

# A simulation-based likelihood for X-ray surveys

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chair of the eROSITA AGN working group

<http://astrost.at/istics/>

Lumiere workshop, 16.01.2025





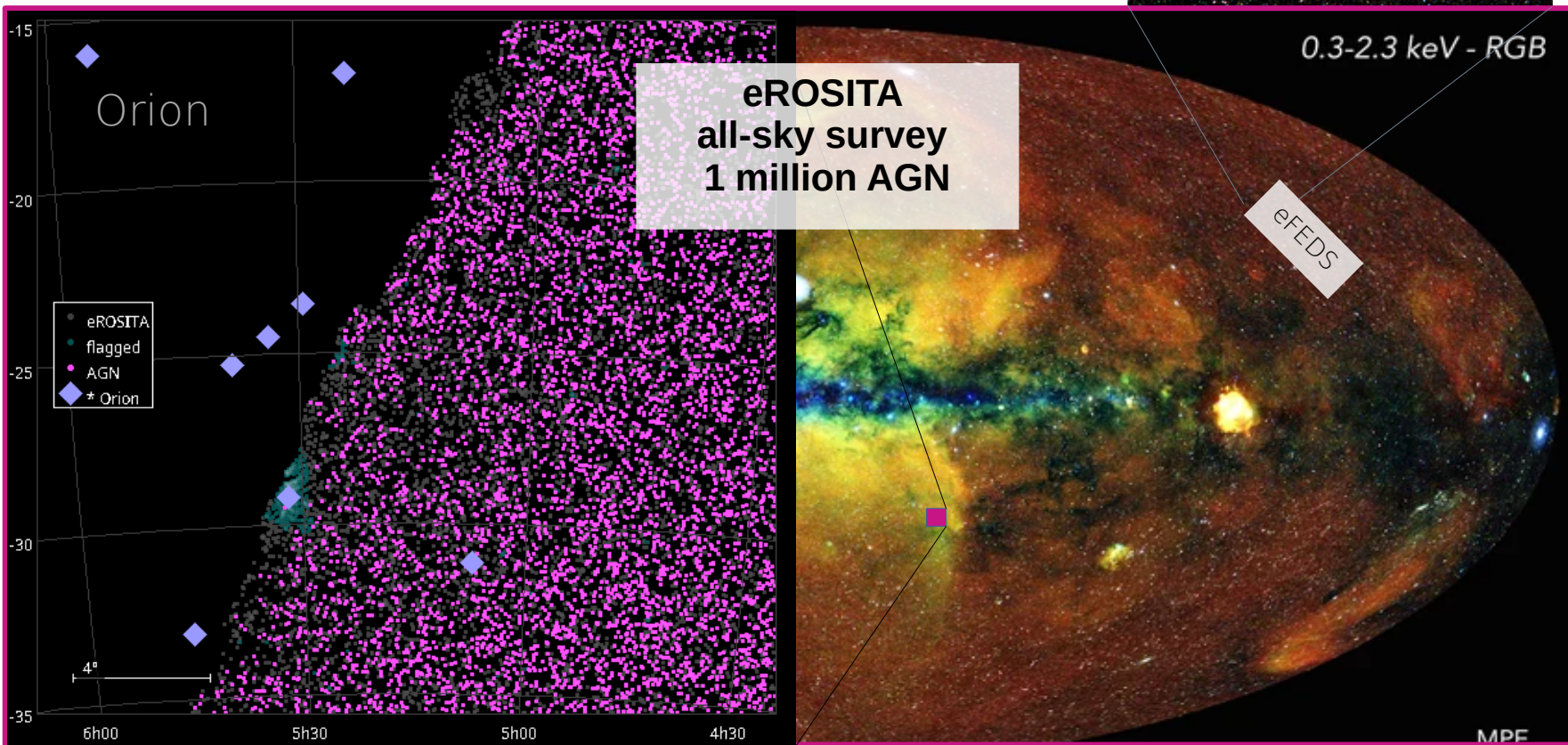
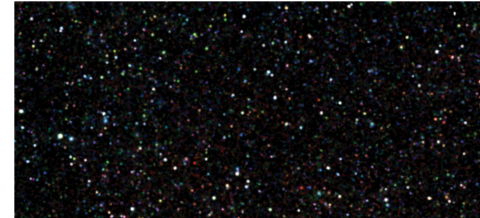


# X-ray localize black holes with



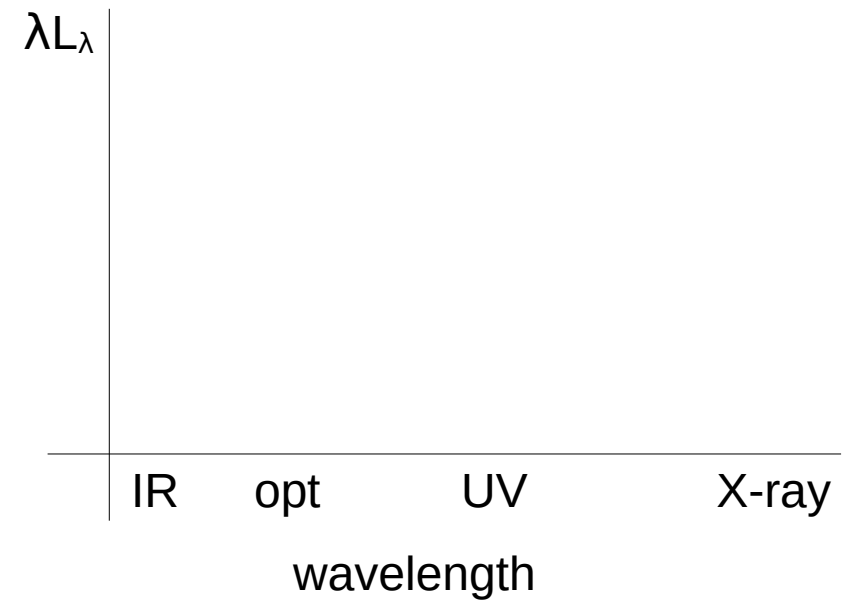
Chair of **eROSITA-DE** AGN working group  
Chair of **SDSS-V** AGN demographics WG

work with 2 BSc, 2 MSc and 3 PhD students



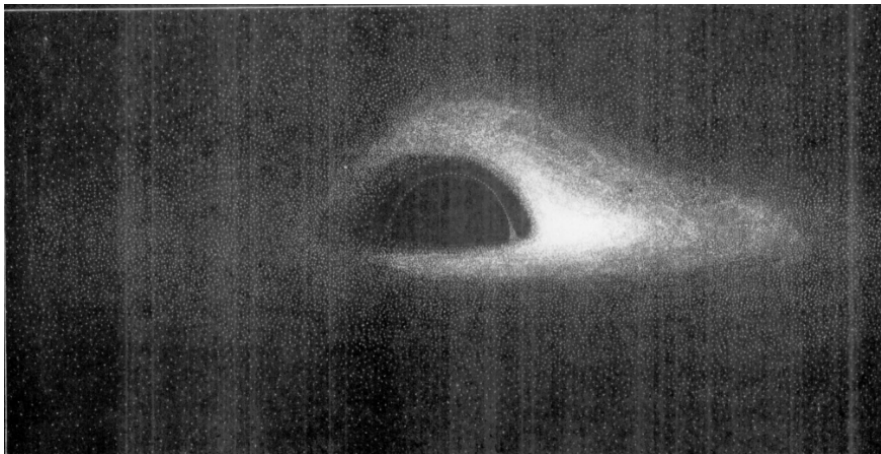
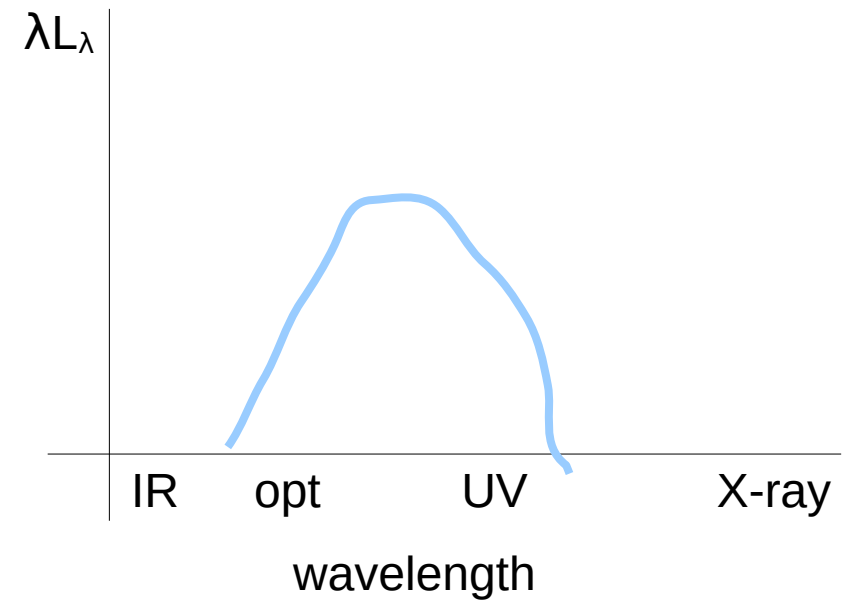
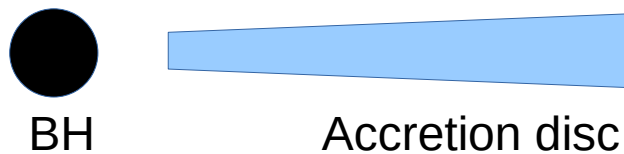


# Emission of a **black** hole





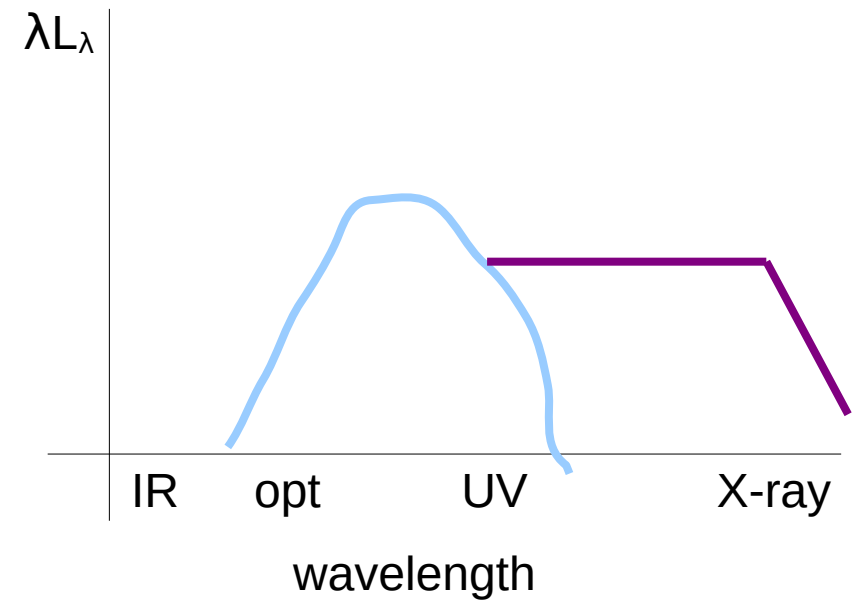
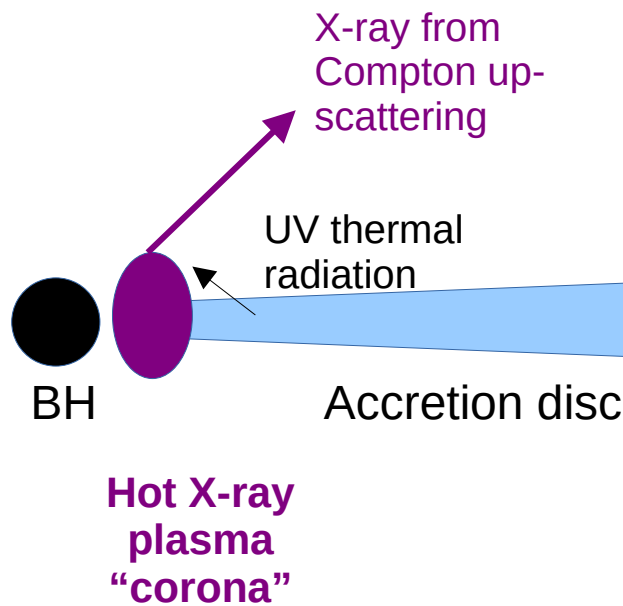
# SED of an **accreting** black hole



Pringle & Rees (1972),  
Shakura & Sunyaev (1973),  
Lynden-Bell & Pringle (1974),  
Luminet (1979)



# X-rays from accreting black holes





# Host galaxies of luminous AGN

$L_{\text{AGN}}$

Accretion  
luminosity

$M_{\text{BH}}$

Black  
hole  
mass

$M_*$

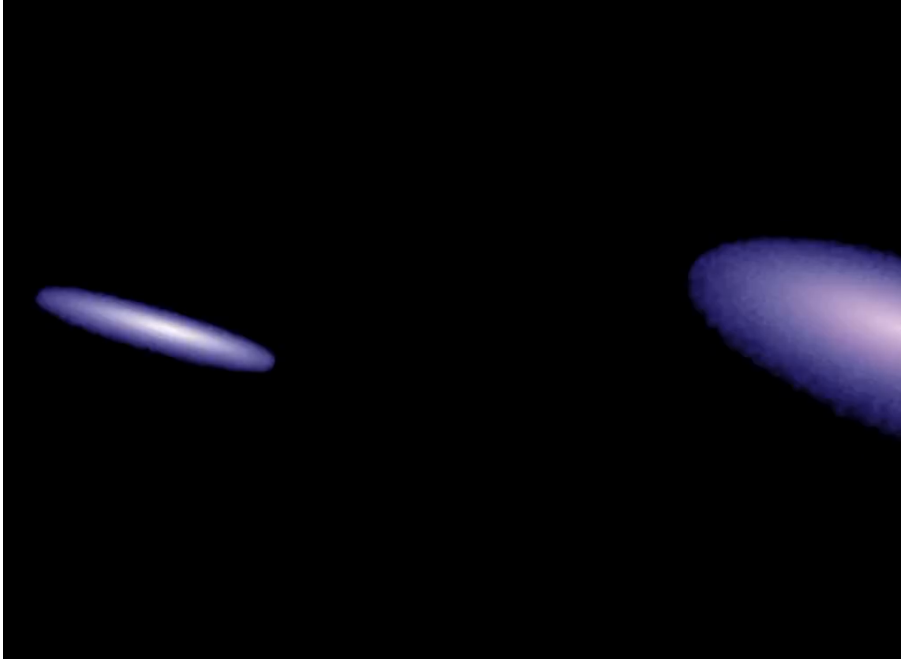
Host galaxy  
stellar mass

SFR

Star  
formation  
rate



# The time-scale challenge



galaxy-AGN connection lost?

+ many important parameters, all related:

AGN:

Galaxy:

luminosityobscuration

M\*

SFR

morphology

Cosmic time

|        |          |           |              |         |           |
|--------|----------|-----------|--------------|---------|-----------|
| high   | none     | dwarf     | quiescent    | merger  | $z > 6$   |
| medium | moderate | Milky Way | star-forming | compact | $z = 1-3$ |
| low    | thick    | massive   | star-burst   | ...     | $z = 0$   |

## Big Data Approach:

huge surveys give many snapshots in time

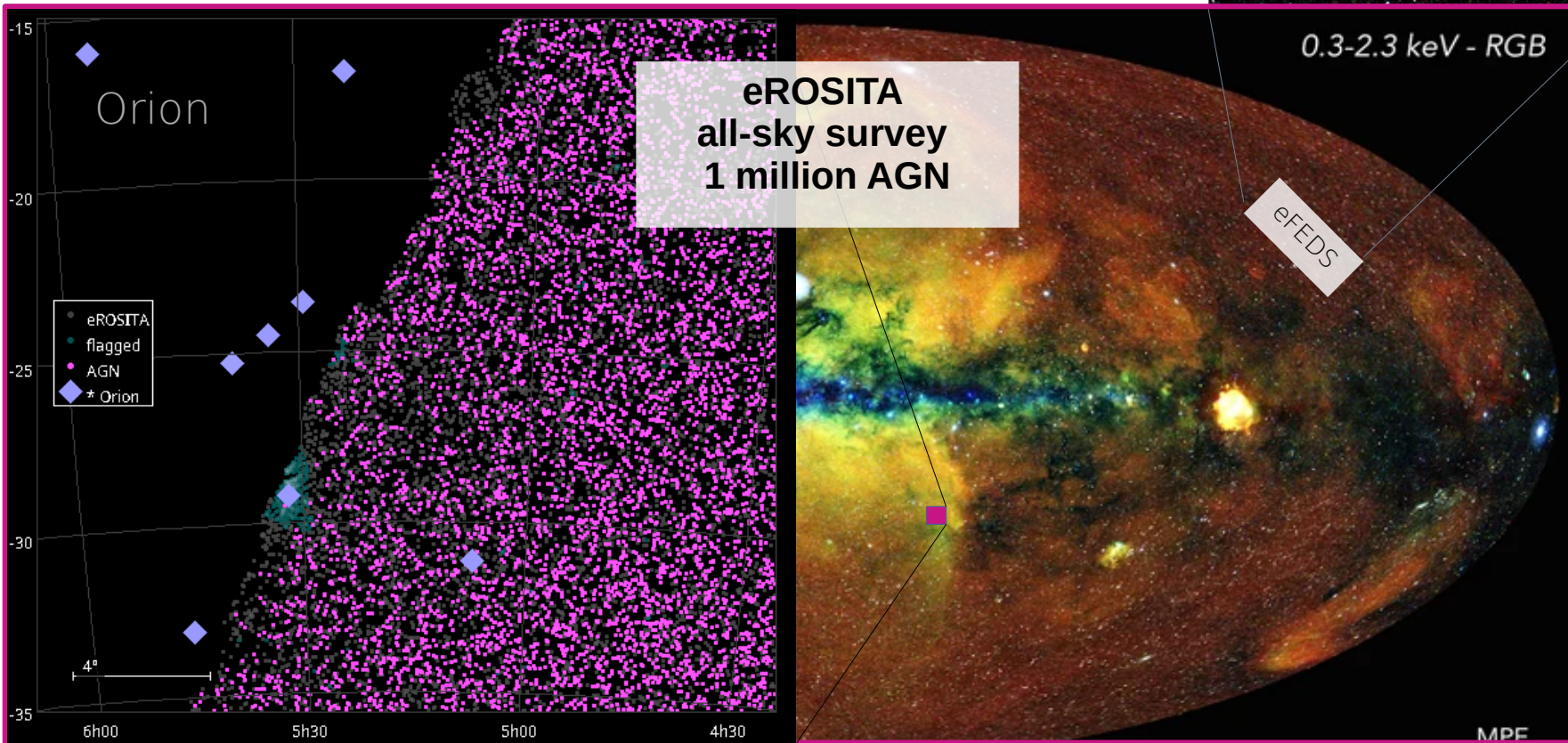
Tease out interdependence statistically



# X-ray localize black holes with

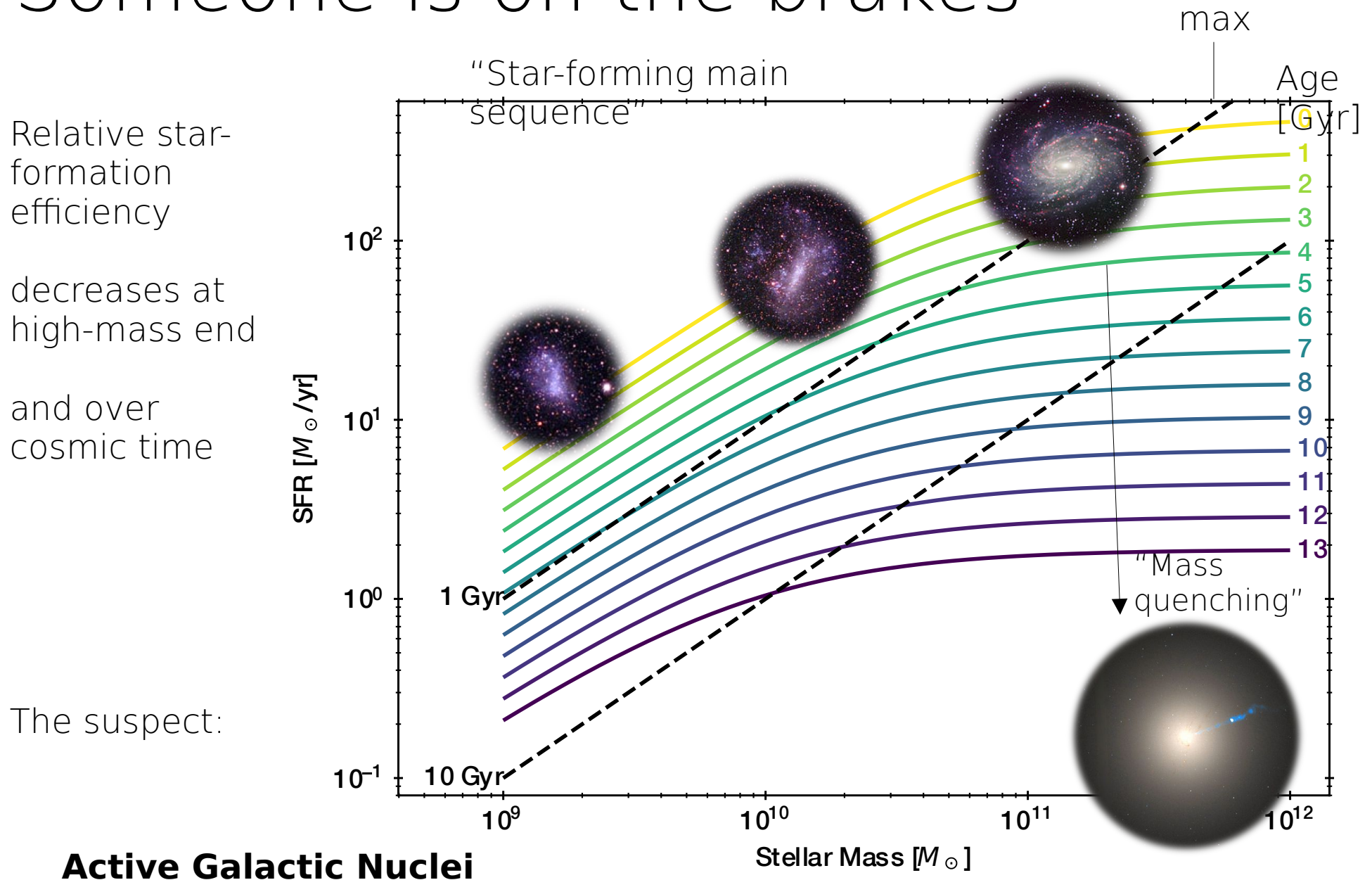


- 1) Detection in X-rays
- 2) Association across wavelengths (NWAY, Salvato, JB+18)
- 3) Photo-z and spec-z (SDSS, 4MOST)
- 4) Study host galaxy undergoing the AGN phase
- 5) Understand the population





# Someone is on the brakes



# Someone is on the brakes



## AGN activation $p(L)$

### Depends at least on

**galaxy mass**, Bongiorno+12, Aird+12

**redshift** e.g. Ueda+03

**star-formation rate** e.g. ,Rosario+12...

**Galaxy morphology** e.g. Kocevski+12...

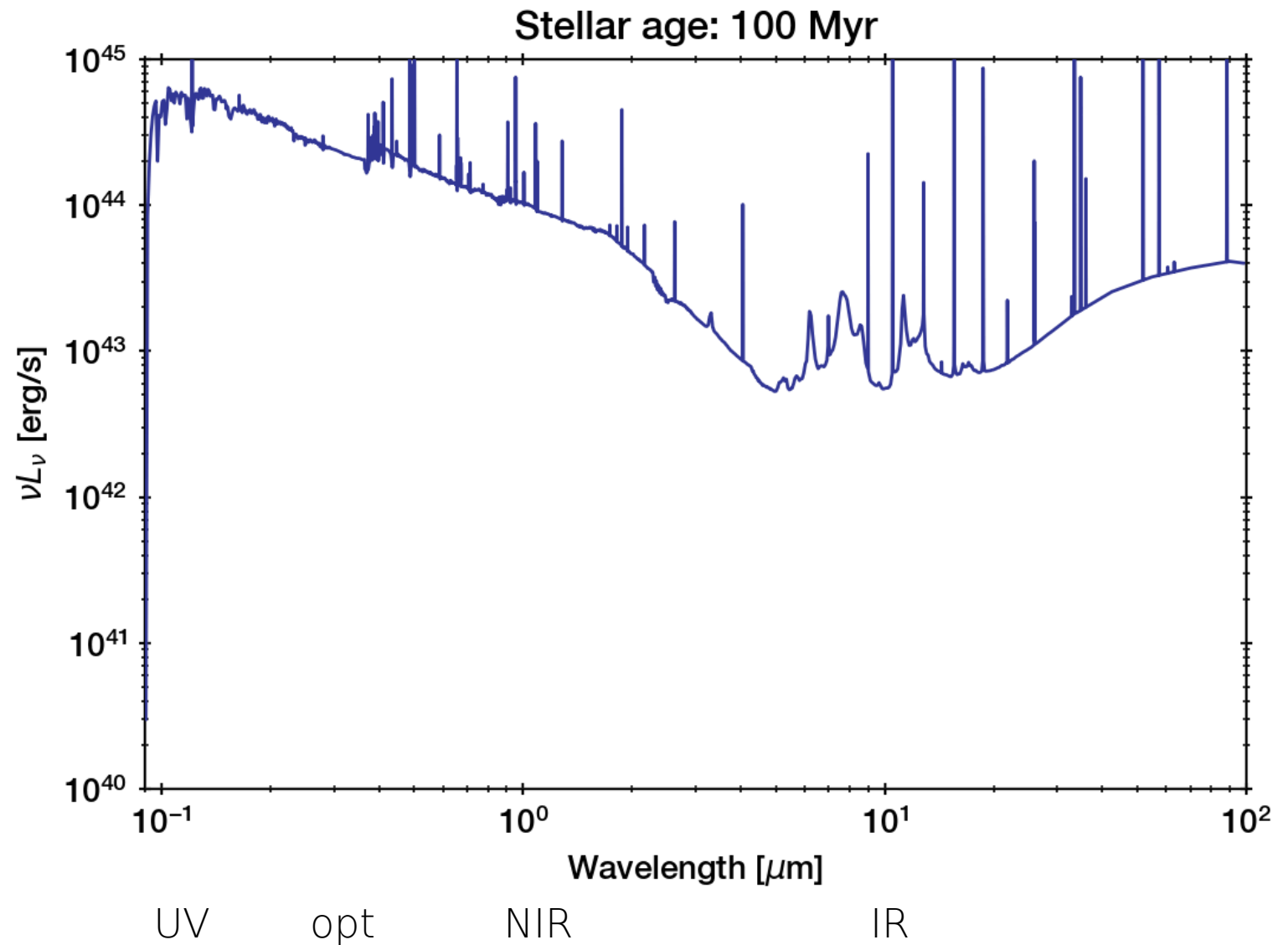
**Obscuration** e.g. Buchner+15...

(and hundreds of papers studying their interplay)



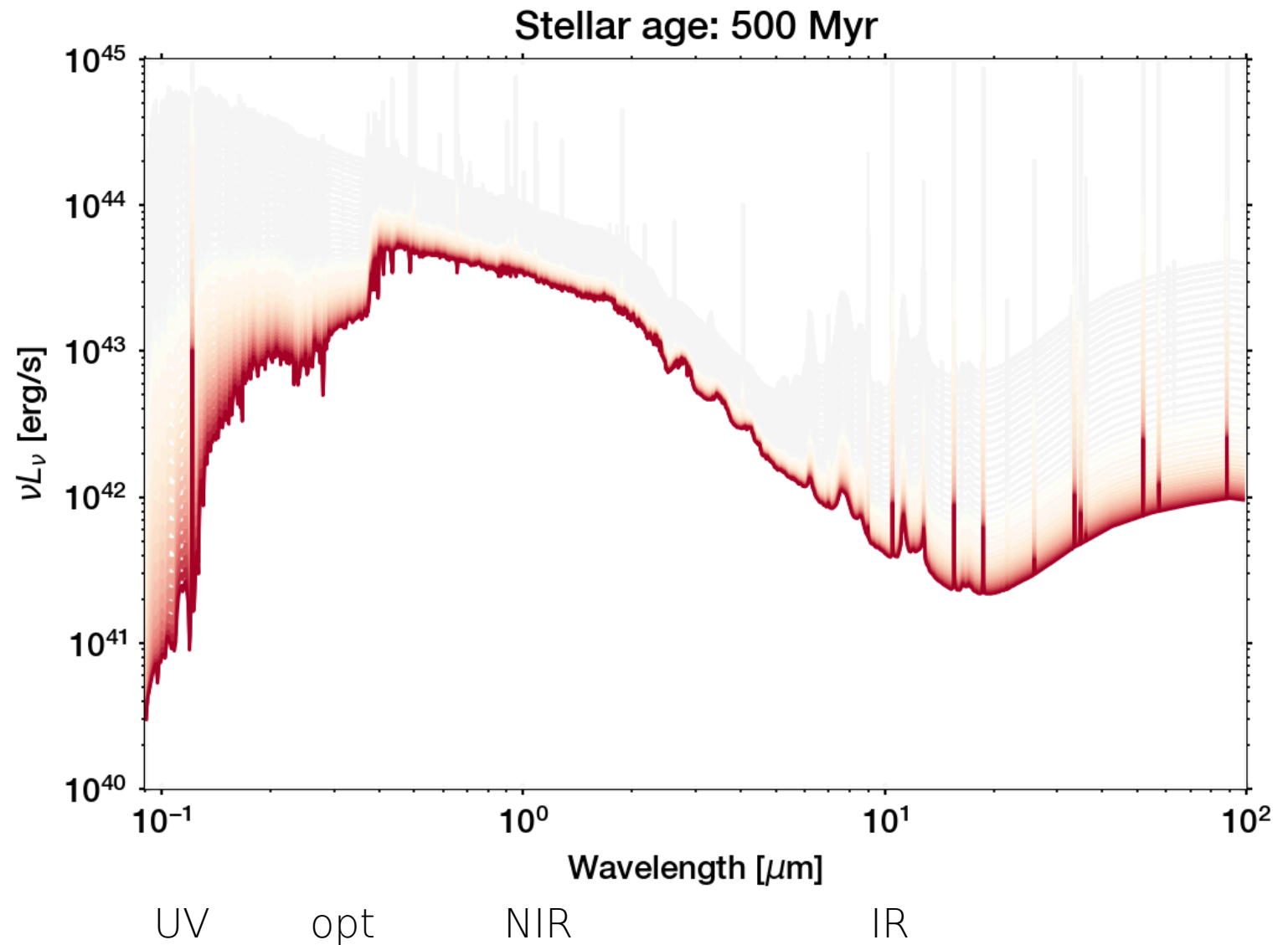
# Galaxies alone

aging from blue to red



# With bright quasar

Outshining host galaxy



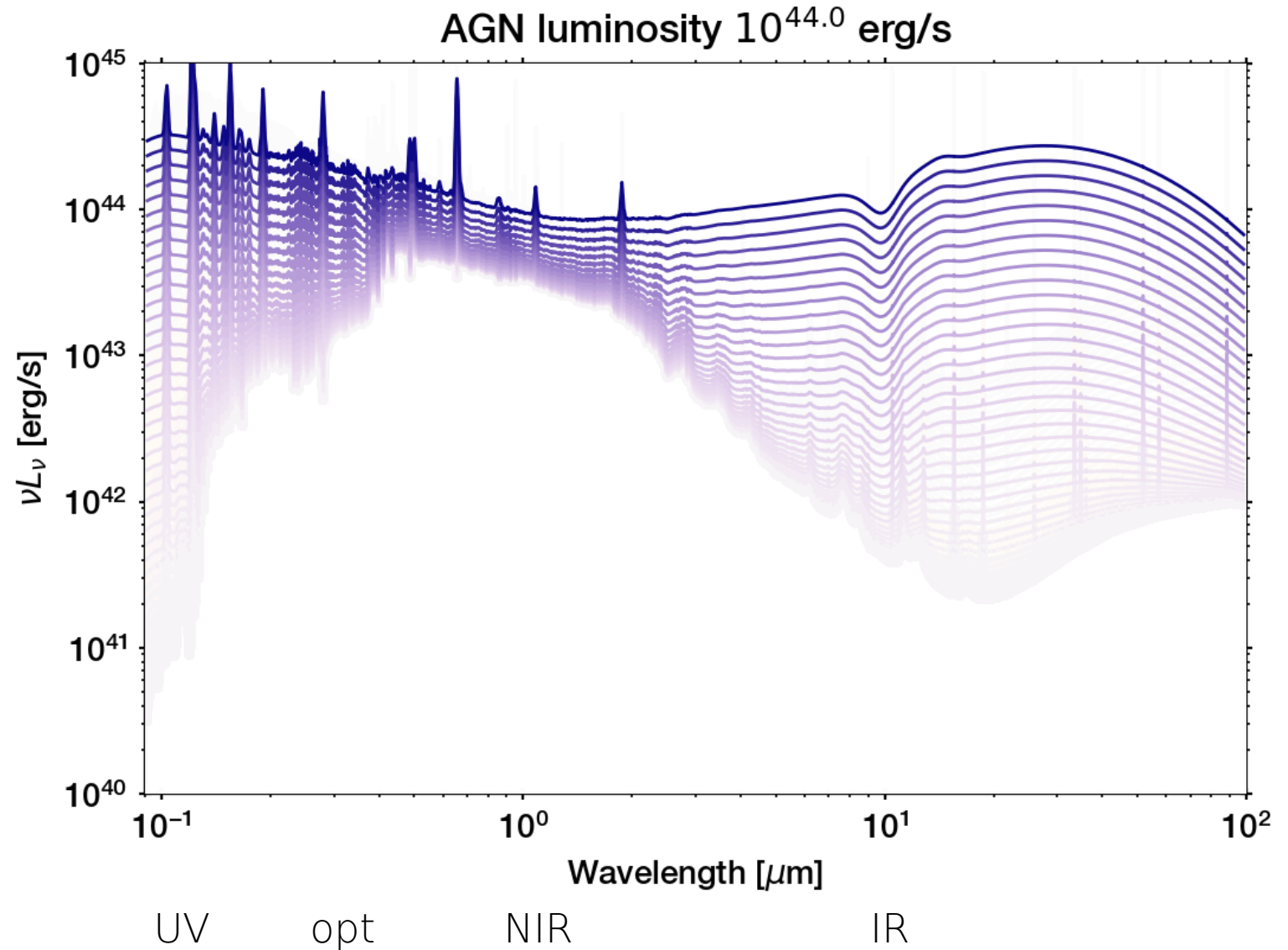


# Some AGN variations

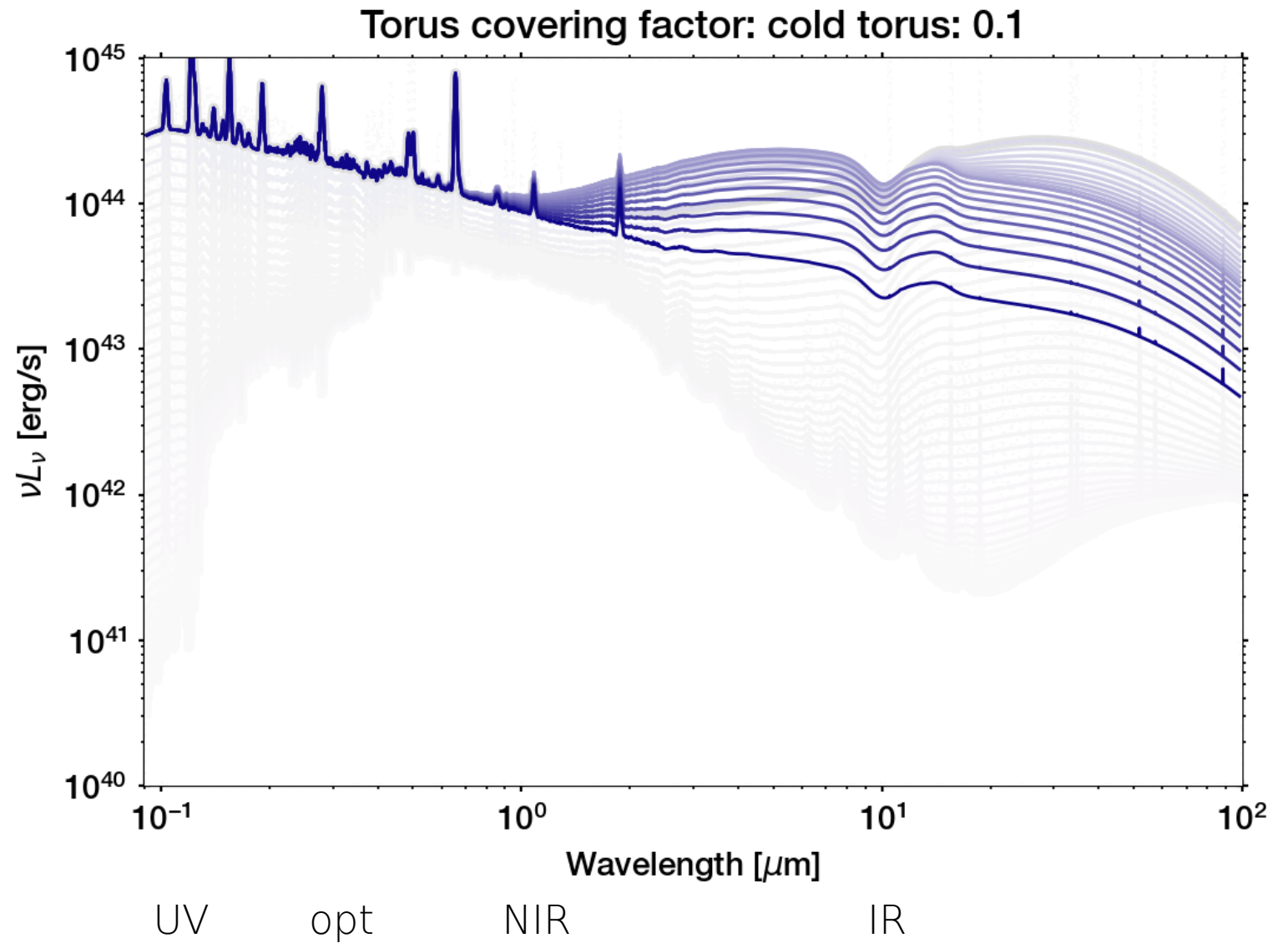


“Torus”  
covering  
factors

Hot dust  
Cold dust



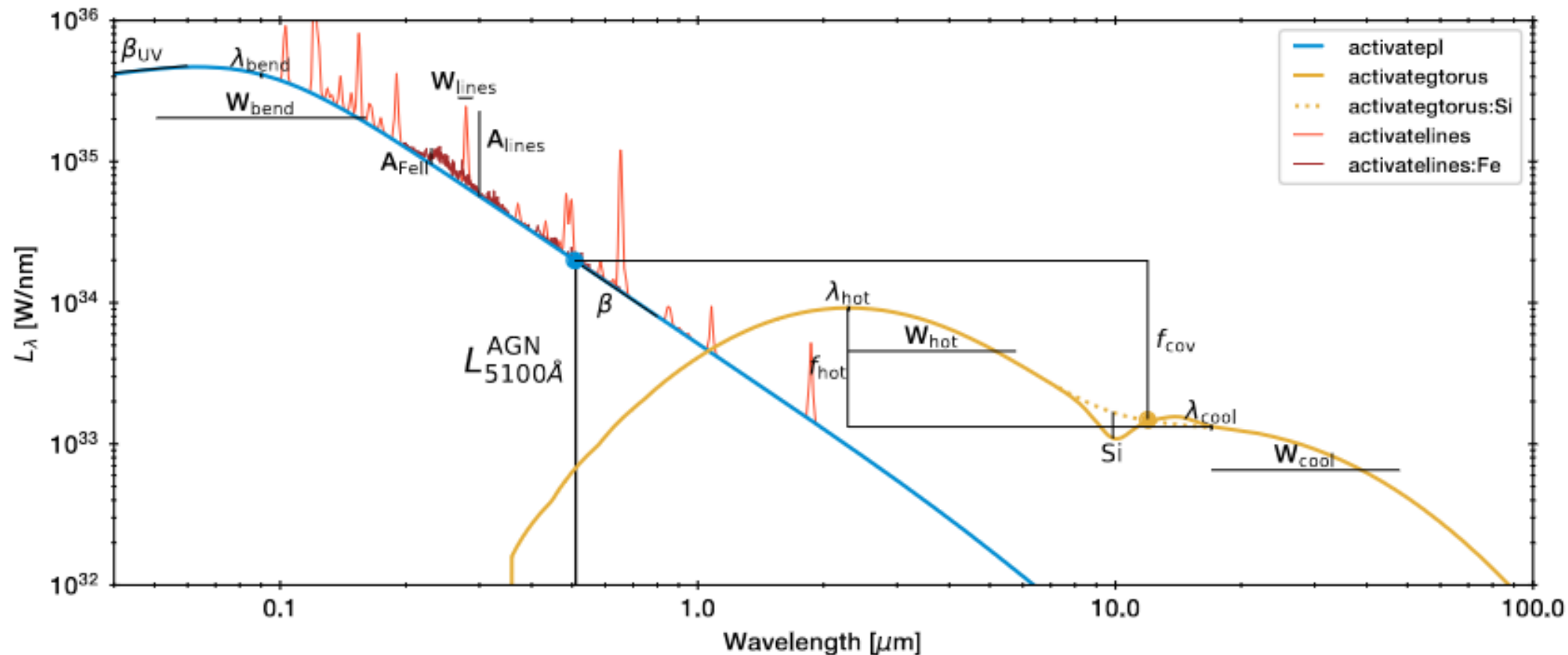
# Obscuration





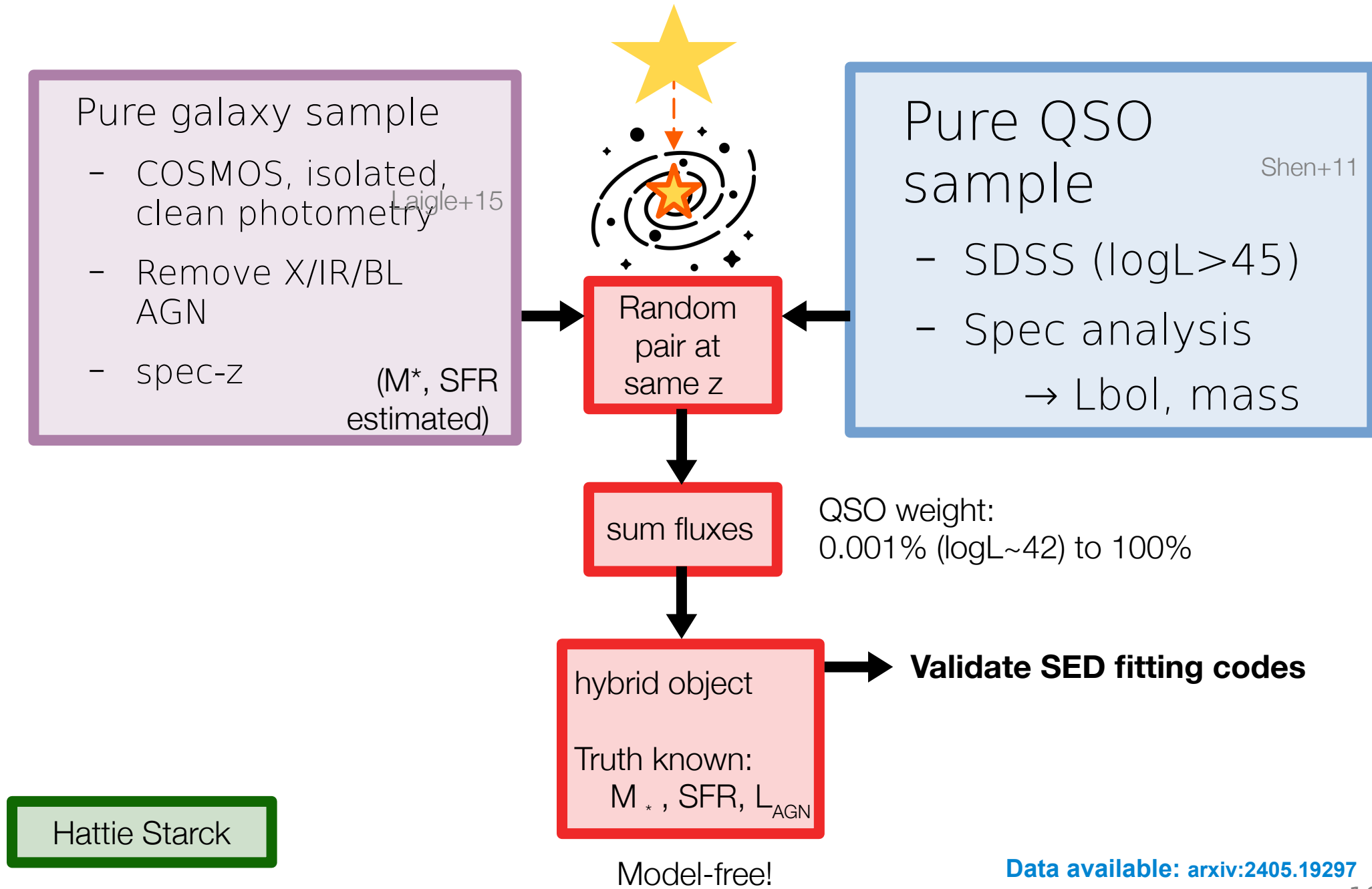
# GRAHSP AGN model components

- flexible, empirical AGN model + model uncertainty
- state-of-the-art Bayesian inference engine UltraNest,  
scales to large samples and many parameters



+ SMC-like nuclear  
reddening

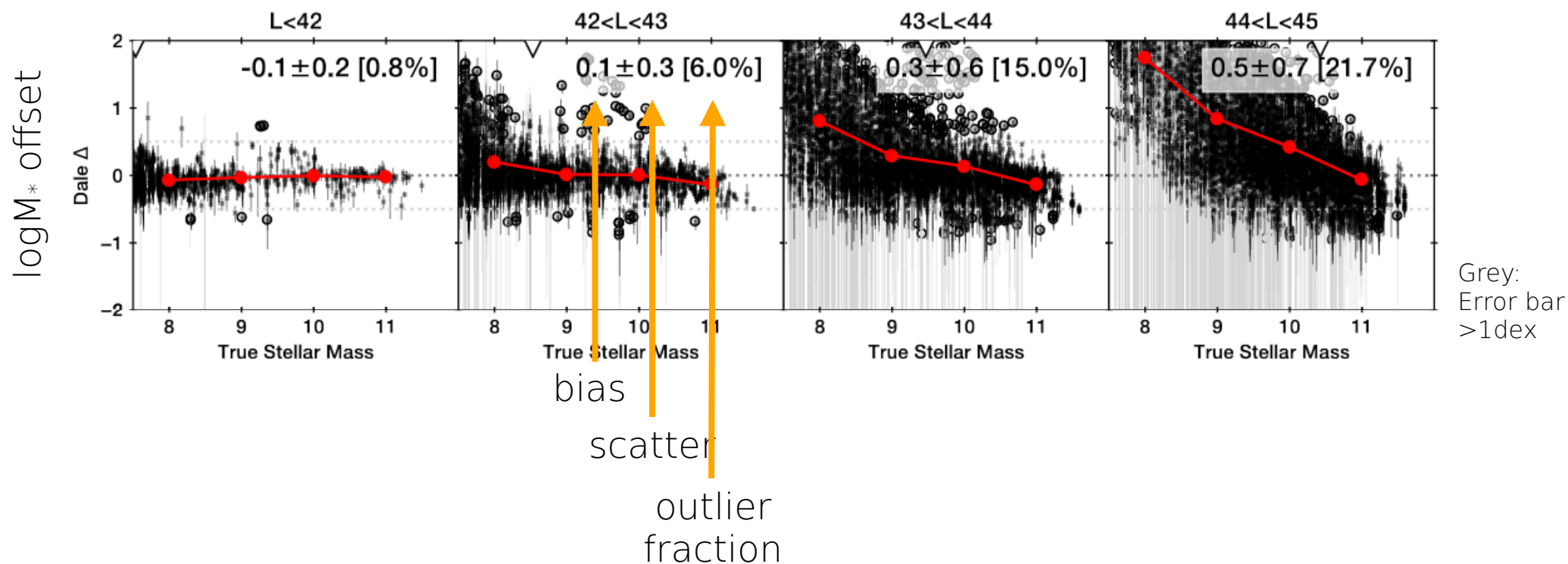
# The Chimeras benchmark



# Results: $M^*$ bias & scatter

bias to AGN light contamination

AGN luminosity  $\rightarrow$

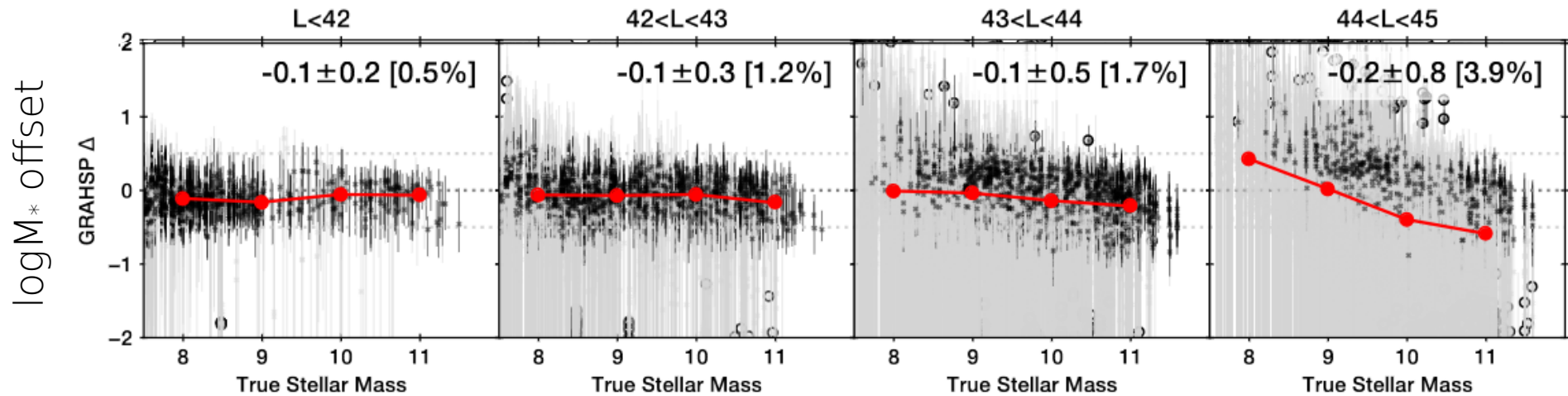


Model details:

- Delayed exponential - star formation episode BC03 SPS
- attenuation & energy-conserving re-emission in IR
- AGN: Dale+14, single parameter for AGN fraction



# Our new tool: GRAHSP



**Unbiased retrieval**: AGN not systematically over-estimated

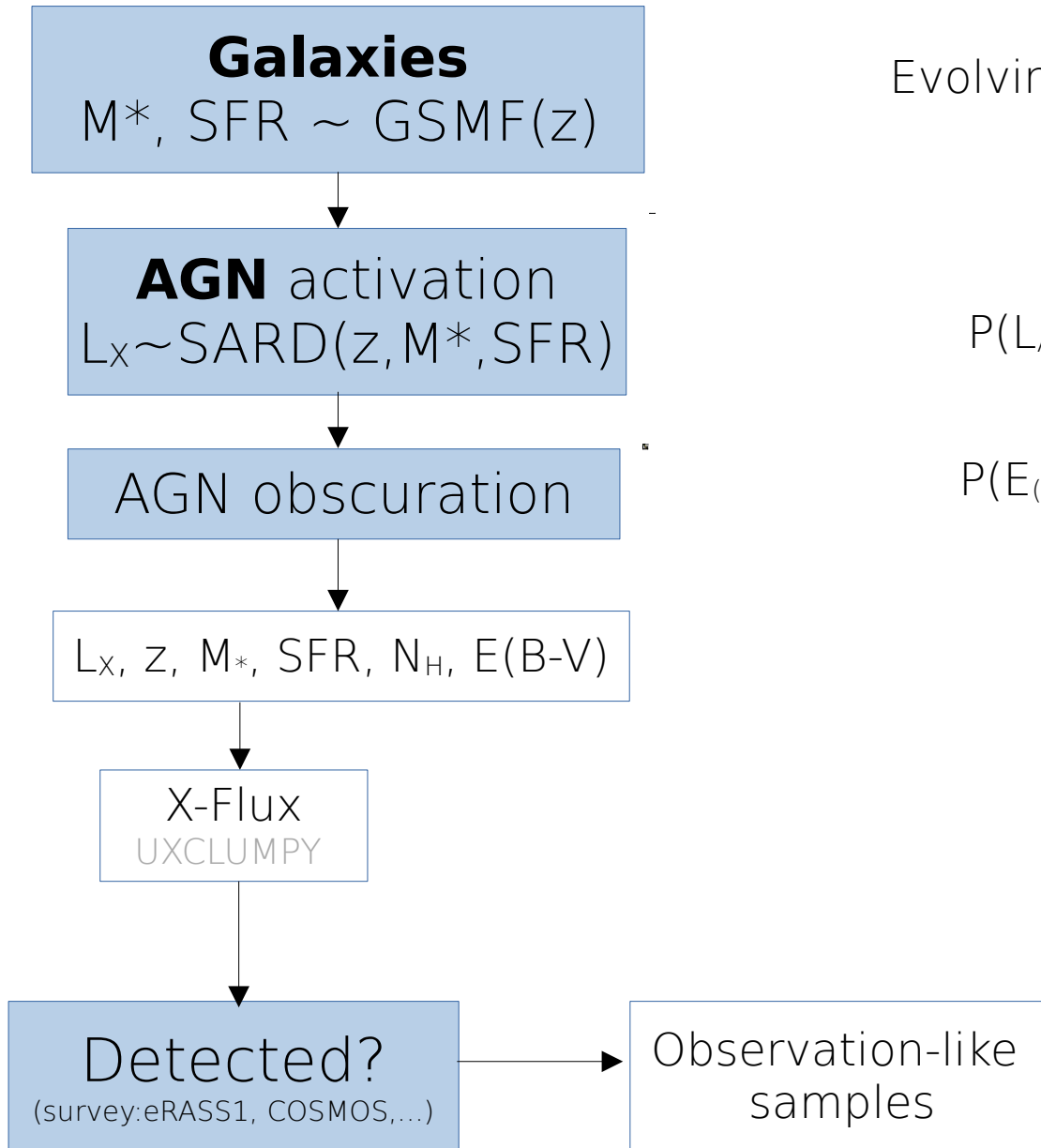
of stellar mass, SFR & AGN luminosity

Realistic error bars – no longer dominated by systematics

**Full details: [arxiv:2405.19297](https://arxiv.org/abs/2405.19297)**

# Simulating the BH Universe

eROSITA+SDSS+DESI+Euclid+LSST+... surveys



Evolving Schechter mass function

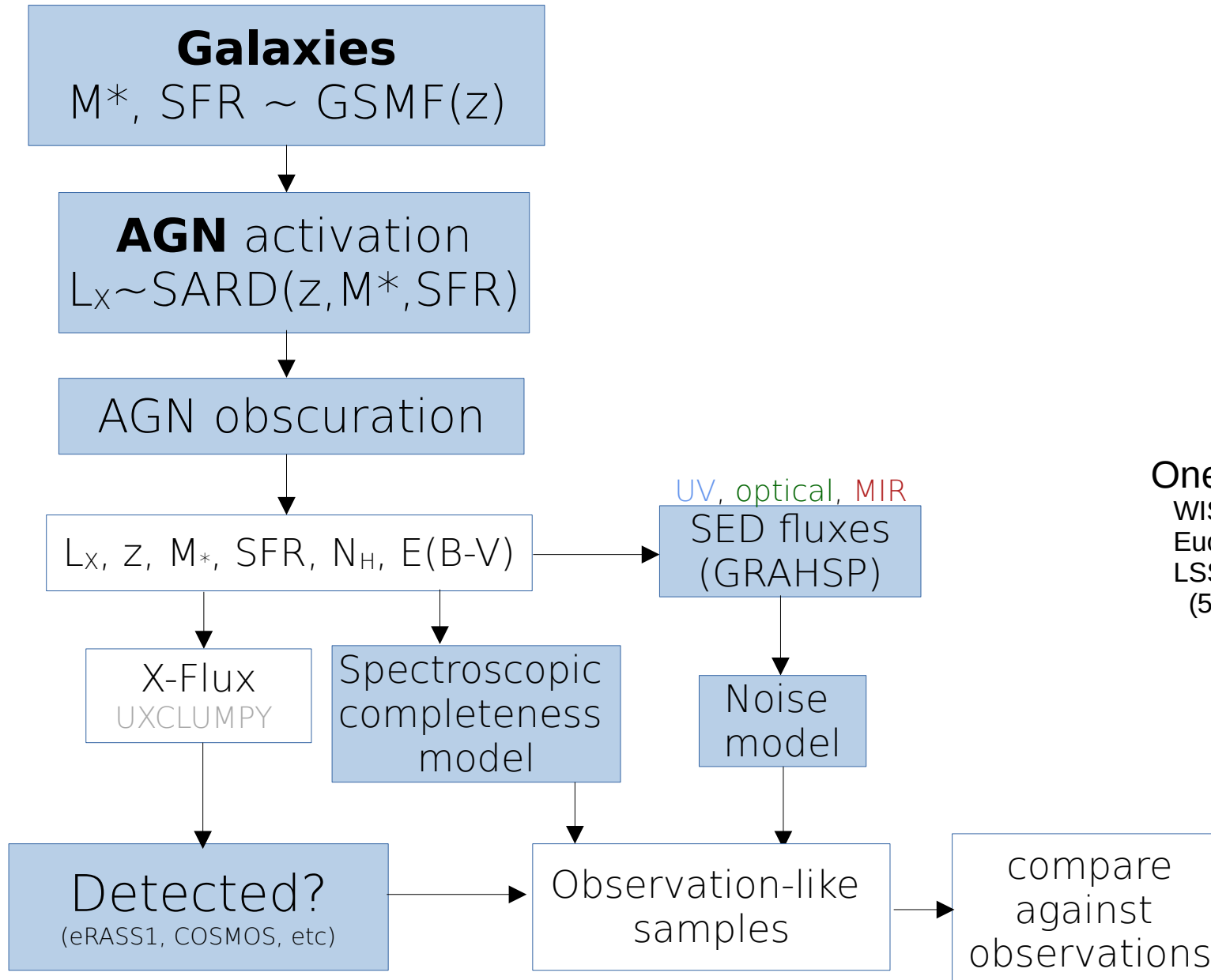
$$P(L_{\text{AGN}} | M^*, \text{SFR})$$

$$P(E_{(B-V)}, N_H | L_{\text{AGN}}, M^*, \text{SFR})$$

# Simulating the BH Universe

eROSITA+SDSS+DESI+Euclid+LSST+... surveys

with Erasmus  
student  
Nikolas Vasilas



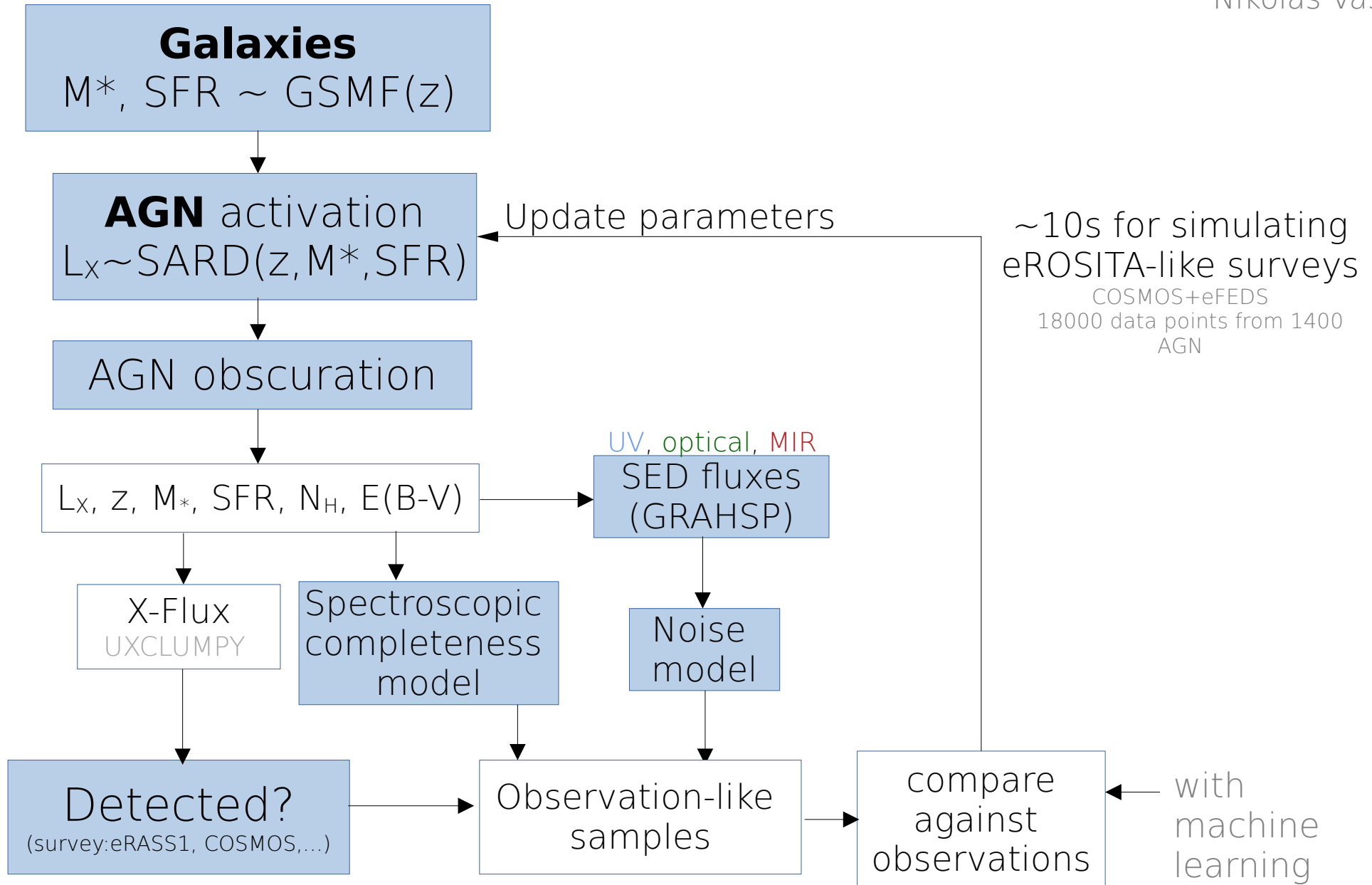
**One-off predictions:**  
WISE: Georgakakis+20  
Euclid/MAMBO: López+24  
LSST/AGILE:  
(560000 CPU hours)



# Simulating the BH Universe

eROSITA+SDSS+DESI+Euclid+LSST+... surveys

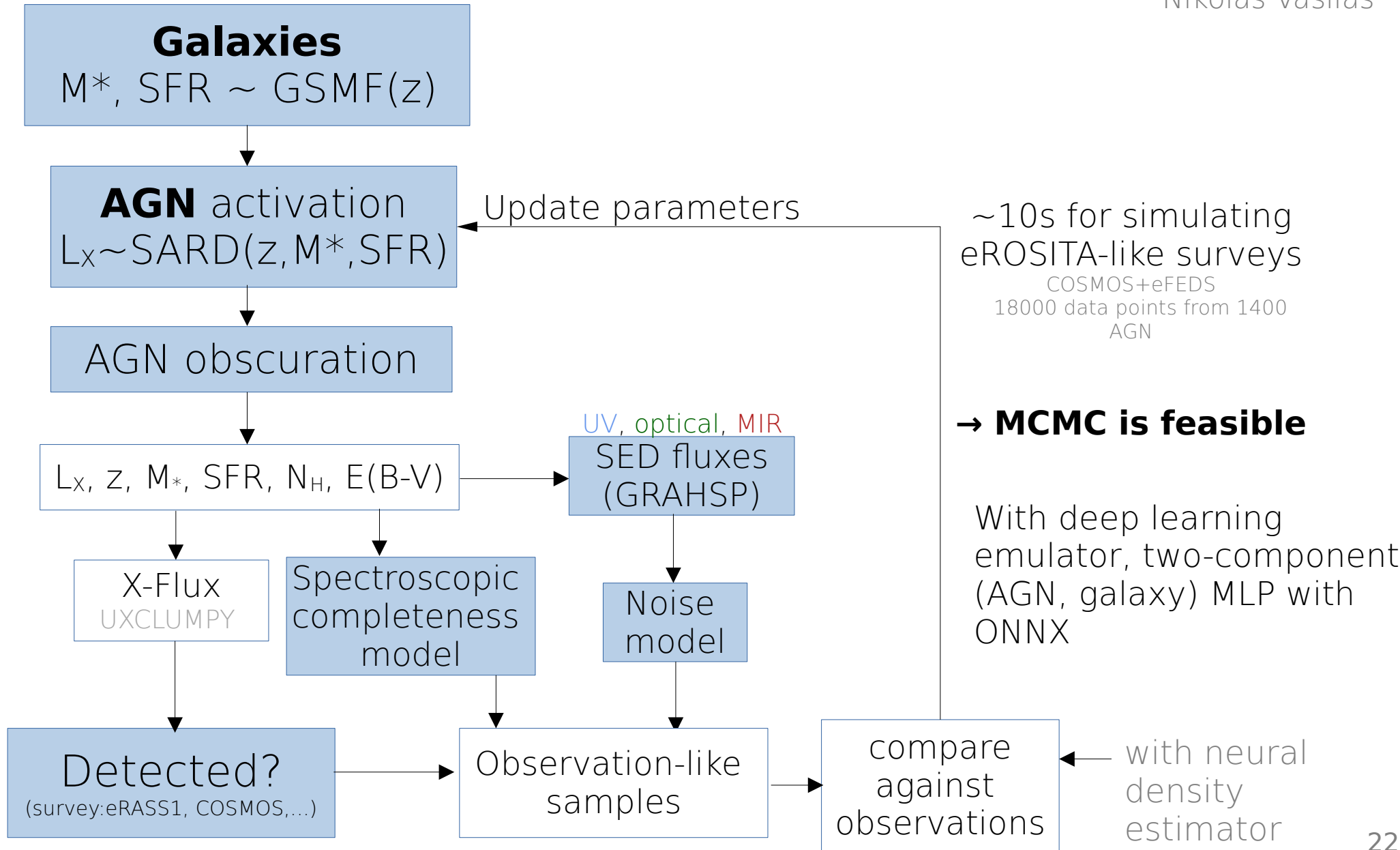
with Erasmus  
student  
Nikolas Vasilas



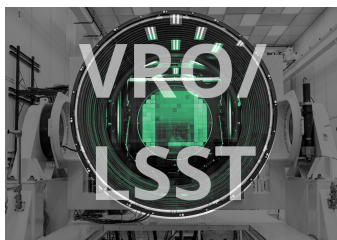
# Simulating the BH Universe

eROSITA+SDSS+DESI+Euclid+LSST+... surveys

with Erasmus  
student  
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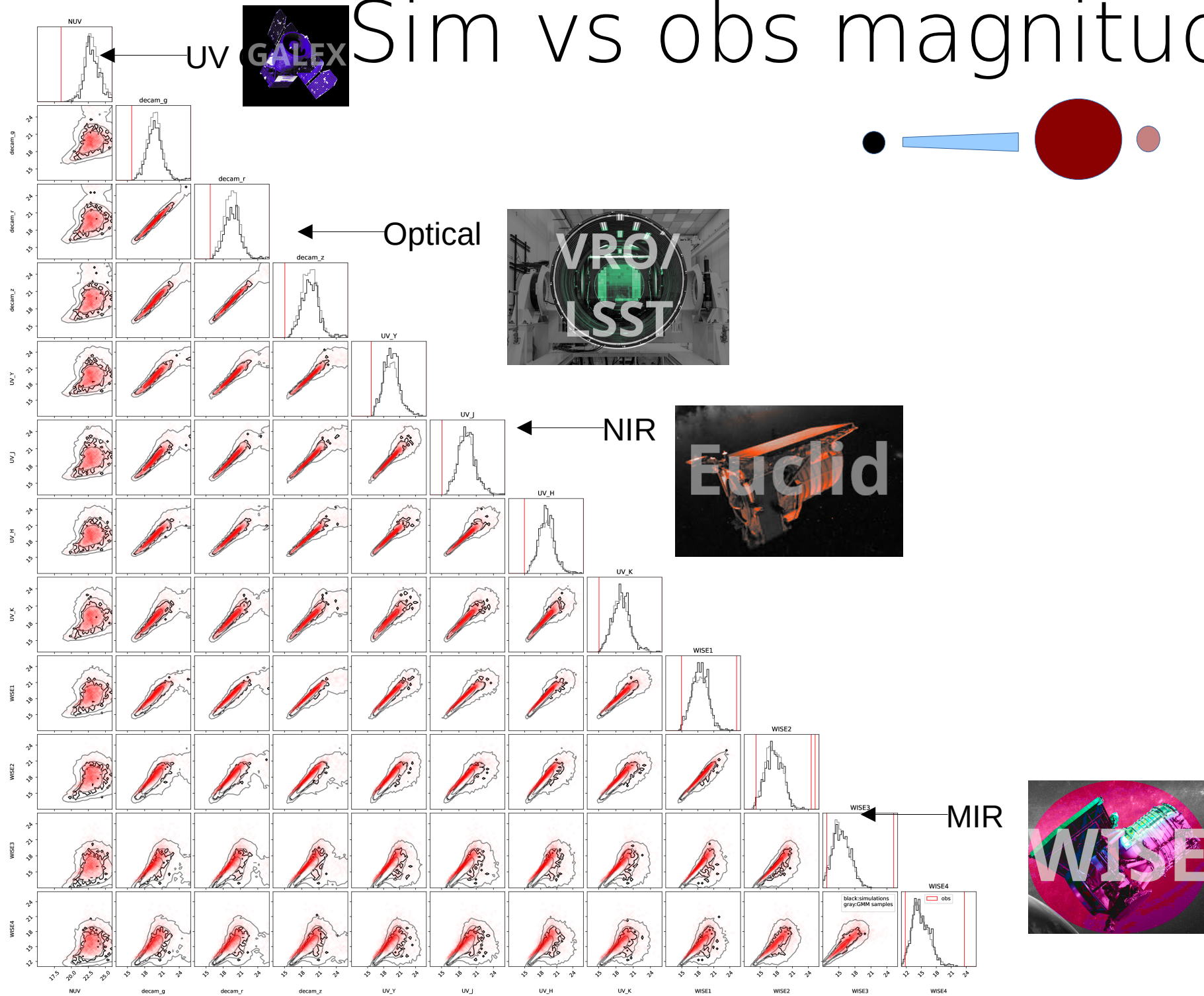


# Sim vs obs magnitudes

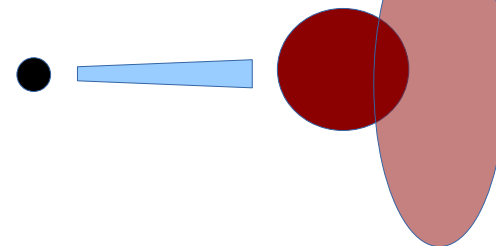
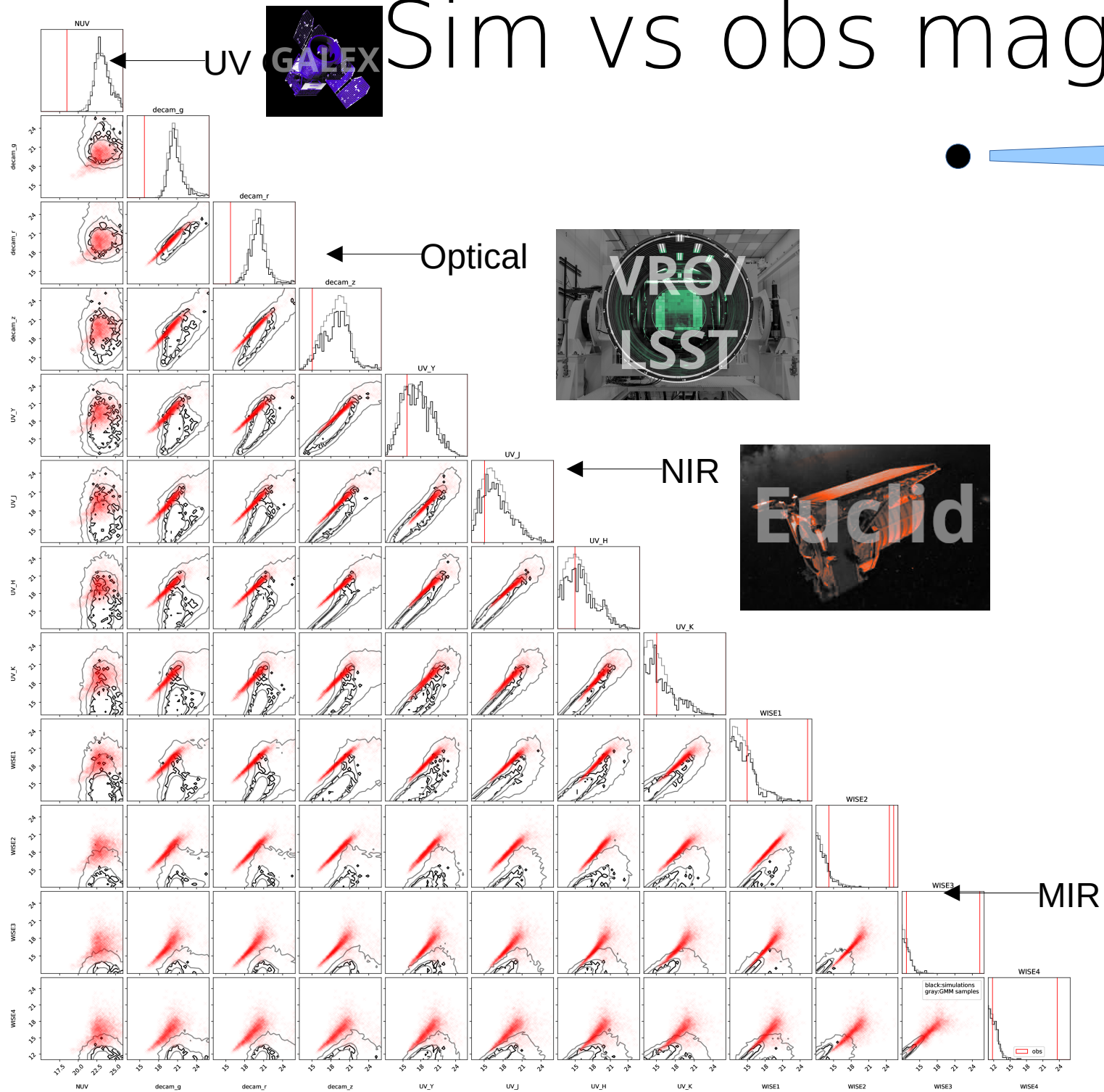




# Sim vs obs magnitudes



# Sim vs obs magnitudes



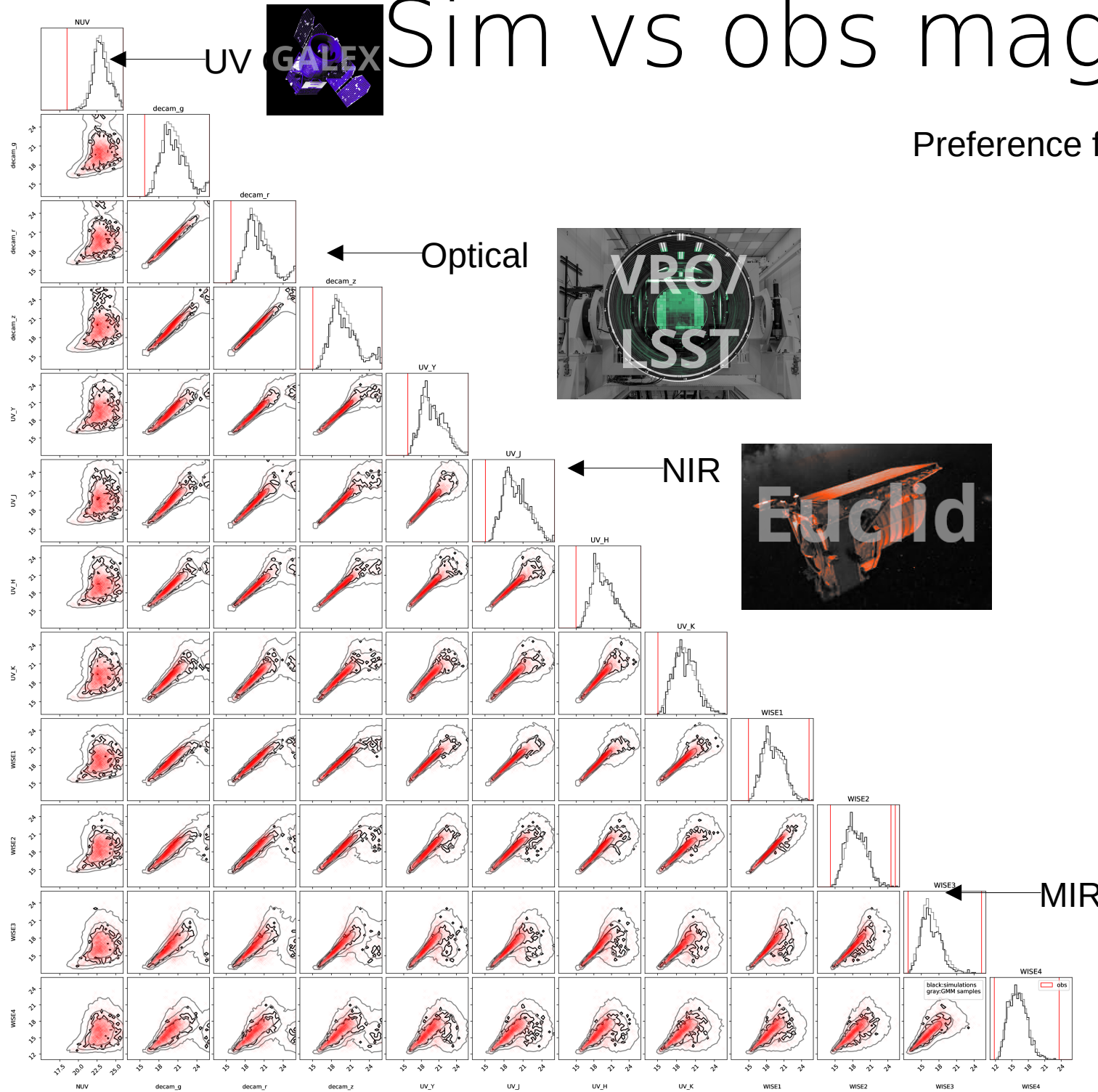
# Sim vs obs magnitudes





# Sim vs obs magnitudes

Preference for quiescent galaxies





# Sim vs obs magnitudes

Preference for star-forming galaxies



# Sim vs obs magnitudes



Super-Eddington: rare  
→ less outflows



# Sim vs obs magnitudes



Super-Eddington: Common  
→ more outflows







# Simulation-based Likelihood

**Goal: Compare data and model high-dimensional distributions**

→ need density estimator

Tested:

- Kernel density estimation
- **Gaussian Mixture Models**

Can support upper limits

**Normalizing flows**

Accurate but slowest

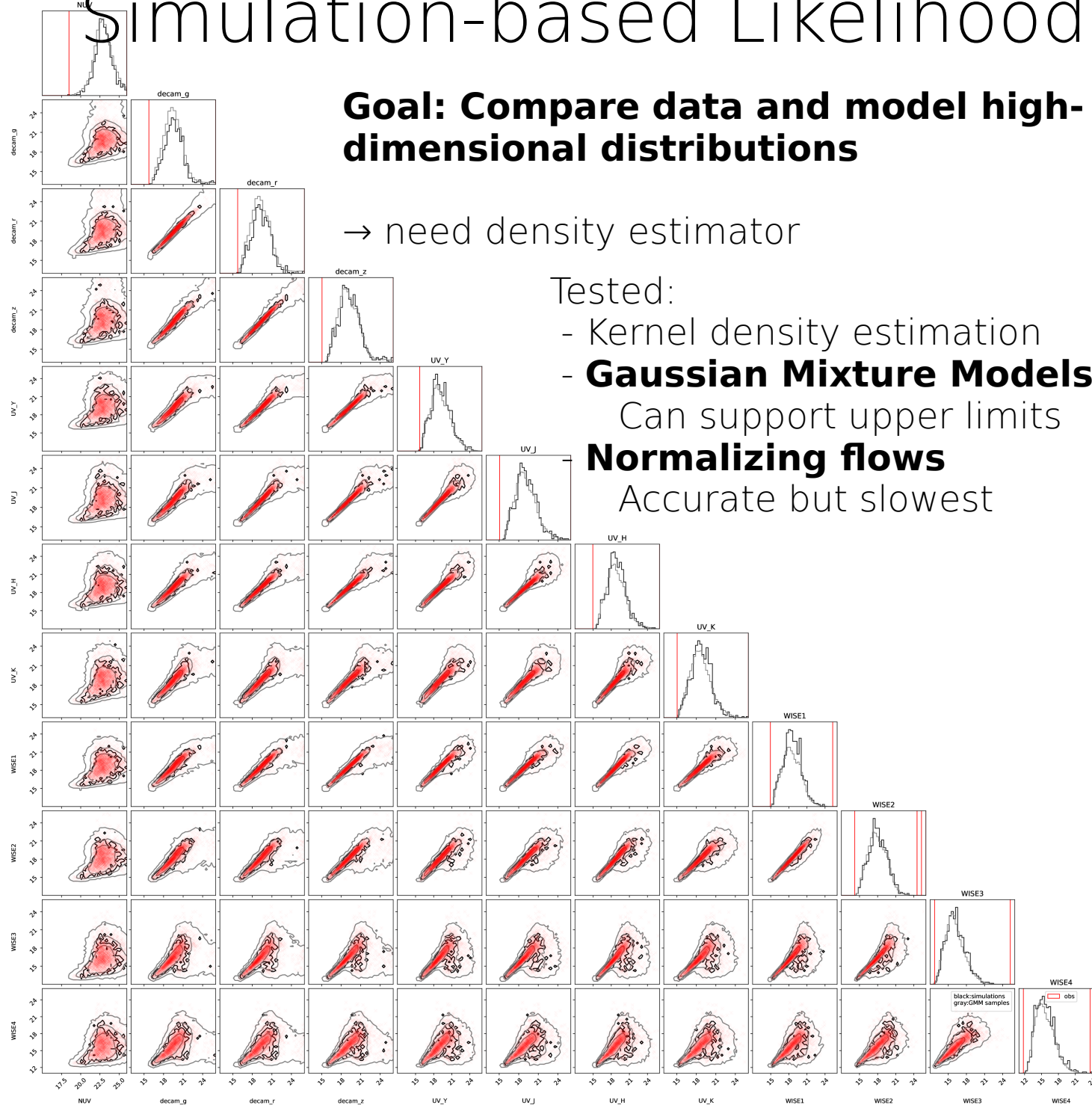
Custom AI-accelerated  
Bayesian inference

Currently:

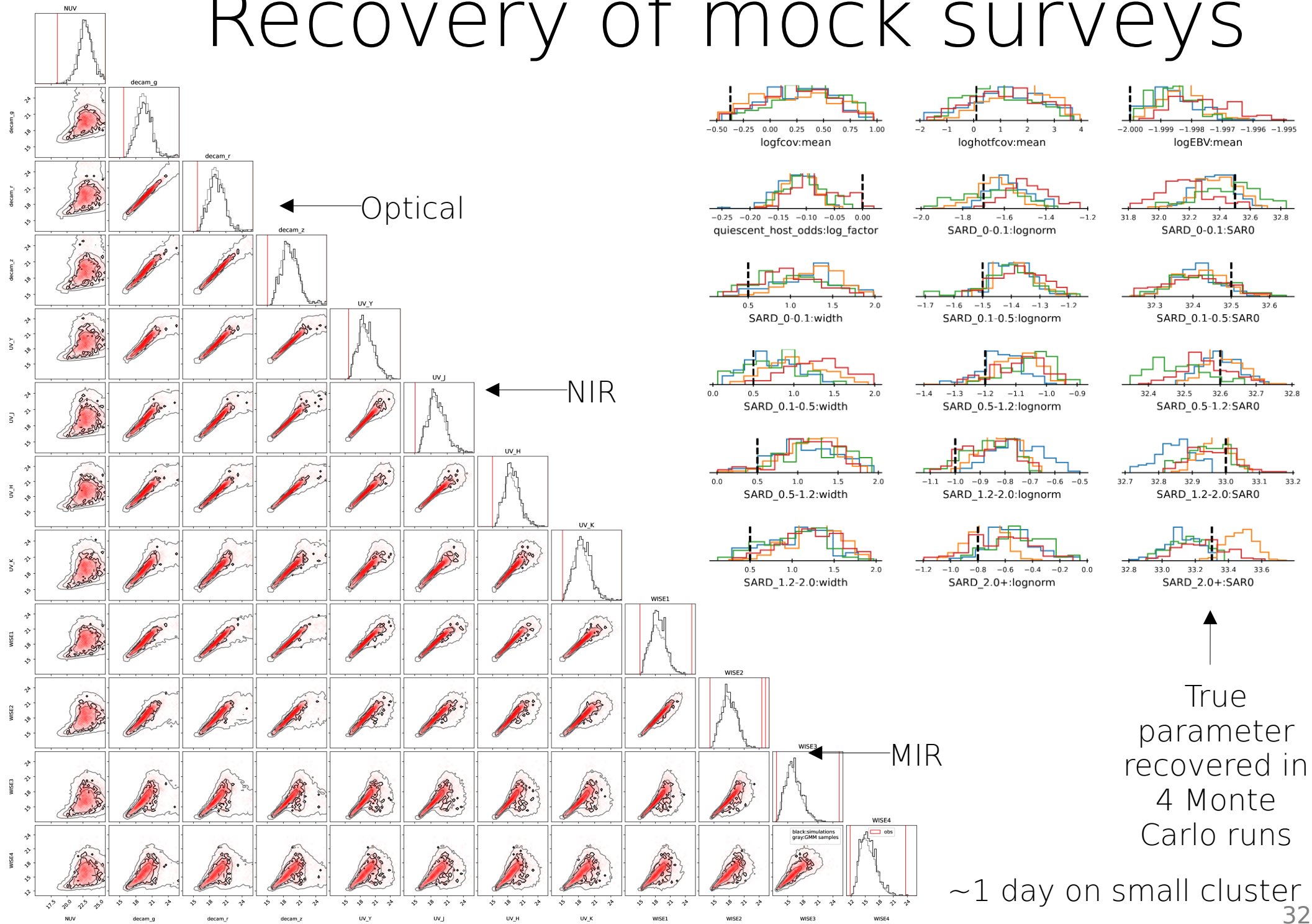
- 1) jax-based GMM - warm up MCMC sampling
- 2) train parametric MDN
- 3) DEMCMC sampling

supports upper limits  
supports photoz+specz

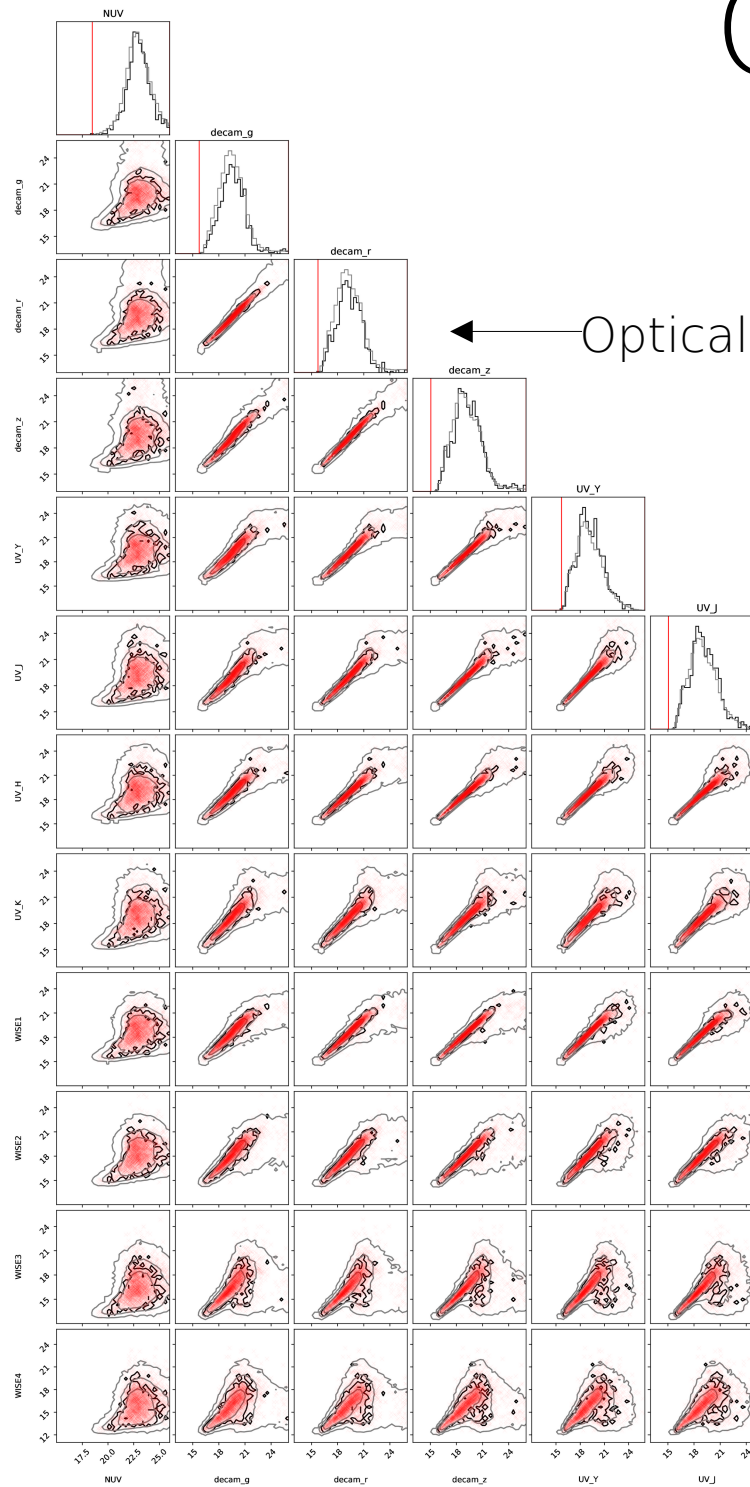
future: sbi end-to-end



# Recovery of mock surveys



# Outlook: future data



**Tackle** the multi-dimensional degeneracies:

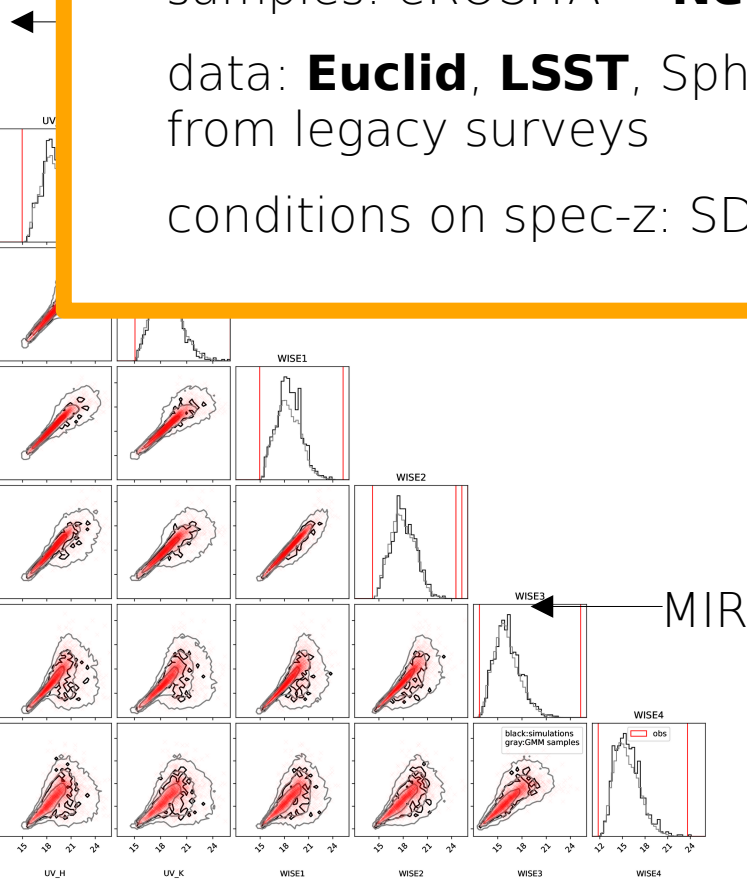
AGN luminosity, obscuration,  
*black hole mass*, host galaxy mass,  
SFR, extinction, *morphology*, *size*

**Ready** for future data:

samples: eROSITA → **NewAthena**

data: **Euclid**, **LSST**, SphereX, ..., + upper limits  
from legacy surveys

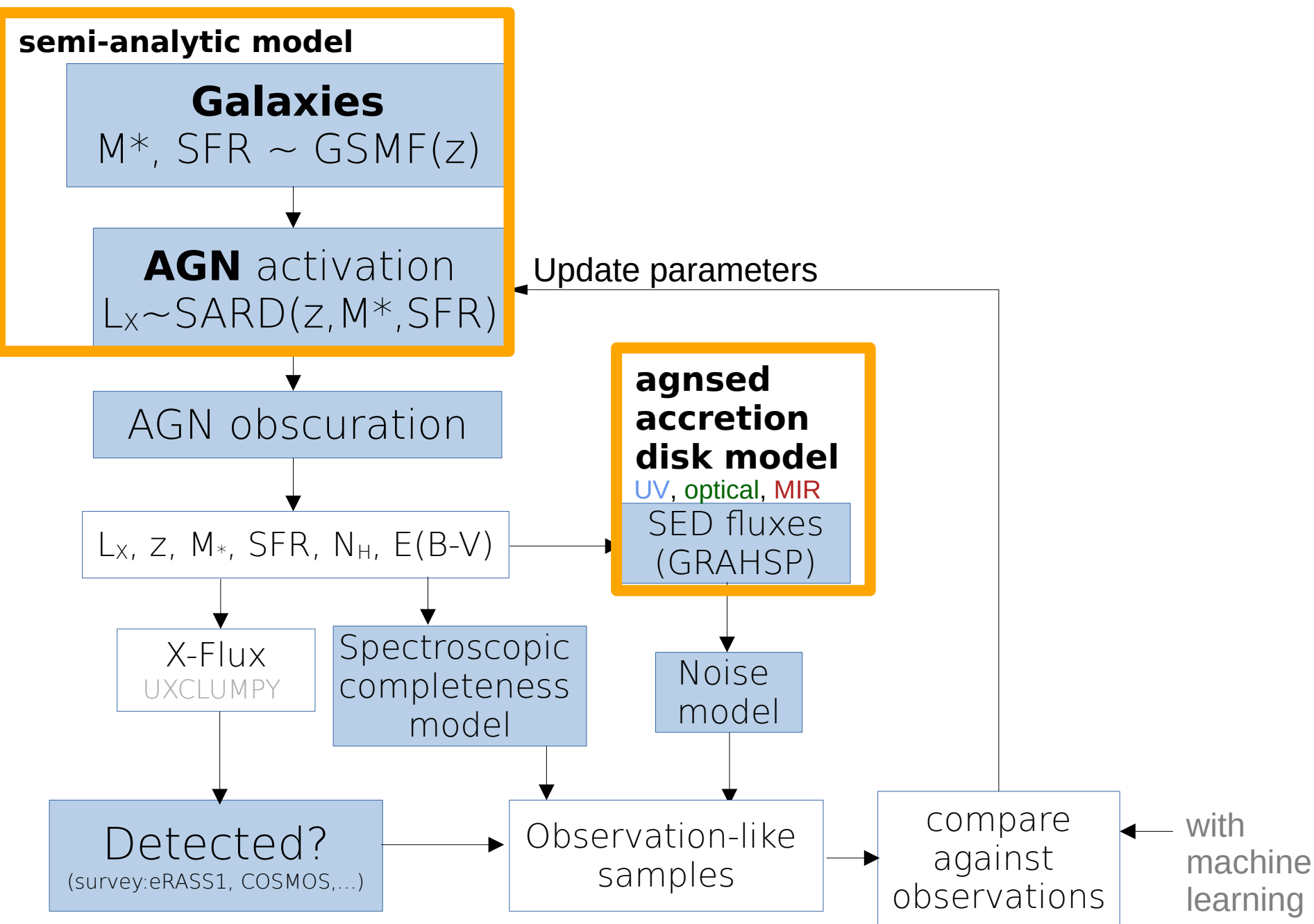
conditions on spec-z: SDSS, **DESI**, **4MOST**



~1 day on small cluster



# Outlook: future physics



# Takehome messages

- “unbiased” SED fitting tool: GRAHSP
  - captures real diversity in AGN
- Precision understanding of the interaction of galaxy-AGN over cosmic time
  - Flickering, highly multi-variate problem, selection effects
  - A new plugin likelihood approach to fitting demographics to real, large surveys
  - New modelling approach

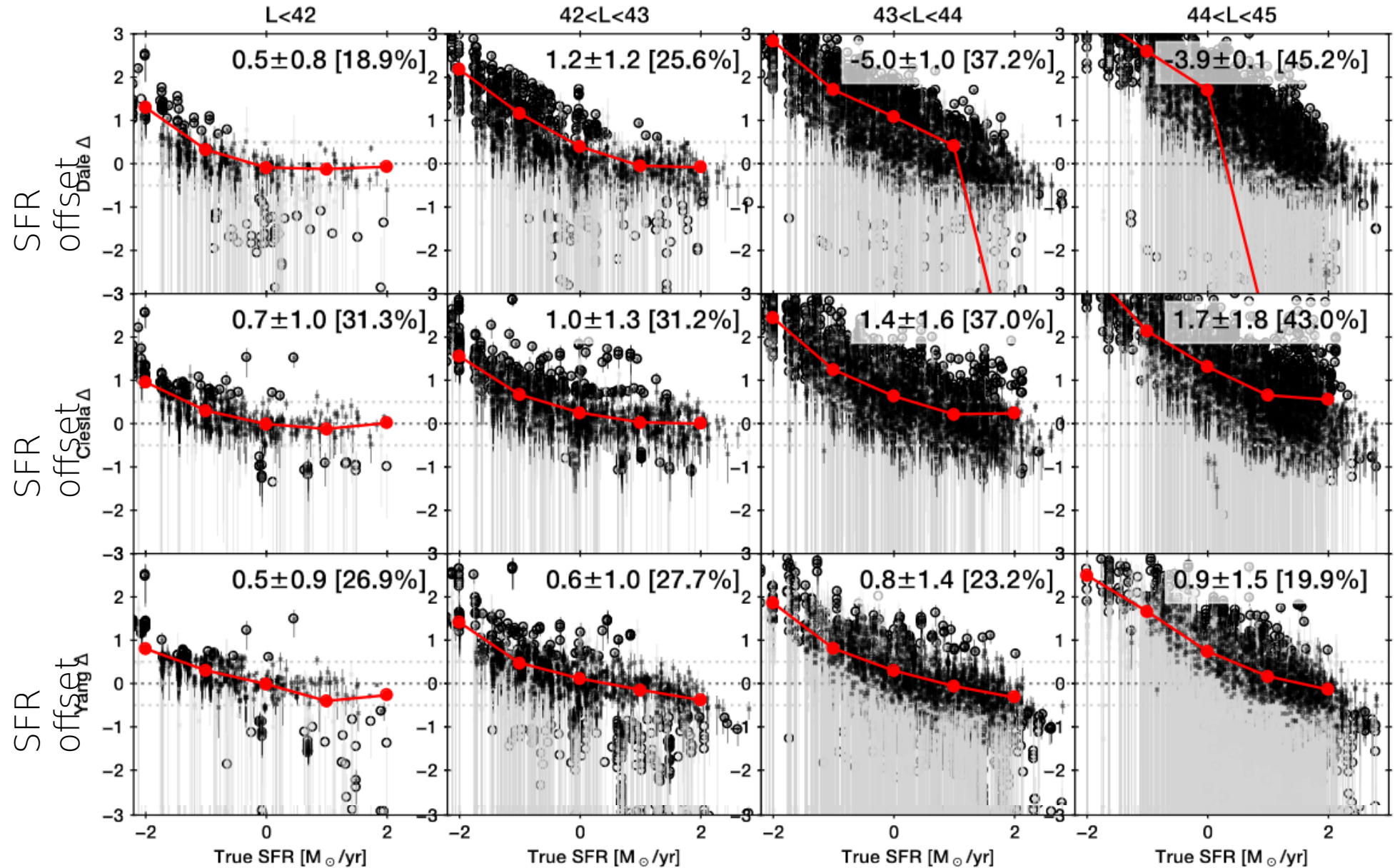
BH physics  
&  
Galaxy evolution  
models



population  
inference

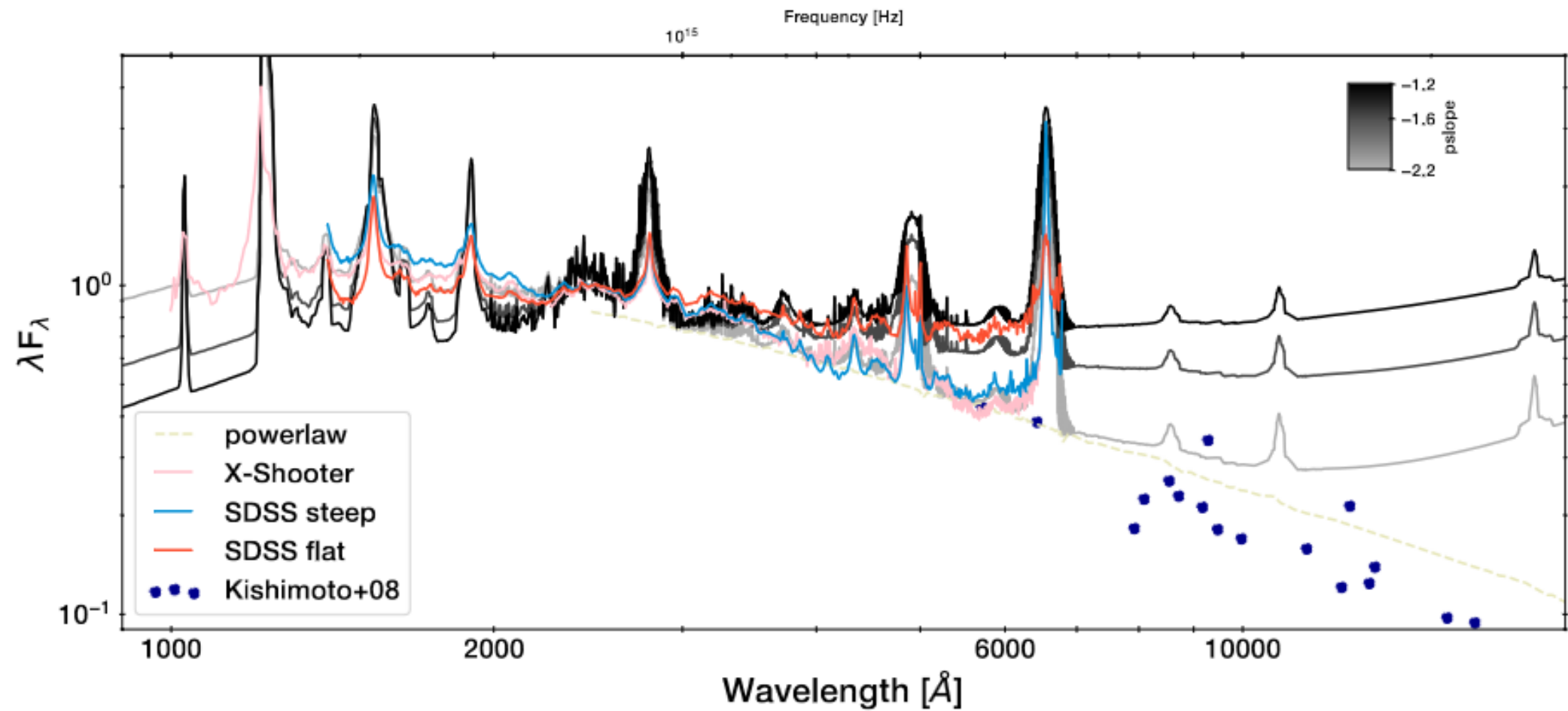


# up-bias & large scatter also for SFR





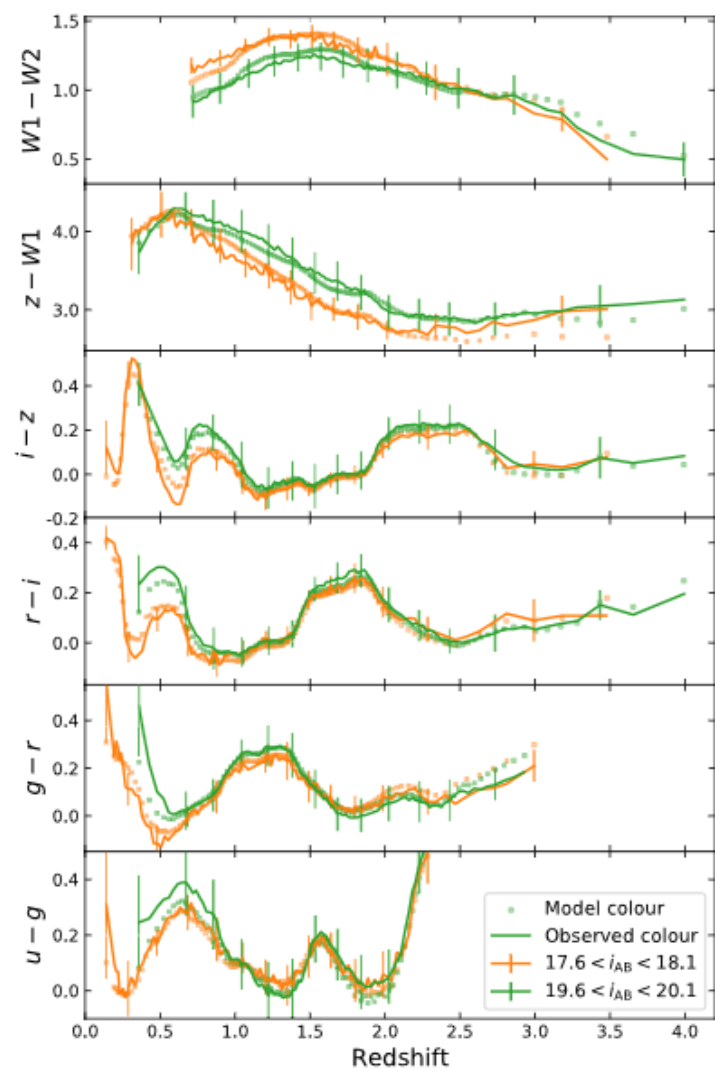
# Test #1: quasar spectra



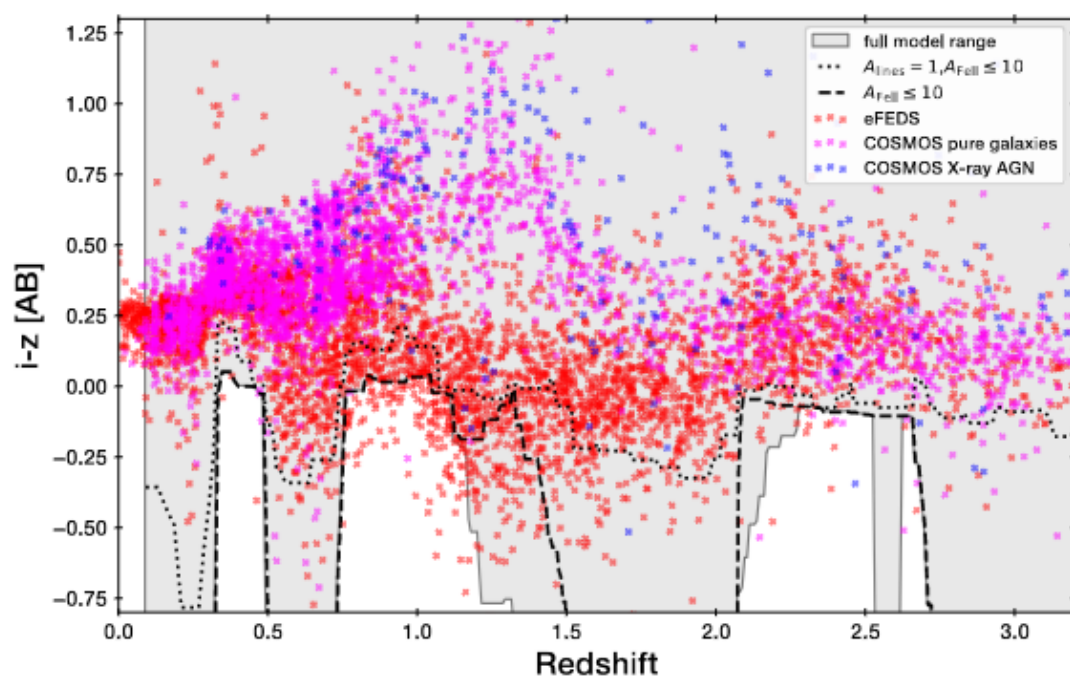
# Test #2: colors

## Average colors of quasars?

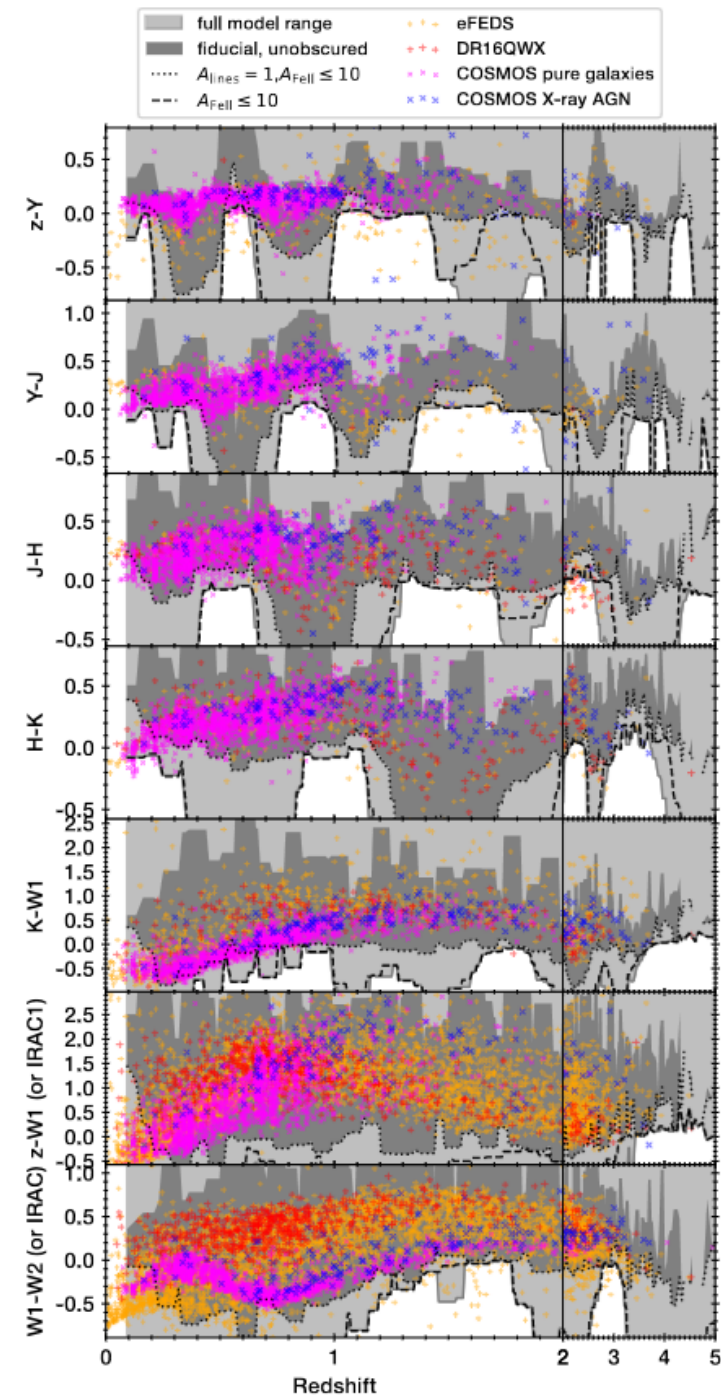
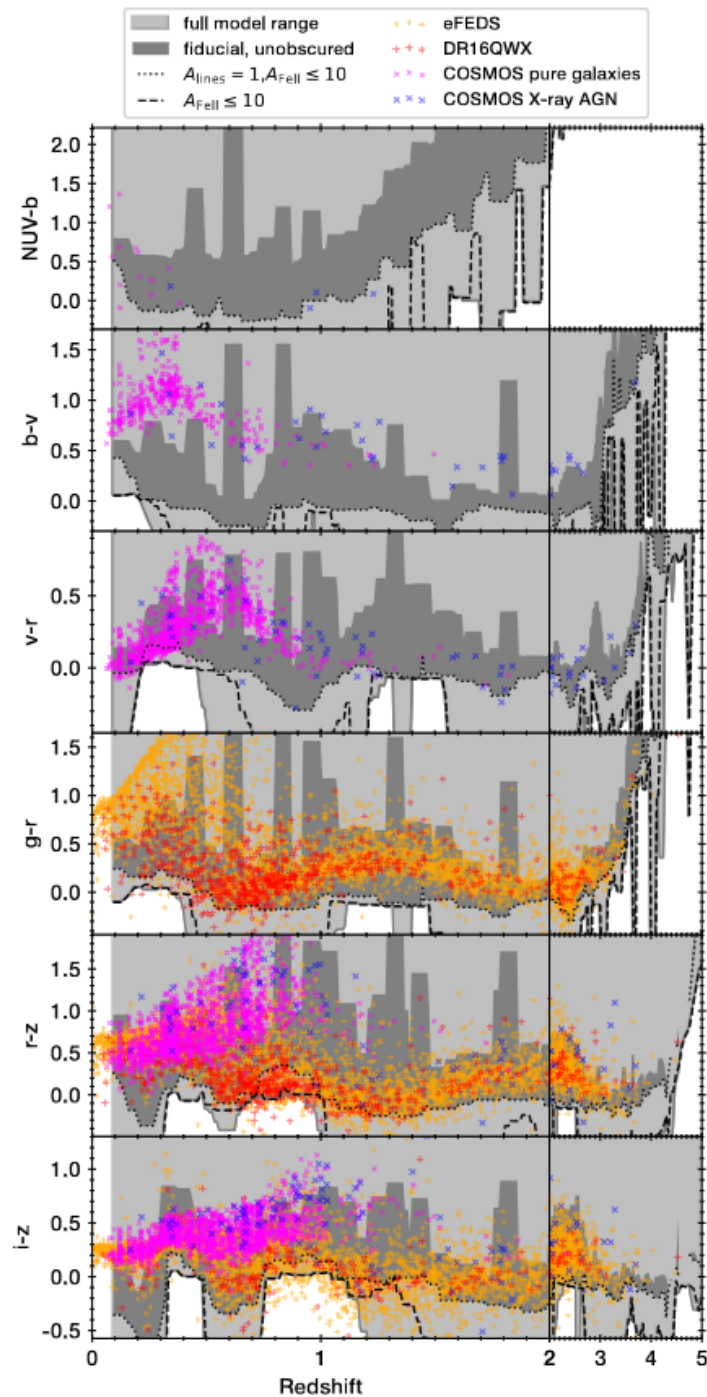
Temple, Hewett & Banerji 2023



## Diversity of colors of AGN & galaxies



# Test #2: full diversity of colors





# Test #3: Brown AGN SED Atlas

- Compilation of spectra and photometry
- Extinction-corrected, aperture-corrected

