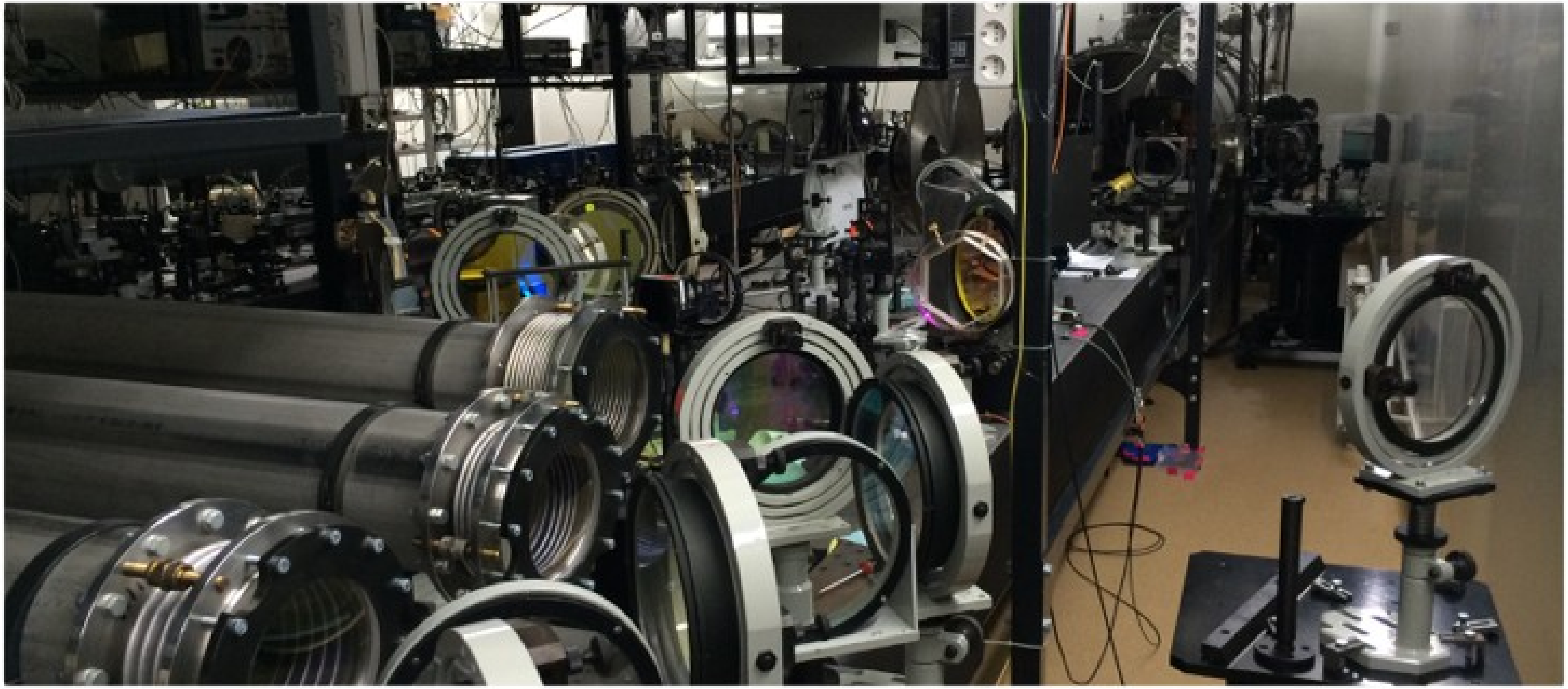

А. Соловьев[1], К. Бурдонов[1], А. Еремеев, В. Гинзбург, Е. Хазанов, А. Кочетков, А. Кузьмин,И. Шайкин, А. Шайкин, В. Яковлев, М. Стародубцев
М. Алхимова, Т.Пикуз, Е. Филиппов, С. Пикуз,
S. N. Chen[1,2], G. Revet[2], S. Pikuz[3], E. Filippov[3], M. Cerchez[4], T. Gangly[2], and **J. Fuchs[1,2]**

Исследования в области физики плазмы и ускорения частиц на субпетаваттном лазерном стенде PEARL

Collaborators

Соловьев А.А.[1]
Бурдонов К.Ф.[1]
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Хазанов Е.А.[1]
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Кузьмин А.А.[1],
Шайкин И.А.[1]
Шайкин А.А.[1]
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Алхимова М.А.[3]
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Пикуз Т.А.[3]

A. Chiardi[4]
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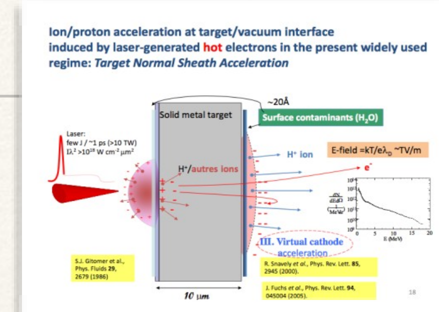
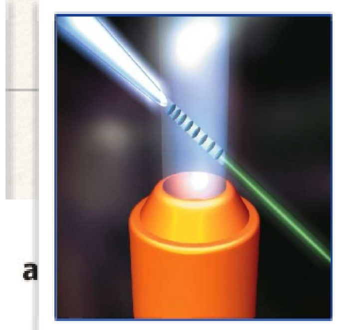
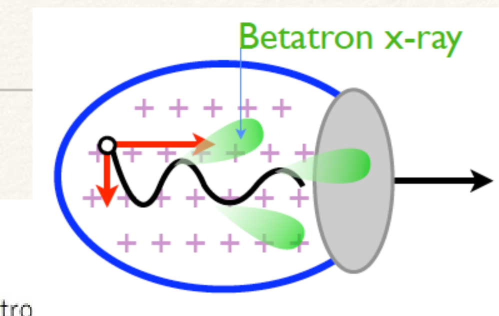
К.Л. Губский
А.П. Кузнецов

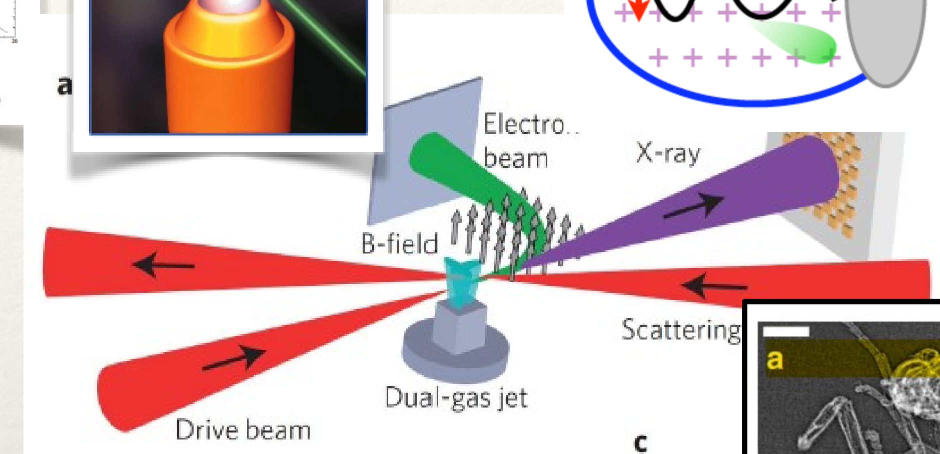
Laser-plasma interaction: applications

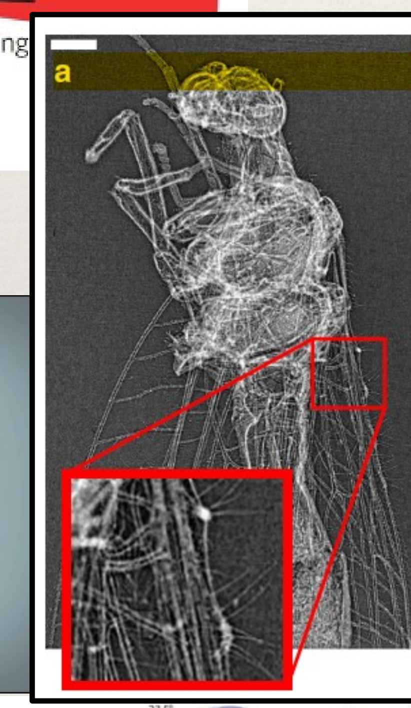
- Laser driven acceleration
  - Particles acceleration
  - X-ray generation.
- Applications
  - Radiotherapy
  - Bio-imaging
- HED physics
  - LabAstro
  - ICF

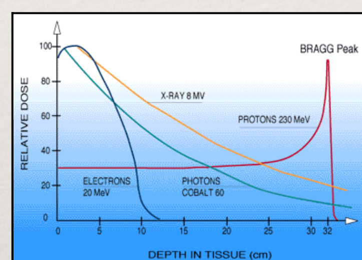


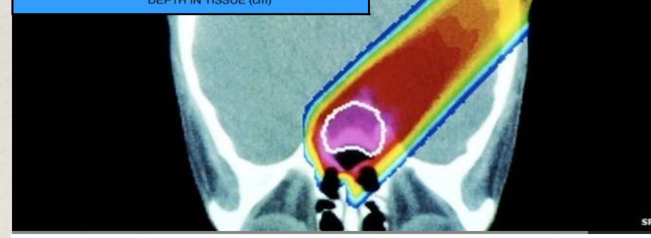


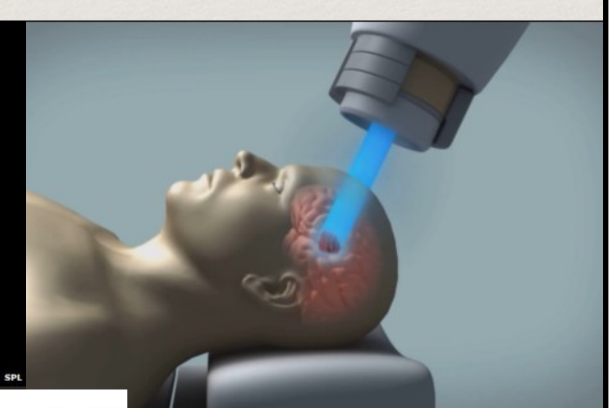


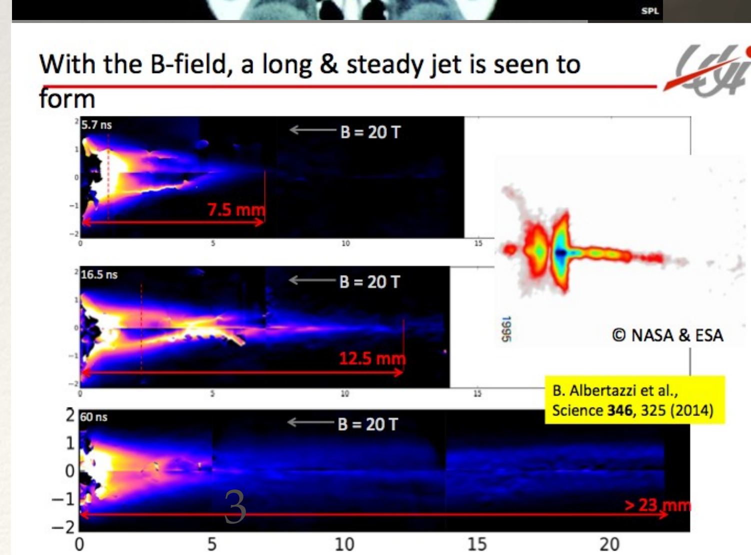


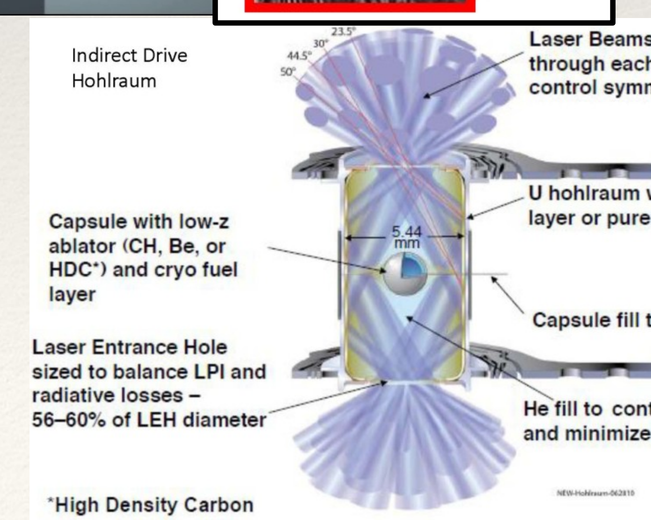




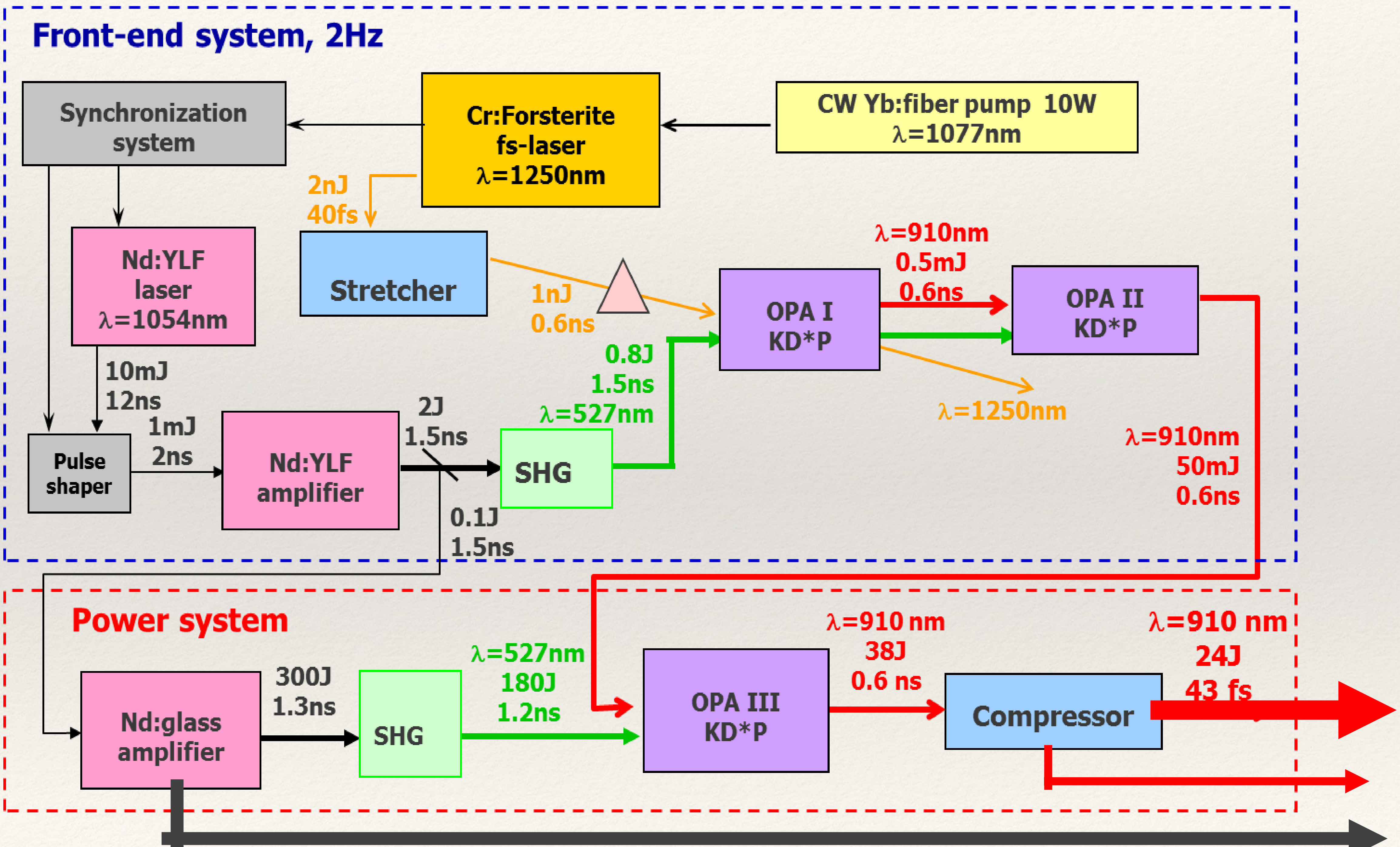








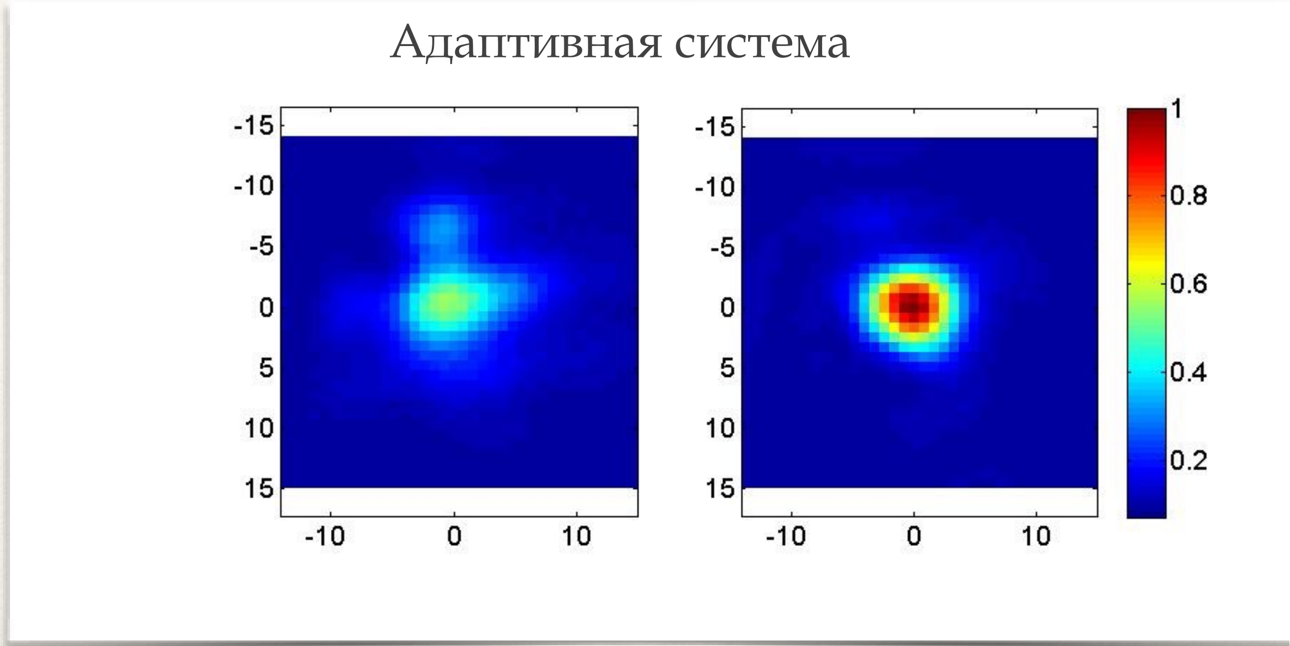
Sub-PW OPCPA PEARL laser facility

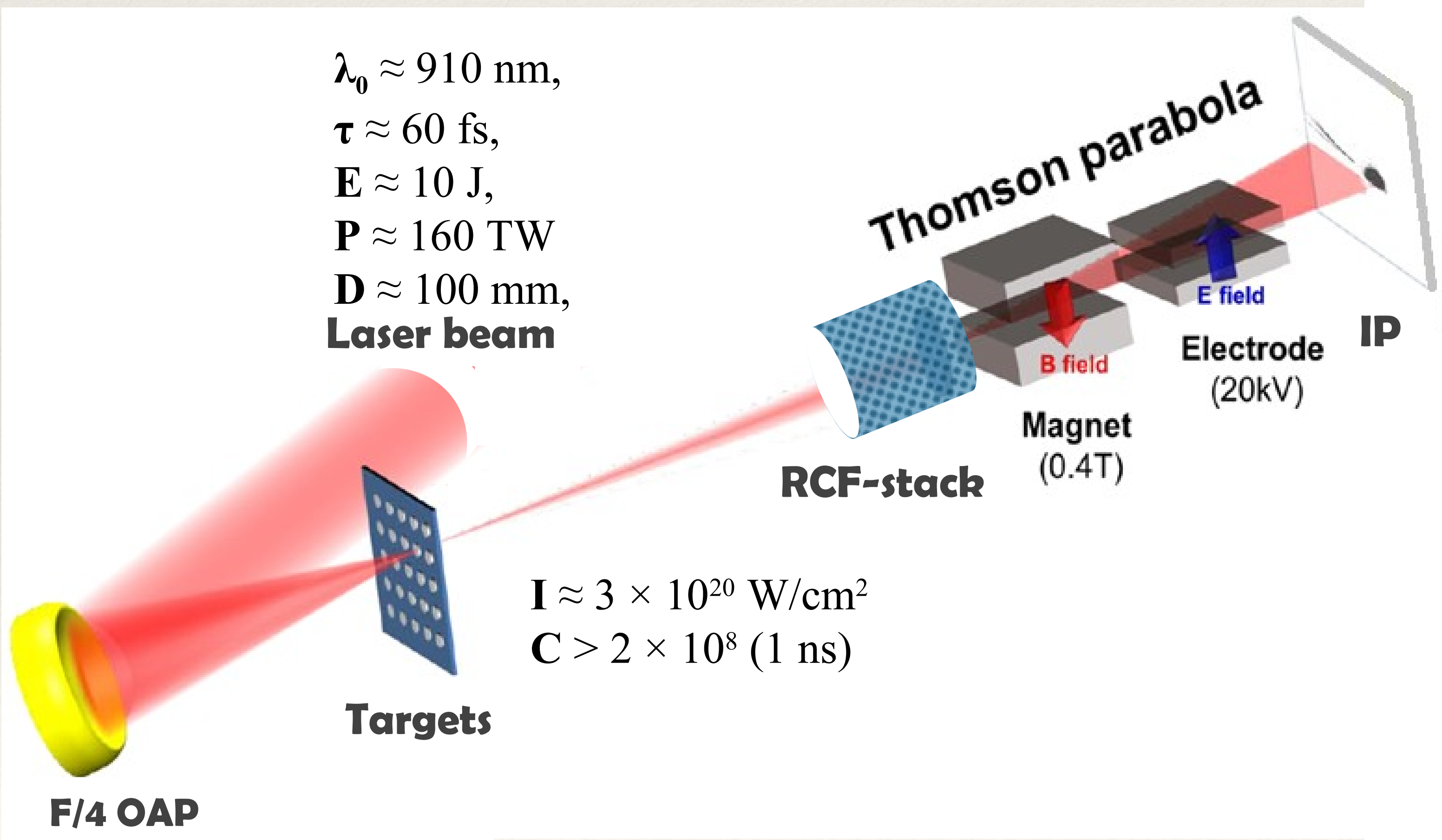


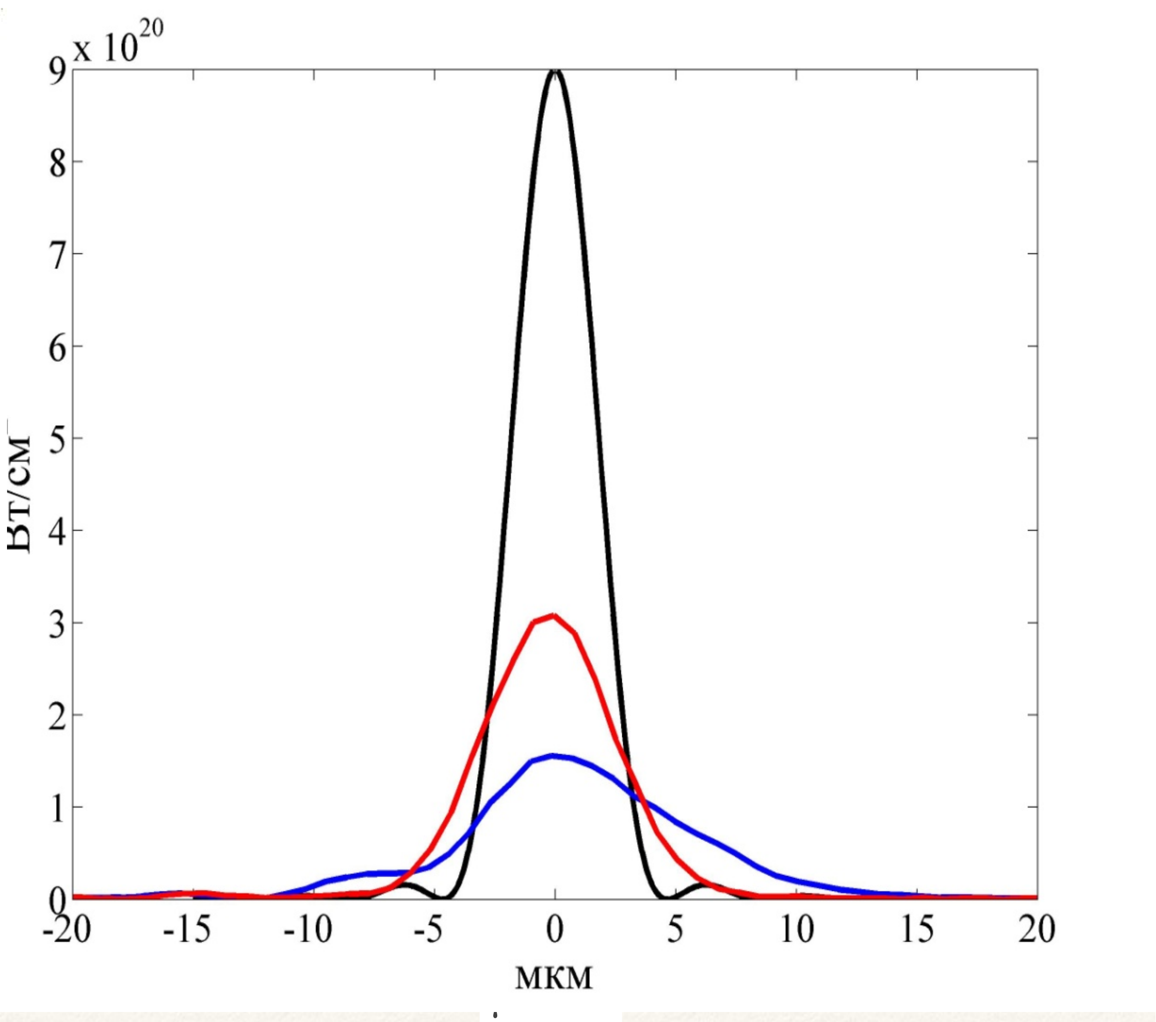
PEARL
Ion acceleration

Ускорение протонов/ионов:

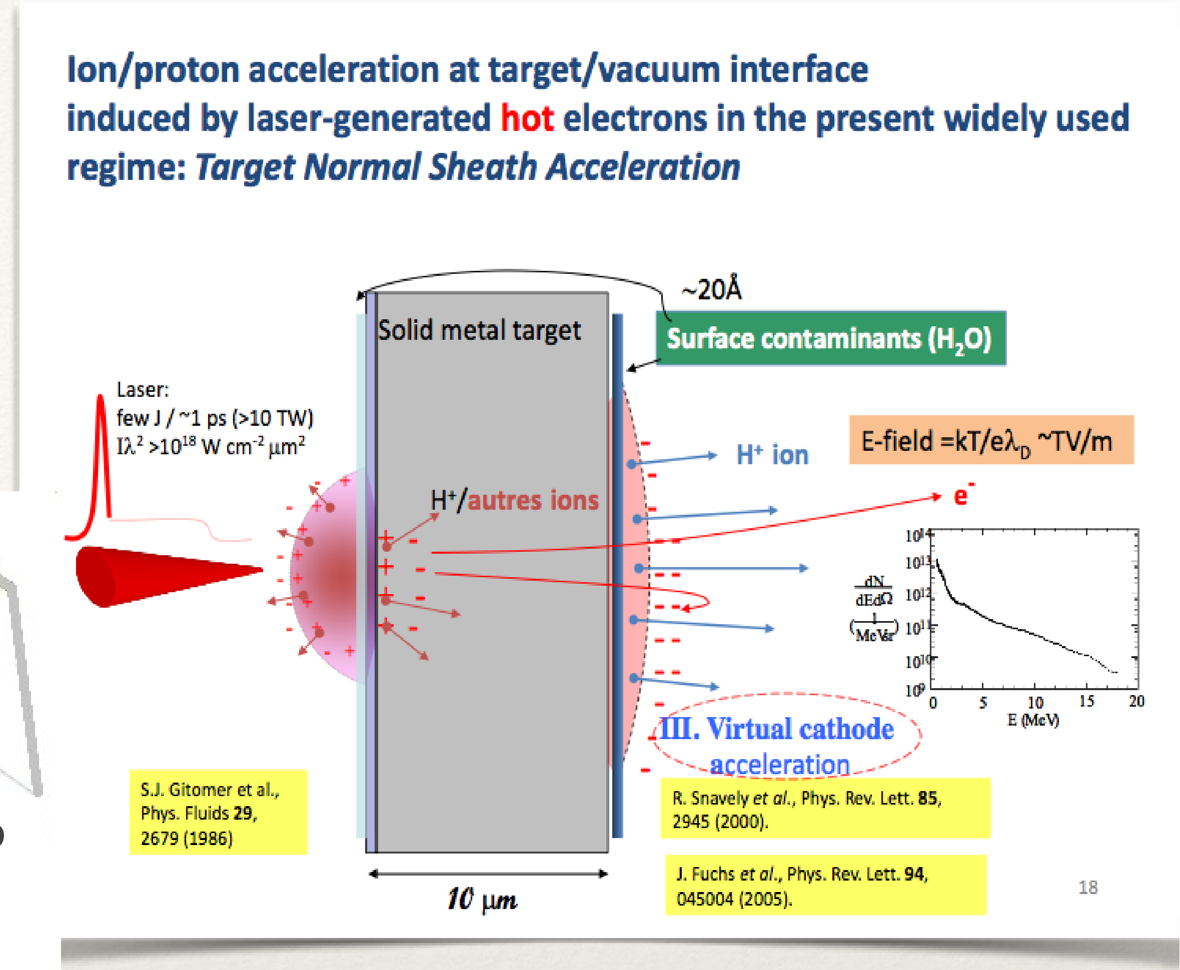
непрозрачная плазма (твердотельные мишени)
острая фокусировка лазерного излучения (высокая I)
высокий контраст лазерного излучения

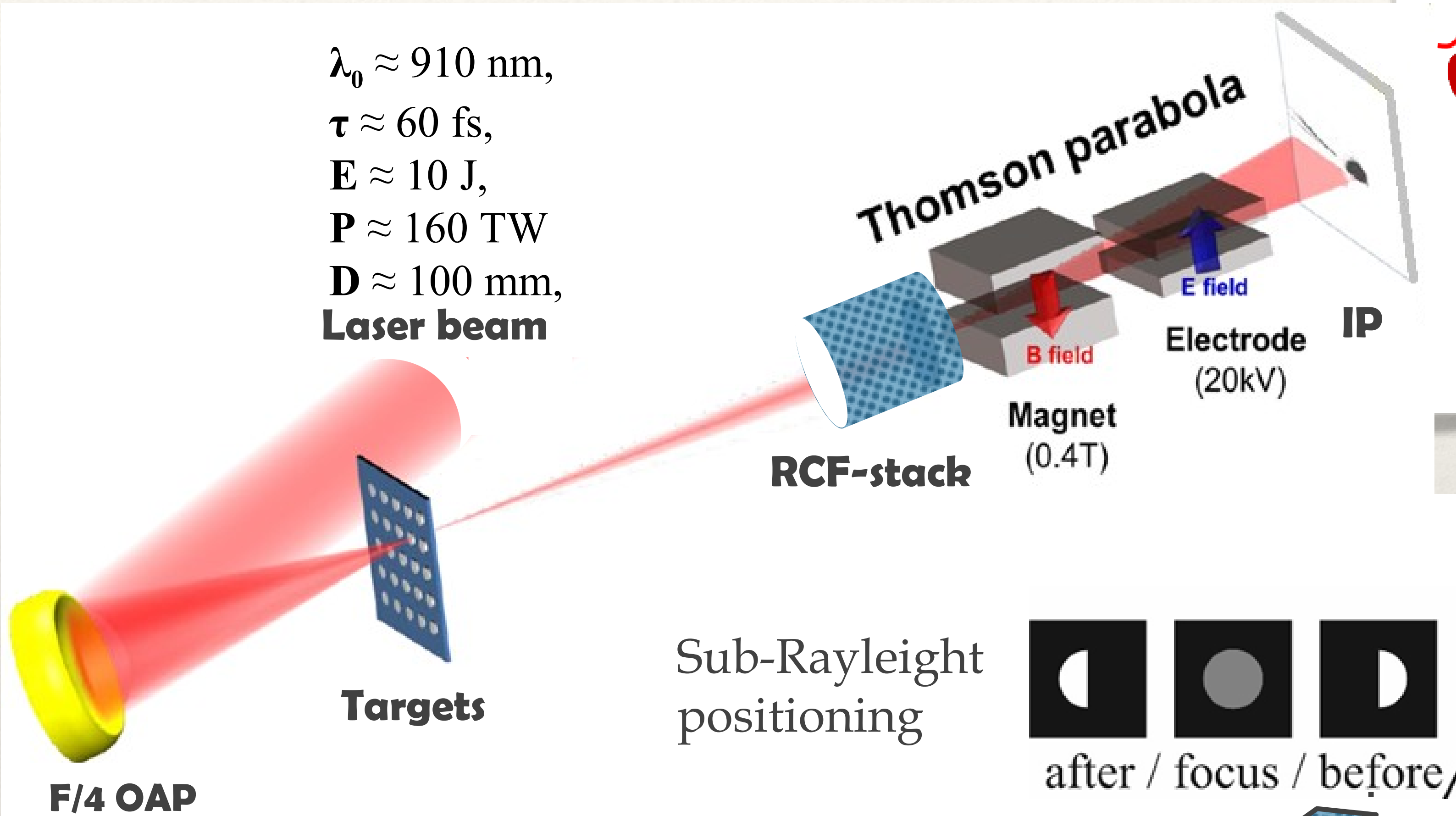




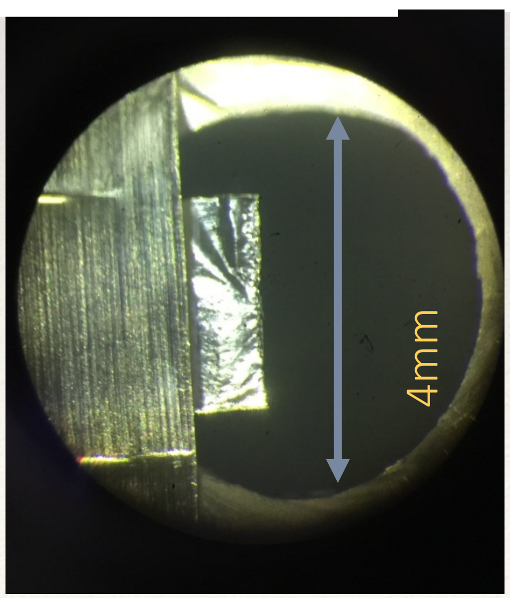


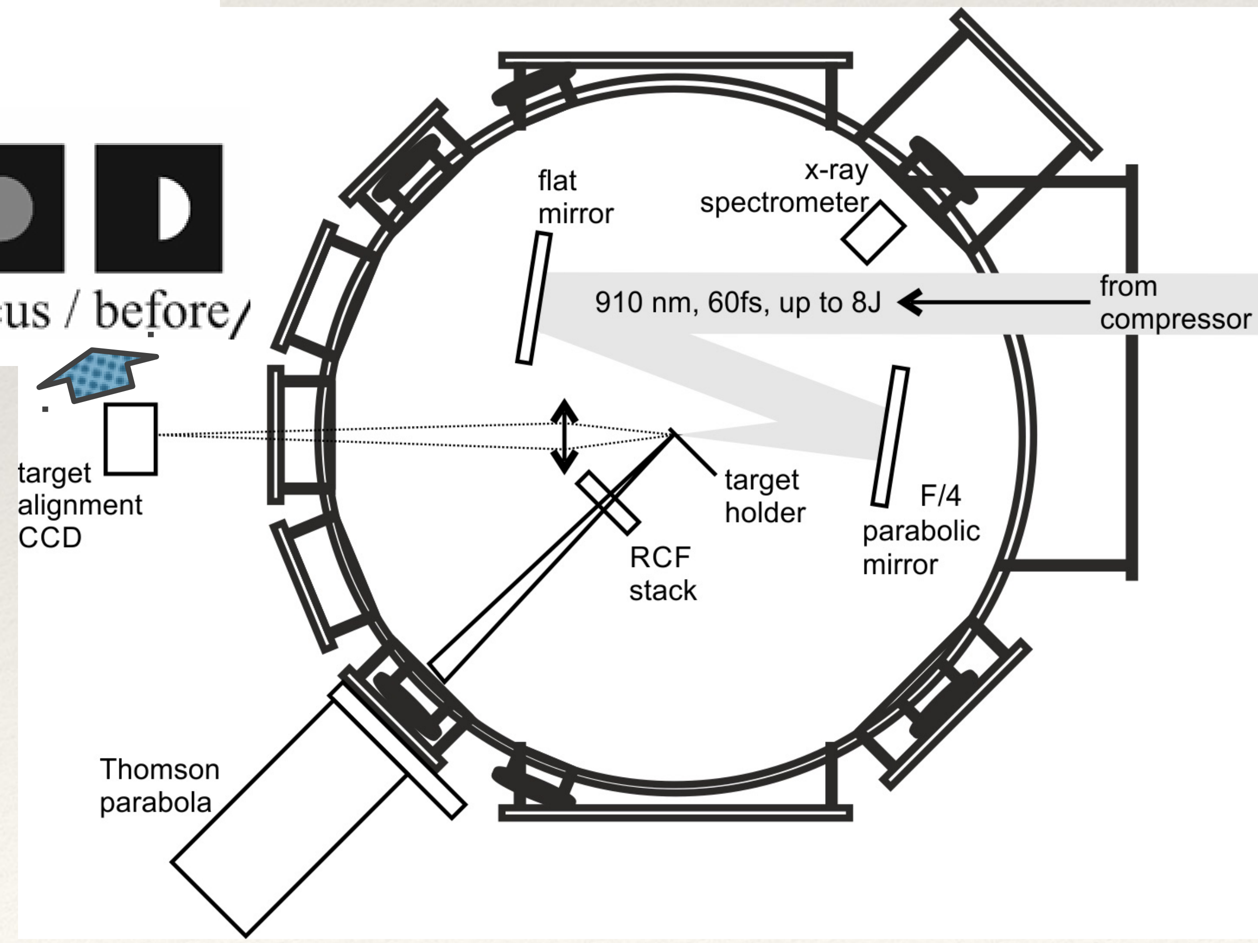
Ion acceleration



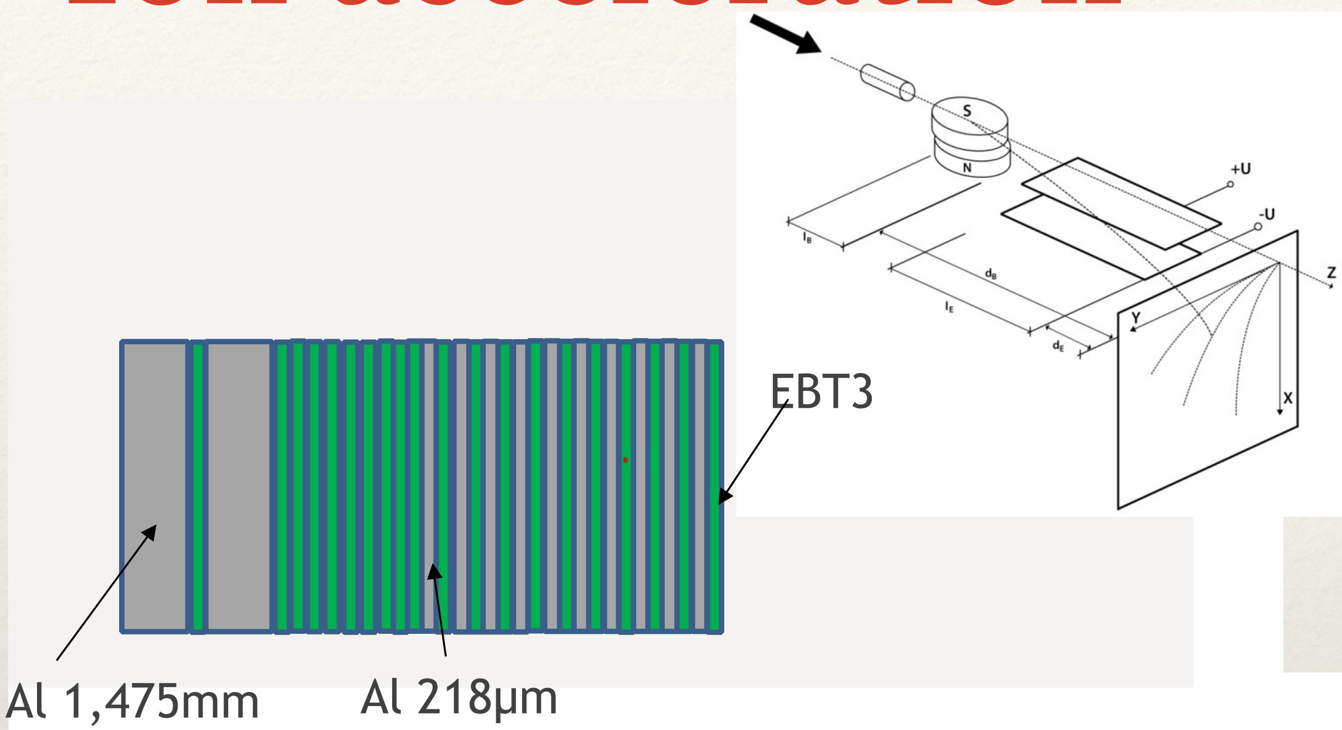


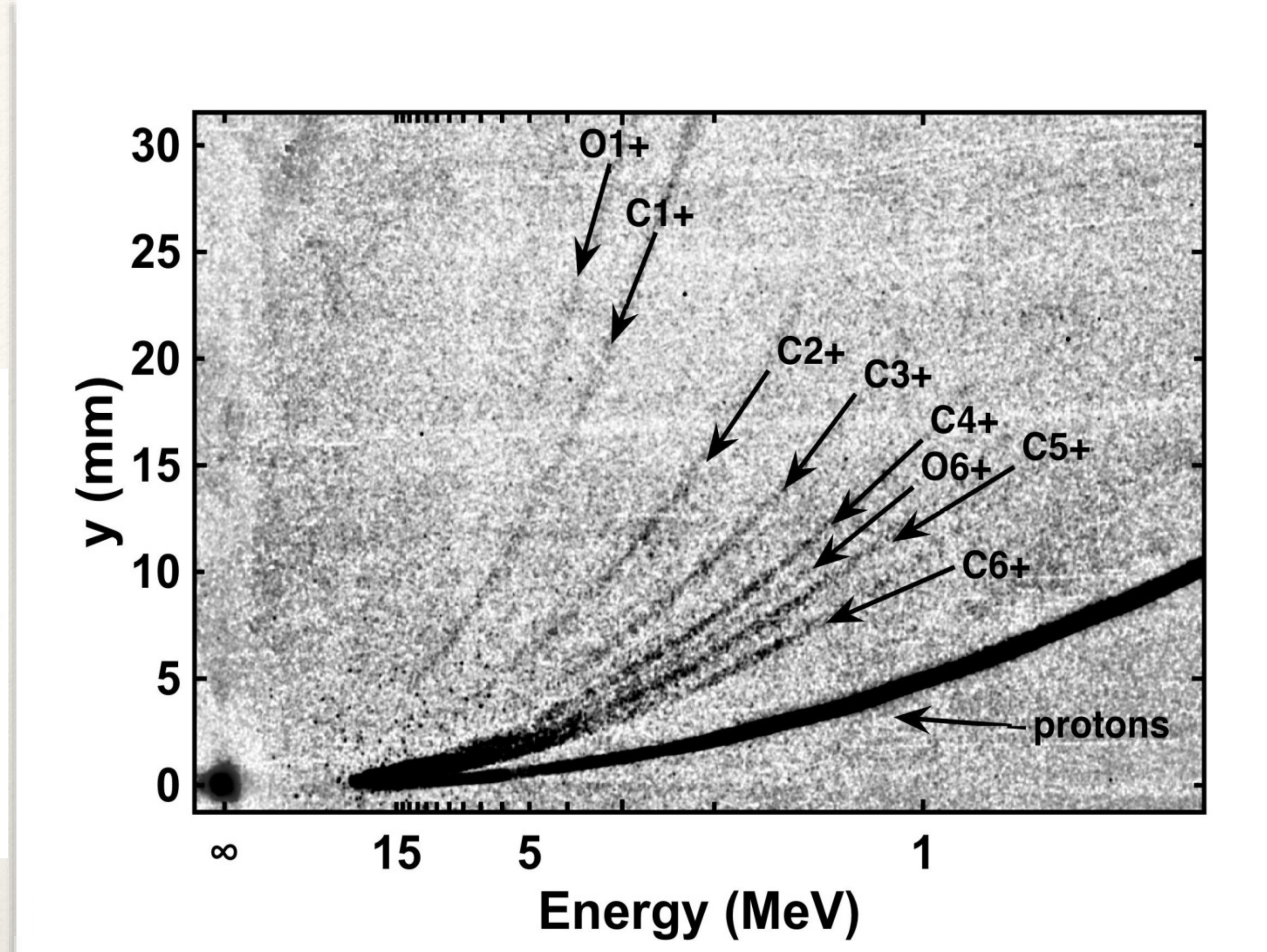
Sub-Rayleight positioning

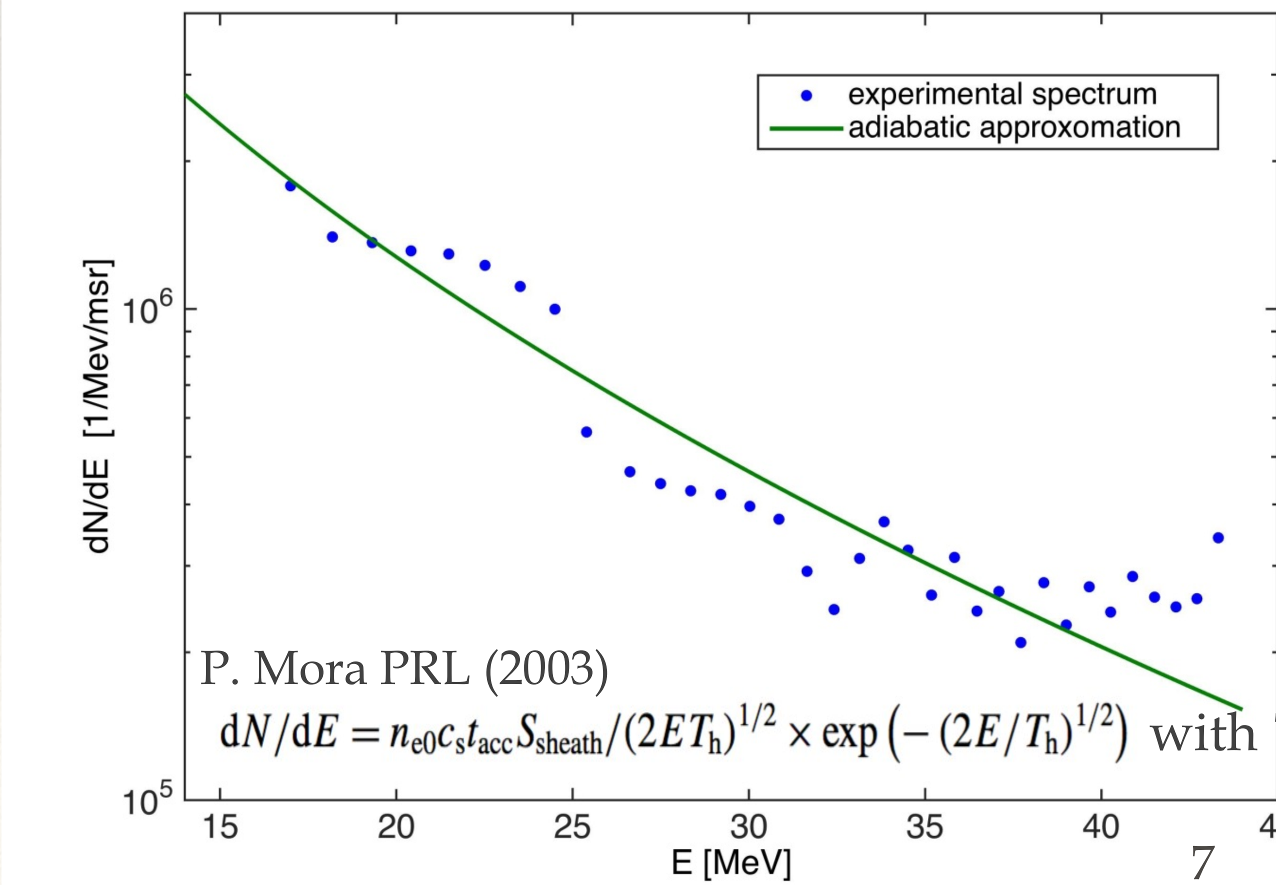




Ion acceleration



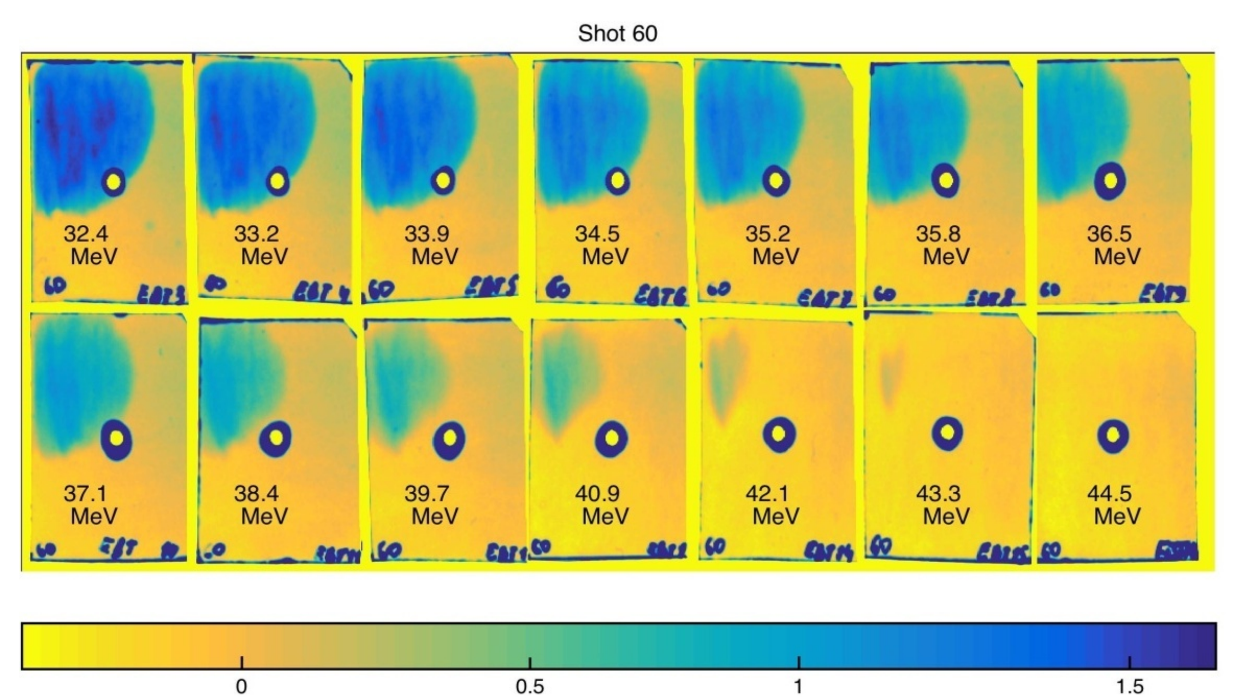




P. Mora PRL (2003)

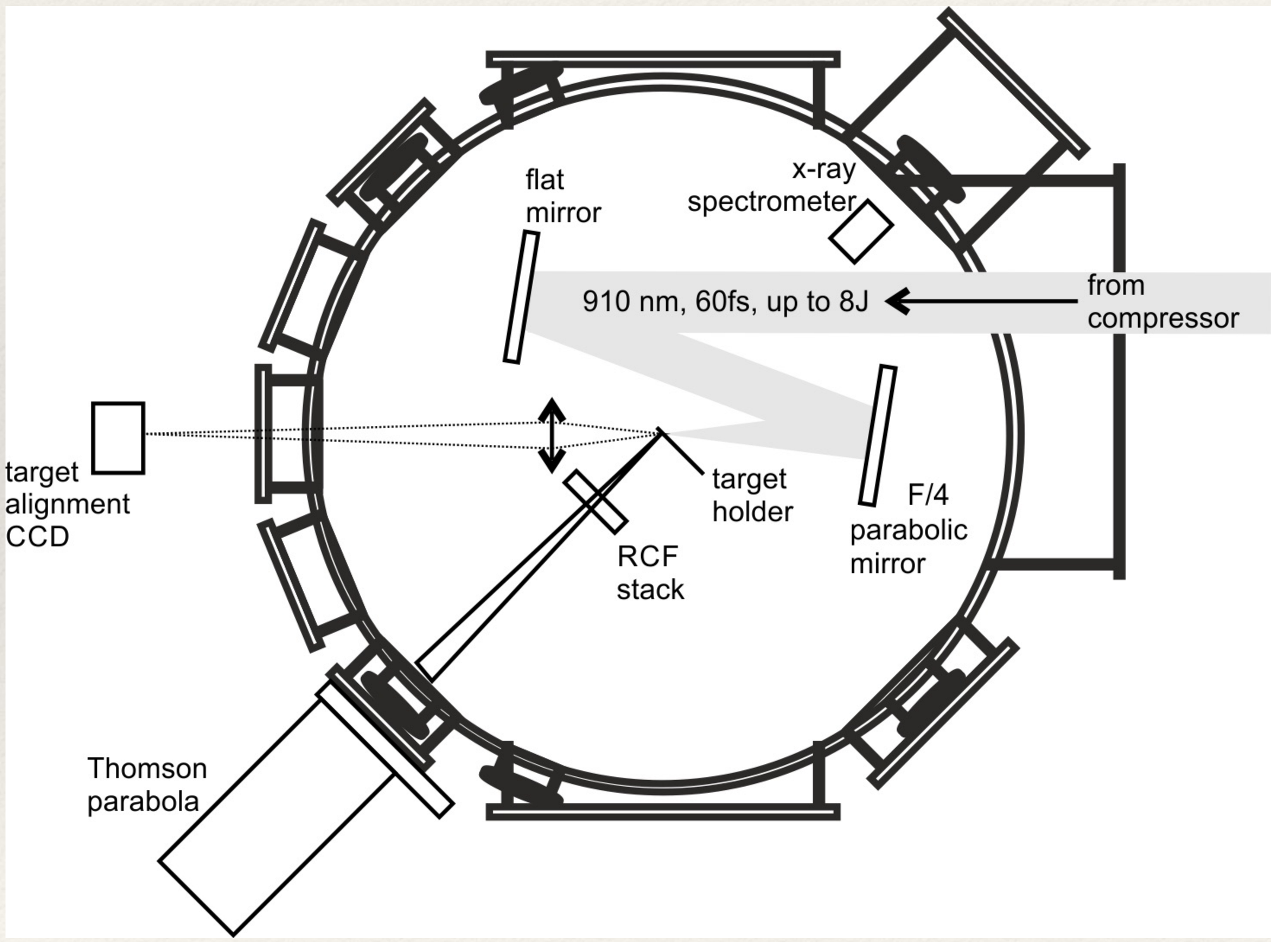
$dN/dE = n_{e0} c_s t_{acc} S_{sheath} / (2ET_h)^{1/2} \times \exp\left(-(2E/T_h)^{1/2}\right)$ with T_h= 3.5 MeV

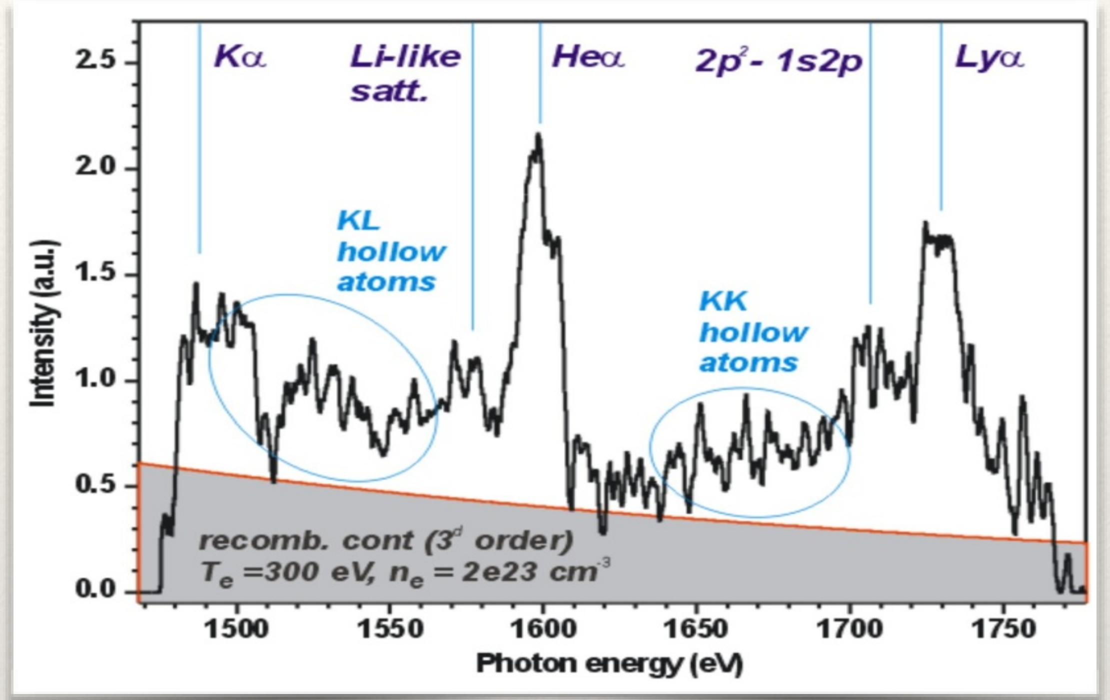
Experimental data:



Ion acceleration: X-ray spectrometry

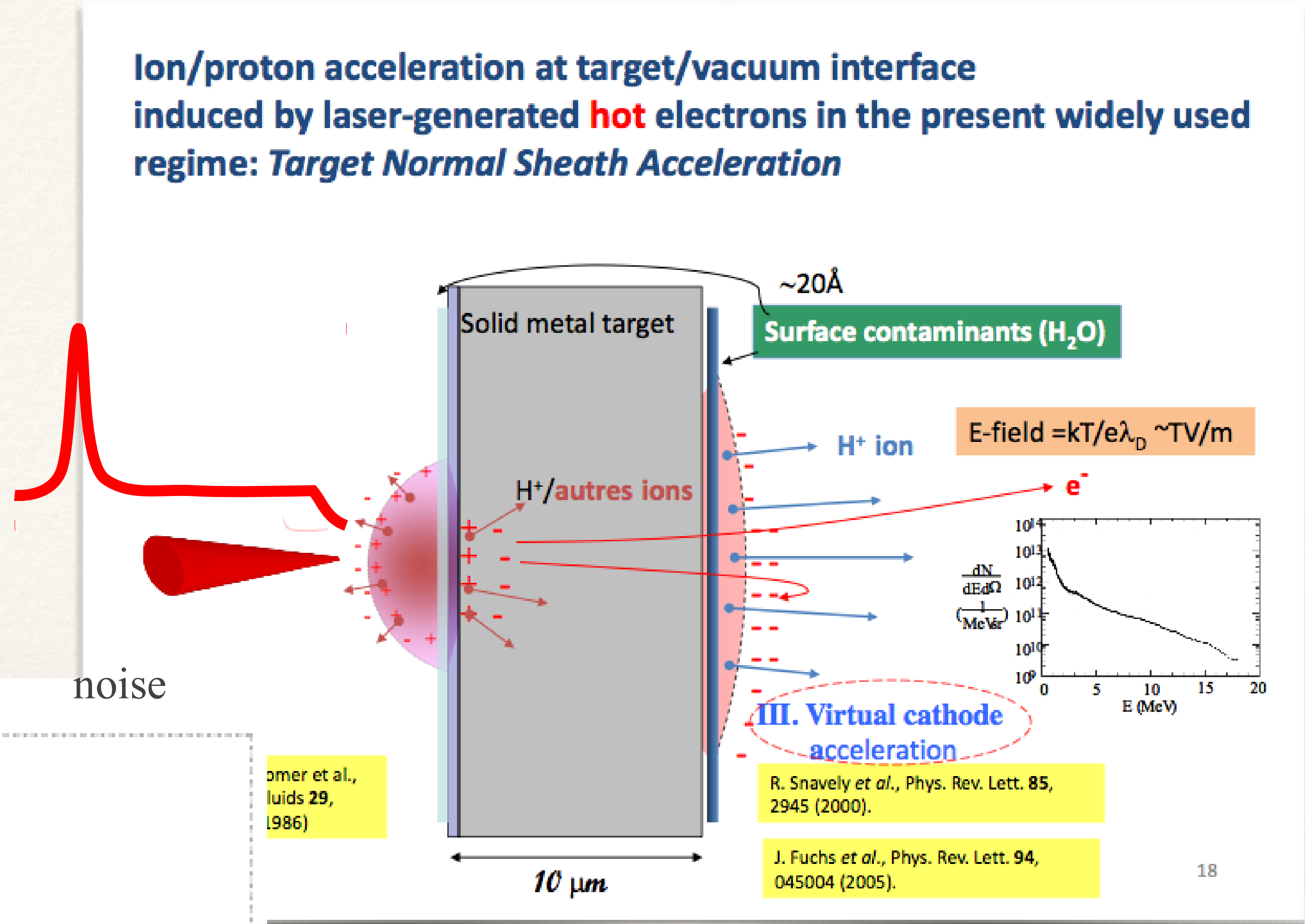
Focusing Spectrometer with Spatial Resolution (FSSR)



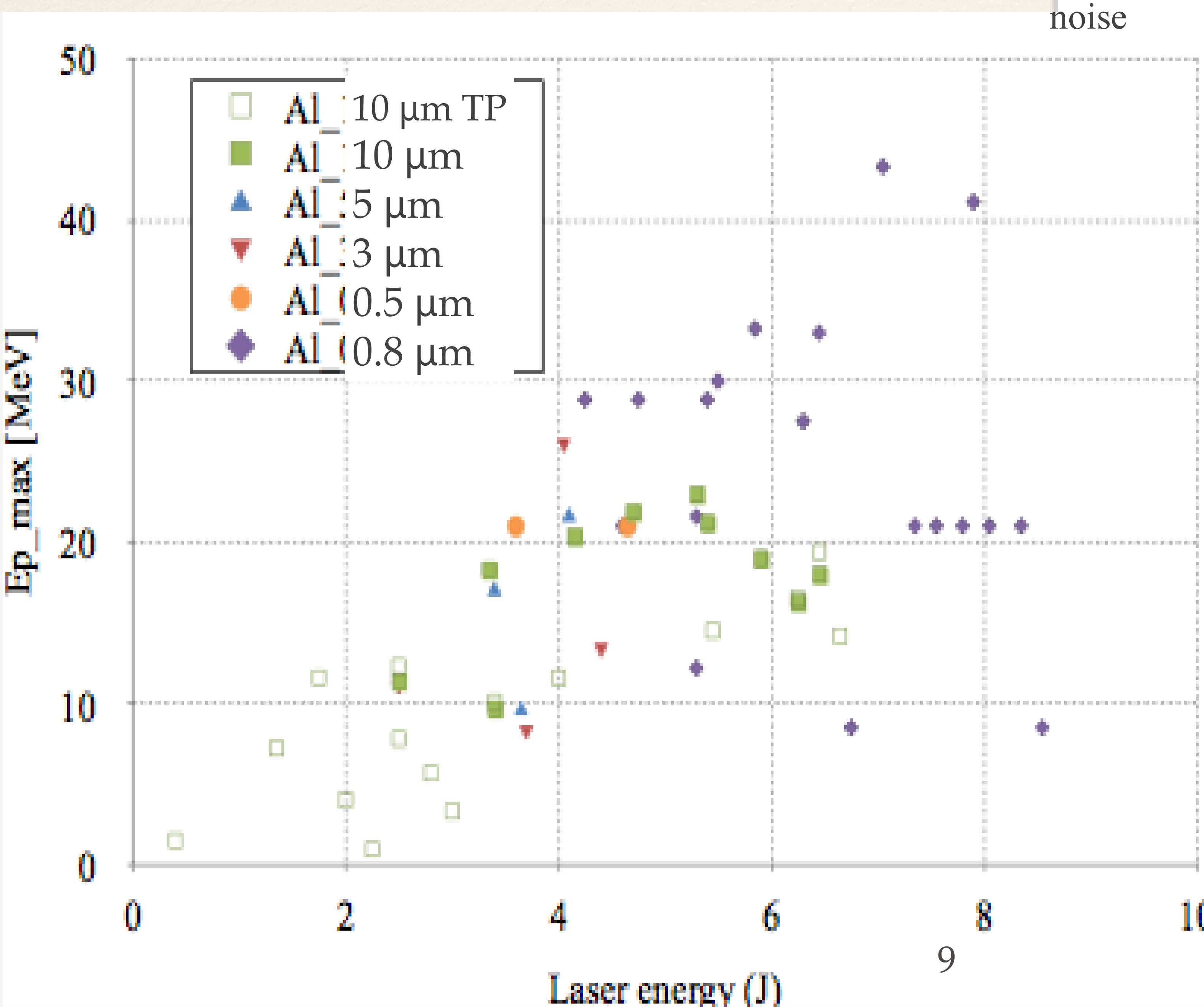


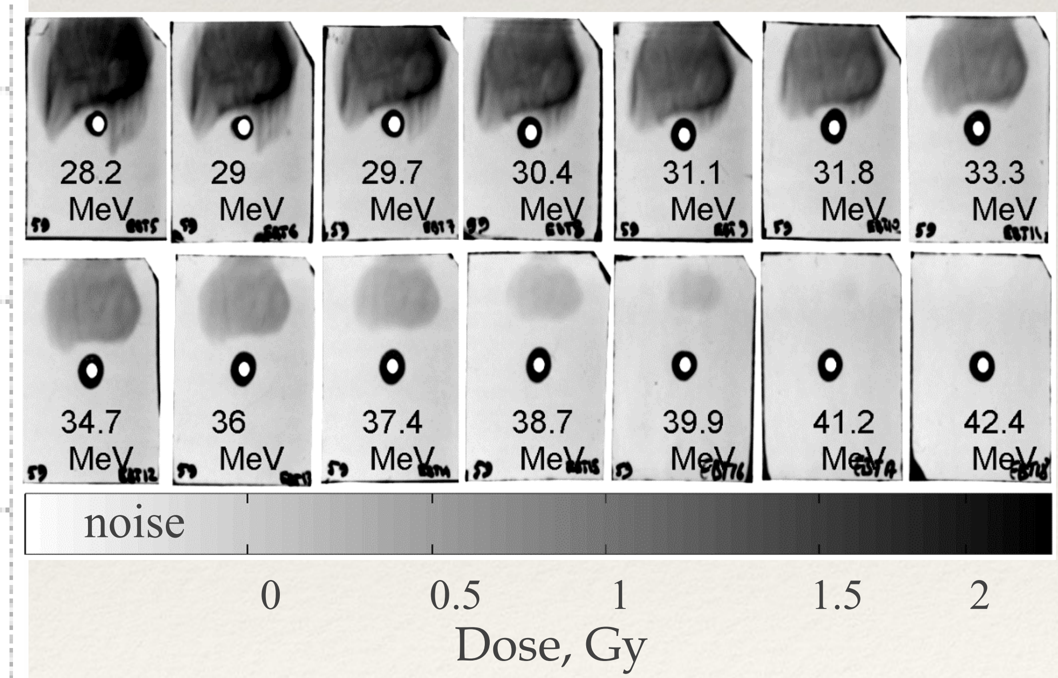
No signature of a significant preplasma at the target front:
the target remains at solid density by the time the main laser pulse arrives

Ion acceleration: statistics

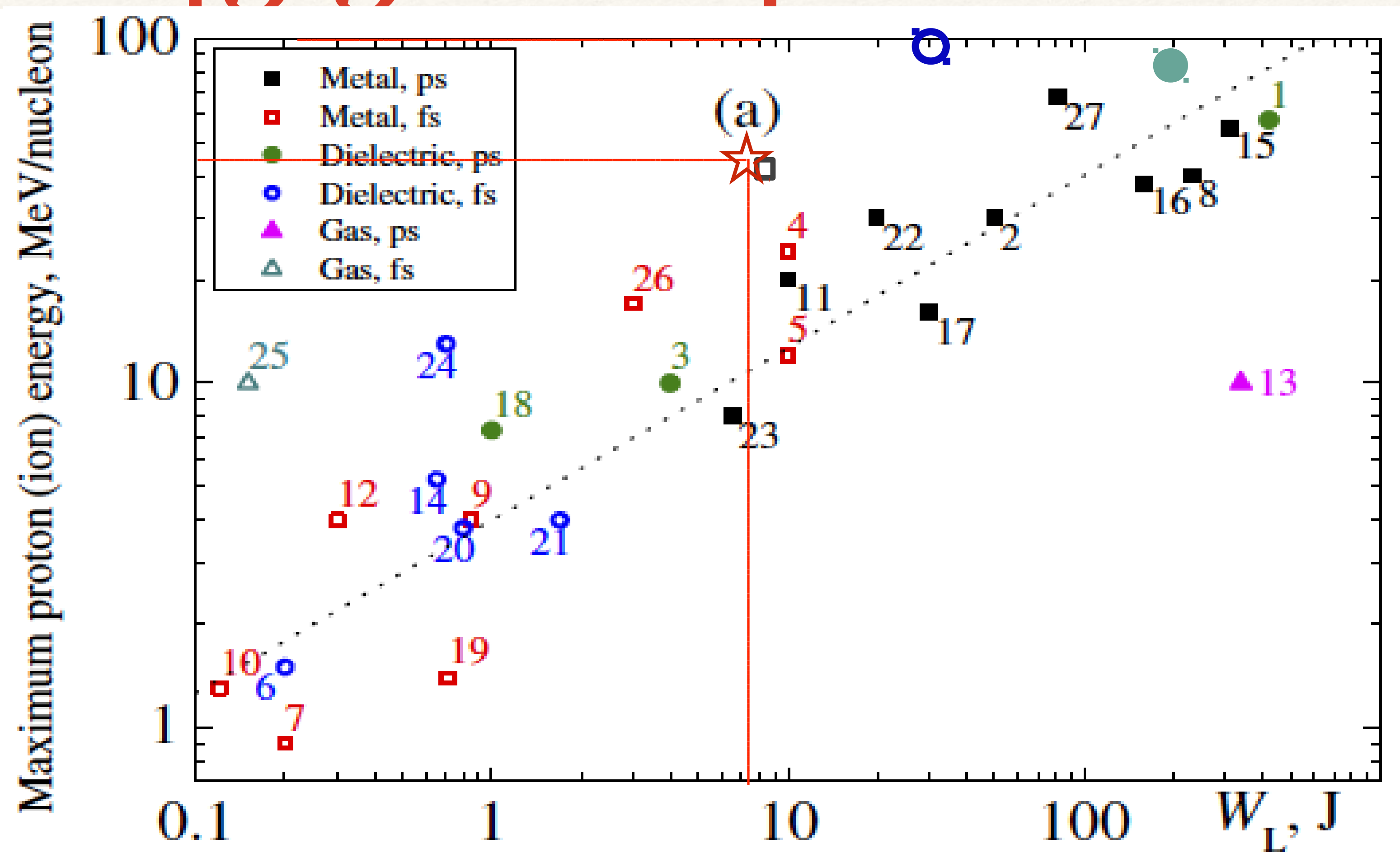


noise





43.3 MeV proton beam



Ogura et al., Optics Letters 37 14 (2012)
41 MeV - TNSA

IAP RAS summer 2015 (SR)
43 MeV - TNSA

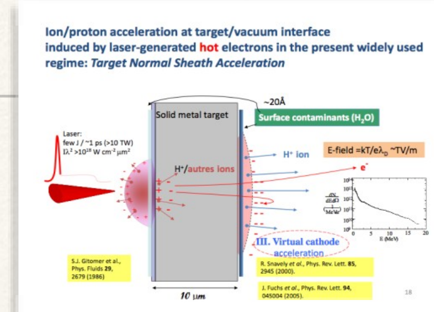
Wagner et al, Phys Rev Letters 116 205002 (2016)
85 MeV - TNSA

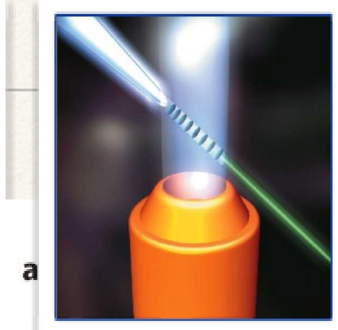
Jong Kim et al, Physics of Plasmas 23 070701 (2016)
93 MeV – RPA (world record for today)

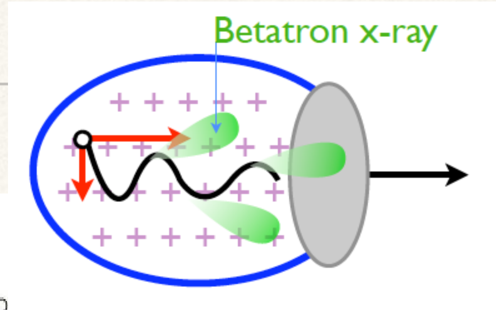
No.	Reference	Pulse energy W_L (J)	Pulse duration τ (fs)	Irradiance I_0 (W cm^{-2})^a	Contrast	Target and thickness (μm)	Incidence angle (°)	Proton/ion energy $\mathcal{E}_{p(i)}$, (MeV/nucleon)
1	Snavely *et al* (2000)	423	500	3×10^{20}	1×10^4	CH 100	0	58
2	Krushelnick *et al* (2000b)	50	1000	5×10^{19}		Al 125	45	30
3	Nemoto *et al* (2001)	4	400	6×10^{18}	5×10^5	Mylar 6	45	10
4	Mackinnon *et al* (2002)	10	100	1×10^{20}	1×10^{10}	Al 3	22	24
5	Patel *et al* (2003)	10	100	5×10^{18}		Al 20	0	12
6	Spencer *et al* (2003)	0.2	60	7×10^{18}	1×10^6	Mylar 23	0	1.5
7	Spencer *et al* (2003)	0.2	60	7×10^{18}	1×10^6	Al 12	0	0.9
8	McKenna *et al* (2004)	233	700	2×10^{20}	1×10^7	Fe 100	45	40
9	Kaluza *et al* (2004)	0.85	150	1.3×10^{19}	2×10^7	Al 20	30	4
10	Oishi *et al* (2005)	0.12	55	6×10^{18}	1×10^5	Cu 5	45	1.3
11	Fuchs *et al* (2006)	10	320	6×10^{19}	1×10^7	Al 20	0 and 40	20
12	Neely *et al* (2006)	0.3	33	1×10^{19}	1×10^{10}	Al 0.1	30	4
13	Willingale *et al* (2006)	340	1000	6×10^{20}	1×10^5	He jet 2000		10
14	Ceccotti *et al* (2007)	0.65	65	5×10^{18}	1×10^{10}	Mylar 0.1	45	5.25
15	Robson *et al* (2007)	310	1000	6×10^{20}	1×10^7	Al 10	45	55
16	Robson *et al* (2007)	160	1000	3.2×10^{20}	1×10^7	Al 10	45	38
17	Robson *et al* (2007)	30	1000	6×10^{19}	1×10^7	Al 10	45	16
18	Antici *et al* (2007)	1	320	1×10^{18}	1×10^{11}	Si_3N_4 0.03	0	7.3
19	Yogo *et al* (2007)	0.71	55	8×10^{18}	1×10^6	Cu 5	45	1.4
20	Yogo *et al* (2008)	0.8	45	1.5×10^{19}	2.5×10^5	Polyimide 7.5	45	3.8
21	Nishiuchi *et al* (2008)	1.7	34	3×10^{19}	2.5×10^7	Polyimide 7.5	45	4
22	Flippo *et al* (2008)	20	600	1.1×10^{19}	1×10^6	Flat-top cone Al 10	0	30
23	Safronov *et al* (2008)	6.5	900	1×10^{19}		Al 2	0	8
24	Henig *et al* (2009b)	0.7	45	5×10^{19}	1×10^{11}	DLC 0.0054	0	13
25	Fukuda *et al* (2009)	0.15	40	7×10^{17}	1×10^6	CO_2+He cluster jet 2000		10
26	Zeil *et al* (2010)	3	30	1×10^{21}	2×10^8	Ti 2 μm	45	17
27	Gaillard *et al* (2011)	82	670	1.5×10^{20}	1×10^9	Flat-top cone Cu 12.5	0	67.5

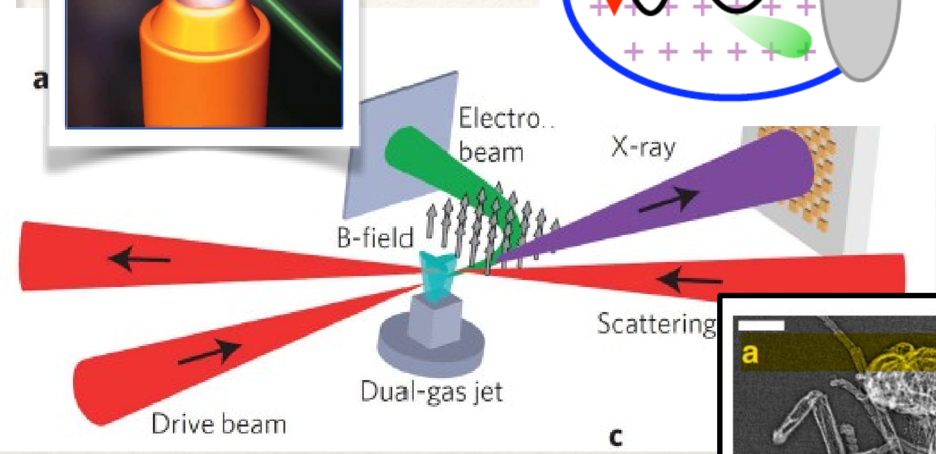
Laser-plasma interaction: applications

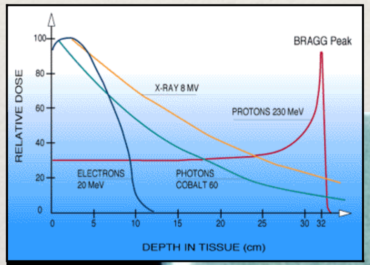
- Laser driven acceleration
  - Particles acceleration
  - X-ray generation.
- Applications
  - Radiotherapy
  - Bio-imaging
- HED physics
  - LabAstro
  - ICF

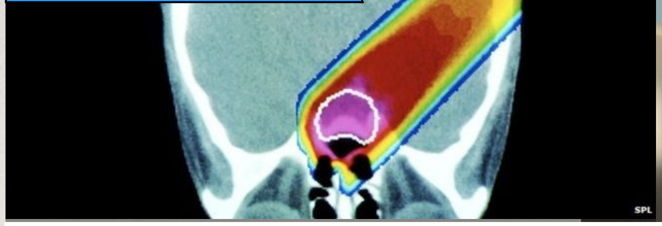


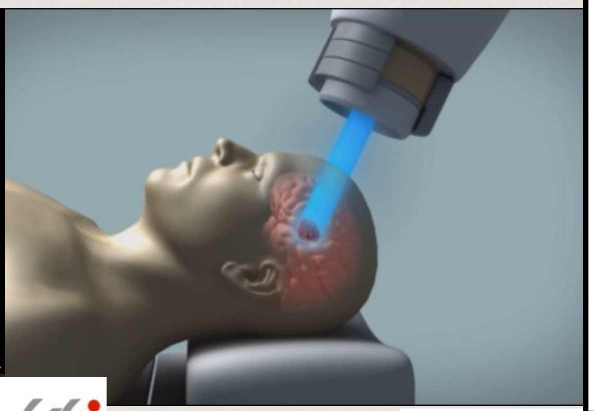


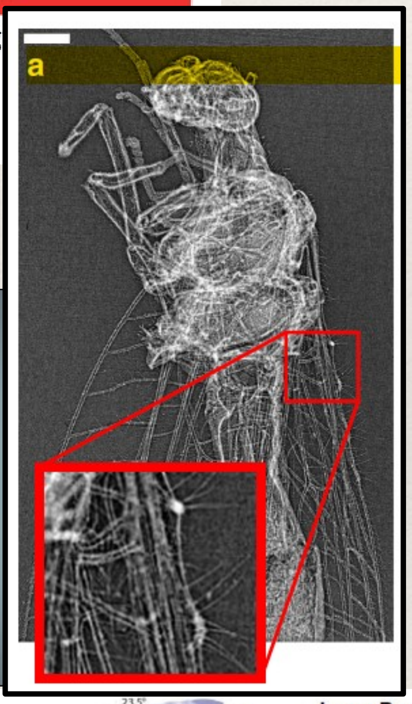


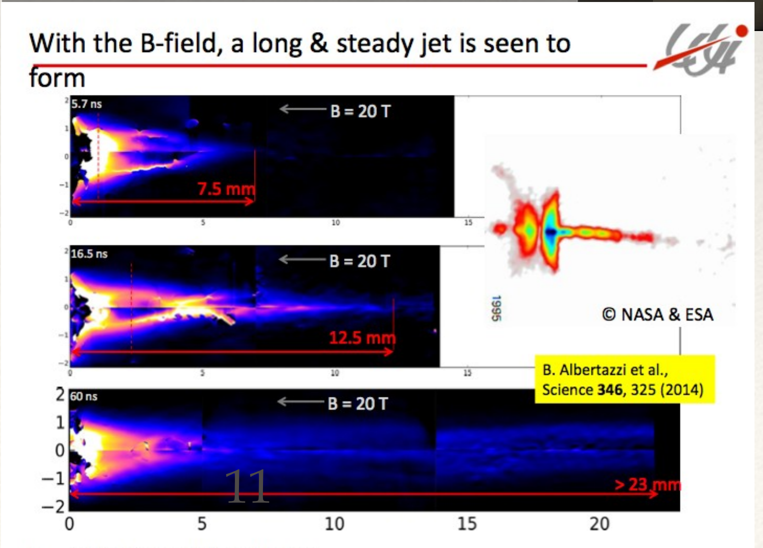


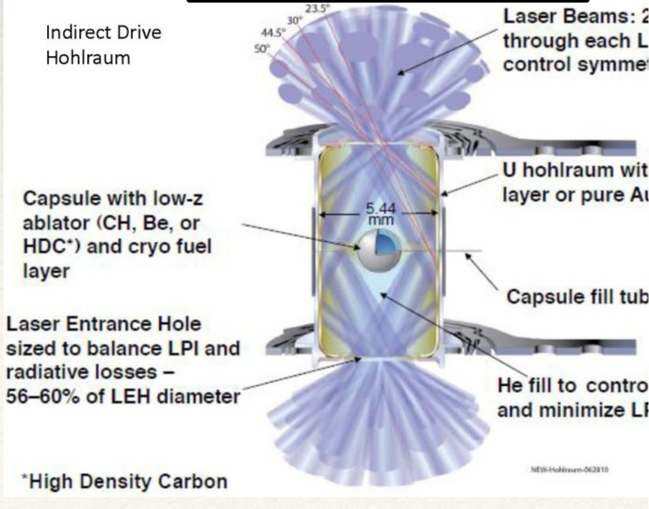






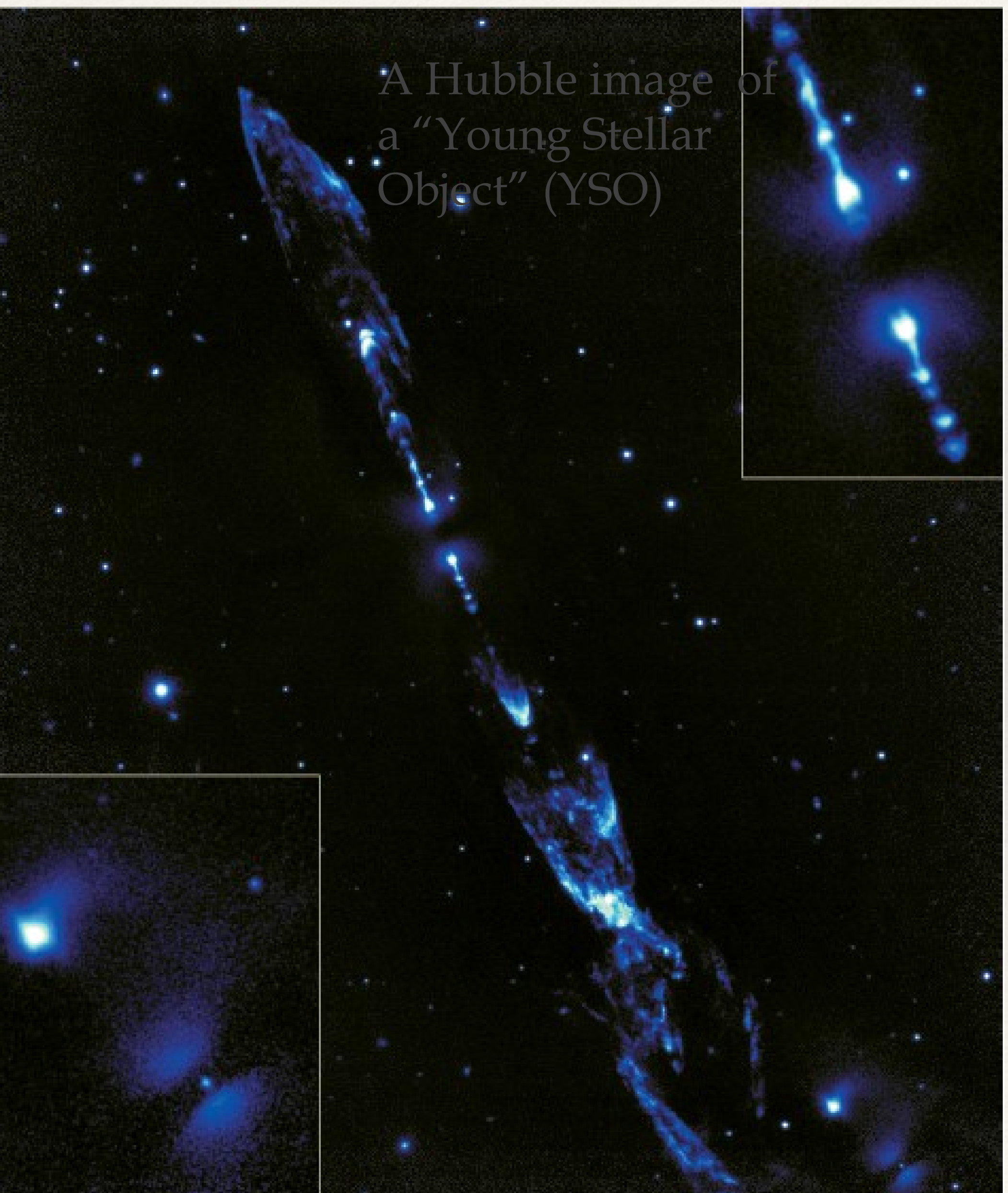


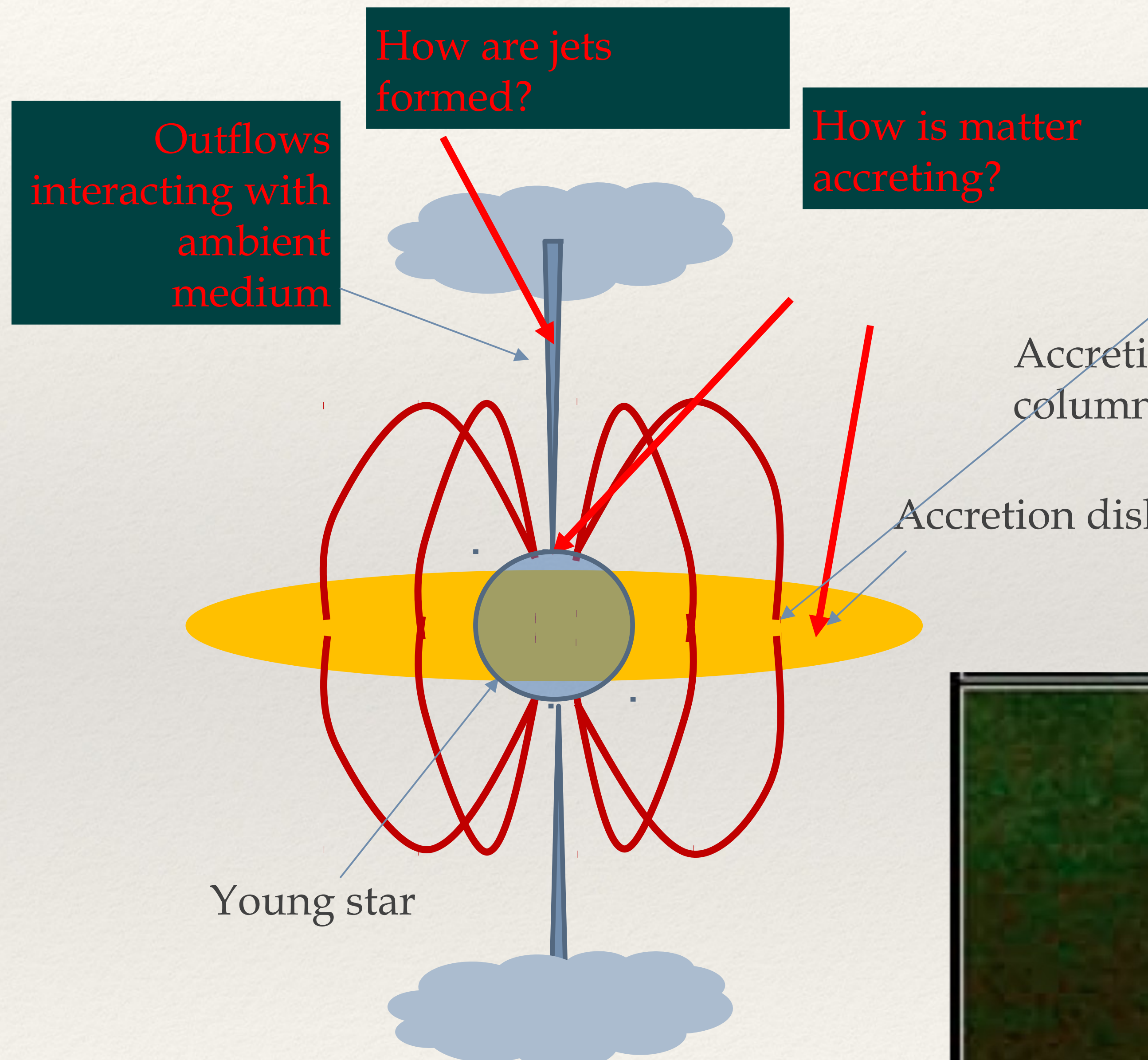


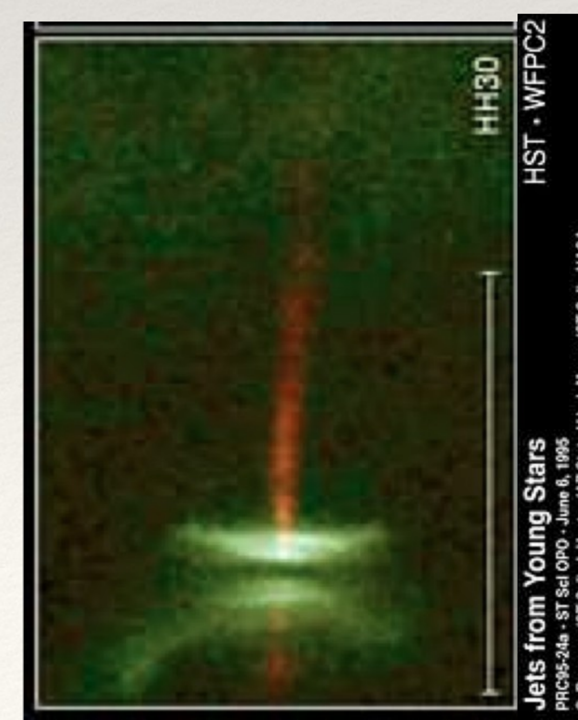


Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena



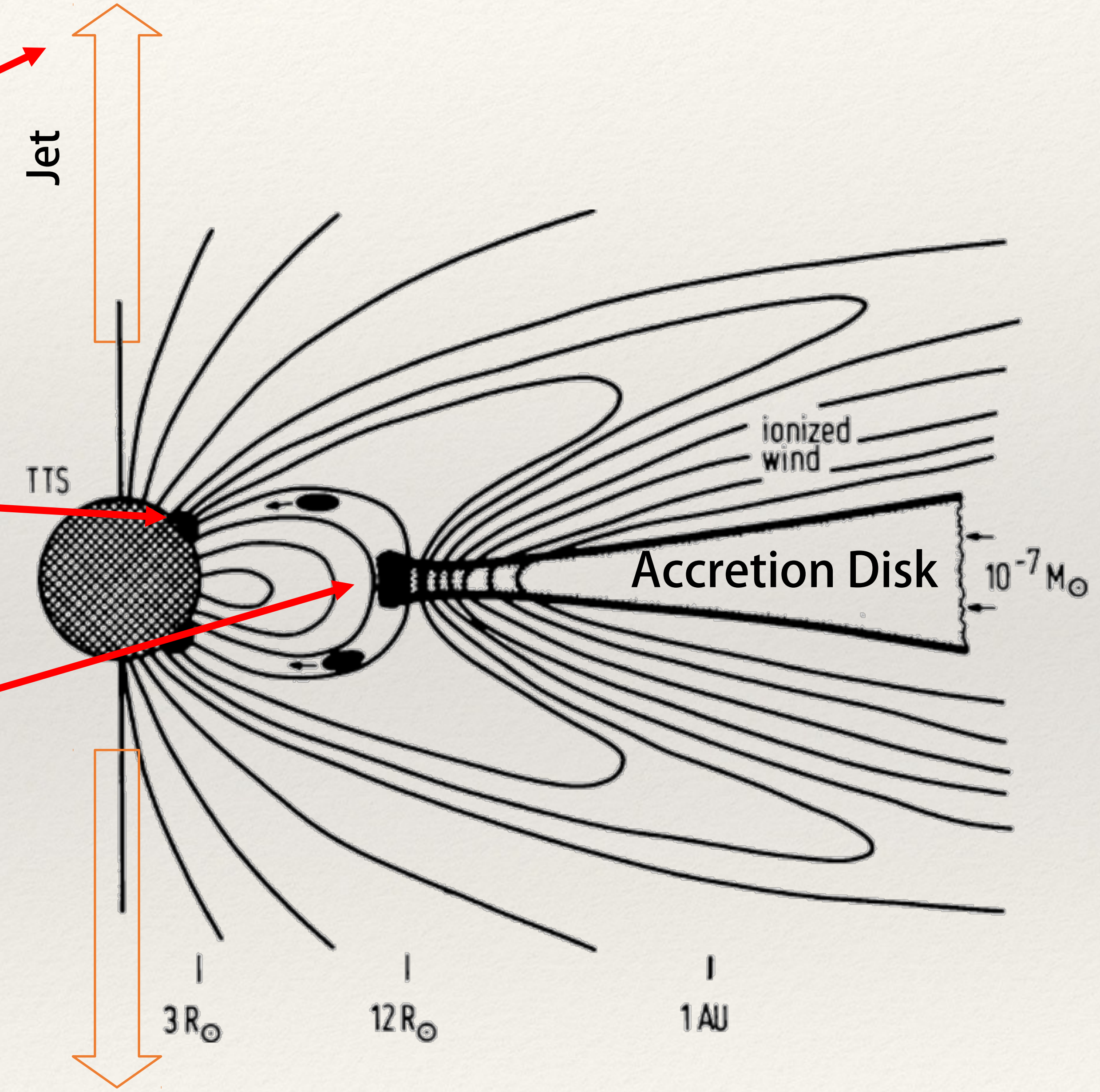




Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena

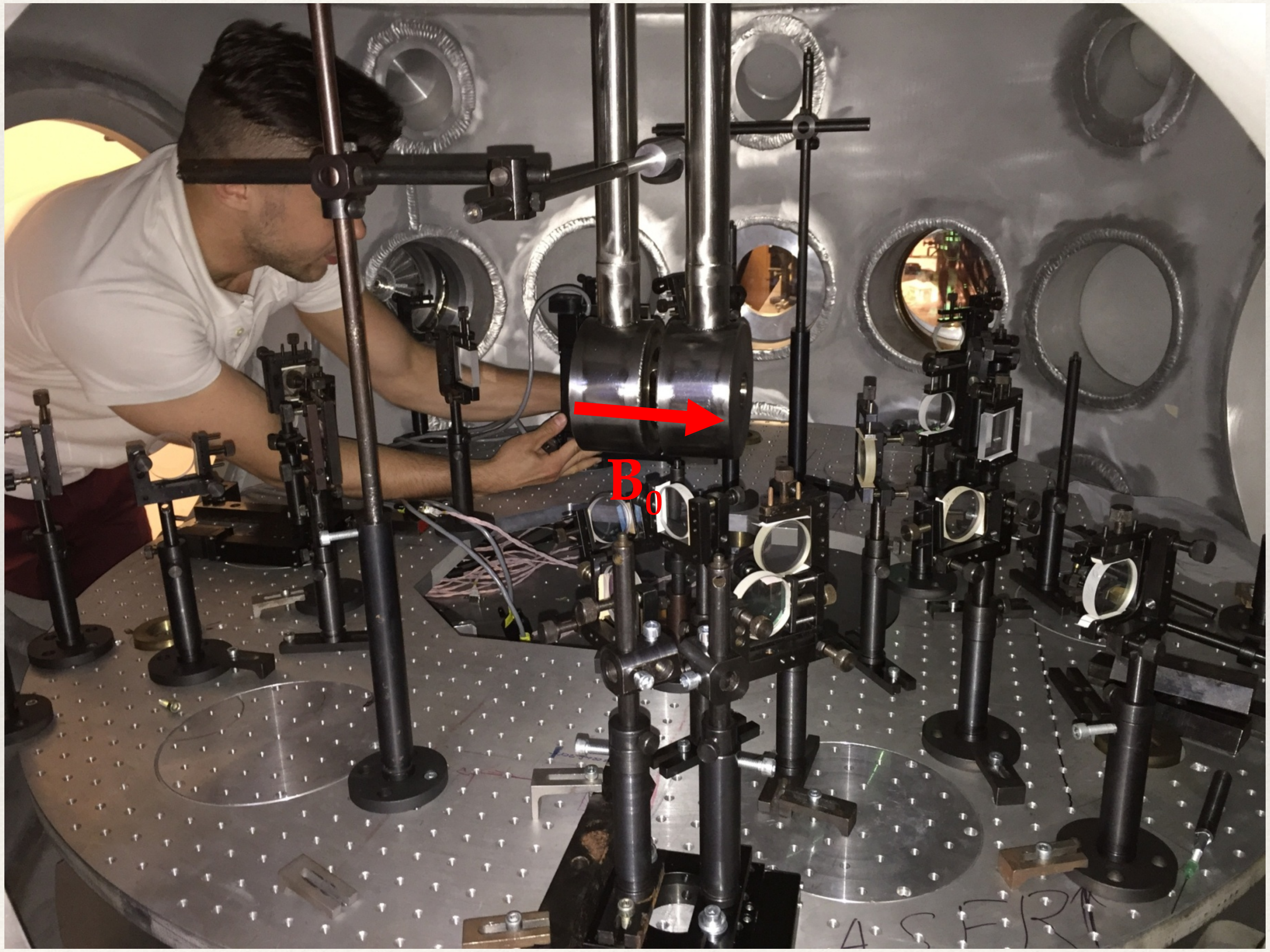
  - ✈ Jet formation:
    effect of poloidal magnetic field.
  - ✈ Accretion column:
    magnetized plasma flow interaction with surface.
  - ✈ Accretion disc dynamics
    in the vicinity of β~1.



Adapted from Camenzind, (1990).

Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena



Ambient magnetic field

- Split pulsed solenoid
- Uniform configuration (20 T)
- "Zero-point" configuration

Laser plasma production

- PEARL pump laser (~100 J, 1 ns, 1054 nm)
- Solid-state targets

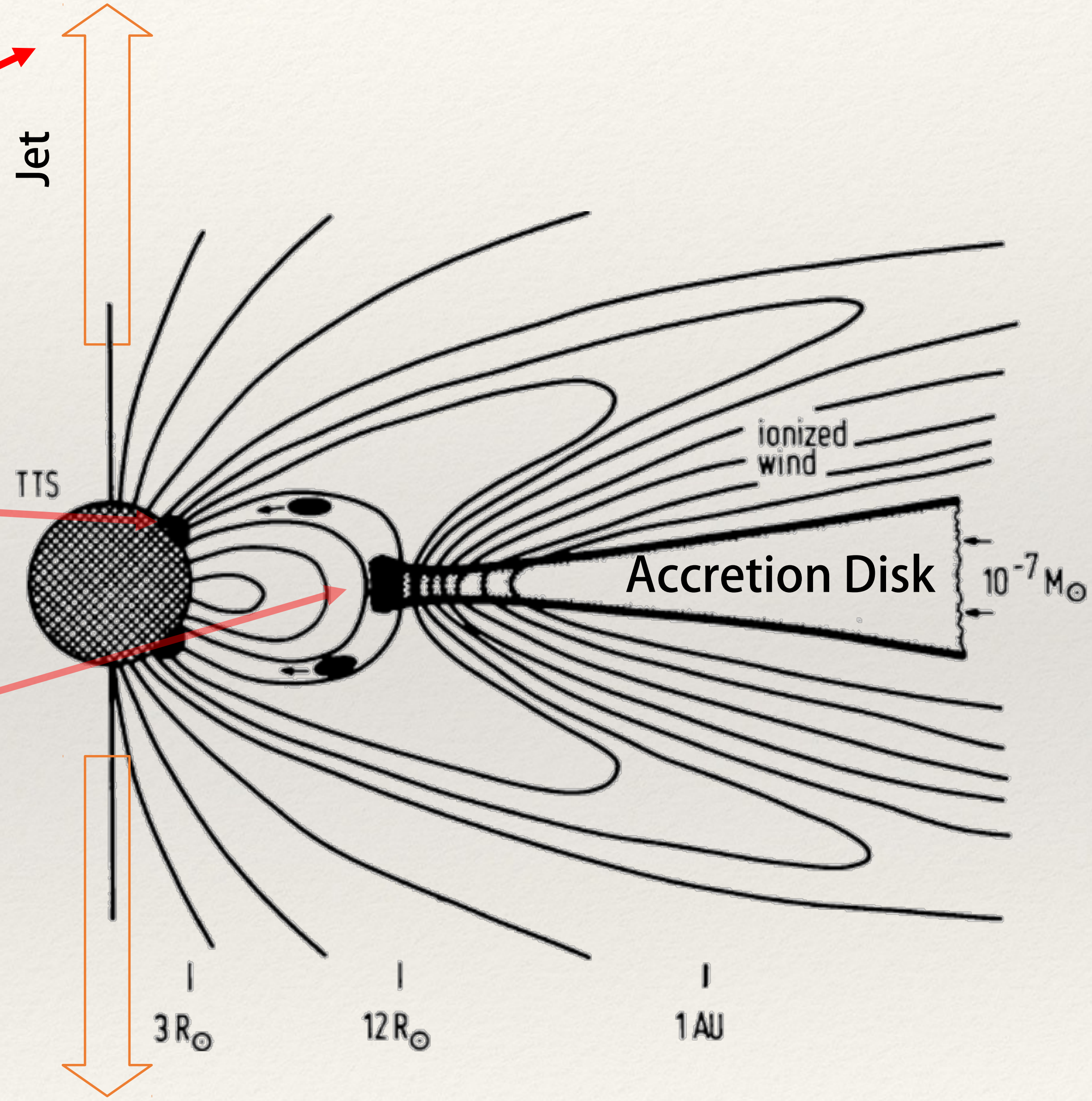
Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena

→ Jet formation:
effect of poloidal magnetic field.

→ Accretion column:
magnetized plasma flow interaction with surface.

→ Accretion disc dynamics
in the vicinity of β~1.

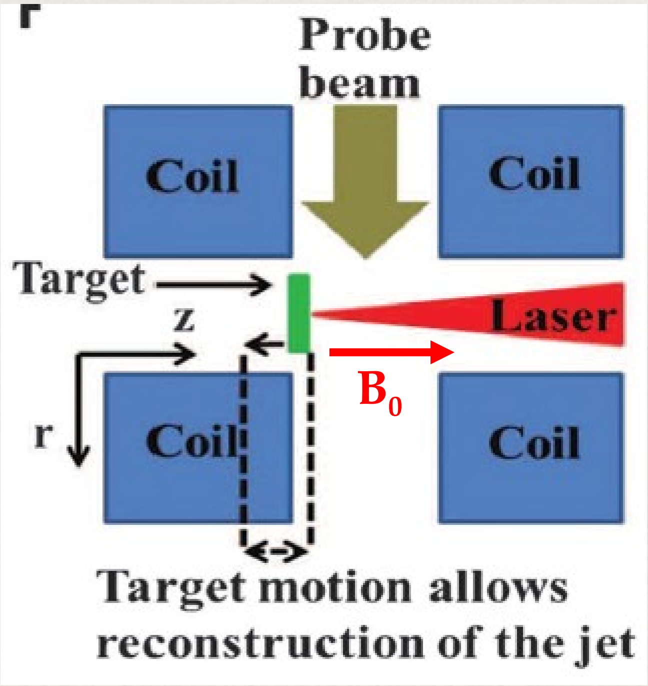


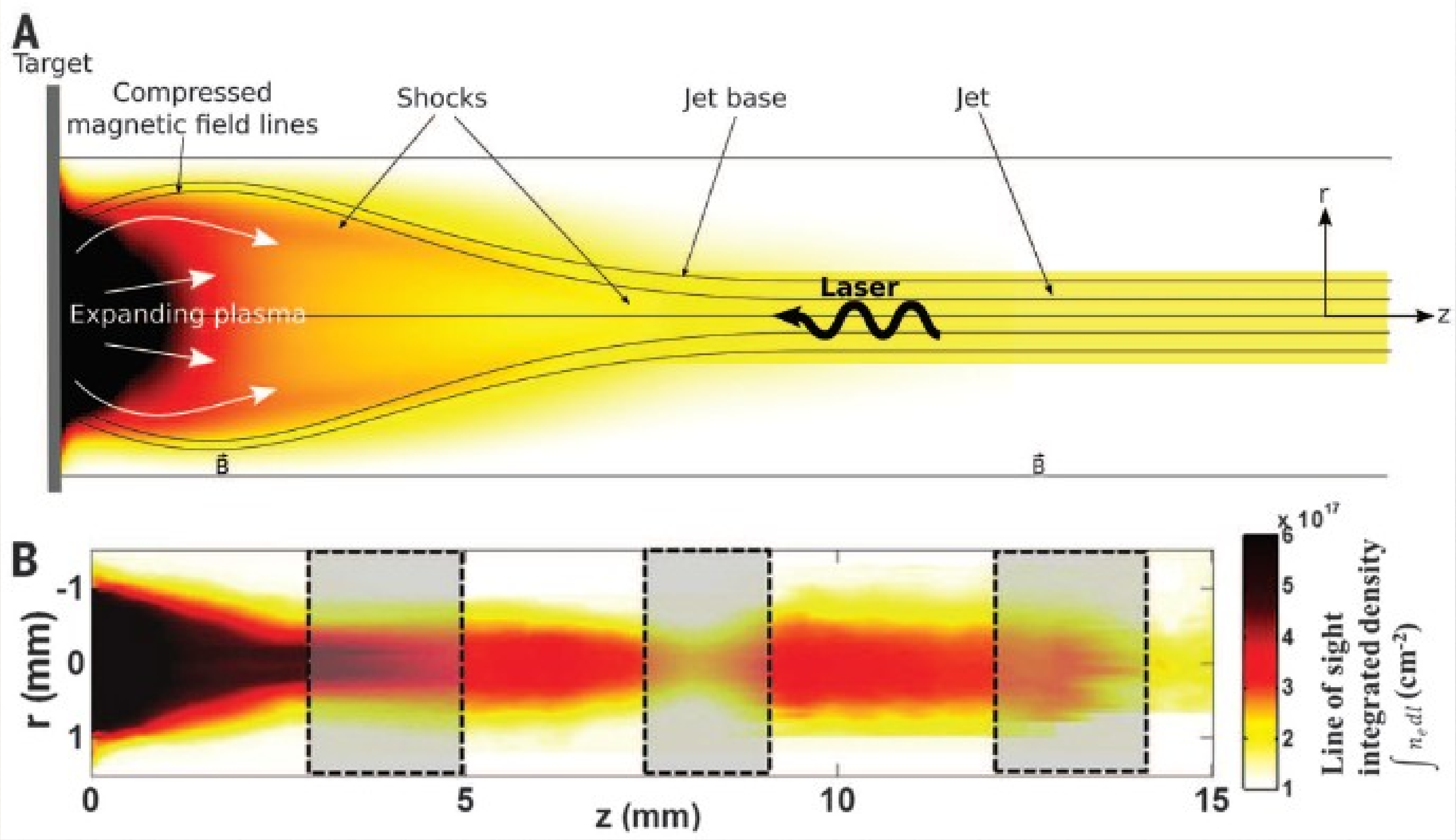
Adapted from Camenzind, (1990).

Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena: jet formation mechanisms

Laser-plasma plume propagating along the ambient magnetic field



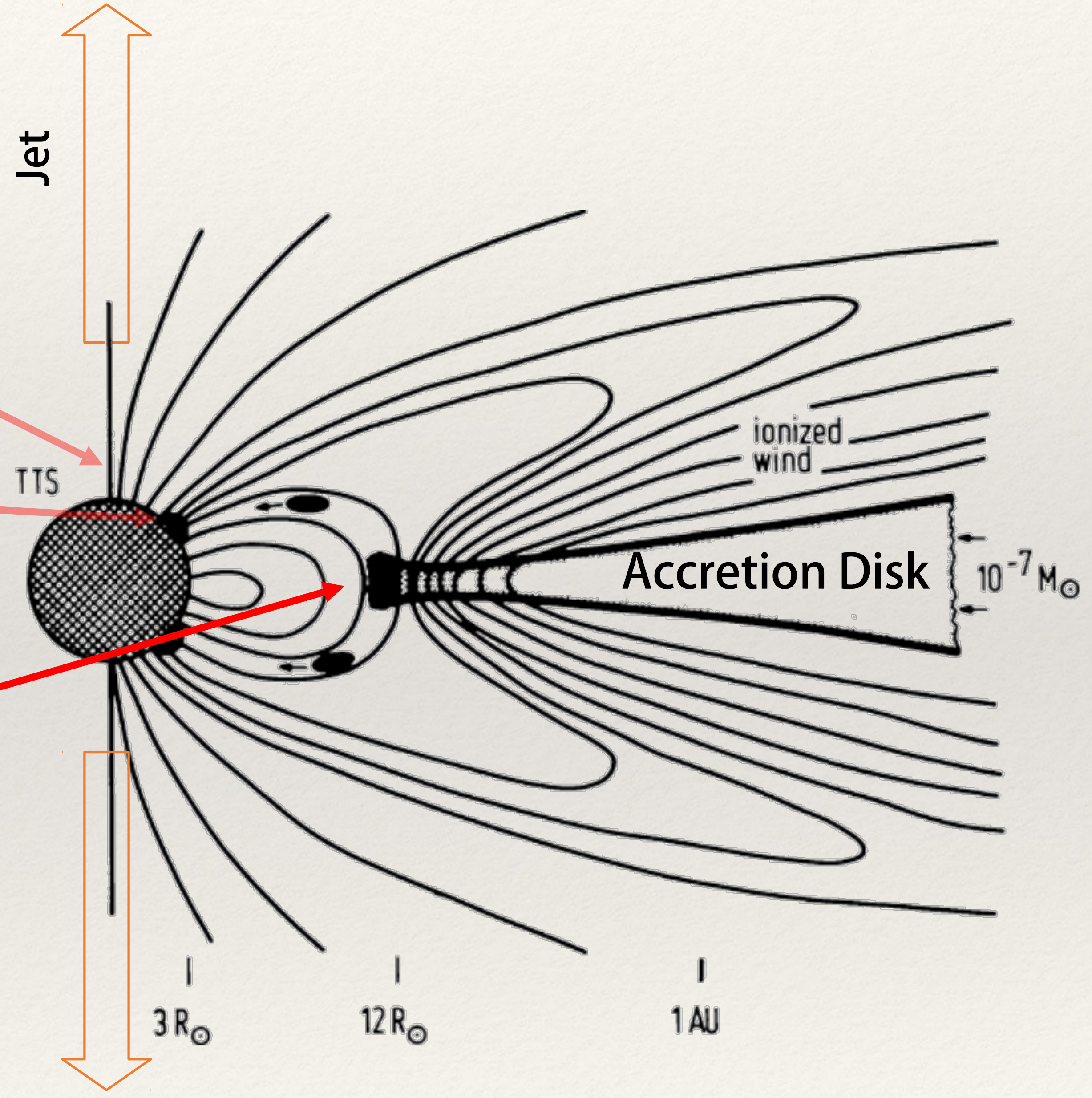


Laboratory formation of a scaled protostellar jet by coaligned poloidal magnetic field
B. Albertazzi *et al.*
Science **346**, 325 (2014);
DOI: 10.1126/science.1259694

Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena

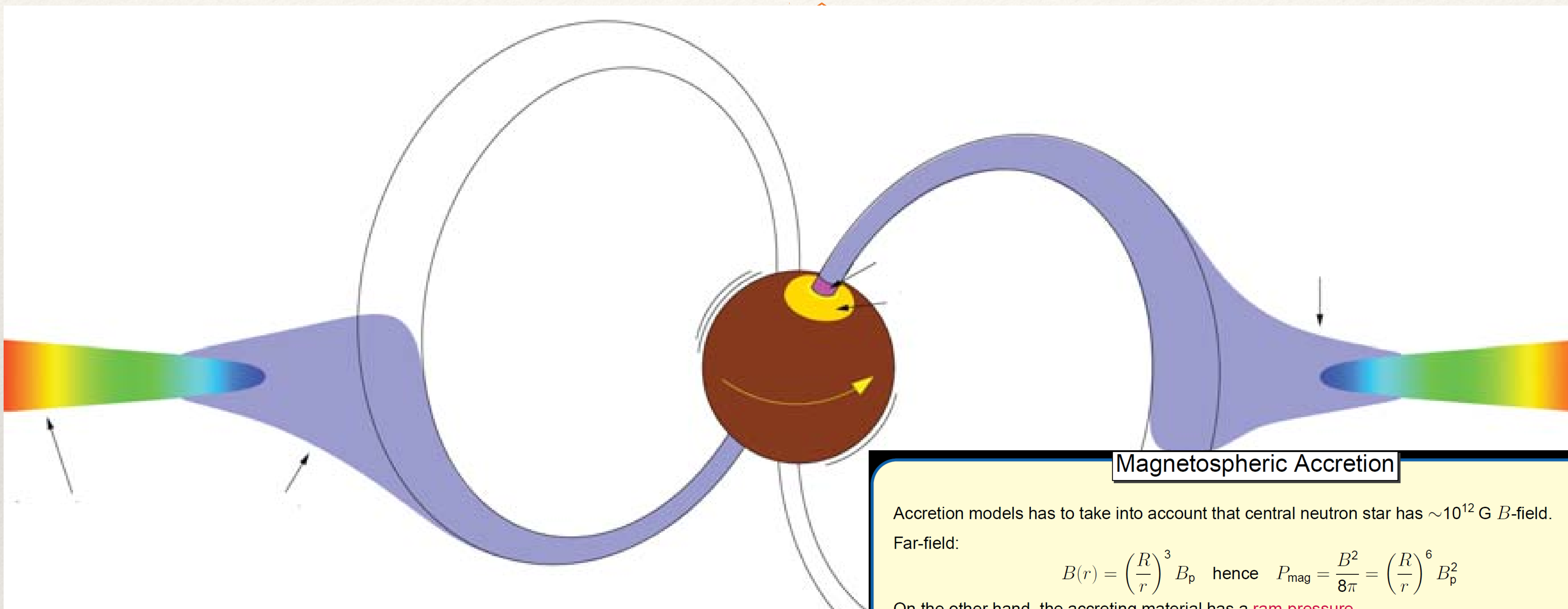
  - Jet formation: effect of poloidal magnetic field.
  - Accretion column: magnetized plasma flow interaction with surface.
  - Accretion disc dynamics in the vicinity of β~1.



Adapted from Camenzind, (1990).

Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena



Gierlinski M., Done C., Barret D., 2002, MNRAS, 331, 141

Magnetospheric Accretion

Accretion models has to take into account that central neutron star has $\sim 10^{12}$ G B-field.

Far-field:

$$B(r) = \left(\frac{R}{r}\right)^3 B_{\rm p} \quad \text{hence} \quad P_{\rm mag} = \frac{B^2}{8\pi} = \left(\frac{R}{r}\right)^6 B_{\rm p}^2$$

On the other hand, the accreting material has a ram-pressure

$$P_{\rm ram} = \rho v^2 \quad \text{or} \quad P_{\rm ram} = \frac{\dot{M}}{4\pi r^2}\left(\frac{2GM}{r}\right)^{1/2}$$

assuming free fall ($v = (2GM/r)^{1/2}$) and spherical symmetry ($\dot{M} = 4\pi r^2 \rho v$).

For $P_{\rm mag} > P_{\rm ram}$, B-field dominates $\Longrightarrow$ plasma couples to B-field lines at the Alfvén radius

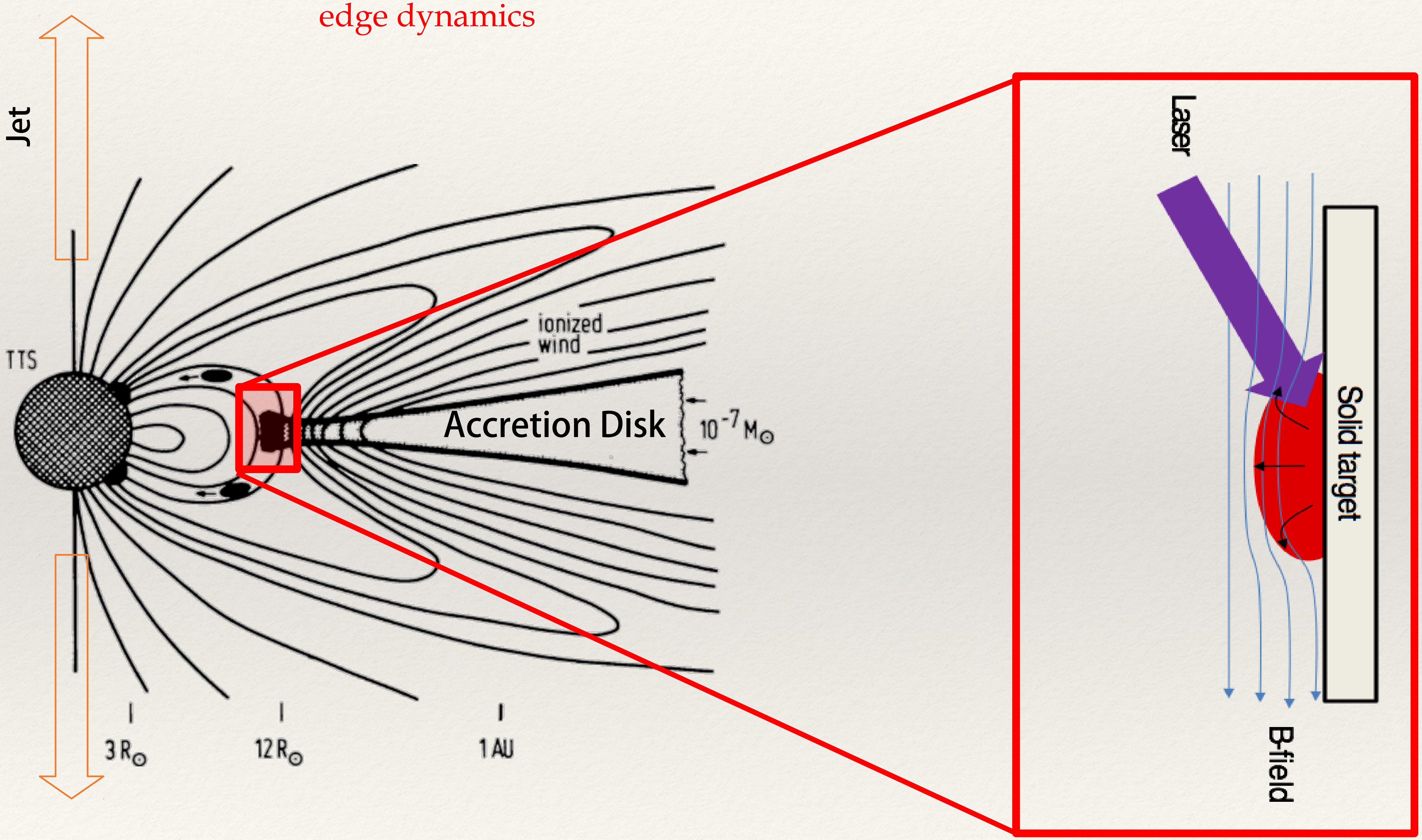
$$r_{\rm mag} = \left(\frac{8\pi^2}{G}\right)^{1/7}\left(\frac{R^{12}B_{\rm p}^4}{M\dot{M}^2}\right)^{1/7}$$

$$= 1800\ \text{km} \left(\frac{R}{10\ \text{km}}\right)^{12/7}\left(\frac{B}{10^{12}\ \text{G}}\right)^{4/7}\left(\frac{M}{1.4\ M_\odot}\right)^{-1/7}\left(\frac{\dot{M}}{10^{-7}\ M_\odot\ \text{yr}^{-1}}\right)^{-2/7}$$

For typical NS parameters, the accretion close to the NS is dominated by the B-field.

Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena: accretion disc edge dynamics

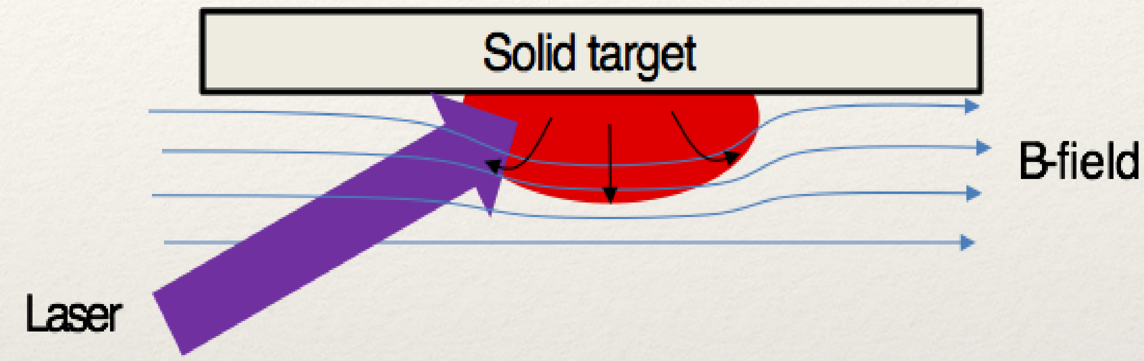


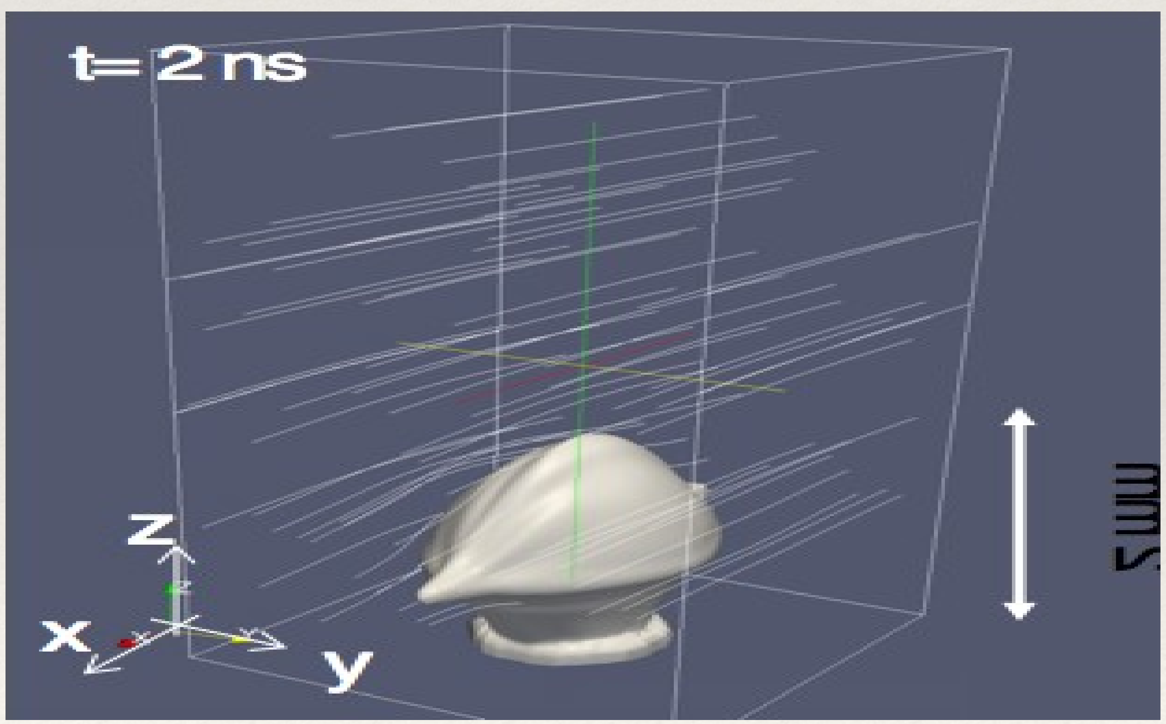
Adapted from Camenzind, (1990).

Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena: accretion disc edge dynamics

Laser-plasma plume
propagating across
the ambient magnetic field





Andrea Ciardi (2016)

expect:

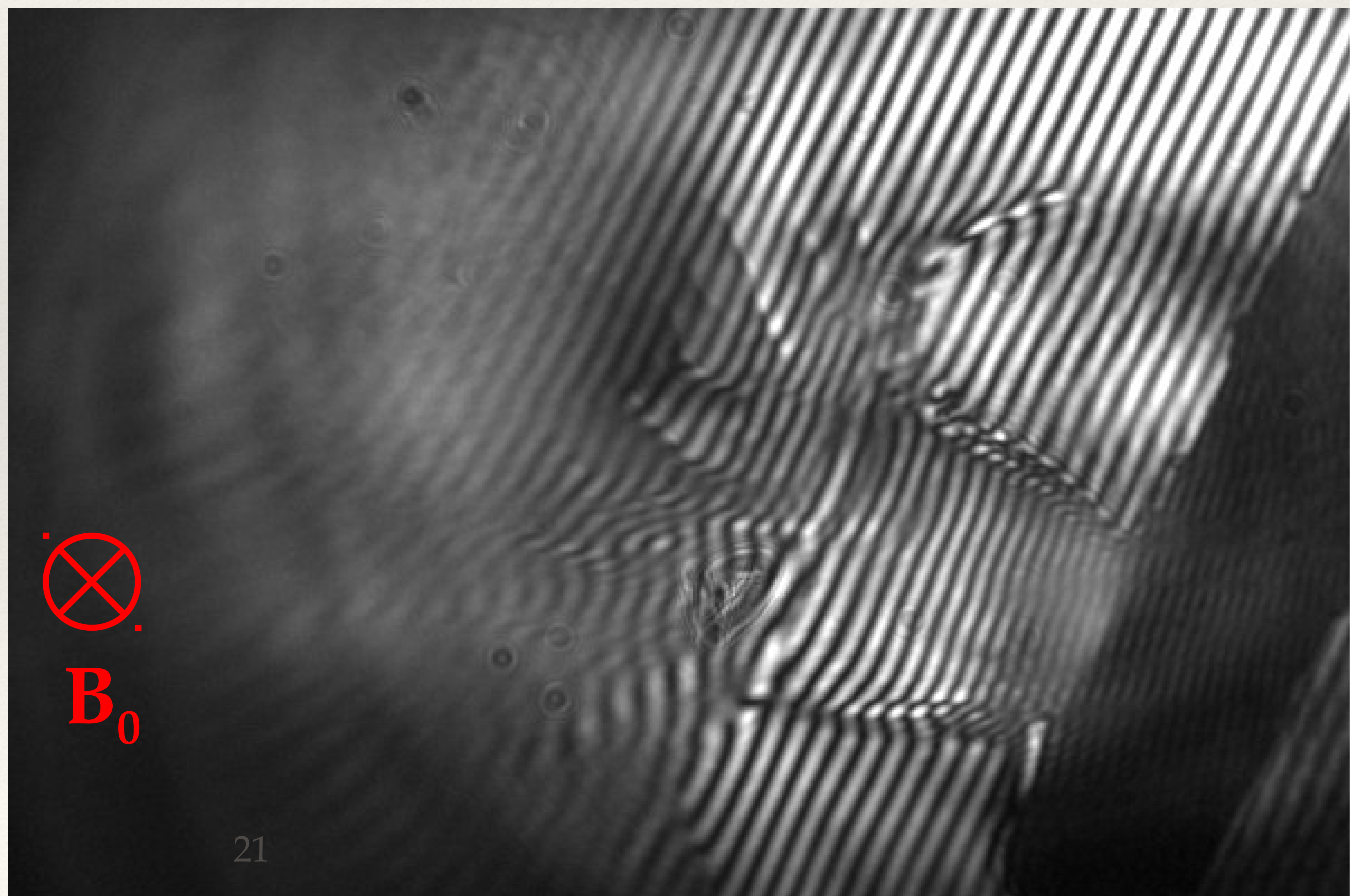
plasma expansion across $\mathbf{B}_0$
is limited by magnetic pressure

further plasma expansion
is along $\mathbf{B}_0$

Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena: accretion disc

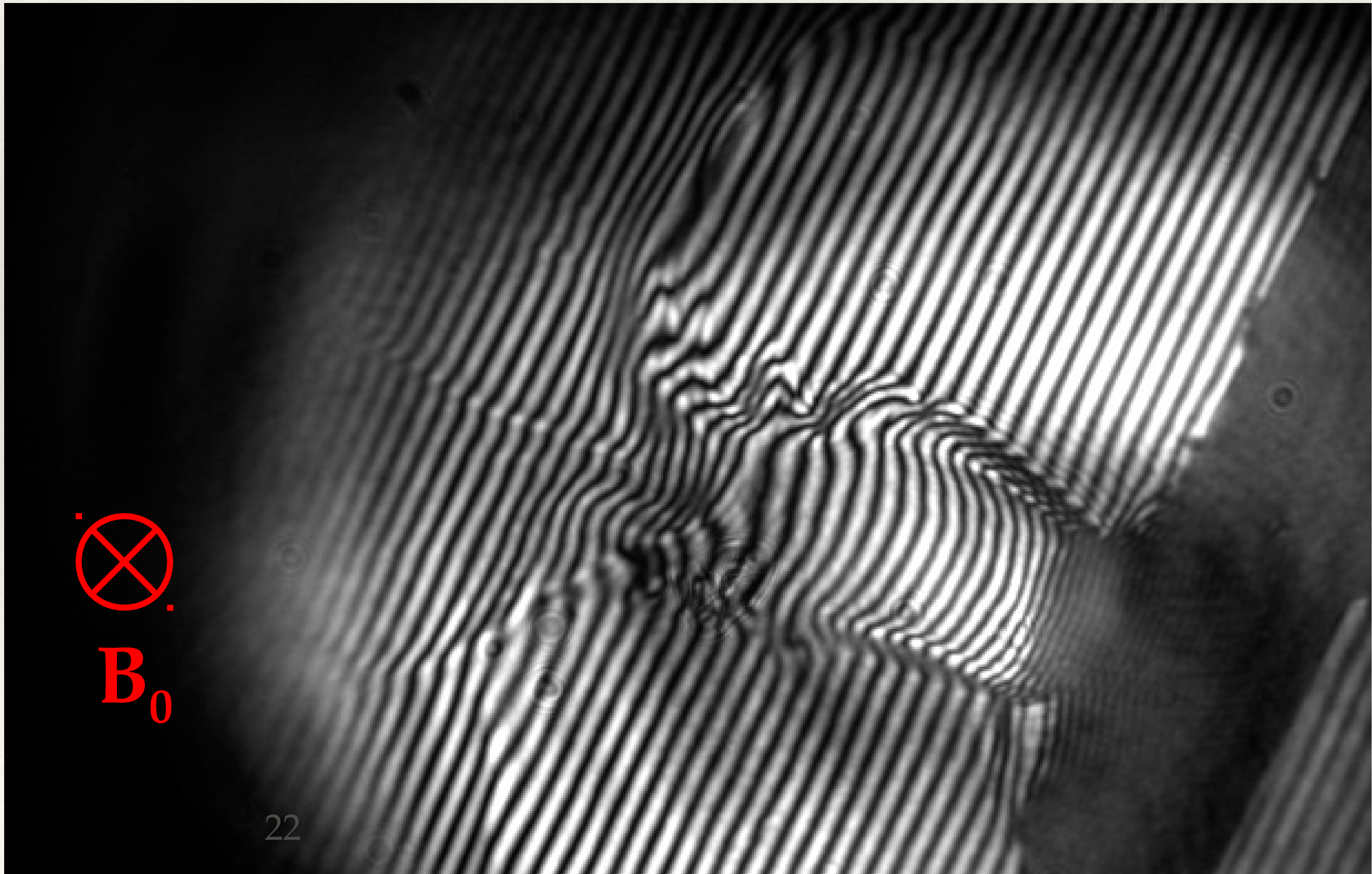
16ns,
25J



Laboratory astrophysics

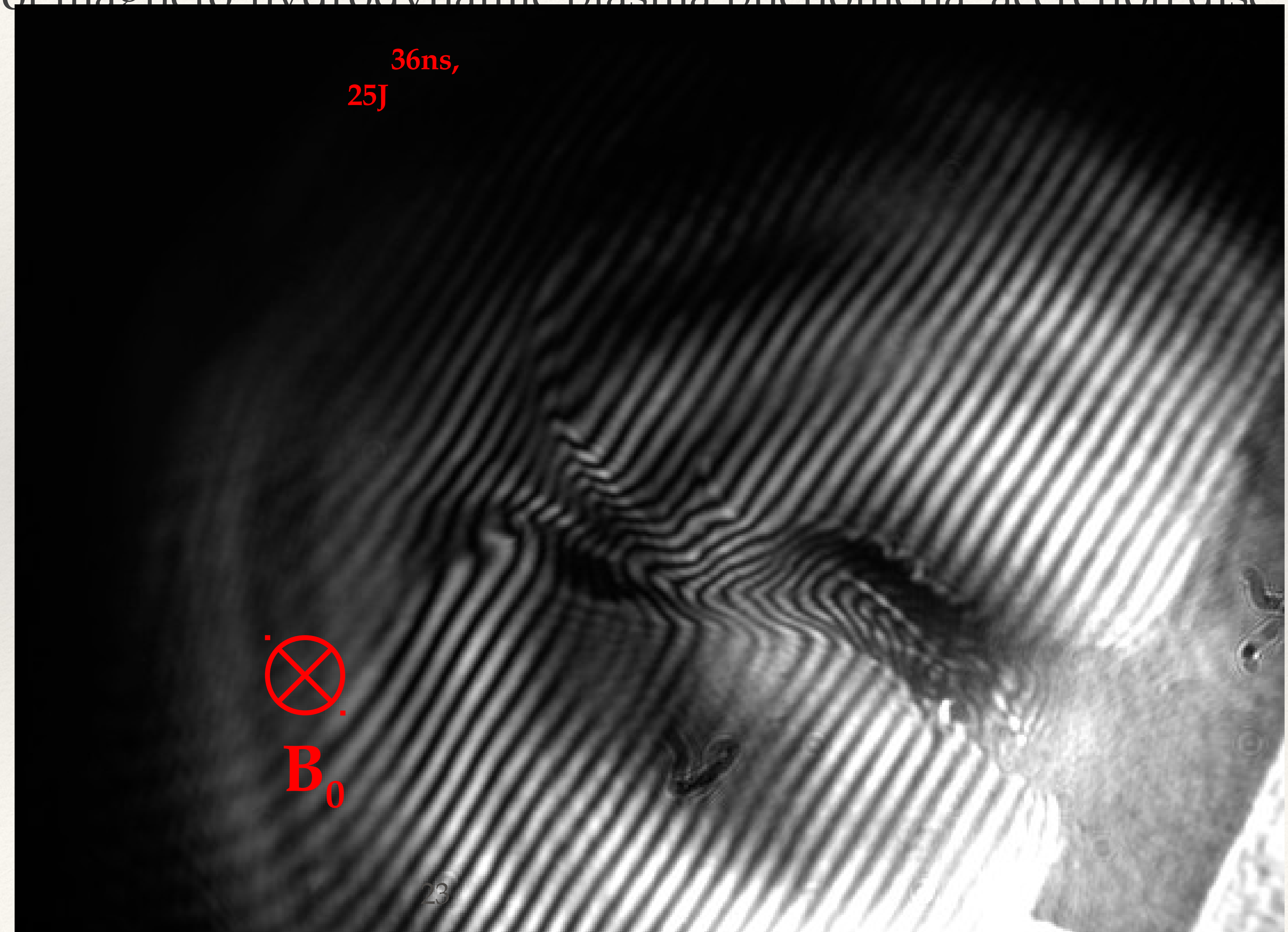
- Modeling of magneto-hydrodynamic plasma phenomena: accretion disc

26ns,
25J



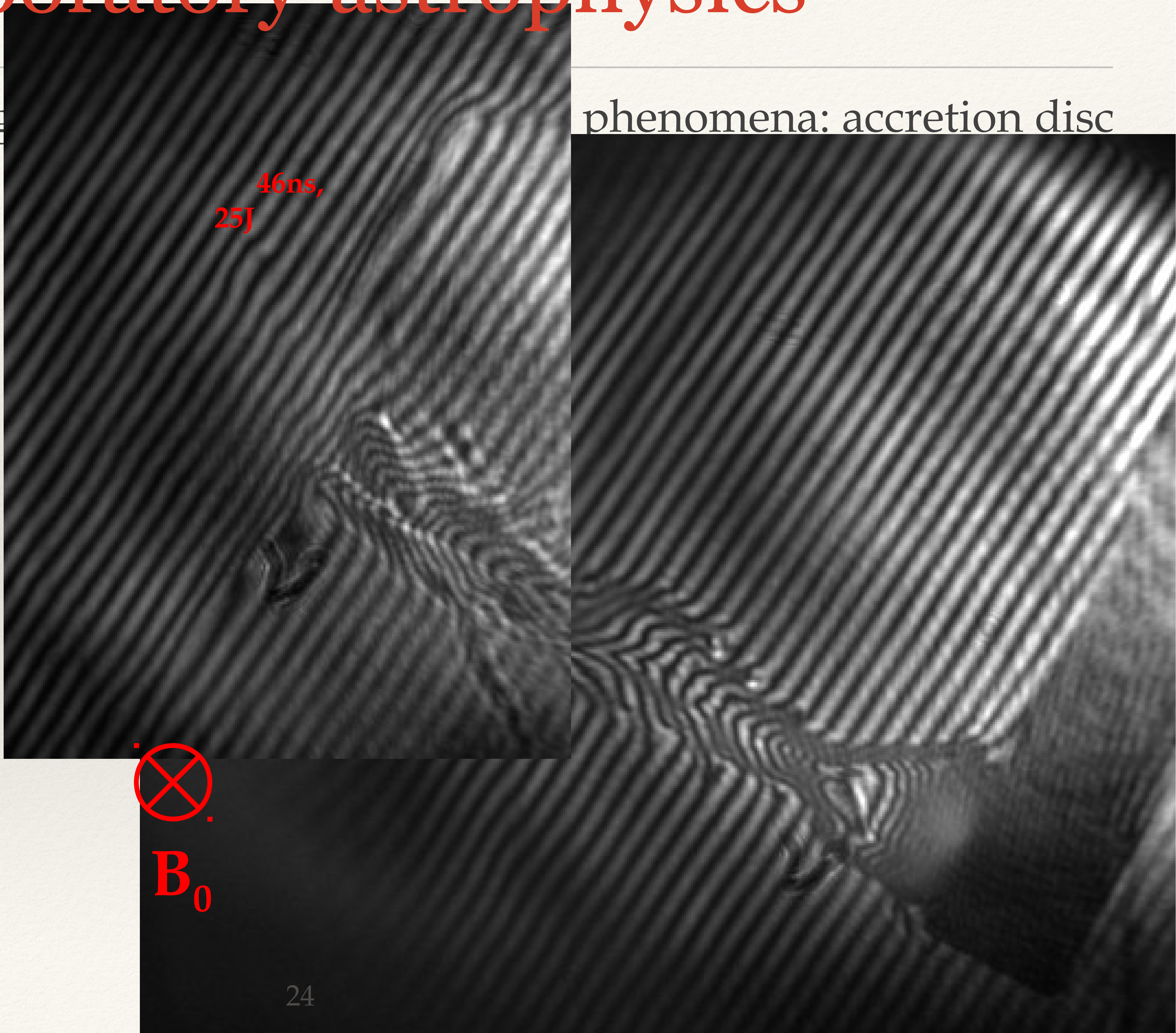
Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena: accretion disc



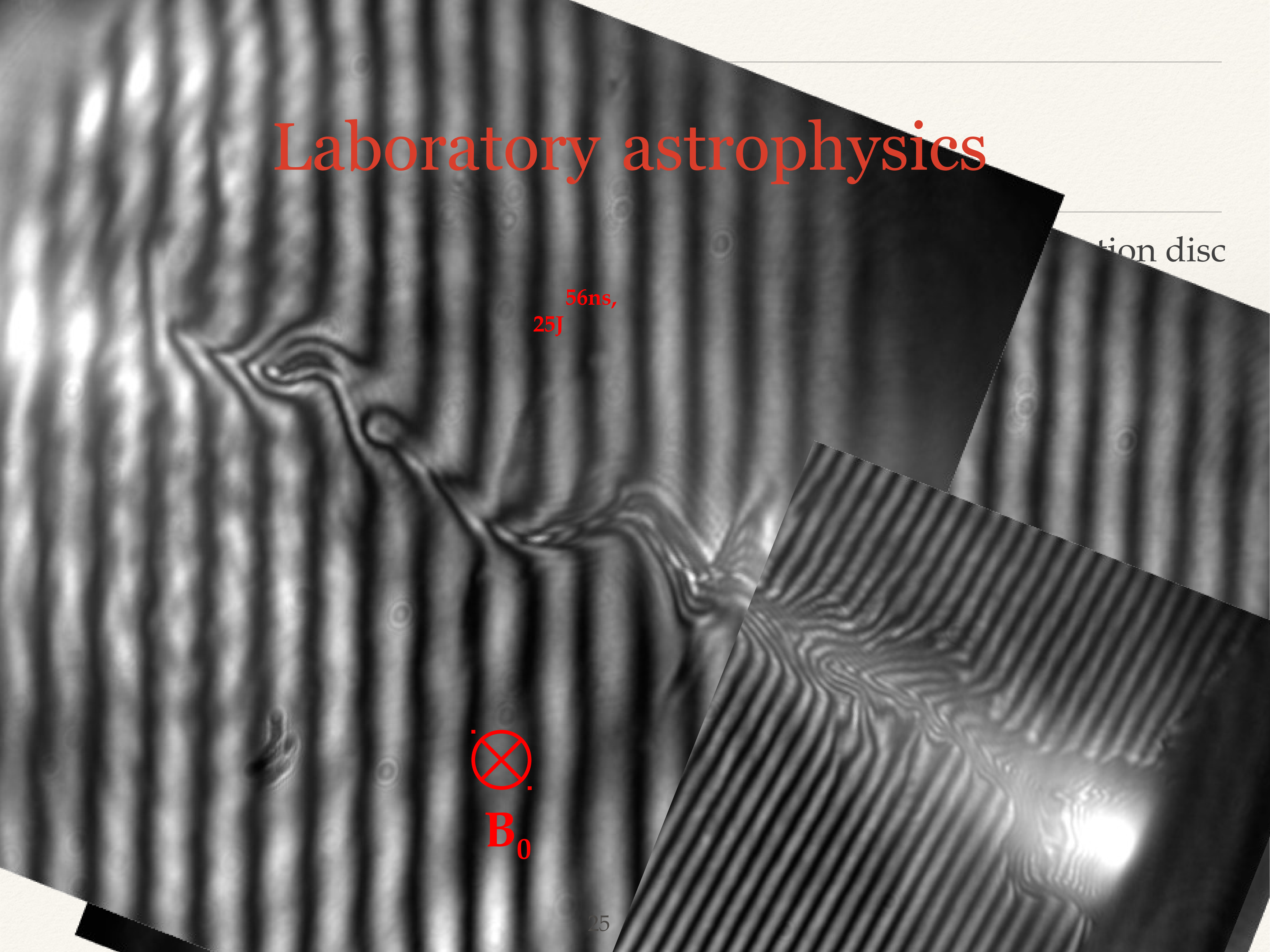
Laboratory astrophysics

- Modeling of mag phenomena: accretion disc



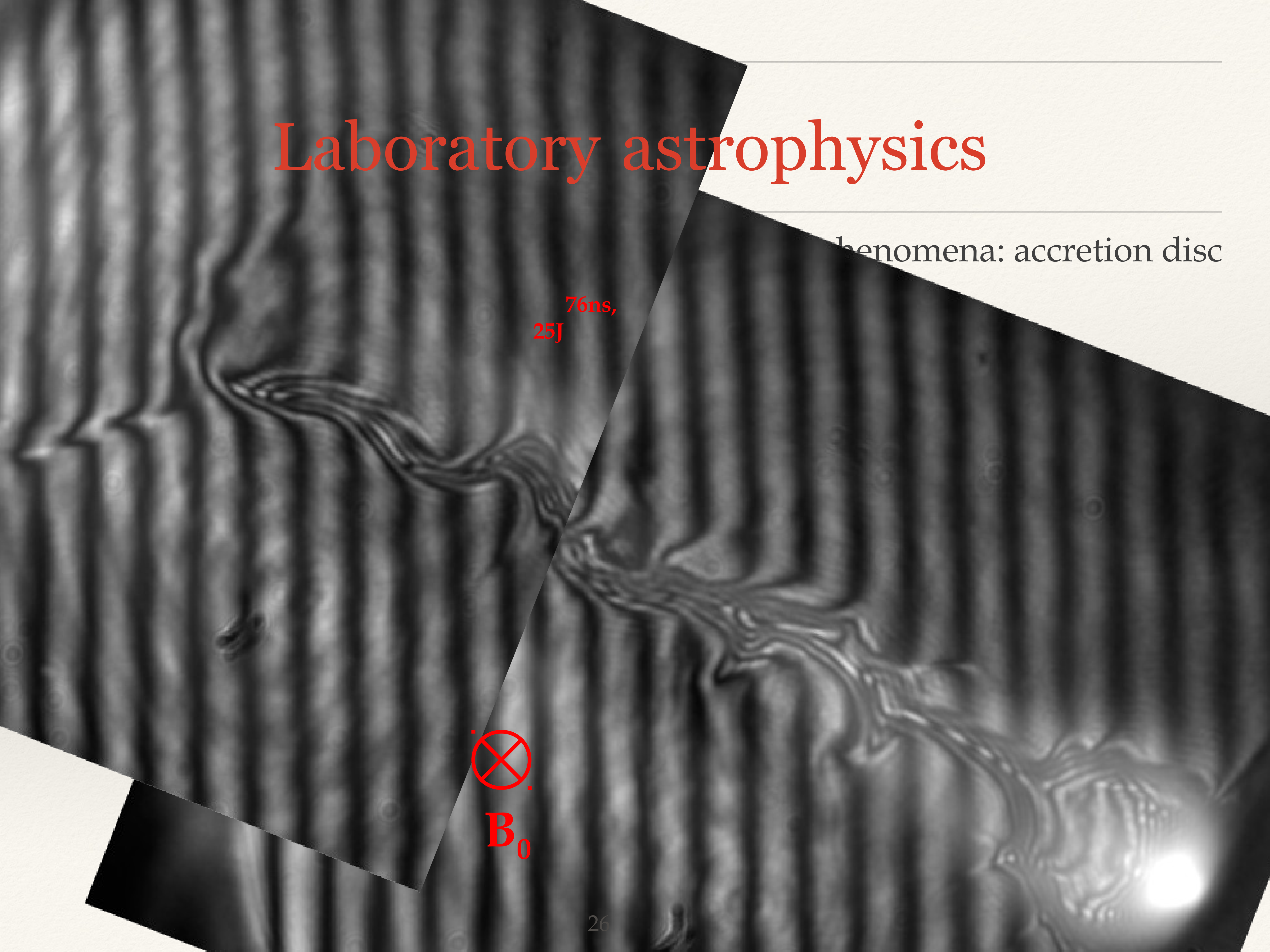
Laboratory astrophysics

tion disc



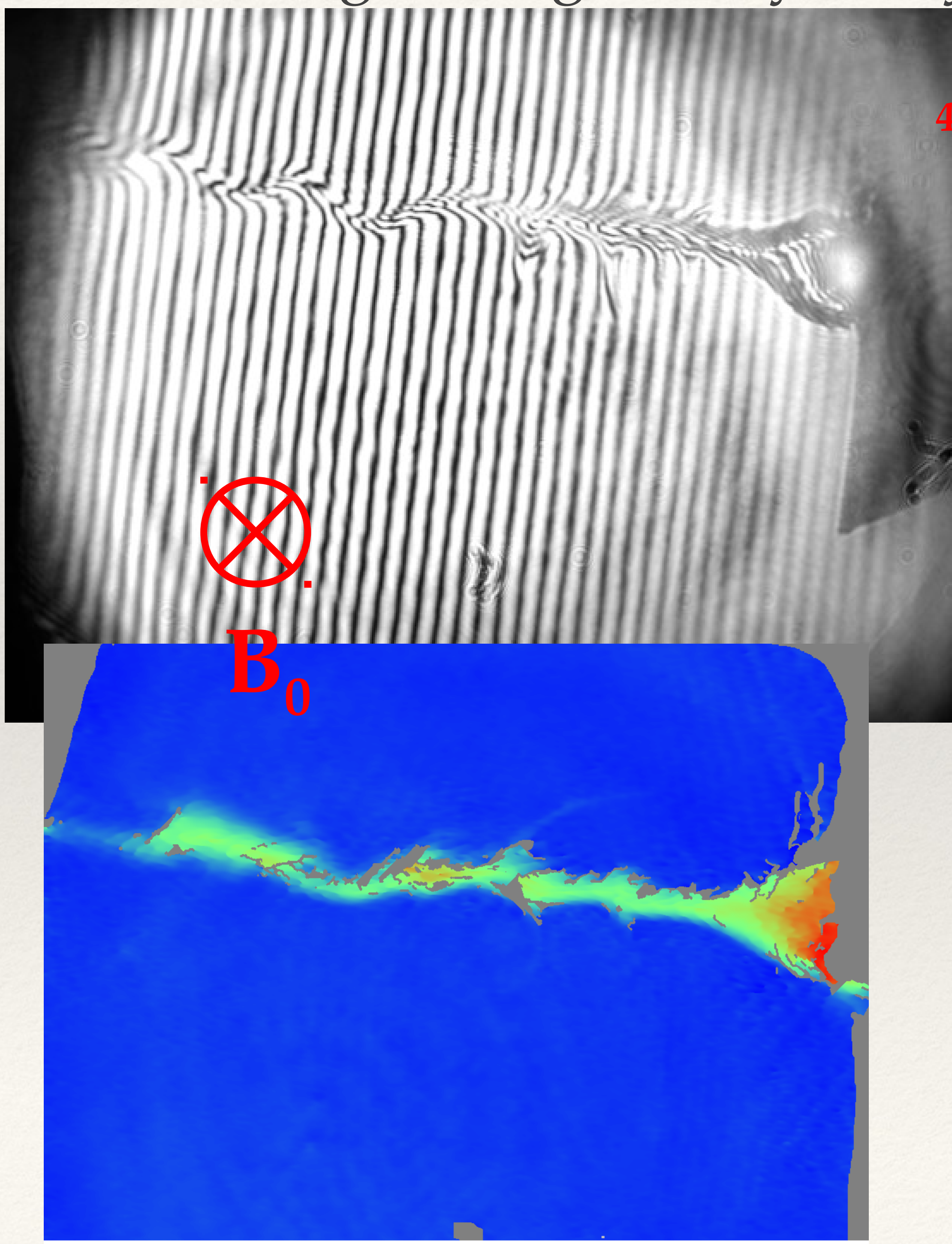
Laboratory astrophysics

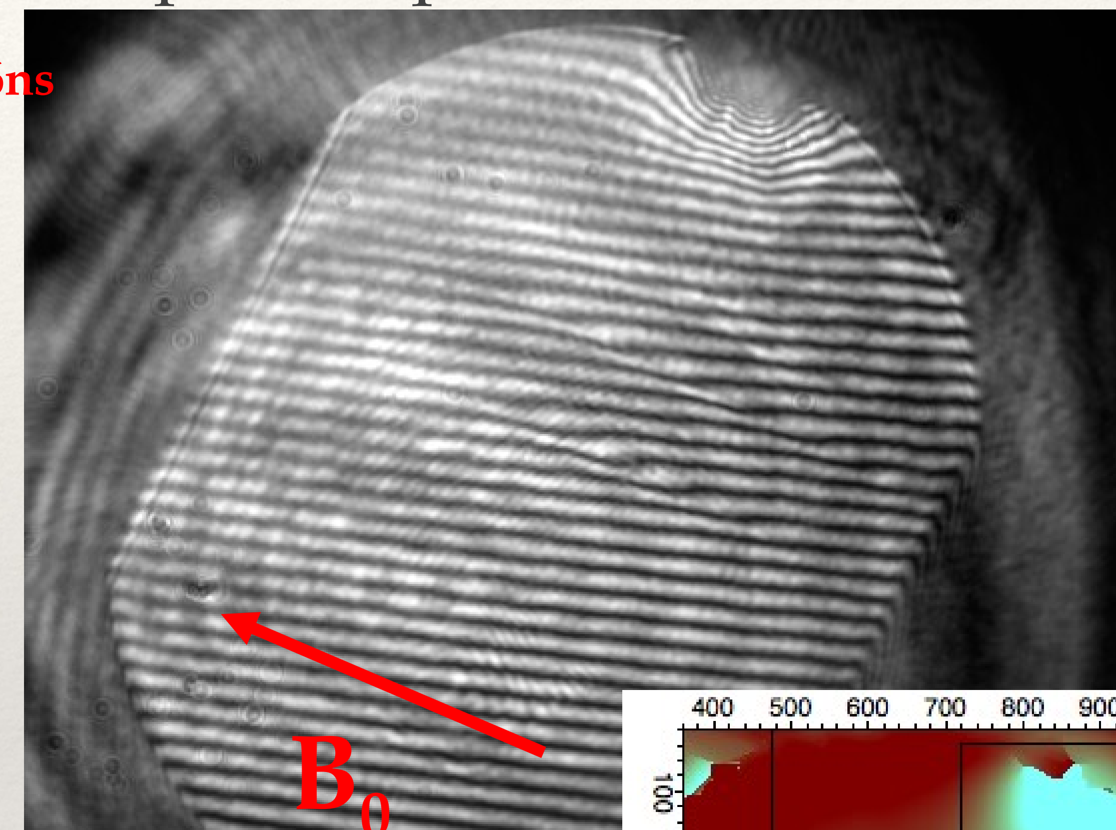
…henomena: accretion disc

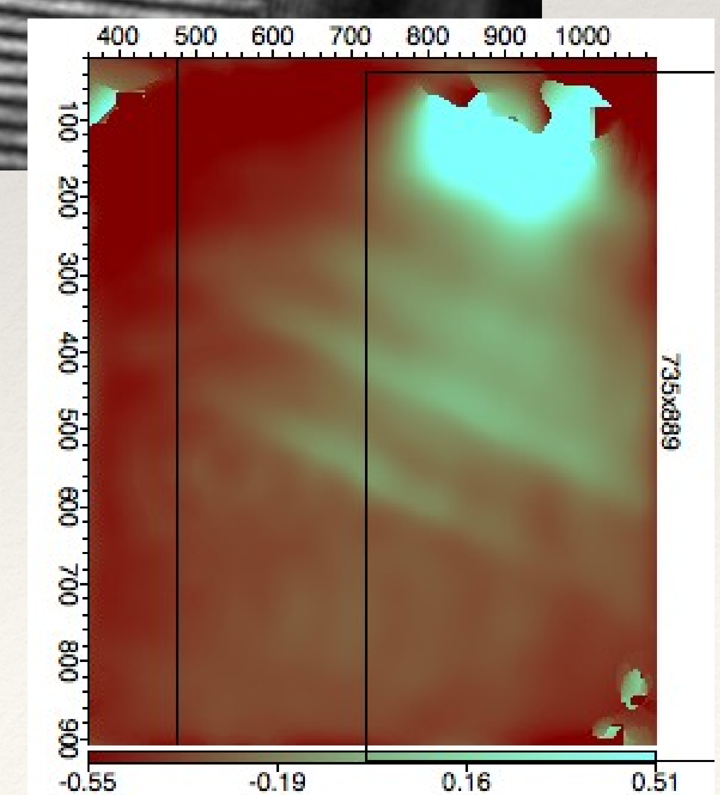


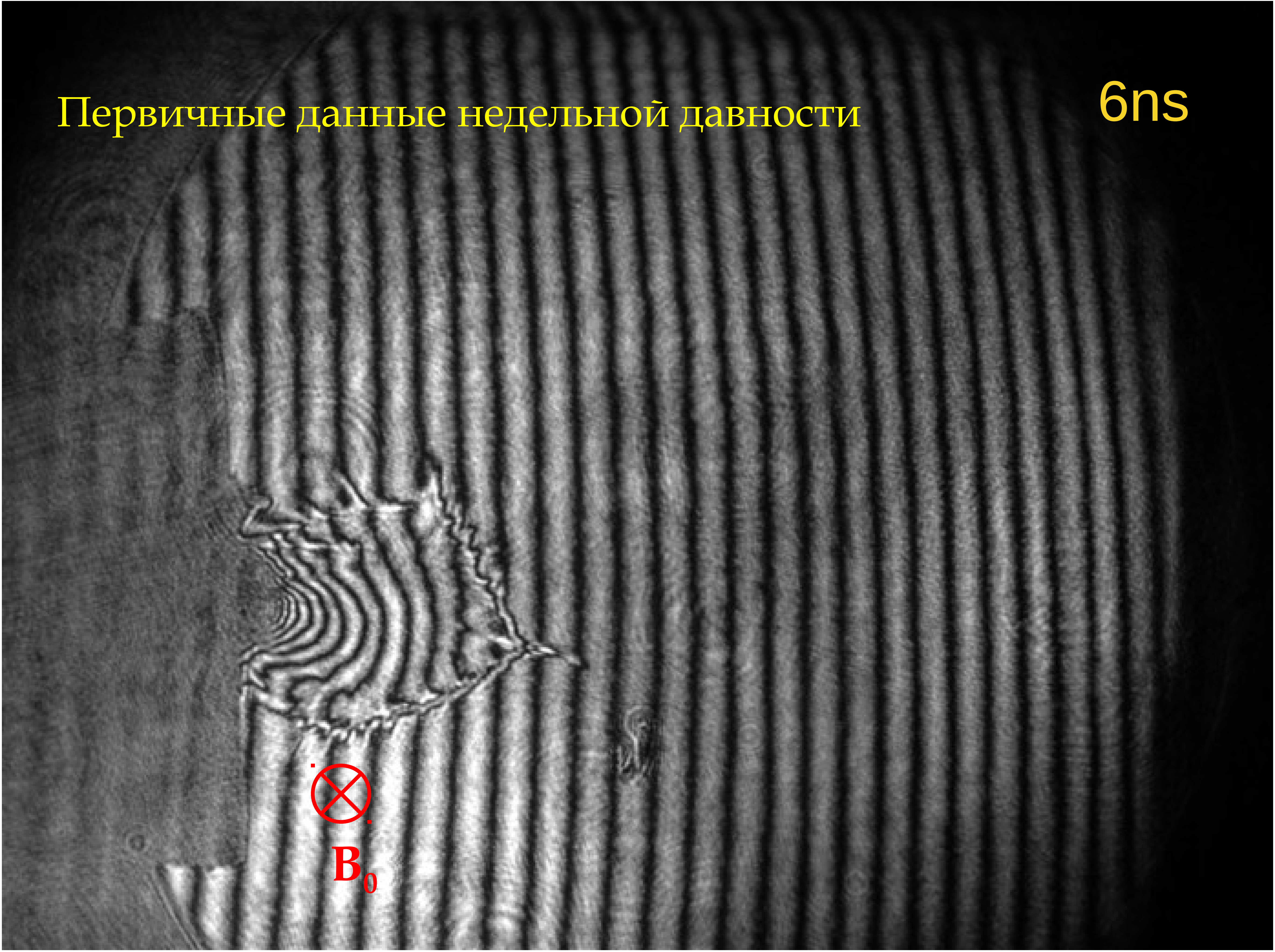
Laboratory astrophysics

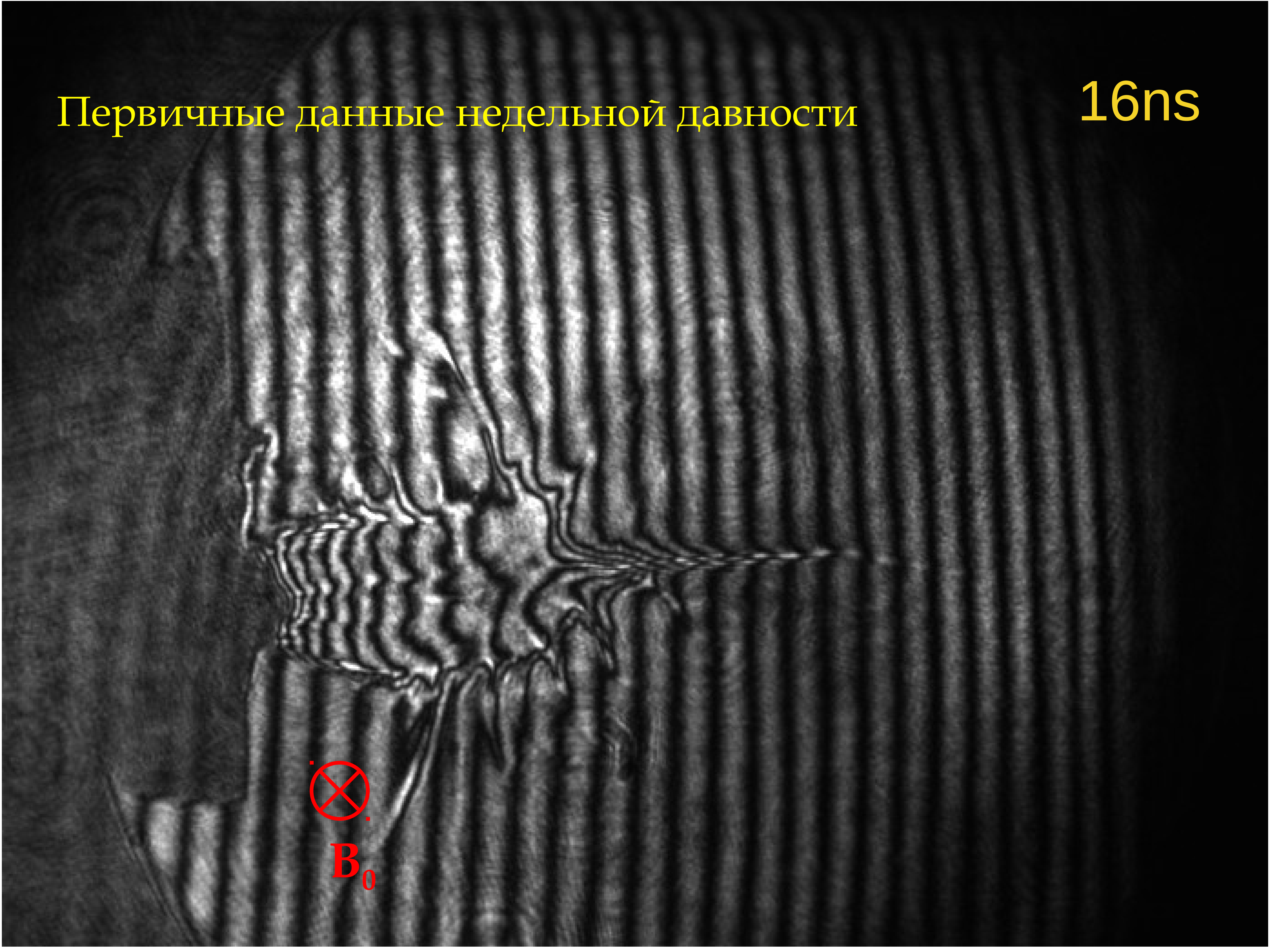
- Modeling of magneto-hydrodynamic plasma phenomena: accretion disc



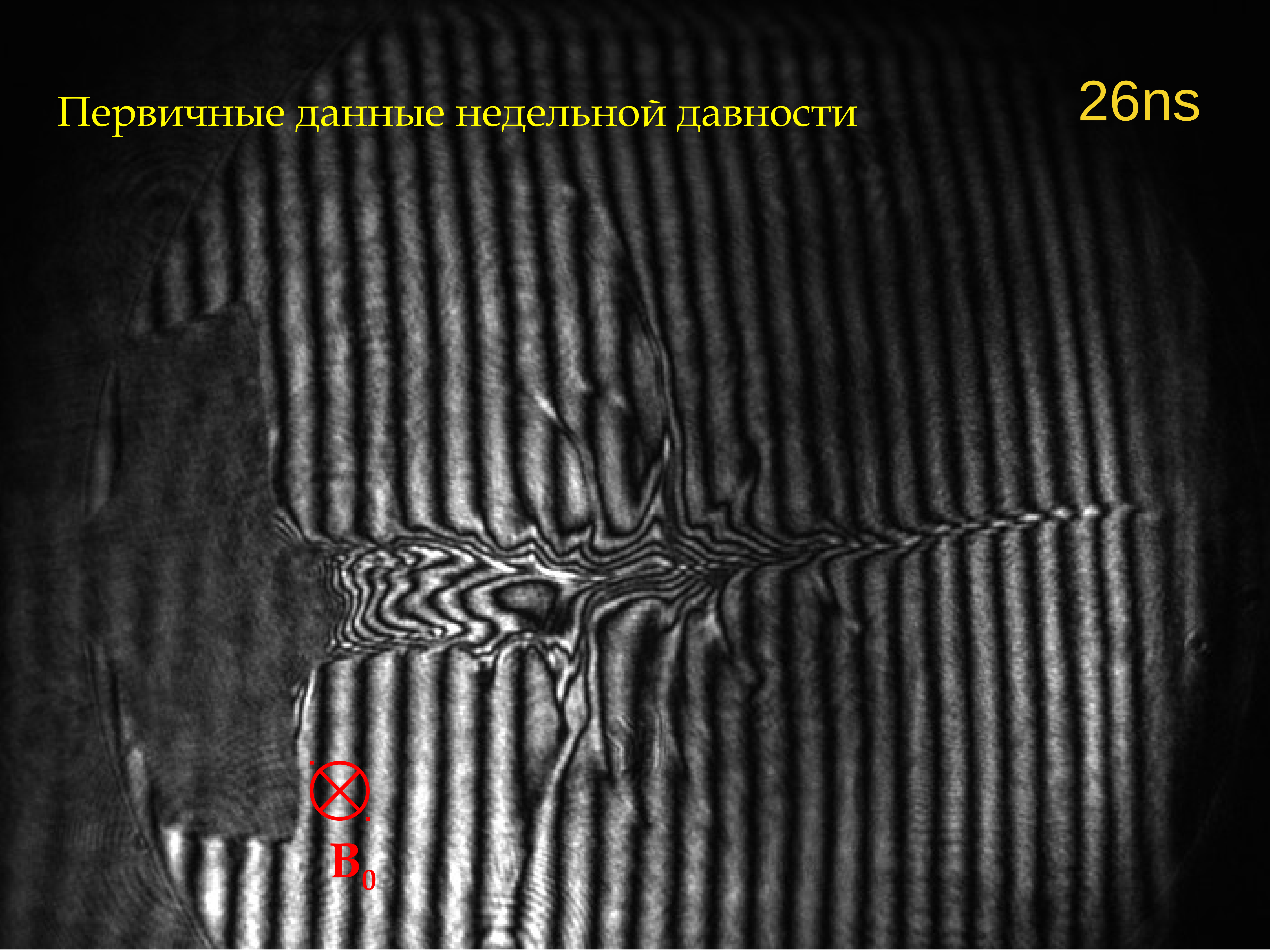


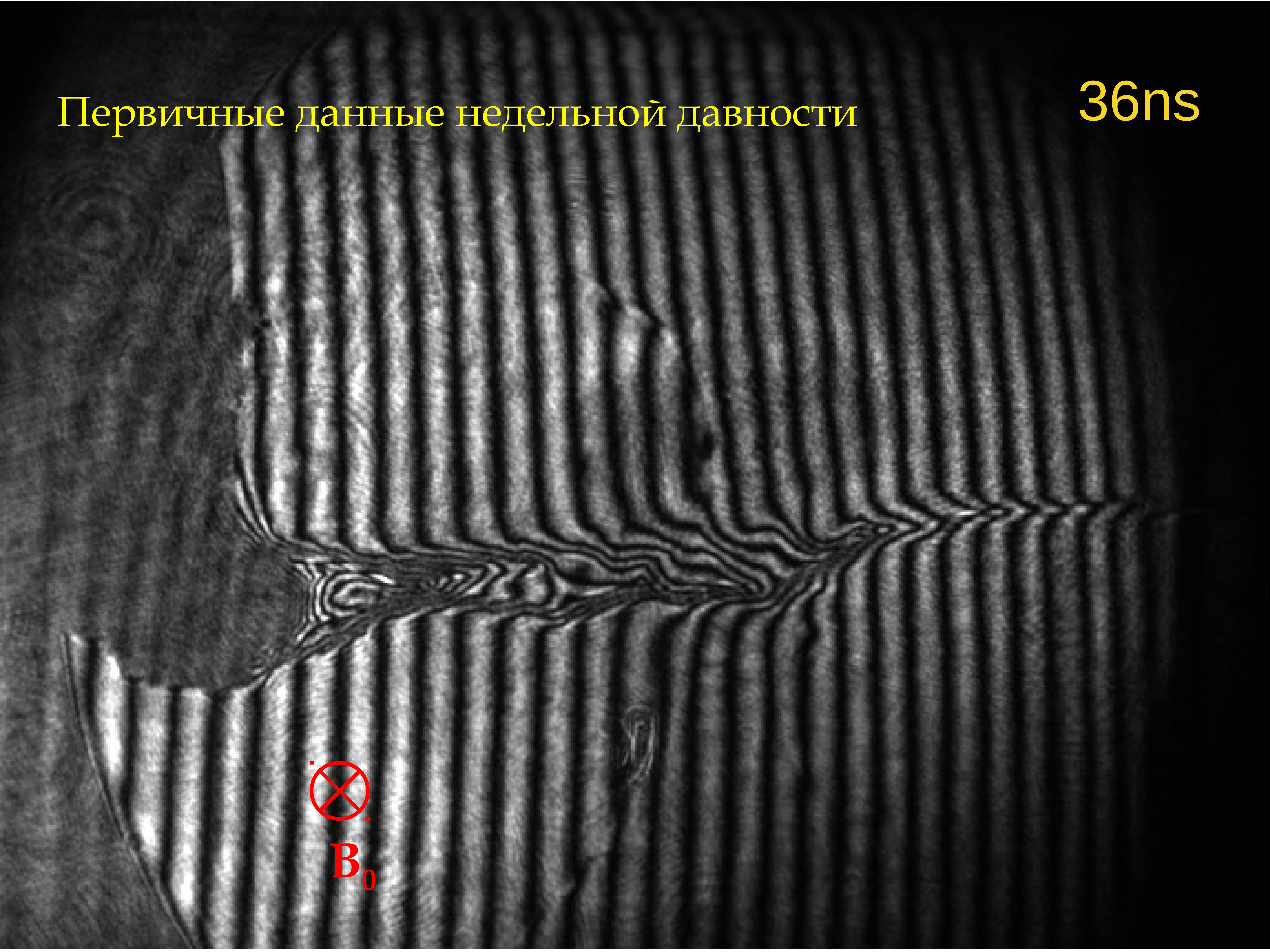



Первичные данные недельной давности
6ns
B0

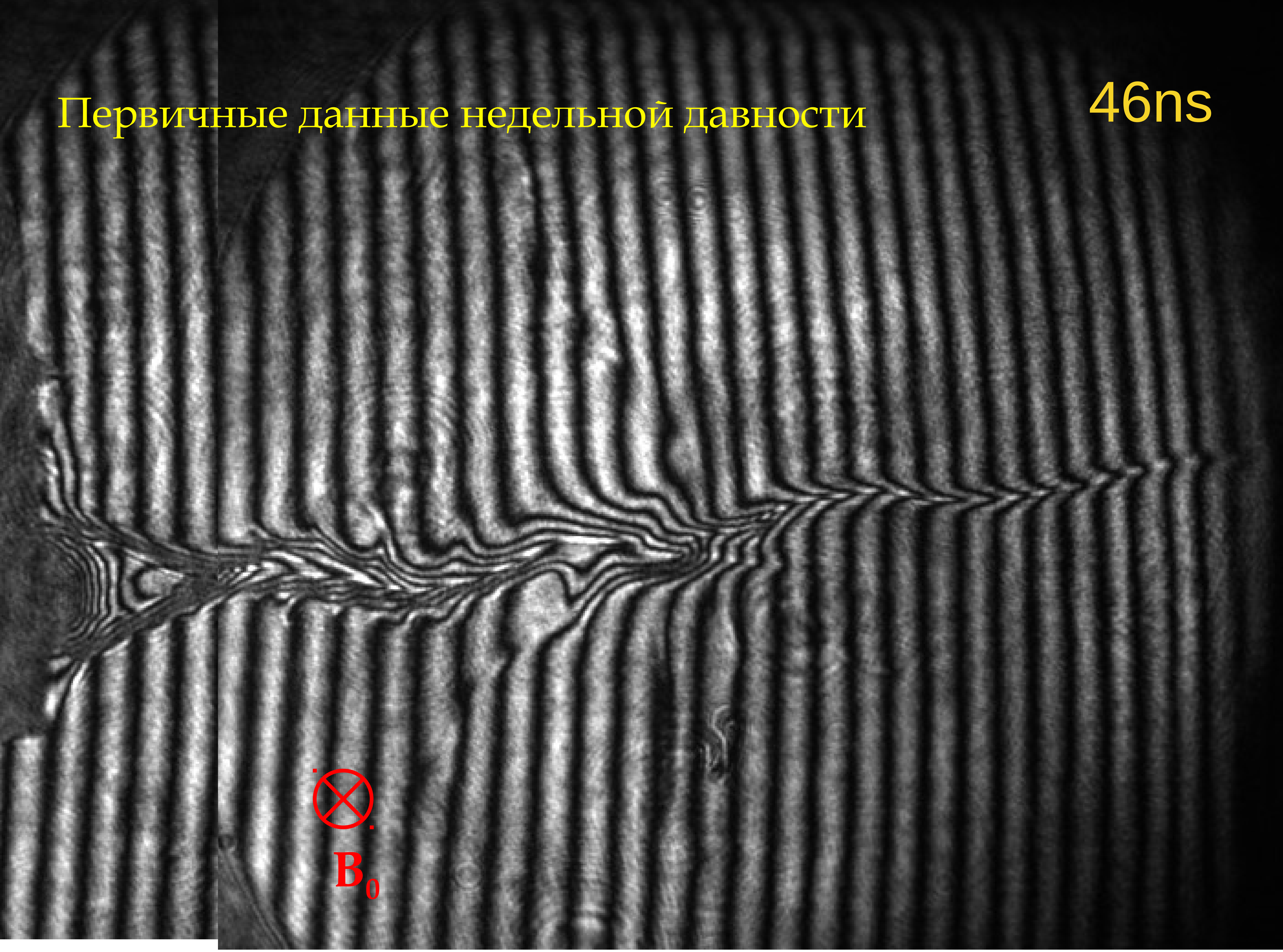

Первичные данные недельной давности
16ns
B0

Первичные данные недельной давности





Первичные данные недельной давности
36ns
B_0


Первичные данные недельной давности
46ns
B0

Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena

Main dynamics:
RT instability ?

Side oscillations:
KH instability ?

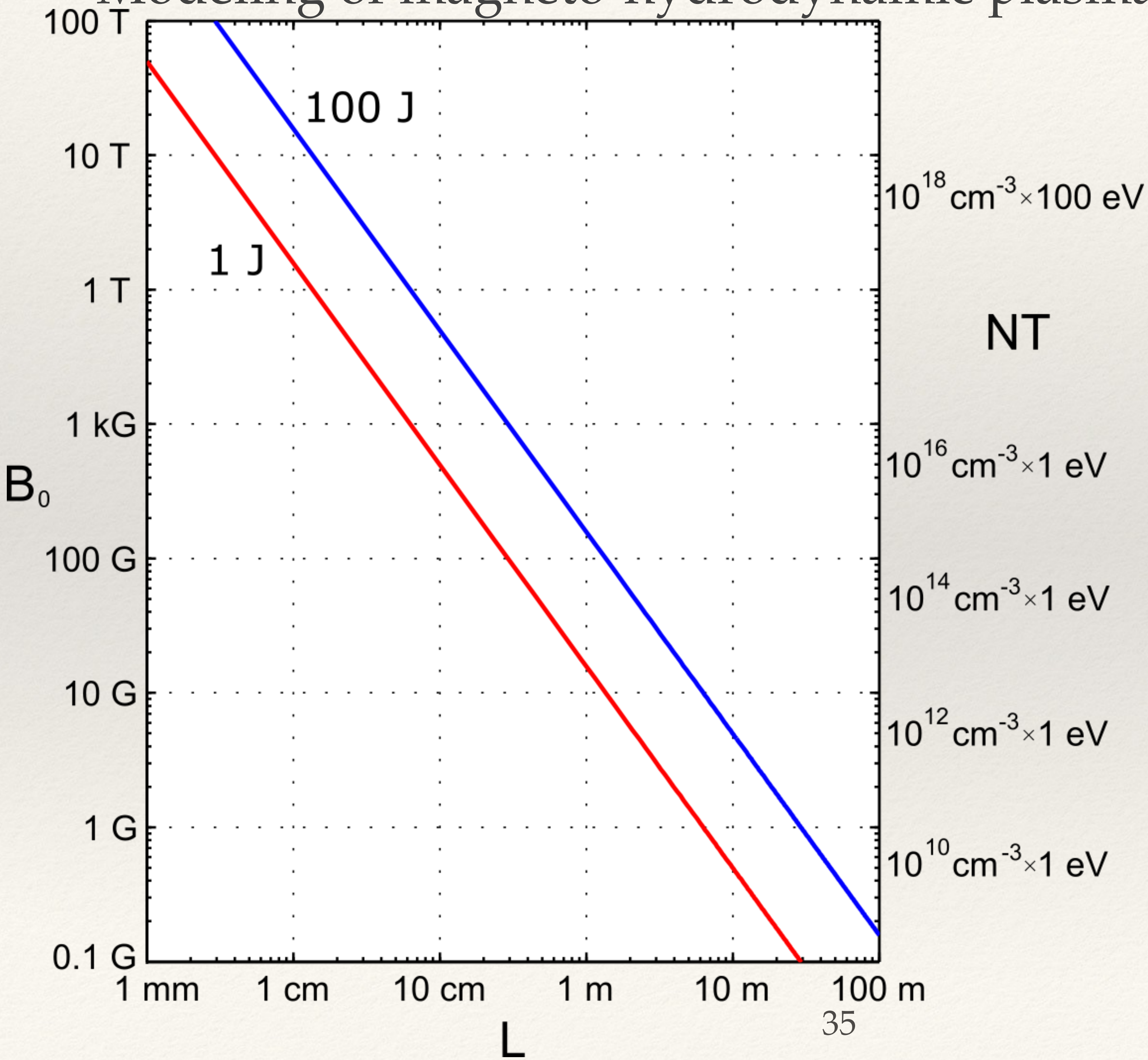
Where are the accretion columns ?
Are the astrophysical accretion models correct ?

Andrea Ciardi (2016)

Incident stream	Laboratory B-Field = $20T$	CTTS B-Field = $1 \times 10^{-3}T$
Material	C_2H_3Cl	H
Electronic density $[n.cm^{-3}]$	1.5×10^{18}	1×10^{11}
Temperature $[eV]$	10	2.6×10^{-1}
Density $[g.cm^{-3}]$	8×10^{-6}	1.7×10^{-13}
Speed accertion flow $[km.s^{-1}]$	1000	500
Sound speed $[km.s^{-1}]$	21	13
Mach number	45	38
Reynolds	2×10^{6}	1×10^{9}
Peclet number	6×10^{3}	5×10^{7}
Magnetic Reynolds	2×10^{2}	1×10^{9}
β	1.5×10^{-2}	6×10^{-2}
l_c/L	7×10^{-3}	2×10^{-8}
Euler number $(v\sqrt{\rho/p})$	6×10^{1}	5×10^{1}
Alfven number $(B/\sqrt{\rho})$	2×10^{2}	1×10^{2}

Laboratory astrophysics

- Modeling of magneto-hydrodynamic plasma phenomena: scaling



$W = NTL^3$

$NT = B^2/8\pi$

Основные результаты

- Российский лазерный комплекс PEARL активно используктся для широкого спектра исспледоваий в области лазерной физики, физики плазмы, в частности среды с высокой плотностью энергии. В частности:
- Проведены экспериментальные исследования лазерного ускорения частиц (электронов и протонов), которые станут основой большого числа прикладных исследований в области медицины, HED физики и пр.
- В настоящее время продолжаются экспериментальные исследования распространения плазмы поперек магнитного поля, способные пролить свет на фундамнтальные вопросы динамики образования звезд и ряда других актуальных задач.