What is the temperature of solar prominences?
First independent determination using ALMA & Hα

Miroslav Bárta, Petr Heinzel, Arek Berlicki
barta@asu.cas.cz

EUROPEAN ARC
ALMA Regional Centre || Czech

Astronomical Institute of the Czech Academy of Sciences

Outline

- **Motivation**: What is the actual physical structure of prominences?
  - It is quite hard to derive prominence properties, namely internal temperature structure (high uncertainty) using standard optical or UV spectroscopy (non-LTE).
  - This uncertainty impacts on the physical nature of prominences: Self-gravity generated or purely preexisting magnetic dips?

- **Methodology:** Relation between Hα integral intensity, kinetic temperature, and T_B at mm wavelengths – a key to independent temperature estimation
  - Theory
  - ALMA visibilities & image simulations = forward modelling

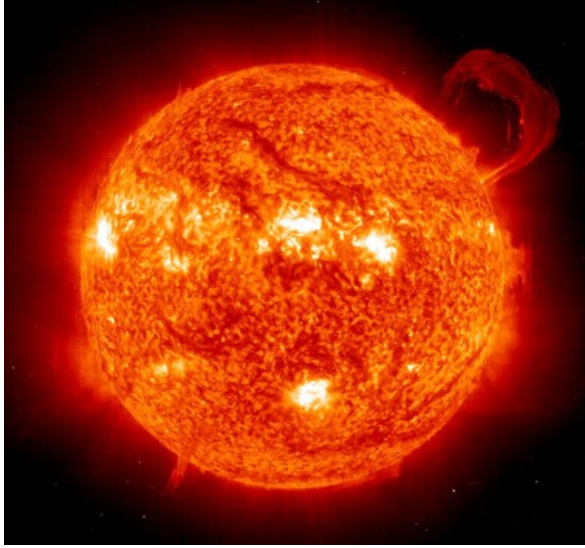
- Inversion of the procedure: **Application** to the real prominence observation with ALMA
  - Basics of ALMA imaging & application to solar observations.
  - ALMA observation of a prominence: Data reduction, imaging and combination => Absolutely calibrated T_B map of prominence at 3mm.
  - Put it together with the Hα integral intensity map => **a map of** (LOS-averaged) **kinetic temperature of a prominence.** Based on Heinzel et al., 2022.

ALMA as a prominence thermometer: First observations

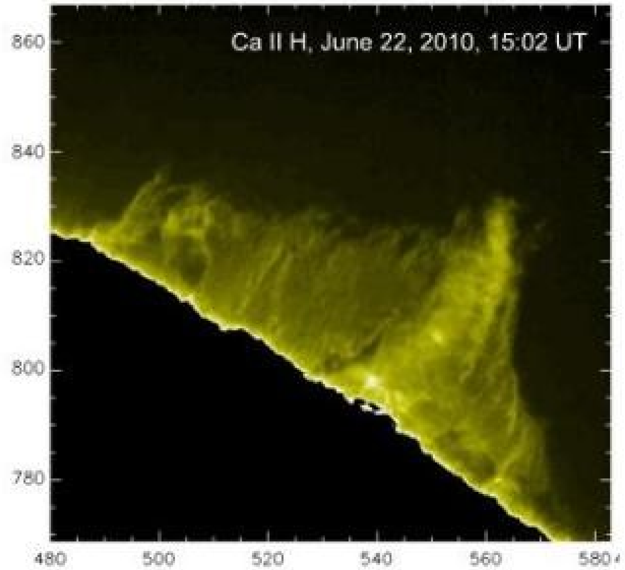
Petr Heinzel,[1,2] Arkadiusz Berlicki,[2,3,1] Miroslav Bárta,[1] Paweł Rudawy,[3] Stanislav Gunár,[1]
Nicolas Labrosse,[4] and Krzysztof Radziszewski[3]

[1] *Astronomical Institute, The Czech Academy of Sciences, 25165 Ondřejov, Czech Republic*
[2] *University of Wrocław, Center of Scientific Excellence - Solar and Stellar Activity, Kopernika 11, 51-622 Wrocław, Poland*
[3] *Astronomical Institute, University of Wrocław, 51-622 Wrocław, Poland*
[4] *Department of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, United Kingdom*

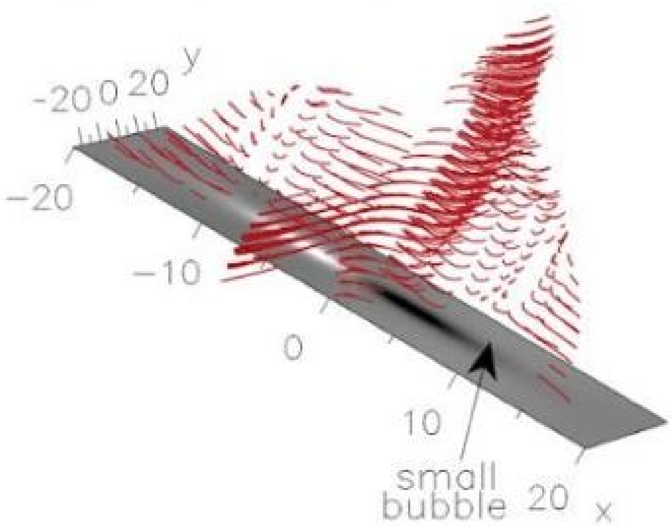
Motivation: Understanding solar prominences



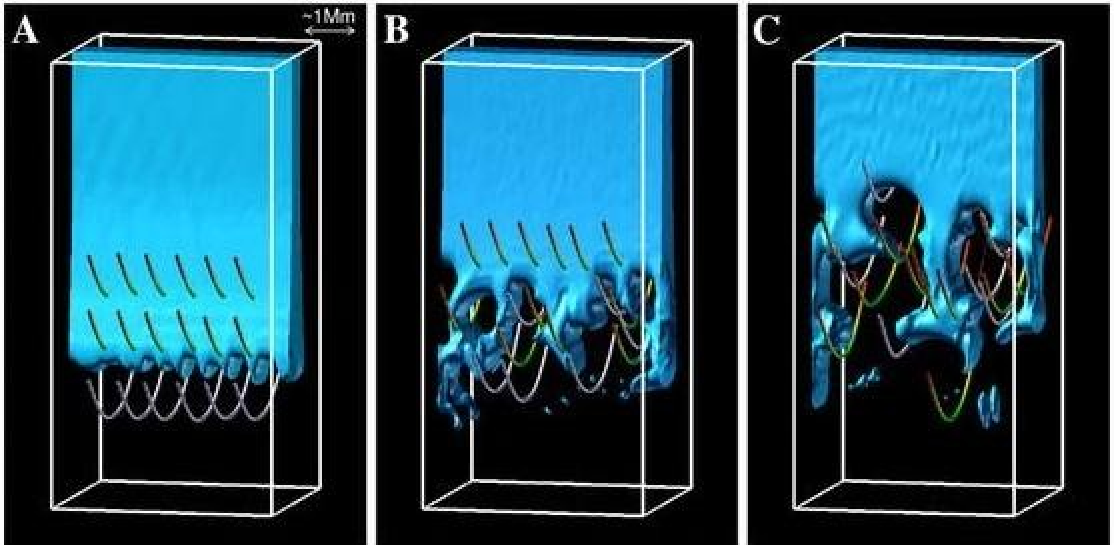
- Basic idea: A cold mass supported by the magnetic field in hotter solar corona
- Hard to derive their properties, namely temperature structure (high uncertainty) using standard optical or UV spectroscopy (non-LTE)
- This uncertainty projects into uncertainty in basic model: Plasma just dropping into the **preexisting magnetic dips** or **self-gravity** plays a role?



Gunar et al. (2016)



Hillier et al. (2018)



T_B at mm wavelengths can be inferred from T_{kin} and E(Hα)

Jejcic & Heinzel (2009)
Heinzel et al. (2015)

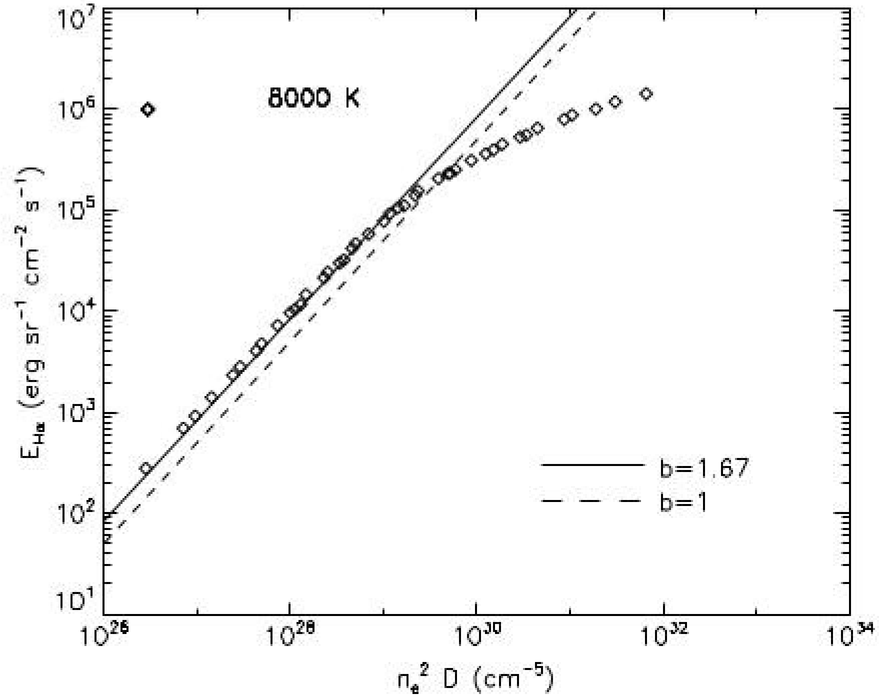
$$E(\mathrm{H}\alpha) = 3.96 \times 10^{-20} b T^{-3/2} \exp^{17\,534/T}\,\mathrm{EM},$$

$$\tau(\nu) = 4.55 \times 10^{17} g_{\mathrm{ff}} f(T) E(\mathrm{H}\alpha)/\nu^2,$$

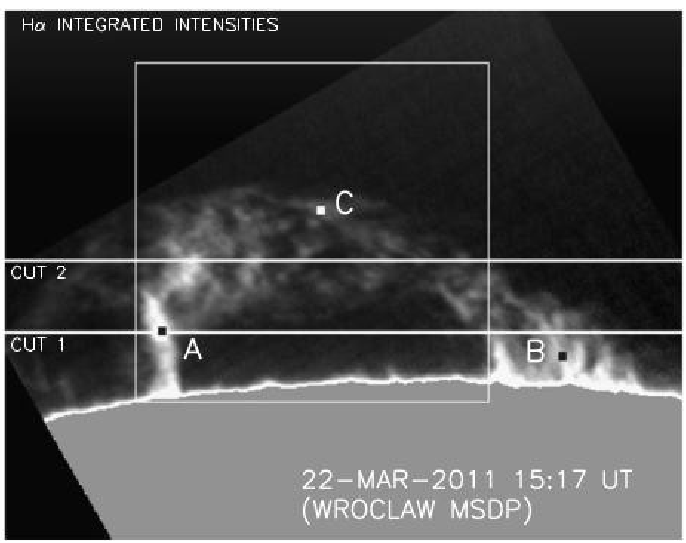
$$f(T) = \exp(-17\,534/T)/b(T)$$

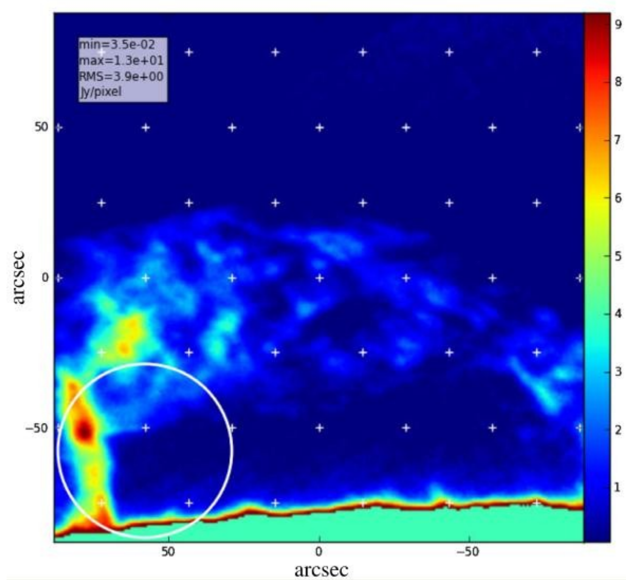
$$T_{\mathrm{b}} = \int T \mathrm{e}^{-t_\nu}\,\mathrm{d}t_\nu = \int T \mathrm{e}^{-t_\nu} \kappa_\nu\,\mathrm{d}l.$$

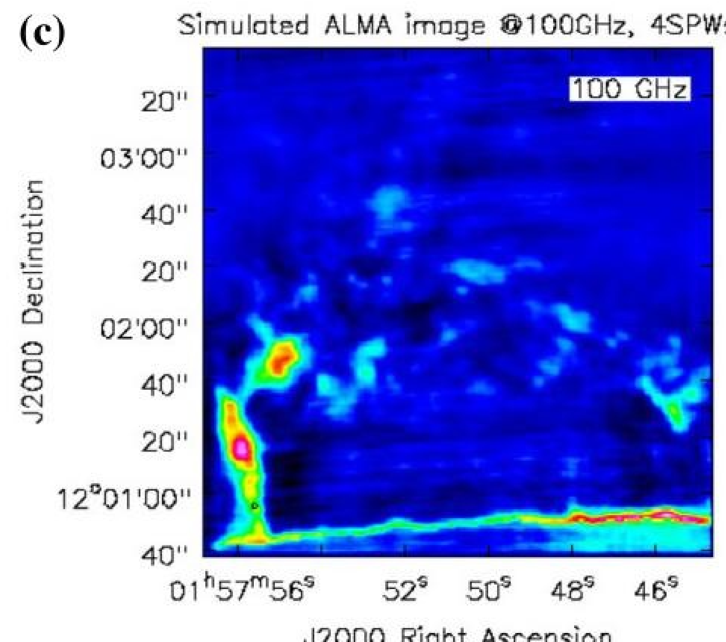
$$\boldsymbol{T_b = F(T_{kin}, E(H\alpha))}$$



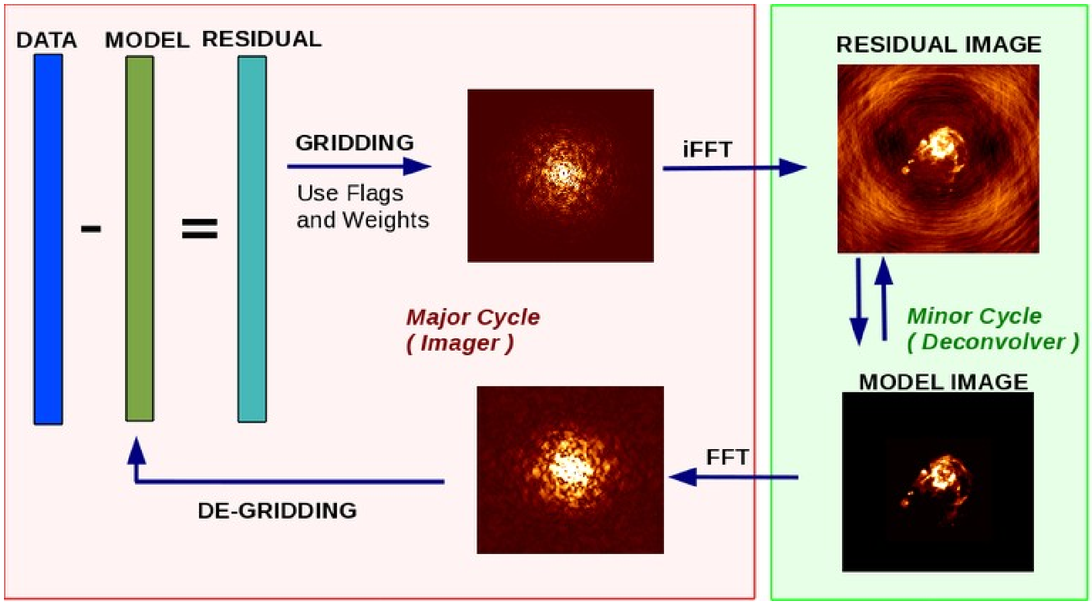
Simulated ALMA image at 3mm

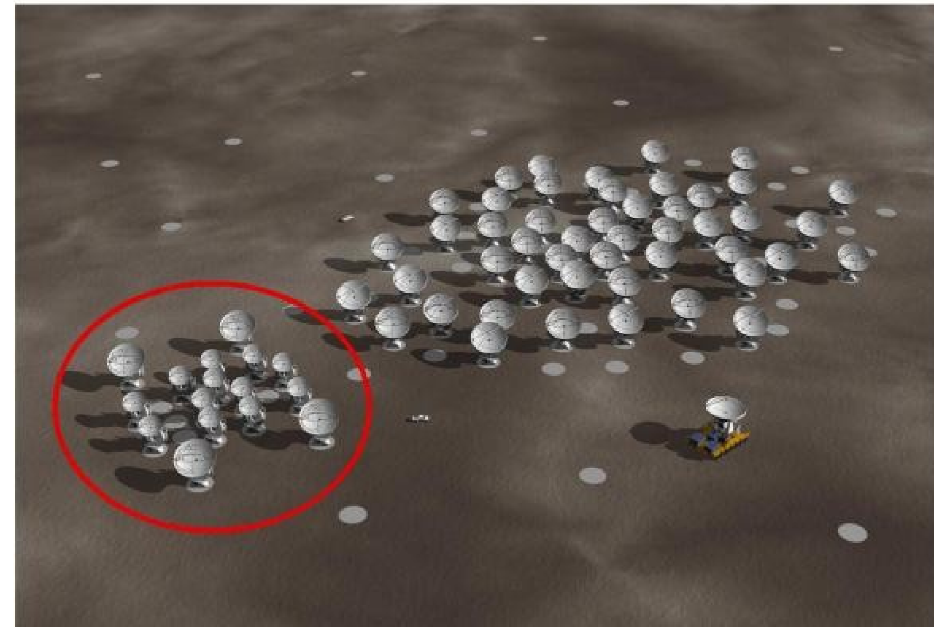


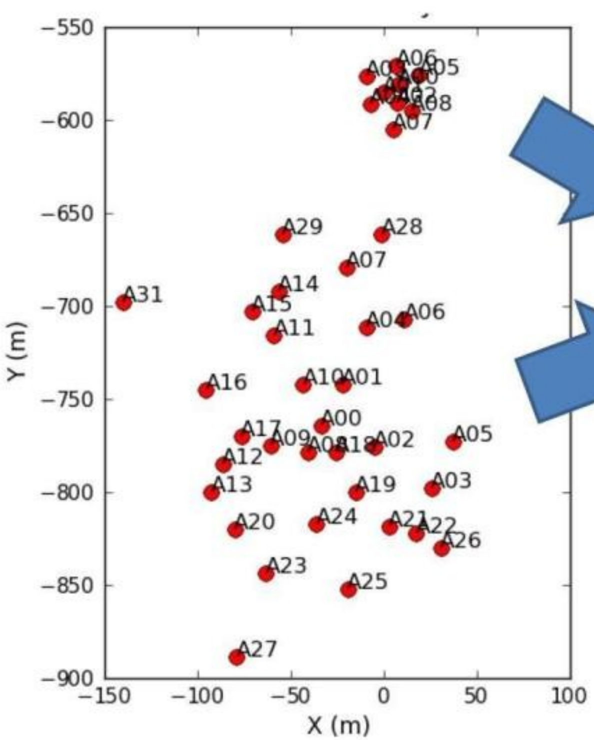


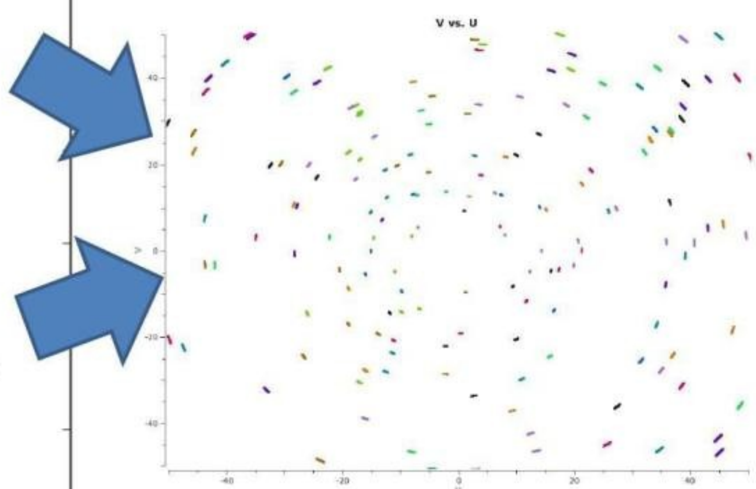


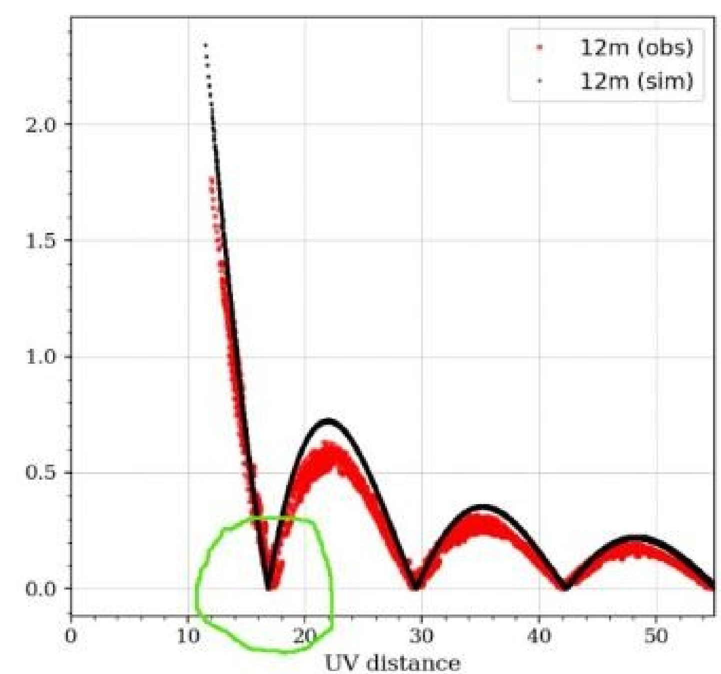
ALMA imaging: Troubles with extended sources (like the Sun...)







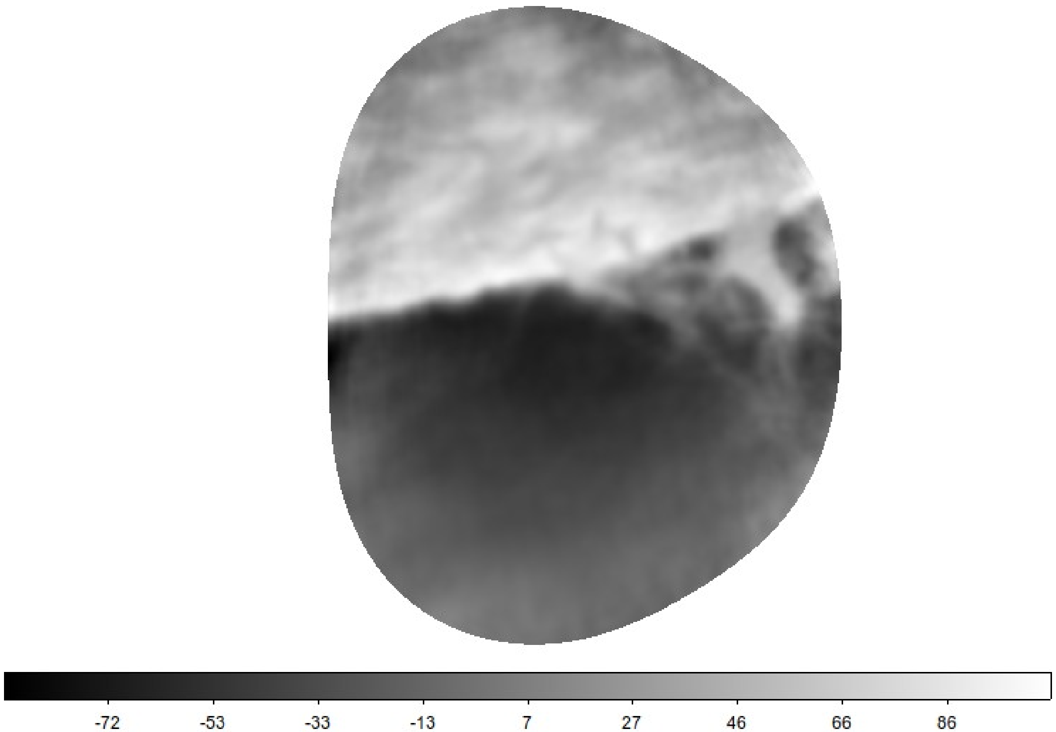




ALMA prominence data

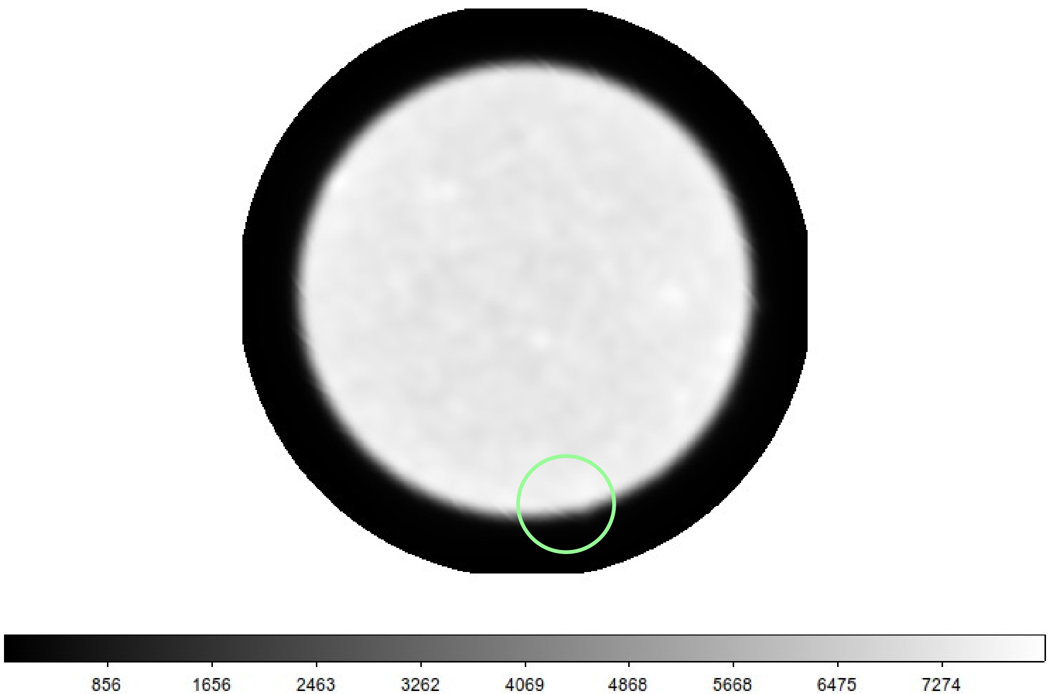
2017.0.01138.S (PI: N. Labrosse) – archival data
April 18, 2018

Interferometric (synthesized Fourier) – detail



Jy/beam, differences w.r.t. average

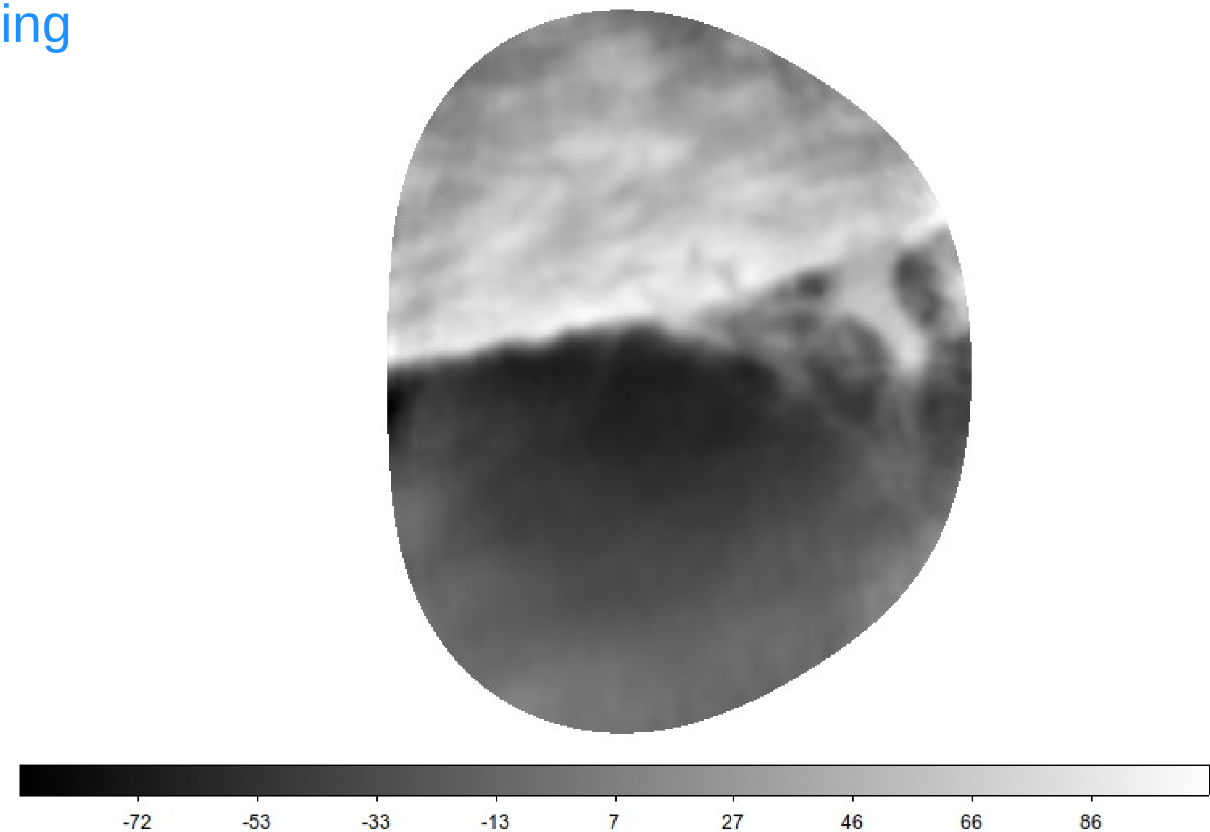
Total power (real) – full disc

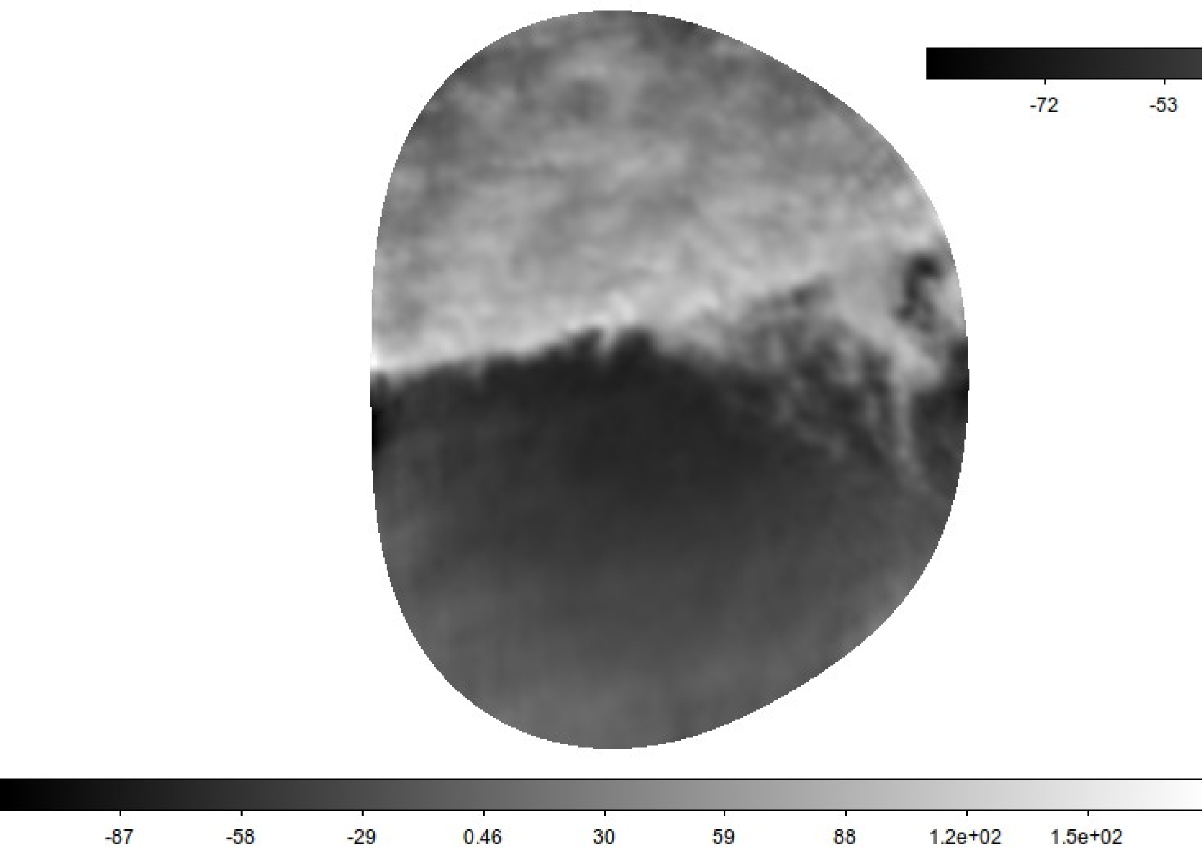


K(elvin), absolute scale

Internal dynamics: Time-domain imaging

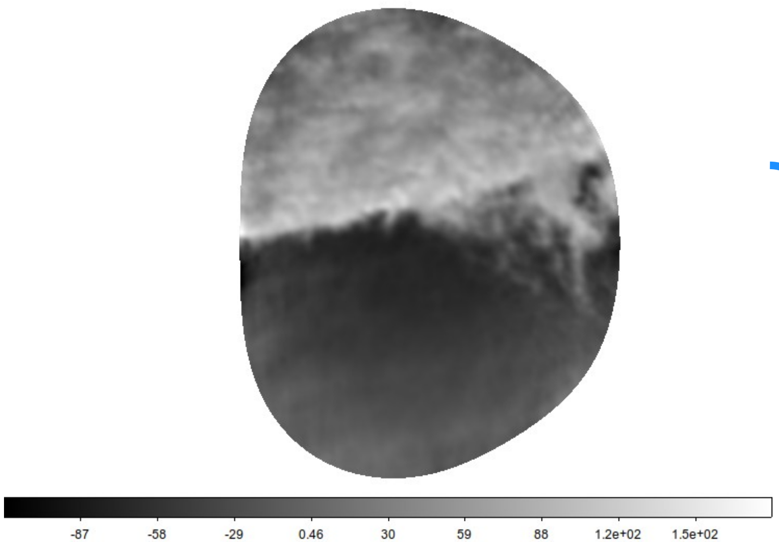
EB integrated (~40min)





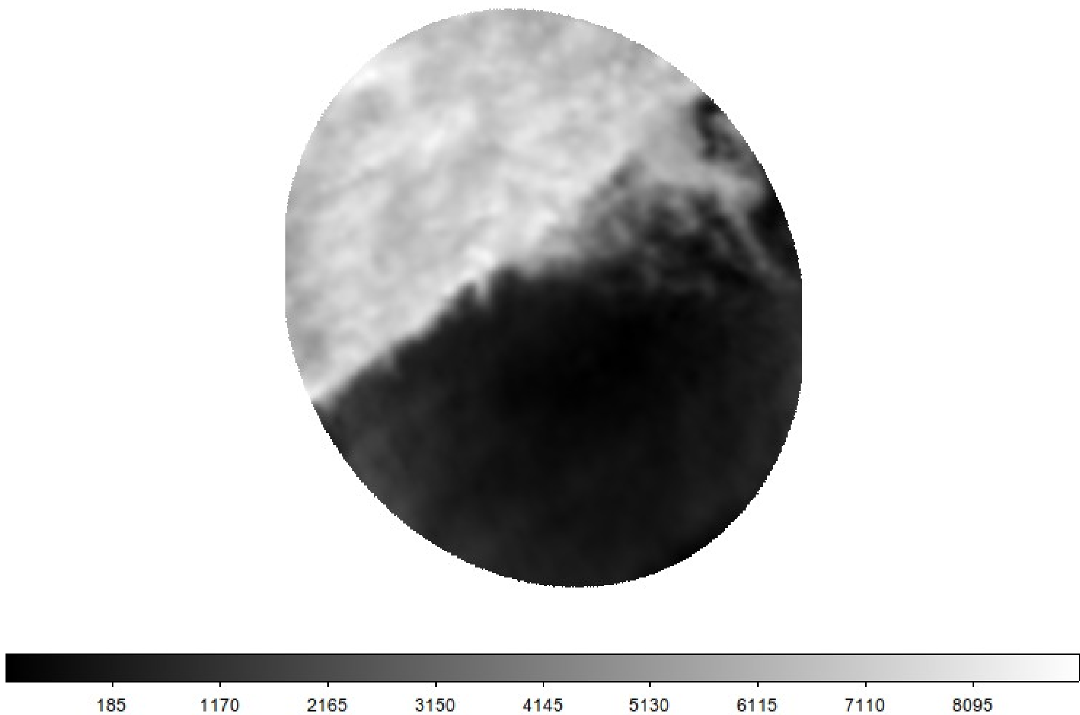
“Snapshot” ~35s

Missing flux – combination INT + TP



+

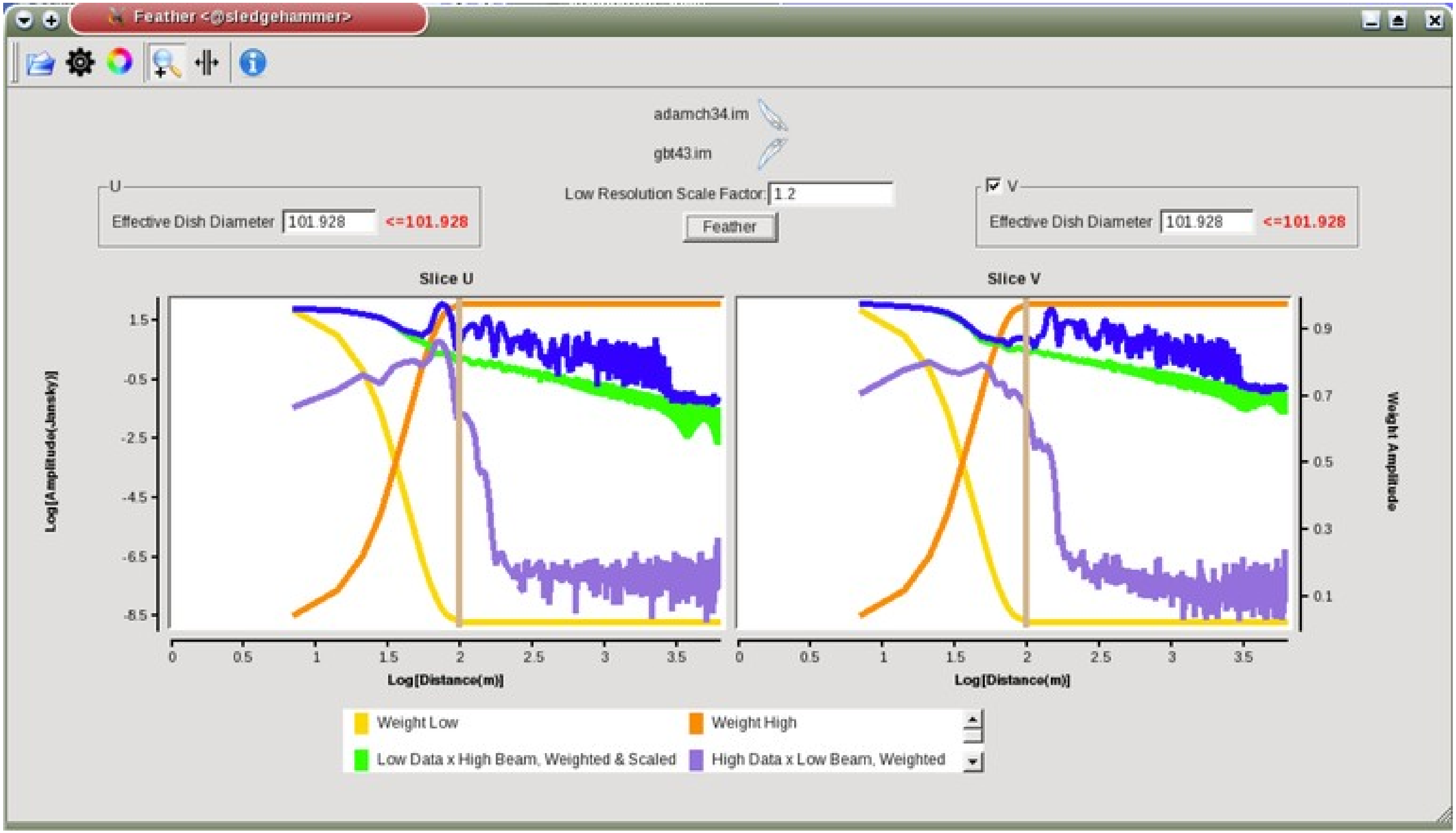
=



- Reference-frame transformation
- Co-alignment, re-gridding, crop
- K → Jy/beam (for TP data), combination, Jy/beam → K (combined)
- Ra,dec → HPC x,y

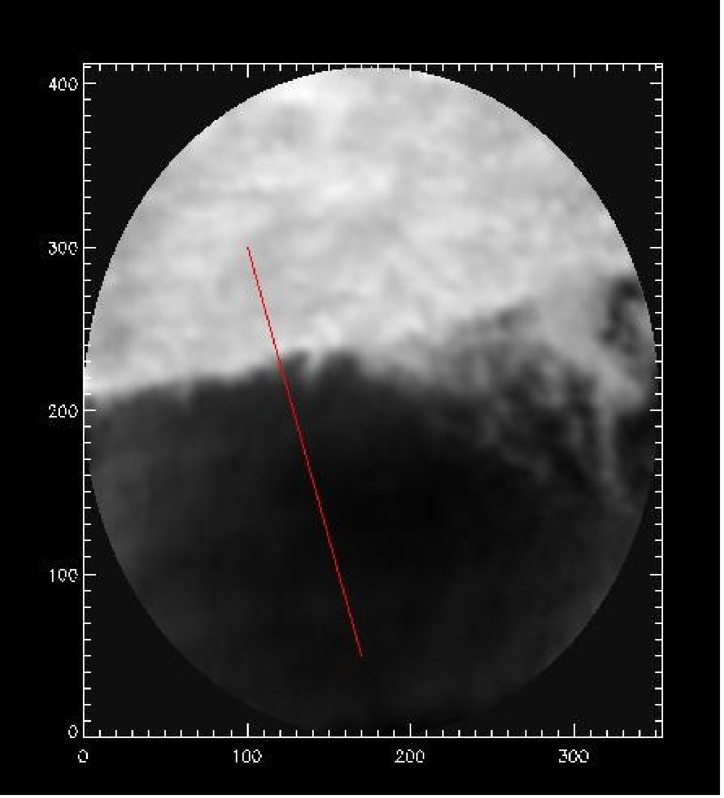
Missing flux – combination INT + TP

CASA::feather()

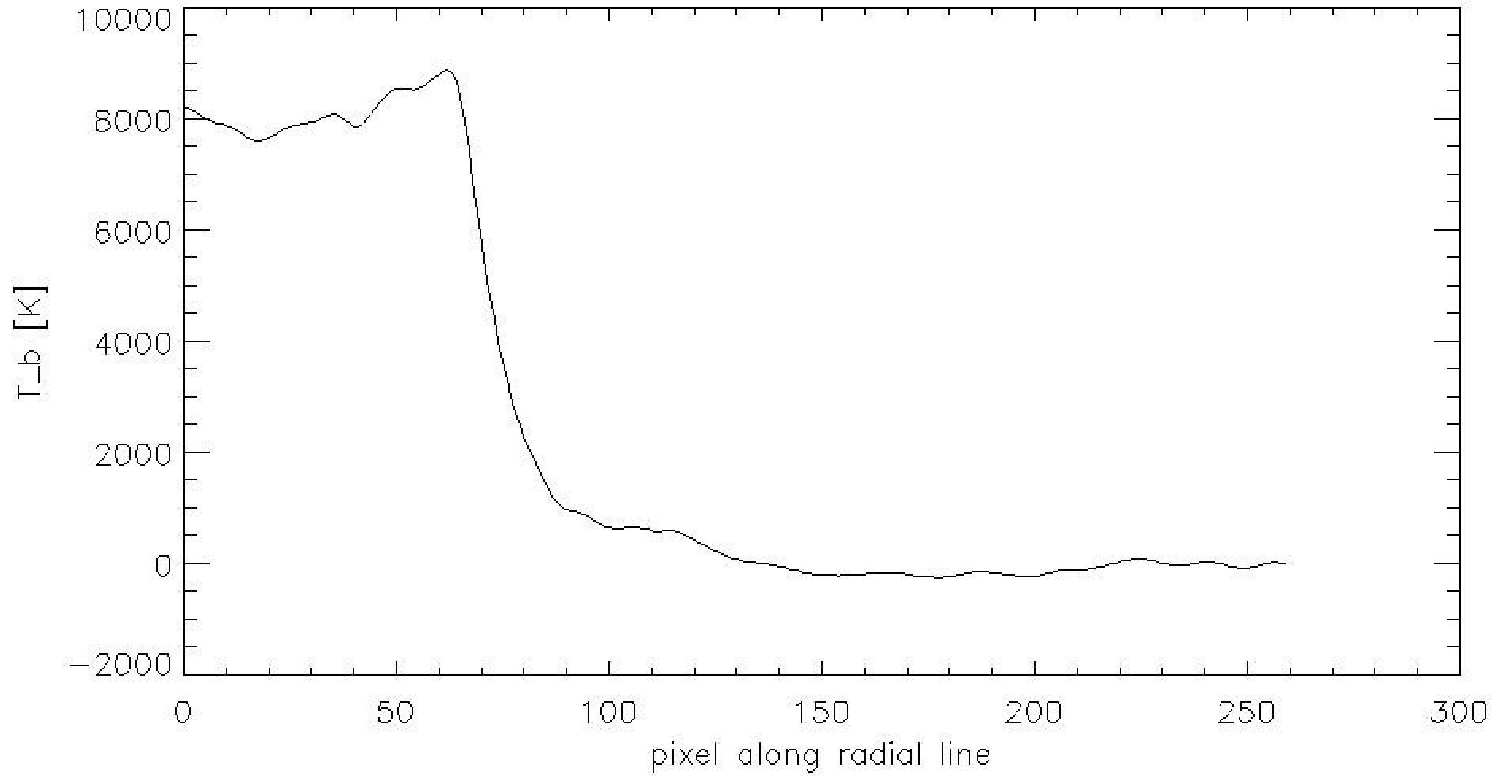


- Basically overlaying INT + TP images + fix for overlapping scales.
- Frequently an issue with disparity of the INT and TP signals: Can be fixed by weight factor.

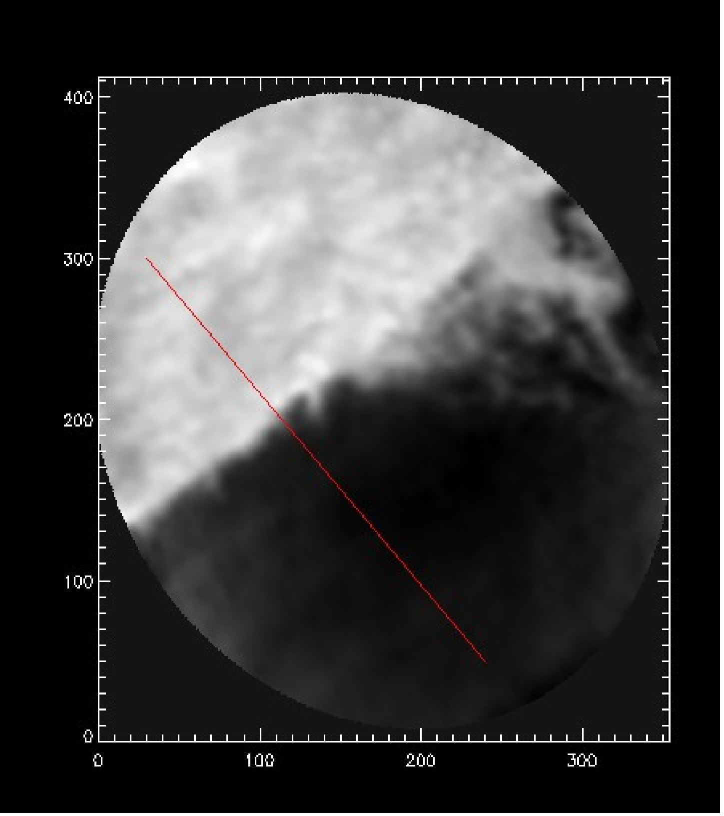
Missing flux – combination INT + TP



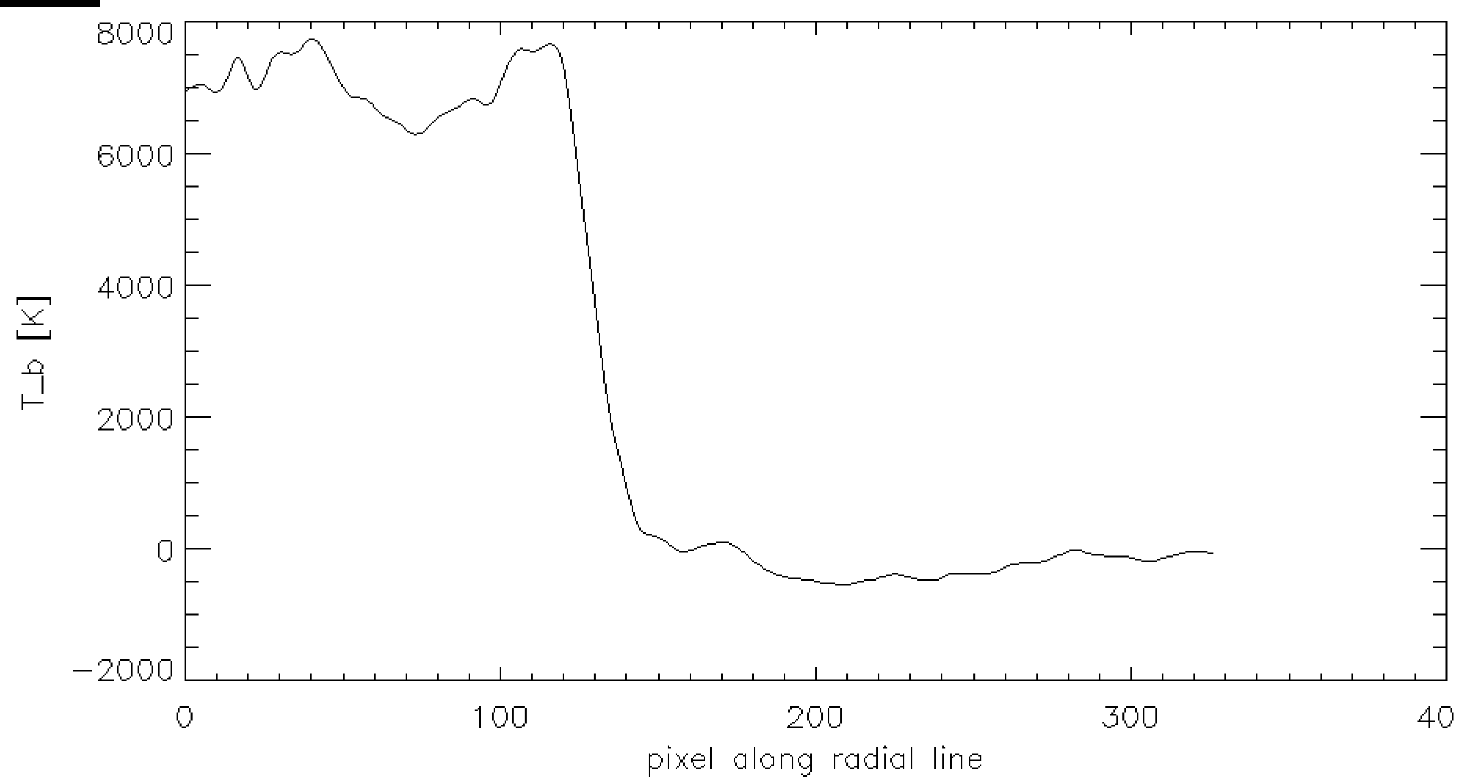
CASA::feather():
relative weight=1.0



Missing flux – combination INT + TP



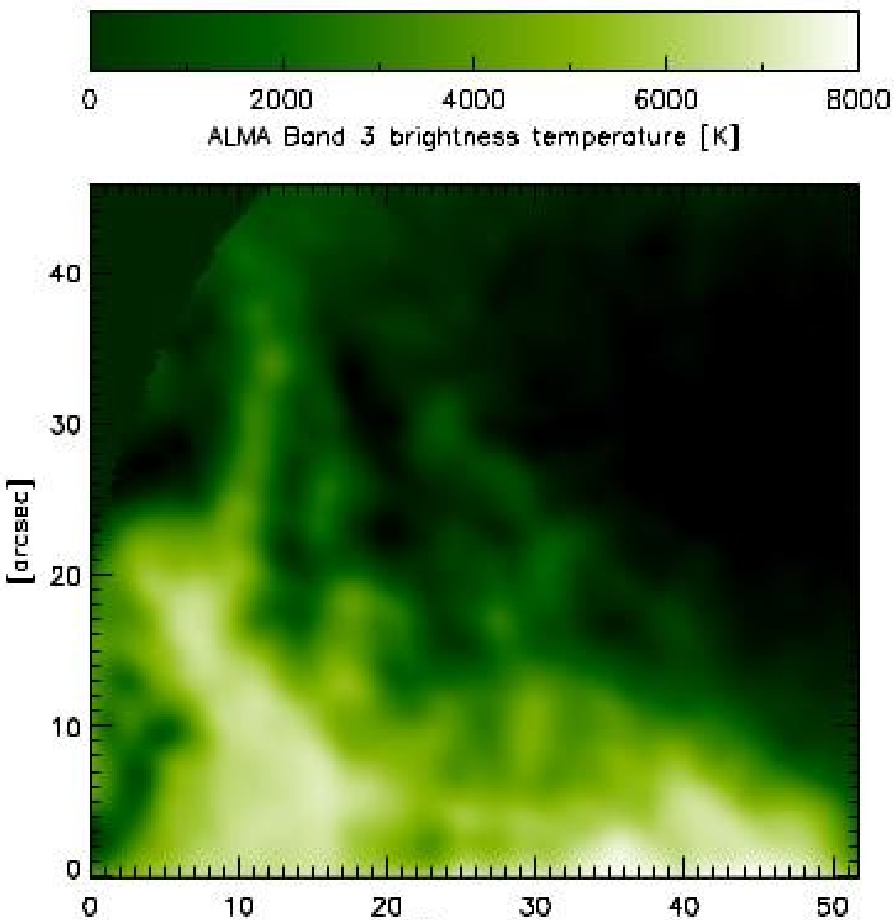
CASA::feather():
relative weight=0.8

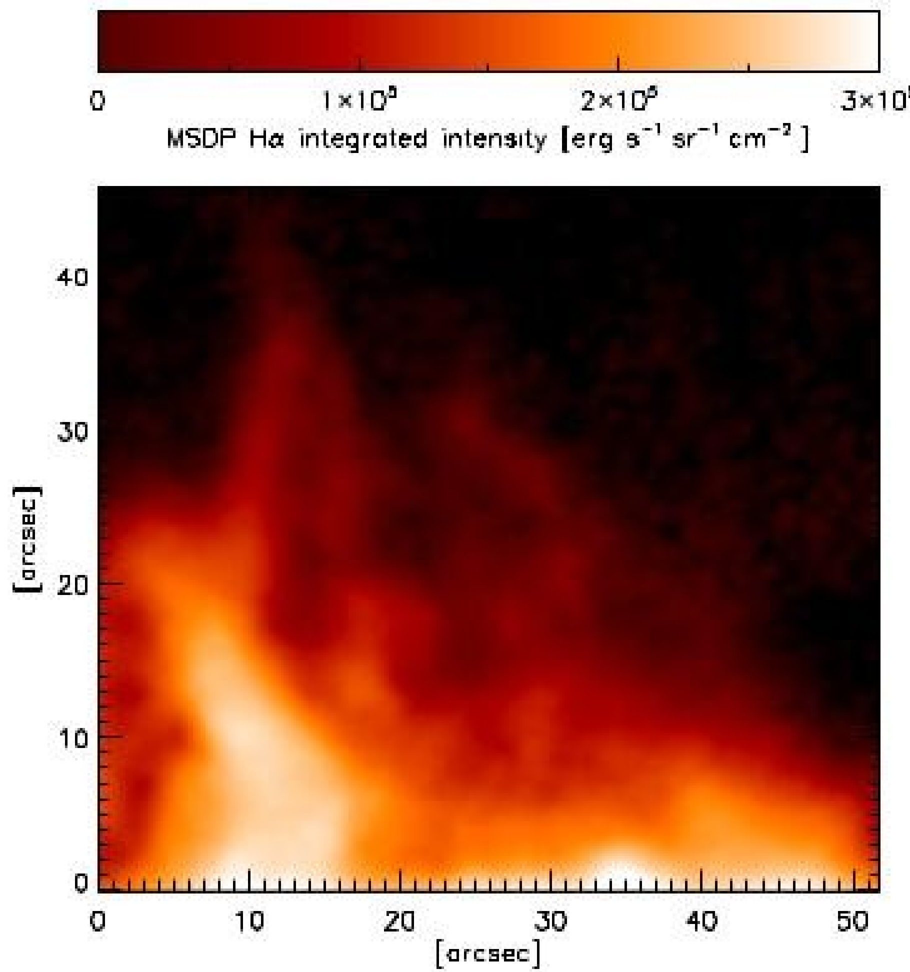


Analysis & results: ALMA 3mm + Hα

$$T_b = F(T_{kin}, E(H\alpha))$$

<u>Idea:</u> Invert this relation to get T_{kin}

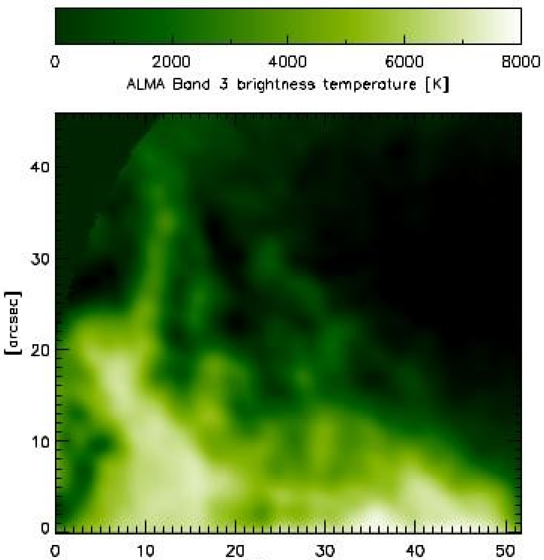


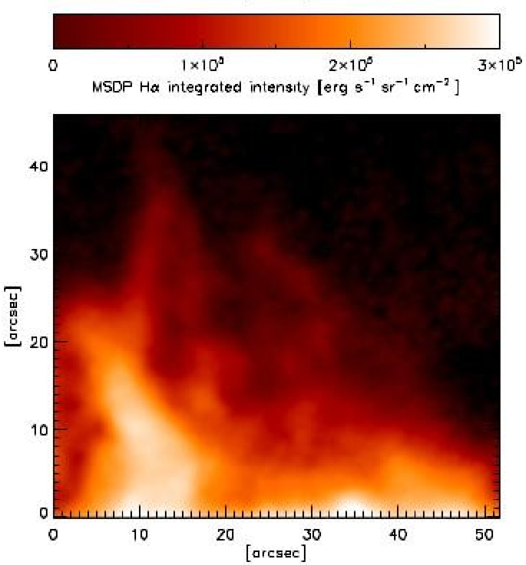


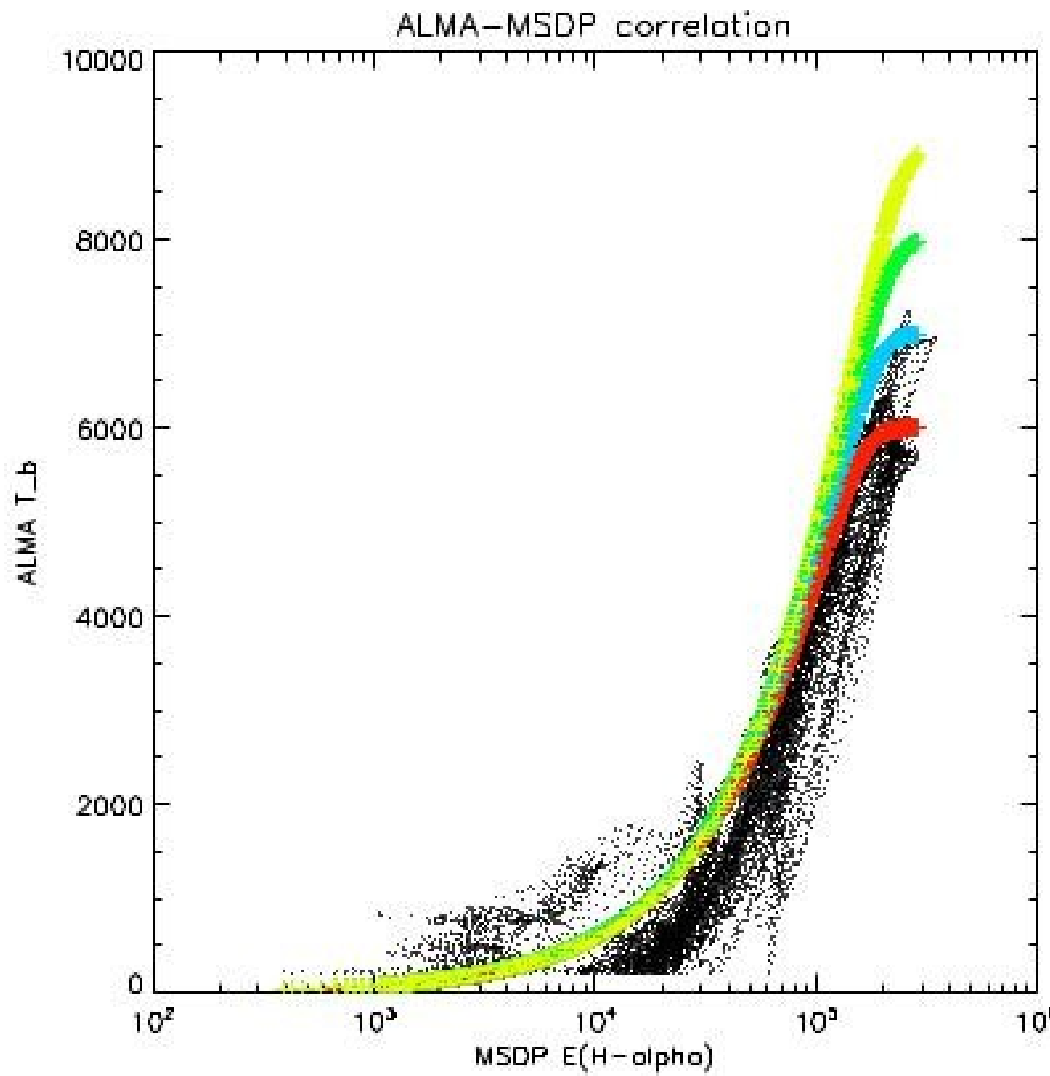
Analysis & results: ALMA 3mm + Hα

$$T_b = F(T_{kin}, E(H\alpha))$$

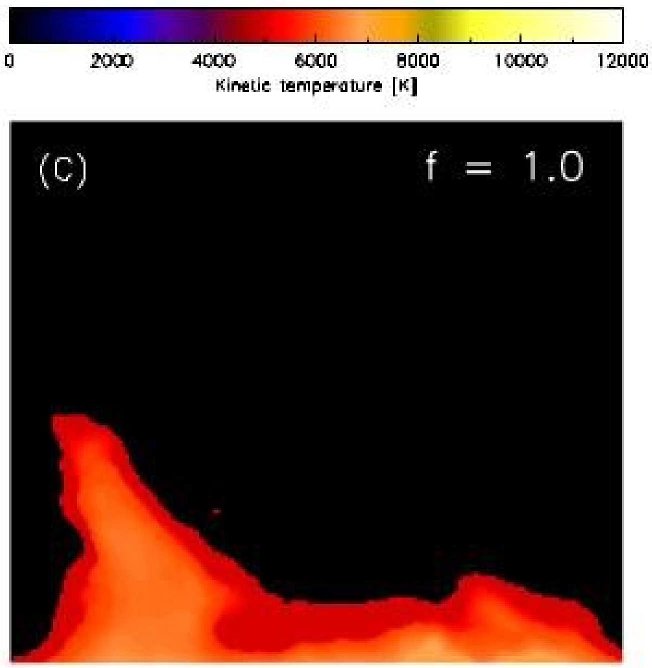
<u>Idea:</u> Invert this relation to get T_{kin}





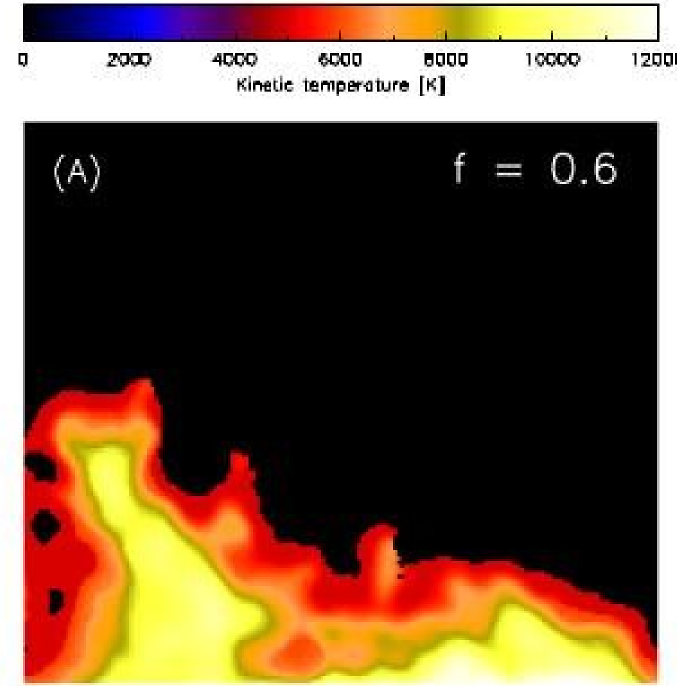


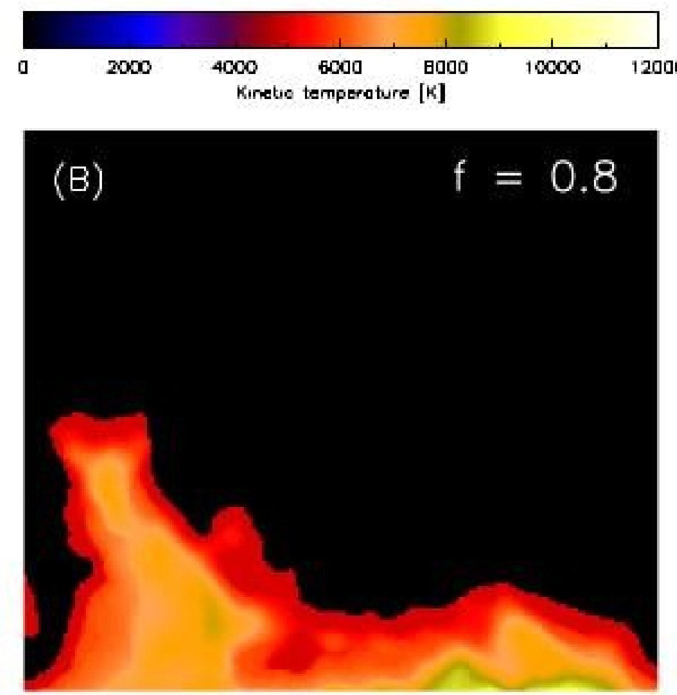
Analysis & results: T_{kin} maps



Still uncertainty in filling factor:

- Integration of variable temperature along LOS
- May have spatially unresolved brighter cores





Summary

- Knowledge of internal temperature structure of prominences is crucial for understanding their basic physics.

- It is hard to infer it form spectroscopy (optical, UV): non-LTE, sensitive dependence on free model parameters → quite a broad range of resulting values.

- A relation exist between total Hα intensity, kinetic plasma temperature and brightness temperature at mm wavelengths: $T_b = F(T_{kin}, E(H\alpha))$

- Using simultaneous observations of the prominence at mm wavelengths and in Hα the relation can be inverted to get T_{kin}

- We applied this procedure to the prominence observed simultaneously by ALMA and Wroclav MSDP on April 18th, 2018. The procedure of ALMA data reduction is not easy but it is straightforward and plausible

- For the first time, thermal structure of the prominence has been inferred this independent way: We have got the T_{kin} maps with spatial resolution ~1.5 arcsec.

- Ambiguities still remain due to unknown filling factor and just averaged T_{kin} profile along LOS.