On the accuracy of the DEM inversion problem

ISSI meeting

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UV Coronal observations

- Corona → Optically thin plasma. Intensity observed in a band *b*

$$I_b = \frac{1}{4\pi}\int_0^\infty R_b(T_e)\, n_e^2 \mathrm{d}l$$

Temperature response function

S_b : Instrument sensibility

$$R_b(T_e) = \sum_{X,\lambda_{ji}} S_b(\lambda_{ji})\, G_{X,\lambda_{ji}}(T_e)$$

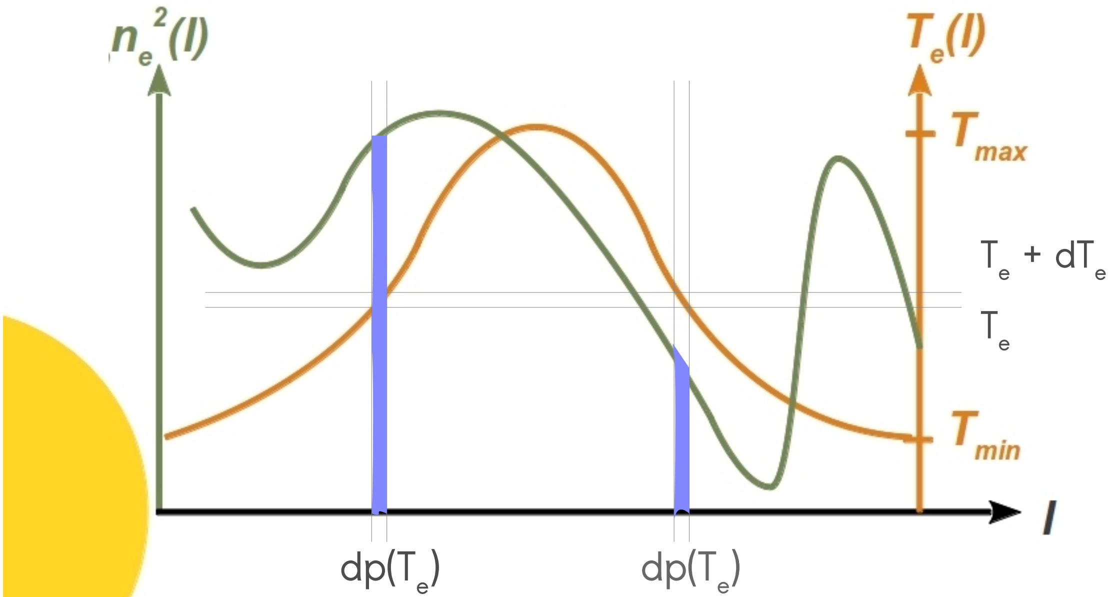
Einstein coefficient spontaneous emission

Contribution function for each emission lines

$$G_{X,\lambda_{ji}}(T_e) = A_{ji}\frac{hc}{\lambda_{ji}}\frac{n_j(X^{+m})}{n_e^2} = A_{ji}\frac{hc}{\lambda_{ji}}\frac{n_j(X^{+m})}{n(X^{+m})}\frac{n(X^{+m})}{n(X)}\frac{n(X)}{n(H)}\frac{n(H)}{n_e}\frac{1}{n_e}, \quad [\mathrm{J\ m^3\ s^{-1}}]$$

Population equilibrium + Ionization Equilibrium + Abundance + Abundance H/e-

The DEM: a powerful but complex tool



$$I_b = \frac{1}{4\pi}\int_0^\infty R_b(T_e(l))n_e^2 \mathrm{d}l$$

$$I_b = \frac{1}{4\pi}\int_0^\infty R_b(T_e)\xi(T_e)\mathrm{d}\, T_e$$

$$\boxed{\xi(T_e) = \sum_{s=p(T_e)} n_e^2 \frac{ds}{dT_e}}$$

$$= n_0^2 \frac{\mathrm{d}p}{\mathrm{d}T_e}$$

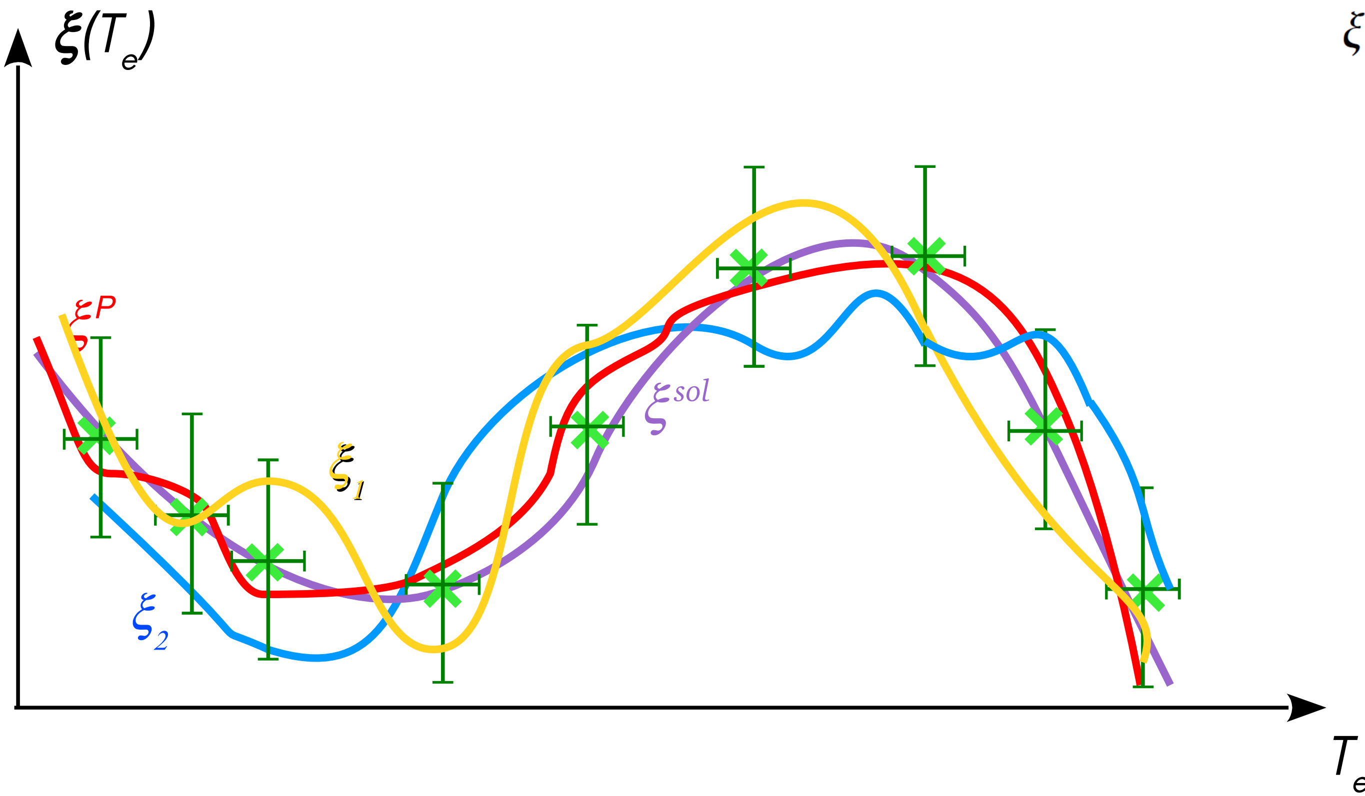
→ n_0^2 : mean density weighted by the inverse of the temperature gradient

(Craig & Brown, 1978)

Be careful with DEM interpretation!

e.g. regions with strong temperature gradient do not contribute a lot

How to test DEM inversion robustness



$$\xi^{sol} = \arg\min_{\xi}[C(\xi)]$$

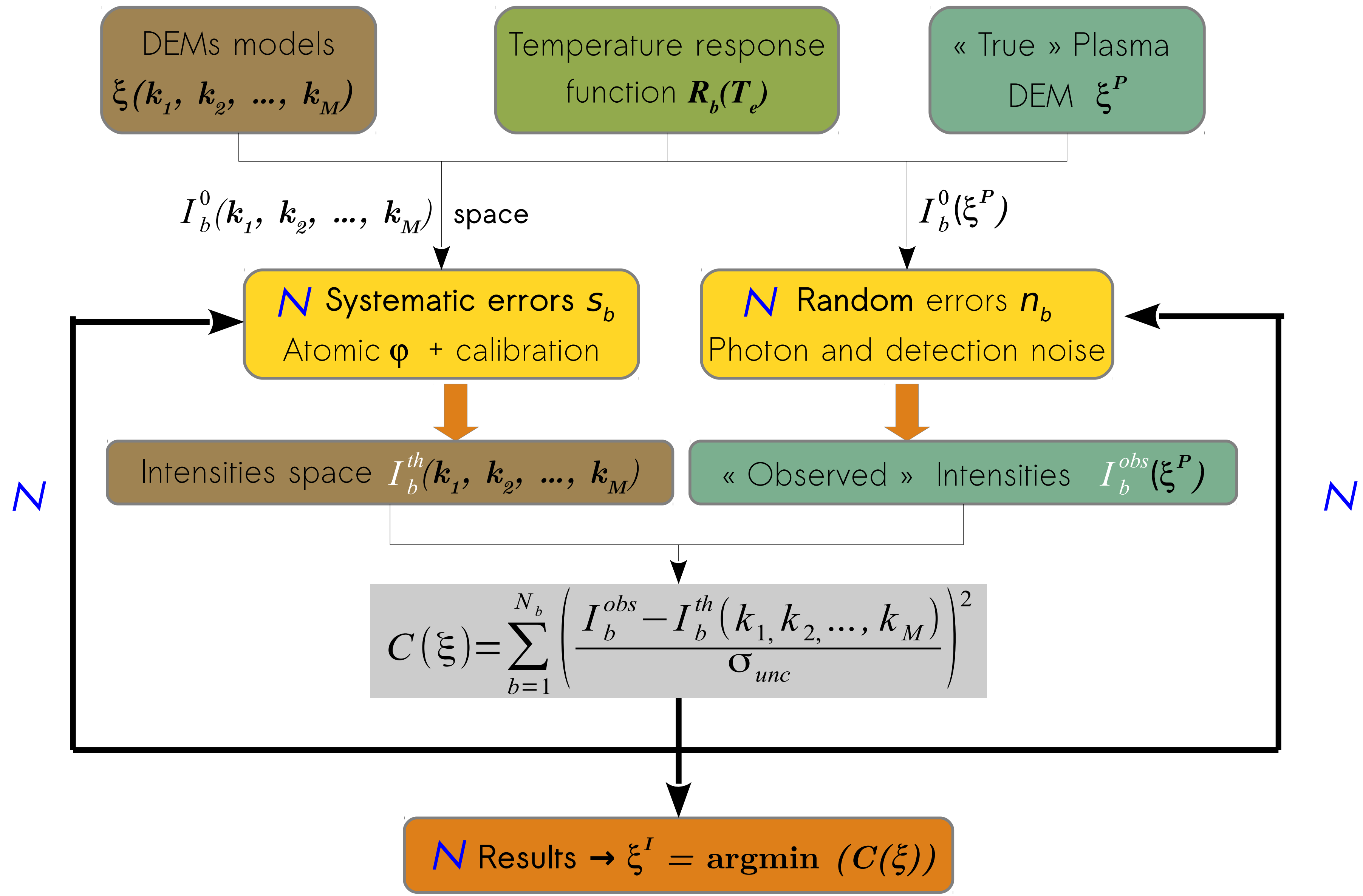
Uncertainties

$\xi^P \neq \xi^{sol}$

Simulation of the inversion process

- Simple scheme : 1. → Simulations of observations + errors by Monte-Carlo
  2. → Inversion process
  3. → Comparison inversion results/Observations

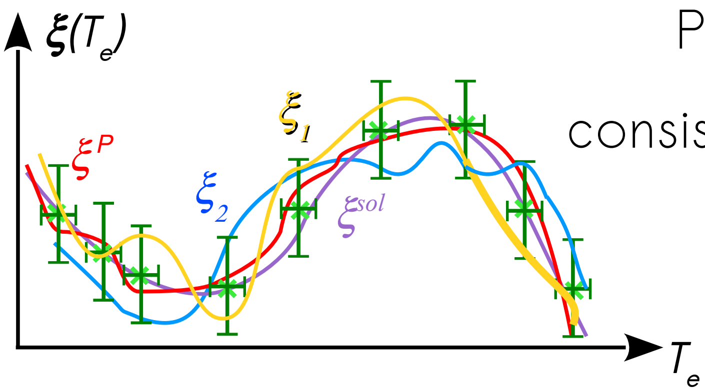
Robustness Analysis



A probabilistic approach

N Results → $\xi^{I} = \mathbf{argmin}\ (C(\xi))$

$\boxed{P(\xi^I|\xi^P)}$: Likelihood function



Probability of all the solutions $\boldsymbol{\xi^I} = \{\boldsymbol{\xi_1}, \boldsymbol{\xi_2}, \boldsymbol{\xi^{sol}}, \ldots\}$ consistent with the data + errors, knowing the initial DEM $\boldsymbol{\xi^P}$

→ *Can't be used on « real data »*

$$\boxed{P(\xi^P|\xi^I)} = \frac{P(\xi^I|\xi^P)P(\xi^P)}{P(\xi^I)}$$

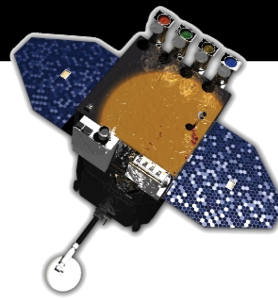
: Probability *a posteriori*
(Bayes' theorem)

Probability of all the DEMs $\boldsymbol{\xi^P}$ consistent with a given inversion result $\boldsymbol{\xi^I}$

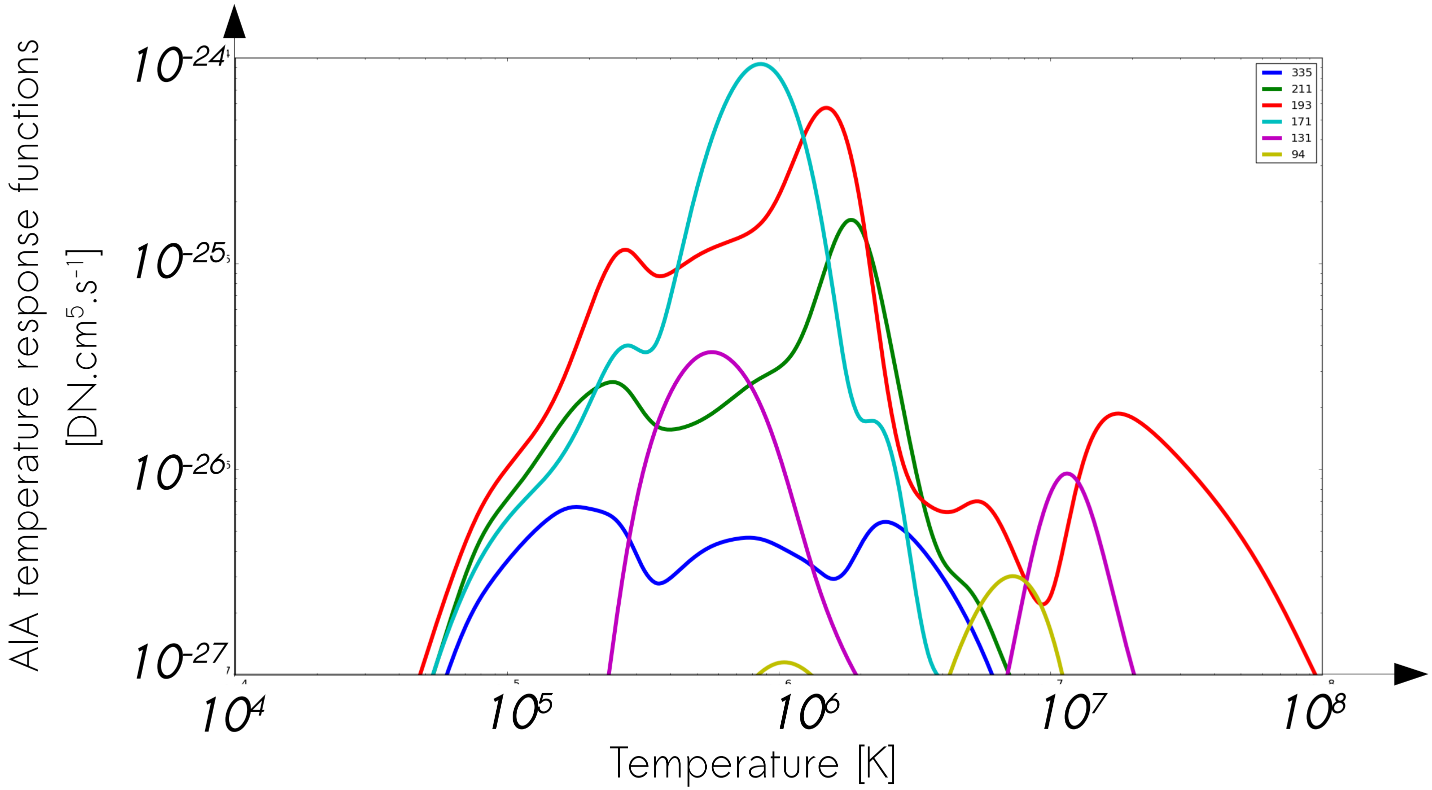
→ *Can be used on « real data »*

Guennou et al. (2012a) and (2012b)

A very simple example



AIA: EUV imager with 6 coronal narrow band channels :
94, 131, 171, 193, 211, 335 Å



Simplest case = Plasmas isothermes

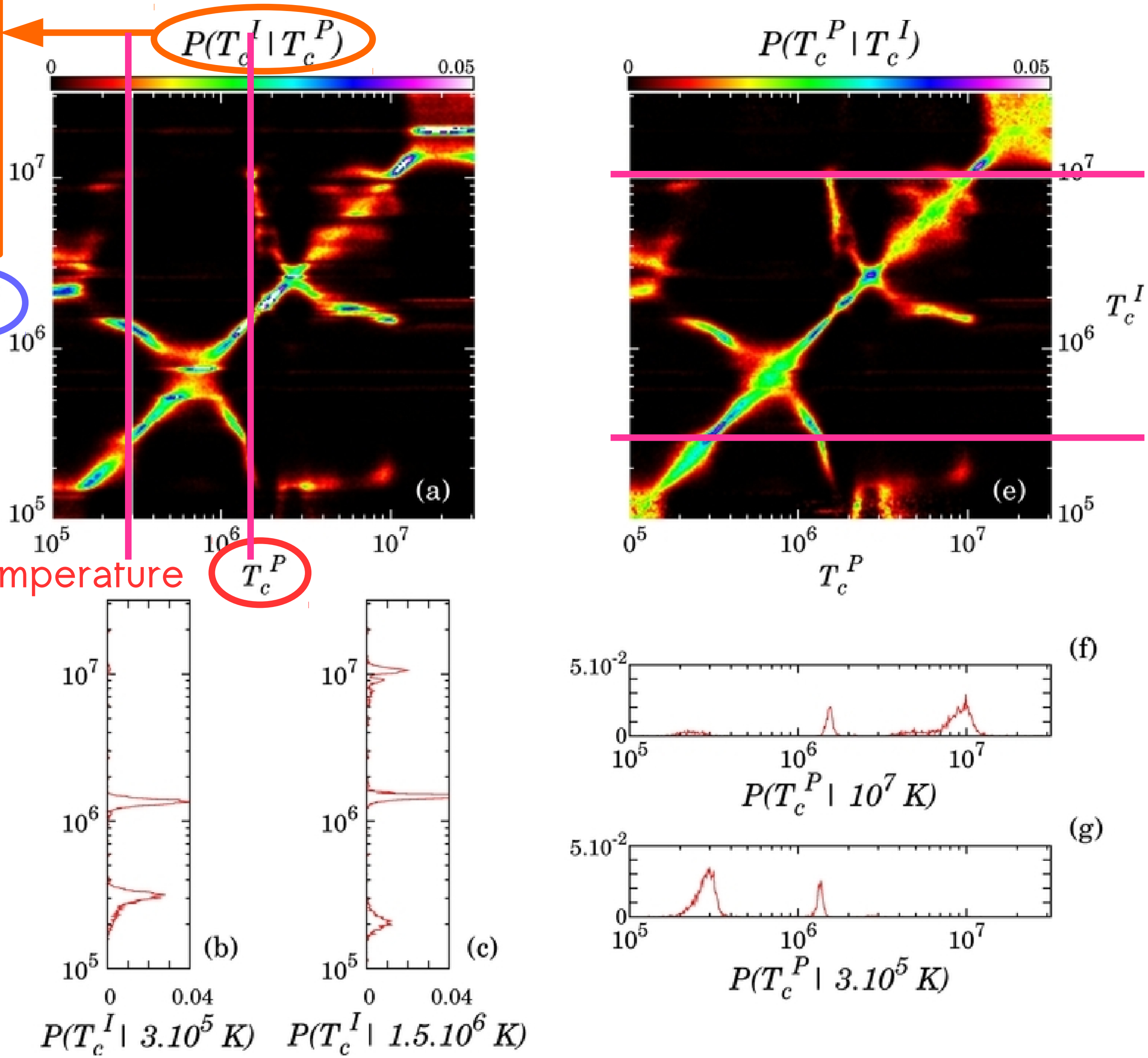
$$\rightarrow \quad \xi_{iso}(T_e) = \mathrm{EM}\ \delta(T_e - T_c)$$

Random n_b	Systematics s_b
Readnoise 21e- RMS	Calibration 25 %
Shotnoise	Atomic physics 25%

Probability of the inversion result, knowing the "True" one

"Measured" temperature

"True" temperature



Probability of the inversion result, knowing the "True" one

"Measured" temperature

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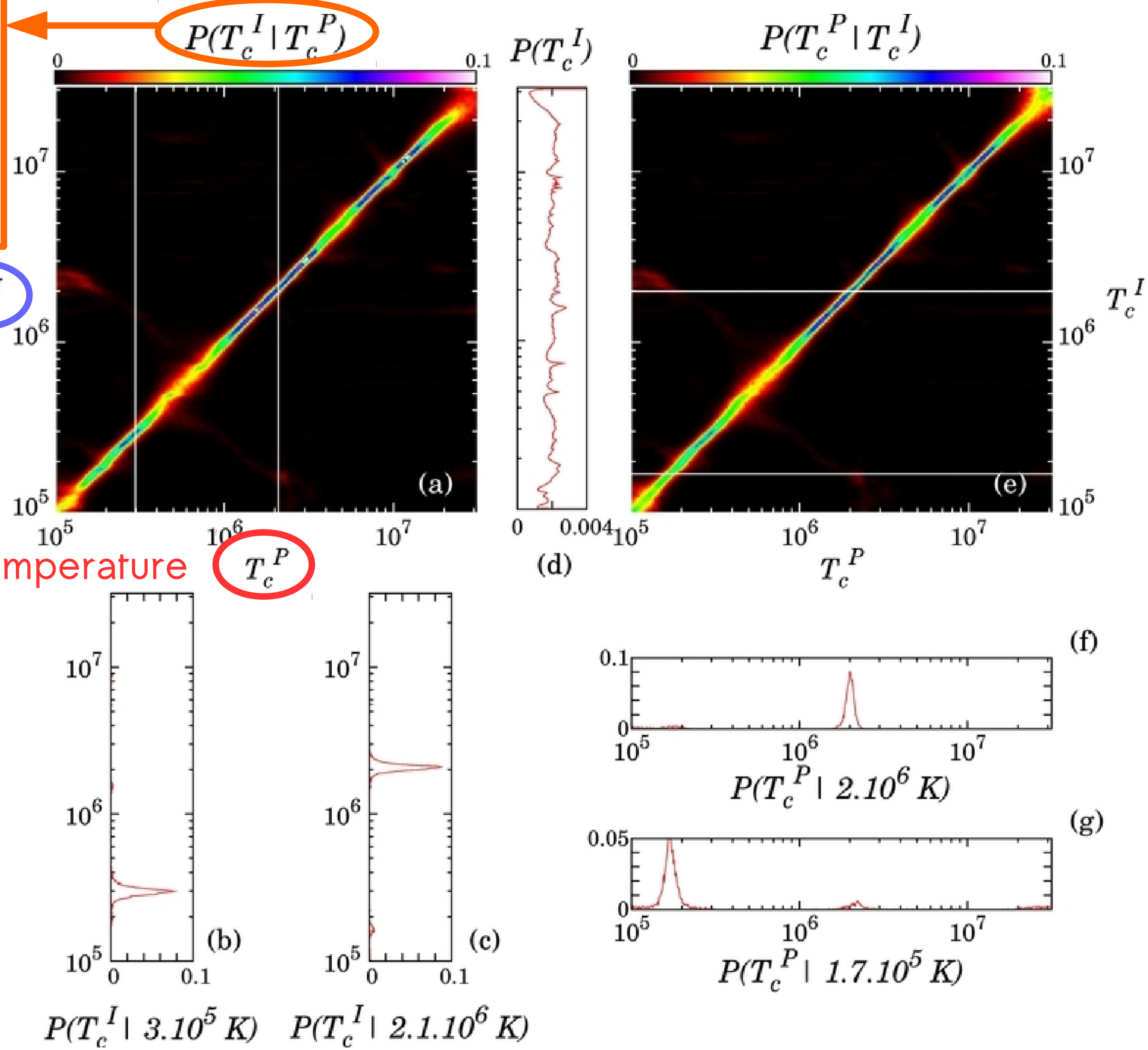
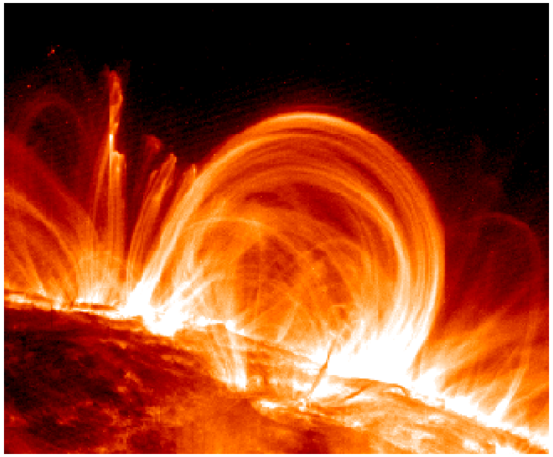
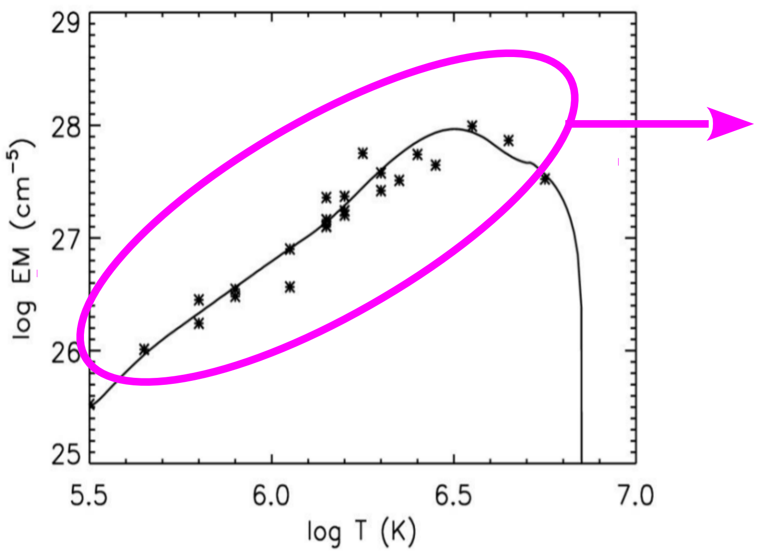


- Can the DEM constrain the timescale of the energy deposition in the solar corona ?



Active Regions DEMs → DEM α T^{α}

(e.g. Jordan 1969, Warren et al. 2011, Schmelz 2012, Winebarger et al. 2012,)



Tripathi, Klimchuk & Mason, (2011)

- DEM Slope

→ Indication of the cold/warm material ratio

→ Timescale of the energy deposition in the solar corona

What is the confidence level on the reconstructed slope ?

Framework : Hinode/EIS

Hinode/EIS set of 30 lines of elements *Fe, Si, Mg, S, Ca, Ar*
→ large temperature coverage $[10^{5.2}: 10^{6.9}]$ K

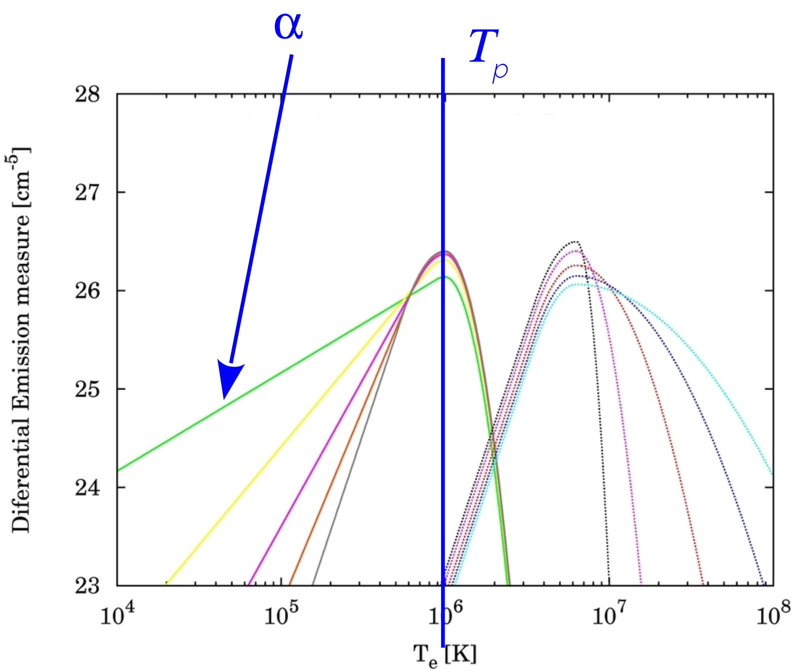
Spectrometer → Isolated emission lines → Detailed treatment of uncertainties :

- ➢ Abundance: 10% à 20 % depending on elements
- ➢ Ionization equilibrium : 10%
- ➢ Atomic parameters : 10%

~ 22-27%
Total uncertainties

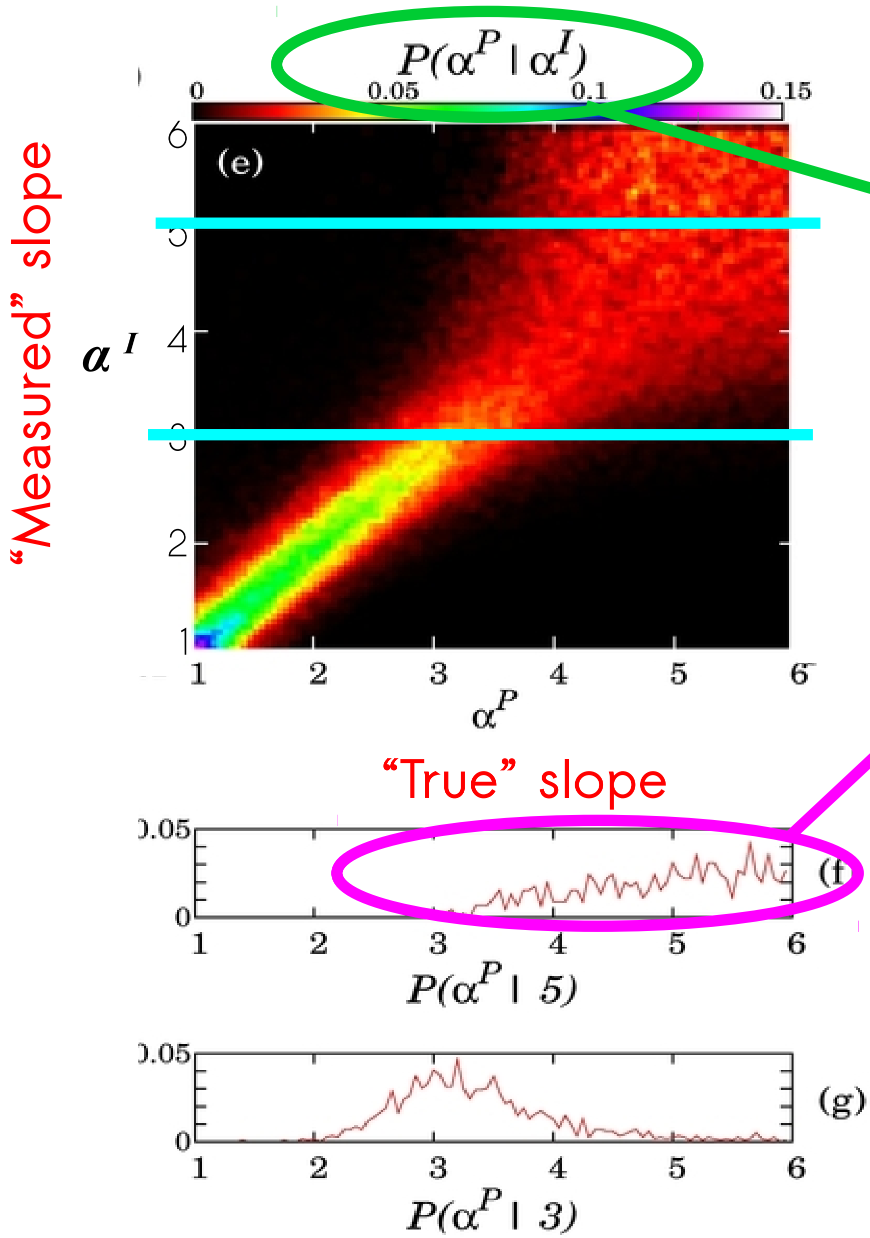
Parametric models of ARs DEMs =
Power law + half a gaussian

$$\boxed{P(\alpha^I, T_p^I | \alpha^P, T_p^P)}$$



Slope probability map

$\log T_c^P = 6.8$



Probability of the *true slope* knowing the *measured* one

Probability distribution of the solutions

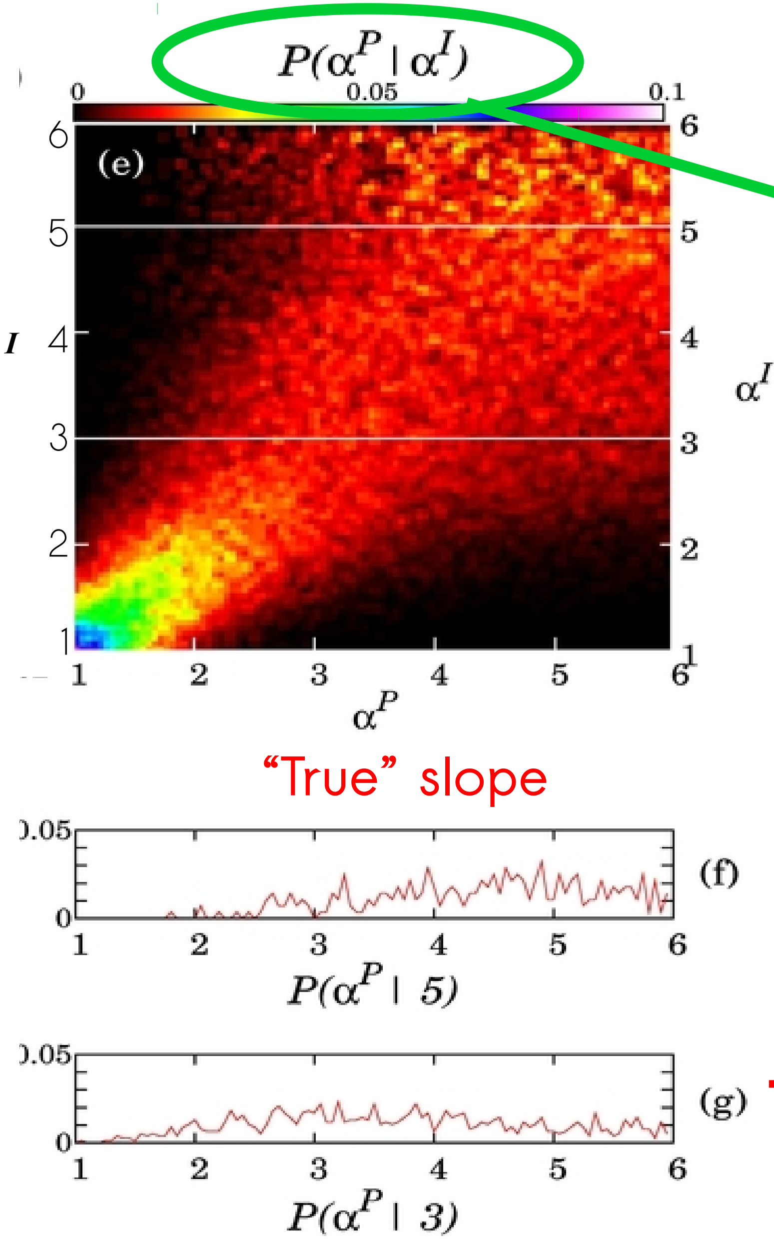
$\alpha^P = 4.9 \pm 0.7$

$\alpha^P = 3.2 \pm 0.6$

$\log T_c^P = 6.5$

“Measured” slope

α^I



“True” slope

Probability of the *true slope* knowing the *measured* one

$\alpha^P = 4.95 \pm 1.07$

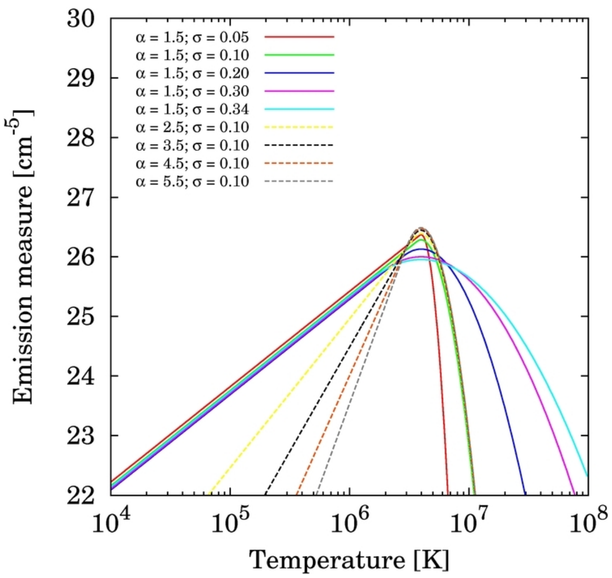
$\alpha^P = 3.42 \pm 1.17$

EIS lines

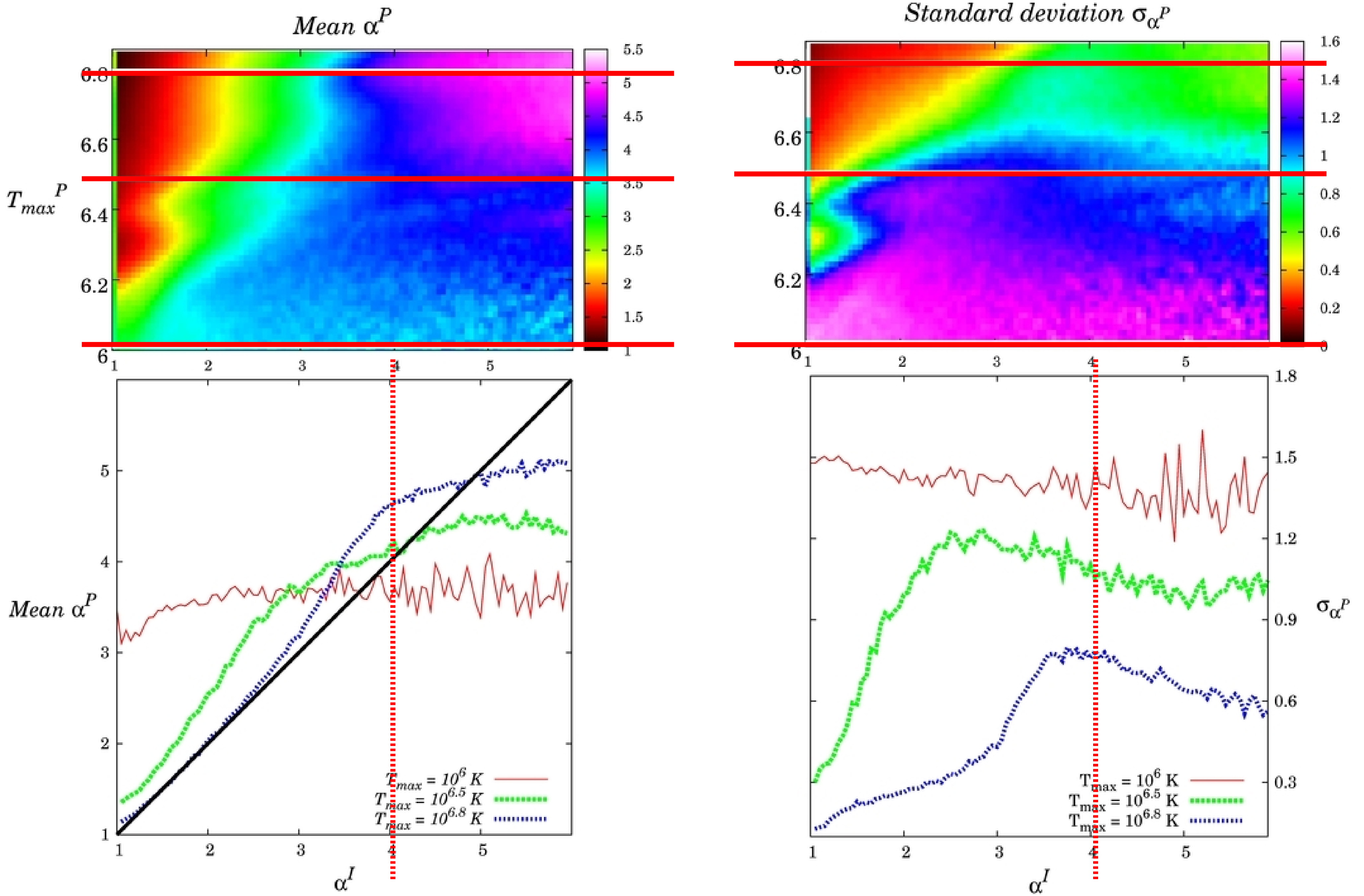
Ions	Wavelength (Å)	$\log(T[K])$	Total uncertainty σ_{unc}
Mg V	276.579	5.45	61.03 %
Mg VI	268.991	5.65	61.03 %
Mg VI	270.391	5.65	61.03 %
Si VII	275.354	5.80	61.03 %
Mg VII[b]	278.404	5.80	62.85 %
Mg VII	280.745	5.80	61.03 %
Fe IX	188.497	5.85	61.03 %
Fe IX	197.865	5.85	61.03 %
Fe X	184.357	6.05	61.03 %
Si IX	258.082	6.05	61.03 %
Fe XI	180.408	6.15	61.03 %
Fe XI	188.232	6.15	61.03 %
Si X	258.371	6.15	61.03 %
Si X	261.044	6.15	61.03 %
S X	264.231	6.15	53.15 %
Fe XII	192.394	6.20	61.03 %
Fe XII	195.119	6.20	61.03 %
Fe XIII	202.044	6.25	61.03 %
Fe XIII	203.828	6.25	61.03 %
Fe XIV	264.790	6.30	61.03 %
Fe XIV	270.522	6.30	61.03 %
Fe XIV[b]	274.204	6.30	62.85 %
Fe XV	284.163	6.35	61.03 %
S XIII[b]	256.685	6.40	55.23 %
Fe XVI	262.976	6.45	61.03 %
Ca XIV	193.866	6.55	61.03 %
Ca XV	200.972	6.65	61.03 %
Ca XVI	208.604	6.70	61.03 %
Ca XVII[b]	192.853	6.75	62.85 %

$T_p = 10^{6.5}$ K

$T_p = 10^{6.8}$ K



Summary of the results



Comparison Observations/Modèles

- EIS DEM capabilities :
  - → Robust reconstruction of isothermal plasma
  - → *Difficulty to constrain the timescale of heating events*

22 Active Region Cores (inter-moss regions)

$\Delta\alpha = \pm 1.0$

	$\alpha \le 2.0$	$2.0 < \alpha \le 2.5$	$2.5 < \alpha \le 3.0$	$3.0 < \alpha \le 3.5$	$\alpha > 3.5$	
α	3	5	3	6	5	36% consistent
$\alpha - \Delta\alpha$	11	6	2	2	1	77% consistent
$\alpha + \Delta\alpha$			3	5	14	0% consistent

Model of low frequency nanoflares → $0.81 \le \alpha \le 2.56$

Schmelz & Pathak (2012)
Tripathi, Klimchuk, & Mason (2011)
Warren, Brooks, & Winebarger (2011)
Warren, Winebarger, & Brooks (2012)
Winebarger et al. (2011)

Bradshaw et al. (2012)

Going further ...

- Adopt more detailed uncertainties, i.e. different from each line

  → Atomic physics experts?

- Include correlations between each uncertainties sources (e.g. ionization equilibrium, ...)

- Test this robustness measurement technique with the new spectrometer Solar Orbiter/Spice

  → Determine the optimal set of lines for various type of coronal structures
  → Determine the optimal observational parameters

Thanks!