How much is that black hole in the window?

(Robustness testing in Stellar Dynamical Modeling)

Berkeley Big BH Bunch:
Emily Liepold
Jacob Pilawa
Matthew Quenneville
Chung-Pei Ma

Emily Liepold, postdoc @ UC Berkeley Astronomy
emilyliepold@berkeley.edu

The context of our science

Overview of how we do our science

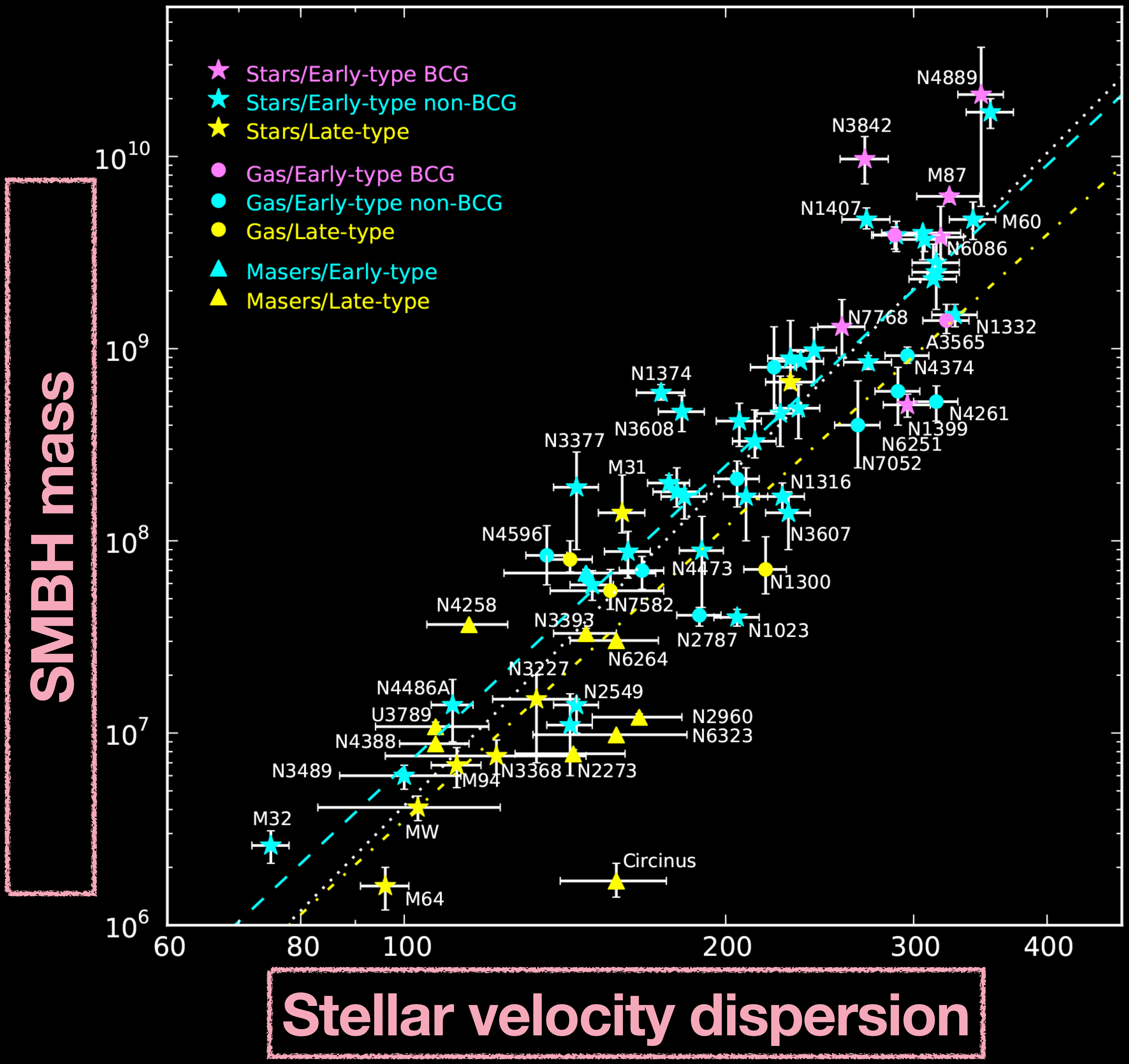
The robustness problem in stellar dynamical modeling

(and our attempts to address that problem)

Case study: The Berkeley group's approach

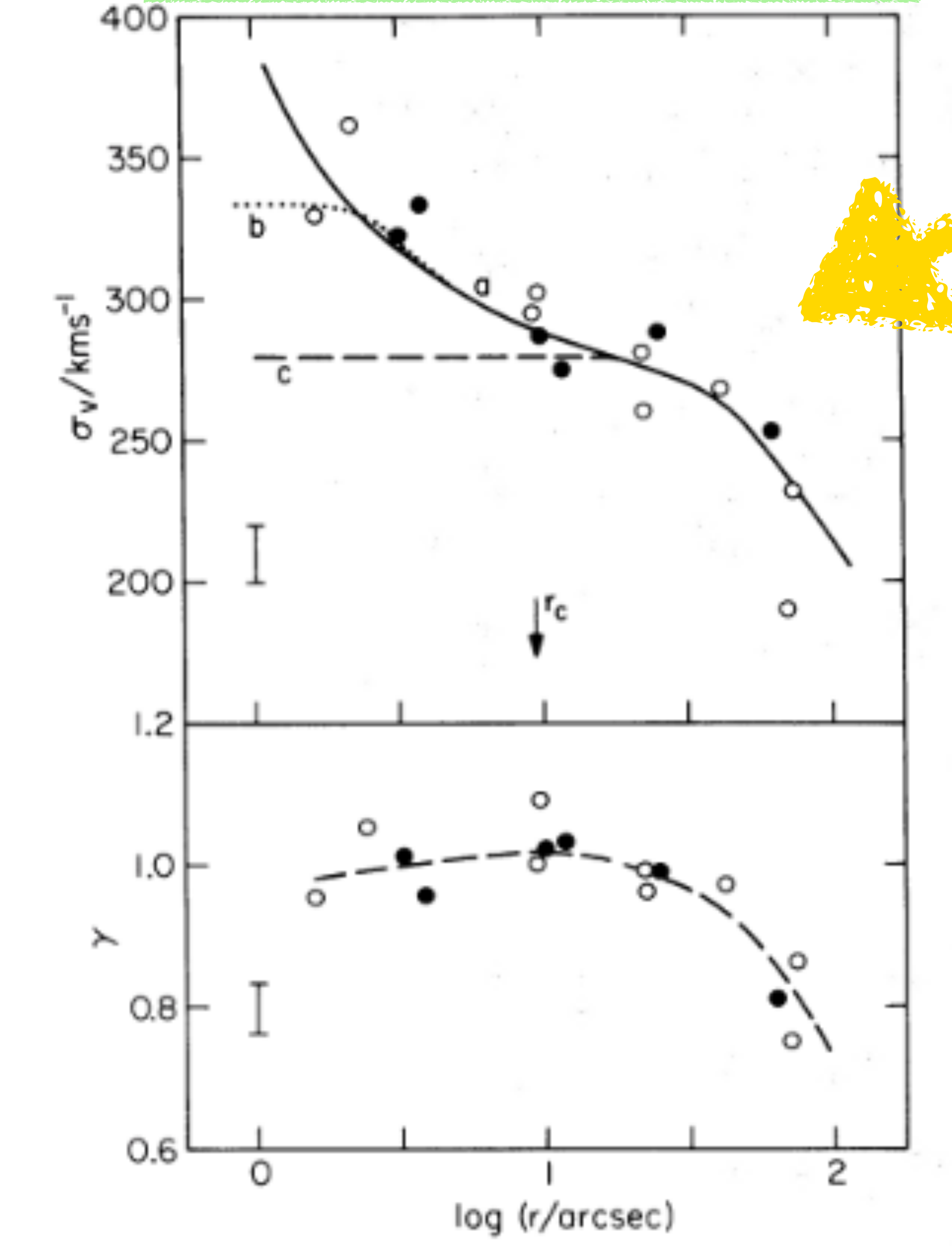
SMBH masses are linked to galaxy properties

- Supermassive black hole masses are ***correlated*** with galaxy properties through coevolution
- The form of the correlation constrains models for coevolution
- Precise constraints on those correlations ***require*** precise measurements of individual SMBH masses and galaxy parameters



High-precision stellar dynamical SMBH measurement is now possible

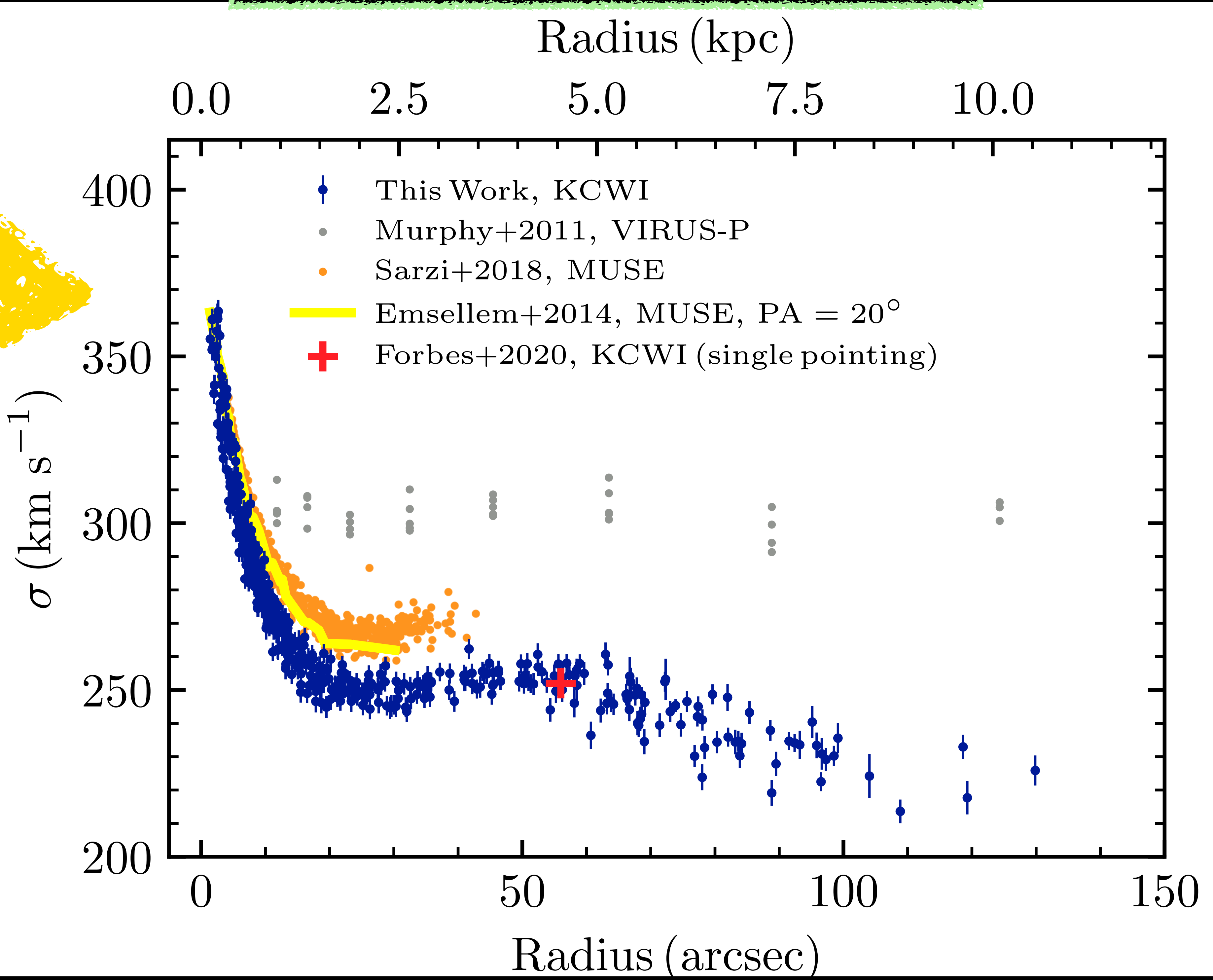
Sargent+78



M87 velocity dispersion profile

Improved data
+
Improved models
=
Improved measurements

Liepold+23



Stellar dynamical modeling

Idea: stellar motions are related to the potential they move within

Higher enclosed mass ≈ Higher stellar velocity

Measure stellar motions → Infer mass distribution

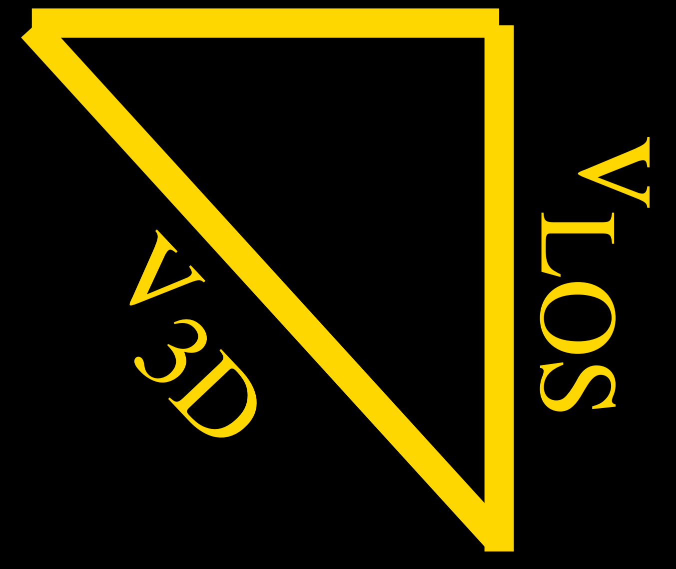
But a complication!

We only measure velocity along line of sight:

Is orbit aligned with LOS and measured velocity is 3D velocity?

Or very misaligned and 3D velocity is ***much*** larger?

Stellar dynamical modeling



Jeans modeling:

Assume:

Specific form for connection between v_{LOS} and v_{3D}

Specific forms for galaxy shape (spherical or axisymmetric)

Schwarzschild orbit modeling:

Model full 3D orbit structure and find the v_{3D} distribution which is most consistent with v_{LOS}.

An extra quirk: the 3D galaxy shape impacts allowed orbits and allowed 3D orbit structure. Very general shapes → very general orbit structures.

(The most general and flexible models are ***triaxial Schwarzschild models)***

How to measure SMBHs

Triaxial Schwarzschild Modeling

Schwarzschild+79
Schwarzschild+93

How to measure SMBHs

Triaxial Schwarzschild Modeling

Schwarzschild+79
Schwarzschild+93

Propose a potential

How to measure SMBHs

Triaxial Schwarzschild Modeling

Schwarzschild+79
Schwarzschild+93

Propose a potential

Integrate $\mathcal{O}(10^5)$ representative stellar orbits

How to measure SMBHs

Triaxial Schwarzschild Modeling

Schwarzschild+79
Schwarzschild+93

Propose a potential

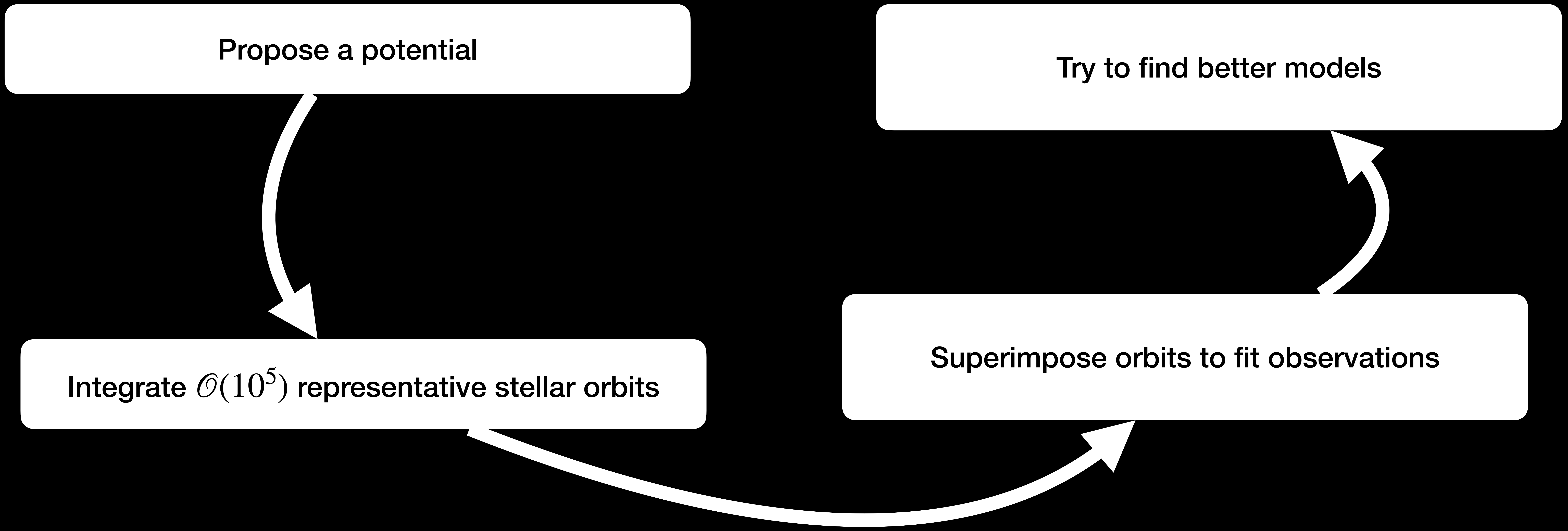
Integrate $\mathcal{O}(10^5)$ representative stellar orbits

Superimpose orbits to fit observations

How to measure SMBHs

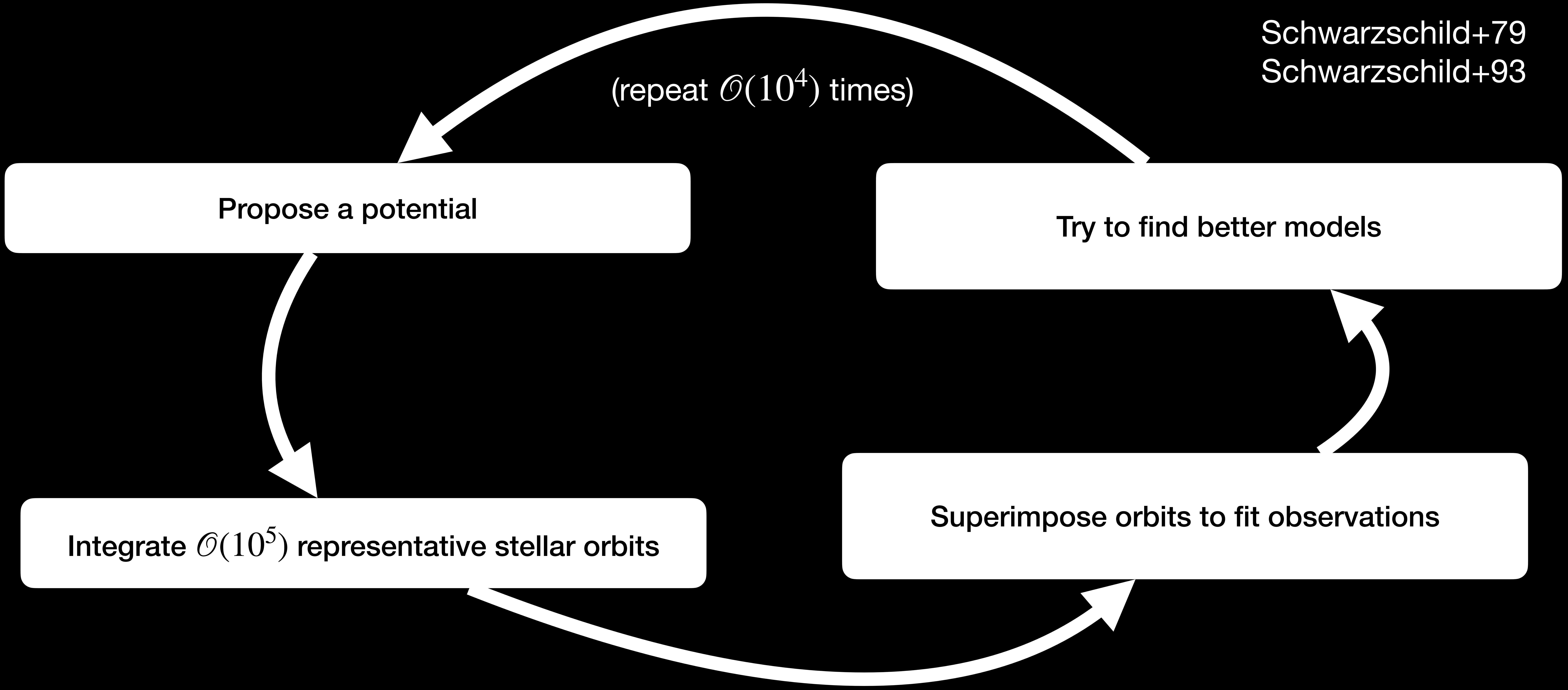
Triaxial Schwarzschild Modeling

Schwarzschild+79
Schwarzschild+93



How to measure SMBHs

Triaxial Schwarzschild Modeling

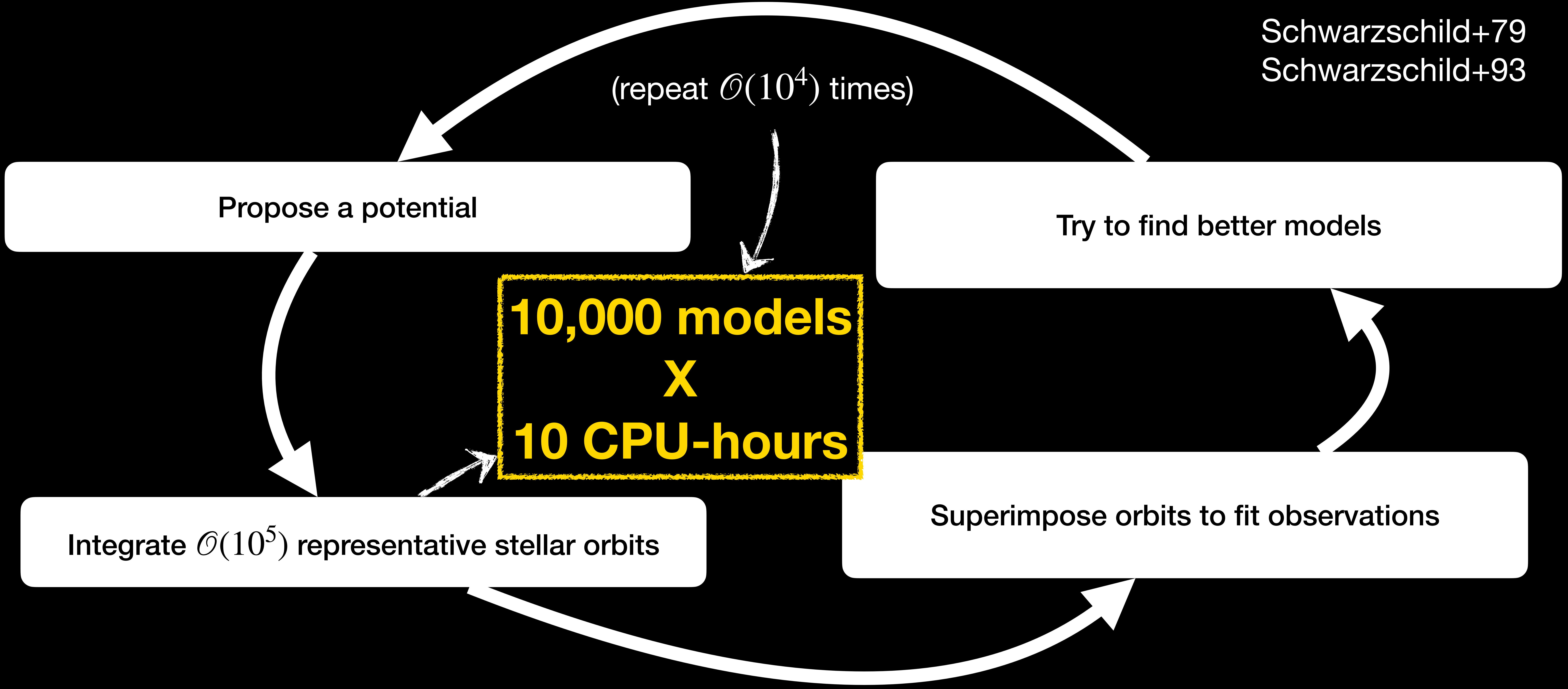


Schwarzschild+79
Schwarzschild+93

How to measure SMBHs

Triaxial Schwarzschild Modeling

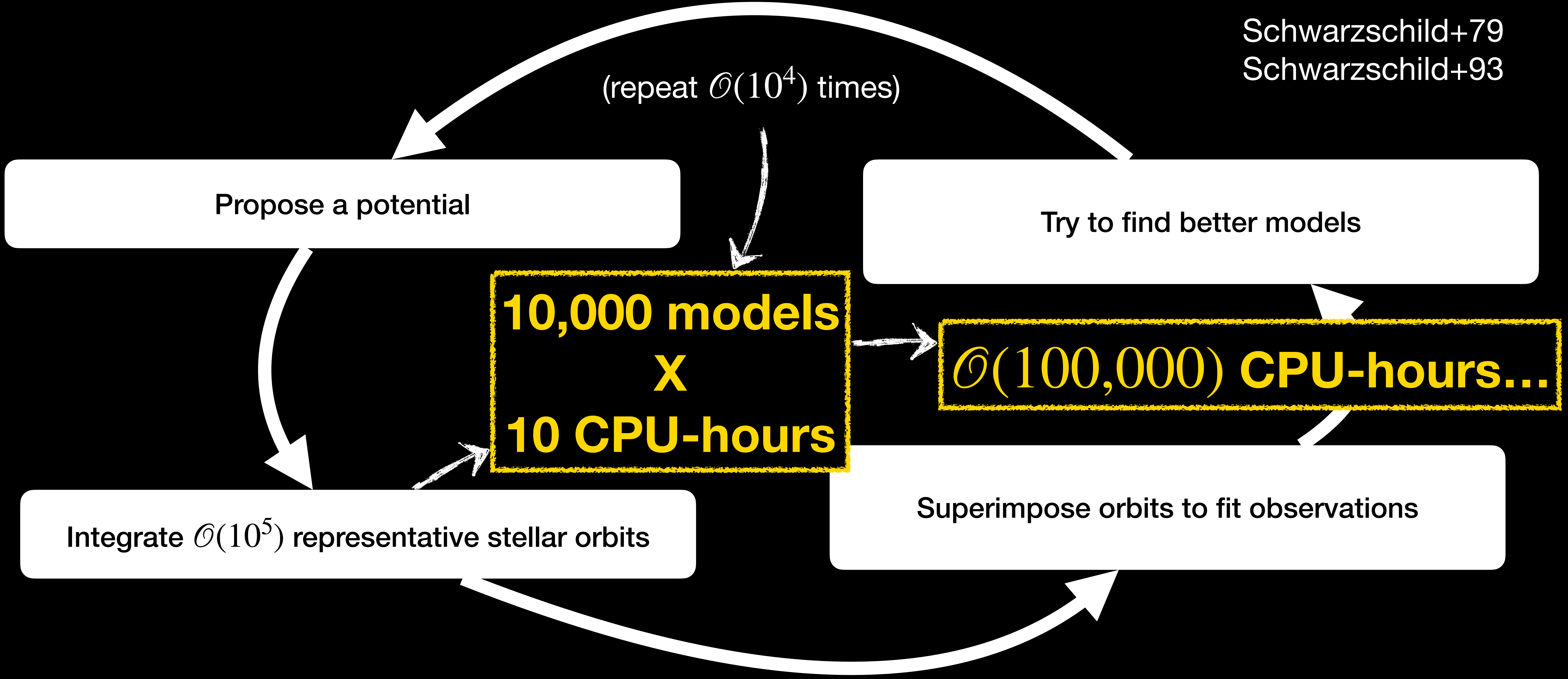
Schwarzschild+79
Schwarzschild+93



How to measure SMBHs

Triaxial Schwarzschild Modeling

Schwarzschild+79
Schwarzschild+93



How to **measure** SMBHs

Triaxial Schwarzschild Modeling

Schwarzschild+79
arzschild+93

Unfortunately, a large-ish parameter-space:

Black hole mass
Stellar Mass-to-light ratio
Dark matter halo mass (1 or 2 parameters)
Intrinsic shape (3 parameters

els

X

10 CPU-hours

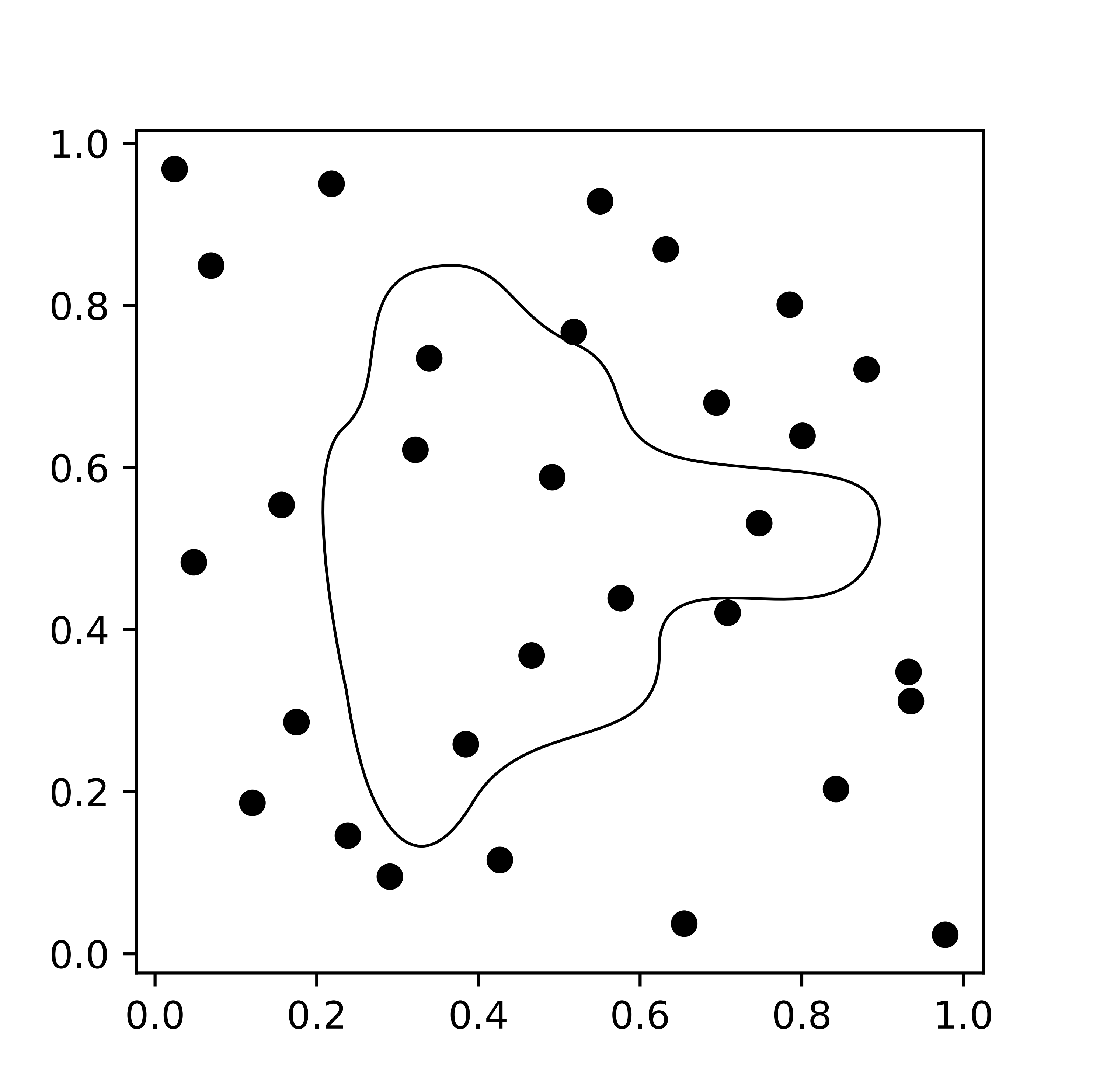
$\mathcal{O}(100{,}000)$ **CPU-hours…**

Integrate $\mathcal{O}(10^5)$ representative stellar orbits

Superimpose orbits to fit observations

Model Search using Gaussian Process regression and iterative search:

- Run uninformed set of models
- Model χ^2 surface with GP
- Populate low $\Delta\chi^2$ volume
- Rinse and Repeat

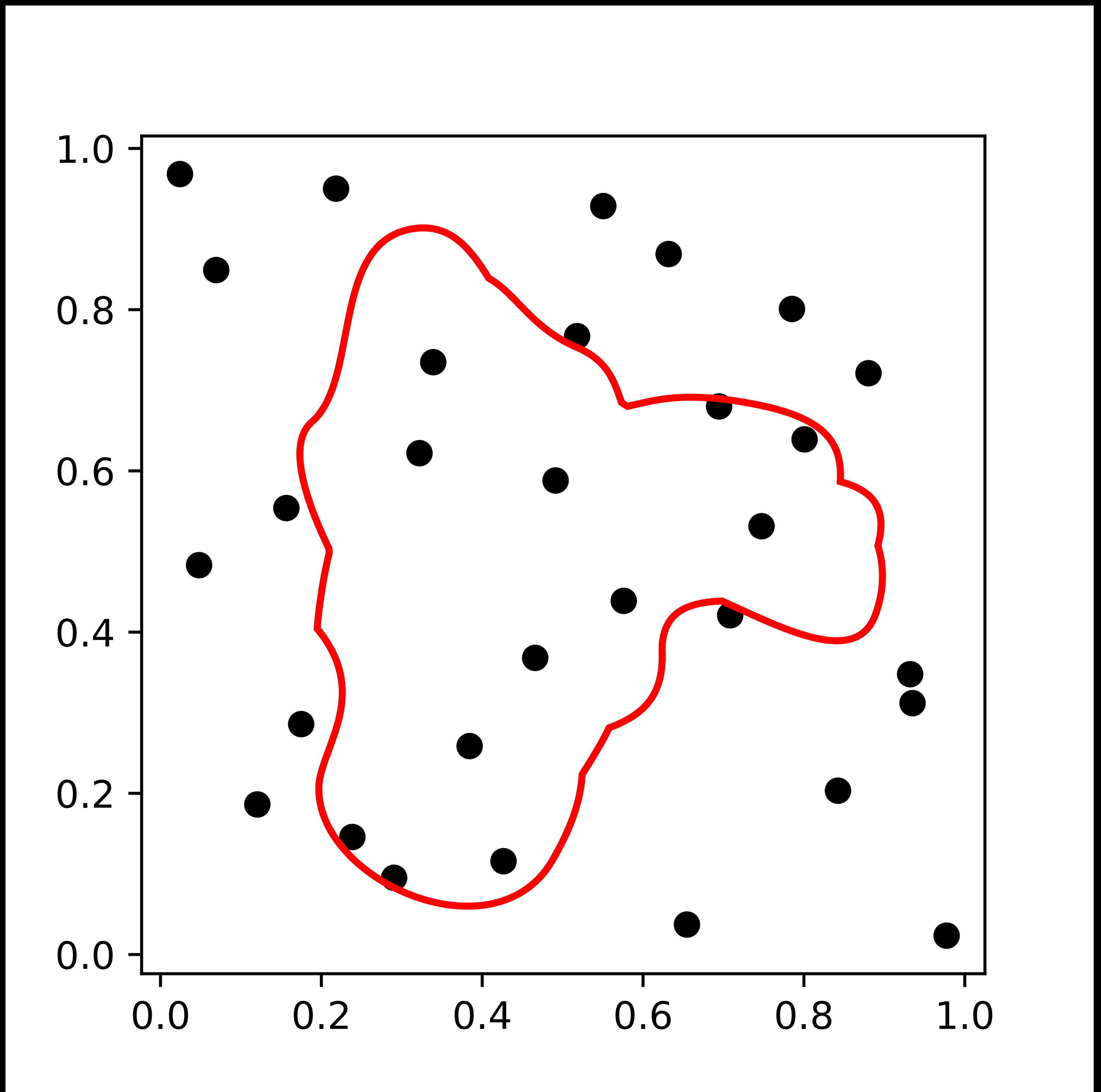


Dynamic Nested Sampling:

- Use GP Surrogate model
- Sample parameter space w/ Dynesty

Model Search using Gaussian Process regression and iterative search:

- Run uninformed set of models
- Model χ^2 surface with GP
- Populate low $\Delta\chi^2$ volume
- Rinse and Repeat

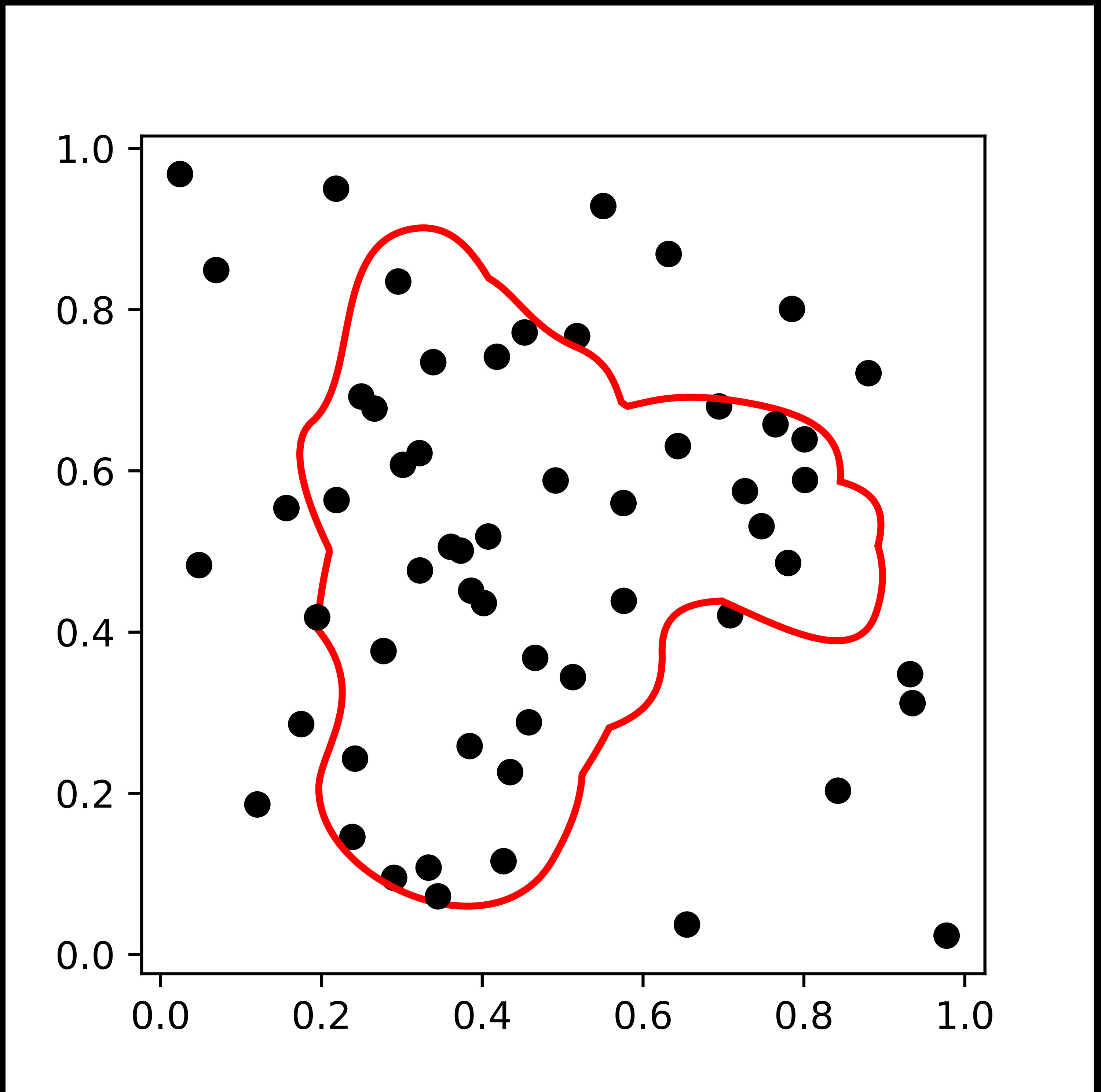


Dynamic Nested Sampling:

- Use GP Surrogate model
- Sample parameter space w/ Dynesty

Model Search using Gaussian Process regression and iterative search:

- Run uninformed set of models
- Model χ^2 surface with GP
- Populate low $\Delta\chi^2$ volume
- Rinse and Repeat

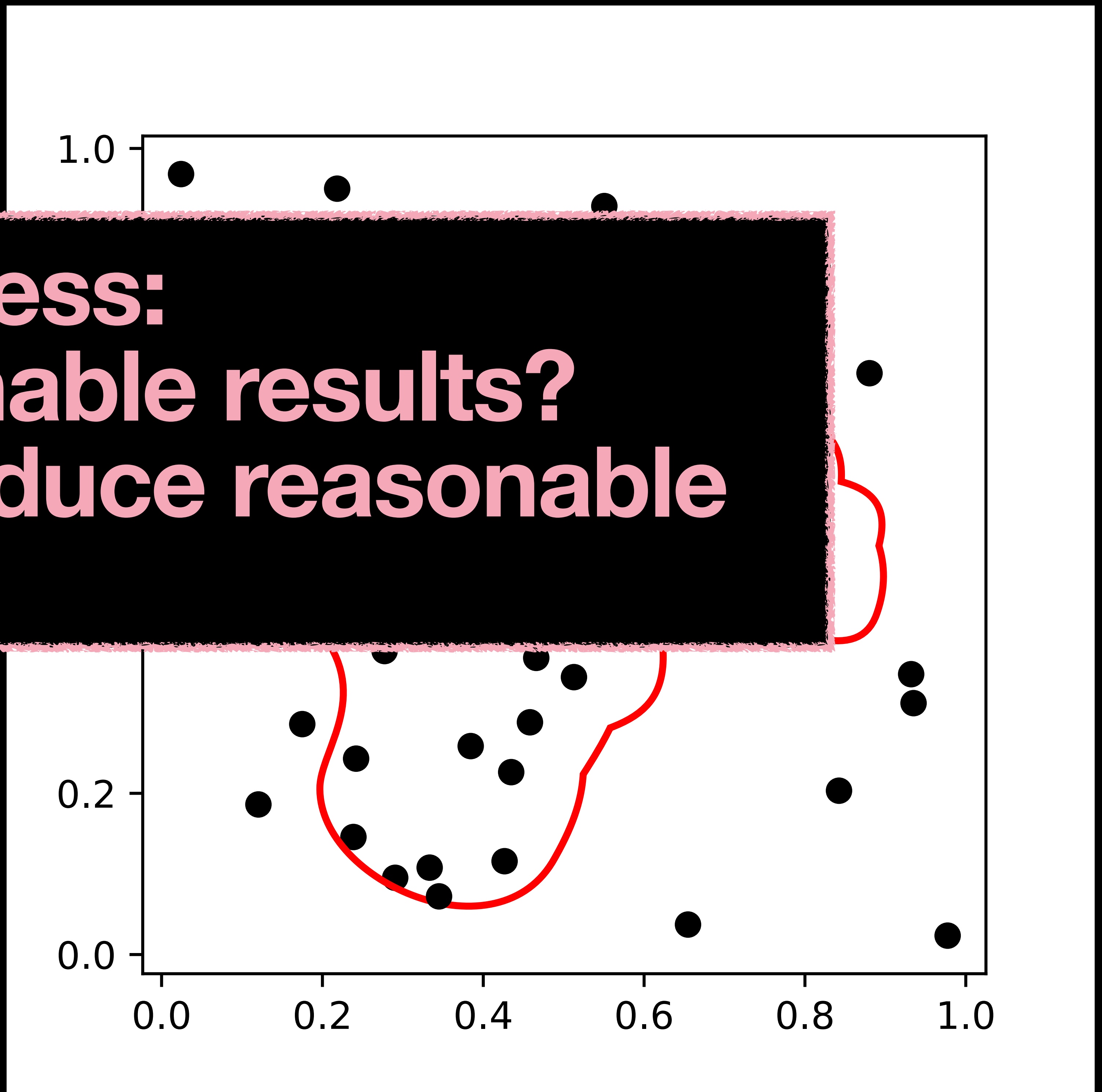


Dynamic Nested Sampling:

- Use GP Surrogate model
- Sample parameter space w/ Dynesty

Model Search using Gaussian Process regression and iterative search:

- Run uninformed set of models
- Mod
- Pop
- Rinse and Repeat



Two layers of robustness:
Do our models produce reasonable results?
Does our parameter inference produce reasonable results?

Dynamic Nested Sampling:

- Use GP Surrogate model
- Sample parameter space w/ Dynesty

The robustness problem in stellar dynamical modeling

Given observations of a galaxy with a set of physical parameters, are our measurements both accurate and precise?

Problem 1:

Triaxial orbit modeling is least assumption-laden stellar dynamical scheme.

Assumptions on galaxy shape, symmetry, orbital structure ***may*** be linked to biases.

→ We can’t compare our models against more sophisticated / comprehensive models

Problem 2:

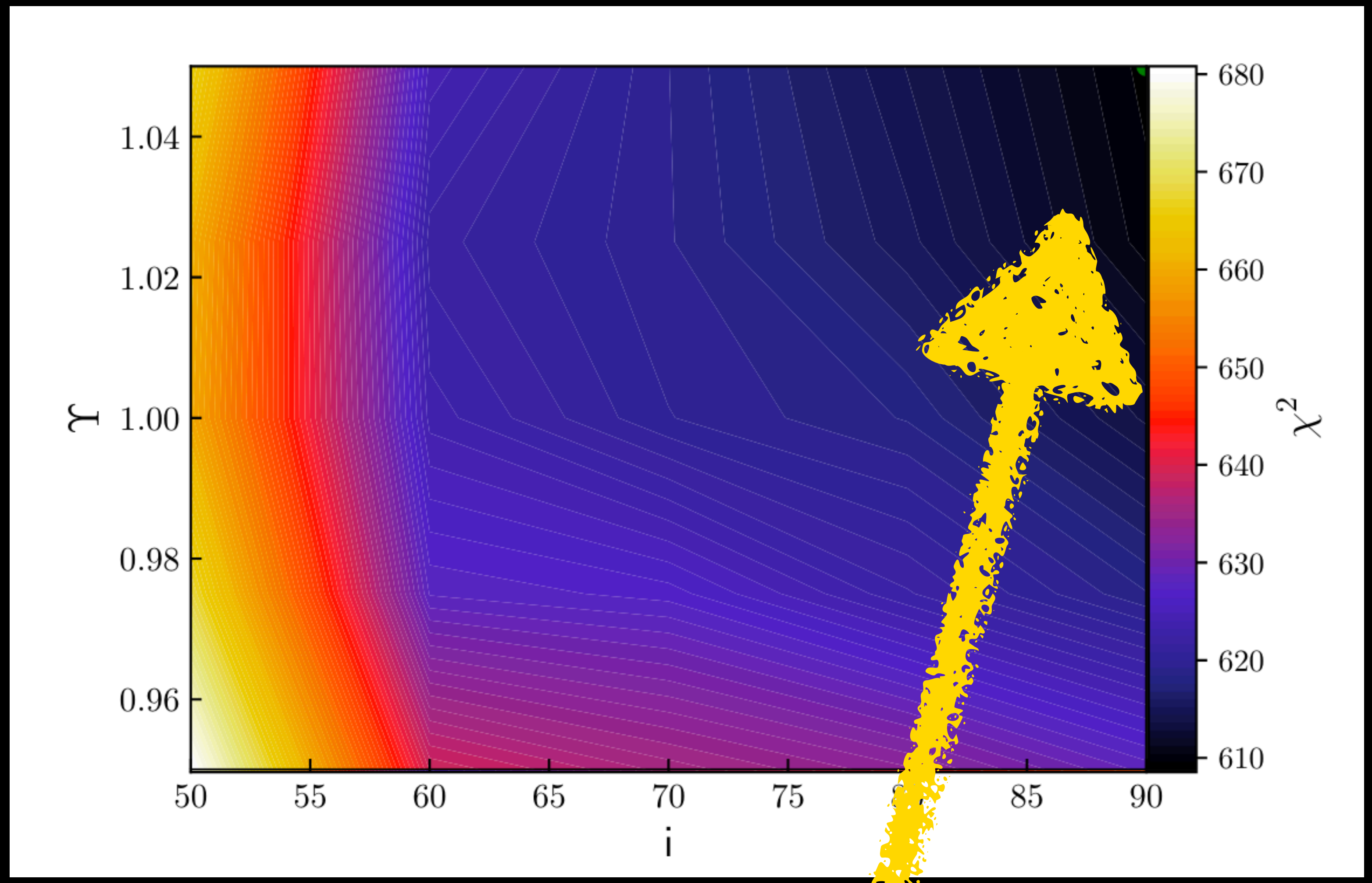
No* robust framework exists for constructing artificial galaxy data for ***triaxial*** galaxies with central SMBHs

→ We can’t* test our models against reference models

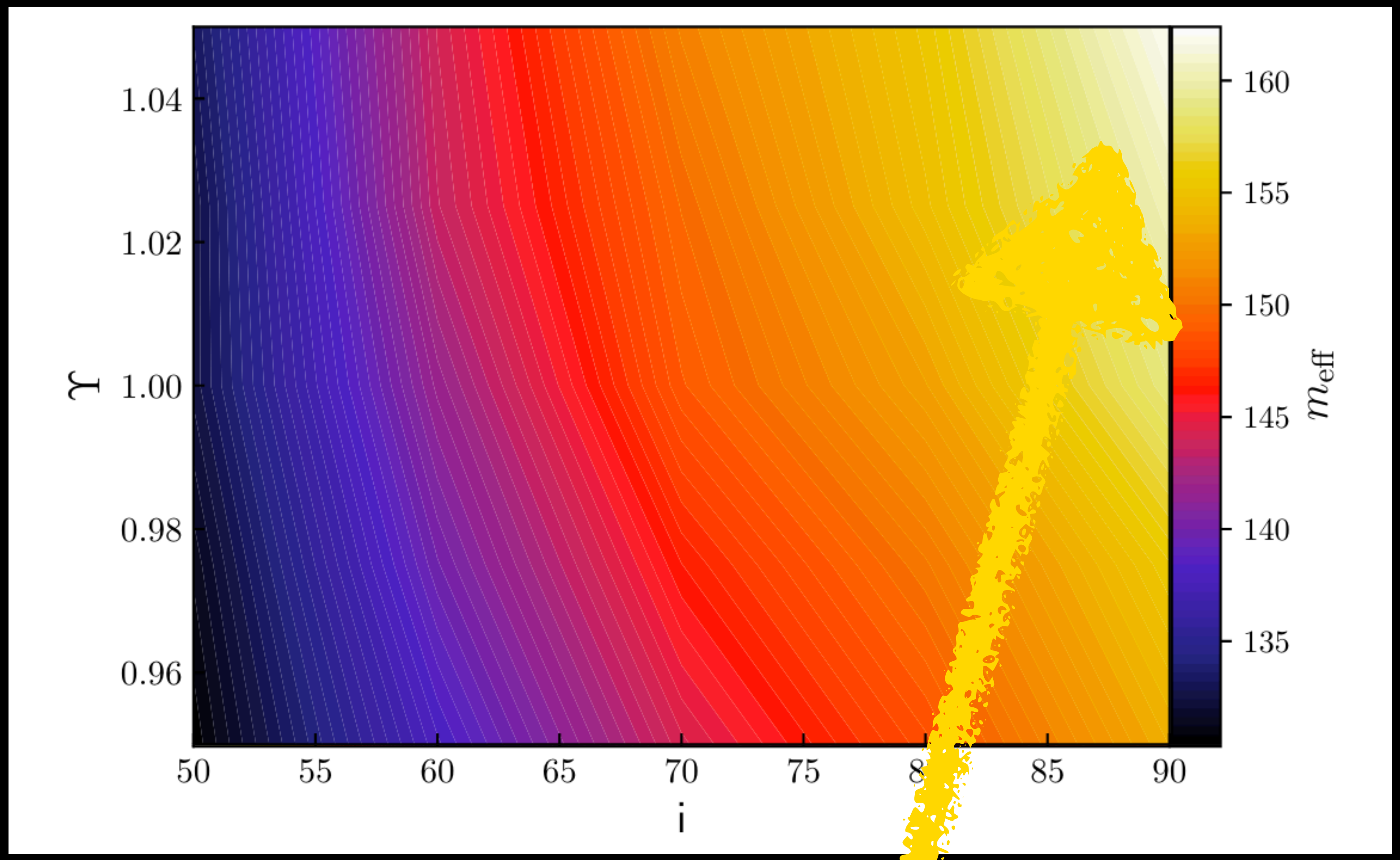
Are orbit models inherently biased? (Lipka + Thomas 2021)

In nonlinear models, the number degrees of freedom ***may*** vary throughout the parameterspace

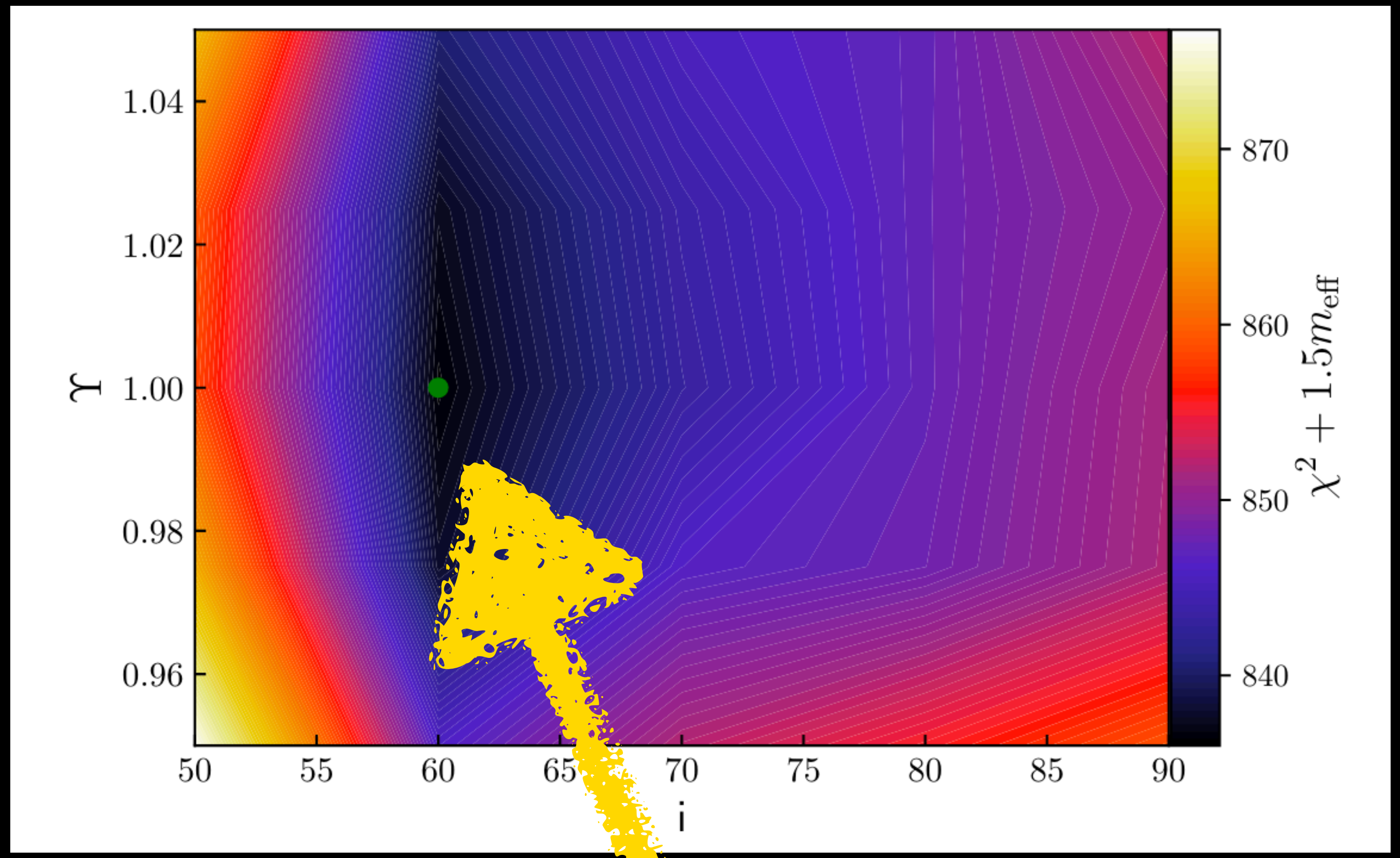
Lipka+Thomas explore number of generalized DOFs in axisymmetric orbit models



Goodness of fit



Number of DOF



Corrected Goodness of fit

Probably not! (Pilawa, Liepold, Ma 2024)

Idea:

Use triaxial Schwarzschild models to create mock galaxy data from real galaxy data

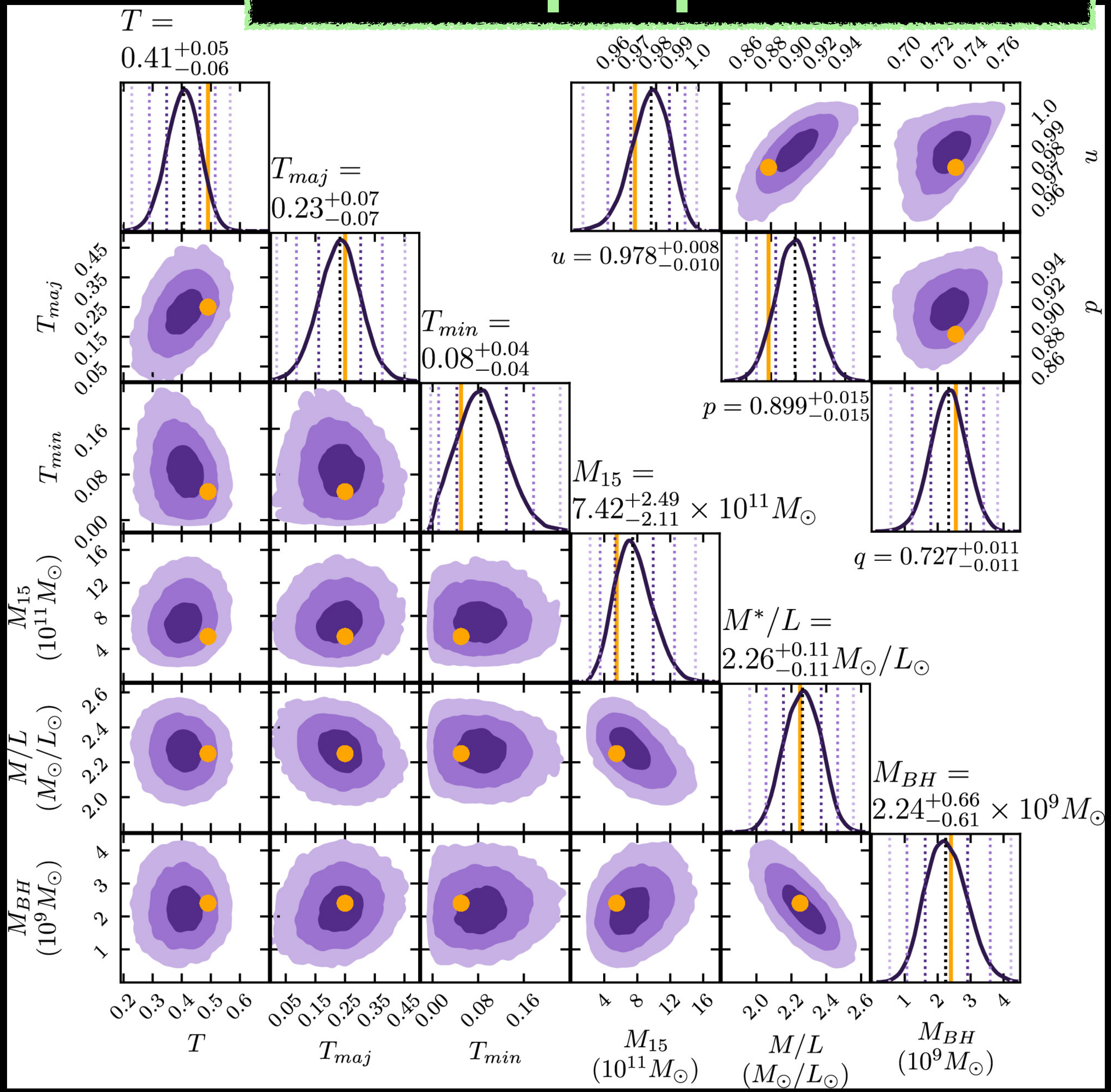
1. Obtain real galaxy data
2. Fit real data with a triaxial orbit model with parameters $\mathscr{P}_i$
3. Obtain predictions for observations from $\mathscr{P}_i$ and nudge those predictions with random noise to produce synthetic observations $\mathscr{O}_{i,j}$
4. Feed synthetic observations into modeling and inference
5. Repeat for many i and j

The resulting models are ***equilibrium***, with ***consistent kinematics*** and ***potential***

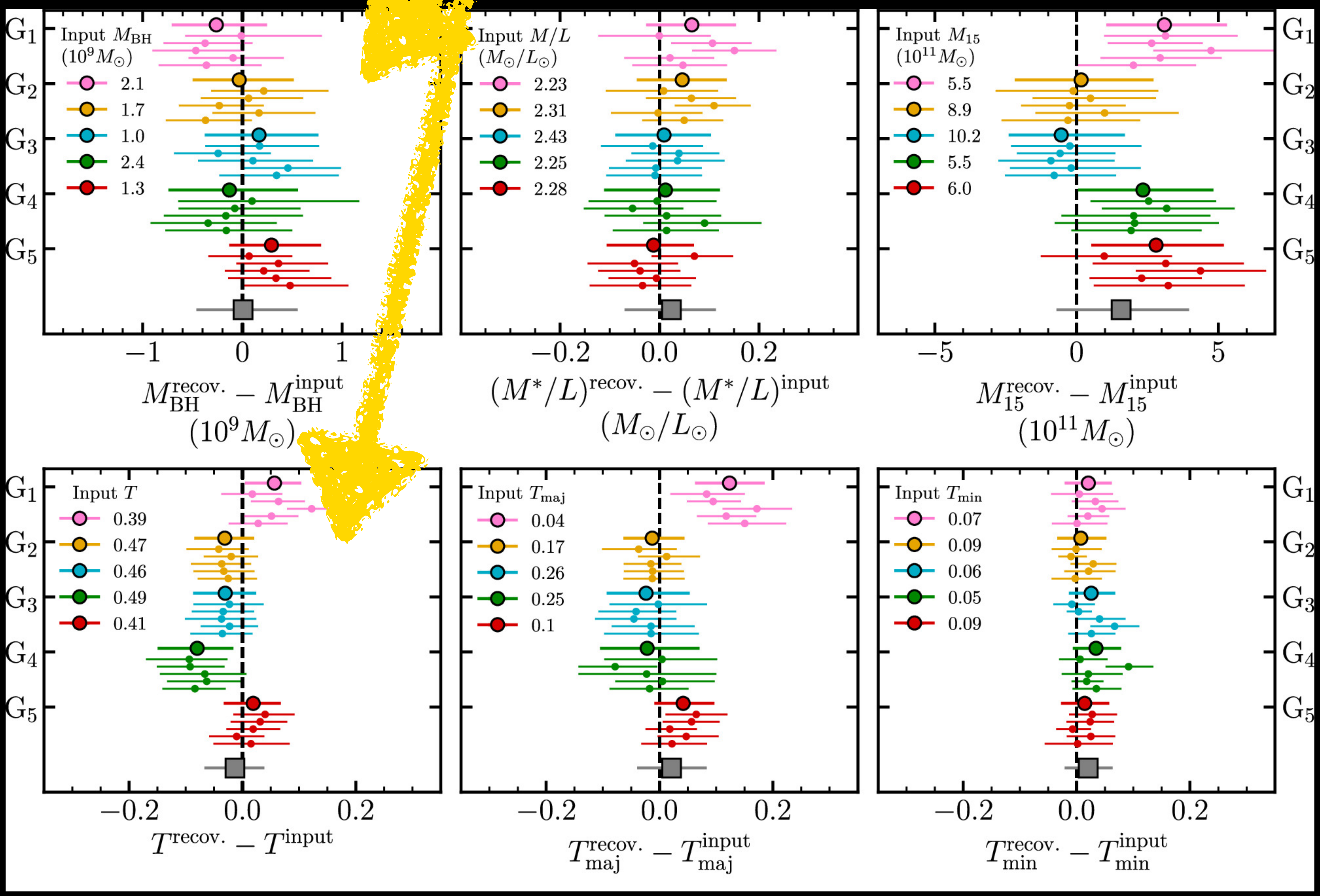
Probably not! (Pilawa, Liepold, Ma 2024)

- Ran 5 models with 5 noise realizations apiece

Example posterior



No apparent consistent bias in mass or shape parameters

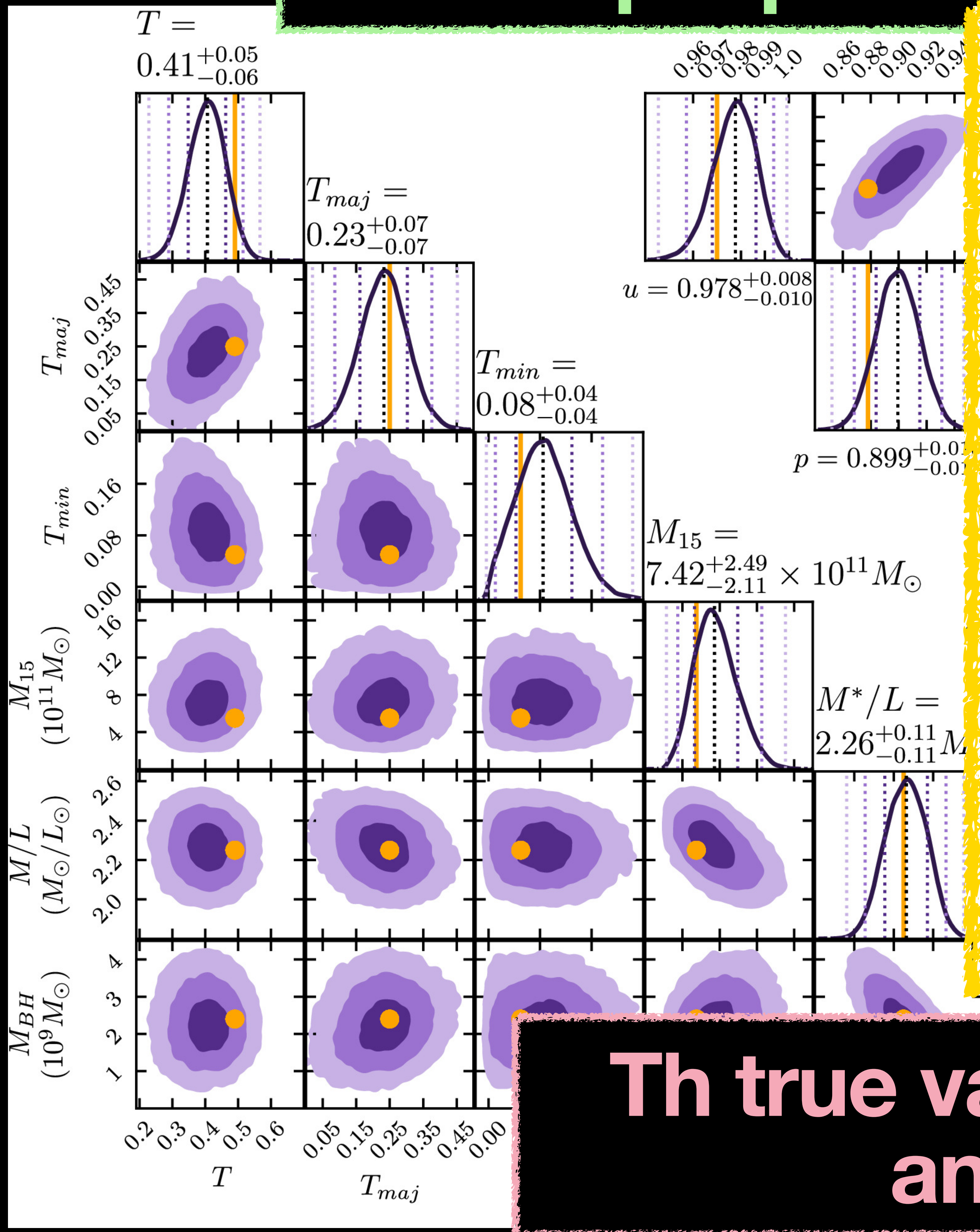


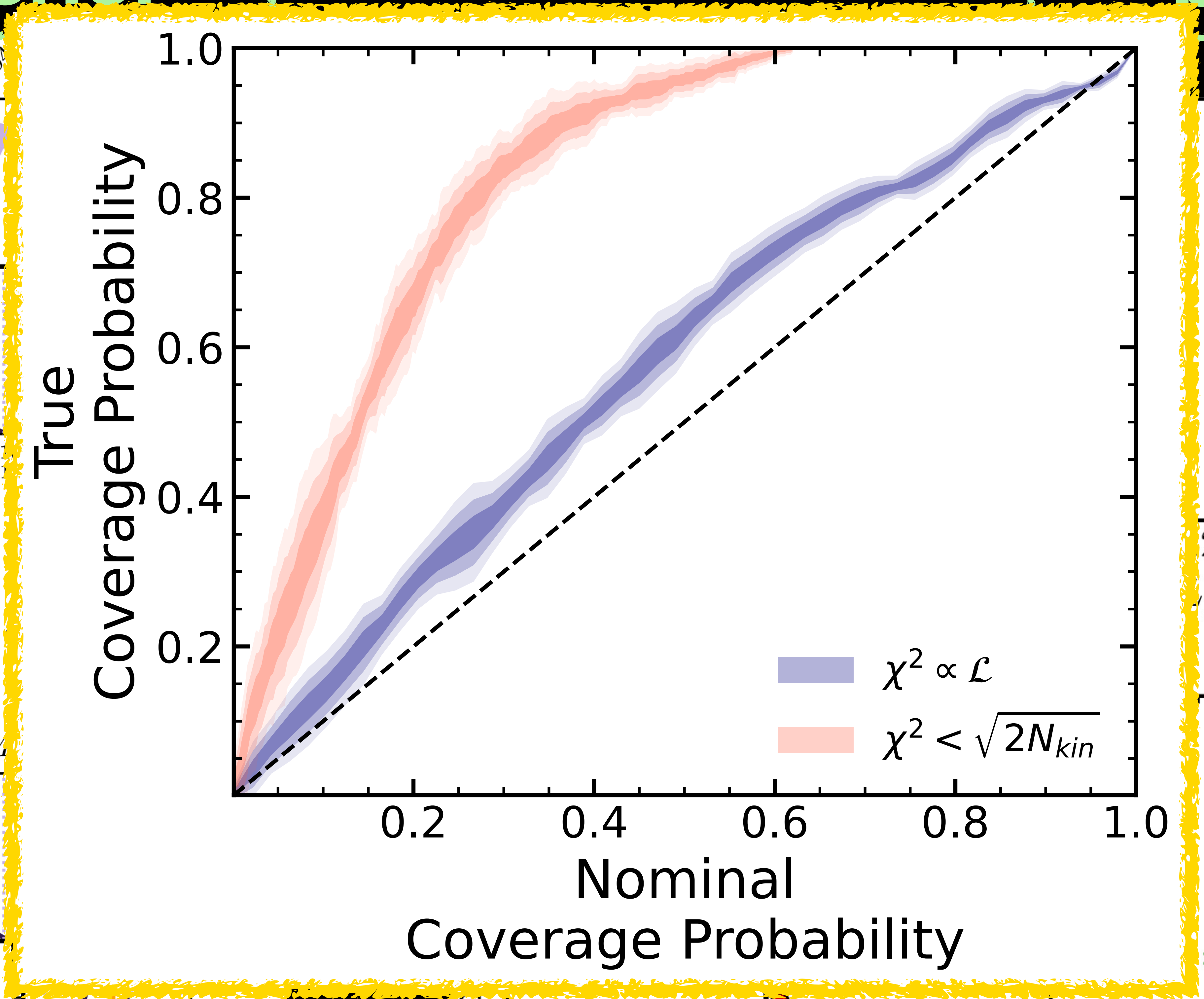
Probably not! (Pilawa, Liepold, Ma 2024)

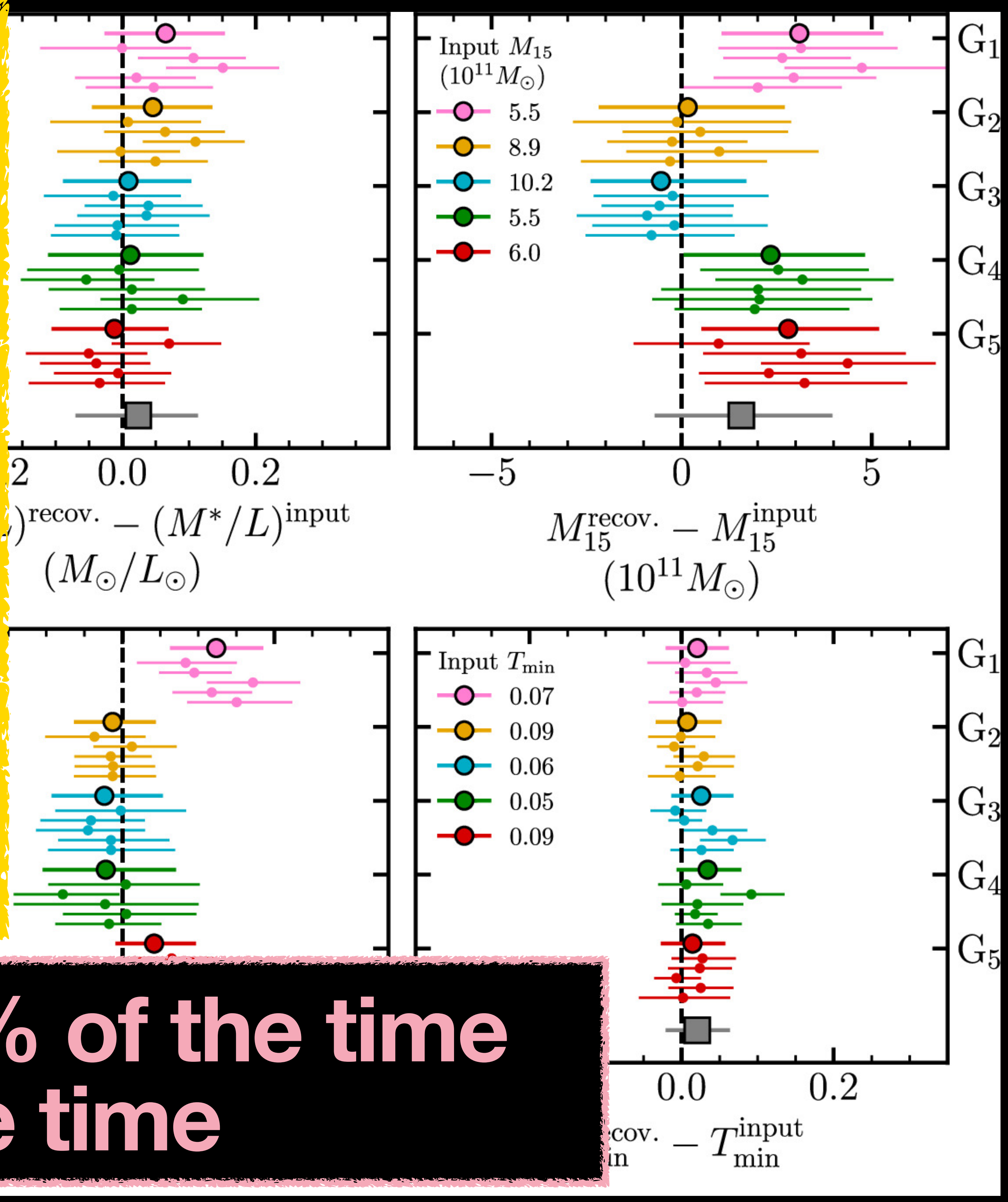
- Ran 5 models with 5 noise realizations apiece

No apparent consistent bias in mass or shape parameters

Example posterior







Th true value was within 68% CR ~75% of the time and within 95% CR ~95% of the time

Black hole masses and galaxy properties are linked

Triaxial Orbit modeling is the most general stellar dynamical modeling method

But it’s quite challenging to know if the answers are correct

(Though our tests suggest that they probably are)

And our iterative scheme seems to reliably converge on reasonable answers