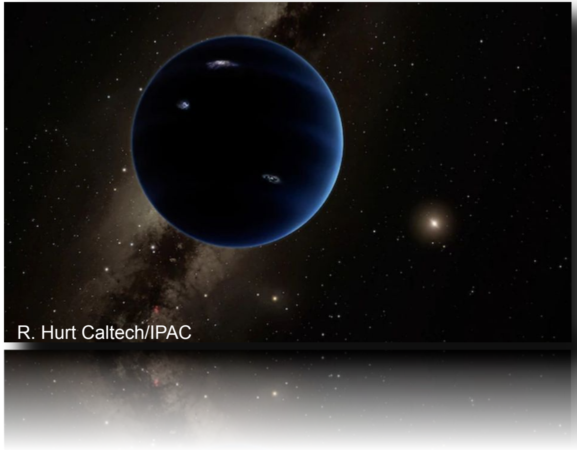
HSC search for Planet Nine:
DIA pipeline performance with synthetic injections

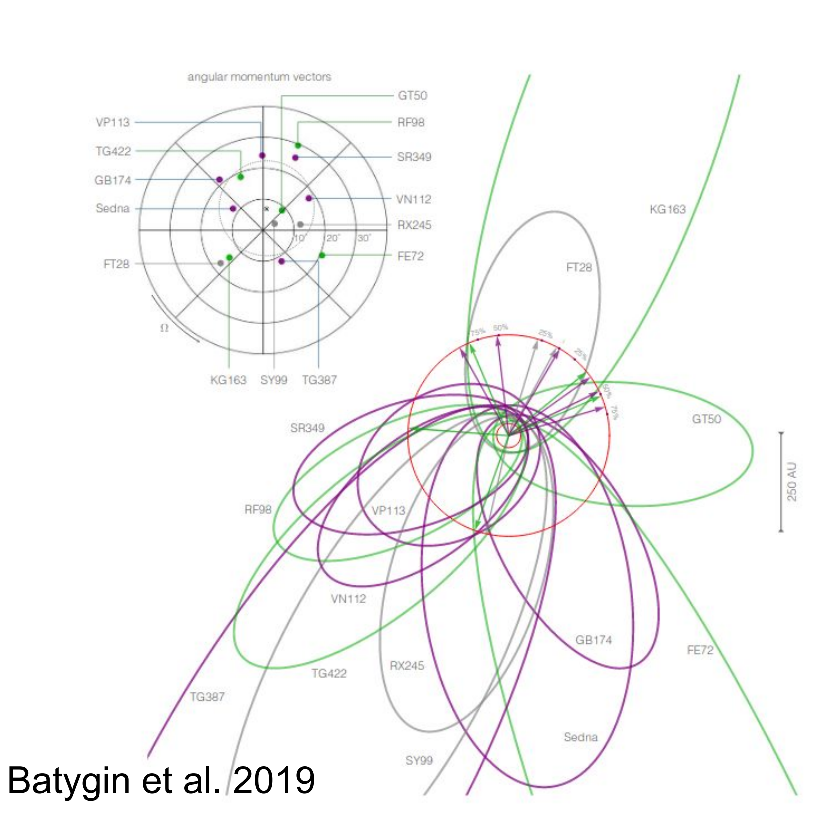


Surhud More (IUCAA)

Mike Brown, Konstantin Batygin (Caltech), Fumi Yoshida (UOEH/CIT), Masahiro Takada, Naoki Yasuda (IPMU), Robert Lupton (Princeton), Shefali Negi (FZU)

Rubin PCW: Aug 9, 2022

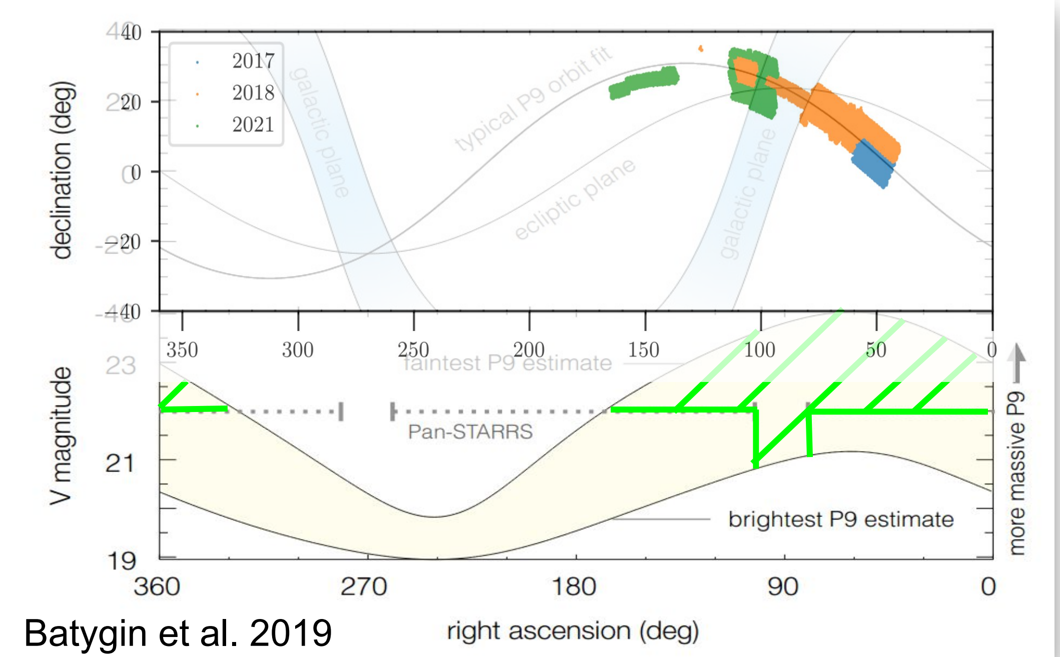
Peculiar orbits in the Kuiper belt



Batygin et al. 2019

- Sedna (Brown et al. 2004) and VP113 (Trujillo and Sheppard 2014) have odd elongated orbits, detached from Neptune. Many more objects discovered since then.
- Objects with semi-major axes beyond 250 AU display physical clustering of orbital parameters.
- Batygin and Brown 2016 propose the existence of Planet Nine to explain this clustering.

Subaru survey for Planet Nine



Batygin et al. 2019

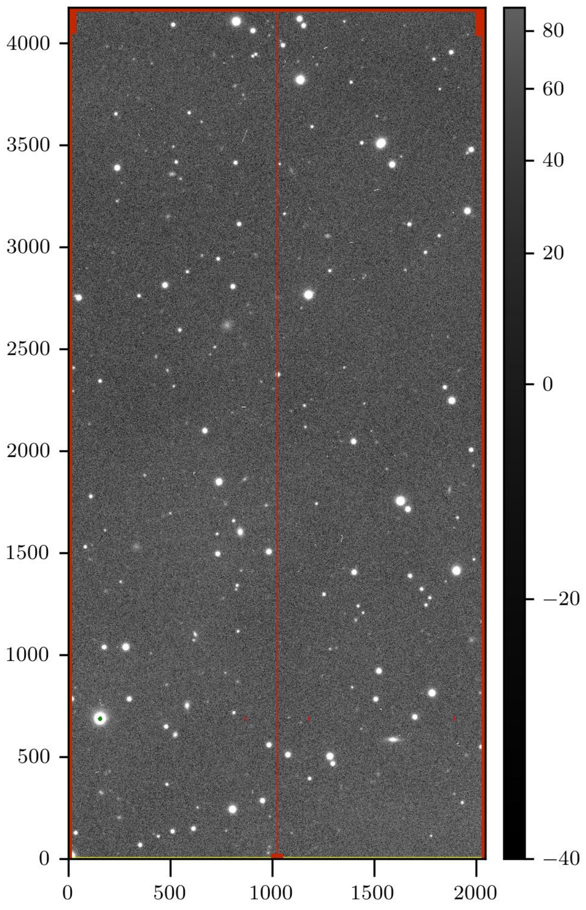
Please ask me for notes if you want to setup gen3 from scratch on a MPI based cluster!

- HSC data reduction performed with the Rubin LSST science pipelines (w_2022_14) at:
  - IUCAA (condor/condor on top of mpi)
  - Kavli IPMU (mpi)
  - FZU (condor)
- A total of 3959 exposures (400k CCD images) from 12.5 usable nights
- 8 TB of raw data

SM et al. (in prep)

Rubin LSST Science Pipelines (gen3)

Calibrated image



- Search for moving objects in HSC images of the same field on different nights
- Create template image by coadding images on the rest of the nights
- Subtract the calibrated image from the template.
- Search for diaSrcObjects that move

SM et al. (in prep)

Rubin LSST Science Pipelines (gen3)

Calibrated image

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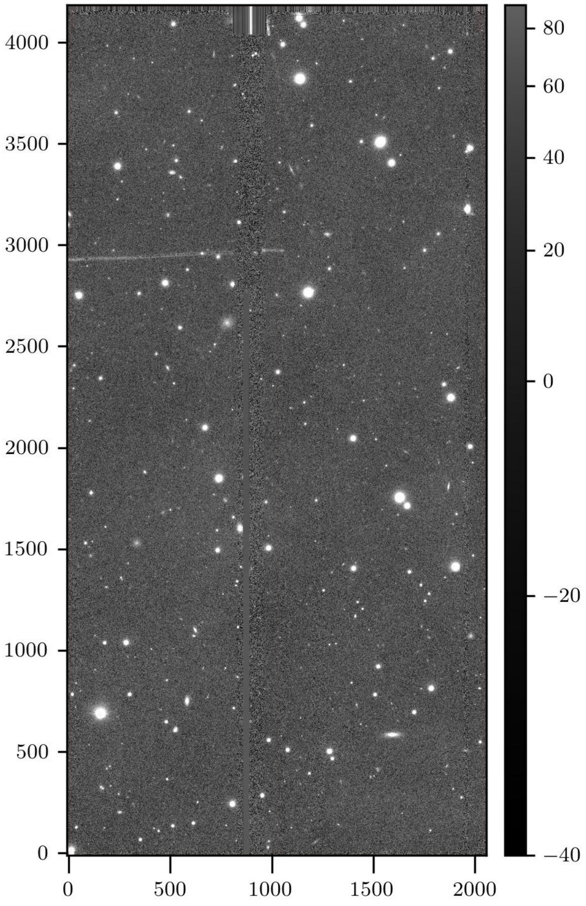
Template from other nights



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SM et al. (in prep)

Rubin LSST Science Pipelines (gen3)

Calibrated image

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Template from other nights

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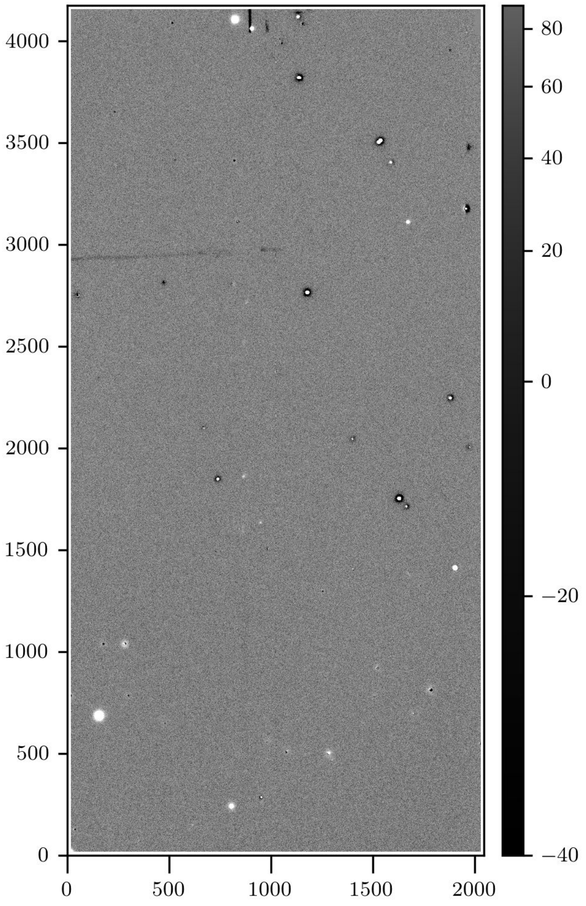
Difference image



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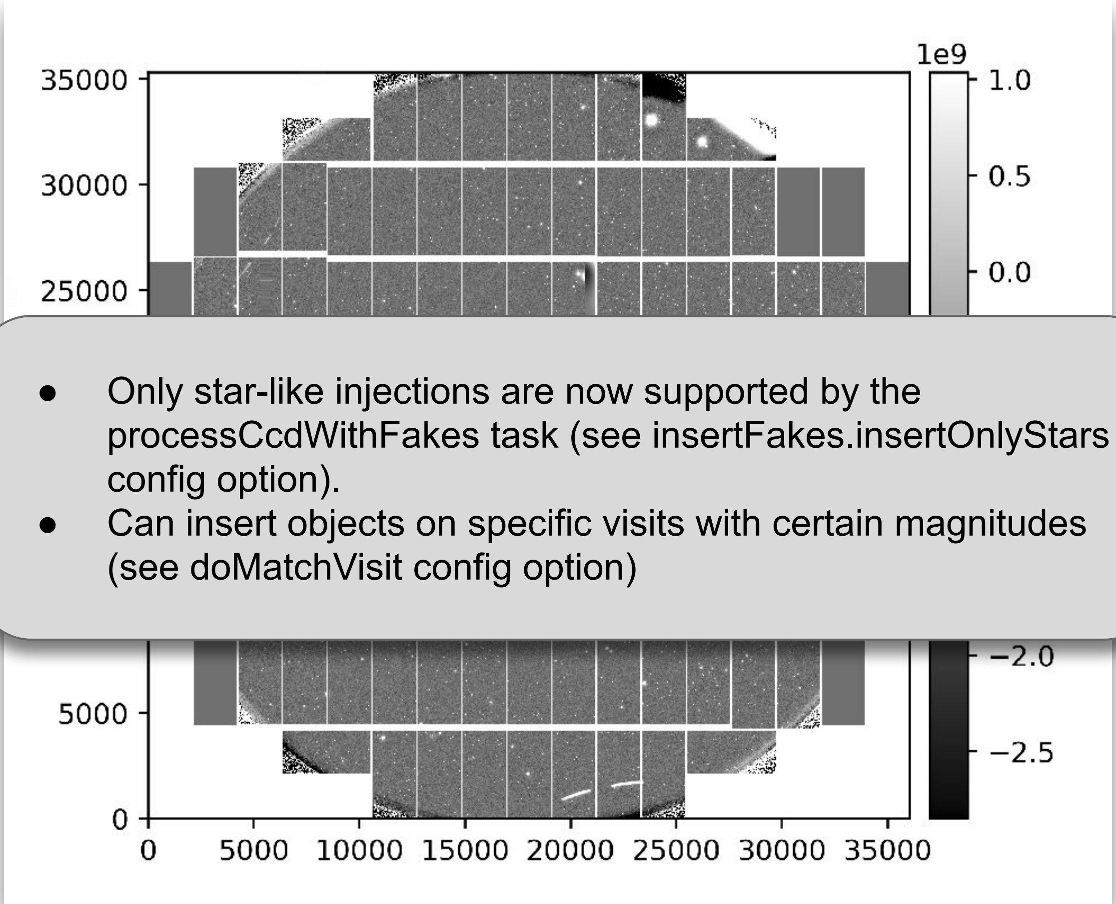
SM et al. (in prep)

Rubin LSST Science Pipelines

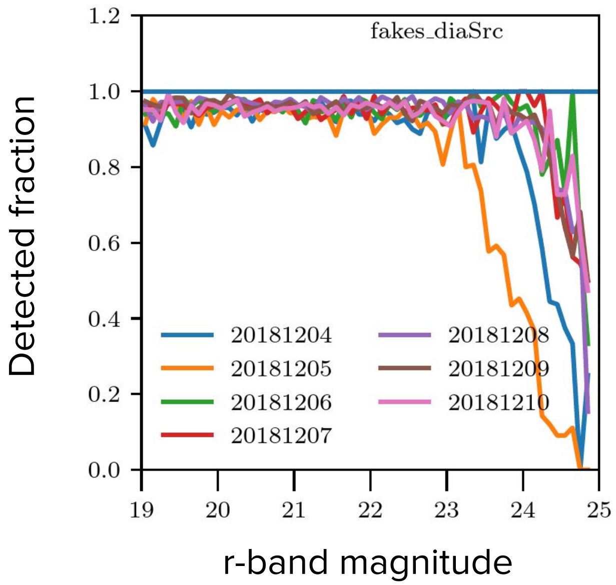


- Only star-like injections are now supported by the processCcdWithFakes task (see insertFakes.insertOnlyStars config option).
- Can insert objects on specific visits with certain magnitudes (see doMatchVisit config option)

- On average about 65 diaSrcObjects per CCD chip.
- Pixel flags can be used to reduce these further by a factor of about 2.
- Characterize the performance of search by injecting synthetic Planet Nines

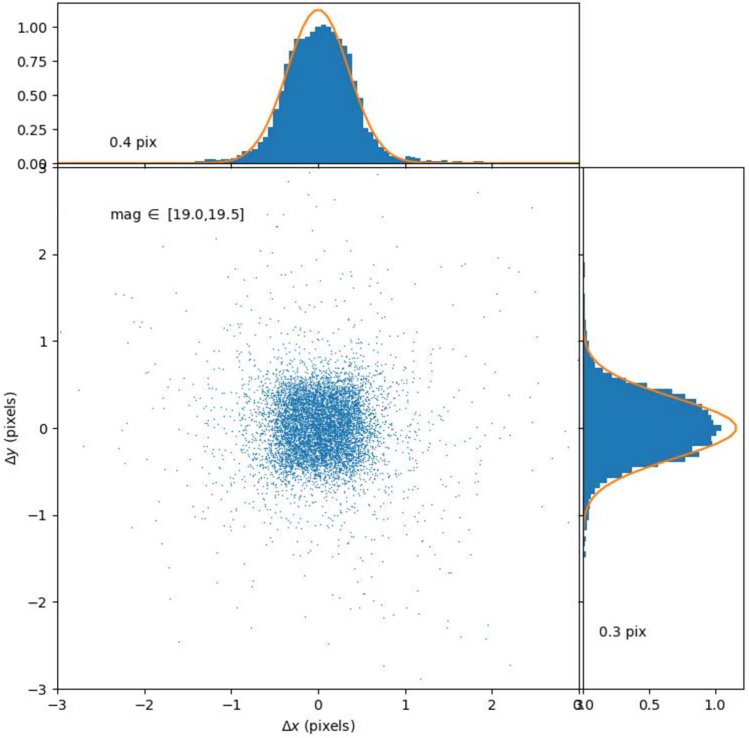
SM et al. (in prep)

Planet Nine injections to characterize pipeline



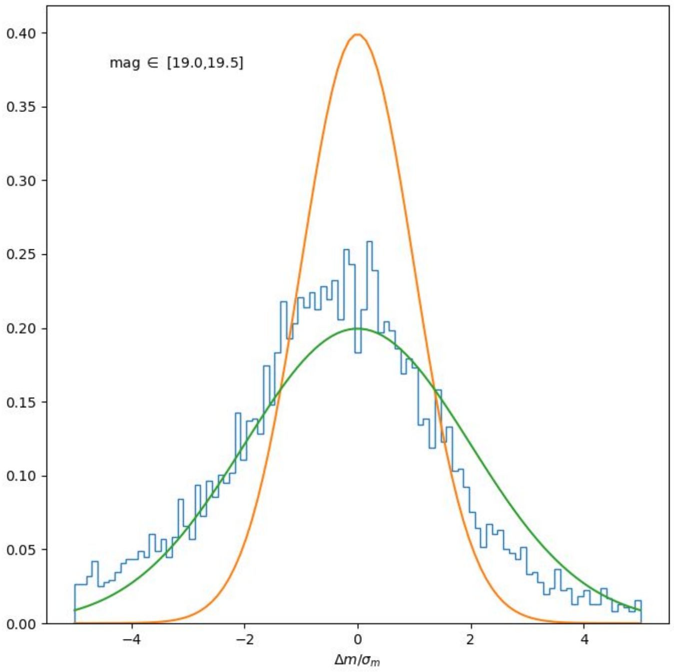
- About 95 percent of injected Planet Nines detected down to the magnitude limit on each night.
- Blending with nearby artefacts causes a loss of about 5%. Adding a deblending step recovers almost all injections (with minimal changes to the normal deblender config).
- A clear dependence of magnitude limit on the average seeing size was seen.

Astrometry



- Astrometry on the difference images better to about 0.4 pixels at the bright end (about 19.0-19.5), while about 1 pixel at the faint end (24.0-24.5)
- Fairly symmetrical distribution in each directions but square-ish residuals in the x-y plane.

Photometry



- Photometry errors are underestimated at the bright end by a factor of about 2.
- Likely because the Poisson error from the synthetic injections is not added to the variance plane
- The errors look better at the fainter end, as the image variance dominates over the Poisson term of the injection.

Backup slides:

SM et al. (in prep)

Planet Nine detection pipeline

Catalog of difference imaging sources


```
ra,dec,visit,detector,magnitude,magnitude_err,magnitude_ap,magnitude_ap_err,psFlux,psFluxErr,totFlux
,totFluxErr,elongation,sizeRatio,pixelFlags_saturatedCenter,jd,mjd,shape_flag_shift,isDipole,pixelFl
ags_interpolatedCenter,pixelFlags_suspectCenter,pixelFlags_edge,fake,mikeId,centroid_neg_flag,xx,yy,
diaSourceId,parentDiaSourceId,pixelFlags_fakeCenter,pixelFlags_fake
94.92699706834765,31.573913043376255,249016,0,23.165648972558685,0.05644782839764048,23.411441938422
364,0.20972099790874732,1966.7103847383971,102.25000310301138,2107.906329941938,84.36214137199782,1.
0552225947313523,,False,2459252.7301428937,59252.23014289352,False,False,False,False,False,False,-99
,False,1648.0084228515625,234.154541015625,106951557618074276,0,False,False
```

SM et al. (in prep)

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ra,dec,visit,detector,magnitude,magnitude_err,magnitude_ap,magnitude_ap_err,psFlux,psFluxErr,totFlux
,totFluxErr,elongation,sizeRatio,pixelFlags_saturatedCenter,jd,mjd,shape_flag_shift,isDipole,pixelFl
ags_interpolatedCenter,pixelFlags_suspectCenter,pixelFlags_edge,fake,mikeId,centroid_neg_flag,xx,yy,
diaSourceId,parentDiaSourceId,pixelFlags_fakeCenter,pixelFlags_fake
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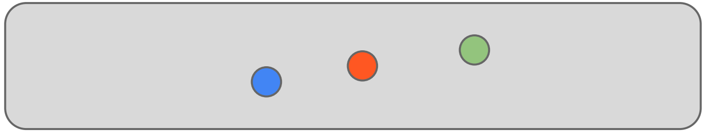
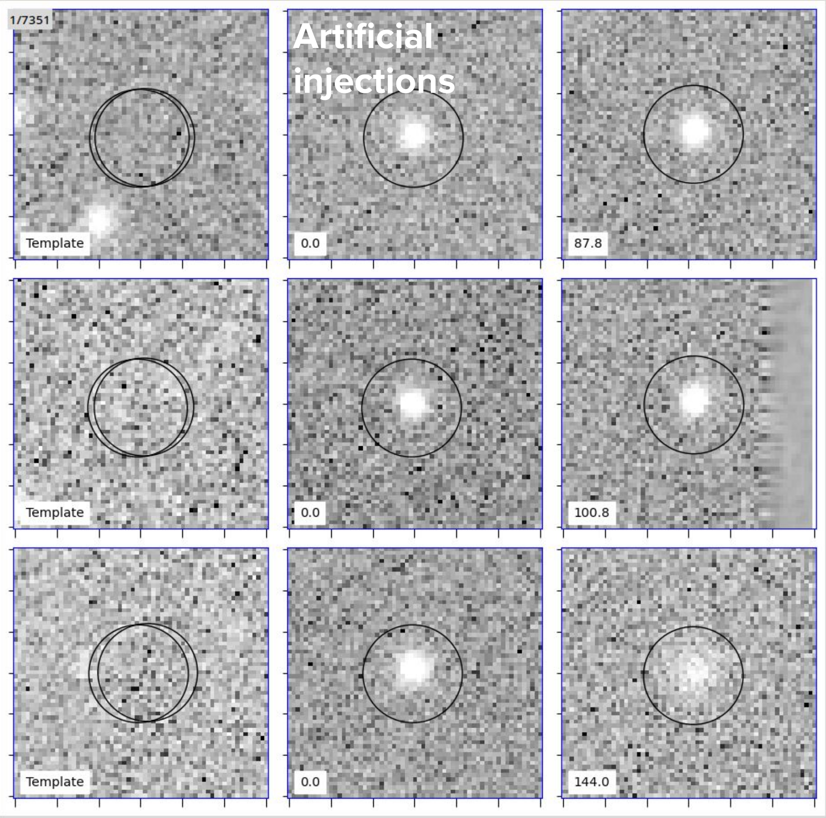


Link potential candidates for Planet nine like orbits

SM et al. (in prep)

Planet Nine

Catalog of difference im

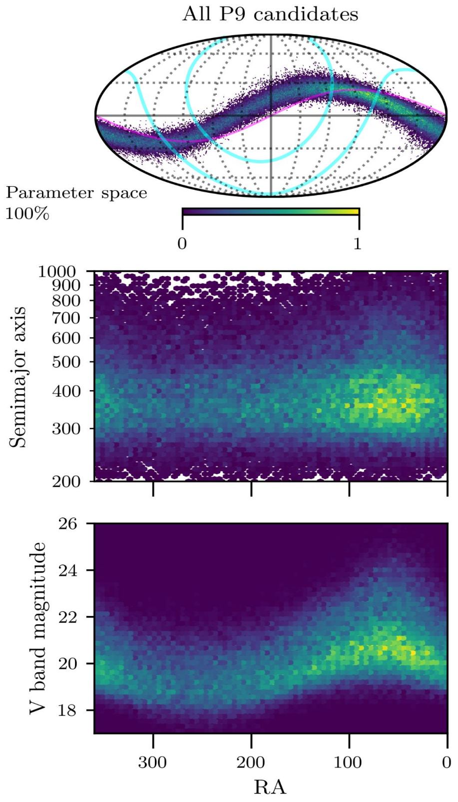


p,magnitude_ap_err,psFlux,psFluxErr,totFlux
er,jd,mjd,shape_flag_shift,isDipole,pixelFl
s_edge,fake,mikeId,centroid_neg_flag,xx,yy,
Flags_fake
2558685,0.05644782839764048,23.411441938422
1138,2107.906329941938,84.36214137199782,1.
352,False,False,False,False,False,False,-99
4276,0,False,False

r Planet nine like orbits

Finalize with visual inspection

Constraints on the parameter space



- Planet Nine search carried out using data from ZTF, Pan-starrs, Dark energy survey, and Subaru HSC
- The joint constraints together rule out about 84 percent of the parameter space.
- A lot of the remaining area is in the galactic plane
- We have been allocated 3 nights in January on Subaru to wrap up the galactic plane on the northern side.

ZTF search: Brown and Batygin 2021, DES search: Belyakov et al. 2022, Pan-Starrs search: Brown et al (in prep), Subaru search: SM et al. (in prep)

SM et al. (in prep)

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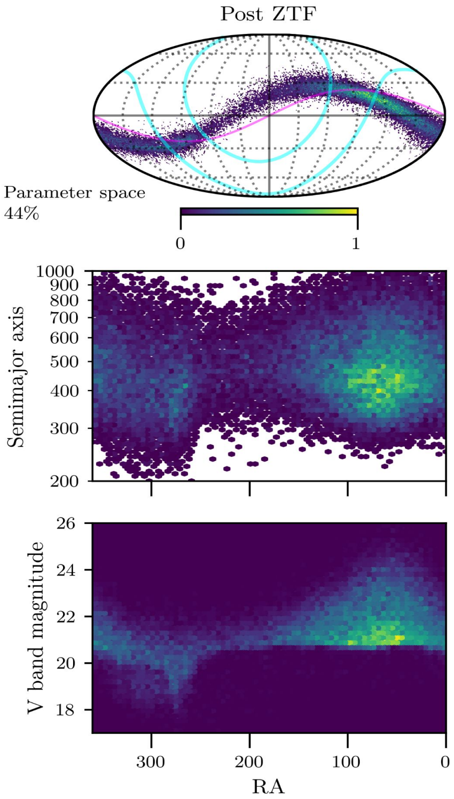

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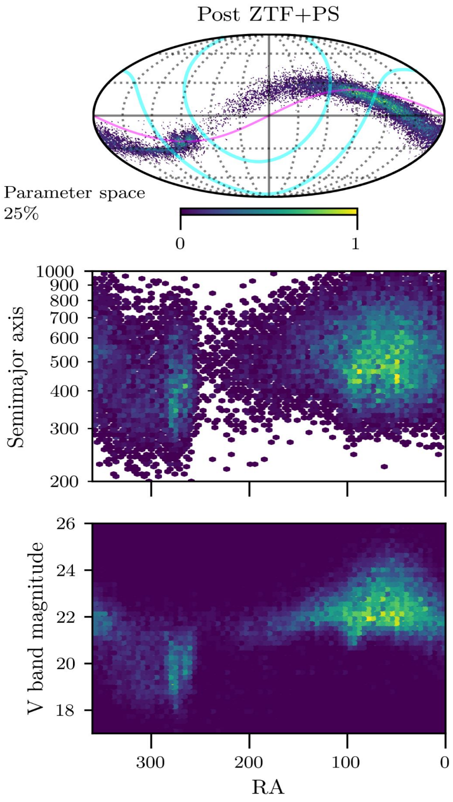

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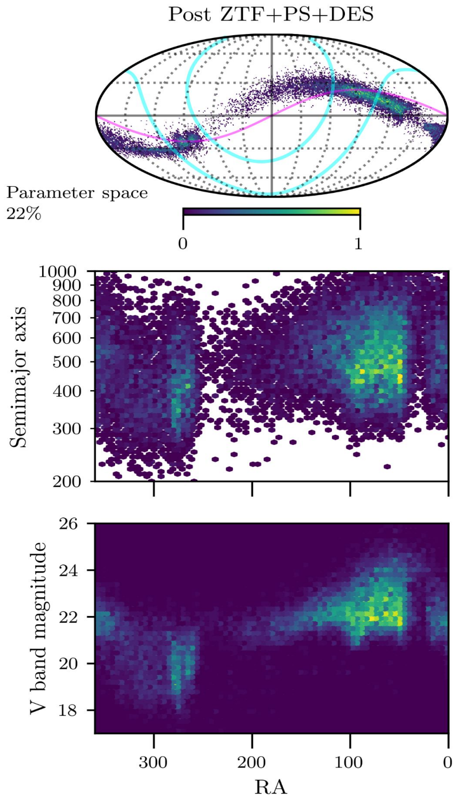

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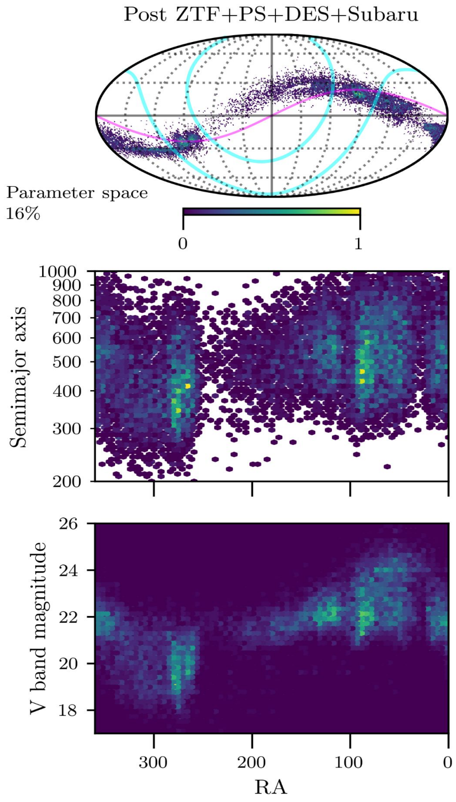

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Backup slides

Calibrated imag

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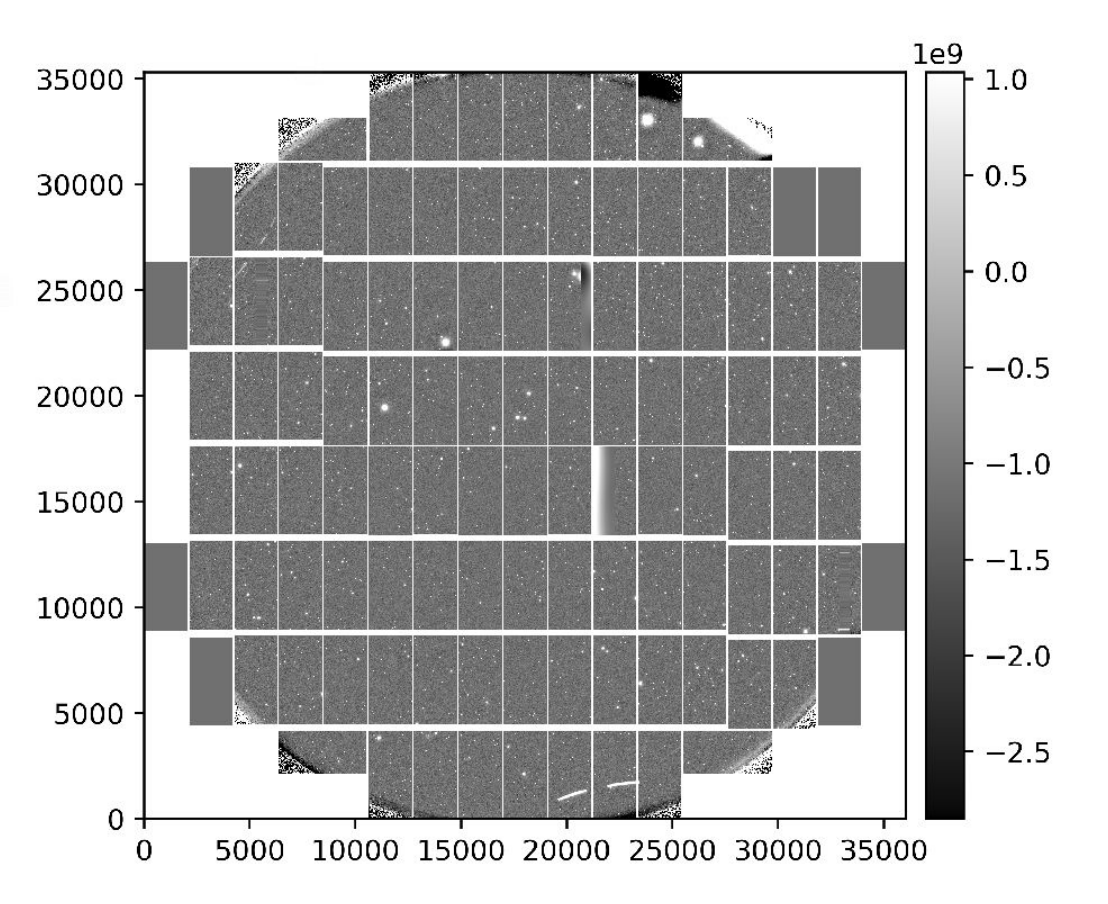

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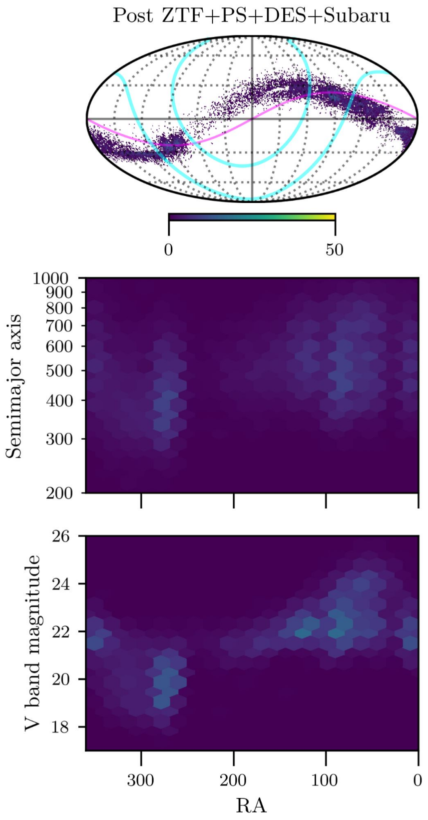
Constraints on the parameter space



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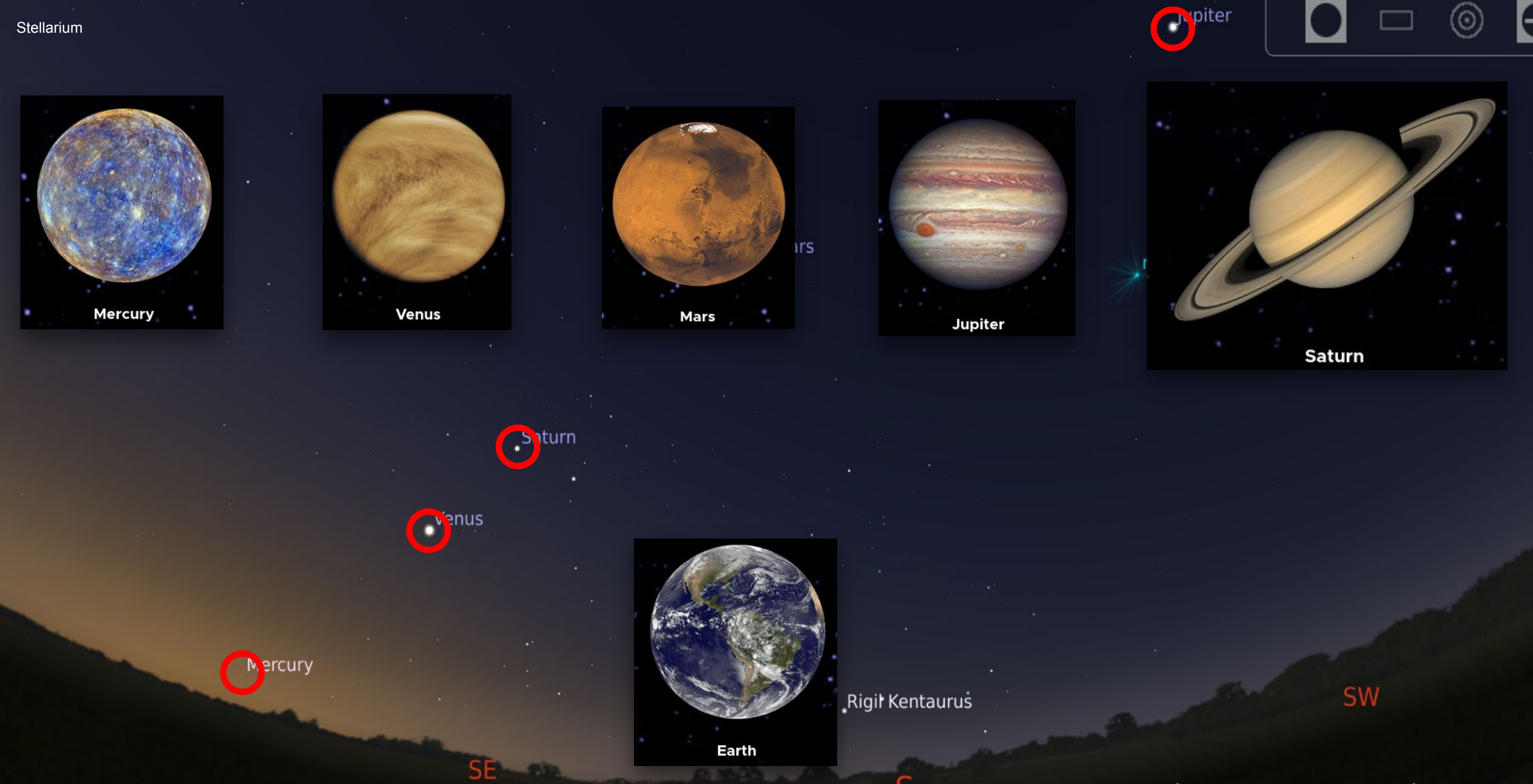
Thank you!

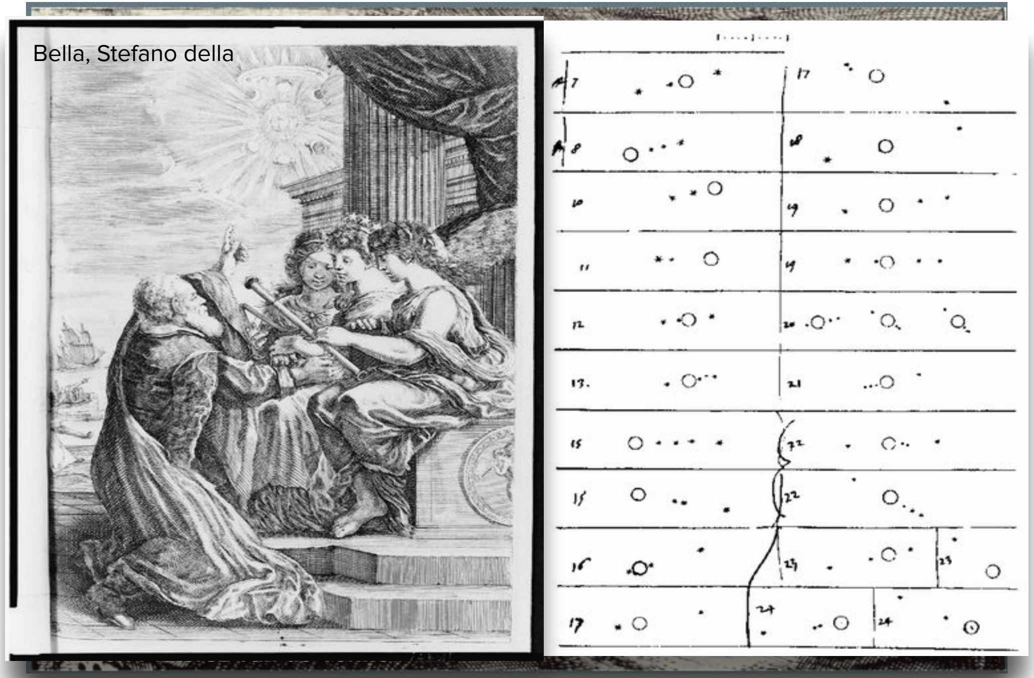

Stellarium
Quadrantids
Alkaid
Alioth
December Leonis Minorids
Kochab
Dubhe
Polaris
NW
N
Patterns of stars in the sky (constellations)
Earth, Pune, 0 m
FOV 60°
17.9 FPS
2022-01-03 10:30:03 UTC+05:30



Planetes asteres: Wandering stars (planets)

Planetary Images: NASA

The invention of the telescope

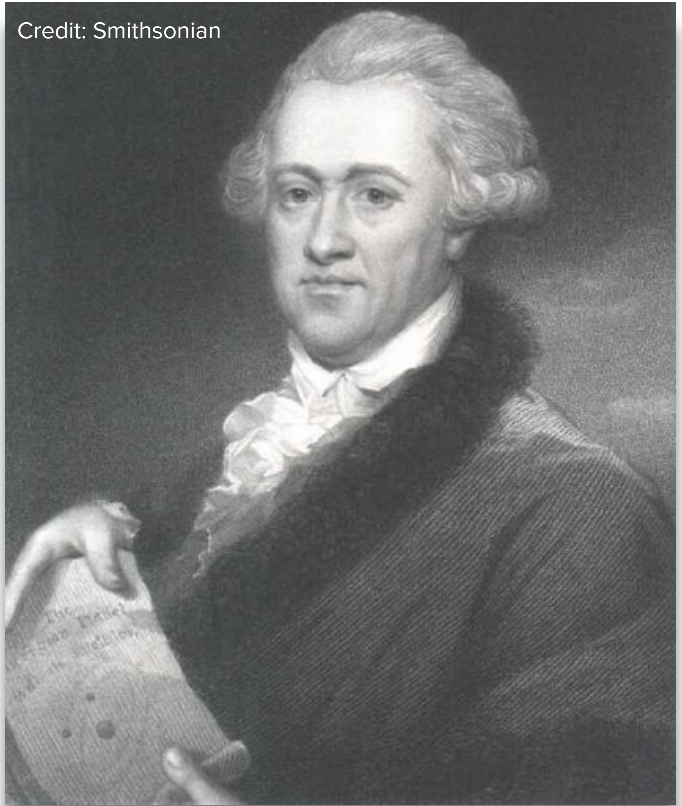


Bella, Stefano della

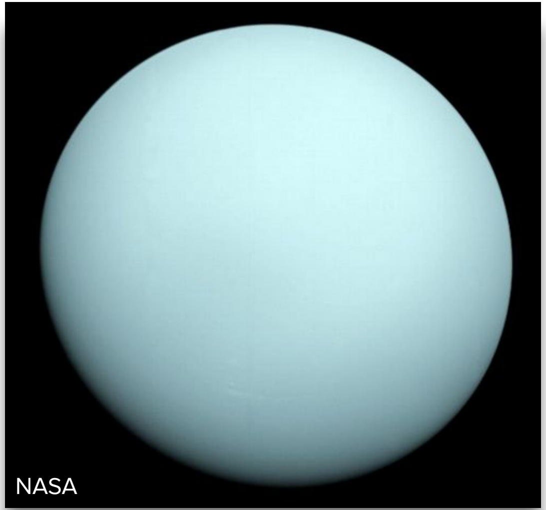
- Lippershey, a Dutch engineer filed the first patent for the telescope in 1608
- It was first invented for terrestrial use, but proved far more consequential to our understanding of the cosmos.
- Galileo discovered the moons of Jupiter and shattered the foundations of geocentric theories of the Universe.

Technological advances drive discoveries!

Discovery of Uranus



Credit: Smithsonian



NASA

- Serendipitously found by William Herschel through a telescope on March 13, 1781
- First believed to be a comet but quickly realized that it was a new planet because of its circular orbit!

The

http://www.sil.si.edu/digita
dentity/fullsize/SIL14-B6-(

ment aux observations modernes, mais qui ne pourront satisfaire convenablement aux observations anciennes. Il fallait se décider entre ces deux partis; j'ai dû m'en tenir au second, comme étant celui qui réunit le plus de probabilités en faveur de la vérité, et je laisse aux tems à venir le soin de faire connaître si la difficulté de concilier les deux systèmes tient réellement à l'inexactitude des observations anciennes, ou si elle dépend de quelque action étrangère et inaperçue, qui aurait agi sur la planète.

Maintenant, en conservant la notation adoptée pour les Tables de Jupiter et de Saturne, on aura de même la formule suivante pour type des équations de condition :

$$(1+2e\cos\varphi)\,x + t(1+2e\cos\varphi)\,y + z\sin\varphi - u\cos\varphi = dV''.$$

En désignant par V'' la longitude héliocentrique d'Uranus, pour la même époque que pour Jupiter et Saturne, j'ai trouvé la formule suivante :

$$V'' = \varphi'' + 154'',63.t.$$

$$\text{I}\ldots\ldots\ldots \left\{\begin{array}{l} +\,(59427'',54 - t.0'',3216)\sin(\varphi''-\varpi'') \\ +\,(\;1733,14 - t.0,0188)\sin 2(\varphi''-\varpi'') \\ +\,(\quad 70,08 - t.0,0011)\sin 3(\varphi''-\varpi'') \\ +\,(\quad\;\, 3,25 - t.0,0001)\sin 4(\varphi''-\varpi'') \\ +\,(\quad\;\, 0,16 - t.0,0000)\sin 5(\varphi''-\varpi''). \end{array}\right.$$

$$\text{II}\ldots\ldots\ldots \left\{\begin{array}{l} +\,68'',55\sin(\varphi'-\varphi''+23^\circ,56) - 12'',49.\sin 2(\varphi'-\varphi'') \\ -\;\;2'',55\sin 3(\varphi'-\varphi'') - 0'',72\sin 4(\varphi'-\varphi'') - 0'',24\sin 5(\varphi'-\varphi''). \end{array}\right.$$

$$\text{III}\ldots\ldots\ldots \left\{\begin{array}{l} -\,(436'',41 - t.0'',034)\sin(\varphi'-2\varphi''+79^\circ,28+t.48'',7) \\ -\quad 5'',07\sin(2\varphi'-4\varphi''+42^\circ,87). \end{array}\right.$$

$$\begin{array}{lll}
\text{IV}\ldots\ldots\ldots & + & 160'',92\sin(\varphi-\varphi'') - 0'',59\sin 2(\varphi-\varphi''). \\
\text{V}\ldots\ldots\ldots & - & 10,60.\sin(\varphi-2\varphi''-16^\circ,50). \\
\text{VI}\ldots\ldots\ldots & + & 7,79.\sin(2\varphi'-3\varphi''+25^\circ,92). \\
\text{VII}\ldots\ldots\ldots & + & 4,07.\sin(\varphi'+5^\circ,09). \\
\text{VIII}\ldots\ldots\ldots & + & 3,89.\sin(2\varphi-\varphi''-11^\circ,49). \\
\text{IX}\ldots\ldots\ldots & + & 3,81.\sin(\varphi+14^\circ,87). \\
\text{X}\ldots\ldots\ldots & + & 2,86.\sin(2\varphi'-5\varphi''+75^\circ,99). \\
\text{XI}\ldots\ldots\ldots & + & 2,55.\sin(2\varphi'-\varphi''-81^\circ,89). \\
\text{XII}\ldots\ldots\ldots & + & 1,38.\sin(3\varphi'-4\varphi''+26^\circ,24).
\end{array}$$

La réduction à l'écliptique est

$$-\,29'',04\sin(2V''-2\theta'').$$

Le rayon vecteur r'' d'Uranus est donné par la formule

$$r'' = 19,212098 - t.0,00000023.$$

Années.	Erreurs.	Années.	Erreurs.	Années.	Erreurs.	Années.	Erreurs.	Années	Erreurs.
1690	+ 98"7	1783	+ 16"7	1792	— 13"0	1803	— 44"5	1814	+ 41"3
1712	+ 62,0	1784	+ 19,4	1793	— 19,5	1804	— 27,8	1815	+ 41,2
1715	— 4,5	1785	+ 6,7	1794	— 13,3	1805	— 38,2	1815	+ 47,6
1750	— 124,0	1785	+ 6,5	1794	— 18,5	1806	— 23,1	1816	+ 49,1
1750	— 101,4	1785	+ 12,5	1795	— 20,6	1806	— 8,5	1816	+ 57,7
1753	— 69,8	1786	+ 11,7	1795	— 25,8	1807	— 26,5	1817	+ 52,9
1756	— 75,7	1786	+ 10,5	1796	— 13,0	1807	— 0,9	1818	+ 56,7
1764	— 23,8	1787	+ 12,1	1796	— 35,0	1808	— 14,1	1819	+ 76,2
1769	+ 10,9	1788	— 8,1	1797	— 18,9	1809	— 19,6		
1771	+ 50,9	1788	+ 8,9	1797	— 37,9	1810	— 5,9		
1781	+ 17,8	1789	— 1,4	1798	— 37,6	1811	+ 9,3		
1781	+ 22,9	1789	+ 23,5	1799	— 53,4	1811	+ 1,0		
1782	+ 27,6	1790	+ 14,8	1799	— 45,4	1812	+ 0,1		
1782	+ 17,7	1790	— 16,9	1800	— 25,8	1812	+ 22,0		
1782	+ 13,9	1791	— 12,6	1801	— 44,3	1813	+ 16,6		
1783	+ 24,9	1791	— 5,1	1802	— 49,7	1813	+ 42,4		
1783	+ 24,8	1792	— 7,6	1802	— 34,2	1814	+ 27,9		

Il est difficile d'admettre que les observations modernes comportent de telles erreurs. On ne peut, non plus, les rejeter sur la théorie, ni sur l'oubli de quelque terme important. Cette théorie est connue, et les soins que j'ai mis à mes calculs ne permettent pas qu'on s'arrête sur ce dernier point. Ce serait donc sur l'exactitude des observations anciennes que le doute retomberait. En effet, il est difficile de s'en défendre, quand on discute les circonstances dans lesquelles elles ont été faites : l'observation de Bradley est unique, le passage n'a été observé qu'au cinquième fil et la hauteur n'a été estimée qu'en degrés et minutes. La même remarque s'applique à l'observation de Mayer. Les observations de Flamsteed sont jugées depuis longtems, et l'on sait que ses instrumens n'étaient ni bien exécutés, ni exactement placés dans le méridien. Quant à celles de Lemonnier, on peut voir dans la Connaissance des Tems pour 1821 ce qu'il est permis d'en penser.

D'après ces considérations, j'ai supprimé les dix-sept observations anciennes et formé de nouvelles Tables avec les seules observations modernes. On peut voir dans le tableau suivant des équations de condition, avec quelle approximation ces dernières sont représentées; une seule va à 32",4 centésimales, ou 10" sexagésimales, et toutes les autres sont généralement beaucoup plus petites. Mais les observations anciennes sont moins bien satisfaites, et l'une des erreurs s'élève jusqu'à 227",7, ou 73",8 sexagésimales.

Telle est donc l'alternative que présente la formation des Tables de la planète Uranus, que si l'on combine les observations anciennes avec les modernes, les premières seront passablement représentées, tandis que les secondes ne le seront pas avec la précision qu'elles comportent; et que si l'on rejette les unes pour ne conserver que les autres, il en résultera des Tables qui auront toute l'exactitude désirable relative-

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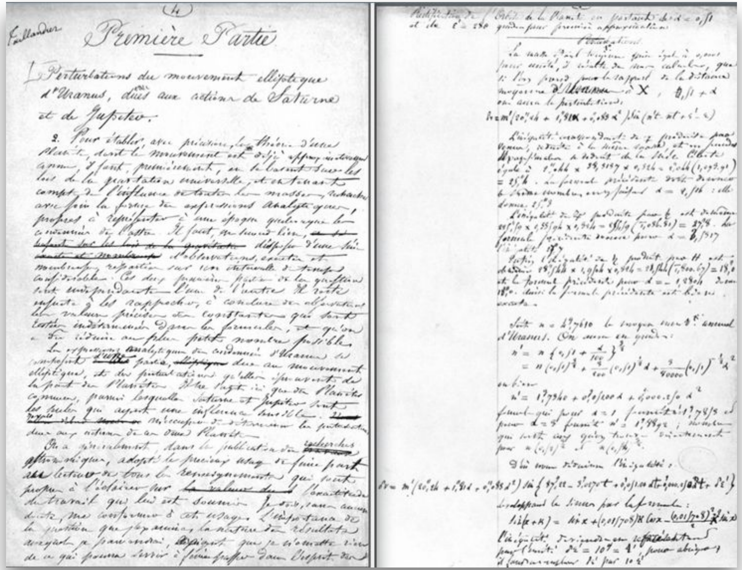
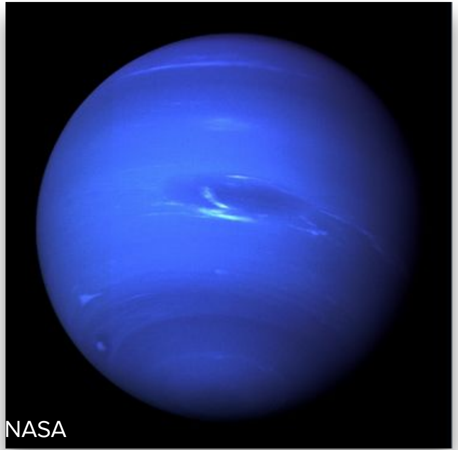
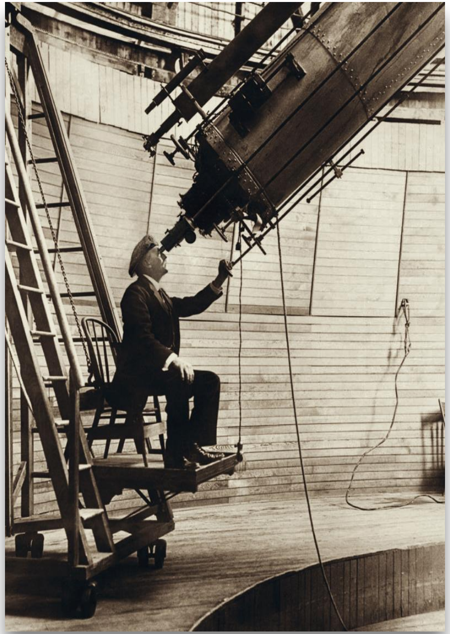
Discovery of Neptune





- The genius of Le Verrier was to use these anomalies to predict the position of a planet which could perturb Uranus from its orbit.
- Found by Johann Galle and Heinrich d’Arrest within hours of observation on Sep 24, 1846

Percival Lowell and search for Planet X



Percival Lowell

Clyde Tombaugh

- Orbital anomalies in Uranus could not be entirely explained by the presence of Neptune.
- Percival Lowell built the Flagstaff observatory in Arizona to search for Planet X
- Unfortunately he died before its discovery.

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NINTH PLANET DISCOVERED ON EDGE OF SOLAR SYSTEM; FIRST FOUND IN 84 YEARS

LIES FAR BEYOND NEPTUNE

Sighted Jan. 21 After 25 Years' Search Begun by Late Percival Lowell.

SEEN AT FLAGSTAFF, ARIZ.

Observatory Staff There Spots It by Special Photo-Telescope —Makes Thorough Check.

ASTRONOMERS HAIL FINDING

The Sphere, Possibly Larger Than Jupiter and 4,000,000,000 Miles Away, Meets Predictions.

By The Associated Press.

FLAGSTAFF, Ariz., March 13.—In the little cluster of orbs which scampers across the sidereal abyss under the name of the solar system there are, be it known, nine instead of a mere eight, worlds.

The presence of a ninth planet in the retinue of the sun, long suspected, was definitely announced here to-

New Planet Compared With Earth and Neptune

Size:
- Earth—8,000 miles in diameter.
- Neptune—32,000.
- New Planet—8,000 or more.

Distance from Sun:
- Earth—One astronomical unit.
- Neptune—Thirty astronomical units.
- New Planet—About fifty units.

Speed of Revolution:
- Earth—19 miles a second.
- Neptune—3½ miles a second.
- New Planet—From 1 to 2 miles a second.

Time of Revolution:
- Earth—One year.
- Neptune—146 Earth-years (entire revolution not yet observed).
- New Planet—Probably 300 to 600 years.

Note—These figures on the new planet are tentative, based upon computations of astronomers here on the Flagstaff announcement.

M'DONALD RALLIES NAVAL CONFERENCE

Prime Minister Devotes Whole Day to Talks With Heads of All the Delegations.

PROHIBITION HAI BY STAGG AS CI ON POST-WAR Y

Chicago Athletic Dire Chief Dry Witness in S Ending in Committee

DRY MEMBER ASSAIL

Celler Is Accused of "Ins Mrs. Peabody by Cha She Prompted Speak

ADJOURN FOR COOLIN

Sherwood Came Under Attacking Anti-Dry Le as "Fanatics."

Special to The New York

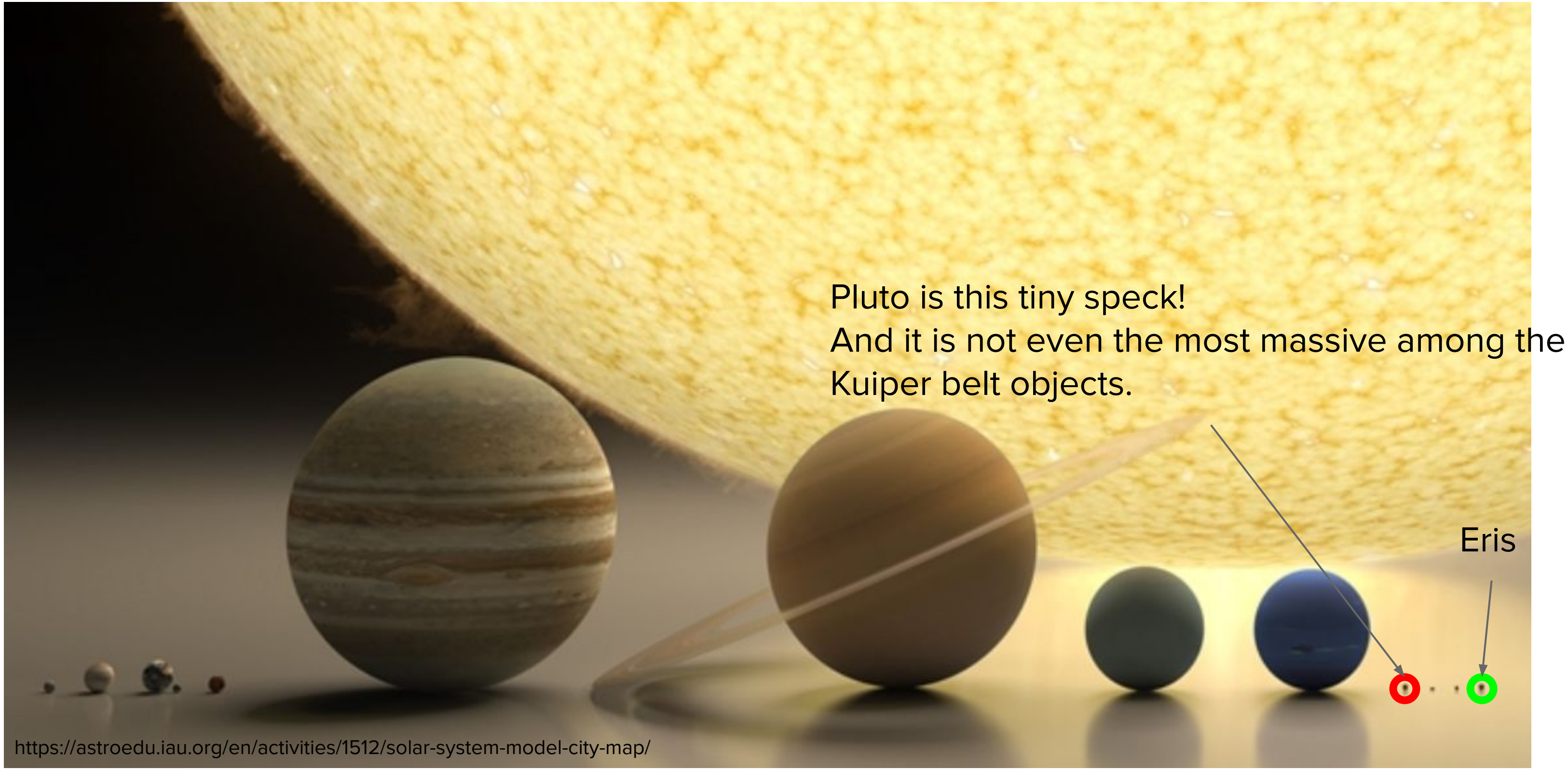
WASHINGTON, March 1 Alonzo Stagg, veteran dir athletics at the University cago, testified before the Judiciary Committee today improved status of the natio under national prohibition.

Mr. Stagg, who headed th dry witnesses at today's he the various modification bill the committee:

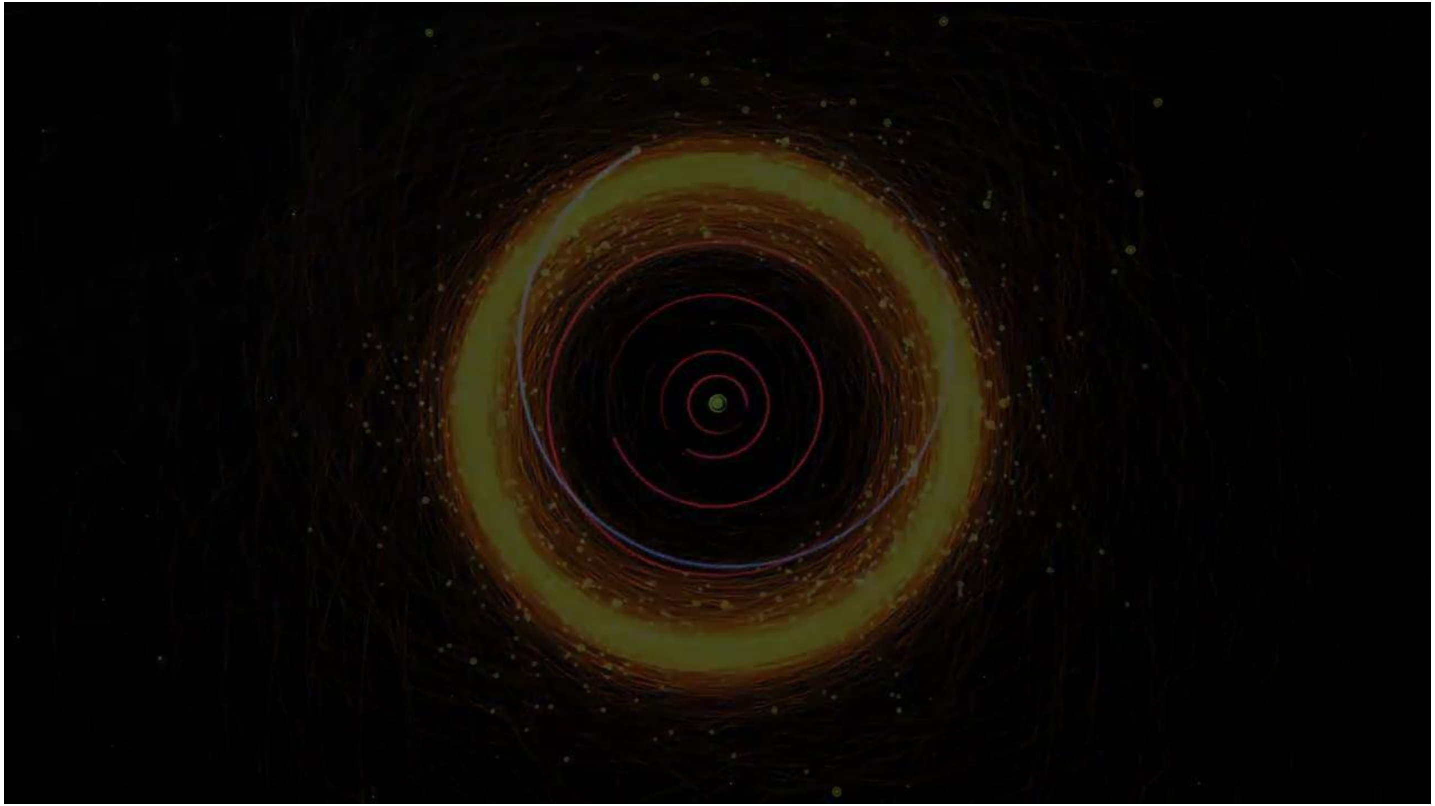
"In my judgment, since pr has been put into effect, hu thousands more children ha fairer start in life than e pre-prohibition days. With th down of the home life and the complexities of new oppo for being misled, I tremble

The New York "Times" front-page Pluto story on March 14, 1930.

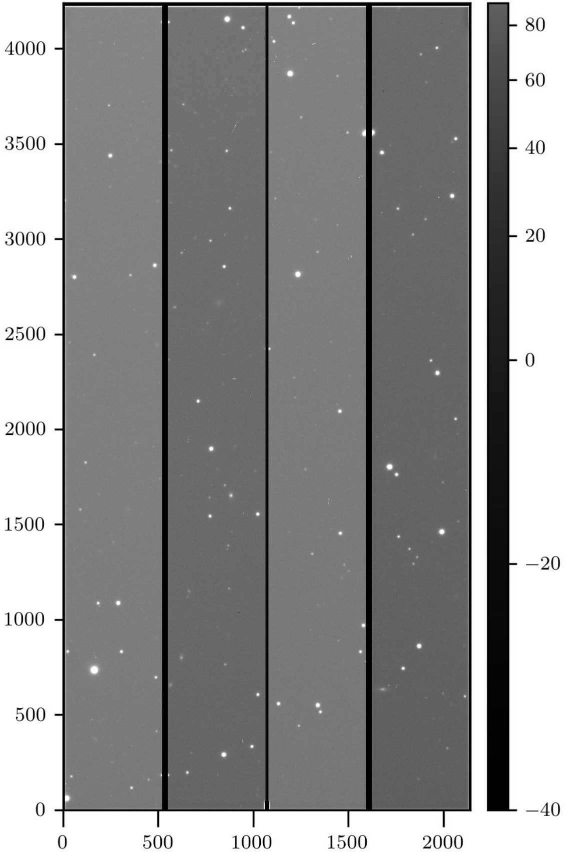
Pluto in context



Pluto and the Kuiper belt

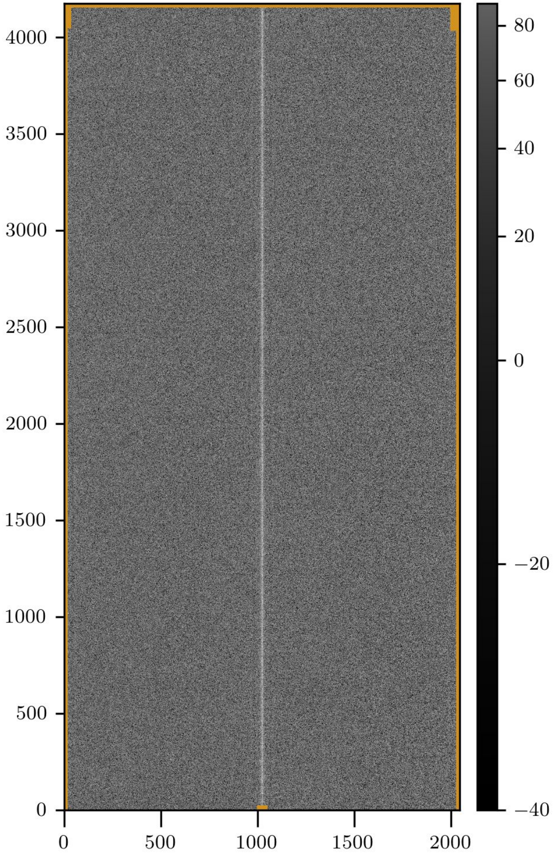


Credit: Michael Brown, Mark Subbarao, Patrick McPike



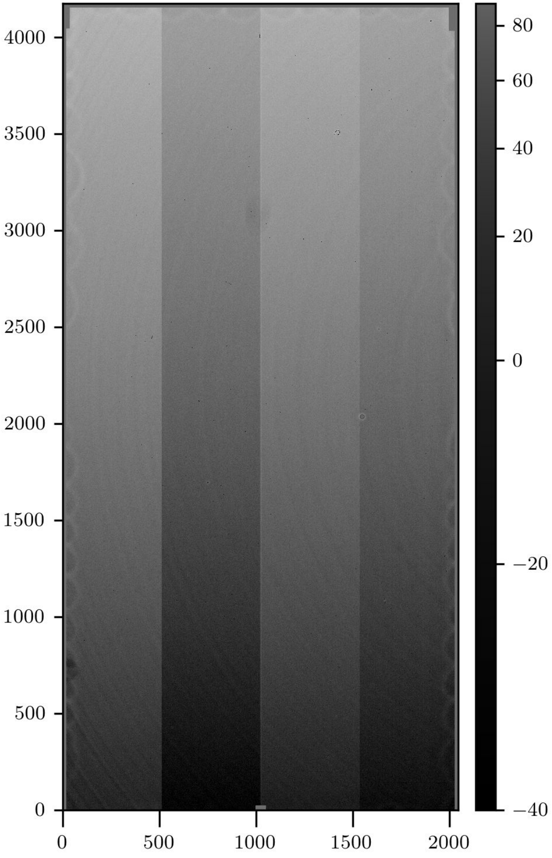
Raw image

Image with zero exposure time

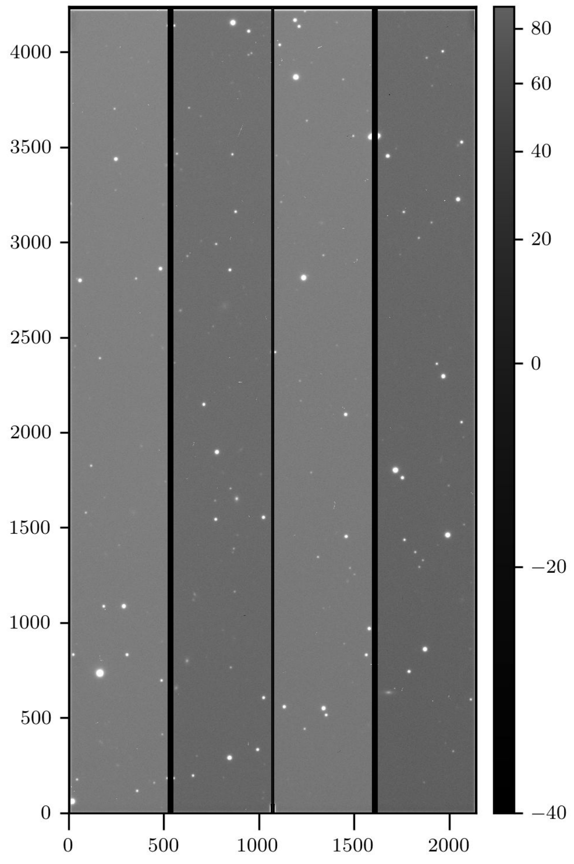


Bias image

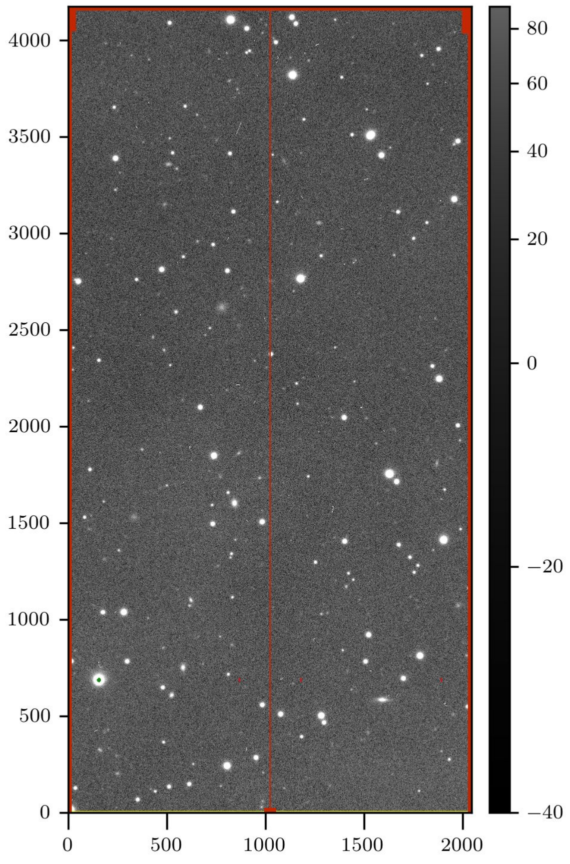
Image with uniform illumination



Flat field

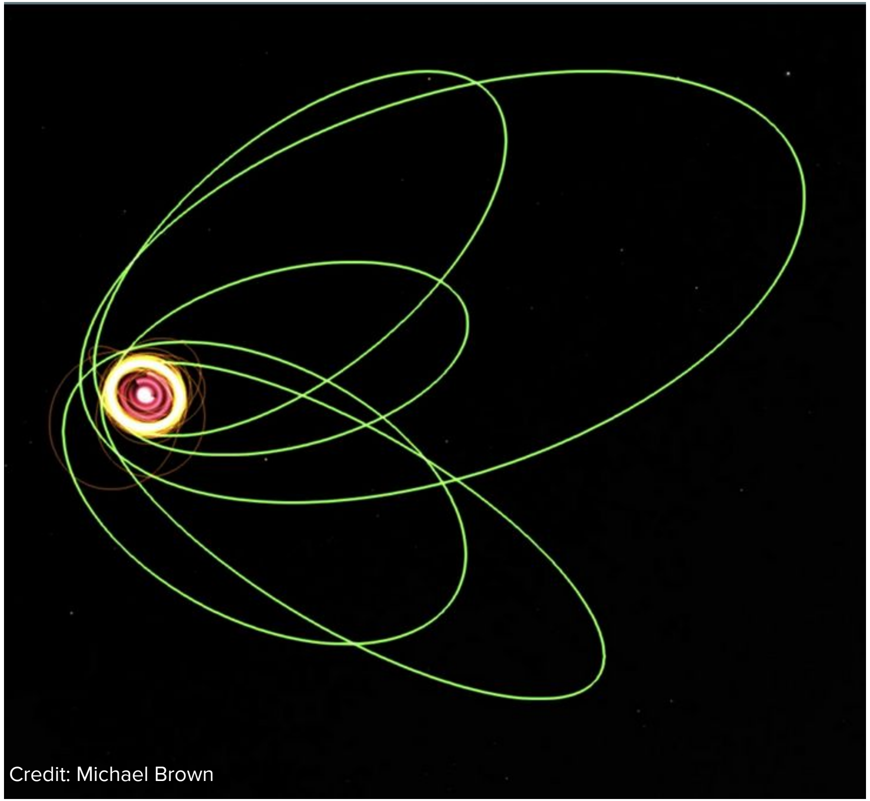


Raw image

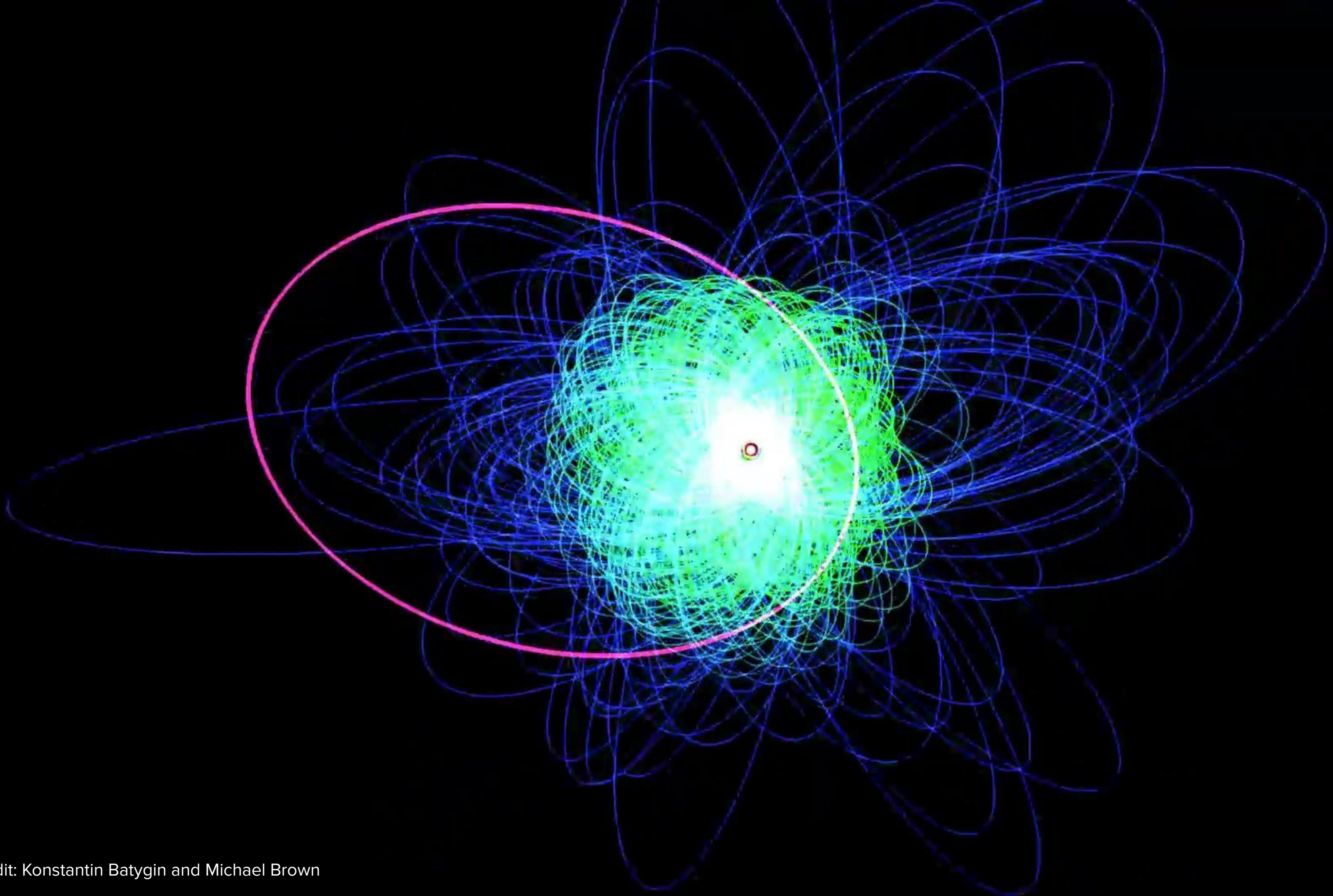


Calibrated image

Peculiar orbits in the Kuiper belt

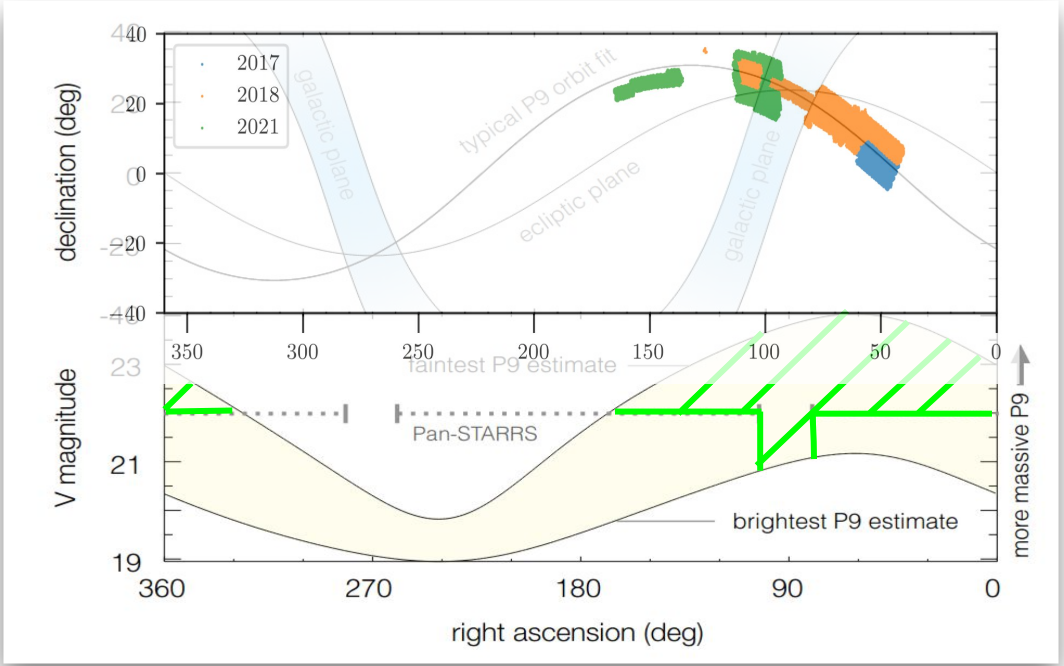


- Sedna, discovered by Mike Brown (Caltech) in 2004, and VP112 (Biden) discovered in 2012 had odd elongated orbits.
- As more such objects were discovered a pattern emerged.
- Objects with semi-major axes beyond 230 AU have peculiarly odd orbits.
- All tilted in one direction compared to the Sun as if someone is pulling them to one side.



Credit: Konstantin Batygin and Michael Brown https://amazingsky.net/tag/dog-star/

Data gathered thus far

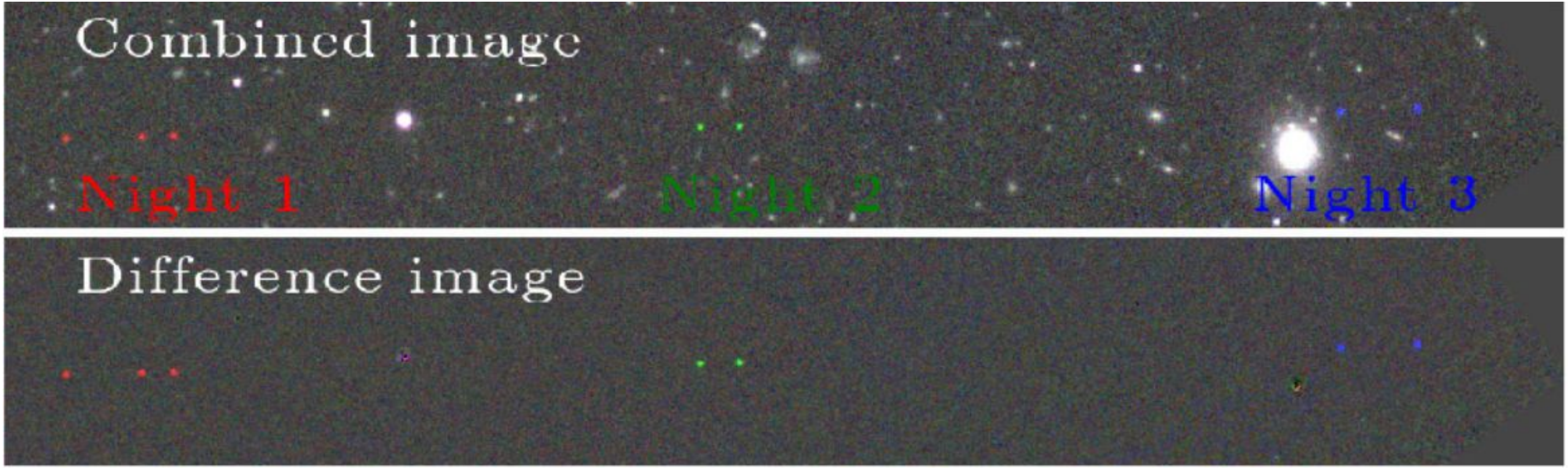


- Right ascension and declination can be thought of as longitudes and latitudes on sky to determine position
- Magnitude tells how bright an object is (smaller the magnitude brighter the object)
- The observed pointing are shown in color.

https://amazingsky.net/tag/dog-star/

The search goes on!

Needle in a haystack!



- Lots of images with terabytes of data. Needs supercomputers to process the images.
- Clever algorithms like difference imaging help in finding moving objects.

Data processing pipeline

Raw images from the telescope

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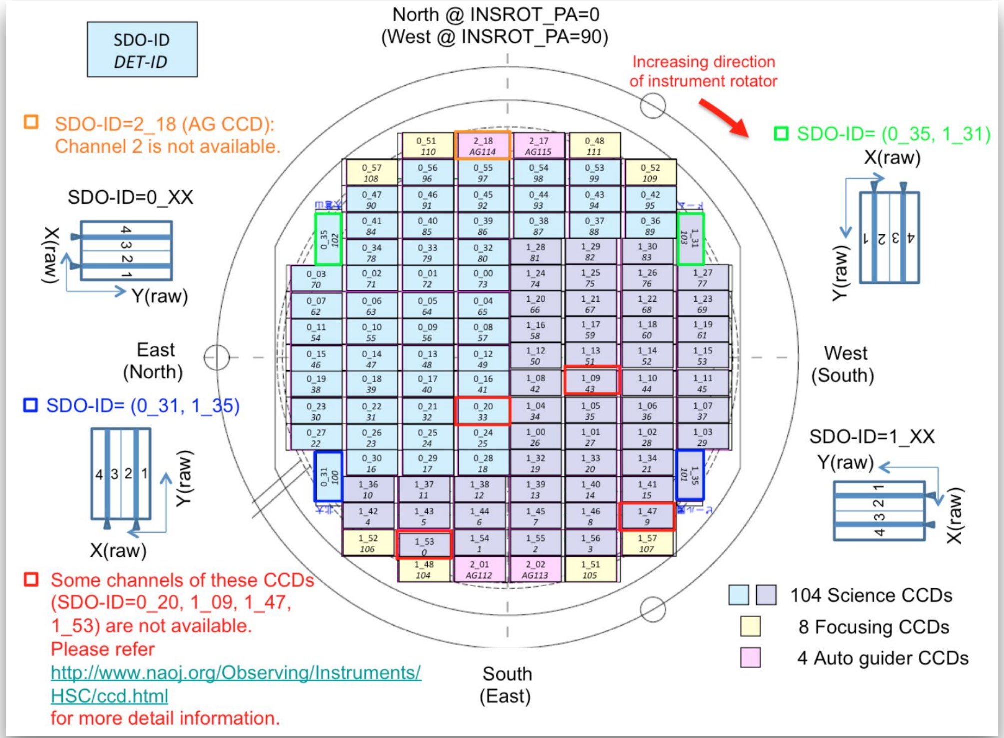
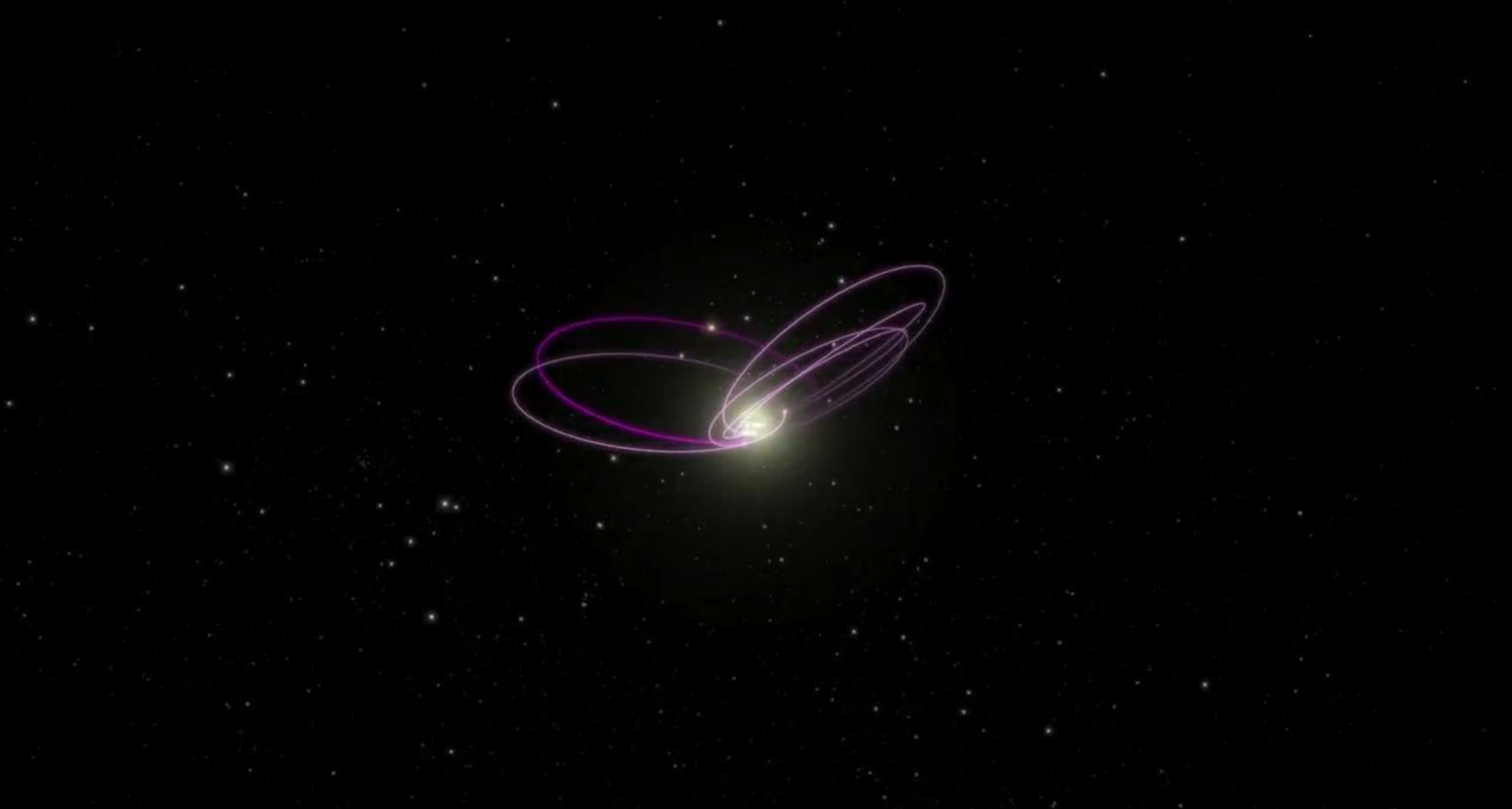
catalogs

Date	Raw	Calibrated	Injected	Differenced
20181204	18720	18414	17232	17051
20181205	15080	14593	13514	13467
20181206	19032	18829	17645	17337
20181207	16744	16579	16579	16433
20181208	35776	35316	35316	34824
20181209	35360	34859	34702	34271
20181210	34840	34344	34187	33835

Hyper Suprime-Cam detector



- Focal plane has 116 CCDs, 104 used for science, 8 are used for focussing, 4 for auto guidance.
- More than 2 GB of data every 90 seconds, > 2500 exposures in total.
- Worry about chip gaps and failed chips.



Credit: Michael Brown/Konstantin Batygin