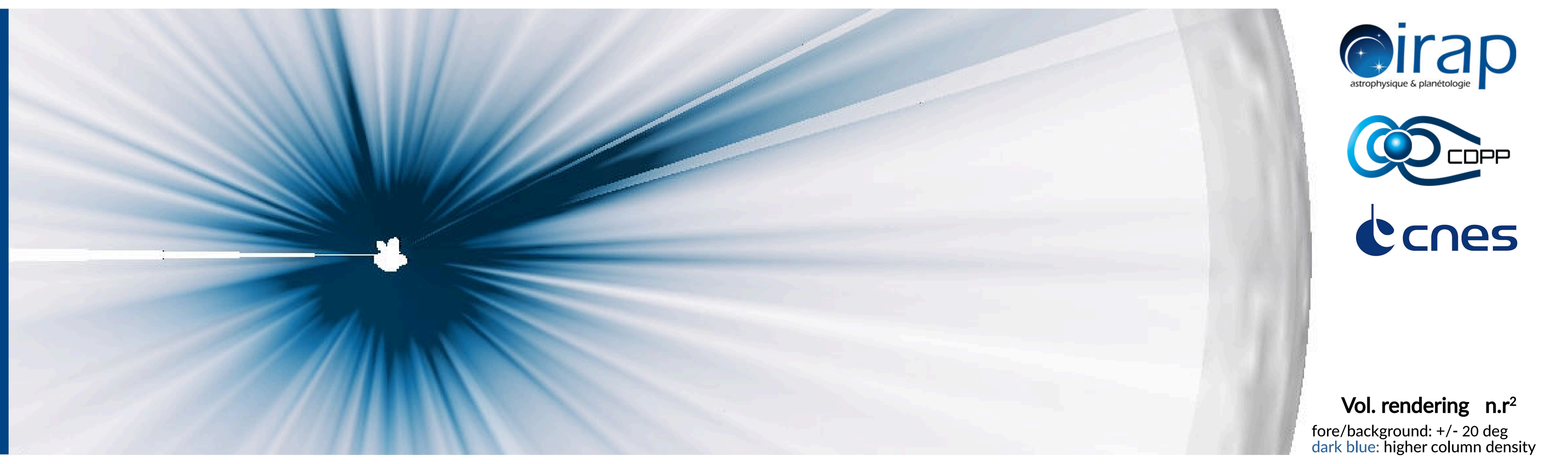
Modeling and forecasting the background solar wind with data-driven physics-based models

M. Lavarra[1], R. F. Pinto[1], A. Rouillard[1], A. Kouloumvakos[1], L. Griton[1], A. Bemporad[2], C. Arge[3], M. Alexandre[1], V. Génot[1]

(michael.lavarra@irap.omp.eu)

[1] IRAP / CNRS-OMP / U. Paul Sabatier, Toulouse, France
[2] INAF – Osservatorio Astrofisico di Torino, Italy
[3] NASA GSFC, MD, USA



Accurate background solar wind simulations

- Physics-based solar wind modeling, from the solar surface to the heliosphere
- Much faster than full 3D MHD models, more physics than empirical methods
- Data-driven, full set of background wind properties (speed, density, temperature, mag. field)
- The pipeline couples mature research models and provides several synthetic diagnostics (white-light and EUV imaging, in-situ time-series) and comparison to observations and spacecraft measurements.

Recent and future advances

- Combine different input magnetogram sources, provide forecasts at different s/c positions
- Flexible setup (full 3D, plane-of-sky, ecliptic, s/c orbit)
- Applications to Parker Solar Probe and Solar Orbiter
- TIme-dependent (impulsive) phenomena, kinetic fluid solar wind model
- Web-based front-end available soon!

SWiFT / MULTI-VP Data-driven solar wind model

1. SWiFT pipeline, using MULTI-VP wind model

SWiFT data-driven pipeline

Sun / surface observations
(magnetograms: HMI, WSO, ADAPT)

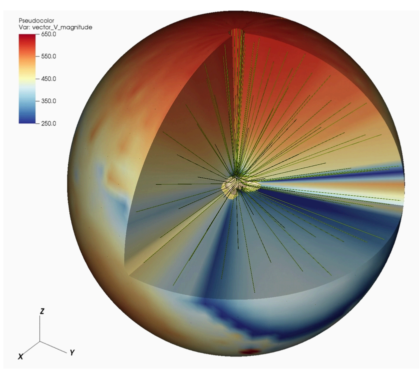
1. Coronal field reconstruction
(PFSS, NLFFF, SolarModels)

2. MULTI-VP

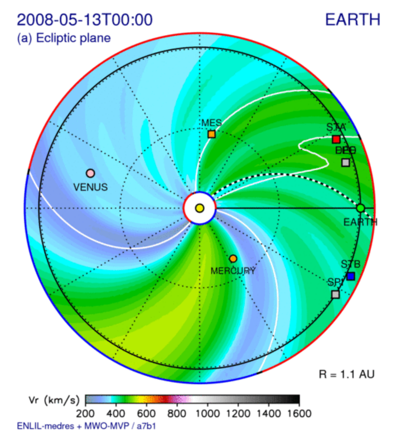
3. Heliospheric propagation
(ENLIL, EUHFORIA)

Earth / interplanetary medium
(S/C data, heliospheric imaging)

Extrapolated magnetic field

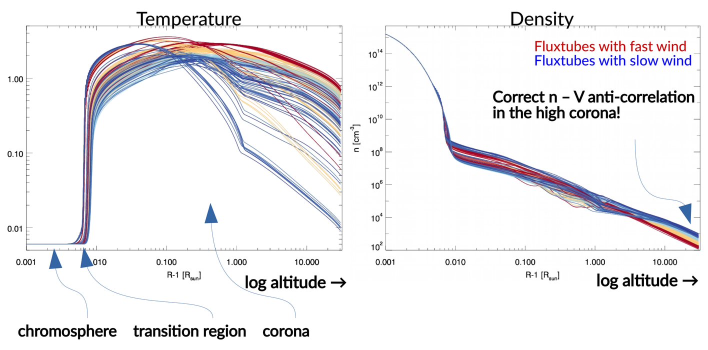


Wind speed 1 – 15 R_{sun}



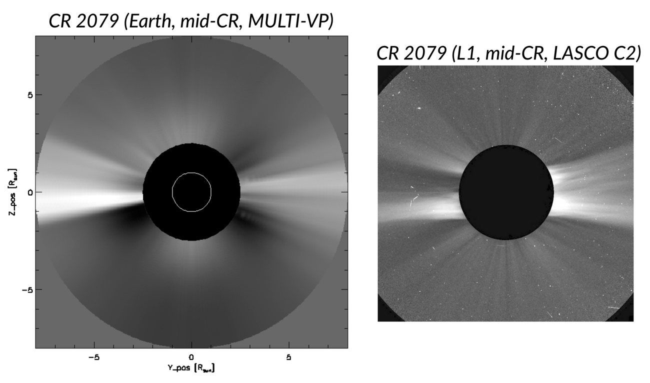
Wind speed 21.5 R_{sun} – 1.1 AU

2. Solar wind formation (corona)



Multiple individual solar wind streams

. coronal heating, rad. cooling, conduction
. 1 to ~60 Rsun, arbitrary lat-lon domain
. correct fast/slow wind distribution, any phase
. transverse pressure balance → correct n-V

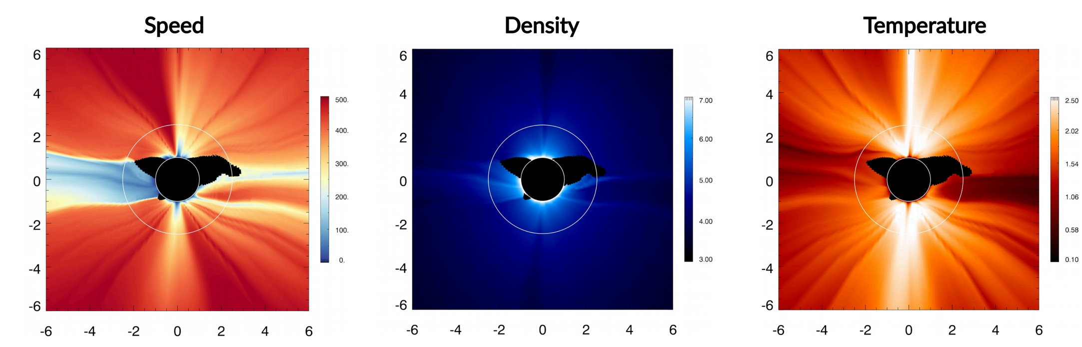


Synthetic white-light imagery

. calculated from 3D density distribution
. check for correct positions of streamer rays, etc.
. sensitivity to errors in the extrapolated field and on the heating model used

(Pinto, Rouillard, *ApJ* 2017)

Solar wind properties in the plane-of-sky



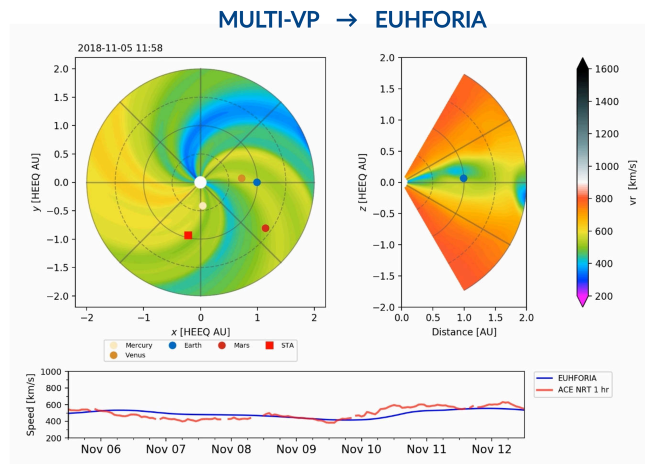
MULTI-VP (plane-of-sky only)
ADAPT / KPVT maps, PFSS + SCS coronal field reconstruction

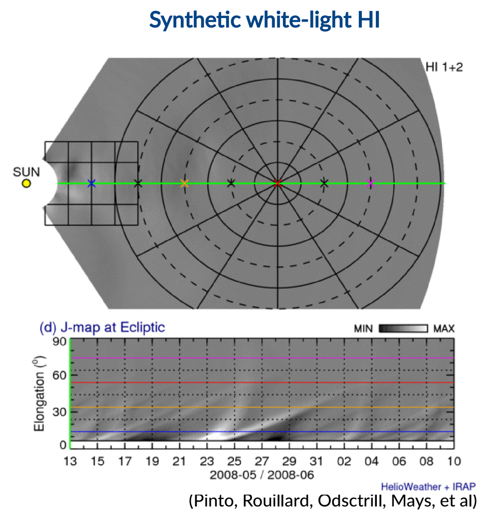
. One month of data (1 – 30 June 1997)
. Visible limb ± ~7 deg foreground/background
. ADAPT ensemble maps, daily cadence

dark patches: streamers, data gaps
white lines: surface, source-surface

(Pinto, Bemporad, Arge, *in prep*)

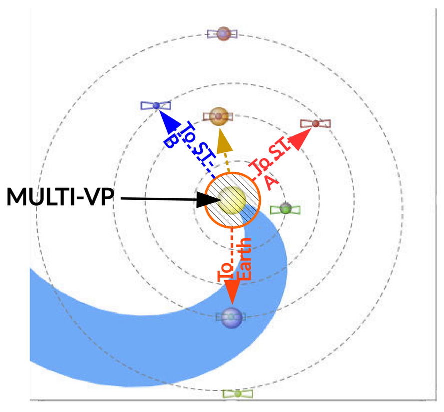
3. Heliospheric propagation





(Pinto, Rouillard, Odstrcil, Mays, et al)

Heliospheric propagation, individual 1D propagation paths

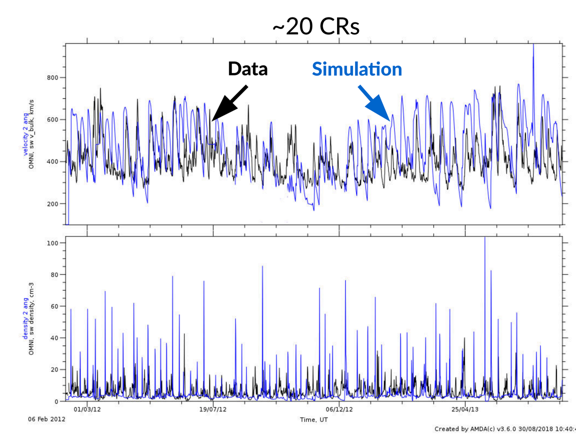


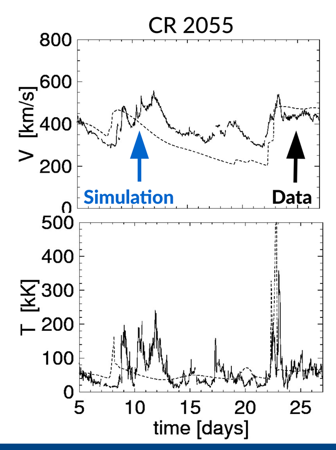
propagationtool.cdpp.eu
(propagation method from Tao et al, 2005)

Forward propagation from output of MULTI-VP
(arbitrary radial paths, any latitude or longitude)

Multiple time-series, at **different orbital positions**, rotation + background field evolution

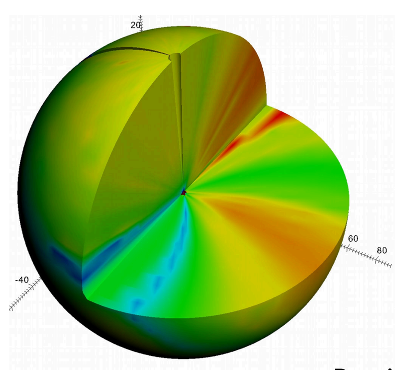
Simulation vs. OMNI





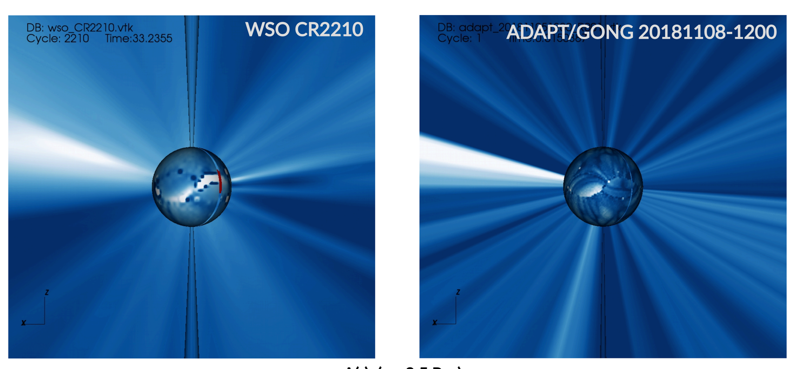
Parker Solar Probe – solar wind context

MULTI-VP extended to 90 R_{sun}



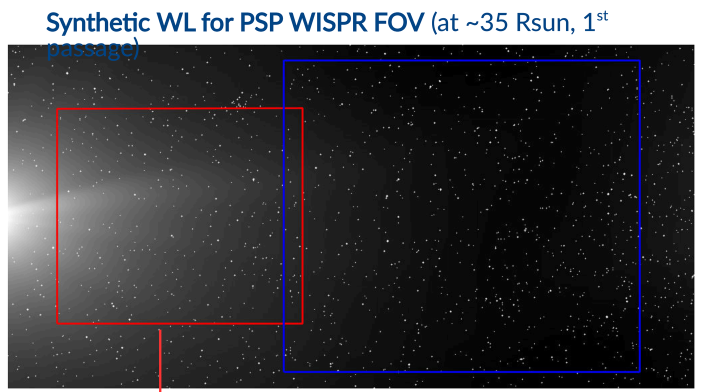
Domain covers Parker Solar Probe's
. perihelions: ~36 → 9 R_{sun}
. radial scan regions (quasi-corotation)

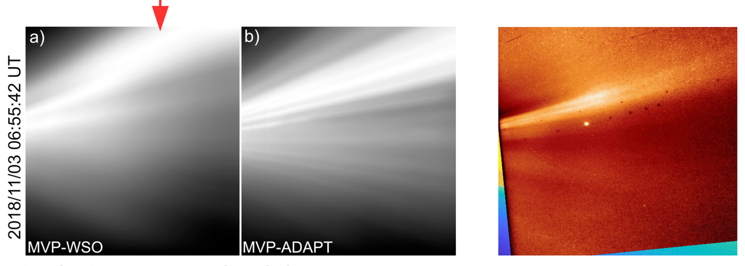
Wind density in the low corona (with different input magnetograms)



$n.A(r)$ ($r > 2.5\ R_{sun}$)

Synthetic WL for PSP WISPR FOV (at ~35 Rsun, 1st passage)

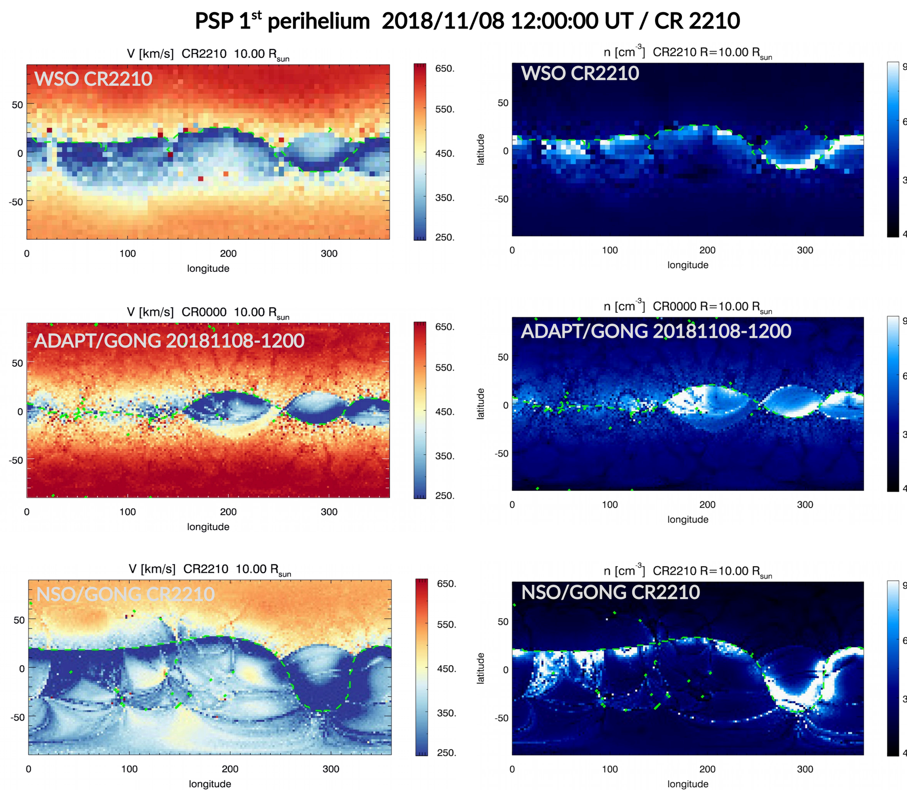




Synthetic MULTI-VP white-light
WISPR FoV (Poirier, Kouloumvakos, et al, 2020)

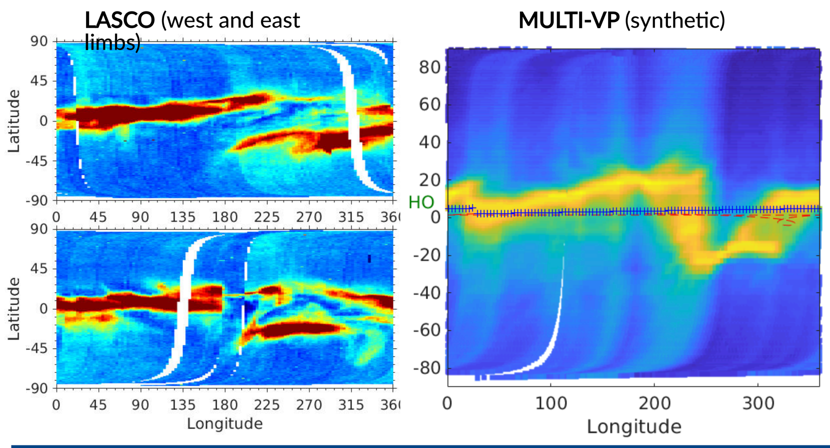
WISPR

Wind speed and density maps at 10 R_{sun} (with different input magnetograms)



- Wind speed distributions very sensitive to polar B flux and also to consequences for flux-tube topologies (expansion factors, inclination)
- Density distributions distributions in better agreement both qualitatively and quantitatively, much less sensitive to polar and open B flux issues
- Qualitative and quantitative differences when using different input magnetograms yet *strong features* are present on all maps
- Further calibration of PFSS and/or heating model required
- Main differences linked to intrinsic features of B-maps angular resolution, less phi-averaging on synchronic maps

White-light Carrington maps (1st passage, PSP on LASCO's p-o-s)

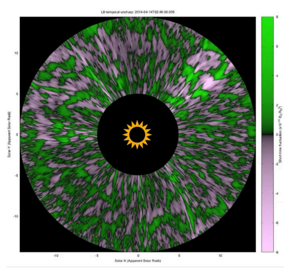


Transient heating, density structures in the corona

Adding variability to the background solar wind

. Solar wind density is highly structured in the low corona
strong radial (ray-like) structure +
continued flow of intermittent compact structures of different sizes
. Many possible sources of intermittency
reconnection, jets, coronal bright points, waves, turbulence, ...
response of the wind / propagation dependent on background conditions

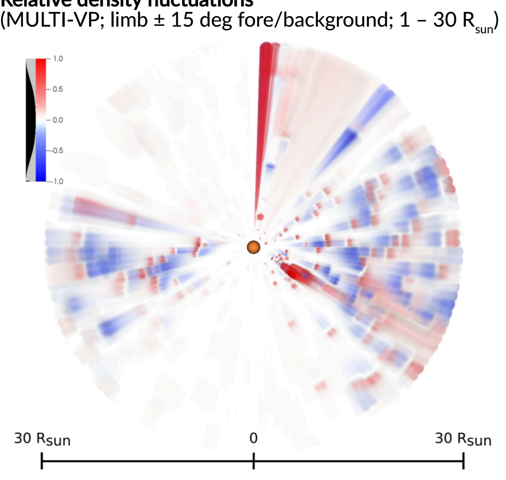
Brightness fluctuations in the low corona
(High cadence STA/COR2; ~5 – 15 R_{sun})



(DeForest, 2018)

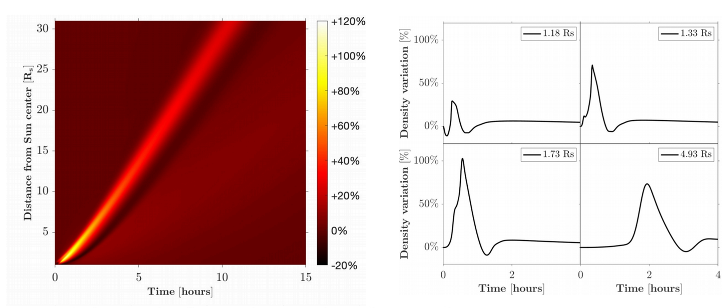
Setup random impulsive heating events in the whole Sun
(coherent with coronal bright point statistics, e.g Alipour & Safari 2015)

Relative density fluctuations
(MULTI-VP; limb ± 15 deg fore/background; 1 – 30 R_{sun})



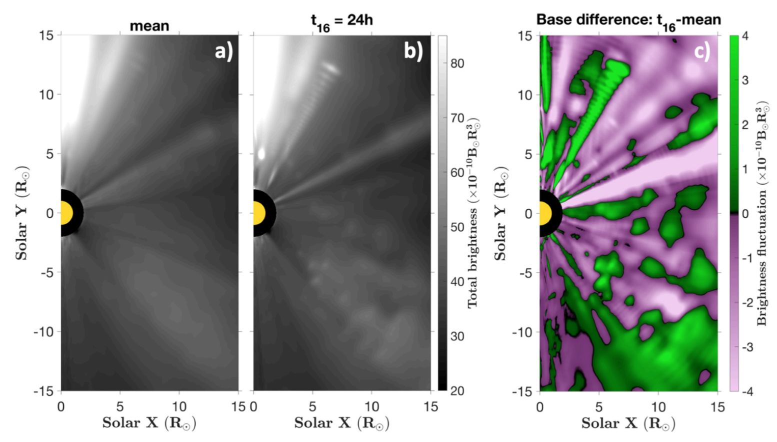
(Griton, et al, 2020)

Response to a single impulsive heating event at the bottom of the corona
(MULTI-VP; single magnetic fluxtube)



Left : density fluctuations on time-distance diagram.
Right : density fluctuations as a function of time at varying heighs.

Synthetic white-light images



ISAM: kinetic-fluid solar wind

ISAM solar wind model

. 1D multispecies (H,He, e-, p, He+, He2+)
assuming bi-maxwellian distribution

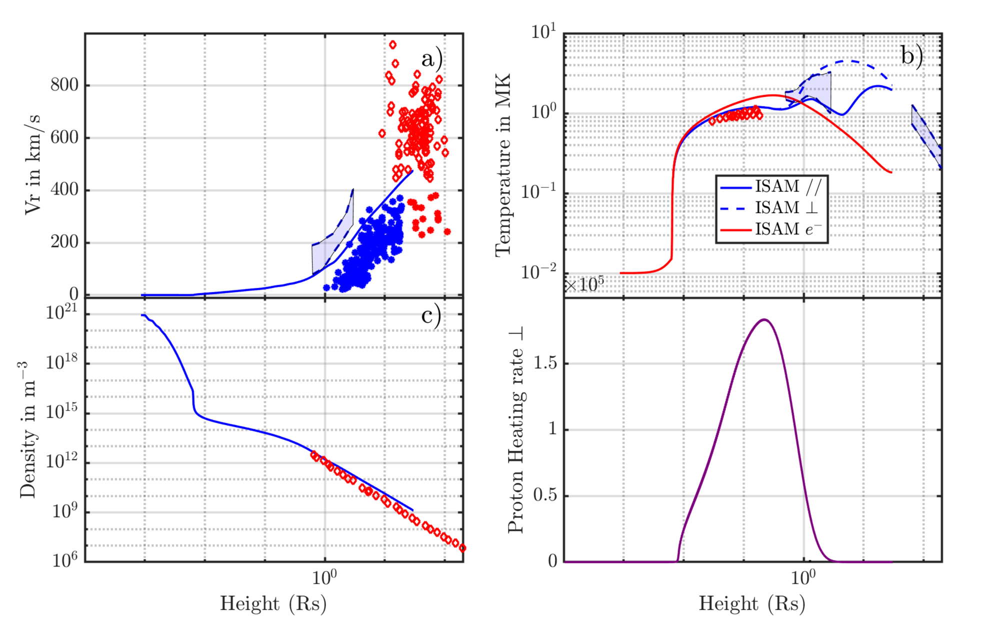
. Solve anisotropy and instabilities (firehose, mirror)

. Self consistent ionization in upper chromosphere and corona

Blue and red lines: ISAM proton and electron profiles (wind speed, density, temperature, heating rate)

Symbols: EISCAT, SoHO/UVCS, WIND-WAVES data (Breen 96, Grall 96, Cranmer 09, Leblanc 98)

(Lavarra, et al, in prep.)



Conclusions

MULTI-VP: global wind model (1 - 60 R_{sun} + coupling with heliosphere), fast computation, alternative to WSA and full 3D MHD models

Heating mechanisms (disentangled from geometrical effects)

Full set of background solar wind properties

Diagnostics (e.g white-light, EUV, V/n/T maps, in-situ measurements; pre/intermediate/final checkpoints)

Data-driving: synoptic and synchonic magnetic maps

Current issues: **Uncertainties related to magnetograms**
(different mag. sources lead to different results)

Quality of the mag. field extrapolations
(open flux problem, false hits/misses due to positional errors)

Coronal rotation
(shape of the spiral, stream arrival times)

Define appropriated validation metrics
(uncertainties and forecast skill)

Work-in-progress: **inclusion of ISAM solar wind model**
(multiple species, kinetic fluids, heating mechanisms)

More physics, time-dependent phenomena
(waves, turbulence, transients)

Data-driving: add local magnetic field maps, improved mag. field extrapolations

Forecast mode: continuous few-days forecast at s/c position