Detecting Earth-like extrasolar planets by gravitational microlensing

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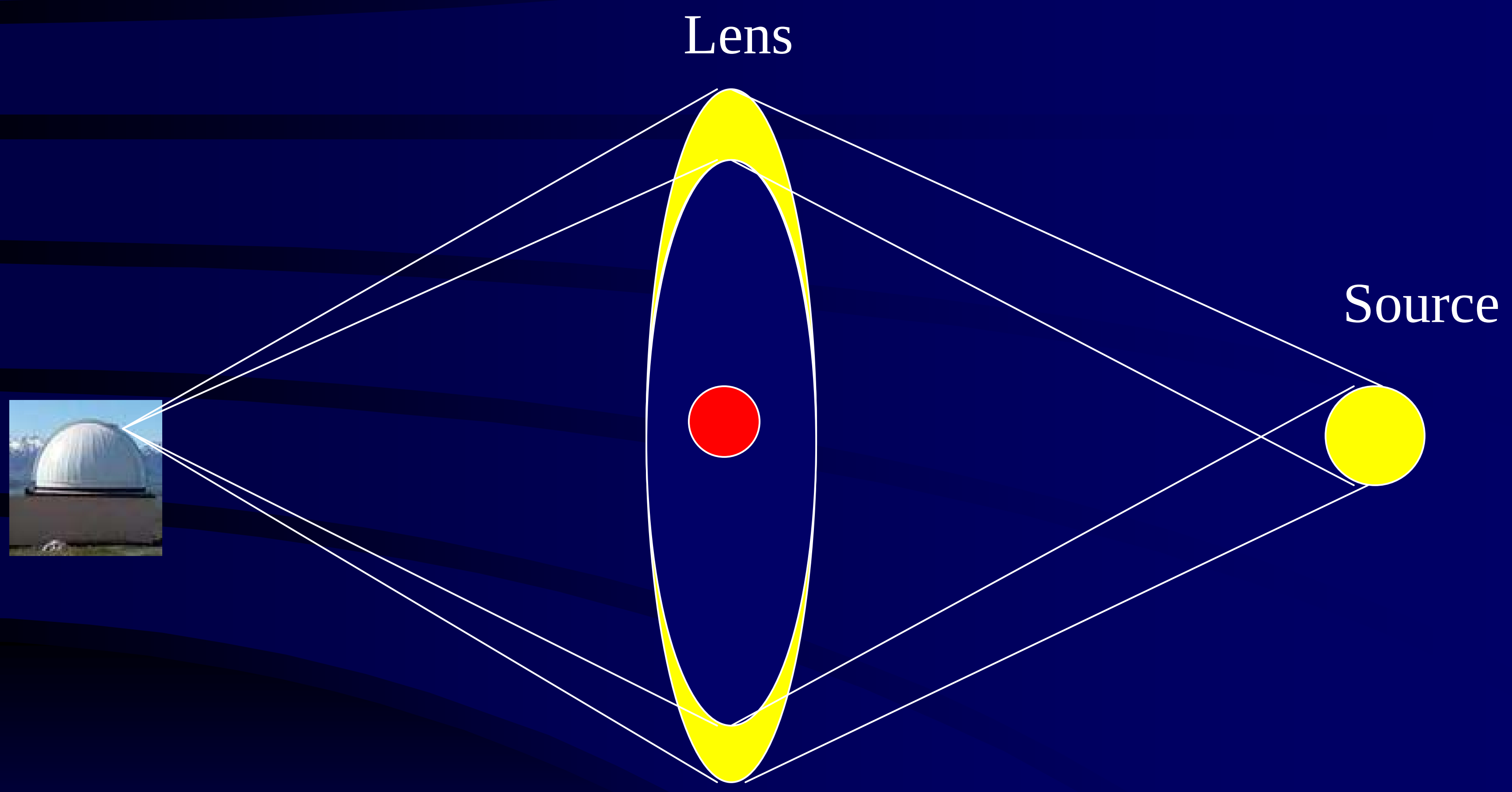
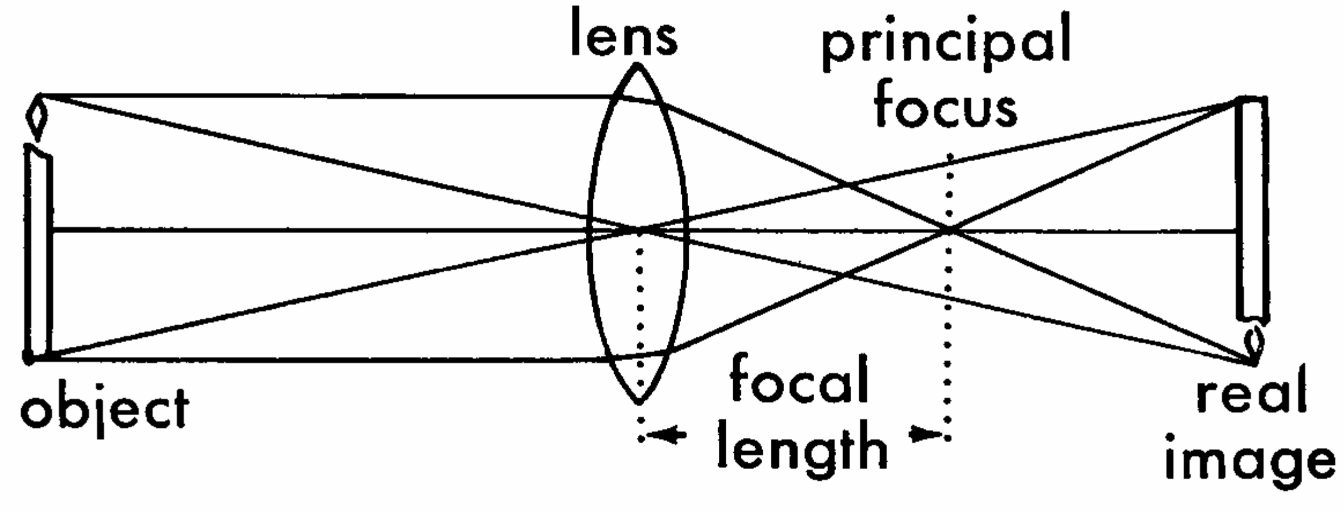
Basics of gravitational lensing

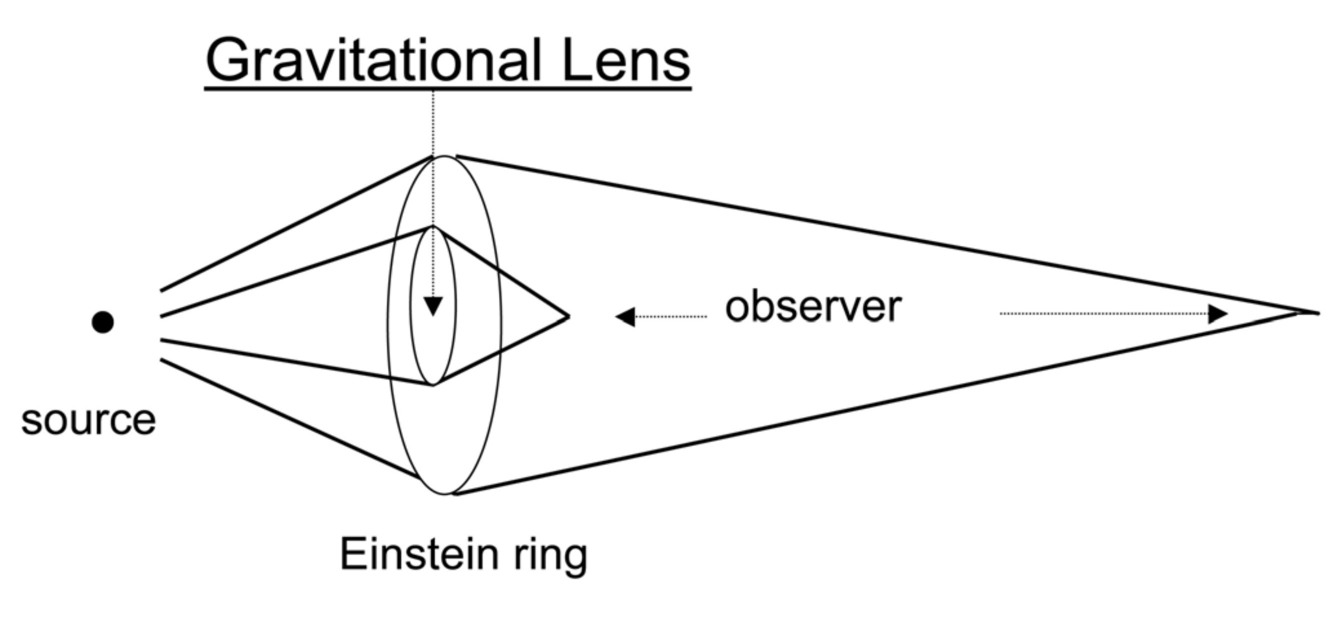


Einstein Ring

Comparison with normal lens:-



True image
Magnified
Fixed focus



Distorted image
Magnified
Variable focus

Demonstration with a glass lens

- Courtesy Sidney Liebes, Princeton

- Magnification approximately 8

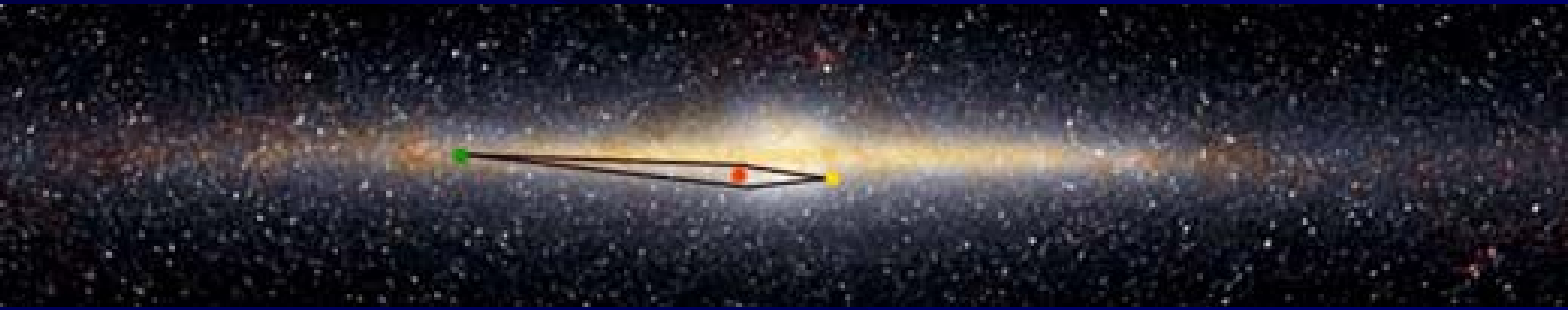
Demonstration with galaxies

- Courtesy Hubble Space Telescope

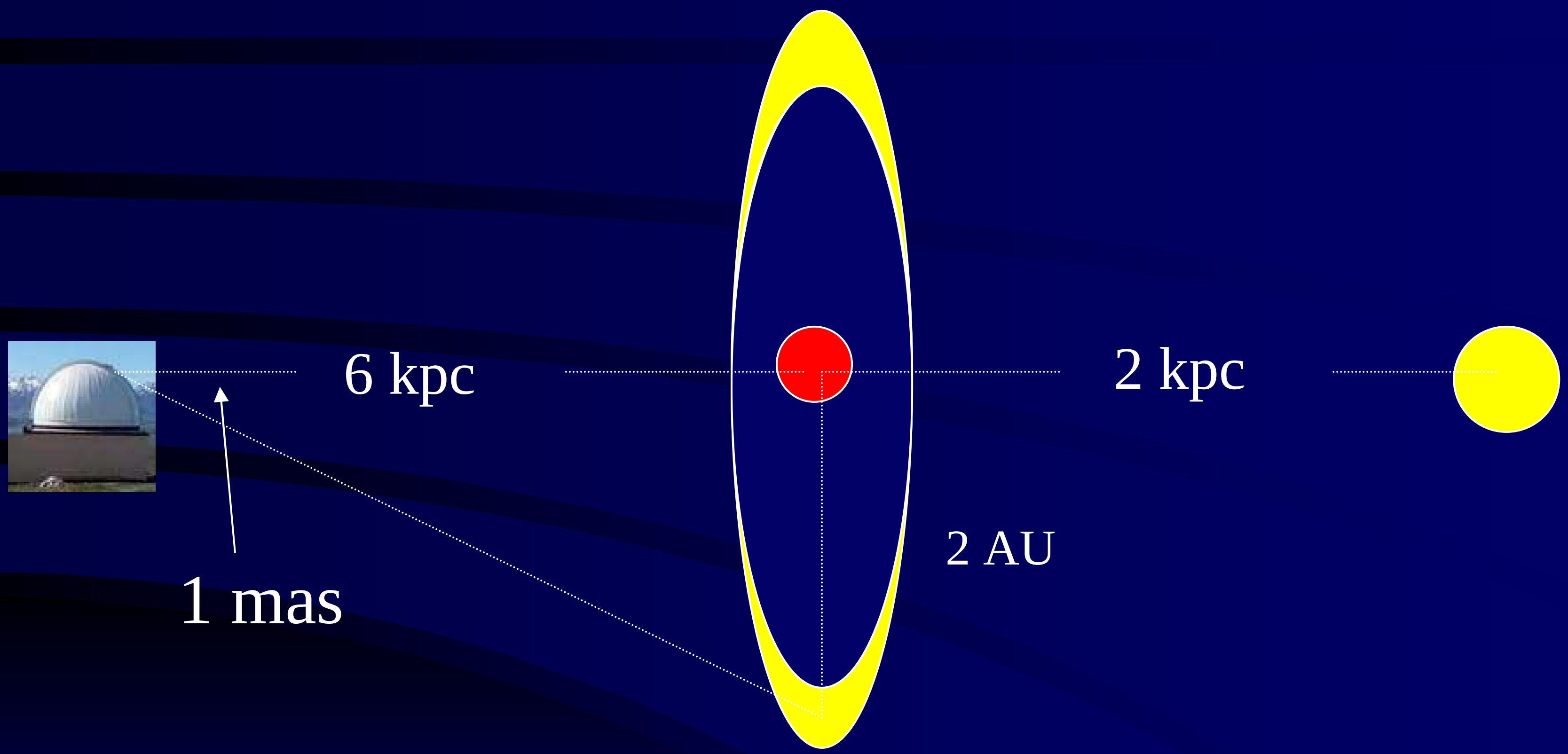
- Magnification approximately 8

Lensing with stars

Readily observed in the galactic bulge

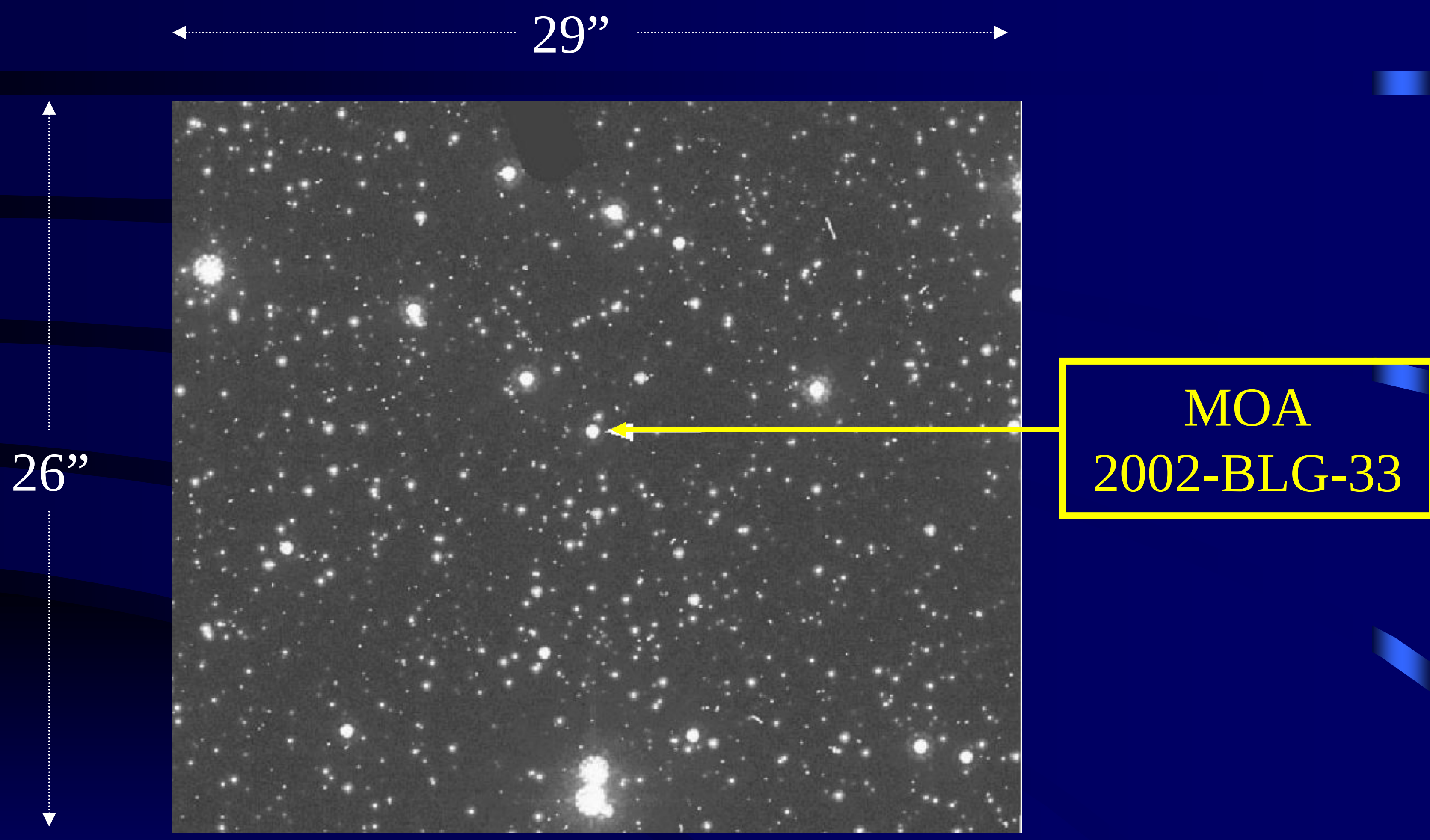


Typical parameters



Magnification ~ 1,000

Galactic Bulge (HST – ACS/HRC)



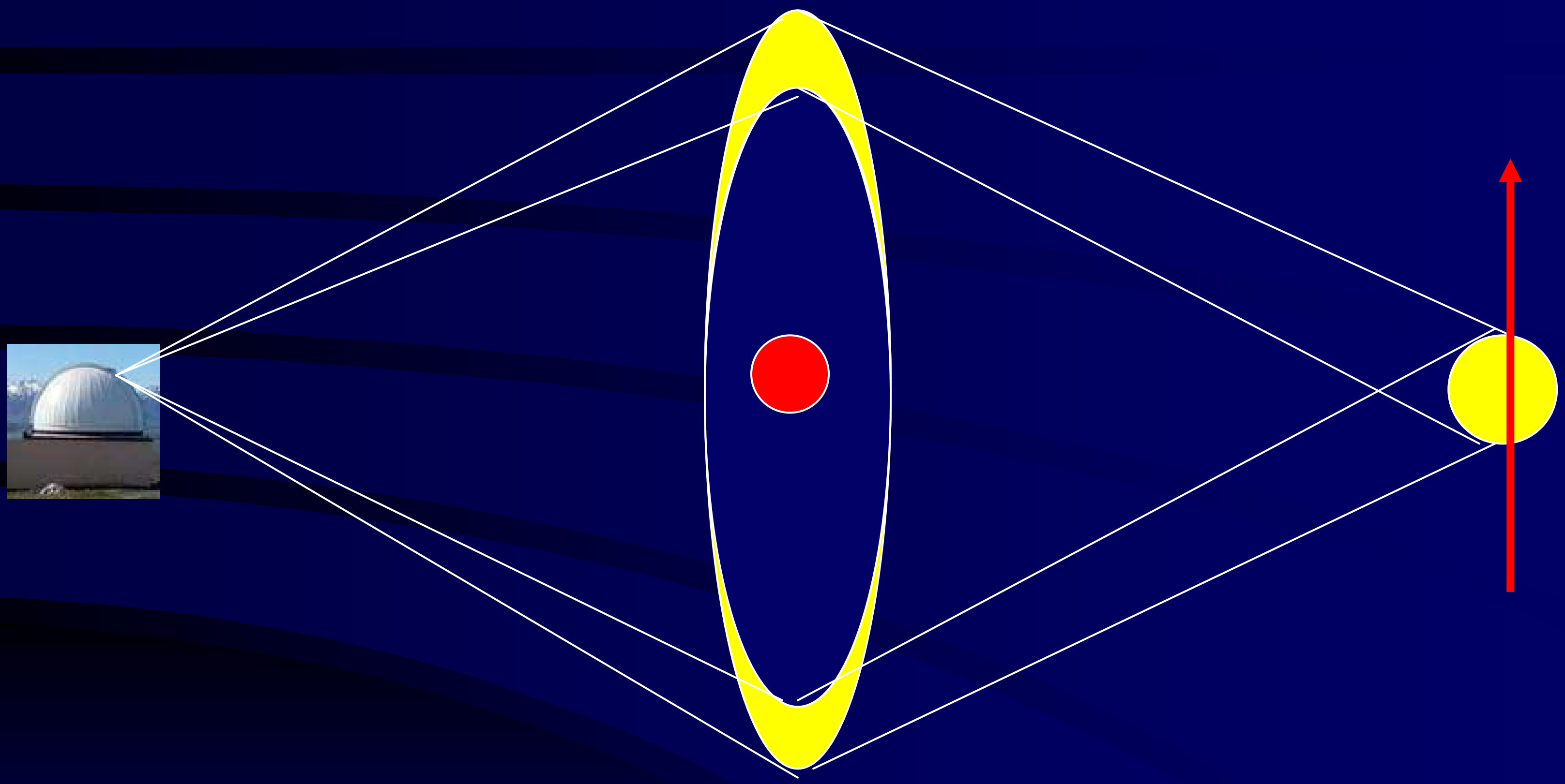
“No chance of observing this phenomenon” - Einstein (1936)

Japan/NZ MOA telescope (NZ)

1.8-m
2 square degrees FoV

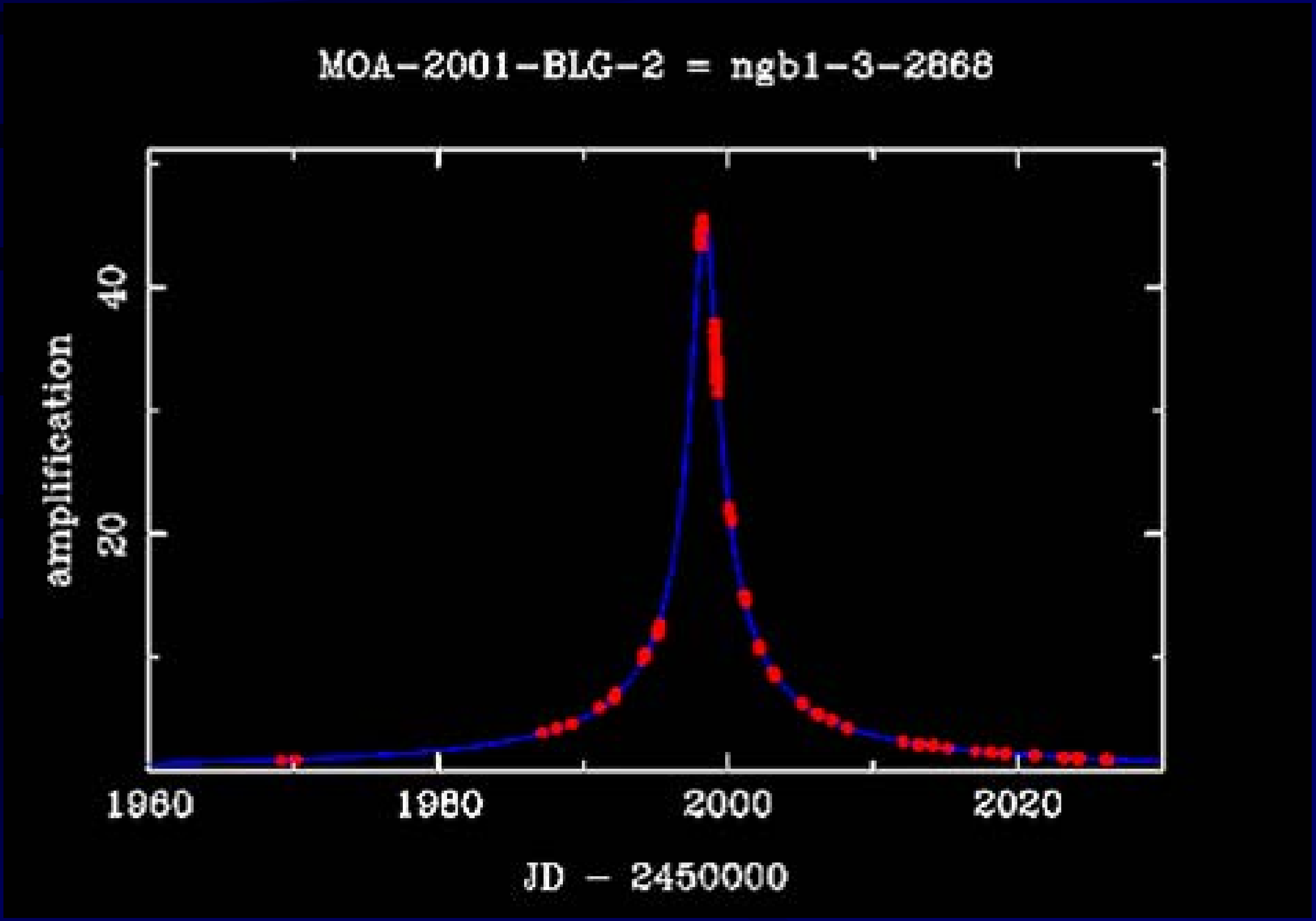
CCD camera
80 million pixels

Light curve



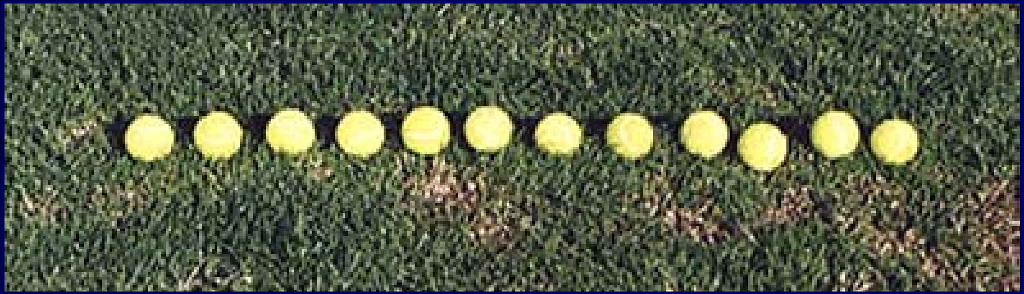
Typical transverse velocity ~ 200 km/sec

Light curve

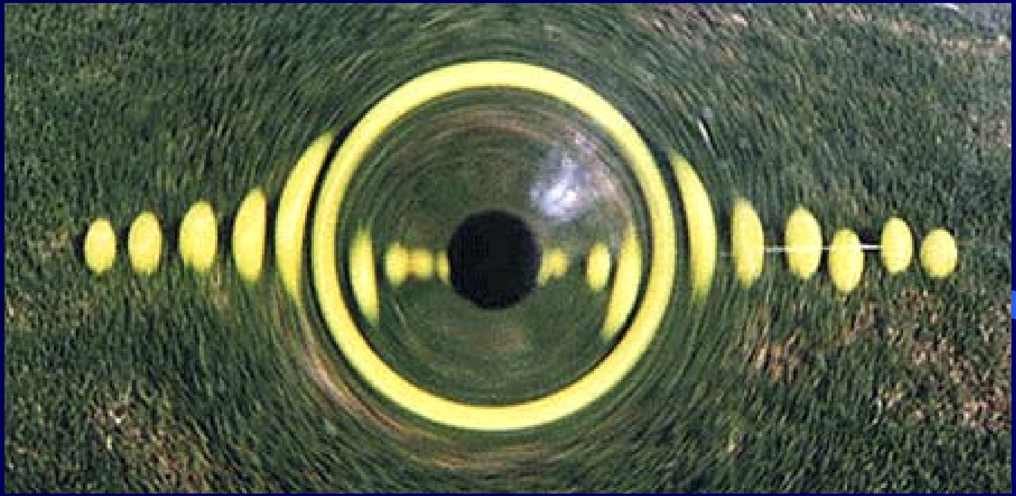


Liebes-Paczynski light curve versus data

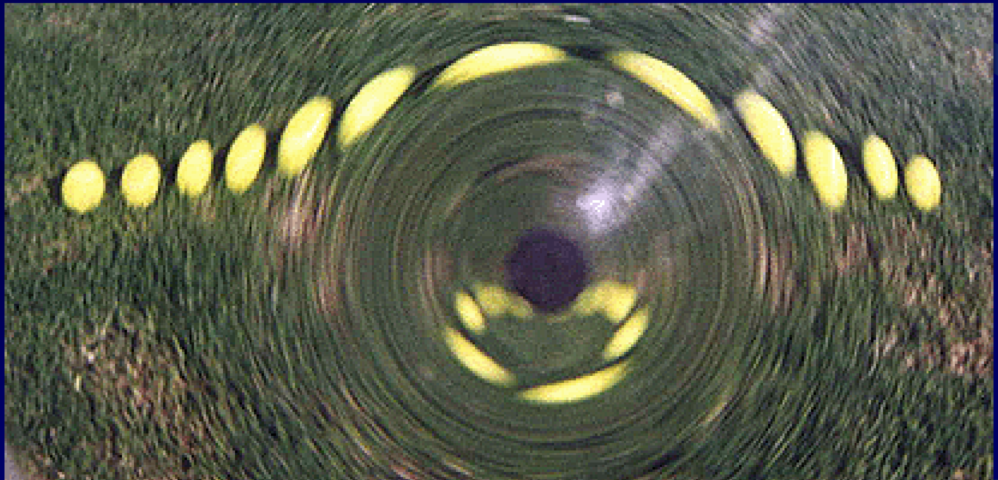
Demonstration with glass lens and tennis balls



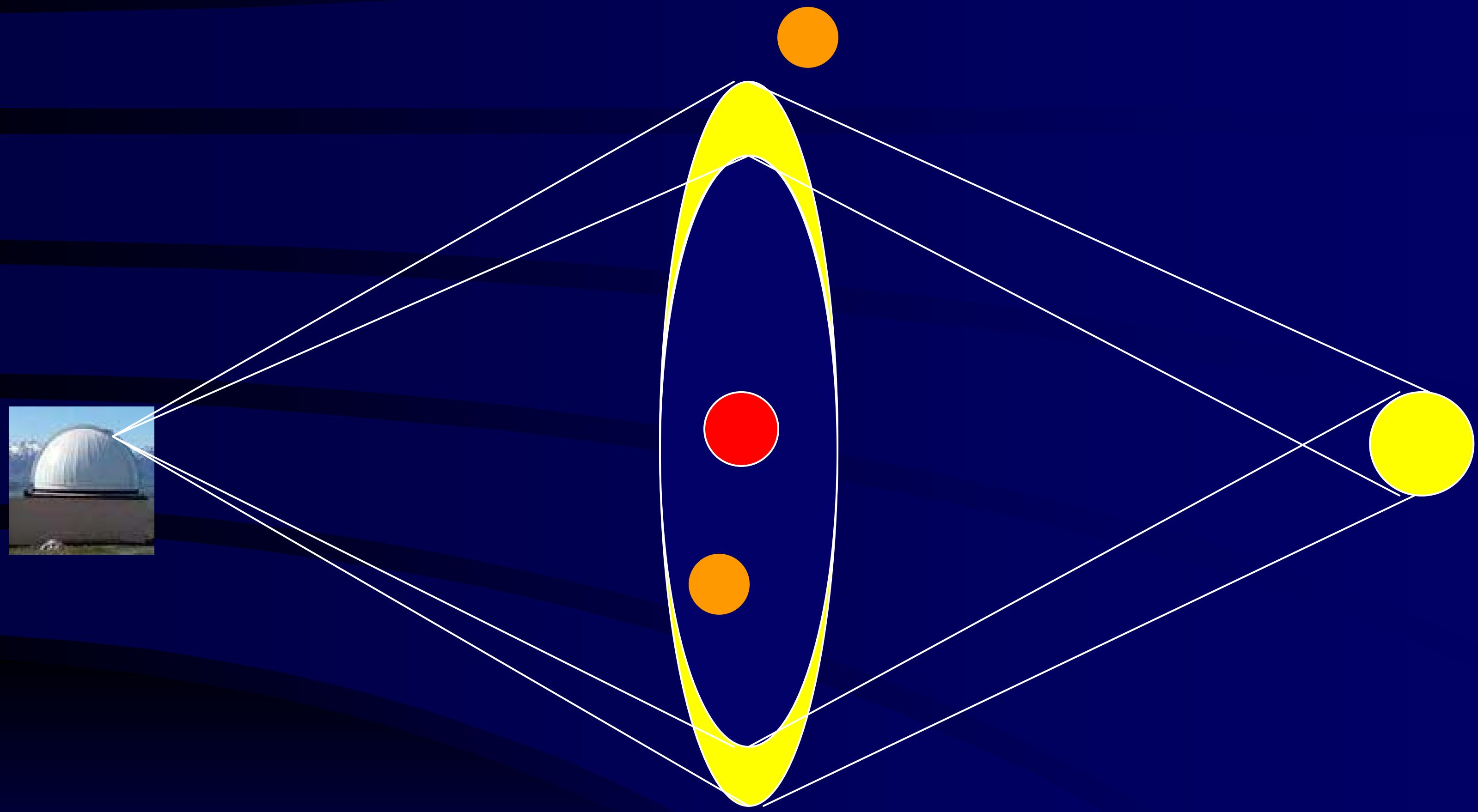
Low impact parameter – high magnification



High impact parameter – low magnification

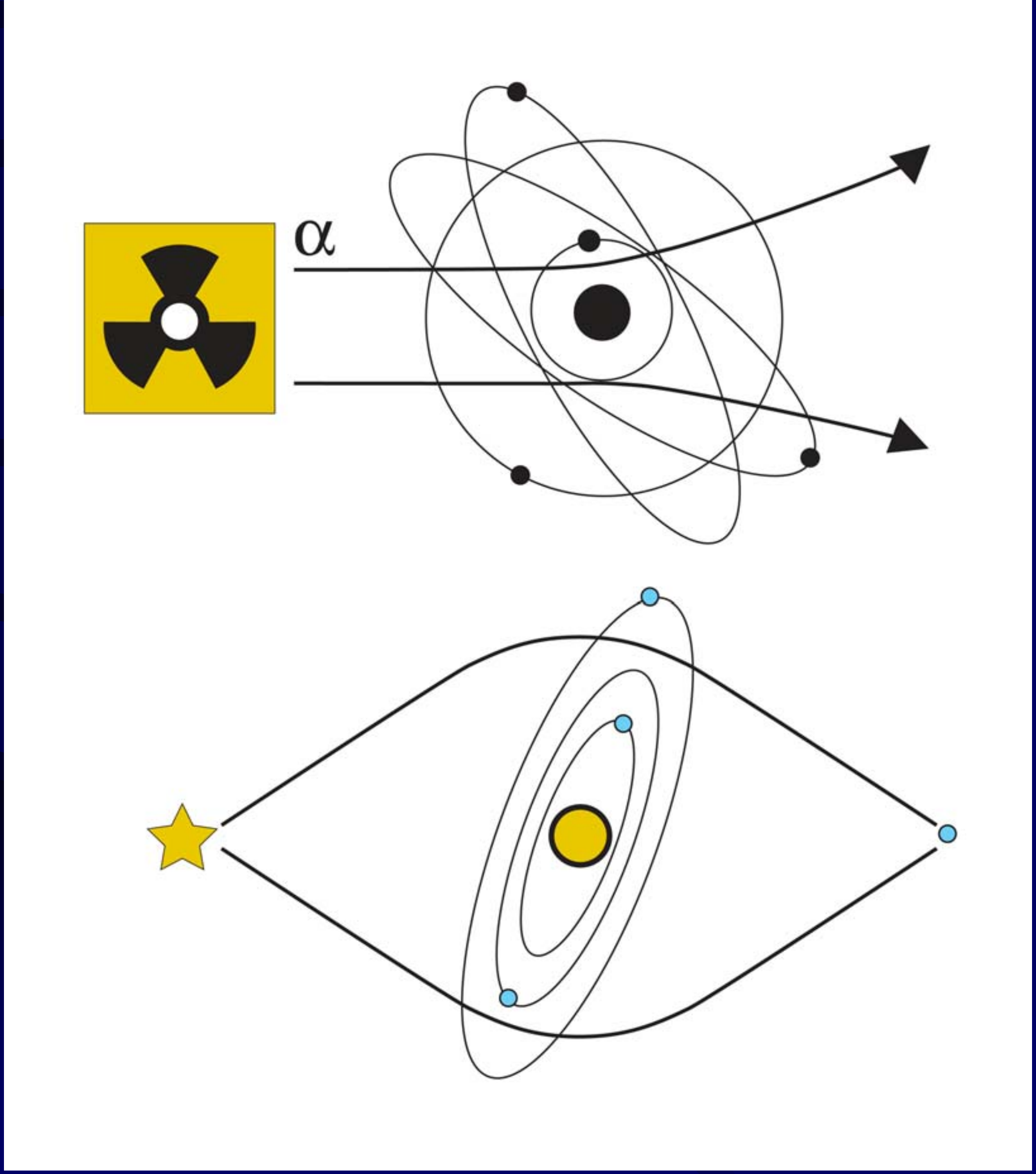


Planetary microlensing

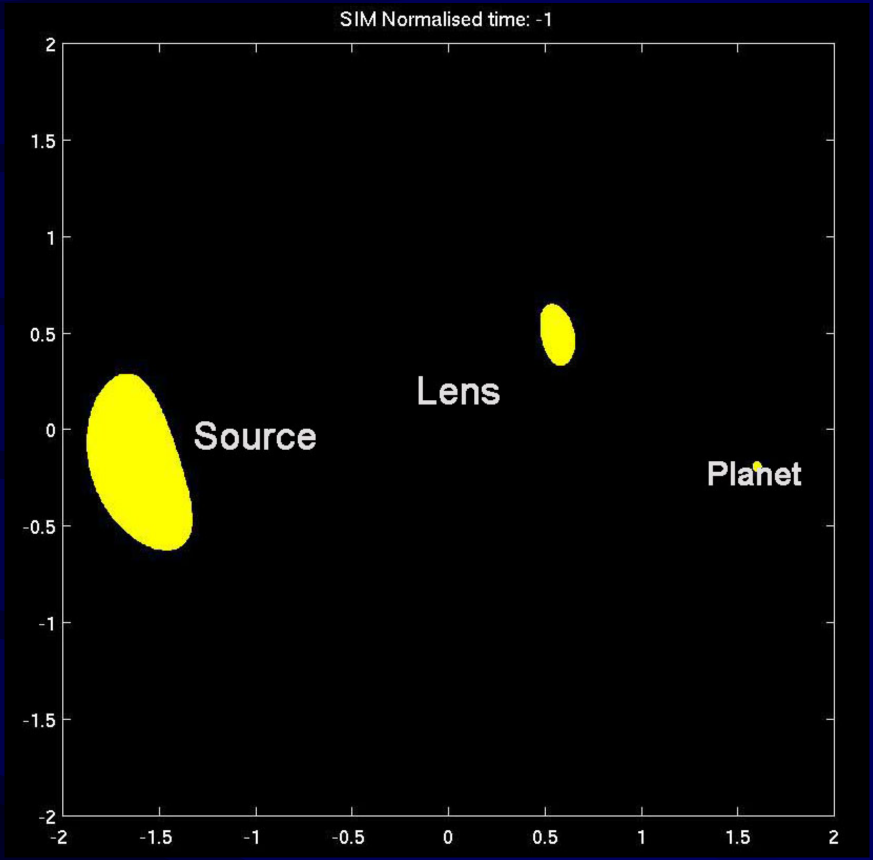


Radius of Einstein ring ~ 2 AU.
Therefore planets perturb the ring.

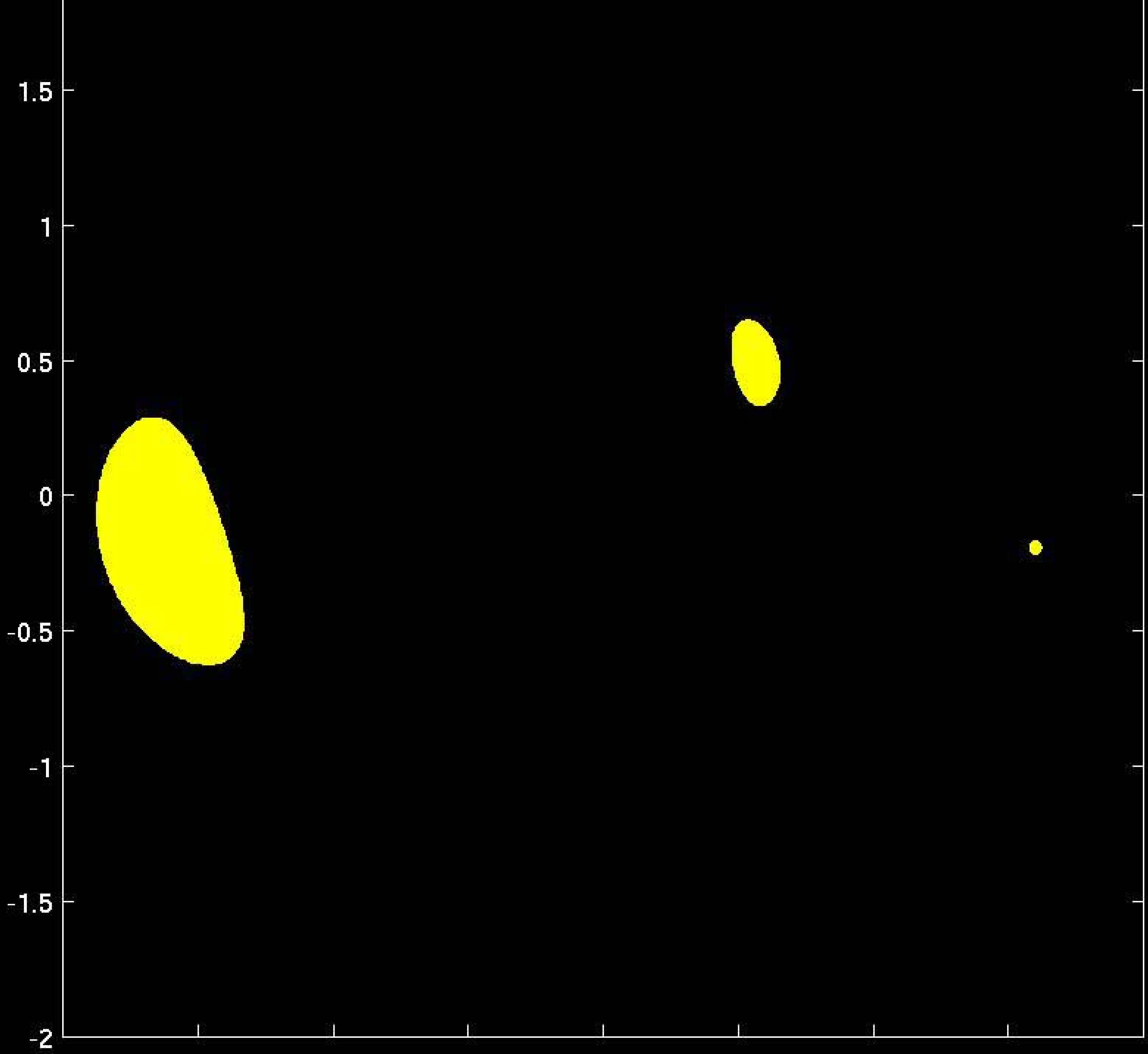
Comparison with Rutherford scattering



View from Earth



- Source star (yellow) is most distant
- Lens star is nearer.
- A planet orbits the lens star.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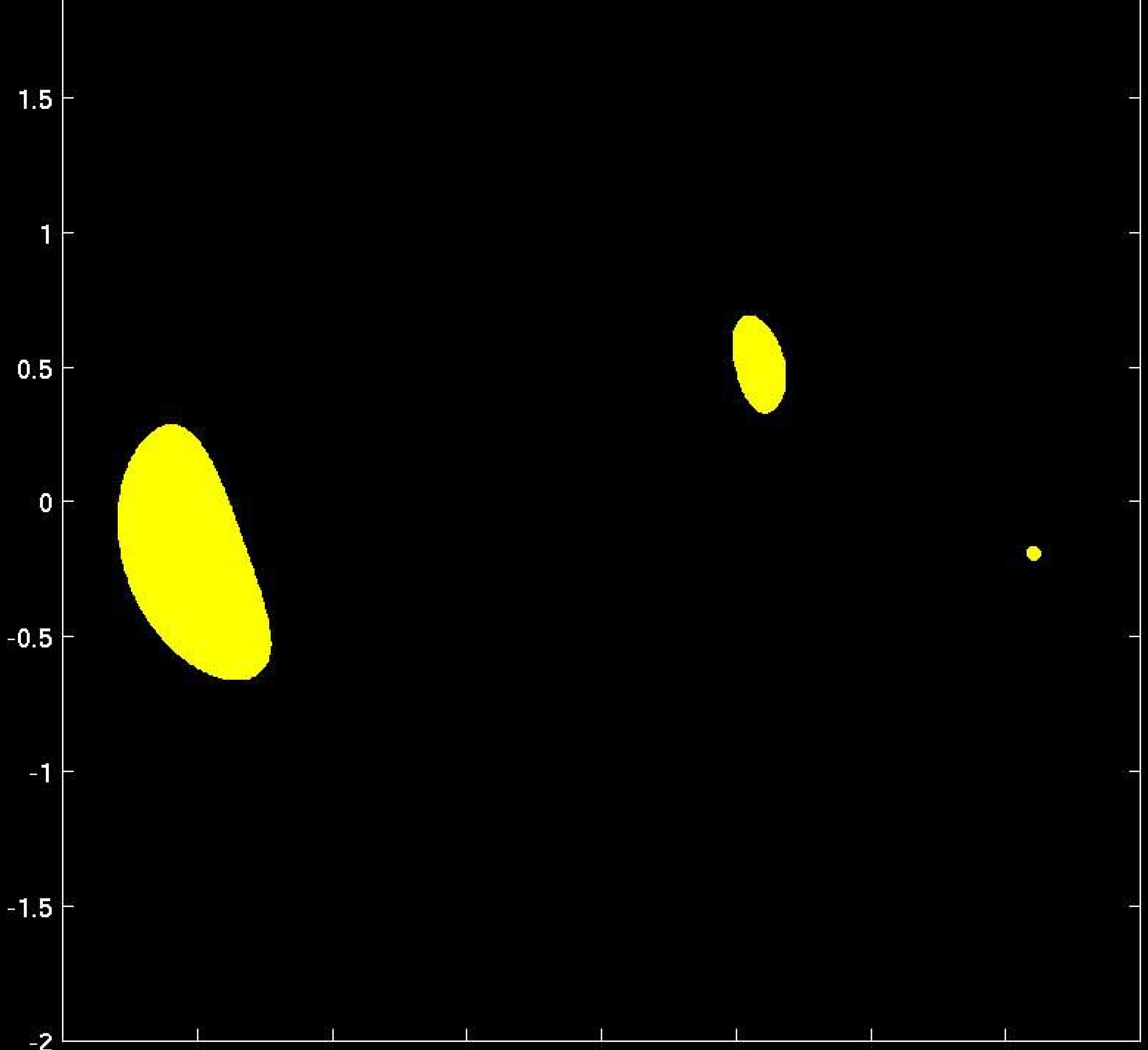
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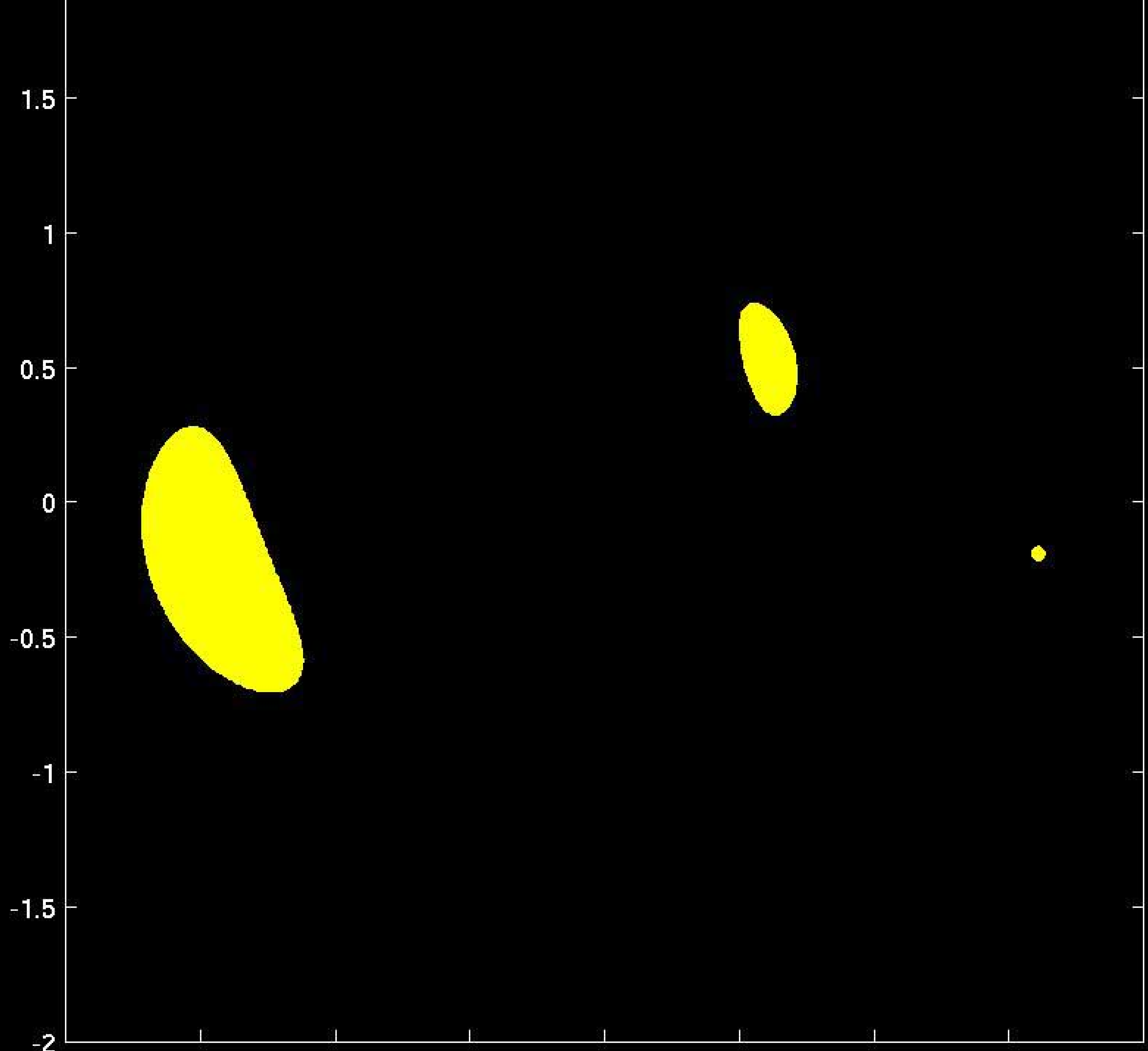

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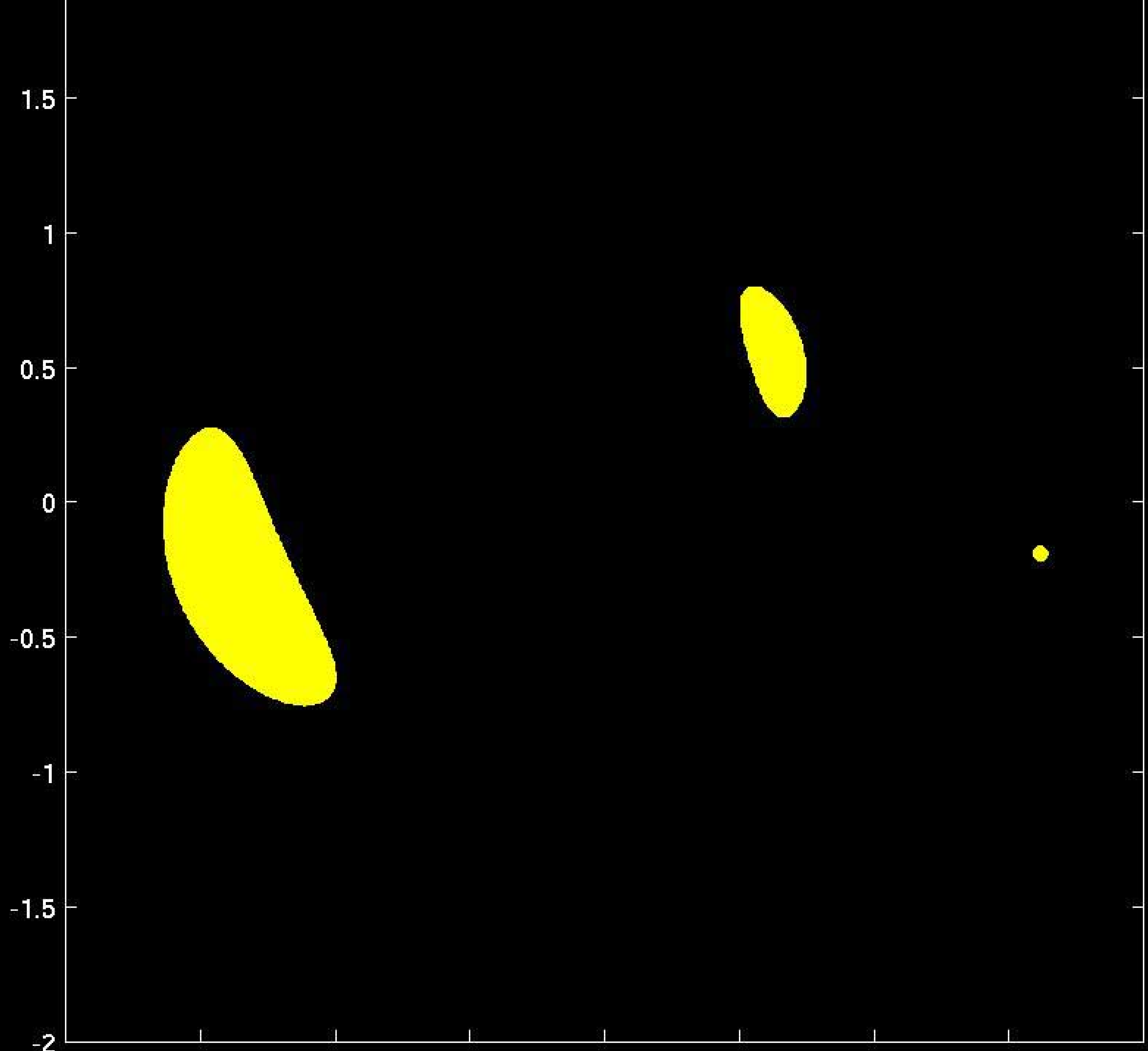
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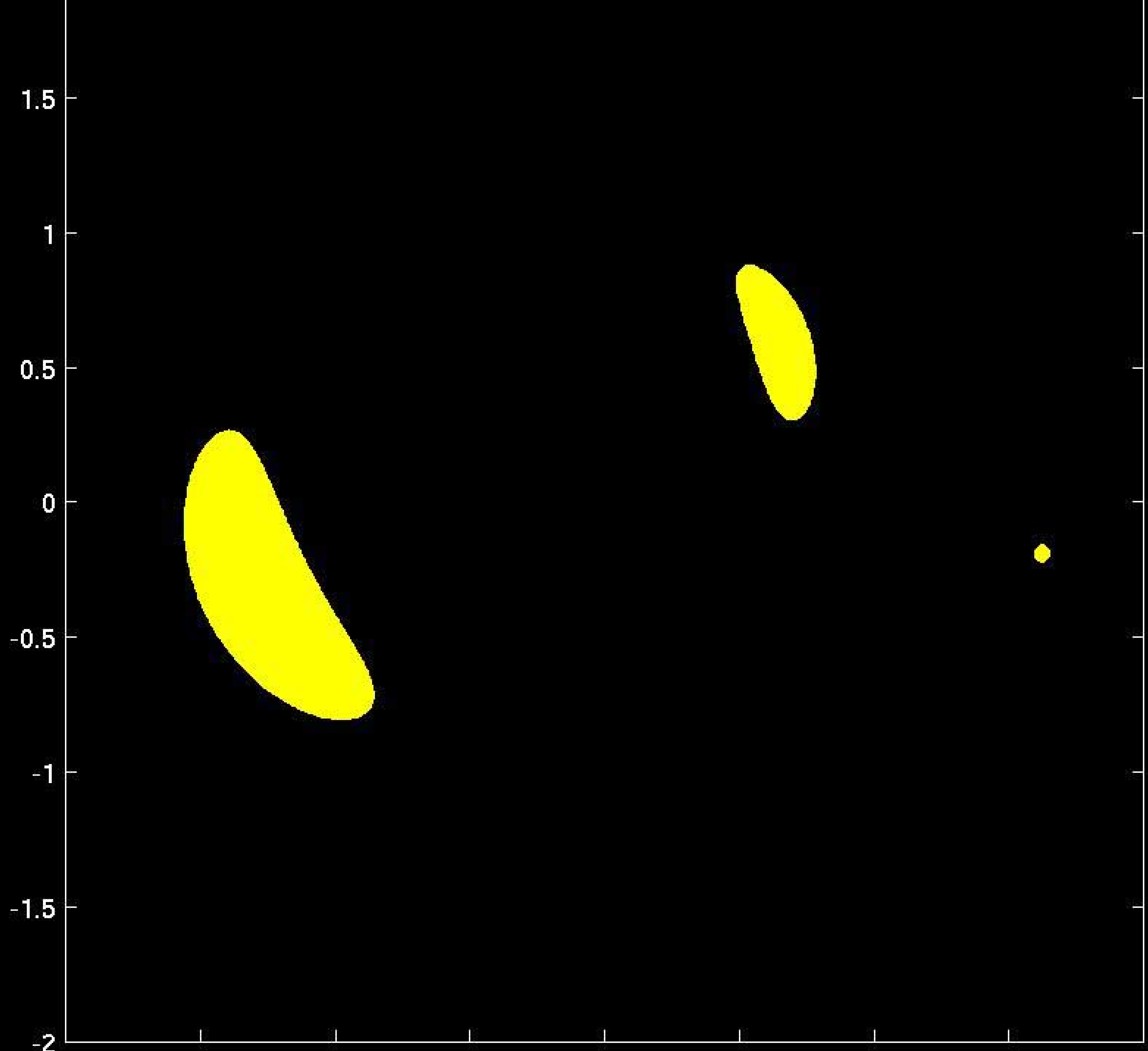
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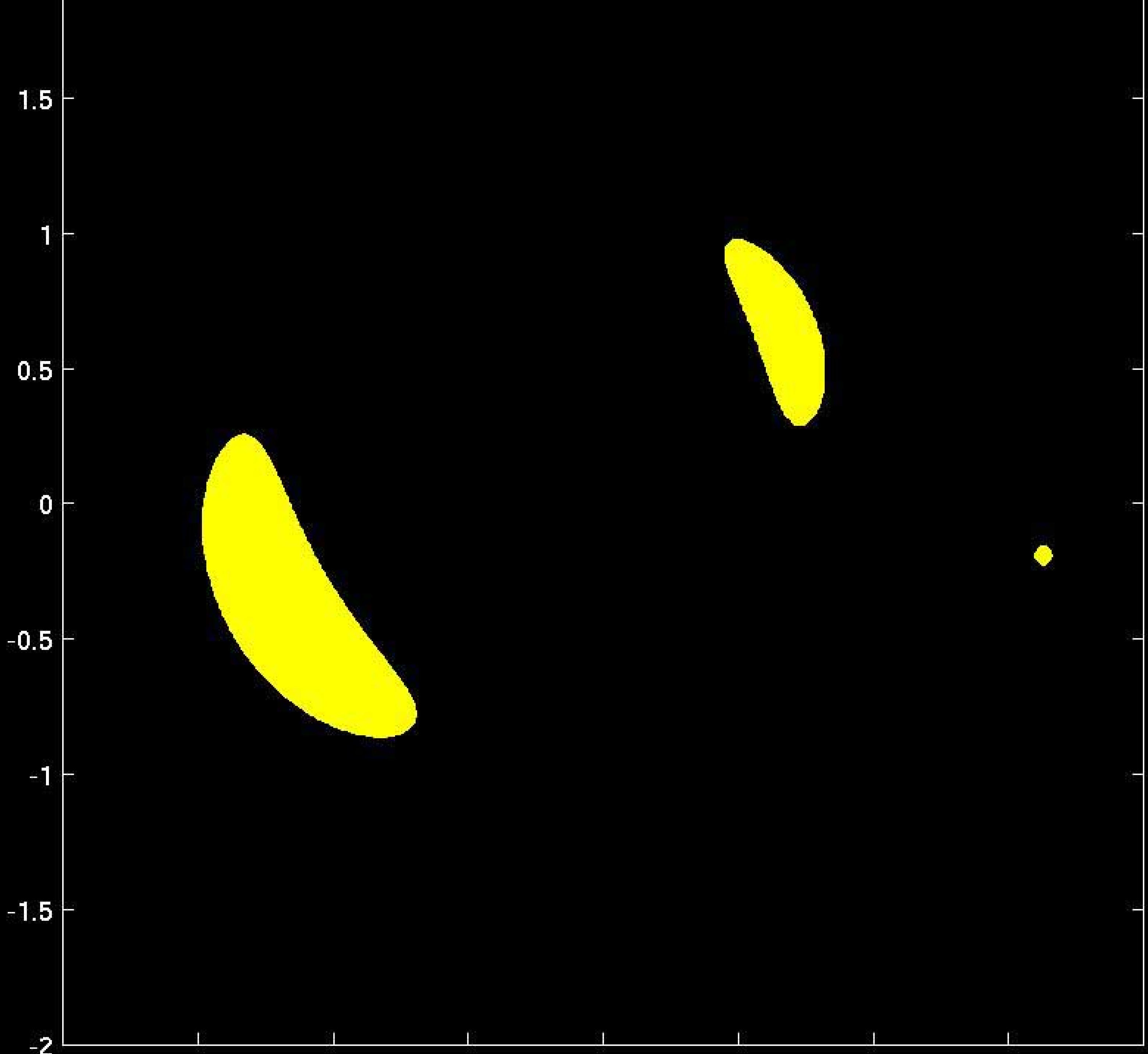
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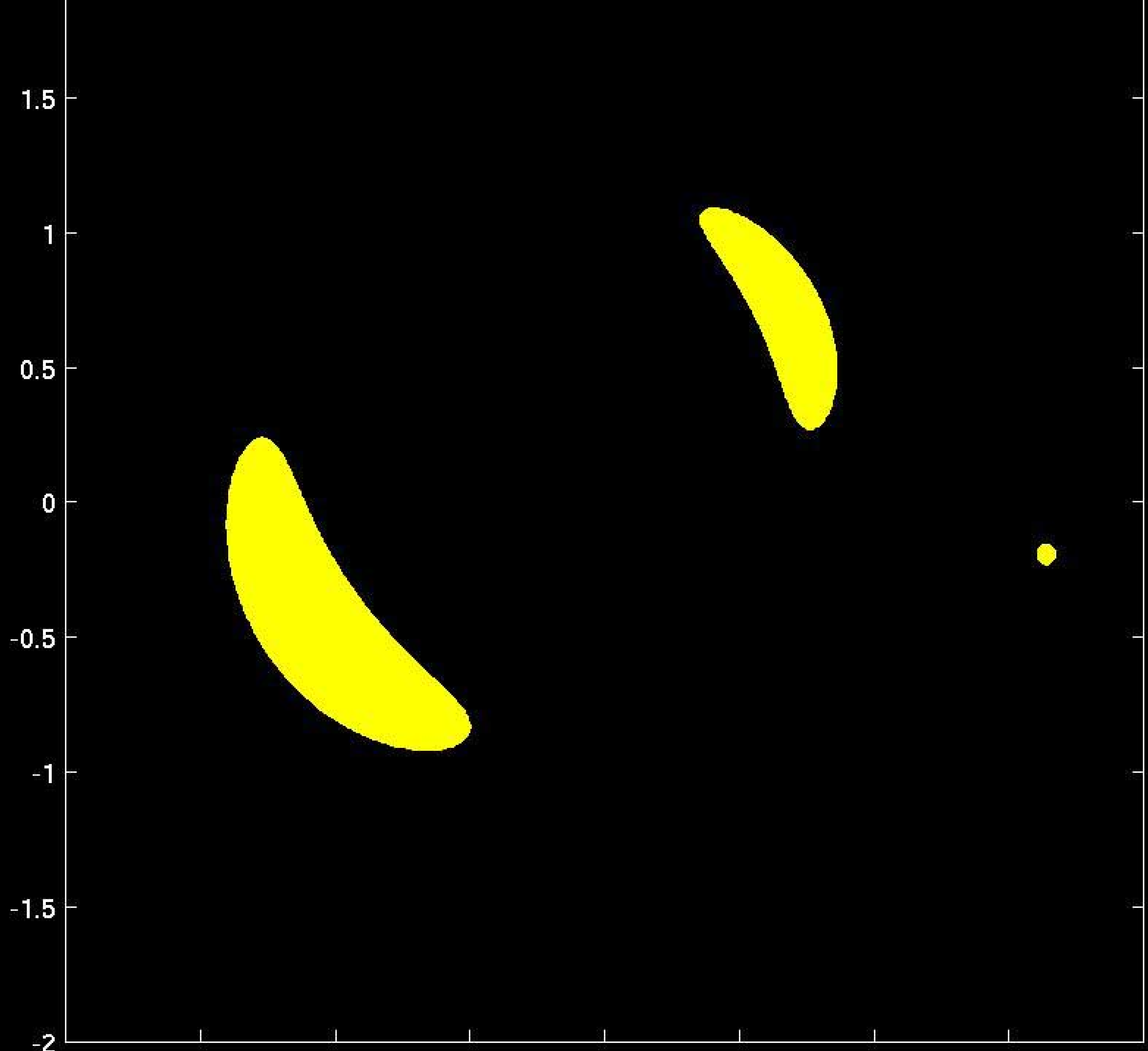

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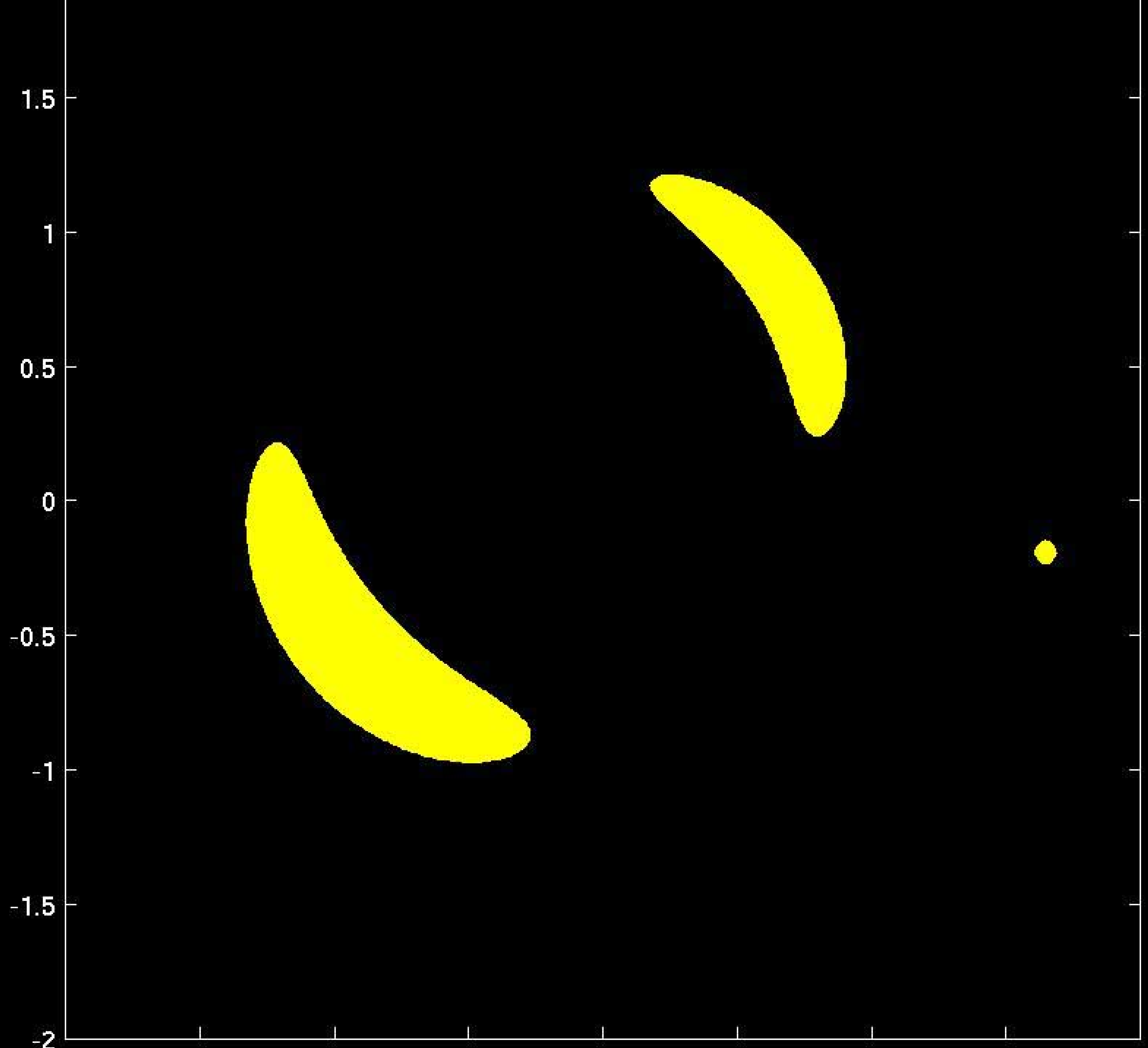

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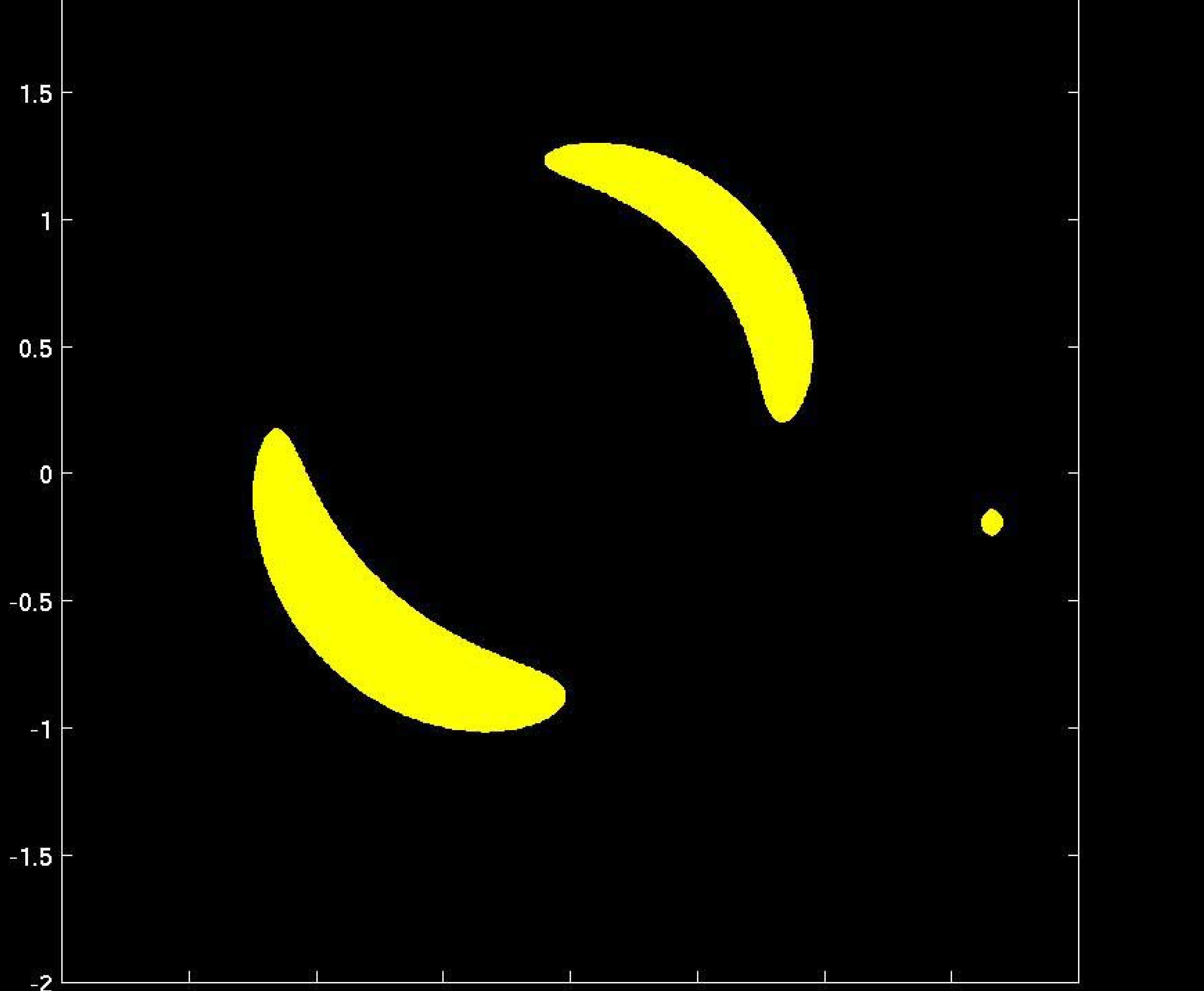

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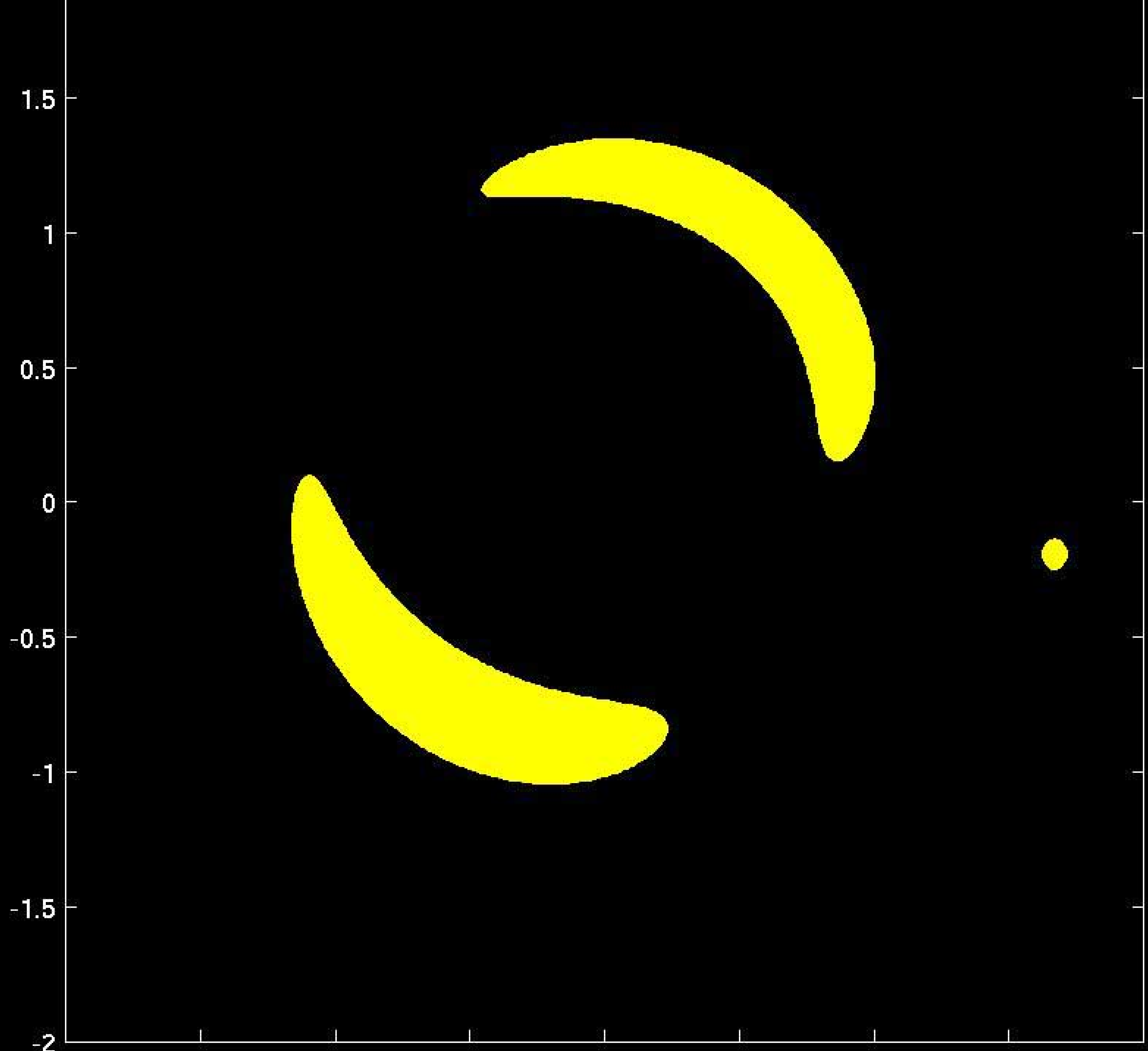

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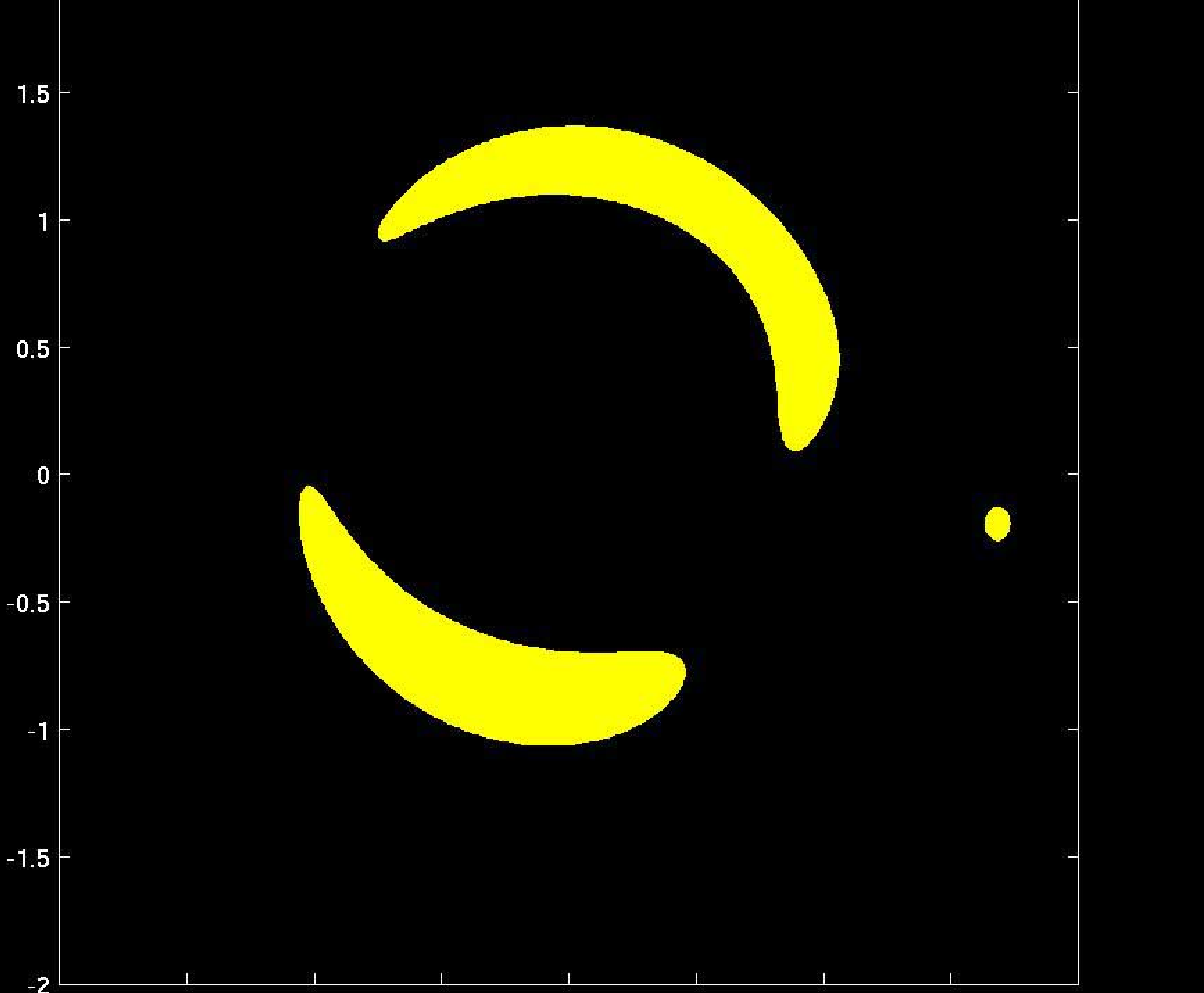

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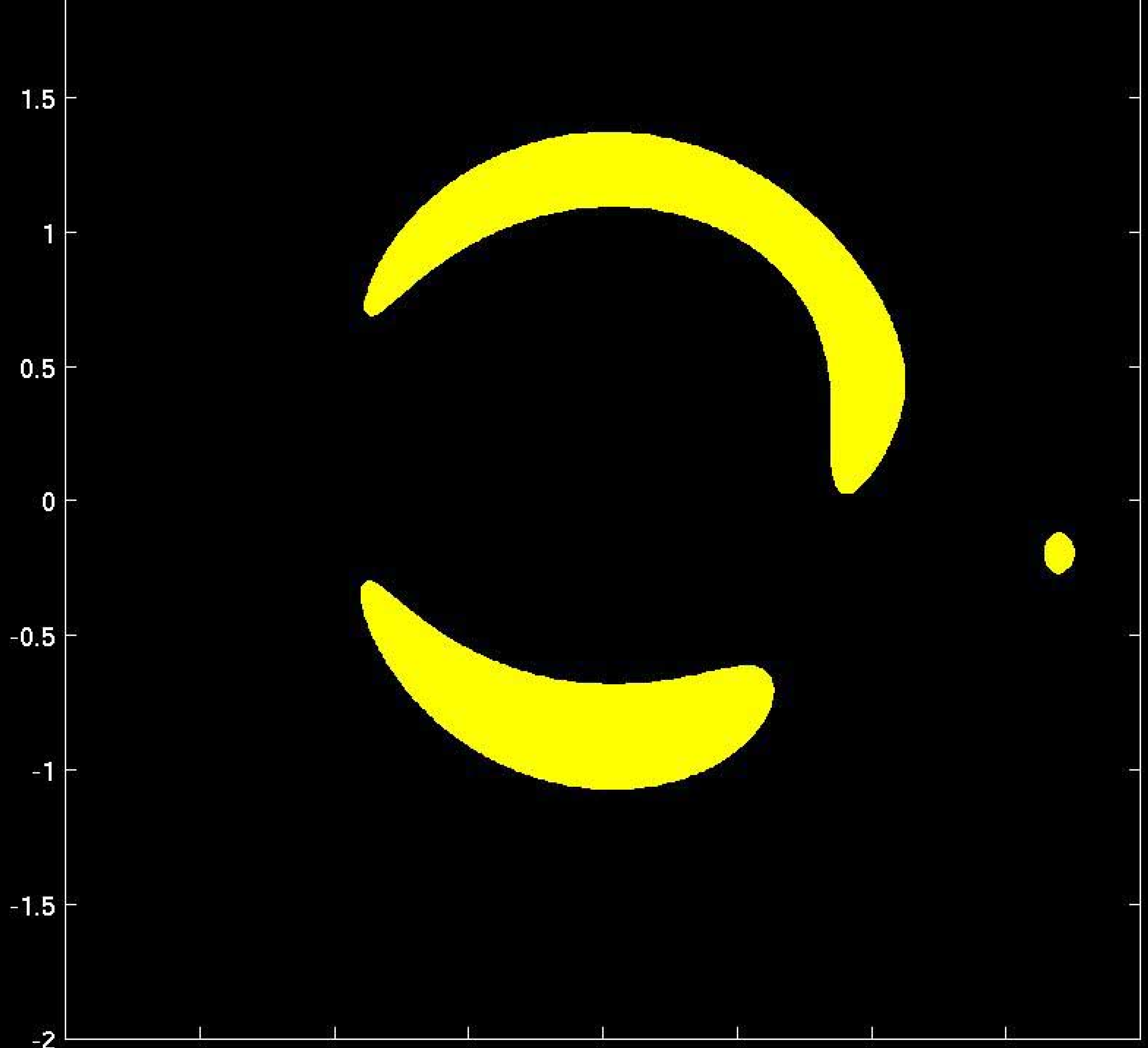
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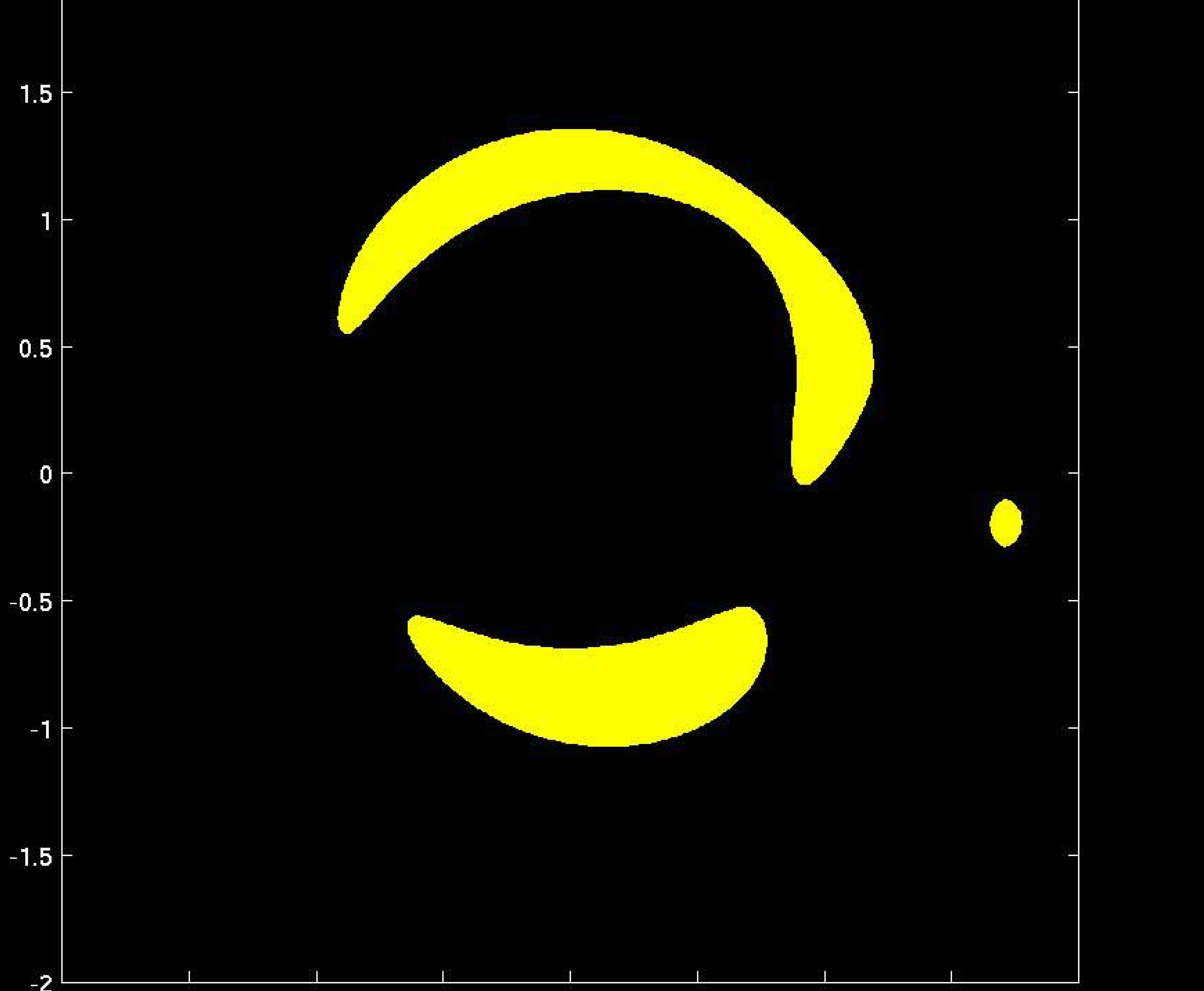

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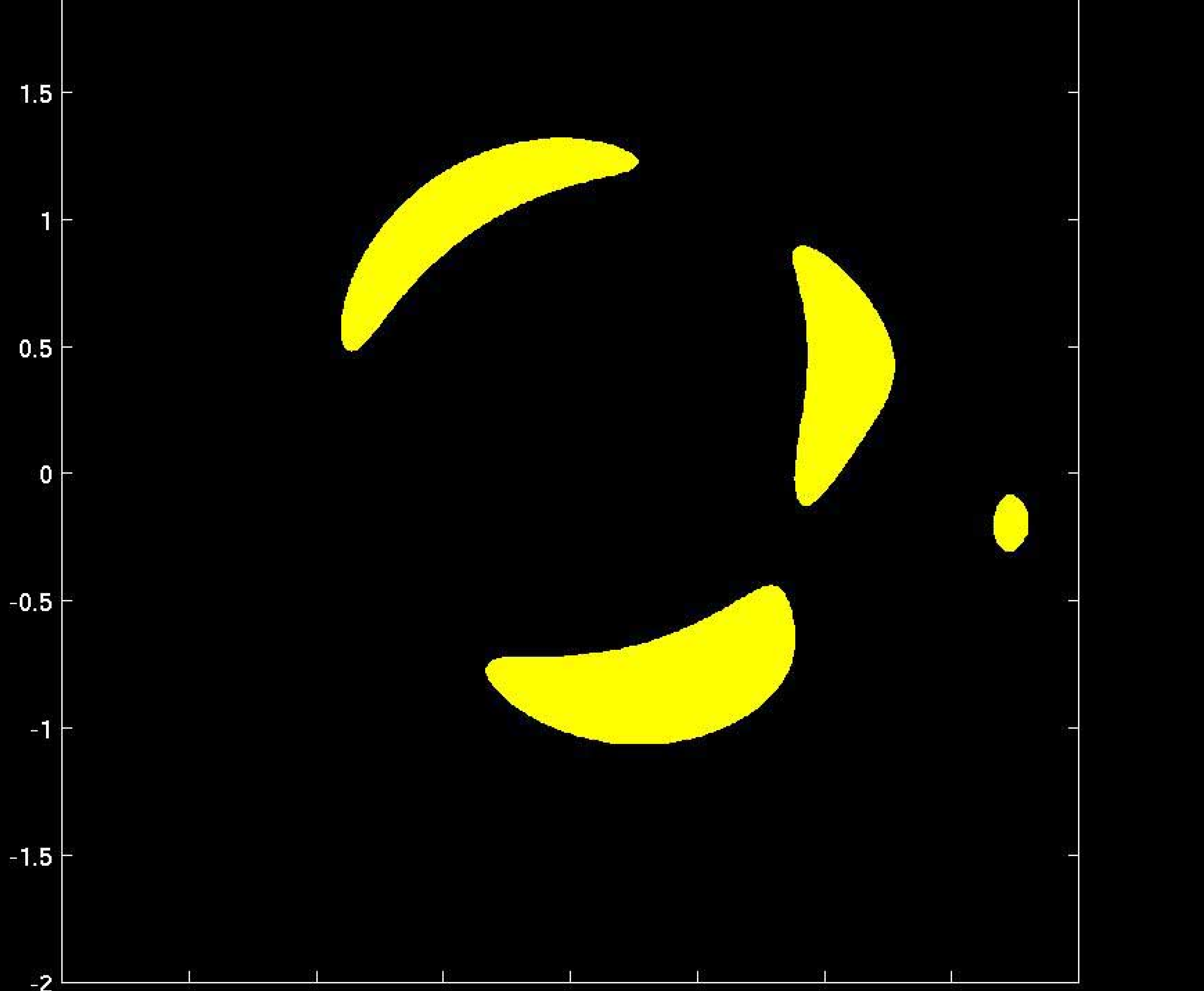
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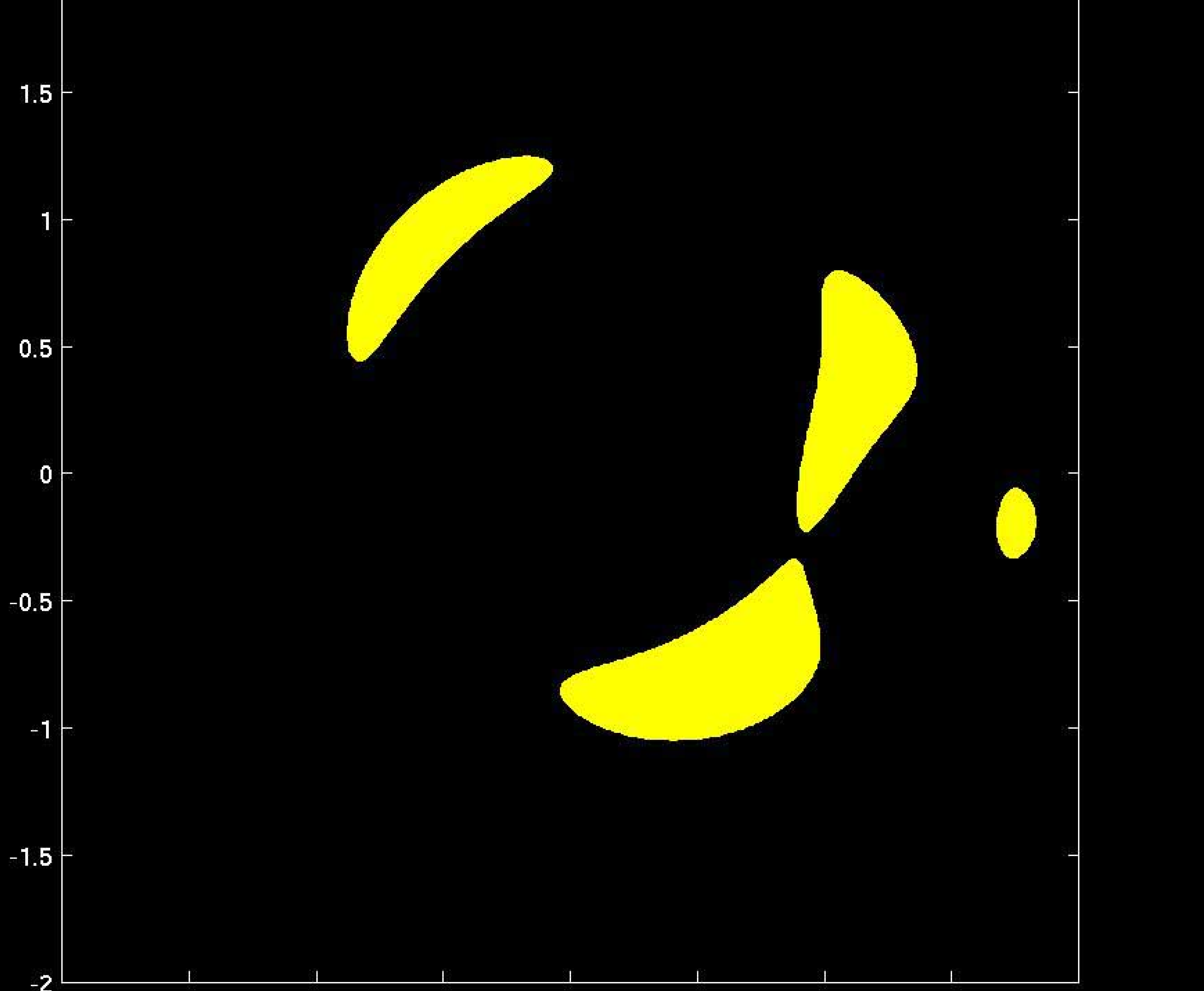

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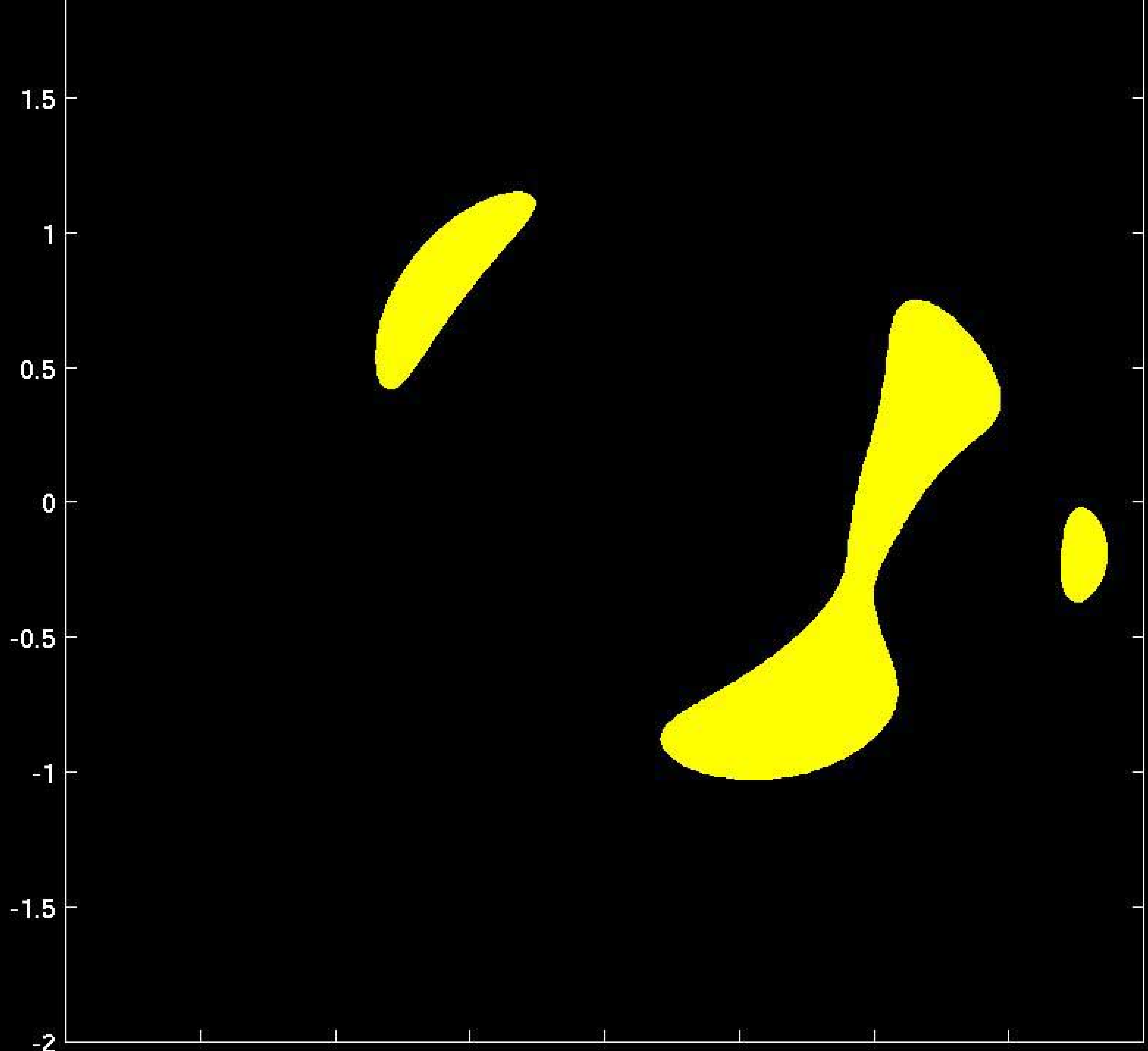

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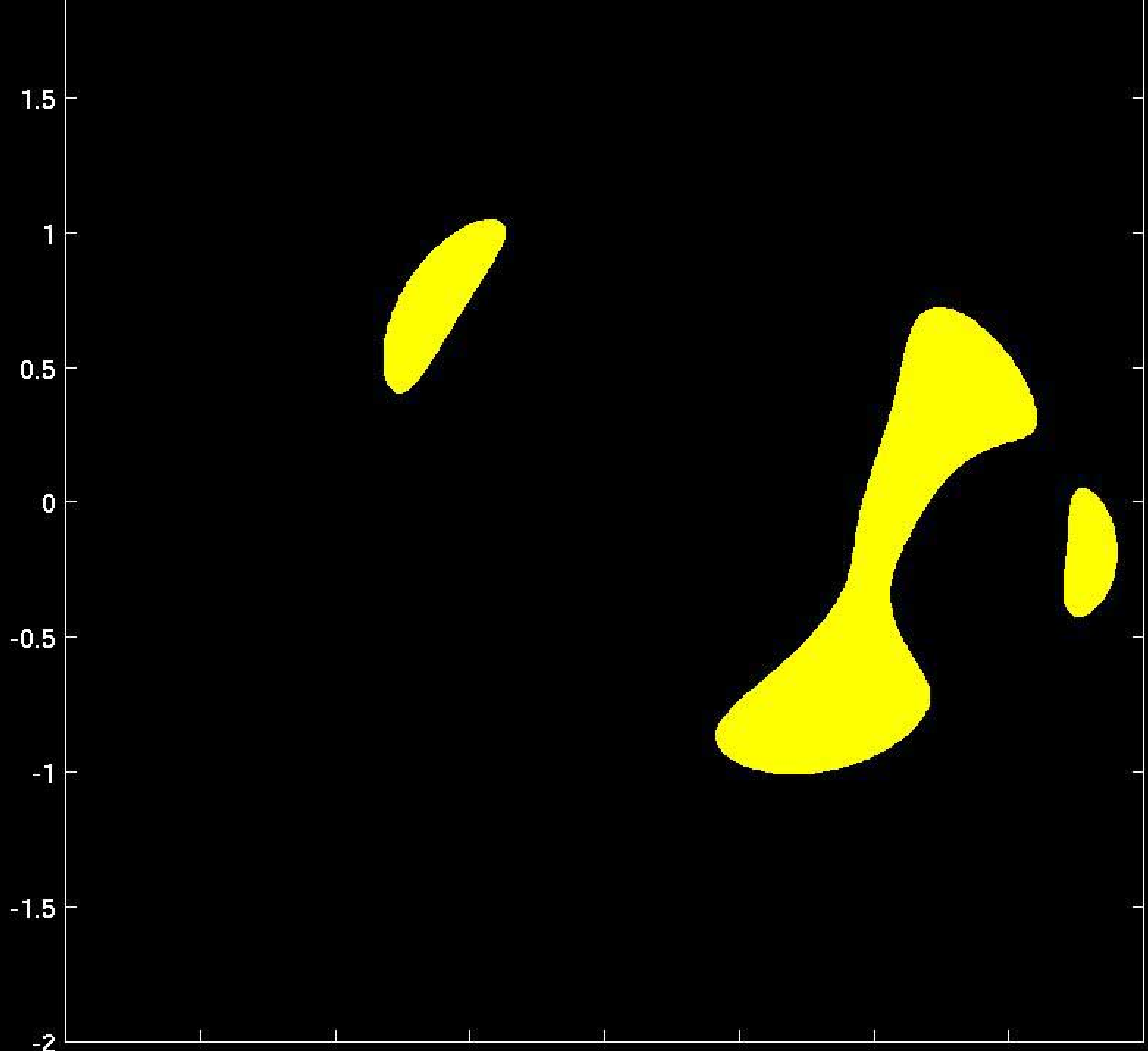

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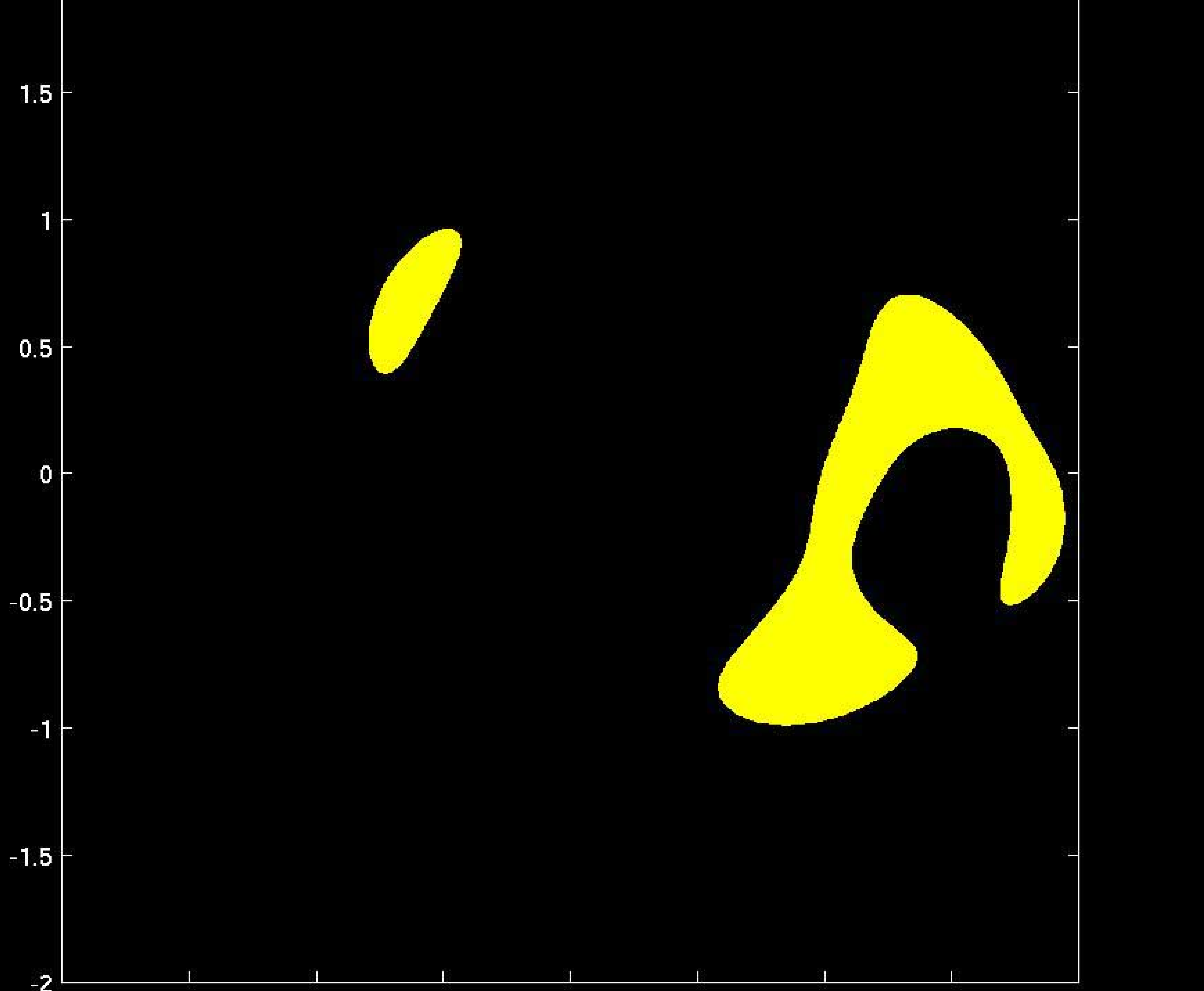

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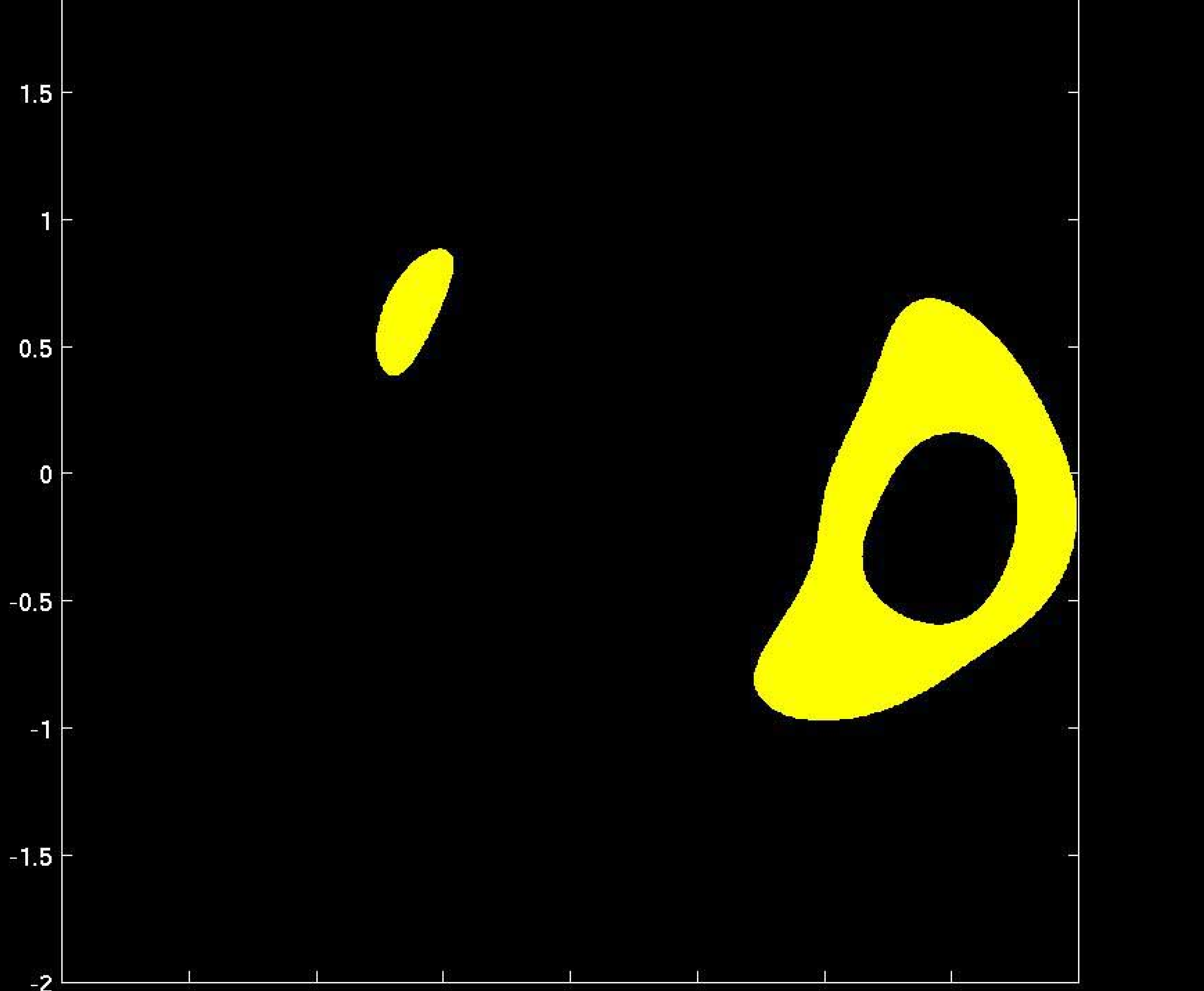
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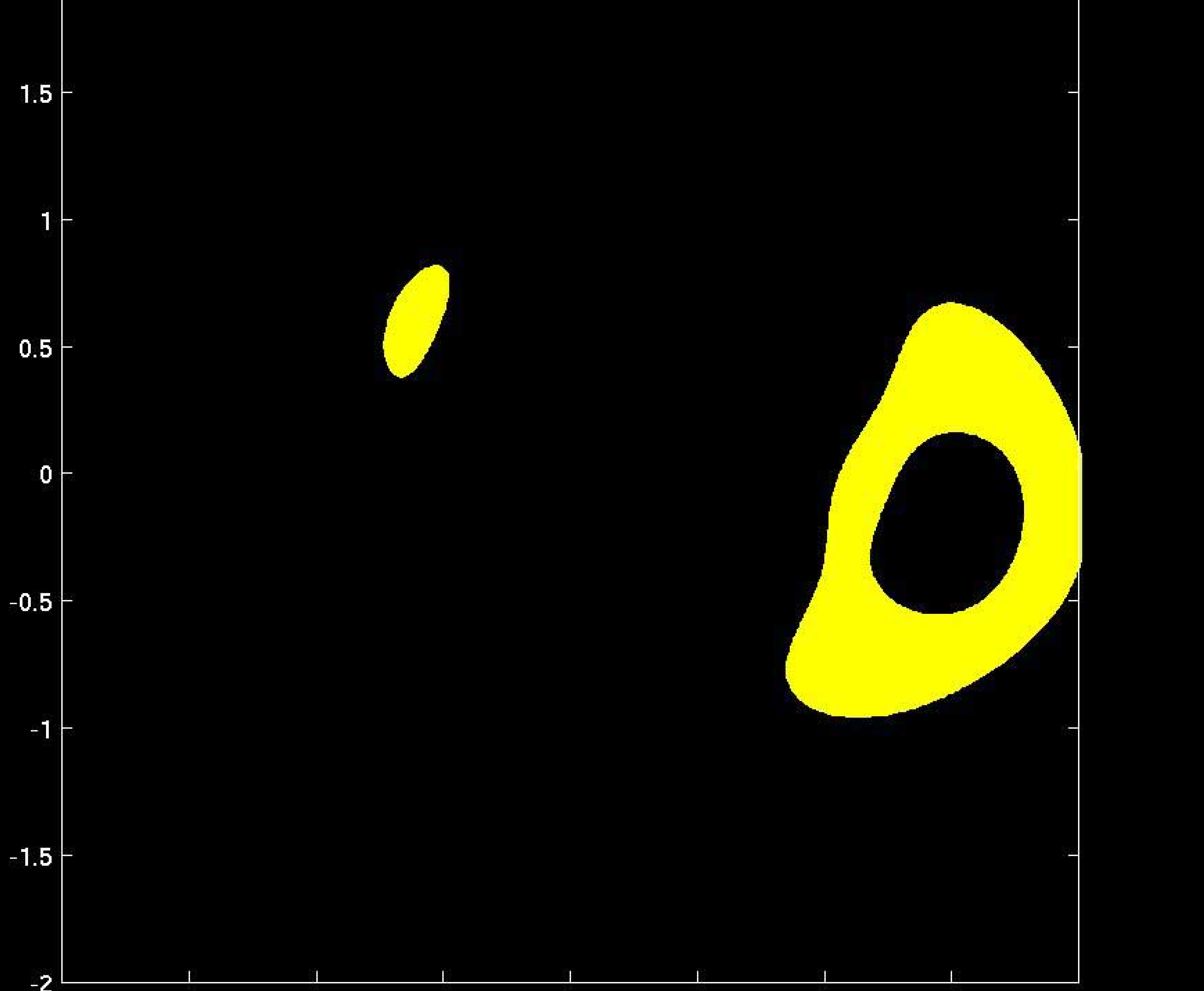

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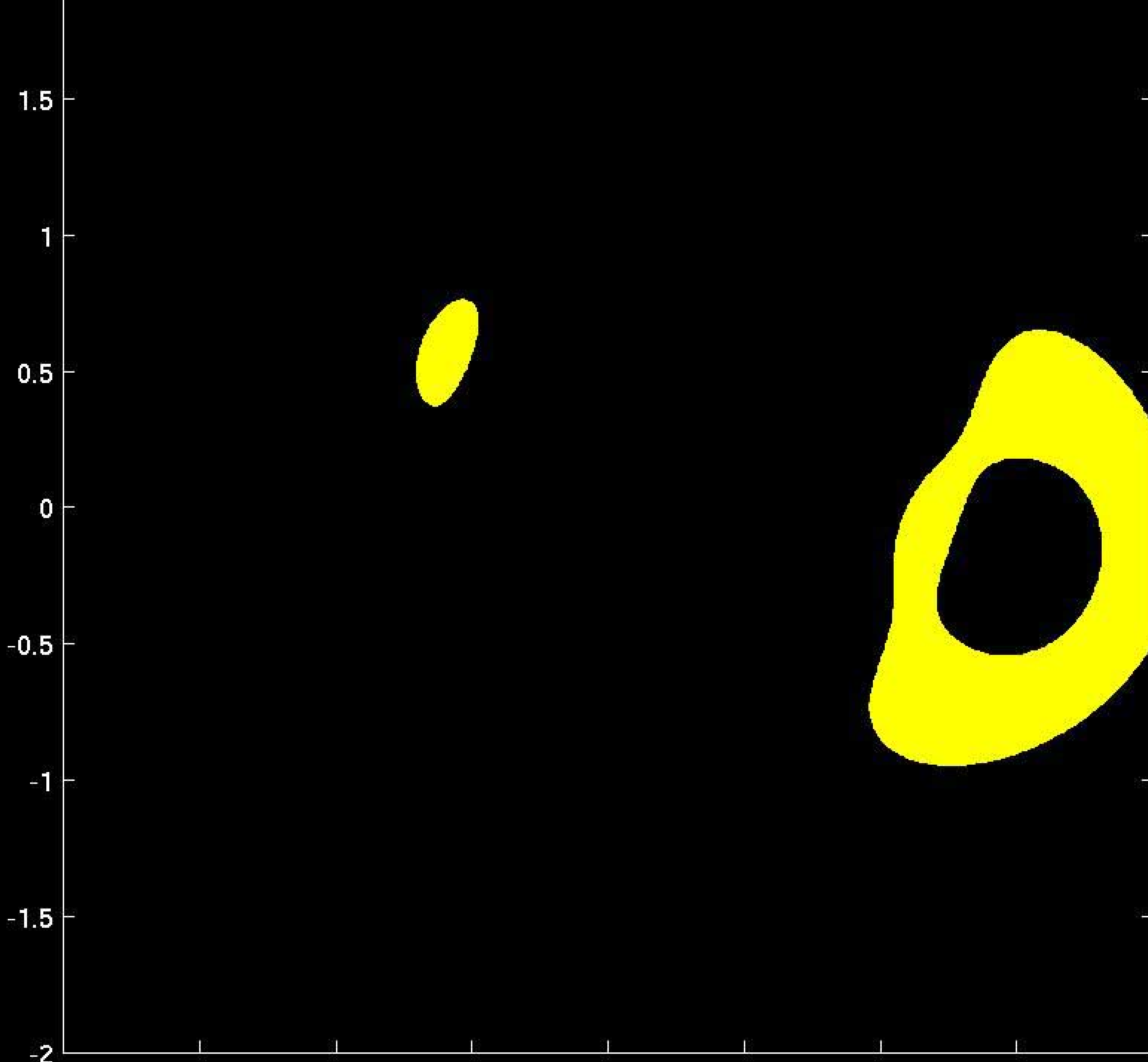
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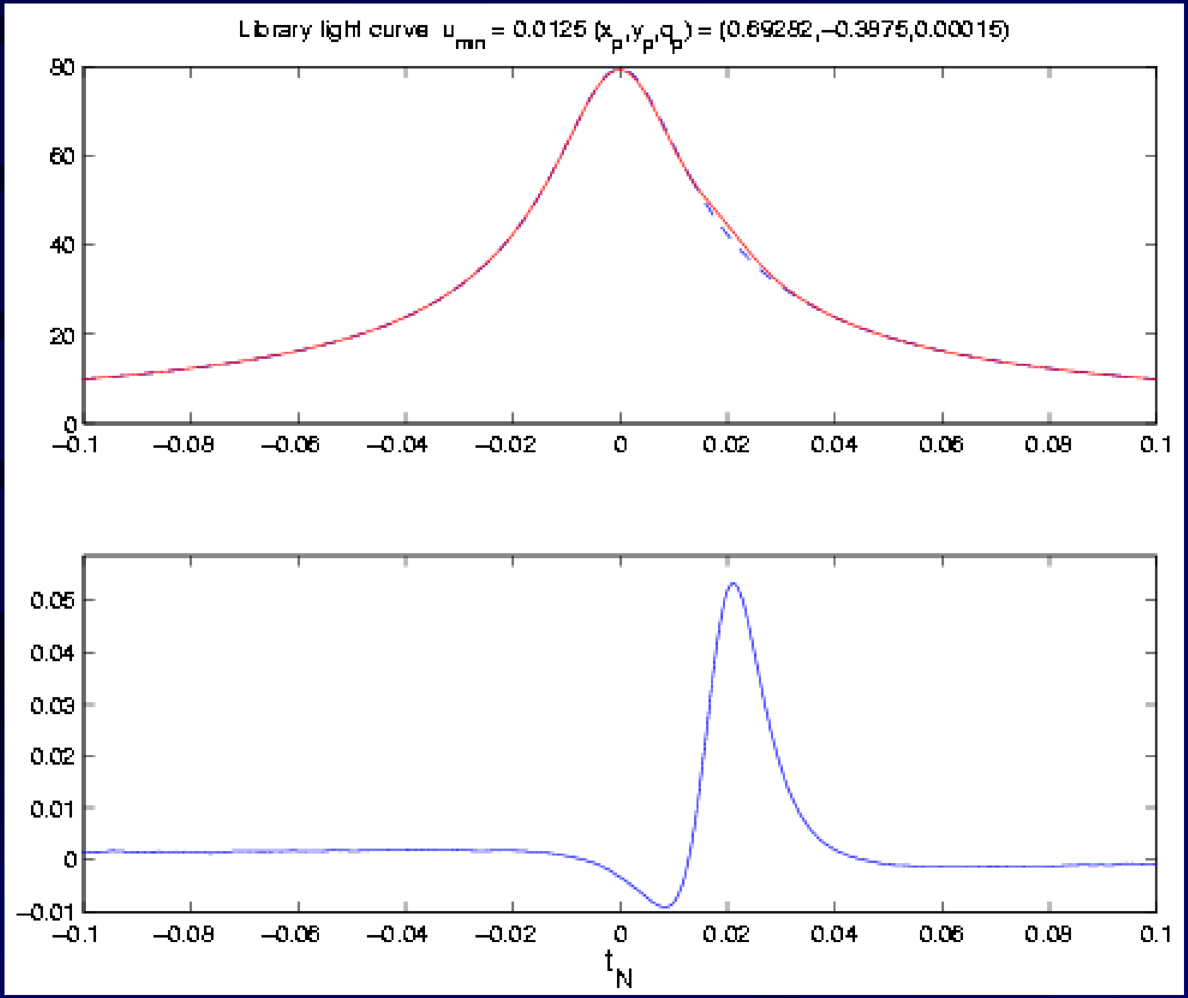
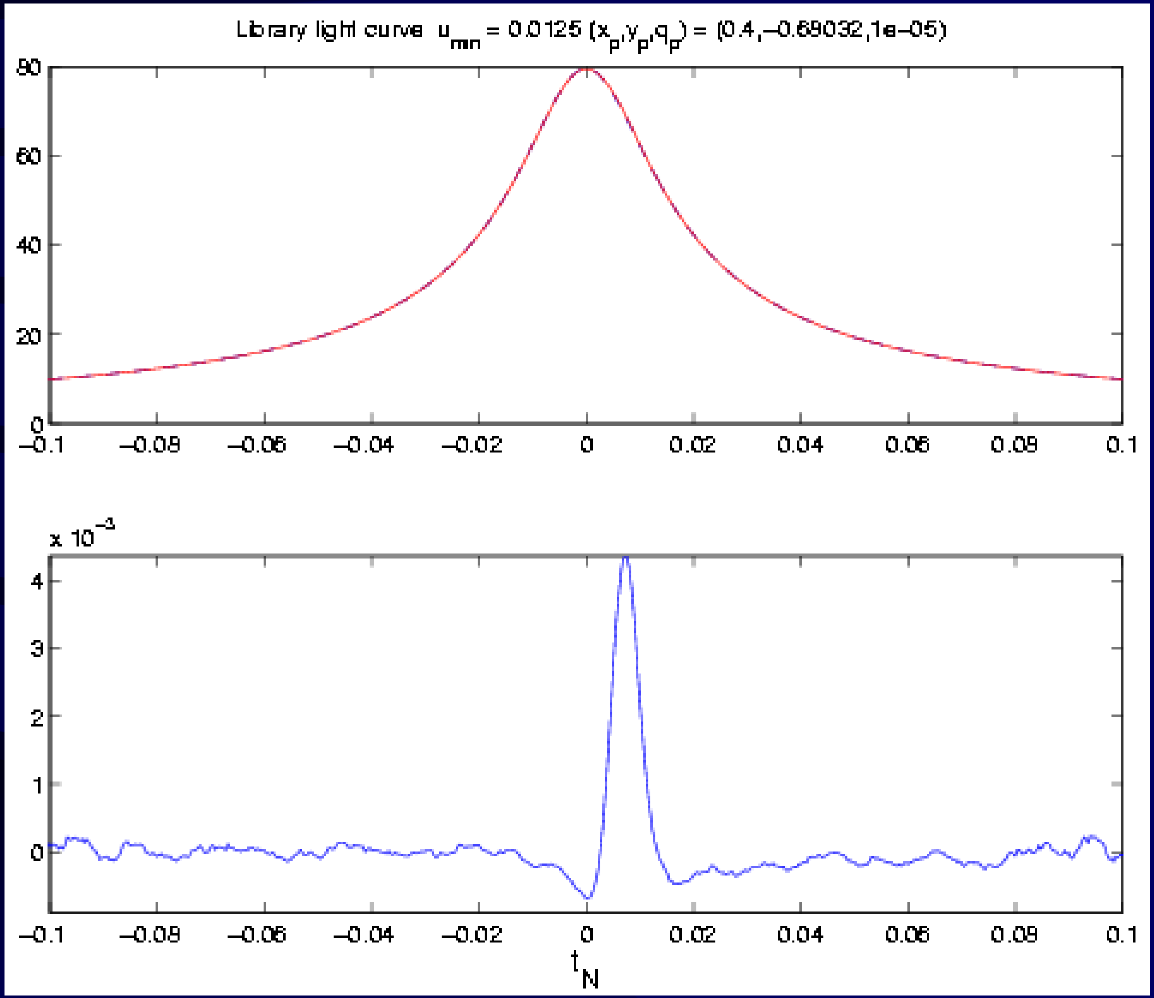
Neptune at ~ 2AU at different θ

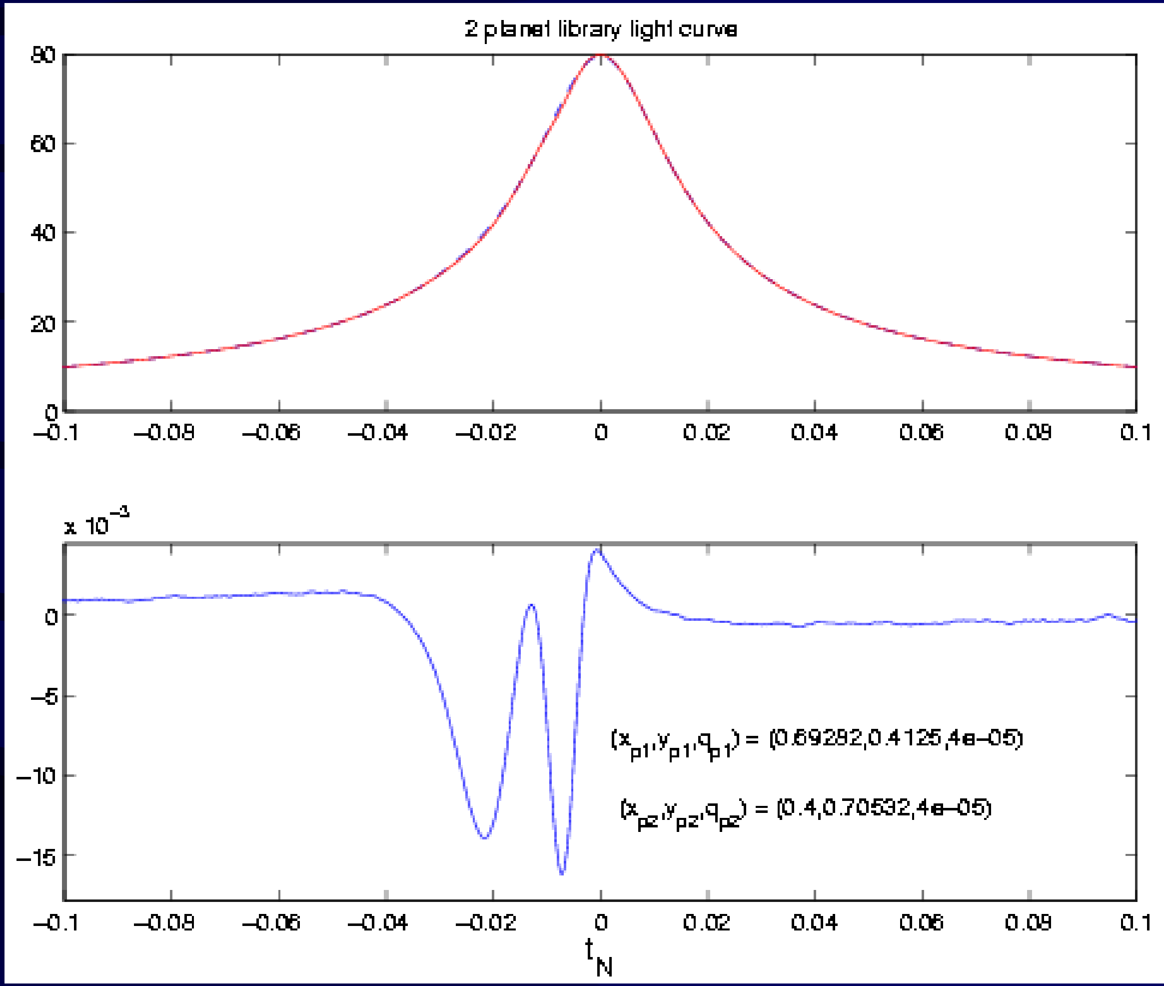


Earth at ~ 2 AU



Perturbation ~ 0.5%

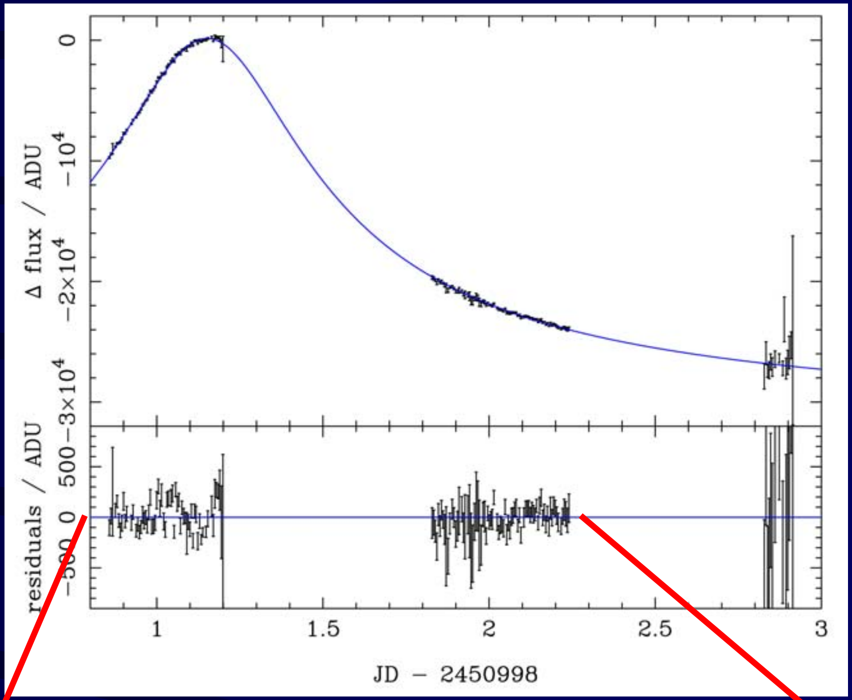
Two planets



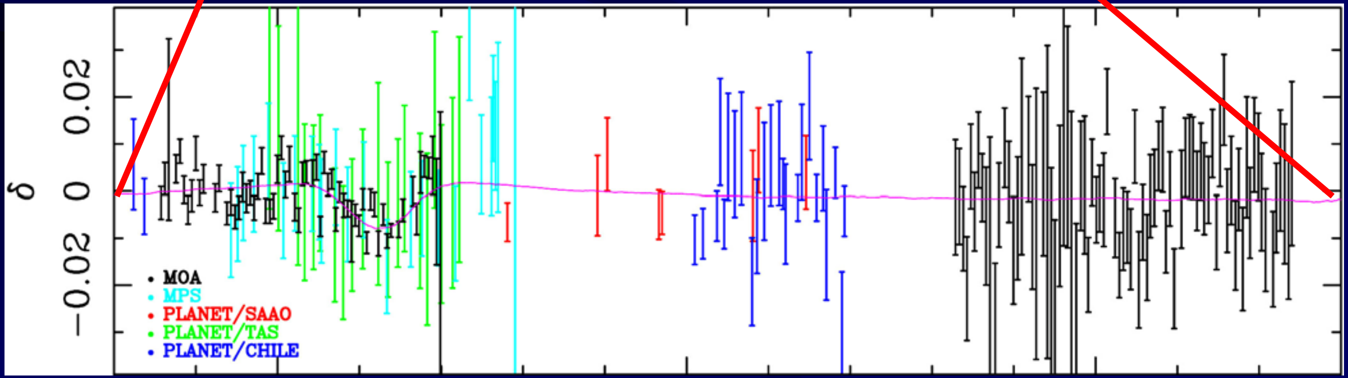
Detectable if $\Delta\theta > 20°$

MACHO 98-BLG-35

MOA data

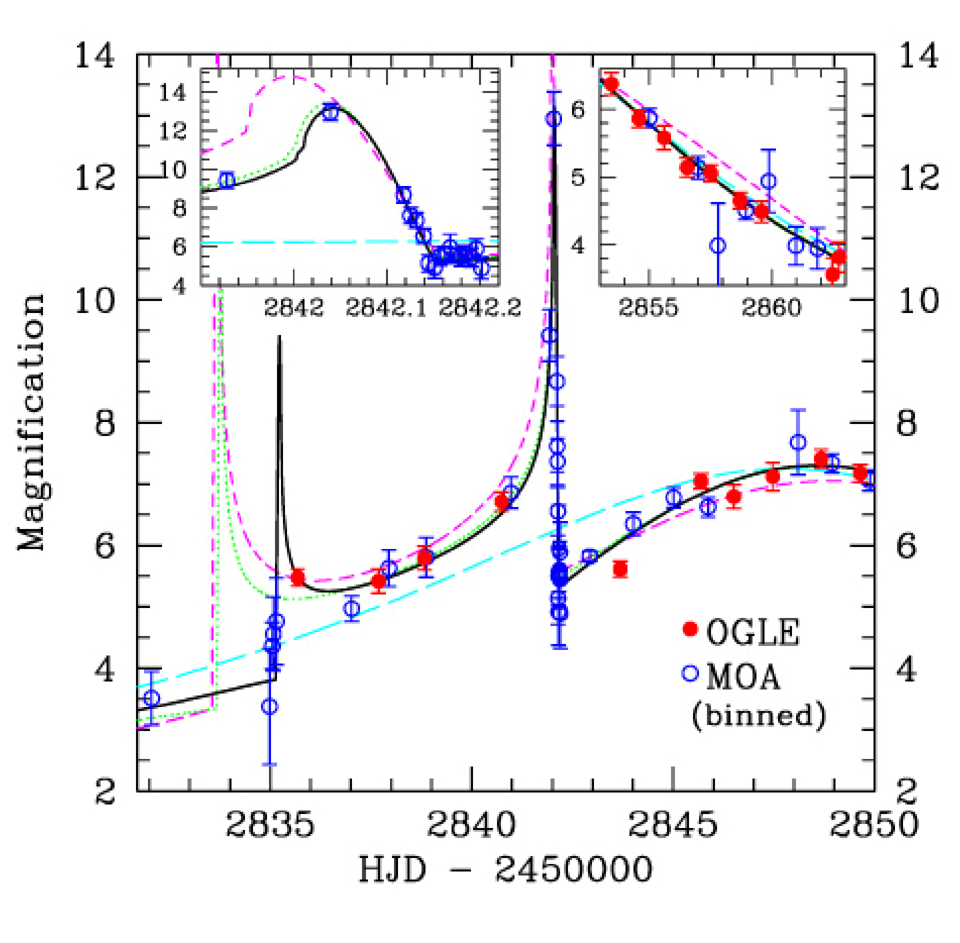


All data



Only Earth-like candidate ($\Delta\chi^2 = 60$); MNRAS **333,** 71 (2002)

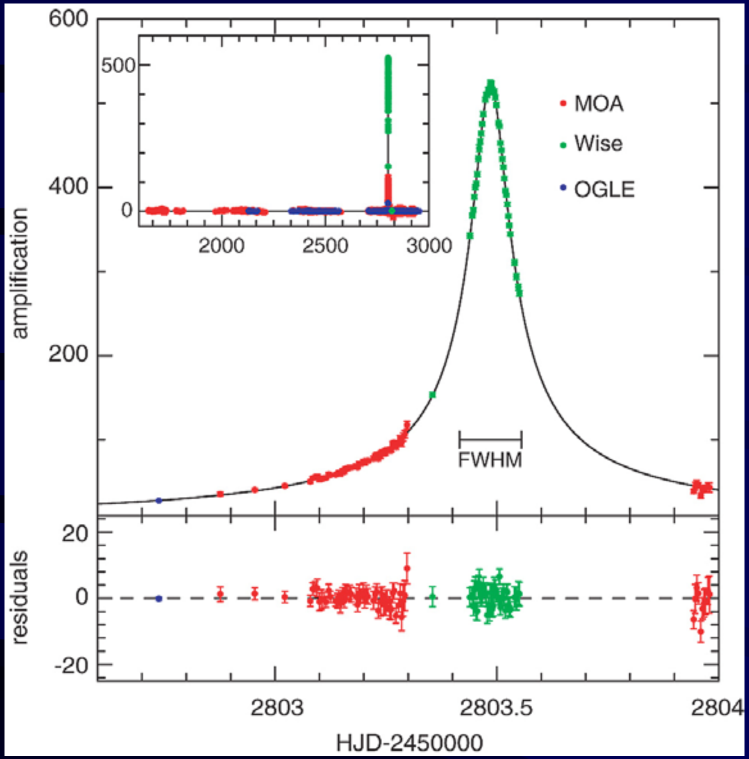
MOA 2003-BLG-53/ OGLE 2003-BLG-235

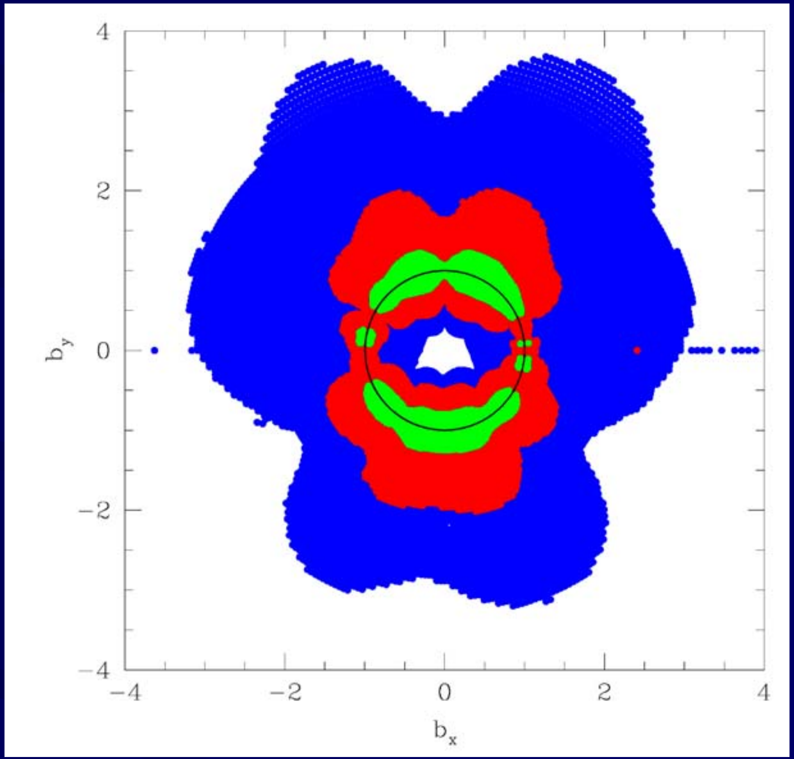


Jupiter-like planet orbiting a red-dwarf in the bulge

ApJ 606,L155, 2004

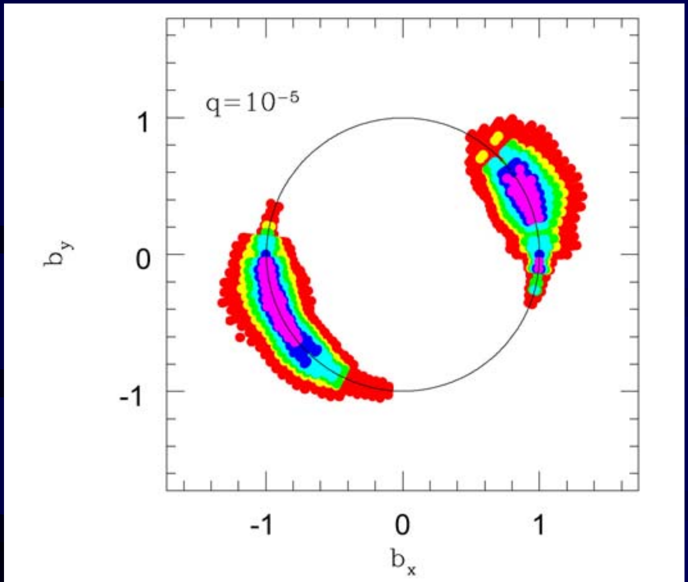
MOA 2003-BLG-32/OGLE 2003-BLG-219

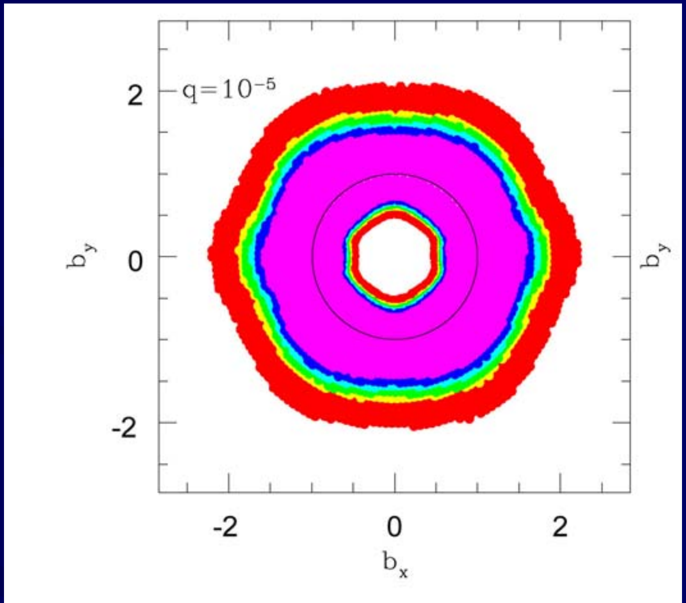




Most sensitive search for extrasolar planets
Science 305, 1264, 2004

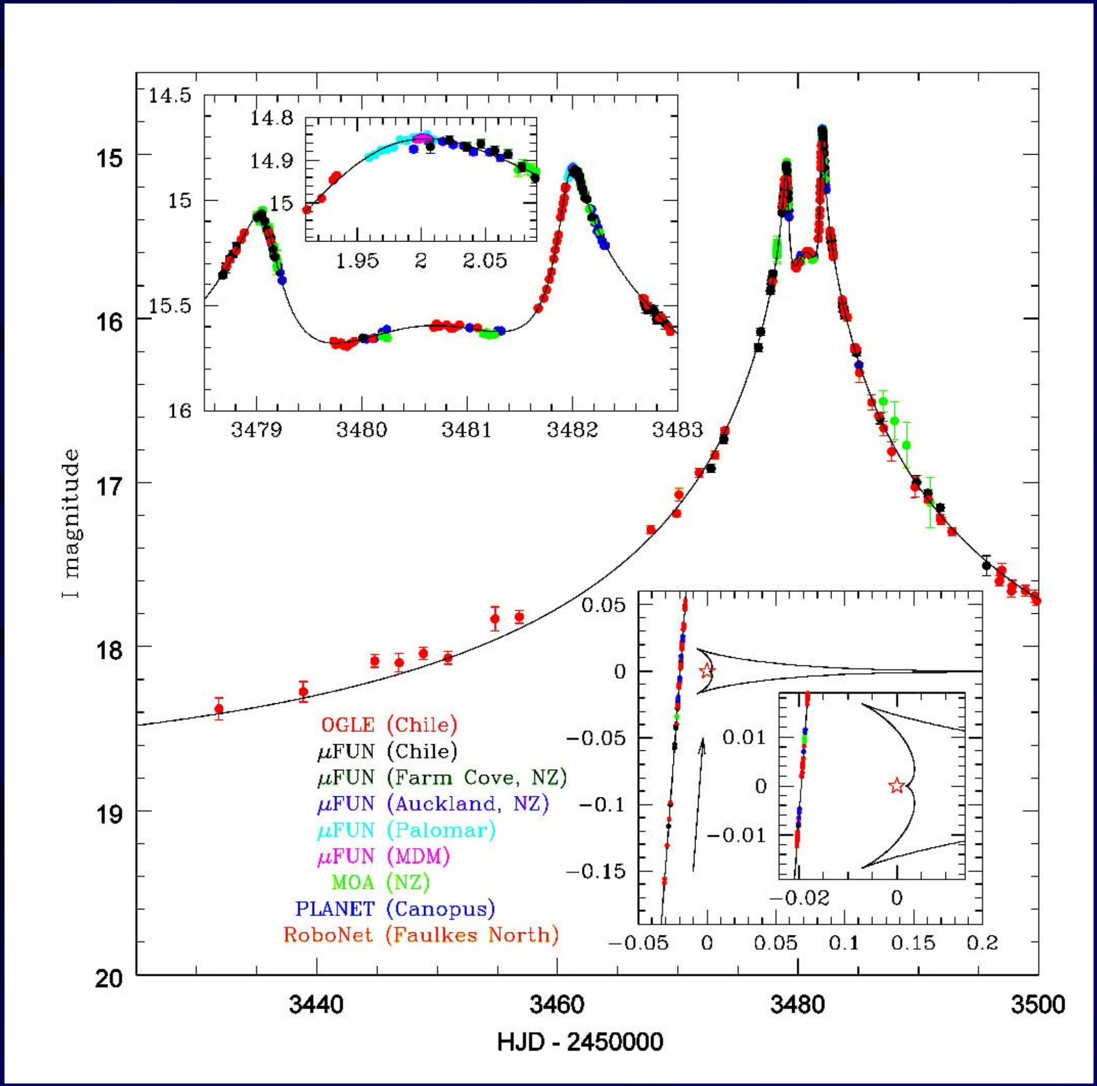
OGLE 2004-BLG-343





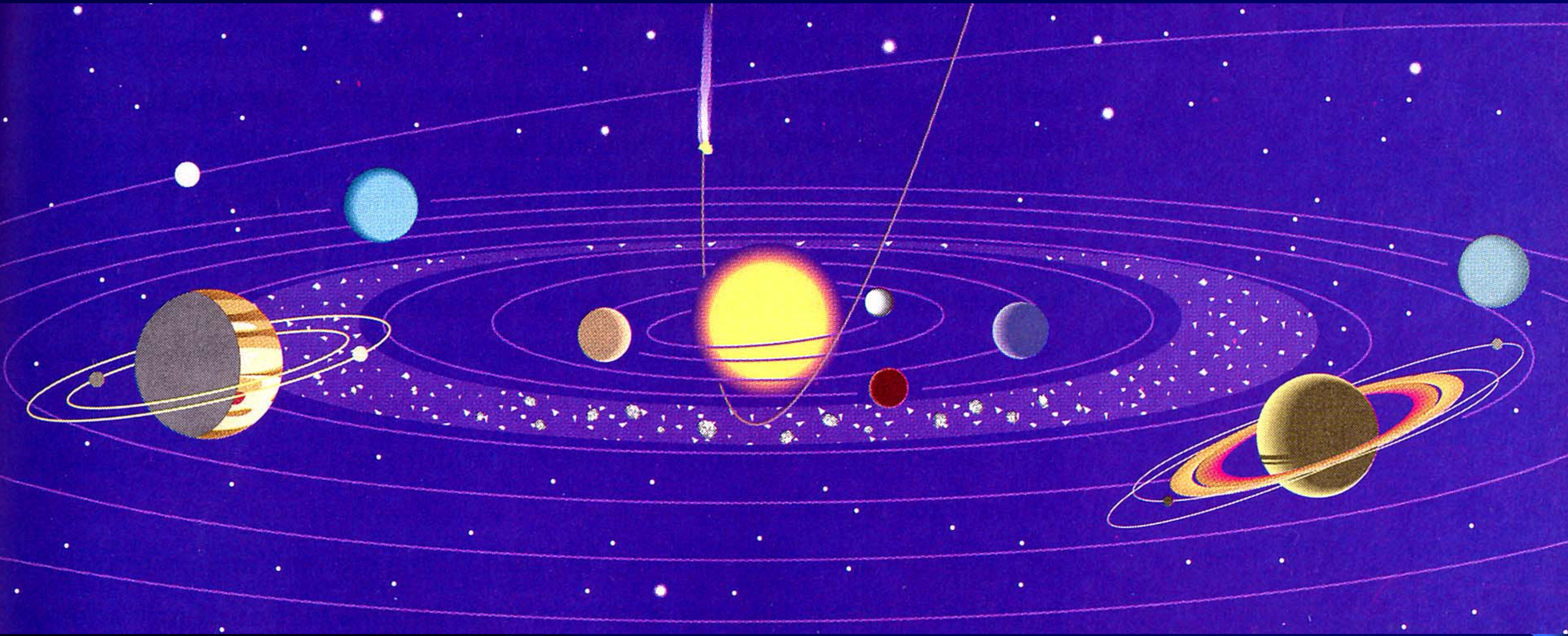
Highest magnification (~3000)
Astro-ph/0507079

OGLE 2005-BLG-071



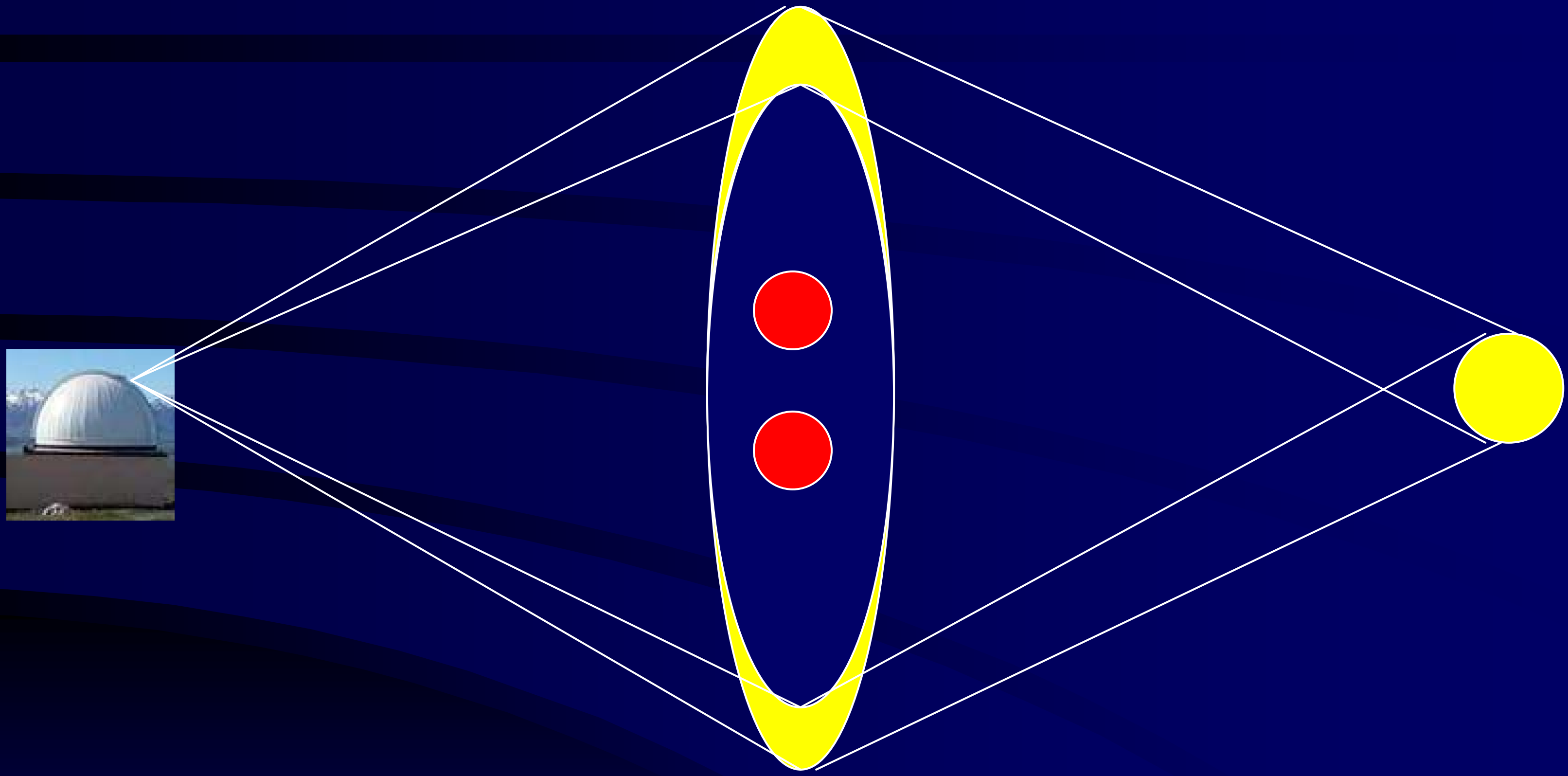
Jovian planet, astro-ph/0505451, ApJL 2005

Summary



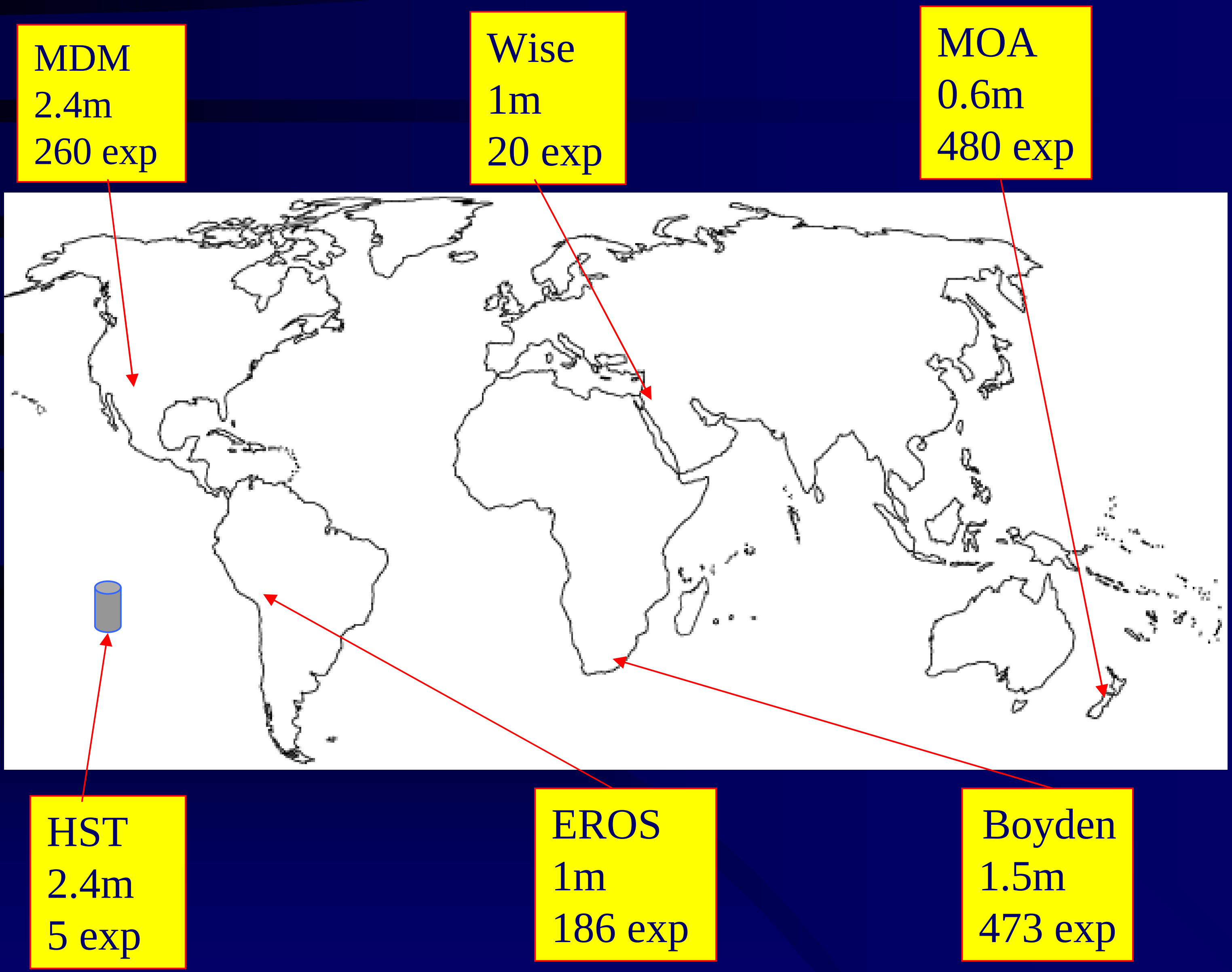
Inner planets: Transits & radial velocity
Outer planets: Microlensing

Binary lens

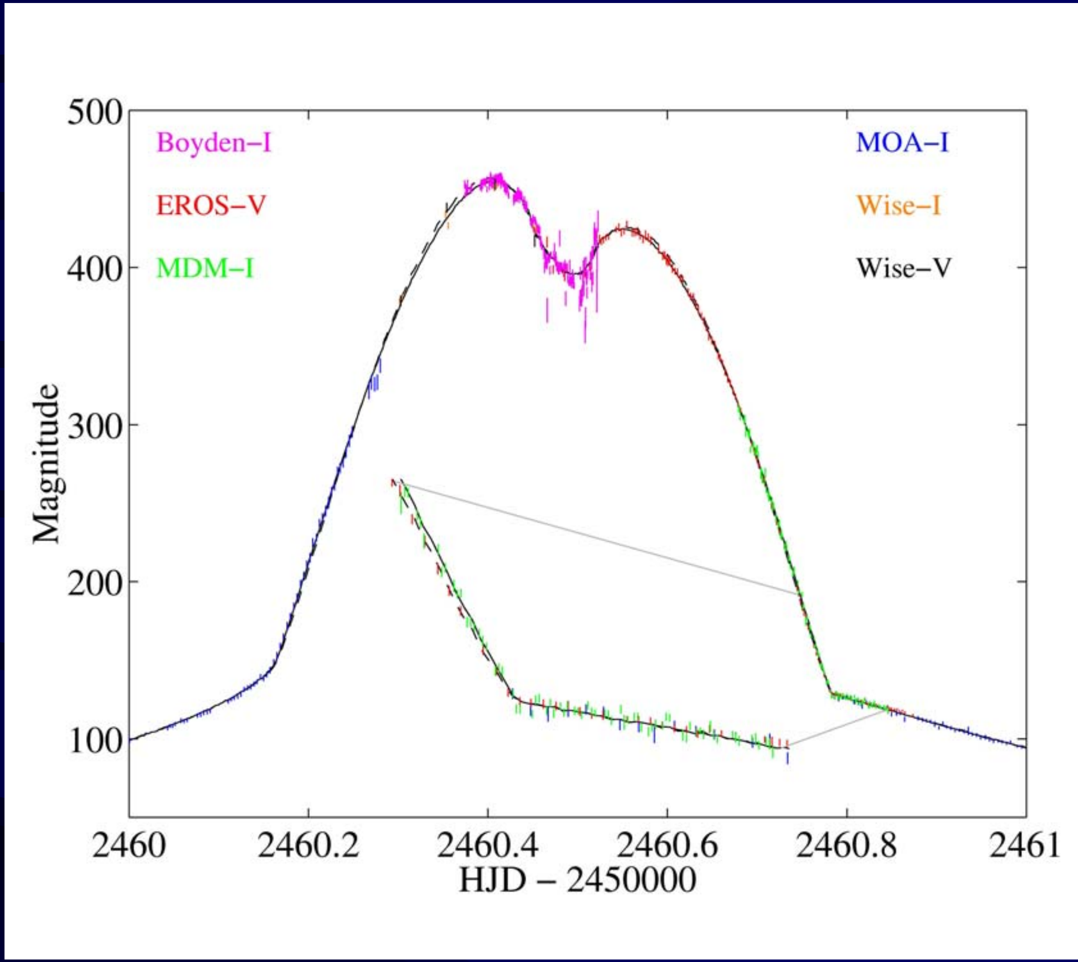


Lateral thinking

MOA 2002-BLG-33

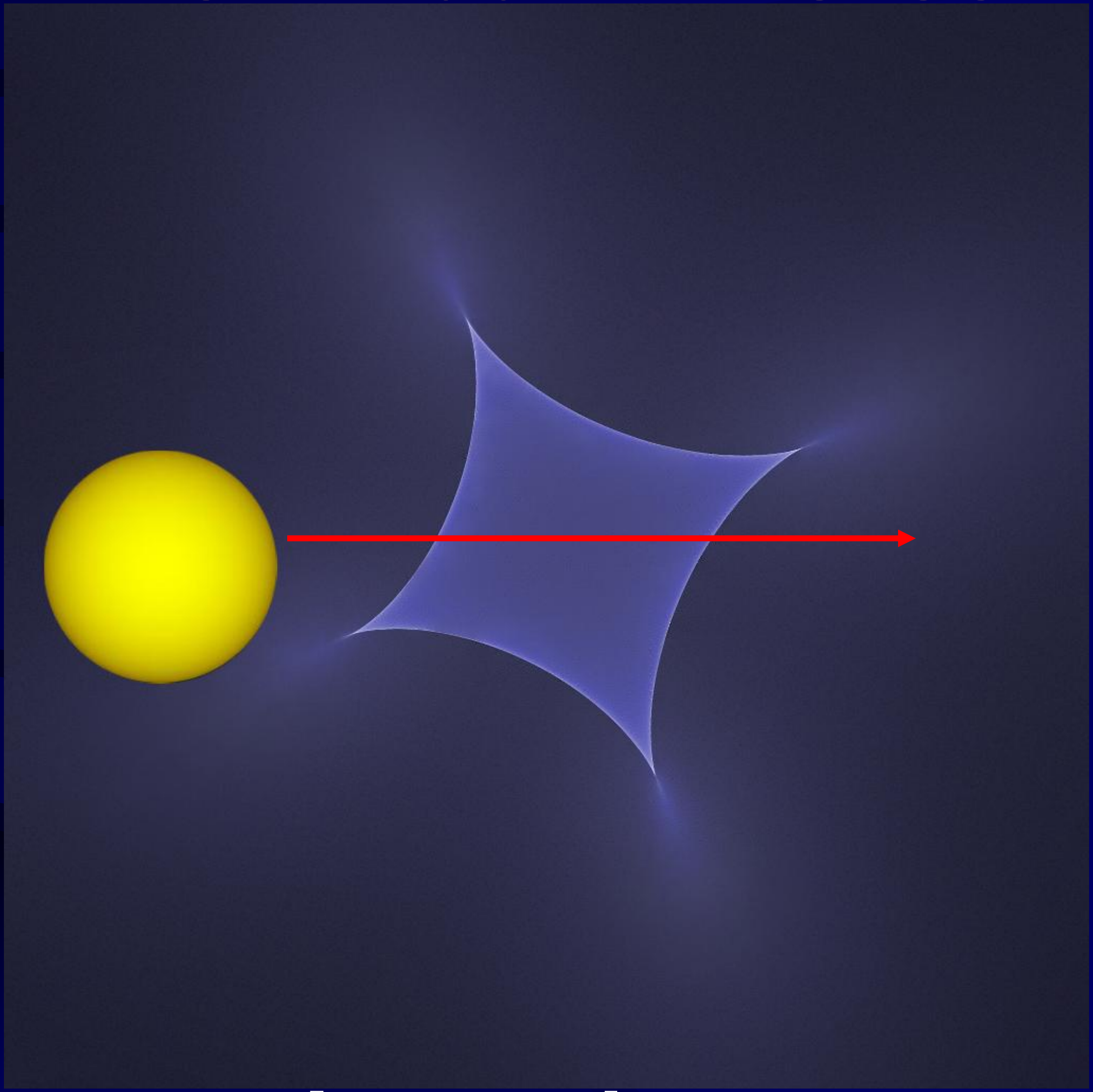


MOA 2002-BLG-33



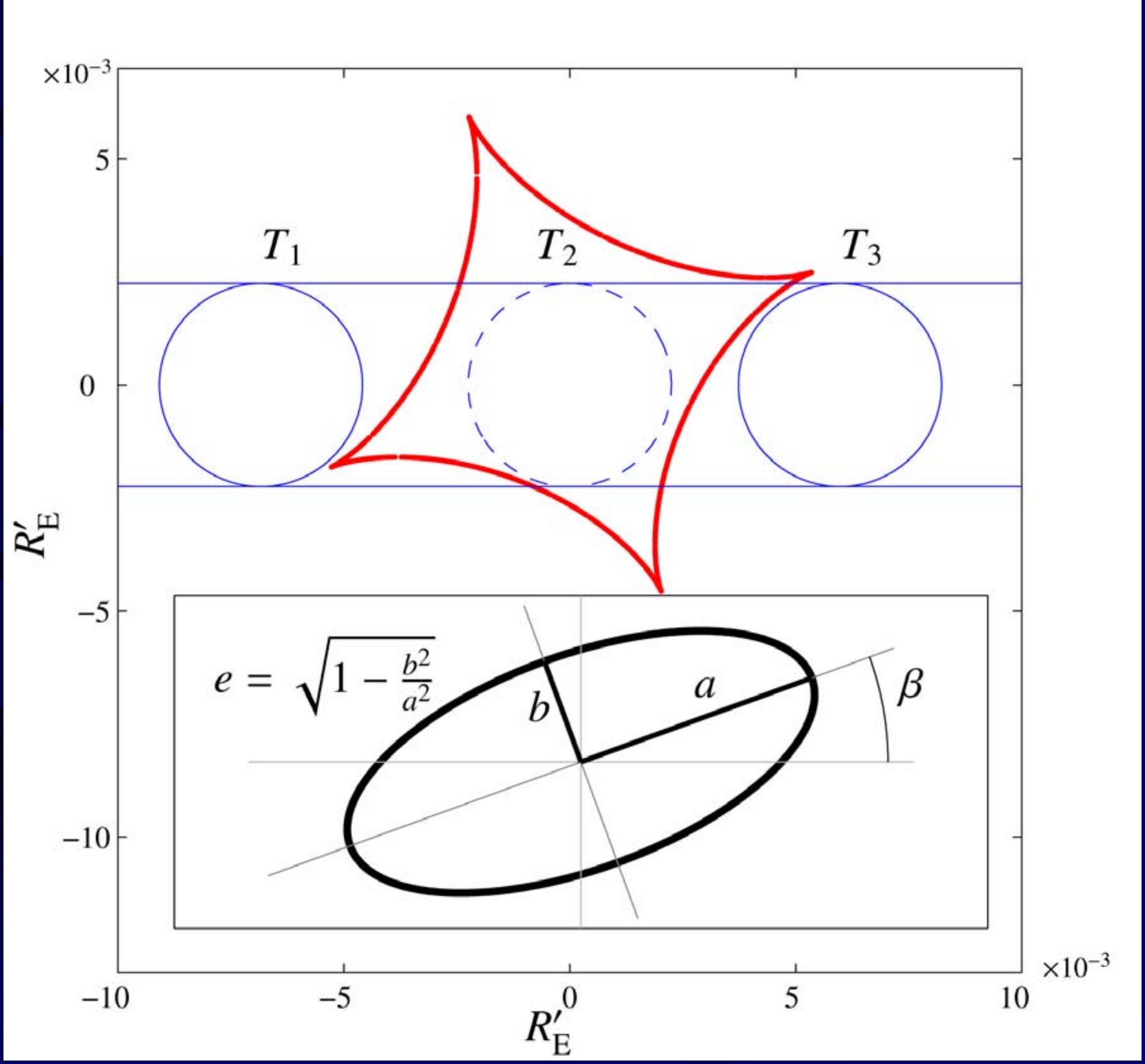
- The light curve determines the lens geometry
- The lens profiles the source

MOA 2002-BLG-33

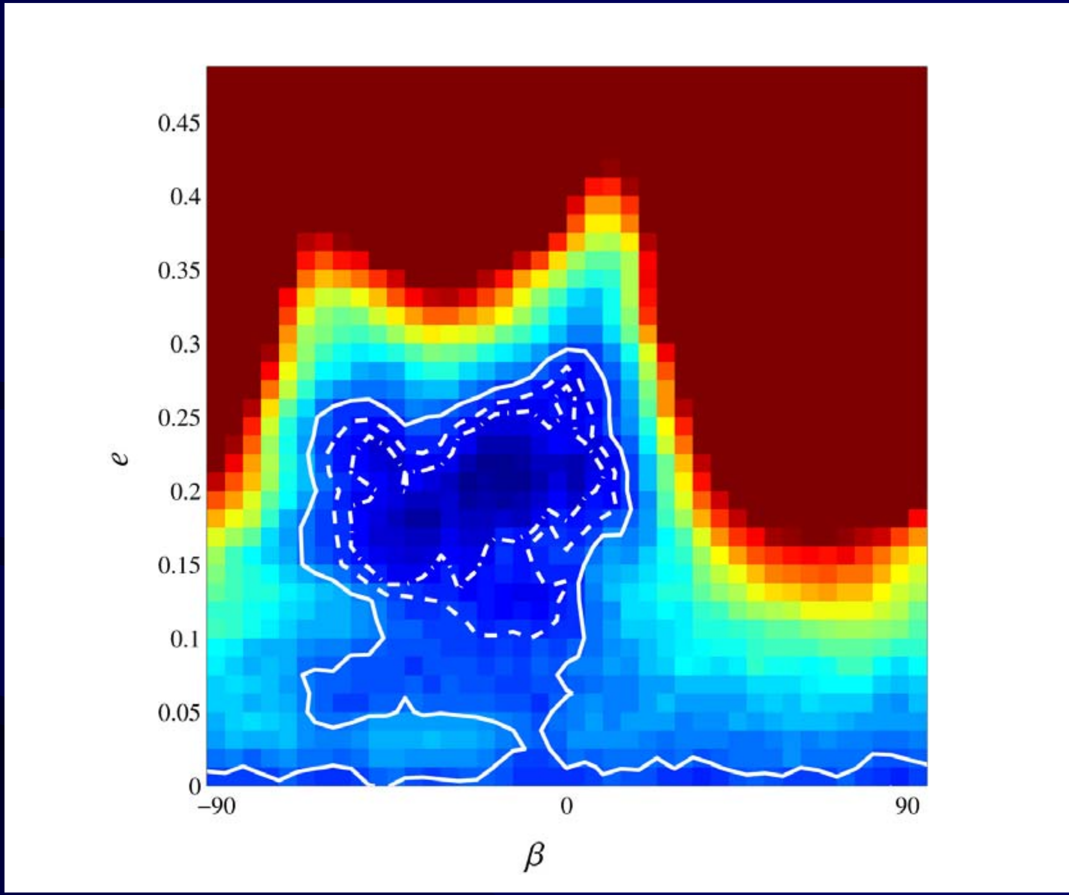


- Caustic crossed in 15.6 hours
- Profiles obtained – entry, exit, top and bottom

Oblateness measurement



χ^2 minimum

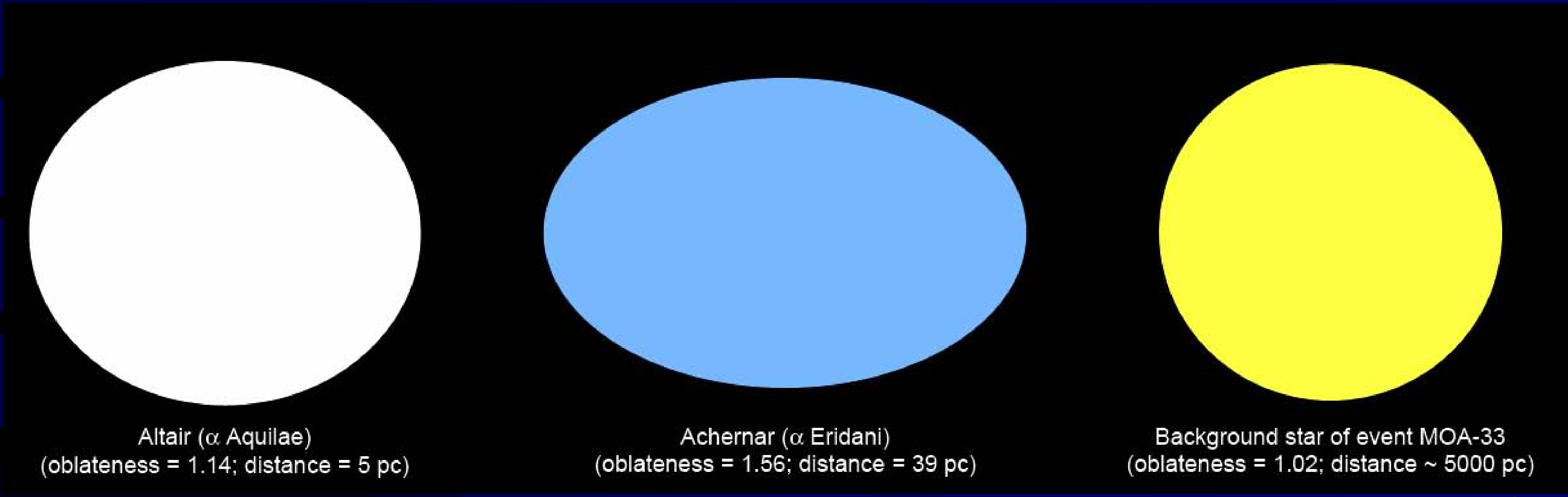


$$e = 0.17 \pm 0.17 \Rightarrow a/b = 1.02 \ {+0.04} - 0.02$$

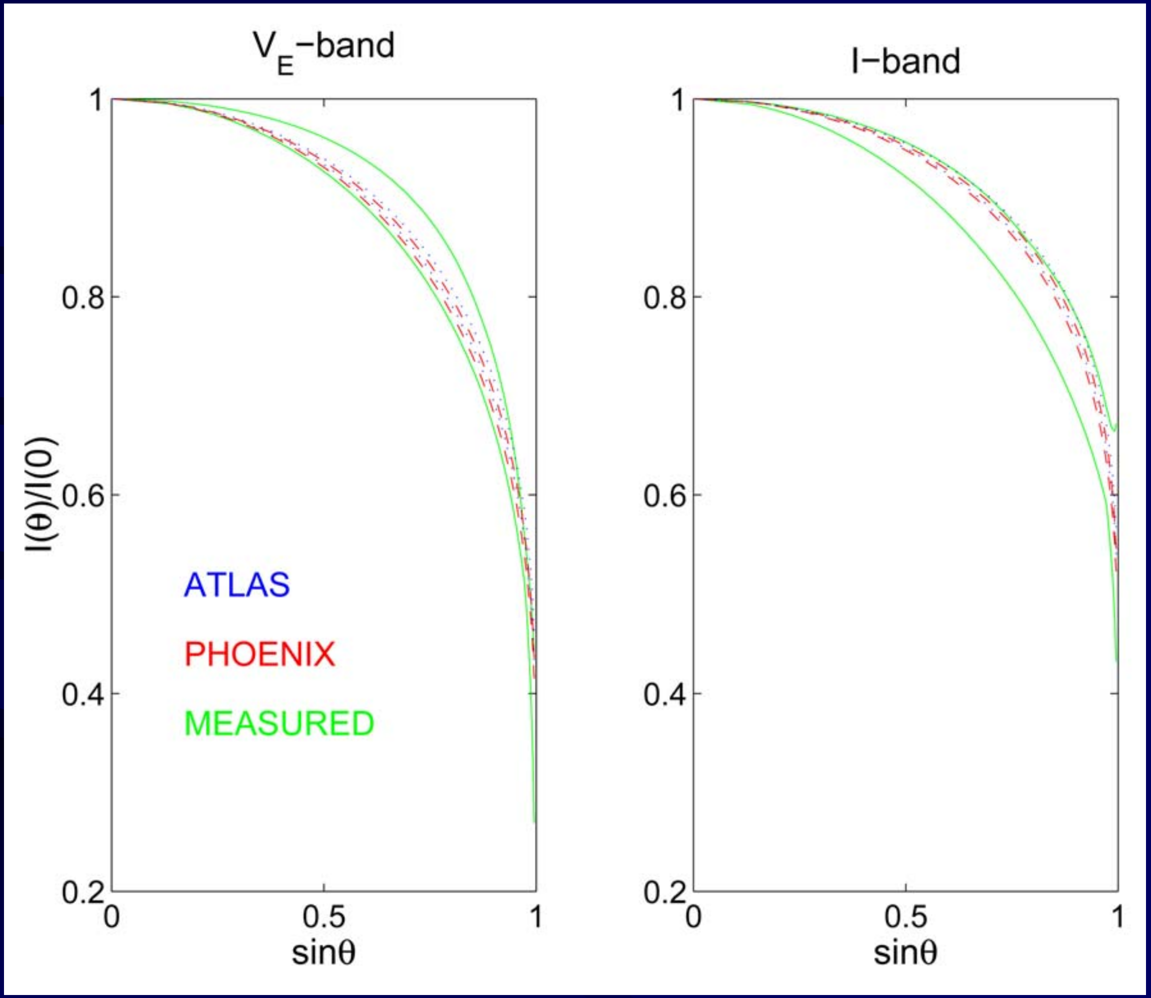
Comparison with interference measurements

Star	m_V	Spectral type	distance (pc)	Oblateness (a/b)
Altair	0.8	A7 IV-V	5	1.140 ± 0.029
Achernar	0.5	B3 Vpe	39	1.56 ± 0.05
MOA-33	19.9	F8 - G2 V	~ 5000	1.02 ± 0.04

Comparison

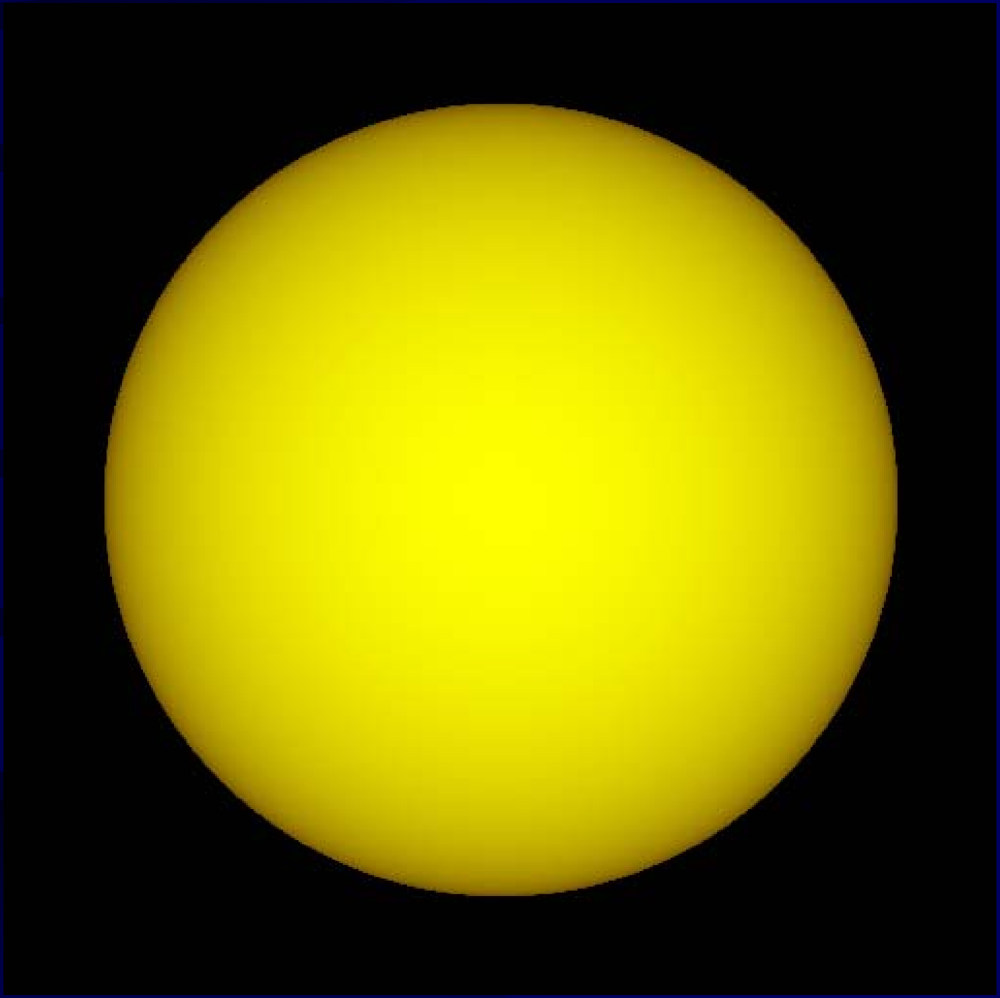

Altair (α Aquilae)
(oblateness = 1.14; distance = 5 pc)
Achernar (α Eridani)
(oblateness = 1.56; distance = 39 pc)
Background star of event MOA-33
(oblateness = 1.02; distance ~ 5000 pc)

Limb darkening measurements



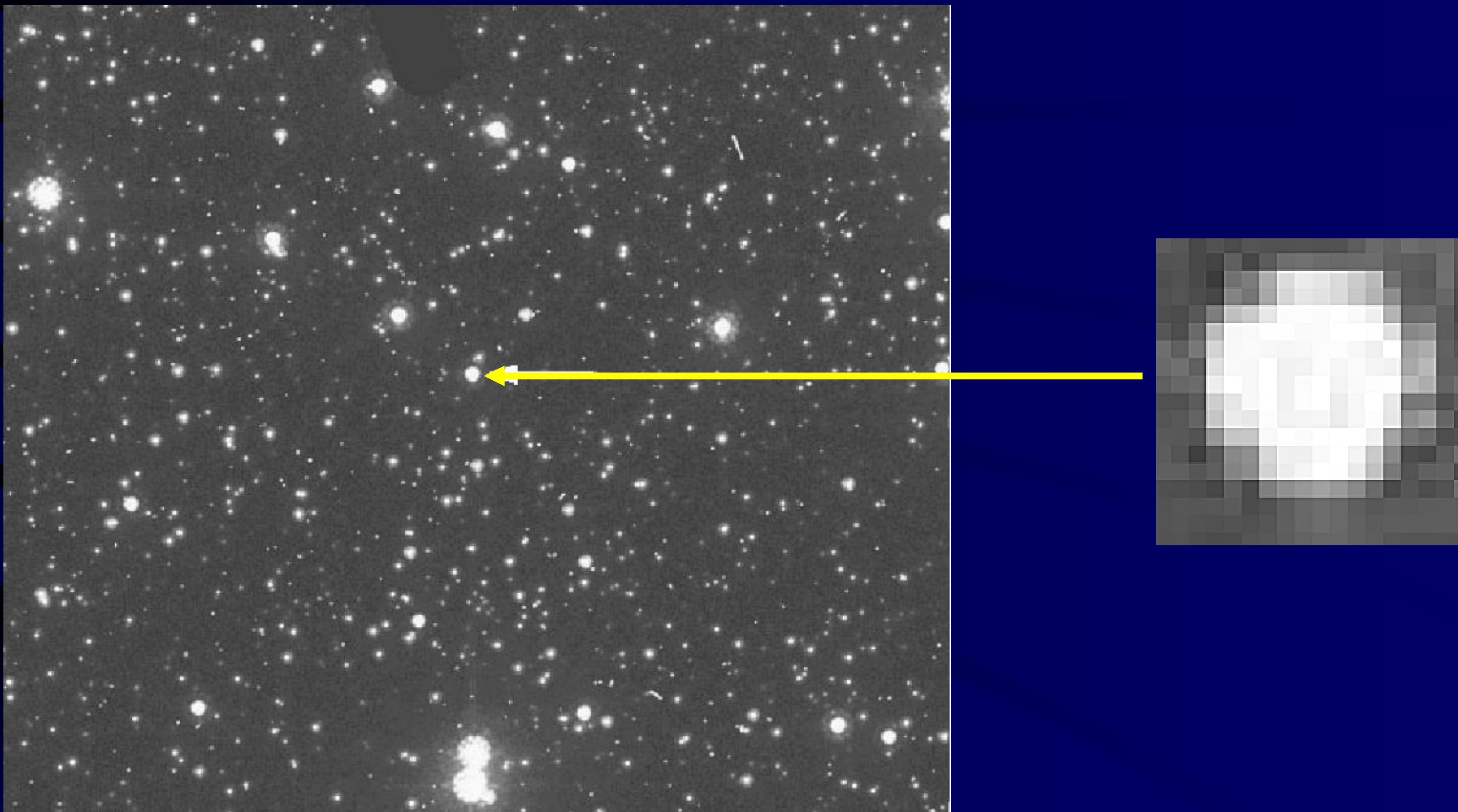
F. Abe et al, A&A, **411,** L493, 2003

Final image



N.J. Rattenbury et al, A&A, 2005

Hubble Space Telescope image

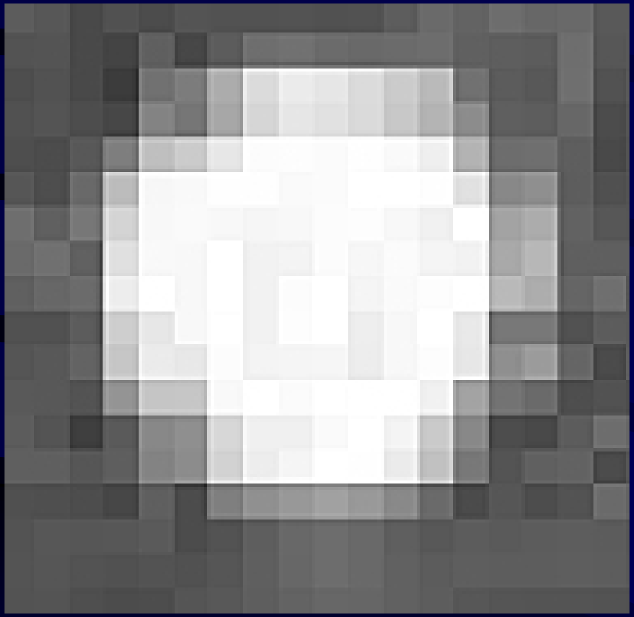


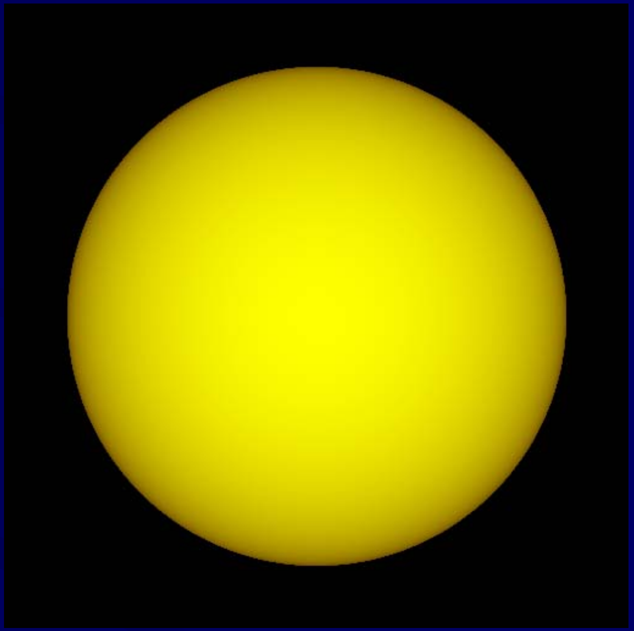
Main-sequence turn-off F8-G2 star – Lydia Philpott

Comparison

Lord Rayleigh

Einstein





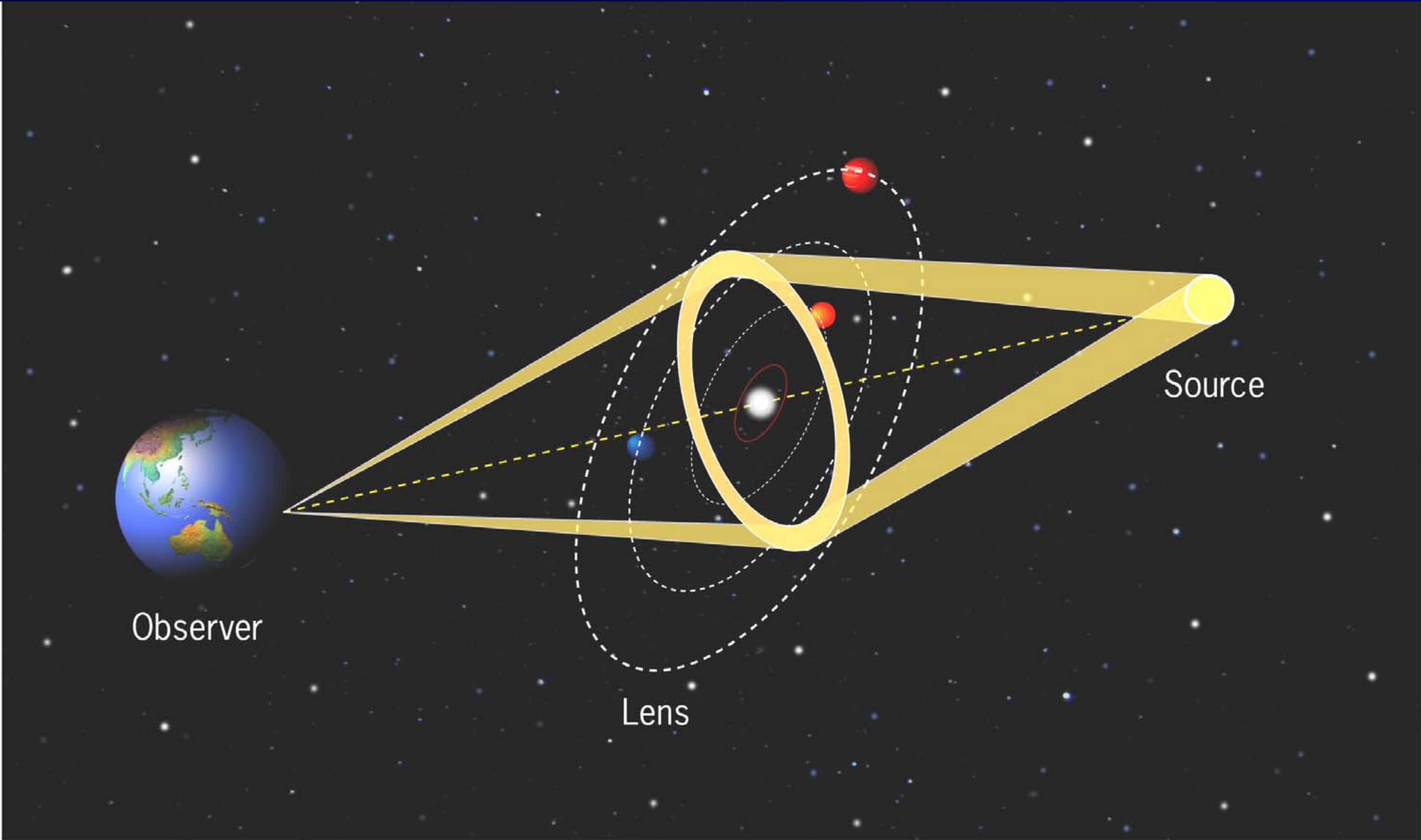
← 0.5 arcsec →

← 2 μ arcsec →

0.05 arcsec

0.04 μas

Future plans



Follow-up network – PLAN A

South Africa, Namibia, Chile,…

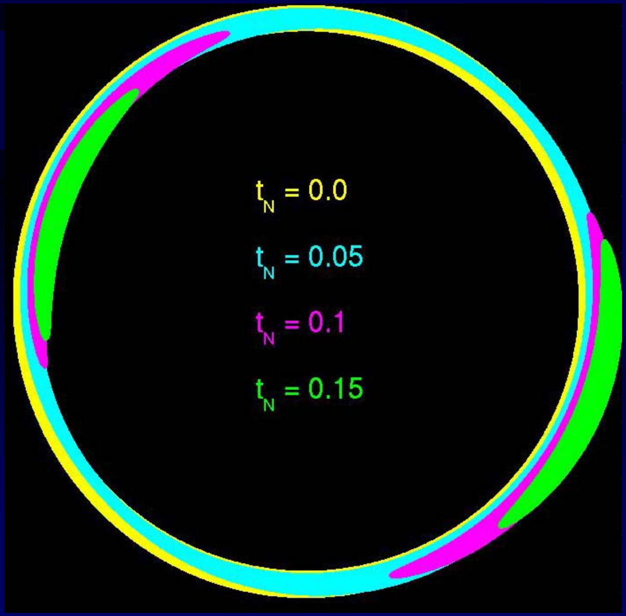
Follow-up network – PLAN B

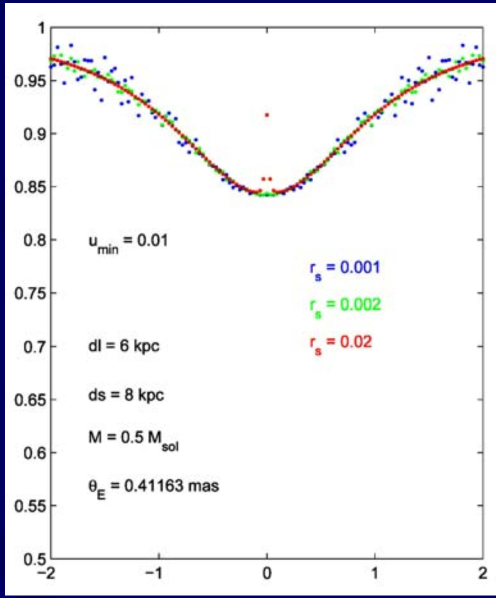
Michael Burton et al, astro-ph/0411612

DOME C - promising site

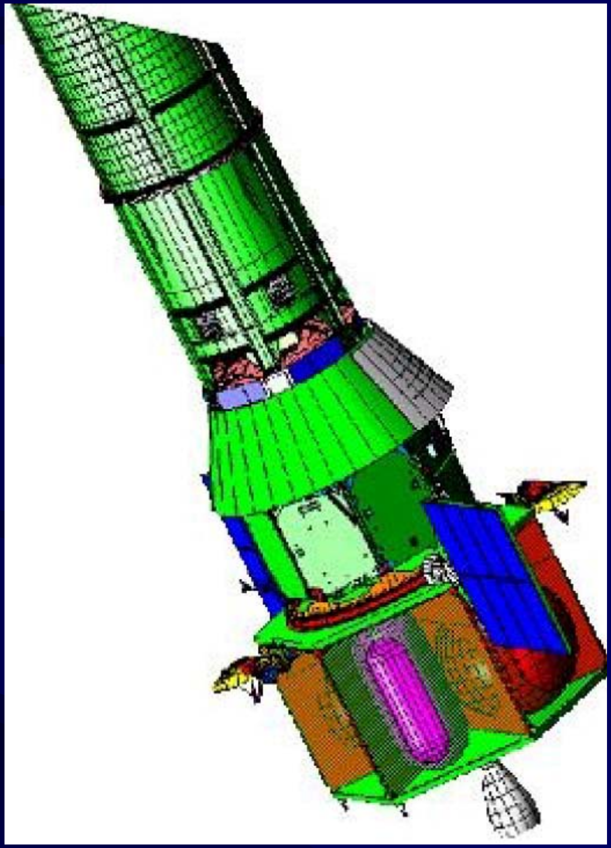
No wind, no cloud, no water vapour, best seeing

Very Large Telescope Interferometer



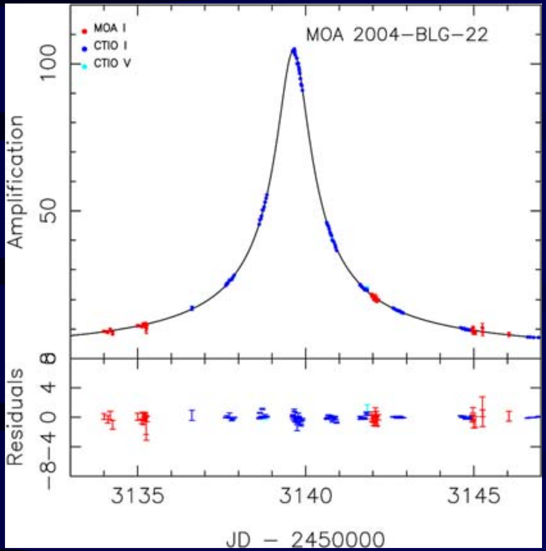


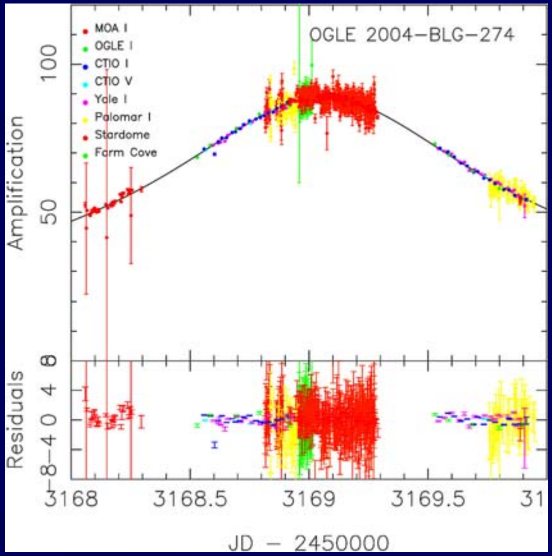
Microlensing Planet Finder

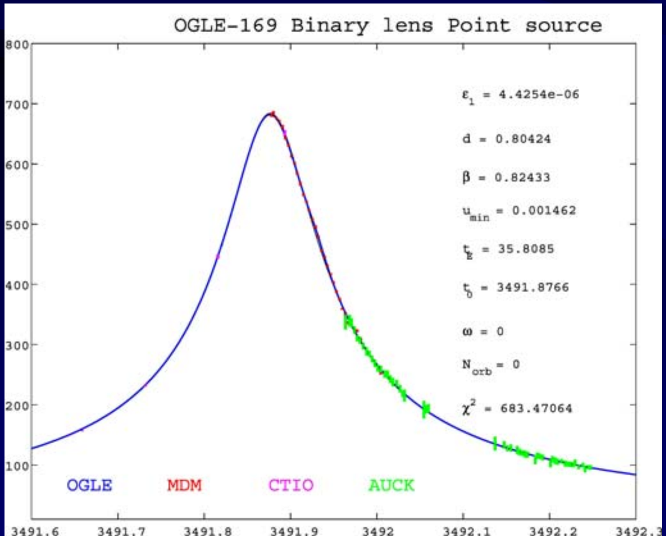


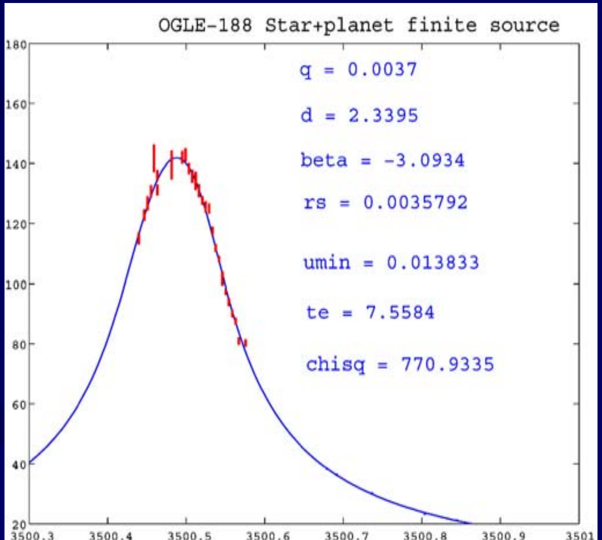
David Bennett et al, astro-ph/0409218

New events


MOA 2004-BLG-22
MOA I
CTIO I
CTIO V
Amplification
Residuals
JD − 2450000


OGLE 2004-BLG-274
MOA I
OGLE I
CTIO I
CTIO V
Yale I
Palomar I
Stardome
Farm Cove
Amplification
Residuals
JD − 2450000


OGLE-169 Binary lens Point source
ε_1 = 4.4254e-06
d = 0.80424
β = 0.82433
u_{min} = 0.001462
t_E = 35.8085
t_0 = 3491.8766
ω = 0
N_{orb} = 0
χ^2 = 683.47064
OGLE
MDM
CTIO
AUCK


OGLE-188 Star+planet finite source
q = 0.0037
d = 2.3395
beta = -3.0934
rs = 0.0035792
umin = 0.013833
te = 7.5584
chisq = 770.9335

64 million dollar question

Is the Standard Model SU(3) × SU(2) × U(1) being studied on other planets?

- Yes! – M. Gell-Mann

  Complexity Vol 1, No. 4, 1995-1996

- Maybe not! – P.Yock

  CERN Courier Vol 43, No. 1, p. 56, 2003

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