Session: ***Observations of the Local Interstellar Medium and Motivations for IMAP***

Poster: **SH41E-2407**

Hypothetical signals beyond the primary ISN He flow as perspective targets for IMAP

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Introduction

- Interstellar Boundary Explorer (**IBEX**) is a small Earth-orbiting spacecraft that successfully investigates the **local interstellar medium** that surrounds **heliosphere**.

- The IBEX-Lo sensor samples **the primary population of interstellar neutral (ISN) helium** with a high signal-to-noise ratio.

- In addition to this strong signal, which has been interpreted as due to a **Maxwell-Boltzmann distribution** of the ISN gas in front of heliosphere (e.g., Bzowski et al. 2012), the observations also revealed **elevated wings** above the background level both in longitude and latitude.

- This signal, dubbed the **Warm Breeze** (Kubiak et al. 2014), is likely the **secondary population of ISN He** created in the outer heliosheath.

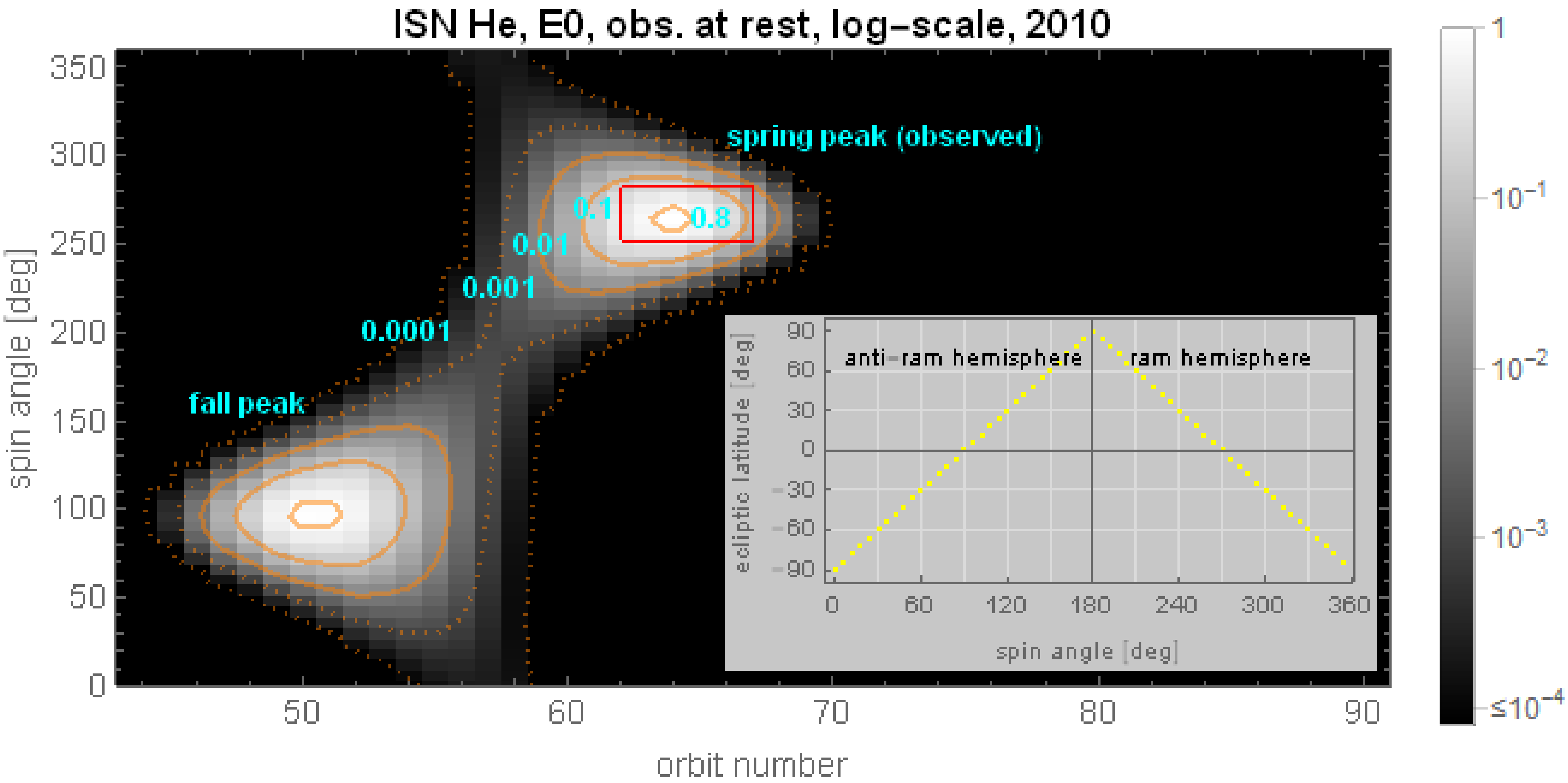
- In addition, IBEX sees an **unexplained background** in the lowest energy channels (Galli et al. 2014, Fuselier et al. 2014).

- In this study, we **hypothesize on departures** from the assumptions adopted so far in the data interpretation that could solve remaining **unexplained features in the IBEX data** or may be **pursued by future IMAP mission**.

- We test the possibility to detect the **fall peak** of the primary ISN He, we compare with observations the hypothesis that the primary ISN He is given by the **kappa distribution** or by a distribution with an **anisotropic temperature** (simulations done with the use of analytic WTPM, see Sokół et al. 2015)

- We point out the **regions on the sky** where to look for the **signatures of the hypothetical signals** and also determine the **energetic requirements for the detector**.

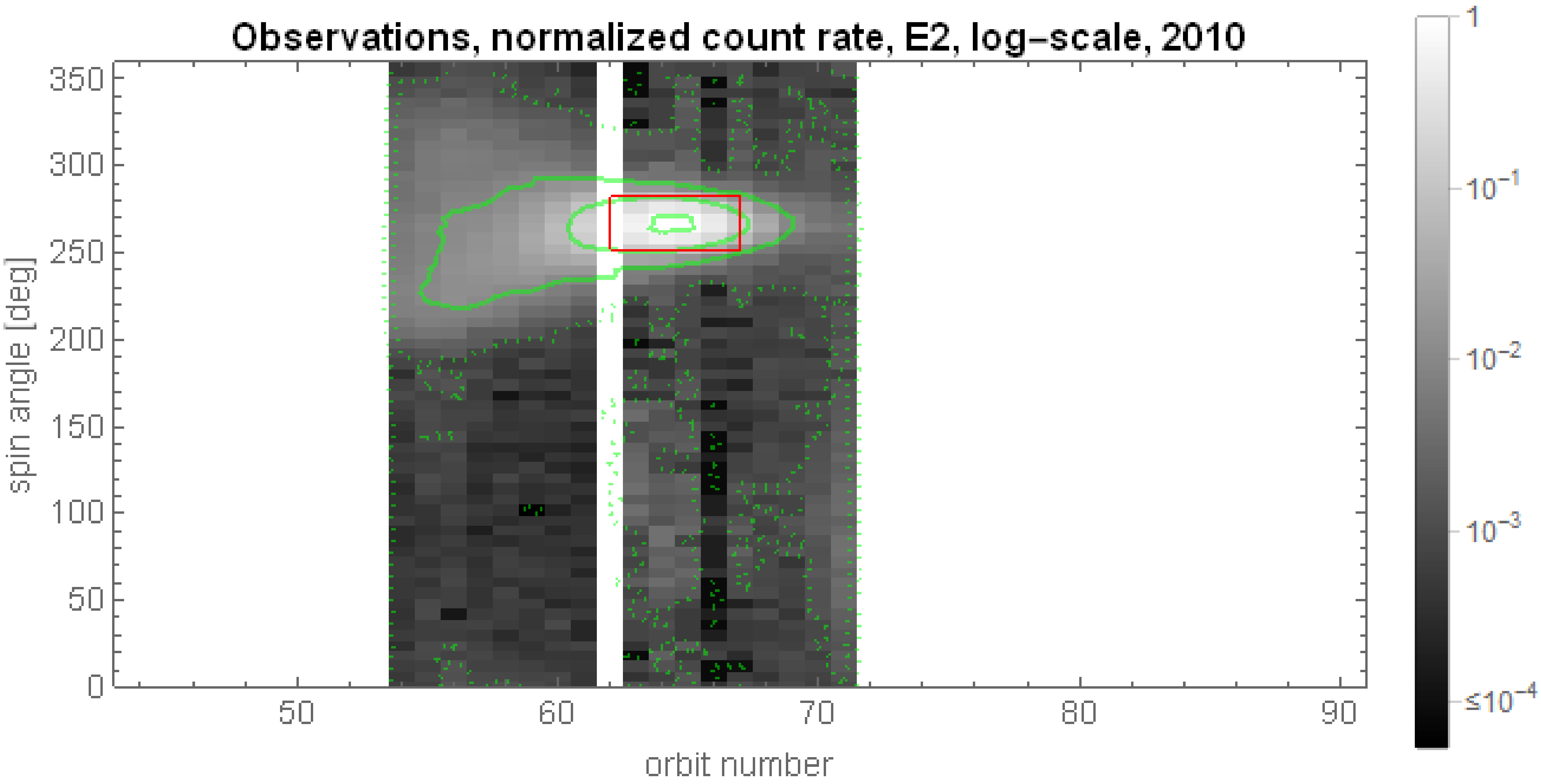
Ideal ISN He signal (V_{sc}=0, E_{thr} = 0)



Simulated full-sky map of the ISN He flux (single Maxwell–Boltzmann population) as it would be seen by a virtual IBEX-Lo located at ecliptic longitudes for orbits 43 through 91 (2009–2010 August 30), at rest in the Sun frame. Shown in the logarithmic scale and rescaled to the peak value. The isocontours cover (with some excess) the whole dynamical range of IBEX-Lo data. The map is shown in the spacecraft reference system. A similar format is used in other sky maps presented in the poster.

For a **motionless detector** and **zero energy threshold**, the ISN He signal would feature **two symmetric peaks (spring and fall)** during the year.

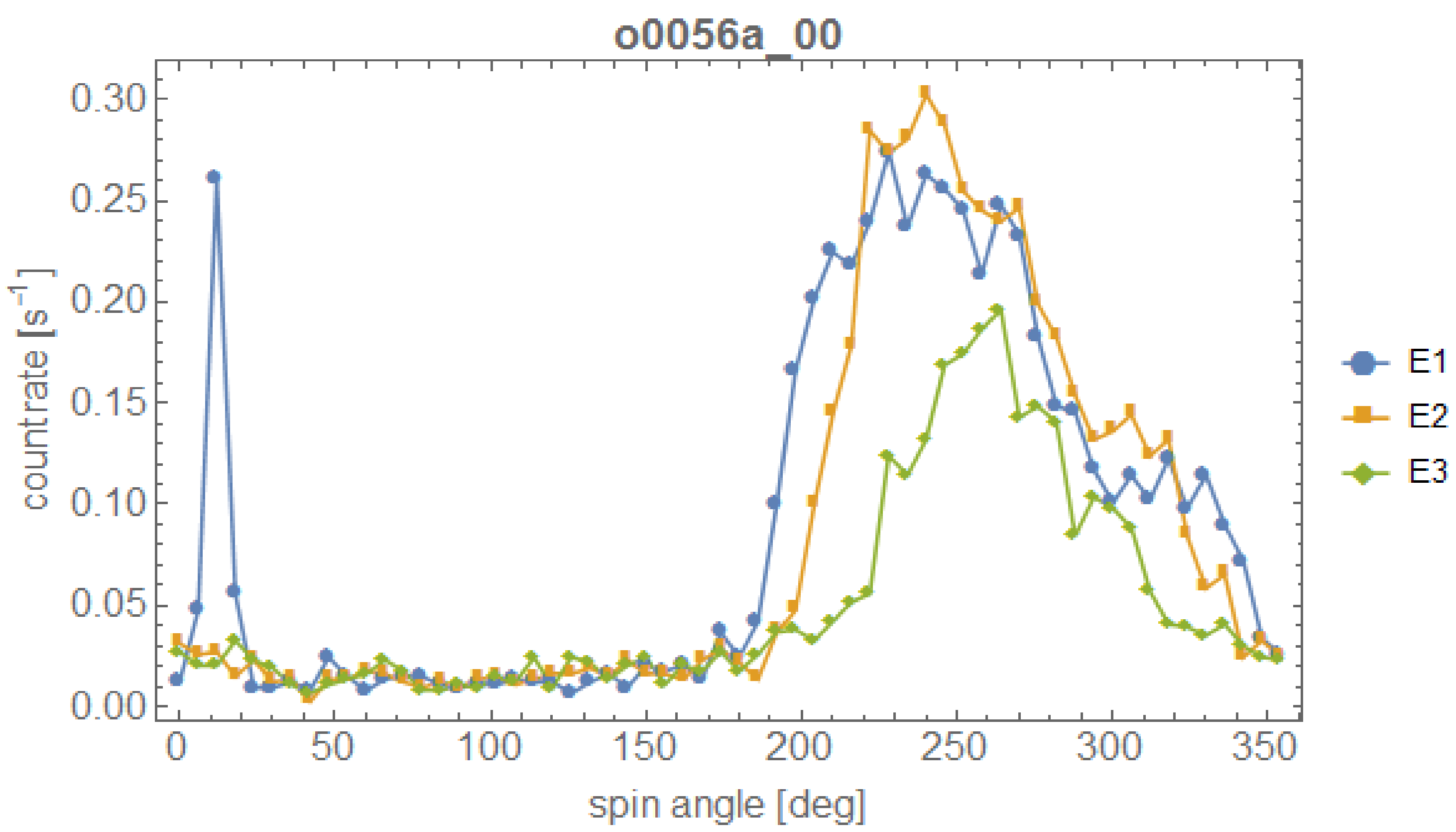
In reality IBEX has seen…



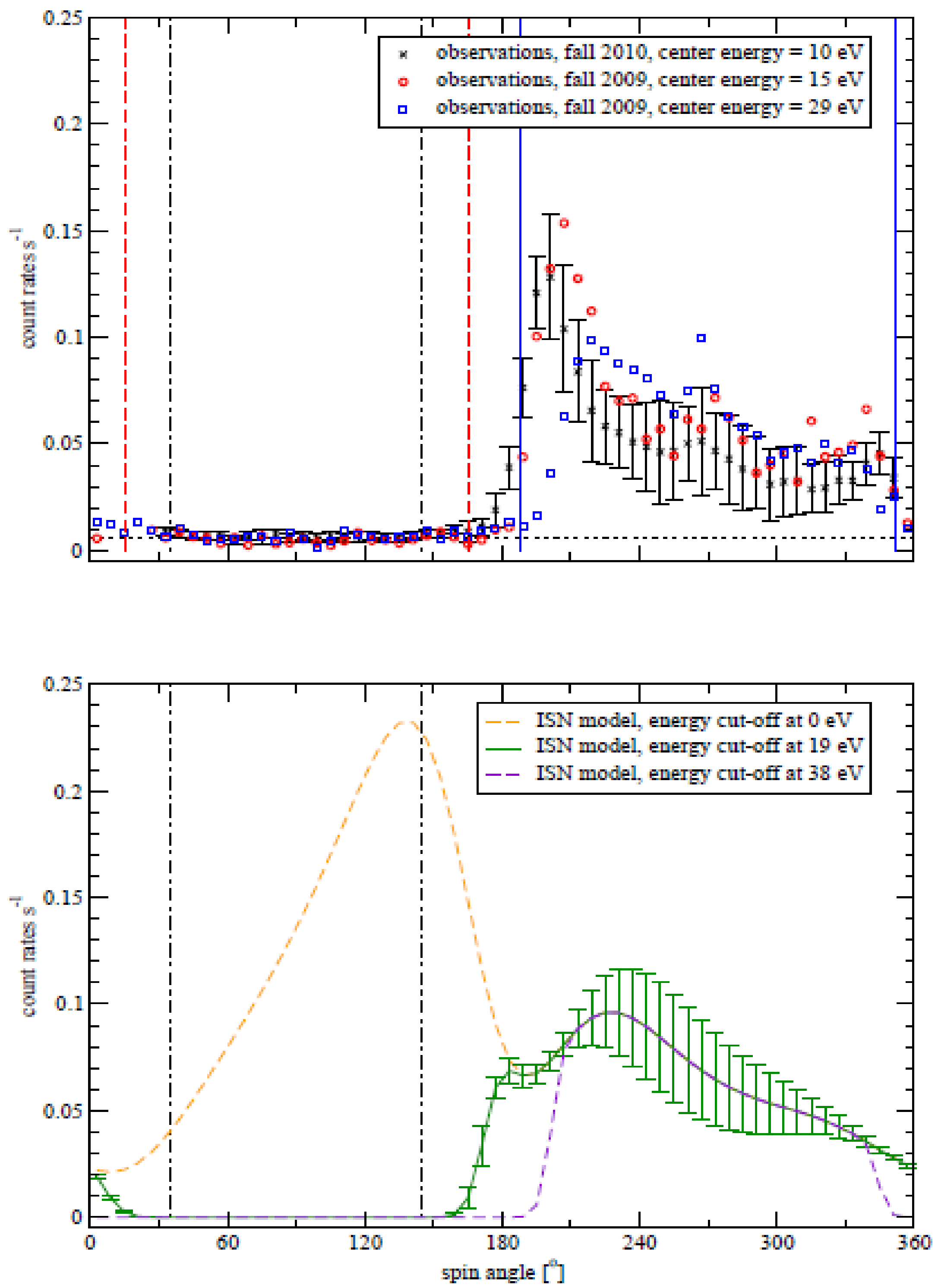
Observations of ISN He by IBEX–Lo in energy step 2 (E2: 19-38 eV), taken in orbits 54 through 72, presented as count rates for observation season 2010, normalized to the seasonal peak value (orbit 64), shown in the logarithmic scale. The isocontour lines mark the intensities of 0.8, 10^{-1}, 10^{-2} (solid lines), 10^{-3}, and 10^{-4} of the peak intensity (broken line). Red rectangle presents the data taken to the analysis by Bzowski et al. 2015. Data from orbit 62 are missing (white block).

In reality IBEX has seen…

- IBEX **moves with Earth** and IBEX-Lo has a **finite energy threshold**
- The existence of this **cutoff confirmed experimentally**, but details are still uncertain
- Observing ISN He in the anti-ram hemisphere is not possible due to the finite energy threshold
- Analysis details in **Galli et al. 2014, 2015**

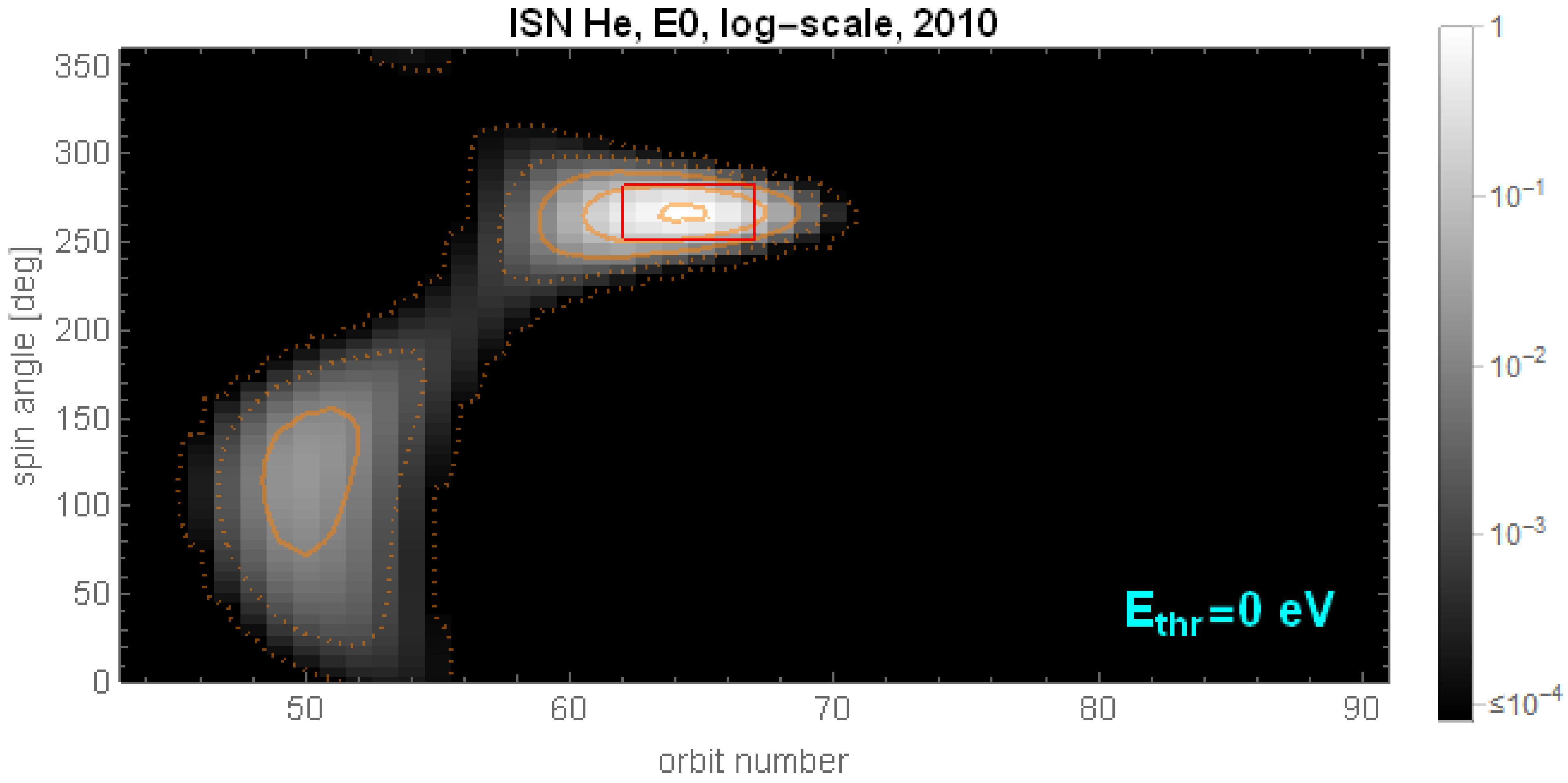


Count rates registered by IBEX-Lo during orbit 56 in three energy steps (E1: 10-19 eV, E2: 19-38 eV, E3: 38-73 eV).



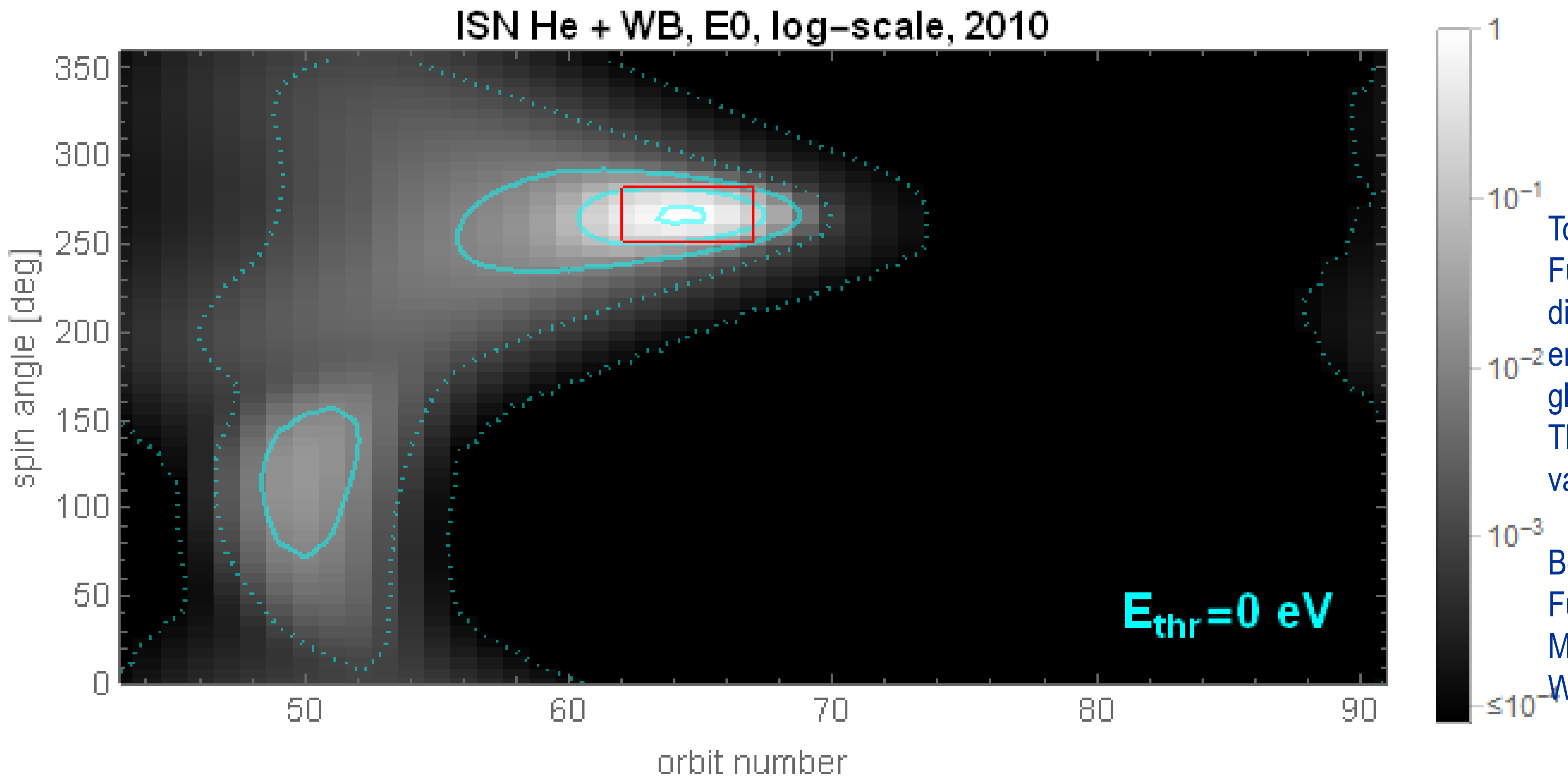
Measured (top) and expected (bottom) count rates due to ISN He during the Fall ISN observation season. The red circles (E1) and blue squares (E2) show observations during the nominal mode in the Fall of 2009 (orbits 51–53), the black "x" denotes the measured count rates during the special mode with the center energy at 10 eV for orbits 99–101. The black dotted line (top) is the background level of 0.0062 cnts s^{-1}. The model results, averaged for orbits 51–53, are shown in the lower panel. (Figure 6 in Galli et al. 2015)

Expected ISN He signal ($V_{sc}=V_{IBEX}$, E_{thr} = 0 eV)



The spacecraft motion around the Sun **reduces** the **fall peak** height to **~2%** of the spring peak.

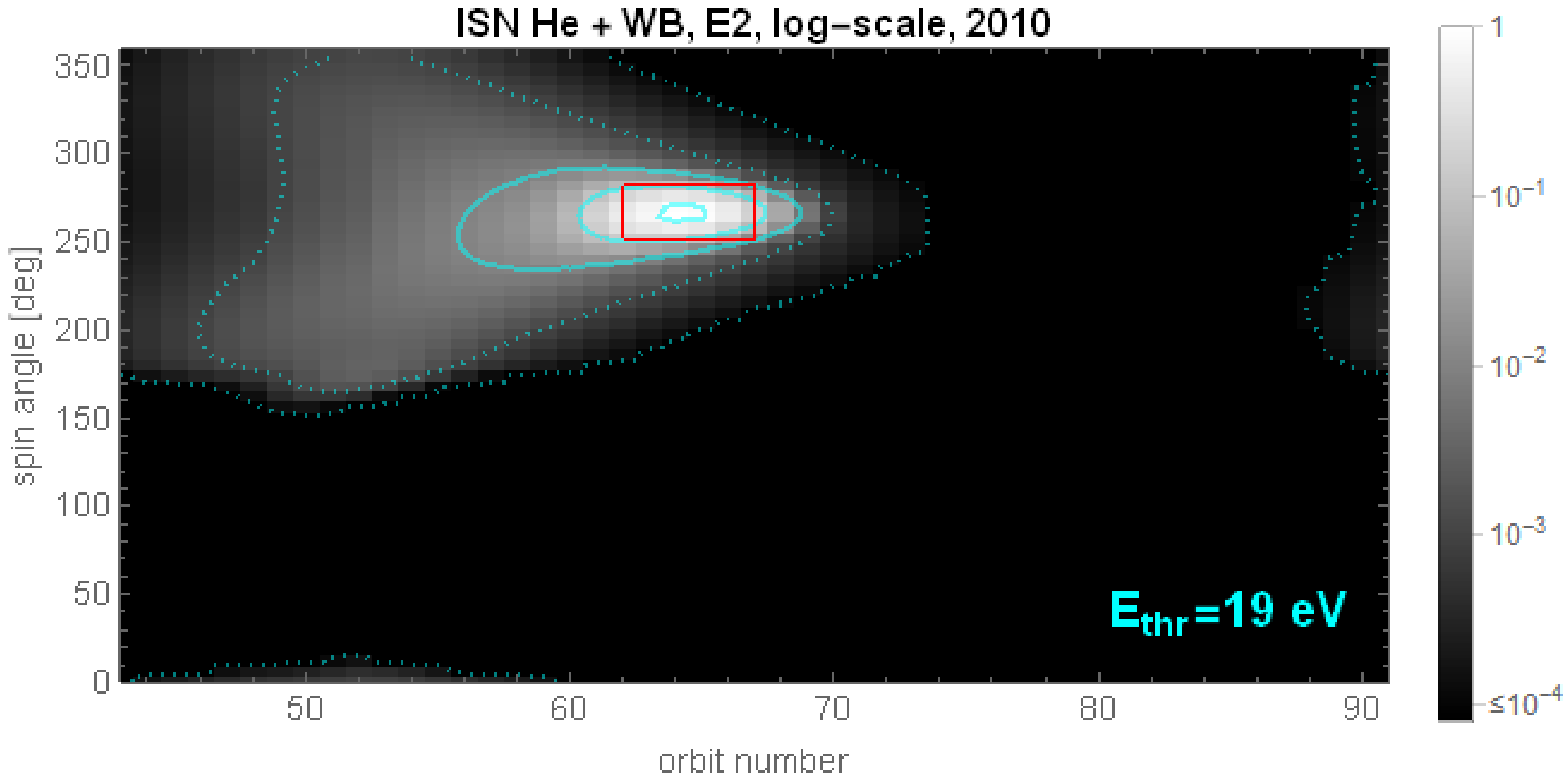
Warm Breeze modifies the signal, mostly in the **ram hemisphere**.



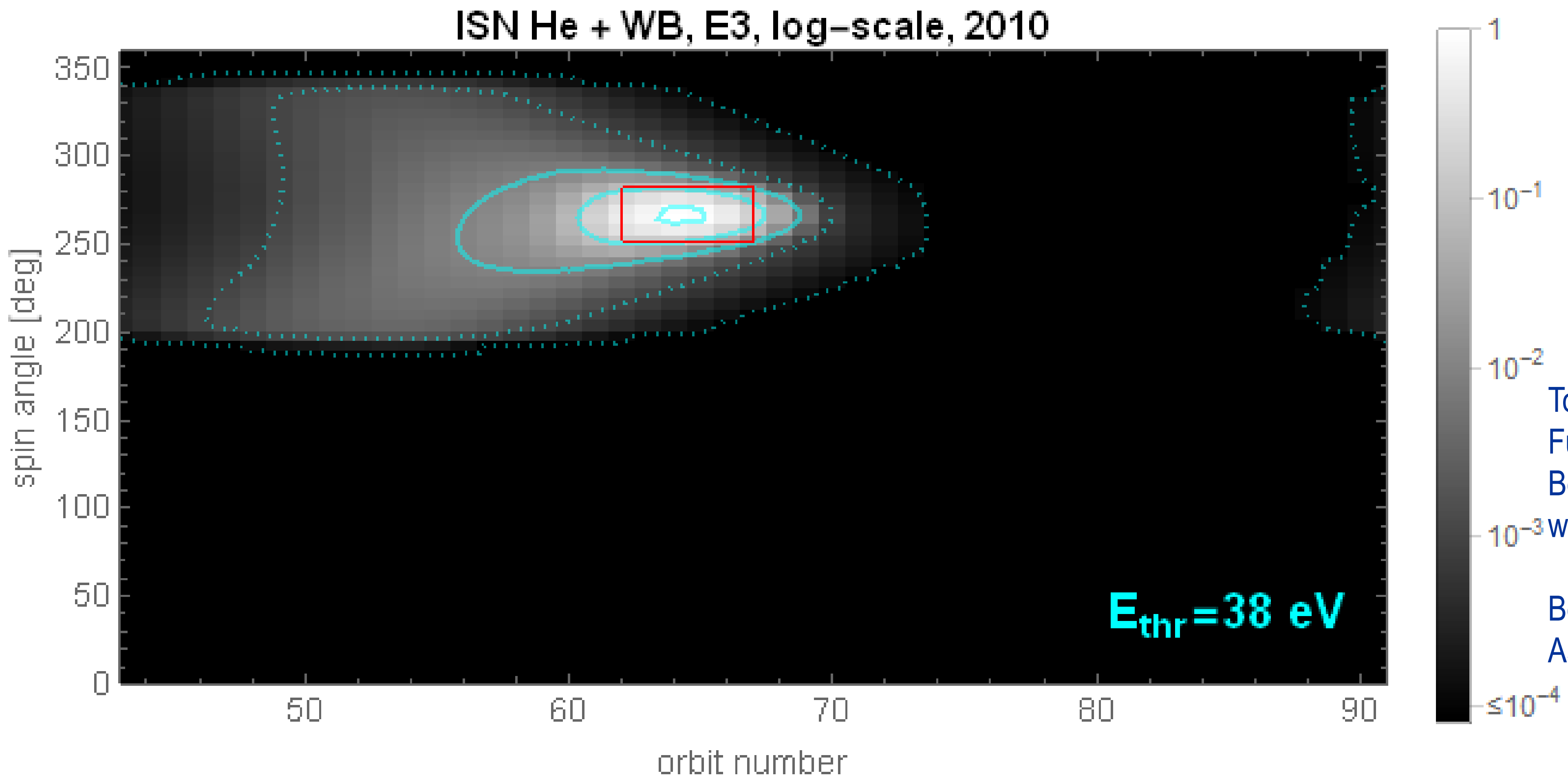
Top:
Full-sky map of the ISN He flux for the single Maxwell–Boltzmann distribution of the primary ISN He as it would be seen by IBEX-Lo if its energy sensitivity was independent of energy. The flux is scaled to the global maximum (spring peak) and presented in the logarithmic scale. The flux distribution on the sky for the values lower than 10^{-4} of the peak value is rendered as totally black.

Bottom:
Full-sky map of the ISN He flux simulated as a superposition of the Maxwell-Boltzmann flux of the ISN He primary population and of the Warm Breeze.

Expected ISN He signal ($V_{sc}=V_{IBEX}$)



Increasing E threshold gradually **fades out** the **fall peak** height and blocks the signal from the anti-ram hemisphere.



Top:
Full-sky map simulated as a superposition of the flux of the Maxwell-Boltzmann ISN He primary population and of the Warm Breeze, calculated with the energy threshold set to 19 eV (like in E2).

Bottom:
As above but with the energy threshold set to 38 eV (E3).

Hypothesis: perhaps ISN He is kappa-like?

- **Maxwell-Boltzmann distribution function:**

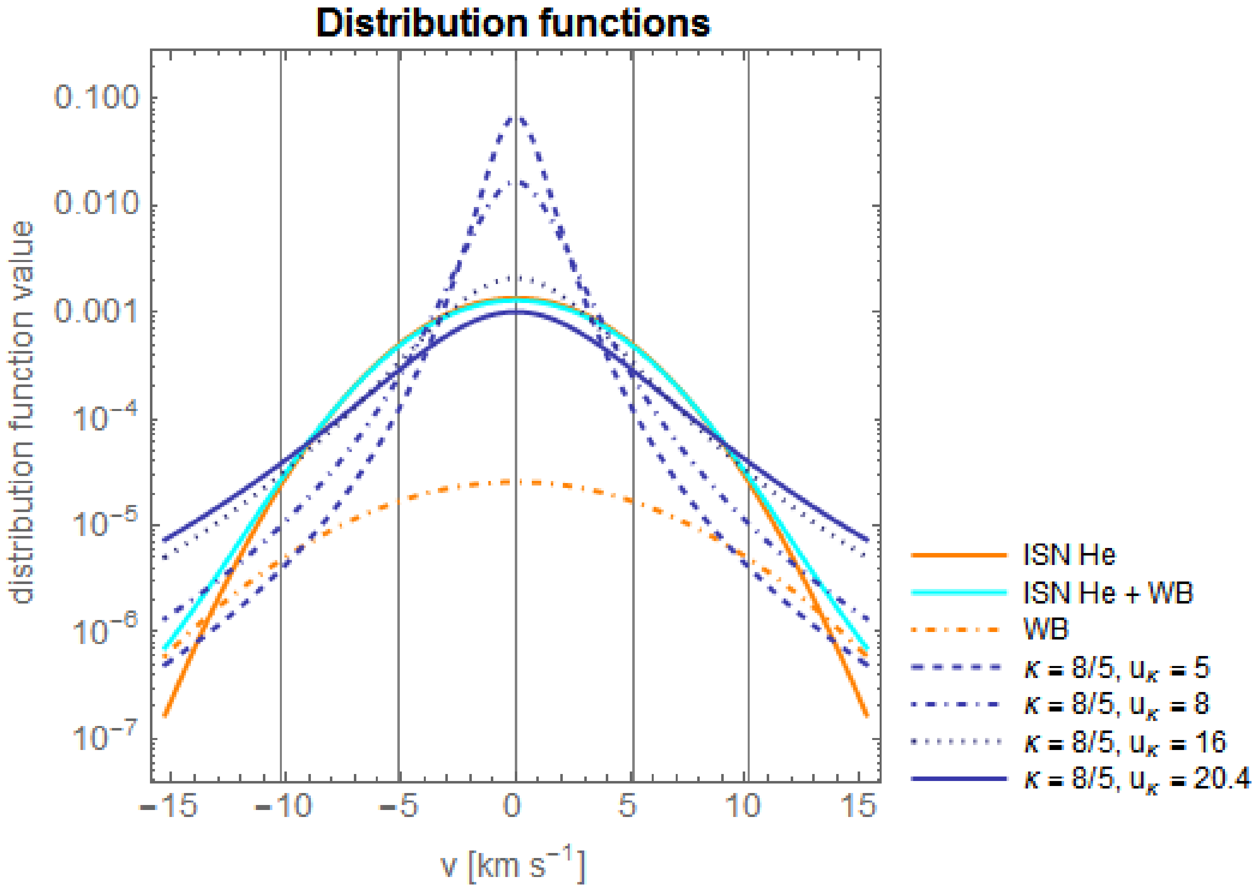
$$f_{M-B}(v, u_{M-B}) = \pi^{-3/2} u_{M-B}^{-3} \exp\left[-\frac{v^2}{u_{M-B}^2}\right]$$

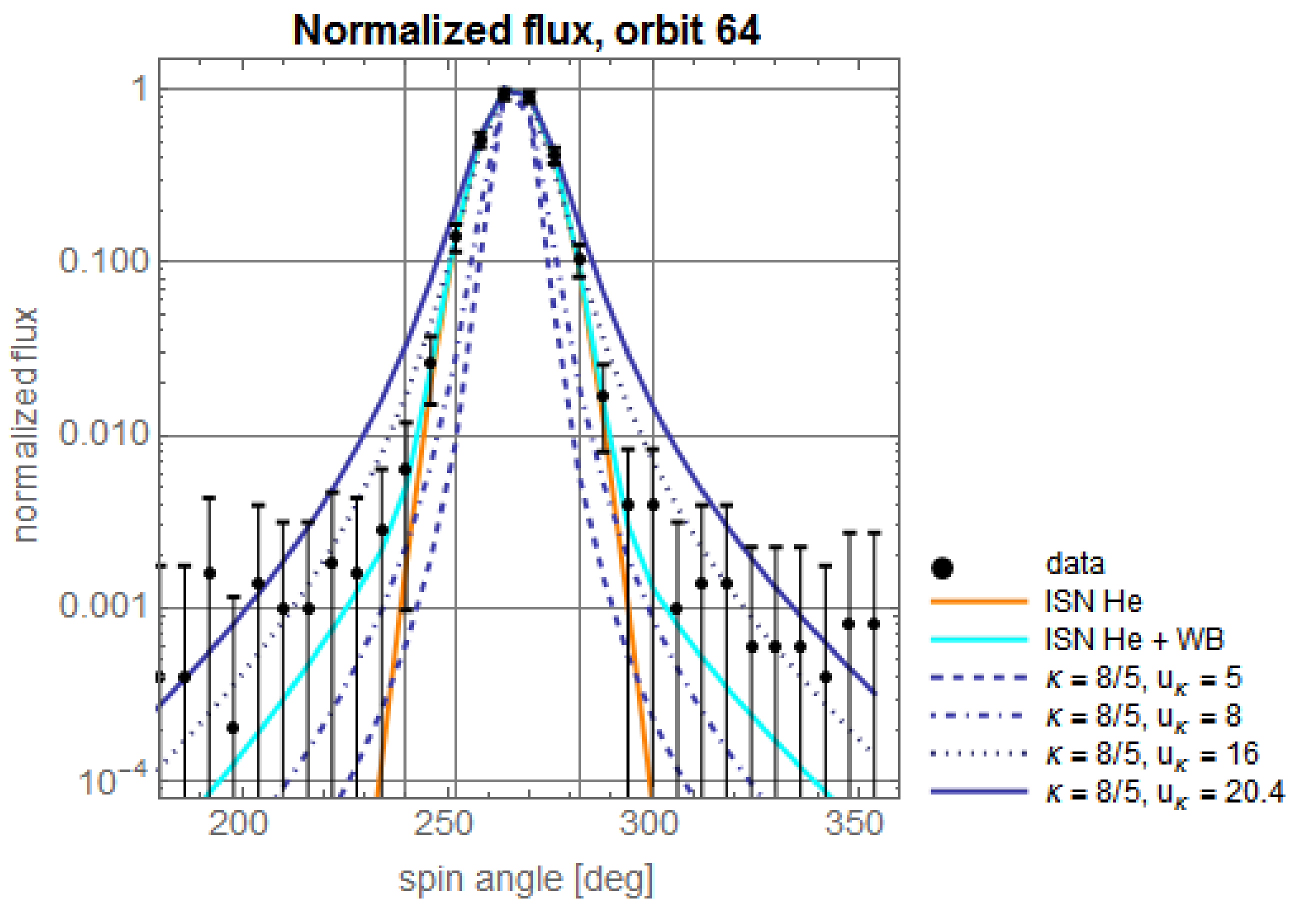
with u_{M-B} being the thermal speed.

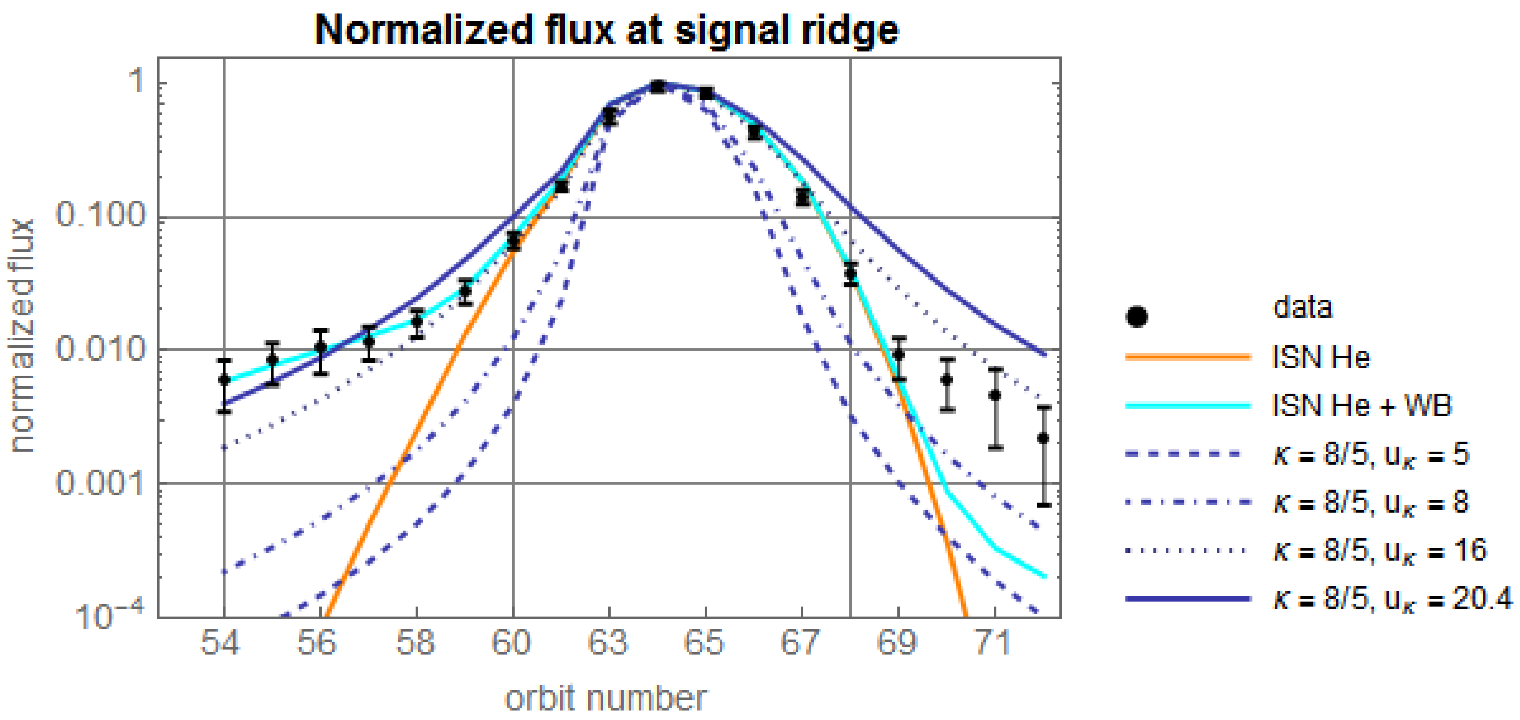
- **Kappa distribution function:**

$$f_\kappa(v, u_\kappa) = \pi^{-3/2} u_\kappa^{-3} \left(\kappa - \frac{3}{2}\right)^{-3/2} \frac{\Gamma(\kappa+1)}{\Gamma\left(\kappa - \frac{1}{2}\right)} \left(\frac{v^2}{\left(\kappa - \frac{3}{2}\right) u_\kappa^2} + 1\right)^{-\kappa-1}$$

with u_κ being the reference speed.

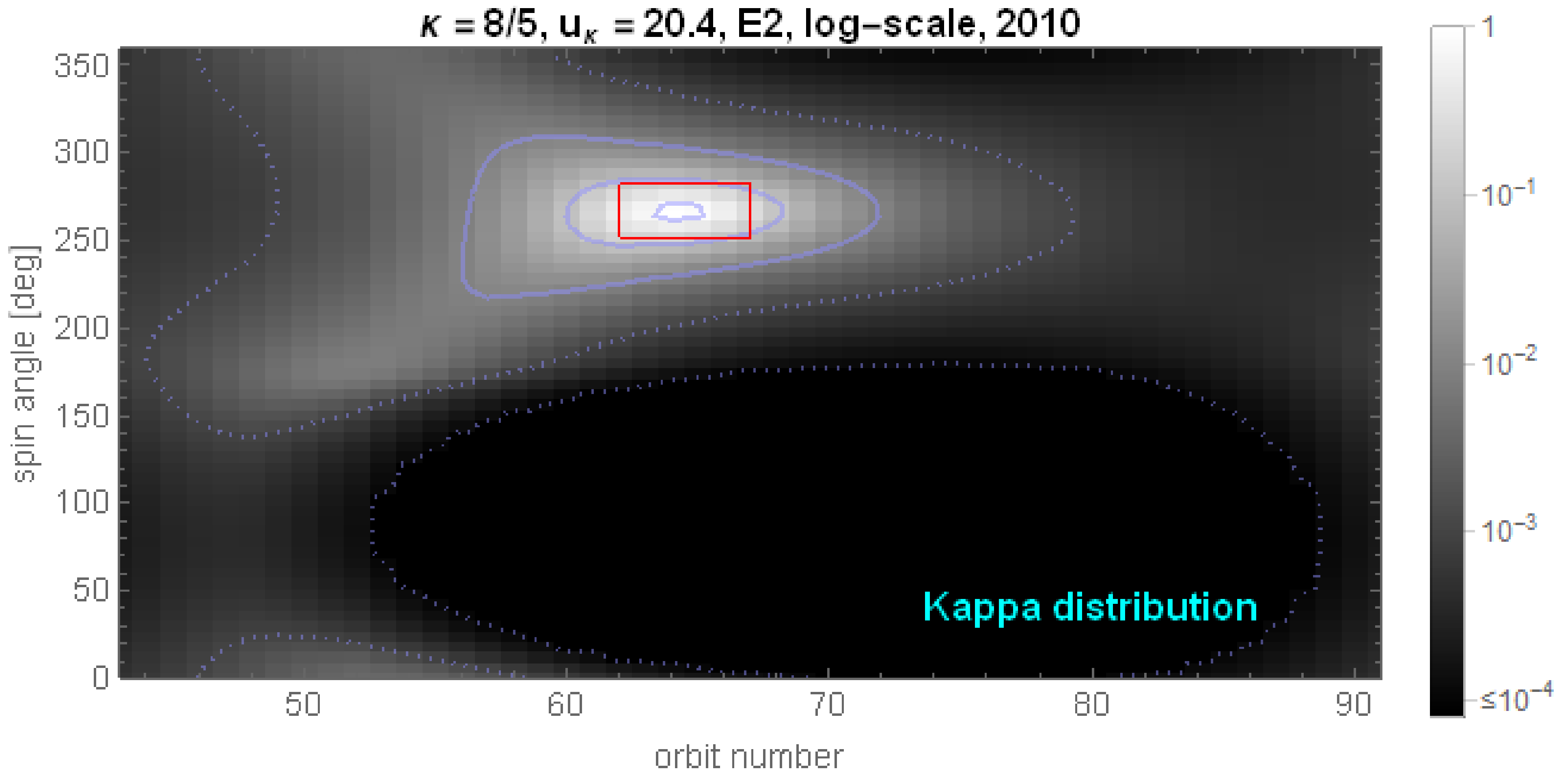






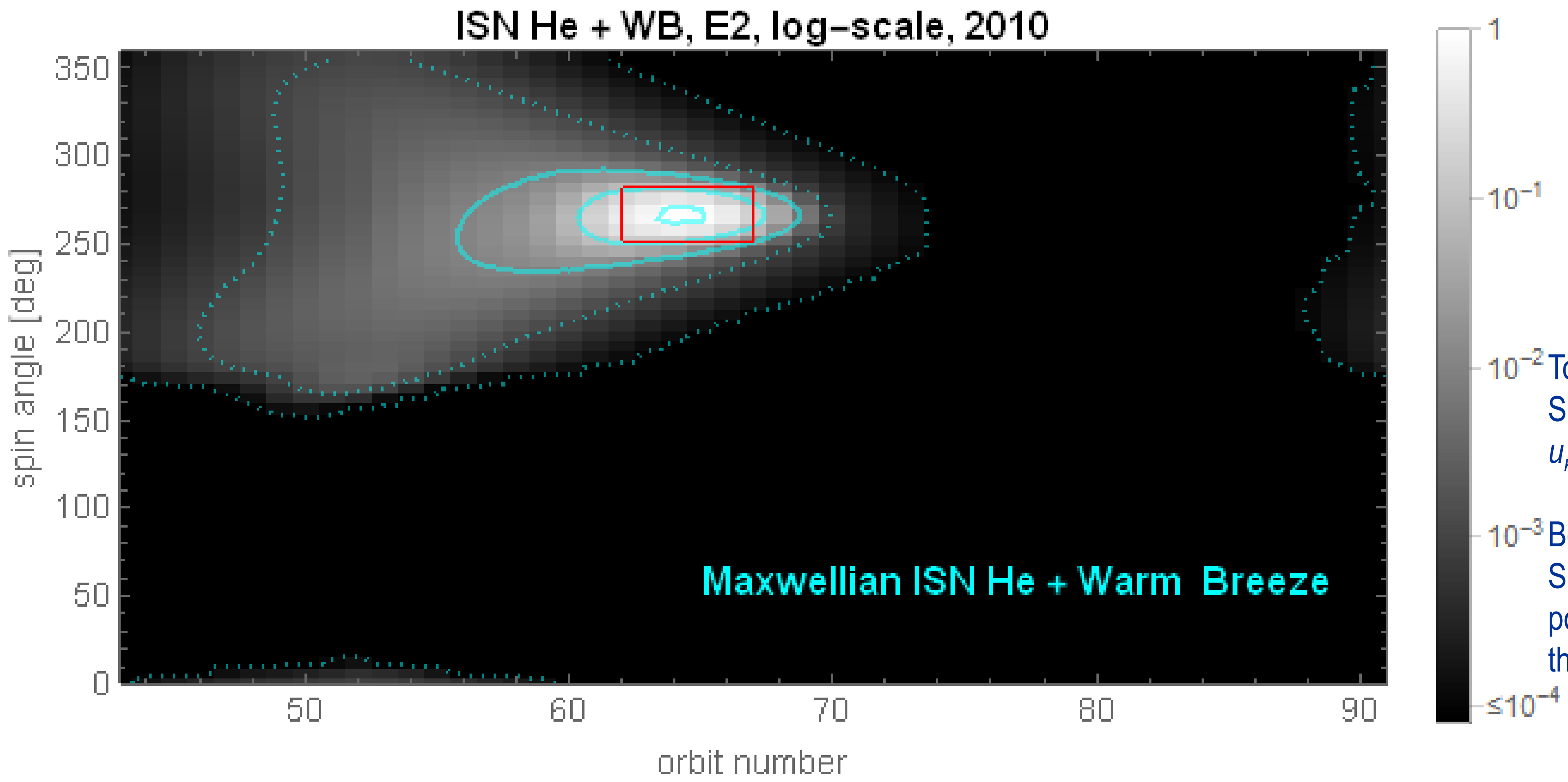
Two cuts through the sky maps. **Top**: cut along the spin-angle for orbit 64 (spring peak, $\lambda_E \sim 136°$, the vertical direction in the sky map plots). **Bottom**: along a fixed spin-angle value of 264°, equal to the spin-angle of the maximum flux in orbit 64.

Hypothesis: perhaps ISN He is kappa-like?



ISN He given by the **kappa distribution does not fit** to the observations in the portion of the sky dominated by ISN He.

The **clearest differences** between the kappa distribution and Maxwellian ISN He + WB is **best visible** in the region currently **blocked by the magnetosphere** → IMAP needed!



Top:
Simulated sky map of ISN He flux due to a kappa ISN He (κ = 8/5, u_κ = 20.4 km s^{-1}), calculated with the energy threshold of 19 eV (E2).

Bottom:
Simulated sky map flux being a composition of two Maxwell-Boltzmann populations of the primary ISN He and the Warm Breeze, calculated with the energy threshold of 19 eV (E2).

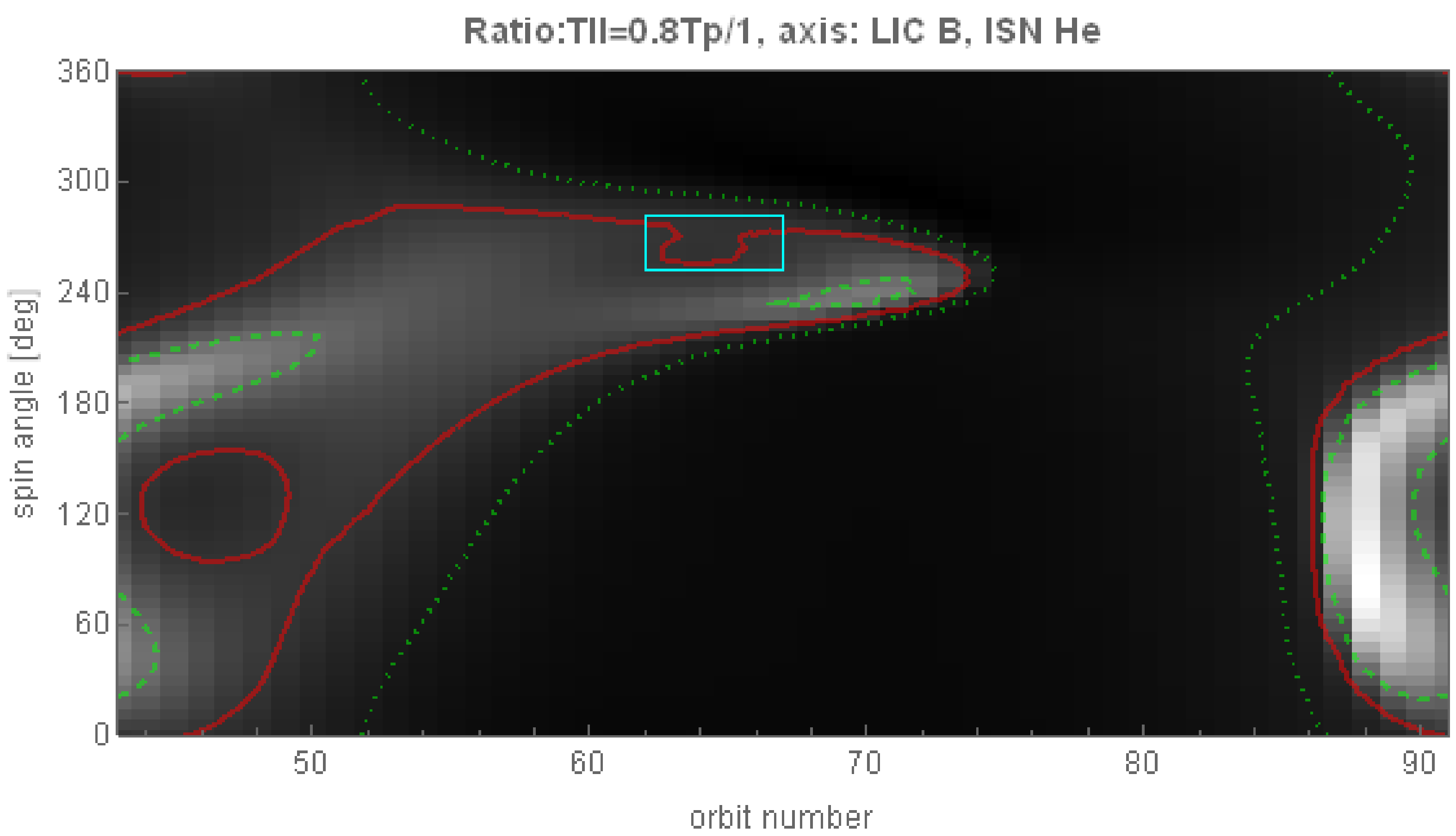
Hypothesis: anisotropy of LIC temperature

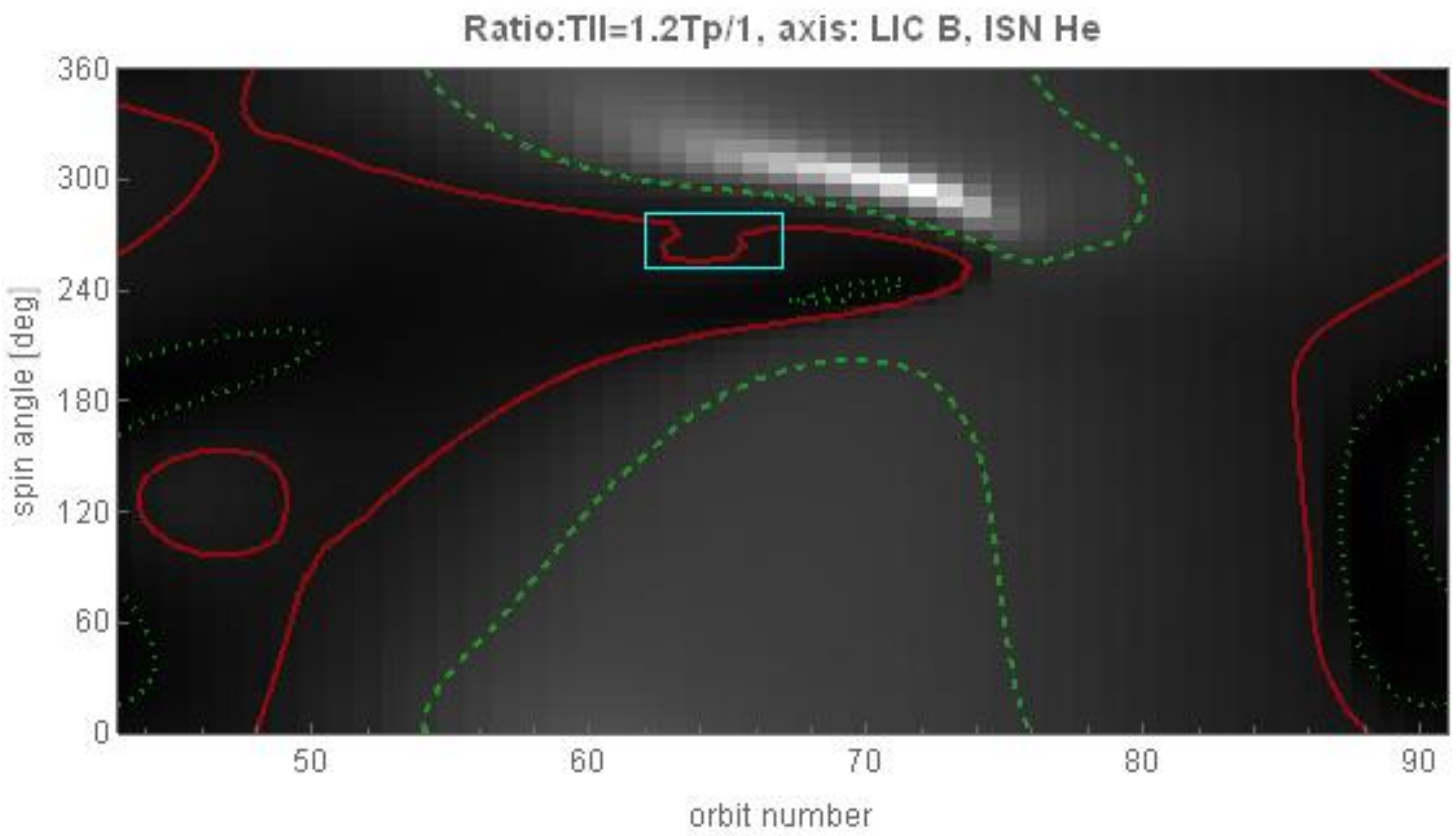
- **Space plasmas** are frequently **anisotropic** (in terms of pressure, velocity distribution functions, etc.)
- In **weakly collisional** plasmas anisotropies often result from (approximate) **conservation of ion magnetic moments** in magnetic fields stretched by dynamical plasma motions (compression, velocity shear, turbulence etc.)
- Attained degree of anisotropy may reflect **local equilibrium** between creation by stretching and destruction by particle collisions
- If a **LIC/LocalBubble boundary layer**, of a thickness ~10^4 AU, is subject to a 10-100 km/s velocity shear, the resulting (Kolmogorov) **turbulence** may generate **plasma pressure anisotropies**
- Expected level of pressure anisotropies: $\frac{p_\perp - p_\parallel}{p_\perp} \sim 0.1 - 3$

- **Two populations** of ISN He: $He_i + He_a$
- **Production of He_a**: $(He^+)_a \rightarrow He_a$
  - radiative recombination of He^+
  - He^+ charge exchange with H and He
- **Destruction of He_a**: $He_a \rightarrow He_i$, $He_a \rightarrow He^+$
  - elastic collisions with He, He^+, H
  - charge exchange with H^+, He^+
- If production = destruction, then for **anisotropic** $(He^+)_a$ constituting **30%** of total He^+, **He_a** could reach **~1%** of total ISN He
- Assume that the **anisotropy axis** is towards the **center of the IBEX Ribbon** (i.e., likely direction of IMF)
- Maintain mean energy per particle (i.e., T)

$$f(v_\parallel, v_\perp) = n_{He} T_\parallel^{-1/2} T_\perp^{-1} \left(\frac{m}{2k_B T_\parallel}\right)^{3/2} \exp\left[-\frac{m_{He}}{3k_B}\left(\frac{v_\parallel^2}{T_\parallel} + \frac{v_\perp^2}{T_\perp}\right)\right] \qquad T = \frac{1}{3}T_\parallel + \frac{2}{3}T_\perp \qquad \frac{T_\parallel}{T_\perp} = a$$

Hypothesis: anisotropy of LIC temperature

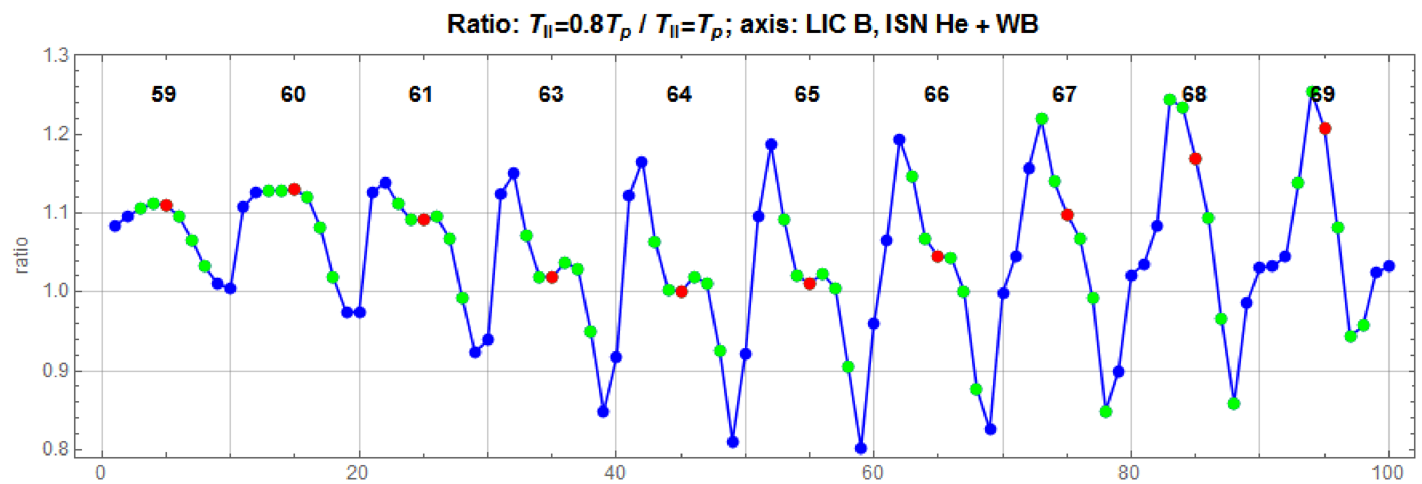


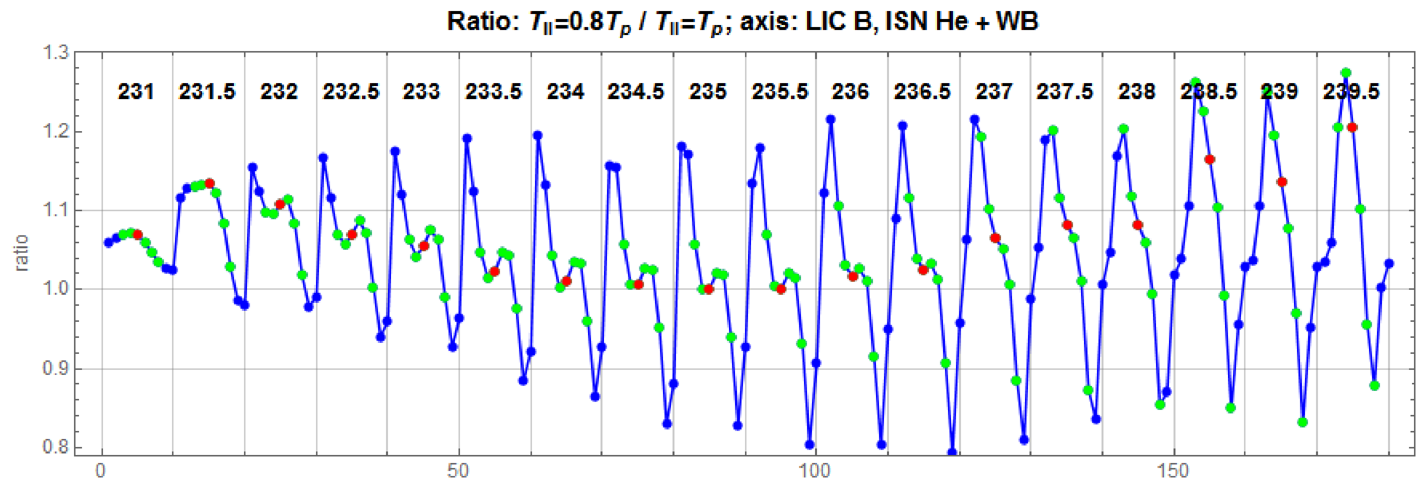


Example full-sky maps of the ratio of the ISN He flux with assumed **anisotropy to** the **isotropic** case.

Lighter/darker gray → higher/smaller ratio

Red contour: ratio =1
Green dashed contour: ratio > 2
Green doted contour: ratio < 0.5





Red: peak pixel;
Green: pixels used in the ISN He analysis (Bzowski et al. 2015)

Summary and conclusions

Fall peak:

- is not detectable due to finite energy threshold of IBEX-Lo

Warm Breeze:

- **Warm Breeze** cannot be explained by a **kappa distribution** function of the ISN He source
- **Warm Breeze must be** a **separate population**
- **Warm Breeze** is so **strong** that it **dominates** over weak signatures of a hypothetical kappa distribution of the ISN He, expected before the peak of primary ISN He

Kappa distribution:

- the **full-sky** pattern of **ISN He** resulting from the **kappa distribution** in the LIC seems to **differ** from the **observed distribution** for low κ values
- if the **primary ISN** is **kappa-like**, then the signatures should be searched on orbits immediately **after** the **ISN peak**

Temperature anisotropy:

- we considered a hypothesis that the **temperature** of the primary ISN He population is **anisotropic**, with the anisotropy axis coincident with the direction of the center of the IBEX Ribbon
- it seems that such an anisotropy of temperature **could be detectable** in the IBEX data, but its location close to the magnetosphere and its energy sensitivity threshold makes the discovery very challenging
- it should show up on the **post-peak** orbits, **center pixels** (in addition to far wings) and also on **pre-peak** orbits and in the **cone** region, but this one is **now blocked** by **magnetosphere**

Summary and conclusions

Perspectives for IMAP:

- weak hypothetical signals (due to anisotropies, non-equilibrium etc. in the parent distribution function) can be an interesting and **prospective targets for IMAP***!

- we **specify the energy and location requirements for IMAP** needed to discover the hypothesized **departures** of the ISN He distribution function **from the equilibrium state** and thus allowing a detailed study of plasma – neutral coupling processes in the interstellar medium

- however, to search for signatures of kappa, T anisotropy etc. we first must better understand the Warm Breeze. The work continues!

* **IMAP** (*Interstellar Mapping and Acceleration Probe*) the next Solar Terrestrial Probe mission for NASA's Heliophysics Division as defined by the National Research Council (NRC; an arm of the United States National Academies) "The 2013–2022 Decadal Survey for Solar and Space Physics (Heliophysics)". The planned IMAP payload includes a low energy ~5–1000 eV neutral atom camera to measure the inflowing H, D, He, O, and Ne with much higher sensitivity and angular resolution than possible on IBEX. Such high precision measurements of He (and other species) will carry on from IBEX and even more strongly constrain models of the ionization state and radiation environment of LISM as well as uncover secondary populations and their detailed distribution functions.

References

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Kubiak et al. 2014, *Warm breeze from the starboard bow: a new population of neutral helium in the heliosphere*, Astrophysical Journal Supplement Series, 213:29 (21pp), doi:10.1088/0067-0049/213/2/29

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The presented study is partially a content of:

Sokół et al. 2015, ***The interstellar neutral He haze in the heliosphere: what can we learn?***, Astrophysical Journal Supplement Series, 220:29 (12pp), doi:10.1088/0067-0049/220/2/29