Central image detection with VLBI

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Strong lensing nomenclature

- **Structure formation at subgalactic scale**
  - **Cusped halo**

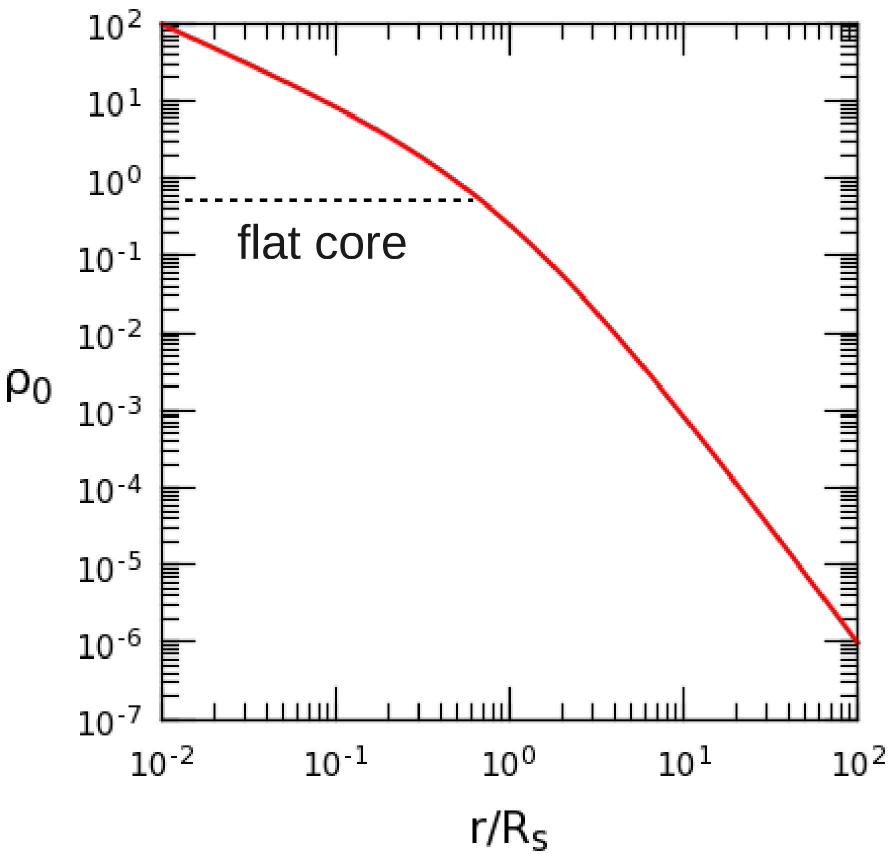
    Central cusp => central image =(odd number theorem)=> the last missing odd image

  - **Satellite galaxies**

    Dwarf galaxies => subhalos => substructure

ΛCDM model stepping down

- **From cluster to galaxy**
  - **NFW profile** => double power-law profile



$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)}$$

$$\rho(r) = \frac{\rho_0}{(r/r_b)^{\beta}[1 + (r/r_b)^2]^{(\eta-\beta)/2}}$$

Lensing configuration

- **Projected planes**

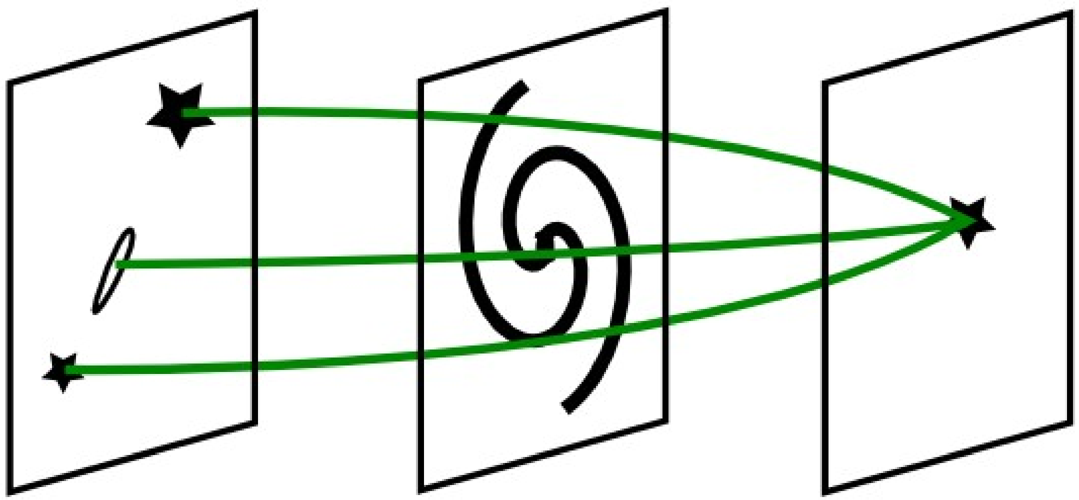
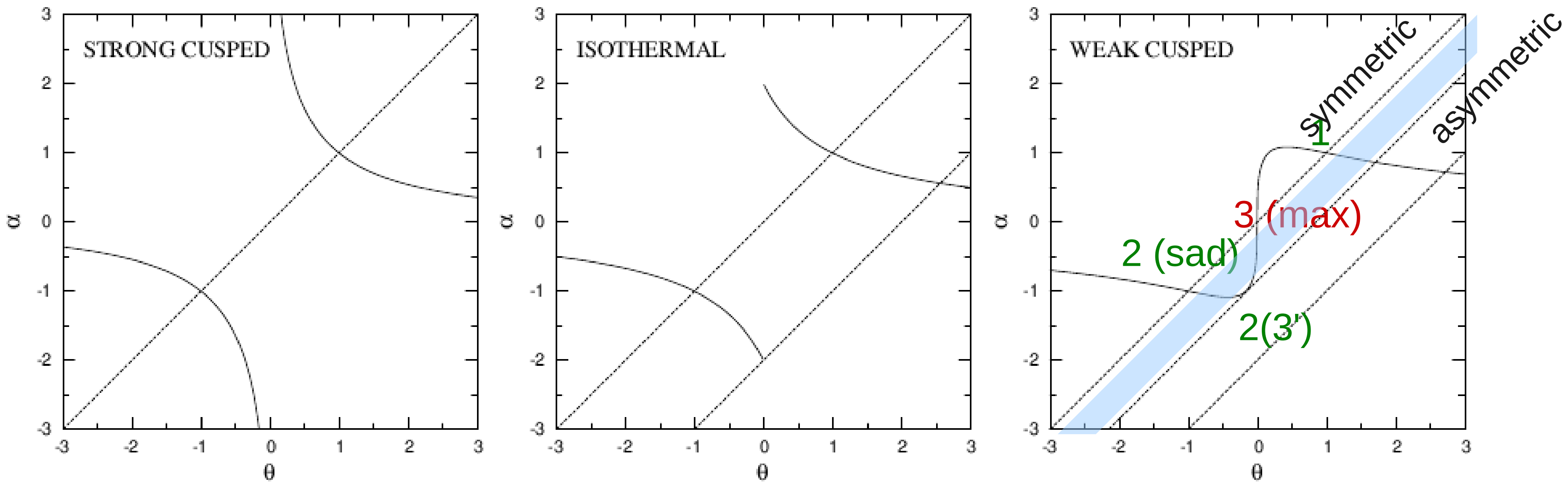


Image plane (f, θ_i) Lens plane (M, θ_d, z_d) Source plane (S, β, z_s)

Lens equation $\boxed{\beta = \theta - \alpha}$

Central image generating

- **Lens equation rewrite** => graph solutions
  - Weak cusped profile



Approaching to sensitivity I

- **The hard ways**

Noise response $$\Delta S_{ij} = \frac{1}{\eta_s}\sqrt{\frac{SEFD_i \cdot SEFD_j}{2\Delta\nu\tau_{acc}}}$$

Antennas – bigger size

Baselines – more big dishes

Receivers – lower noise

Bandwidth – wider band

Recording – more data rate

Correlating – less signal loss

Approaching to sensitivity II

- **The soft ways**

- Integration – observation time difficult to get
- Data quality
  - Image stacking
  - Visibility combination
- Analysis
  - Calibration
  - <u>Decovolution</u> →
    - non-unique
    - lossy
    - residual rms

Deconvolution

- **Ill-posed inverse problem**

$$I^D = I * B \longrightarrow I = I^D *^{-1} B$$

- **Inverting methods**

Iteration – $I_n = I_{n-1} + \lambda(I^D - I_{n-1} * B)$ CLEAN

(contraction mapping) (point-like)

Regularization – $P = \chi^2 + \lambda\langle I|H|I\rangle$ MEM/MLM

$H \to 0, \lambda \to 0 \longrightarrow$ LSM (extended)

Translation – $V = \mathcal{F}\{I\}$ *uv* model fitting

CLEAN bias

Convolution: injective mapping

=> **Deconvolution:** non-unique solutions

=> **CLEAN:** biased (scattered sidelobe flux cannot be fully restored)

=> **Source strength:** weakened

=> **rms statistics:** { inconsistent, non-objective }

Frequentist method

- **Signal injections**

Signals —Input→ [Black Box **CLEAN**] —Output→ Frequency counts

- **Hypothesis test** (Neyman construction)

Null & Alternative: $\begin{cases} H_0 : D(S) \leqslant D_0, \\ H_1 : D(S) > D_0. \end{cases}$ ⇒ $CL(S_0) = P(D \geqslant D_0 | S_0)$

- **Prior for Bayesian**

Conditional injection:

"Luminosity function" vs. Uniformly most powerful sampling

CL —*Bayesian theorem*→ Posterior probability: $P(S \leqslant S_0 | D \geqslant D_0)$

A central image candidate

- **JVAS B1030+074**
  - Radio source

    High resolution observables with VLBI
  - Double-image system

    Less symmetric than quad system
  - High flux ratio

    Very asymmetric => non-diminished central image

A real example

- **Central image detection in B1030+074**

  Instrument: HSA ≡ VLBA+Gb+Y27+Ar+Eb

  Band: 1.7 GHz (L)

  Effective integration time: ~ 4 hours

  Data rate: 256 Mb/s

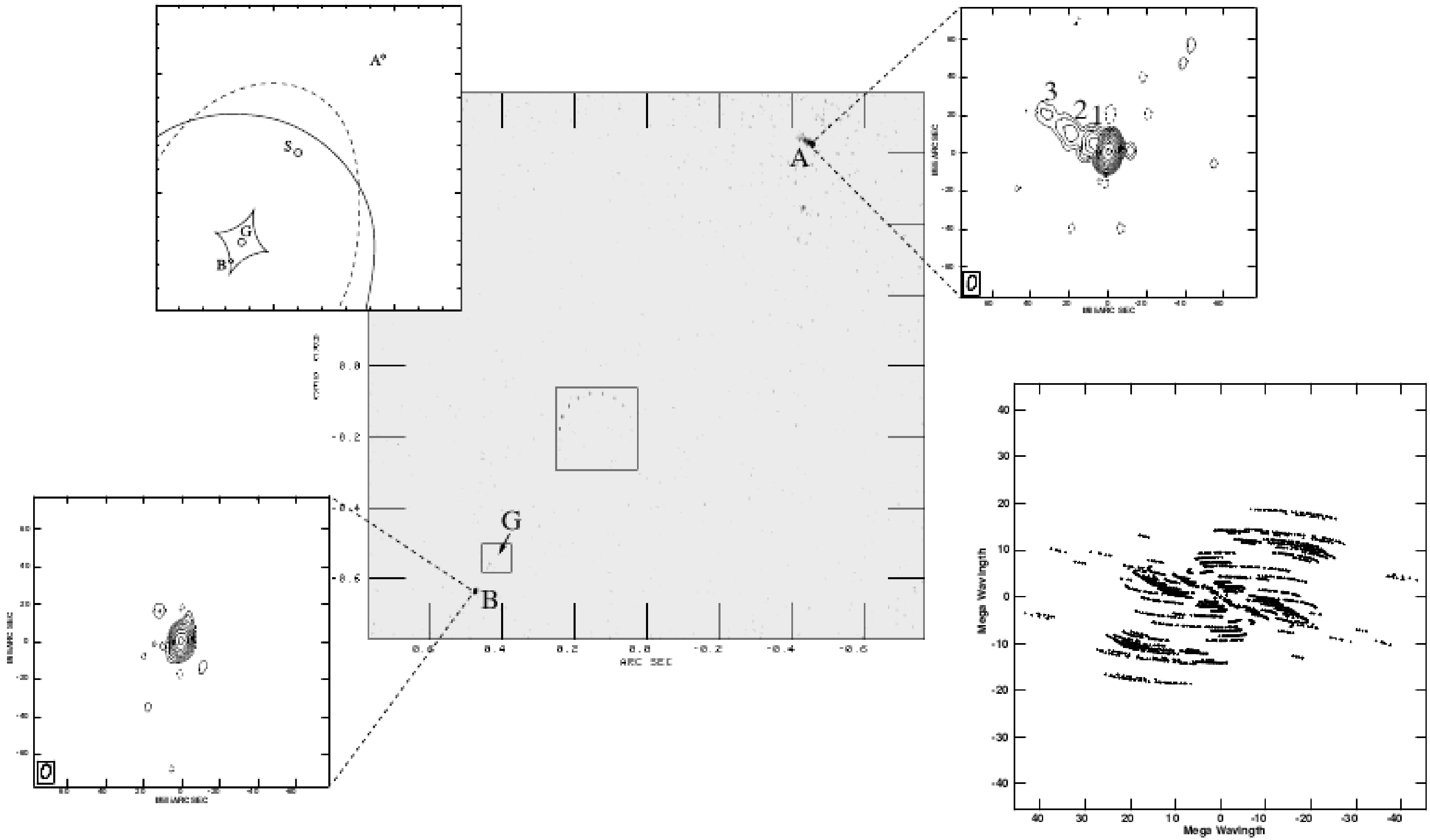
- **Result achieved**

  Sensitivity claimed: 3.5μJy/beam

  Sensitivity CLEANed: 20μJy/beam

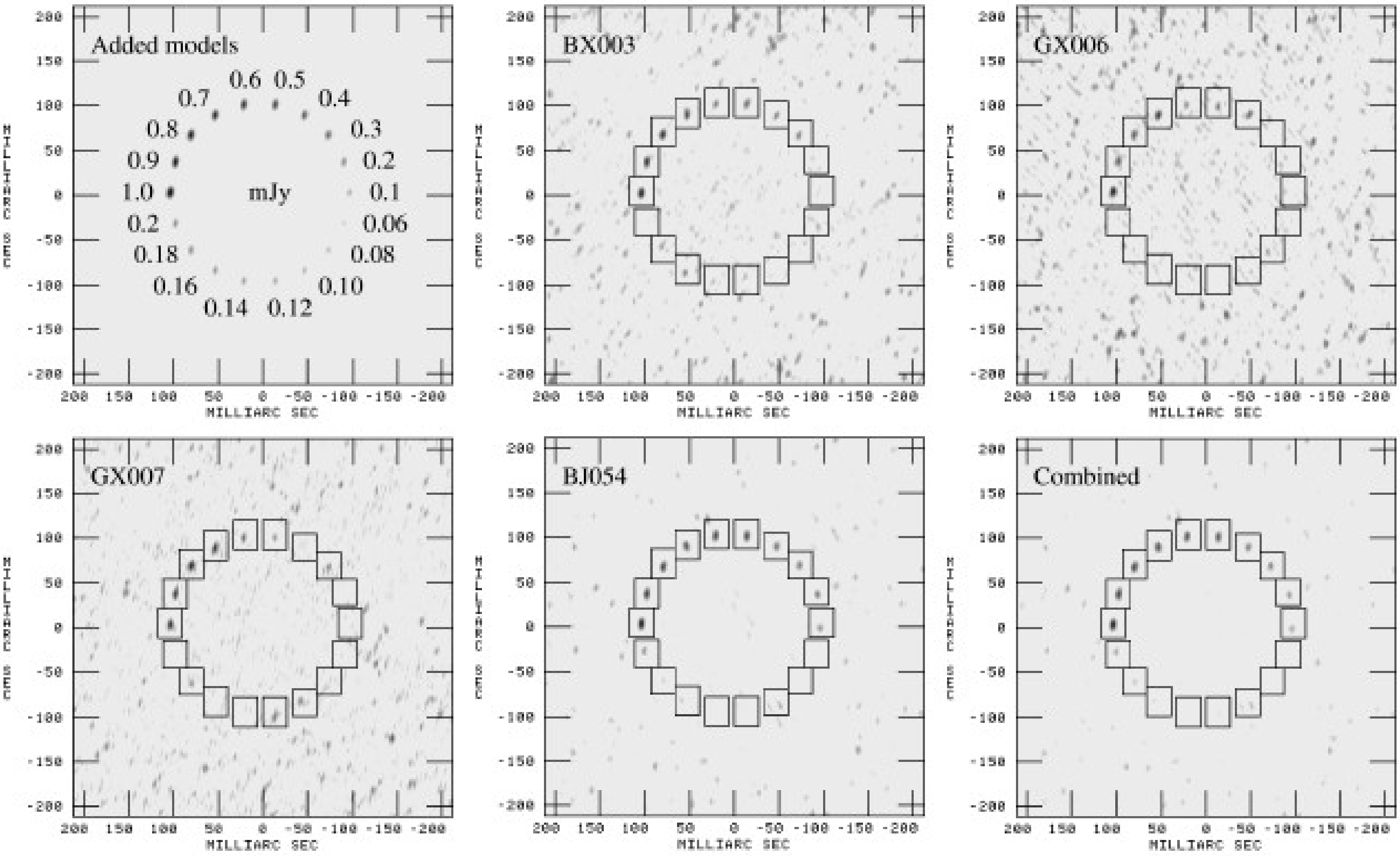
  Sensitivity objective: 180μJy/beam (CL90%)

VLBI (HSA) image



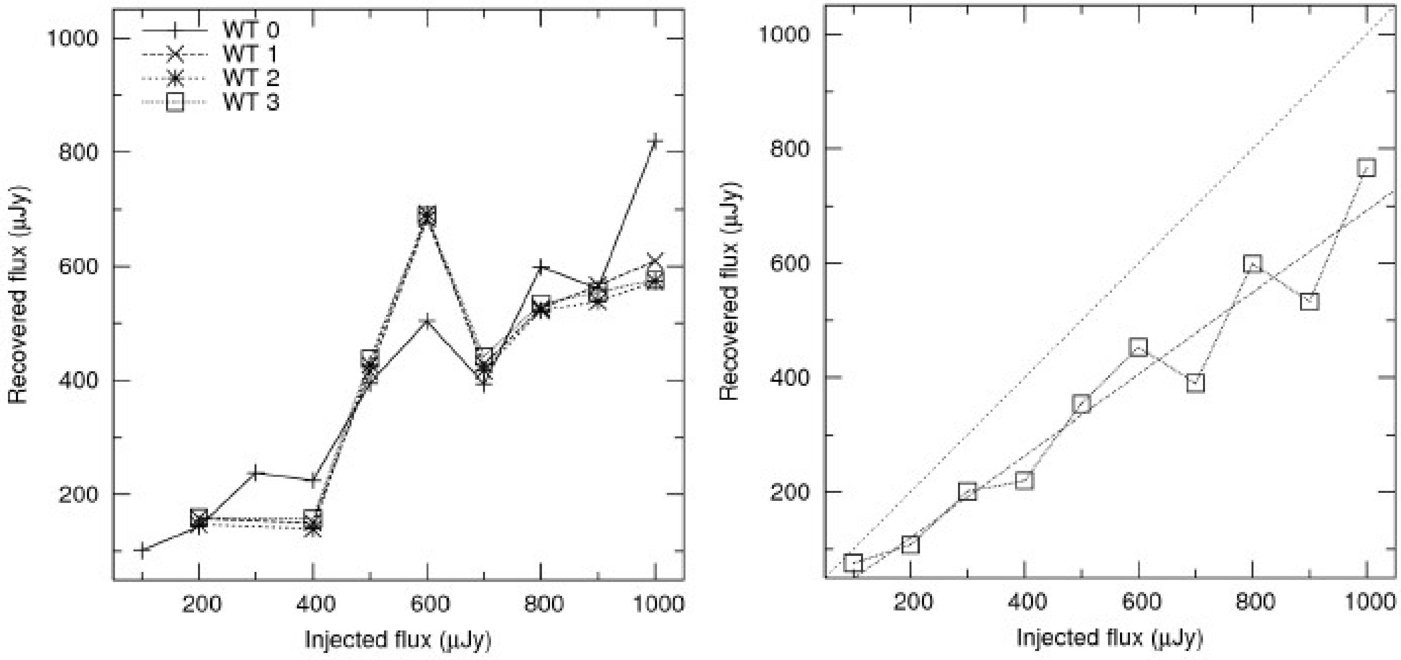
(Zhang et al. 2007)

Ring recovery test



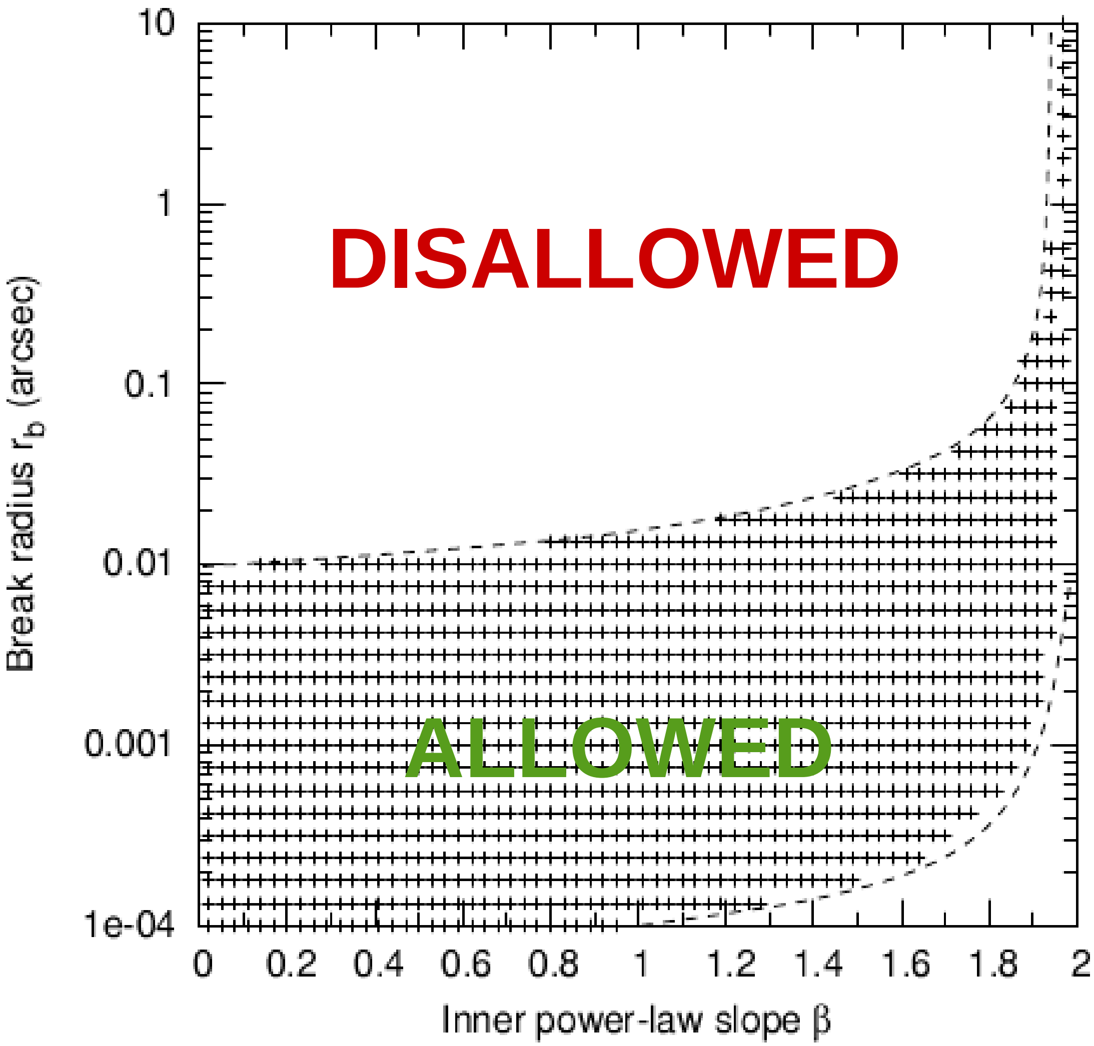
CLEAN loss and weightings

- No clear correlation to weighting schemes
- Up to 30% flux loss in CLEAN procedure

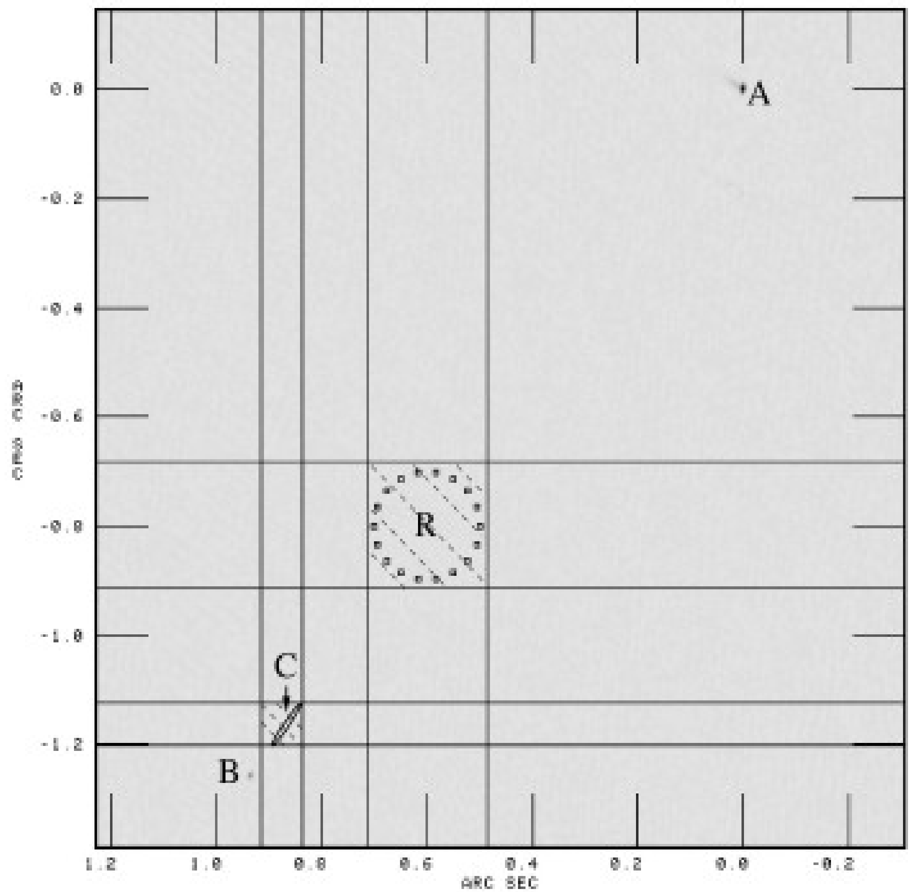


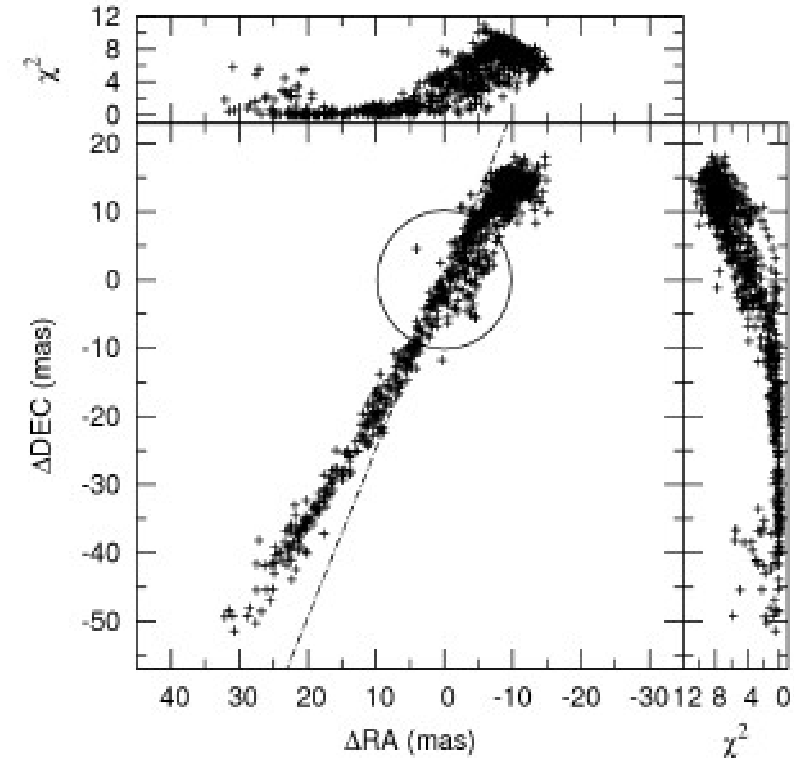
Under-constrained model

- r_b- β relation
- M_{bh}- β degeneracy
- Parameter grid
  - UMP sampling
  - Model prediction

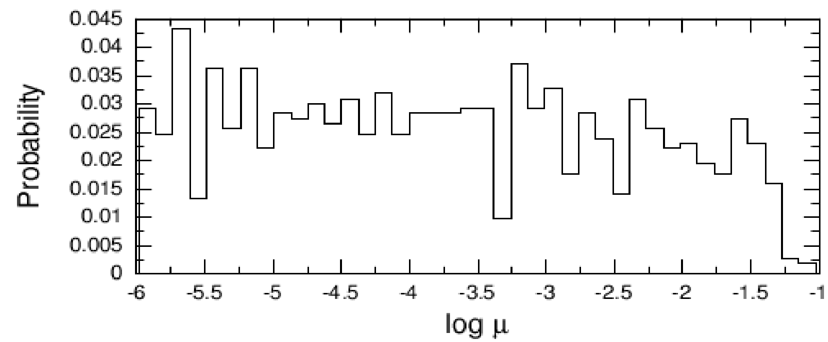


Central image “club”



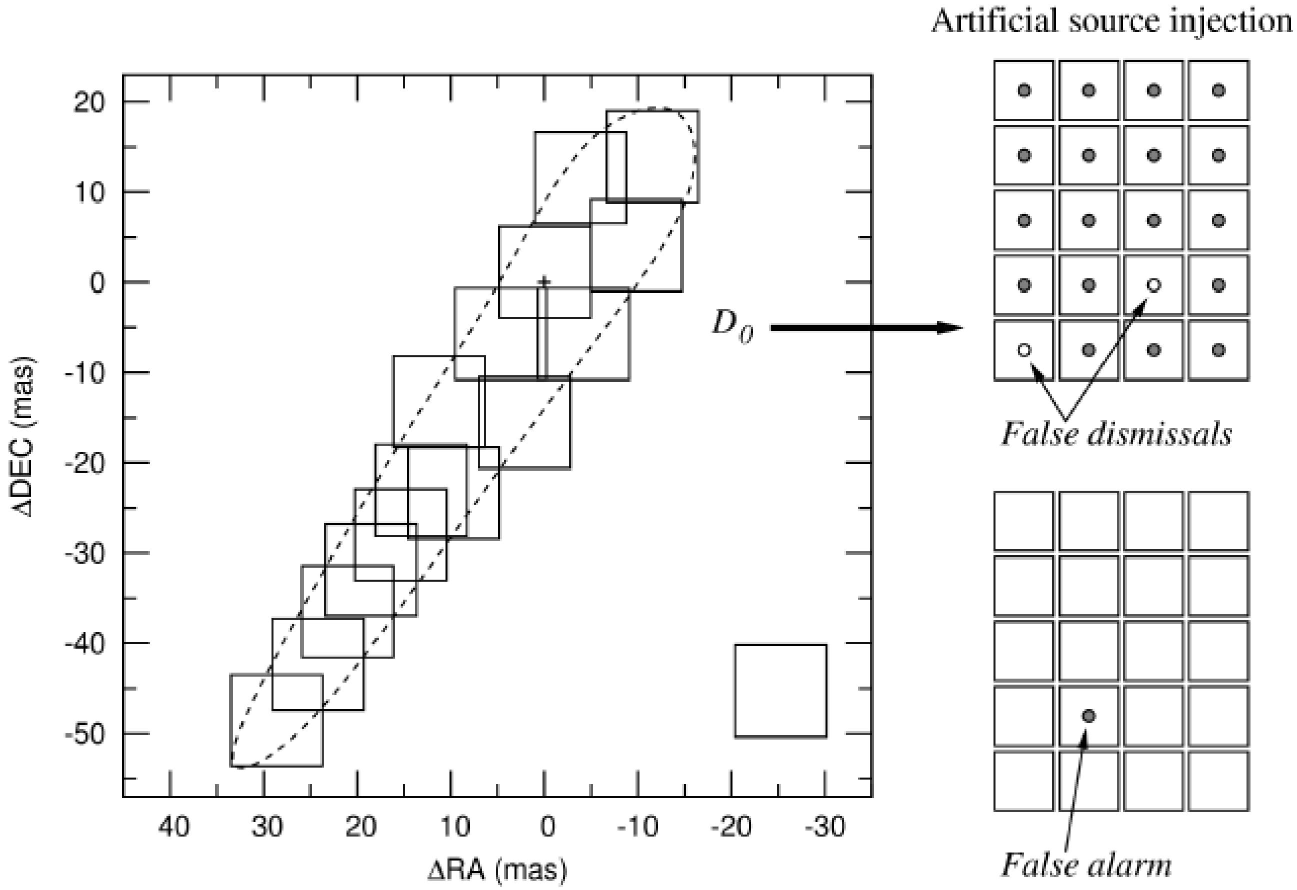


“Luminosity function”



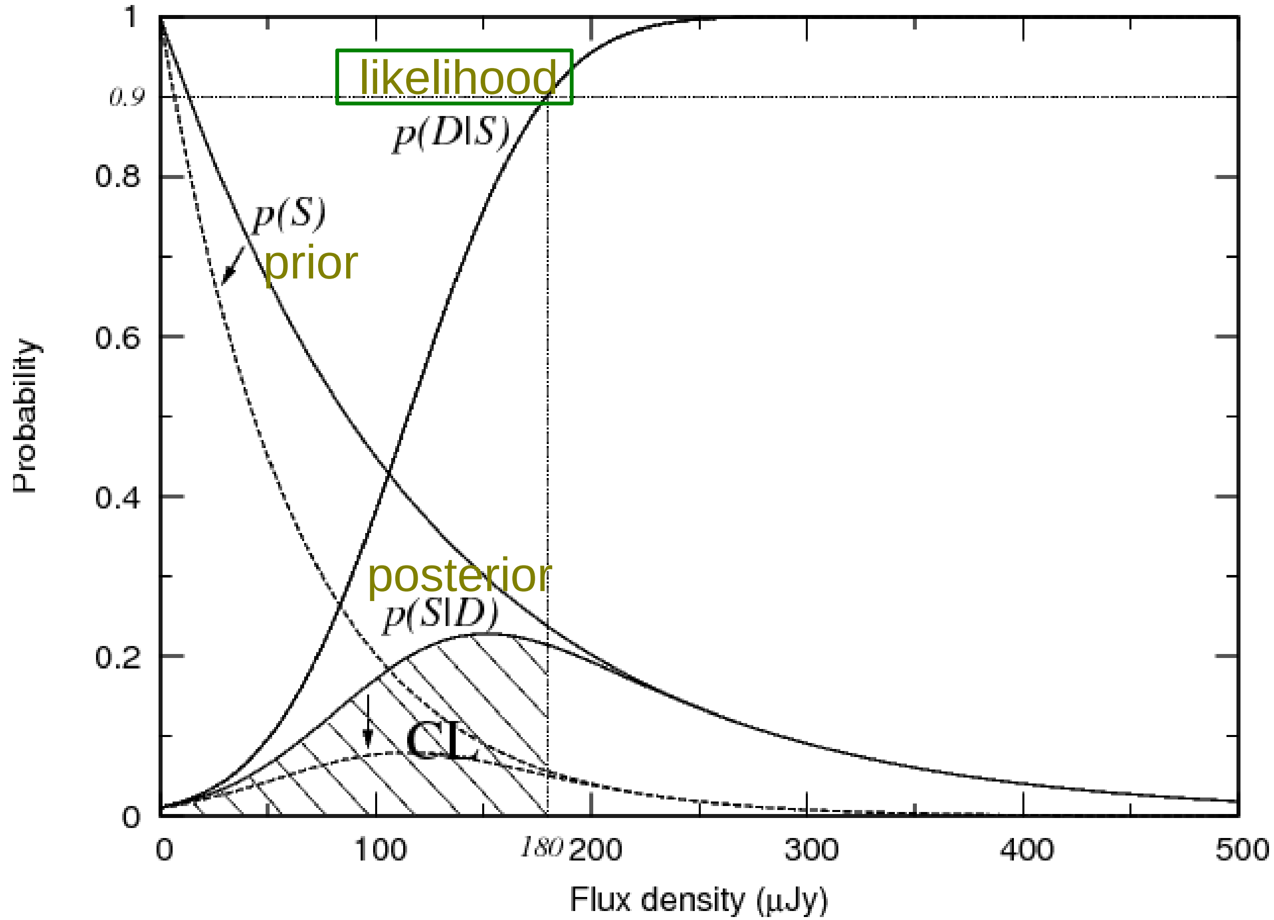
Frequentist statistics

- **90% injections recovered** (18 out of 20)



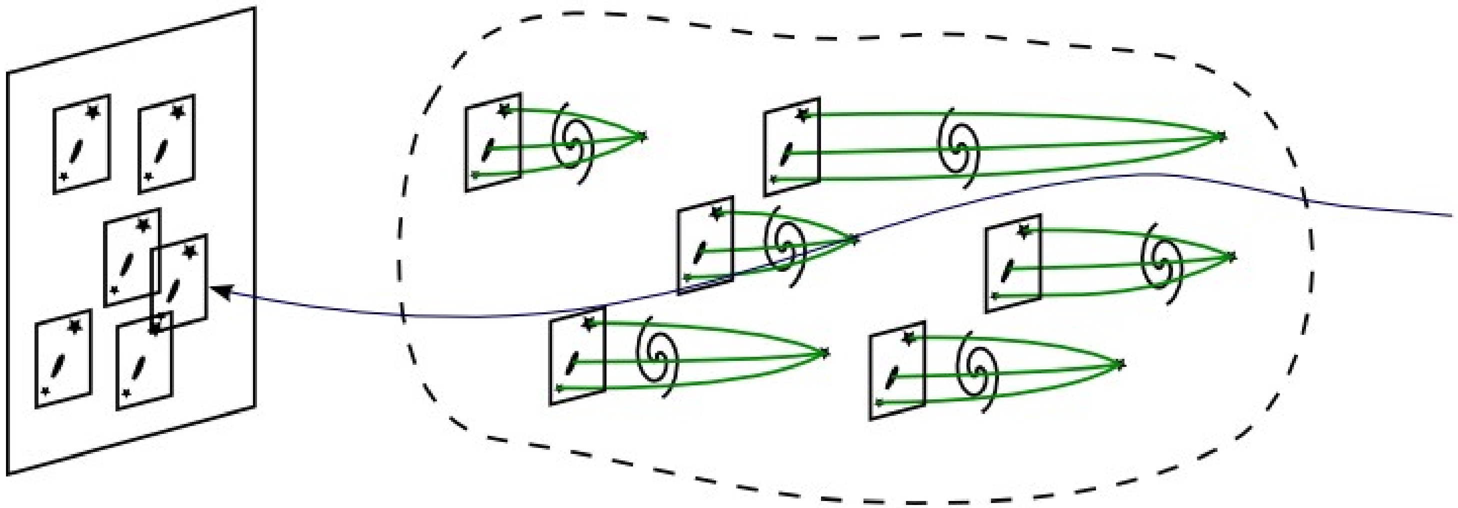
Towards Bayesian

- **Bayes' formula** $$P(S|D) = \frac{P(D|S)P(S)}{P(D)}$$



Detectability with a prior chain

- **Galaxy-quasar lensing paths**



- **Mock lens simulation**

$$P_{cen} = P(f_{cen} > f_{thr}, \Delta\theta_{cen,sad} > \theta_{res}, (M, \theta_d, z_d), (S, \beta, z_s))$$

$$\Rightarrow \quad P_{cen} = P(\mu_{cen} > \mu_0) P(S > f_{thr}\mu_0) P_{len}$$

Conclusions

- Current detection/non-detection with VLBI limit is frequentist
- Detectability requires a realistic “luminosity function” of lensed central image
- N-body simulations currently cannot provide plausible priors since at subgalactic scale they need be testified first
- Observationally the real solution to central image relies on future lens samples and real detections