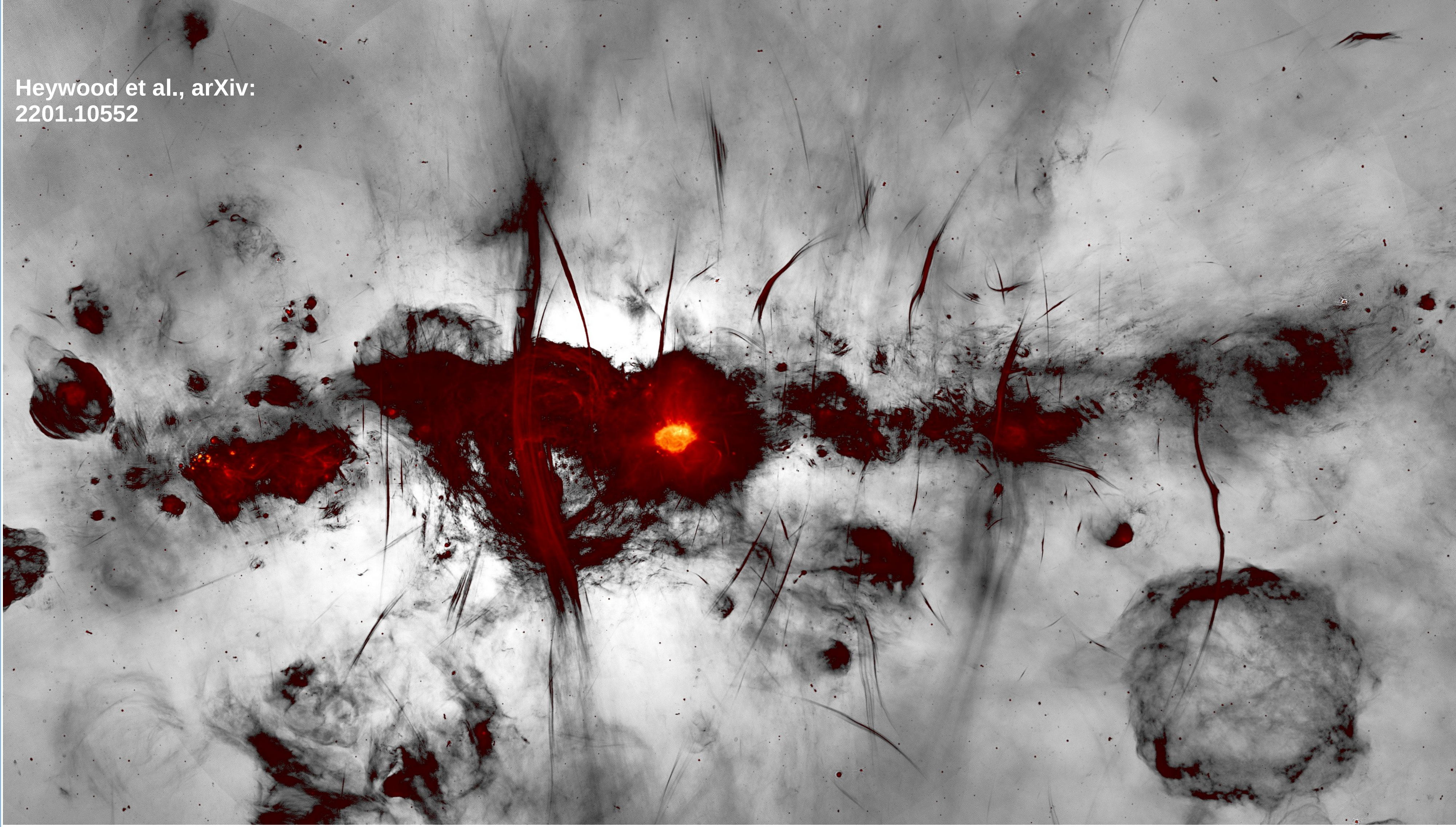
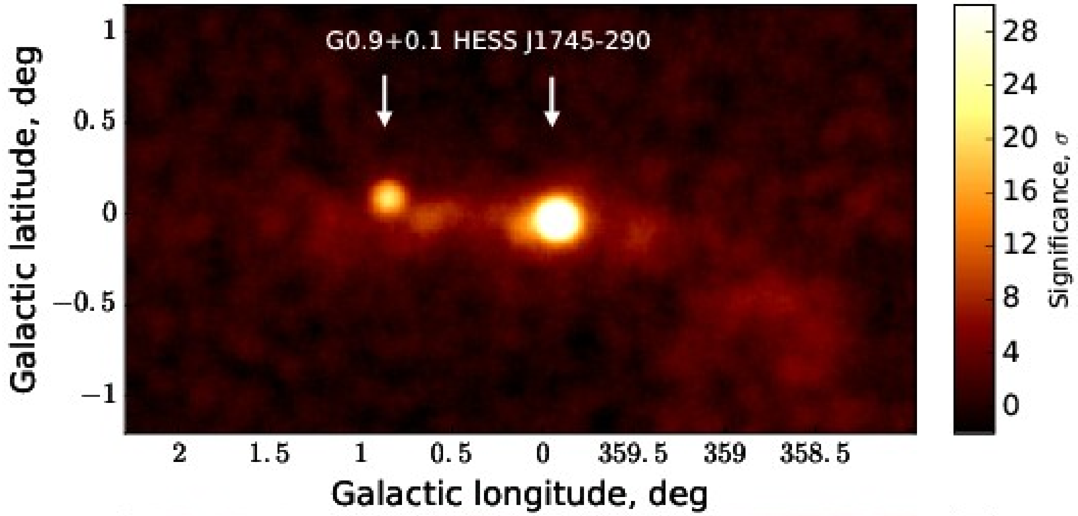


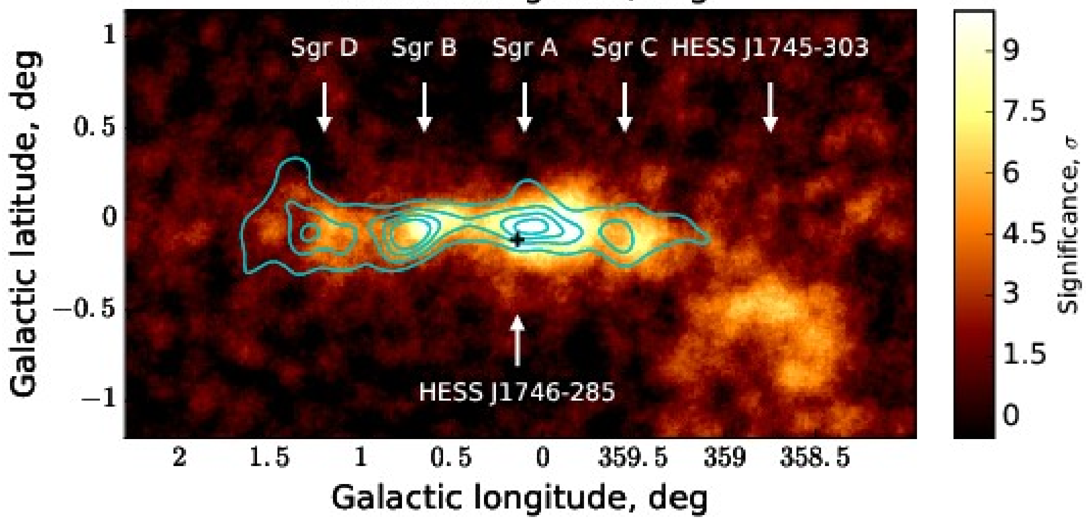
γ-γ absorption in the Galactic Center: insights on the 3d geometry of H.E.S.S. J1745-290

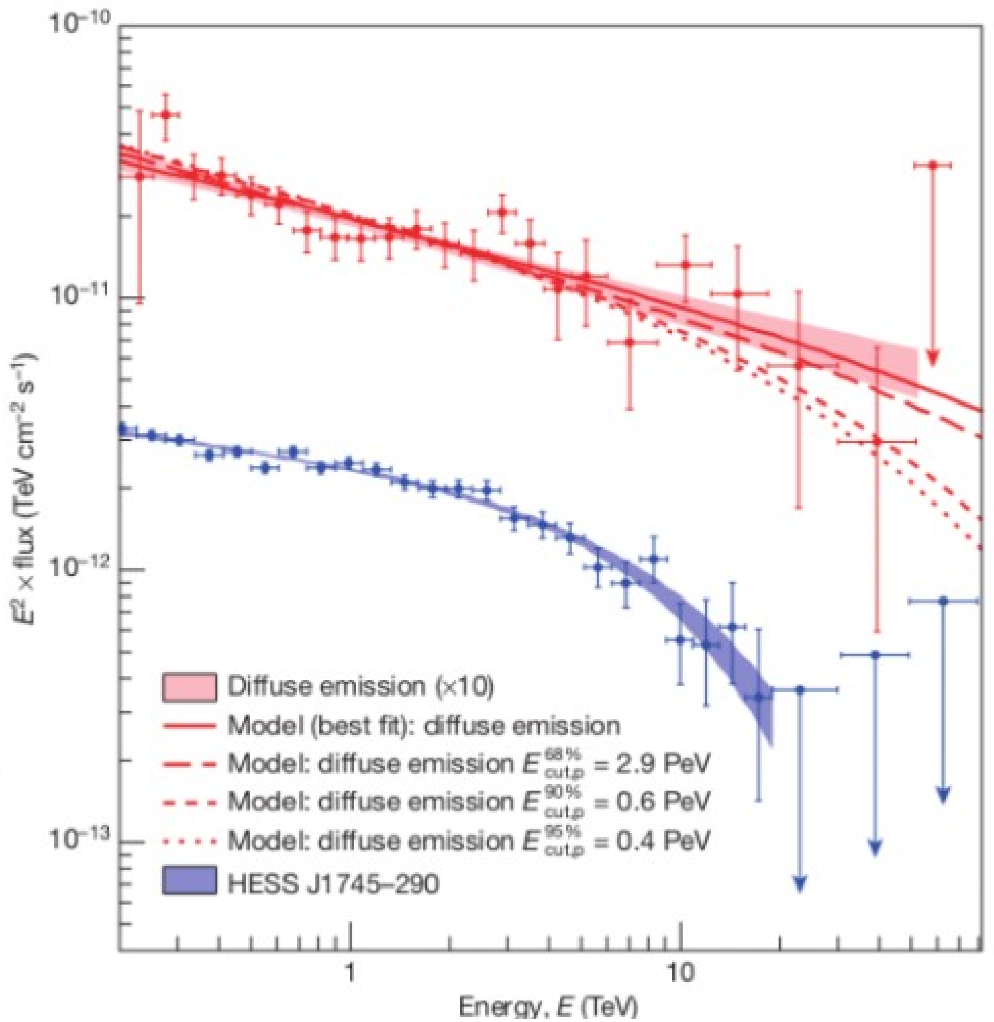
Francesco Conte with Richard Tuffs

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

The Galactic Center in the gamma sky



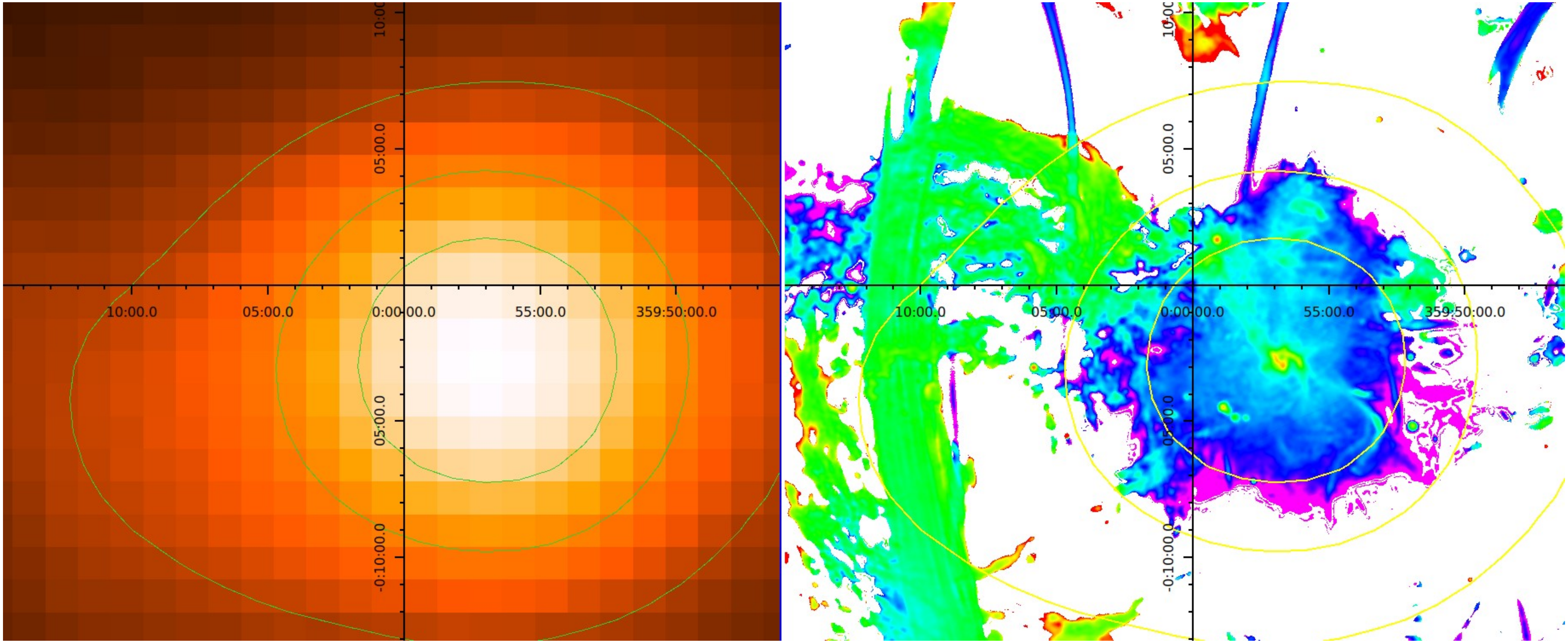




[H.E.S.S. Collaboration, Characterising the VHE diffuse emission in the central 200 pc of our Galaxy with H.E.S.S., 2017]
[H.E.S.S. Collaboration, Acceleration of PeV protons in the Galactic Centre, 2016]

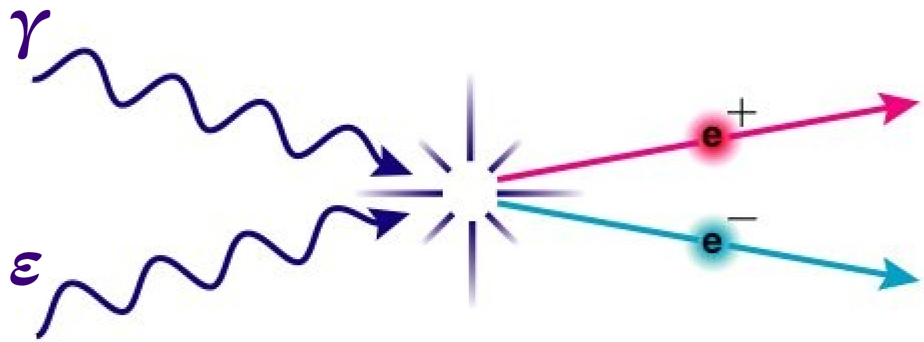
Is this break inherent to the source or is it due to absorption?

The Galactic Center in the gamma sky



- H.E.S.S. PSF: ~5 arcminutes wide
- MeerKAT (see also SOFIA/HERSCHEL later): focus on the central arcminute around SgrA*
- What about CTA?

e^+e^- pair production



- Easy exercise of relativistic kinematics! Suppose γ is the bullet and ε the target, colliding with an angle θ. The produced electron is labeled with e.

- 4-Momentum $\mathbf{p}$ is $\left(\frac{E}{c}, -\vec{p}\right)$, Energy $E = \sqrt{p^2c^2 + m^2c^4}$

- Imposing energy conservation:

$$E_\gamma + E_\epsilon = 2E_e \quad \rightarrow \quad E_\gamma^2 + E_\epsilon^2 + 2E_\gamma E_\epsilon - 4E_e^2 = 0$$

$$\boxed{E_\gamma E_\epsilon (1 - \cos(\theta)) = 2E_e^2}$$

- Imposing momentum conservation:

$$\vec{p_\gamma} + \vec{p_\epsilon} = \vec{p}_{e+} + \vec{p}_{e-} = 0 \quad \rightarrow \quad E_\gamma^2 + E_\epsilon^2 + 2E_\gamma E_\epsilon \cos(\theta) = 0$$

e⁺e⁻ pair production: IR target radiation field

$$\sigma_\epsilon = \frac{3}{16}\sigma_T(1-\beta^2)\left[2\beta(\beta^2-2)+(3-\beta^4)\ln\frac{1+\beta}{1-\beta}\right]$$

[Jauch and Rohrlich, 1955]

where β is the electron v/c, and can be easily found by noticing that:

$$E_e^2 = \gamma_L^2 m^2 c^4 = \frac{m^2c^4}{1-\beta^2}$$

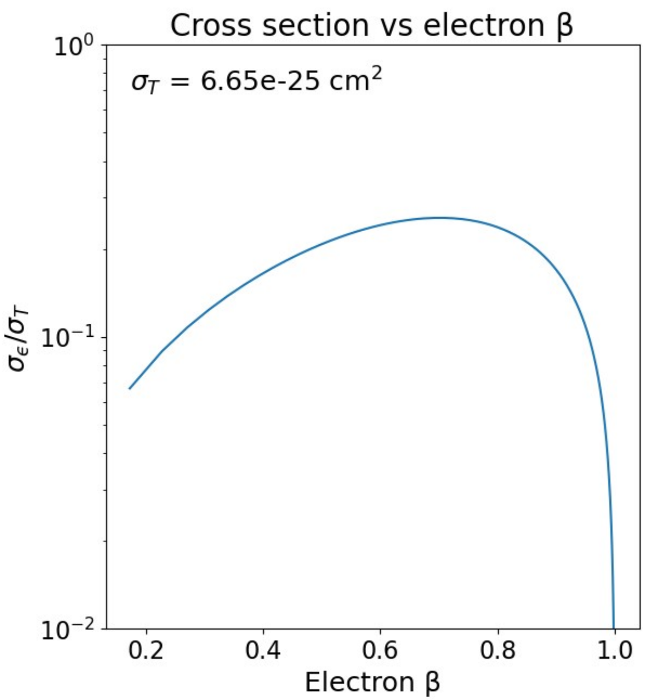
and remembering that

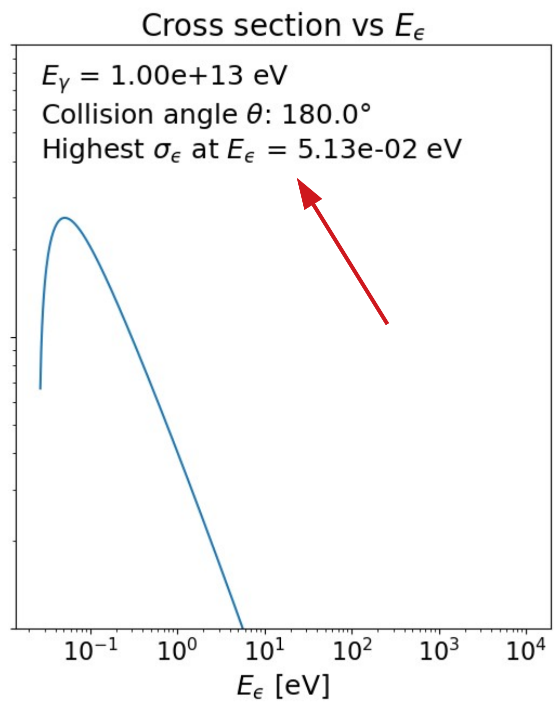
$$E_\gamma E_\epsilon(1-\cos(\theta)) = 2E_e^2$$

we get:

$$\beta = \sqrt{1-\frac{2m^2c^4}{E_\gamma E_\epsilon(1-\cos(\theta))}}$$

which must be inserted in σ_ϵ.





$$\boxed{\tau_\epsilon(\vec{r}_0) = \int_{\vec{r}_0}^{R} \sigma_\epsilon n_\epsilon(\vec{r})d\vec{r}}$$

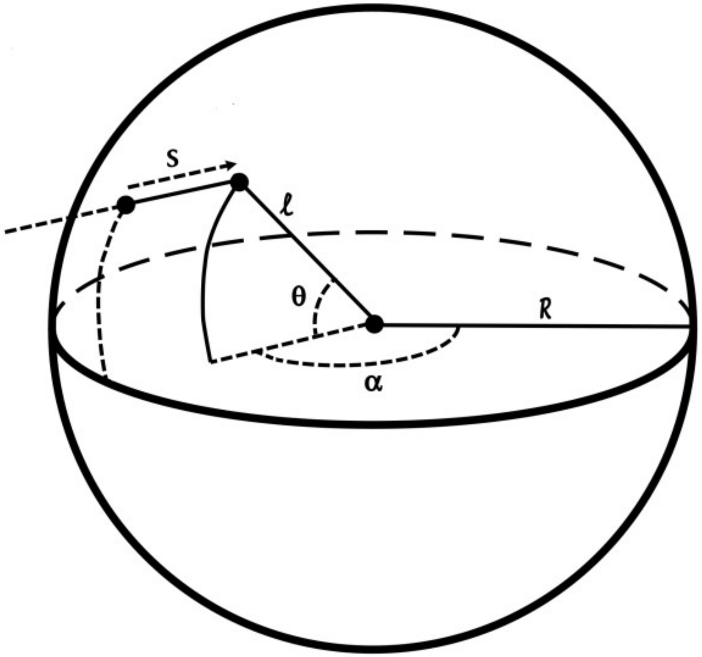
The collision is always head-on!
The maximum absorption around 10 TeV is due to 15-30 μm photons

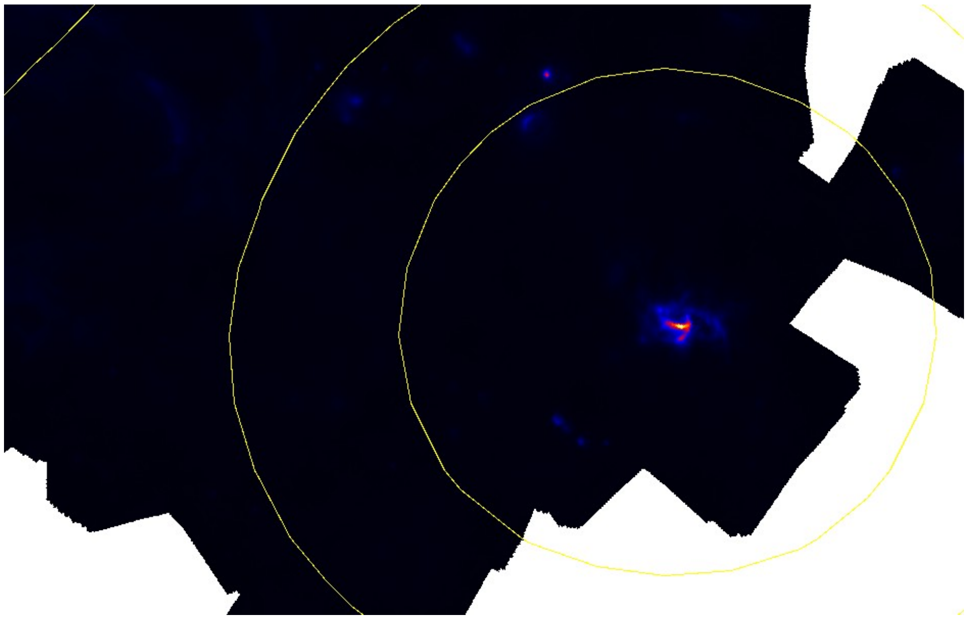
Outline of the project

Major goal: investigating the γ-γ absorption in the Galactic Center

- Compute the IR 3D emissivity model for the different components
- Derive the total IR radiation field
- Calculate the pair production opacity
- Derive the total absorption
- Model different source spectra/geometries
- Compare to observations, make predictions
- Gamma astronomy with arcsec precision?

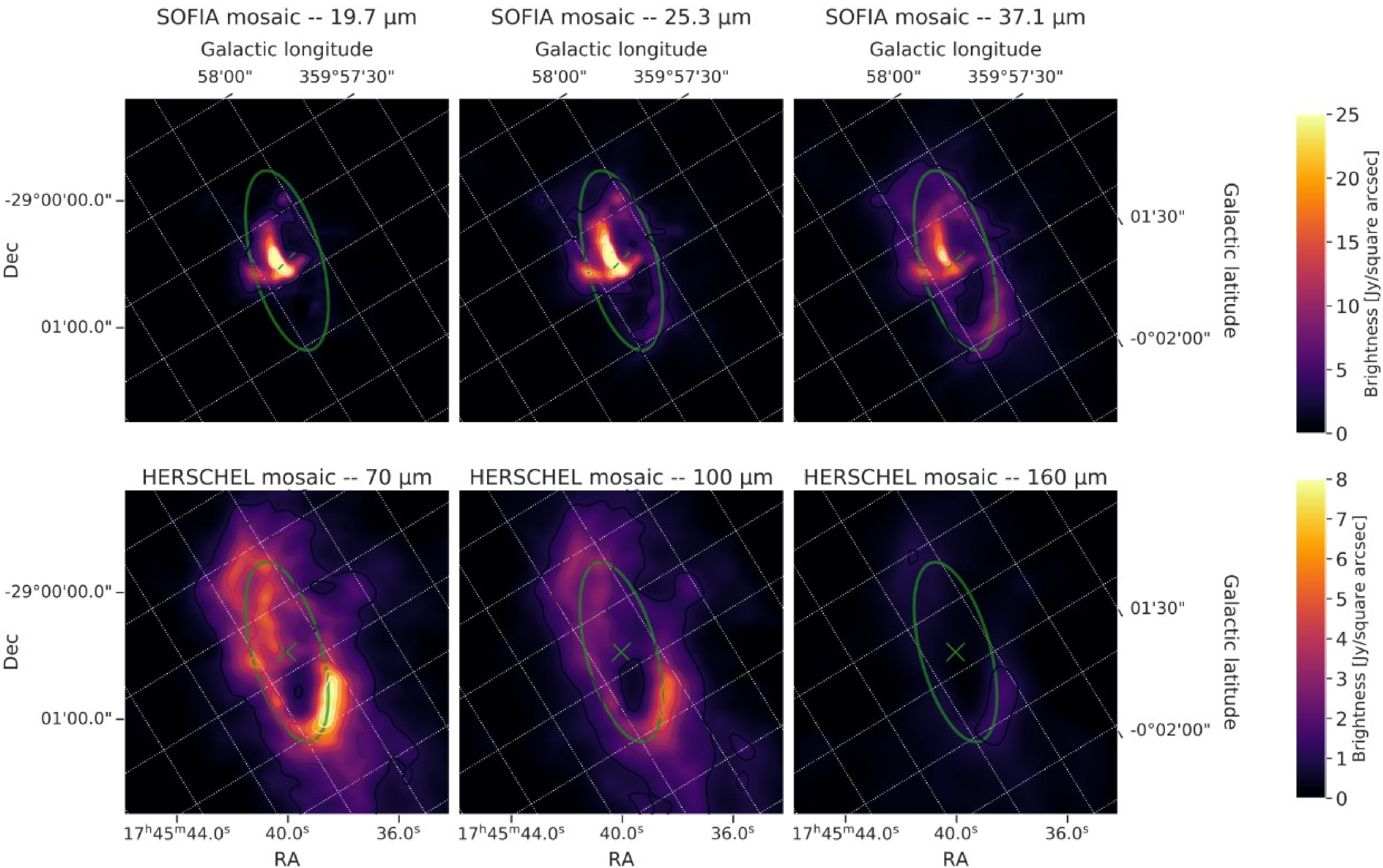
$$\tau_\epsilon(\vec{r}_0) = \int_{\vec{r}_0}^{R} \sigma_\epsilon n_\epsilon(\vec{r}) d\vec{r}$$





- Comparison to the H.E.S.S. data
  - do we predict a cut-off?
  - does the model match the data? Does it favor any particular geometry?
- Is CTA able to differentiate between different geometries?

The inner few parsecs in the IR sky: dust maps

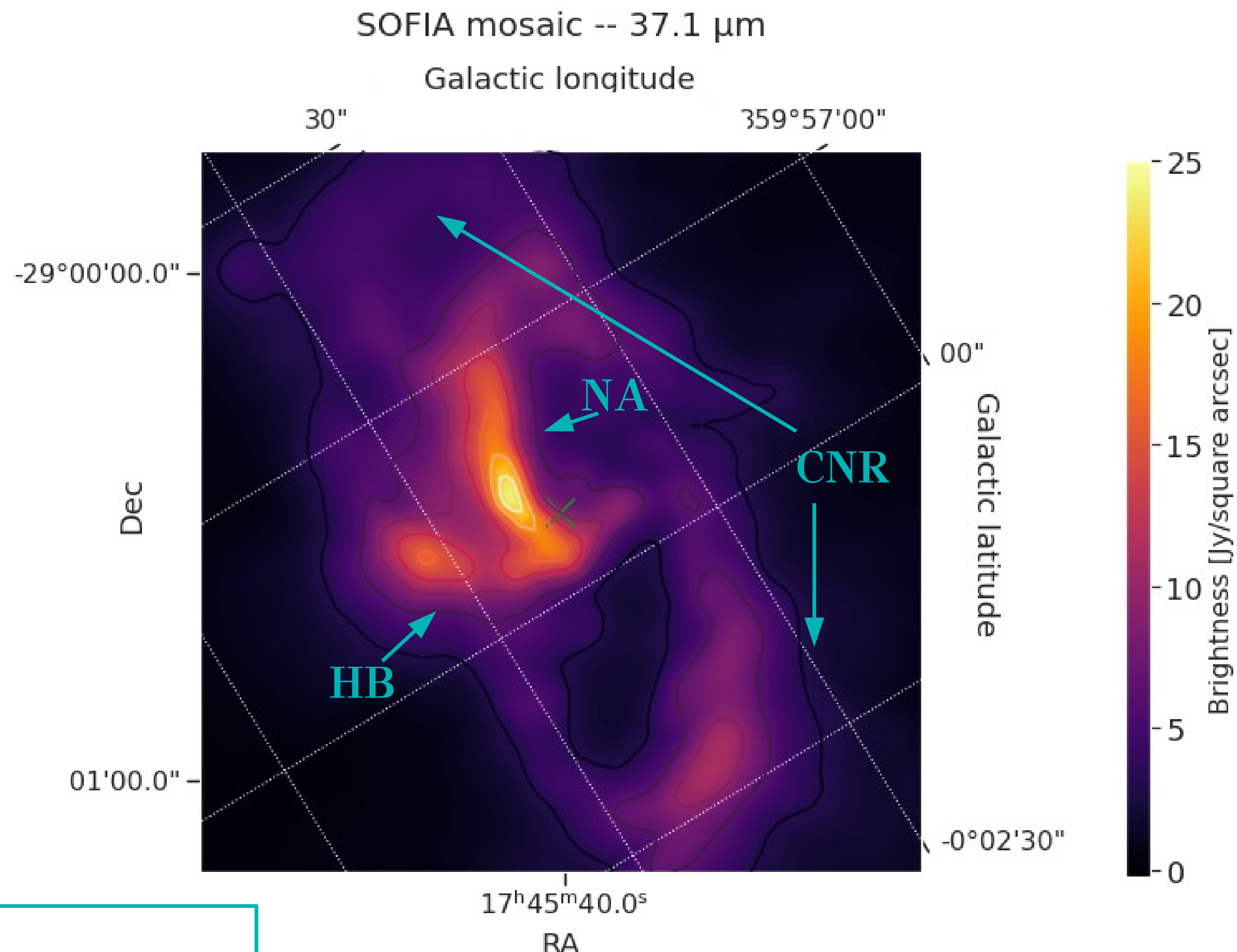


Inner structures at first glance

Maps used:

- 8 μm: MSX A band
- 11 μm: MSX C band
- 15 μm: MSX D band
- 20 μm: SOFIA
- 25 μm: SOFIA
- 31 μm: SOFIA
- 37 μm: SOFIA
- 70 μm: Herschel PACS
- 110 μm: Herschel PACS
- 160 μm: Herschel PACS

- plus VLA (rec lines?)

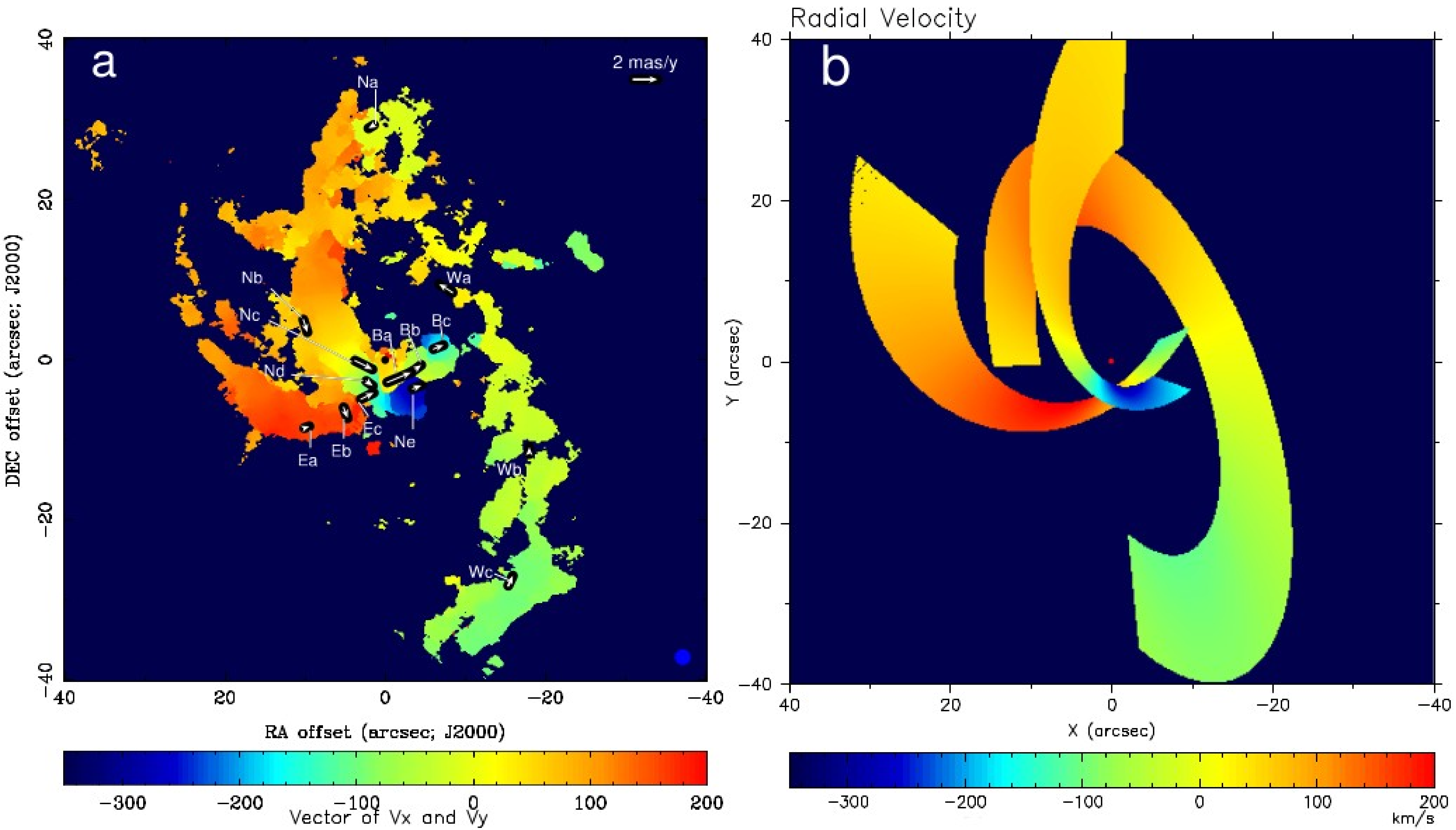


Structures clearly visible:

- 2 spirals (NA, HB)
- Circum-nuclear ring/disk (CNR/CND)

- (+ Galactic bulge (GB))

3d geometry: VLA observations @3.6 cm



[Zhao J. et al., Dynamics of Ionized Gas at the Galactic Center: VLA Observations of the 3D Velocity Field and Location of the Ionized Streams in Sagittarius A West, 2009]

The story so far

Main points so far:

- I want to investigate absorption by the IR radiation field, especially in the 15-30 μm band, to motivate the bright source spectral break at 5-10 TeV seen by H.E.S.S. (and VERITAS).
- We see at least 3 filaments, two of which (NA, HB) are closer to SgrA* (in 2d!) and look hotter than the CNR – they emit a lot in 20-25 μm!
- The CNR is better traced by longer wavelengths (40+ μm).
- Temperature radial gradient compatible with a central heater.
- We have knowledge of the 3d orbital parameters of the three said structures

(Second) fitting approach

I fit the data in order to obtain:
- mass M
- an additional background

for a composite dust component modeling both the UV illumination and IR illumination B/M

$$\frac{dB_\nu(\nu_{em},\vec{r})}{dM_d} = \frac{3}{4\Delta l^2}\frac{\sum_i \int B_\nu^{sg,(i)}(a,\nu_{em},\vec{r})a^2 n^{(i)}(a)da}{\sum_i \rho^{(i)}\int a^3 n^{(i)}(a)da}$$

$$\frac{dB_\nu(\nu_{em},\vec{r})}{dM_d} = \frac{B_\nu^{pix}(\nu_{em},\vec{r})}{M_d^{pix}(\vec{r})}$$

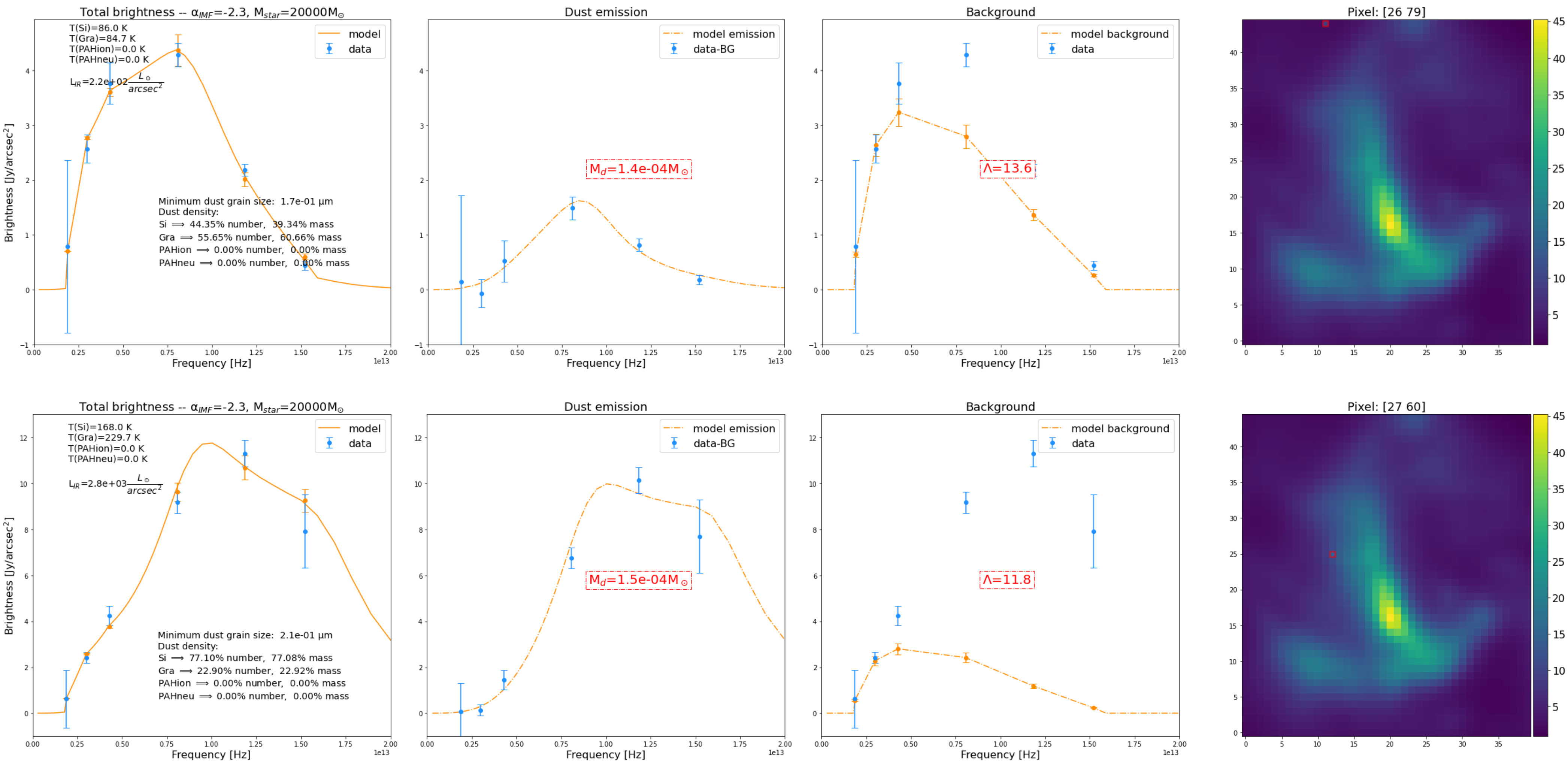
- Assumptions:
  - chemical mixture of graphite, silicates, ionised and neutral PAH
  - dust grains not in thermal equilibrium: T=T(a)
  - the UV source (nuclear star cluster NSC) is modeled: it retains the information on the distance r to its center
  - For each line of sight, the fit is done for all the structure orbital planes at the same time

$$B_\nu^{k,\,model}(\nu_j) = \sum_s \frac{dB_\nu(\nu_j,\vec{r}_s^{\,k})}{dM_d}\cdot M_d(\vec{r}_s^{\,k}) + B_\nu^{BG}(\nu_j)\cdot\Lambda^k$$

M and B(a,ν,r,τ) are 3d maps after the fit

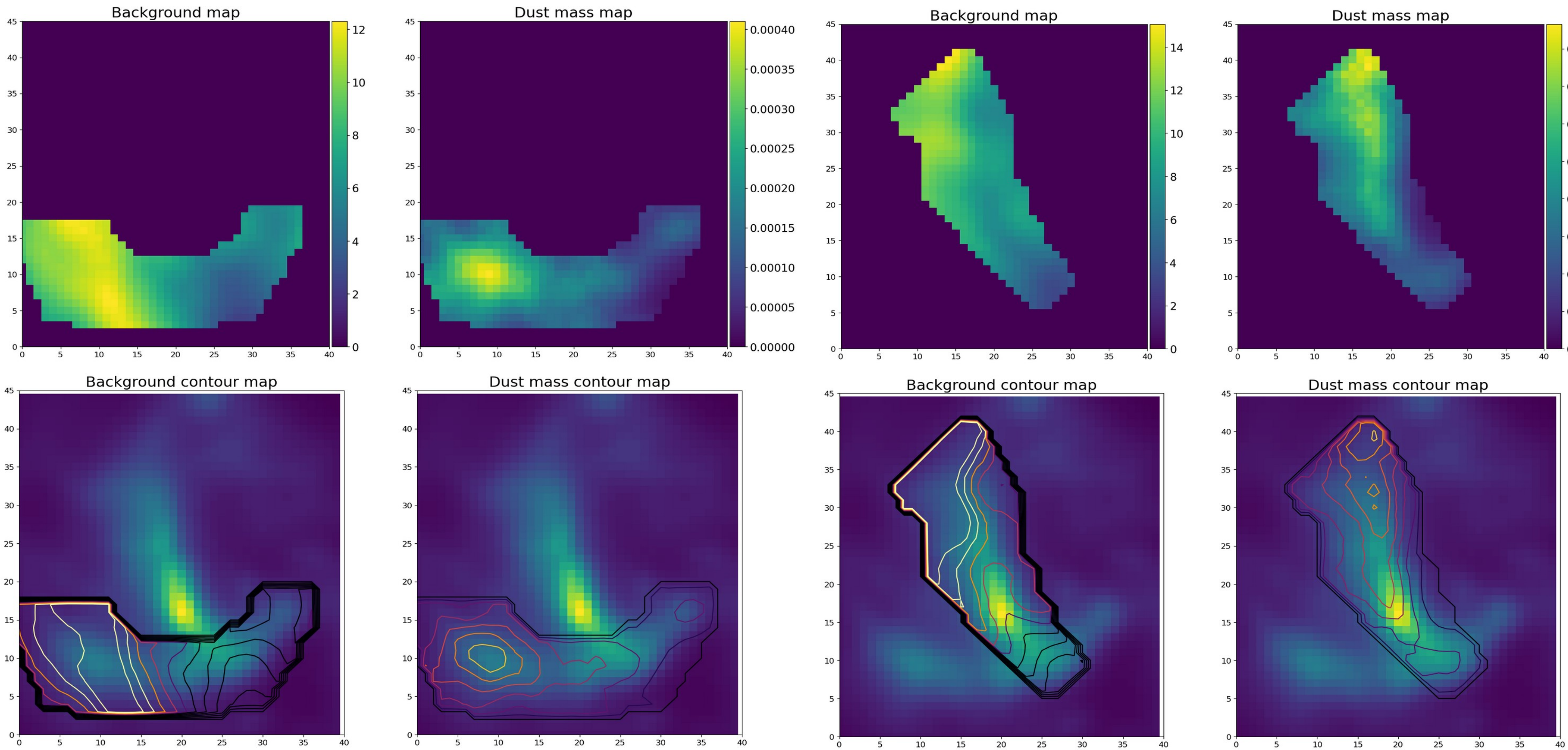
Uncertainties:
- NSC parameters:
  - age (highest star mass)
  - IMF spectral index
  - total mass in stars
- Dust models:
  - line of sight extinction
  - emission model
  - size distribution (calibrated locally and assumed universal)
- Calibration of the background SED
- ...

(New) fits



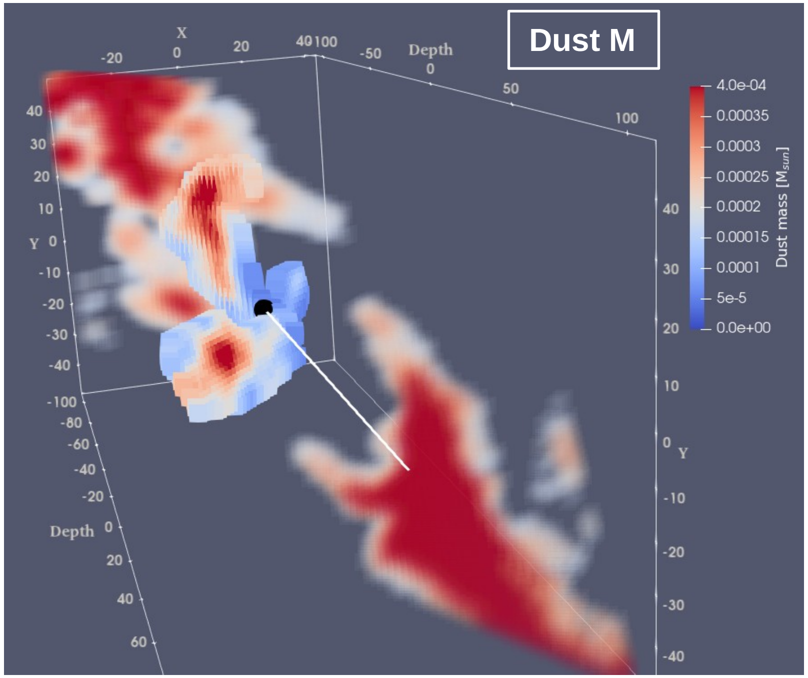
Not much degeneracy between the modeled emission (2nd column) and the modeled background (3rd column), since they have different peaks/dependencies

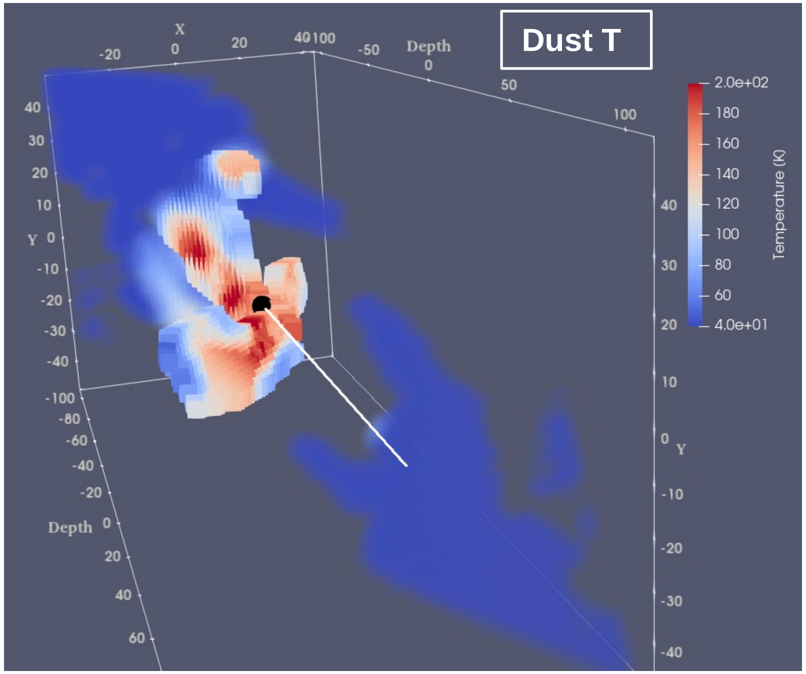
Mass and Temperature 2d maps



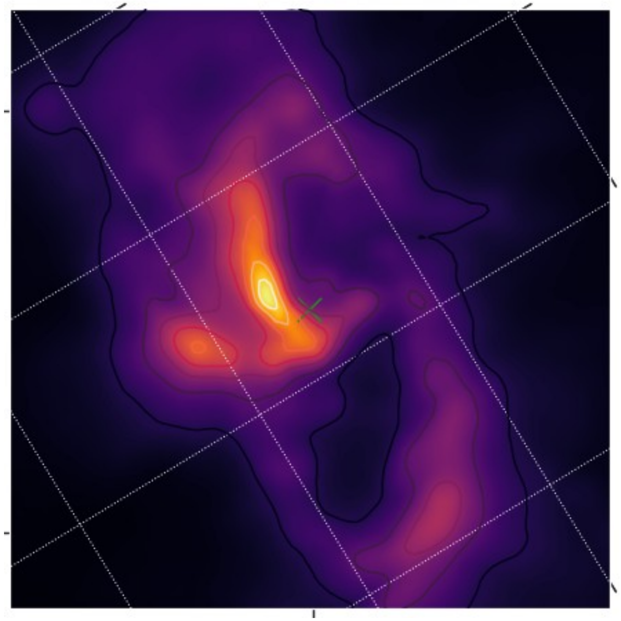
- Background structures easily visible on both filaments
- Dust mass accumulates towards north on the NA – coherent with the outflow paradigm

3D maps of the inner 4 parsecs

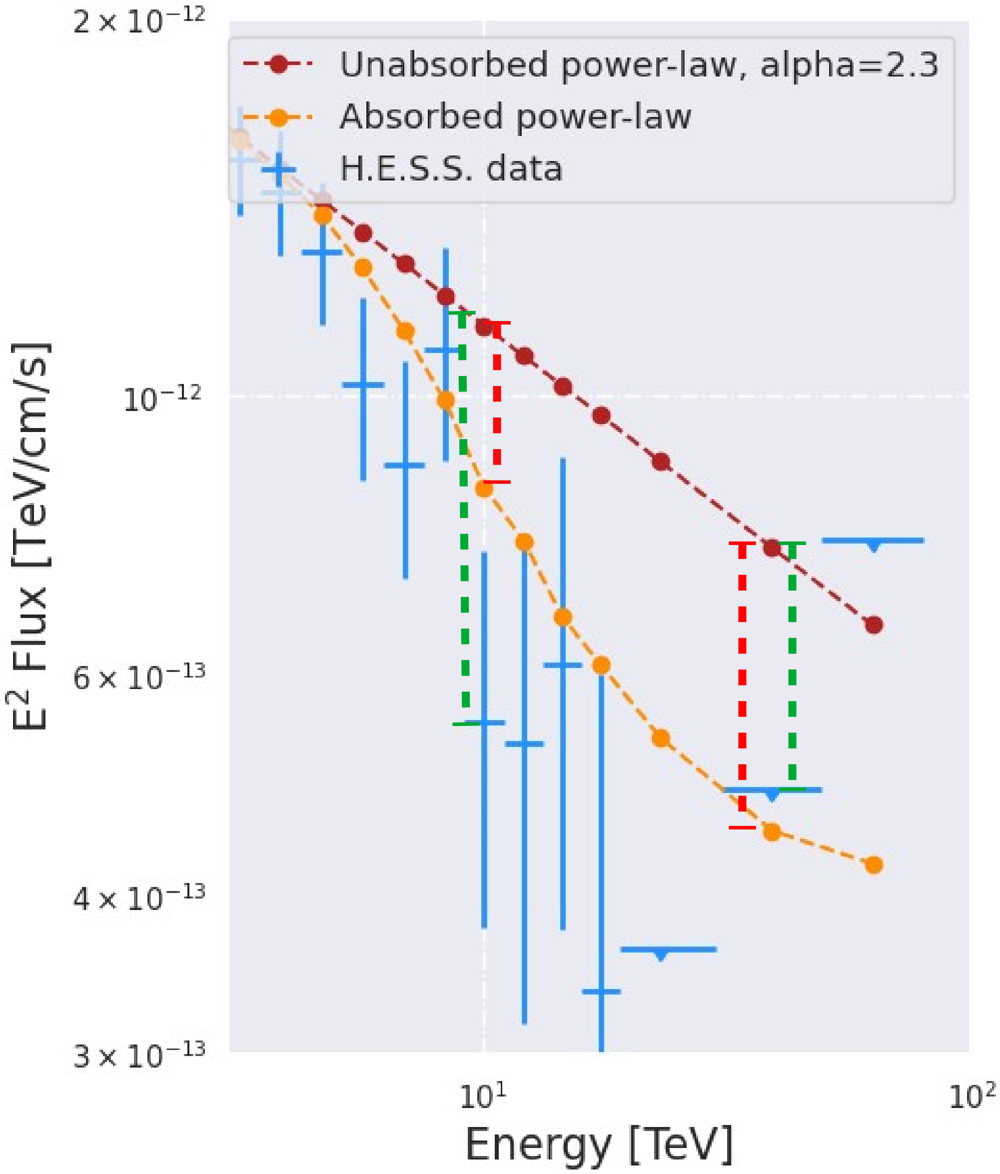




- Filaments hotter towards the SgrA*, but the mass tends to accumulate farther away – outward streams
- The translucent structure is the highly inclined CNR



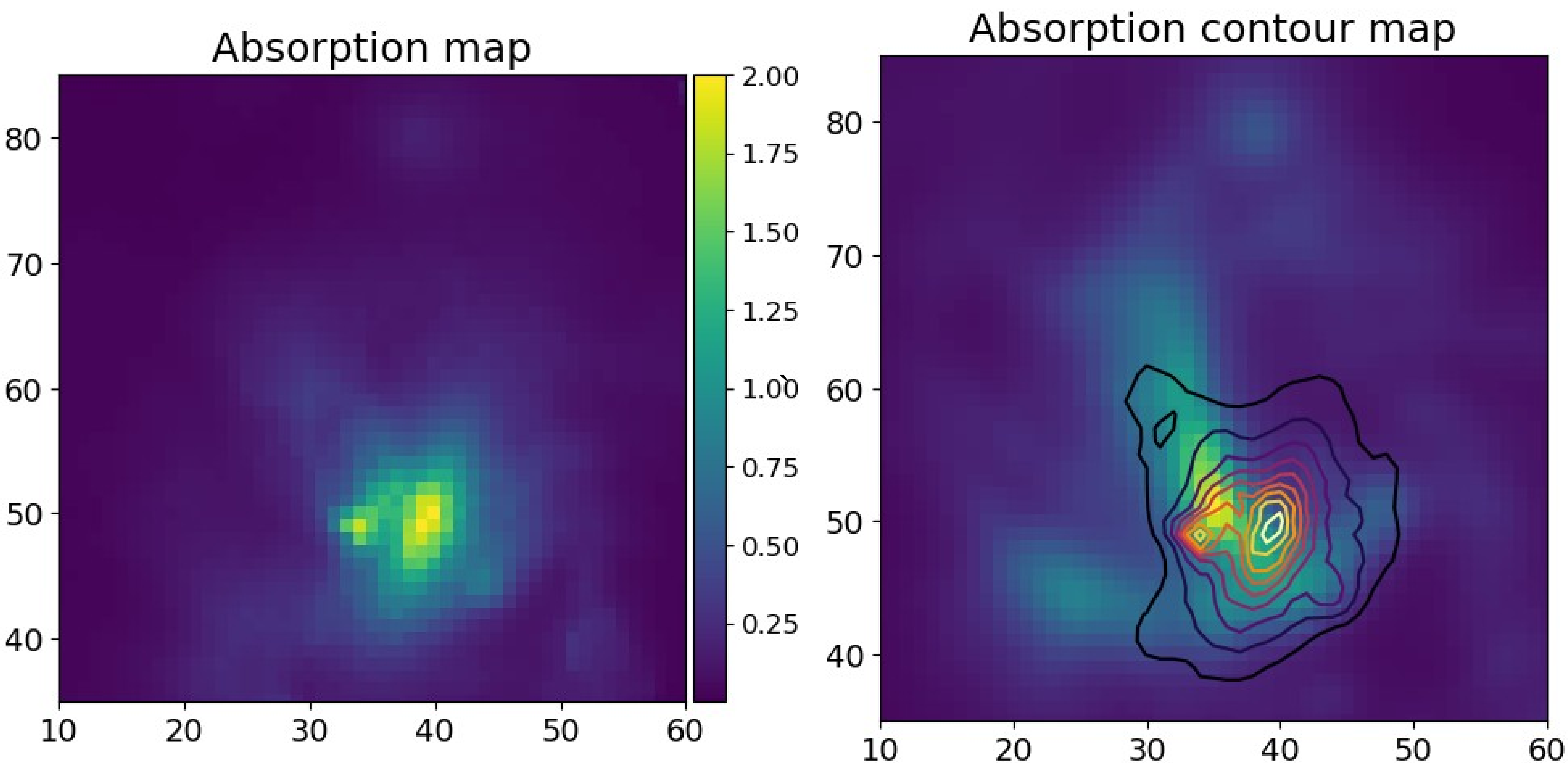
2d absorption map



- Absorption efficiency φ defined as the ratio of the absorbed flux at a given energy to the needed absorption at that energy
- Two parameters:
  - φ_1(E~10TeV)
  - φ_2(E~39TeV)
- In this case:
  - φ_1
    - absorption ~25%
    - needed absorption ~50%
    - absorption efficiency φ_1 ~0.5
  - φ_2
    - absorption ~35%
    - needed absorption ~25%
    - absorption efficiency φ_2 ~1.1

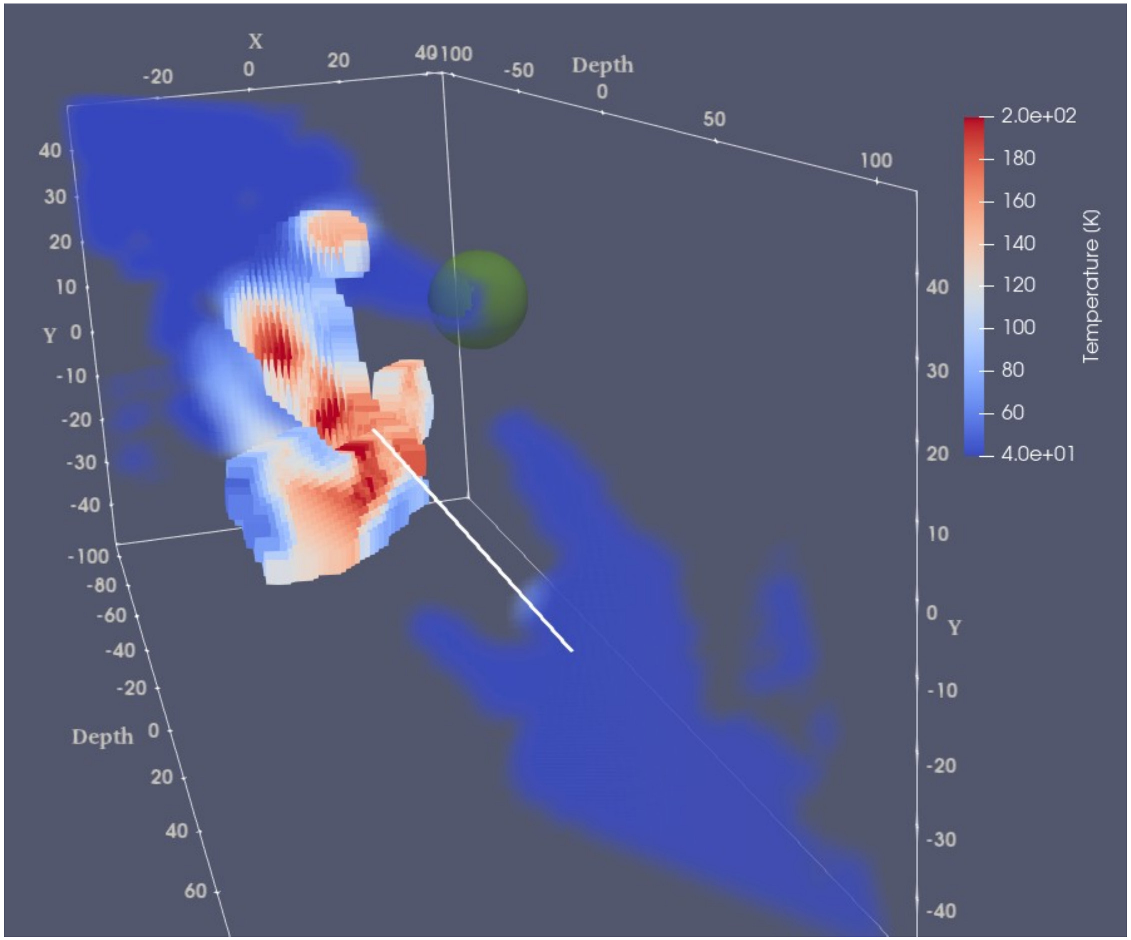
$$\boxed{\varphi = (\varphi_1 + \varphi_2) / 2}$$

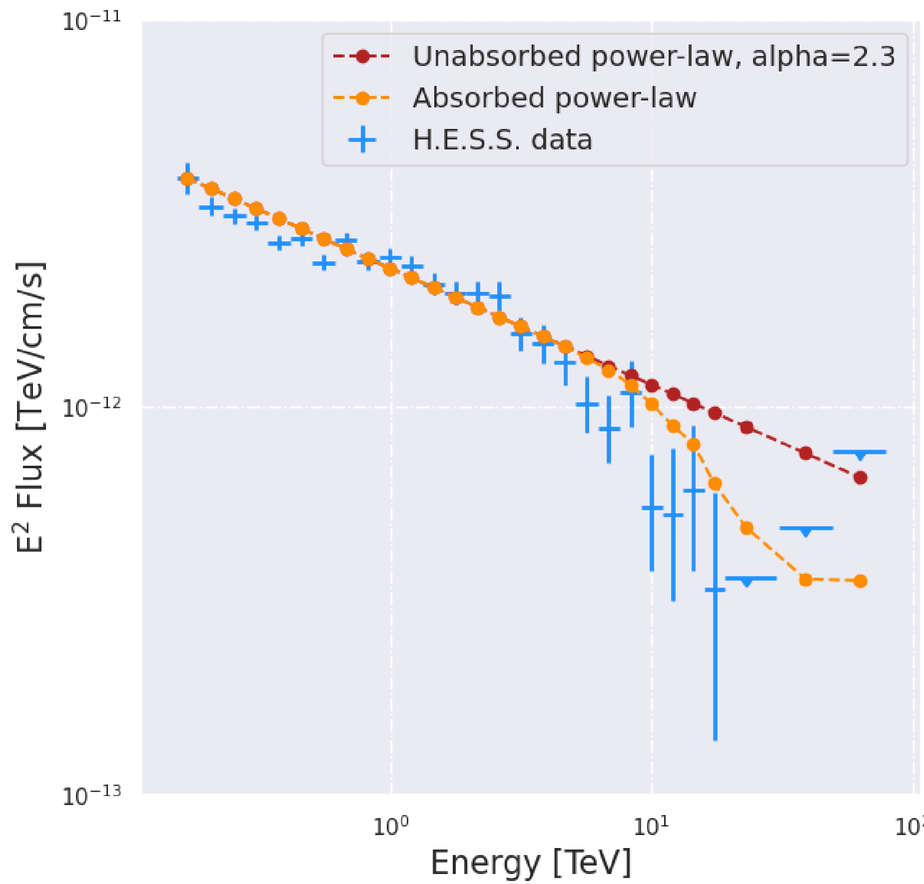
2d absorption map



- Absorption contours (up to φ=0.7 in the picture) radially concentrated around the middle of the crossing of the two warm filaments, as expected
- To absorb at both 10 TeV and 40 TeV you need both "warm" and "cold" emissions

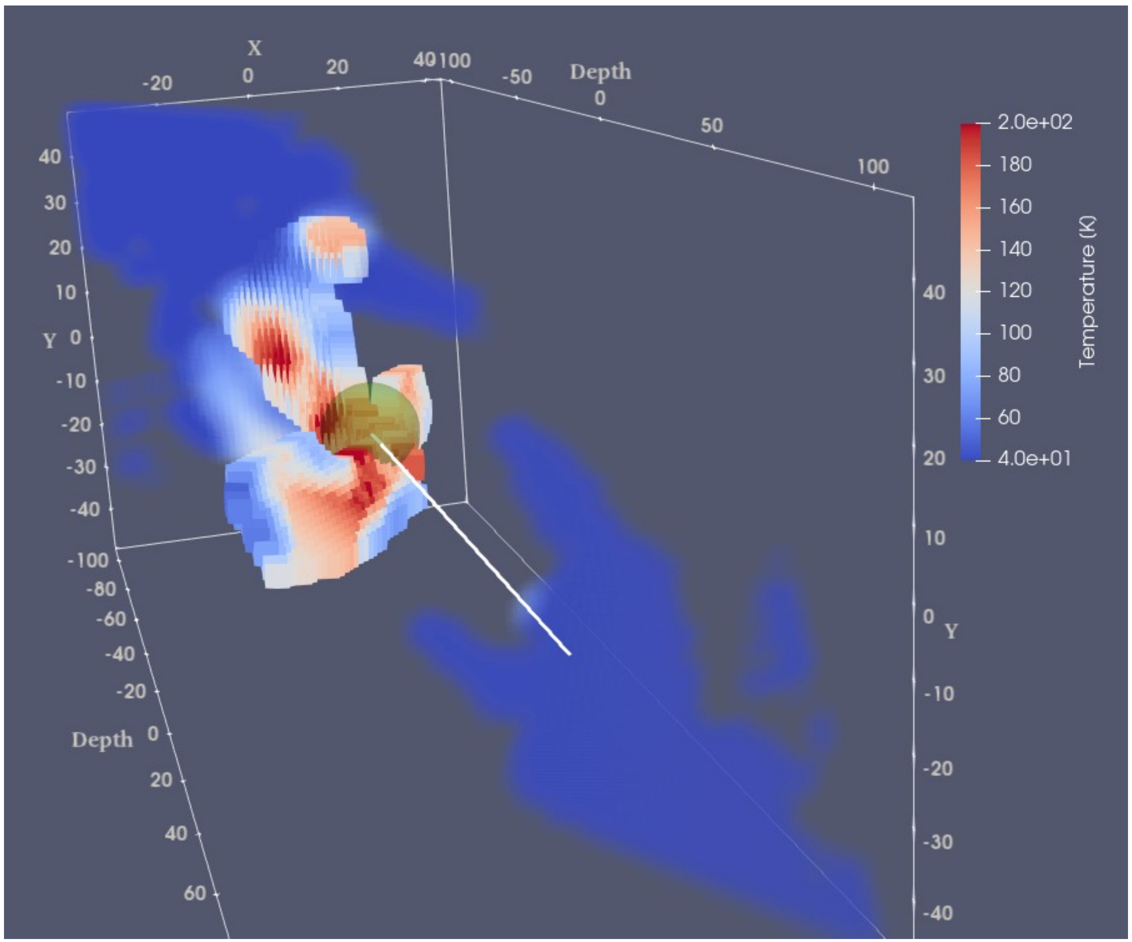
3d absorption map: offset gamma source

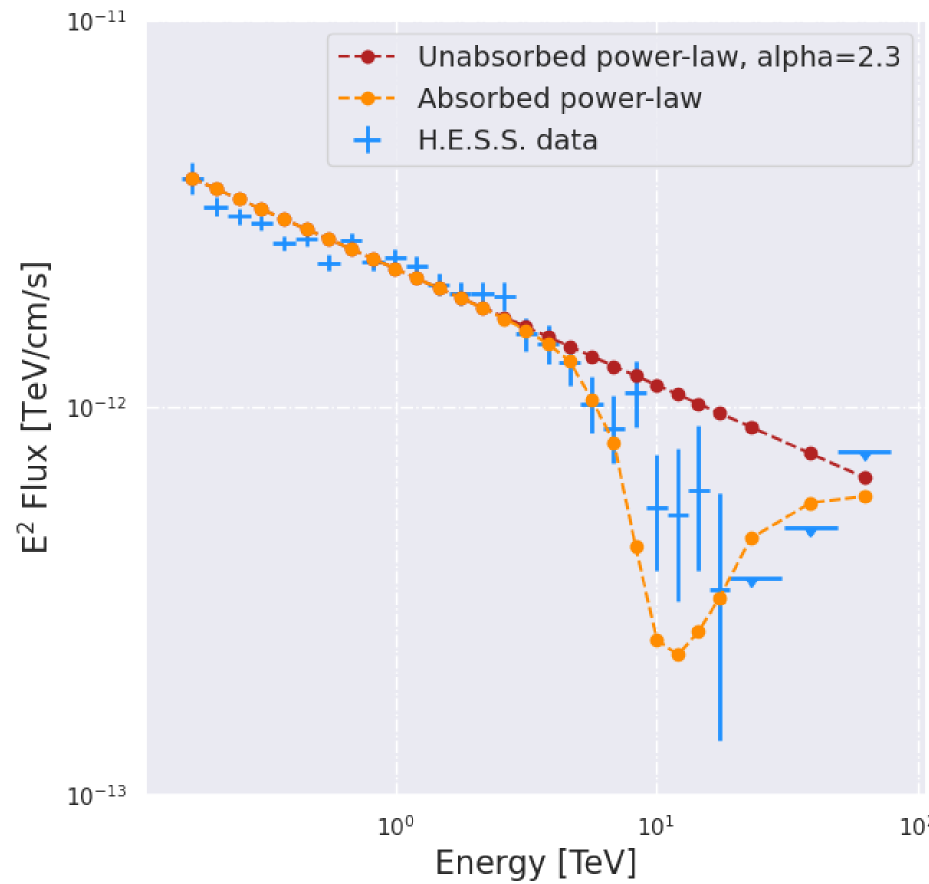




- Embedded in the cold dust ring:
  - High absorption at 40+ TeV
- No warm structures in line of sight:
  - Very low absorption at 10 TeV

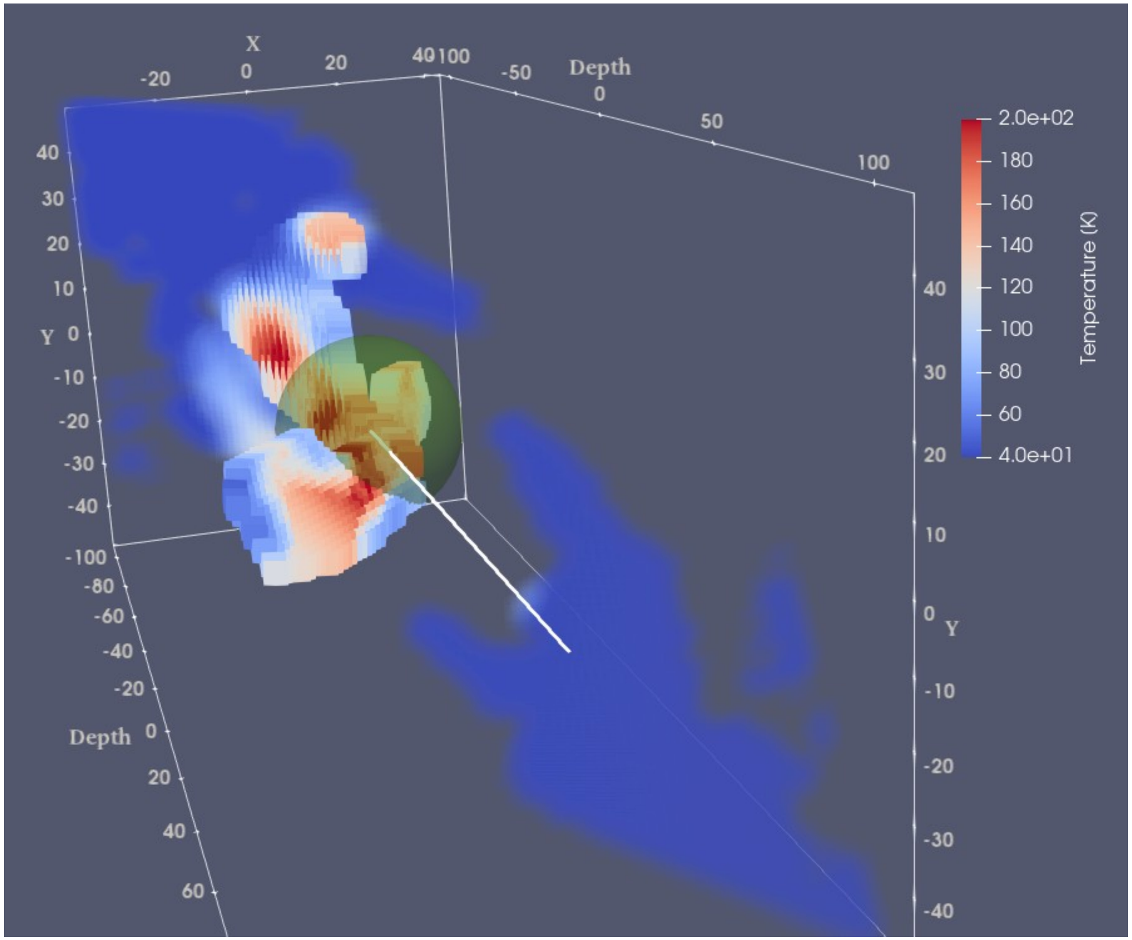
3d absorption map: centered gamma source (1)

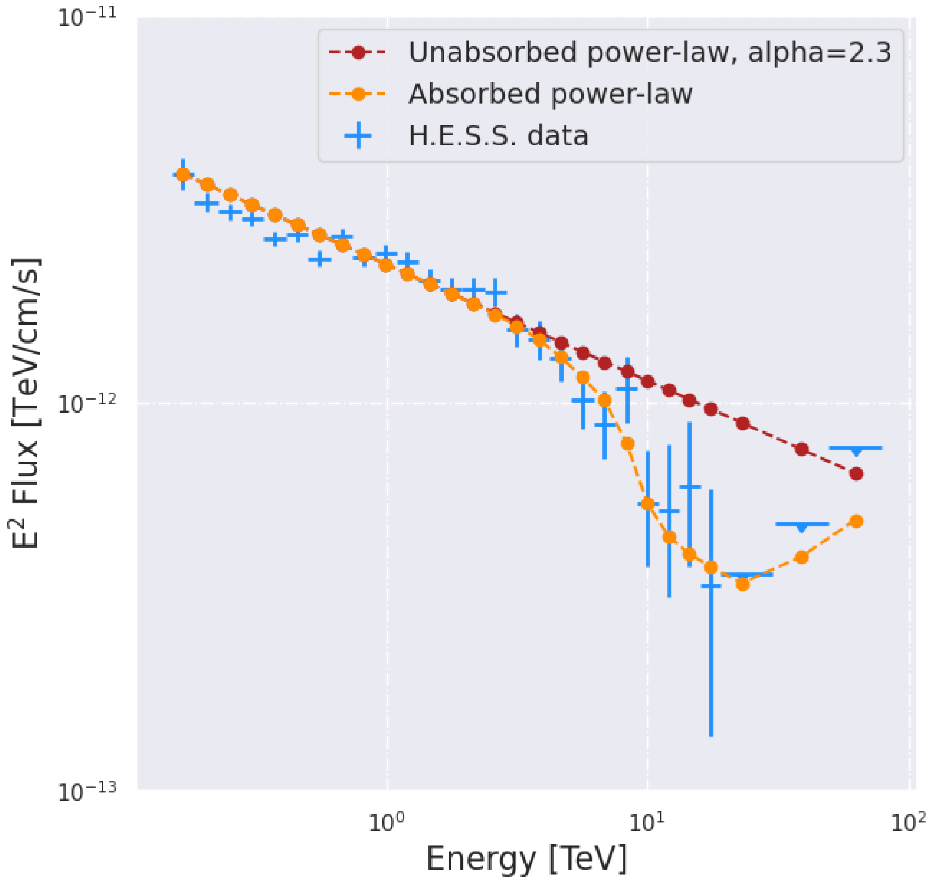




- Embedded in the hot zone:
  - (Too) high absorption at 10 TeV
- No cold structures in line of sight:
  - Low(ish) absorption at 40 TeV

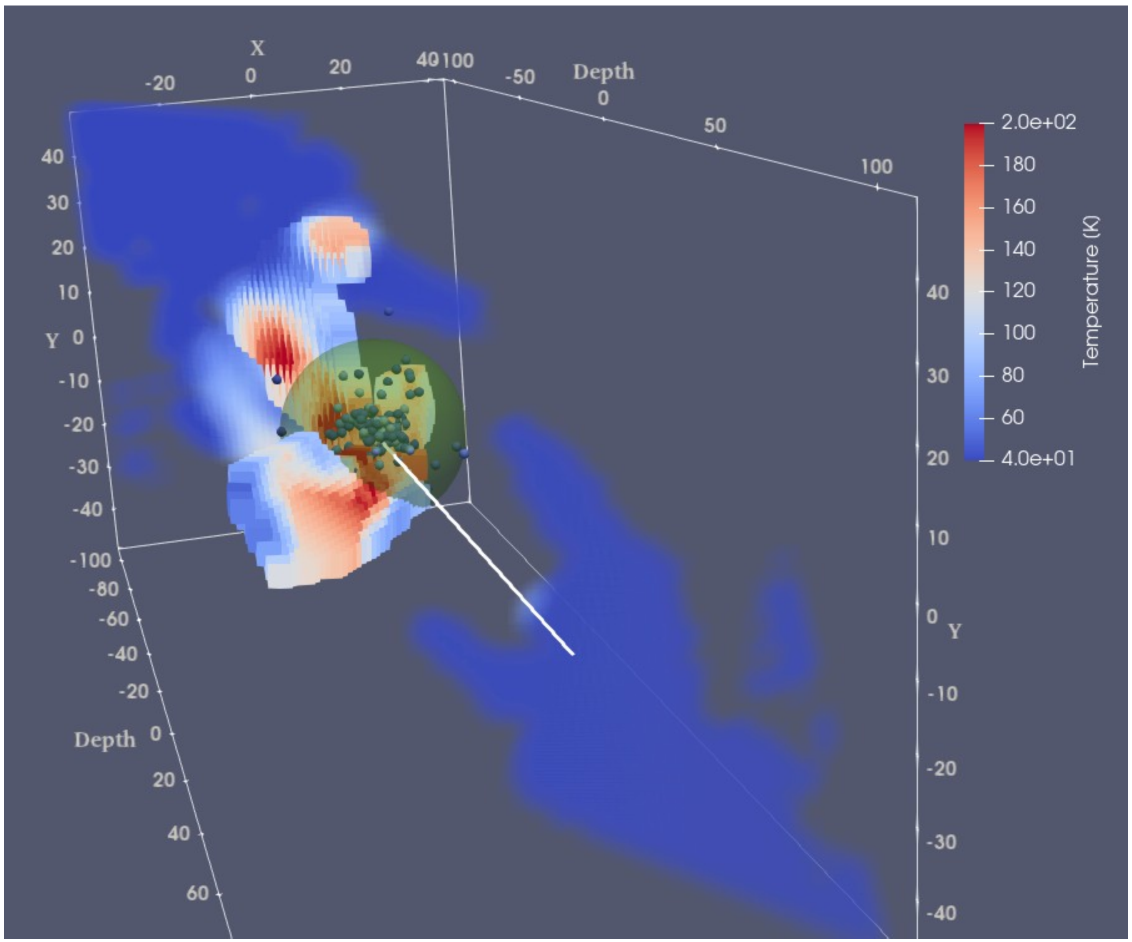
3d absorption map: centered gamma source (2)

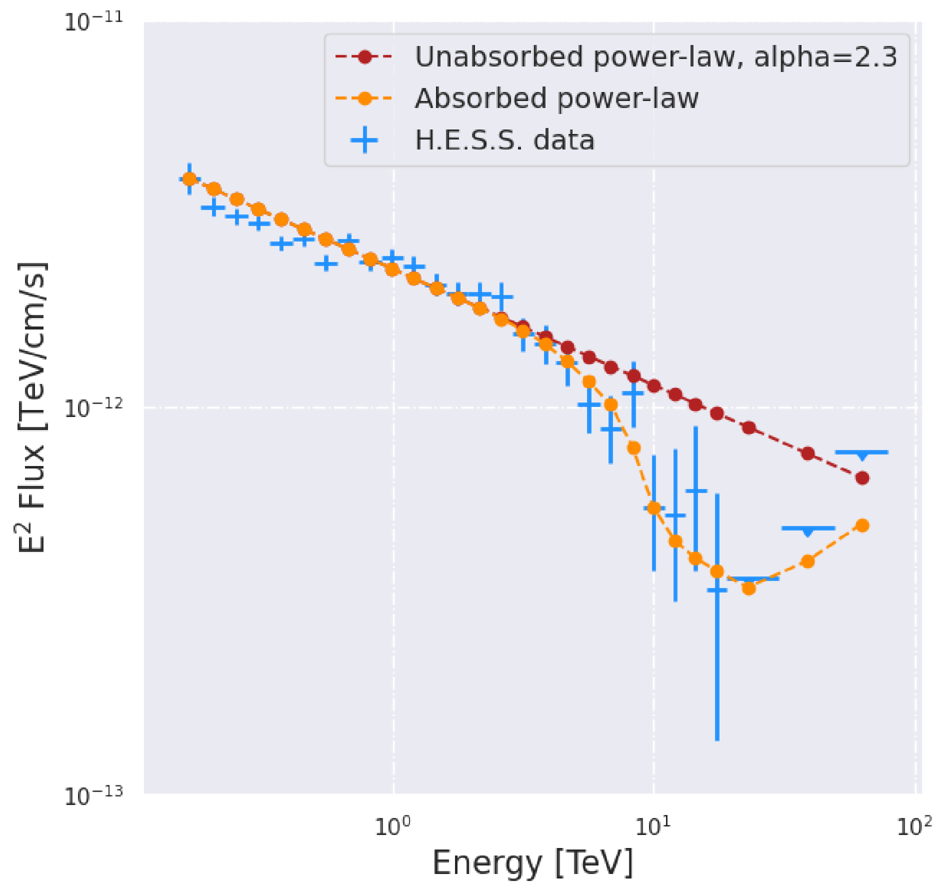




- Embedded in the hot zone but also peripheral parts:
  - High absorption at 10 TeV (but not too high)
- Large enough to be in the line of sight of colder structures:
  - Decent absorption at 40 TeV

3d absorption map: centered gamma source (2)





- Embedded in the hot zone but also peripheral parts:
  - High absorption at 10 TeV (but not too high)
- Large enough to be in the line of sight of colder structures:
  - Decent absorption at 40 TeV

- The comparison to the NSC distribution could be a nice starting point for next talk!

Conclusions

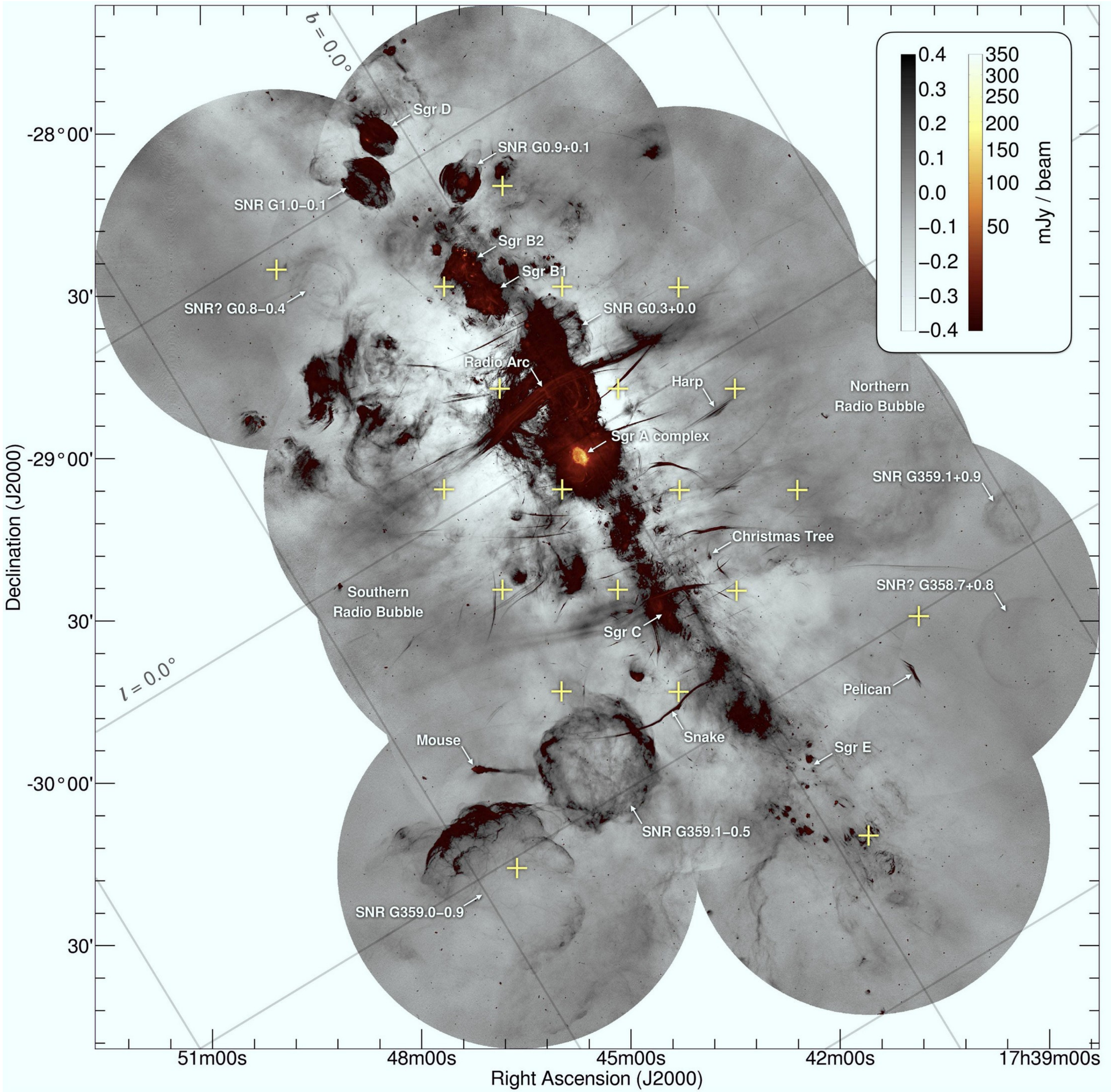
- The spectral feature of H.E.S.S. 1745-290 at ~5-10 TeV could be interpreted as absorption due to the IR background.
- This assumption allows for a spatial investigation of the source geometry (position, size).
- Investigation at 100+ TeV should be an independent proof of this – CTA could prove it spectrally and spatially.
- Most of the uncertainties are due to the dust models or to the NSC modeling.
- Nevertheless, introducing an appropriate additional cooling mechanism, even higher mass NSCs (or with top-heavier IMFs) can fit the data – there is some level of degeneracy, so we can't derive much information on the NSC mass.
- Next steps:
  - IC cascades
  - Simulate 3d pp collisions

References

- On MeerKAT:
  - [Heywood et al., arXiv: 2201.10552]
- On H.E.S.S. Galactic Plane survey and the Galactic Center:
  - [H.E.S.S. Collaboration, Characterising the VHE diffuse emission in the central 200 pc of our Galaxy with H.E.S.S., 2017]
  - [H.E.S.S. Collaboration, Acceleration of PeV protons in the Galactic Centre, 2016]
  - [H.E.S.S. Collaboration, The H.E.S.S. Galactic plane survey, 2018]
- On the NSC orbital parameters:
  - [Feldmeier-Krause et al., arXiv: 1509.04707]
- On the calculation of radiation fields from toroidal structures:
  - [Popescu&Tuffs, Radiation fields in star-forming galaxies: the disk, thin disk and bulge, 2013]

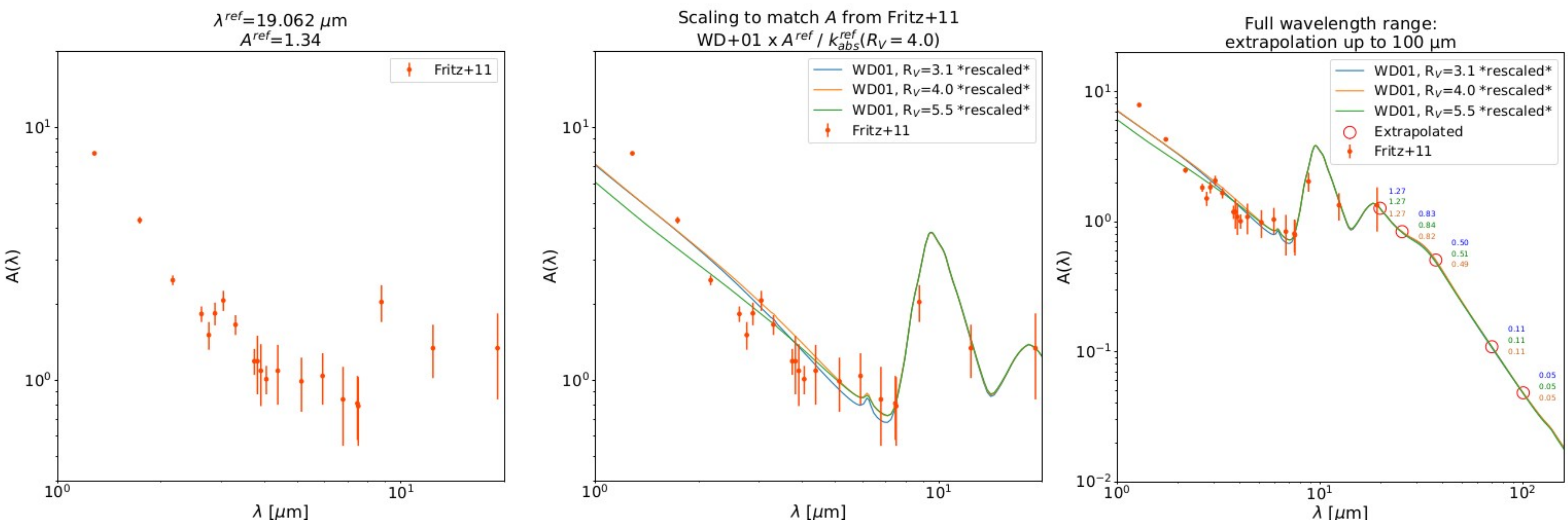
Backup Slides

The Galactic Center in the radio sky



Heywood et al., arXiv: 2201.10552

Line of sight extinction



- **Assumption**: the extinction is dominated by absorption at λ > 20 μm
- Anchoring the dust absorption model to the los extinction curves at 19 μm
- Extrapolating the extinction values for λ up to 160 μm
- (But anchoring on a peak!)

First fitting approach

Fit the data in order to obtain:
- dust mass M
- dust temperature T
- for n_c components.

Modified Planck function

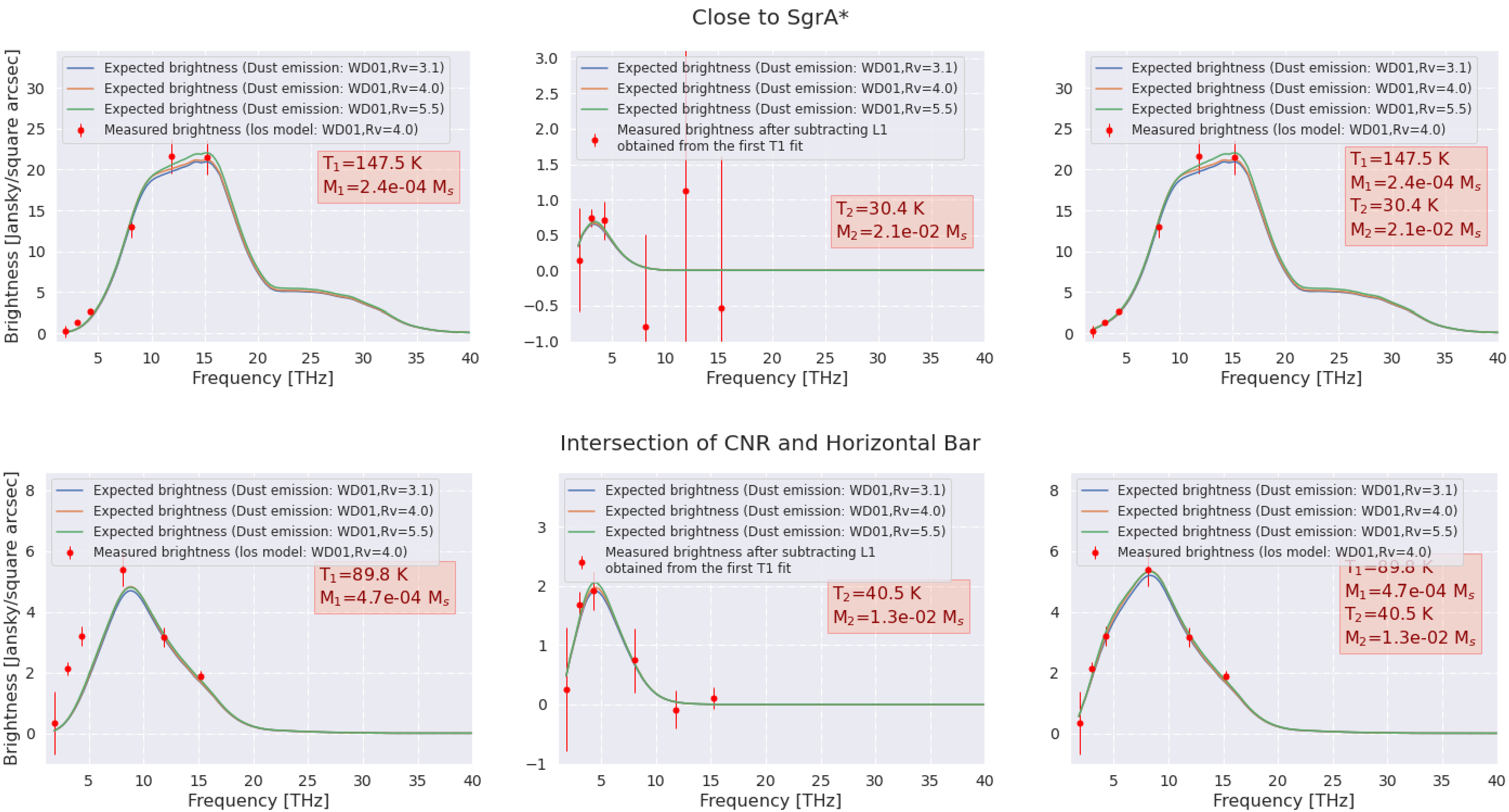
$$\widetilde{B} = \sum_{i=1}^{n_c} \widetilde{B}_\nu^{(i)} = \sum_{i=1}^{n_c} k_\nu M_d^{(i)} \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT^{(i)}} - 1}$$

k(a,ν): mass absorption coefficient
a: dust grain radius
Q_{abs}: dust grain absorption efficiency

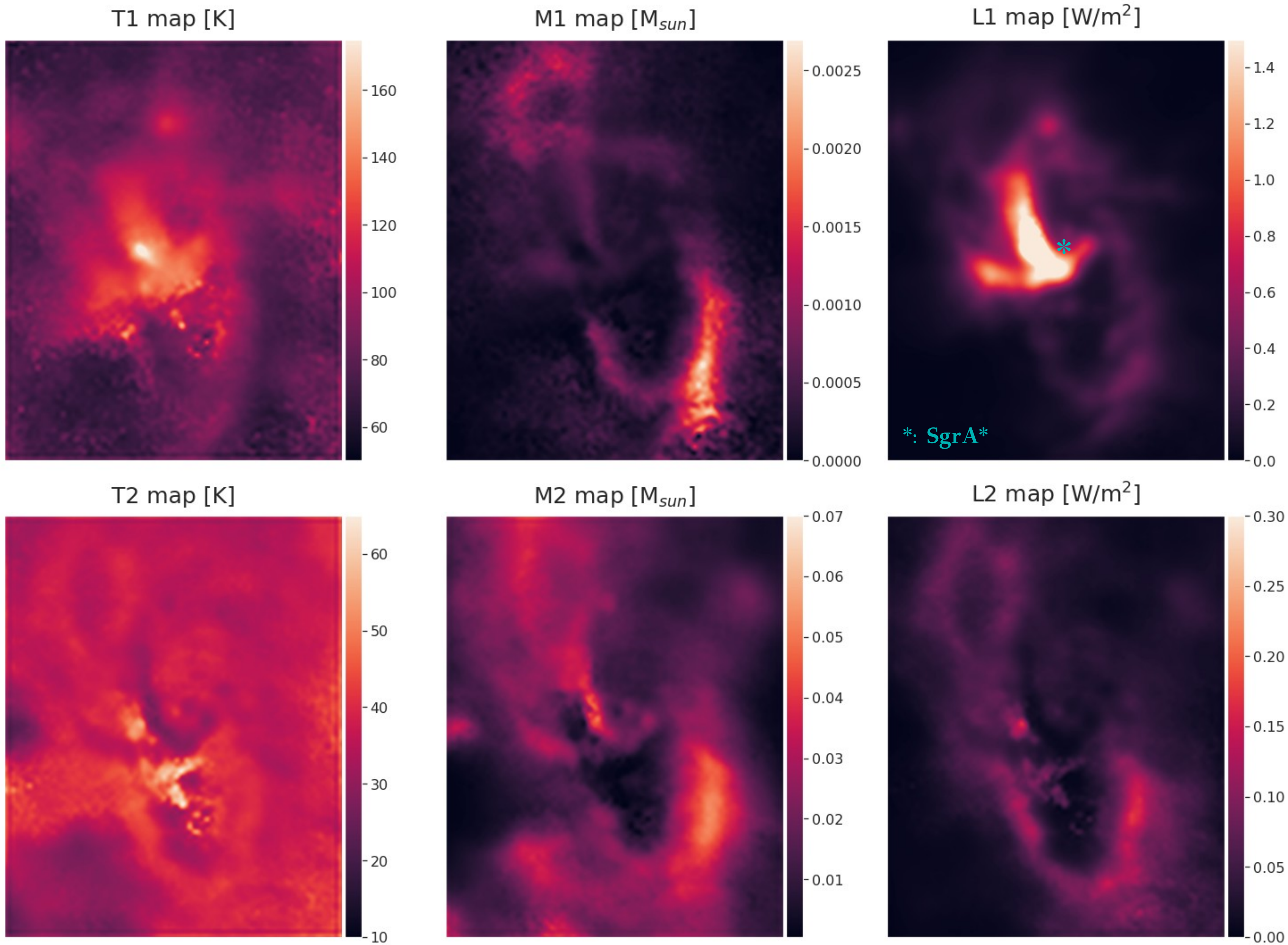
$$k(a, \nu_{em}) = \pi a^2 \frac{Q_{abs}(a, \nu_{em})}{M_d} \sim \nu_{em}^\beta$$

IR maps at 6 different frequencies, 2 parameters: 2 dust components fitted
- a "warm" component (T_1 ~ 100-200 K) ideally coupled to the ionised gas (the one "absorbing" the most)
- a "cold" neutral component (T_2 ~ 30-70 K).

Modified Planck fits



Dust mass and temperature (2d)

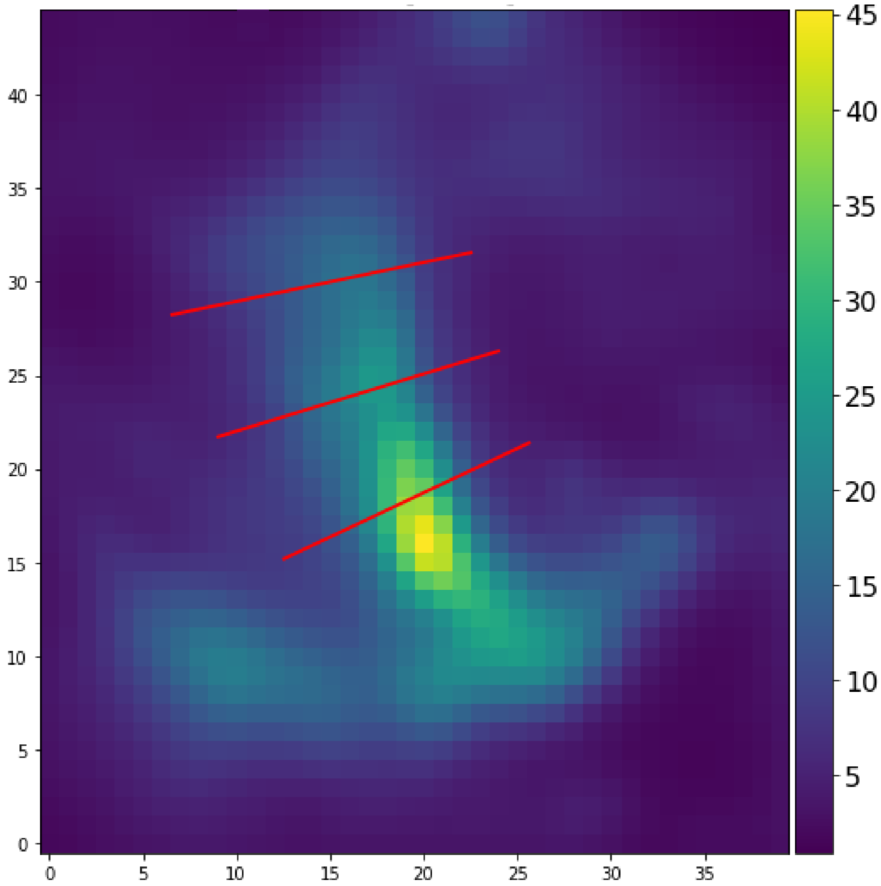


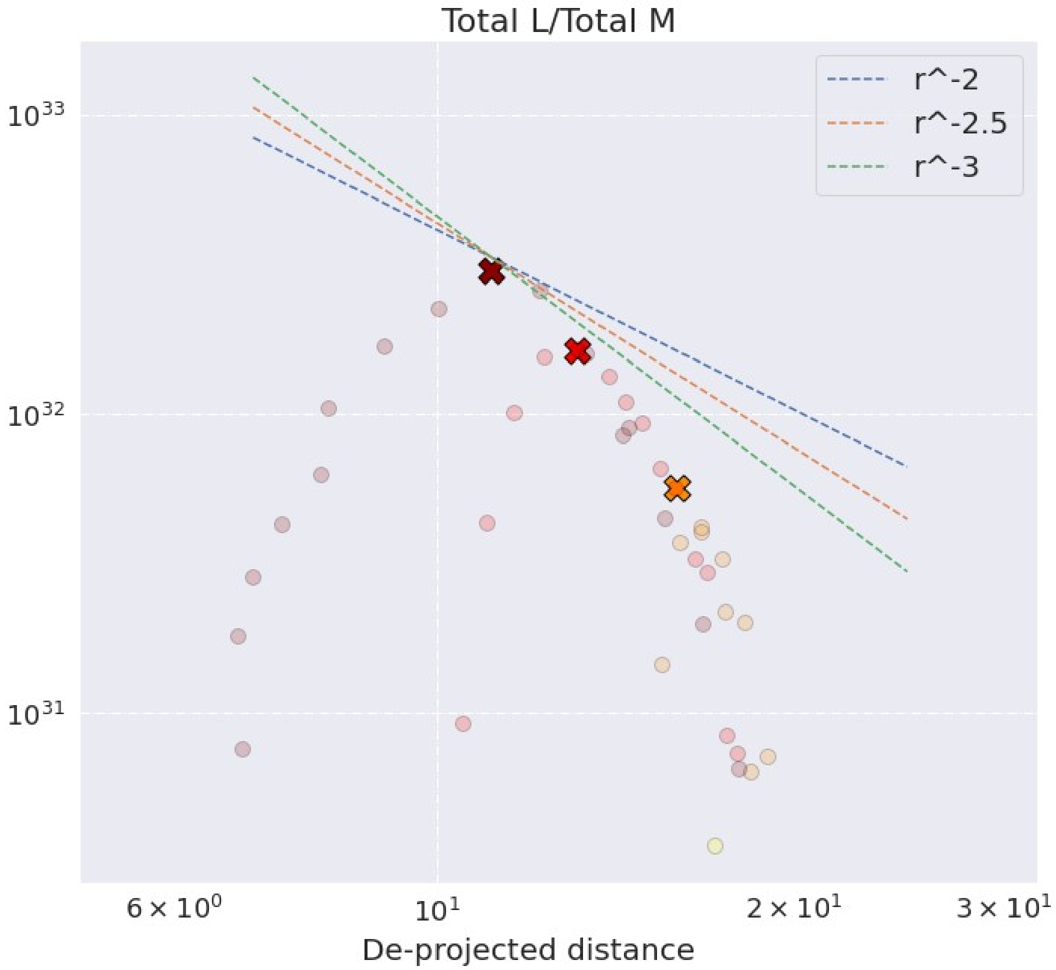
$\boxed{M_2 \gg M_1}$

$\boxed{L_1 \gg L_2}$

But still 2d maps...

A critical test: illumination profile





- Quick test: extracting total L/M on slices on the (de-projected) NA
- At large distances, the illumination should decrease as $1/r^2$
- But it doesn't – large pollution by cold and massive structures with a different geometry

The story so far #2

Main points so far:

- Assumptions:
  - two dust components
  - each component is in thermal equilibrium (same temperature for all grains, irrespective of their radius).
  - the UV source is located in the inner parsec

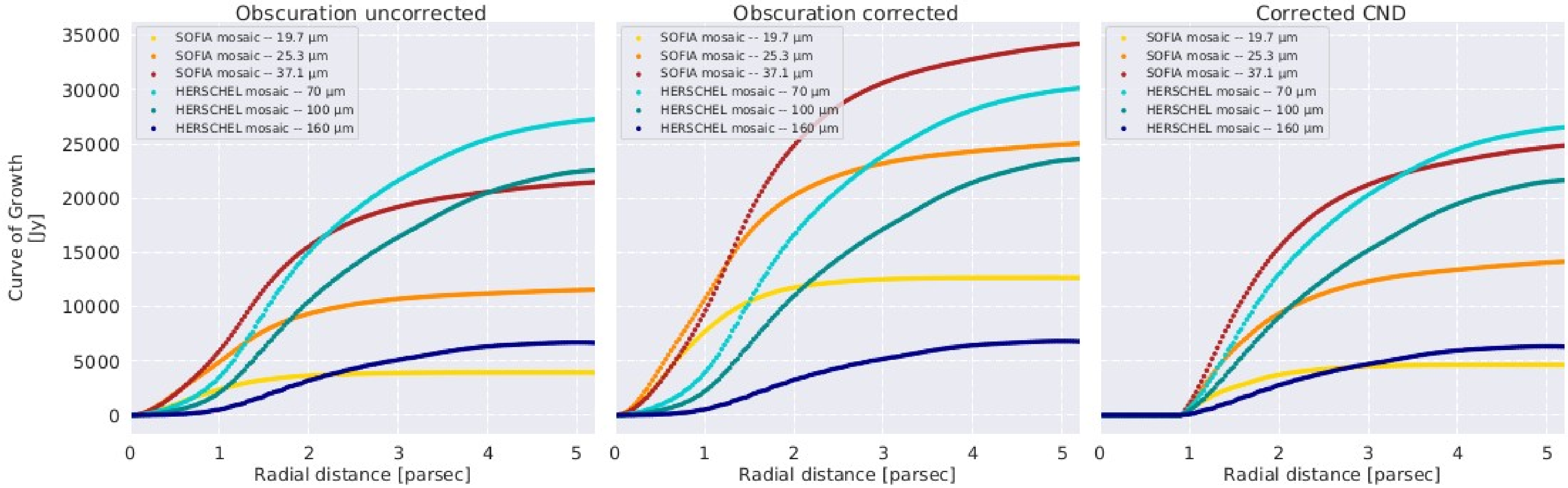
- Using a modified Planck fit, I derived mass and temperature maps for the inner few parsecs (they look good, which doesn't hurt)
  - the cold component dominates the mass
  - the warm dominates the brightness.

- M and T are still 2d maps after the fit

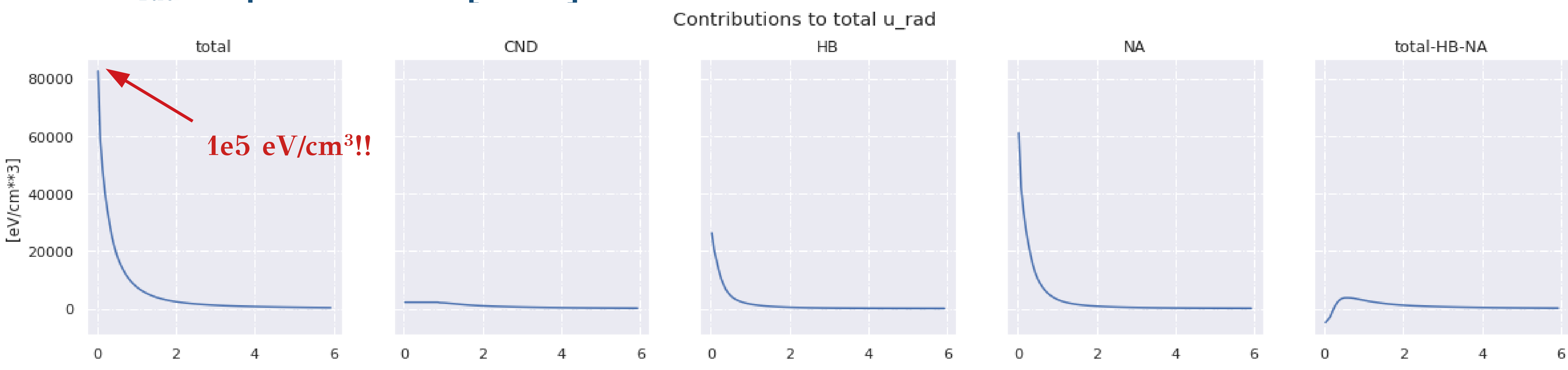
- The L/M profile at large distances from the emitter should go as $1/r^2$, and it doesn't. There's a problem with the background/cold component, which I couldn't separate from the warm component.

- Not reliable – the 3d information needs to be provided by the fit!

Simplified model for the 3d IR u_{rad}



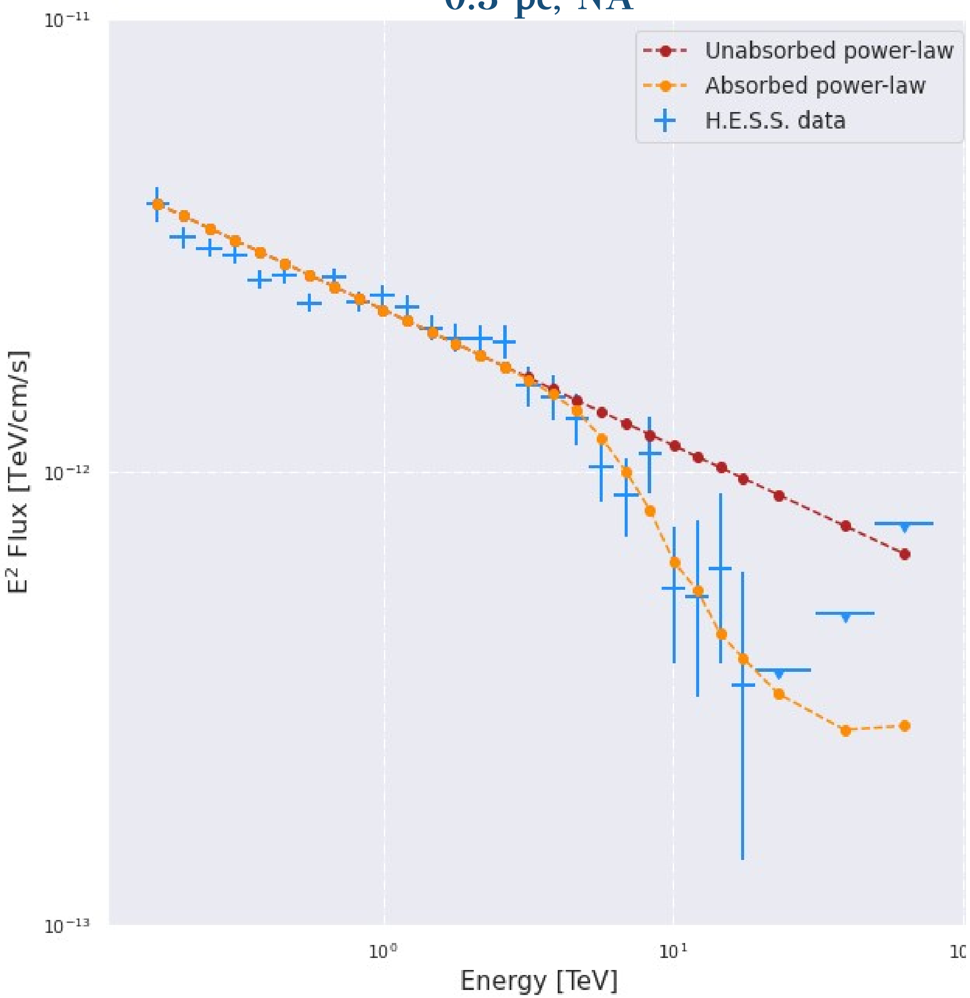
- Simulate isotropic emission from the CND using the enclosed energy profile
- Add 2 warm torii, modeled using the previous fits T and M
  - u_{rad}: Popescu&Tuffs [2013]



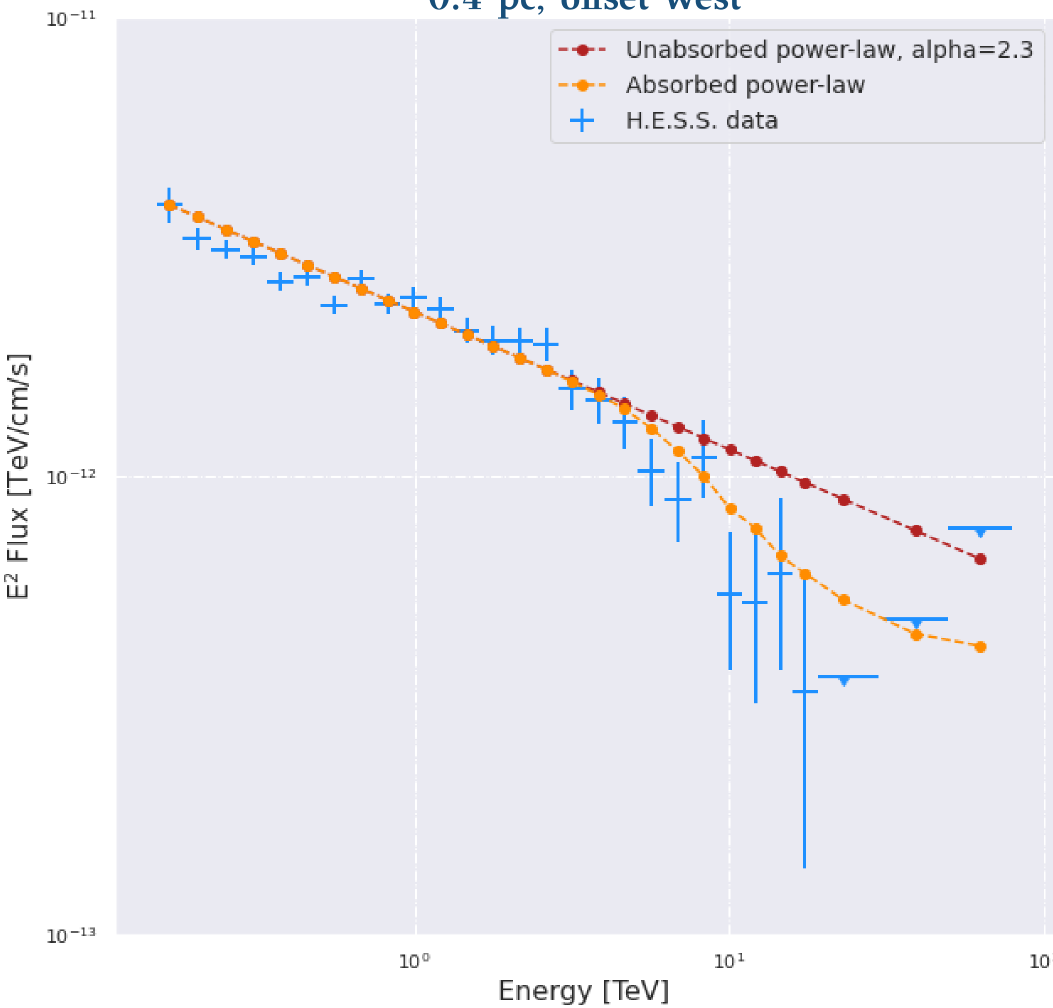
A promising result

- Power-law: diffuse emission in the H.E.S.S. GC paper [2016]
- Keeping in mind the (unabsorbed) diffuse emission contribution (H.E.S.S. GC paper [2017])

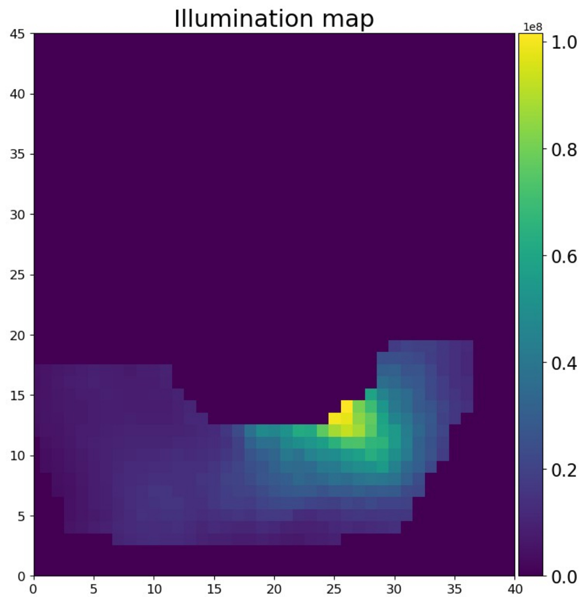
0.3 pc, NA

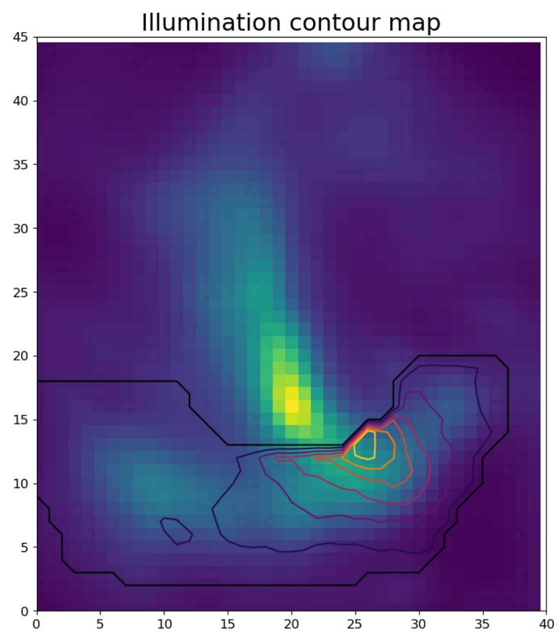


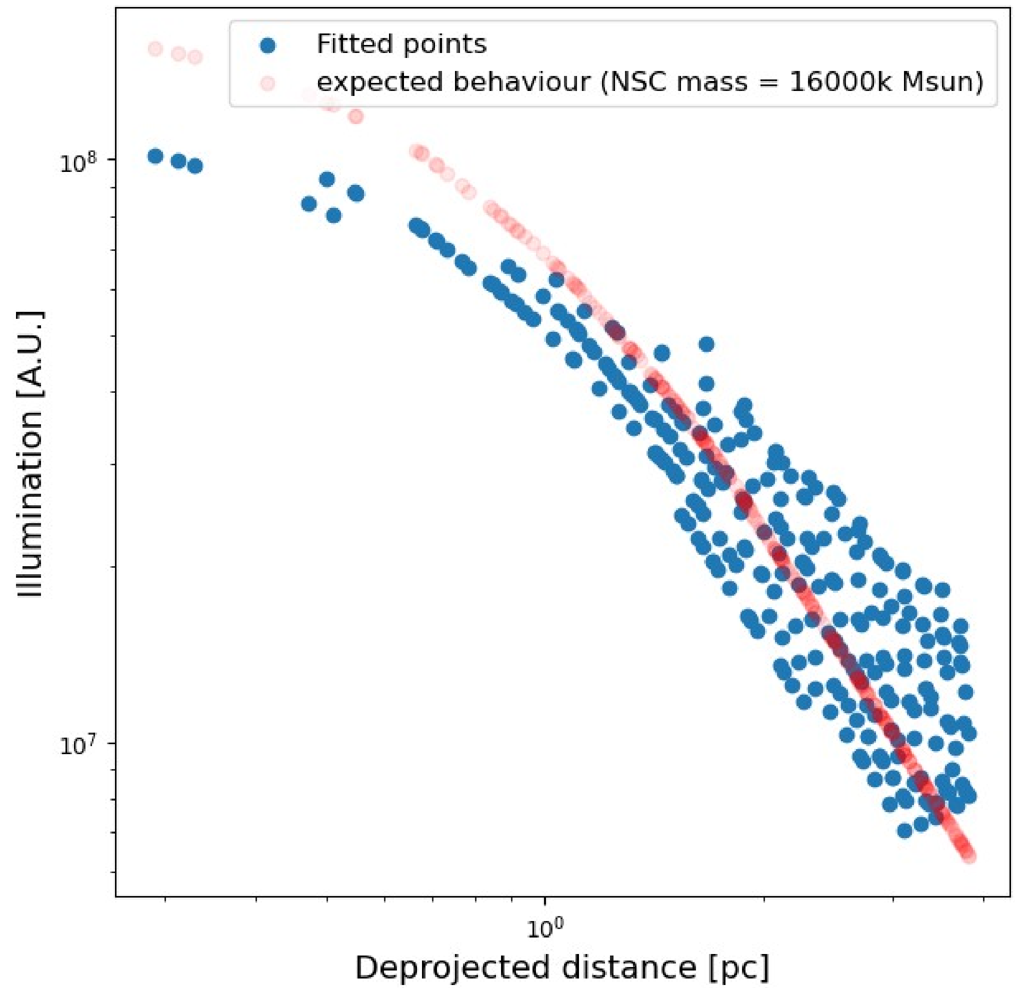
0.4 pc, offset west



Illumination test

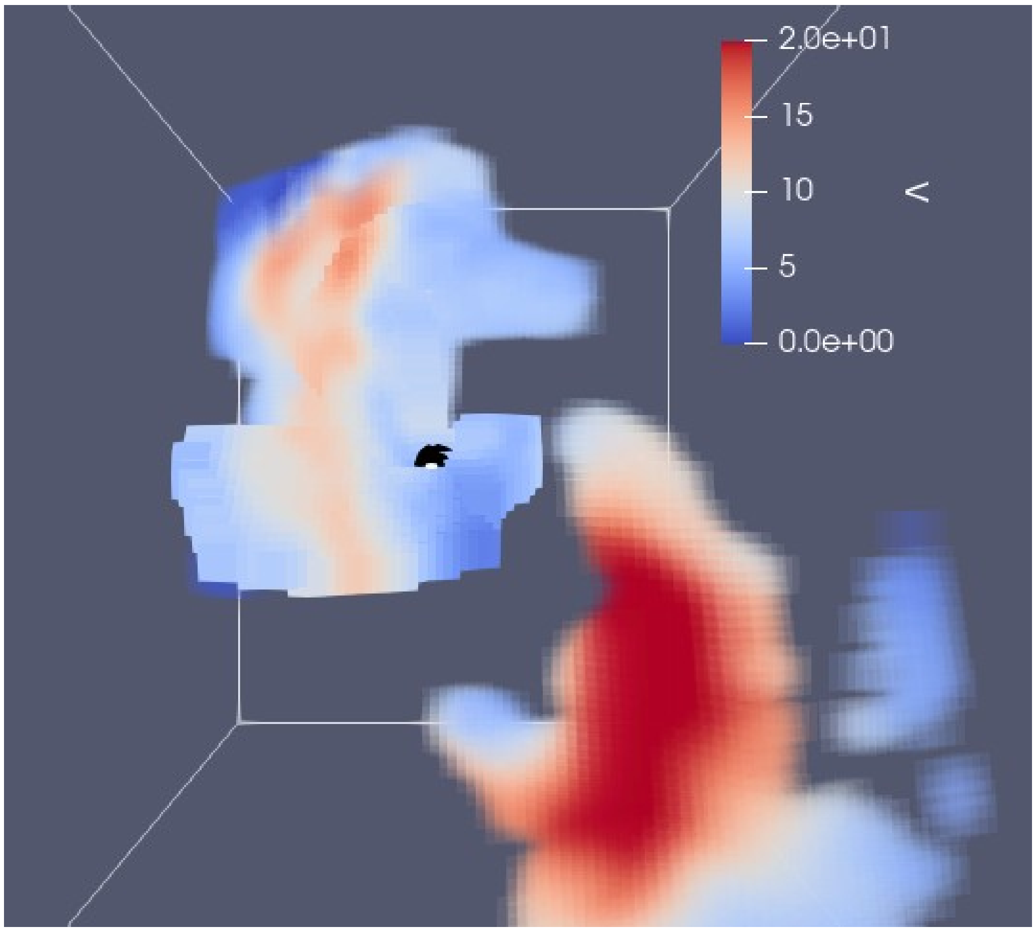


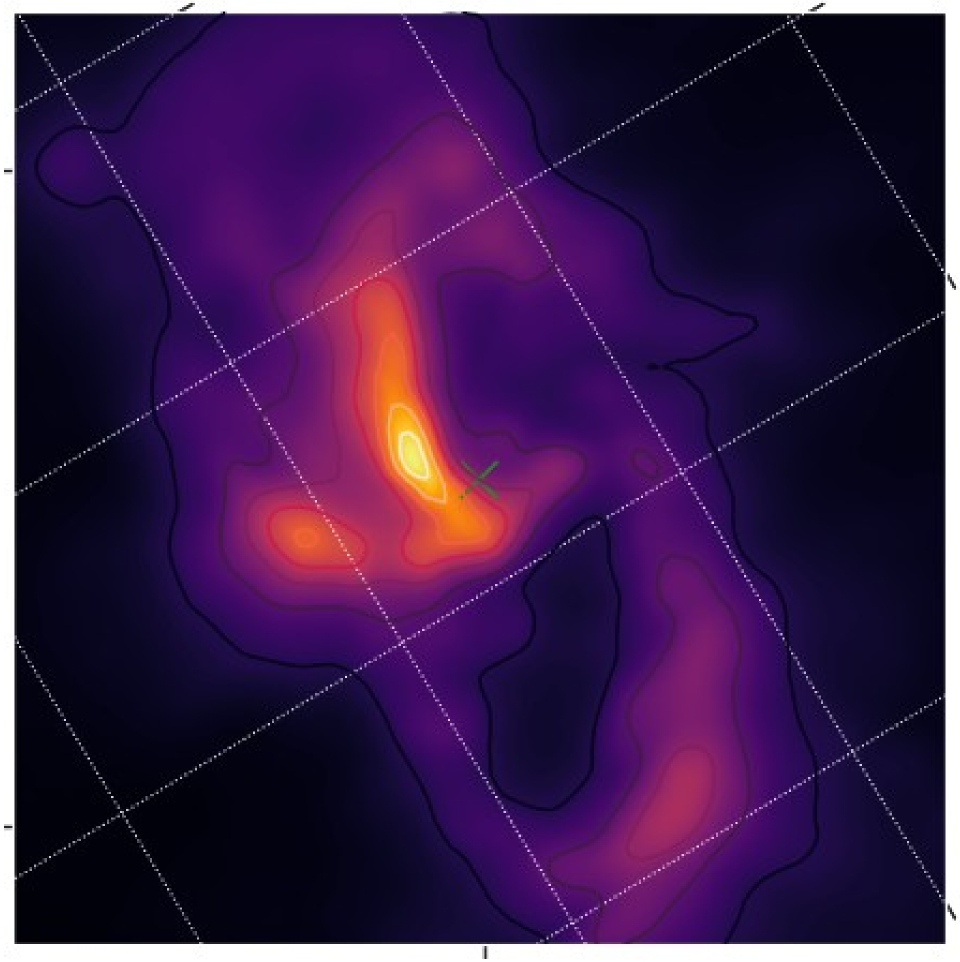




- Inverse square law test passed!
- The illumination spots concentrate on SgrA* position and expand radially

3d background: the Λ parameter





- The Λ parameter allows us to track the cold disk on the hot filaments!
- No other big relevant background components

Second fitting approach: formulas

For a given dust grain or radius a, given a UV radiation field density u_{rad}, the absorbed luminosity is:

$$L_{abs}^{sg,(i)}(a,\vec{r}) = \int \pi a^2 Q_{abs}^{(i)}(a,\nu) u_{rad,\nu}^{(i)}(\nu,\vec{r}) c d\nu$$

while the emitted luminosity is:

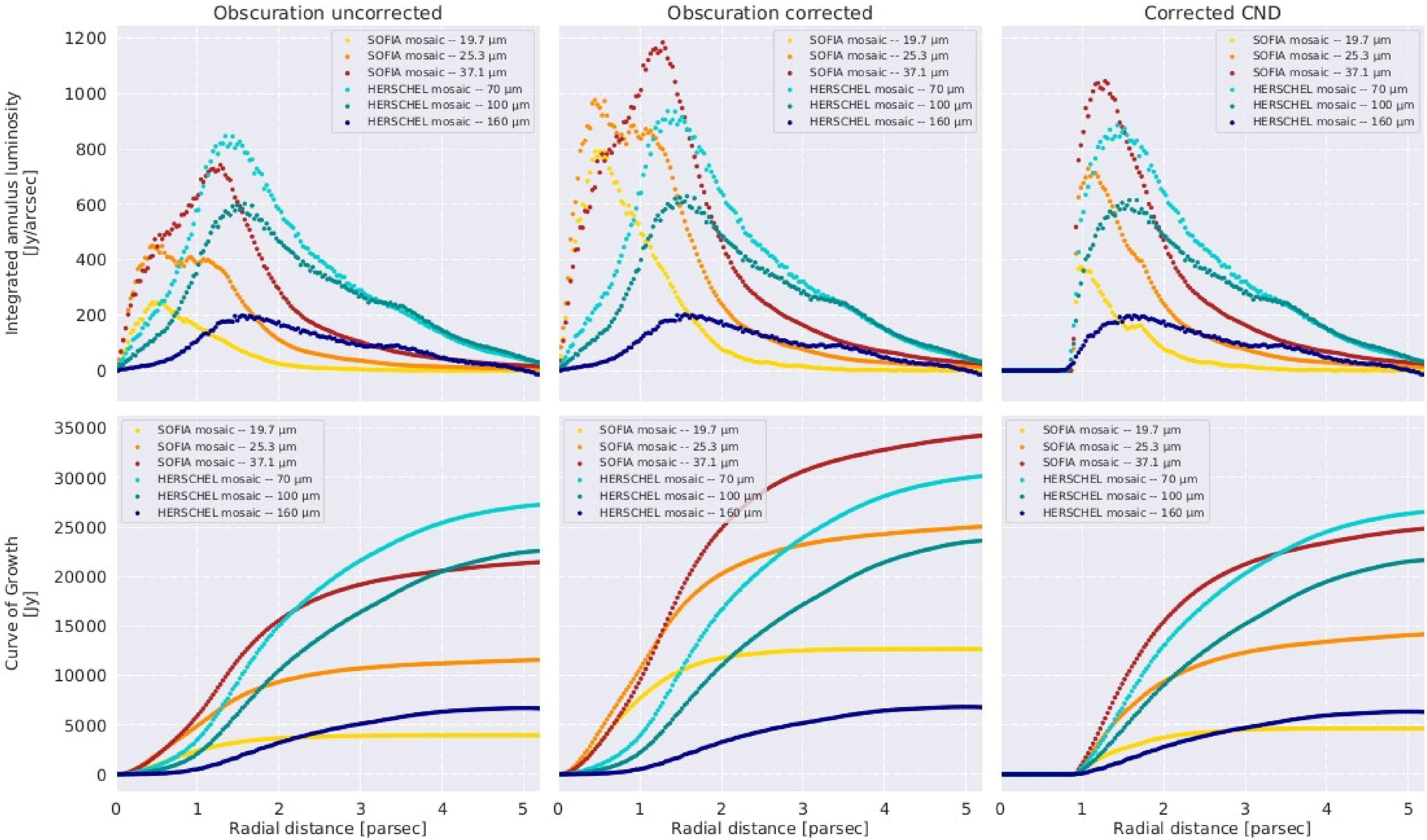
$$L_{em}^{sg,(i)}(a,\vec{r}) = \int 4\pi^2 a^2 Q_{abs}^{(i)}(a,\nu) BB_\nu(\nu, T_g^{(i)}(a,\vec{r})) d\nu$$

where BB_ν is the black body formula. Then the temperature is found by solving the integral equation

$$L_{abs}^{sg,(i)}(a,\vec{r}) = L_{em}^{sg,(i)}(a,\vec{r}) \qquad \int f(\nu, T_g) d\nu - D = 0$$

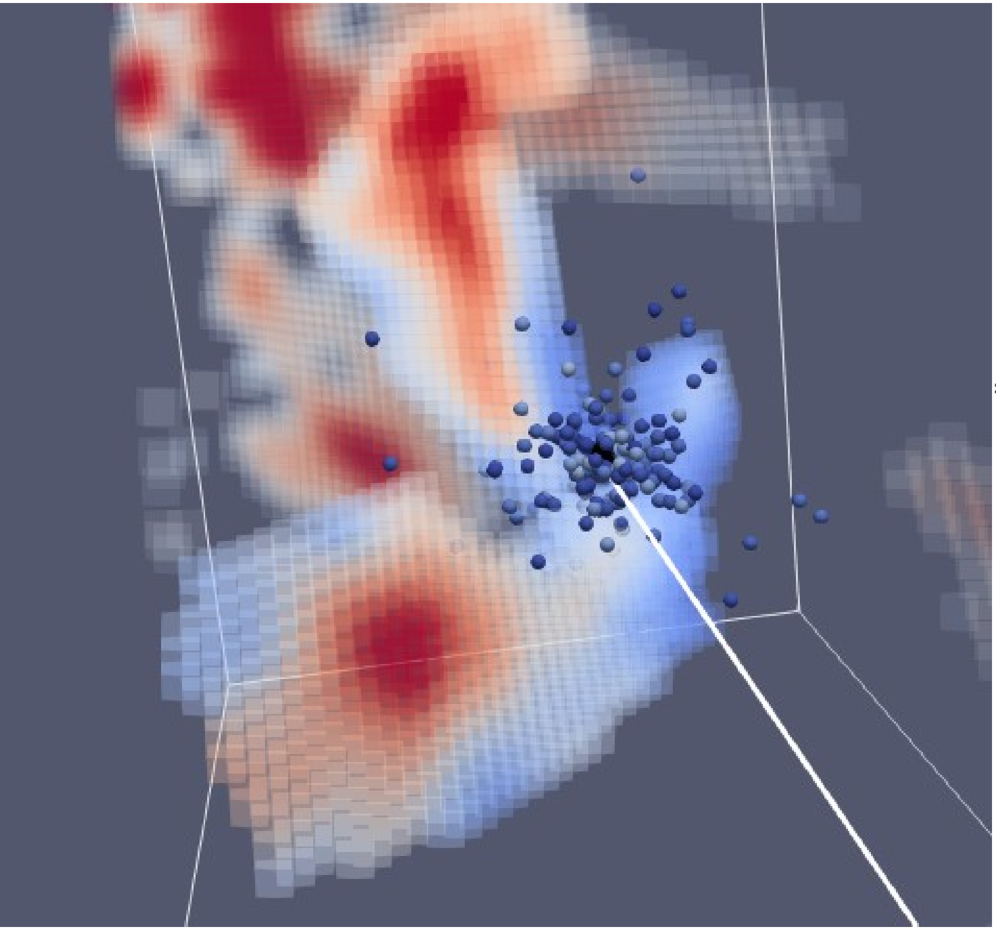
and from the temperature we can calculate the brightness as usual.

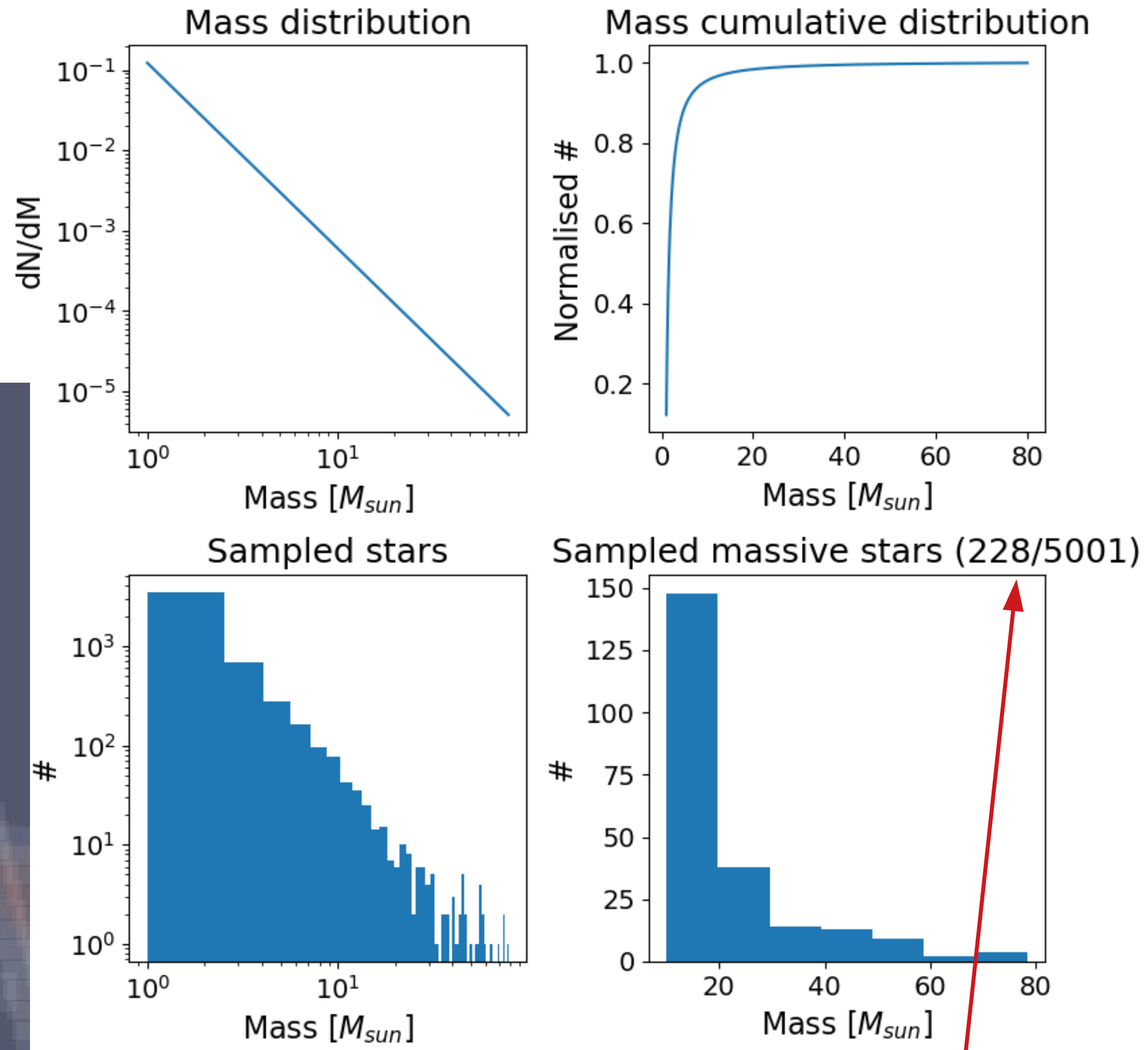
Curve of Growth and the Central Heater



Nuclear Star Cluster

- Parameters investigated:
  - IMF spectral index
  - Maximum single star mass
  - Total cluster mass

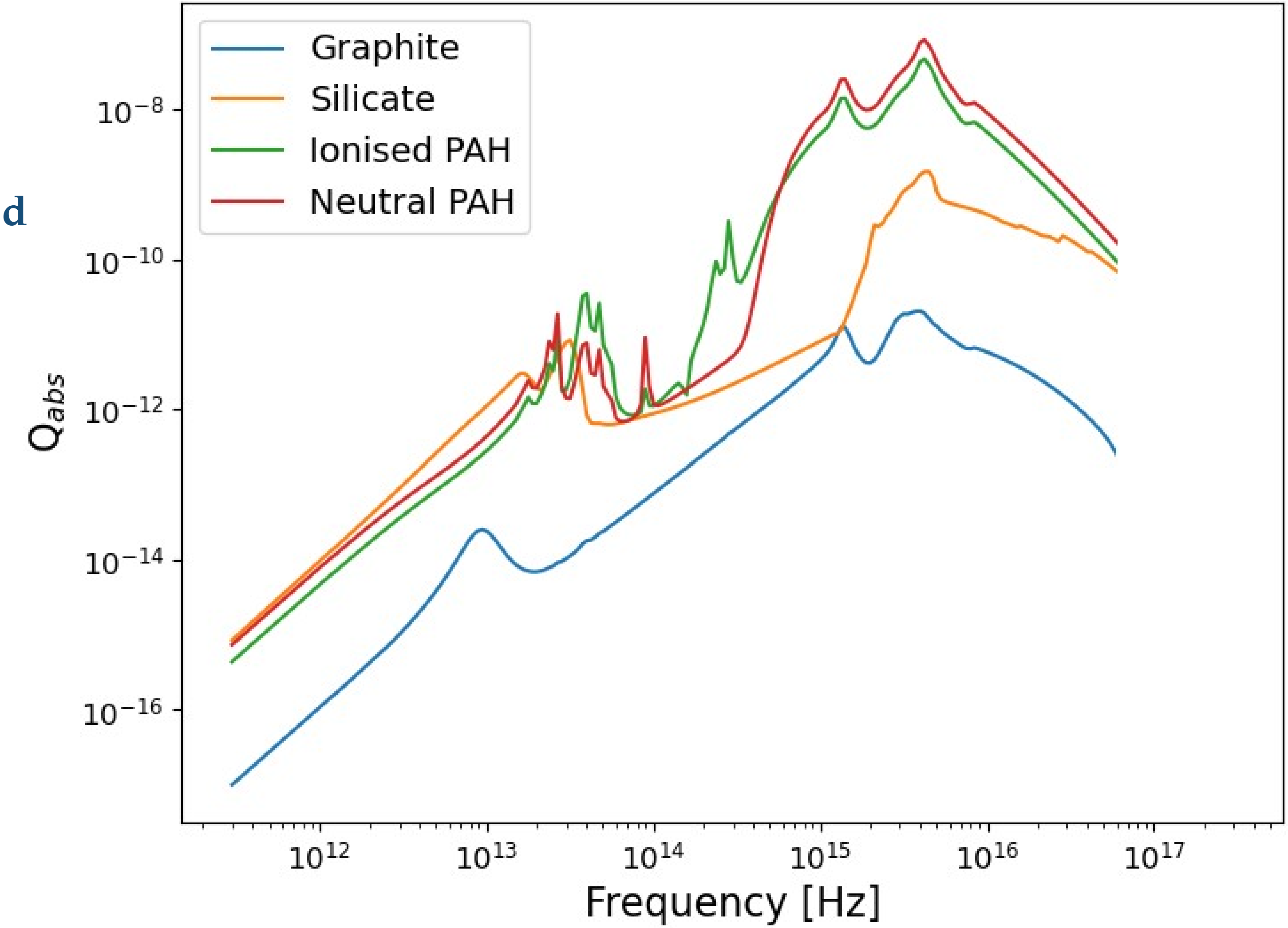




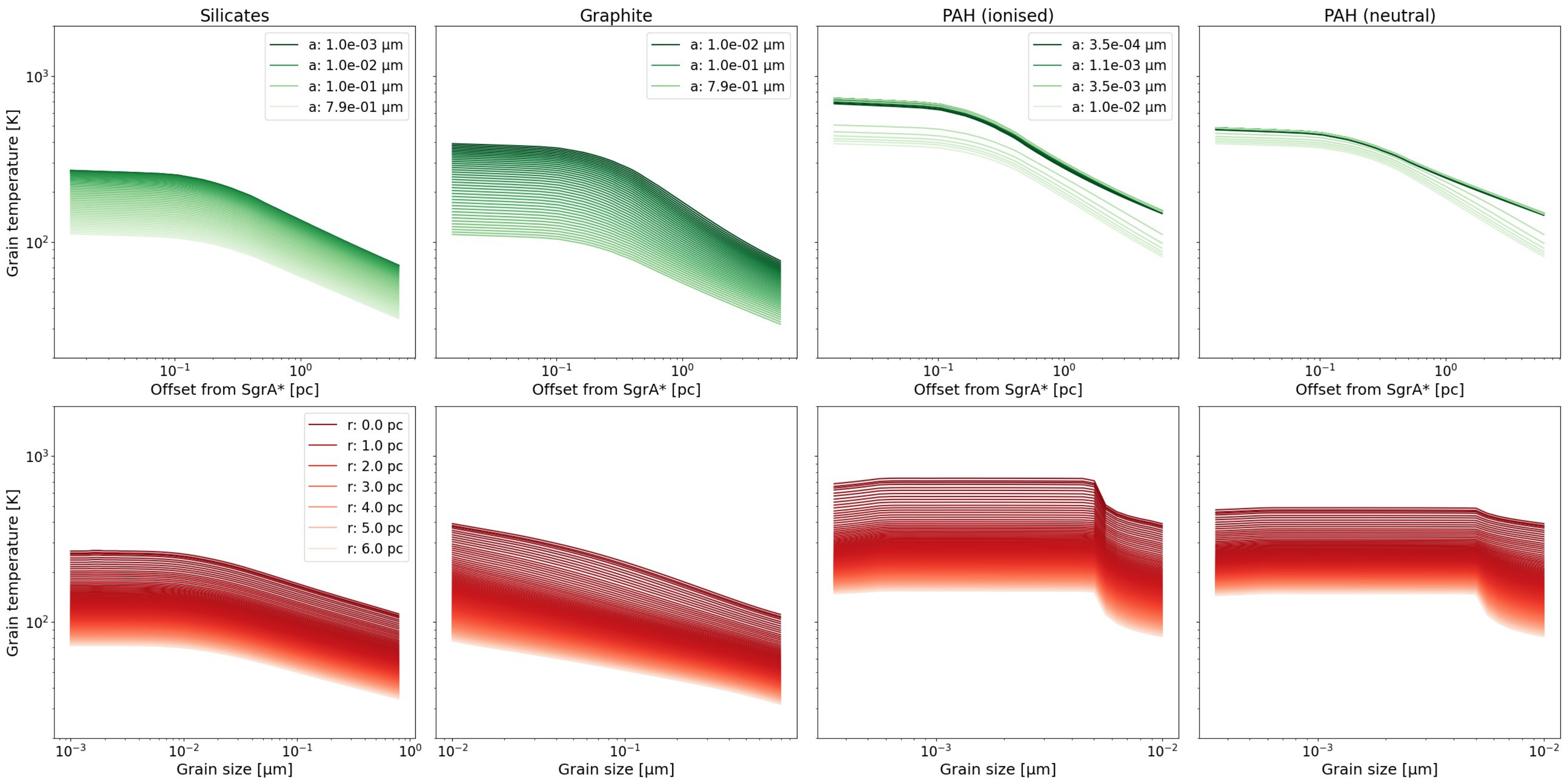
(in less than a cubic parsec!!)

Absorption and scattering profile: dust physics

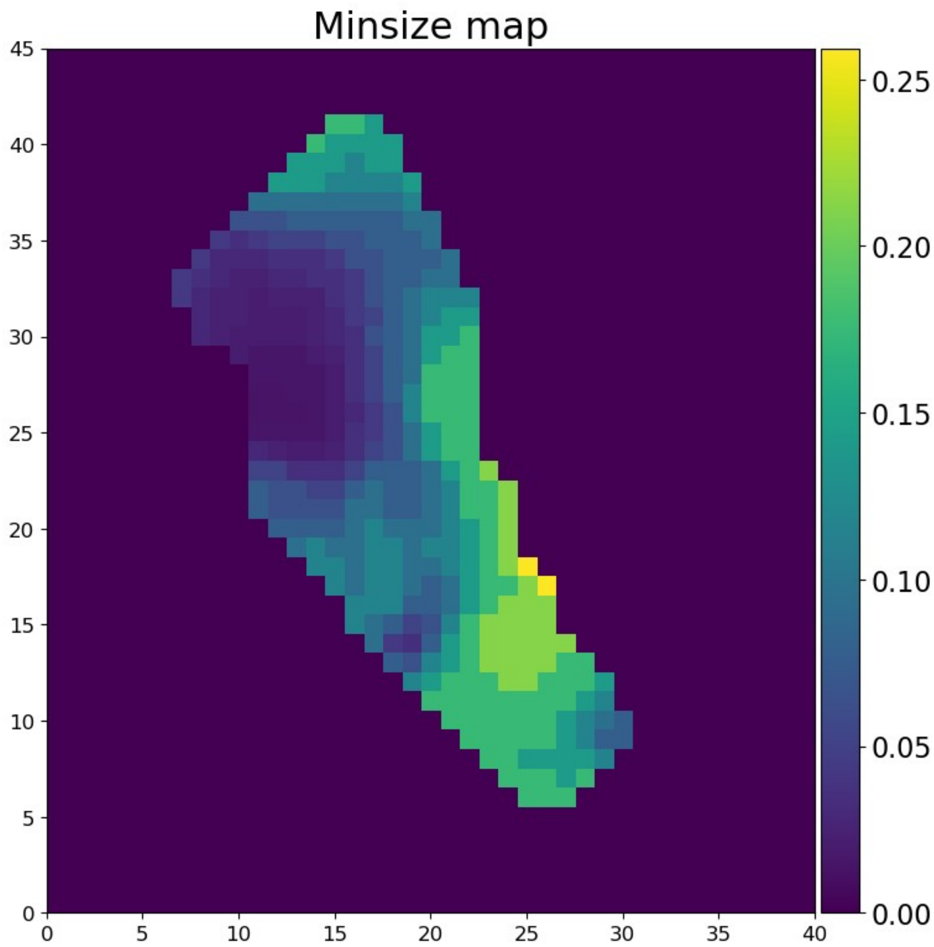
- Absorption (thus emission) at high frequency is dominated by PAHs
- At low frequency, Silicate is also important
- Most absorption at around 0.1 micron
- While the emission is "almost thermal" (see First fitting approach" slide)

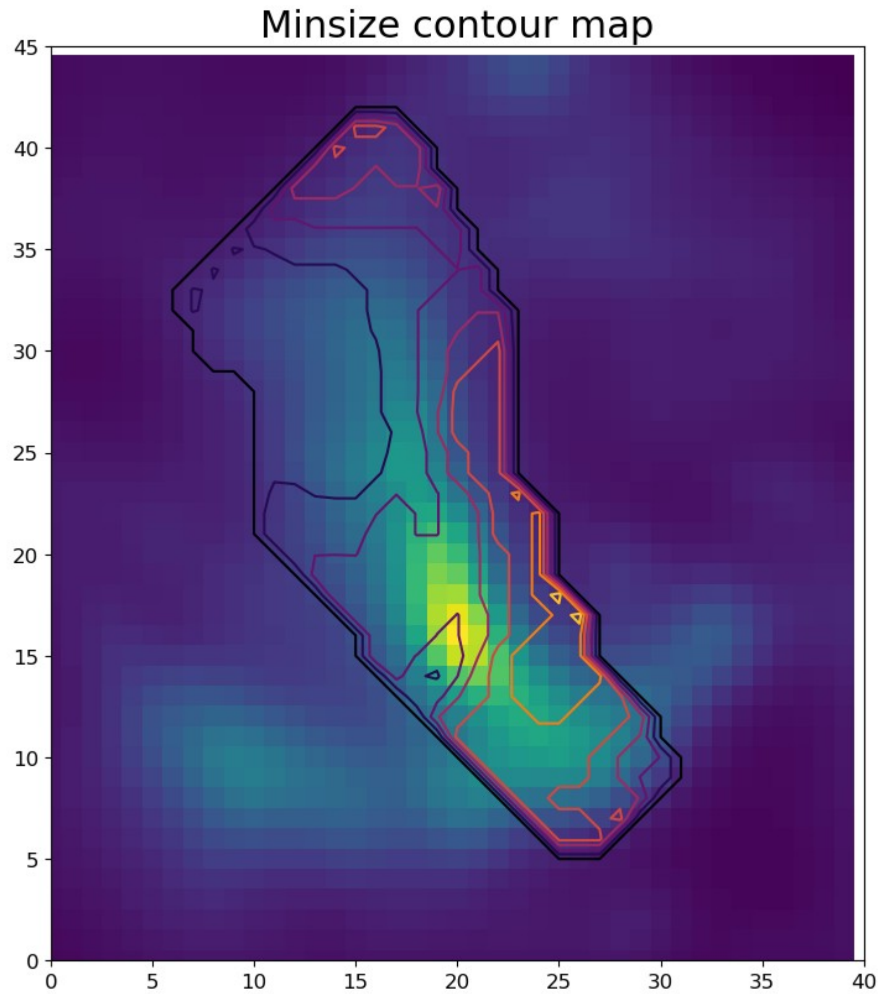


Temperature plots for dust species



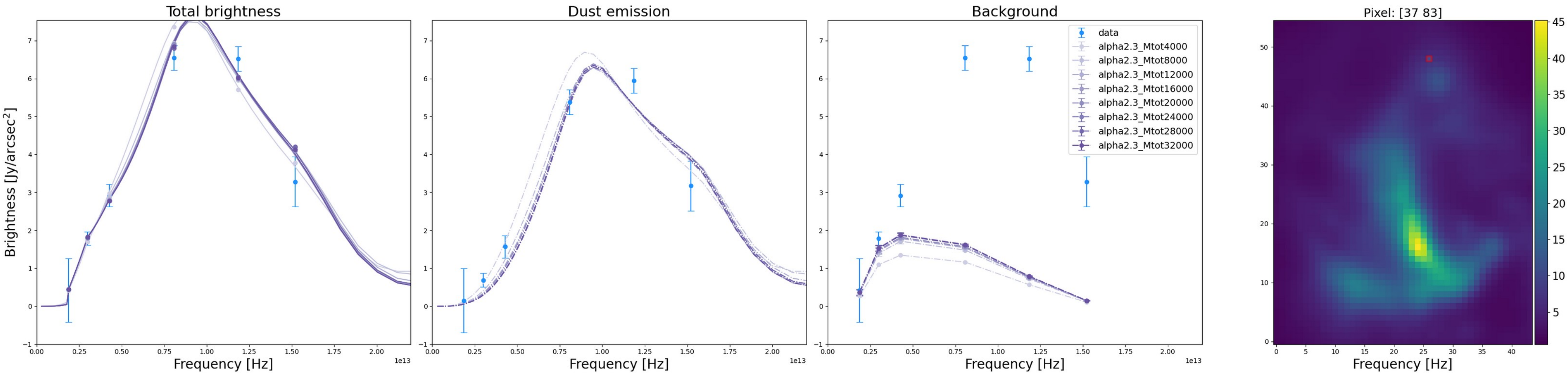
Lowering the temperature: minimum grain size





- By increasing the minimum grain size, we can allow higher UV illuminations to fit the data (since the lower grains are also the hottest)
- Degeneracy of the derived mass!
- But physical limits (radiation pressure) on the smallest grain size – the highest NSC masses are not physically motivated

Lowering the temperature: minimum grain size



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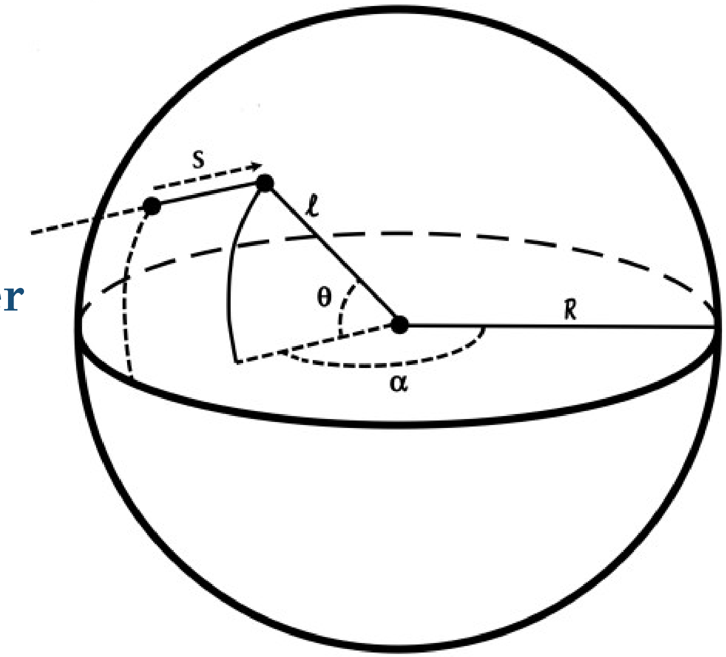
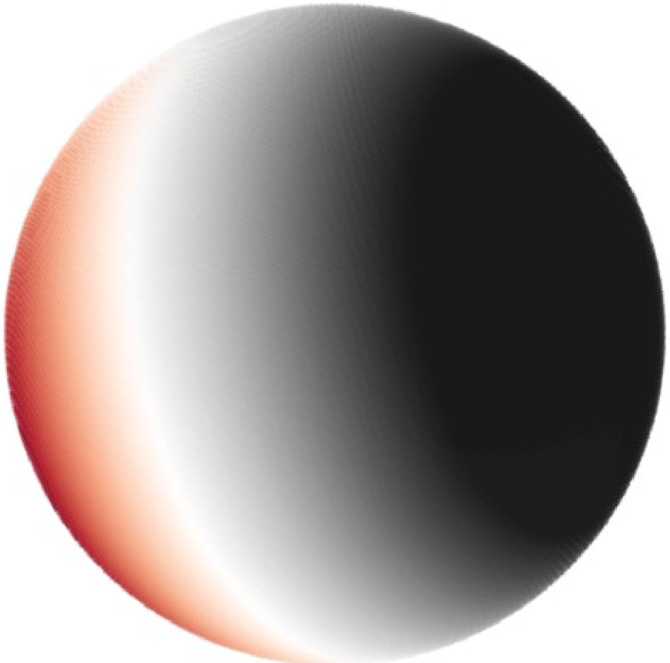
Lowering the temperature: dust opacity

- Dust clumped on smallest scales – UV shielding on the inner part
- No IR shielding



(a) 3d depiction of a clump illuminated by a single source (in the direction of s).



(b) High-transparency temperature simulation of a clump illuminated by a single source.

$$u^{\hat{s}}_{rad,\nu}(\nu,\tilde{s}) = u^{\hat{s},out}_{rad,\nu}(\nu)\exp\left(-\tilde{s}\cdot\frac{d\tau(\nu)}{d\tilde{s}}\right)$$

$$\exp\left(-x\frac{Q_{ext}(\nu)}{Q_{ext}(\nu_{ref})}\right) = \exp\left(-x\frac{\sum_i\int Q^{(i)}_{ext}(a,\nu)n^{(i)}(a)da}{\sum_i\int Q^{(i)}_{ext}(a,\nu_{ref})n^{(i)}(a)da}\right)$$

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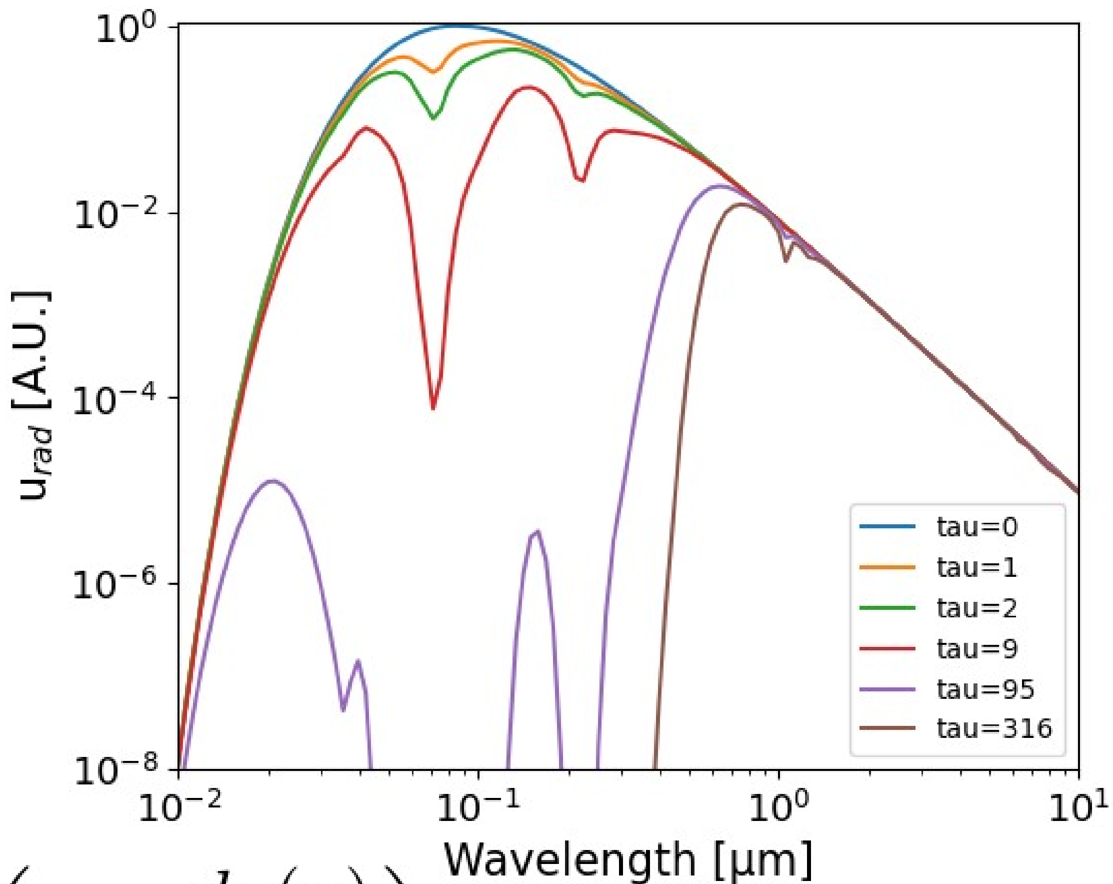

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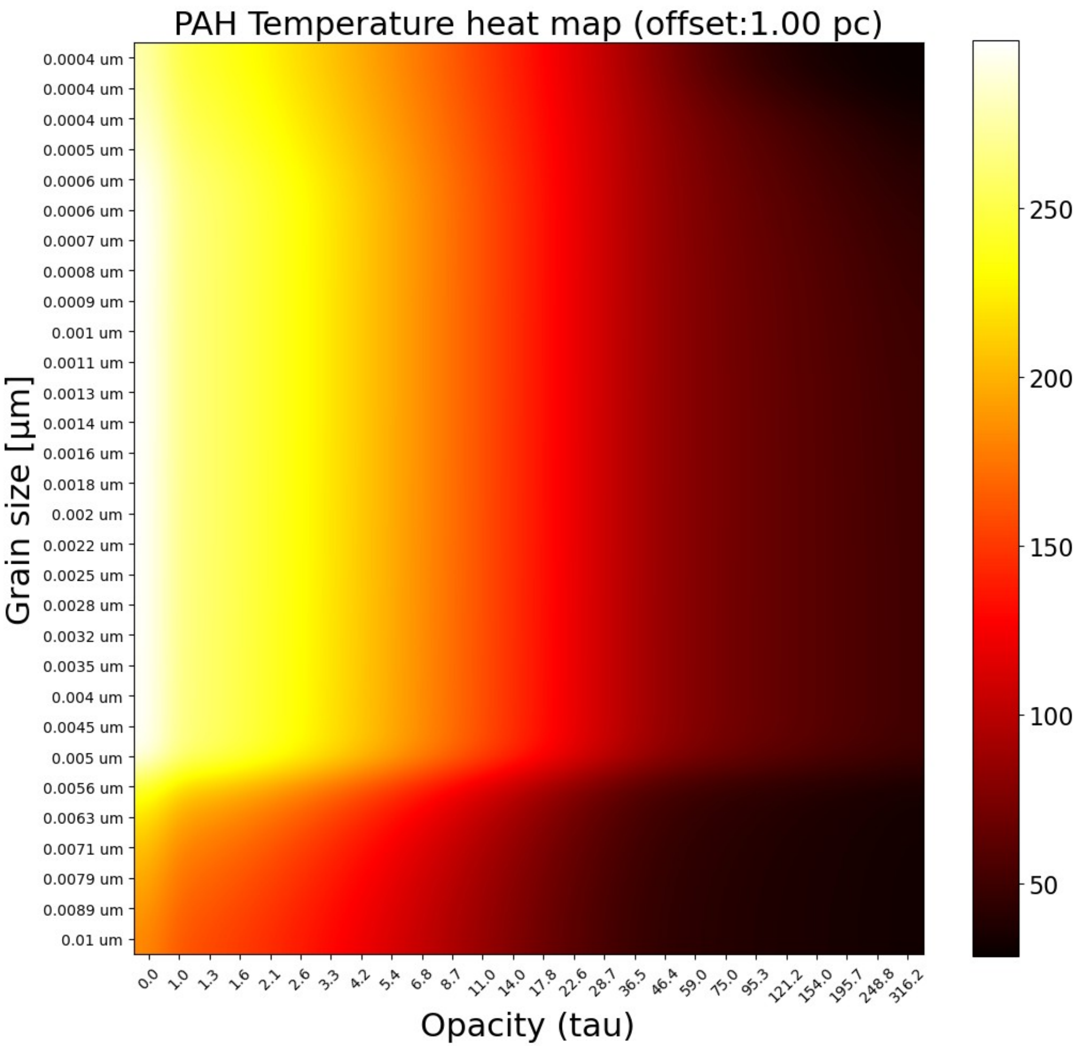
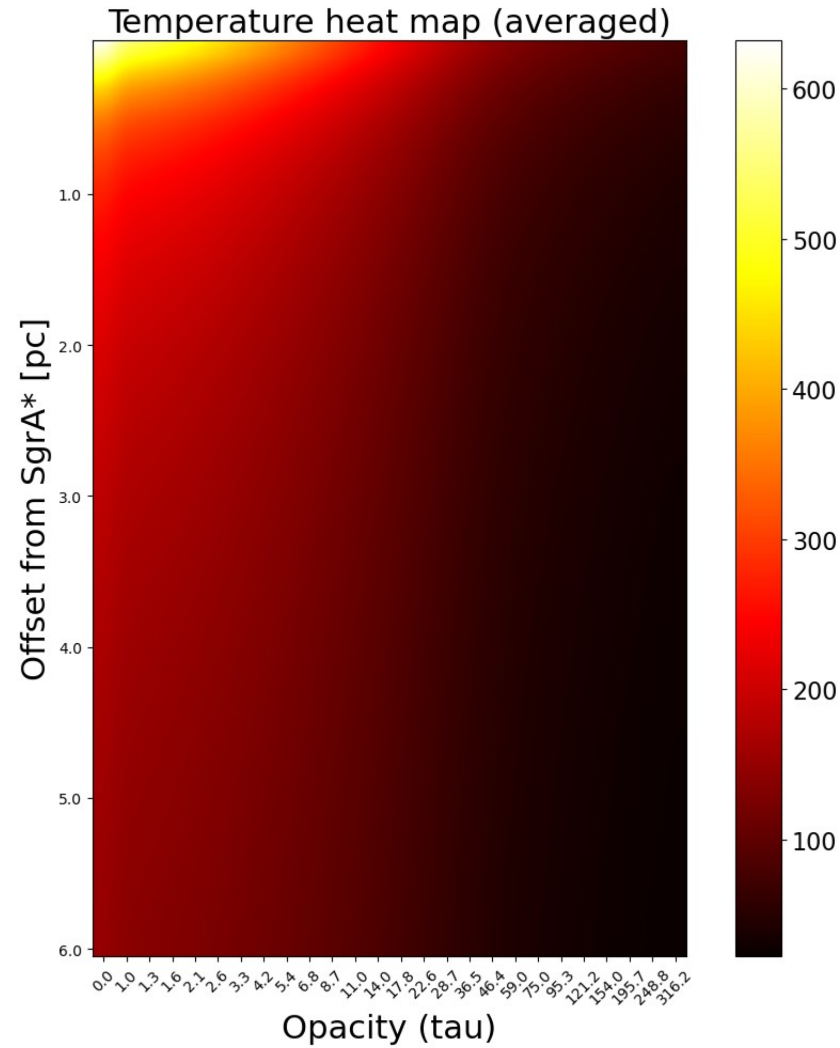
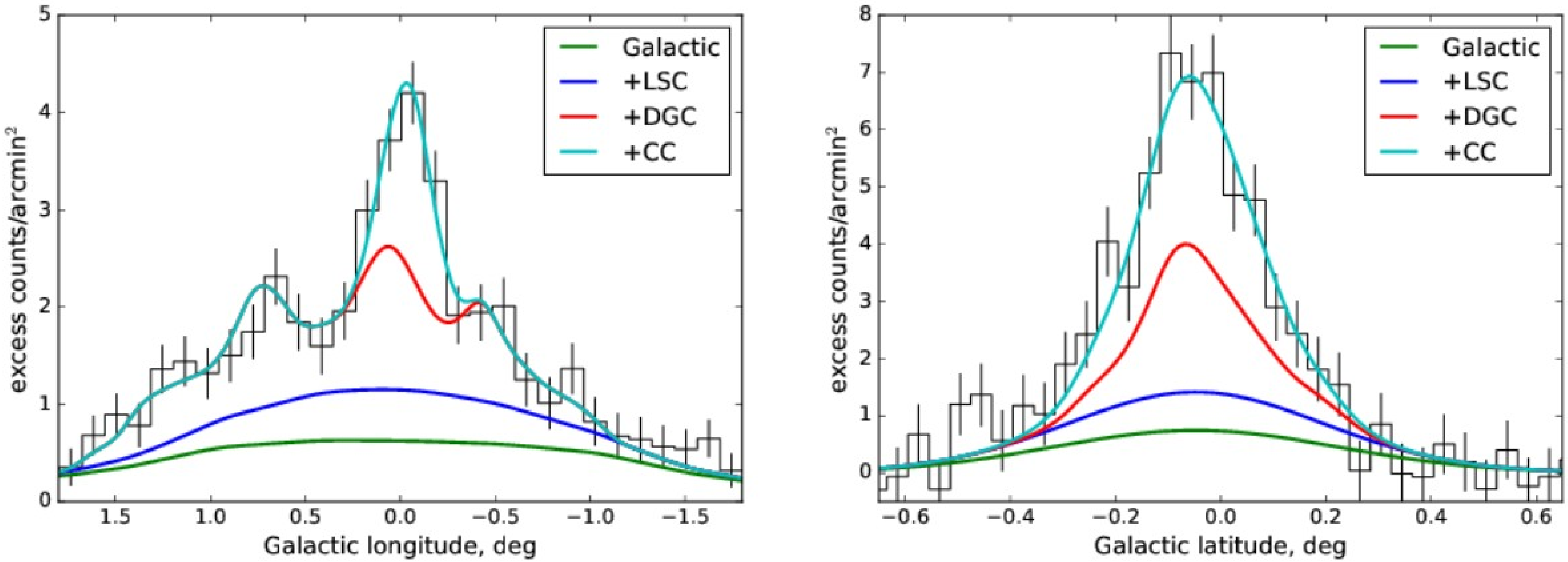
Lowering the temperature: dust opacity





Excess counts in the GC



[H.E.S.S. Collaboration, Characterising the VHE diffuse emission in the central 200 pc of our Galaxy with H.E.S.S., 2017]

- The diffuse emission dominates the excess map (J1745-290 subtracted) over the large scale emission and the Galactic emission