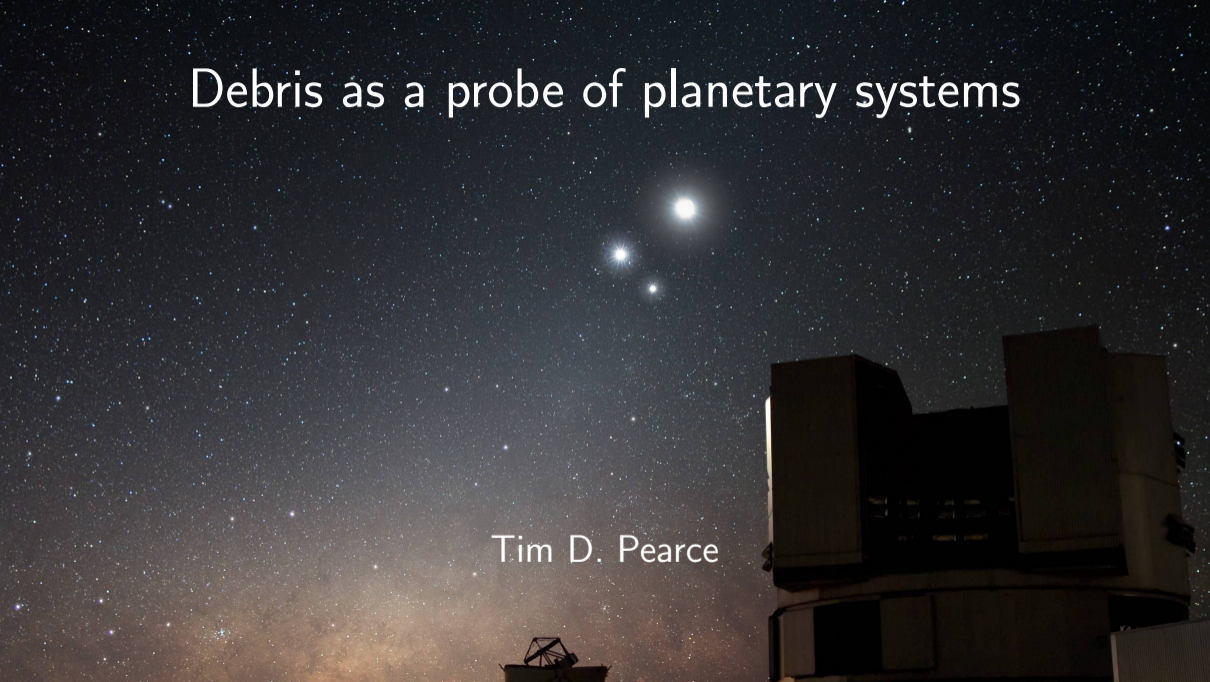


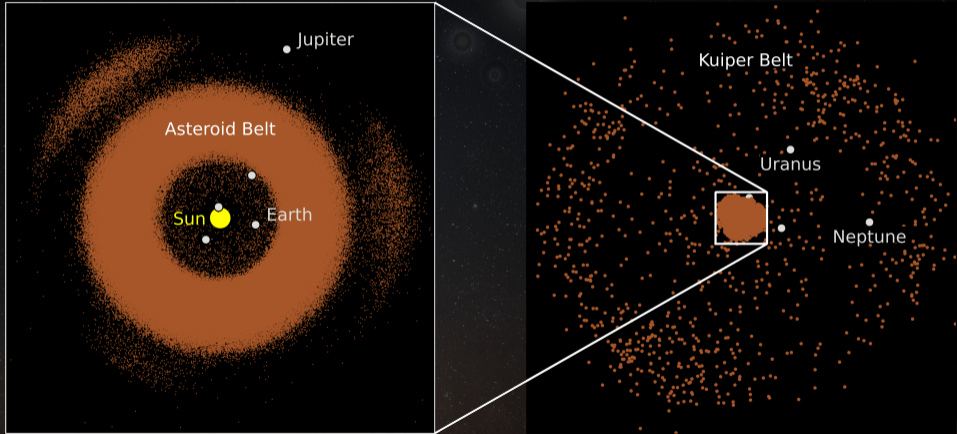
Debris as a probe of planetary systems

Tim D. Pearce



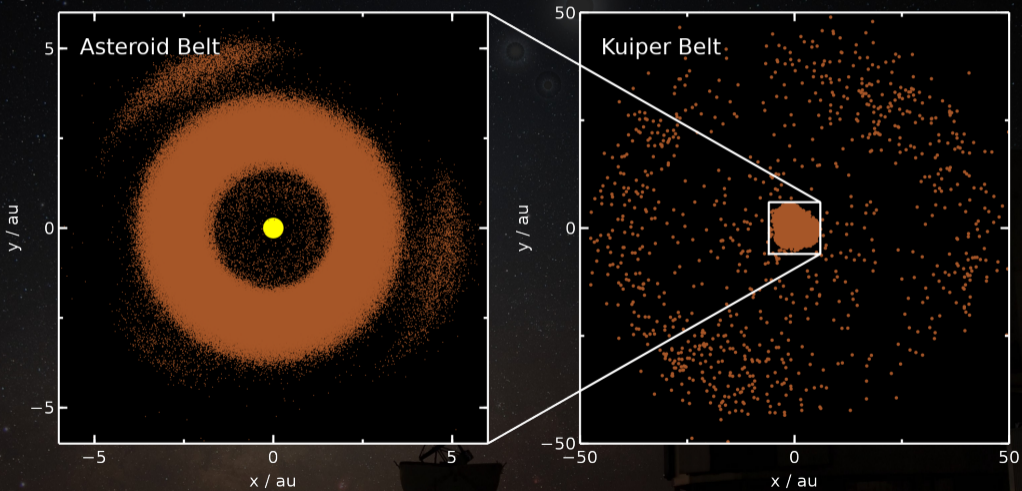
Debris discs 101

Solar System:



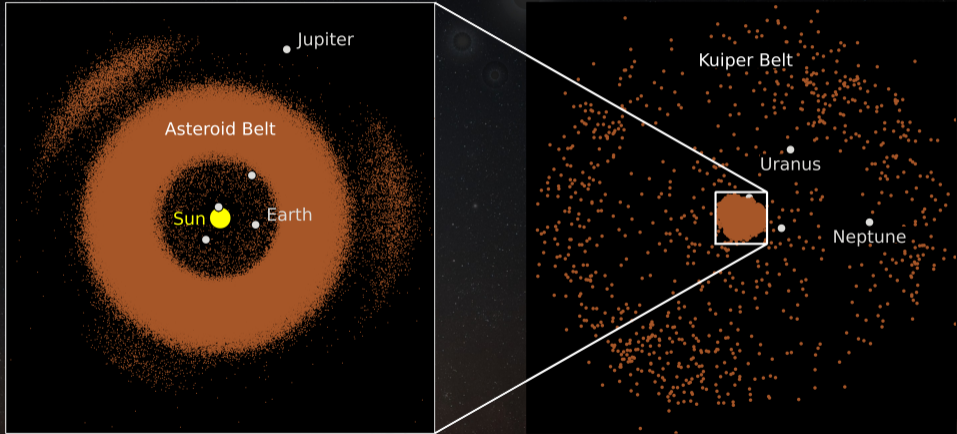
Debris discs 101

Solar System:



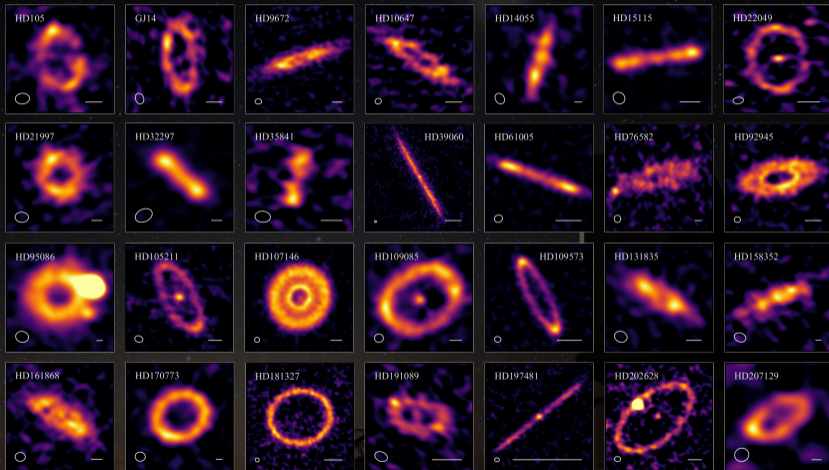
Debris discs 101

Solar System:

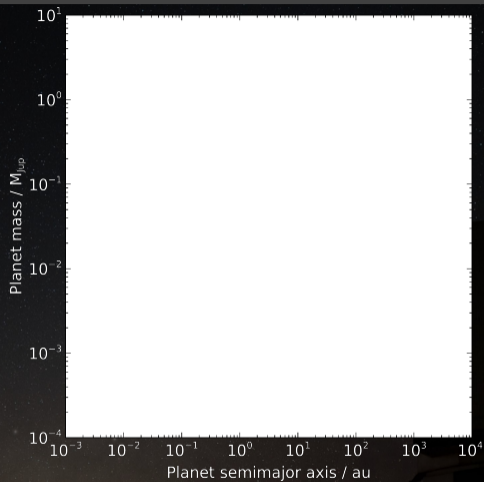


Debris discs 101

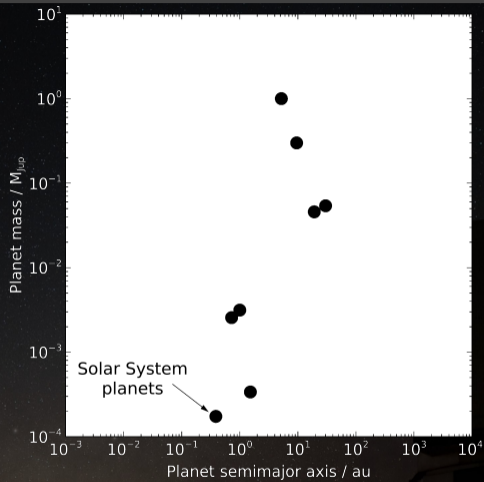
Extrasolar debris discs:



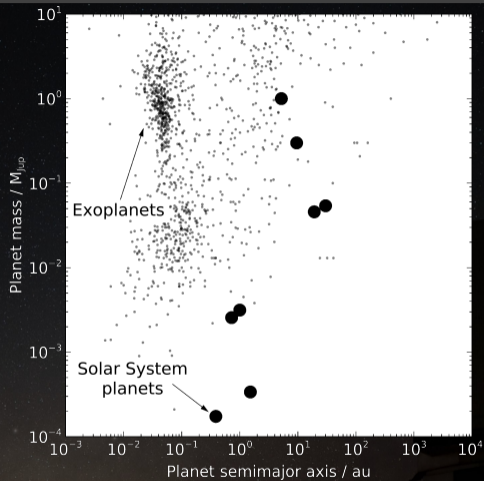
Debris discs as planetary probes



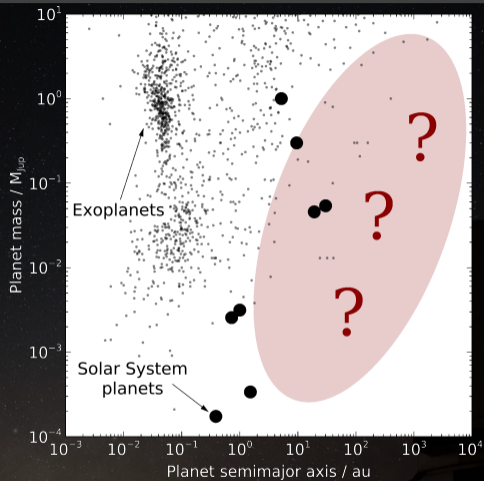
Debris discs as planetary probes



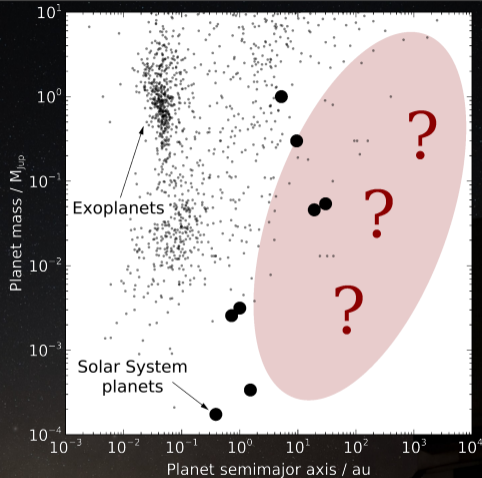
Debris discs as planetary probes



Debris discs as planetary probes

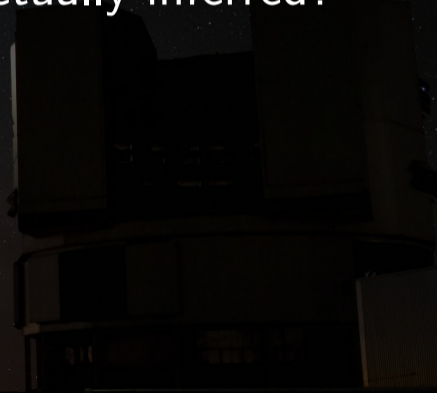


Debris discs as planetary probes



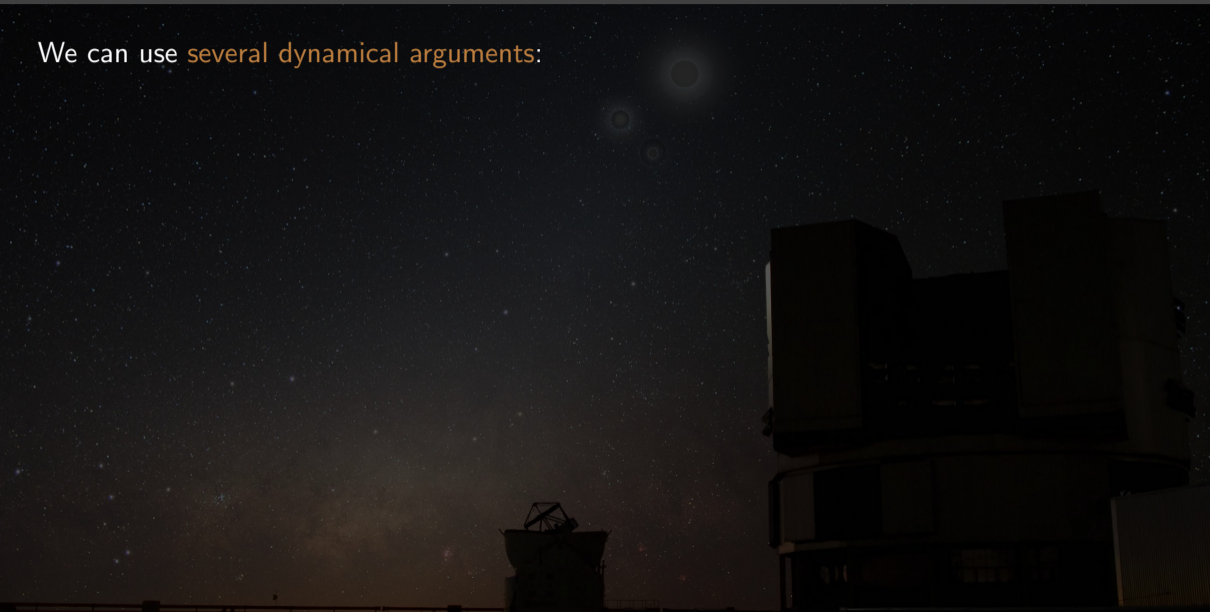
⇒ Debris discs can probe the **outer regions** of planetary systems

How are planet parameters actually inferred?



Inferring planets from debris discs

We can use **several dynamical arguments**:



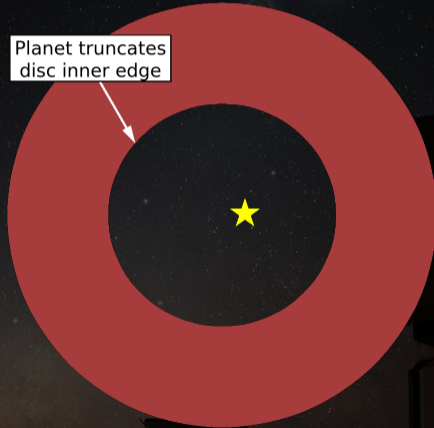
Inferring planets from debris discs

We can use **several dynamical arguments**:



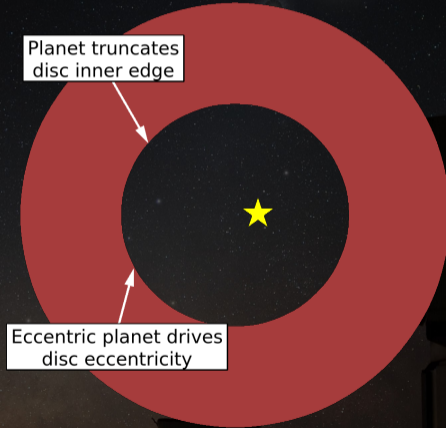
Inferring planets from debris discs

We can use **several dynamical arguments**:



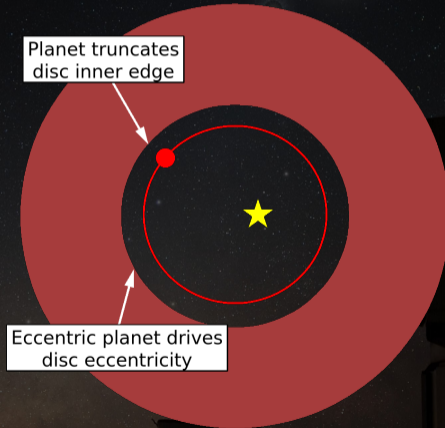
Inferring planets from debris discs

We can use **several dynamical arguments**:



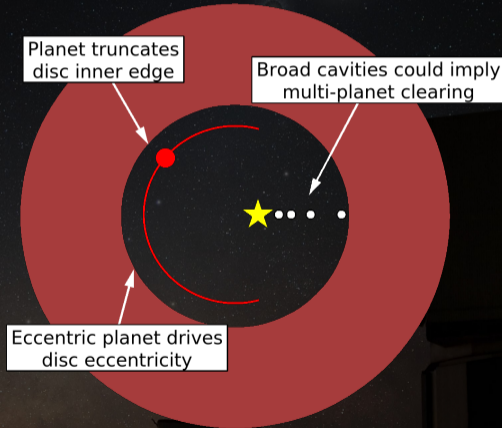
Infering planets from debris discs

We can use **several dynamical arguments**:



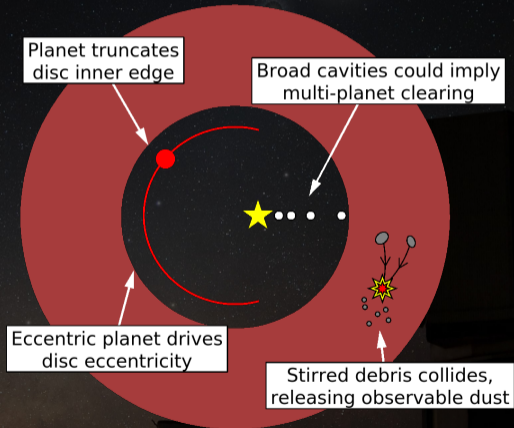
Inferring planets from debris discs

We can use **several dynamical arguments**:



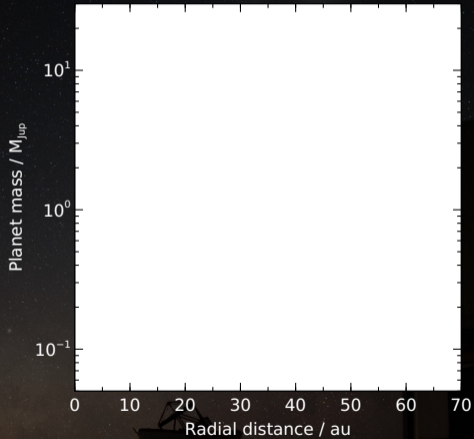
Inferring planets from debris discs

We can use **several dynamical arguments:**



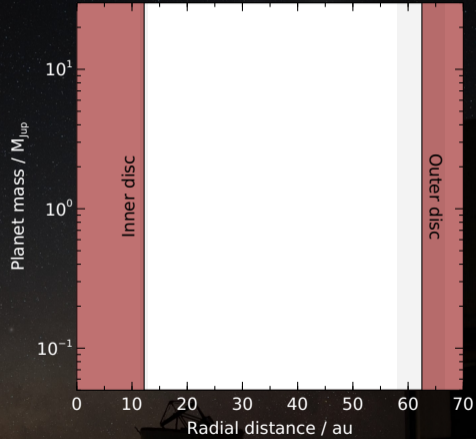
What it looks like in practice...

Example: 49 Ceti



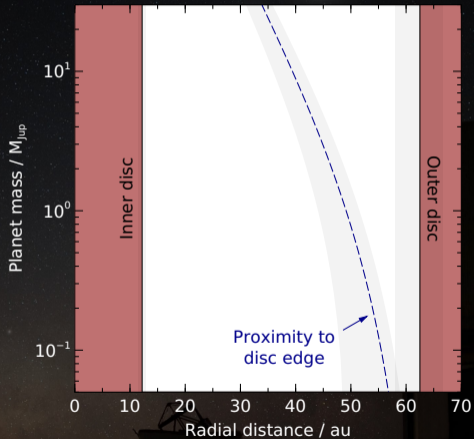
What it looks like in practice...

Example: 49 Ceti



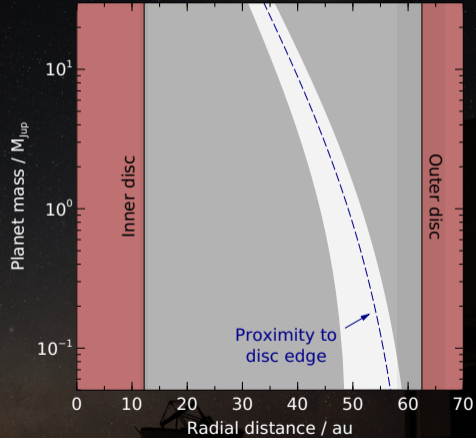
What it looks like in practice...

Example: 49 Ceti



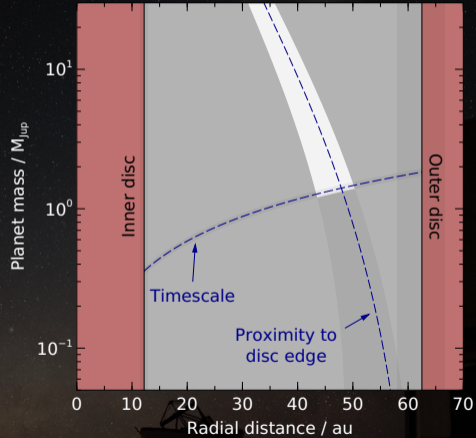
What it looks like in practice...

Example: 49 Ceti



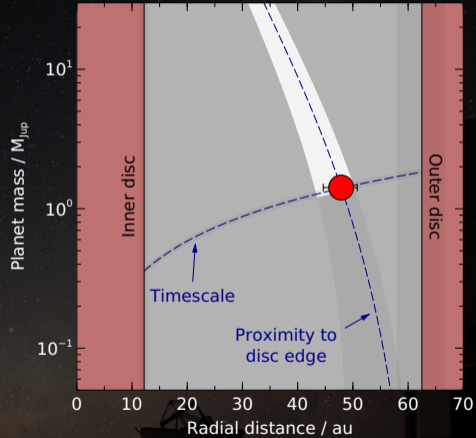
What it looks like in practice...

Example: 49 Ceti



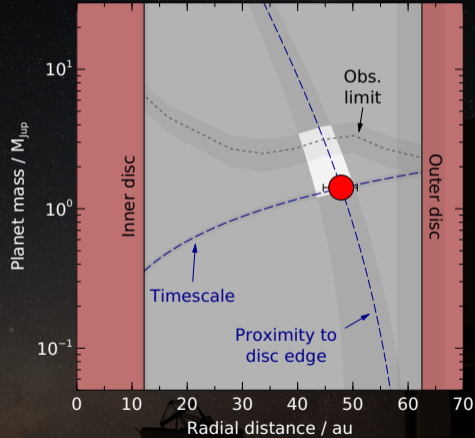
What it looks like in practice...

Example: 49 Ceti



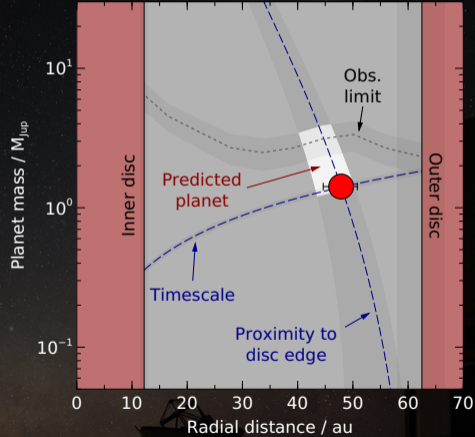
What it looks like in practice...

Example: 49 Ceti



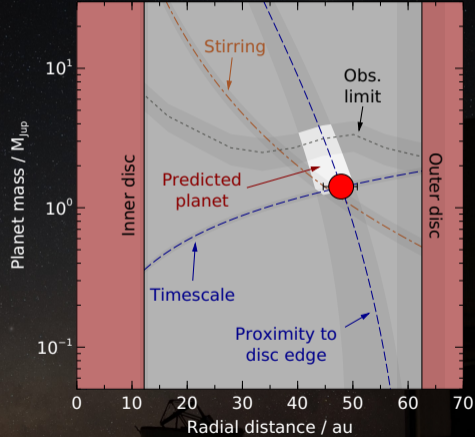
What it looks like in practice...

Example: 49 Ceti



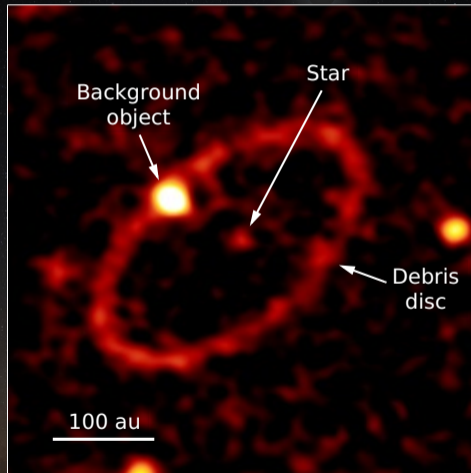
What it looks like in practice...

Example: 49 Ceti



What it looks like in practice...

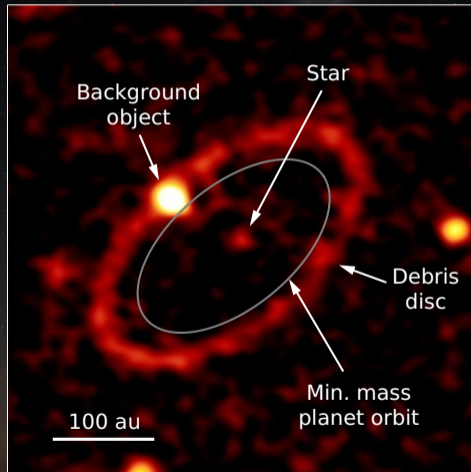
Example: HD 202628



ALMA: Faramaz et al. 2019

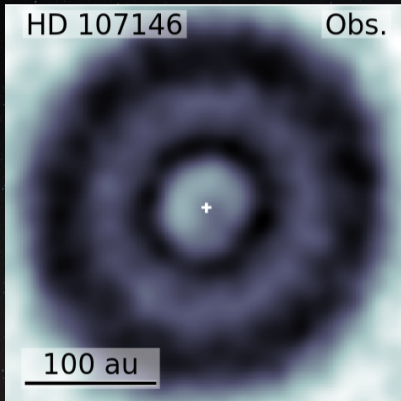
What it looks like in practice...

Example: HD 202628



Inferring planets from debris discs II

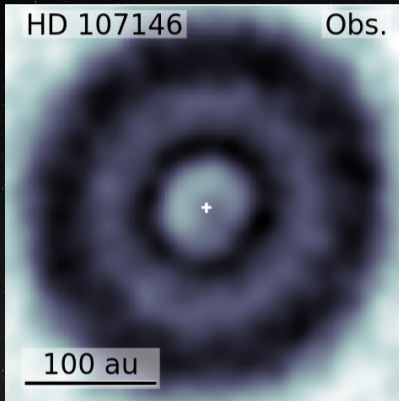
Sometimes there are **radial** or **azimuthal** asymmetries:



?

Inferring planets from debris discs II

Sometimes there are **radial or azimuthal asymmetries**:

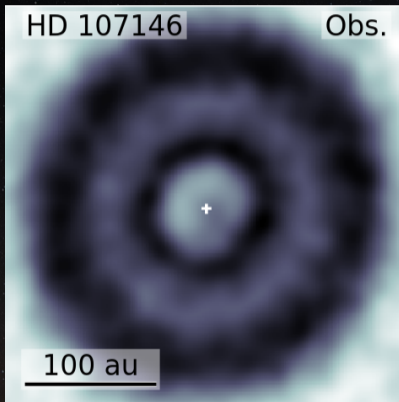


?

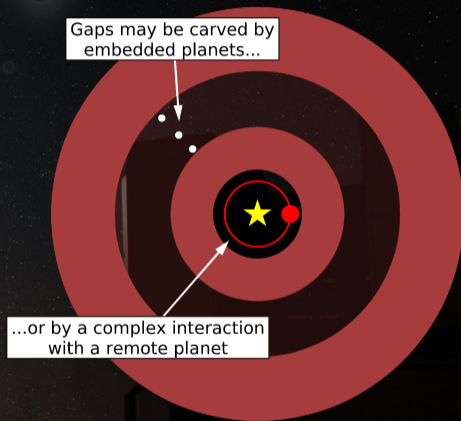


Inferring planets from debris discs II

Sometimes there are **radial or azimuthal asymmetries**:

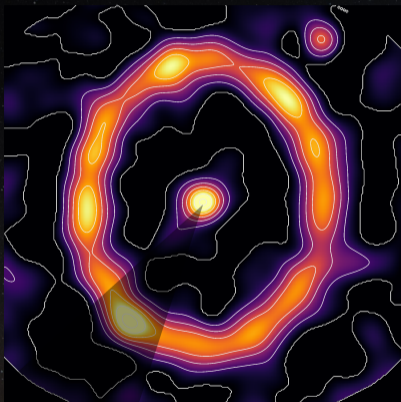


?

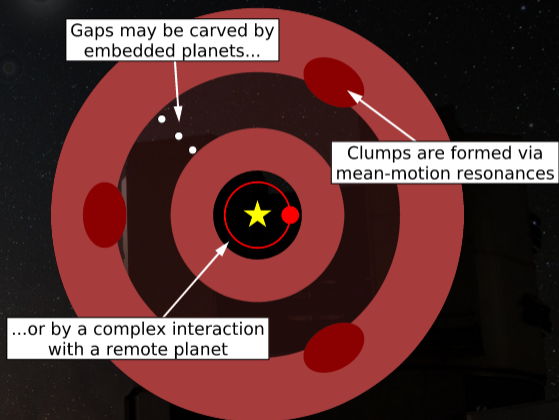


Inferring planets from debris discs II

Sometimes there are **radial or azimuthal asymmetries**:



Booth et al. 2023



E.g. Faber & Quillen 2007; Shannon et al. 2016; Fricke, Pearce & Löhne 2022; Pearce & Wyatt 2015; Yelverton et al. 2019; Sefilian, Rafikov & Wyatt 2021, 2023; Ozerov et al. 2000; Wyatt 2006; Krivov et al. 2007

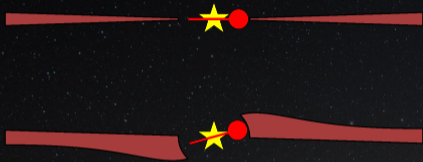
Inferring planets from debris discs III

Constraints from **vertical structure**:



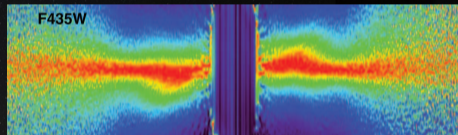
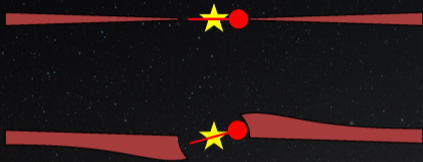
Inferring planets from debris discs III

Constraints from **vertical structure**:



Inferring planets from debris discs III

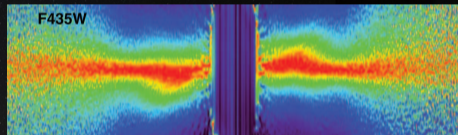
Constraints from **vertical structure**:



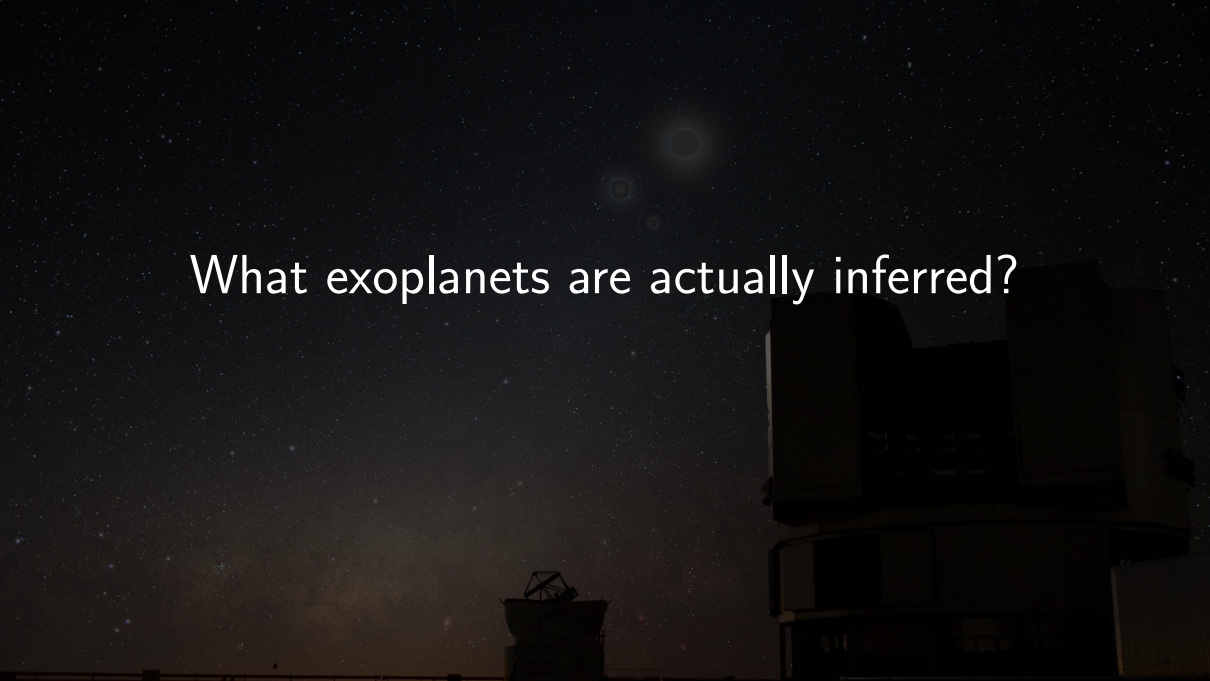
β Pic: Golimowski et al. 2006

Inferring planets from debris discs III

Constraints from **vertical structure**:

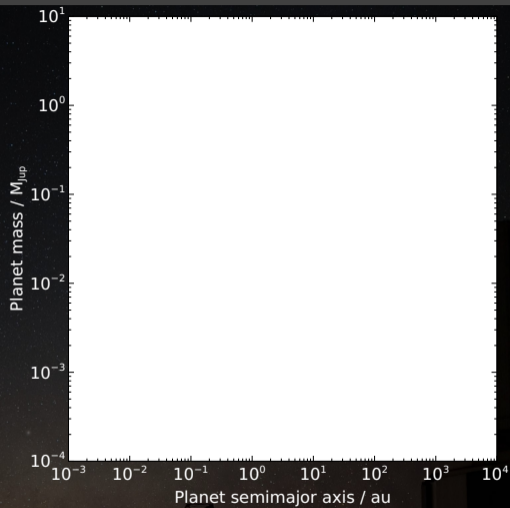


β Pic: Golimowski et al. 2006

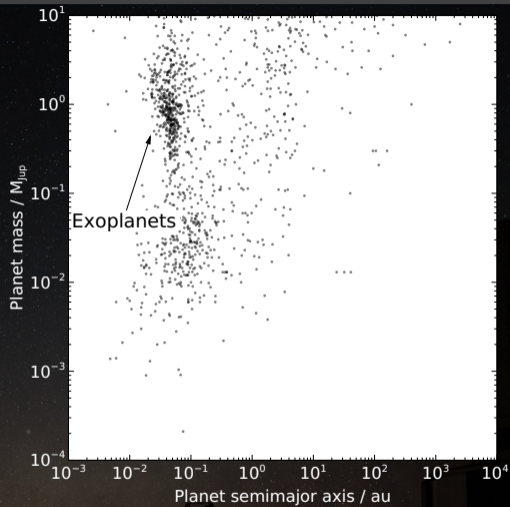
A dark night sky filled with stars, with the silhouettes of astronomical observatories visible at the bottom. The text "What exoplanets are actually inferred?" is centered in white.

What exoplanets are actually inferred?

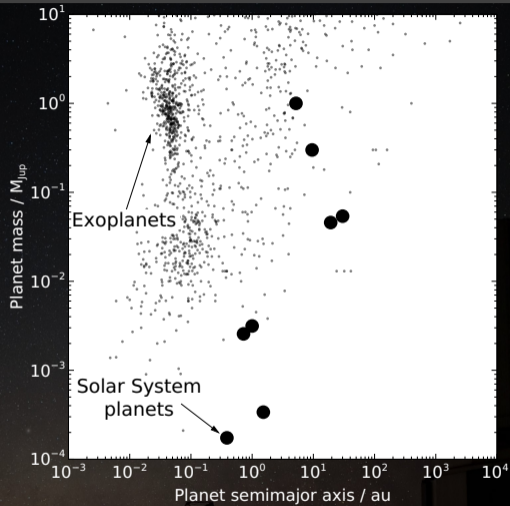
Inferred planets vs. known planet population



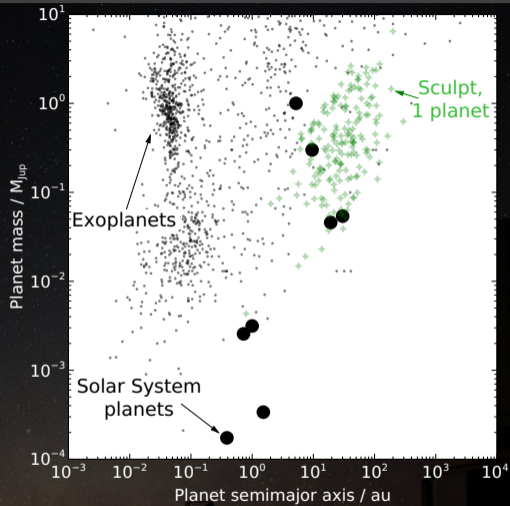
Inferred planets vs. known planet population



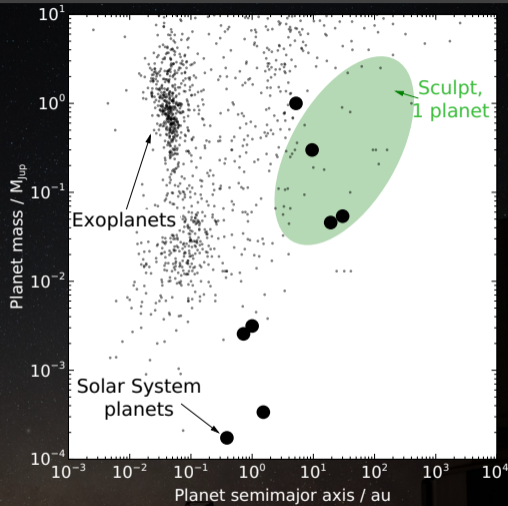
Inferred planets vs. known planet population



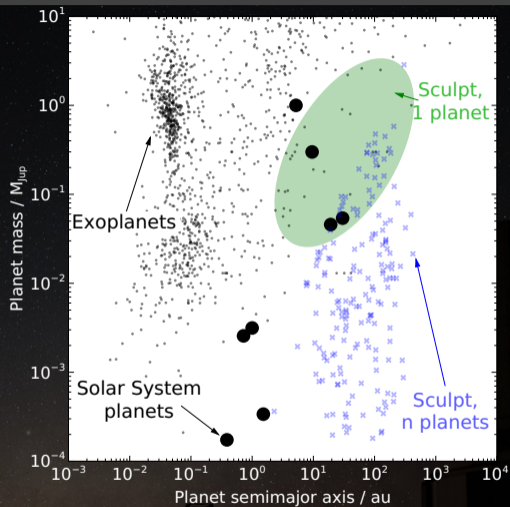
Inferred planets vs. known planet population



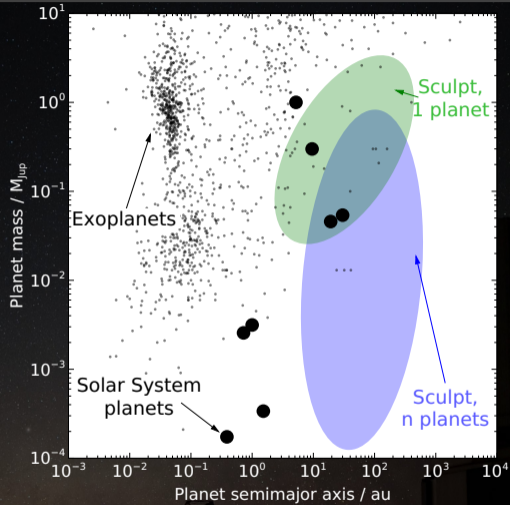
Inferred planets vs. known planet population



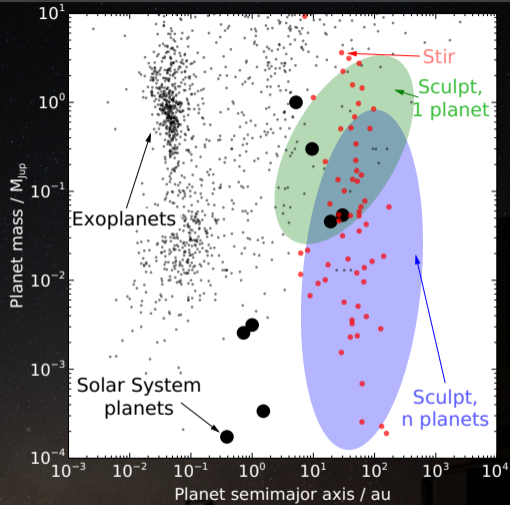
Inferred planets vs. known planet population



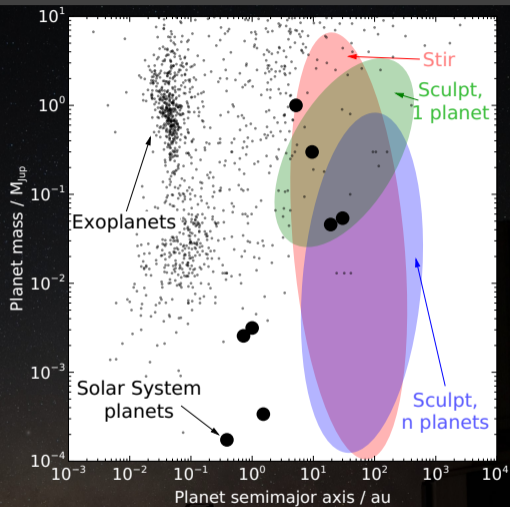
Inferred planets vs. known planet population



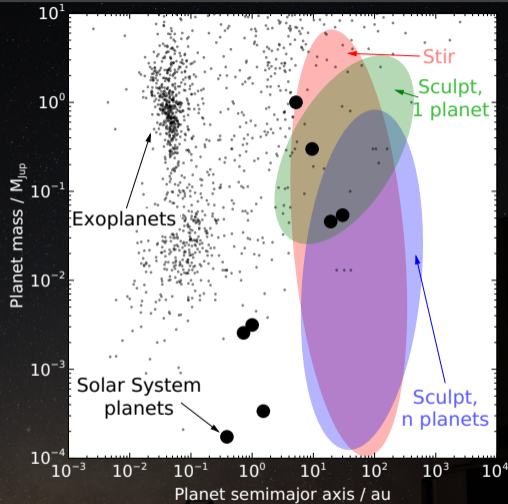
Inferred planets vs. known planet population



Inferred planets vs. known planet population



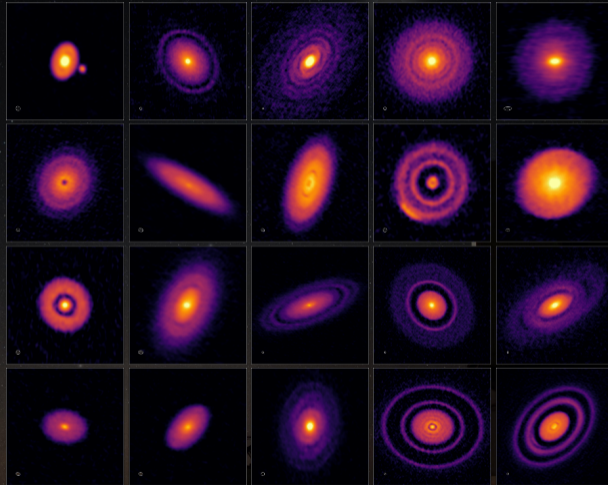
Inferred planets vs. known planet population



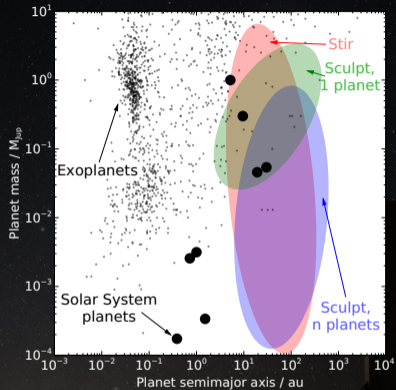
⇒ Debris discs imply a planet population **very different** to those known

Comparison to inferred forming planets

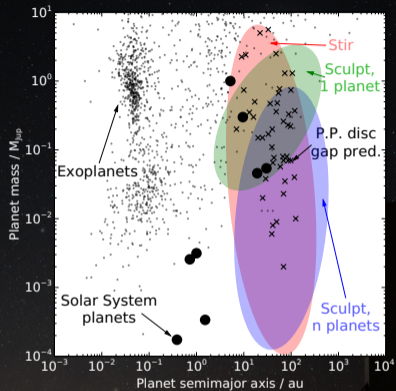
Protoplanetary discs with ALMA:



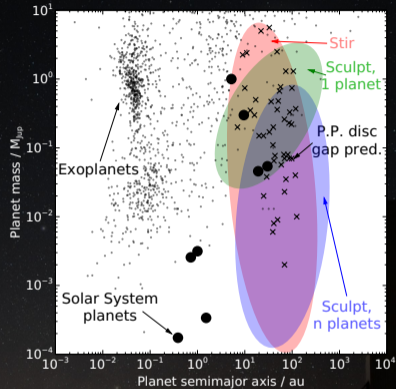
Comparison to inferred forming planets



Comparison to inferred forming planets

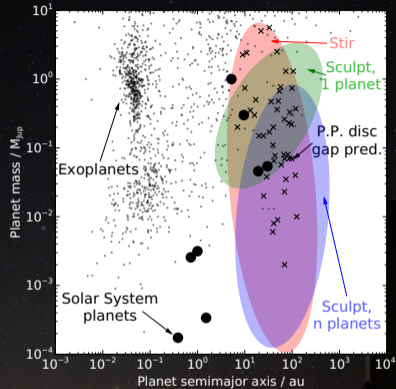


Comparison to inferred forming planets



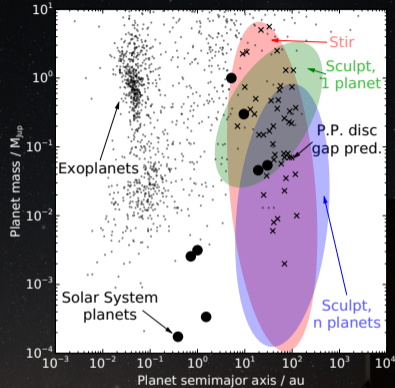
- Planets inferred from debris **match** those inferred to be forming in **protoplanetary discs**

Comparison to inferred forming planets



- Planets inferred from debris **match** those inferred to be forming in **protoplanetary discs**
- Forming planets **don't migrate inwards** as far as thought?

Comparison to inferred forming planets



- Planets inferred from debris **match** those inferred to be forming in **protoplanetary discs**
- Forming planets **don't migrate inwards** as far as thought?
- Or young planets **quickly sculpt debris** before migrating in?

The Future



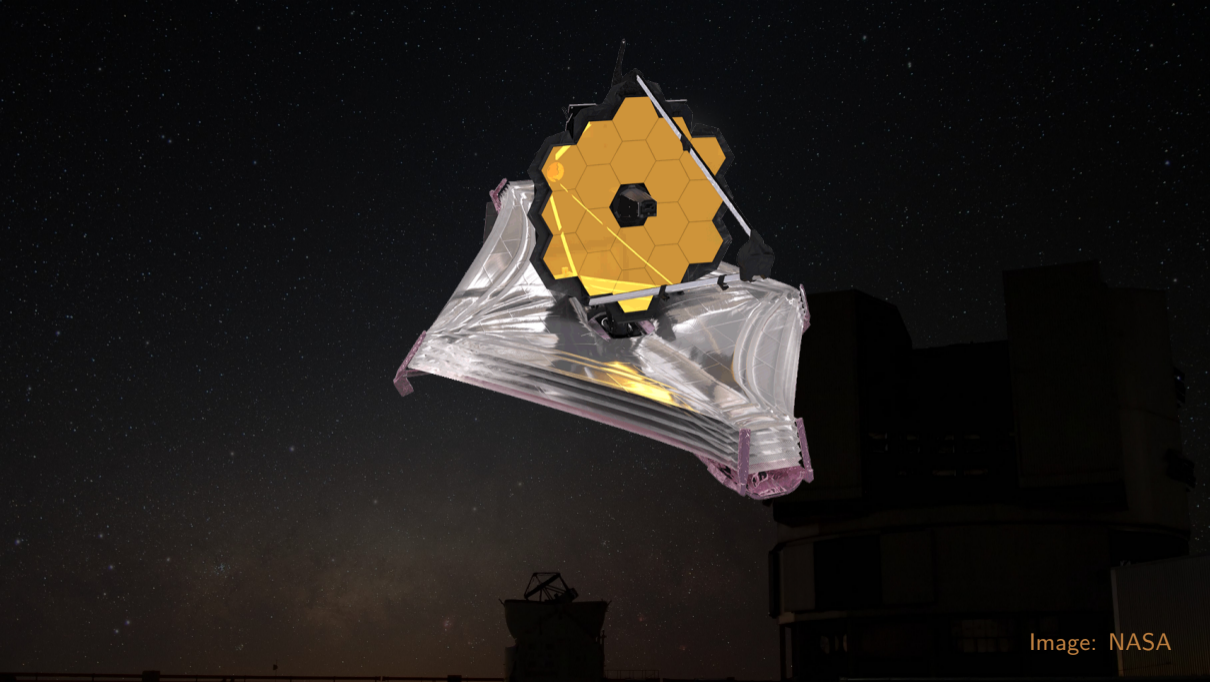
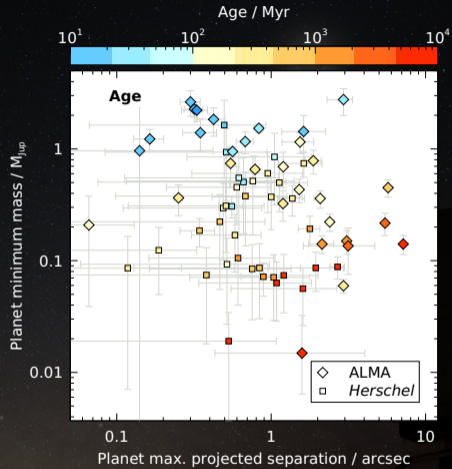


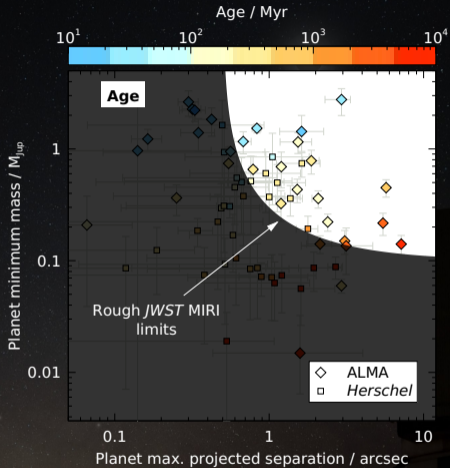
Image: NASA

Future planet detections



Inferred planets: Pearce et al. 2022

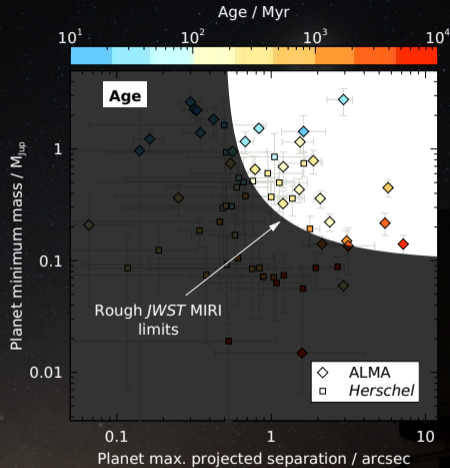
Future planet detections



Inferred planets: Pearce et al. 2022

Rough JWST curves based on Carter et al. 2021

Future planet detections



⇒ Many planets interacting with debris discs should be visible to *JWST*

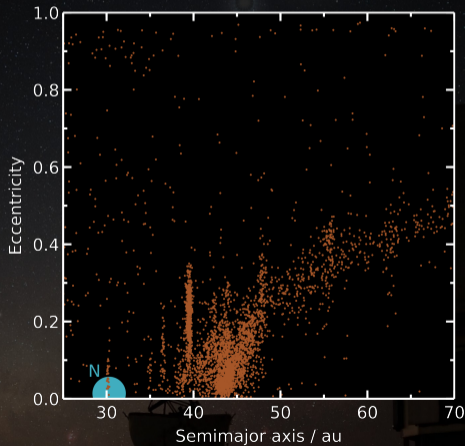
What could we learn by pairing *JWST* data
with planet-debris-interaction theory?

Evolutionary histories of planetary systems



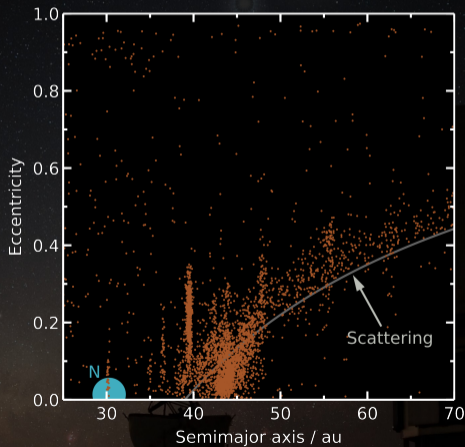
Evolutionary histories of planetary systems

Kuiper Belt



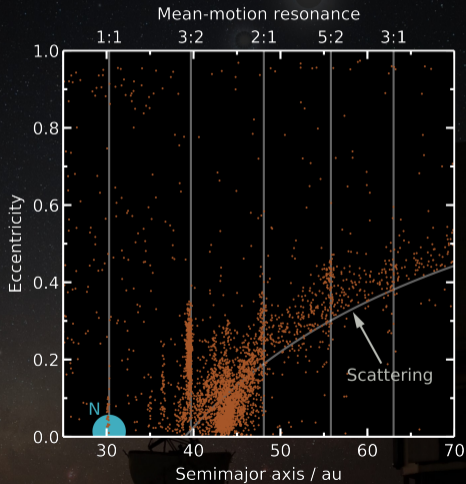
Evolutionary histories of planetary systems

Kuiper Belt



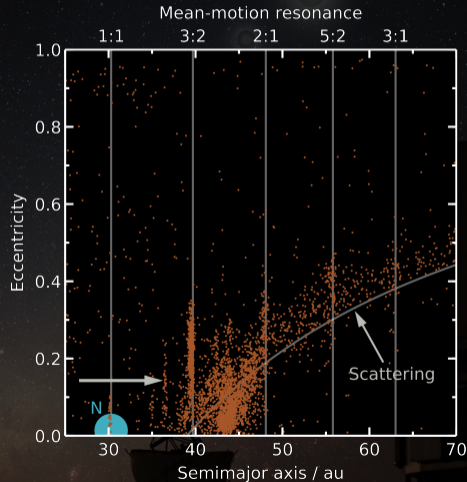
Evolutionary histories of planetary systems

Kuiper Belt



Evolutionary histories of planetary systems

Kuiper Belt

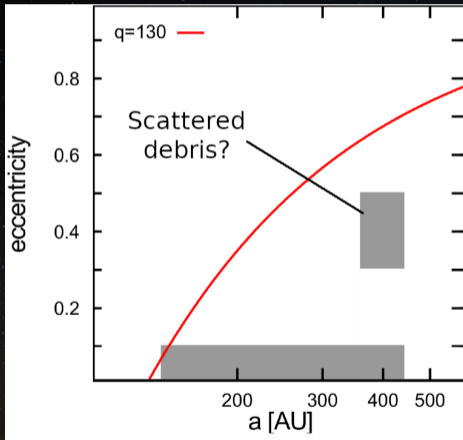


E.g. Tsiganis et al. 2005; Levison et al. 2008; Nesvorný 2015

Ephemerides: JPL

Evolutionary histories of planetary systems

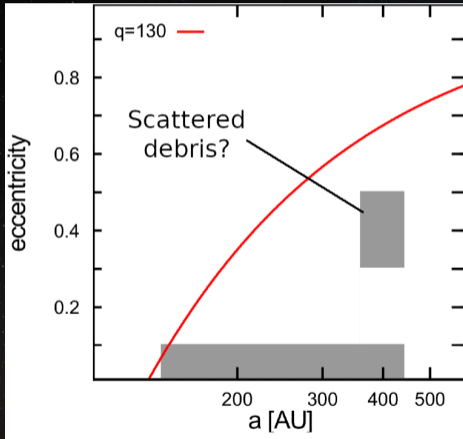
We're close to doing this for **extrasolar debris discs** too:



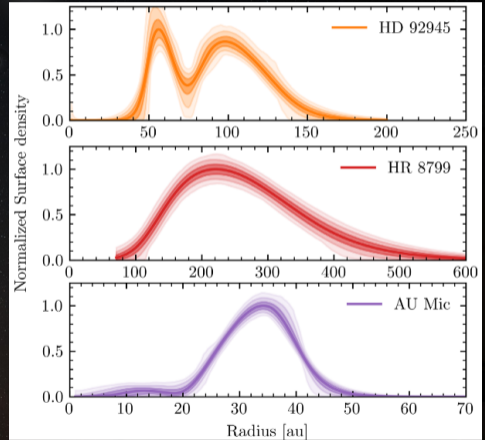
HR 8799: Adapted from Geiler et al. 2019

Evolutionary histories of planetary systems

We're close to doing this for **extrasolar debris discs** too:



HR 8799: Adapted from Geiler et al. 2019

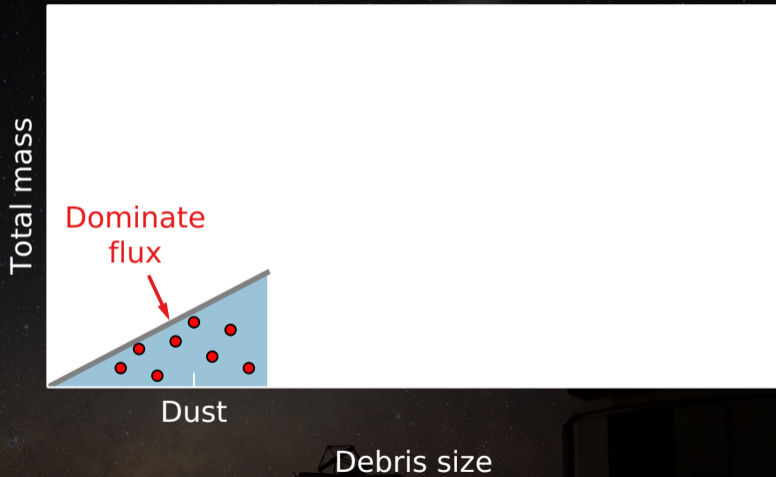


Adapted from Marino 2021

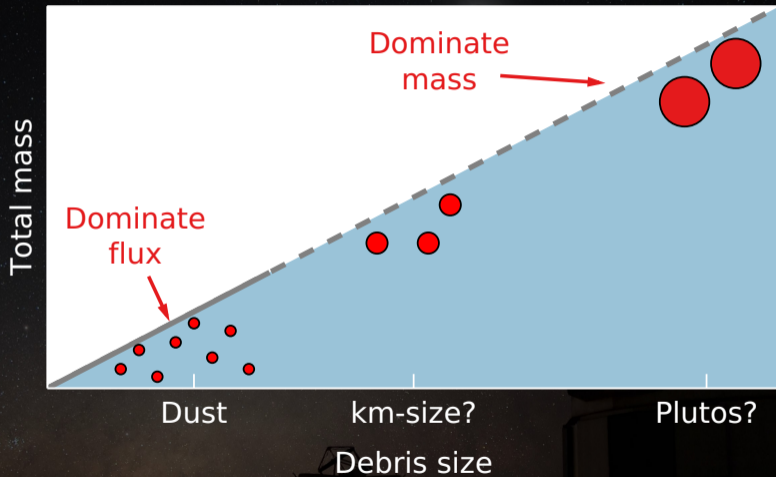
Debris-disc masses



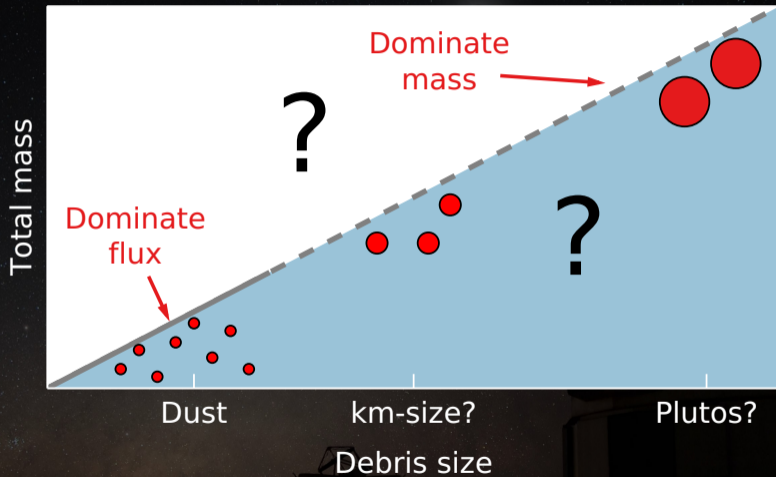
Debris-disc masses



Debris-disc masses



Debris-disc masses



Debris-disc masses are unknown!

Debris-disc masses



Sefilian, Rafikov & Wyatt 2021

See also: [Ida, Larwood & Burkert 2000](#); [Kirsh et al. 2009](#); [Pearce & Wyatt 2015](#); [Yelverton et al. 2019](#); [Friebe, Pearce & Löhne 2022](#); [Sefilian, Rafikov & Wyatt 2023](#)

Debris-disc masses



Sefilian, Rafikov & Wyatt 2021

Debris-planet interactions would directly probe debris-disc masses

See also: Ida, Larwood & Burkert 2000; Kirsh et al. 2009; Pearce & Wyatt 2015; Yelverton et al. 2019; Friebe, Pearce & Löhne 2022; Sefilian, Rafikov & Wyatt 2023

JWST won't find everything!

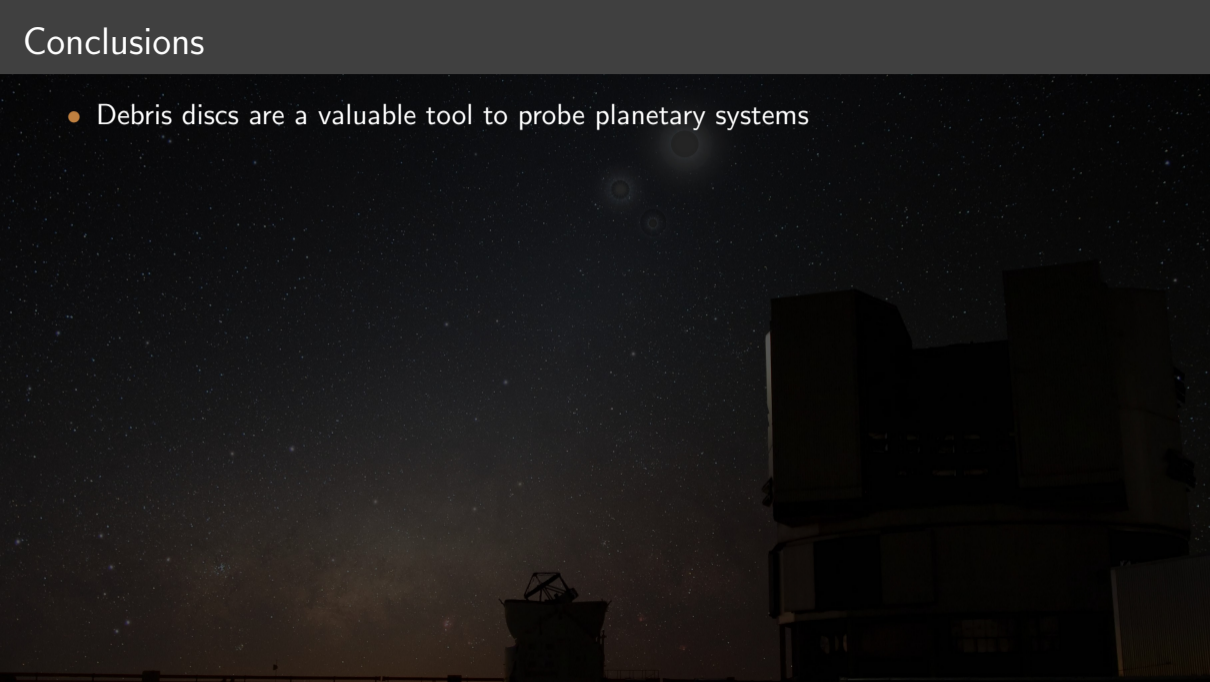


JWST won't find everything!

⇒ Debris will still provide the best constrains on outer planets for years to come

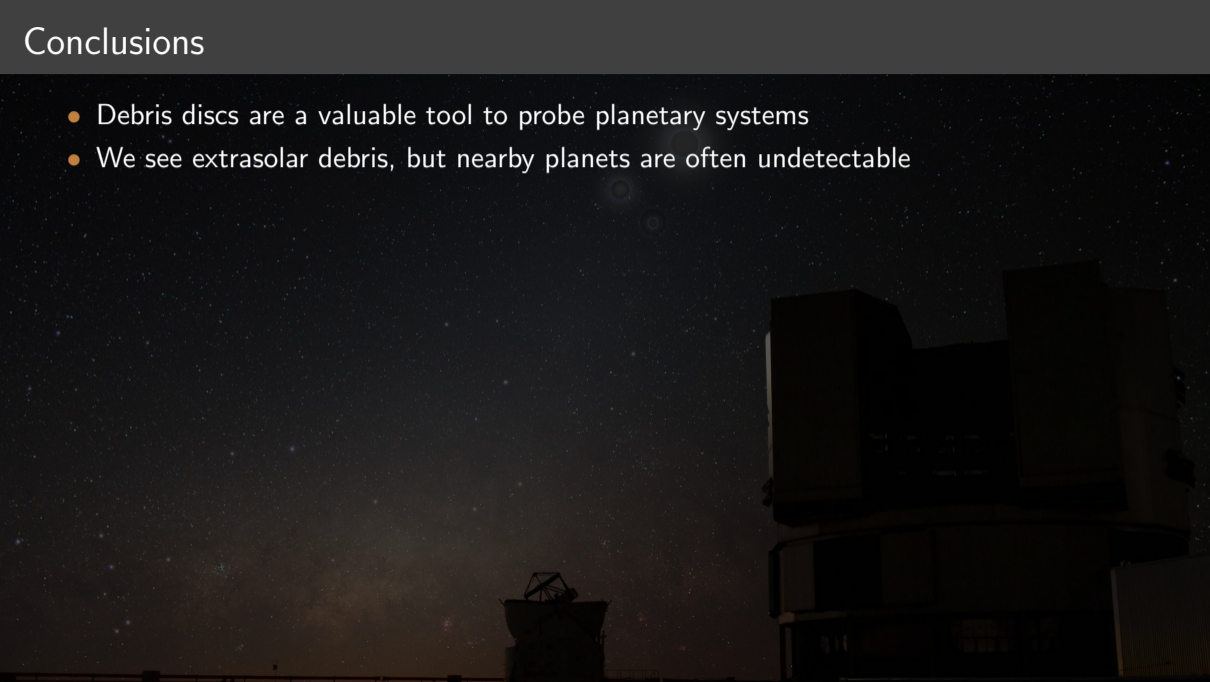
Conclusions

- Debris discs are a valuable tool to probe planetary systems



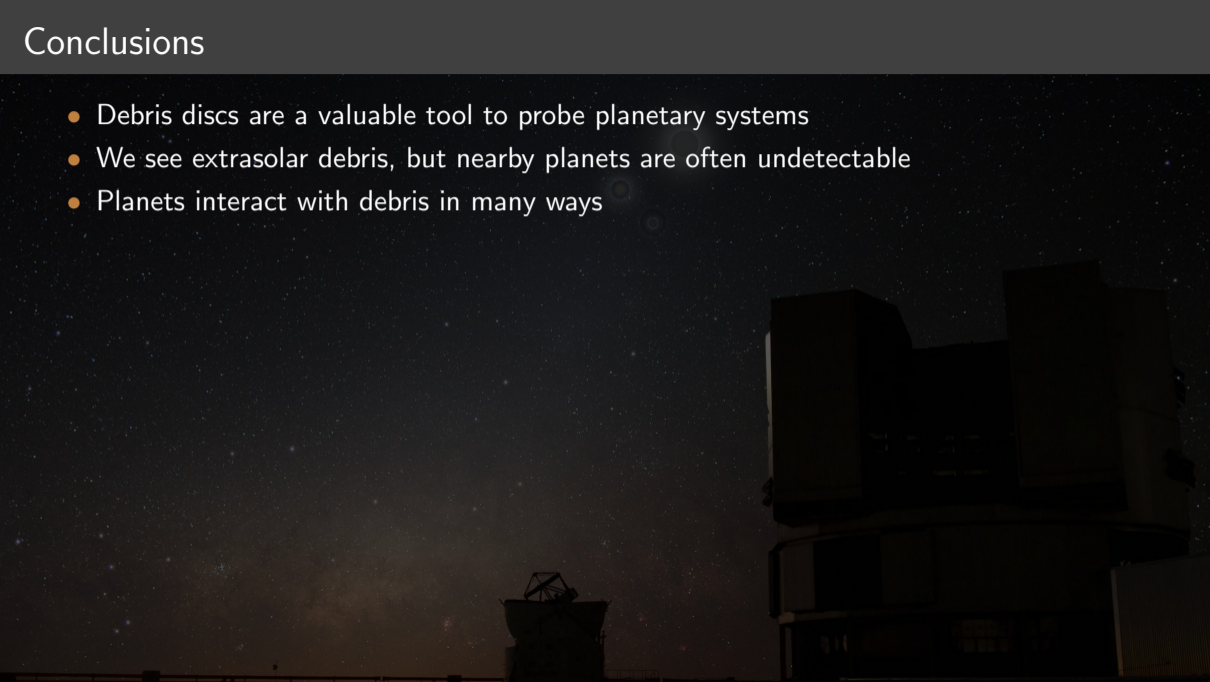
Conclusions

- Debris discs are a valuable tool to probe planetary systems
- We see extrasolar debris, but nearby planets are often undetectable



Conclusions

- Debris discs are a valuable tool to probe planetary systems
- We see extrasolar debris, but nearby planets are often undetectable
- Planets interact with debris in many ways



Conclusions

- Debris discs are a valuable tool to probe planetary systems
- We see extrasolar debris, but nearby planets are often undetectable
- Planets interact with debris in many ways
- Planet parameters can be constrained from debris-disc features

Conclusions

- Debris discs are a valuable tool to probe planetary systems
- We see extrasolar debris, but nearby planets are often undetectable
- Planets interact with debris in many ways
- Planet parameters can be constrained from debris-disc features
- Planets inferred from debris discs are very different to those known

Conclusions

- Debris discs are a valuable tool to probe planetary systems
- We see extrasolar debris, but nearby planets are often undetectable
- Planets interact with debris in many ways
- Planet parameters can be constrained from debris-disc features
- Planets inferred from debris discs are very different to those known
- However, they strongly resemble planets inferred to be forming in protoplanetary discs

Conclusions

- Debris discs are a valuable tool to probe planetary systems
- We see extrasolar debris, but nearby planets are often undetectable
- Planets interact with debris in many ways
- Planet parameters can be constrained from debris-disc features
- Planets inferred from debris discs are very different to those known
- However, they strongly resemble planets inferred to be forming in protoplanetary discs
- *JWST* should detect some (but not all) debris-inferred planets

Conclusions

- Debris discs are a valuable tool to probe planetary systems
- We see extrasolar debris, but nearby planets are often undetectable
- Planets interact with debris in many ways
- Planet parameters can be constrained from debris-disc features
- Planets inferred from debris discs are very different to those known
- However, they strongly resemble planets inferred to be forming in protoplanetary discs
- *JWST* should detect some (but not all) debris-inferred planets
- We are starting to use debris-planet interactions to probe fundamental system properties

Conclusions

- Debris discs are a valuable tool to probe planetary systems
- We see extrasolar debris, but nearby planets are often undetectable
- Planets interact with debris in many ways
- Planet parameters can be constrained from debris-disc features
- Planets inferred from debris discs are very different to those known
- However, they strongly resemble planets inferred to be forming in protoplanetary discs
- *JWST* should detect some (but not all) debris-inferred planets
- We are starting to use debris-planet interactions to probe fundamental system properties

Questions?

Bibliography

- Andrews S. M. et al., 2018, ApJ, 869, L41
Augereau J. C. et al., 2001, A&A, 370, 447
Batygin K., Brown M. E., 2016, AJ, 151, 22
Batygin K., Morbidelli A., 2017, AJ, 154, 229
Bernardinelli P. H. et al., 2020, Planet. Sci. J., 1, 28
Beust H., 2016, A&A, 590, L2
Beust H. et al., 2014, A&A, 561, A43
Booth M. et al., 2023, MNRAS, 521, 6180
Carter A. L. et al., 2021, MNRAS, 501, 1999
Chiang E. et al., 2009, ApJ, 693, 734
Choquet É. et al., 2017, ApJ, 834, L12
Dahlqvist C. H. et al., 2022, arXiv e-prints, arXiv:2208.09204
Faber P., Quillen A. C., 2007, MNRAS, 382, 1823
Farago F., Laskar J., 2010, MNRAS, 401, 1189
Faramaz V. et al., 2015, A&A, 573, A87
Faramaz V. et al., 2014, A&A, 563, A72
Faramaz V. et al., 2019, AJ, 158, 162
Friebe M. F., Pearce T. D., Löhne T., 2022, MNRAS, 512, 4441
Gáspár A., Rieke G., 2020, Proceedings of the National Academy of Science, 117, 9712
Gáspár A. et al., 2023, Nature Astronomy, 7, 790
Geiler F. et al., 2019, MNRAS, 483, 332
Golimowski D. A. et al., 2006, AJ, 131, 3109
Ida S., Larwood J., Burkert A., 2000, ApJ, 528, 351
Janson M. et al., 2012, ApJ, 747, 116
Kalas P. et al., 2008, Science, 322, 1345
Kalas P., Graham J. R., Clampin M., 2005, Nature, 435, 1067
Kalas P. et al., 2013, ApJ, 775, 56
Kennedy G. M. et al., 2012, MNRAS, 421, 2264
Kenyon S. J., Bromley B. C., 2008, ApJS, 179, 451
Kirsh D. R. et al., 2009, Icarus, 199, 197
Krivov A. V. et al., 2007, A&A, 462, 199
Krivov A. V., Wyatt M. C., 2021, MNRAS, 500, 718
Levison H. F. et al., 2008, Icarus, 196, 258
Lodato G. et al., 2019, MNRAS, 486, 453
Marino S., 2021, MNRAS, 503, 5100
Marino S. et al., 2018, MNRAS, 479, 5423
Mouillet D. et al., 1997, MNRAS, 292, 896
Mustill A. J., Wyatt M. C., 2009, MNRAS, 399, 1403
Mustill A. J., Wyatt M. C., 2012, MNRAS, 419, 3074
Napier K. J. et al., 2021, Planet. Sci. J., 2, 59
Nesvorný D., 2015, AJ, 150, 73
Ozernoy L. M. et al., 2000, ApJ, 537, L147
Pearce T. D. et al., 2021, MNRAS, 503, 4767
Pearce T. D. et al., 2022, A&A, 659, A135
Pearce T. D., Wyatt M. C., 2014, MNRAS, 443, 2541
Pearce T. D., Wyatt M. C., 2015, MNRAS, 453, 3329
Quillen A. C., 2006, MNRAS, 372, L14
Sefilian A. A., Rafikov R. R., Wyatt M. C., 2021, ApJ, 910, 13
Sefilian A. A., Rafikov R. R., Wyatt M. C., 2023, ApJ, 954, 100
Shannon A. et al., 2016, MNRAS, 462, L116
Sheppard S. S., Trujillo C., 2016, AJ, 152, 221
Su K. Y. L. et al., 2013, ApJ, 763, 118
Tsiganis K. et al., 2005, Nature, 435, 459
Wisdom J., 1980, AJ, 85, 1122
Wyatt M. C., 2006, ApJ, 639, 1153
Yelverton B. et al., 2019, MNRAS, 488, 3588

VLT Image: ESO

Additional slides



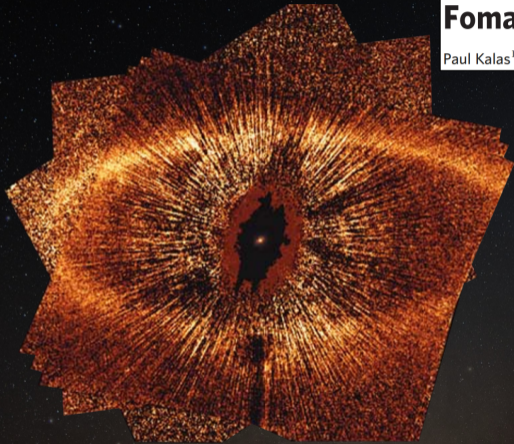
It's not always straightforward! Case study: Fomalhaut



It's not always straightforward! Case study: **Fomalhaut**

A planetary system as the origin of structure in Fomalhaut's dust belt

Paul Kalas¹, James R. Graham¹ & Mark Clampin²



It's not always straightforward! Case study: **Fomalhaut**

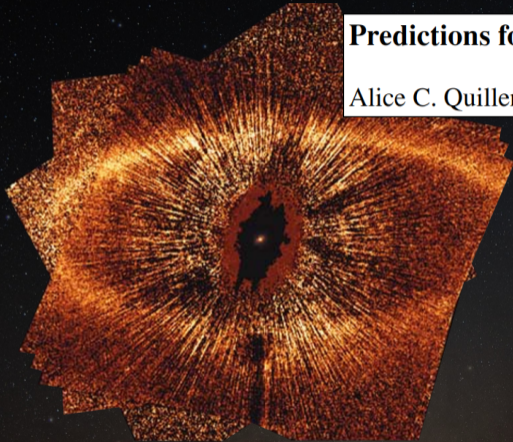
A planetary system as the origin of structure in
Fomalhaut's dust belt

Paul Kalas¹, James R. Graham¹ & Mark Clampin²

2005

Predictions for a planet just inside Fomalhaut's eccentric ring

Alice C. Quillen[★]



It's not always straightforward! Case study: Fomalhaut

A planetary system as the origin of structure in Fomalhaut's dust belt

Paul Kalas¹, James R. Graham¹ & Mark Clampin²

2005

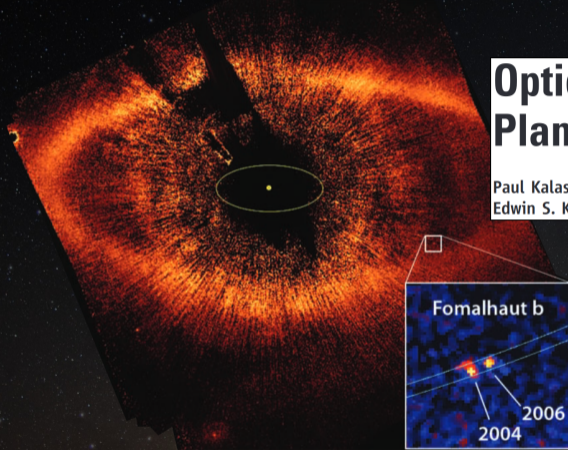
Predictions for a planet just inside Fomalhaut's eccentric ring

Alice C. Quillen^{*}

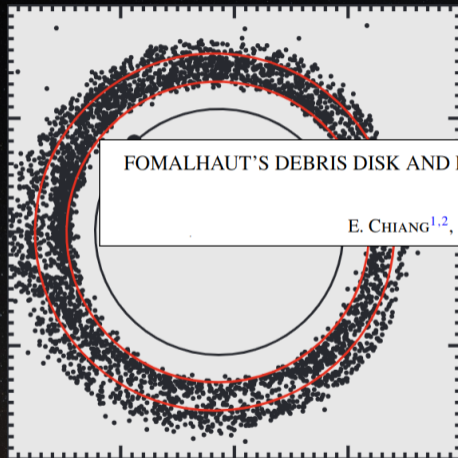
2006

Optical Images of an Exosolar Planet 25 Light-Years from Earth

Paul Kalas,^{1*} James R. Graham,¹ Eugene Chiang,^{1,2} Michael P. Fitzgerald,³ Mark Clampin,⁴ Edwin S. Kite,² Karl Stapelfeldt,⁵ Christian Marois,⁶ John Krist⁵



It's not always straightforward! Case study: Fomalhaut



A planetary system as the origin of structure in Fomalhaut's dust belt

Paul Kalas¹, James R. Graham¹ & Mark Clampin²

2005

Predictions for a planet just inside Fomalhaut's eccentric ring

Alice C. Quillen^{*}

2006

Optical Images of an Exosolar Planet 25 Light-Years from Earth

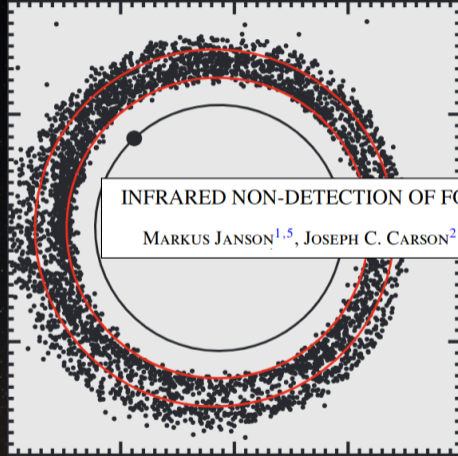
Paul Kalas,^{1*} James R. Graham,¹ Eugene Chiang,^{1,2} Michael P. Fitzgerald,³ Mark Clampin,⁴ Edwin S. Kite,² Karl Stapelfeldt,⁵ Christian Marois,⁶ John Krist⁷

2008

FOMALHAUT'S DEBRIS DISK AND PLANET: CONSTRAINING THE MASS OF FOMALHAUT B FROM DISK MORPHOLOGY

E. CHIANG^{1,2}, E. KITE², P. KALAS¹, J. R. GRAHAM¹, AND M. CLAMPIN³

It's not always straightforward! Case study: Fomalhaut



INFRARED NON-DETECTION OF FOMALHAUT b: IMPLICATIONS FOR THE PLANET INTERPRETATION

MARKUS JANSON^{1,5}, JOSEPH C. CARSON², DAVID LAFRENIÈRE³, DAVID S. SPIEGEL⁴, JOHN R. BENT², AND PALMER WONG²

A planetary system as the origin of structure in Fomalhaut's dust belt

Paul Kalas¹, James R. Graham¹ & Mark Clampin²

2005

Predictions for a planet just inside Fomalhaut's eccentric ring

Alice C. Quillen^{*}

2006

Optical Images of an Exosolar Planet 25 Light-Years from Earth

Paul Kalas,^{1*} James R. Graham,² Eugene Chiang,^{1,2} Michael P. Fitzgerald,³ Mark Clampin,⁴ Edwin S. Kite,⁵ Karl Stapelfeldt,⁶ Christian Marois,⁶ John Krist⁷

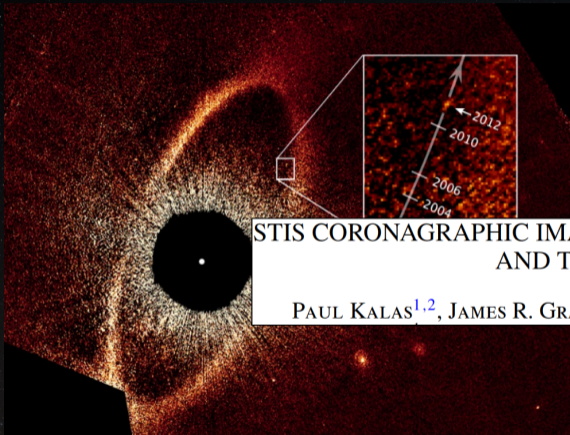
2008

FOMALHAUT'S DEBRIS DISK AND PLANET: CONSTRAINING THE MASS OF FOMALHAUT b FROM DISK MORPHOLOGY

B. Carson^{2,5}, E. Kite⁵, P. Kalas¹, J. R. Graham¹, and M. Clampin²

2009

It's not always straightforward! Case study: Fomalhaut



A planetary system as the origin of structure in Fomalhaut's dust belt

Paul Kalas¹, James R. Graham¹ & Mark Clampin²

2005

Predictions for a planet just inside Fomalhaut's eccentric ring

Alice C. Quillen^{*}

2006

Optical Images of an Exosolar Planet 25 Light-Years from Earth

Paul Kalas,^{1*} James R. Graham,² Eugene Chiang,^{1,2} Michael P. Fitzgerald,³ Mark Clampin,⁴ Edwin S. Kite,² Karl Stapelfeldt,⁵ Christian Marois,⁶ John Krist⁷

2008

FOMALHAUT'S DEBRIS DISK AND PLANET: CONSTRAINING THE MASS OF FOMALHAUT b FROM DISK MORPHOLOGY

B. Crank^{1,2}, E. Kite², P. Kalas¹, J. R. Graham¹, and M. Clampin⁴

2009

INFRARED NON-DETECTION OF FOMALHAUT b: IMPLICATIONS FOR THE PLANET INTERPRETATION

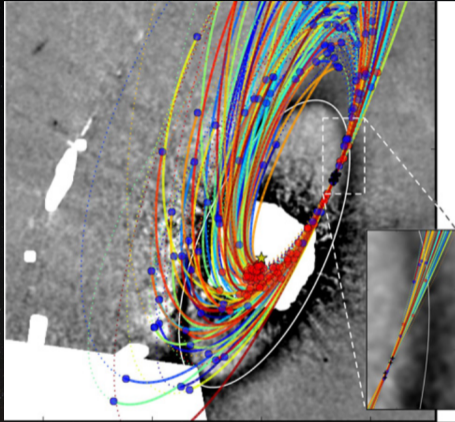
Markis Fossum¹, James C. Casali², David Lattese³, David S. Storch⁴, Ben B. Rea⁵, and Patrick Wong⁶

2012

STIS CORONAGRAPHIC IMAGING OF FOMALHAUT: MAIN BELT STRUCTURE AND THE ORBIT OF FOMALHAUT *b*

PAUL KALAS^{1,2}, JAMES R. GRAHAM^{1,3}, MICHAEL P. FITZGERALD⁴, AND MARK CLAMPIN⁵

It's not always straightforward! Case study: Fomalhaut



A planetary system as the origin of structure in Fomalhaut's dust belt

Paul Kalas¹, James R. Graham¹, & Mark Clampin²

2005

Predictions for a planet just inside Fomalhaut's eccentric ring

Alice C. Quillen^{*}

2006

Optical Images of an Exosolar Planet 25 Light-Years from Earth

Paul Kalas,^{1*} James R. Graham,¹ Eugene Chiang,^{1,2} Michael P. Fitzgerald,³ Mark Clampin,⁴ Edwin S. Kite,⁵ Karl Stapelfeldt,⁶ Christian Marois,⁶ John Krist⁷

2008

FOMALHAUT'S DEBRIS DISK AND PLANET: CONSTRAINING THE MASS OF FOMALHAUT b FROM DISK MORPHOLOGY

B. CRAND^{1,2}, E. KITE¹, P. KALAS¹, J. R. GRAHAM¹, AND M. CLAMPIN³

2009

INFRARED NON-DETECTION OF FOMALHAUT b: IMPLICATIONS FOR THE PLANET INTERPRETATION

MARKUS LÖNNER¹, JAMES C. CASSELL², DAVID LAFRENIÈRE³, DAVID S. SPOCKE⁴, BART B. REED⁵, AND PATRICK WONG⁶

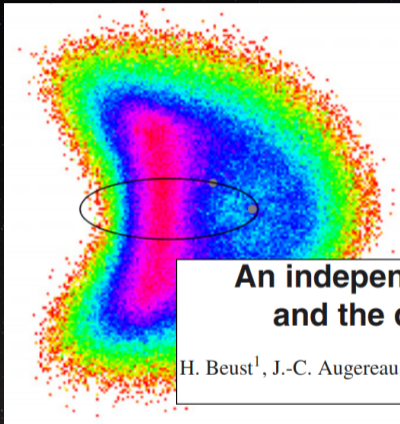
2012

STIS CORONAGRAPHIC IMAGING OF FOMALHAUT: MAIN BELT STRUCTURE AND THE ORBIT OF FOMALHAUT b

PAUL KALAS^{1,2}, JAMES R. GRAHAM^{1,3}, MICHAEL P. FITZGERALD⁴, AND MARK CLAMPIN⁵

2013

It's not always straightforward! Case study: Fomalhaut



A planetary system as the origin of structure in Fomalhaut's dust belt

Paul Kalas¹, James R. Graham¹ & Mark Clampin²

2005

Predictions for a planet just inside Fomalhaut's eccentric ring

Alice C. Quillen*

2006

Optical Images of an Exosolar Planet 25 Light-Years from Earth

Paul Kalas,^{1*} James R. Graham,¹ Eugene Chiang,^{1,2} Michael P. Fitzgerald,³ Mark Clampin,⁴ Edwin S. Kite,² Karl Stapelfeldt,⁵ Christian Marois,⁶ John Krist⁷

2008

FOMALHAUT'S DEBRIS DISK AND PLANET: CONSTRAINING THE MASS OF FOMALHAUT b FROM DISK MORPHOLOGY

B. CHANG^{1,2}, E. KITE², P. KALAS¹, J. R. GRAHAM¹, AND M. CLAMPIN⁴

2009

INFRARED NON-DETECTION OF FOMALHAUT b: IMPLICATIONS FOR THE PLANET INTERPRETATION

MARKS LUSSEN¹, JAMES C. CASSELL², DAVID LAFRENIERE³, DAVID S. SPOCK⁴, JAMES B. BEAL⁵, AND PATRICK WONG⁶

2012

STIS CORONAGRAPHIC IMAGING OF FOMALHAUT: MAIN BELT STRUCTURE AND THE ORBIT OF FOMALHAUT b

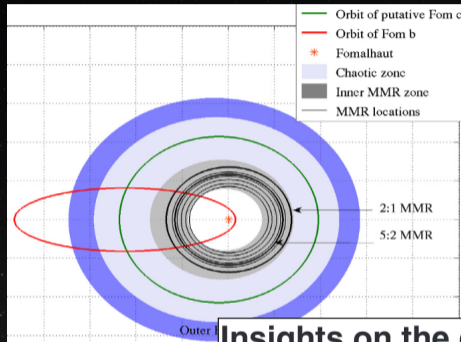
PAUL KALAS^{1,2}, JAMES R. GRAHAM^{1,3}, MICHAEL P. FITZGERALD⁴, AND MARK CLAMPIN⁵

2013

An independent determination of Fomalhaut b's orbit and the dynamical effects on the outer dust belt

H. Beust¹, J.-C. Augereau¹, A. Bonsor¹, J. R. Graham³, P. Kalas³, J. Lebreton¹, A.-M. Lagrange¹, S. Ertel¹, V. Faramaz¹, and P. Thébaud²

It's not always straightforward! Case study: Fomalhaut



A planetary system as the origin of structure in Fomalhaut's dust belt

Paul Kalas¹, James R. Graham¹ & Mark Clampin²

2005

Predictions for a planet just inside Fomalhaut's eccentric ring

Alice C. Quillen*

2006

Optical Images of an Exosolar Planet 25 Light-Years from Earth

Paul Kalas,^{1*} James R. Graham,¹ Eugene Chiang,^{1,2} Michael P. Fitzgerald,³ Mark Clampin,⁴ Edwin S. Kite,⁵ Karl Stapelfeldt,⁶ Christian Marois,⁶ John Krist⁷

2008

FOMALHAUT'S DEBRIS DISK AND PLANET: CONSTRAINING THE MASS OF FOMALHAUT b FROM DISK MORPHOLOGY

B. Craven^{1,2}, E. Kite¹, P. Kalas¹, J. R. Graham¹, and M. Clampin³

2009

INFRARED NON-DETECTION OF FOMALHAUT b: IMPLICATIONS FOR THE PLANET INTERPRETATION

Markis Jovanović¹, James C. Casse², David Laffont^{3,4}, David S. Storch⁵, Jean-Benoît Réa⁶, and Patrick Woit⁷

2012

STIS CORONAGRAPHIC IMAGING OF FOMALHAUT: MAIN BELT STRUCTURE AND THE ORBIT OF FOMALHAUT b

PAUL KALAS^{1,2}, JAMES R. GRAHAM^{1,3}, MICHAEL P. FITZGERALD⁴, AND MARK CLAMPIN⁵

2013

An independent determination of Fomalhaut b's orbit and the dynamical effects on the outer dust belt

H. Beust¹, J.-C. Augereau¹, A. Bosser¹, J. R. Graham¹, P. Kalas¹, J. Lebreton¹, A.-M. Lagrange¹, S. Eiroa², V. Faramaz¹, and P. Thébaud¹

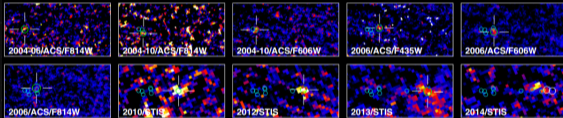
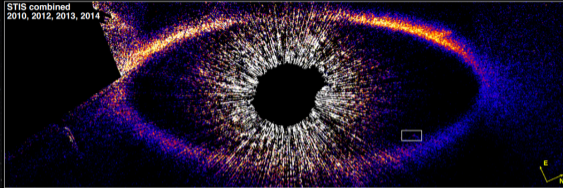
2014

Insights on the dynamical history of the Fomalhaut system

Investigating the Fom c hypothesis

V. Faramaz^{1,2}, H. Beust^{1,2}, J.-C. Augereau^{1,2}, P. Kalas³, and J. R. Graham³

It's not always straightforward! Case study: Fomalhaut



A planetary system as the origin of structure in Fomalhaut's dust belt

Paul Kalas¹, James R. Graham² & Mark Clampin²

2005

Predictions for a planet just inside Fomalhaut's eccentric ring

Alice C. Quillen^{*}

2006

Optical Images of an Exosolar Planet 25 Light-Years from Earth

Paul Kalas,^{1*} James R. Graham,² Eugene Chiang,^{1,2} Michael P. Fitzgerald,³ Mark Clampin,² Edwin S. Kite,² Karl Stapelfeldt,³ Christian Marois,⁴ John Krist¹

2008

FOMALHAUT'S DEBRIS DISK AND PLANET: CONSTRAINING THE MASS OF FOMALHAUT b FROM DISK MORPHOLOGY

E. Chiang^{1,2}, E. Kite², P. Kalas¹, J. R. Graham², and M. Clampin²

2009

INFRARED NON-DETECTION OF FOMALHAUT b: IMPLICATIONS FOR THE PLANET INTERPRETATION

Markis Jovanović,¹ Joana C. Casasol,² David Lazzarini,² David S. Stolze,² Ivan B. Bica,² and Patrizia Woit²

2012

STIS CORONAGRAPHIC IMAGING OF FOMALHAUT: MAIN BELT STRUCTURE AND THE ORBIT OF FOMALHAUT b

PAUL KALAS^{1,2}, JAMES R. GRAHAM², MICHAEL P. FITZGERALD³, AND MARK CLAMPIN²

2013

An independent determination of Fomalhaut b's orbit and the dynamical effects on the outer dust belt

H. Bess¹, J.-C. Augereau¹, A. Bosser¹, J. R. Graham², P. Kalas¹, J. Lebreton¹, A.-M. Lagrange¹, S. Eiroa¹, V. Farnaud¹, and P. Thébaud¹

2014

Insights on the dynamical history of the Fomalhaut system

Investigating the Fom c hypothesis

V. Farnaud^{1,2}, H. Bess^{1,2}, J.-C. Augereau^{1,2}, P. Kalas¹, and J. R. Graham²

2015

New HST data and modeling reveal a massive planetesimal collision around Fomalhaut

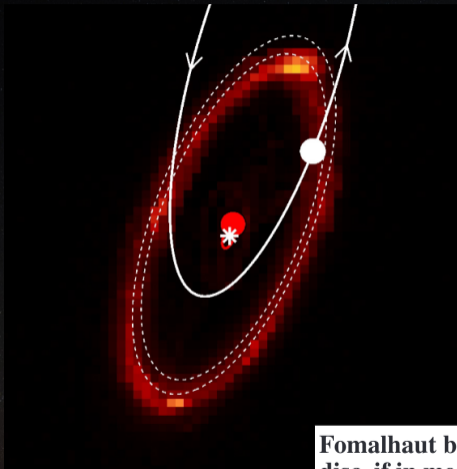
András Gáspár^{a,1} and George H. Rieke^a

2020

New HST data and modeling reveal a massive planetesimal collision around Fomalhaut

András Gáspár^{a,1} and George H. Rieke^a

It's not always straightforward! Case study: Fomalhaut



A planetary system as the origin of structure in Fomalhaut's dust belt

Paul Kalas¹, James R. Graham¹ & Mark Clampin²

2005

Predictions for a planet just inside Fomalhaut's eccentric ring

Alice C. Quillen*

2006

Optical Images of an Exosolar Planet 25 Light-Years from Earth

Paul Kalas,^{1*} James R. Graham,¹ Eugene Chiang,^{1,2} Michael P. Fitzgerald,³ Mark Clampin,⁴ Edwin S. Kite,² Karl Stapelfeldt,⁵ Christian Marois,⁶ John Krist¹

2008

FOMALHAUT'S DEBRIS DISK AND PLANET: CONSTRAINING THE MASS OF FOMALHAUT b FROM DISK MORPHOLOGY

B. CHANG^{1,2}, E. KITE¹, P. KALAS¹, J. R. GRAHAM¹, AND M. CLAMPIN²

2009

INFRARED NON-DETECTION OF FOMALHAUT b: IMPLICATIONS FOR THE PLANET INTERPRETATION

MARKS LUSSEN¹, JAMES C. CASANO¹, DAVID LAFRENIERE², DAVID S. SPOCK¹, JAMES B. BEUST¹, AND PEDRO WONG²

2012

STIS CORONAGRAPHIC IMAGING OF FOMALHAUT: MAIN BELT STRUCTURE AND THE ORBIT OF FOMALHAUT b

PAUL KALAS^{1,2}, JAMES R. GRAHAM^{1,3}, MICHAEL P. FITZGERALD⁴, AND MARK CLAMPIN⁵

2013

An independent determination of Fomalhaut b's orbit and the dynamical effects on the outer dust belt

H. Beust¹, J.-C. Augereau¹, A. Bosser¹, J. R. Graham¹, P. Kalas¹, J. Lebreton¹, A.-M. Lagrange¹, S. Eiroa¹, V. Faramaz¹, and P. Thébaud¹

2014

Insights on the dynamical history of the Fomalhaut system

Investigating the Fom c hypothesis

V. Faramaz^{1,2}, H. Beust^{1,2}, J.-C. Augereau^{1,2}, P. Kalas¹, and J. R. Graham¹

2015

New HST data and modeling reveal a massive planetesimal collision around Fomalhaut

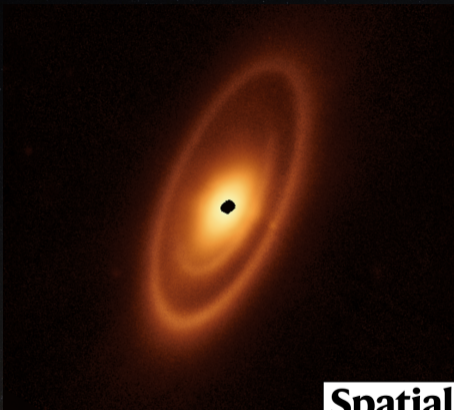
Andrés Gáspár¹ and George H. Rieke¹

2020

Fomalhaut b could be massive and sculpting the narrow, eccentric debris disc, if in mean-motion resonance with it

Tim D. Pearce¹,^{1*} Hervé Beust,² Virginie Faramaz,³ Mark Booth,¹ Alexander V. Krivov,¹ Torsten Löhne¹ and Pedro P. Poblete¹

It's not always straightforward! Case study: Fomalhaut



A planetary system as the origin of structure in Fomalhaut's dust belt

Paul Kalas¹, James R. Graham¹ & Mark Clampin²

2005

Predictions for a planet just inside Fomalhaut's eccentric ring

Alice C. Quillen*

2006

Optical Images of an Exosolar Planet 25 Light-Years from Earth

Paul Kalas,^{1*} James R. Graham,¹ Eugene Chiang,^{1,2} Michael P. Fitzgerald,³ Mark Clampin,⁴ Edwin S. Kite,² Karl Stapelfeldt,⁵ Christian Marois,⁶ John Krist¹

2008

FOMALHAUT'S DEBRIS DISK AND PLANET: CONSTRAINING THE MASS OF FOMALHAUT b FROM DISK MORPHOLOGY

B. CHANG^{1,2}, E. KITE², P. KALAS¹, J. R. GRAHAM¹, AND M. CLAMPIN⁴

2009

INFRARED NON-DETECTION OF FOMALHAUT b: IMPLICATIONS FOR THE PLANET INTERPRETATION

MARIN LUSSEN¹, JAMES C. CASSELL², DAVID LAFRENIERE³, DAVID S. SPOCK⁴, JESS B. BEAL⁵, AND PAULINA WONG²

2012

STIS CORONAGRAPHIC IMAGING OF FOMALHAUT: MAIN BELT STRUCTURE AND THE ORBIT OF FOMALHAUT b

PAUL KALAS^{1,2}, JAMES R. GRAHAM^{1,3}, MICHAEL P. FITZGERALD⁴, AND MARK CLAMPIN⁵

2013

An independent determination of Fomalhaut b's orbit and the dynamical effects on the outer dust belt

H. BEAL¹, J.-C. AUGEREAU¹, A. BOSSOY¹, J. R. GRAHAM¹, P. KALAS¹, J. LEBRETTE¹, A.-M. LAGRANGE¹, S. ERIC¹, V. FARINAZI², AND P. THIBAUD²

2014

Insights on the dynamical history of the Fomalhaut system

Investigating the Fom c hypothesis

V. FARINAZI^{1,2}, H. BEAL^{1,2}, J.-C. AUGEREAU^{1,2}, P. KALAS¹, AND J. R. GRAHAM¹

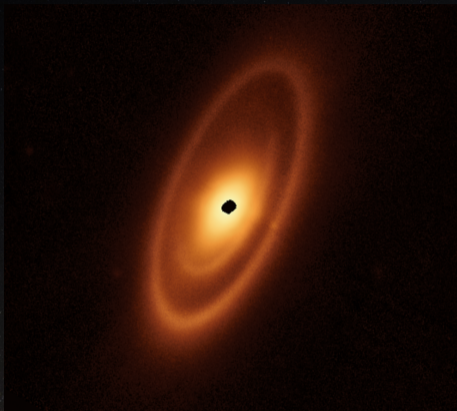
2015

Now HST data and modeling reveal a massive

Spatially resolved imaging of the inner Fomalhaut disk using JWST/MIRI

Andr s G sp r¹ ✉, Schuyler Grace Wolff¹, George H. Rieke¹,
Jarron M. Leisenring¹, Jane Morrison¹, Kate Y. L. Su¹, Kimberly Ward-Duong²,
Jonathan Aguilar³, Marie Ygouf⁴, Charles Beichman⁴, Jorge Llop-Sayson⁵
& Geoffrey Bryden⁴

It's not always straightforward! Case study: Fomalhaut



A planetary system as the origin of structure in Fomalhaut's dust belt

Paul Kalas¹, James R. Graham¹ & Mark Clampin²

2005

Predictions for a planet just inside Fomalhaut's eccentric ring

Alice C. Quillen^{*}

2006

Optical Images of an Exosolar Planet 25 Light-Years from Earth

Paul Kalas,^{1*} James R. Graham,¹ Eugene Chiang,^{1,2} Michael P. Fitzgerald,³ Mark Clampin,⁴ Edwin S. Kite,² Karl Stapelfeldt,⁵ Christian Marois,⁶ John Krist¹

2008

FOMALHAUT'S DEBRIS DISK AND PLANET: CONSTRAINING THE MASS OF FOMALHAUT b FROM DISK MORPHOLOGY

B. CHANG^{1,2}, E. KITE², P. KALAS¹, J. R. GRAHAM¹, AND M. CLAMPIN⁴

2009

INFRARED NON-DETECTION OF FOMALHAUT b: IMPLICATIONS FOR THE PLANET INTERPRETATION

MARIN LISOZI^{1,2}, JAMES C. CASSELL¹, DAVID LAFRENIERE¹, DAVID S. SPOCK¹, IAN B. BEAU¹, AND PALAK WONG¹

2012

STIS CORONAGRAPHIC IMAGING OF FOMALHAUT: MAIN BELT STRUCTURE AND THE ORBIT OF FOMALHAUT b

PAUL KALAS^{1,2}, JAMES R. GRAHAM^{1,3}, MICHAEL P. FITZGERALD⁴, AND MARK CLAMPIN⁵

2013

An independent determination of Fomalhaut b's orbit and the dynamical effects on the outer dust belt

H. Beau¹, J.-C. Augereau¹, A. Bosser¹, J. R. Graham¹, P. Kalas¹, J. Lebreton¹, A.-M. Lagrange¹, S. Eiroa¹, V. Faramaz¹, and P. Thébaud¹

2014

Insights on the dynamical history of the Fomalhaut system

Investigating the Fom c hypothesis

V. Faramaz^{1,2}, H. Beau^{1,2}, J.-C. Augereau^{1,2}, P. Kalas¹, and J. R. Graham¹

2015

New HST data and modeling reveal a massive planetesimal collision around Fomalhaut

Andris Gáspár¹ and George H. Rieke¹

2020

Fomalhaut b could be massive and sculpting the narrow, eccentric debris disc, if in mean-motion resonance with it

Tim D. Pearce^{1,2}, Hervé Beust¹, Virginie Faramaz¹, Mark Booth¹, Alexander V. Krivov¹, Torsten Löhne¹ and Pedro P. Pohlke¹

2021

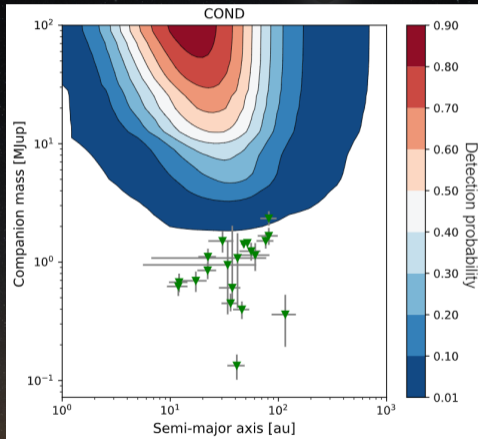
Spatially resolved imaging of the inner Fomalhaut disk using JWST/MIRI

Andris Gáspár¹, Shelley Grace Hurler¹, George H. Rieke¹, James M. Leino¹, Jesse Morzinski¹, Kate V. Lo¹, Kimberly Ward-Duong¹, Jonathan Aguilar¹, Maria Tyska¹, Charles Bell¹, Jorge López-Soto¹ & Geoffrey Bryden¹

2023

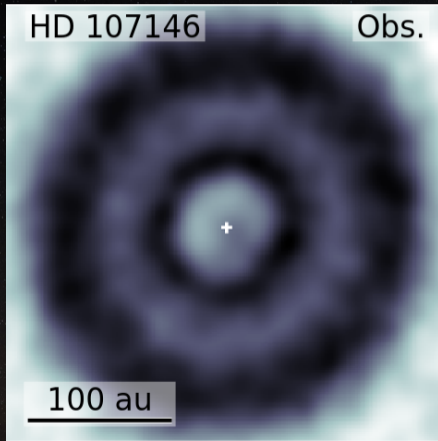
Future planet detections

SPHERE is getting close too!



Evolutionary histories of planetary systems

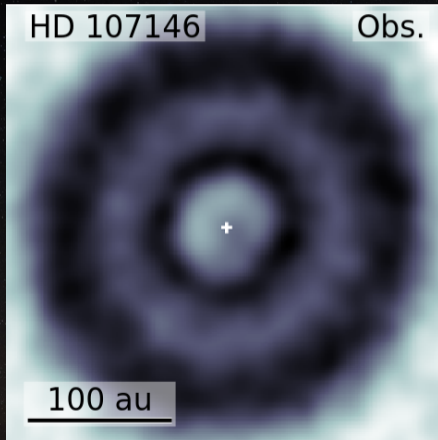
HD 107146



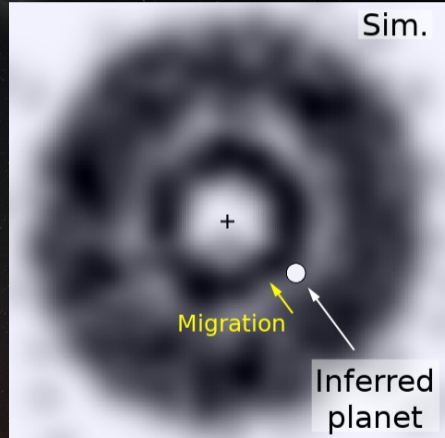
ALMA observation: ?

Evolutionary histories of planetary systems

HD 107146



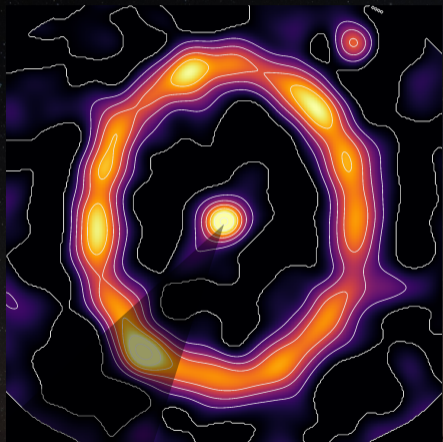
ALMA observation: ?



Simulation: Friebe, Pearce & Löhne 2022

Evolutionary histories of planetary systems

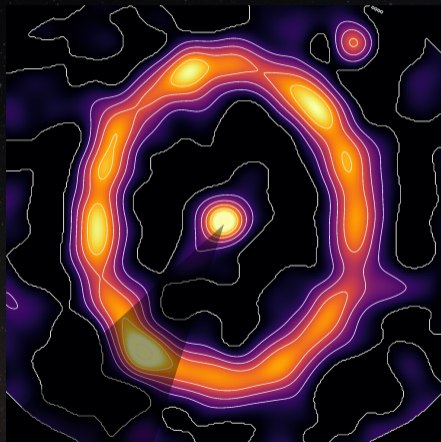
ϵ Eri



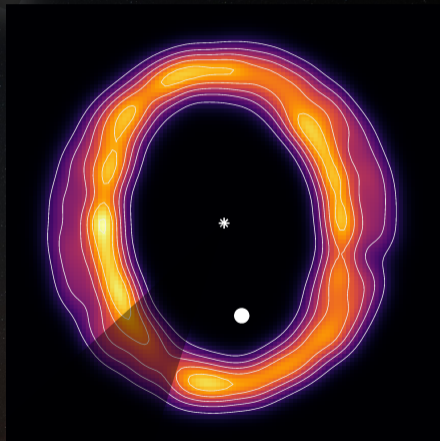
ALMA observation

Evolutionary histories of planetary systems

ϵ Eri



ALMA observation



Simulation

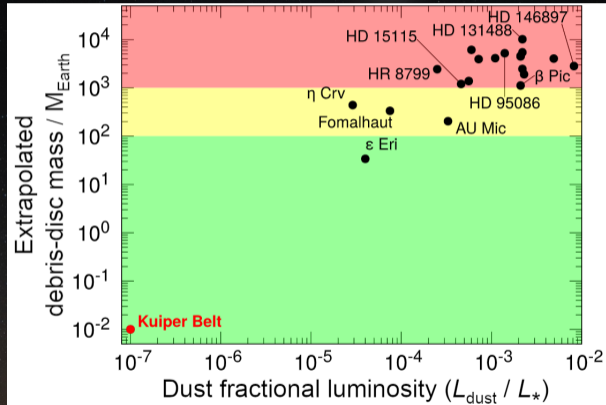
Debris-disc masses

⇒ 'Debris-disc mass problem'



Debris-disc masses

⇒ 'Debris-disc mass problem'



Adapted from Krivov & Wyatt 2021

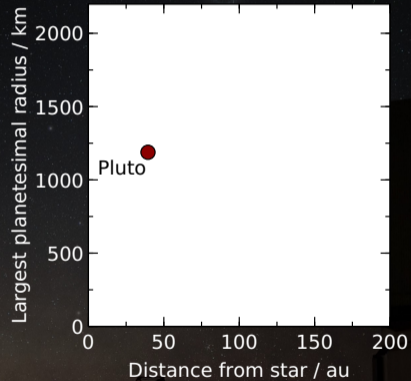
Debris-disc masses

How large are primordial planetesimals?



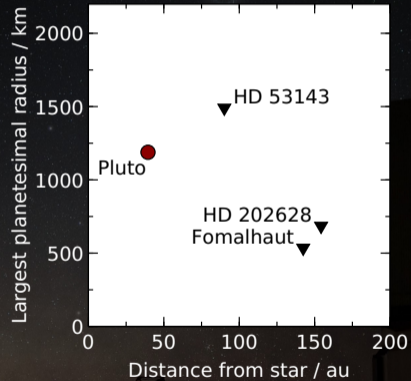
Debris-disc masses

How large are primordial planetesimals?

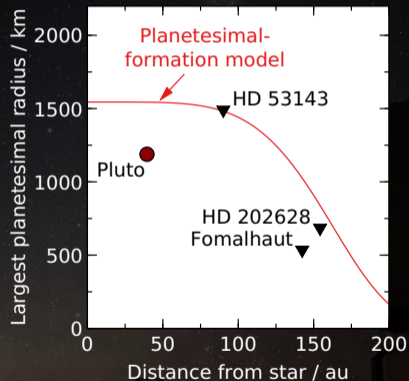


Debris-disc masses

How large are primordial planetesimals?

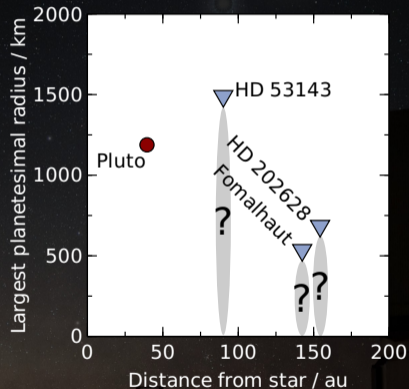


How large are primordial planetesimals?



Debris-disc masses

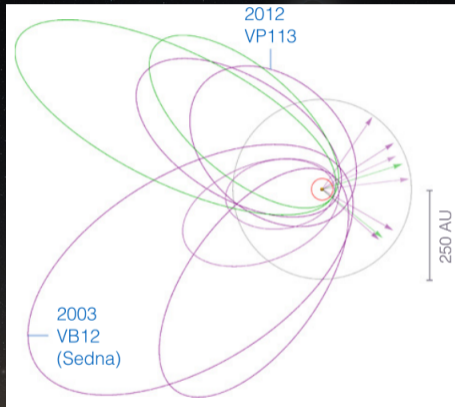
How large are primordial planetesimals?



⇒ Debris-disc masses would **directly probe primordial planetesimal sizes**

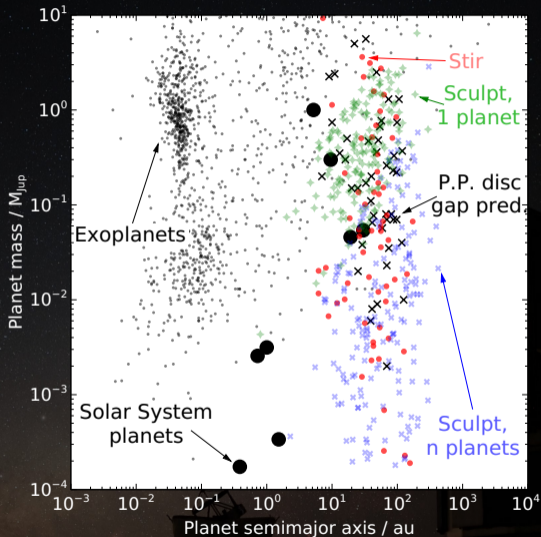
It's not always straightforward! II

Planet 9

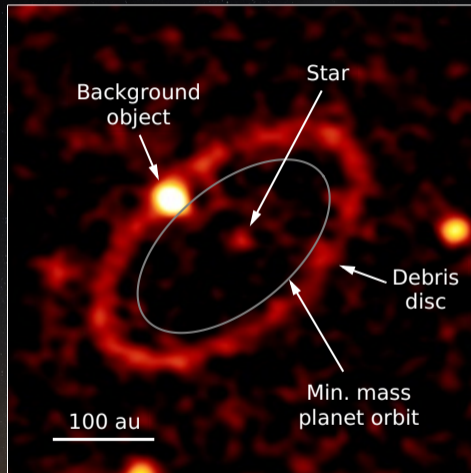


Batygin & Brown 2016

Comparing planet populations

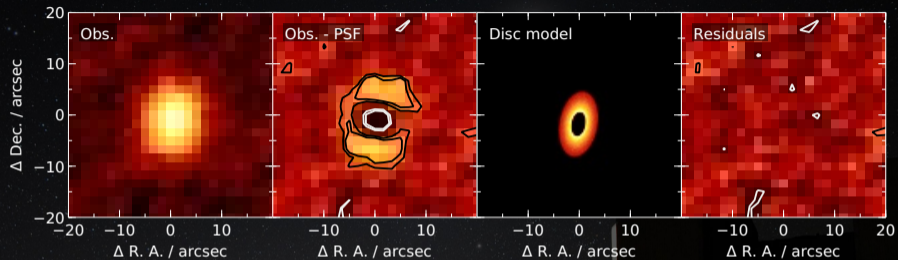


Debris-disc data



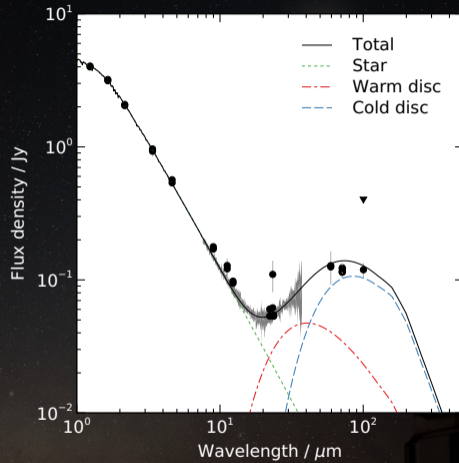
Not all disc data are equal! ALMA is best

Debris-disc data



Not all disc data are equal! ALMA is best, then *Herschel*

Debris-disc data



Not all disc data are equal! ALMA is best, then *Herschel*, then SED