Overcoming Confusion Noise with PRIMAger

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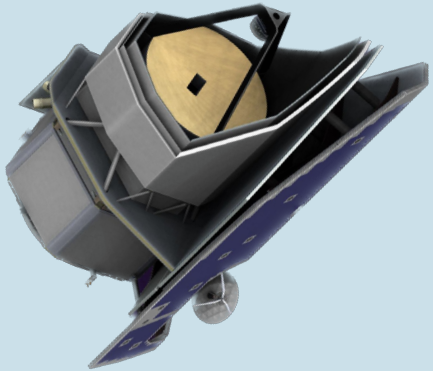
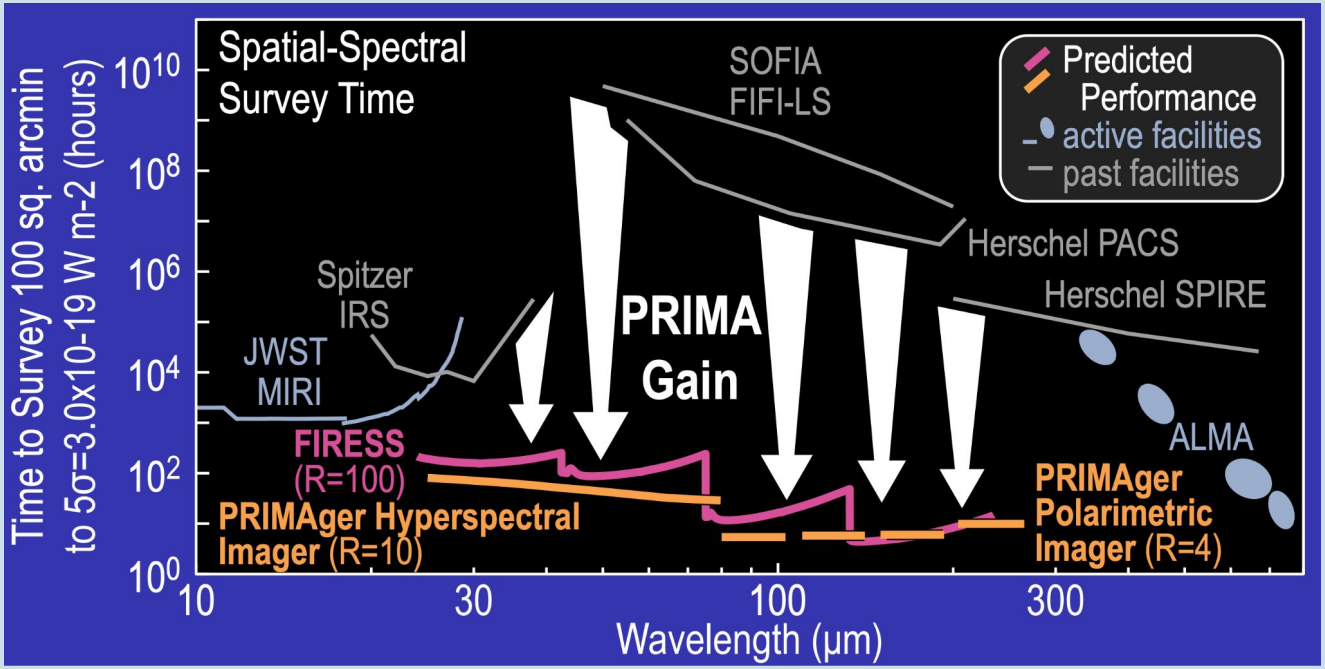
Significantly improved sensitivity and mapping speed compared to previous FIR space-based telescopes!

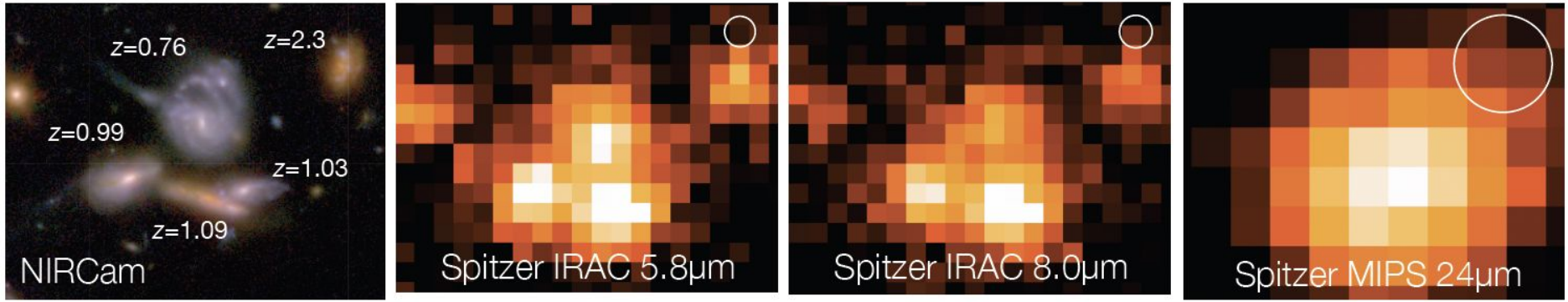




Just one problem...

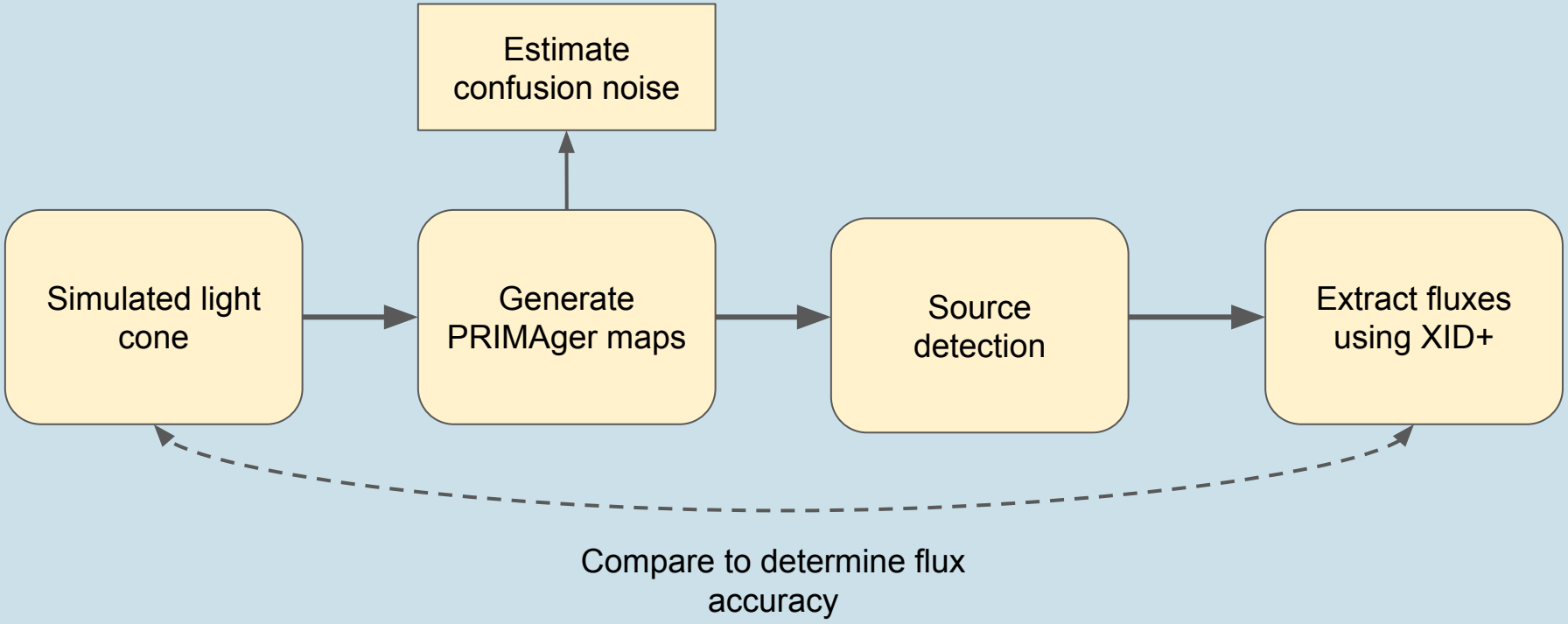
- For the same mirror diameter, longer wavelengths suffer worse angular resolution
- Leads to a larger beam profile for longer wavelengths, increasing the **confusion noise**
  - Due to several faint sources being located within a single beam leading to background fluctuations
  - Only the brightest objects emerge above these fluctuations from unresolved faint sources
- At FIR and sub-mm wavelengths, **the confusion noise is often greater than the instrumental noise**

Just one problem...



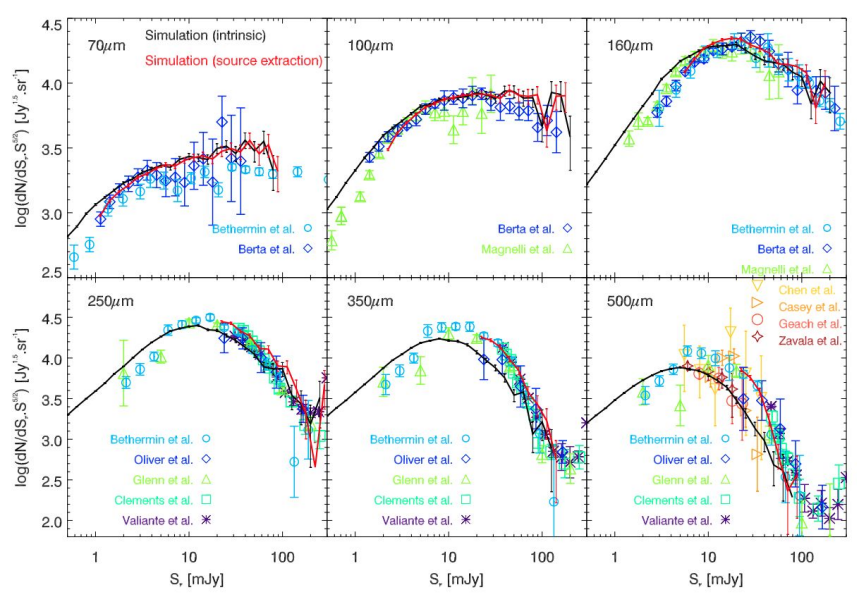
Shivaei+2024

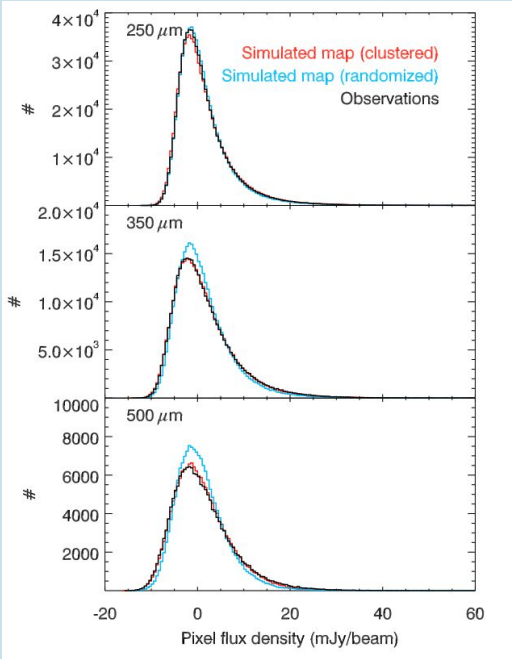
Workflow


Estimate confusion noise
Simulated light cone
Generate PRIMAger maps
Source detection
Extract fluxes using XID+
Compare to determine flux accuracy

Simulated lightcone

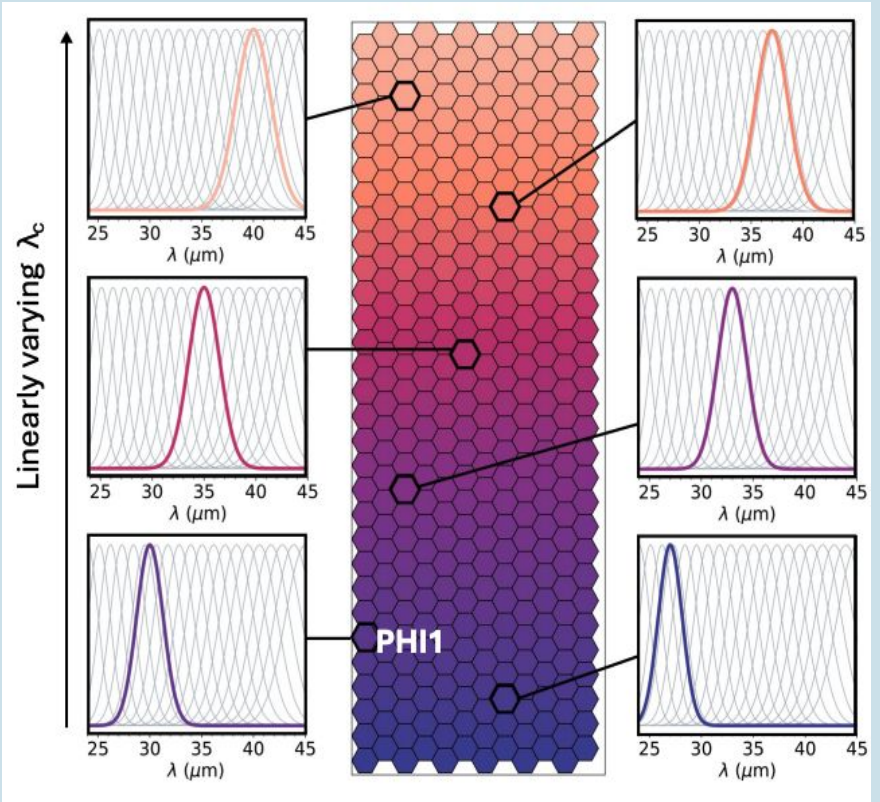
- Béthermin+2024 used the SIDES simulation (Béthermin+2017) to generate synthetic PRIMAger maps





Simulated PRIMAger maps

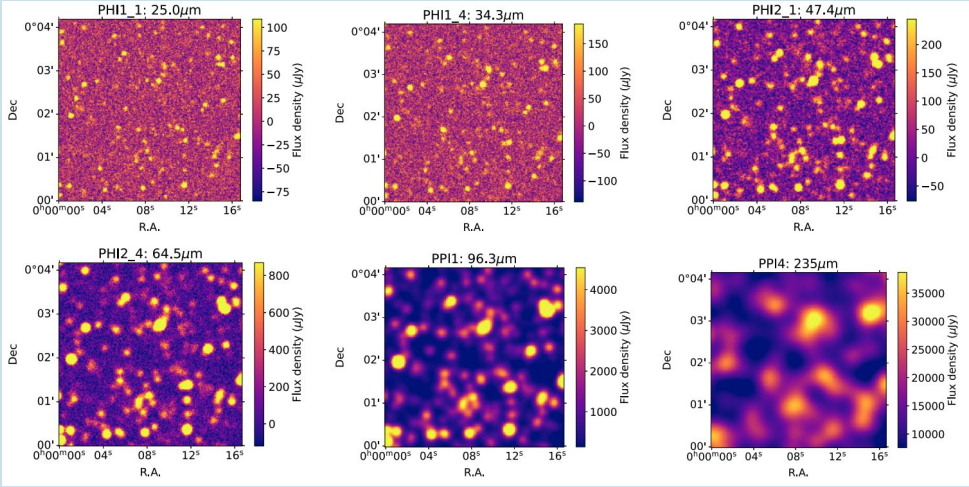
- SIDES generates SEDs for 5.4M galaxies within 2 deg^2 lightcone spanning 0 < z < 10
- Integrate those over the representative PRIMAger channels:
  - 6 continuous channels spanning the wavelength range of each of the hyperspectral bands (PHI1_1-6 and PHI2_1-6) with R ~ 10
  - 4 channels representing each of the polarimetry filters (PPI1-4) with R~4

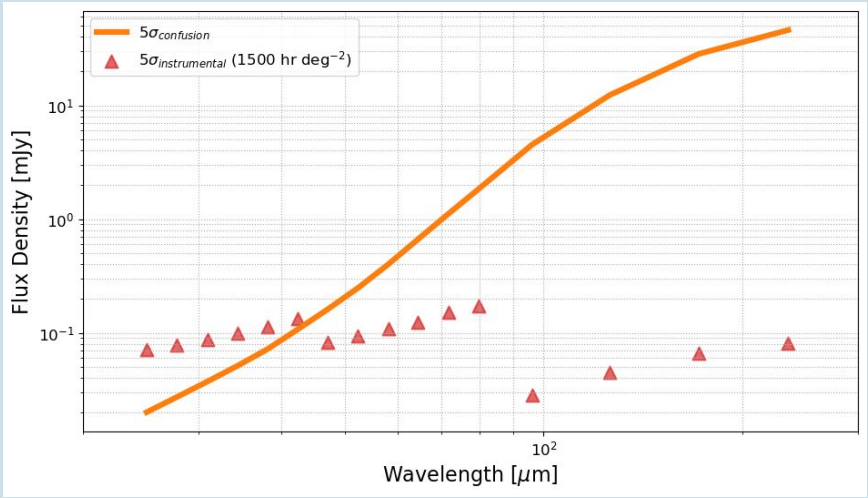


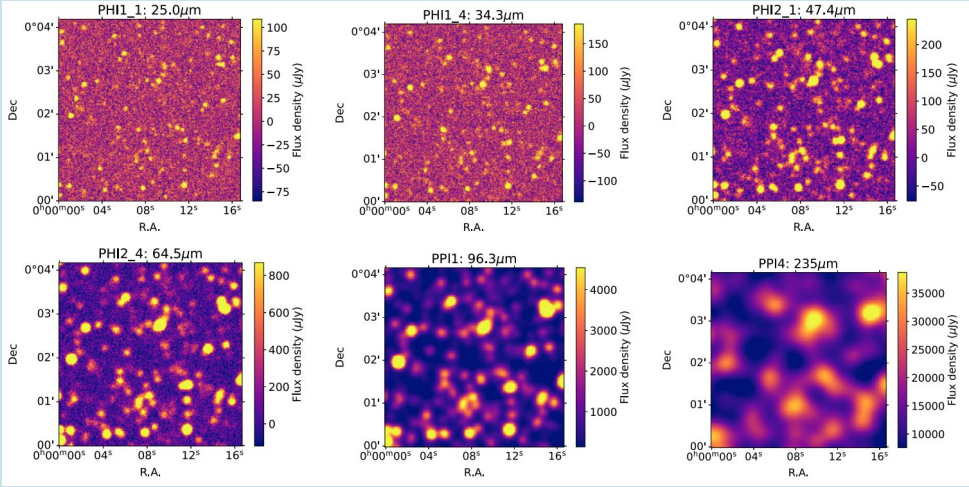
Simulated PRIMAger maps

- Maps are generated from SIDES lightcone catalogue assuming Gaussian beams
  - Inherently contain confusion noise which is estimated using a 5σ-clipping process
- Simulated instrumental noise is then added to the maps
  - Gaussian noise is added to each pixel based on point source sensitivities for an assumed deep 1500 hr deg^{-2} survey

Channel	Central wavelength [μm]	Estimated beam FWHM [″]	Sensitivity ($5\sigma_{inst}$) [μJy]	Classical confusion ($5\sigma_{conf}$) [μJy]
PHI1_1	25.0	4.1	70	20
PHI1_2	27.8	4.3	79	27
PHI1_3	30.9	4.6	88	37
PHI1_4	34.3	4.9	99	51
PHI1_5	38.1	5.2	114	71
PHI1_6	42.6	5.7	134	107
PHI2_1	47.4	6.2	83	161
PHI2_2	52.3	6.7	94	249
PHI2_3	58.1	7.3	108	401
PHI2_4	64.5	8.0	123	667
PHI2_5	71.7	8.8	153	1120
PHI2_6	79.7	9.7	172	1850
PPI1	96.3	11.6	29	4520
PPI2	126	15.0	45	12300
PPI3	172	20.3	67	28 400
PPI4	235	27.6	82	46 000


PHI1_1: 25.0μm
PHI1_4: 34.3μm
PHI2_1: 47.4μm
PHI2_4: 64.5μm
PPI1: 96.3μm
PPI4: 235μm
Dec
R.A.
Flux density (μJy)


$5\sigma_{confusion}$
$5\sigma_{instrumental}$ (1500 hr deg^{-2})
Flux Density [mJy]
Wavelength [μm]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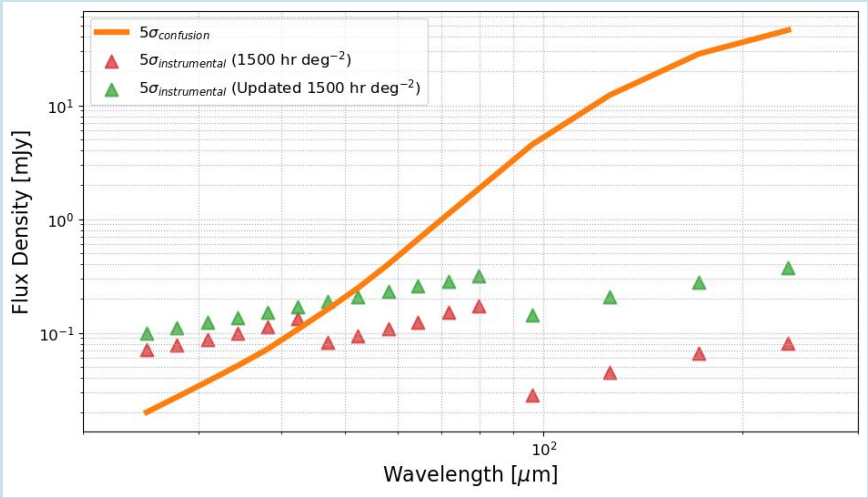
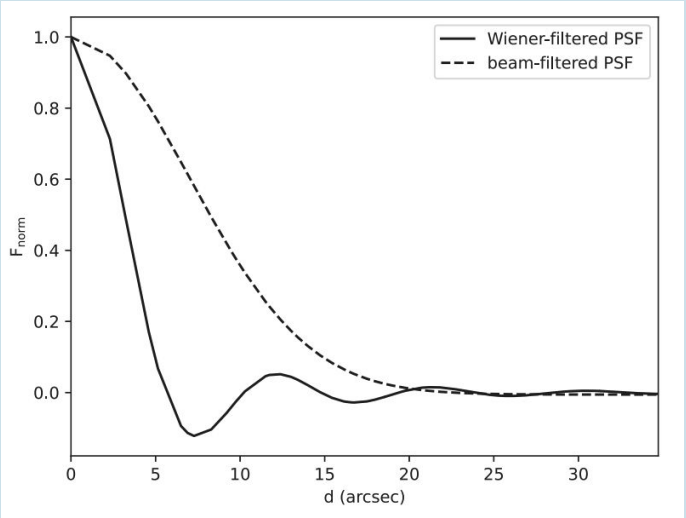

$5\sigma_{confusion}$
$5\sigma_{instrumental}$ (1500 hr deg^{-2})
$5\sigma_{instrumental}$ (Updated 1500 hr deg^{-2})
Flux Density [mJy]
Wavelength [μm]

Source detection

- **XID+ de-blends maps using the positions of known sources and requires a catalogue containing their prior positions**
- Blind detection is conducted by finding peaks in the maps after applying a Wiener filter to maximise the S/N ratio
  - Used previously for confusion-limited data
  - It is a compromise between:
    - the uncorrelated instrumental noise (benefits from a wider kernel)
    - the spatially correlated confusion noise (benefits from a narrower kernel and local background removal)

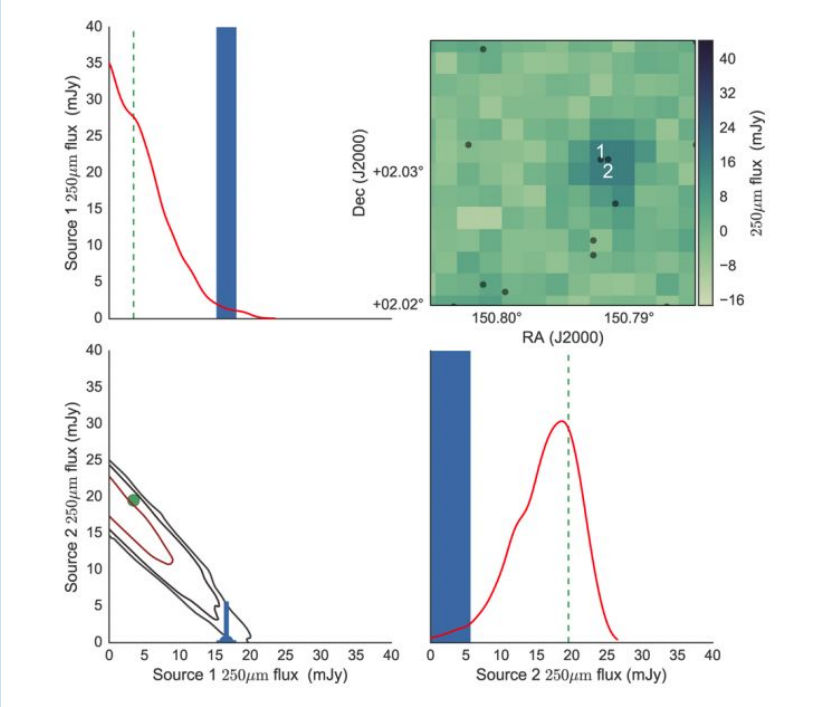


⇒ produces catalogue of ~83k sources over 2deg^2

XID+

- Developed by Hurley et al. 2017
- It's a prior-based source photometry and deblending tool
- It uses a probabilistic Bayesian framework which includes prior information on source positions

$$\boldsymbol{d} = \sum_{i=1}^{N} \boldsymbol{P}\boldsymbol{S}_i + N(0, \Sigma_{\text{inst}}) + N(\boldsymbol{B}, \Sigma_{\text{conf}})$$



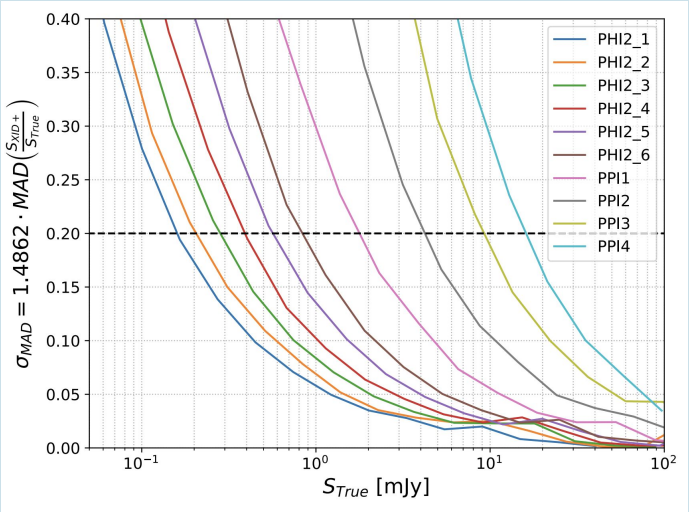
Joint and Marginalised posterior plot of two correlated sources that are 2 arcsec apart (Figure 6 from *Hurley et al. 2017*)

Flux modelling accuracy metric

- To quantify the flux accuracy of XID+, we define the ‘limiting flux’ statistic:

$$\sigma_{\mathrm{MAD}}(S_{\mathrm{true}}) = 1.4862 \cdot \mathrm{Median}\left(\frac{S_{\mathrm{obs}}}{S_{\mathrm{true}}} - \mathrm{Median}\left(\frac{S_{\mathrm{obs}}}{S_{\mathrm{true}}}\right)\right)$$

$$S_{\mathrm{limiting}} = S_{\mathrm{true}}\Big|_{\sigma_{\mathrm{MAD}}=0.2}$$

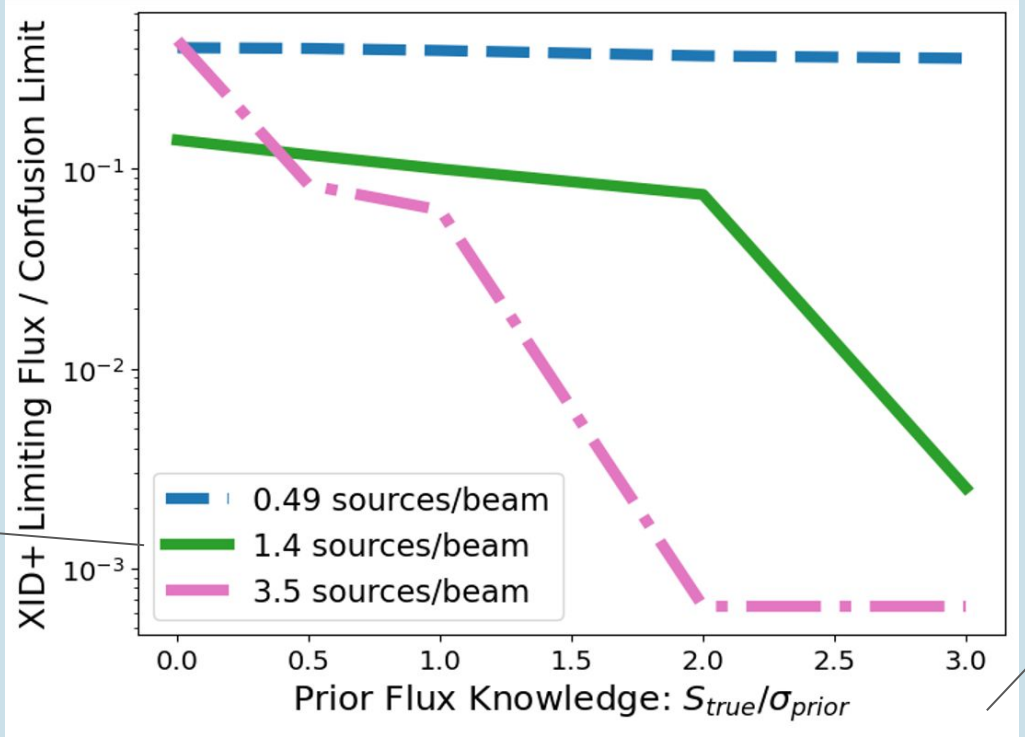


XID+: Impact of prior knowledge

- How does the amount of prior knowledge provided to XID+ impact it's modelling?
- We consider:
  - Varying the density of sources included in the prior source position catalogue
    - Use the blind detected, Wiener-filtered catalogue (~83k sources)
    - And a 'Deep catalogue' made from a simple flux cut to the full SIDES catalogue, keeping sources with $S_{25\mu m} > 1\mu Jy$ (~590k sources)
  - Varying the prior flux distribution for the sources

XID+: Impact of prior knowledge

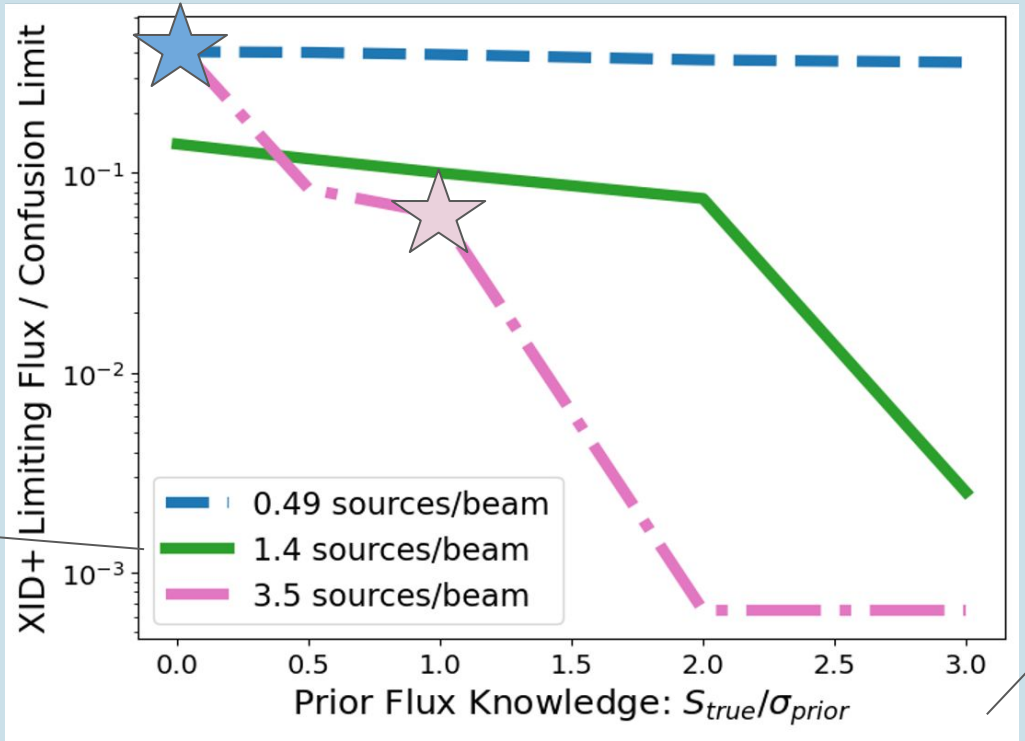
Increasing density of prior catalogue of source positions



Gaussian flux priors centred on the sources' true flux (S_{true}) with standard deviations (σ_{prior}) of 2.0, 1.0, 0.5 and 0.3 times the true flux

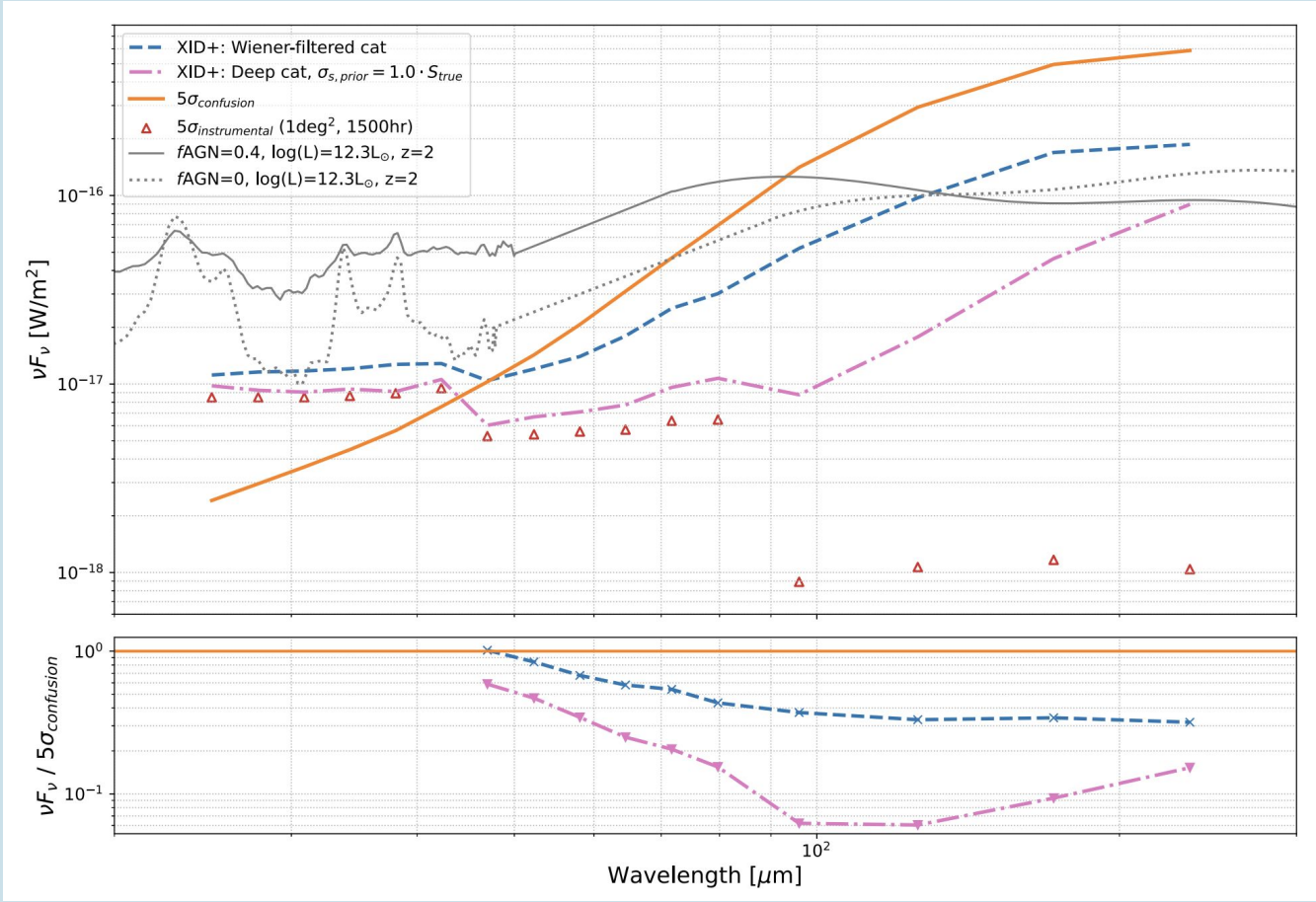
XID+: Impact of prior knowledge

Increasing density of prior catalogue of source positions

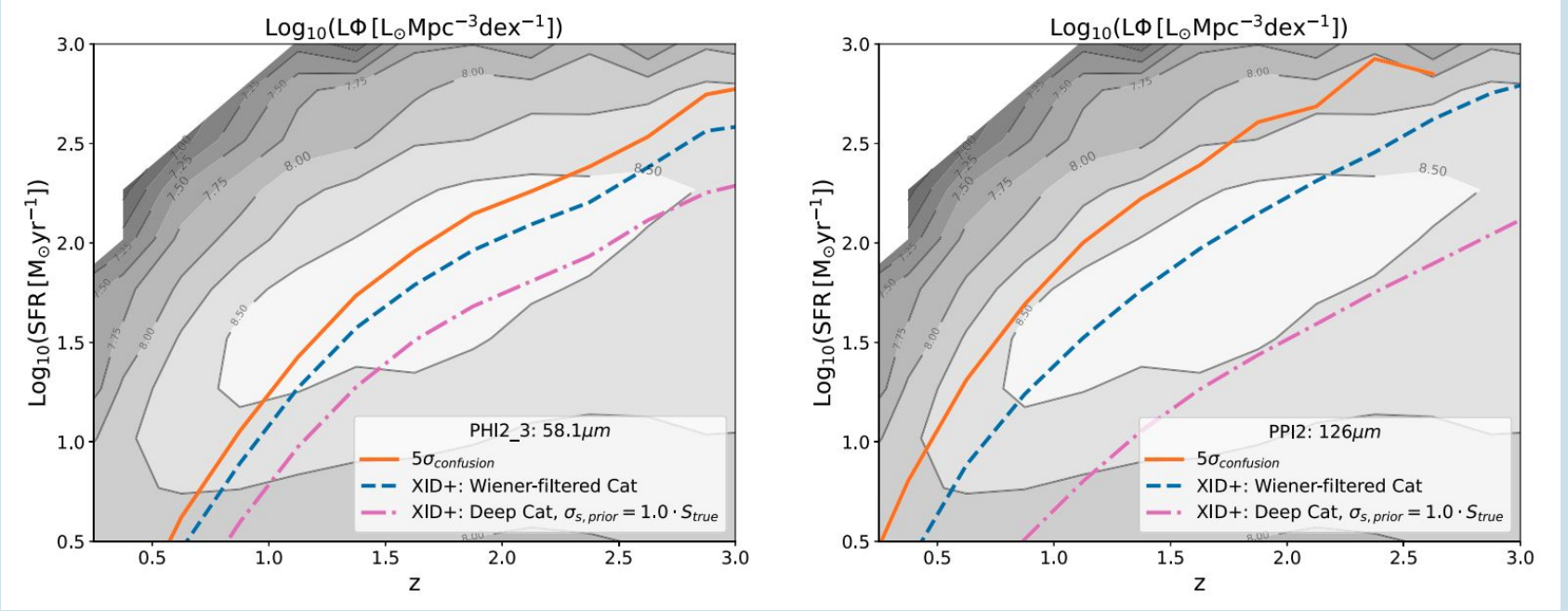


Gaussian flux priors centred on the sources' true flux (S_{true}) with standard deviations (σ_{prior}) of 2.0, 1.0, 0.5 and 0.3 times the true flux

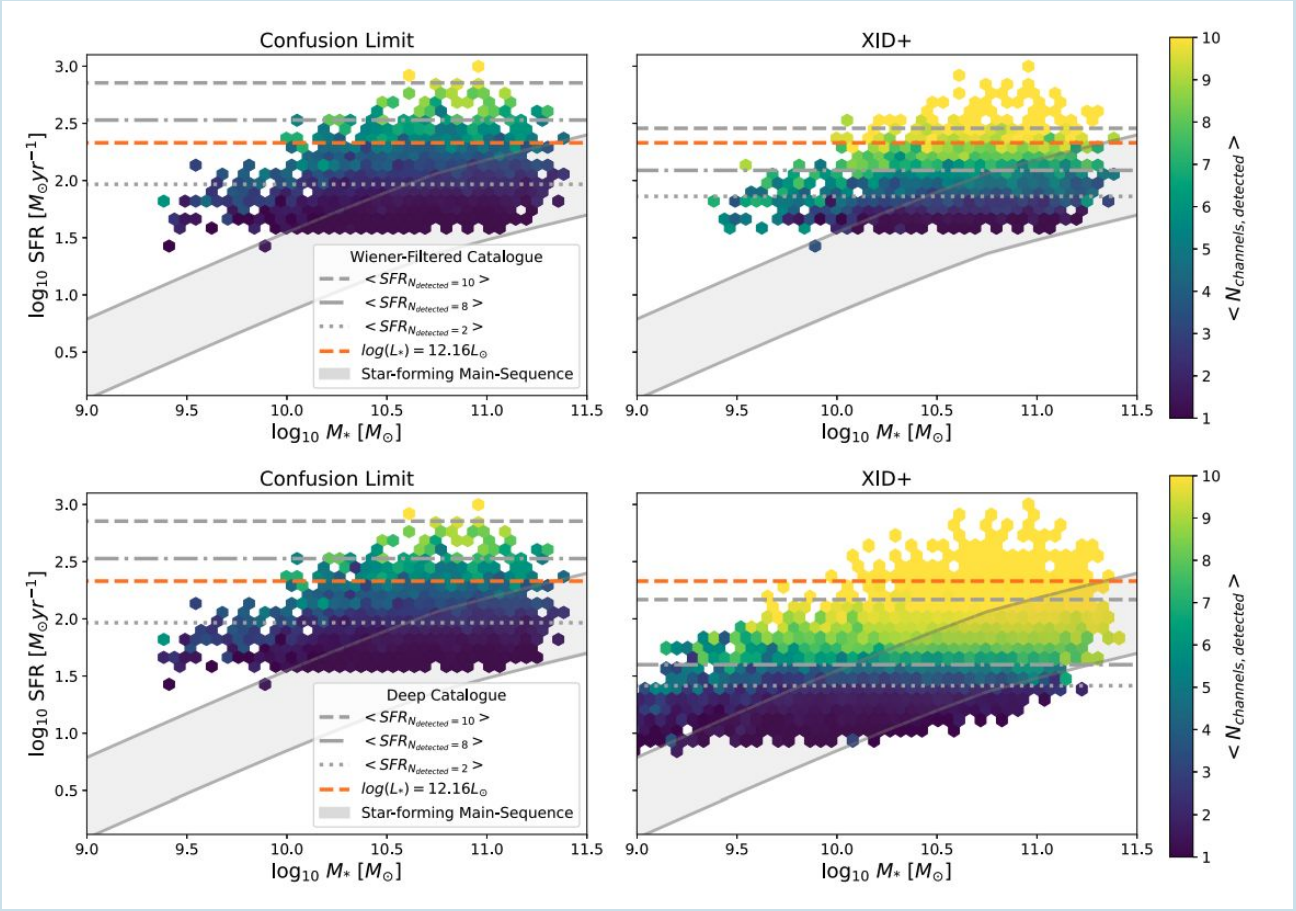
Results:


XID+: Wiener-filtered cat
XID+: Deep cat, $\sigma_{s,prior} = 1.0 \cdot S_{true}$
$5\sigma_{confusion}$
$5\sigma_{instrumental}$ (1deg^2, 1500hr)
fAGN=0.4, log(L)=12.3L$_\odot$, z=2
fAGN=0, log(L)=12.3L$_\odot$, z=2
10^{-16}
10^{-17}
10^{-18}
νF_ν [W/m^2]
10^{0}
10^{-1}
νF_ν / $5\sigma_{confusion}$
10^{2}
Wavelength [μm]

Redshift-SFR plane



How well can we sample the SEDs of z~2 sources?



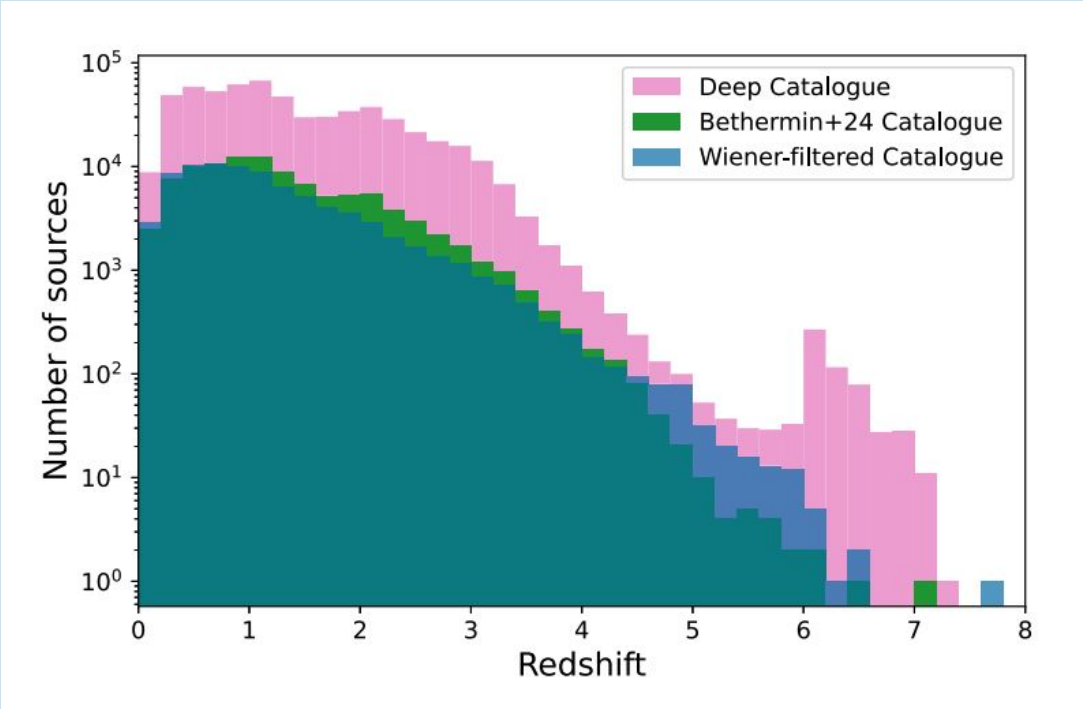
Ongoing Investigations

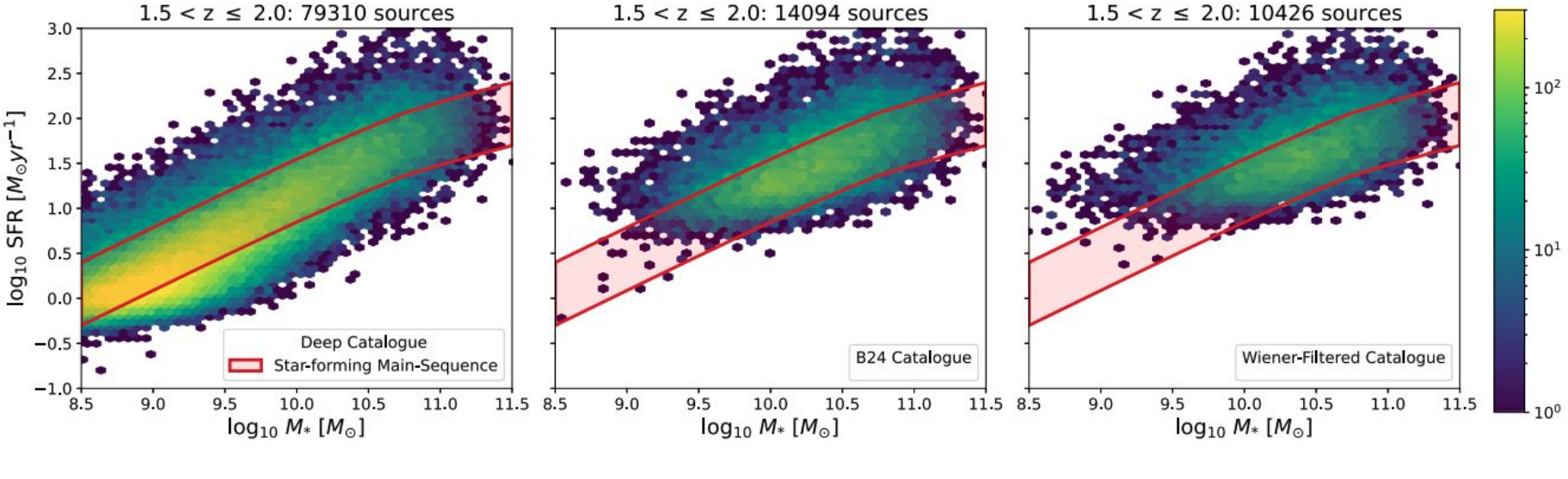
- Incorporating more realistic beam profiles
- Include cirrus to maps to determine impact on XID+ modelling
- Demonstrate that the higher density source catalogues and weak flux prior information can be achieved
- Leveraging non-confused hyperspectral SED information

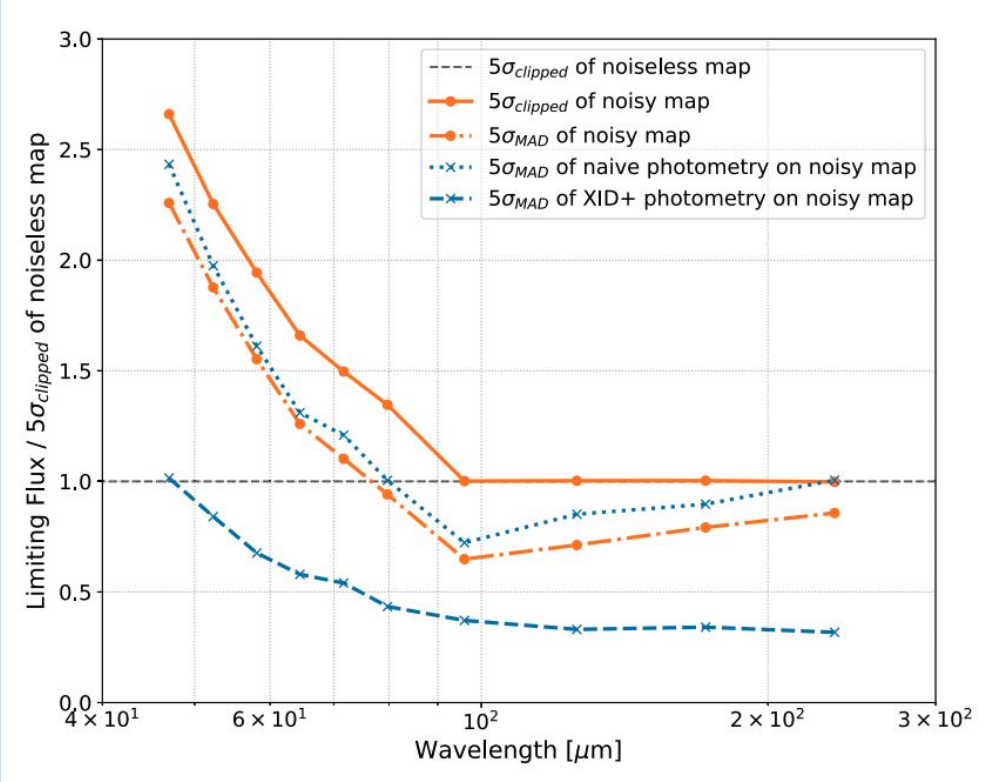
⇒ See Longji Bings talk later today!

Summary

- Need PRIMA to fill the FIR data gap between JWST and ALMA which covers the peak of galaxy SEDs around cosmic noon
- Mock PRIMAger maps were generated using SIDES and the confusion noise in each channel was estimated
- Demonstrated that we can produce catalogues of galaxies with high purity from blind source detection
- Able to accurately recover the fluxes of sources below the confusion limits for all confusion-dominated maps
    - Gain of a factor of ~2-3 between 72-235μm for blind detected sources with no prior flux information
    - ~Order of magnitude gain with higher density source catalogue and some prior flux knowledge


Deep Catalogue
Bethermin+24 Catalogue
Wiener-filtered Catalogue
Number of sources
10^5
10^4
10^3
10^2
10^1
10^0
0
1
2
3
4
5
6
7
8
Redshift


1.5 < z ≤ 2.0: 79310 sources
1.5 < z ≤ 2.0: 14094 sources
1.5 < z ≤ 2.0: 10426 sources
log10 SFR [M⊙yr−1]
log10 M* [M⊙]
Deep Catalogue
Star-forming Main-Sequence
B24 Catalogue
Wiener-Filtered Catalogue


3.0
2.5
2.0
1.5
1.0
0.5
0.0
Limiting Flux / $5\sigma_{clipped}$ of noiseless map
4×10^1
6×10^1
10^2
2×10^2
3×10^2
Wavelength [μm]
$5\sigma_{clipped}$ of noiseless map
$5\sigma_{clipped}$ of noisy map
$5\sigma_{MAD}$ of noisy map
$5\sigma_{MAD}$ of naive photometry on noisy map
$5\sigma_{MAD}$ of XID+ photometry on noisy map