GNOME: Search for Topological Defect Dark Matter

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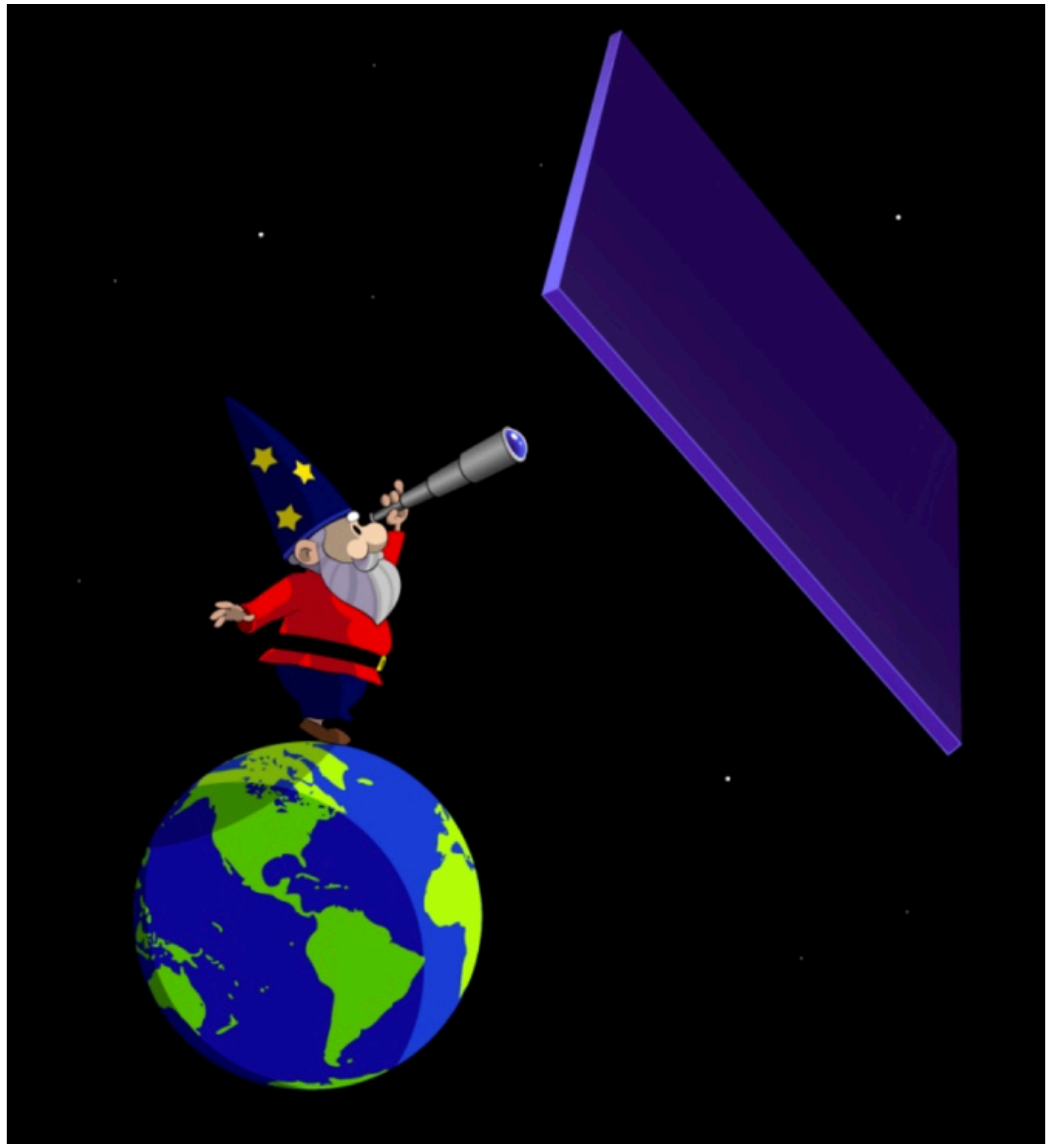


Axion-Like Particle Domain Walls

- Axions are pseudo-scalar boson from spontaneously broken from the Peccei-Quinn U(1) symmetry.

- Axion like-particles (ALPs) are generalized model of the axion, from spontaneously broken axial U(1) symmetry beyond the standard model.

- ALPs are similar to axion, but have less theoretical restrictions:

    - They do not have a relationship between the mass and coupling.

    - They can form a stable domain wall (DW) [1,2,3].

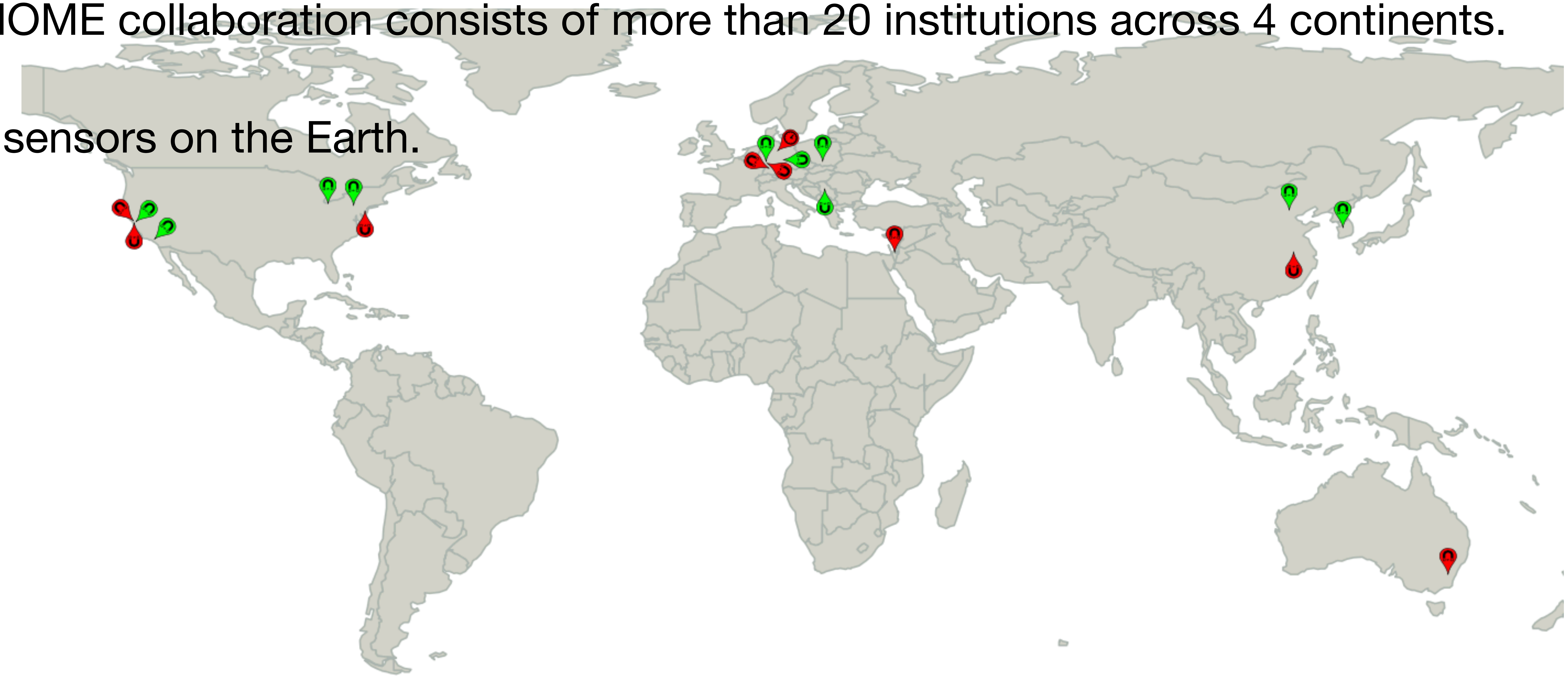
    - They can evade astrophysical observations (e.g. SN1987A) [4,5].

- ALPs can be a localized dark matter around the solar system as a form of DW.

[1] G. Lazarides and Q. Shafi. Axion models with no domain wall problem. Physics Letters B, 115(1):21 – 25, 1982.
[2] T. Hiramatsu, M. Kawasaki, K. Saikawa, and T. Sekiguchi. Axion cosmology with long-lived domain walls. Journal of Cosmology and Astroparticle Physics, 2013(01):001–001, jan 2013.
[3] P. P. Avelino. Parameter-free velocity-dependent one-scale model for domain walls. Phys. Rev. D, 101:023514, Jan 2020.
[4] W. DeRocco, P. W. Graham, and S. Rajendran. Exploring the robustness of stellar cooling constraints on light particles. Phys. Rev. D, 102:075015, Oct 2020.
[5] N. Bar, K. Blum, and G. D'Amico. Is there a supernova bound on axions? Phys. Rev. D, 101:123025, Jun 2020.

GNOME

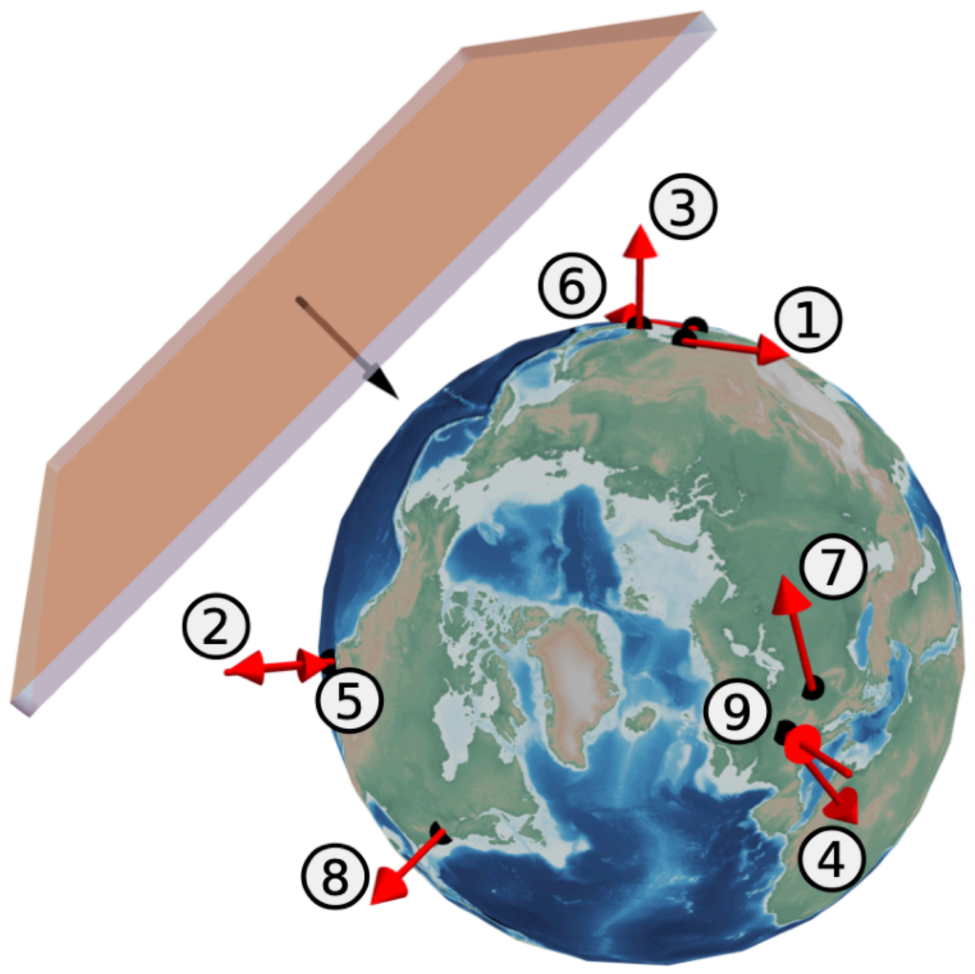
- Global Network of Optical Magnetometers for Exotic physics searches [1,2,3]
- GNOME collaboration consists of more than 20 institutions across 4 continents.
- 17 sensors on the Earth.

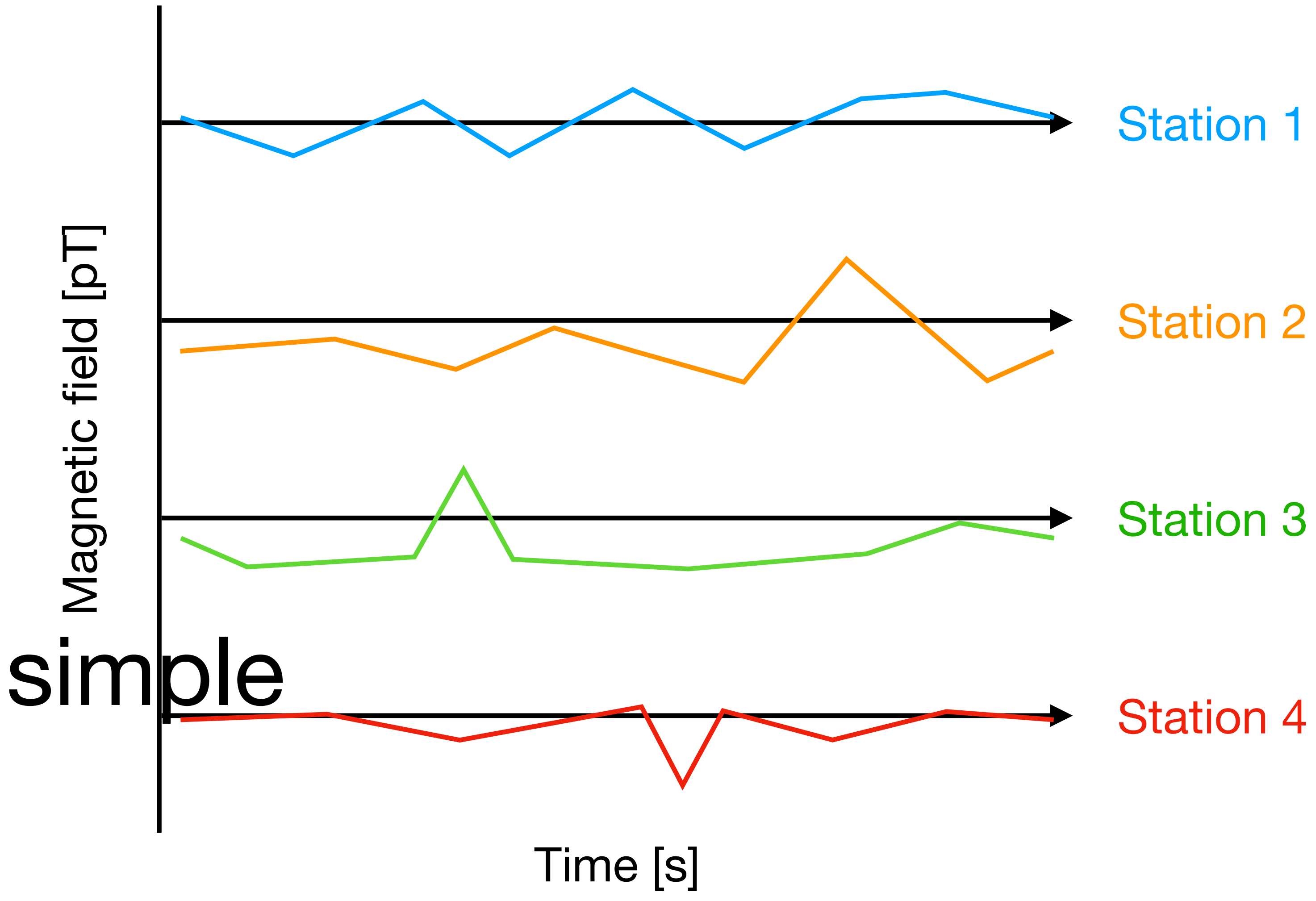


[1] S. Pustelny, et al., The Global Network of Optical Magnetometers for Exotic physics (GNOME): A novel scheme to search for physics beyond the Standard Model. Annalen der Physik, 525:659–670, Sept. 2013.
[2] S. Afach, et al., Characterization of the global network of optical magnetometers to search for exotic physics (gnome). Physics of the Dark Universe, 22:162 – 180, 2018.
[3] S. Afach, et al., Search for topological defect dark matter using the global network of optical magnetometers for exotic physics searches (gnome), 2021.

GNOME for ALP DW Search

- We are looking for localized dark matter models such as ALP DW.
- Detector to test a localized dark matter density:
  - A synchronized network of geographically separated sensors
- Sensor to search for the dark matter:
  - Spin-dependent interaction with atomic magnetometers
- Why ALP DW?
  - Theoretical freedom, suitable mass range, and geometrically simple





Domain-wall Spin-dependent Interaction

- ALPs can have a spin-dependent interaction to atomic spins [1,2].

- Interaction Hamiltonian of the atomic spin: $H_{\mathrm{int}} = \frac{(\hbar c)^{\frac{3}{2}}}{f_{\mathrm{int}}} \hat{S} \cdot \vec{\nabla} a + \gamma \vec{S} \cdot \vec{B}$

  Spin interaction due to magnetic field

  Spin interaction due to ALP field

- Rearrangement: $H_{\mathrm{int}} = \gamma \vec{S} \cdot \left(\vec{B}_{\mathrm{ALP}} + \vec{B} \right)$

- Pseudo-magnetic field:

$$\vec{B}_{\mathrm{ALP}} = \frac{4}{\mu_B} \frac{f_{\mathrm{SB}}}{f_{\mathrm{int}}} m_a c^2 \frac{\sigma_s}{g_{F,s}} \hat{x}$$

$$a(x) = \frac{4 f_{\mathrm{SB}}}{\sqrt{\hbar c}} \arctan \left(\exp \left(\frac{m_a c^2}{\hbar c} x \right) \right)$$

- This is not a real magnetic field, but a substitution having the tesla unit.

- Atomic magnetometer will detect it:

$$H_{\mathrm{int}} = \gamma \vec{S} \cdot \left(\vec{B}_{\mathrm{ALP}} + \vec{B} \right) \approx \gamma \vec{S} \cdot \vec{B}_{\mathrm{ALP}}, \quad \vec{B} \approx 0$$

magnetic shielding

[1] M. Pospelov, et al. Detecting Domain Walls of Axionlike Models Using Terrestrial Experiments. Physical Review Letters, 110(2):021803,
[2] S. Afach, et al., Search for topological defect dark matter using the global network of optical magnetometers for exotic physics searches

Pseudo-magnetic Field from Interaction

- What the magnetometer measured is a projected pseudo-magnetic field:

$$\vec{B}_{\mathrm{ALP}} = \frac{4}{\mu_B}\frac{f_{\mathrm{SB}}}{f_{\mathrm{int}}}m_a c^2 \frac{\sigma_s}{g_{F,s}}\hat{x} \longrightarrow B_{\mathrm{ALP}} = \frac{4}{\mu_B}\frac{f_{\mathrm{SB}}}{f_{\mathrm{int}}}m_a c^2 \frac{\sigma_s}{g_{F,s}}\cos\psi_s$$

Compound factor

ALP field factor Magnetometer factor

- There are further parameters to determine the domain-wall signal on a magnetometer:
  - Domain-wall density:

$$\rho_{\mathrm{DW}} \approx \frac{\sigma}{L} = \frac{1}{L}\int \frac{dx}{\hbar c}\left|\frac{da}{dx}\right|^2 = \frac{8 f_{\mathrm{SB}} m_a c^2}{L\hbar^2 c^2} \longrightarrow f_{\mathrm{SB}}\sqrt{m_a c^2} = \hbar c\sqrt{\frac{L\rho_{\mathrm{DW}}}{8}}$$

L Size of domain
ρ_{DW} DW density

  - Domain-wall thickness

$$d = \frac{2\hbar c}{m_a c^2}$$

Domain-wall Signal

- Amplitude

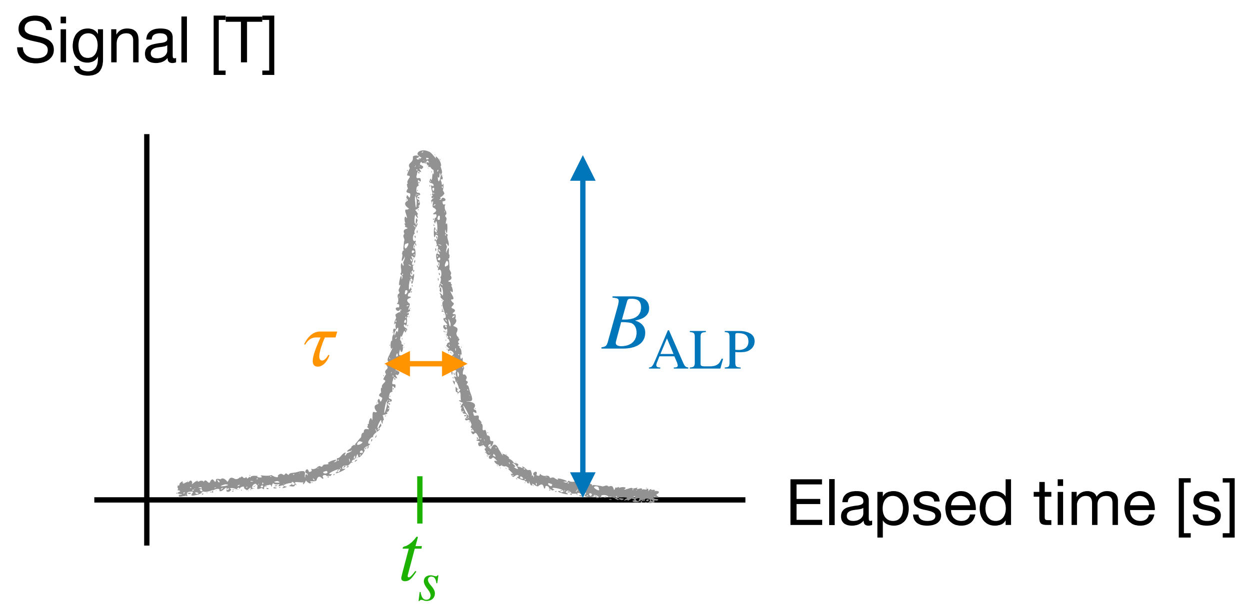
$$B_{\mathrm{ALP}} = \frac{4}{\mu_B}\frac{f_{\mathrm{SB}}}{f_{\mathrm{int}}} m_a c^2 \frac{\sigma_s}{g_{F,s}} \cos\psi_s = B_s \frac{1}{f_{\mathrm{int}}}\sqrt{m_a c^2}\cos\psi_s$$

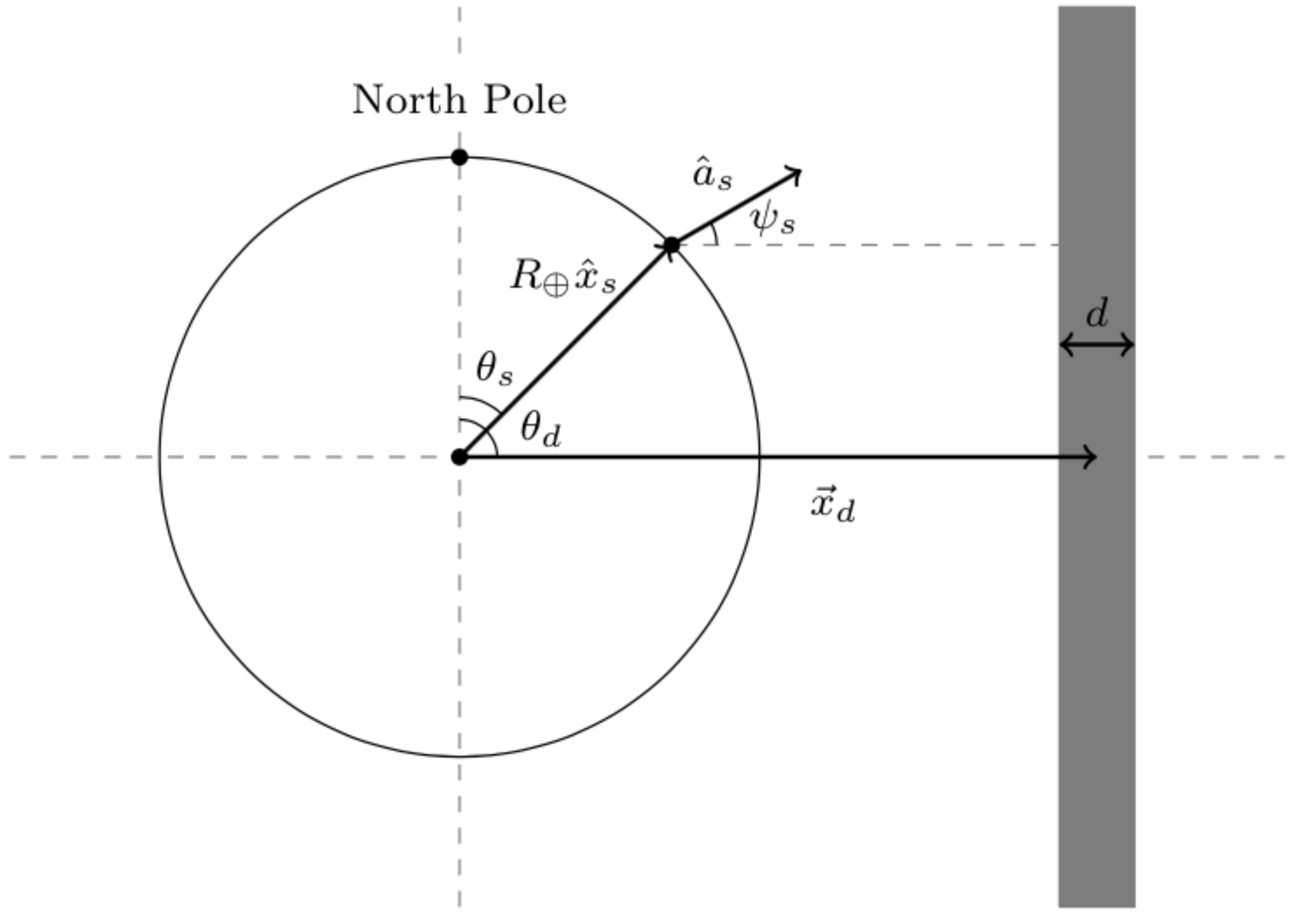
- Duration

$$\tau = \frac{d}{|v|} = \frac{2\hbar c}{m_a c^2 |v|}$$

- Timing

$$t_s = \frac{(\vec{x}_d - \vec{x}_s)\cdot\hat{x}_d}{|v|}$$



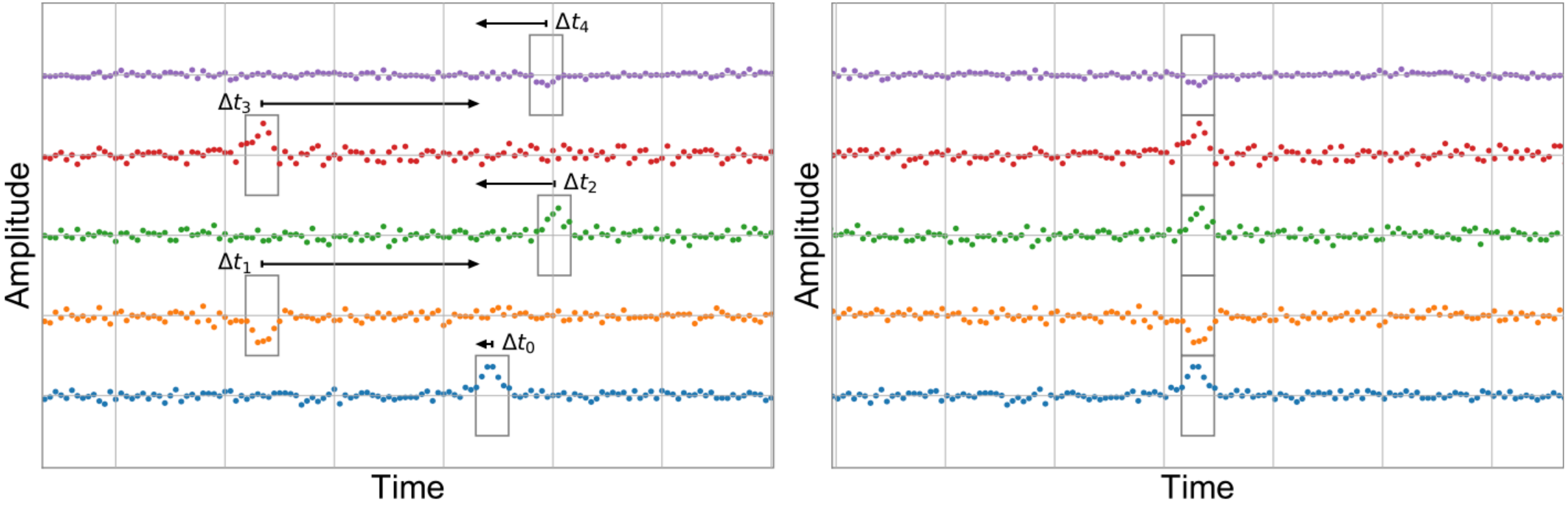


Amplitude and timing are unique to sensor

- GNOME has a number of magnetometer sensors in the world, installed at different locations.
- Pairs of the domain-wall signal amplitude and timing are all distinct for each sensor.

Former Analysis Method

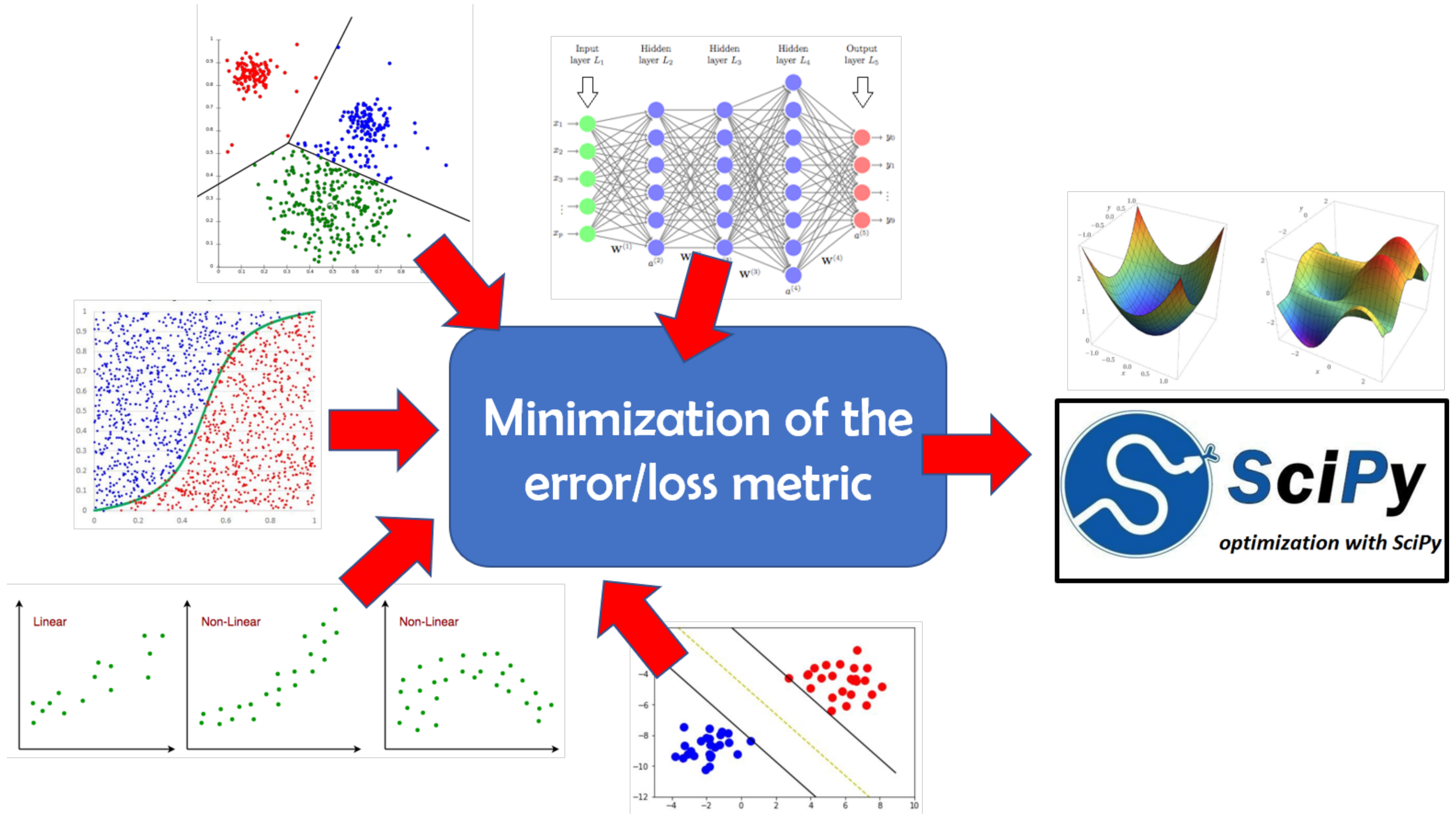
- DW coincidence check with velocity scanning by time shifting among stations
- DW consistence check with DW orientation and sensitive directions of stations
- DW significance check with simulated false positive events



[1] H. Masia-Roig, et al., Analysis method for detecting topological defect dark matter with a global magnetometer network. Physics of the Dark Universe, 28:100494, 2020.

Signal Detection: Minimization Problem

- Minimization of $f\left(x_{i+1}\right) = f\left(x_i\right) - \vec{\gamma} \cdot \vec{\nabla} f\left(x_i\right)$ where $\vec{\nabla} f = 0$ requires well-designed optimization setup.
  - Appropriate $f(x)$: cost function
  - Appropriate x_0: grid estimation
  - Appropriate $\vec{\gamma}$: adaptive momentum



Minimization is a what Machine Learning does [1].

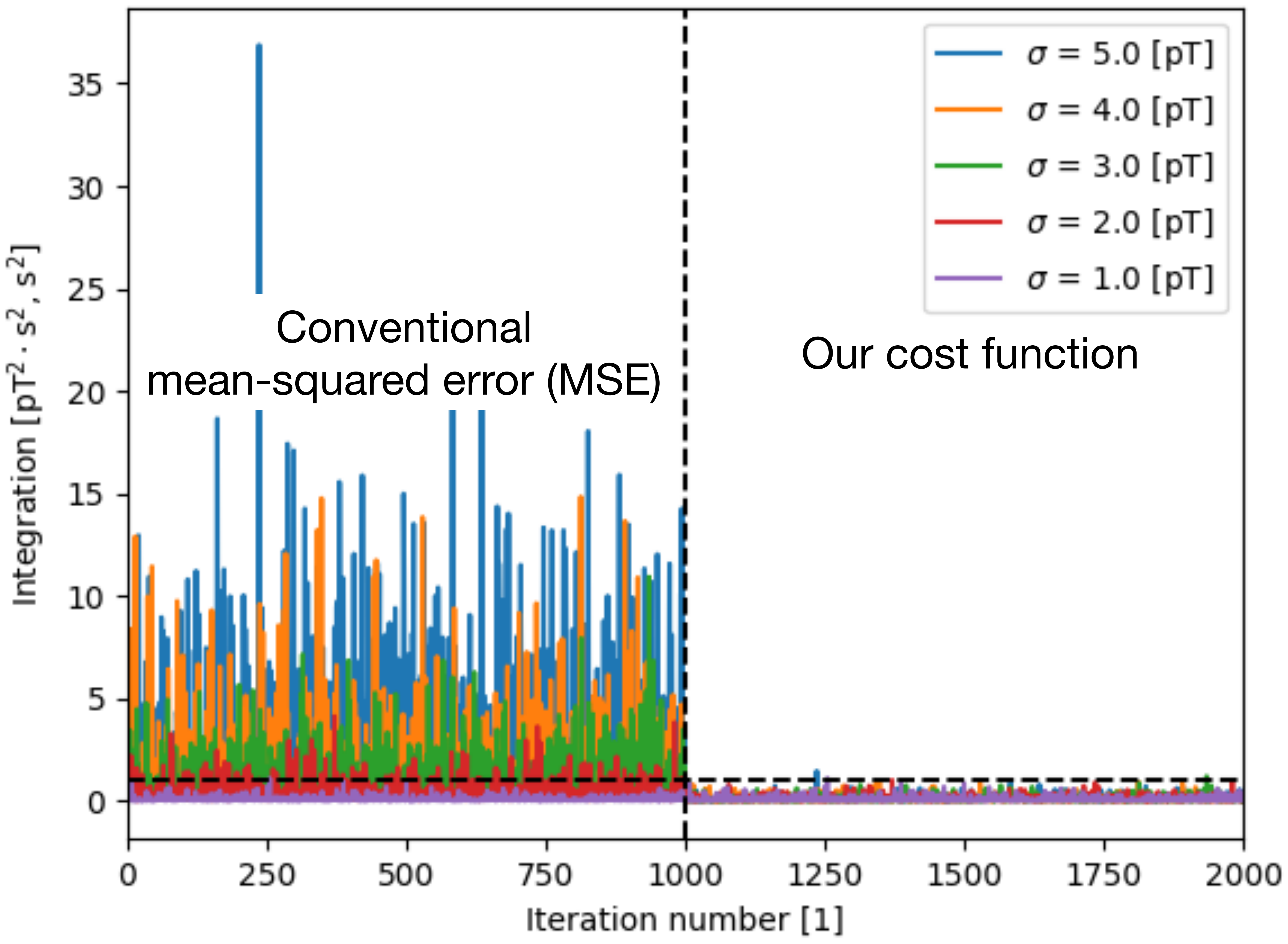
[1] Tirthajyoti Sarkar, Optimization with SciPy and application ideas to machine learning, towards data science

Cost function

- Minimization of $f\left(x_{i+1}\right) = f\left(x_i\right) - \vec{\gamma} \cdot \vec{\nabla} f\left(x_i\right)$ where $\vec{\nabla} f = 0$ requires well-designed optimization setup.
  - Appropriate $f(x)$: cost function

$$f(x) = \frac{1}{N} \sum_s \frac{1}{\left(\sigma_s \text{ s}\right)^2 \mathcal{T}} \int_0^{\mathcal{T}} \left(\int_0^t \left(S_s(t') - \tilde{S}_s(t'; x) \right) dt' \right)^2 dt$$

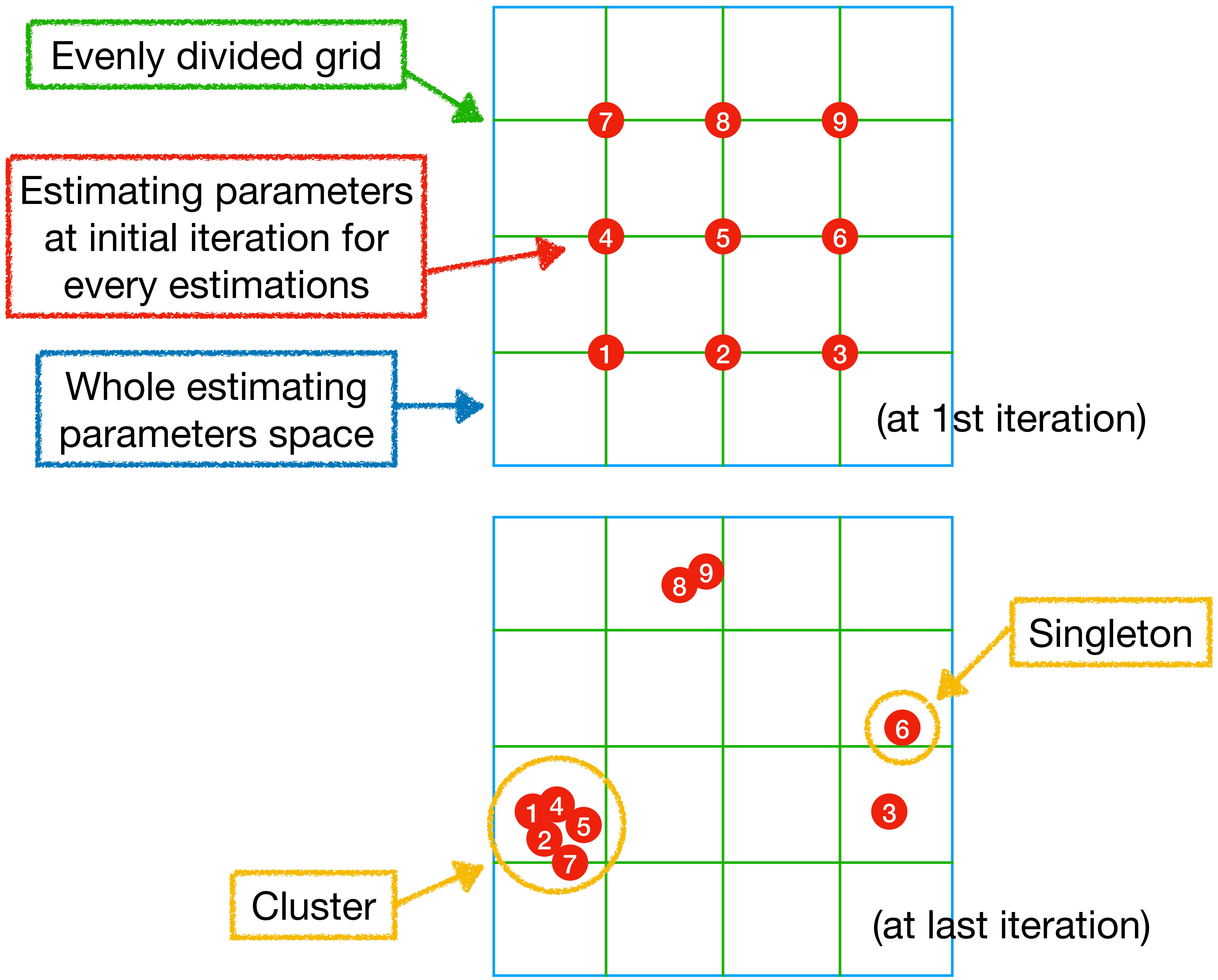
- Independent of
  - # of stations
  - Standard deviation of station



Simulations of cost function for Gaussian noises

Grid Estimation

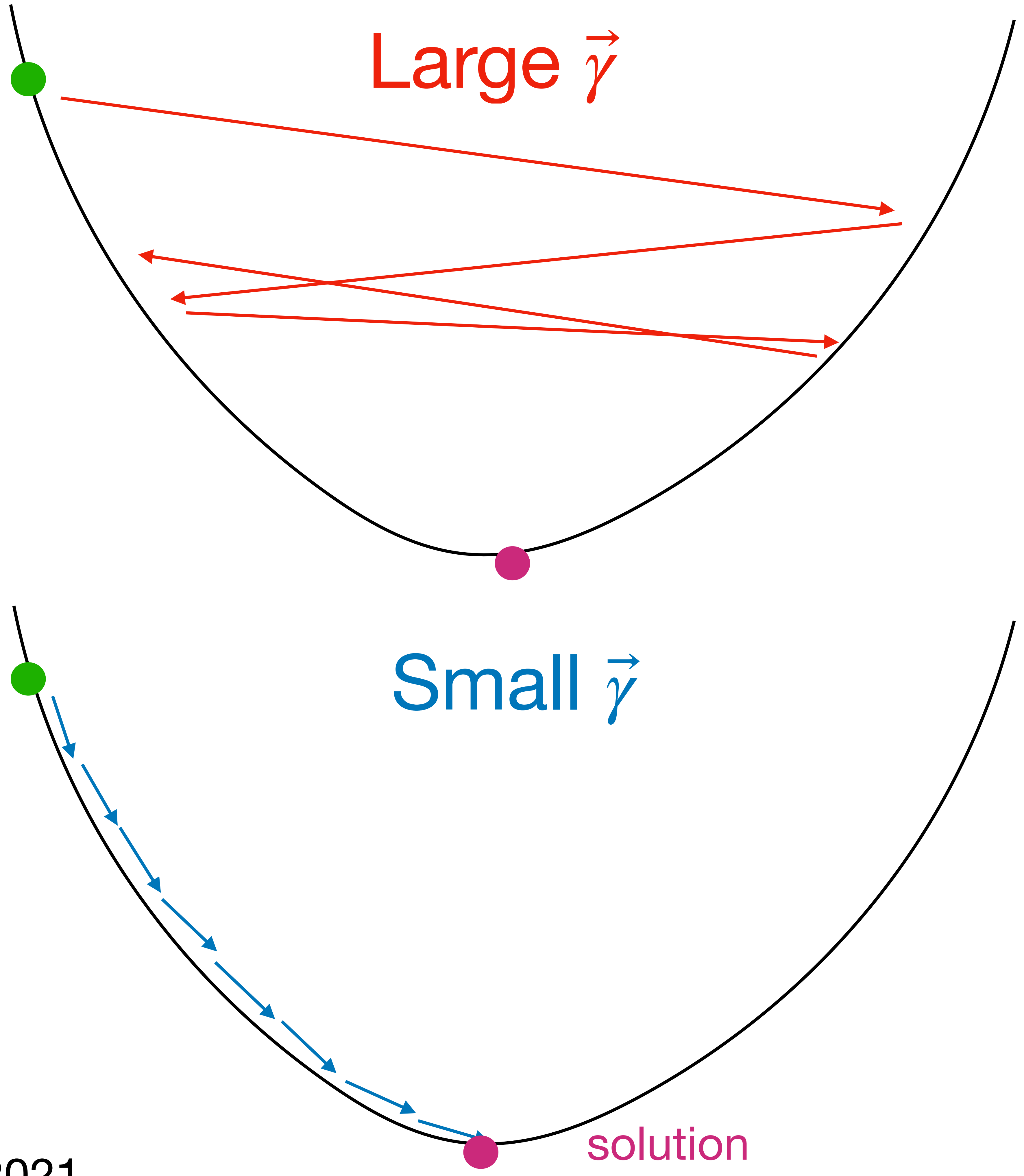
- Minimization of $f\left(x_{i+1}\right) = f\left(x_i\right) - \vec{\gamma} \cdot \vec{\nabla} f\left(x_i\right)$ where $\vec{\nabla} f = 0$ requires well-designed optimization setup.
  - Appropriate $f(x)$: cost function
  - Appropriate x_0: grid estimation



Adaptive Momentum

- Minimization of $f\left(x_{i+1}\right) = f\left(x_i\right) - \vec{\gamma} \cdot \vec{\nabla} f\left(x_i\right)$ where $\vec{\nabla} f = 0$ requires well-designed optimization setup.
  - Appropriate $f(x)$: cost function
  - Appropriate x_0: grid estimation
  - Appropriate $\vec{\gamma}$: adaptive momentum

$$\vec{\gamma} = \vec{\gamma}(i)$$



Estimation of Optimization Parameters

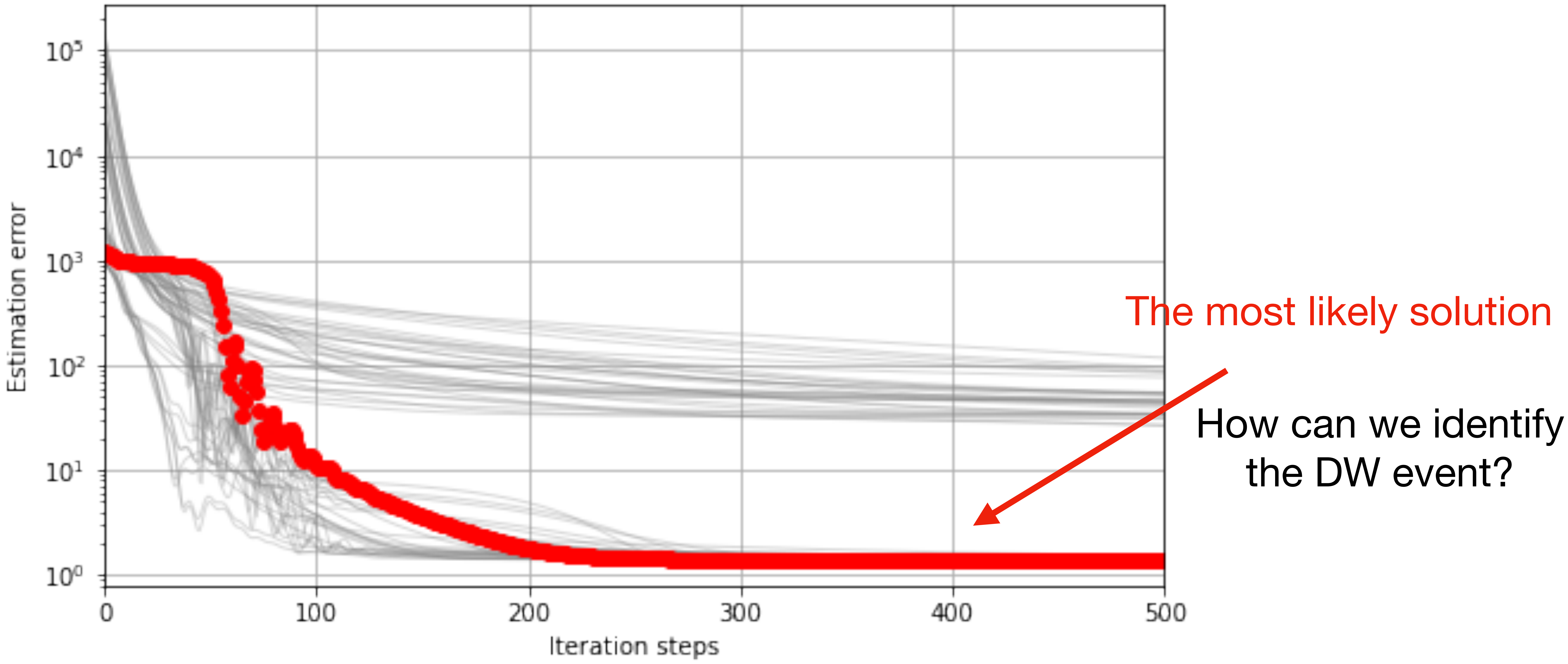
- The cost function is minimized when the optimization parameters correspond to the ALP DW crossing event IF exists.

- The optimization process estimates the ALP parameters.

	Parameters	Symbols	Estimation ranges	Normalization maps $f(x): x \mapsto f(x)$
ALP	mass	$m_a c^2$	$(10^{-15}\text{ eV}, 10^{-11}\text{ eV})$	$(\log_{10}(x/\text{eV}) + 15)/4$
	interaction scale	f_{int}	$(10^4\text{ GeV}, 10^8\text{ GeV})$	$(\log_{10}(x/\text{GeV}) - 4)/4$
Direction	polar angle	θ_d	$[0, \pi]$	x/π
	azimuthal angle	ϕ_d	$[0, 2\pi)$	$x/2\pi$
Timing	relative speed	$\lvert\vec{v}_d\rvert$	$(100\text{ kmps}, 550\text{ kmps})$	$(x - 100\text{ kmps})/450\text{ kmps}$
	relative position	$\lvert\vec{p}_d\rvert$	$(6.4\times10^3\text{ km}, 12\times10^3\text{ km})$	$(x - 6.4\times10^3\text{ km})/5.6\times10^3\text{ km}$

Tracing Estimation Error

- Estimation error with respect to the optimization iteration step for each grid point (2 grid lines for each parameter):



How can we identify the DW event?

Criterion for Estimation Errors

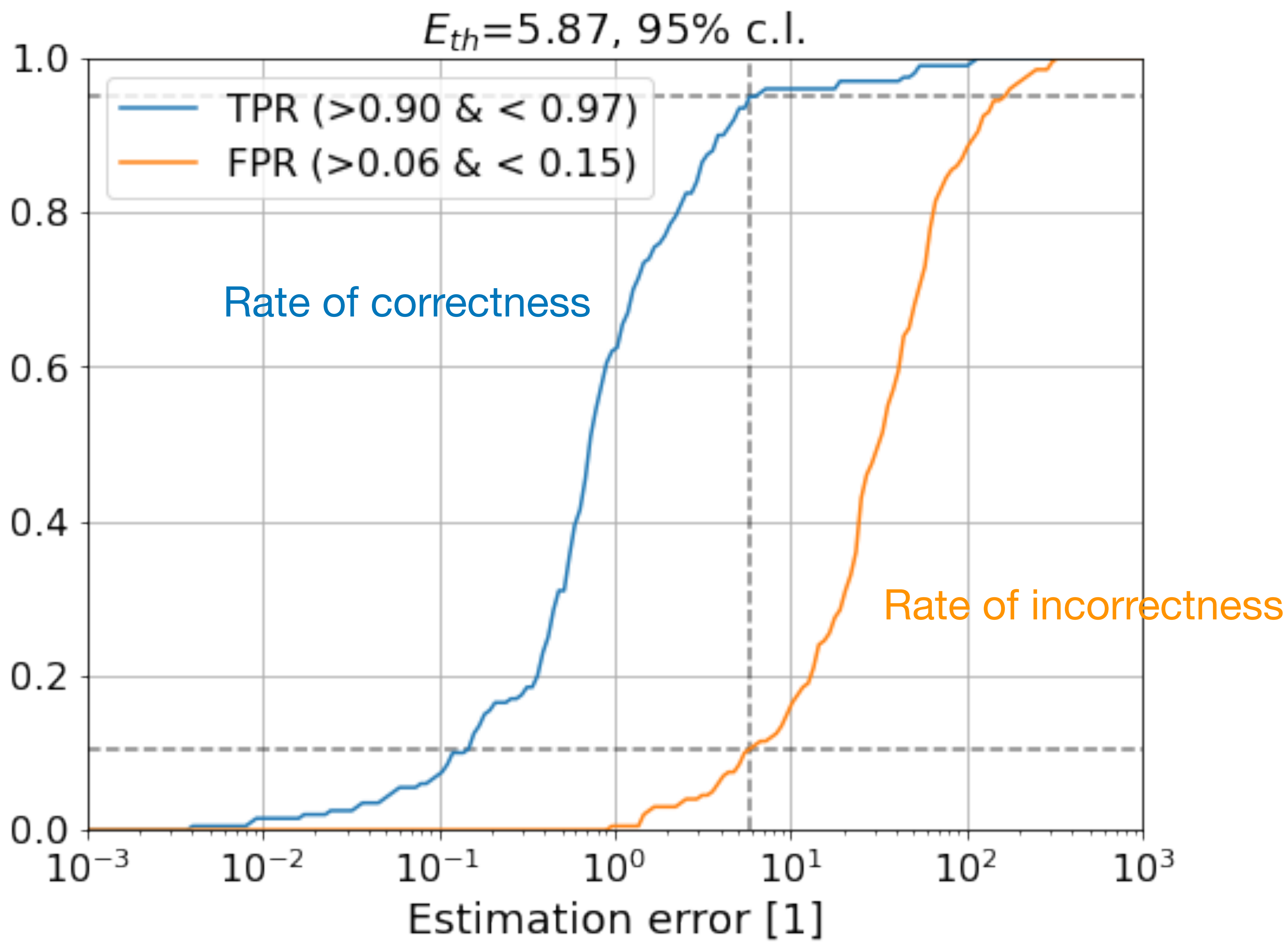
- This analysis method is tested under simulations: w/ and w/o domain-wall crossing events.
- 400 simulations with random variables.
- Confidence interval by Wilson score [1,2]

$$\mathrm{CL}_- = \max\left\{0, \frac{2np + z^2 - \left(z\sqrt{z^2 - \frac{1}{n} + 4np(1-p) + (4p-2)} + 1\right)}{2(n+z^2)}\right\}$$

$$\mathrm{CL}_+ = \min\left\{1, \frac{2np + z^2 + \left(z\sqrt{z^2 - \frac{1}{n} + 4np(1-p) - (4p-2)} + 1\right)}{2(n+z^2)}\right\}$$

$$n = 400, \quad p_{\mathrm{TPR}} = 0.95, \; p_{\mathrm{FPR}} = 0.10, \quad z = 1.96$$

- Binary classification of the analyzed result



[1] E. B. Wilson and G. N. Lewis. The space-time manifold of relativity. the non-euclidean geometry of mechanics and electromagnetics. Proceedings of the American Academy of Arts and Sciences, 48(11):389– 507, 1912.
[2] R. G. Newcombe, Statistics in Medicine 17, 857 (1998)

Parameter Space Optimization

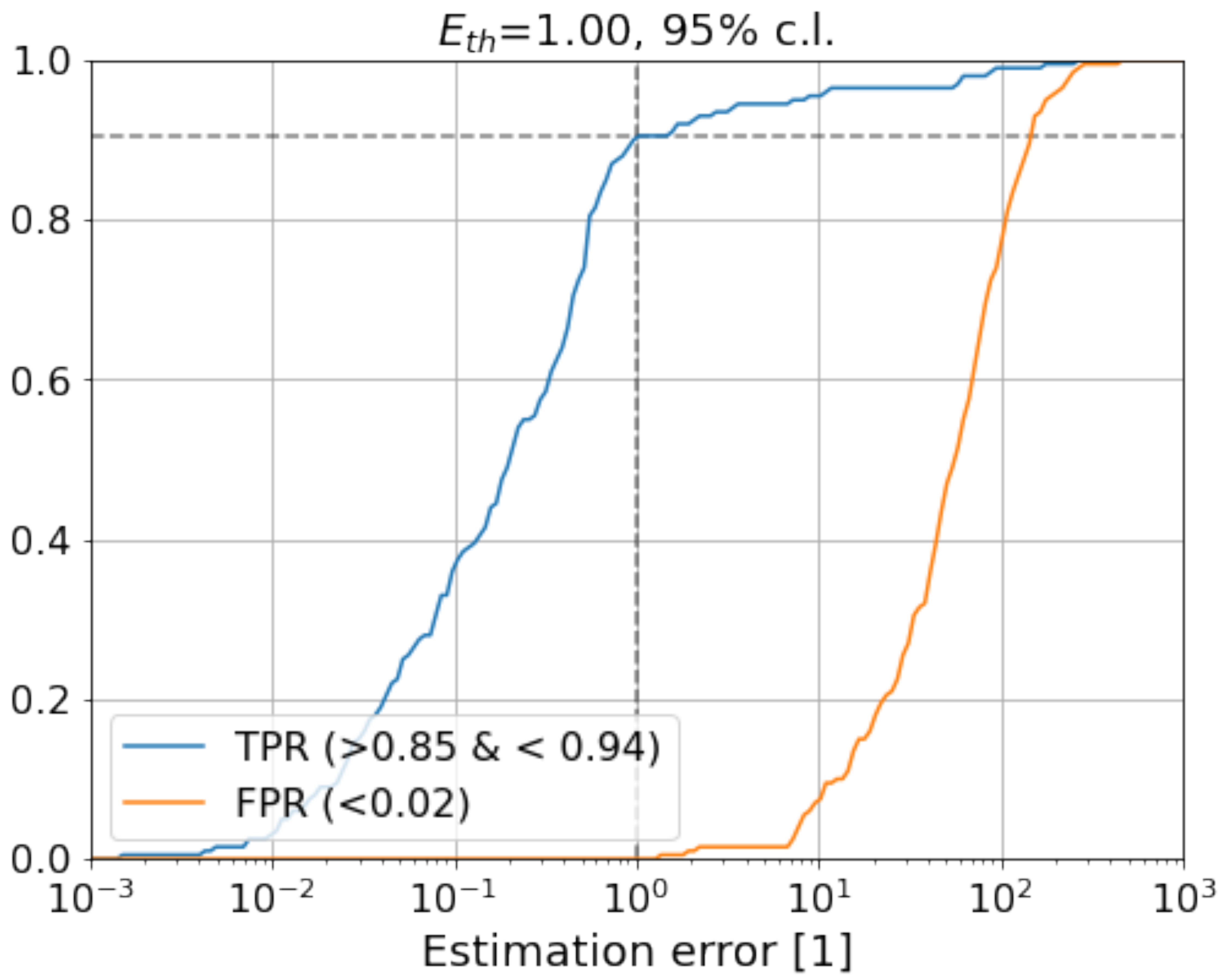
- Recall: the optimization process estimates the ALP parameters.

- True positives: how well they are estimated

$$\text{distance} = \sqrt{\left(\left(m_a c^2\right)_{\text{sol}} - \left(m_a c^2\right)_{\text{est}}\right)^2 + \left(\left(f_{\text{eff}}\right)_{\text{sol}} - \left(f_{\text{eff}}\right)_{\text{est}}\right)^2}$$

- Figure of merits:
  - # of fractions for distance < 0.02 ×
  - Area of the parameter space

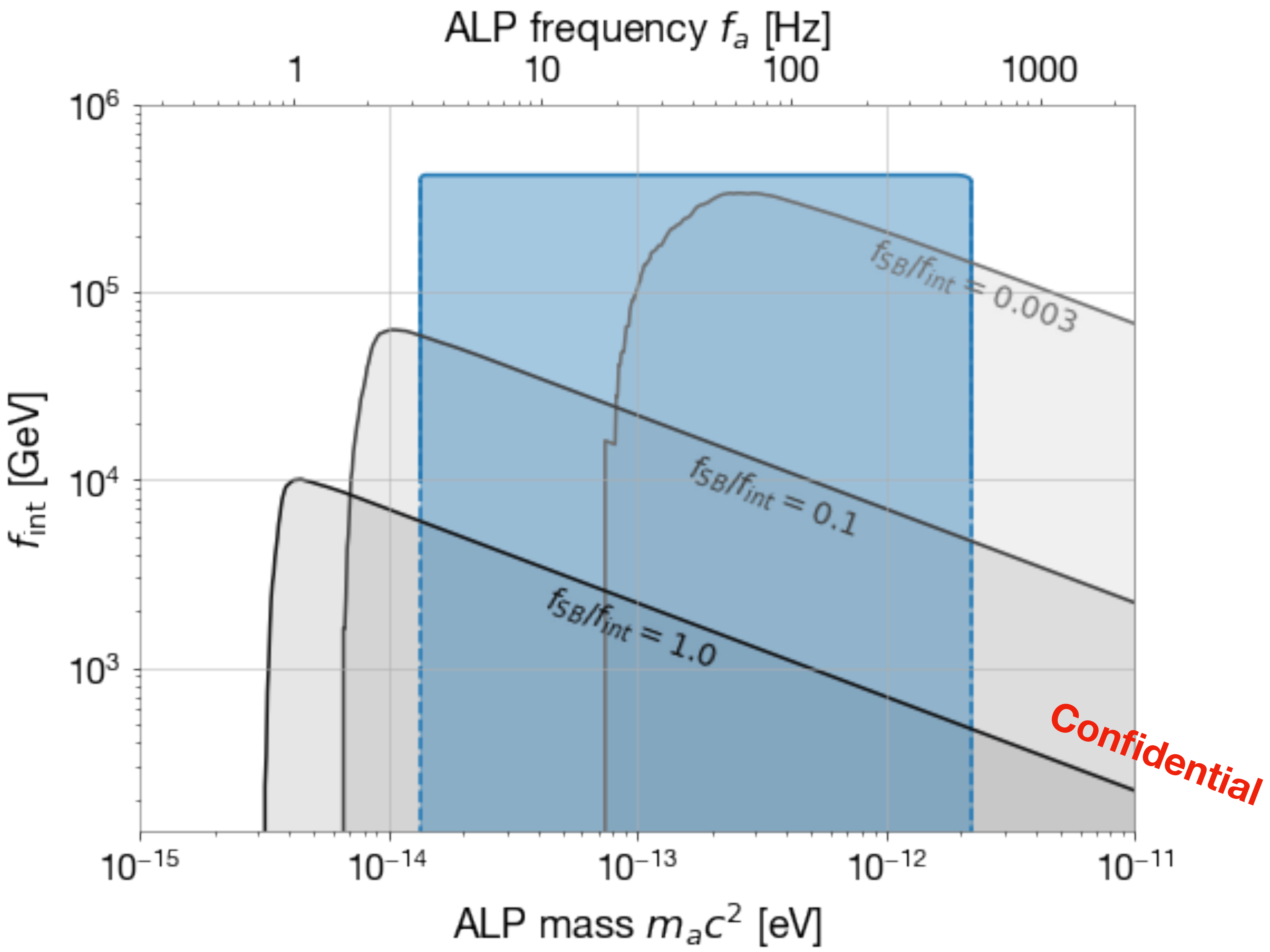
- TPR and FPR are separated by optimization



$n = 400, \quad p_{\text{TPR}} = 0.91, \; p_{\text{FPR}} = 0.00, \quad z = 1.96$

Projected Parameter Space

- Projected parameter space which can be covered by this analysis method (95% C.L.):



[1] S. Afach, et al., Search for topological defect dark matter using the global network of optical magnetometers for exotic physics searches (gnome), 2021.