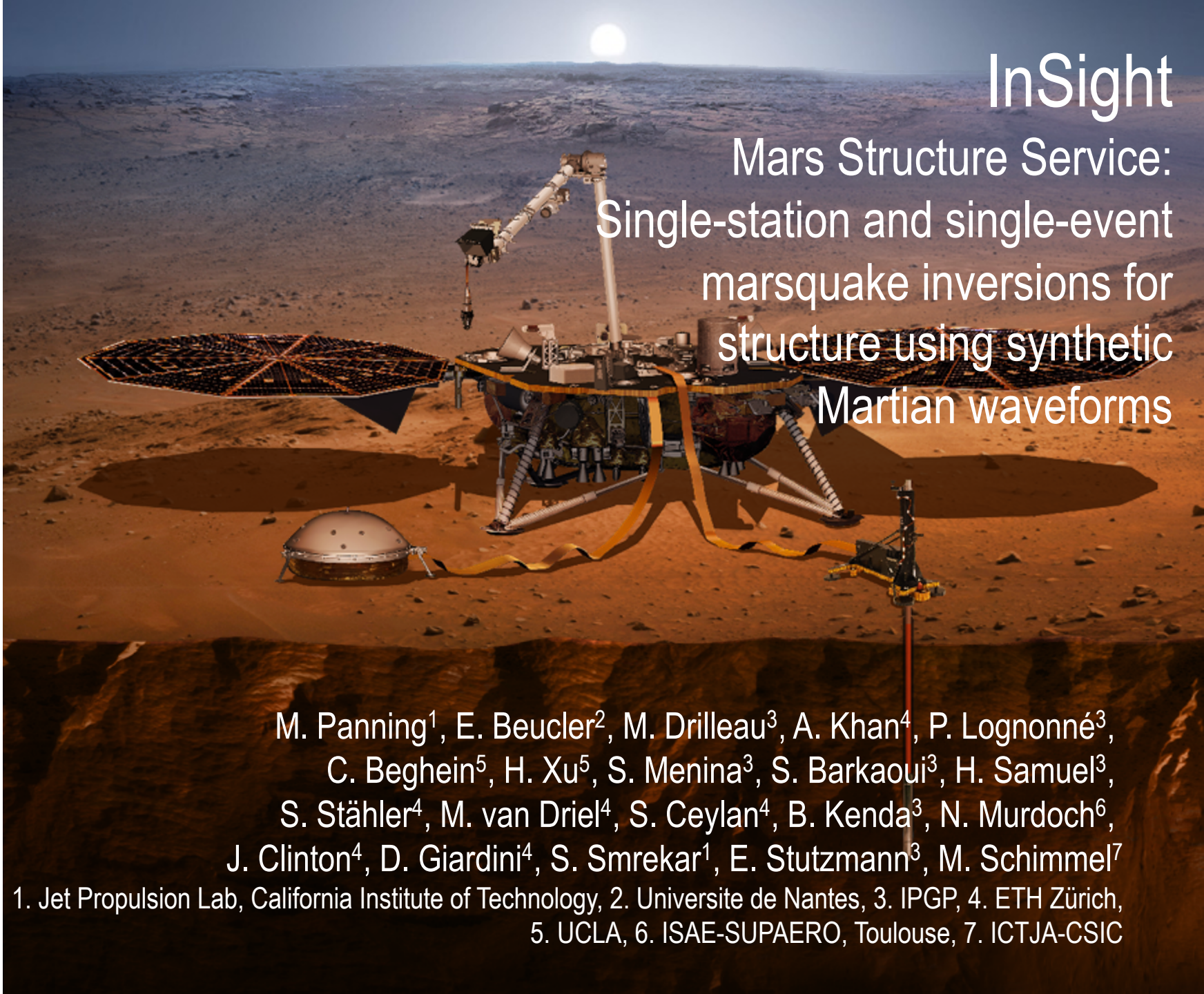


InSight

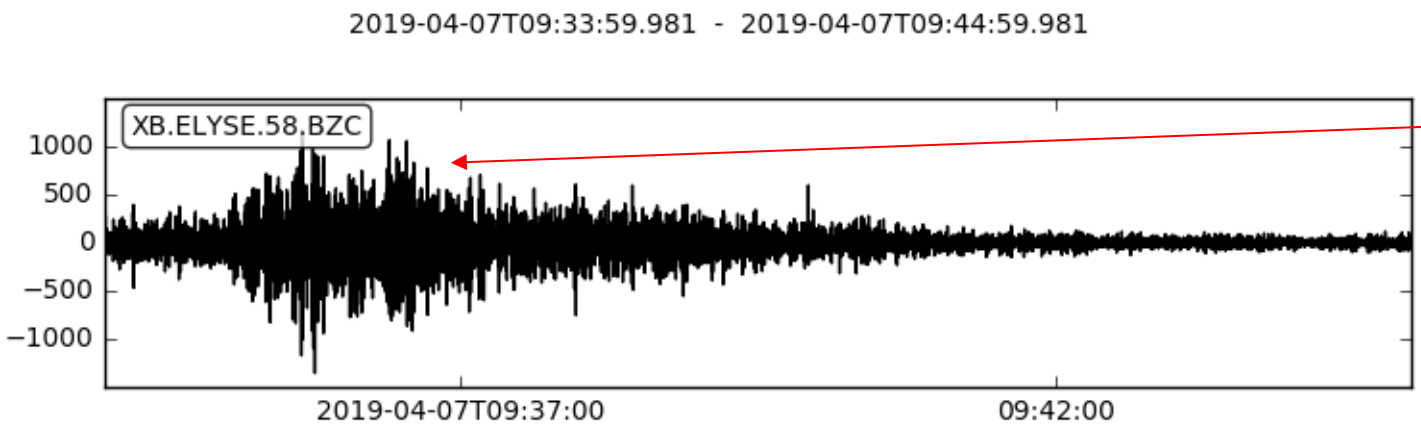
Mars Structure Service: Single-station and single-event marsquake inversions for structure using synthetic Martian waveforms

M. Panning[1], E. Beucler[2], M. Drilleau[3], A. Khan[4], P. Lognonné[3], C. Beghein[5], H. Xu[5], S. Menina[3], S. Barkaoui[3], H. Samuel[3], S. Stähler[4], M. van Driel[4], S. Ceylan[4], B. Kenda[3], N. Murdoch[6], J. Clinton[4], D. Giardini[4], S. Smrekar[1], E. Stutzmann[3], M. Schimmel[7]

1. Jet Propulsion Lab, California Institute of Technology, 2. Universite de Nantes, 3. IPGP, 4. ETH Zürich, 5. UCLA, 6. ISAE-SUPAERO, Toulouse, 7. ICTJA-CSIC

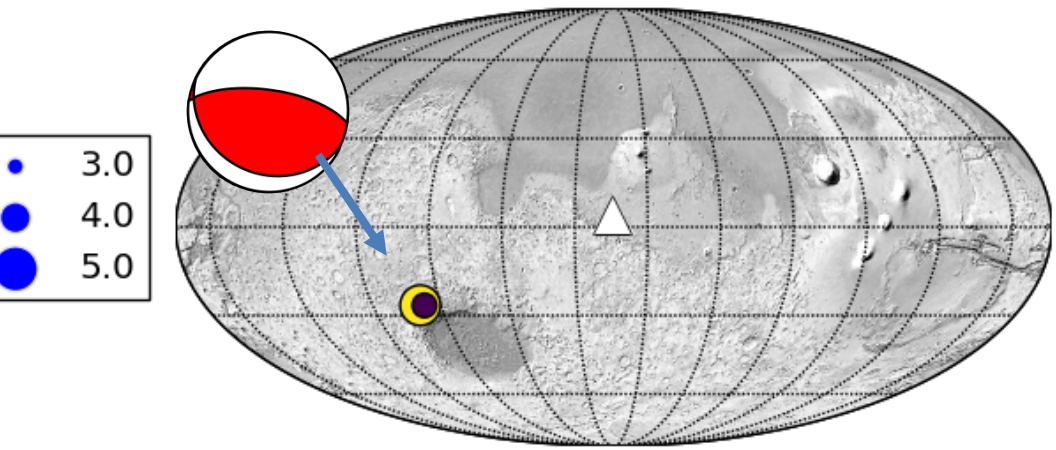
Testing out structure inversions

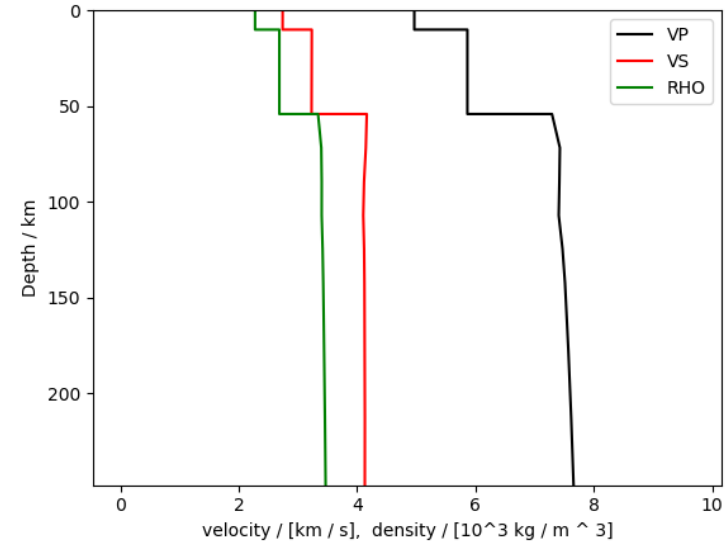
- Before landing, the Mars Structure Service conducted a blind test on a single synthesized event
- While we have now been on the surface of Mars, and have up to 4 potential Marsquakes, none are yet big enough to locate or use for structure inversion
- Our first modeling for deep structure will likely be based on a single event, so this practice is important!
- We test 6 methods in 2 different classes of models. While models are very broadly consistent, significant differences remain and estimated uncertainties need to be refined



Not yet ready for deep structure inversion!

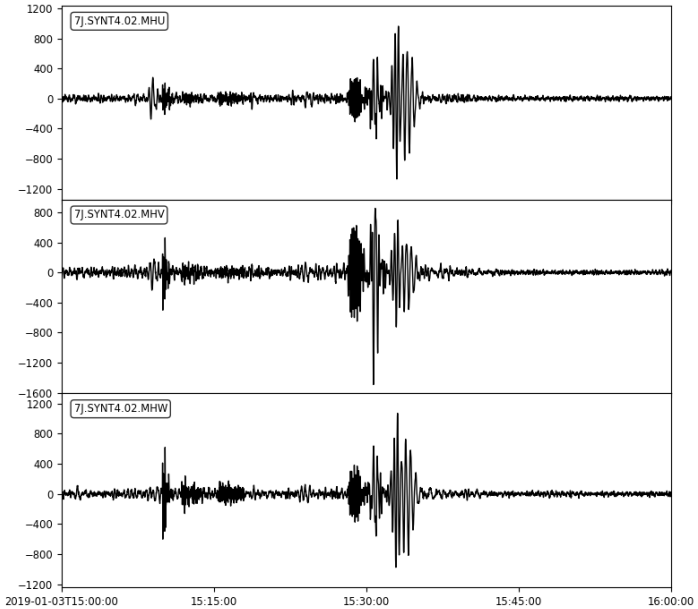
The blind test event and 1D base model





True location:

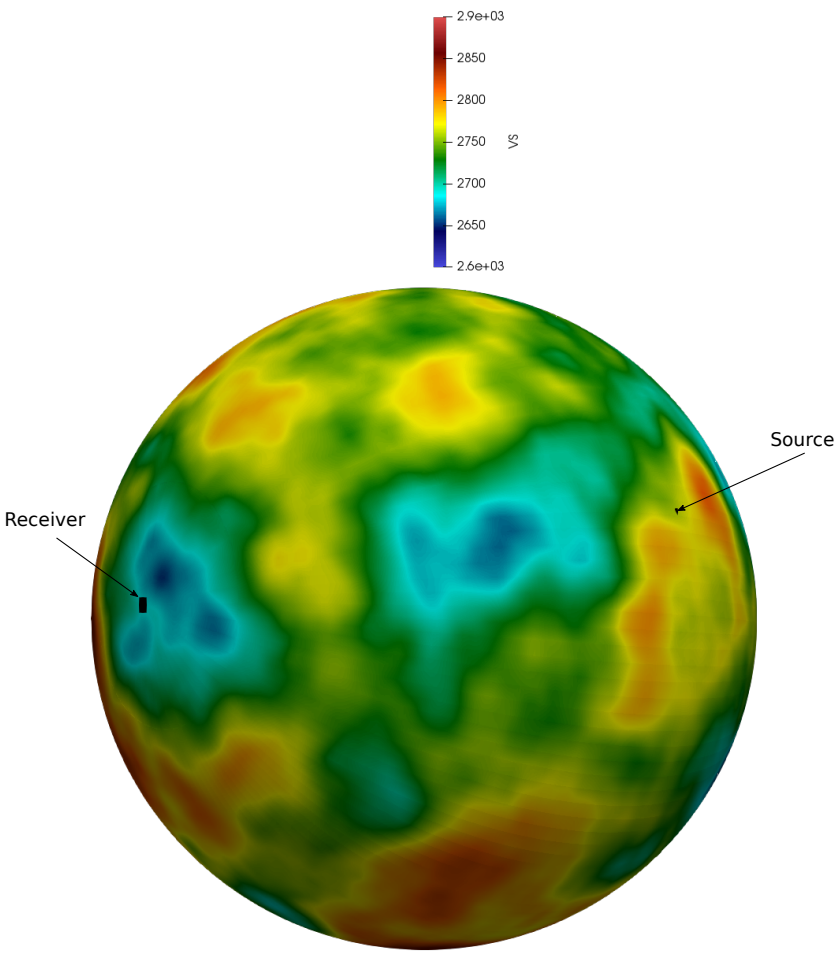
- 26.443 S
- 50.920 E
- Epicentral distance: **87.6** degrees
  R1 → 5183.1 km
  R2 → 16113.9 km
- Depth: **38.438** km
- Mw: **4.46**
- t0 (UTC): **15:00:30.0**



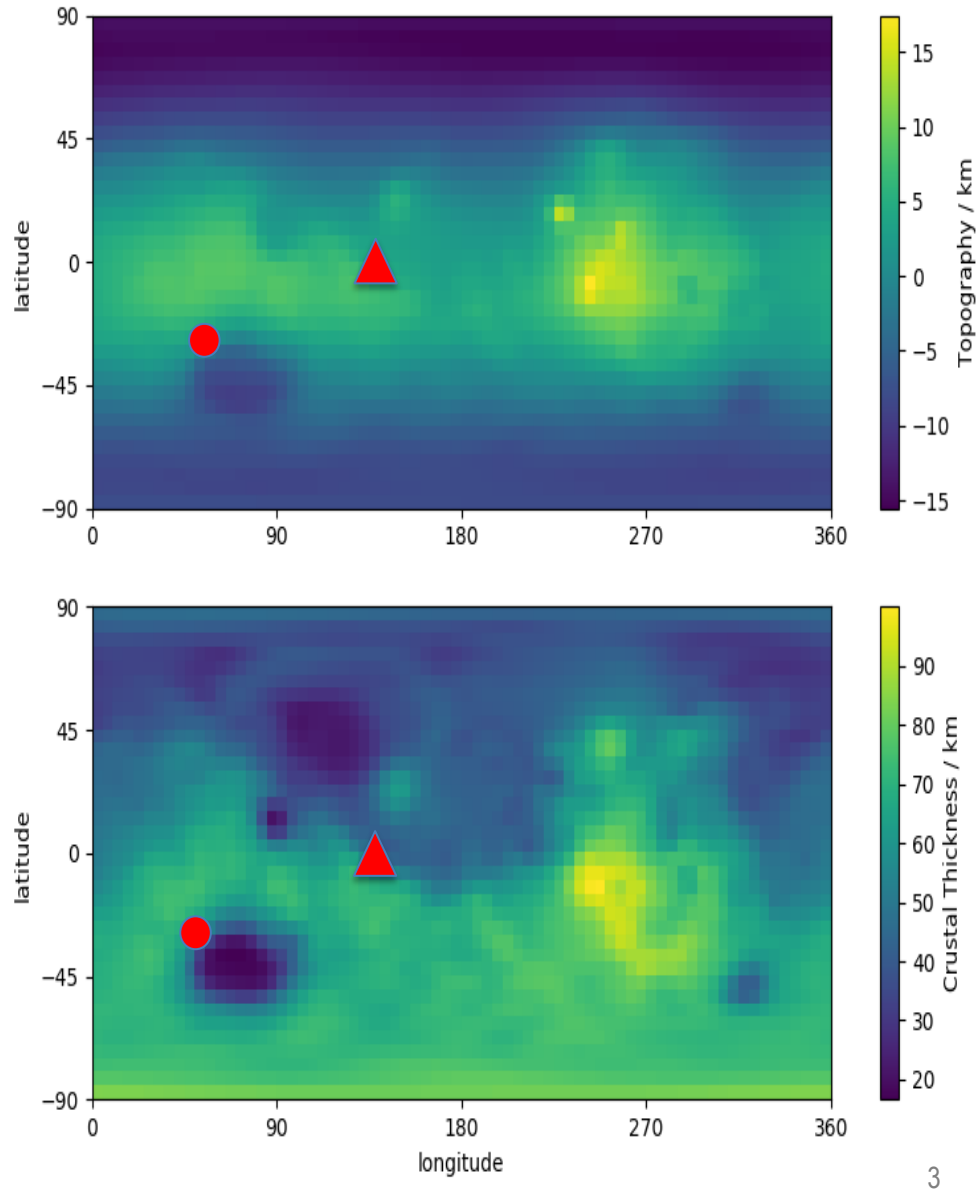
Data is included in modeled Mars noise (real Mars noise is a little less)

3D variations

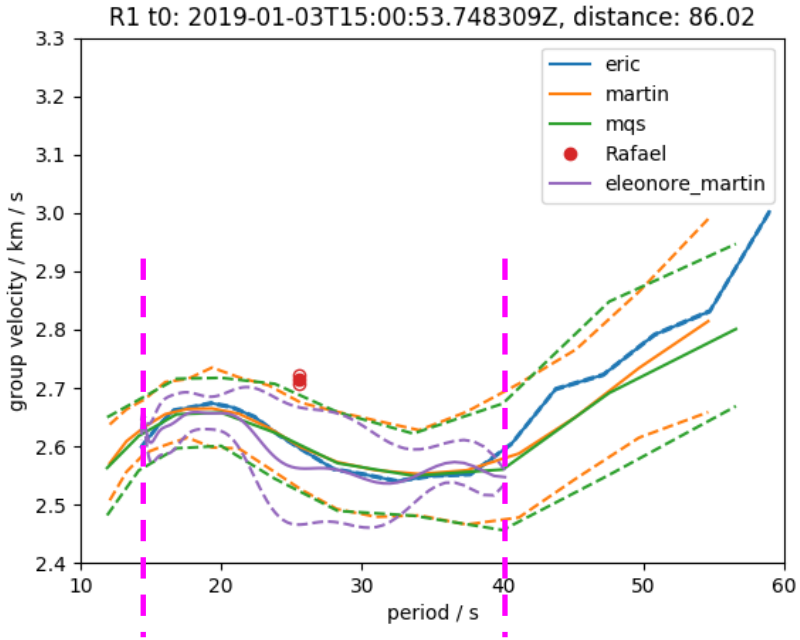
- Topography
- Crustal thickness
- Seismic velocities

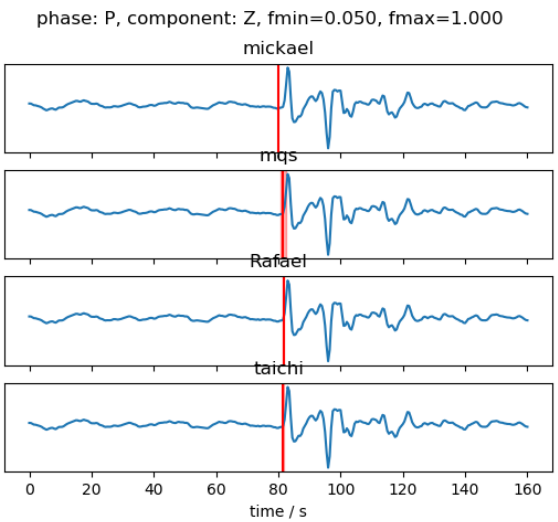


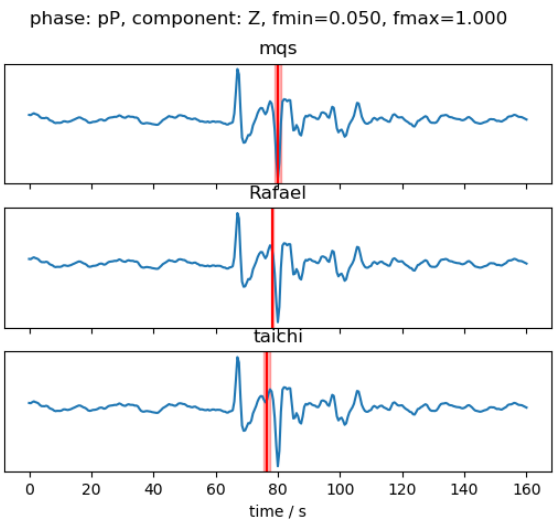
Smrekar et al. (2019)

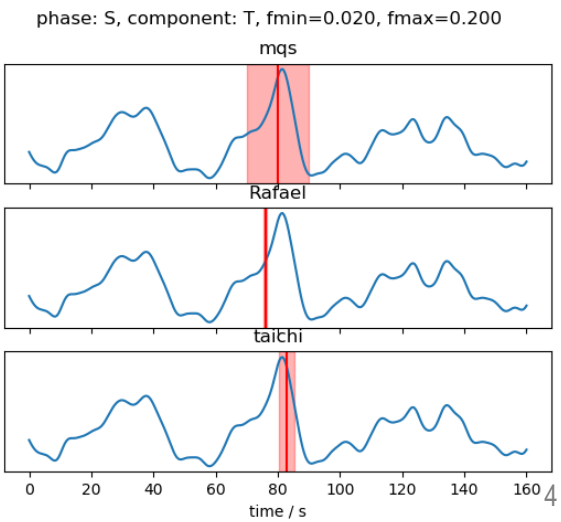


Body wave and surface wave measurements









Inversion methods

	M1			M2		
	M1a	M1b	M1c	M2a	M2b	M2c
Data	Surface waves + Body waves (MQS values)	Surface waves (LPG values)	Surface waves waveforms	Surface waves + Body waves (MQS values)	Surface waves + Body waves (MQS values)	Surface waves + Body waves (MQS values)
Quake relocation	yes	no (MQS value)	yes	yes	yes	yes
Inverse problem	McMC	McMC	McMC	McMC	McMC	Grid search
Misfit function calculated on	Differential arrival times	Group velocities	Waveforms	Travel times and group velocities	Differential arrival times	Travel times
Inverted structure parameters	Vp, Vs	Vp, Vs, Density	Vs	Vp, Vs, Density in crust and comp and T in mantle	Vp, Vs, Density in crust, Mantle and core convective T, viscosity, activation energy, activation volume	Vp, Vs, Density of a priori models based on geodynamical parameters

Inversion methods

	M1			M2		
	M1a	M1b	M1c	M2a	M2b	M2c
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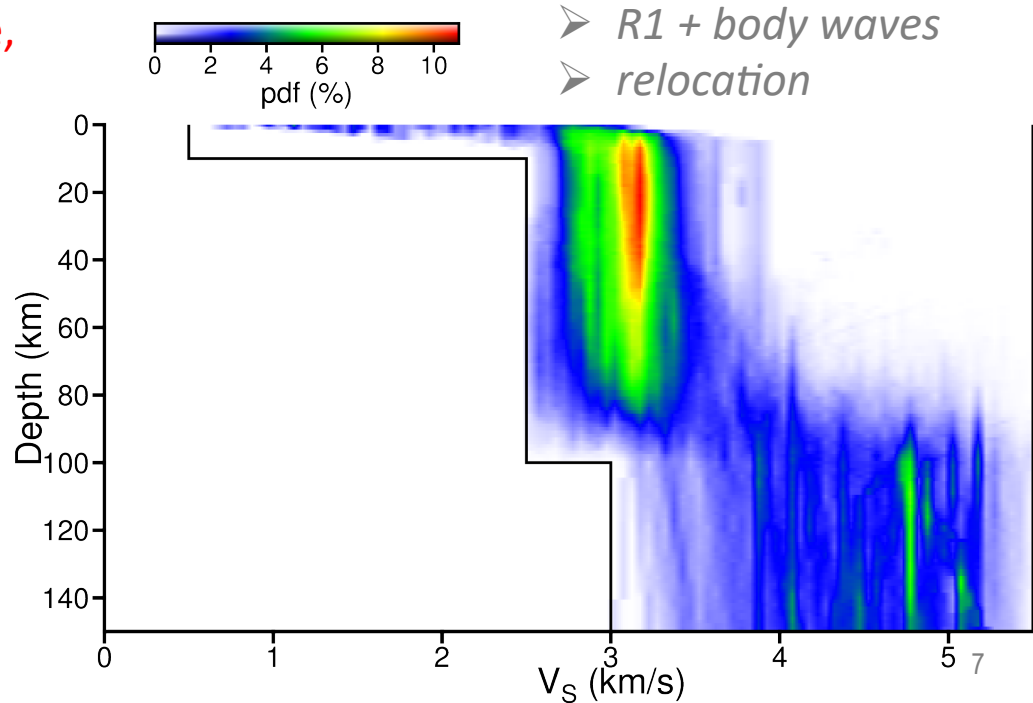
M1a *M. Drilleau, S. Menina*

- **Inversion** of surface waves and body waves arrival times (*Drilleau et al., 2013 ; Panning et al., 2015, 2017*)
- **Forward problem**
  - for surface waves: MINEOS (*Gilbert and Dziewonski, 1975*)
  - for body waves: Deptable (*Shearer, 2009*)
- **Inverse problem**: Markov chains Monte Carlo algorithm
- **Parameterization**: 3 layers in the crust (depth variables)
  + cubic Bézier curves in the mantle
- **Parameters**: Vp, Vs, epicentral distance, origin time, depth
- **Wide prior domain on Vp, Vs**
- Scaling relations between seismic velocities and density
- **Misfit calculation**: differential travel times between tP and tS, tpP, tR



- *R1 + body waves*
- *relocation*

Non-linear explorations of surface wave group velocity pdf

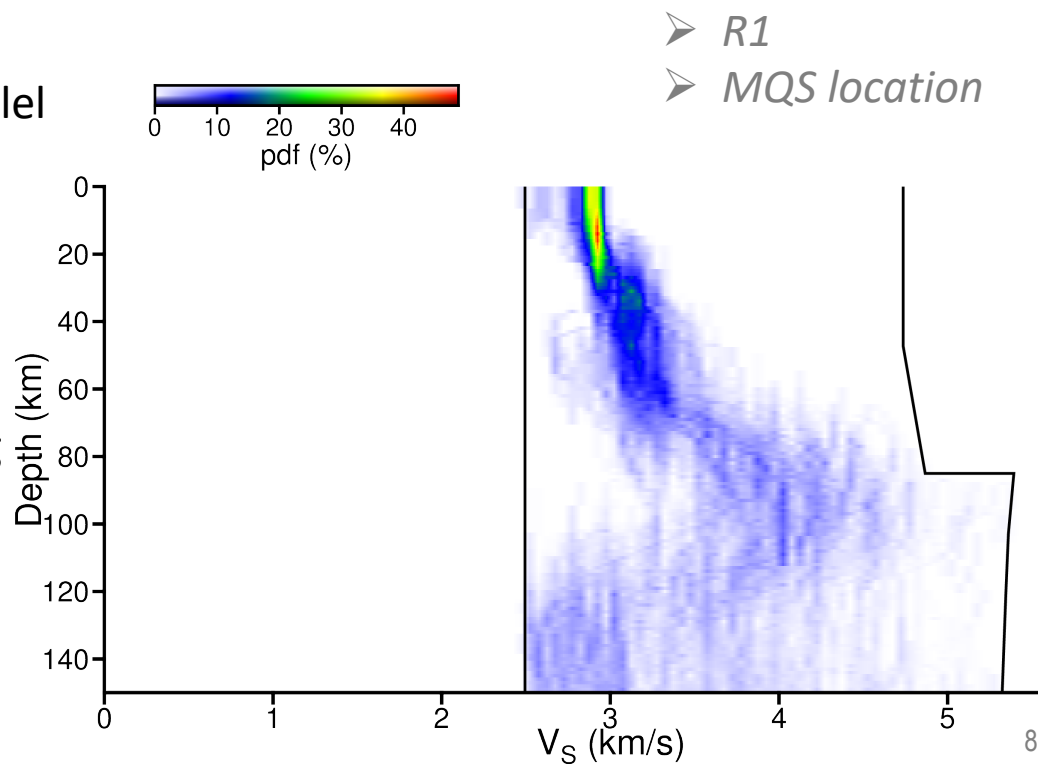
(based *on Drilleau et al., 2013; Panning et al., 2015, 2017; Gaudot 2016*) - in prep.

Forward problem:

- Rayleigh wave group velocities → MINEOS (*Gilbert and Dziewonski, 1975*)
- Each model is made using C1 Bézier curves (using randomly 5 to 7 Bézier points)
- Exploration range between 0-250 km depth

Inversion scheme:

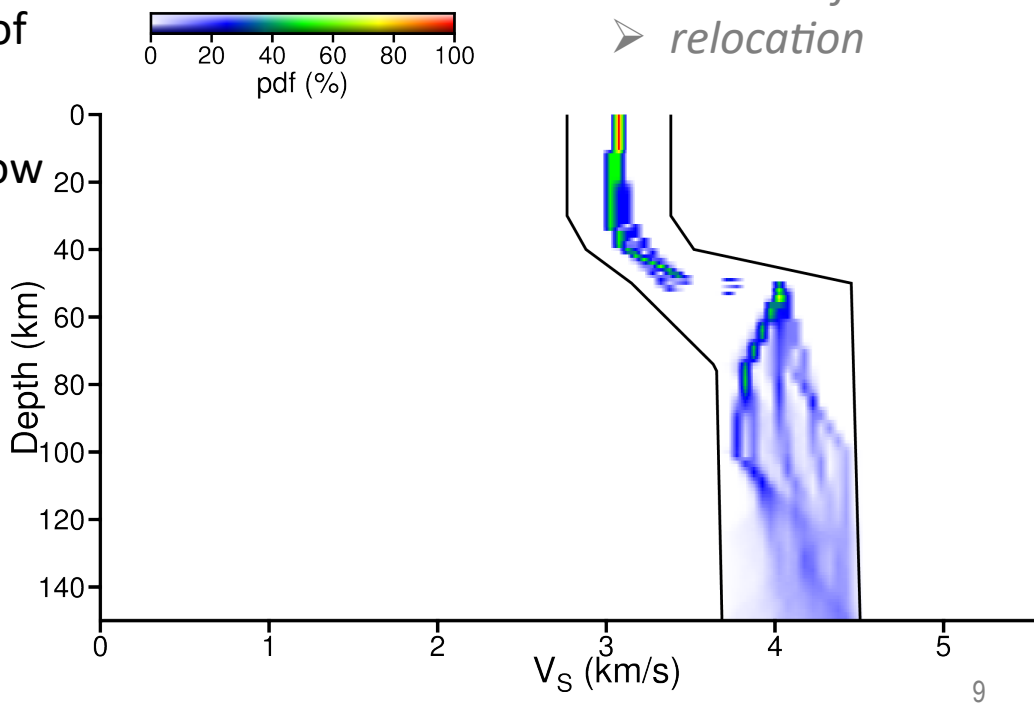
- 70 Markov chains are running in parallel
- The priors are wide but consistent with numerical concerns for low velocities at shallow depth
- Parameters: VSv, VPv, RHO, ETA, XI
- The goodness of fit is computed using an empirical likelihood
- 10000 iterations for each chain
- Posterior densities are based on the 10000 best models



M1c *C. Beghein, H. Xu*

- Waveform modeling using Mineos (Z component only, fundamental mode)
- McMC to search for Vs models to fit filtered waveform using perturbation theory
- Obtain distribution of Vs models and phase velocities
- Inversion of the CMT
- Vs structure in the crust was first tuned manually to roughly fit the data
- Allow Vs perturbation relative to reference model in range [-10%, +10%]
- Misfit defined as the sum of squares of the difference between data and synthetics within selected time window
- 8 Markov Chains in parallel
- For each chain, 60,000 models were sampled after a 'burn-in' of 80,000 models
- Tested different starting models from Zheng et al (2015)

- *R1 waveform*
- *relocation*



Inversion methods

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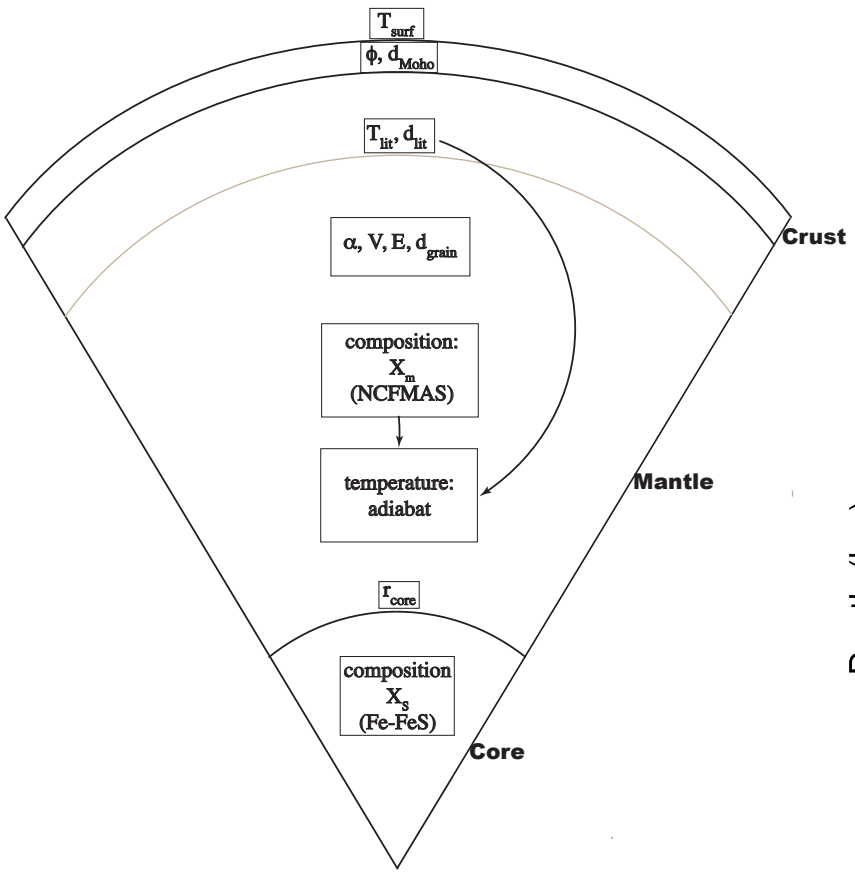
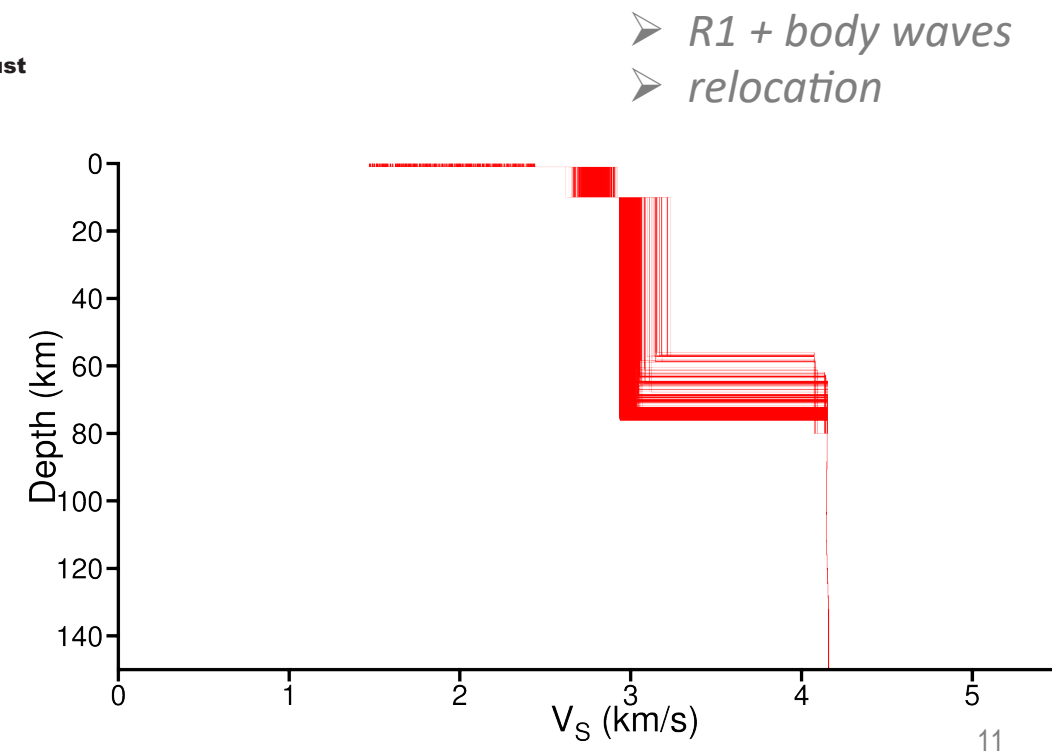
Misfit function calculated on	Differential arrival times	Group velocities	Waveforms	Travel times and group velocities	Differential arrival times	Travel times
Inverted structure parameters	Vp, Vs	Vp, Vs, Density	Vs	Vp, Vs, Density in crust and comp and T in mantle	Vp, Vs, Density in crust, Mantle and core convective T, viscosity, activation energy, activation volume	Vp, Vs, Density of a priori models based on geodynamical parameters

M2a *A. Khan*

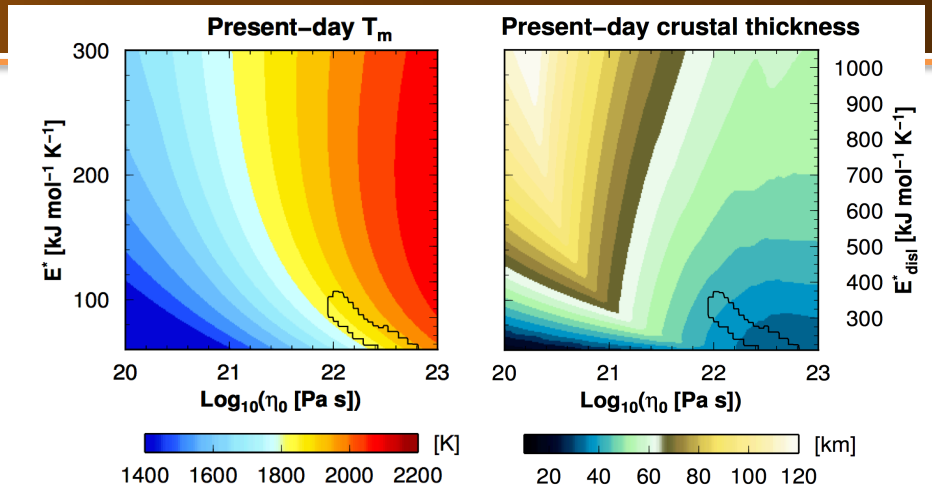
- Inversion of surface waves and body waves arrival times for interior structure and event parameters.
- « Structural » model parameters are shown in the figure. Note that crust is parameterized using density, P- and S-wave velocity.





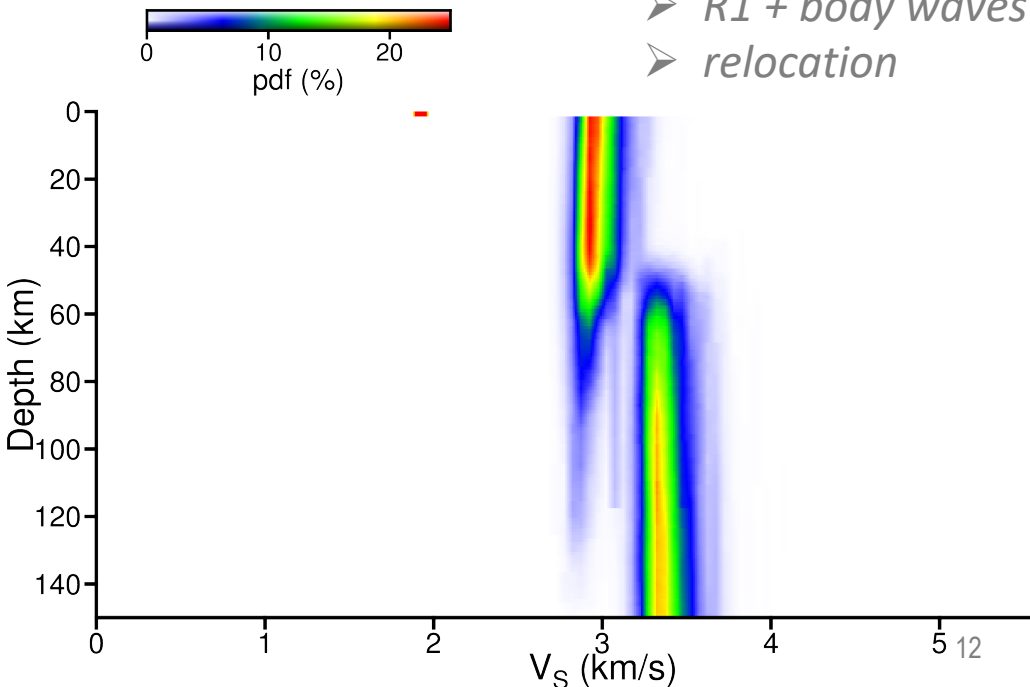
M2b *H. Samuel, M. Drilleau*

- Investigation of the Mars' cooling history by modeling its thermal evolution
- Parameters:
  - The initial core and mantle convecting temperatures
  - The viscous rheology of the Martian mantle
  - The activation energy
  - The activation volume
  - The core radius
  - + epicentral distance, depth
- Strong trade-offs between Mars' thermal state and its mantle rheology



Samuel et al., accepted in Nature.

- *R1 + body waves*
- *relocation*



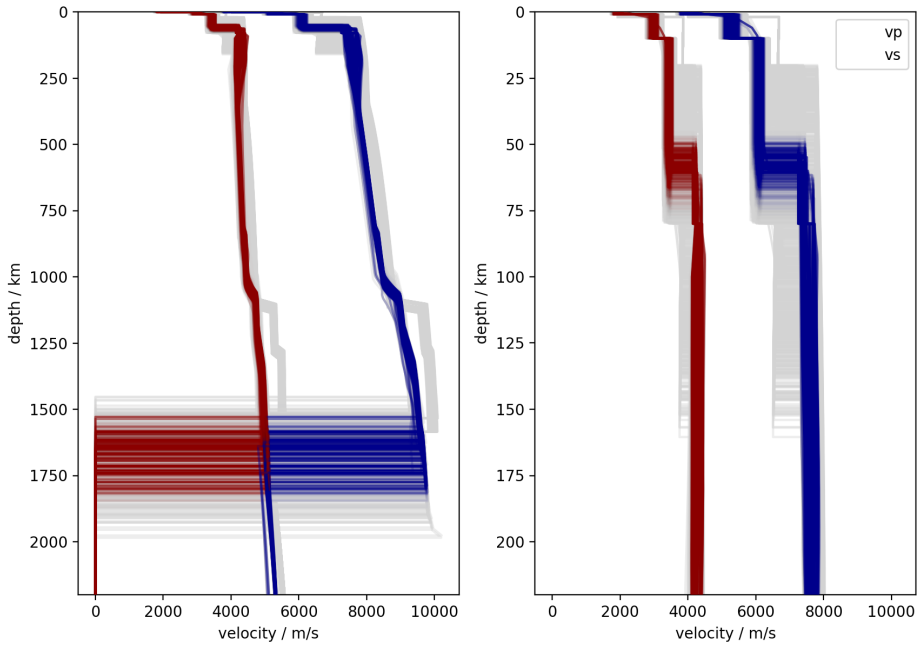
M2c *S. Stähler, M. van Driel, Marsquake Service*

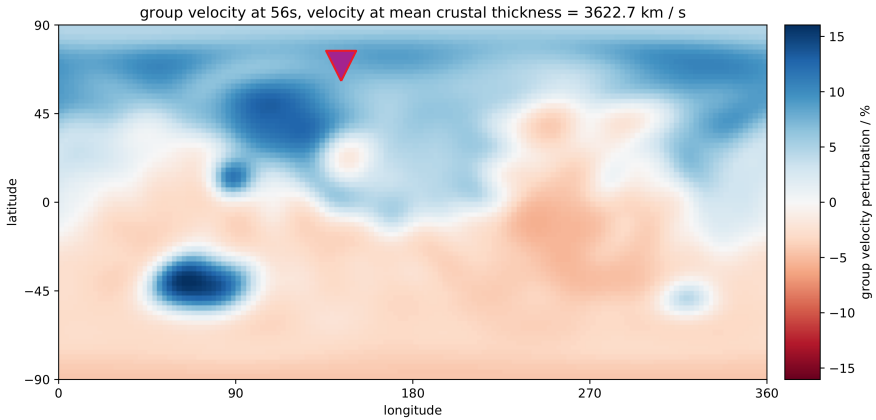
- Uses 2000+ a priori models (vp, vs, rho) from different authors:
  - now: Khan, Rivoldini, Samuel
  - Upcoming: Gudkova, Nimmo, King

- Calculates probability of:
  - Mantle Model (vp, vs)
  - Source depth
  - Source distance

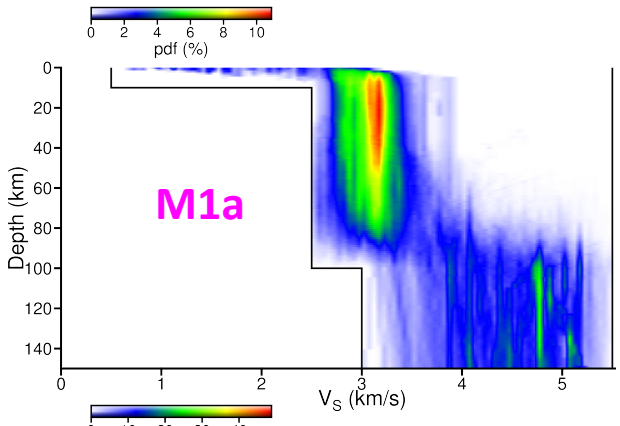
- Data:
  - All body waves
  - R1/G1 phases 10s – 120s (if detectable)

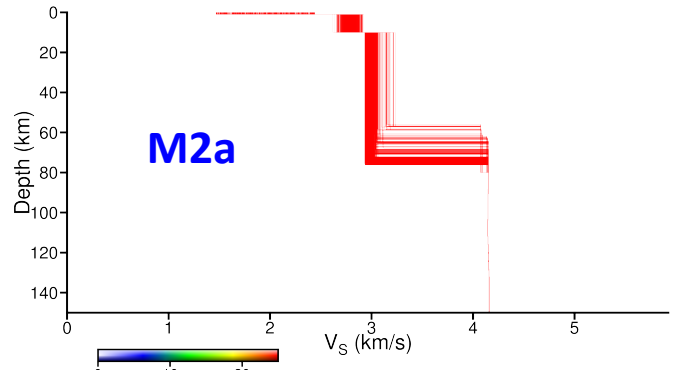
- 3D correction based on:
  - Gravity maps
  - Density contrast over Moho in each model

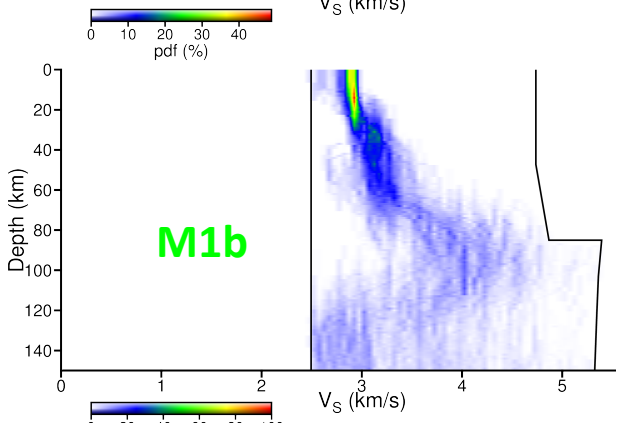


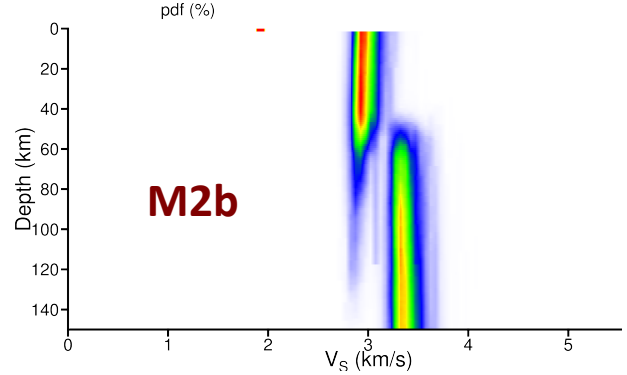


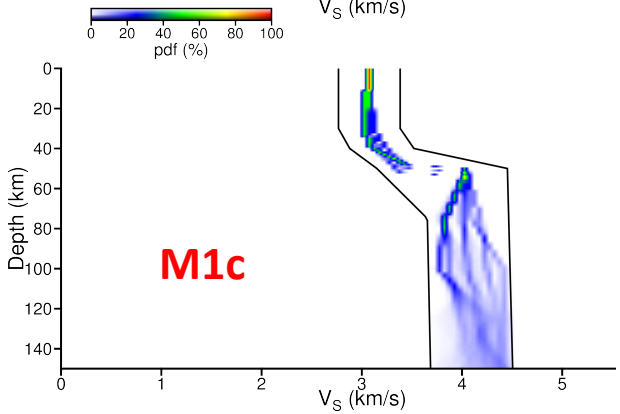
Inversion of first orbit Rayleigh wave



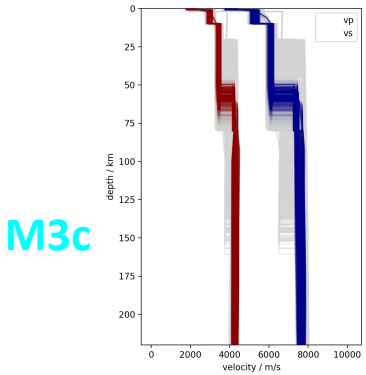




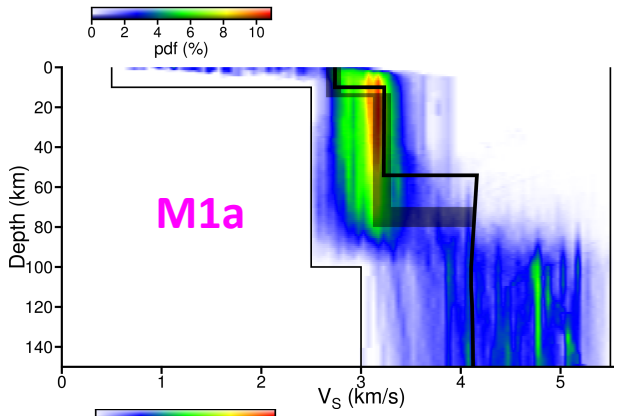


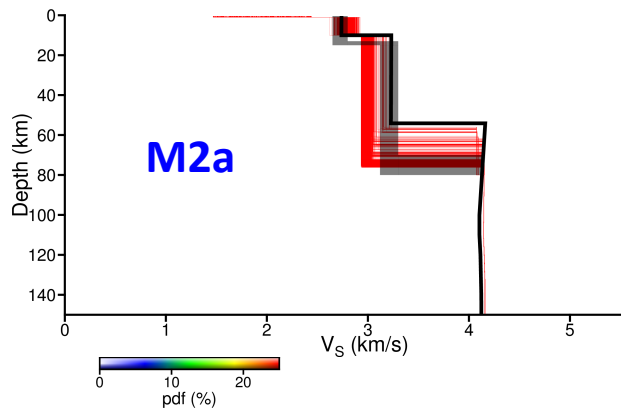


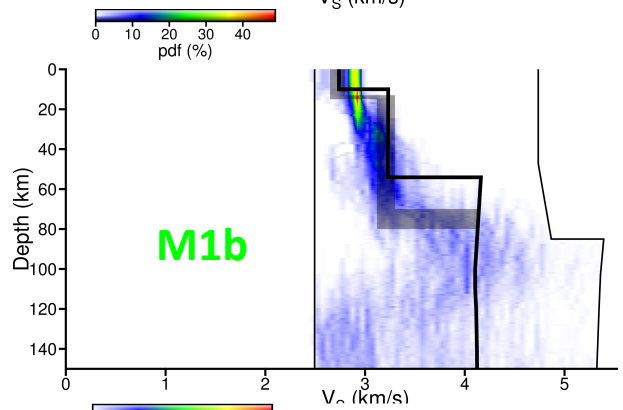
Where is the true averaged model along the minor arc ????

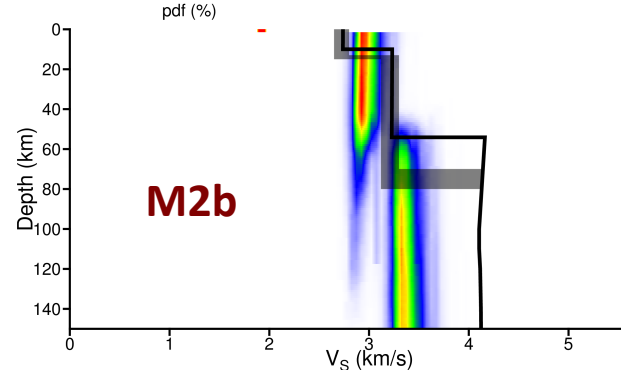


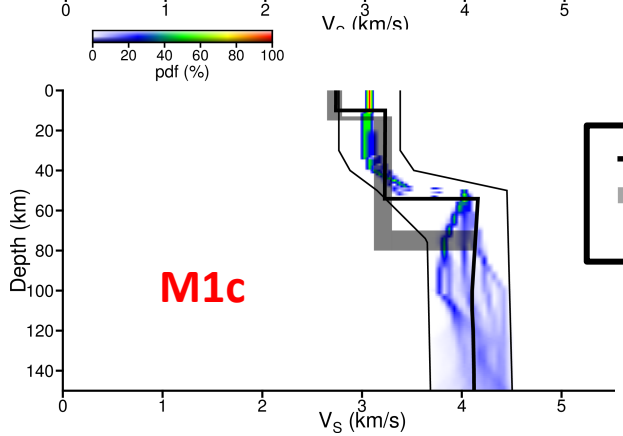
Inversion of first orbit Rayleigh wave



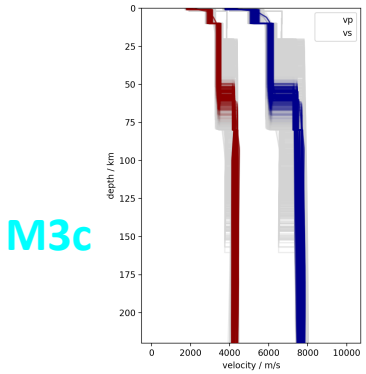




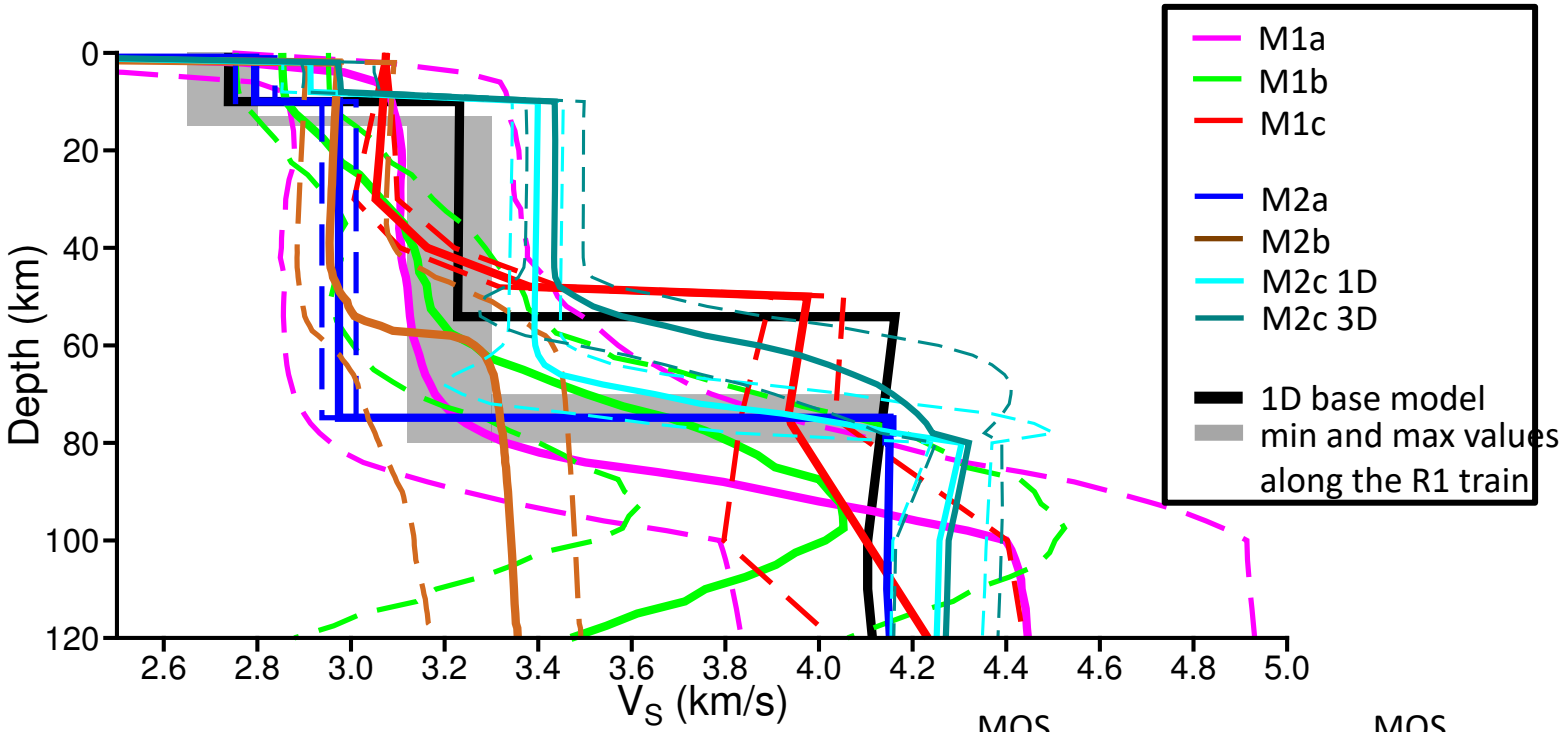


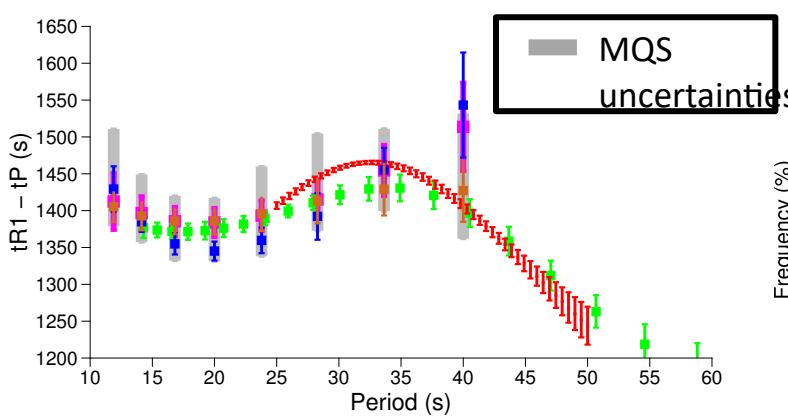


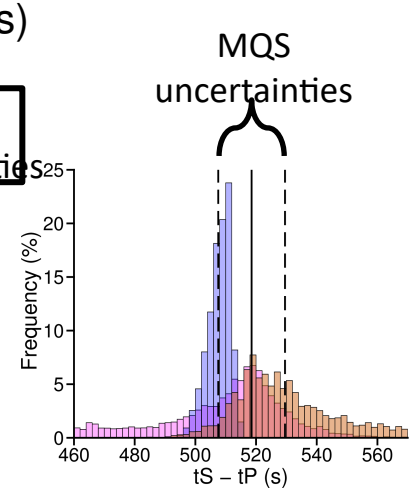
1D base model
min and max values along the R1 train

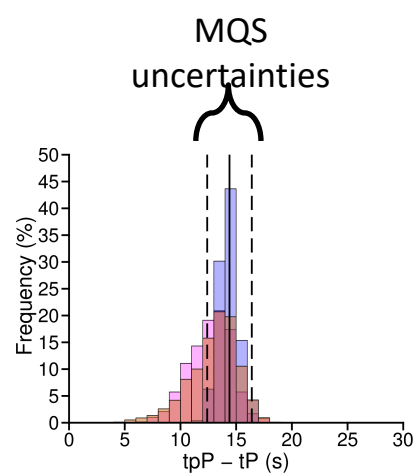


Inversion of first orbit Rayleigh wave

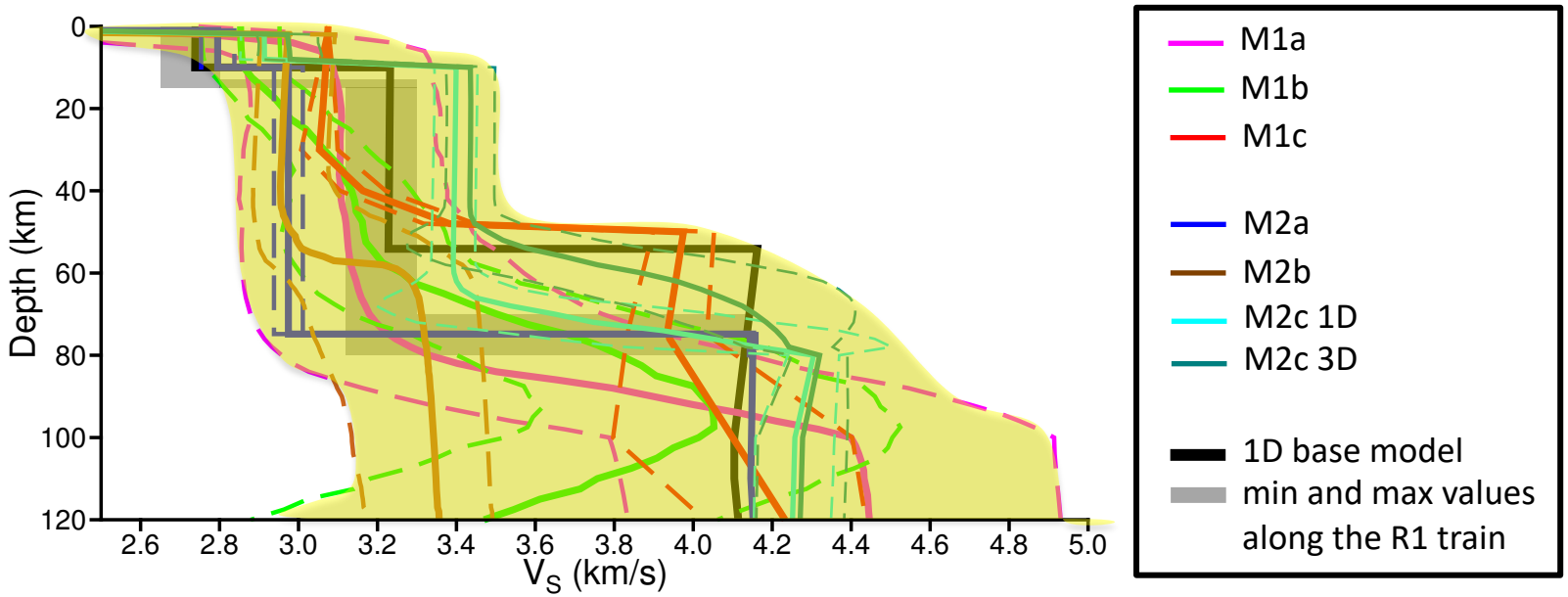








Conclusion



- Mars is somewhere here in the yellow envelope – a range of approaches is good!
- Error bars do not overlap and often exclude true model
- The differences are due to:
  - → different datasets (MQS/LPG/waveforms)
  - → presence/absence of body waves
  - → location and origin time fixed/inverted
  - → choice of the misfit calculation
  - → choice of the parameterization
  - → choice of the prior
- More tests are needed (and underway