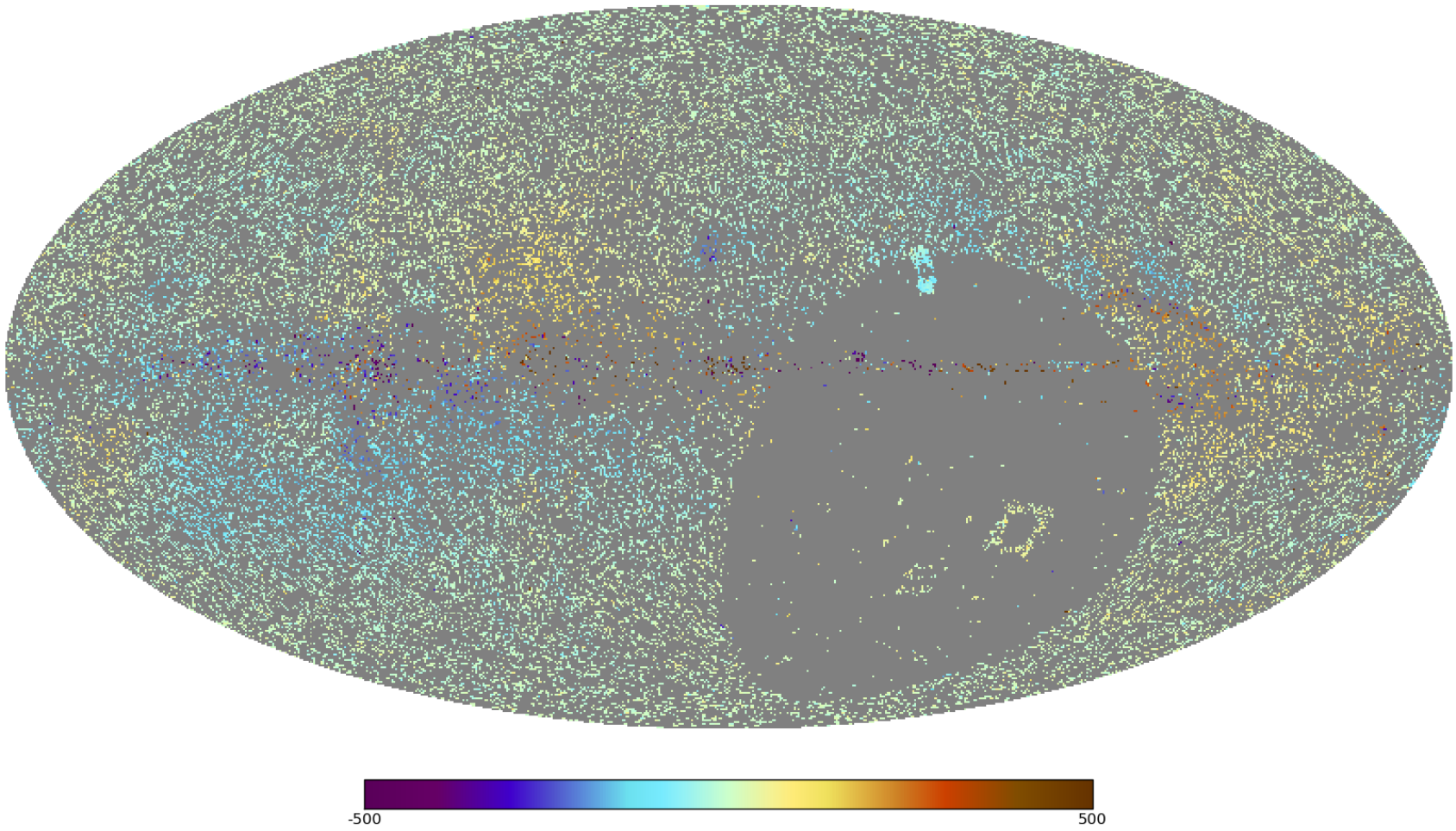




Faraday depth: $\phi \propto \int_{r_{\rm source}}^{0} (1+z)^{-2}\, n_{\rm e}\, B_r\, {\rm d}r$

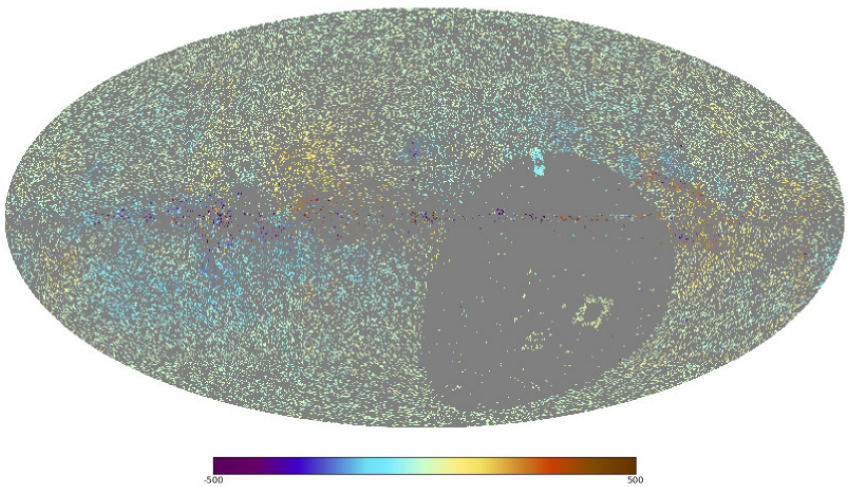
$$\phi = \phi_{\rm MW} + \phi_{\rm extragalactic}$$

$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$



$\gtrsim$ 40 000 data points

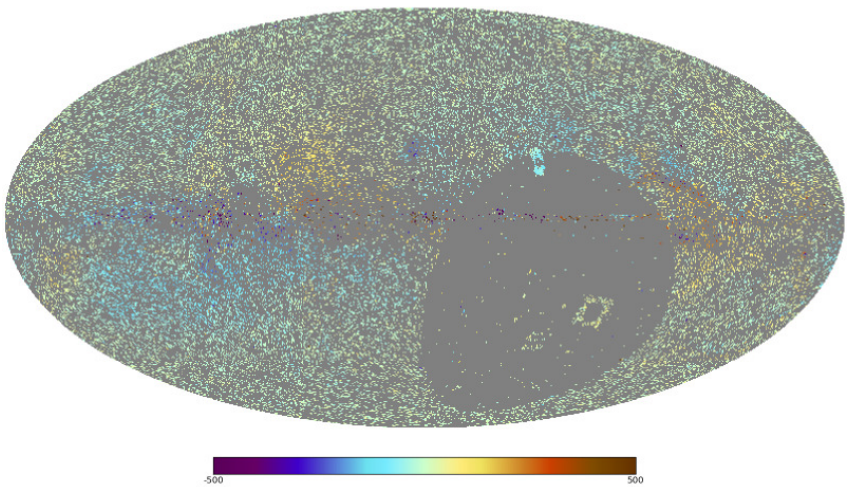
$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$



Challenges

- Regions without data
- Galactic/extragalactic split unknown
- Uncertain uncertainties

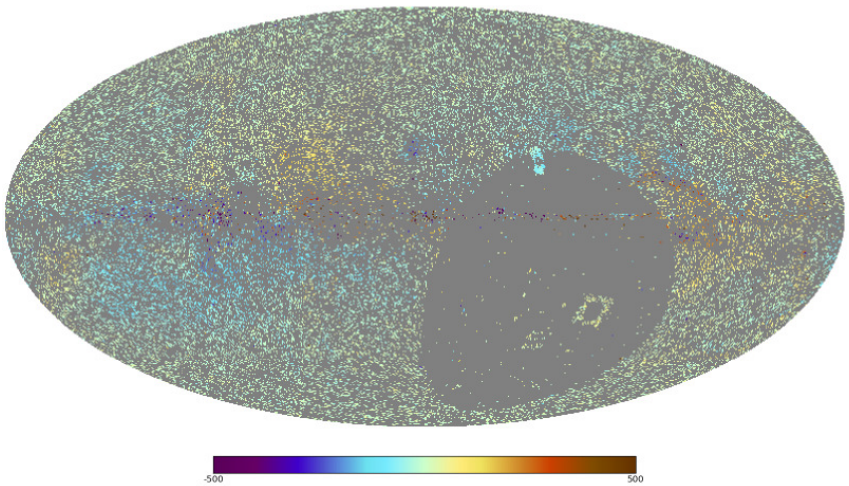
$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$

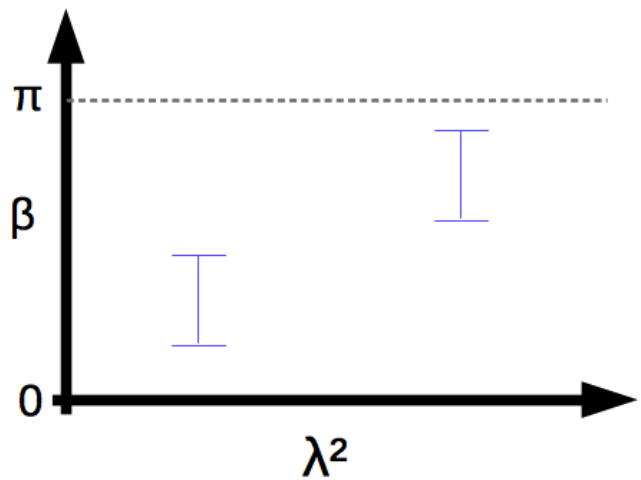


Challenges

- Regions without data
- Galactic/extragalactic split unknown
- Uncertain uncertainties
  - $n\,\pi$ ambiguity
  - multiple components along a LOS
  - ionosphere
  - ...

$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$





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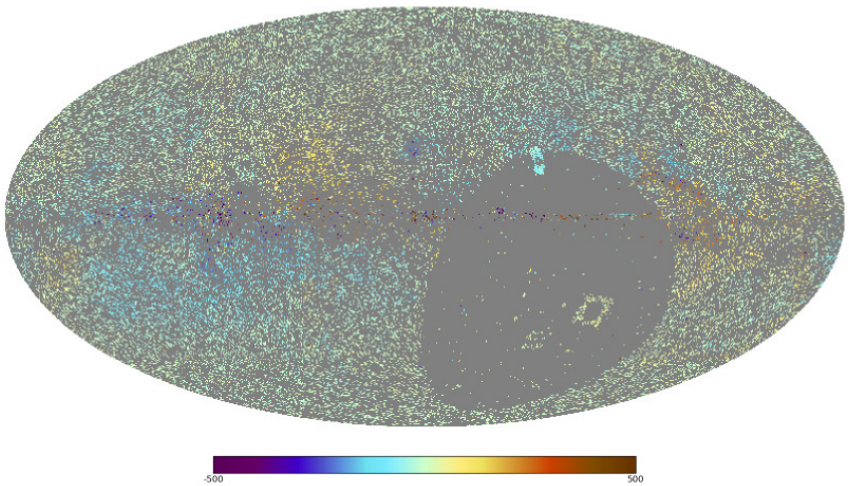

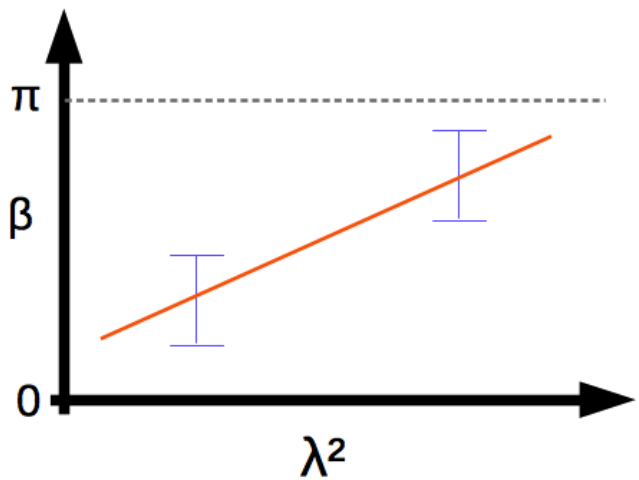

Challenges

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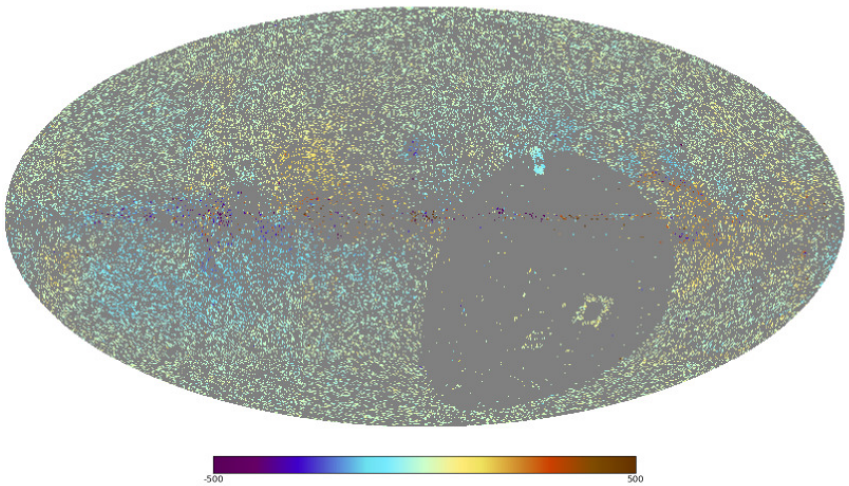
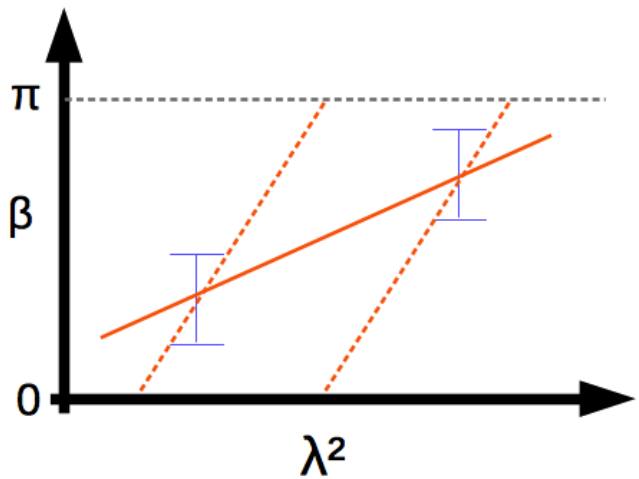
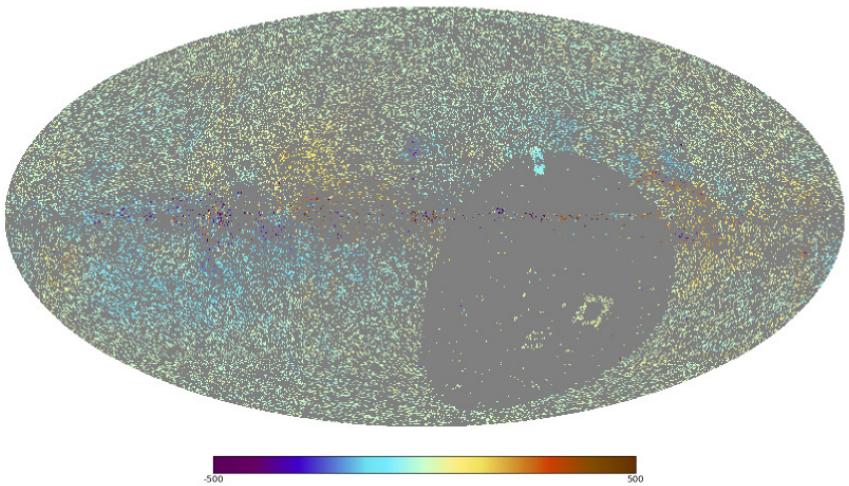


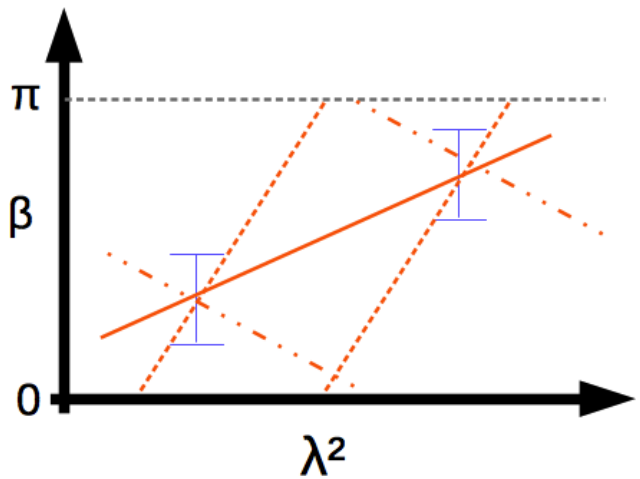


Challenges

- Regions without data
- Galactic/extragalactic split unknown
- Uncertain uncertainties
  - $n\,\pi$ ambiguity
  - multiple components along a LOS
  - ionosphere
  - ...

$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$

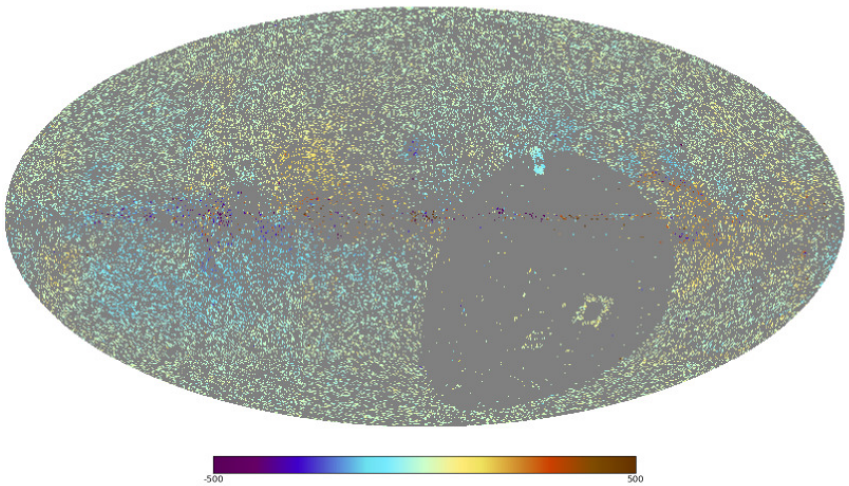


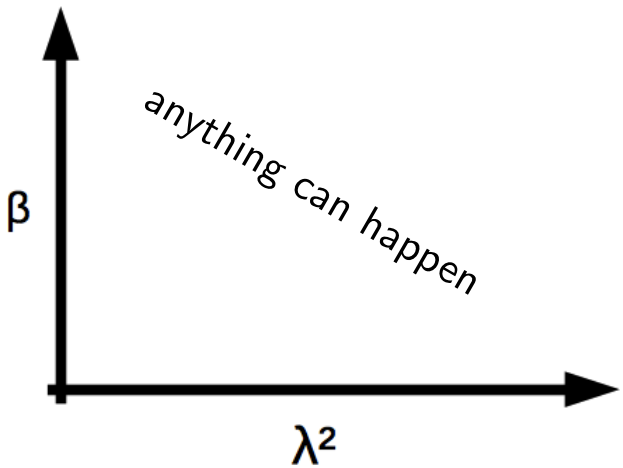


Challenges

- Regions without data
- Galactic/extragalactic split unknown
- Uncertain uncertainties
  - $n\,\pi$ ambiguity
  - multiple components along a LOS
  - ionosphere
  - ...

$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$

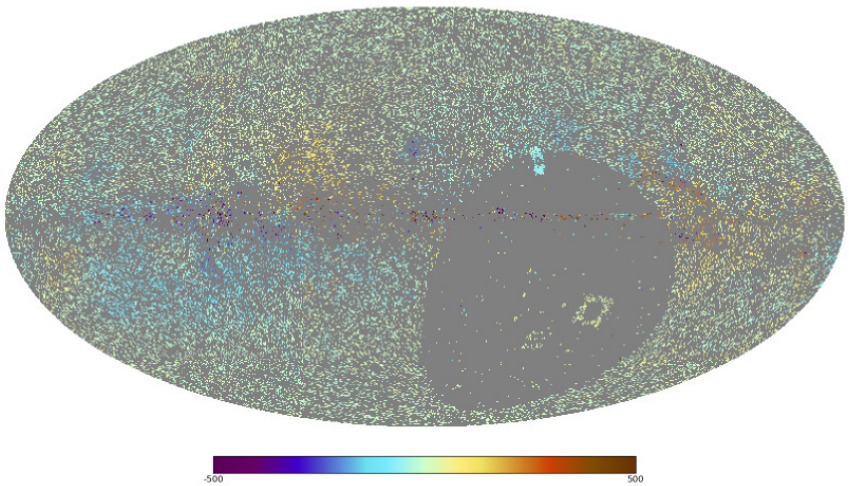




Challenges

- Regions without data
- Galactic/extragalactic split unknown
- Uncertain uncertainties
  - $n\,\pi$ ambiguity
  - multiple components along a LOS
  - ionosphere
  - ...

$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$



Challenges

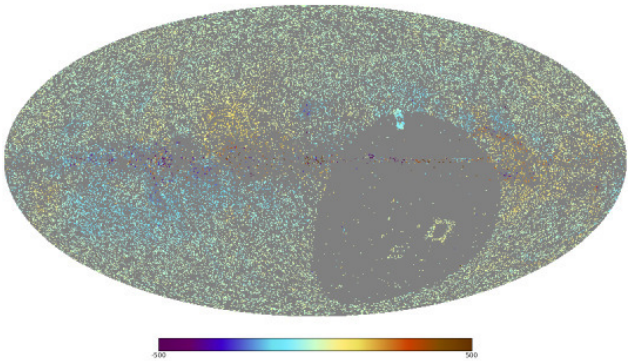
- Regions without data
- Galactic/extragalactic split unknown
- Uncertain uncertainties
  - $n\,\pi$ ambiguity
  - multiple components along a LOS
  - ionosphere
  - ...

$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + \phi_{\mathrm{ionosphere}}(t) + n$$

$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$

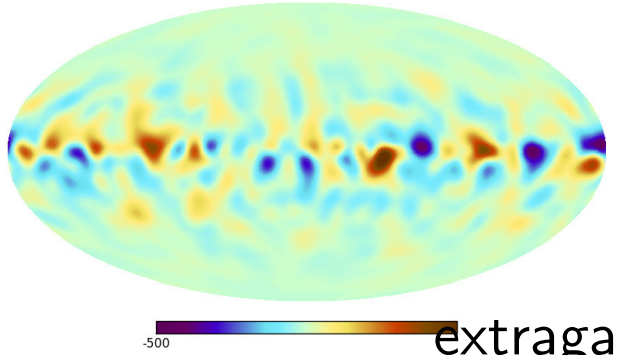
$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$

data



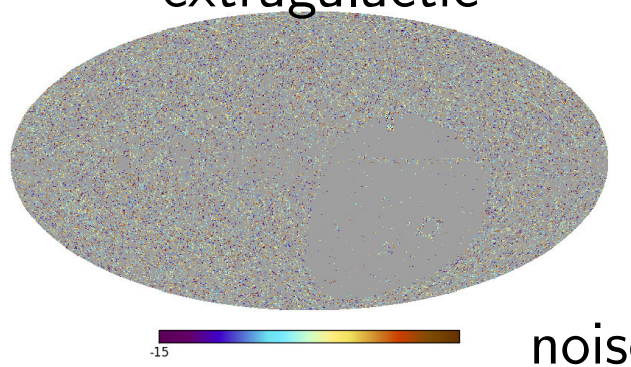
=

Galactic



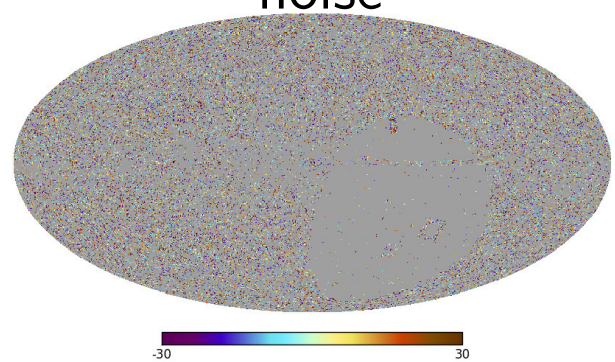
extragalactic

+



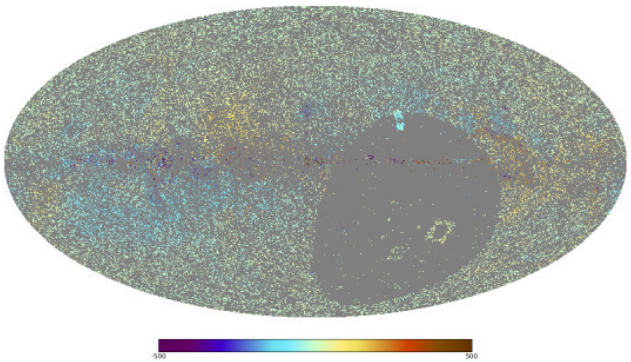
noise

+



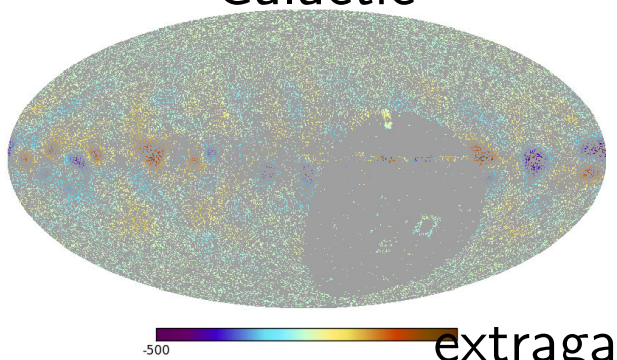
$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$

data



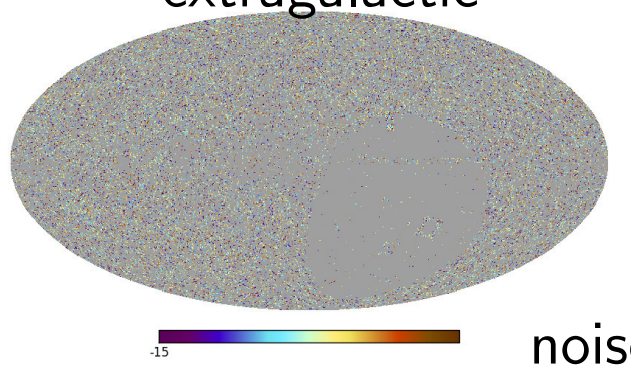
=

Galactic



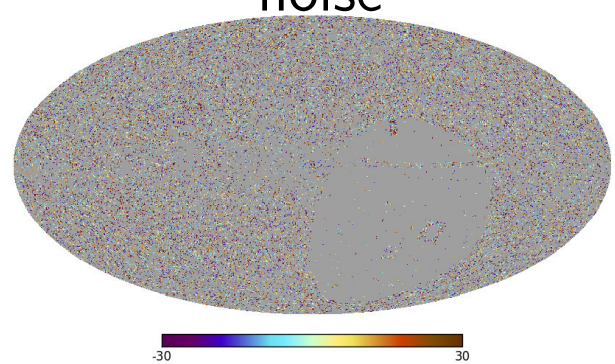
extragalactic

+



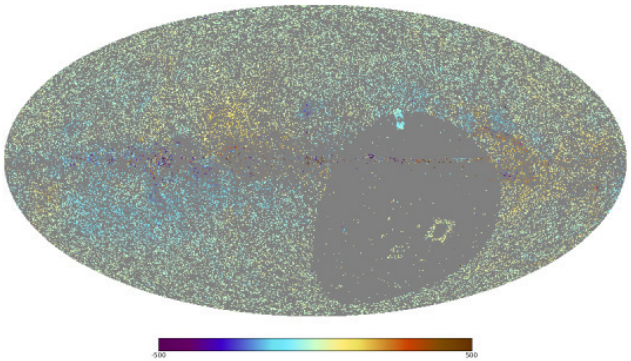
noise

+



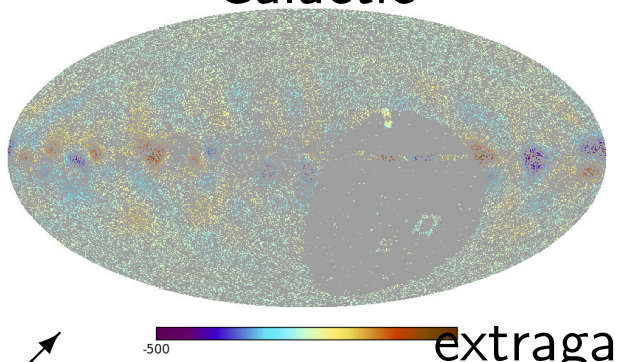
$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$

data



=

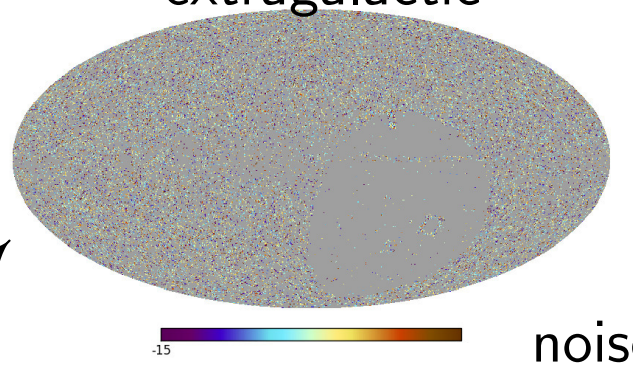
Galactic



correlated

+

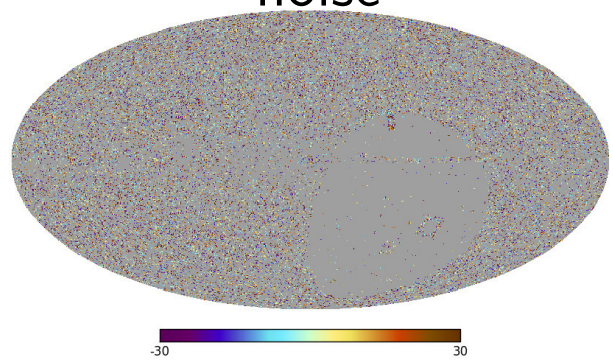
extragalactic

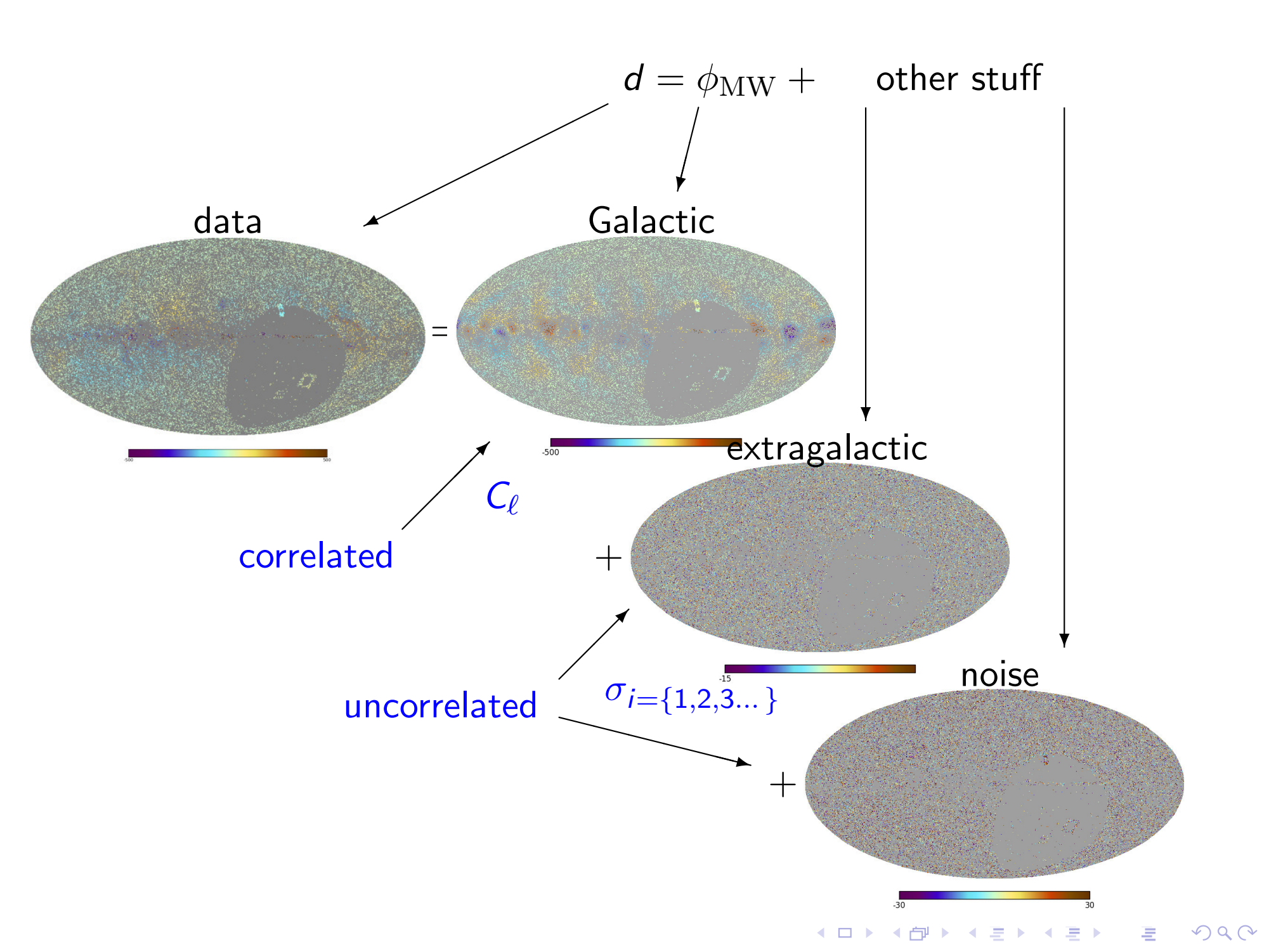


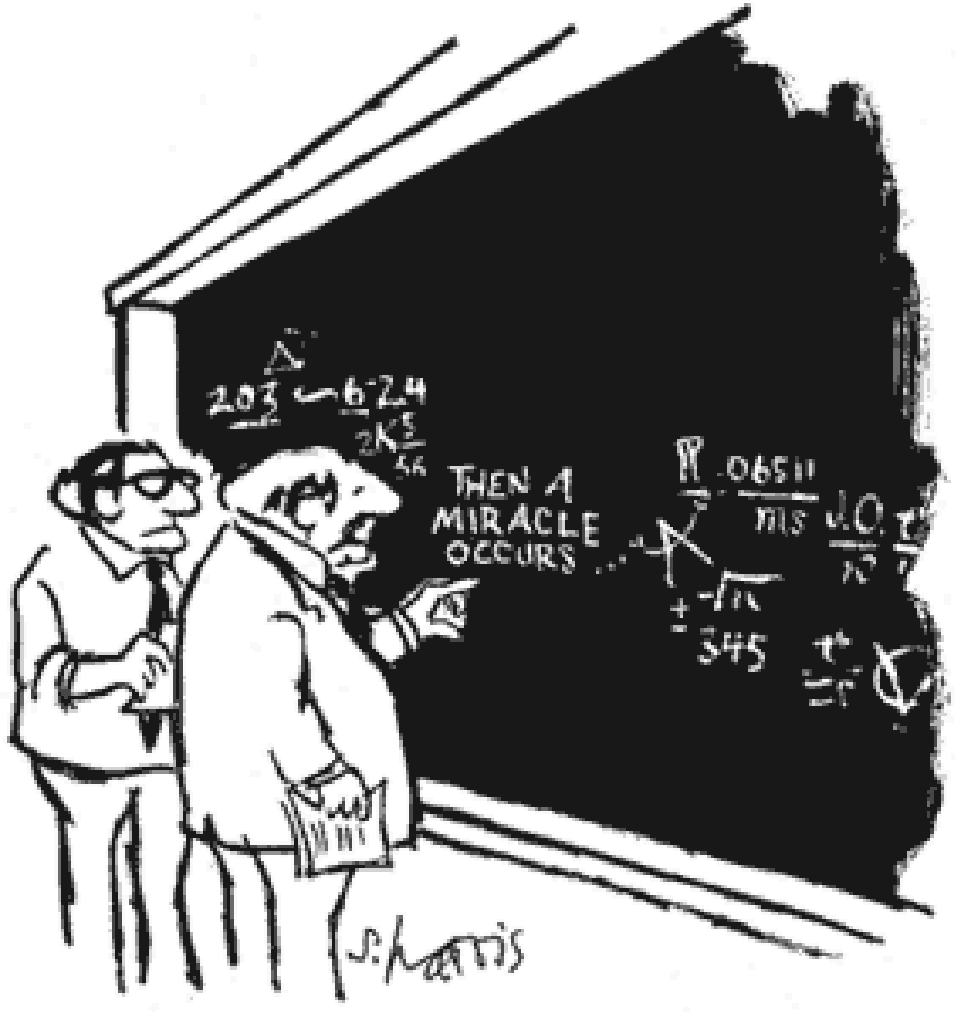
uncorrelated

+

noise

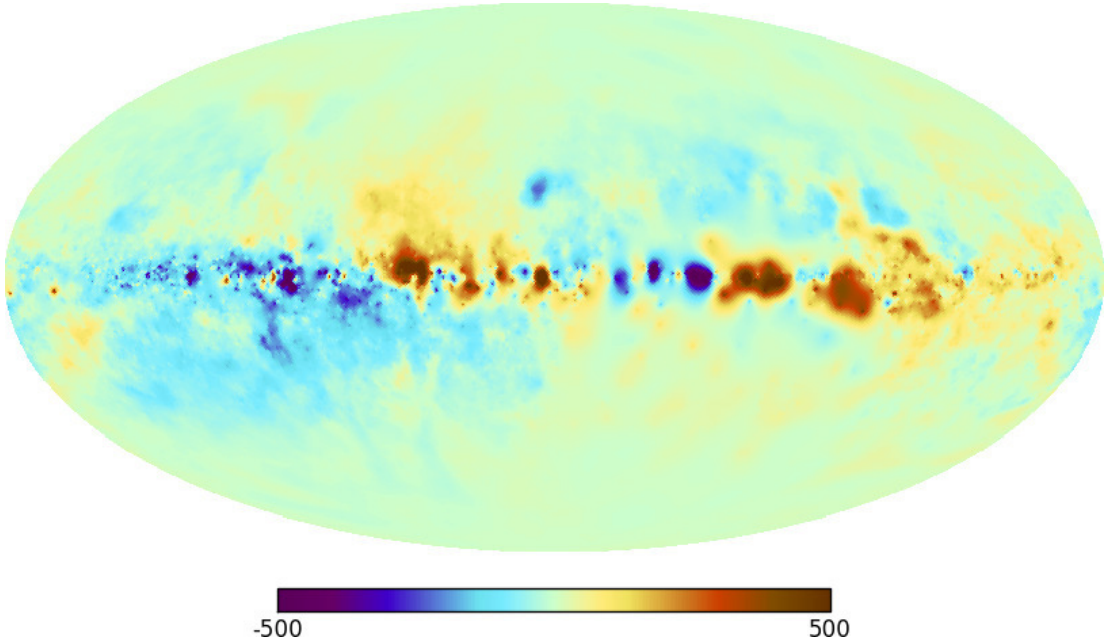



$d = \phi_{\mathrm{MW}} +$
other stuff
data
Galactic
=
-500
extragalactic
C_ℓ
correlated
+
-15
noise
uncorrelated
$\sigma_{i=\{1,2,3\ldots\}}$
+
-30
30

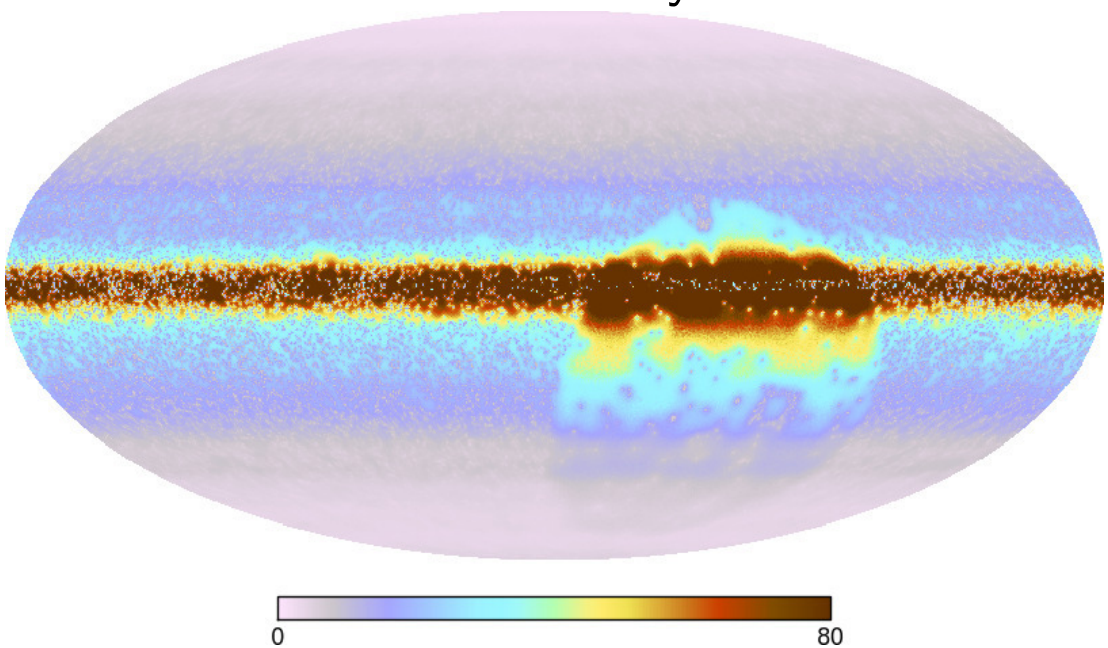


"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

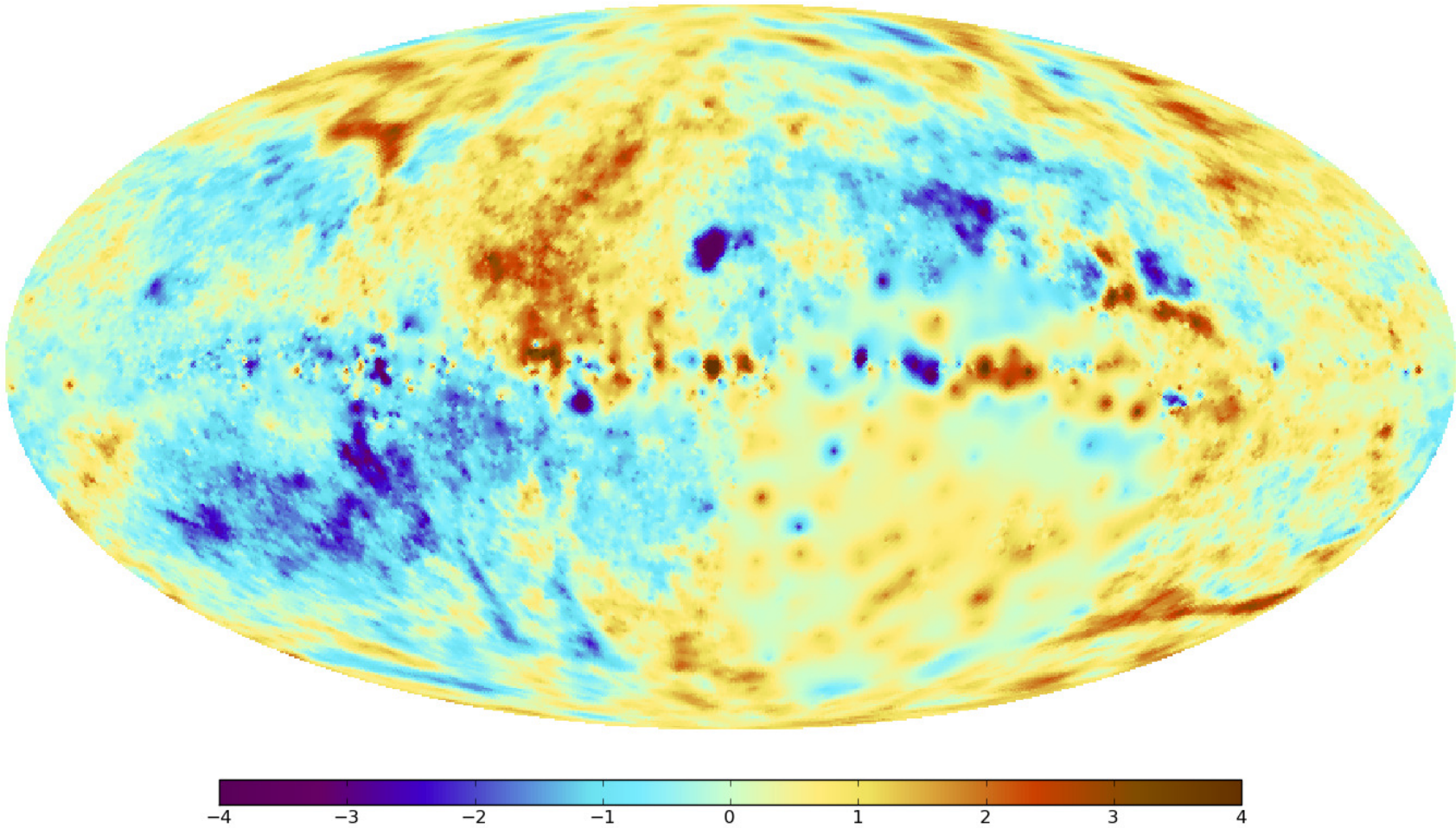
Galactic Faraday depth

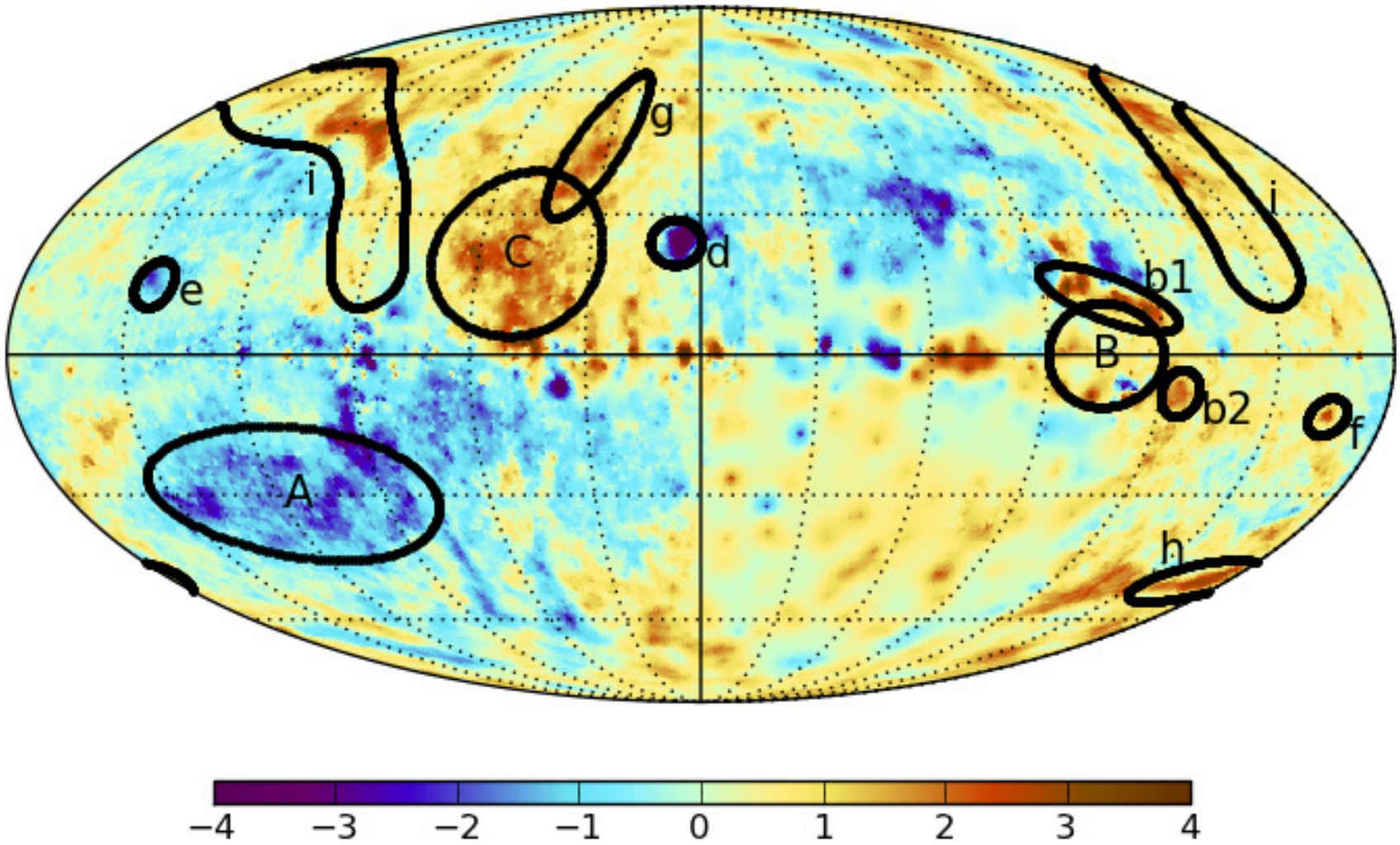


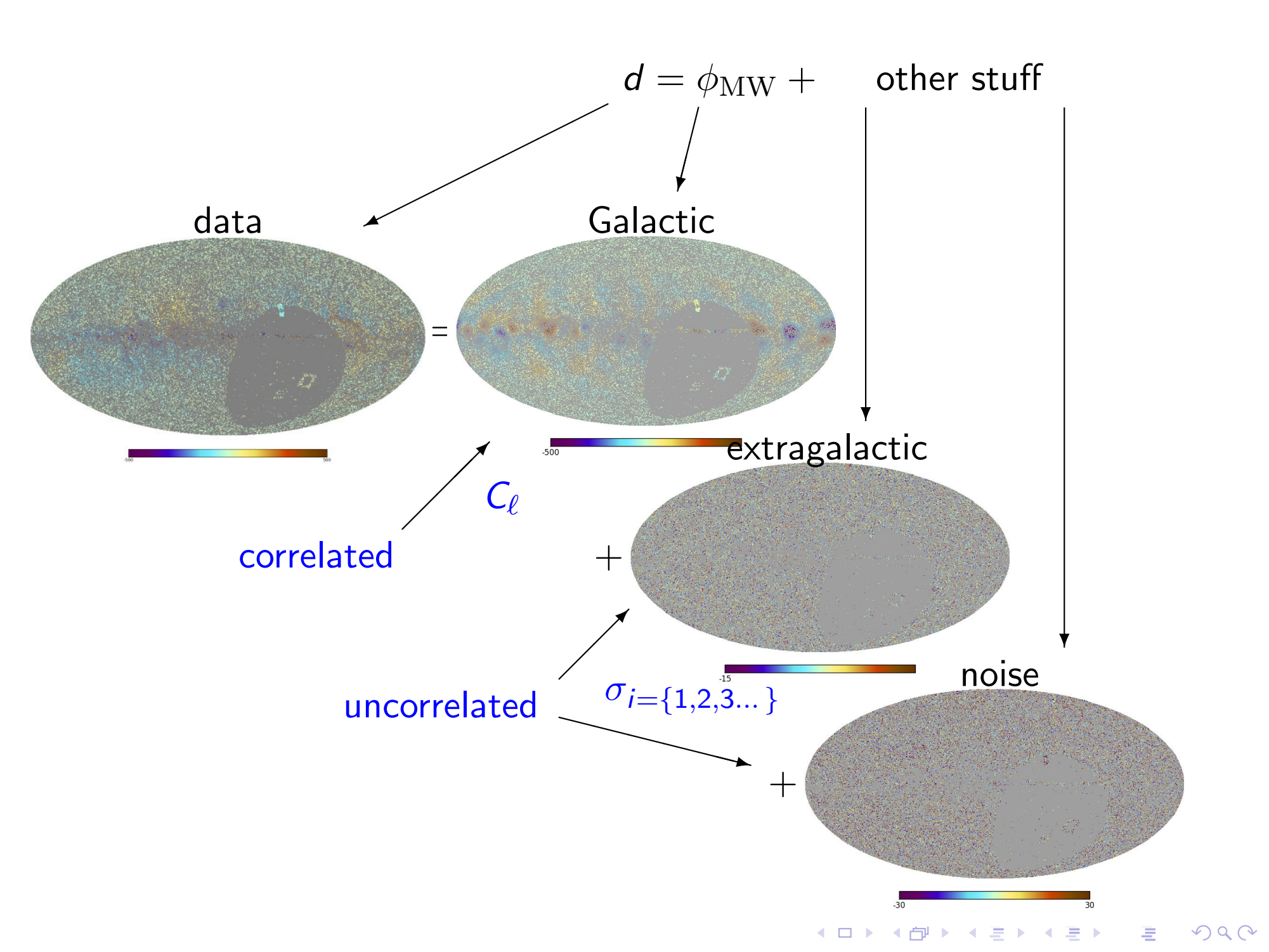
uncertainty



NO et al., A&A, 2012/2015; arXiv:1111.6186 / arXiv:1404.3701

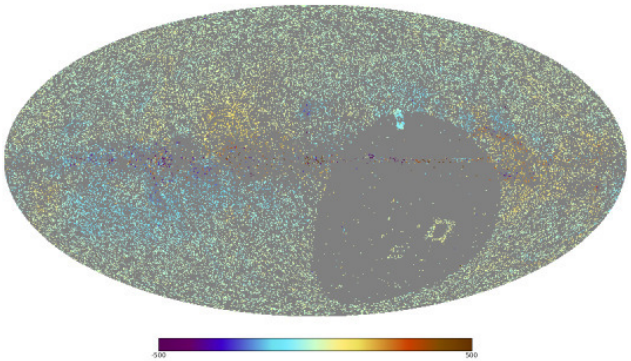

−4
−3
−2
−1
0
1
2
3
4


g
i
C
d
j
e
b1
B
b2
f
A
h
−4
−3
−2
−1
0
1
2
3
4


$d = \phi_{\mathrm{MW}} +$
other stuff
data
Galactic
=
-500
extragalactic
C_ℓ
correlated
+
-15
noise
uncorrelated
$\sigma_{i=\{1,2,3\ldots\}}$
+
-30
30

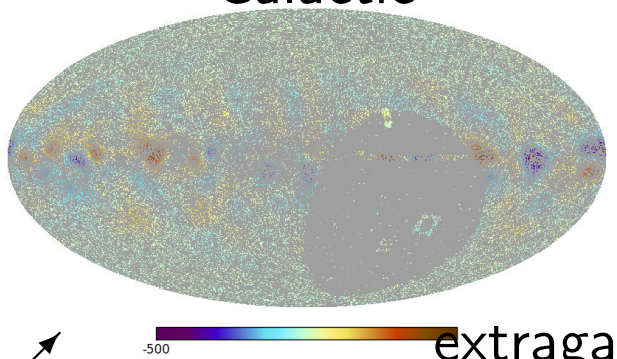
$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$

data

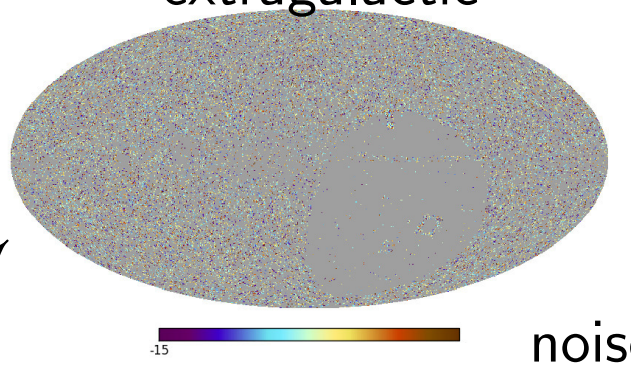


=

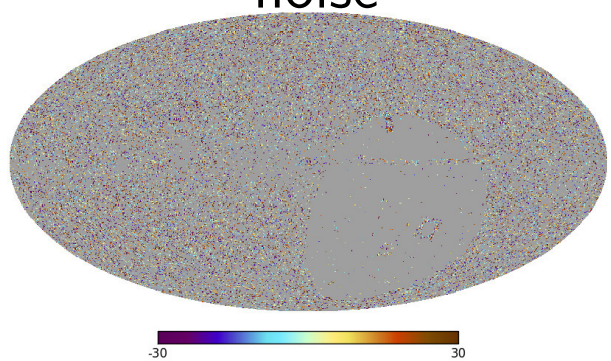
Galactic



extragalactic



noise



correlated

C_ℓ

+

σ_{e}

uncorrelated

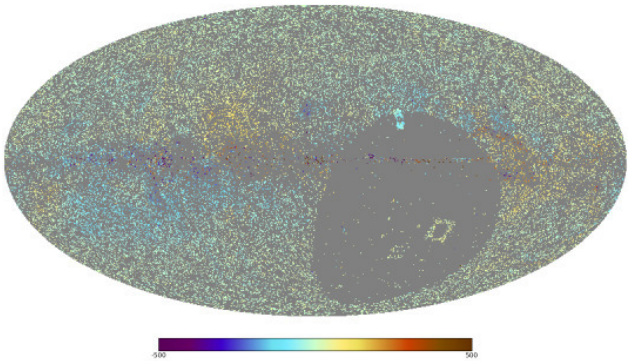
degenerate

$\sigma_{i=\{1,2,3,\ldots\}}$

+

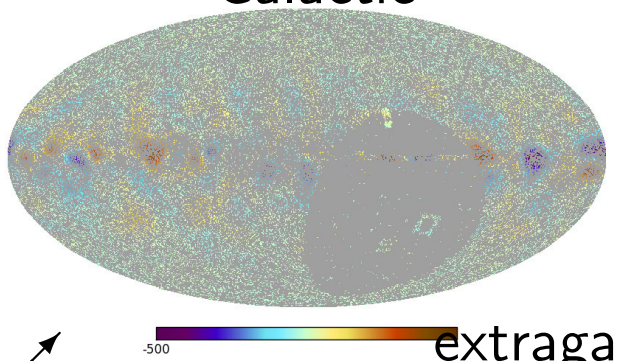
$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$

data

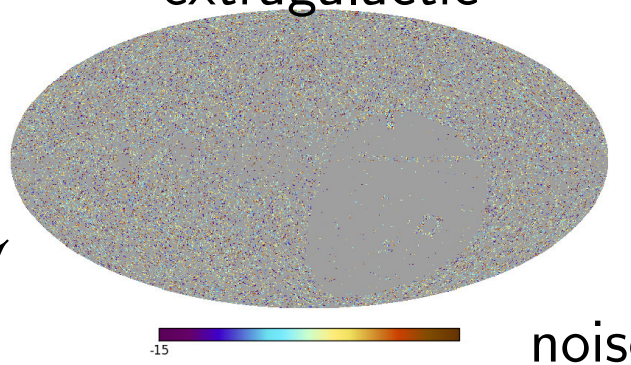


=

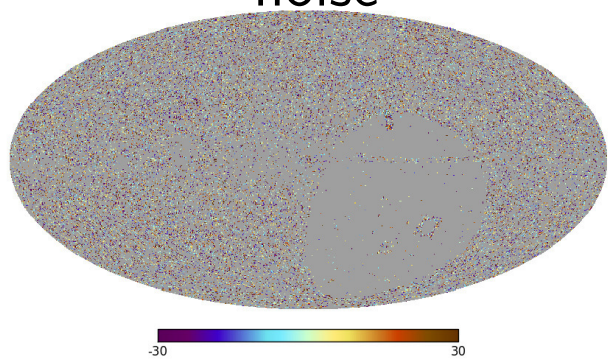
Galactic



extragalactic



noise



correlated

C_ℓ

+

σ_{e}

uncorrelated

degenerate

$\sigma_{i=\{1,2,3,\ldots\}}$

+

idea: find subset of data for which noise statistics are perfectly known

Results:

- $\sigma_{\mathrm{e}} \lesssim 7\,\mathrm{rad/m^2}$
- constraints on extragalactic contributions for individual sources very weak

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- $\sigma_{\mathrm{e}} \lesssim 7\,\mathrm{rad/m^2}$
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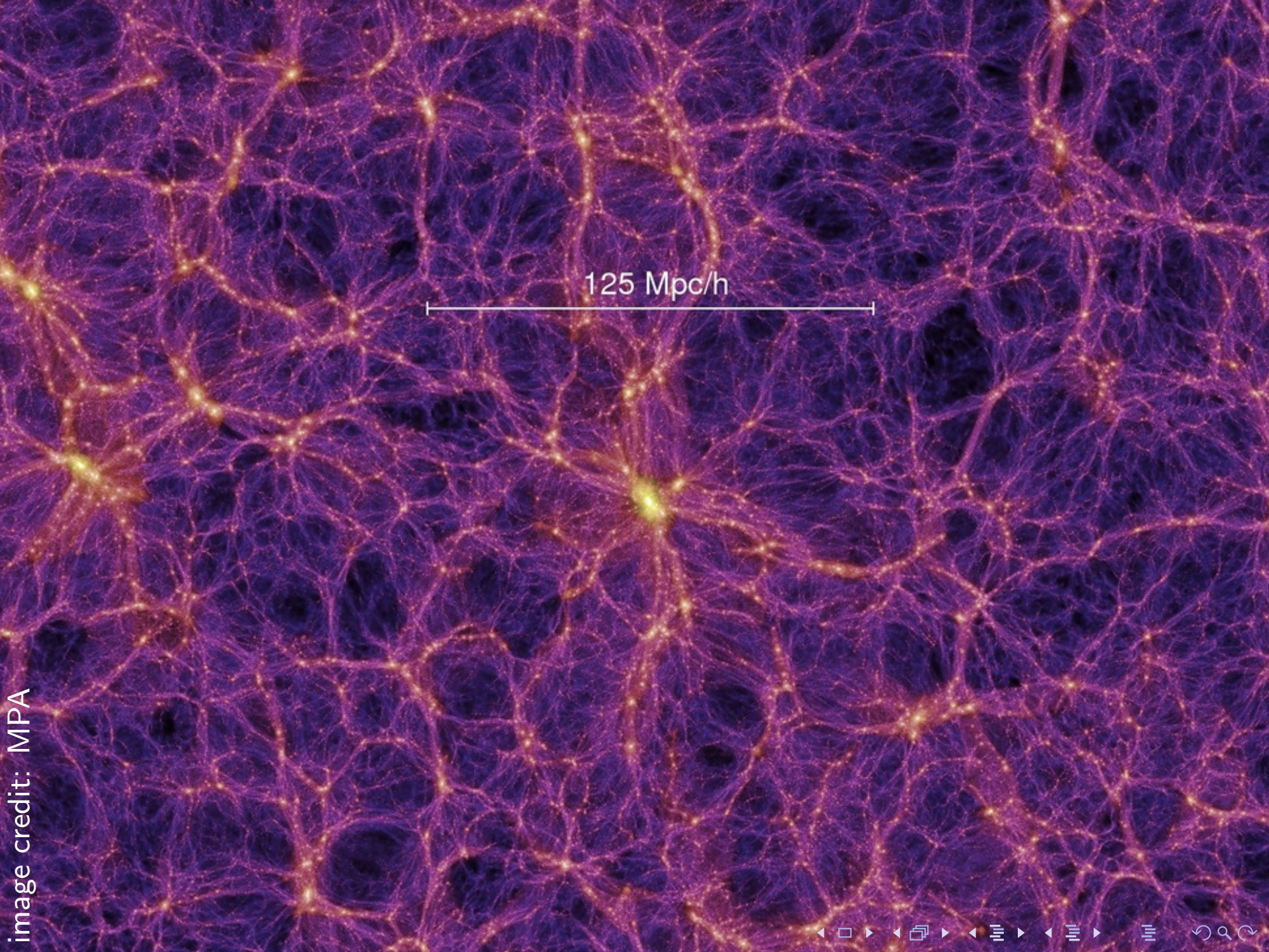


image credit: MPA

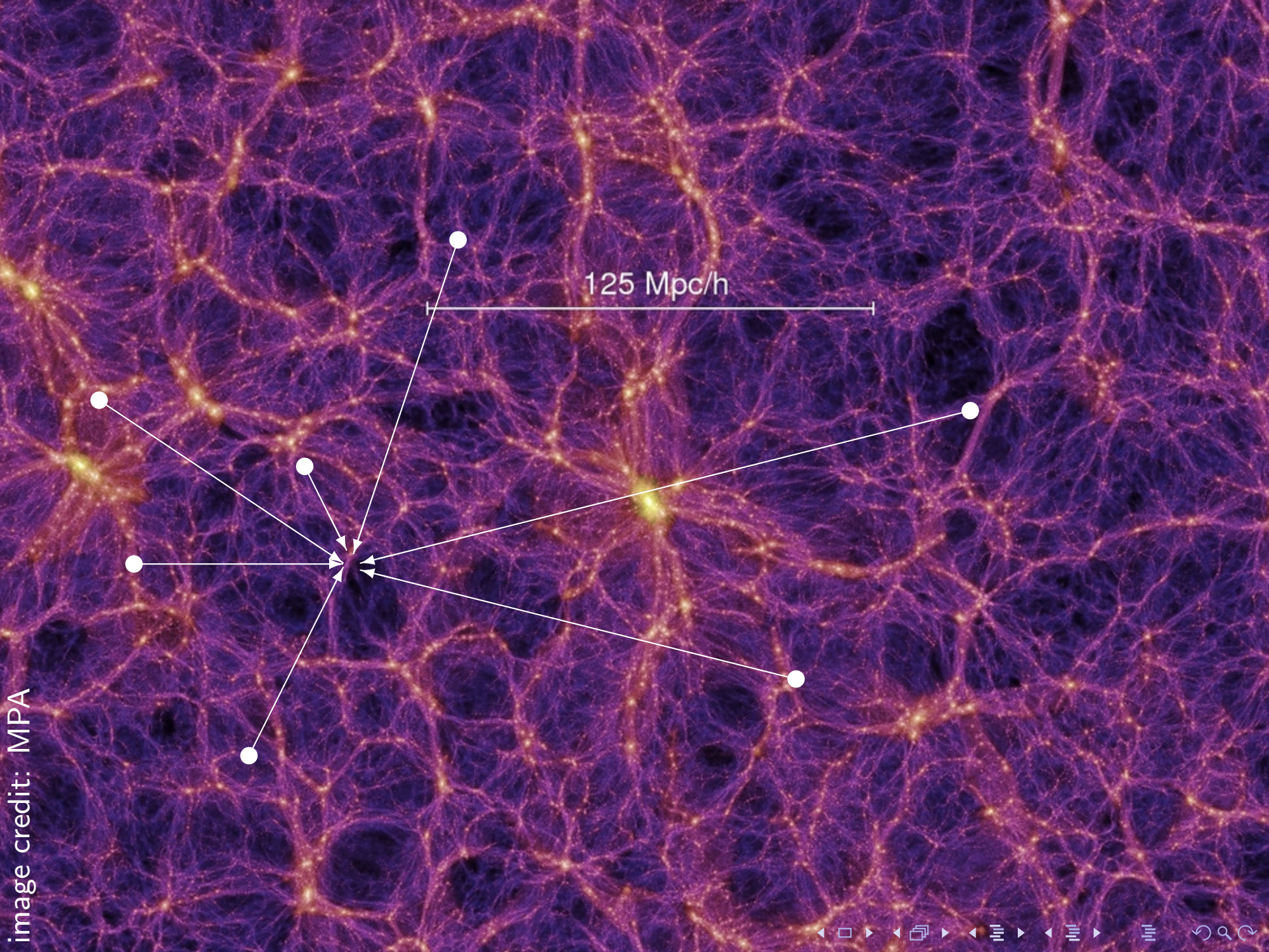
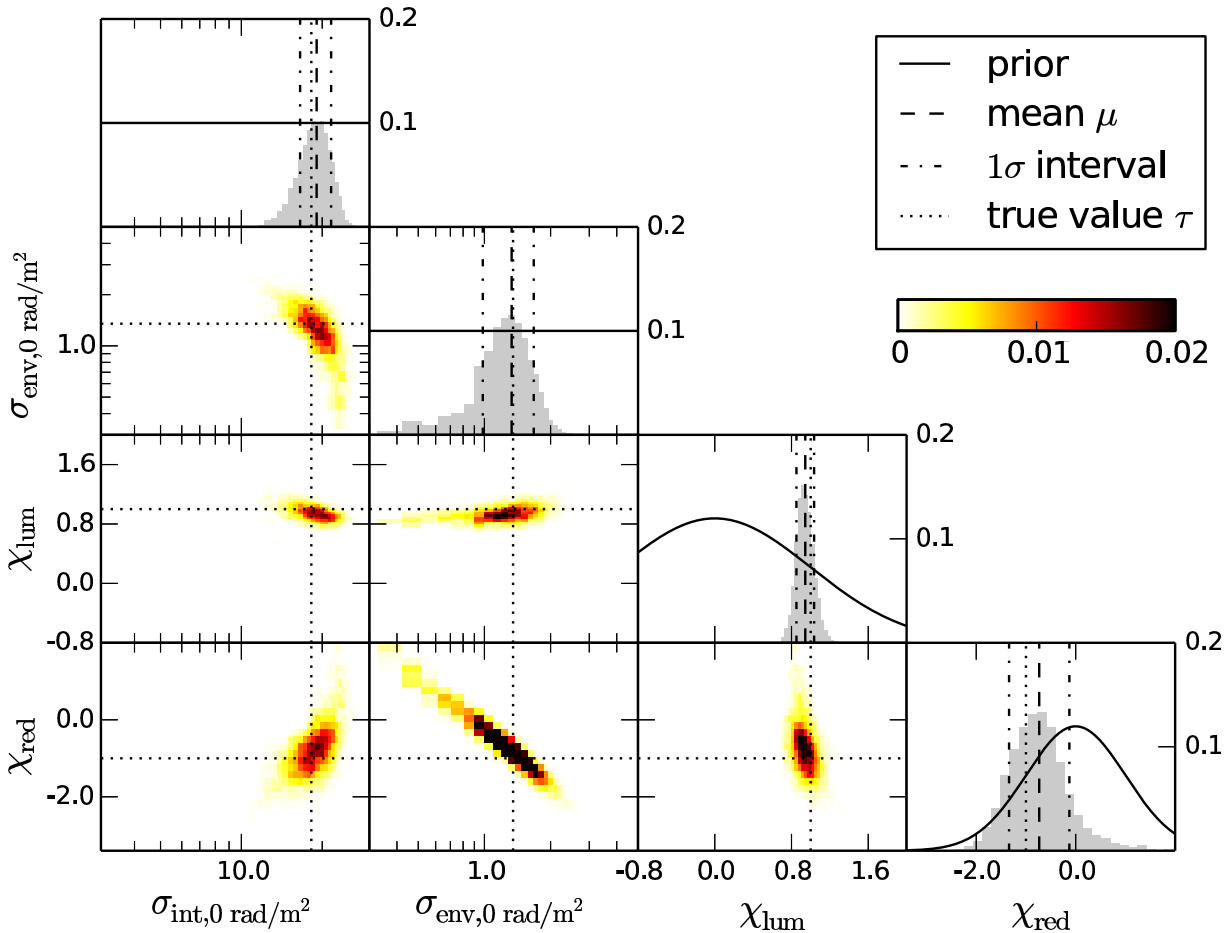


image credit: MPA

$$\sigma_{\mathrm{e},i}^2 \propto \left(\frac{L}{L_0}\right)^{\chi_{\mathrm{lum}}} \frac{\sigma_{\mathrm{int}}^2}{(1+z_i)^4} + \frac{D_i}{D_0}\,\sigma_{\mathrm{env}}^2$$

$$D_i = \int_0^{z_i} \frac{c}{H(z)}\,(1+z)^{4+\chi_{\mathrm{red}}}\,\mathrm{d}z$$

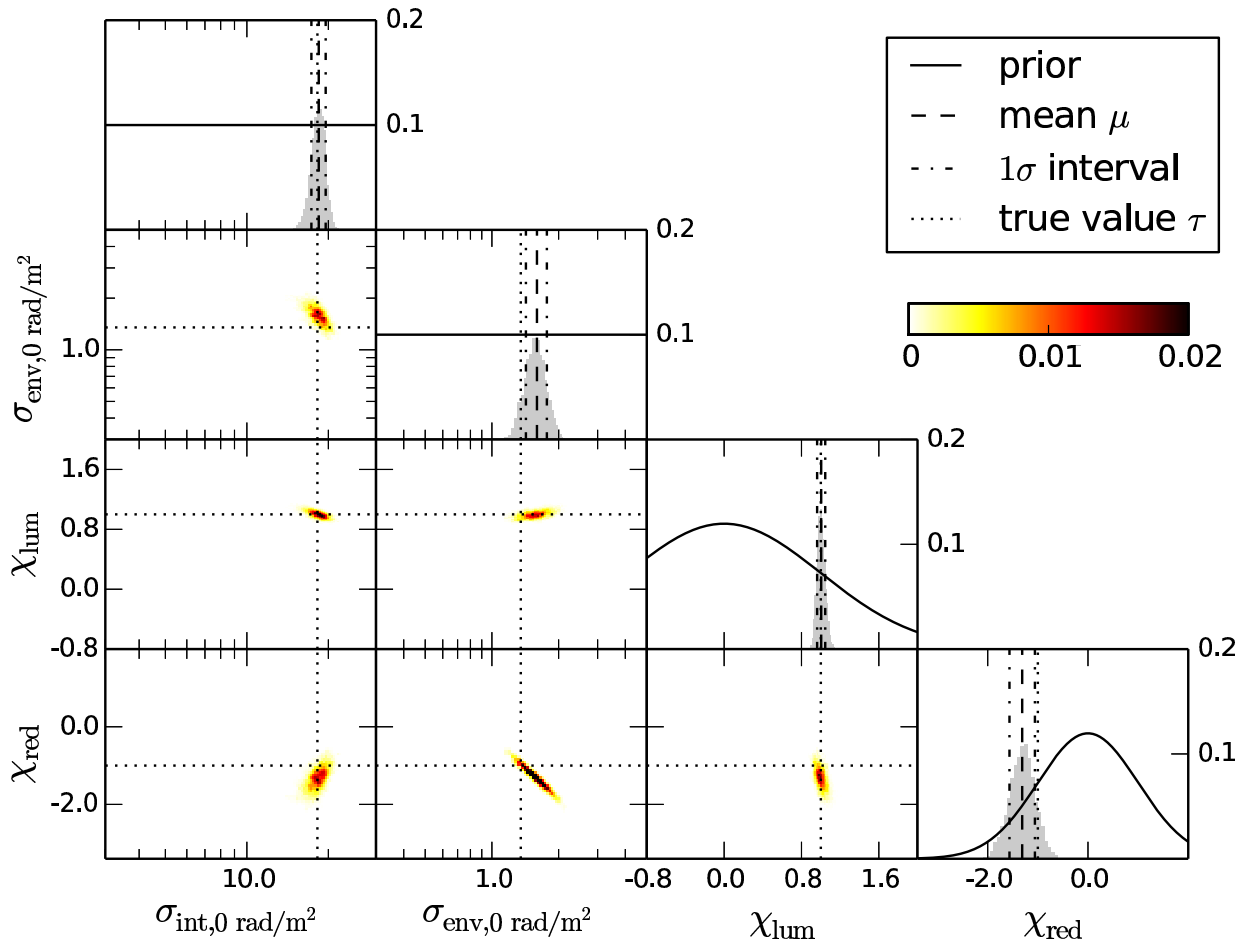


4003 lines of sight

V. Vacca, NO, et al.; arXiv:1509.00747

$$\sigma^2_{\mathrm{e},i} \propto \left(\frac{L}{L_0}\right)^{\chi_{\mathrm{lum}}} \frac{\sigma^2_{\mathrm{int}}}{(1+z_i)^4} + \frac{D_i}{D_0}\,\sigma^2_{\mathrm{env}}$$

$$D_i = \int_0^{z_i} \frac{c}{H(z)}\,(1+z)^{4+\chi_{\mathrm{red}}}\,\mathrm{d}z$$



41632 lines of sight

V. Vacca, NO, et al.; arXiv:1509.00747

Summary

- Faraday rotation probes B-fields on (almost) all scales
- Galactic contribution (correlated) can be separated from rest (uncorrelated)
- Rest can be statistically split into extragalactic and noise
- Uncertainties are large and need to be understood

Outlook

- Large-scale structure information to be included
- More sophisticated treatment of observational uncertainties desirable

Results: http://www.mpa-garching.mpg.de/ift/faraday/