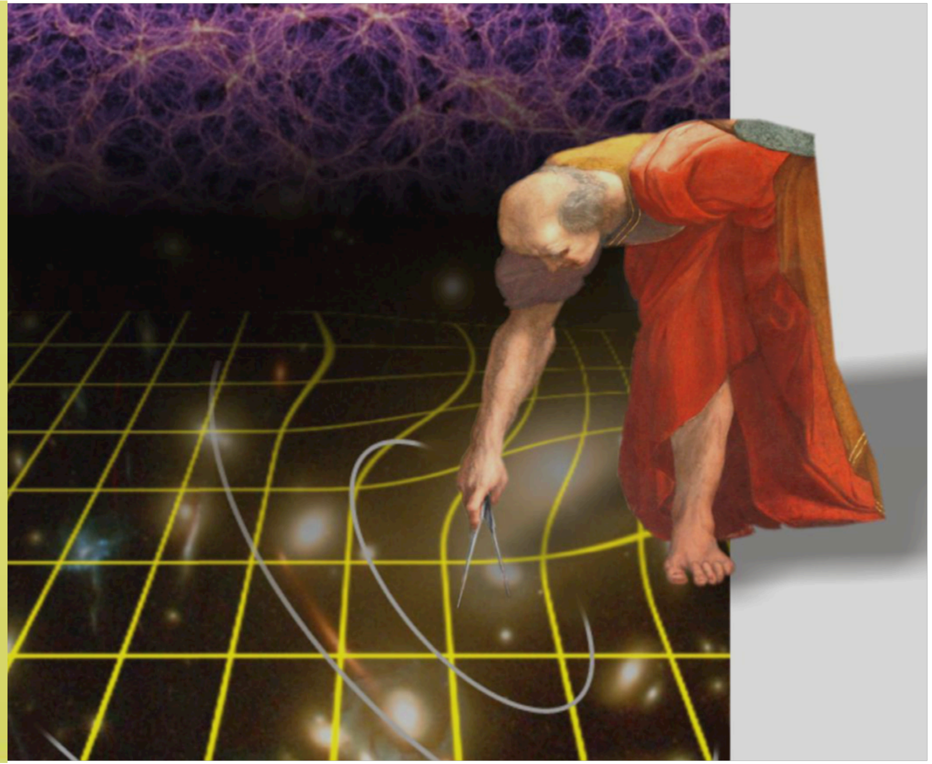
100 Years of Gravitational Lensing

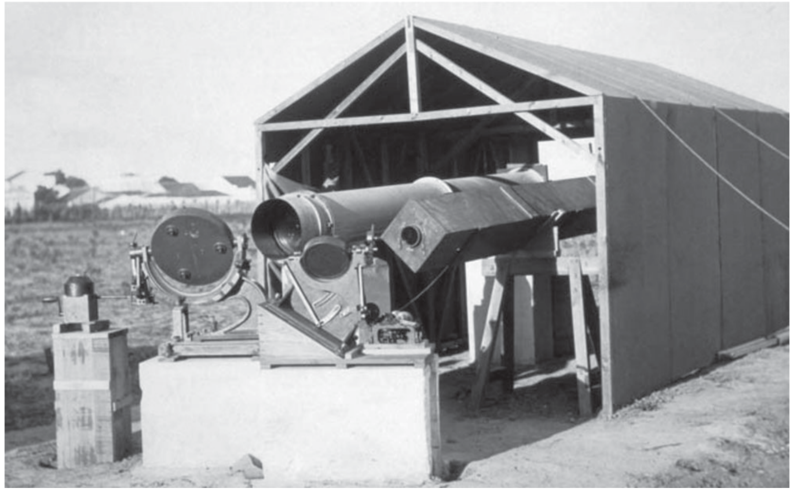
Ismael Tereno
(IA - FCUL)

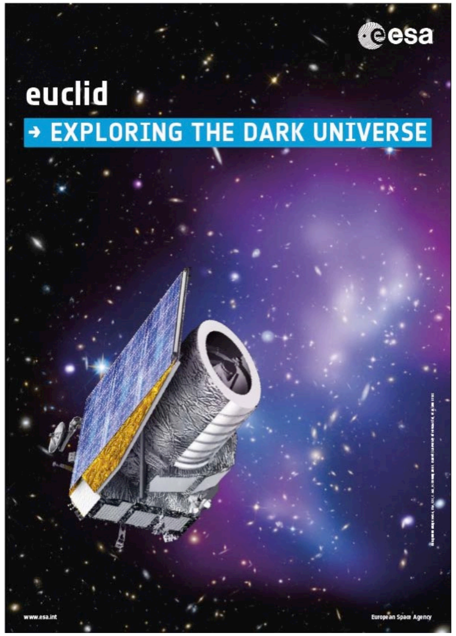
Príncipe, 27 May 2019

from Eddington to Euclid



100 Years of Gravitational Lensing





1919 ⟷ 2019

Paradigm shifting theory (General Relativity)

→ needs to be tested with observations

Paradigm shifting observations (Acceleration of the Universe)

→ need independent observations to understand if GR needs to be modified

0 Light deflection in a gravitational field

1 1919: the Eclipse expedition

2 Gravitational Lensing

3 2019: the Euclid space mission

0

Light deflection in a gravitational field:

the basic Gravitational Lensing effect

Einstein 1911, Annalen der Physik

"On the influence of gravity on the propagation of light "

4. *Über den Einfluß der Schwerkraft auf die Ausbreitung des Lichtes;*
von A. Einstein.

Die Frage, ob die Ausbreitung des Lichtes durch die Schwere beinflußt wird, habe ich schon an einer vor 3 Jahren erschienenen Abhandlung zu beantworten gesucht.[1]) Ich komme

Application to the light deflection near the Sun

Discussion of the problem based on the **Equivalence Principle**

Gravitational field ←→ Acceleration of the reference system

The principle of relativity also applies to systems that are accelerated relative to one another

Bern
1907

I was sitting in a chair in the patent office in Bern when all of a sudden a thought occurred to me: 'If a person falls freely he will not feel his own weight'. I was startled. This simple thought made a deep impression upon me. It impelled me towards a theory of gravitation.

The happiest thought
(Einstein's apple)

Photon travel time from ceiling to floor t = h/c
Floor's velocity increased by g h/c
Frequency shift Δν/ν = Δv/c = gh/c^2
Time dilation Δt/t = gh/c^2
Equivalence principle → time dilation = ΔΨ/c^2

Minkowski space-time in an accelerated frame

$$ds^2 = -\left(1 + \frac{2\Psi}{c^2}\right) c^2 dt^2 + dx^2$$

Travelling time of a light ray computed from

$$\frac{cdt}{dx} = \left(1 + 2\Psi/c^2\right)^{-1/2} \approx 1 - \frac{\Psi}{c^2}$$

Speed of light decreases in the gravitational field ($\Psi < 0$), there is an effective refraction index n = c/v > 1

$$\frac{v}{c} \approx 1 + \frac{\Psi}{c^2}$$

Koordinatenursprung die Zeit gemessen wird. Nennen wir c_0 die Lichtgeschwindigkeit im Koordinatenanfangspunkt, so wird daher die Lichtgeschwindigkeit c in einem Orte vom Gravitationspotential Φ durch die Beziehung

(3) $$c = c_0\left(1 + \frac{\Phi}{c^2}\right)$$

With a non-uniform gravitational potential there is a bending of the light trajectory

$$\frac{(c_1 - c_2)\, dt}{1} = -\frac{\partial c}{\partial n'}\, dt$$

Fermat's principle: (geometrical optics)
The path that light takes between 2 points is the one that takes the least time:

The extremal light path followed from A to B must verify,

$$\delta \int_A^B n(\vec{x}) dx = 0 = \delta \int_{\lambda_A}^{\lambda_B} n(\vec{x}(\lambda)) \frac{dx}{d\lambda} d\lambda = \delta \int_{\lambda_A}^{\lambda_B} n(\vec{x}(\lambda)) |\dot{\vec{x}}| d\lambda = \delta \int_{\lambda_A}^{\lambda_B} L(x, \dot{x}; \lambda) d\lambda$$

This term is identified with a Lagrangian and the evolution of \vec x can be computed:

$$\frac{d}{d\lambda}\frac{\partial L}{\partial \dot{x}_i} - \frac{\partial L}{\partial x_i} = 0 = \frac{d}{d\lambda}(n(\vec{x})\vec{u}_x) - \vec{\nabla} n = n\dot{\vec{u}}_x + (\vec{\nabla} n.\vec{u}_x)\vec{u}_x - \vec{\nabla} n$$

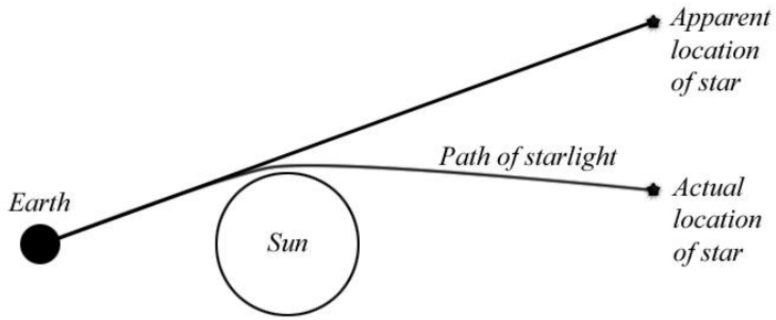
$\vec{u}_x$ is a normalized vector along $\vec{x}$, i.e., tangent to the path.

$$\dot{\vec{u}}_x = \frac{d^2\vec{x}}{d\lambda^2} = \frac{1}{n(\vec{x})}\left(\vec{\nabla} n - (\vec{\nabla} n.\vec{u}_x)\vec{u}_x\right) = \frac{1}{n(\vec{x})}\vec{\nabla}_\perp n(\vec{x}) = (1+\frac{\Psi}{c^2})(-\frac{1}{c^2}\vec{\nabla}_\perp \Psi) \approx -\frac{1}{c^2}\vec{\nabla}_\perp \Psi$$

Total deflection angle:

$$\vec{\alpha} = -\frac{1}{c^2}\int_{\lambda_A}^{\lambda_B} \dot{\vec{u}}_x \, d\lambda = \frac{1}{c^2}\int_{\lambda_A}^{\lambda_B} \vec{\nabla}_\perp \Psi \, d\lambda$$

Light path pulled towards the deflector → image appears to be away from the deflector



$$\alpha = \frac{1}{c^2}\int_{\vartheta=-\frac{\pi}{2}}^{\vartheta=+\frac{\pi}{2}} \frac{k\,M}{r^2}\cos\vartheta \cdot ds = \frac{2\,k\,M}{c^2\,\Delta}$$

At the Sun's limb, the deviation is 0.875 arcsec

This is the so-called Newtonian deflection.

This result had been derived by von Soldner in 1801 - Newtonian corpuscular theory of light - deviation of particles with v=c (and Cavendish 1784 - unpublished)

(C. Will 1988)

The particle emitted with velocity v=c at infinity, follows a hyperbolic trajectory.

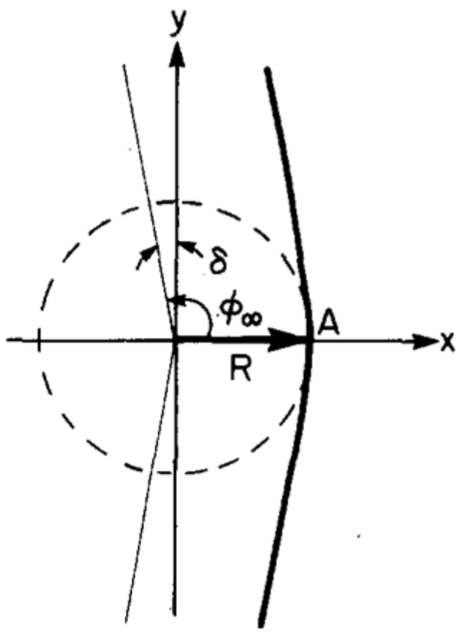
$$\frac{d^2\mathbf{x}}{dt^2} = -\frac{Gm\mathbf{x}}{r^3}$$

$$r = R(1+e)/(1+e\cos\phi),$$

$$r^2\frac{d\phi}{dt} = [GmR(1+e)]^{1/2},$$

$$v^2 = \frac{Gm}{R(1+e)}(1+2e\cos\phi+e^2)$$

$$c^2 = v^2|_{\phi=\phi_\infty} = [Gm/R(1+e)](e^2-1)$$
$$= Gm(e-1)/R.$$



$$\sin\delta = 1/e.$$

$$\boxed{\Delta\theta \equiv 2\delta \simeq 2\sin\delta \simeq 2\epsilon = 2Gm/Rc^2}$$

Gravity is the space-time curvature

The metric now also contains perturbations on the spatial part

$$ds^2 = -\left(1 + \frac{2\Psi}{c^2}\right) c^2 dt^2 + \left(1 - \frac{2\Phi}{c^2}\right) dx^2$$

Travelling time of a light ray computed from

$$\frac{cdt}{dx} = \left(1 + 2\Psi/c^2\right)^{-1/2} \left(1 - 2\Phi/c^2\right)^{1/2} \approx 1 - \frac{\Psi + \Phi}{c^2}$$

$$\nabla^2\Psi - 3\mathcal{H}(\Psi' + \mathcal{H}\Phi) + \mathcal{H}\nabla^2(h' - w) = 4\pi G a^2 \bar{\rho}\delta$$

$$\Psi' + \mathcal{H}\Phi = -4\pi G a^2(\bar{\rho} + \bar{p})(v + w)$$

$$\Psi'' + \mathcal{H}(\Phi' + 2\Psi') + (2\mathcal{H}' + \mathcal{H}^2)\Phi = 4\pi G a^2\left(\bar{p}\delta_p + \frac{2}{3}\nabla^2\Pi\right)$$

$$\Psi - \Phi + (h' - w)' + 2\mathcal{H}(h' - w) = 8\pi G a^2\Pi$$

Einstein equations : (cosmology, perturbed RW metric) scalar perturbations, linearized, first-order. Gauge freedom (Newtonian): h =w = 0

If no anisotropic stress →

In GR: Φ = Ψ → **the factor of 2**

$$\vec{\alpha} = \frac{2}{c^2}\int_{\lambda_A}^{\lambda_B} \vec{\nabla}_\perp \Psi \, d\lambda$$

At the Sun's limb, the deviation is 1.75 arcsec

$= 4\ Gm/Rc^2$

1

The 1919 Eclipse expedition:

Measuring the deflection of light in the Sun’s gravitational field

Dyson, Eddington and Davidson Nov 1919, Phil. Trans. Roy. Soc. London

IX. *A Determination of the Deflection of Light by the Sun's Gravitational Field, from Observations made at the Total Eclipse of May* 29, 1919.

By Sir F. W. DYSON, *F.R.S., Astronomer Royal, Prof.* A. S. EDDINGTON, *F.R.S., and Mr.* C. DAVIDSON.

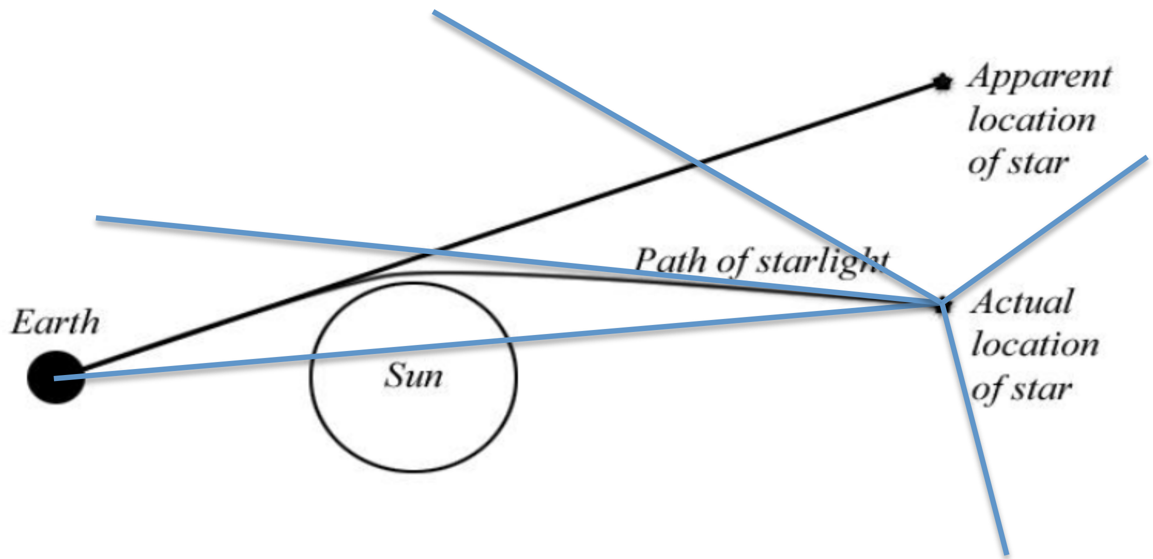
The goal: what is the effect produced by a gravitational field on the path of light?

(1) The path is uninfluenced by gravitation.

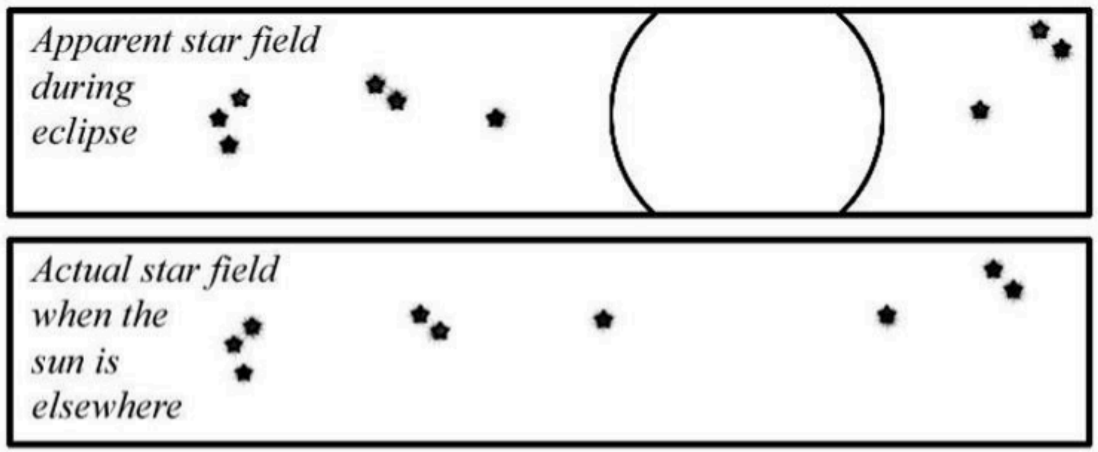
(2) The energy or mass of light is subject to gravitation in the same way as ordinary matter. If the law of gravitation is strictly the Newtonian law, this leads to an apparent displacement of a star close to the sun's limb amounting to $0''\cdot 87$ outwards.

(3) The course of a ray of light is in accordance with EINSTEIN's generalised relativity theory. This leads to an apparent displacement of a star at the limb amounting to $1''\cdot 75$ outwards.

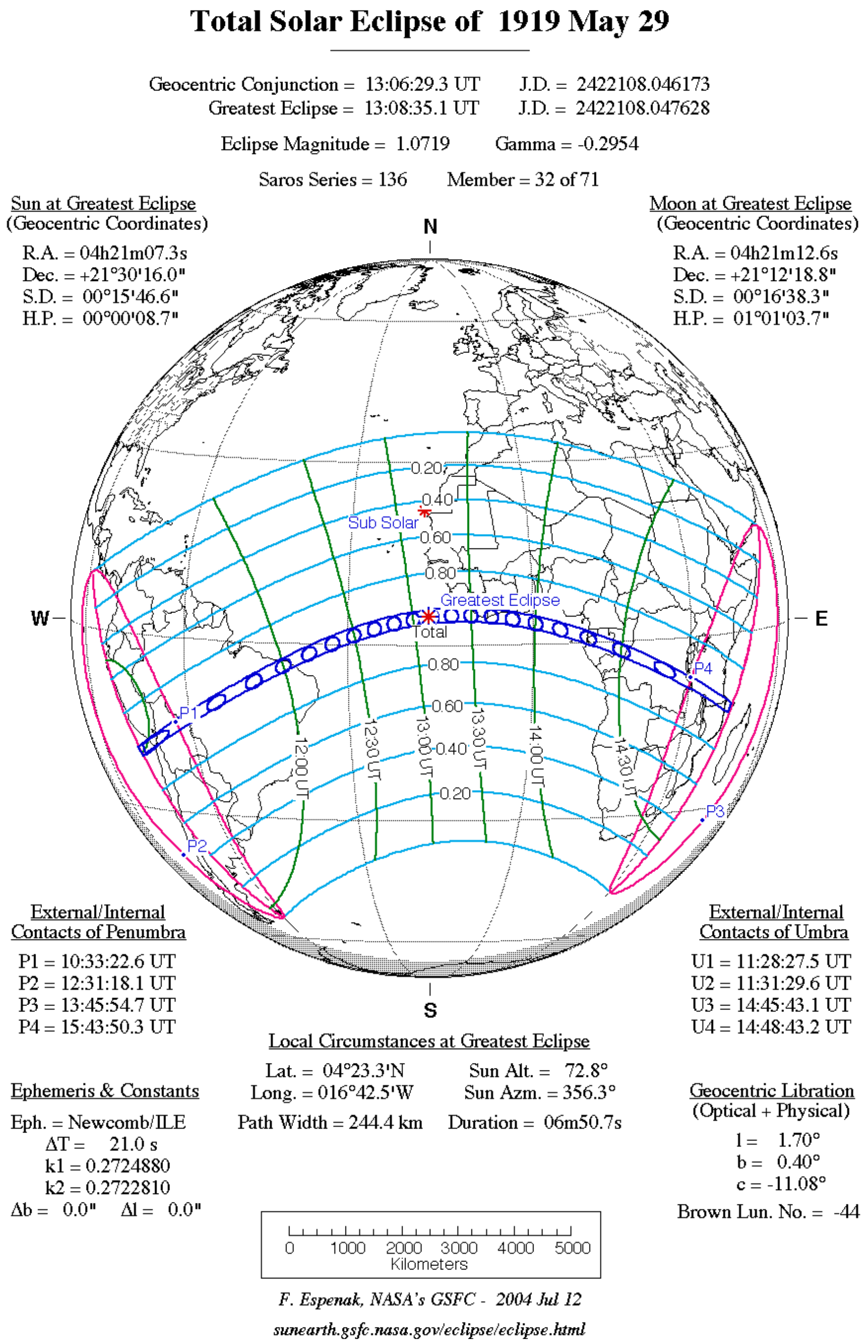
Total Solar Eclipse

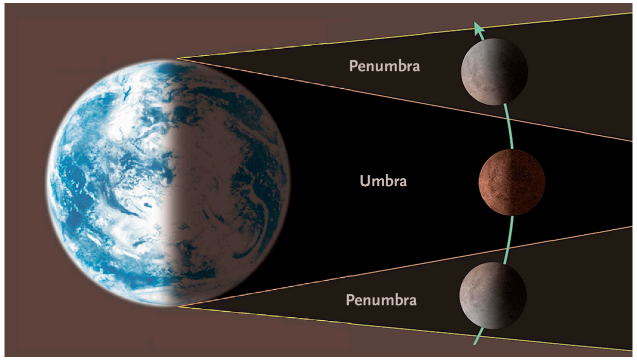


Observe the position of stars during a solar eclipse and observe again a few weeks later (or earlier)



Preparing the expedition





Magnitude (diameter) : 1.07
Maximum duration: 6m50s

2 groups:

Príncipe (São Tomé e Príncipe, Portugal): Eddington and Cottingham

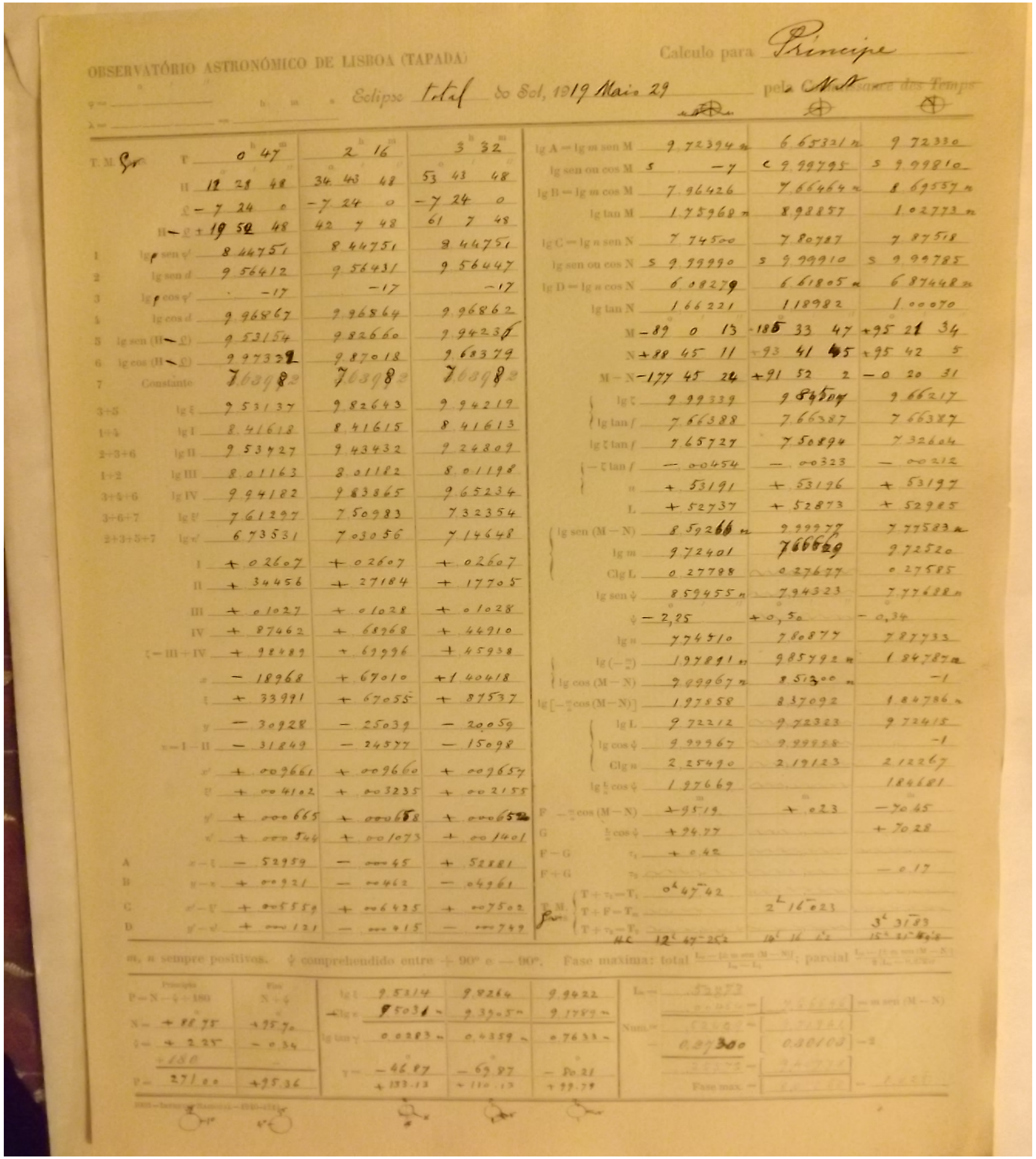
Sobral (Ceará, Brasil): Davidson and Crommelin

Eclipse at Sobral at around 9h (local) and 2 hours later at Príncipe.
The locations differ ~3h in longitude → eclipse at Príncipe at around 14h (local)

(NASA)

Ephemerides calculations

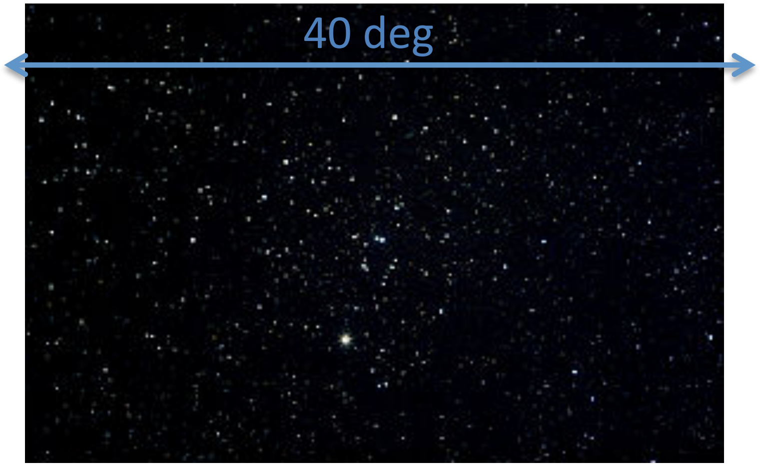
Data for Principe computed at OAL (Observatório Astronómico de Lisboa) on special eclipse sheets!

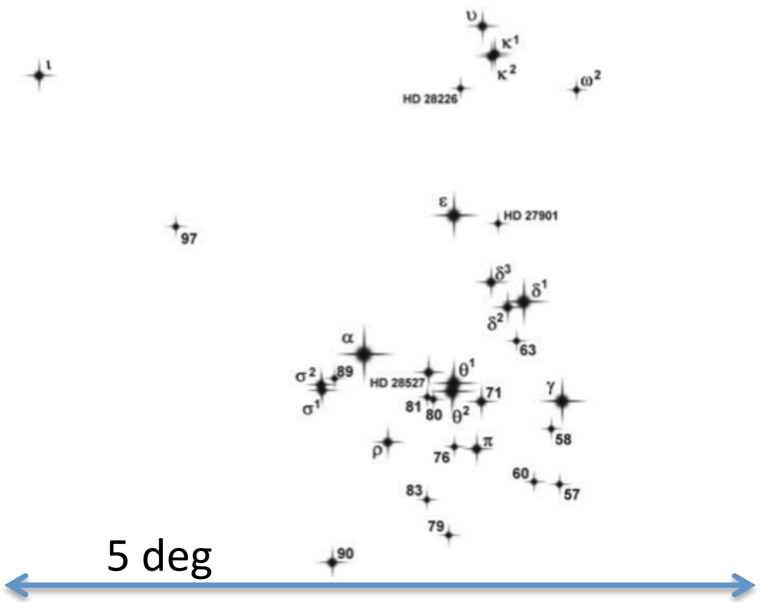


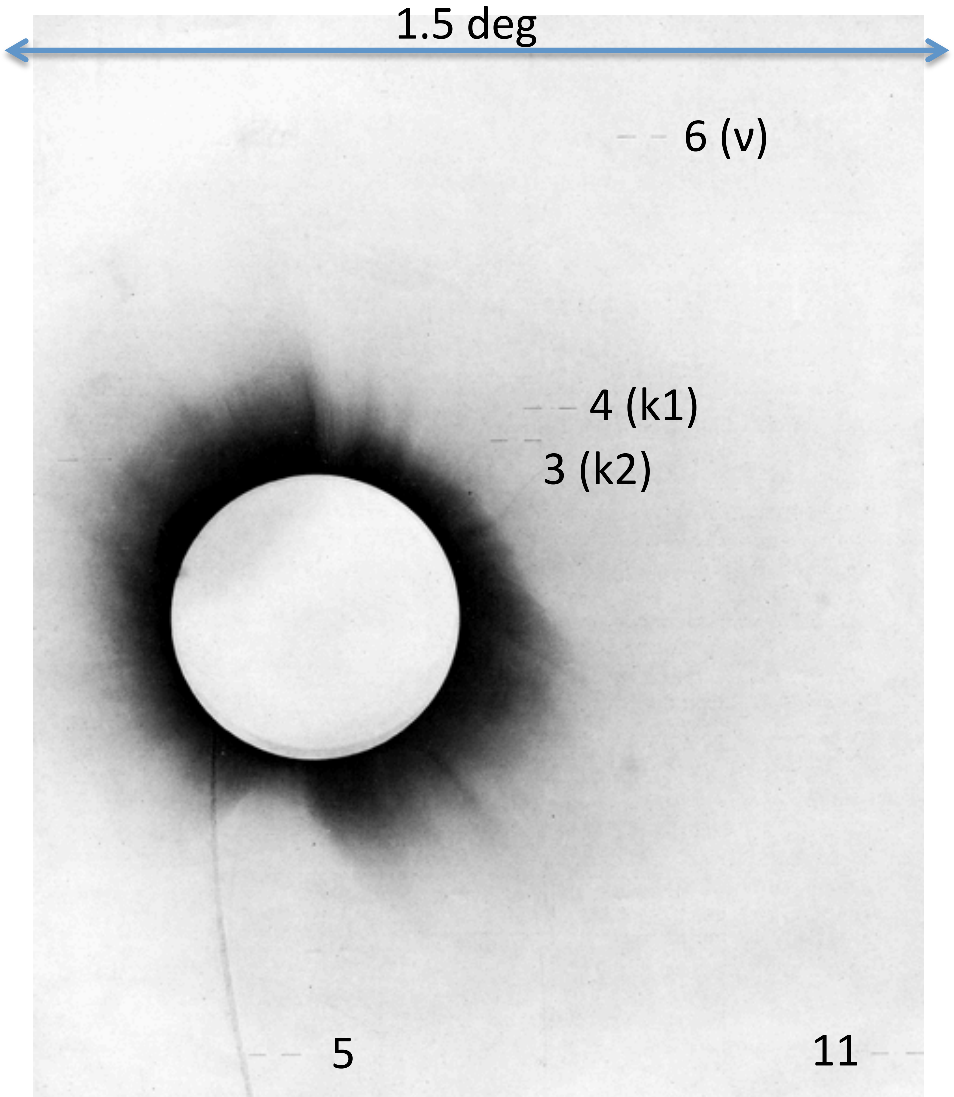
(OAL archives)

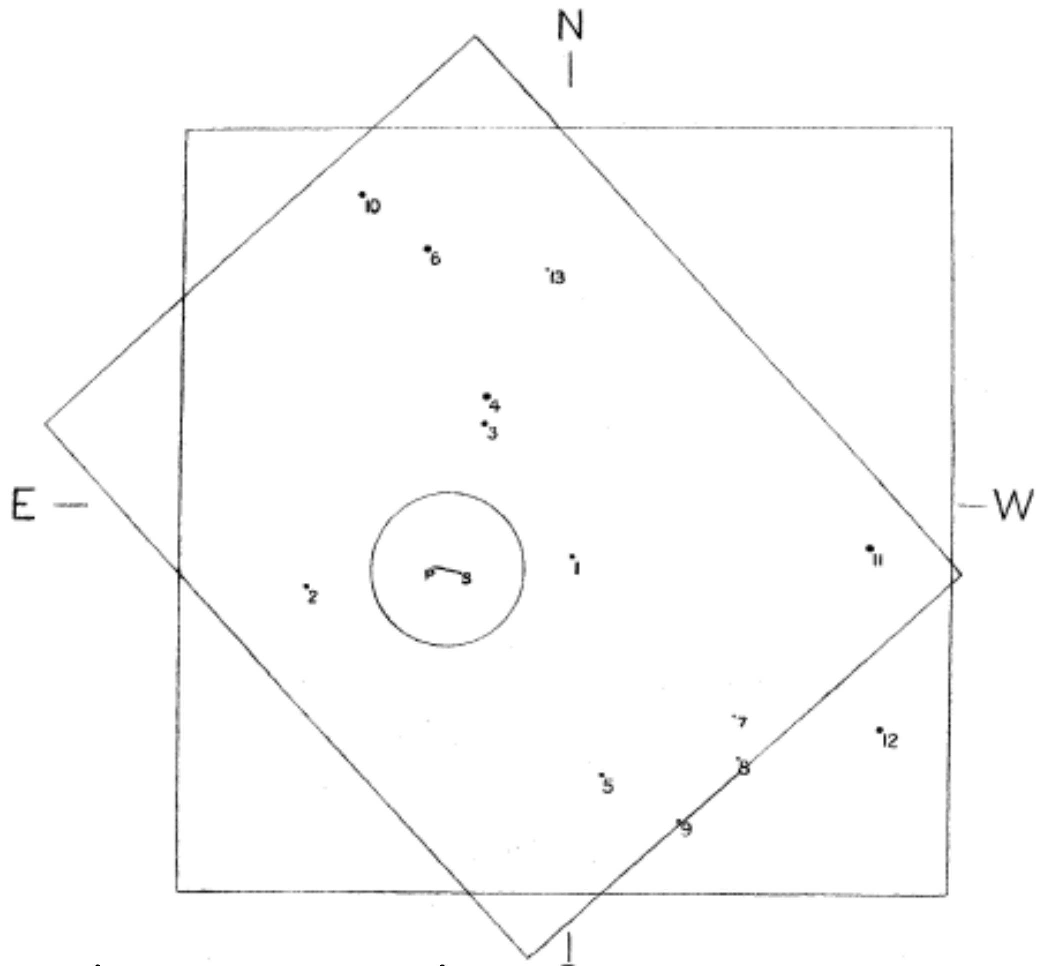
The target

Good opportunity because of many stars in the background - the **Hyades open star cluster** - with 400 stars, including most stars of the Taurus constellation “V-shape”









Large photographic plates: 10 x 8 inches
and 16 x 16 cm

Wide field: FoV ~ 6 deg^2

No.	Names.	Photog. Mag.	Co-ordinates. Unit = 50′.		Gravitational displacement.			
					Sobral.		Principe.	
			x.	y.	x.	y.	x.	y.
		m.			″	″	″	″
1	B.D., 21°, 641	7·0	+0·026	−0·200	−1·31	+0·20	−1·04	+0·09
2	Piazzi, IV, 82	5·8	+1·079	−0·328	+0·85	−0·09	+1·02	−0·16
3	κ^2 Tauri	5·5	+0·348	+0·360	−0·12	+0·87	−0·28	+0·81
4	κ^1 Tauri	4·5	+0·334	+0·472	−0·10	+0·73	−0·21	+0·70
5	Piazzi, IV, 61	6·0	−0·160	−1·107	−0·31	−0·43	−0·31	−0·38
6	υ Tauri	4·5	+0·587	+1·099	+0·04	+0·40	+0·01	+0·41
7	B.D., 20°, 741	7·0	−0·707	−0·864	−0·38	−0·20	−0·35	−0·17
8	B.D., 20°, 740	7·0	−0·727	−1·040	−0·33	−0·22	−0·29	−0·20
9	Piazzi, IV, 53	7·0	−0·483	−1·303	−0·26	−0·30	−0·26	−0·27
10	72 Tauri	5·5	+0·860	+1·321	+0·09	+0·32	+0·07	+0·34
11	66 Tauri	5·5	−1·261	−0·160	−0·32	+0·02	−0·30	+0·01
12	53 Tauri	5·5	−1·311	−0·918	−0·28	−0·10	−0·26	−0·09
13	B.D., 22°, 688	8·0	+0·089	+1·007	−0·17	+0·40	−0·14	+0·39

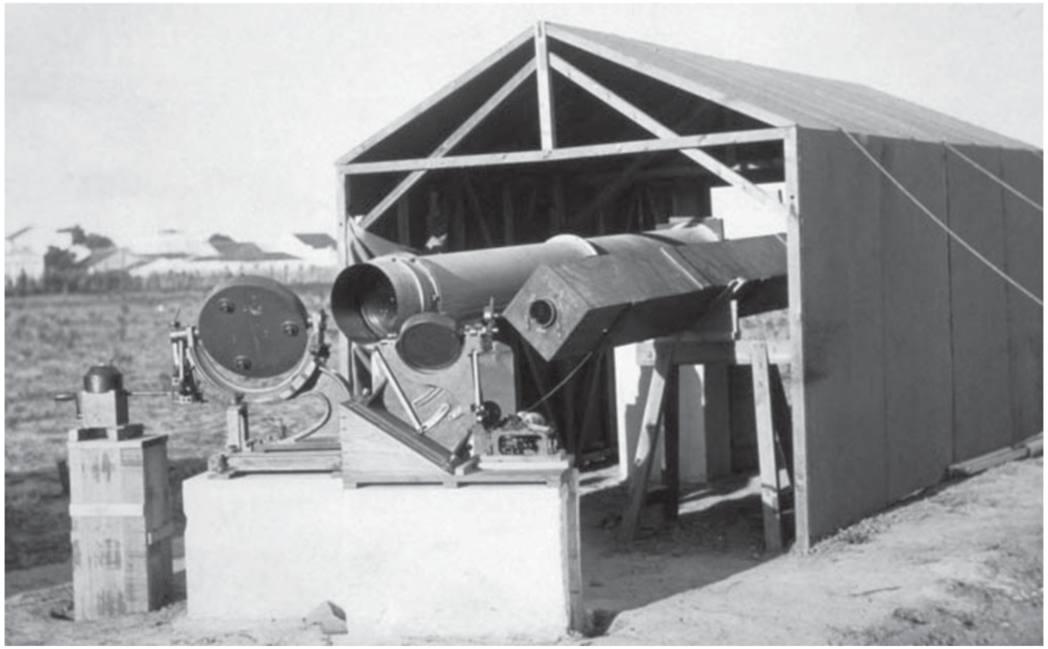
- Stars standard coordinates (ra, dec) , no Sun, written with respect to an origin in the field, in units of 50 arcmin

- Expected x and y displacement (GR) at those positions. They are different in Sobral and Príncipe, because in 2 hours the Sun moved noticeably with respect to the fixed stars (Earth orbital movement).

Instruments

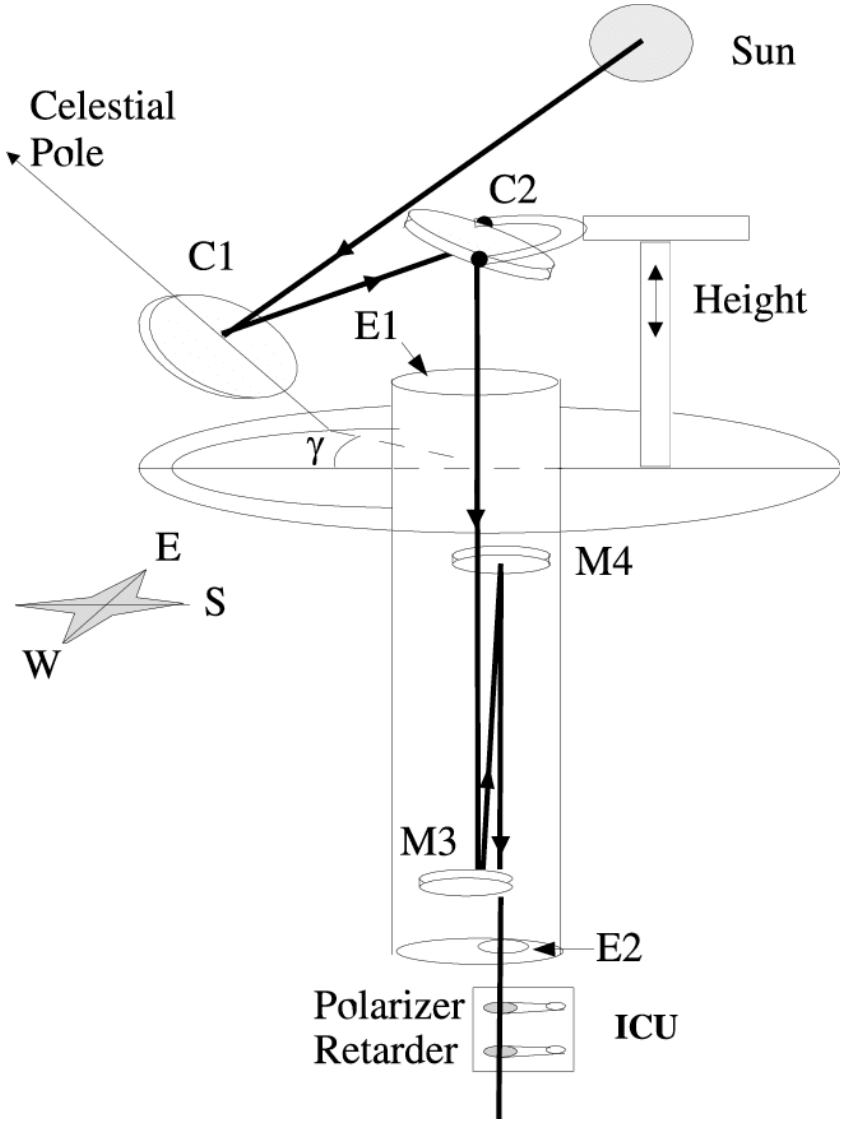
Optical astrographic refractor **telescopes**:

- 13-inch aperture, 3.43m focus → FoV ~ 6 sqdeg
- 4-inch aperture, 19-feet focus → FoV ~ 5 sqdeg



The telescopes are used with (respectively) 16-inch and 8-inch **coelostats** (mirrors) attached to clocks

- follow the rotation of the sky by rotating the mirrors - more practical to set up than an equatorial mount.



2 tons of luggage!

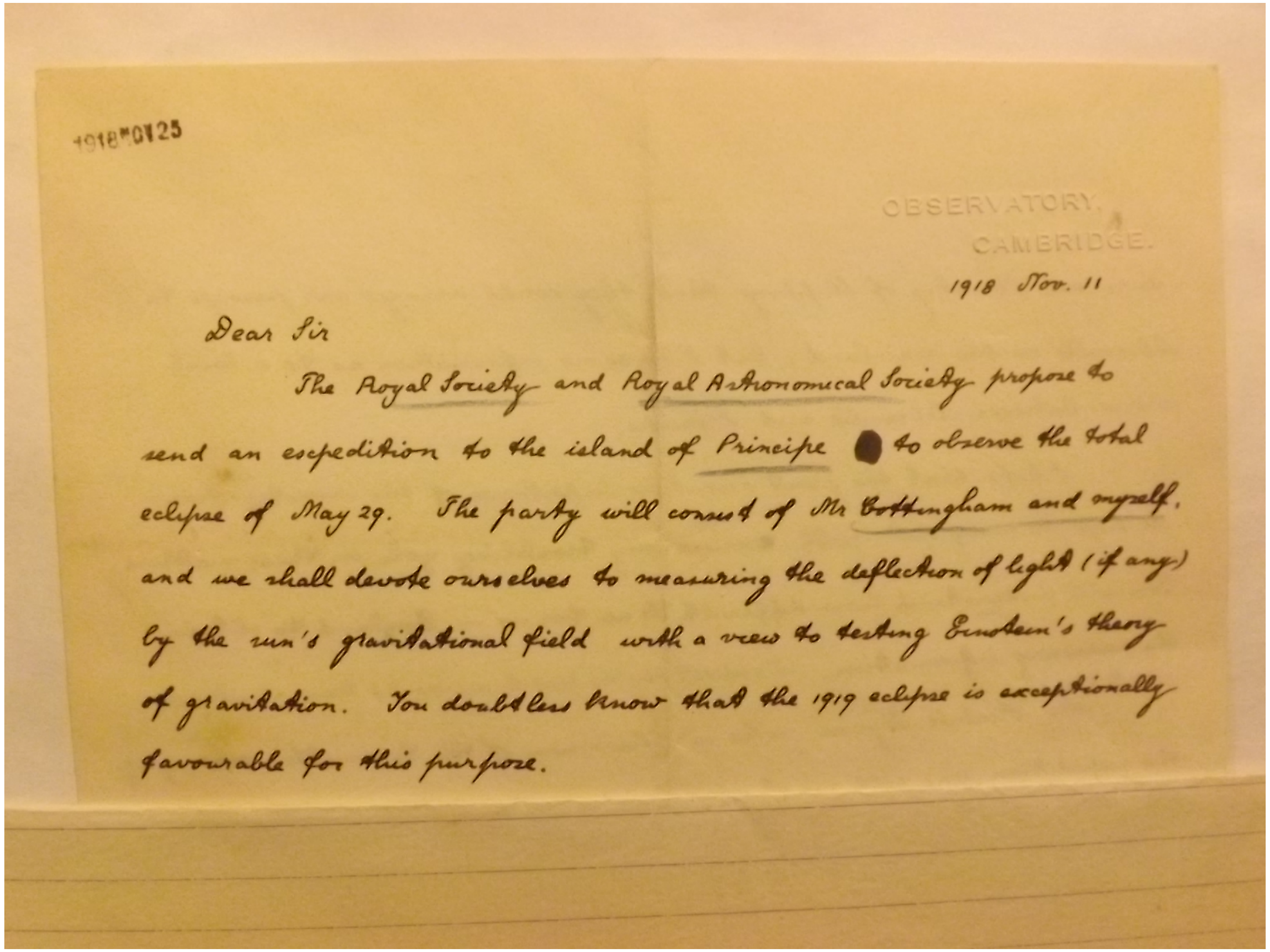
Logistics: connection with the Astronomical Observatory of Lisbon (OAL)

Immediately on Nov 11, 1918 - armistice day! - Eddington started an exchange of letters with Frederico Oom (sub-director of OAL), asking for help regarding

- transportation to Principe

- lodgings, sites for the observations, resources available

Nov 11



1918 NOV 25

OBSERVATORY,
CAMBRIDGE.

1918 Nov. 11

Dear Sir

The Royal Society and Royal Astronomical Society propose to send an expedition to the island of Principe to observe the total eclipse of May 29. The party will consist of Mr Cottingham and myself, and we shall devote ourselves to measuring the deflection of light (if any) by the sun's gravitational field with a view to testing Einstein's theory of gravitation. You doubtless know that the 1919 eclipse is exceptionally favourable for this purpose.

(OAL archives)

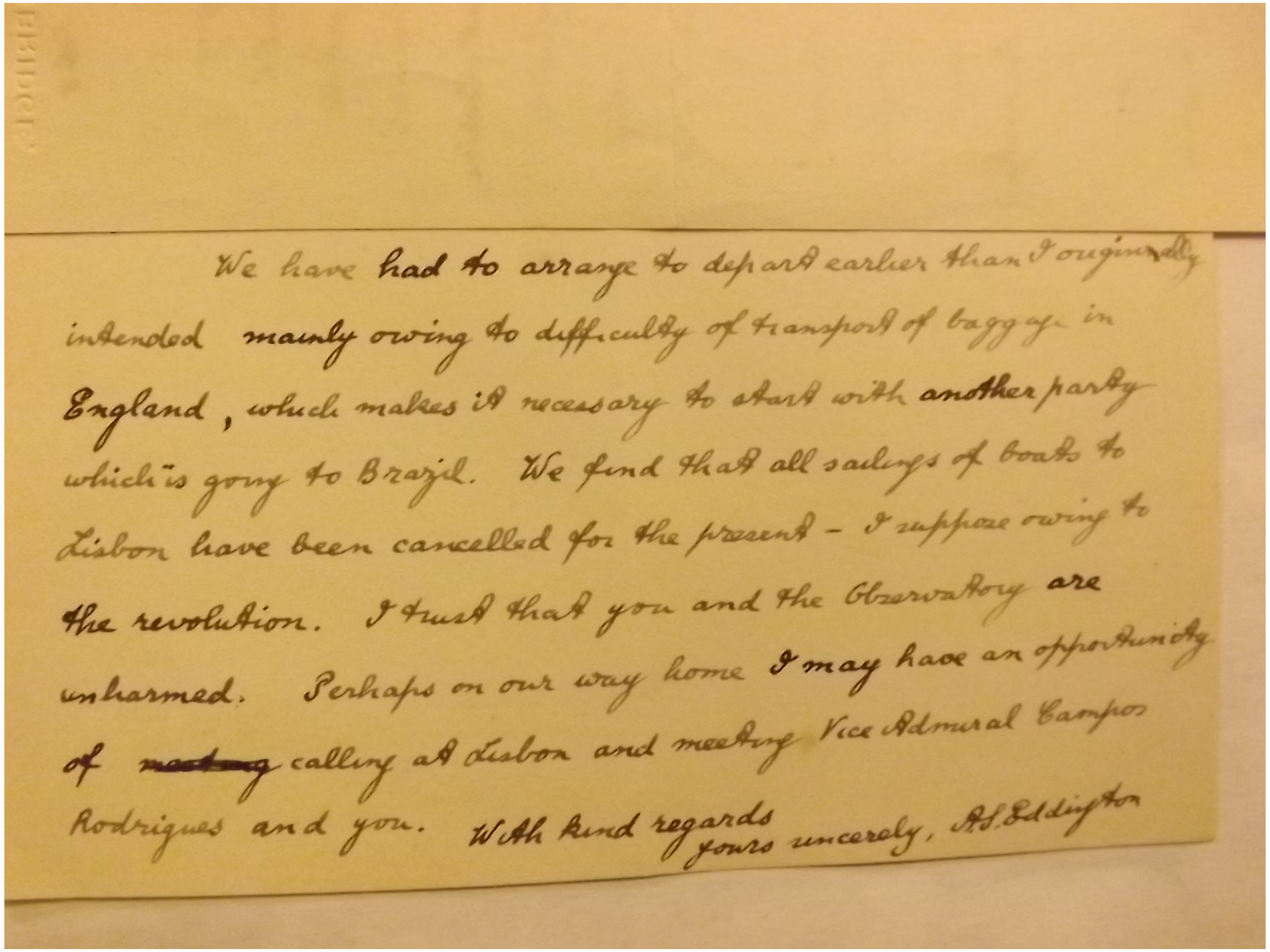
Change of plans

The journey should have been:

Liverpool - Lisbon
Lisbon - Principe

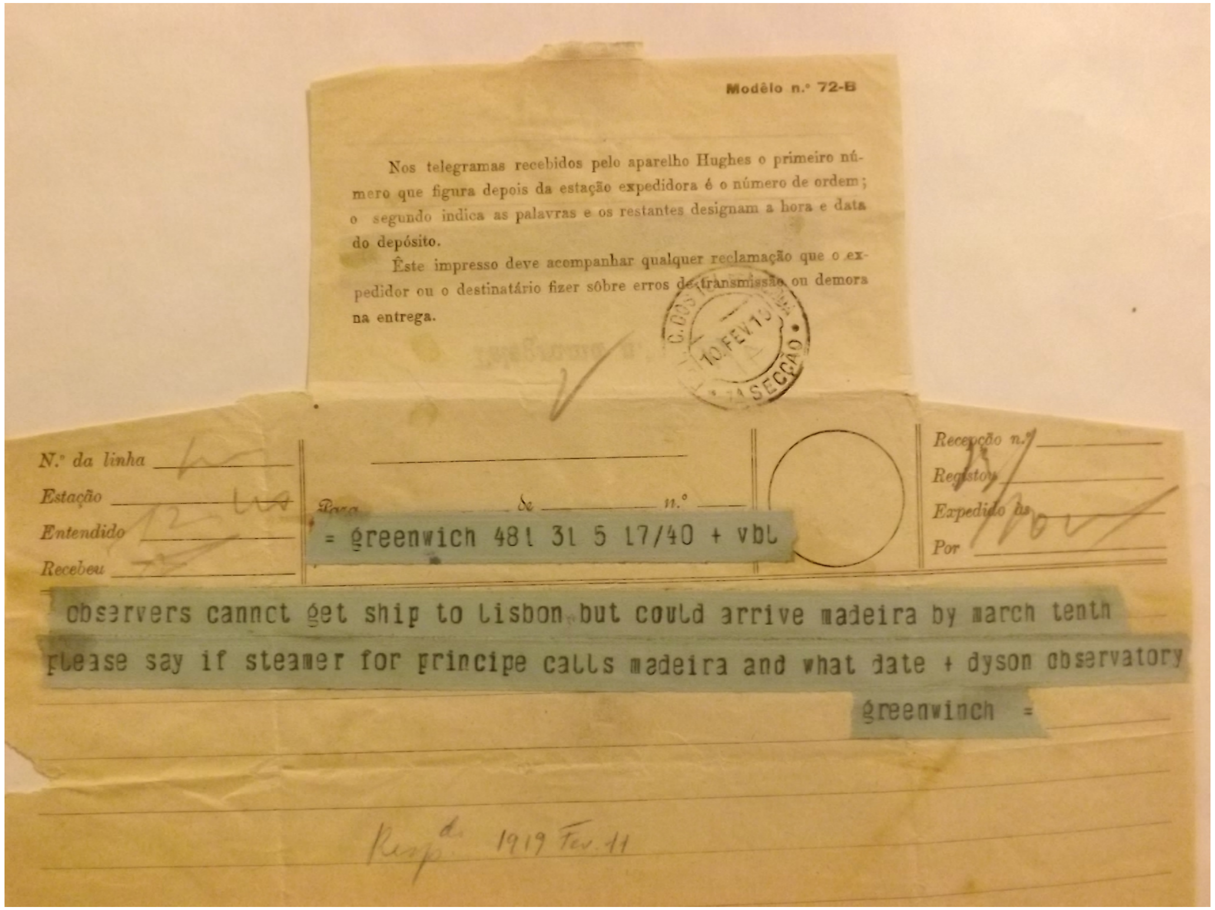
but Eddington mentions that ships to Lisbon were cancelled due to the revolution:

Paiva Couceiro - monarquia do norte, jan -feb 1919



We have had to arrange to depart earlier than I originally intended mainly owing to difficulty of transport of baggage in England, which makes it necessary to start with another party which is going to Brazil. We find that all sailings of boats to Lisbon have been cancelled for the present – I suppose owing to the revolution. I trust that you and the Observatory are unharmed. Perhaps on our way home I may have an opportunity of ~~meeting~~ calling at Lisbon and meeting Vice Admiral Campos Rodrigues and you. With kind regards
yours sincerely, A.S. Eddington

Feb 8


Modêlo n.º 72-B

Nos telegramas recebidos pelo aparelho Hughes o primeiro número que figura depois da estação expedidora é o número de ordem; o segundo indica as palavras e os restantes designam a hora e data do depósito.

Êste impresso deve acompanhar qualquer reclamação que o expedidor ou o destinatário fizer sôbre erros de transmissão ou demora na entrega.

10 FEV 19

N.º da linha
Estação
Entendido
Recebeu

Para n.º

Recepção n.º
Registo
Expedido às
Por

= greenwich 481 31 5 17/40 + vbl

observers cannct get ship to lisbon but could arrive madeira by march tenth please say if steamer for principe calls madeira and what date + dyson observatory greenwich =

Resp.da 1919 Fev. 11

Feb 11

Telegram from Dyson, saying that the 2 groups will travel together to Madeira island (instead of Lisbon)

From there, the ship will continue to Brasil (Pará), while the Príncipe group will wait for another ship.

A large number of letters from F. Oom to Centro Colonial and Companhia Nacional de Navegação

trying to make sure that a ship Lisboa - São Tomé will make a stop in Madeira on purpose to pick up Eddington and Cottingham

peito que tomo a liberdade de importunar agora V.Exa.

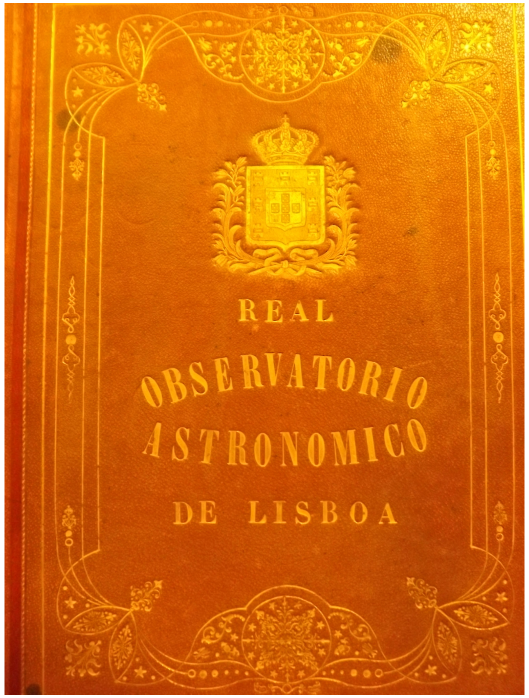
Não pôde a missão obter transporte para Lisboa em data conveniente. Só conseguiu alcançar passagem de Inglaterra directamente para a Madeira, onde devem chegar por 10 de Março. Nestes termos é-lhes decerto impossível apanhar alí o paquete para o Príncipe que sai de Lisboa a 7 de Março. Teriam de esperar na Madeira um mês, com notável incómodo e prejuizo para os seus planos e trabalhos.

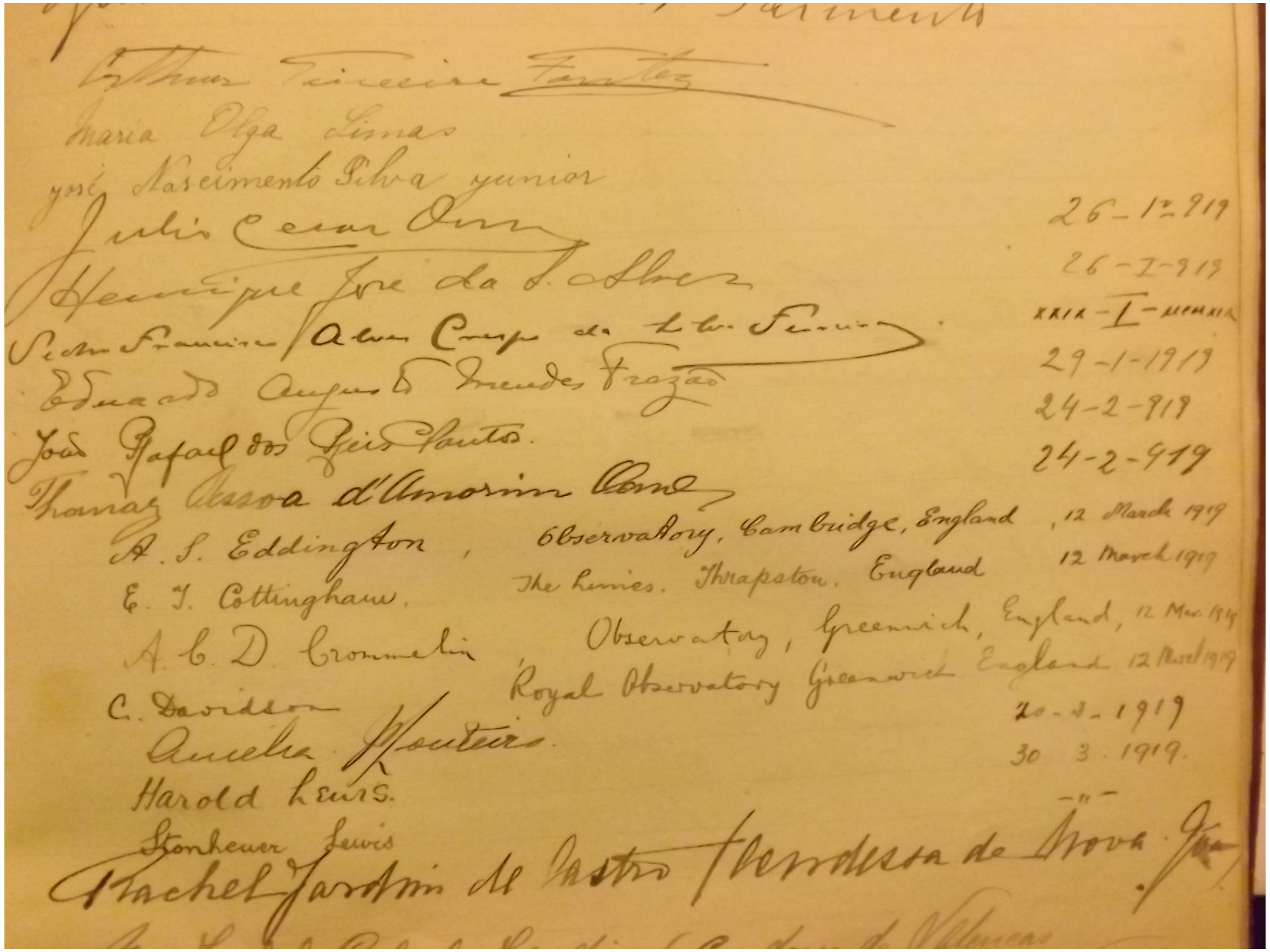
Por isso ouso esperar que mais esta vez a C.N.N. manifes- o seu nunca desmentido interesse por assuntos desta ordem, e consinta que o paquete para o Principe, que sai de Lisboa a 22 de Março, faça por excepção escala na Madeira, afim de nêle poder seguir viagem a referida missão scientífica inglêsa.

Devo ainda acrescentar que os delicados e valiosos ins- trumentos desta missão exigem o maior cuidado, tanto na carga e descarga, como no acondicionamento a bordo. Confío porem plenamente que, a tal respeito, bastará recomendar o caso aos oficiais e pessoal do navio, e assim o solicito tambem da condescendência de V.Exa.

In Lisbon

But the ship stopped in Lisbon after all, on the way to Madeira and they spend a few hours in Lisbon, on march 12, with F. Oom.





Maria Olga Limas
José Nascimento Silva junior
Julio Cesar Oom 26-1-919
Henrique José da S. Alves 26-I-919
XXIX-I-MCMXIX
29-1-1919
Eduardo Augusto Mendes Frazão 24-2-919
João Rafael dos Reis Santos 24-2-919
Thomaz Pessoa d'Amorim
A. S. Eddington, Observatory, Cambridge, England, 12 March 1919
E. T. Cottingham, The Limes, Thrapston, England 12 March 1919
A. C. D. Crommelin Observatory, Greenwich, England, 12 Mar. 1919
C. Davidson Royal Observatory Greenwich England 12 March 1919
20-3-1919
30 3 1919
Harold Lewis
Stonhewer Lewis
Rachel Jardim de Castro

Visitor's book

O Observatório Astronómico de Lisboa (Tapada)

Deve

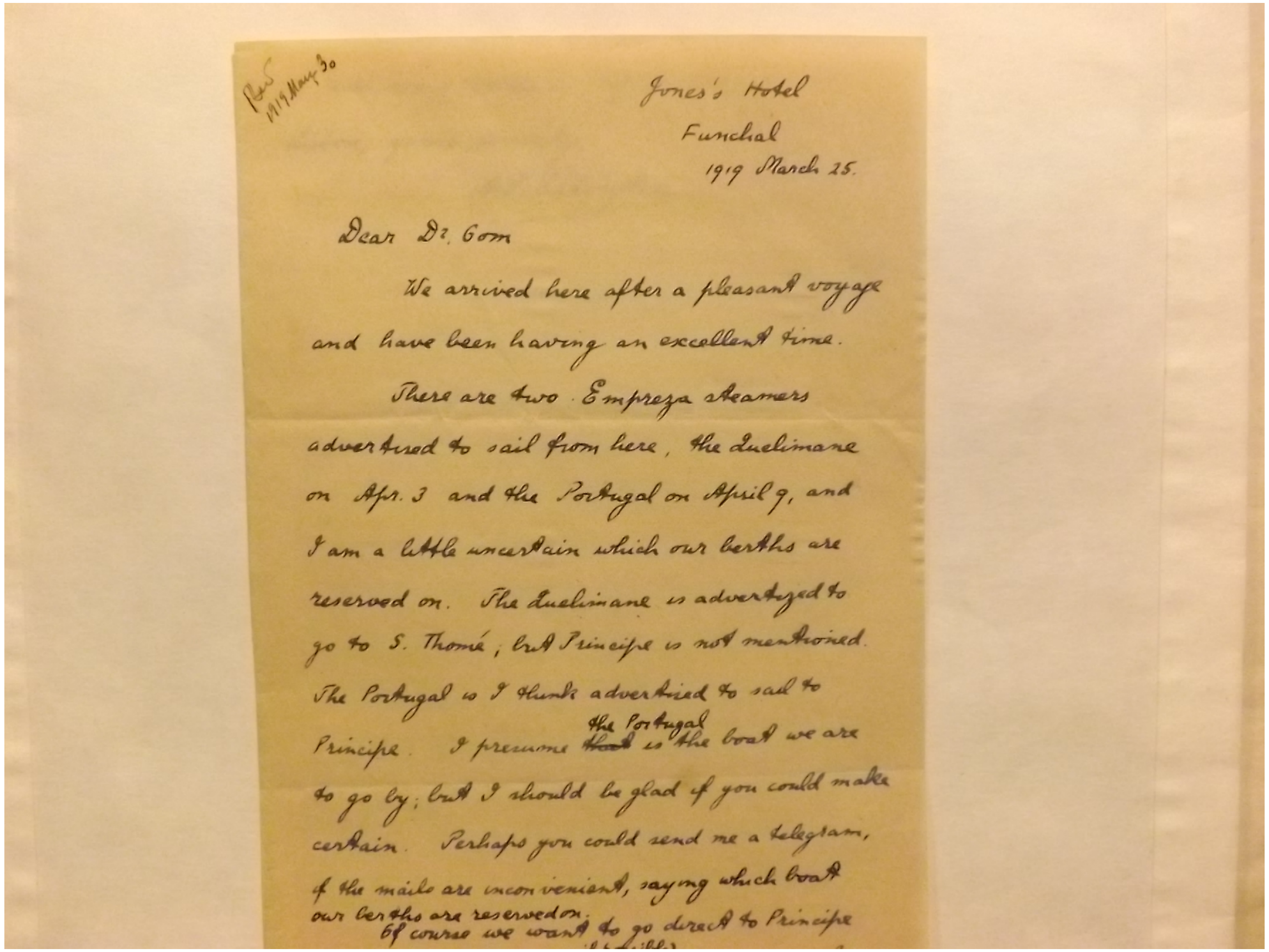
a Frederico Oom

Pelo pagamento do aluguer, por 3 horas, de um automóvel de praça, para condução dos 4 astrónomos das missões oficiais inglezas destinadas a observar o eclipse de 29 de Maio de 1919 na Ilha do Príncipe e no Pará, no dia da sua estada em Lisboa, a 12 de Março de 1919 . . . 24$–

Reimboursement form to F. Oom, for renting a taxi for 3 hours in Lisbon

In Madeira

More requests concerning the ship



Recd 1919 May 30

Jones's Hotel
Funchal
1919 March 25.

Dear Dr. Gom

We arrived here after a pleasant voyage and have been having an excellent time.

There are two Empreza steamers advertised to sail from here, the Quelimane on Apr. 3 and the Portugal on April 9, and I am a little uncertain which our berths are reserved on. The Quelimane is advertised to go to S. Thomé; but Principe is not mentioned. The Portugal is I think advertised to sail to Principe. I presume ~~that~~ the Portugal is the boat we are to go by; but I should be glad if you could make certain. Perhaps you could send me a telegram, if the mails are inconvienient, saying which boat our berths are reserved on.
Of course we want to go direct to Principe

Mar 25

They stayed in Madeira from March 14 to April 9

The journey to Príncipe lasted from April 9 to April 23

In Príncipe

Arrival to Santo António on April 23

Roça Sundy

The observations: **Sobral, the self-calibration method** (4-inch telescope)

Take several exposures of the field during the eclipse (eclipse plates), hoping to get as many stars as possible

Take several exposures of the same field (comparison plates) without the Sun, with the field at the same altitude in the sky and similar conditions of temperature:

> the Sun moves ~30 degrees per month (2 hours in the sky, with respect to the “fixed” stars).
> For an eclipse at 9 am, in 1.5 month the field is visible at dawn → need to wait a few weeks → comparison plaques taken at Sobral 6 weeks later.

Take also one reference exposure, same condition as the comparison (scale plate):

> the micrometer was not suitable to measurements on these large plates, so the measurements were done by overlapping the eclipse (or comparison) plates with a scale plate (held together by clips) - an intermediate plate to provide points of reference

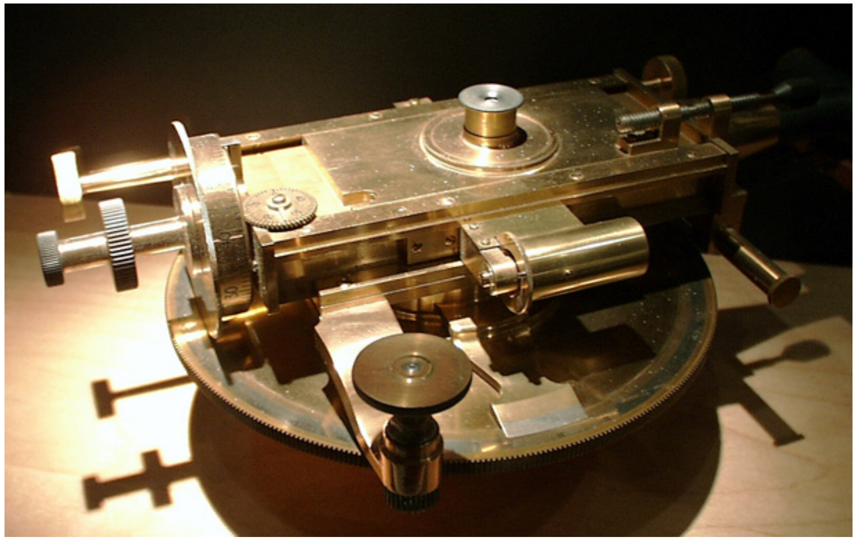
TABLE II.—Eclipse Plates—Scale.

No. of Star.	I.		II.		III.		IV.		V.		VII.		VIII.	
	Dx.	Dy.	Dx.	Dy.	Dx.	Dy.	Dx.	Dy.	Dx.	Dy.	Dx.	Dy.	Dx.	Dy.
	r	r	r	r	r	r	r	r	r	r	r	r	r	r
11	−1·411	−0·554	−1·416	−1·324	+0·592	+0·956	+0·563	+1·238	+0·406	+0·970	−1·456	+0·964	−1·285	−1·195
5	−1·048	−0·338	−1·221	−1·312	+0·756	+0·843	+0·683	+1·226	+0·468	+0·861	−1·267	+0·777	−1·152	−1·332
4	−1·216	+0·114	−1·054	−0·944	+0·979	+1·172	+0·849	+1·524	+0·721	+1·167	−1·028	+1·142	−0·927	−0·930
3	−1·237	+0·150	−1·079	−0·862	+0·958	+1·244	+0·861	+1·587	+0·733	+1·234	−1·010	+1·185	−0·897	−0·894
6	−1·342	+0·124	−1·012	−0·932	+1·052	+1·197	+0·894	+1·564	+0·798	+1·130	−0·888	+1·125	−0·838	−0·937
10	−1·289	+0·205	−0·999	−0·948	+1·157	+1·211	+0·934	+1·522	+0·864	+1·119	−0·820	+1·072	−0·768	−0·964
2	−0·789	+0·109	−0·733	−1·019	+1·256	+0·924	+1·177	+1·373	+0·995	+0·935	−0·768	+0·892	−0·585	−1·166
	−1·500*	−0·554	−1·500	−1·324	+0·500	+0·843	+0·500	+1·226	+0·400	+0·861	−1·500	+0·777	−1·300	−1·322

Overlay of I - VIII eclipse plates with the scale plate.

(Dx, Dy) are the positions (x,y) of the 7 usable stars in the eclipse plate measured with respect to the origin of the scale plate.

The positions are given in units of number of revolutions of the micrometer (1 r = 6.25 arcsec), in the reference of the scale plate.



What contributes to the displacements?

The positions Dx, Dy in the eclipse plates are modeled as:

$$ax + by + c + \alpha E_x = Dx$$

$$dx + ey + f + \alpha E_y = Dy$$

x, y (in arcsec, or r) - position in the reference (scale) plate

a, b, c - are **calibration parameters**

a - multiplicative factor accounting for differences in scale between the plates due to difference in focus, in temperature, plates expansion

b - response of displacement in x due to displacement in y - it accounts for misalignment between overlaid plates c - additive factor to account for x-off-set between overlaid plates

(and analogously for the Dy calibration parameters d, e, f)

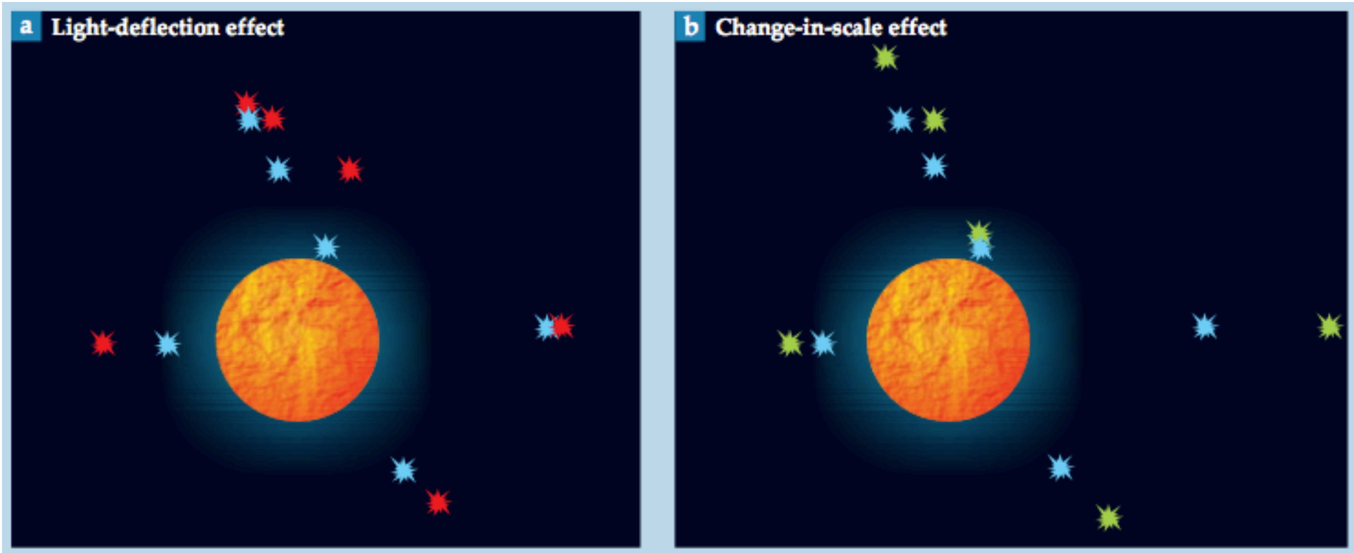
Ex,Ey (dimensionless) - gravitational displacement at (x,y) assuming GR, normalized by a reference gravitational displacement (defined at 50 arcmin from the center of the Sun and assuming GR)

α (in arcsec, or r) - the actual **reference gravitational displacement** - the **physical parameter** we want to estimate

The 4 parameters (α, a, b, c) will be estimated simultaneously → self-calibration and degeneracies

The scaling calibration (a) is the parameter most degenerate with α , since the observable (Dx) have similar dependencies on both (linear with x)

However, the degeneracy is broken by measuring several stars across the field, because their effects are opposite:



There may be also systematic effects. These are not modeled with **nuisance parameters**, but are directly computed and subtracted:

- parallax - neglected because << 1arcsec (Hyades is far at 40pc)

- differential diffraction and aberration - computed and subtracted

The parameters estimation

The parameters are constant in one plate.

The system of equations for all 7 stars in one plate is A p =d,
where the dimensions are A: 7 x 4, p: 4 x 1 (the parameter vector), d: 7 x 1 (the data vector Dx).

No.	Right Ascension.	Declination.
11	$c-0\cdot160b-1\cdot261a-0\cdot587\alpha$	$f-1\cdot261d-0\cdot160e+0\cdot036\alpha$
5	$c-1\cdot107b-0\cdot160a-0\cdot557\alpha$	$f-0\cdot160d-1\cdot107e-0\cdot789\alpha$
4	$c+0\cdot472b+0\cdot334a-0\cdot186\alpha$	$f+0\cdot334d+0\cdot472e+1\cdot336\alpha$
3	$c+0\cdot360b+0\cdot348a-0\cdot222\alpha$	$f+0\cdot348d+0\cdot360e+1\cdot574\alpha$
6	$c+1\cdot099b+0\cdot587a+0\cdot080\alpha$	$f+0\cdot587d+1\cdot099e+0\cdot726\alpha$
10	$c+1\cdot321b+0\cdot860a+0\cdot158\alpha$	$f+0\cdot860d+1\cdot321e+0\cdot589\alpha$
2	$c-0\cdot328b+1\cdot079a+1\cdot540\alpha$	$f+1\cdot079d-0\cdot328e-0\cdot156\alpha$

The parameters cannot be computed uniquely, but a least-squares solution can be found using the method of the normal equations, i.e., solving instead the system:

$$A^T A\, p = A^T d \qquad (4 \times 4\ ,\ 4 \times 1,\ 4 \times 1)$$

This estimates the 4 parameters using the data of one plate.

The procedure is repeated for the **7 plates and for the 2 datasets** : Dx and Dy

The results can be combined, since α must be the same on all plates (while the calibration parameters may vary).

The procedure is also applied to the overlaid comparison-scale plates, which result in non-zero α values : a systematic value that is subtracted from the α obtained before.

Right Ascension.		Declination.	
Eclipse — Scale.	Comparison — Scale.	Eclipse — Scale.	Comparison — Scale.
r	r	r	r
+0·098	+0·042	+0·126	+0·044
+0·126	+0·024	+0·139	+0·007
+0·107	−0·015	+0·114	+0·021
+0·148	+0·018	+0·111	+0·010
+0·140	+0·020	+0·137	+0·040
+0·073	+0·005	+0·139	+0·060
+0·145	+0·008	+0·136	+0·036
Mean +0·120	+0·015	+0·129	+0·031

Finally:

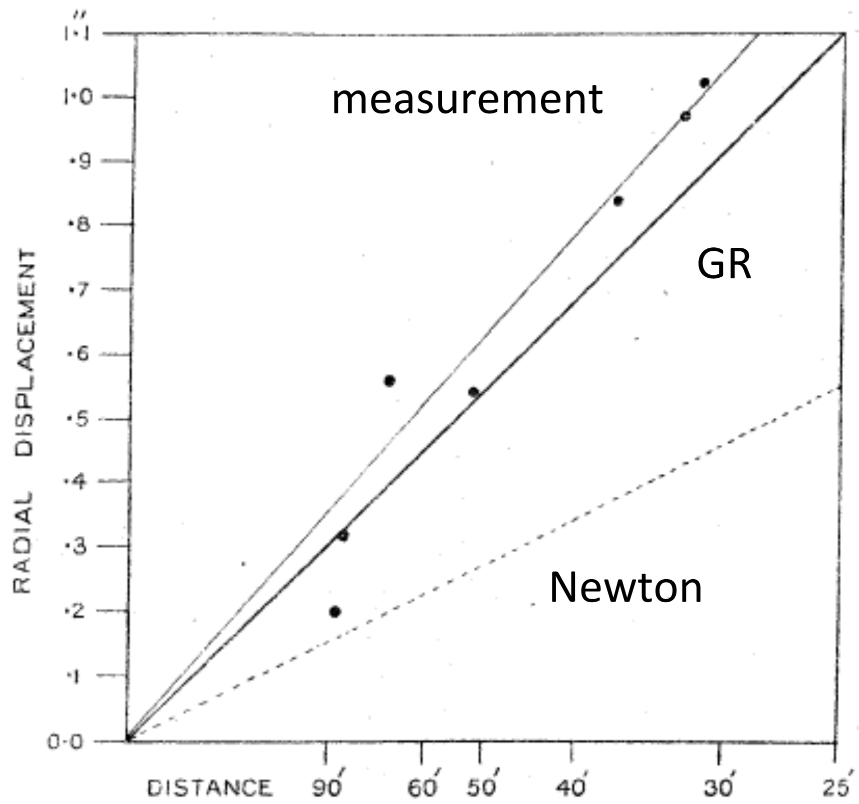
- α is averaged across the plates,
- the scale plate eliminated and
- a weighted average is made between the results from the Dx and Dy analyses

- The result is $\alpha = +0^{r} \cdot 100 = +0'' \cdot 625.$

This value refers to the reference position at 50 arcmin from the Sun's center.

The radius of the Sun is 15.8 arcmin
→ deflection at the limb is

$$\boxed{1''.98 \pm 0''.12}$$



Error analysis

Note that all measurements are presented without errors.

The final quoted **uncertainty** of 0.12'' is computed as the standard deviation of α between the various plates, divided by sqrt(28) - the number of independent datasets used (2 datasets from 14 plates).

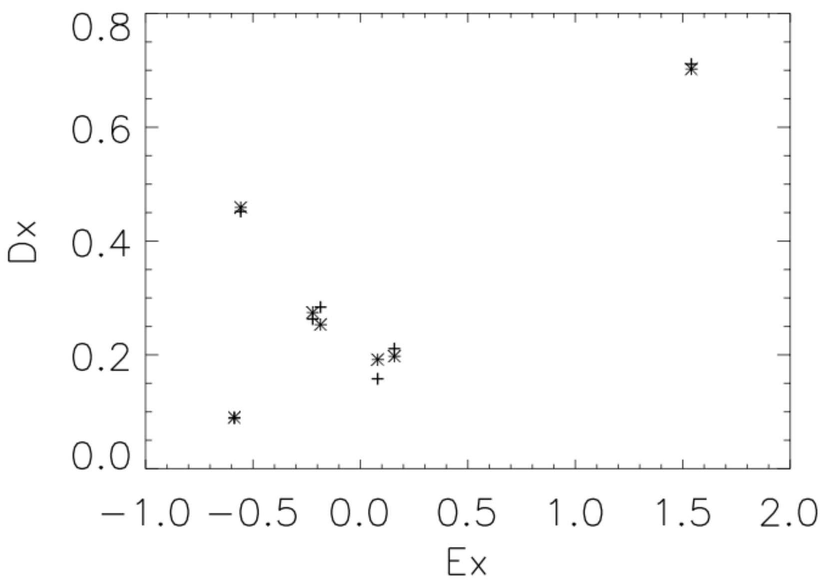
New error analysis

Made for the Dx data of 1 plate - **considering the residuals of the method of the normal equations**.

Inserting the resulting parameters in the original equation

$$ax + by + c + \alpha E_x = Dx$$

we get Dx values that differ from the measured ones. Since the parameters are computed from this “fit”, their uncertainty is related to the residuals.



An uncertainty equal to the average residual (DX_obs-Dx_fit)^2 is assigned to each star

How does this uncertainty propagate to the parameters?

It can be computed from the **Fisher matrix**:

$$F_{ij} = \sum_{\mathrm{star}} \frac{\partial D_x}{\partial p_i} \frac{1}{\sigma_{\mathrm{star}}^2} \frac{\partial D_x}{\partial p_j}$$

where the derivatives are computed at the fiducial values of the parameters (taken to be the estimated values).

The inverse of this 4 x 4 matrix is the covariance matrix in the parameters' space, containing the information on the uncertainty and correlation between the parameters.

For the first eclipse plate, the result is (1σ marginalized error)

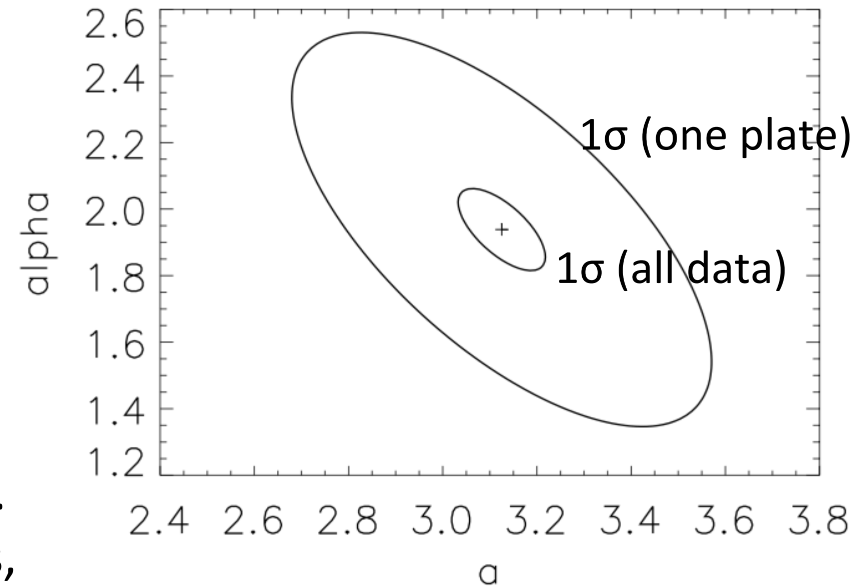
$$\alpha = 1.93'' \pm 0.39''$$

This is the result from just one plate.
We still need to add the fisher matrices of the 28 datasets.

If they are all identical, the final error is just a factor of sqrt(28) smaller, i.e.,

$$\alpha = 1.98'' \pm 0.07''$$

This method also allows us to find out correlations between the parameters



Note: The 13-inch telescope at Sobral. The images were diffused, out of focus, probably due to sun's heat on the mirror. The analysis yielded: (no error quoted). $0''\cdot 93$

The observations: **Príncipe, the external calibration method**

The instrument and observation set-up used in Príncipe were similar to the ones used in Sobral - coelostat, astrographic telescope (13-inch).

There were however some important differences between the observation conditions:

- **Cloudy skies** -

cons: the observations were made through a thin layer of clouds,
most of the eclipse plates show very few stars, and brightness changes from plate to plate and even within plates.
Mainly 2 (out of 16) plates used in the analysis (showing 5 stars: 3,4,5,6,11, which are the most useful), all others discarded or used with low weight.

pros: the brighter stars are not over-exposed, so measured with higher precision.
Also helped in keeping a remarkably uniform temperature (less than 4deg change during the whole stay, including day and night) → very important to the stability of the scale.

- Observations made in the afternoon -

cons: need to wait months before the field is visible at night (at the same altitude), so comparison plates had been taken months earlier in Oxford

pro: this forced the team to also make observations of another field at the same occasion in Oxford (check plates), around Arcturus, which was at a similar altitude.
The check field was observed again at Príncipe, with the same instrument, a few days before the eclipse. Differences between the pairs eclipse-comparison and check-check would show systematics.

So, they were lucky:

The **check field** turned out to be more crucial than supposed because due to the small number of stars observed it would not be possible to apply a global fit (the self-calibration method) and there would be no results from Príncipe.

In addition, there was a problem with the **star tracking** that forced to observe the check field at Príncipe with short exposures → turned out to match well the cloudy conditions with longer exposures.

The method

The check plates are compared
(no gravitational effect)

$$\Delta x = ax + by + c$$
$$\Delta y = dx + ey + f$$

Using the normal equations, the calibration parameters are found.

The check-check change in scale is assumed to be the same for the eclipse-comparison and their values are inserted in
(the external calibration method)

$$ax + by + c + \alpha E_x = Dx$$

$$dx + ey + f + \alpha E_y = Dy$$

However, the remaining displacements were not consistent in x and y, probably due to imperfect driving of the clock. The x (right-ascension) data is considered to be systematics. It is used to further subtract a dx (orientation) term in the equation for Dy.

Then, the computed nuisance effects due to aberration and diffraction are computed and subtracted.

Finally, the only term remaining must be the gravitational one,
and the eclipse-comparison data can be fully used to estimate α.

The residual error of each subtraction/correction is considered. The various errors are added and propagated to an error on α.

Combining the 4 results (from 2 plates), the final result quoted (at the limb) is:

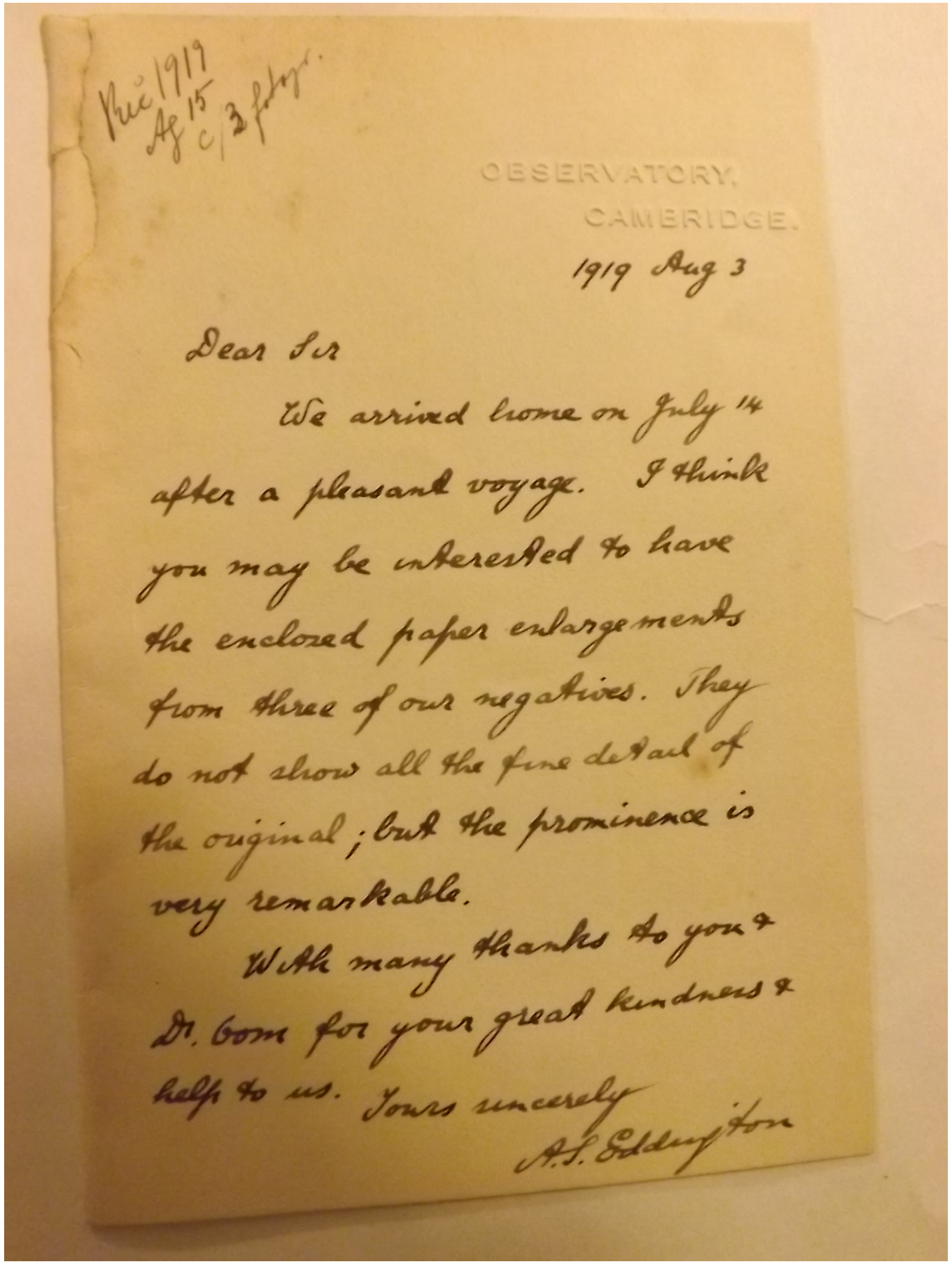
$$\boxed{1''\cdot 61 \pm 0''\cdot 30.}$$

Comparison of methods:
Using an external field in principle leads to lower statistical uncertainty on the estimated parameter (higher precision), but it can introduce bias leading to loss of accuracy.

The use of conservative errors to try to avoid biases, plus having only 4 instead of 28 datasets explains the larger uncertainty obtained for the Príncipe result.

Returning home

Eddington sends
3 prints to OAL



Rec 1919
Ag 15
c/3 fotogr.

OBSERVATORY,
CAMBRIDGE.

1919 Aug 3

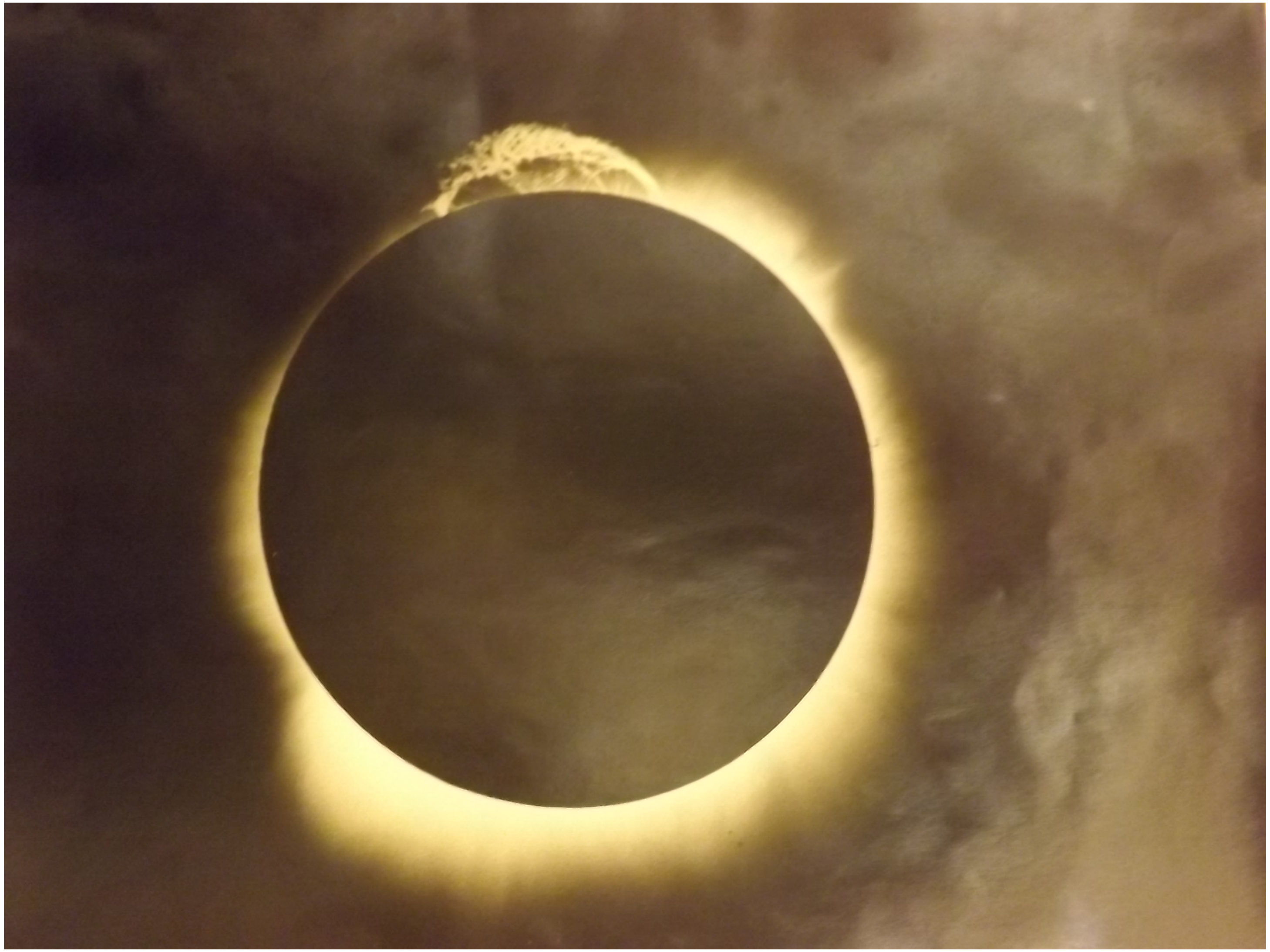
Dear Sir

We arrived home on July 14 after a pleasant voyage. I think you may be interested to have the enclosed paper enlargements from three of our negatives. They do not show all the fine detail of the original; but the prominence is very remarkable.

With many thanks to you & Dr. Oom for your great kindness & help to us. Yours sincerely

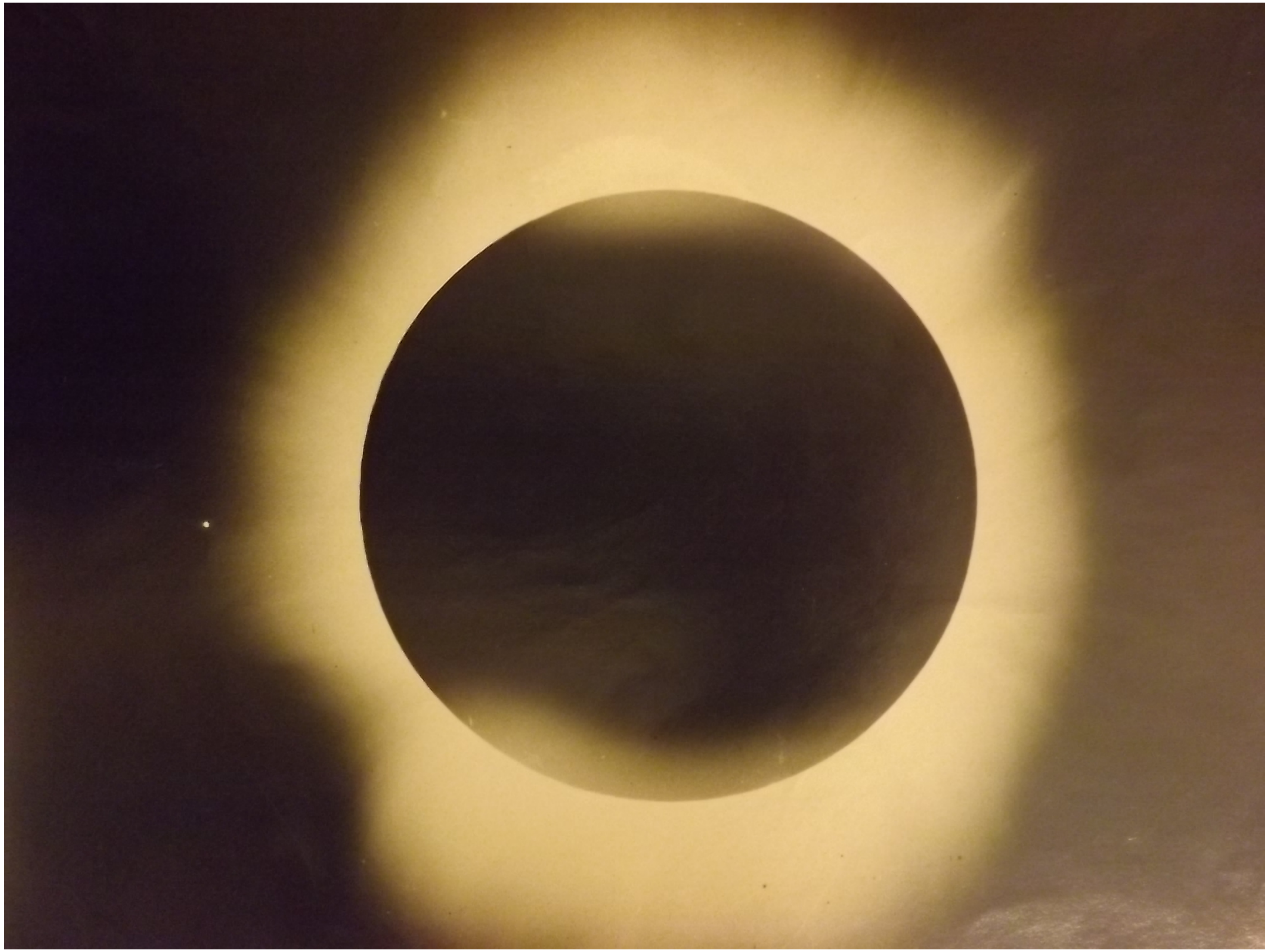
A.S. Eddington

Aug 3



(OAL archives)

Enlargement of plate R, t_exp = 20s , through thin clouds



(OAL archives)

Enlargement of plate X, t_exp = 3s , clear skies,
one of the two plates used in the analysis

OAL: a job well done

OBSERVATORIO
ASTRONOMICO
DE
LISBOA
(TAPADA)

No.1105.

Exmo. Sr.
Presidente do Centro Colonial

Tendo regressado da Ilha do Príncipe a Lisboa, em
trânsito para Inglaterra, a missão astronómica ingleza
que naqela ilha observou o eclipse do Sol em 28 de Maio,
tenho a honra e a satisfação de informar V.Exa. ter a
dita missão manifestado a este Observató
tremo reconhecimento pela maneira genero
como foi recebida e auxiliada pelo Exmo.
Carneiro e pela Companhia de Agricultura

Por isso rogo a V.Exa. se digne ace
mais profundos agradecimentos, em nome d
tório, pela maneira brilhante como foi
o desejo daquelas ilustres astrónomos t
mim ao Centro Colonial, congratulando-me
mais uma vez demostrada perante o mundo
alta compreensão que os portuguêses, em
e sempre, teem da hospitalidade e dos i
Sciéncia.

Saúde e Frate

Observatório Astronómico de Lisboa
4 de Julho de 1919.

O DIREC

The director of OAL reporting the success of the expedition to the colonial representatives and thanking again the support of the owner of Roça Sundy.

... transmitido por
mim ao Centro Colonial, congratulando-me por vêr assim
mais uma vez demostrada perante o mundo Scientífico a
alta compreensão que os portuguêses, em toda a parte
e sempre, teem da hospitalidade e dos interesses da
Sciéncia.

Saúde e Fraternidade

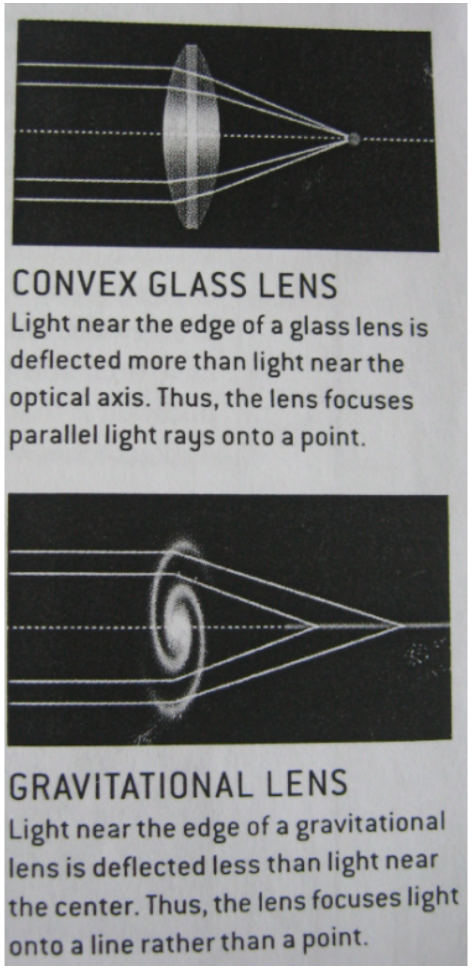
Observatório Astronómico de Lisboa (Tapada), em
4 de Julho de 1919.

O DIRECTOR,

Jul 4

2 Gravitational Lensing

The 1919 observations opened the way for a new field of astrophysics: **gravitational lensing**, the effect of deflection of light by a gravitational field


CONVEX GLASS LENS

Light near the edge of a glass lens is deflected more than light near the optical axis. Thus, the lens focuses parallel light rays onto a point.

GRAVITATIONAL LENS

Light near the edge of a gravitational lens is deflected less than light near the center. Thus, the lens focuses light onto a line rather than a point.

Some properties of gravitational lensing

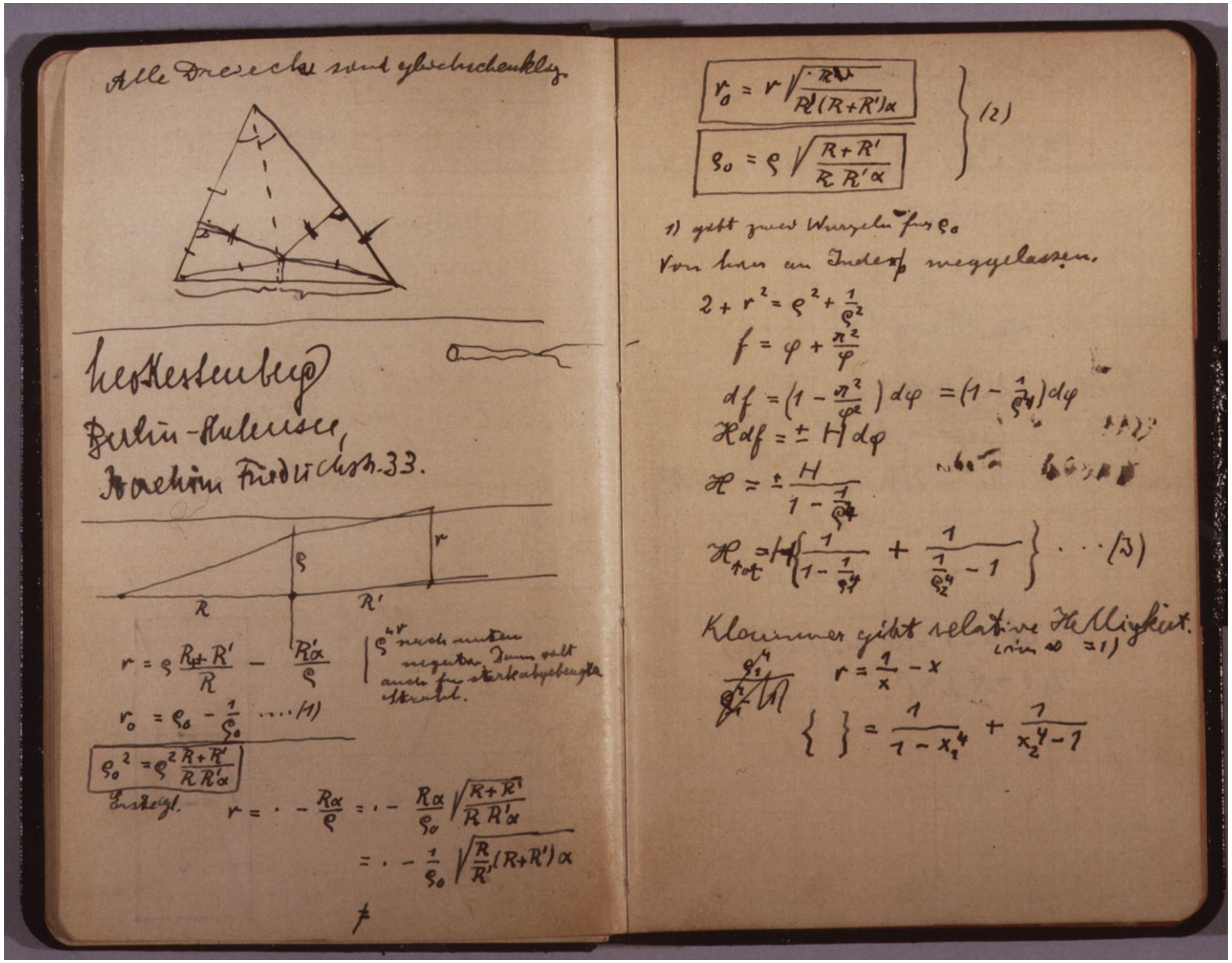
- does not have a focal point
- produces no emission or absorption of photons
- it is achromatic , no frequency shift from source to image
- it is independent of luminosity
- conserves surface brightness

There are many more lensing effects besides the light deflection of a point source by a spherical mass:

- **Change of position** of images
- **Distortion** of extended sources
- **Multiple images**
- **Time-delays**
- **Magnification**: increase of size + conservation of brightness $\rightarrow$ increase of flux (**natural telescope**)
- **Demagnification**

Einstein 1912, Notebook

Unpublished work, described in Renn, Sauer, Stachel 1997
“The origin of gravitational lensing”



Lens equation

Double images

Magnification factor

with the factor of 2 missing

Gravitational Lensing:

the dark ages - a tidal effect impossible to observe

No astrophysical interest

It seems it was more like a curiosity, since it was thought there was no great chance of observing this phenomenon:

small displacements

lensed image would be overwhelmed by the brightness of the lens

Even the deflection at the Sun's limb was very difficult to measure.

Some later eclipse expeditions could not reproduce Eddington's result, others did. Controversies about the measurement.

But reanalyses of the same data gave similar results. Einstein centenary reanalysis (1979):

A comparison of data

Instrument	1919 result	1979 result
4-inch lens	1.98″ ± 0.18″	1.90″ ± 0.11″
Astrographic lens	0.93″	1.55″ ± 0.34″

1920 - 1960 Very few publications on Gravitational Lensing

Chowlson 1924 - multiple images (star-star), ring

Etherington 1933 - conservation of surface brightness

Einstein 1936

"Lens-like action of a star by the deviation of light in the gravitational field"

LENS–LIKE ACTION OF A STAR BY THE DEVIATION OF LIGHT IN THE GRAVITATIONAL FIELD

SOME time ago, R. W. Mandl paid me a visit and asked me to publish the results of a little calculation, which I had made at his request. This note complies with his wish.

New calculations (with the factor of 2) for:

The **Einstein ring**

It follows from the law of deviation that an observer situated exactly on the extension of the central line $\overline{AB}$ will perceive, instead of a point-like star A, a luminius circle of the angular radius β around the center of B, where

$$\beta = \sqrt{\alpha_0 \frac{R_0}{D}}.$$

Of course, there is no hope of observing this phenomenon directly. First, we shall scarcely ever approach closely enough to such a central line. Second, the angle β will defy the resolving power of our instruments. For, α_0 being of the order of magnitude of one second of arc, the angle R_0/D, under which the deviating star B is seen, is much smaller. Therefore, the light coming from the luminous circle can not be distinguished by an observer as geometrically different from that coming from the star B, but simply will manifest itself as increased apparent brightness of B.

Magnification

The apparent brightness of A will be increased by the lens-like action of the gravitational field of B in the ratio q. This q will be considerably larger than unity only if x is so small that the observed positions of A and B coincide, within the resolving power of our instruments. Simple geometric considerations lead to the expression

$$q = \frac{l}{x} \cdot \frac{1 + \frac{x^2}{2l^2}}{\sqrt{1 + \frac{x^2}{4l^2}}},$$

where

$$l = \sqrt{\alpha_0 D R_0}.$$

Therefore, there is no great chance of observing this phenomenon, even if dazzling by the light of the much nearer star B is disregarded. This apparent amplification of q by the lens-like action of the star B is a most curious effect, not so much for its becoming infinite, with x vanishing, but since with increasing distance D of the observer not only does it not decrease, but even increases proportionally to $\sqrt{D}$.

The increase of magnification with the distance turned out to be key for the future of gravitational lensing: to go **extragalactic**

Zwicky 1937: galaxies could act as gravitational lenses, and also be used to detect dark matter

Gravitational Lensing:

the 1960's renaissance

A new potential source

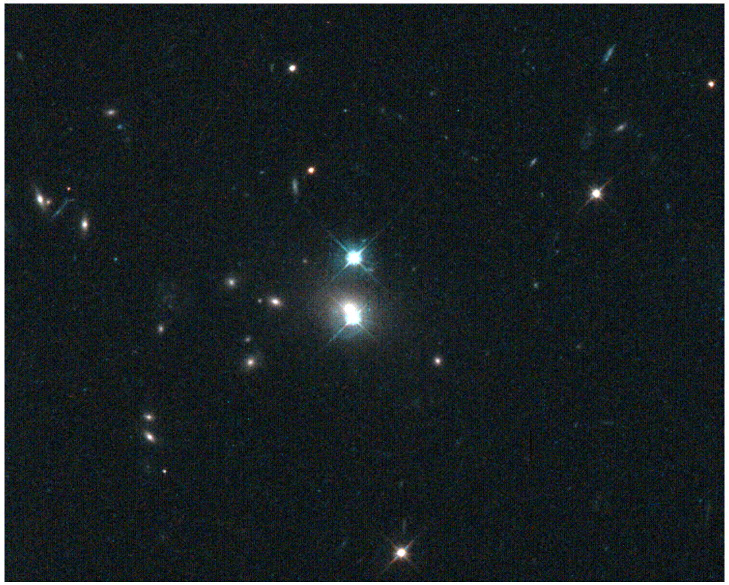
Discovery of quasars (Schmidt 1963): very distant, luminous and compact objects → good lensing sources

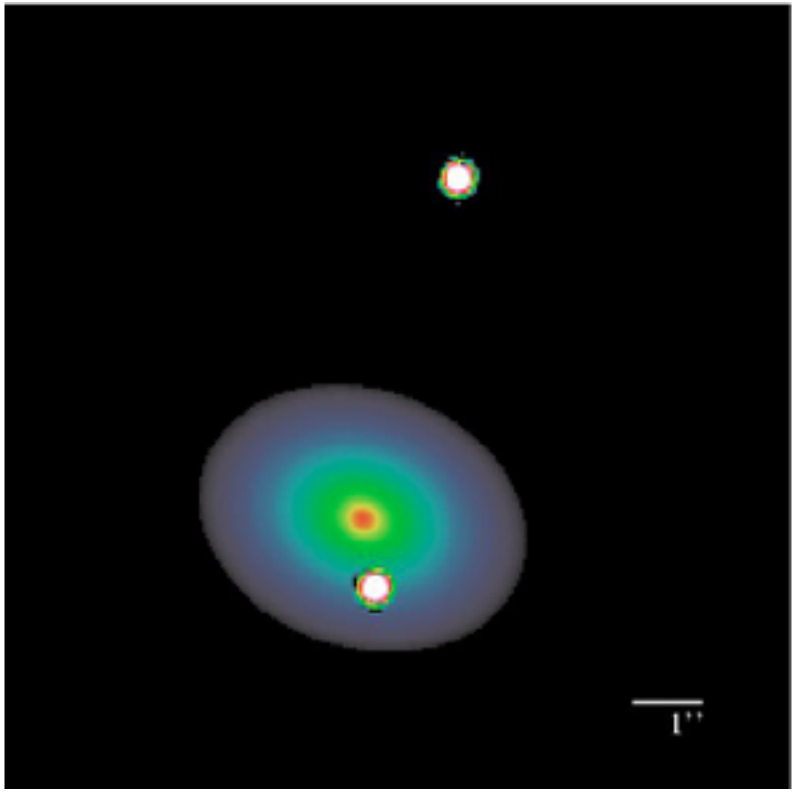
First observation of the lensing effect (Walsh, Carswell and Weymann 1979)

z_lens (galaxy) = 0.36

z_source (quasar) = 1.4

separation = 5''.7



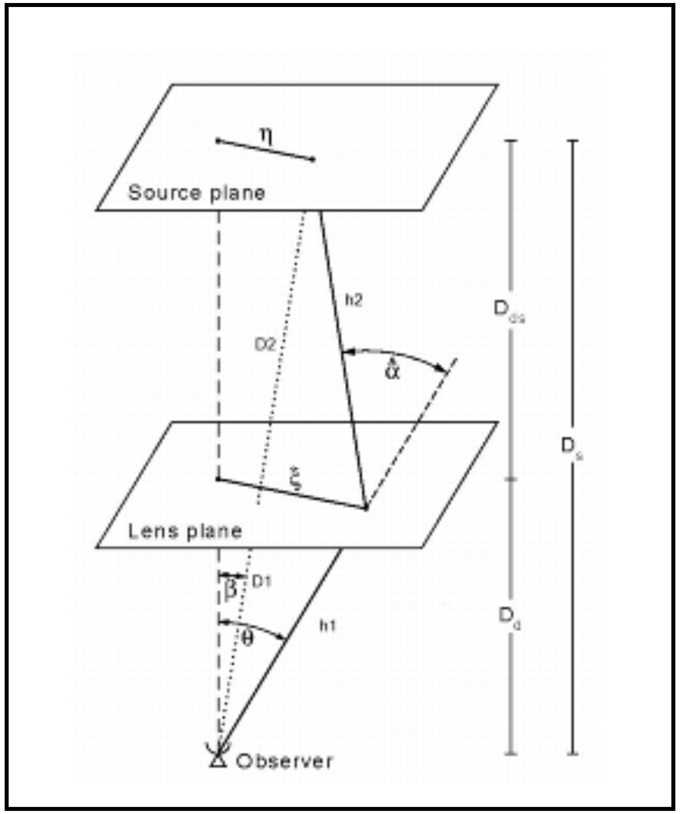


New theoretical developments

Klimov 1963: galaxy-galaxy lensing

Liebes 1964: star-star lensing

Refsdal 1964:
cosmological applications;
evolution of a bundle of
geodesics (Sachs);
time-delay



optical axis

source position

impact
parameter

deflection
angle

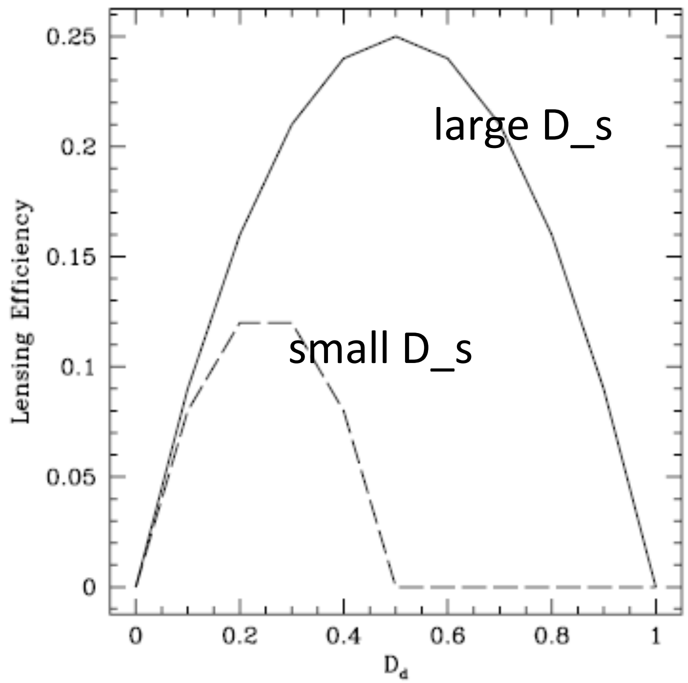
image position

The lens equation

$$D_s\vec{\theta} = D_s\vec{\beta} + 2D_{ds}\frac{\hat{\vec{\alpha}}}{2}$$ (vector addition on the source plane)

The lens equation is a mapping between source and image planes.

The central quantity of gravitational lensing is the vectorial field α which contains the dependence on the deflection potential.



The **deflection field** contains the physics of the lens, and the gravity model

$$\vec{\alpha} = -\frac{2}{c^2}\int_{\lambda_A}^{\lambda_B} \dot{\vec{u}}_x \, d\lambda = \frac{2}{c^2}\int_{\lambda_A}^{\lambda_B} \vec{\nabla}_{\perp}\Phi \, d\lambda,$$

It depends on the gradient of the potential on the lens plane → on the 2D projection of the mass density of the lens on the lens plane

The lens equation can be written in the form,

$$\vec{x}(\vec{\theta}, w) = f_K(w)\vec{\theta} - \frac{2}{c^2}\int_0^w dw' \, f_K(w - w')\left[\vec{\nabla}_{\perp}\Phi(\vec{x}(\vec{\theta}, w'), w') - \vec{\nabla}_{\perp}\Phi(0, w')\right] \Leftrightarrow$$

$$\Leftrightarrow \beta_i(\vec{\theta}, w) = \theta_i - \frac{2}{c^2}\int_0^w dw' \, \frac{f_K(w - w')}{f_K(w)} f_K(w')\left[\Phi_{,i}\left(\vec{x}(\vec{\theta}, w'), w'\right) - \Phi_{,i}\left(0, w'\right)\right].$$

integration over comoving cosmological distances

Distortion and Magnification

Extended sources are differentially distorted by the tidal field of the lens (spatial derivatives of alpha). Local linearization:

$$\beta(\theta) = \beta(\theta_0) + A(\theta_0).(\theta - \theta_0)$$ + higher-orders

Amplification matrix

$$A_{ij}(\theta) = \frac{\partial \beta_i}{\partial \theta_j} = \left(\delta_{ij} - \frac{\partial \alpha_i}{\partial \theta_j}\right)$$

symmetrical traceless
antisymmetrical
trace

$$A = \begin{bmatrix} \sigma_1 & \sigma_2 \\ \sigma_2 & -\sigma_1 \end{bmatrix} + \begin{bmatrix} 0 & \omega \\ -\omega & 0 \end{bmatrix} + \begin{bmatrix} \Theta/2 & 0 \\ 0 & \Theta/2 \end{bmatrix}$$

3 independent **distortions**: **shear, rotation, convergence**

$$\begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix}$$

magnification

$$\mu = \frac{1}{det\, A} = \frac{1}{(1-\kappa)^2 - \gamma^2}$$

Gravitational Lensing:

the modern times

A multitude of lensing systems and applications

det A = 0 defines critical lines in the image plane,
mapped to caustic lines in the source plane:

- Defining regions of high distortion and multiple images:

Spherical lens

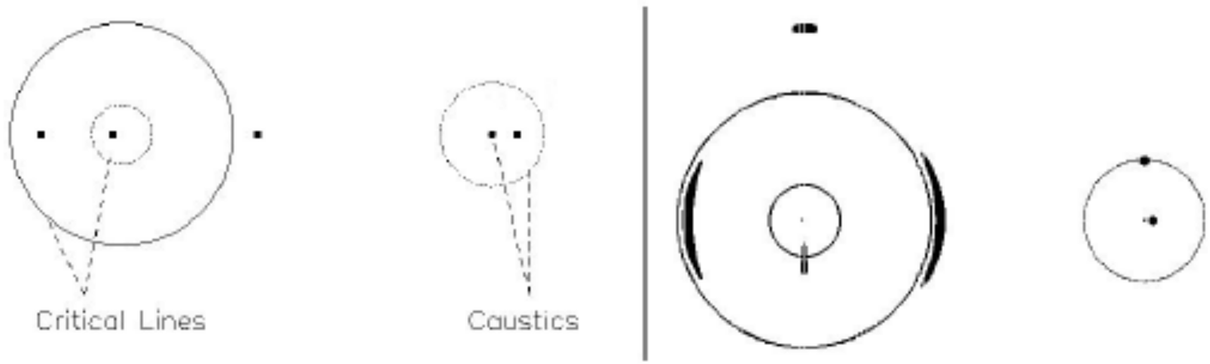
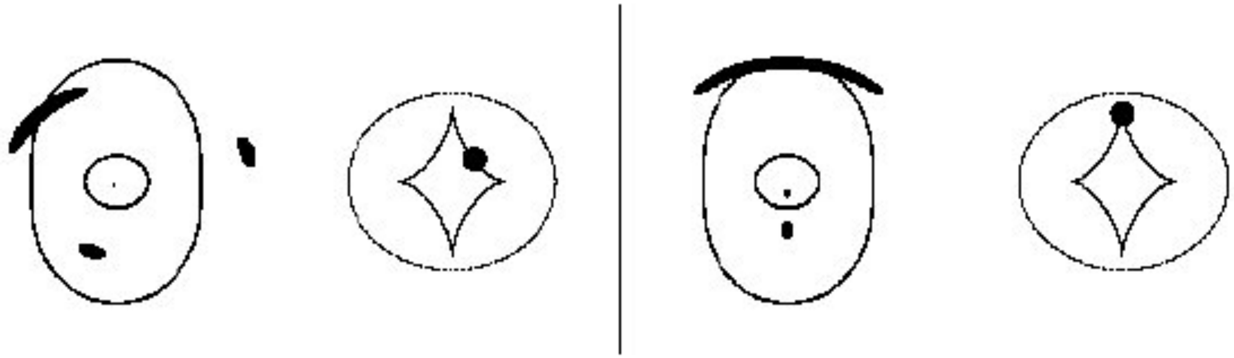


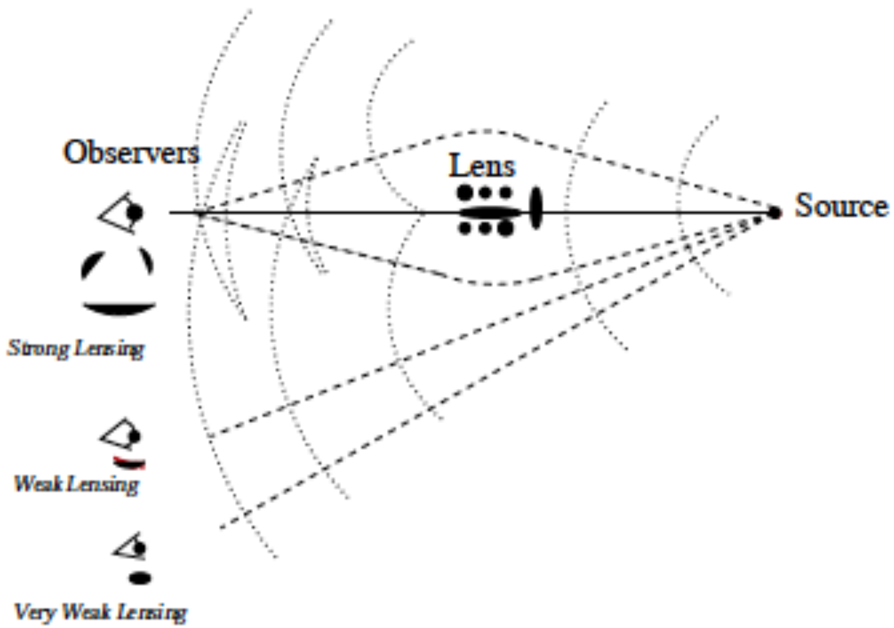
image point source image extended source

Elliptical lens



- Defining regions of small k, no arcs or multiple images:

This defines 2 regimes: Strong Lensing / Weak Lensing

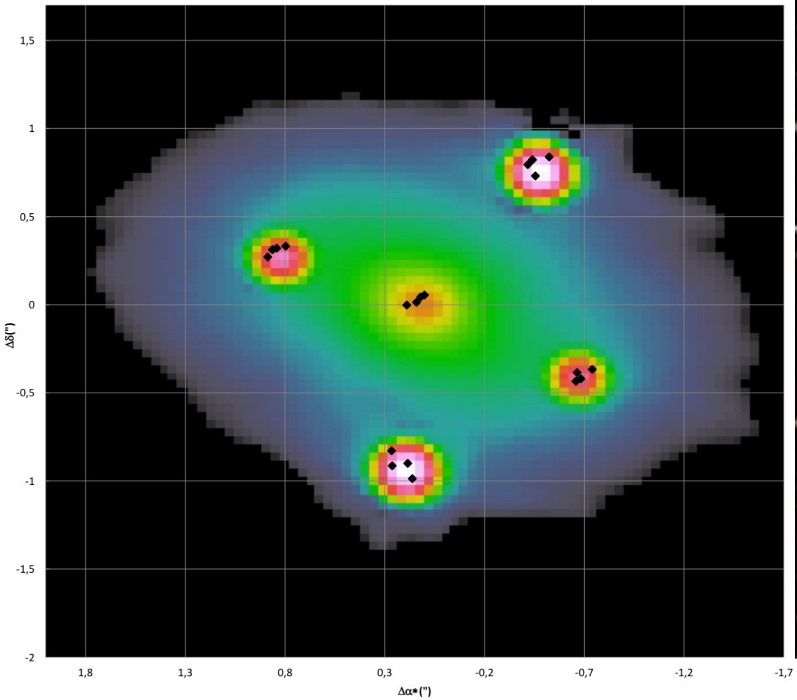


that exist in various scales and astrophysical systems

#	Source	Lens	Effects	Applications
1	Quasar	Galaxy	**SL:** multiple images, Einstein rings, time delays, **ML:** variable lightcurves	mass of galaxies, satellites, substructure, H_0, Ω_Λ, size of quasars
2	Star (extra-galactic)	Compact object (galactic)	**ML:** peak in lightcurve	dark matter in Milky Way halo
3	Star (galactic)	Star (galactic)	**ML:** perturbed peak in lightcurve	extrasolar planets, MW inner structure, M31 structure, limb darkening
4	Galaxy	Cluster	**SL:** multiple images, giant arcs **WL:** arclets, magnification bias	total mass of cluster, Ω_Λ, redshifts, cluster mass profile, clusters morphology
5	Galaxy	Galaxy	**StWL:** ellipticity bias, shear-galaxy correlation	galaxies parameters, haloes properties
6	Galaxy	Large scale structure	**StWL:** cosmic shear, shear-shear correlation	cosmological parameters, matter power spectrum
7	Quasar	Large scale structure	**StWL:** cosmic magnification, quasar-galaxy correlation	cosmological parameters, matter power spectrum, bias
8	Last Scattering surface	Large scale structure	**StWL:** smoothing of CMB T-T correlation	cosmological parameters from lensed C_ℓ, matter power spectrum

Galaxy strong lensing:
RCS2 032727-132623
(HST)

Quasar strong lensing:
Einstein Cross
(Gaia)



Galaxy weak lensing:
Bullet Cluster
(HST, Chandra, ESO)

In all systems the observed effects of GL allow us to constrain the lens model:

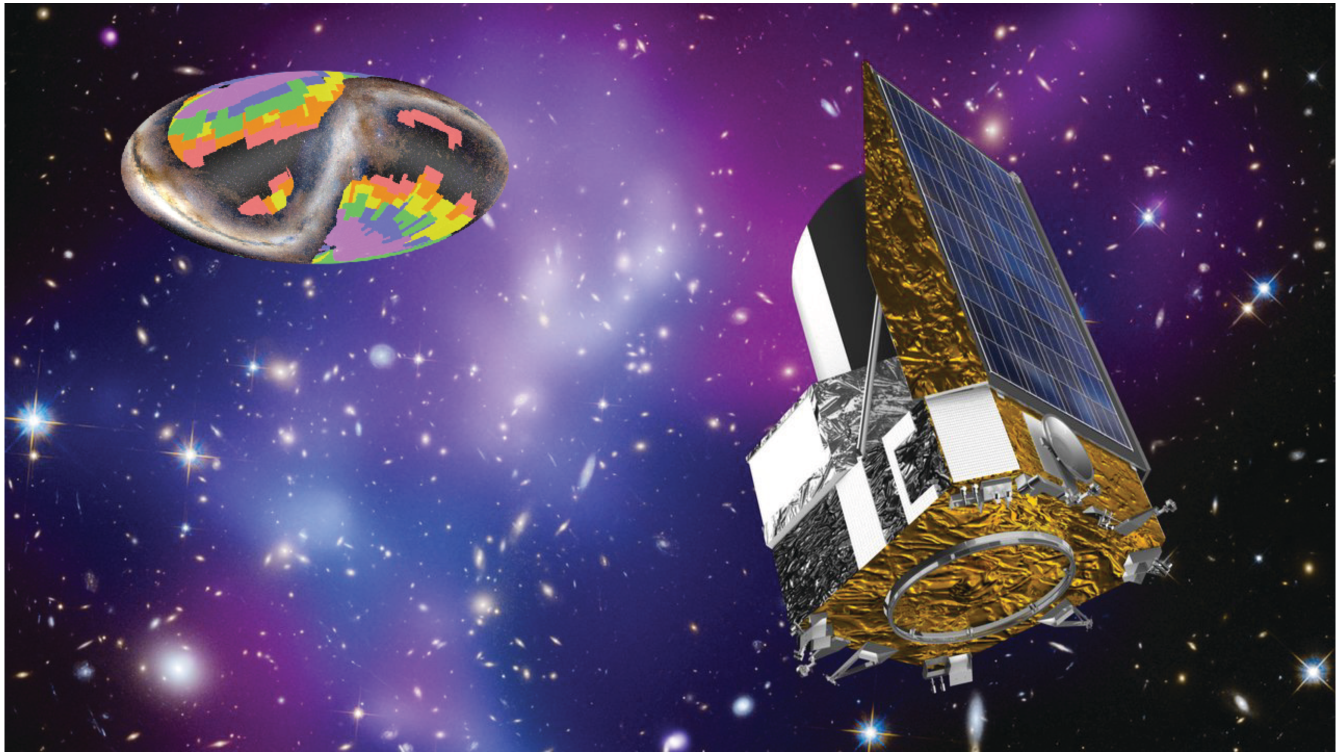
measure the images positions, distortions or fluxes + measure the distances to the lens and to the source → the deflection field produced by the lens → its gravitational potential → the total mass and matter distribution in the lens.

If we already know the mass of the lens (if the lens model is known) → then **it is also a way to test gravity**.

3

The Euclid space mission

Testing General Relativity 100 years later (on large scales)



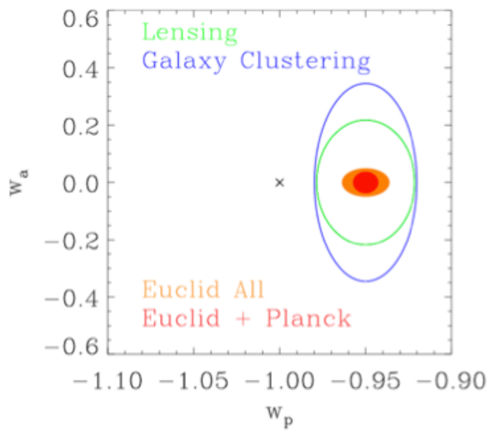
ESA Cosmic Vision M2 mission

Launching date: 2022

euclid

Euclid consortium

Its goal is to understand the nature of dark energy and dark matter by:



- reaching a dark energy 1σ Figure-of-Merit > 400
- testing the cold dark matter paradigm, measuring the sum of the neutrino masses with 1σ < 0.03eV
- measuring the growth rate parameter γ with 1σ < 0.02, and constrain gravity potentials Ψ and Φ separately
- constraining initial conditions, n_s, non-Gaussianity

Two cosmological probes

Galaxy Clustering: measurements of 3D galaxy positions (in redshift space) → 3D positions in coordinate space (peculiar velocities) → 3D correlation function of galaxies → 3D correlation function of dark matter

Weak Lensing cosmic shear: measurements of galaxy shapes (ellipticities) → tomographic correlation function of lensing shear → correlation function of dark matter

The combination of the two probes is **a modern-day cosmological test of GR** using light deflection:

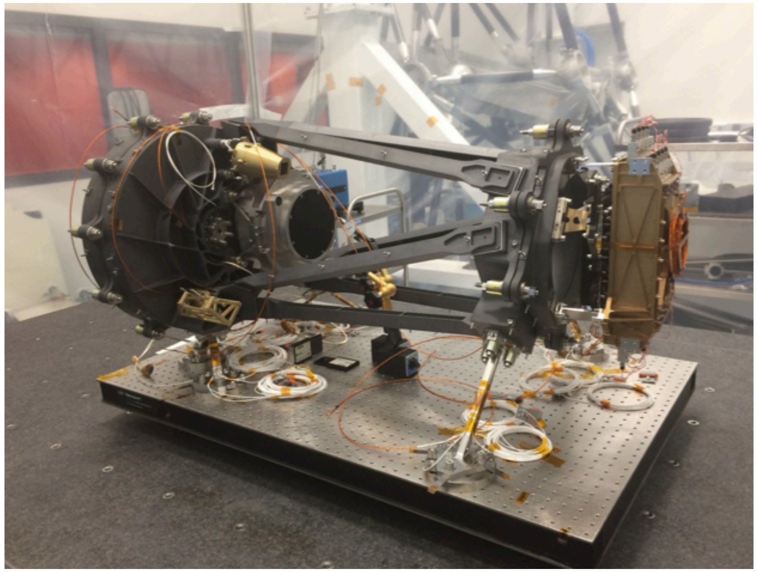
- GC depends on the peculiar velocity field of non-relativistic particles → related to $\nabla \Psi$

- WL depends on null geodesics → related to $\nabla^2(\Phi + \Psi)$

However this test is not the heir of the eclipse measurements → that would be an **astrometry** mission like Gaia (with a precision of 10^-5 arcsec).

Two instruments

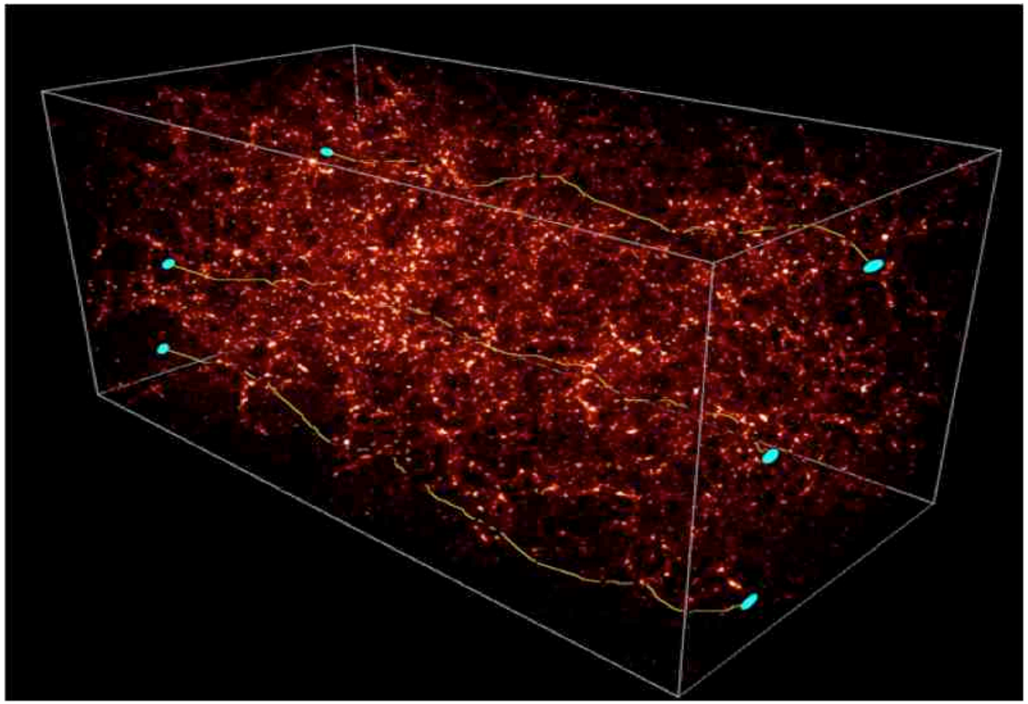
VIS (Visible imager): Broad filter 500 - 900 nm , detection limit m_AB = 24.5 (10σ extended source) → enabling accurate galaxy shape measurements of an average of 30 galaxies per sq.arcmin

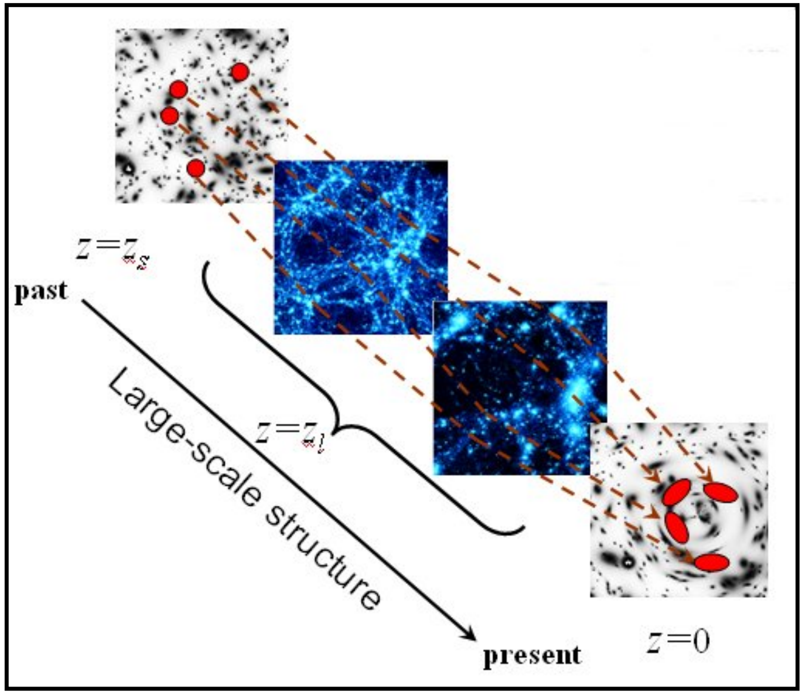


NISP (Near infra-red spectrometer and photometer): NIR photometry down to m_AB = 24 (5σ point source) in Y, J, H bands filter 500 - 900 nm; and slitless spectroscopy in 0.92-1.85 μm for Hα emission lines with flux-limit f_Hα = 2 × 10^-16 erg /cm^2 /s → enabling accurate redshift measurements of an average of 1700 galaxies per sq.deg

Cosmic shear: a cosmological gravitational lensing system

The large-scale structure of dark matter (the lens) produces a differential deflection on the light emitted by extended sources (background galaxies) → shear and convergence distortions.





It is a direct tracer of the dark matter distribution

The first detection of cosmic shear was considered **evidence for the large-scale structure of dark matter**

4 papers submitted do arXiv on march 2000 by 4 independent teams

Detection of correlated galaxy ellipticities from CFHT data: first evidence for gravitational lensing by large-scale structures ⋆

L. Van Waerbeke[1], Y. Mellier[2,3], T. Erben[4], J.C. Cuillandre[5], F. Bernardeau[6], R. Maoli[2,3], E. Bertin[2,3], H.J. Mc Cracken[7], O. Le Fèvre[7], B. Fort[2], M. Dantel-Fort[3], B. Jain[8], P. Schneider[4]

Detection of Weak Gravitational Lensing by Large-scale Structure

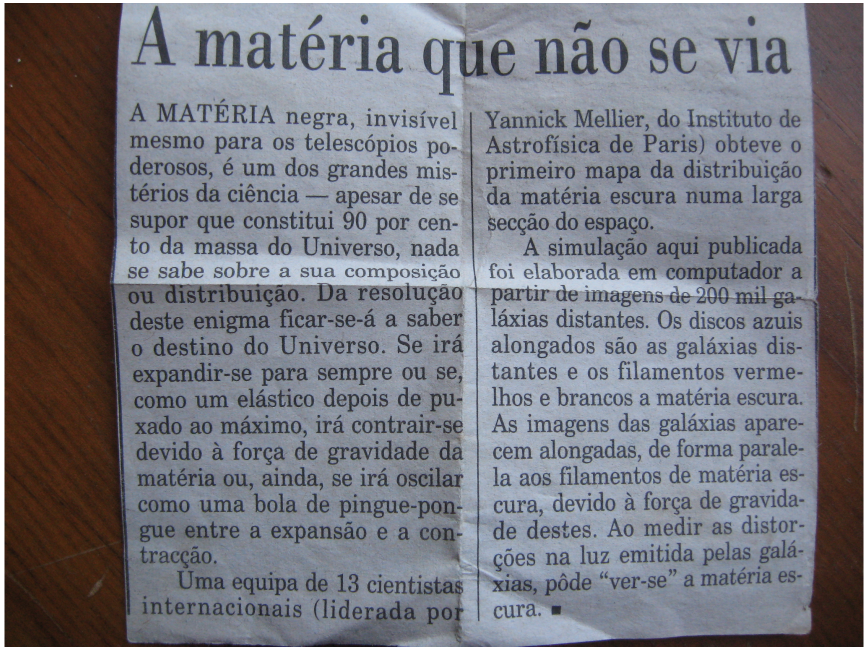
David J. Bacon,[1⋆] Alexandre R. Refregier[1] & Richard S. Ellis[1,2]

Detection of weak gravitational lensing distortions of distant galaxies by cosmic dark matter at large scales

David M. Wittman*, J. Anthony Tyson, David Kirkman, Ian Dell'Antonio[†], and Gary Bernstein[‡]

LARGE-SCALE COSMIC SHEAR MEASUREMENTS

NICK KAISER, GILLIAN WILSON AND GERARD A. LUPPINO


A matéria que não se via

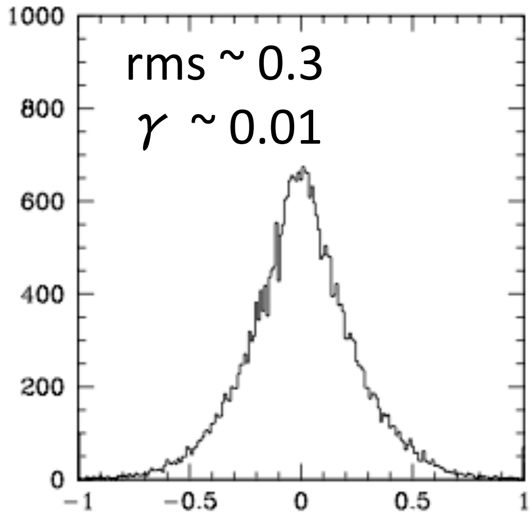
A MATÉRIA negra, invisível mesmo para os telescópios poderosos, é um dos grandes mistérios da ciência — apesar de se supor que constitui 90 por cento da massa do Universo, nada se sabe sobre a sua composição ou distribuição. Da resolução deste enigma ficar-se-á a saber o destino do Universo. Se irá expandir-se para sempre ou se, como um elástico depois de puxado ao máximo, irá contrair-se devido à força de gravidade da matéria ou, ainda, se irá oscilar como uma bola de pingue-pongue entre a expansão e a contracção.

Uma equipa de 13 cientistas internacionais (liderada por Yannick Mellier, do Instituto de Astrofísica de Paris) obteve o primeiro mapa da distribuição da matéria escura numa larga secção do espaço.

A simulação aqui publicada foi elaborada em computador a partir de imagens de 200 mil galáxias distantes. Os discos azuis alongados são as galáxias distantes e os filamentos vermelhos e brancos a matéria escura. As imagens das galáxias aparecem alongadas, de forma paralela aos filamentos de matéria escura, devido à força de gravidade destes. Ao medir as distorções na luz emitida pelas galáxias, pôde "ver-se" a matéria escura. ■

In Eddington's observations, they could "**remove the lens** out of the way" and measure the original and lensed positions.

Here we cannot remove the lens. How do we compare the original and lensed shapes? It is not possible to detect the lensing effect on a single galaxy because its original shape is not known and the cosmological effect is sub-dominant.

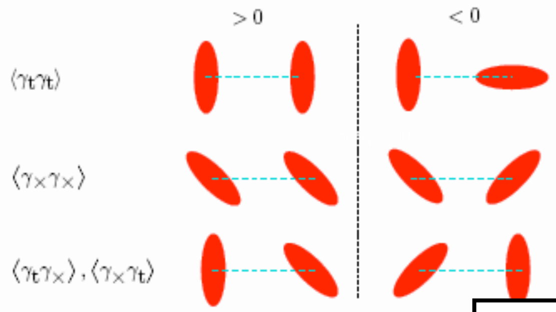


Look for **correlations** → it is a **statistical measurement**.

If the source galaxies are **randomly orientated** → off-diagonal correlations are the cosmological gravitational lensing signal (but may also include astrophysical biases)

The statistical properties of the convergence and shear fields are related to statistical properties of the lensing potential field.

Correlation of the shear at two points yields four quantities



Parity conservation $\longrightarrow \langle\gamma_t\gamma_\times\rangle = \langle\gamma_\times\gamma_t\rangle = 0$

Shear two-point correlation function (2PCF)

$$\xi_+(\vartheta) = \langle\gamma_t\gamma_t\rangle(\vartheta) + \langle\gamma_\times\gamma_\times\rangle(\vartheta)$$
$$\xi_-(\vartheta) = \langle\gamma_t\gamma_t\rangle(\vartheta) - \langle\gamma_\times\gamma_\times\rangle(\vartheta)$$

Ex: matter power spectrum

$$\boxed{P_\gamma^{ij}(\ell) = \frac{9}{4}\,\Omega_{\rm m}^2 H_0^4 \int_0^{w_{\rm h}} dw \frac{g_i(w) g_j(w)}{a^2(w)}\, \Sigma^2(a) P_\delta\left(\frac{\ell}{w}, w\right)}$$

The tomographic power spectrum of shear (for various source redshifts) has information on:

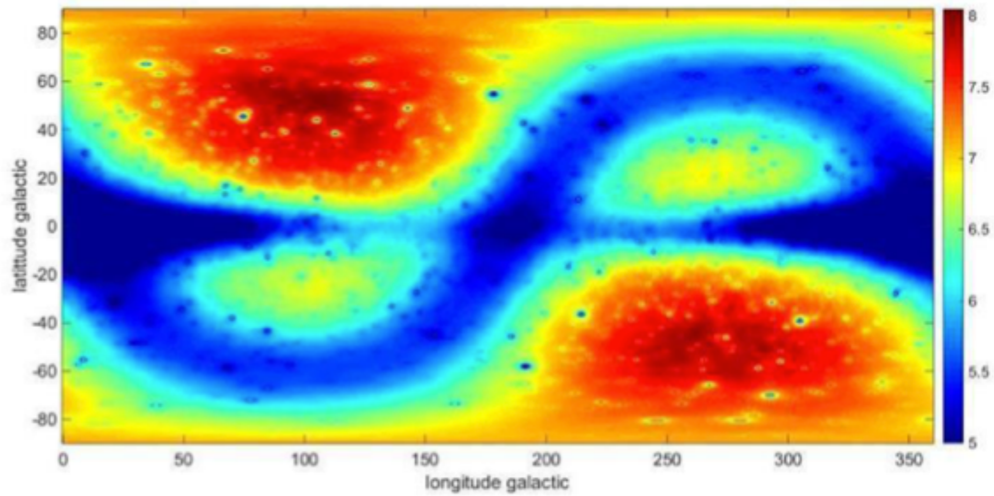
- evolution of the matter power spectrum → dark energy
- shape of the matter power spectrum → initial conditions
- amplitude of the matter power spectrum → gravity $\Sigma(a) = Q(a)(1+\eta(a)/2)$

$\Psi = (1+\eta)\Phi$ G_eff = G Q

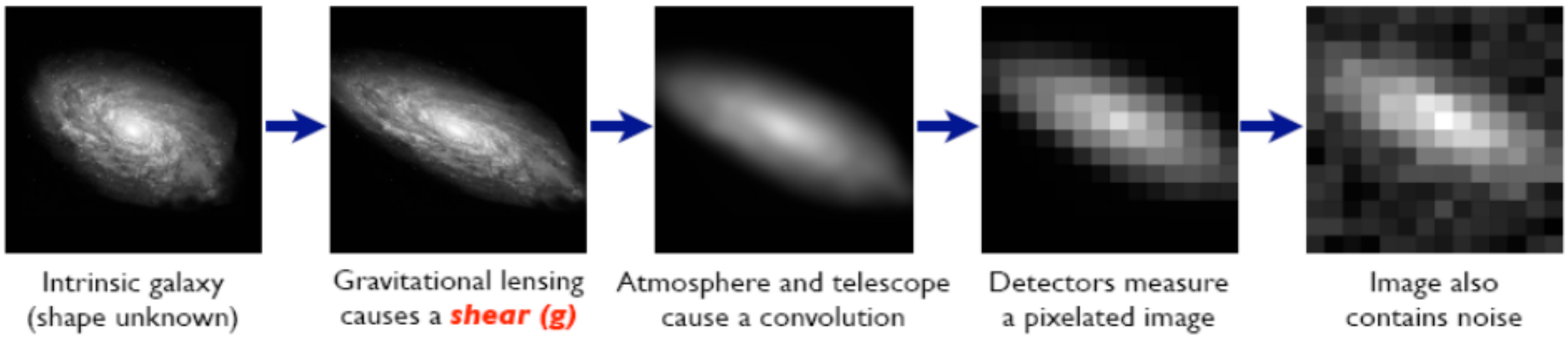
To reach the requirements on the cosmological parameters, **the measurements need to have very high precision and accuracy:**

shape measurement bias < 0.001
mean redshift 1σ < 0.002

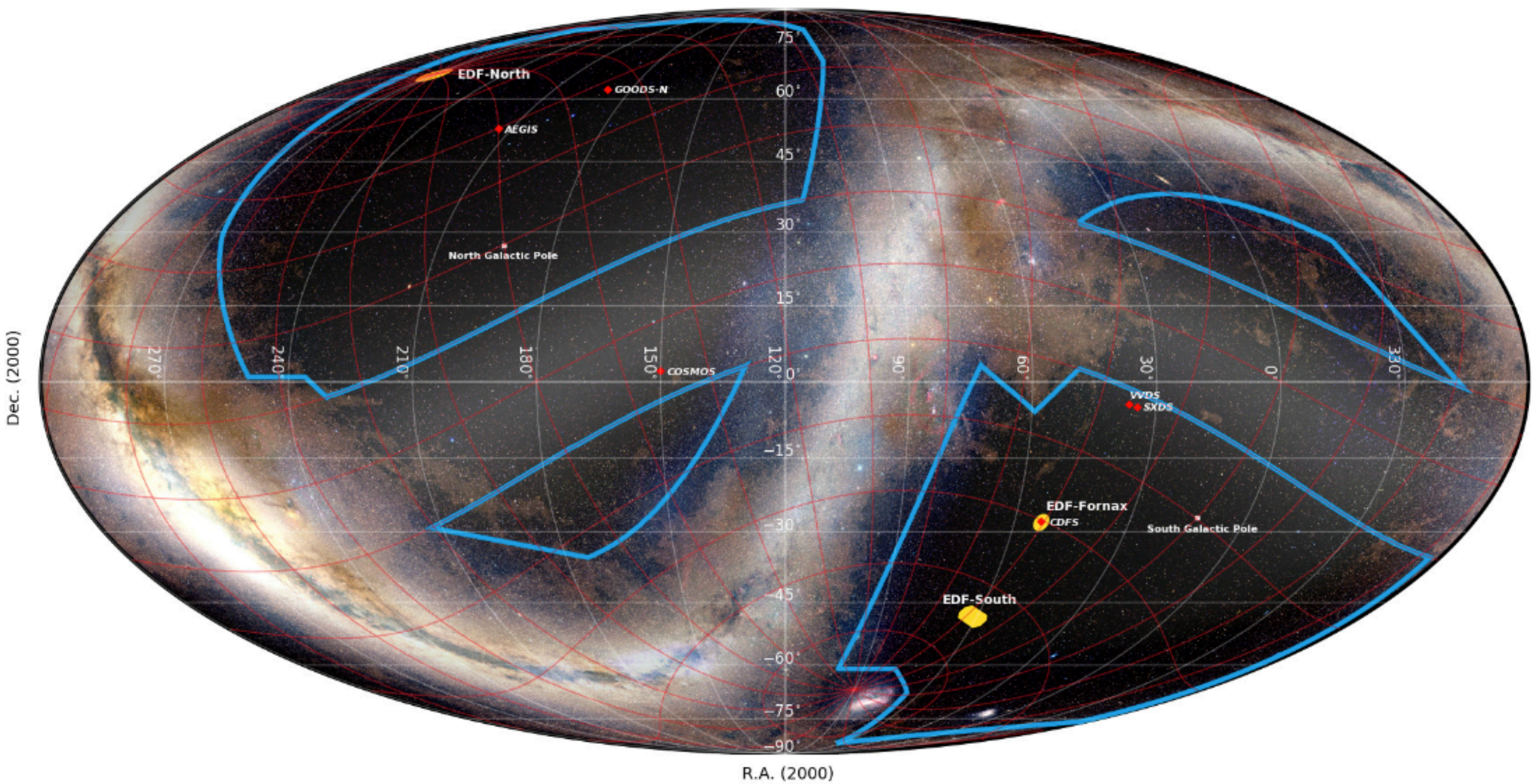
Need to go to space to enable the image quality and stability in the visible band required for WL, and dramatically increase the SNR in the NIR bands.



Galaxies: Intrinsic galaxy shapes to measured image:



The requirement is to build an extra-galactic sky survey with
15 000 sqdeg → ~ 10^9 WL galaxies and 50 million spectroscopic redshifts
and complementary ground-based observations for photometric redshits



The Euclid Wide Survey (EWS) with the Euclid Deep Survey (EDF) and the deep Euclid Calibration Fields [Mollweide Equatorial]

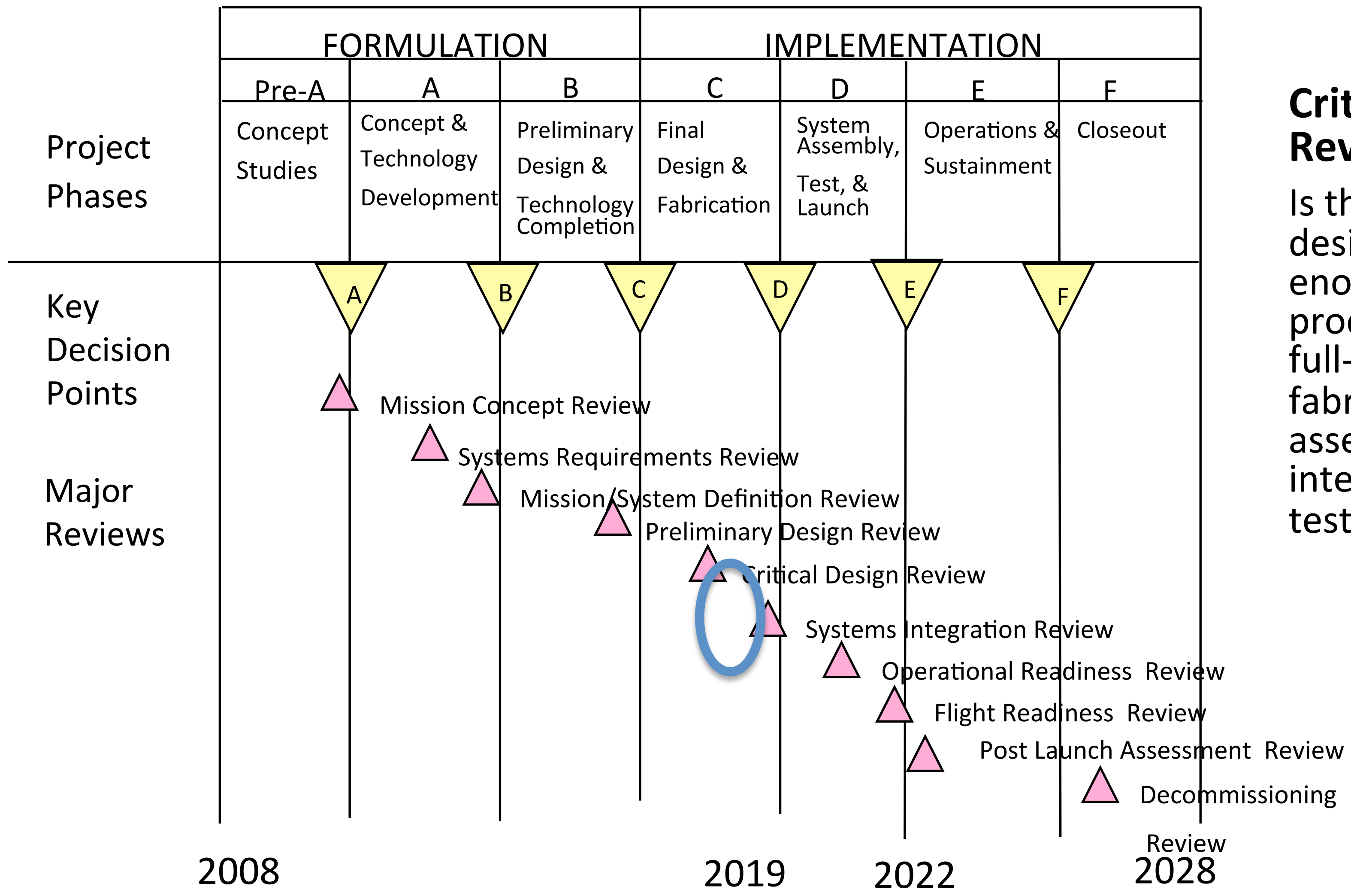
Euclid Wide Survey : 15,000 deg.^{2}

Euclid Deep Fields : North=10 deg.^{2}, Fornax=10 deg.^{2}, South=20 deg.^{2}

Euclid deep calibration fields marker (diamond not to scale)

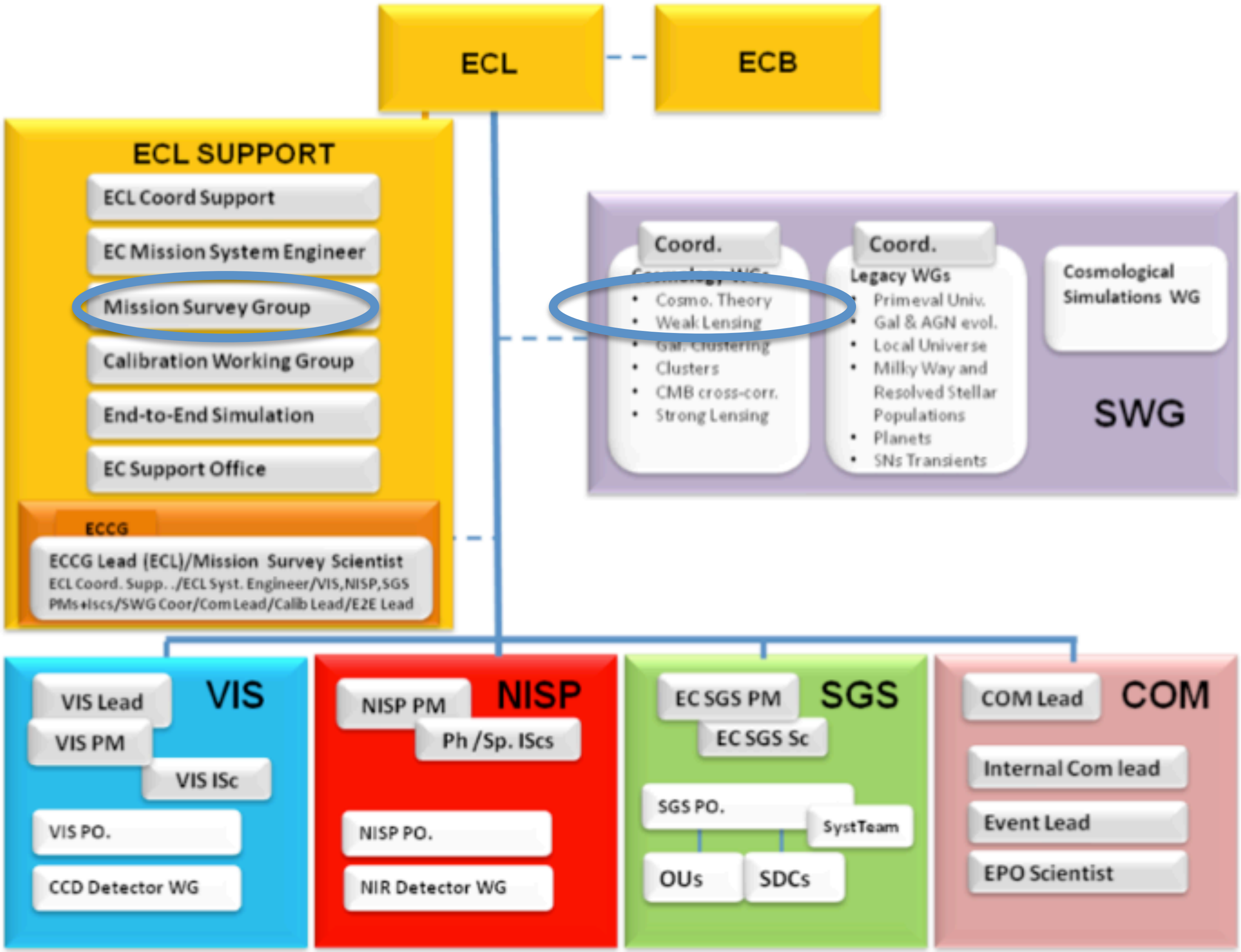
Background image: Euclid Consortium / A. Mellinger / Planck Collaboration

The Euclid Collaboration defines and implements the mission. It consists on the Euclid Consortium with 1500 members from 200 institutions in 14 European countries, and Canada and USA + ESA + industrial partners

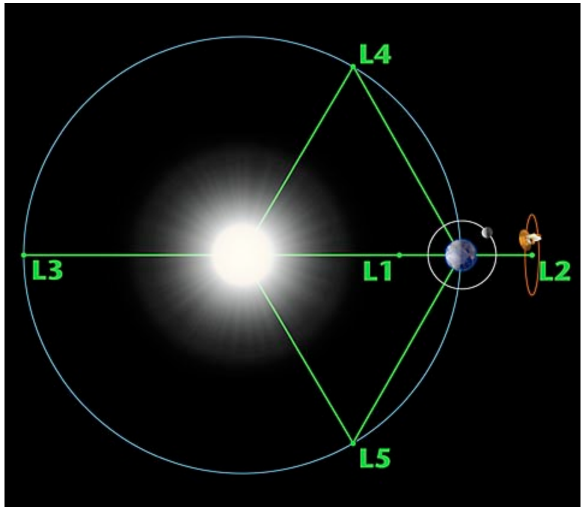


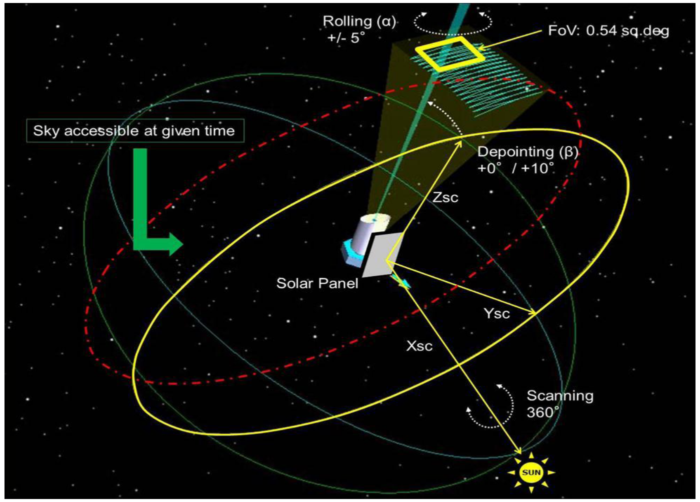
Critical Design Review:

Is the system design mature enough to proceed with full-scale fabrication, assembly, integration and test?


ECL
ECB
ECL SUPPORT
ECL Coord Support
EC Mission System Engineer
Mission Survey Group
Calibration Working Group
End-to-End Simulation
EC Support Office
ECCG
ECCG Lead (ECL)/Mission Survey Scientist
ECL Coord. Supp../ECL Syst. Engineer/VIS,NISP,SGS PMs+Iscs/SWG Coor/Com Lead/Calib Lead/E2E Lead
Coord.
Cosmo. Theory
Weak Lensing
Gal. Clustering
Clusters
CMB cross-corr.
Strong Lensing
Coord.
Legacy WGs
Primeval Univ.
Gal & AGN evol.
Local Universe
Milky Way and Resolved Stellar Populations
Planets
SNs Transients
Cosmological Simulations WG
SWG
VIS
VIS Lead
VIS PM
VIS ISc
VIS PO.
CCD Detector WG
NISP
NISP PM
Ph /Sp. IScs
NISP PO.
NIR Detector WG
SGS
EC SGS PM
EC SGS Sc
SGS PO.
SystTeam
OUs
SDCs
COM
COM Lead
Internal Com lead
Event Lead
EPO Scientist

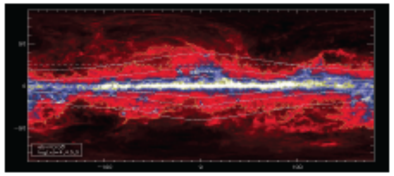
Euclid Survey Working Group



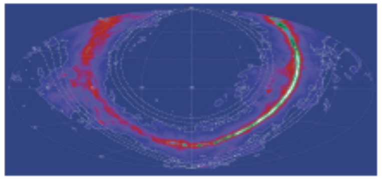


Survey Implementation : find optimal solutions for 6-year sequences of fields (FoVs) in a step-and-stare observing procedure with constraints:

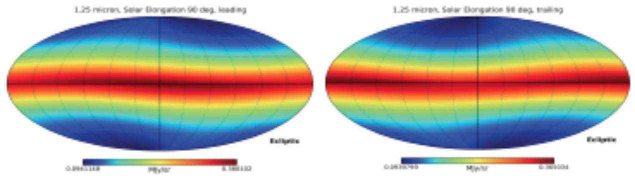
- operational (Solar-aspect-angle range, propellant limitation, maximum number of telescope pointings)
- scientific (coverage > 15000 deg2, holes, exposure time, number density of galaxies)
- environmental (extinction, zodiacal light background, bright stars)
- calibration plan (targets and cadence)
- deep fields (40 deg2, 2 mag deeper)



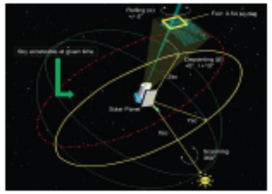
DUST : Extinction in the galactic plane (E(B-V) contours)



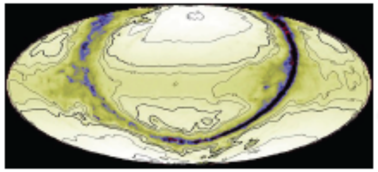
STAR DENSITY: Contamination in galactic plane



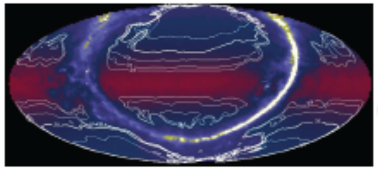
ZODIACAL LIGHT emission maps: Contamination in the ecliptic plane (with leading/trailing asymmetry)



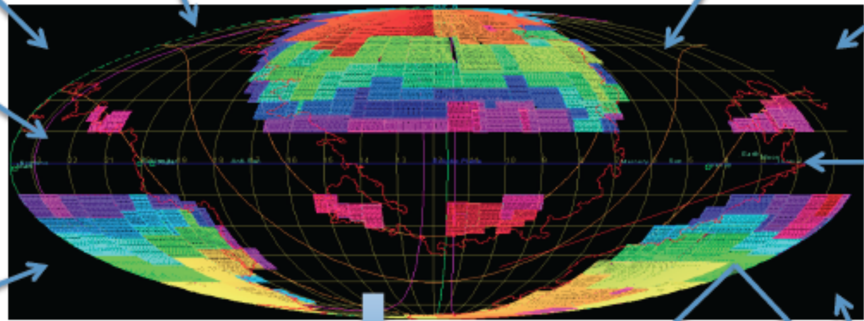
SPACECRAFT: limited range of rotations (in pitch ~ SAA and roll ~ α) ; limited propeller



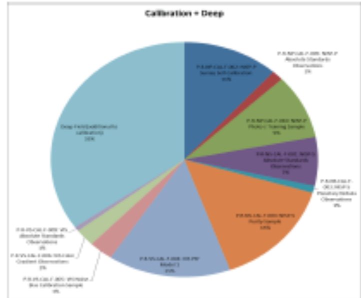
WEAK LENSING SAMPLING: galaxy density contours (arcmin^{-2})



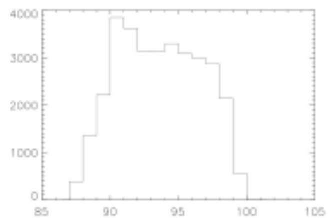
GALAXY CLUSTERING SAMPLING: galaxy density contours (arcmin^{-2})



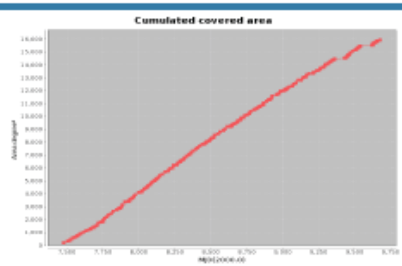
REFERENCE SURVEY: in ecliptic coordinates; color code (red to blue) shows the scheduled observation sequence. Released in the Mission Operations Concept Document, Dec 2013)



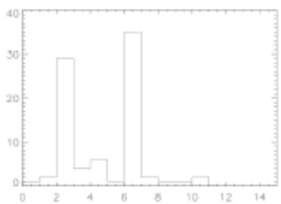
CALIBRATION PLAN: distribution of science and instrument calibrations, including targets and cadences



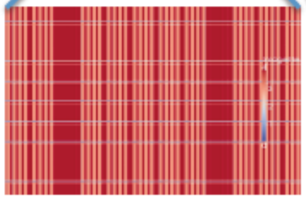
Histogram of Solar Aspect Angle over the total 40 000 pointings



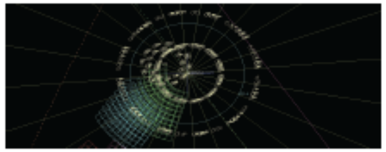
Rate of survey coverage with time. 15000 deg^2 are reached in 5.5 years



Histogram of duration of calibration sequences (in days) over the total time



INTEGRATION TIME maps: number counts per pixel over the dither sequence for 1 FoV



CALIBRATION TARGETS: high ecliptic latitudes; Deep fields; HST fields

Described in the first **key paper** of Euclid:

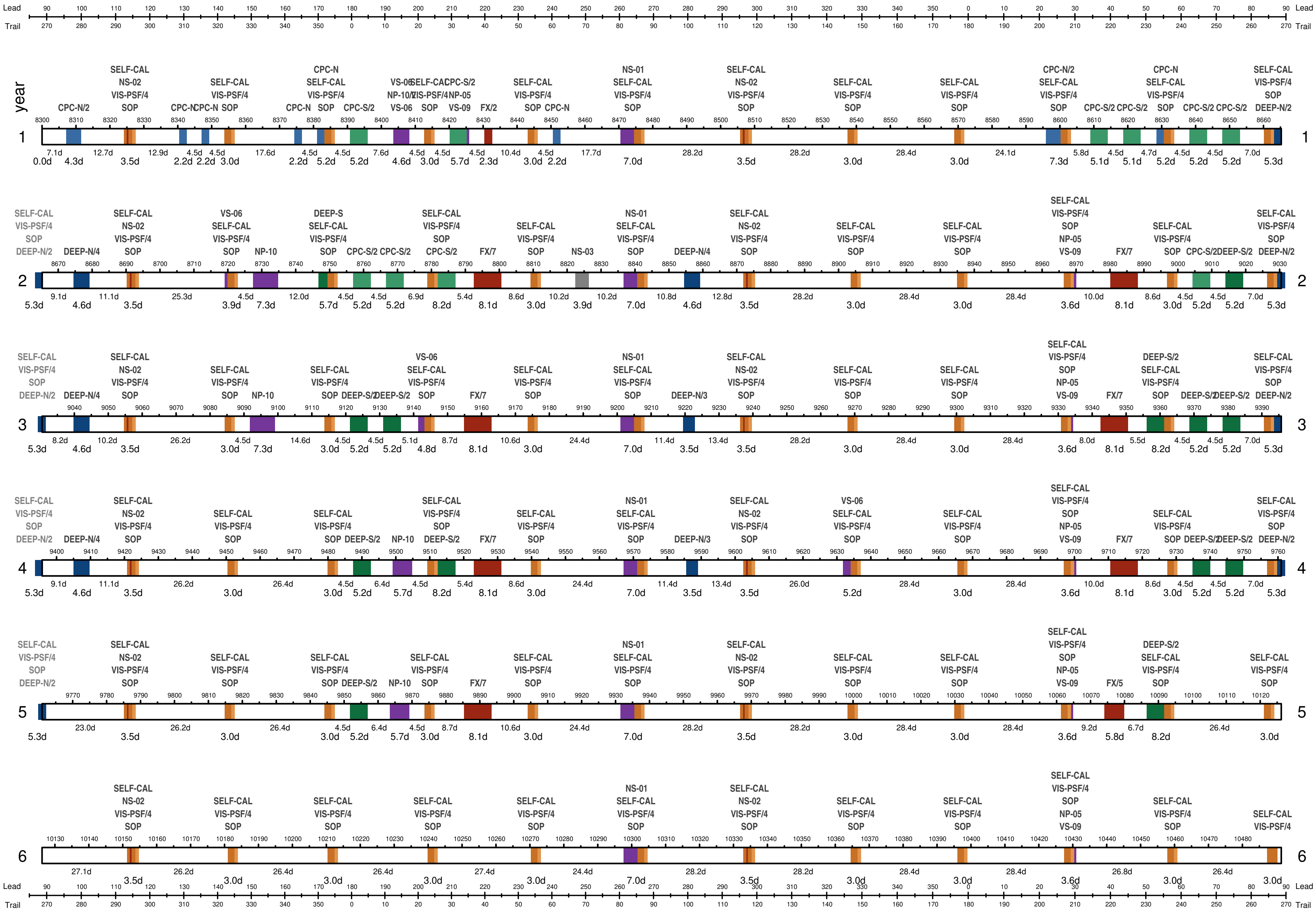
Euclid Preparation I. The Euclid Reference Survey: status at the Preliminary Design Review

Scaramella R.[1], Amiaux J.[2], Mellier Y.[2,3], Burigana C.[4,5,6], Carvalho C. S.[7], Cuillandre J.-C.[8], Da Silva A.[9,10], De Rosa A.[11], Dinis J.[9,10], Hudelot P.[2], Maiorano E.[11], Maris M.[12], Tereno I.[10,7], Laureijs R.[13], Buenadicha G.[13], Dupac X.[14], Gomez–Alvarez P.[14], Hoar J.[14], Lorenzo Alvarez J.[13], Racca G.[13], Saavedra Criado G.[13], Schwartz J.[15], Vavrek, R.[14], Venancio, L.[13], Garilli B.[16], Guzzo L.[17], Hoekstra H.[18], Kitching T.[19], Percival W.[20], Meneghetti M.[4], Scodeggio M.[20], Wachter S.[21] + 150 co-authors

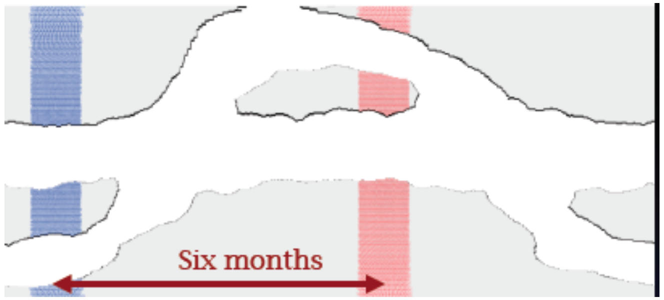
EUCLID CALIBRATION SCHEDULE: starting at 8300.0 / 2022-09-21T23:59:23

Calibration and Deep Fields

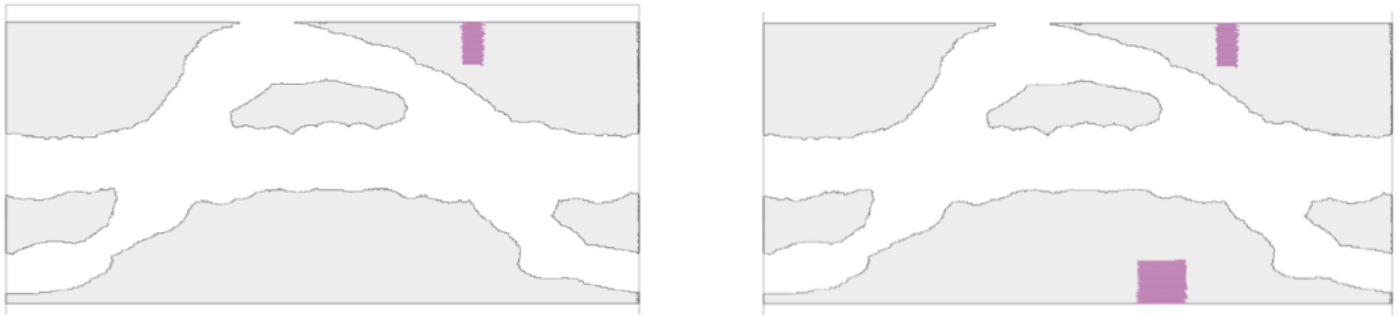
ECSURV - Apr 2019



Euclid Wide Survey

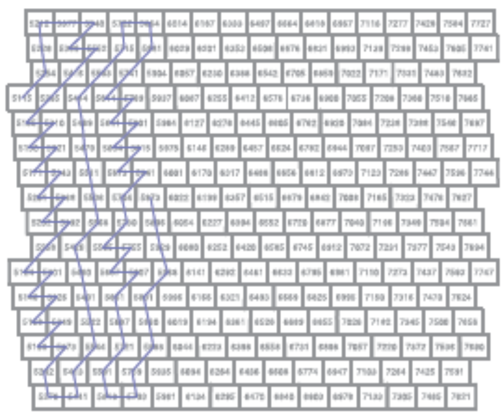


Patches



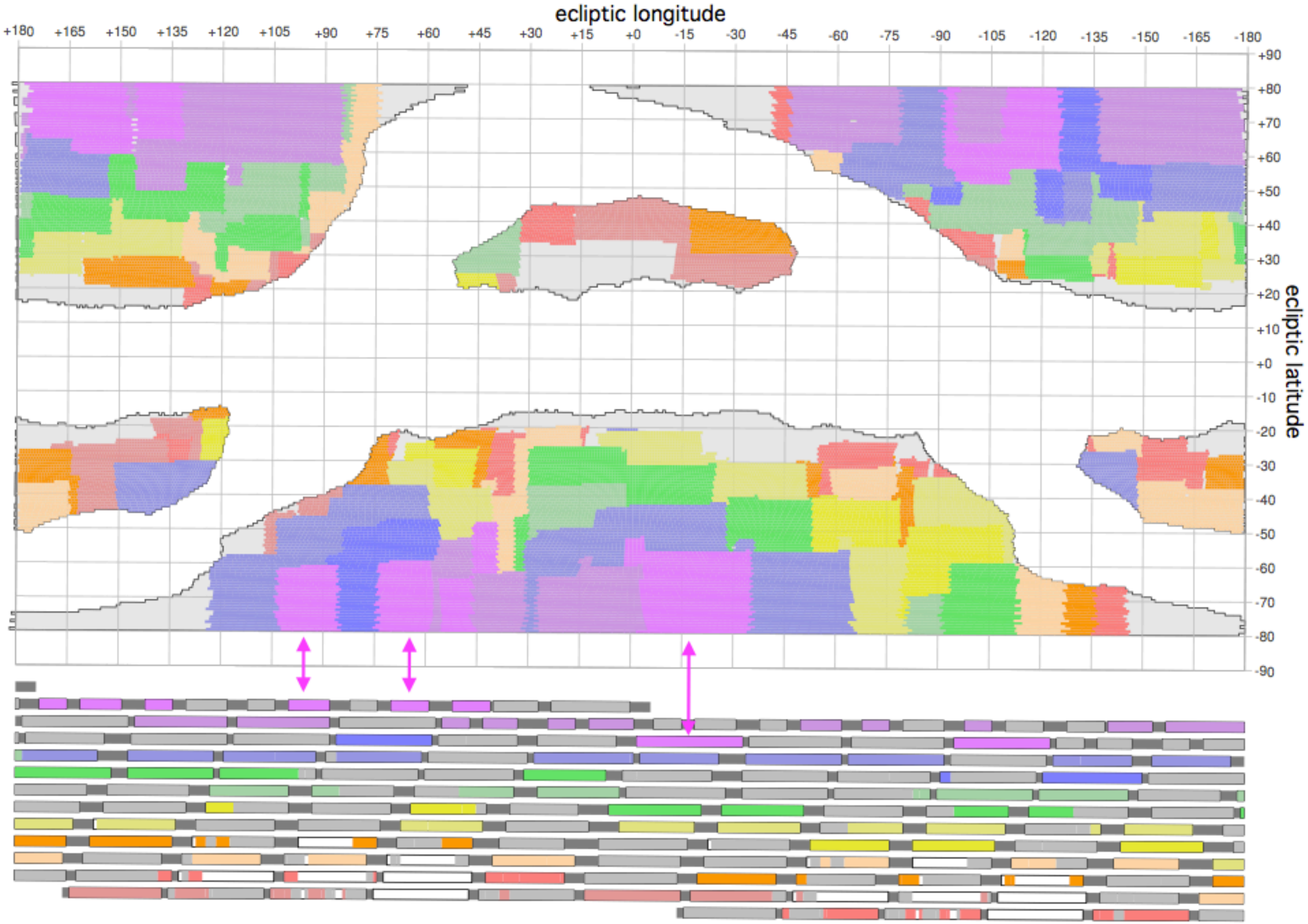
Tiling the patches

Patch tiling algorithm



A tiling sequence is computed by finding a valid observation sequence, traversing the fields with small-slews. This is computed iteratively.

The Euclid Reference Survey



Euclid Weak Lensing Science Working Group

Key Project: HOWLS

Use N-body + lensing simulations → create convergence maps
(5deg x 5deg, noiseless and noisy)

for various cosmological parameters and cosmological models

Measure **higher-order correlation functions** to assess if Euclid should measure them as part of the official data products for the data releases:

- forecasts with HOS
- correlations between the various HOS → optimize combinations

HOWLS (Higher Order Weak Lensing Statistics)

Goals:

- Compare different higher order statistics on the same set of mass maps
- Quantify systematic effects of the mass reconstruction

Step 1: (presented at SWG-WL Milan)

- Correlations between probes

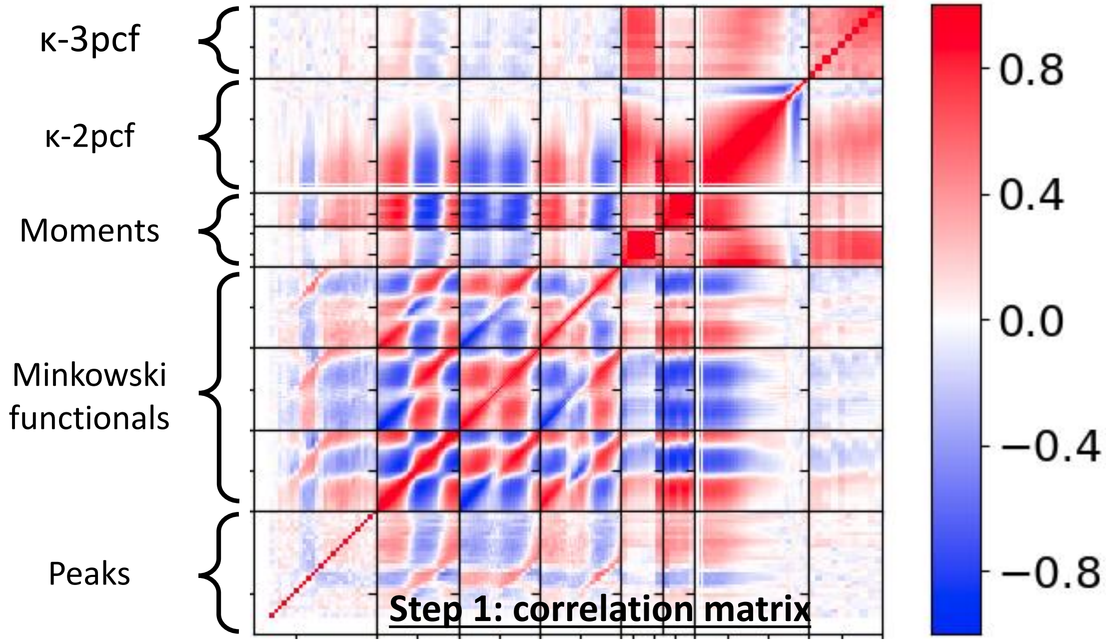
Step 2:

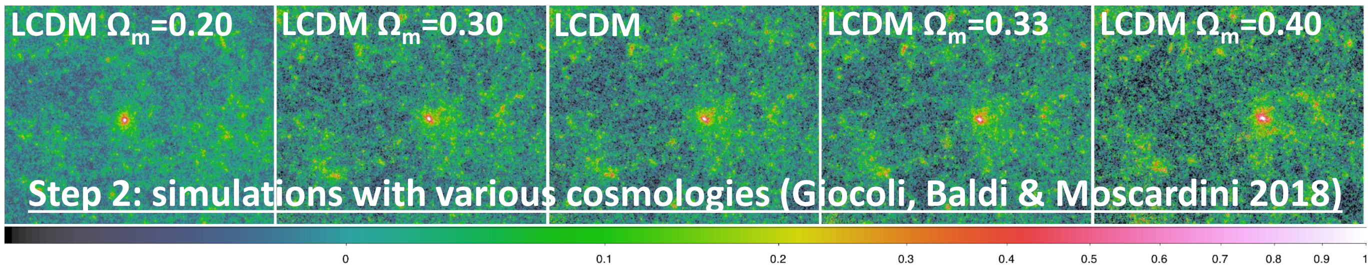
- Fisher information on Ω_m, σ_8, w

Step 3:

- Systematics

More in splinter S08 (Wednesday morning)





Main participants:
Carolina Parroni, Martina Vicinanza, Austin Peel, Sandrine Pires, Martin Kilbinger, Vincenzo Cardone, Ismael Tereno, Marco Baldi, Carlo Giocoli, Nicolas Martinet

Euclid Theory Science Working Group

Key Project: Constraining dark matter properties

Constrain cosmological models where the dark matter particle is not the standard CDM particle.

E.g.: warm dark matter; sterile neutrinos; axions (i.e. fuzzy dark Matter); dark matter-dark radiation interactions; primordial black holes; unified dark matter.

Need to model: background evolution, linear perturbations, non-linear regime (including marginalization over baryonic corrections)

The case of **Unified Dark Matter - Dark Energy models** (UDM)

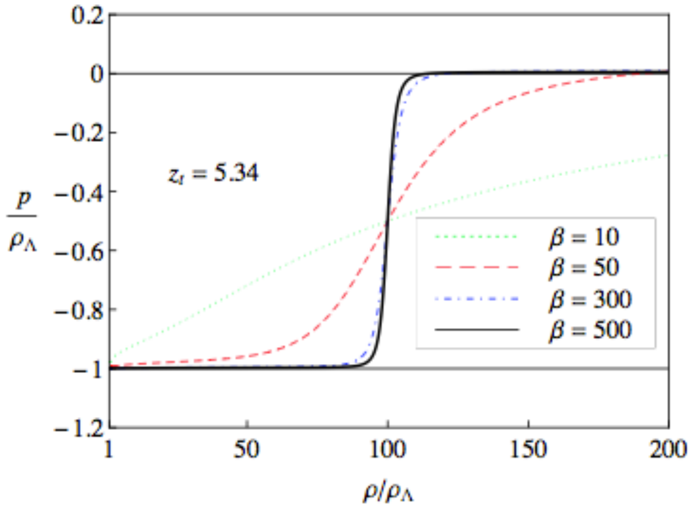
Participants: M. Baldi, D. Bertacca, D. Castelão, S. Camera, F. Pace, A. Rozas-Fernandez, I. Tereno

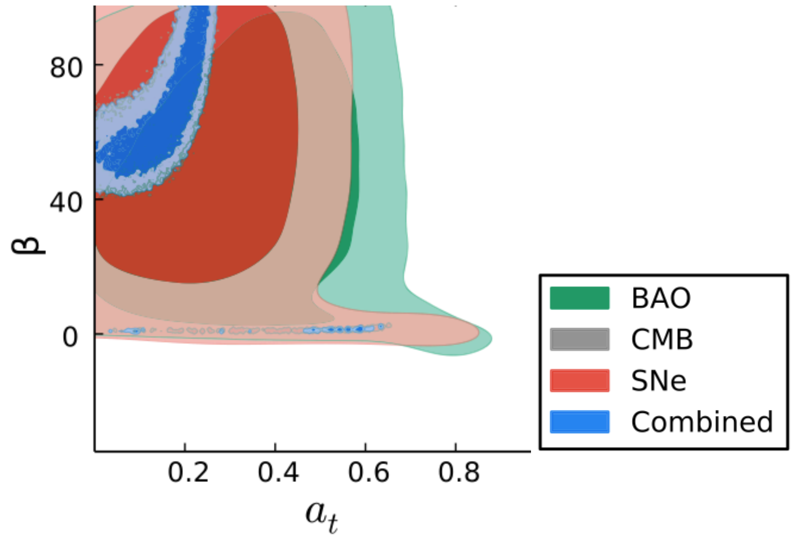
In UDM models, a single cosmological fluid behaves first as DM and later as DE. As DE, pressure is not zero → non-zero sound speed → density oscillations → working against structure formation

However, if the transition between the 2 regimes is fast that problem can be avoided.

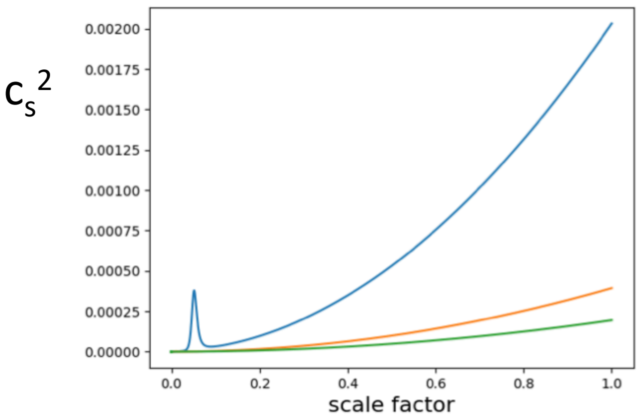
Goal: what limits can we find for the rapidity and epoch of transition that are compatible with future Euclid data?

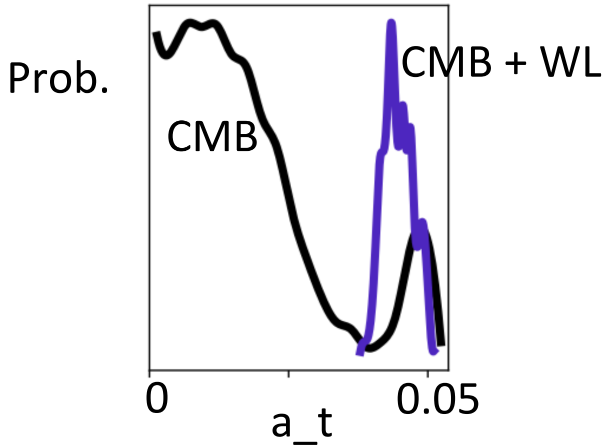
Step 1: Background evolution (Leanizbarrutia, Rozas-Fernandez, Tereno, 2017)





Step 2: Linear perturbations (Castelão, Rozas-Fernandez, Tereno, in prep)





Step 3: Non-linear perturbations (within the key project)

The Science Working Groups

Weak lensing SWG

Galaxy clustering SWG

Milky Way and Resolved Stellar Populations SWG

Cosmological Theory SWG

Strong lensing SWG

Solar System Object SWG

Galaxy & AGN evolution SWG

Clusters of galaxies SWG

Local Universe SWG

Cosmological Simulations SWG

CMB Cross-correlations SWG

Extrasolar planets SWG

SNe and Transients SWG

Primeval Universe SWG

The Inter-SWG Taskforce

The Science Data Centres

The Organisational Units

OU-VIS - Visual imaging

OU-SHE - Shear measurements

OU-NIR - Near-IR imaging

OU-SIR - Near-IR spectroscopy

OU-SPE - Spectroscopic measurements

OU-SIM - Simulations of Euclid data

OU-EXT - Data external to Euclid

OU-MER - Merging of external and Euclid data

OU-LE3 - Level 3 data

OU-PHZ - Photometric redshifts

100 Years of Gravitational Lensing Observations

… we’ve come a long way …