Probing the properties and evolution of dust in Perseus B1-E with combined CFHT/WIRCam near-IR and Herschel far-IR imaging.

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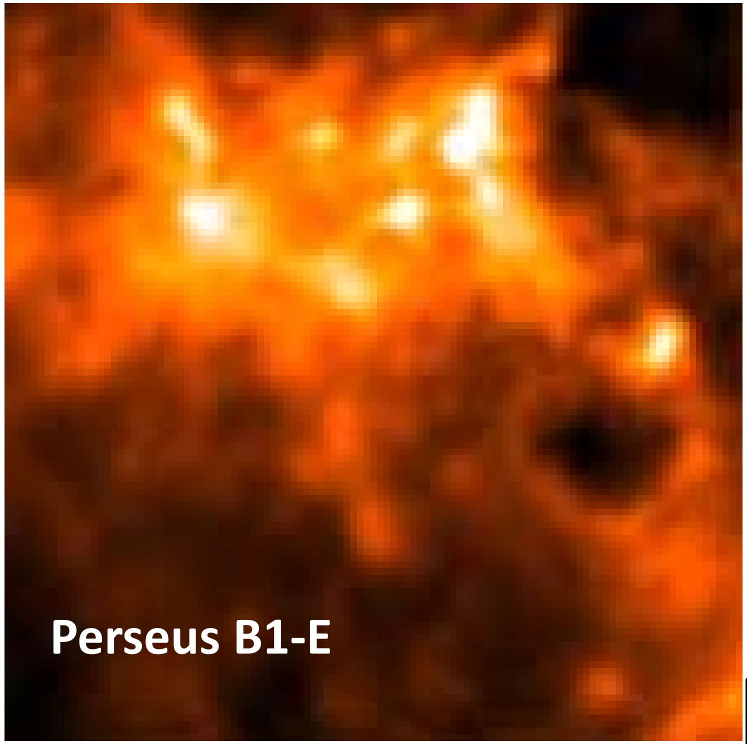
Why dust?

- **Mapping the mass distribution of H_2 in the ISM is key to understanding the physics of star formation**
- **However, H_2 is impossible to observe directly (no emission/absorption lines in any observational window)**
- **So gas mass in *inferred* using a tracer such as dust**
- **Dust-to-gas mass ratio is *constant* across many environments**
- **Therefore dust provides an effective tracer of H_2**
- **However, critical to understand how dust properties affect mass estimates (*focus of our research*)**

Method I: Measure mass (column density) from observations of dust thermal emission maps



Herschel 500μm thermal map
Bright areas = high column density.
[Sadavoy+2012, 2015]

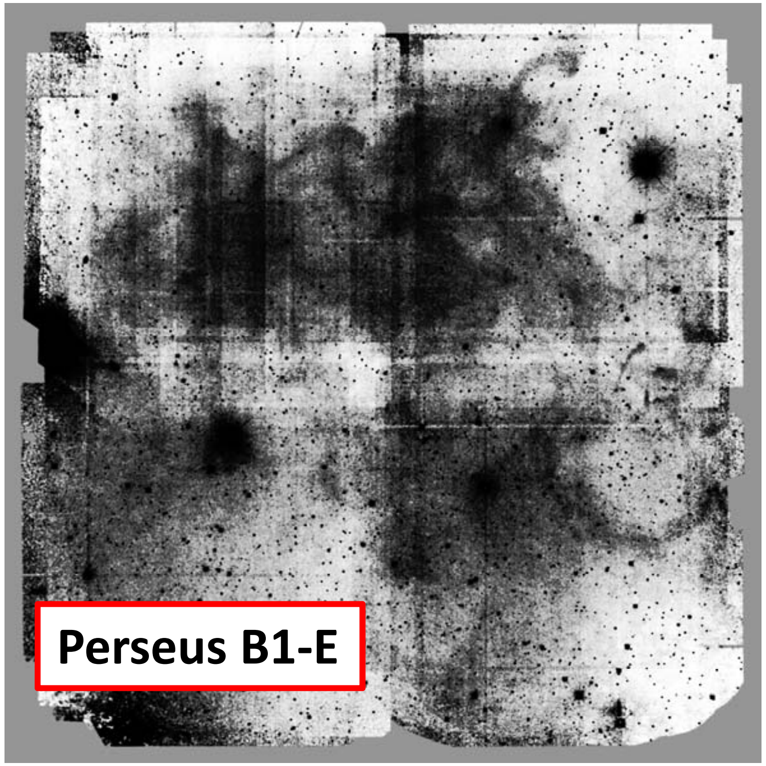
- Dust grains in molecular clouds (at T ~ 10K) emit radiation primarily at FIR/sub-mm wavelengths
- The observed flux is directly proportional to dust temperature, T, and column density, $N(H_2)$

$$I_\nu = \mu m_H B_\nu(T) \kappa_\nu N(H_2)$$

- **Unknown dust opacities, κ_ν can lead to significant uncertainties (factor of a few) in mass estimates.**

Optical depth: $\tau_\nu = \kappa_\nu N(H_2)$

Method 2: Dust extinction maps
NICE / NICER / NICEST *[Lombardi, 2009]*



CFHT WIRCam J-band extinction map.
[PI: D. Johnstone, CFHT DDT 2012]

- Dust absorption causes extinction of background stars (mostly G, K giants)
- Extinction is wavelength dependent (causes ***reddening***)

$$m_\lambda = M_\lambda + \mu + A_\lambda$$

$$A_\lambda \geq 0$$

$$\frac{dA_\lambda}{d\lambda} < 0$$

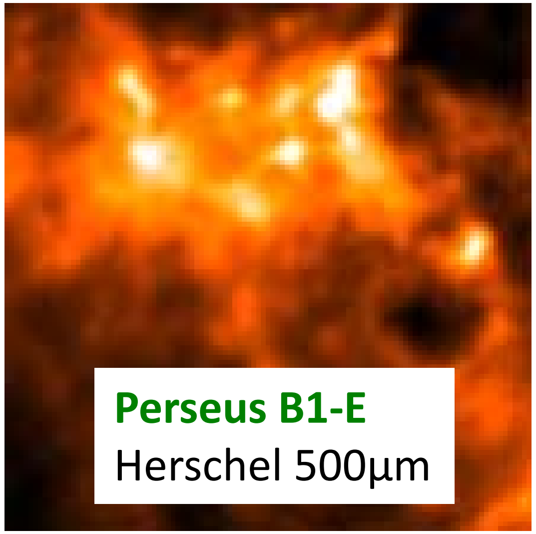
- **Unknown normalization (zero point) of reddening vectors can lead to significant uncertainties (factor of a few) in mass estimates.**

Key questions
Can we do better by combining both methods?

1. How well do dust properties in nIR and fIR correlate?
2. Can we use the number counts of sources for additional constraints on the nIR/fIR opacity ratio?
3. Do dust properties evolve with column density?
4. Is the nIR/fIR opacity ratio a function of environment?

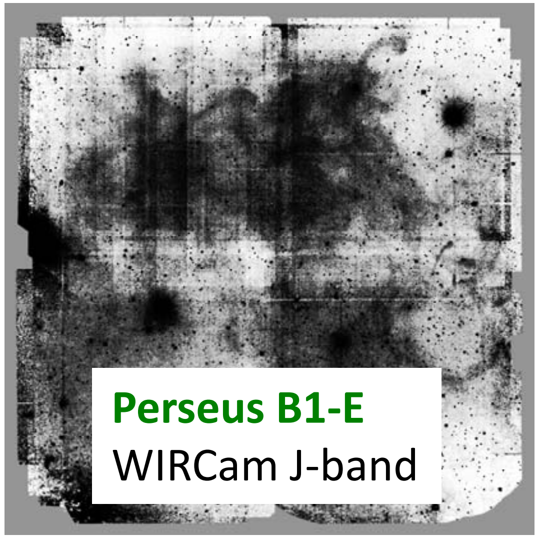
Test case

Herschel 500µm + CFHT/WIRCam JHK$_s$ data



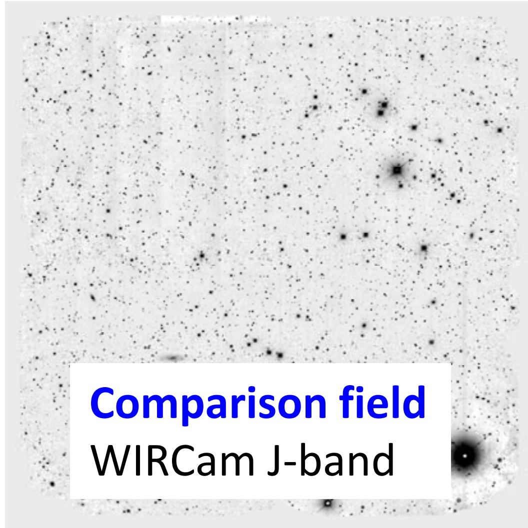
RA: 03:36:11.6
Dec: +31:06:10.0
Gal lat: -19.8
Beam: 36”
Scan rate: 60”/s
Limiting flux:

No embedded proto-stars



FOV 20’x20’
J, H , Ks bands
J: 540s
H: 480s
Ks: 250s

On Field

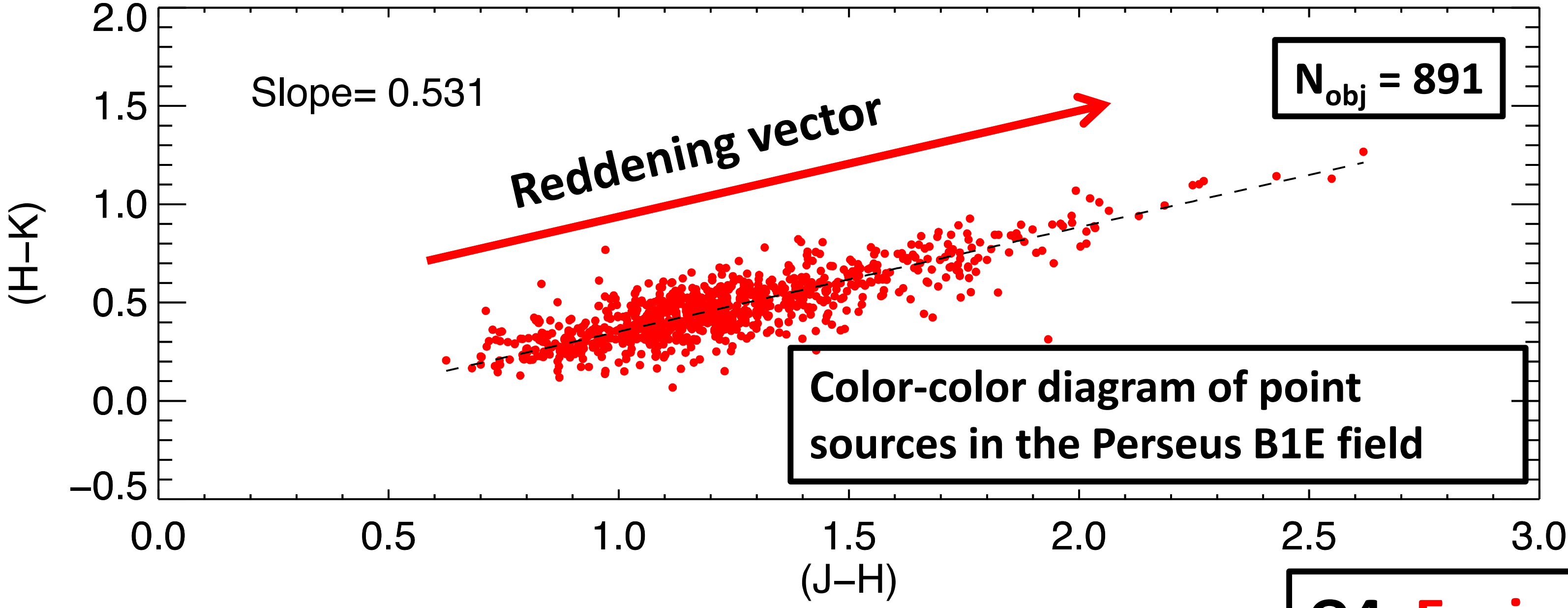


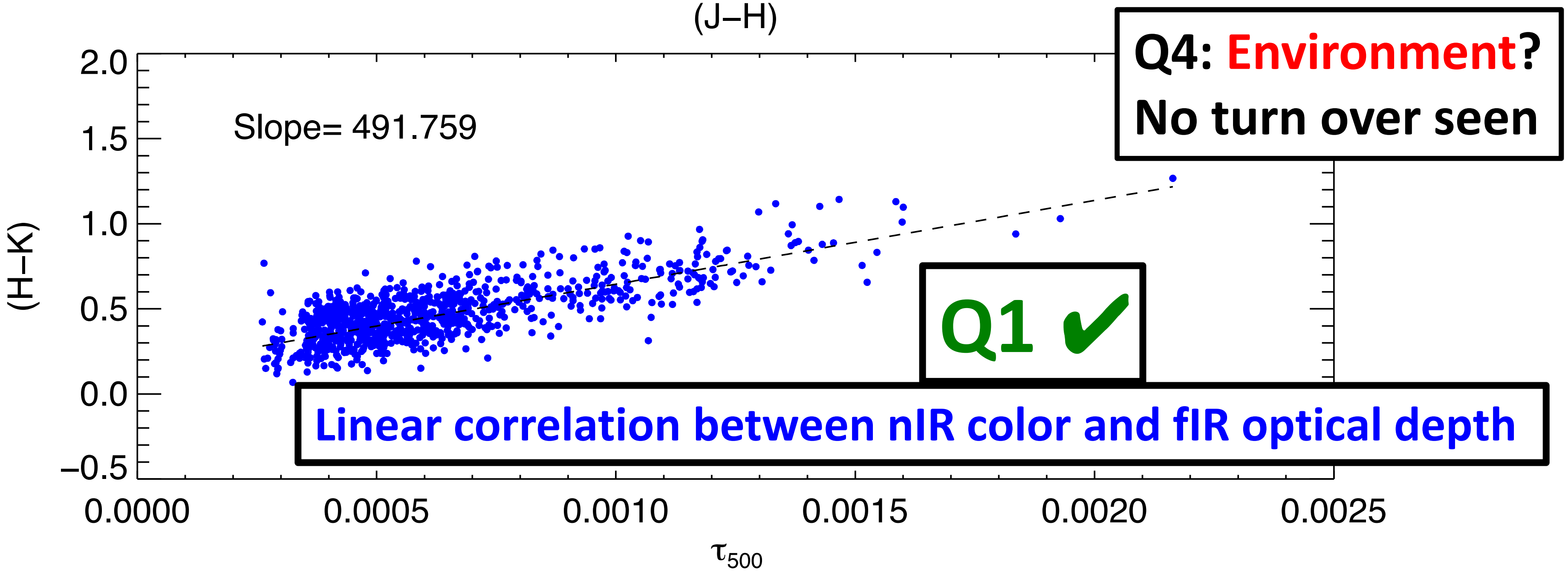
RA: 03:32:13.8
Dec: +34:45:28.8
Gal lat: -14.7
PSF : 0.9”
Ks mag ≤ 18.2

Off Field

Standard CFHT data processing + Terapix stacking
Only point sources with good photometry selected with cuts in half light radius, photometric error, and completeness estimation in all three filters.

‘ON field’ dust properties in the nIR and fIR





Analysis strategy

Two known quantities:

1. Slope of color-color diagram, $(\kappa_H - \kappa_{Ks})/(\kappa_J - \kappa_H) = n$
2. Slope of color-optical depth, $(\kappa_H - \kappa_{Ks})/\kappa_{500} = m$

Four unknown opacities: κ_J κ_H κ_{Ks} κ_{500}

Caveat: We can only determine ratios of opacities, we have no leverage on their absolute values.

Relate (κ_J/κ_{Ks}), (κ_H/κ_{Ks}) to $(\kappa_{Ks}/\kappa_{500})$ with two equations

Treat **$(\kappa_{Ks}/\kappa_{500})$ as a free parameter**

To constrain $(\kappa_{Ks}/\kappa_{500})$ we use **number counts** of background sources

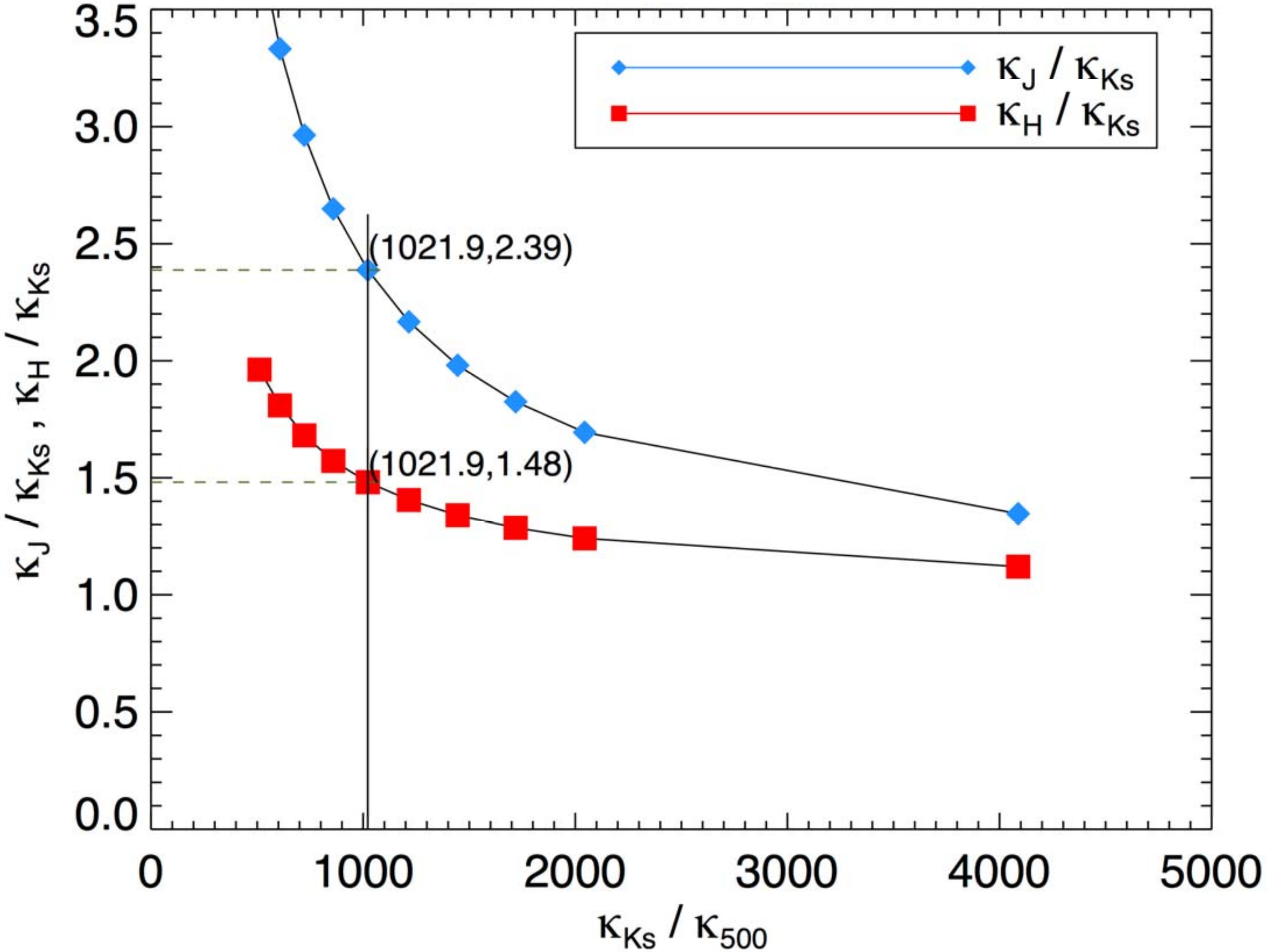
Analysis steps

For each $\kappa_{Ks}/\ \kappa_{500}$ (=opacity ratio) value, generate ***synthetic on-field observation***

1. Randomly distribute off-field objects behind the dust in the Perseus B1-E (= the on-field)
2. For each object, use the Herschel optical depth at that location, to compute the extinction and reddening
3. Apply photometric error and completeness cuts to reddened objects (the same as in the actual WIRCam observations)
4. Compare with actual Perseus B1-E observations using
   i. normalized distributions of colors and magnitudes
   ii. number of objects
5. Repeat this exercise in a Monte-Carlo sense (100 times)
5. Generate χ^2 and K-S statistical measures for comparisons

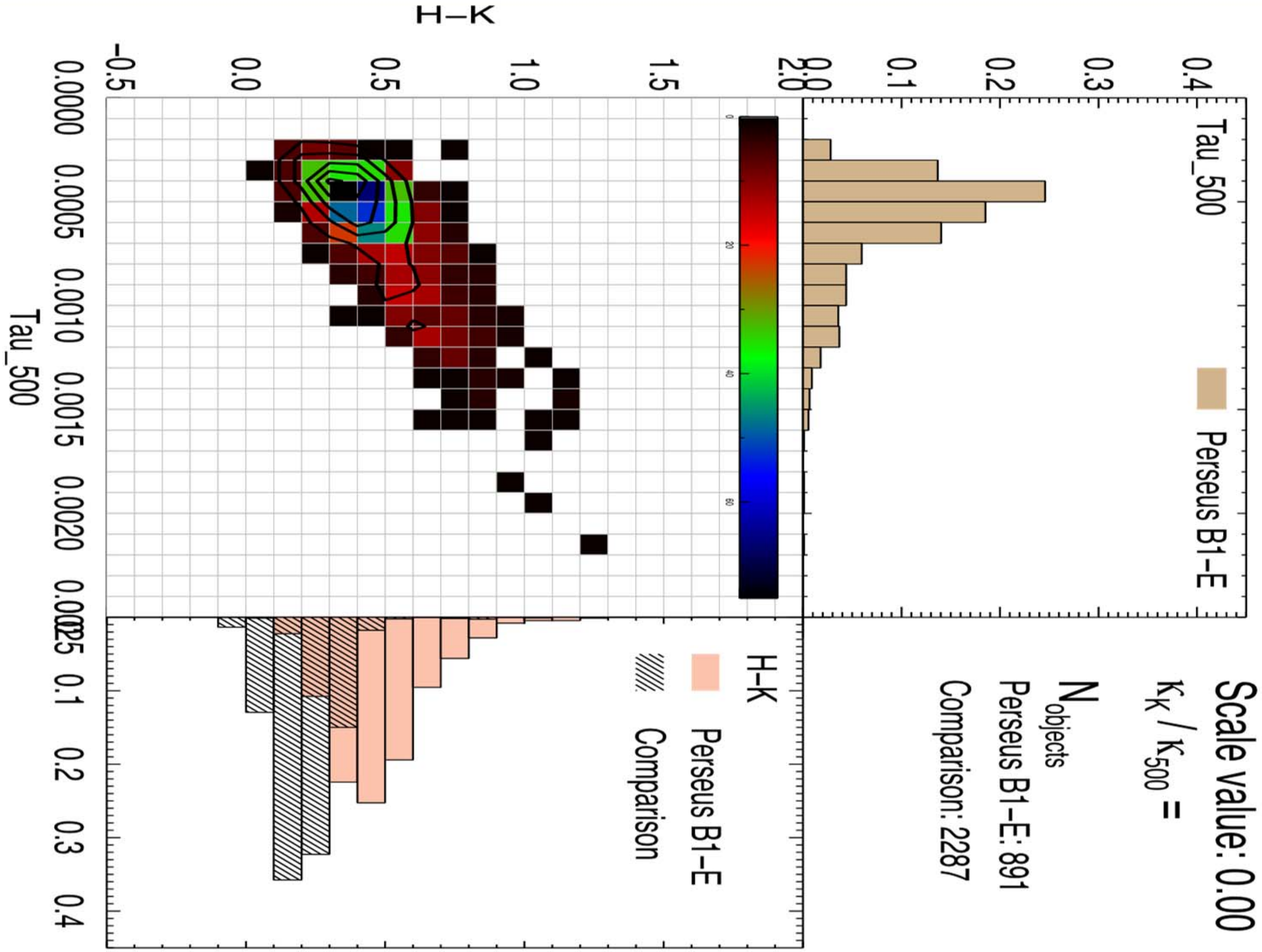
➔ Obtain 'optimal' ($\kappa_{Ks}/\ \kappa_{500}$) value.

Range of opacity ratios (κ_{Ks} / κ_{500}) tested



The fiducial value (κ_{Ks}/ κ_{500}) = 1022 [Indebetouw+2005]
Corresponding ratios of (κ_J /κ_{Ks}), and (κ_H /κ_{Ks}) indicated

Comparison of optical depth and (H-K) color



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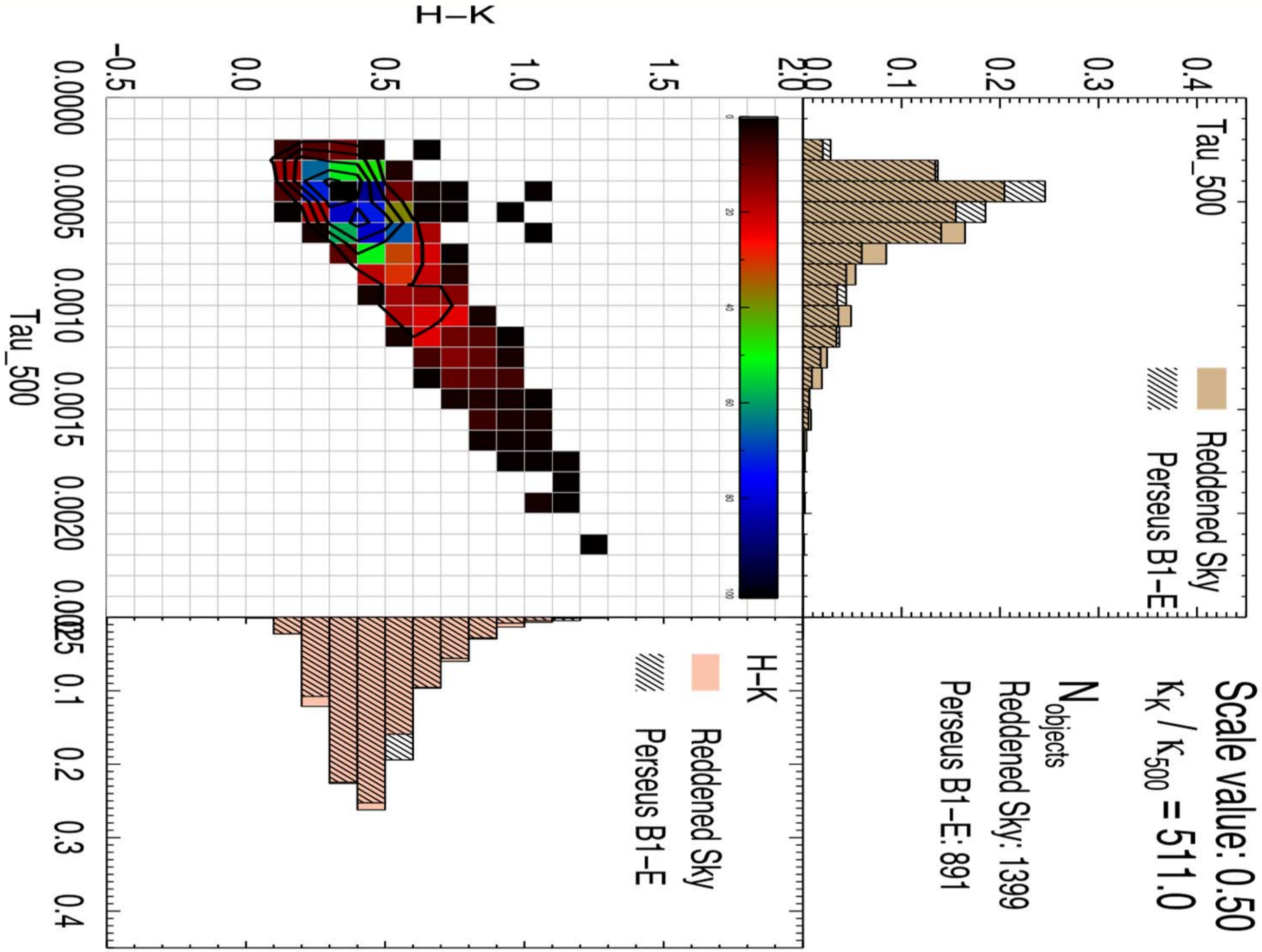

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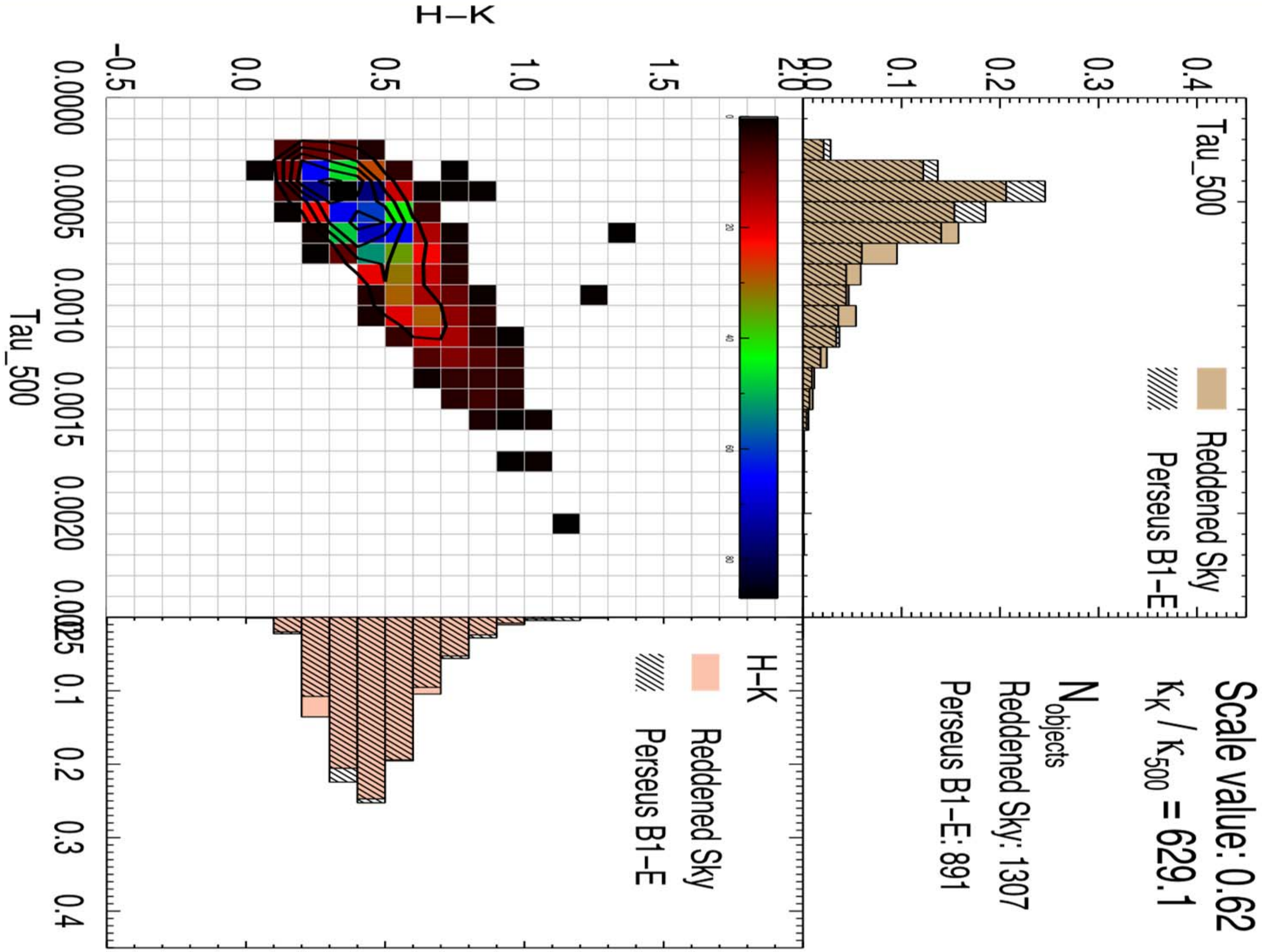

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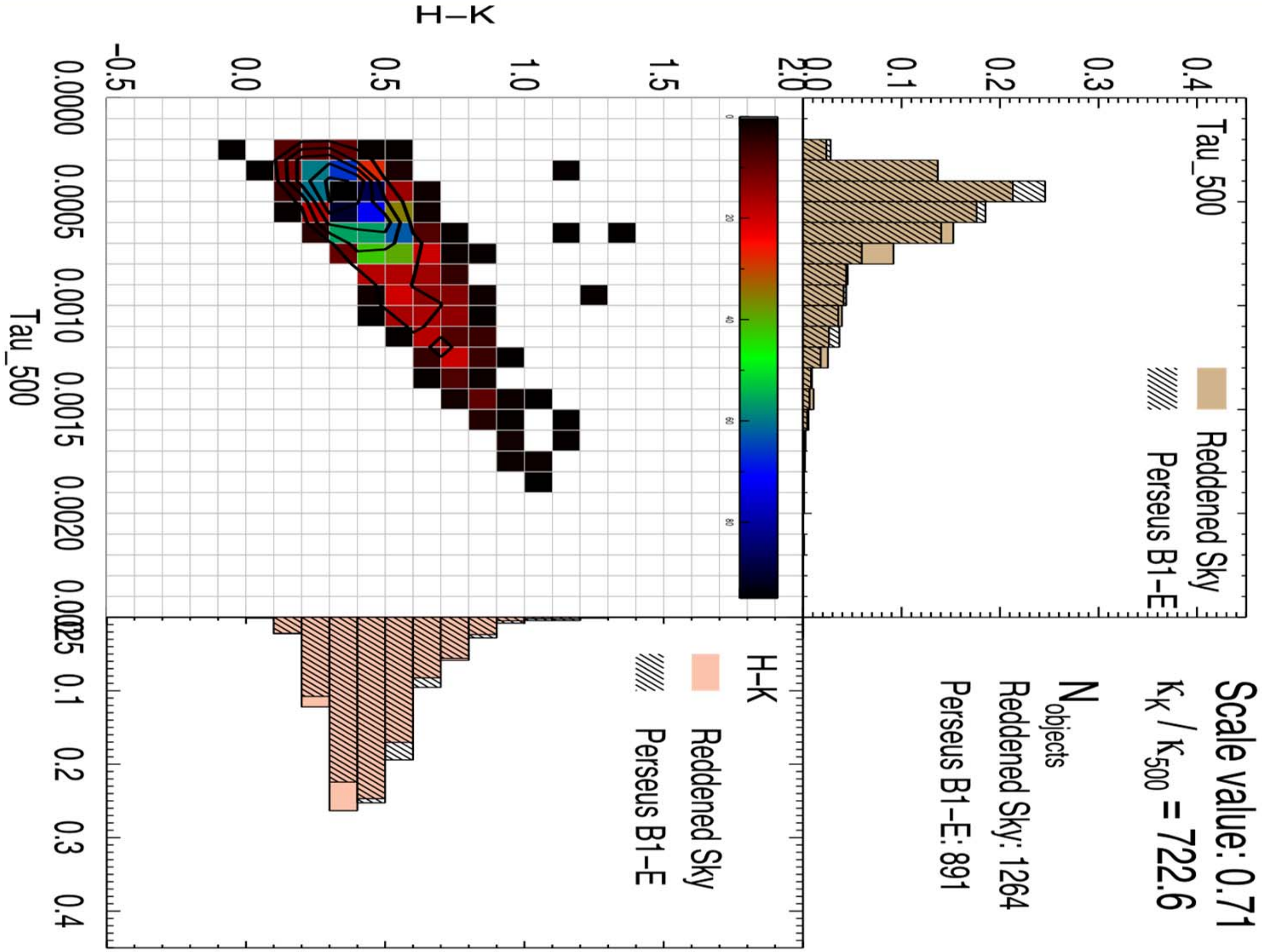

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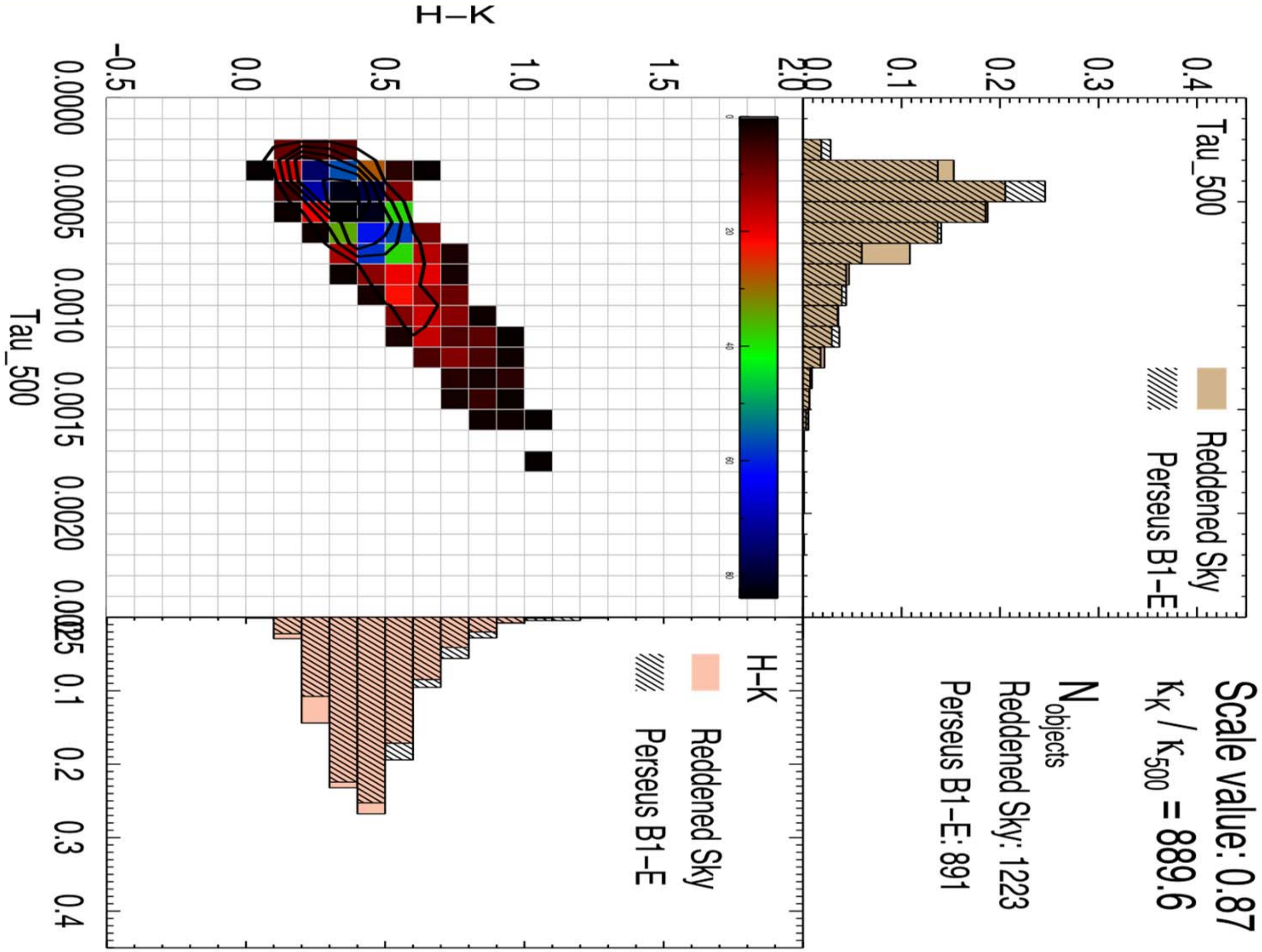

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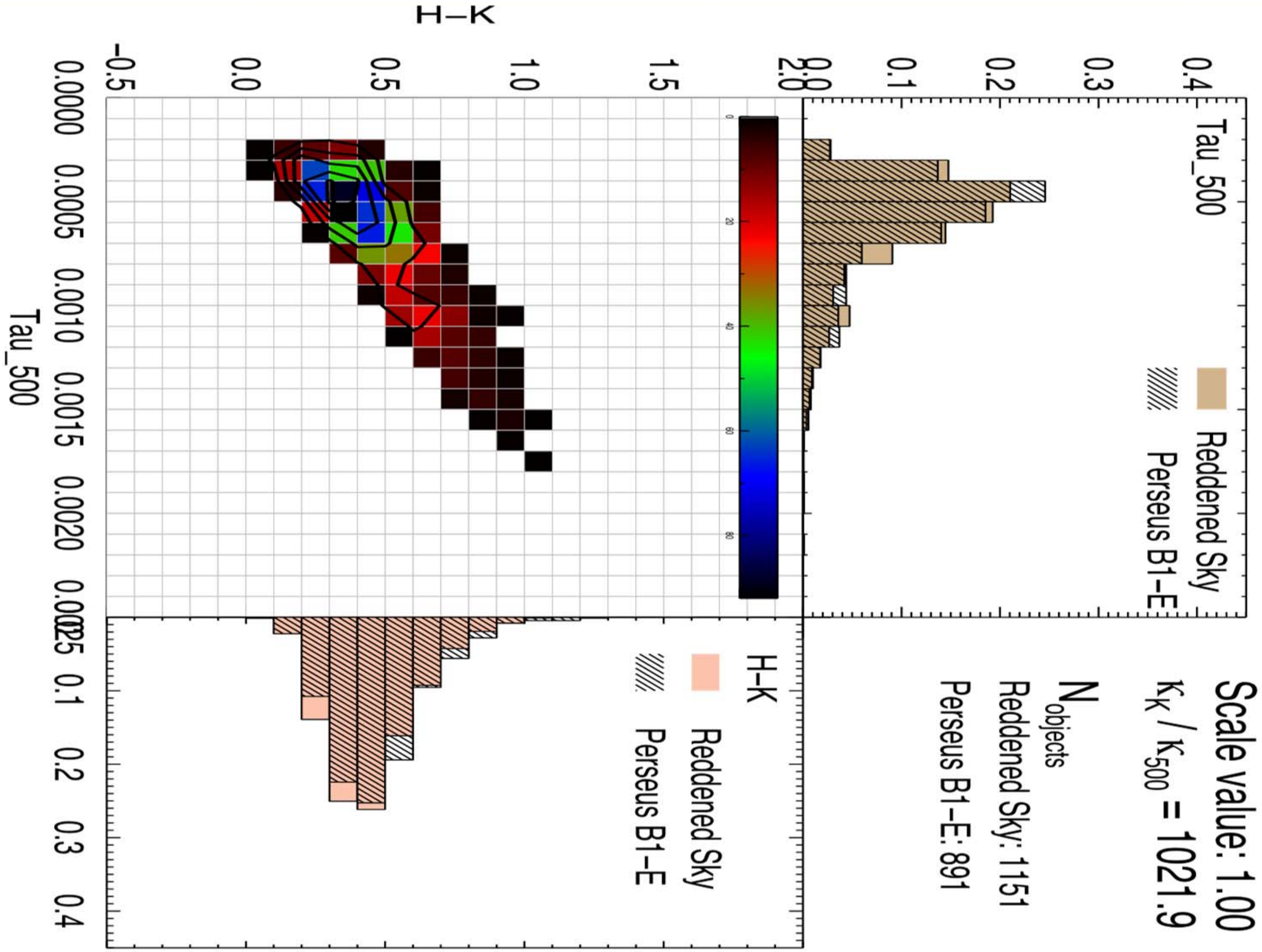

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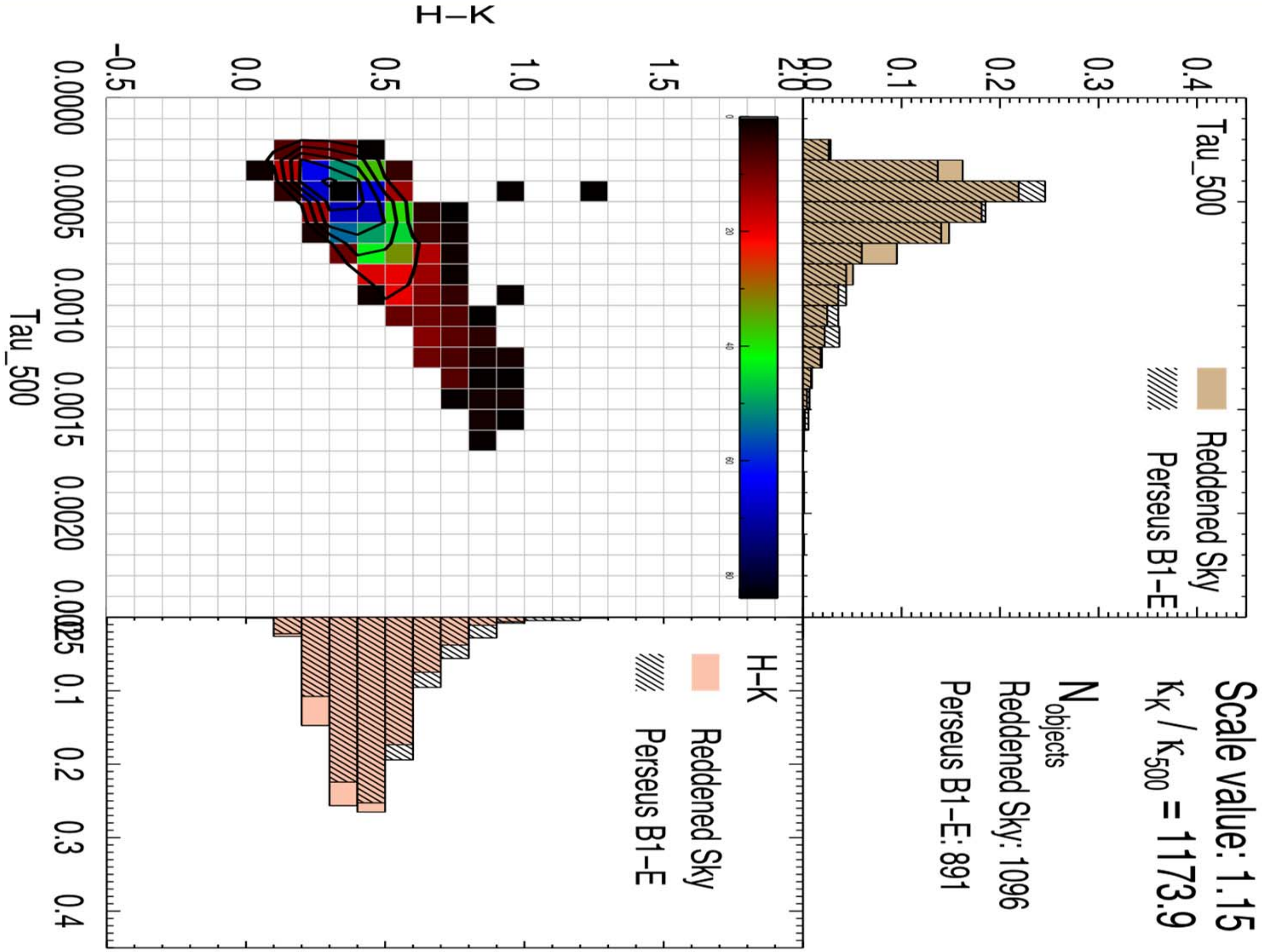

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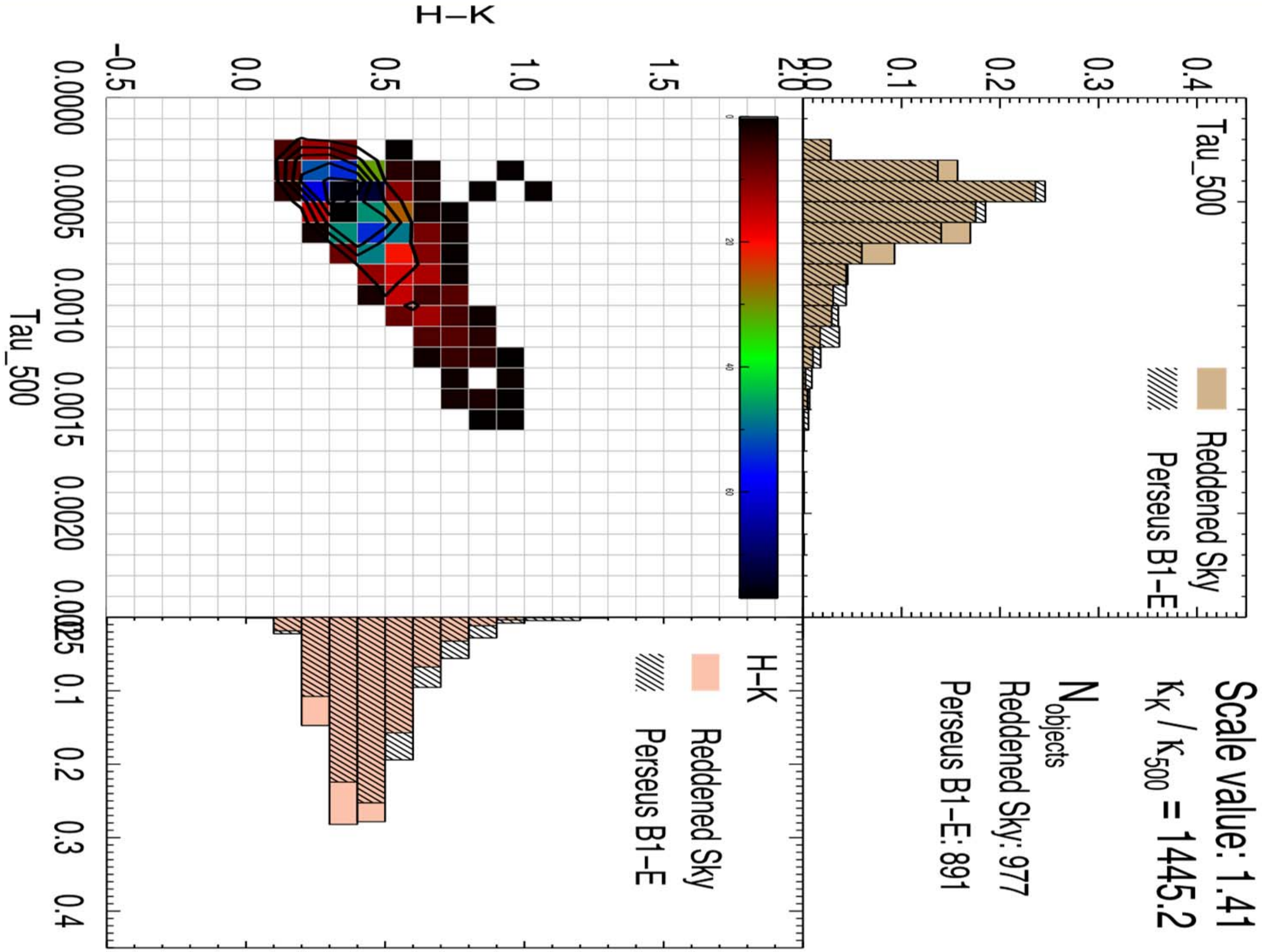

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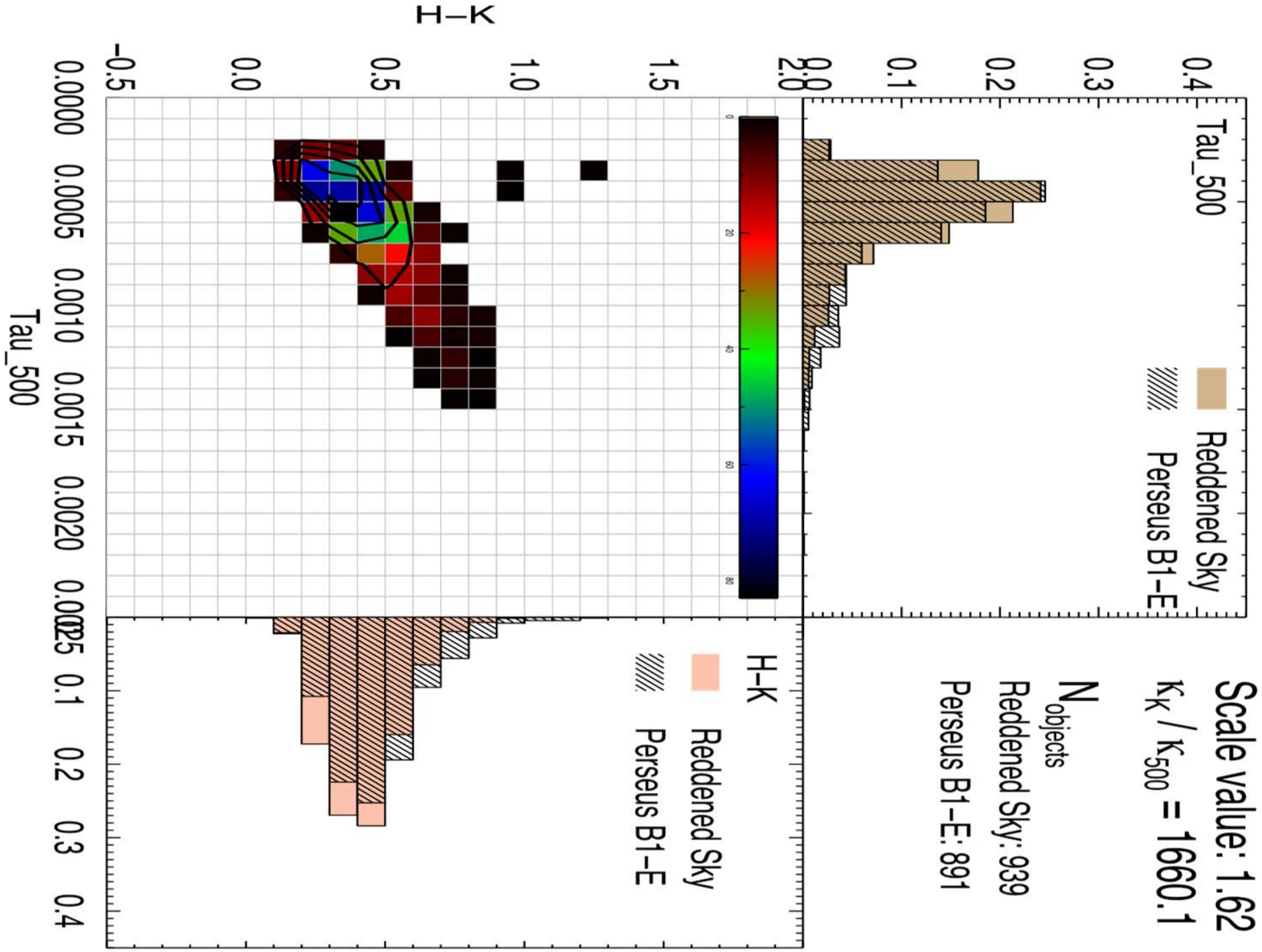

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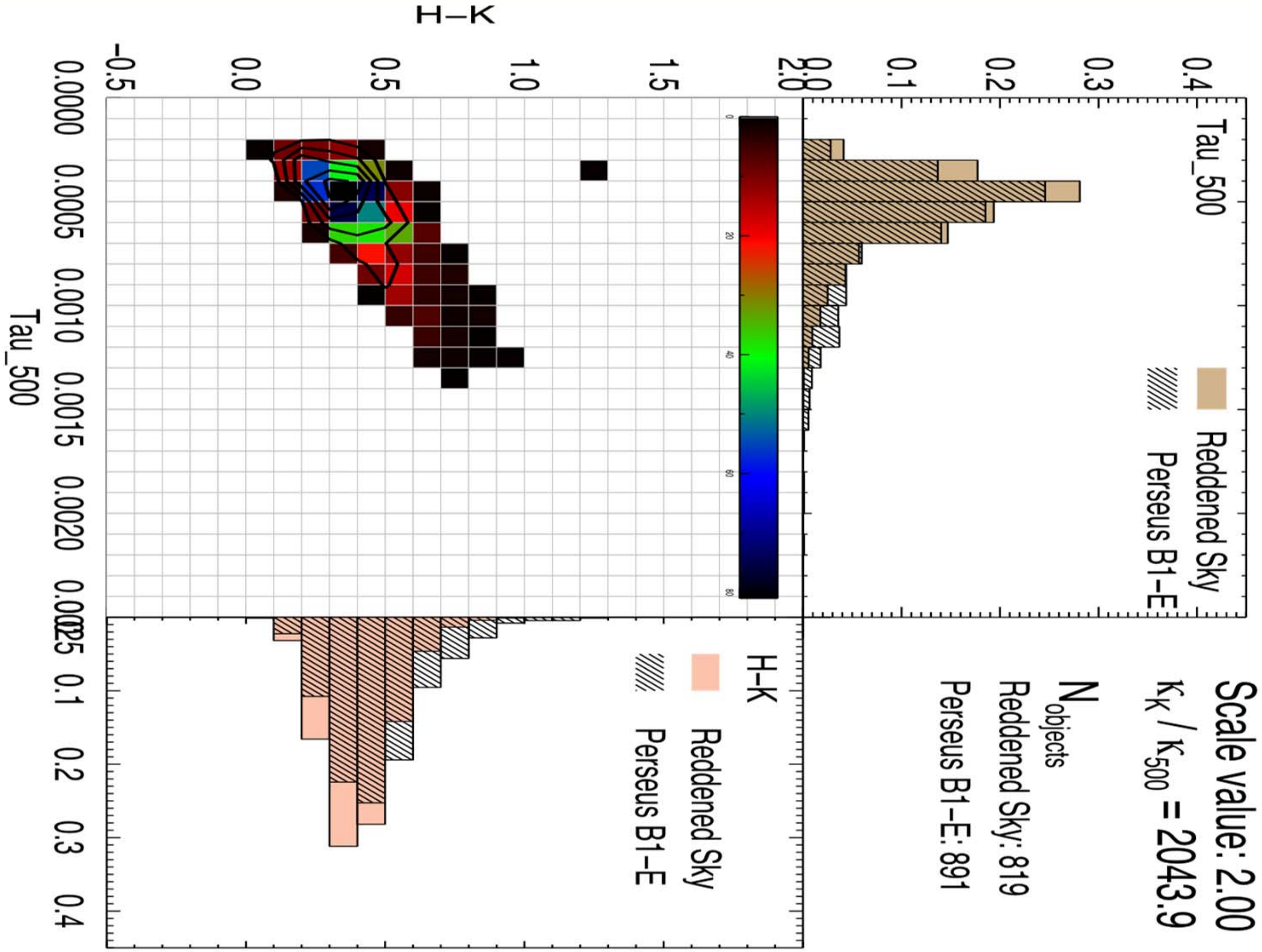
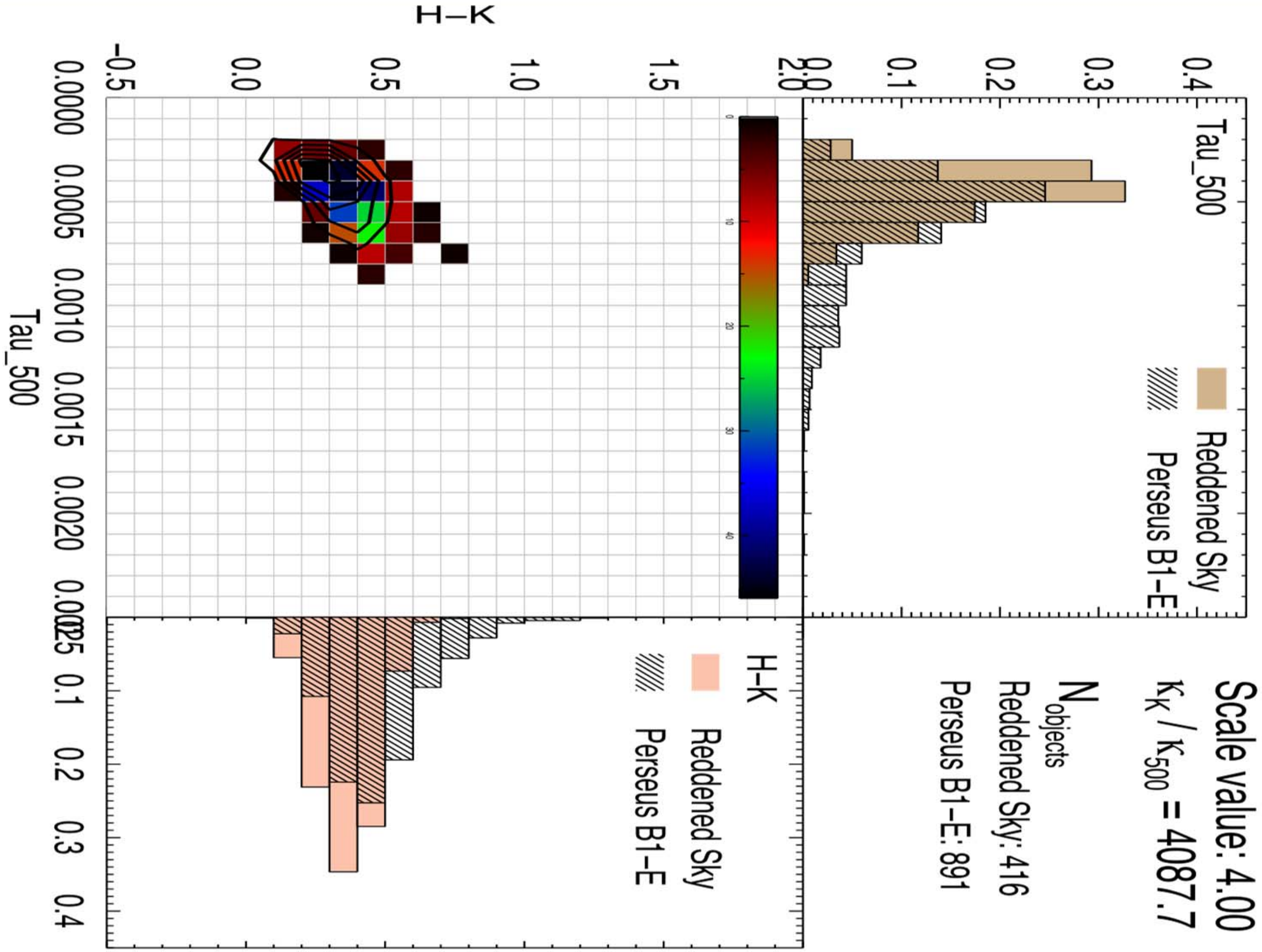
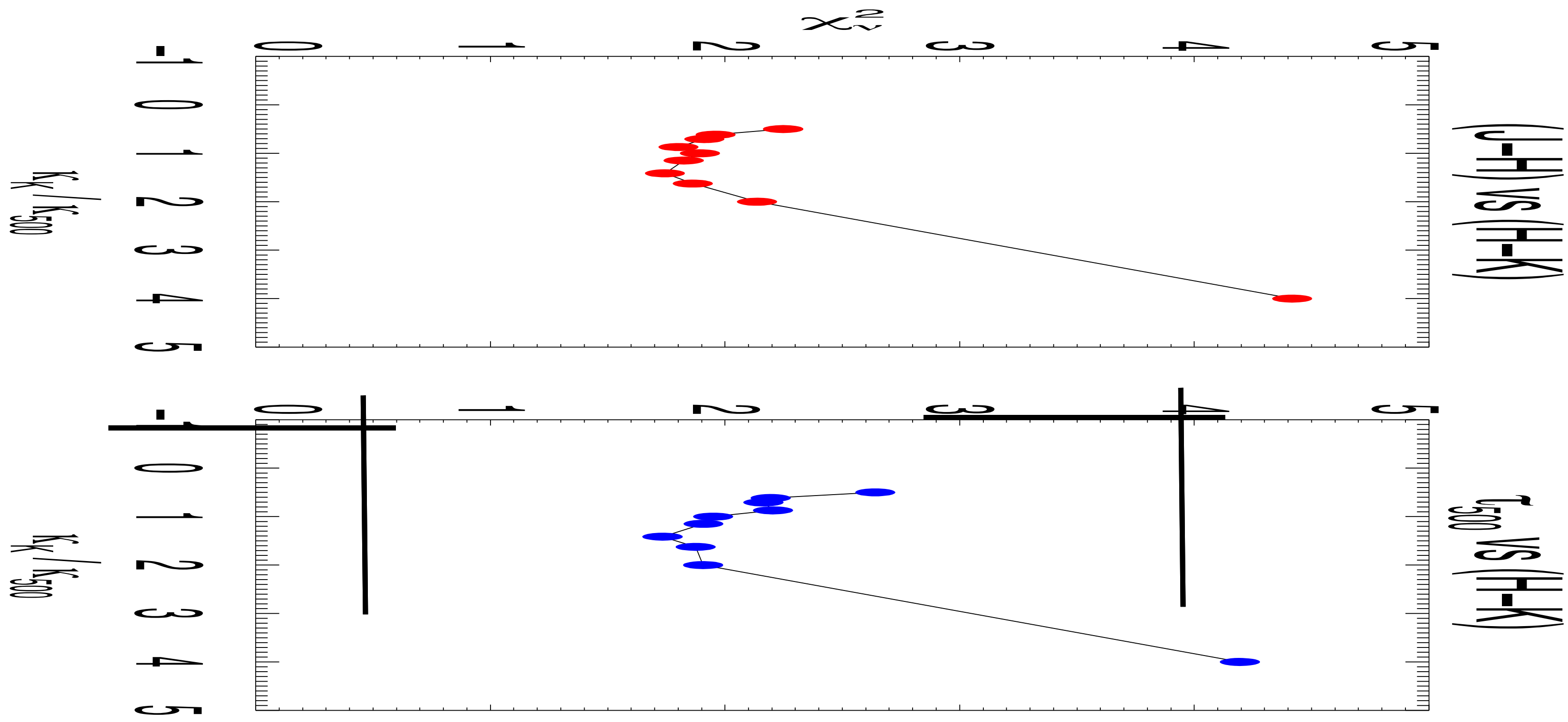


Comparison of optical depth and (H-K) color



Current results



- ✓ Trends observed in the χ^2 and the K-S statistical tests.
- ✓ Reduced χ^2 are consistent with $(\kappa_{Ks}/\ \kappa_{500})$ = 1.4*1022 = 1431
- ✓ No evolution seen in dust properties with increasing column densities (at our observing depth)

Ongoing and future work

- Returned number counts are marginally higher than observed numbers in B1-E.
- Completeness estimates rigorously tested
- Need to account for differences in fIR beam (36”) and nIR PSF (1”)? Include substructure in dust distribution?
- Does the optimal (κ_{Ks}/ κ_{500}) for Perseus B1-E apply universally? To be investigated with data from four other similar star forming regions.
- Acronym for this approach? ***Awesome***!