Slow positron extraction from DAΦNE

Paolo Valente

Ferrara, 13/02/2018

Motivations & assumptions

Extracted ”long” positron beam motivated by:

- Dark sector searches in positron annihilations (PADME-type experiments)
- Crystal channeling experiments with positrons (parametric radiation, crystal undulators, etc.)
- Test positron beam

Assume:

- Minimal modifications to the infrastructure
- Compatibility with synchrotron light facility

Why searching for a dark sector

Properties of **dark matter**:

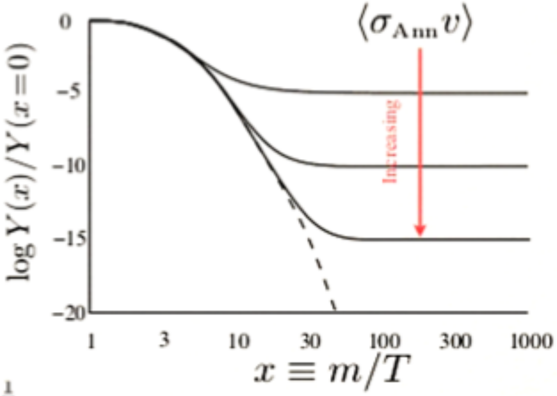
- Dominant with respect to baryonic matter: $\rho_{\mathrm{DM}} \sim 5\ \rho_{\mathrm{b}}$
- **Suppressed** interactions with QCD and QED
- **Suppressed self-interactions** $\frac{\sigma}{m_{\mathrm{DM}}} < 1\ \mathrm{barn/GeV}$
- At least one stable DM particle
- **May or may not** been in thermal equilibrium with SM particles.
- If part of the same bath: freeze-out gives relic density
- **Freeze-out**: $m_{DM} \sim$ TeV if **weakly interacting**

Lee-Weinberg

$$\dot{n} + 3Hn = (n^2 - n_{\mathrm{eq}}^2)\langle\sigma_{\mathrm{ann}} v\rangle$$

$$n_{\mathrm{eq}} \sim e^{-m/T}\ s$$

$$Y_{\mathrm{dm}} = n_{\mathrm{dm}}/s$$

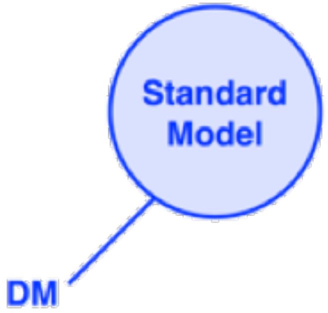


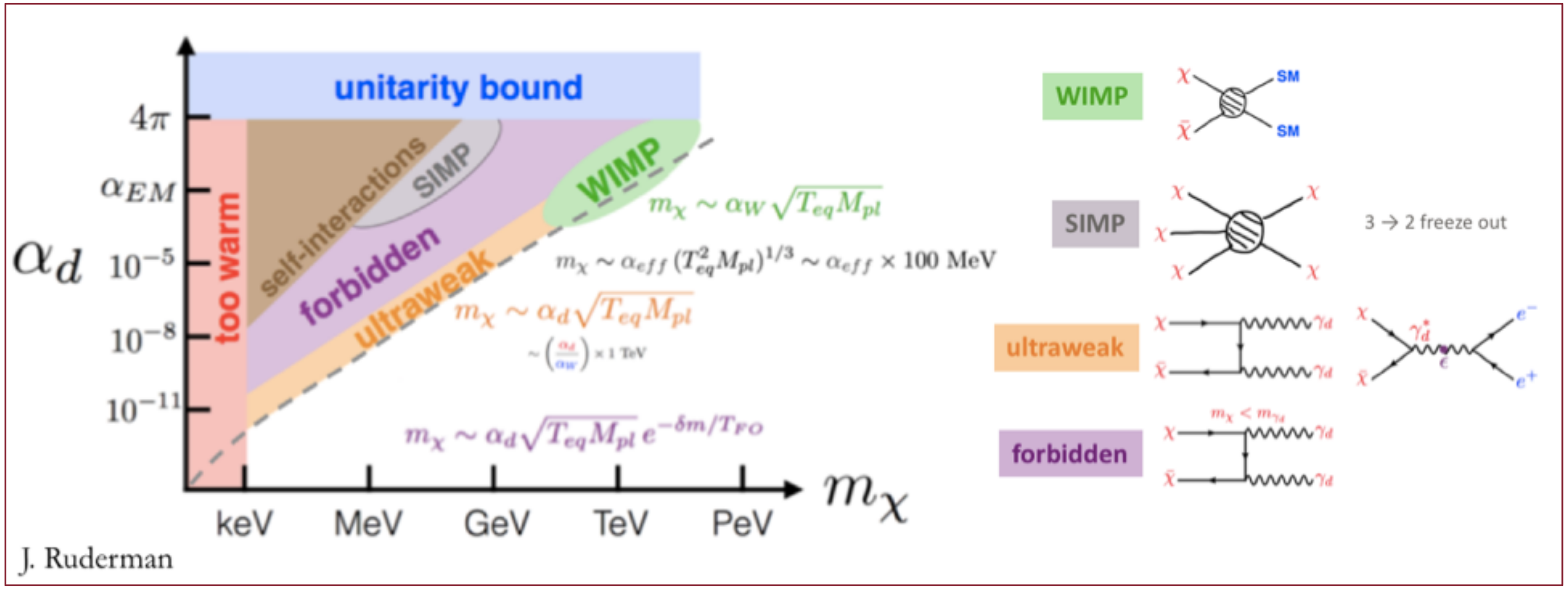
$$m_{\mathrm{dm}} \simeq \alpha\left(T_{\mathrm{eq}} M_{\mathrm{Pl}}/x_F\right)^{\frac{1}{2}}$$

Why searching for a dark sector

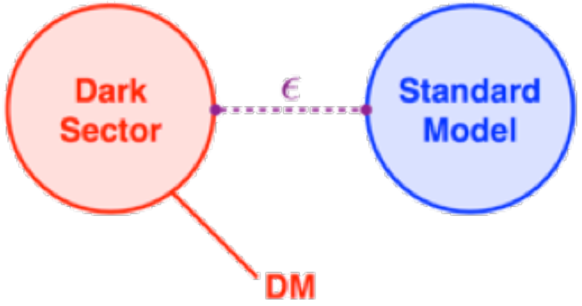
Solutions to **no WIMP at ~1 TeV**

- Non-thermal or quasi-thermal models
    - **Freeze-in**, axions, asymmetric DM, gravitino…
- Dark freeze-out of an **almost secluded** DM sector
    - DM does not annihilate into SM particles (at least not directly)
    - The two thermal baths (SM and DM) can have different temperatures





J. Ruderman

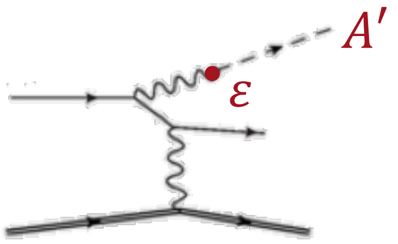


- At least one «**portal**» carrying both DM and SM quantum numbers:
    - Vector (dark photon)
    - Axial vector
    - Scalar (dark Higgs)
    - Fermion

Dark photon production and decay

Production:

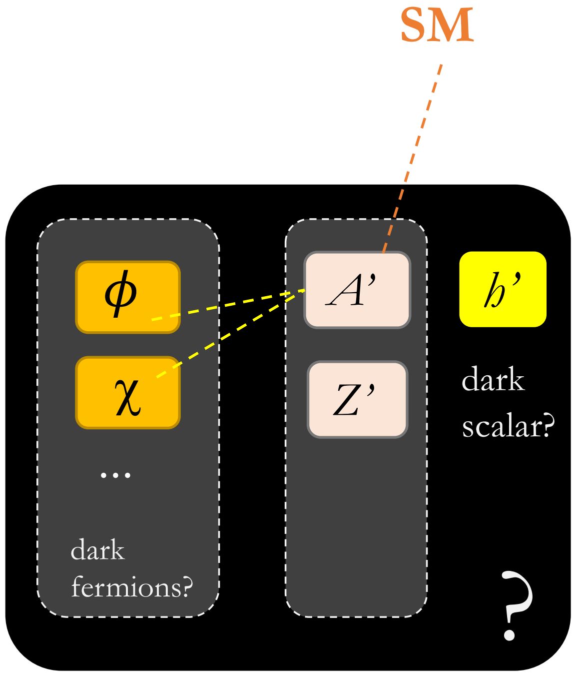
- In any process with an ordinary photon, we can substitute it with a **dark photon** (*A'*):
  - *A'*-strahlung
    - Electron dump and thin-target experiments (visible decays)
    - Missing energy/missing momentum (invisible decays)
  - π^0,η decays
  - e^+e^- annihilations (**missing energy**)



- In the case of **axion-like particles**, we also have the Primakov production mechanism

Decay: two possibilities

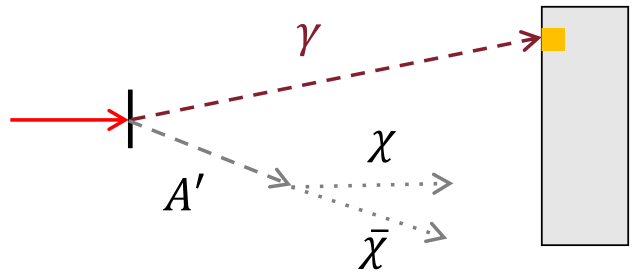
- Looking for decays to SM particles (**lepton pairs** or hadrons if above threshold) or the so-called "**visible**" decays; limits generally rely on the assumption that ***A'*→ leptons** is dominant, i.e. the dark photon is the **lightest particle in the dark sector**
- Not looking at the final state, removing the latter assumption, relying on missing energy/momentum or missing mass for identifying "**invisible**" decays ***A'*→ $\chi\chi$**

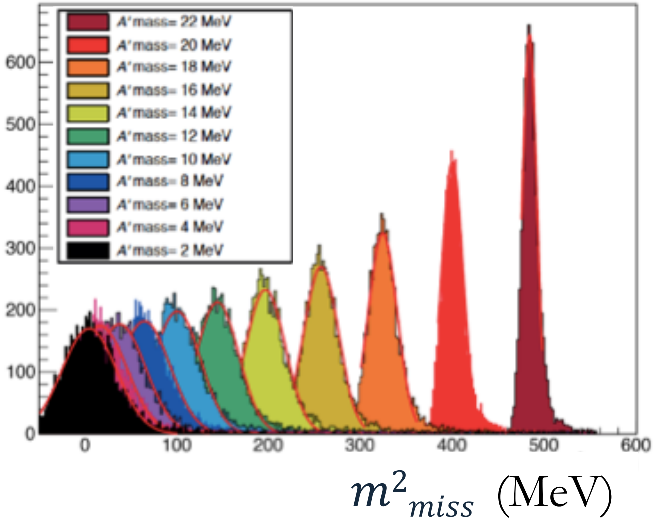


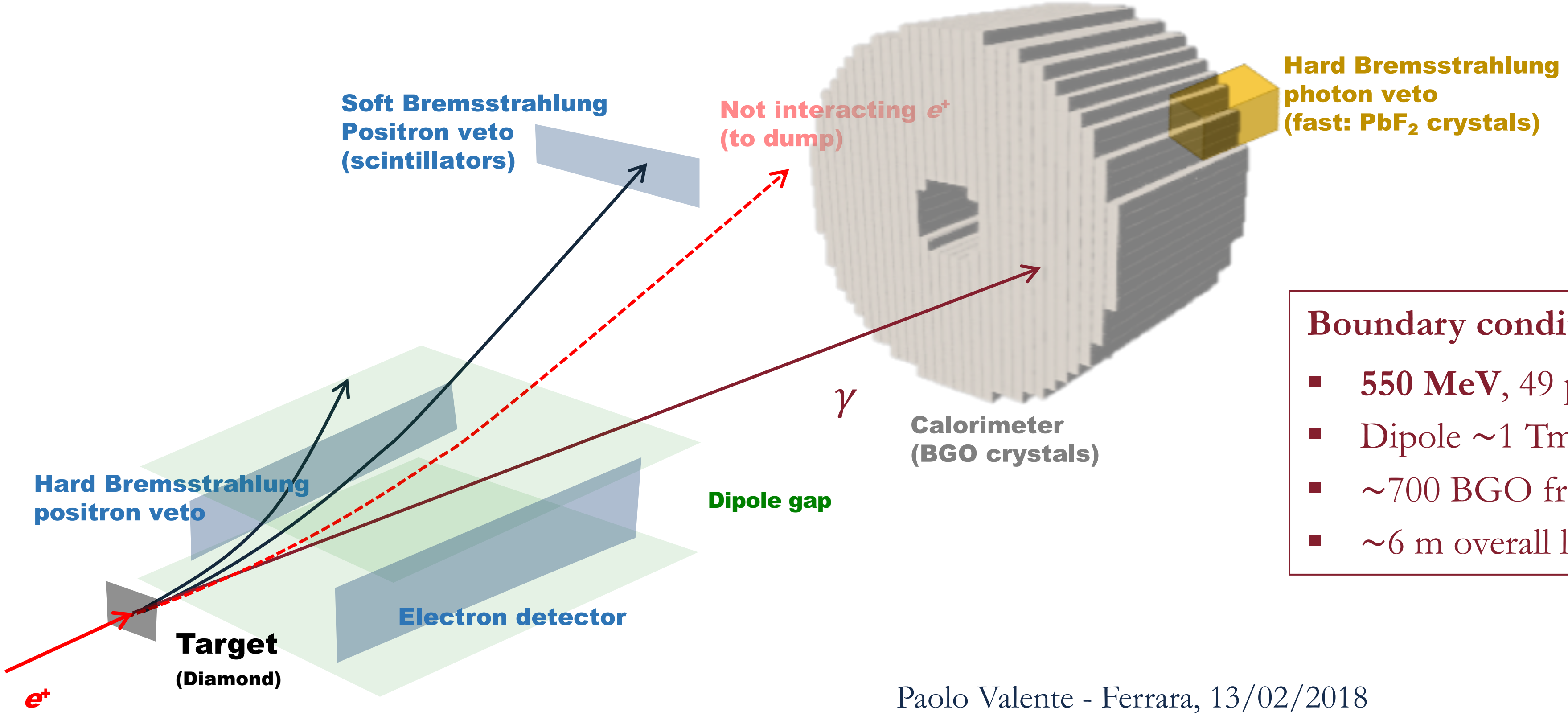
Dark Sector

PADME experiment

- **Positron beam** with **known 4-momentum**
  1. Small energy and angular spread
  2. Small transverse spot
- Precisely measure the **photon momentum**
- Compute $m^2_{miss} = (P_{\gamma} - P_{e^+})^2$



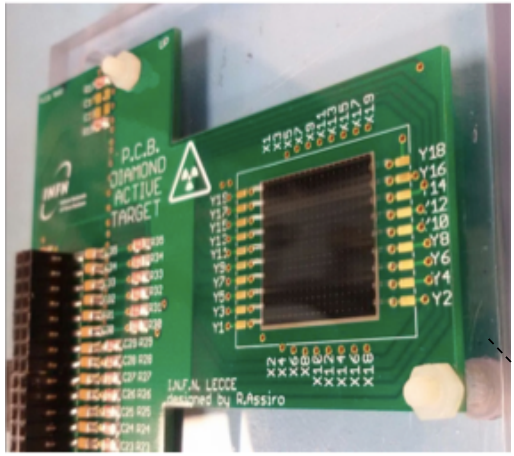




Boundary conditions

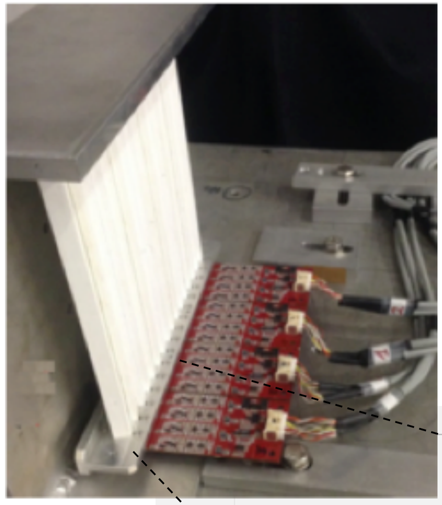
- **550 MeV**, 49 pulses/s, **200 ns** long from DAΦNE LINAC
- Dipole ~1 Tm, 23 cm gap **available** from CERN SPS
- ~700 BGO from L3 calorimeter endcap **available**
- ~6 m overall length available in BTF hall

PADME experiment

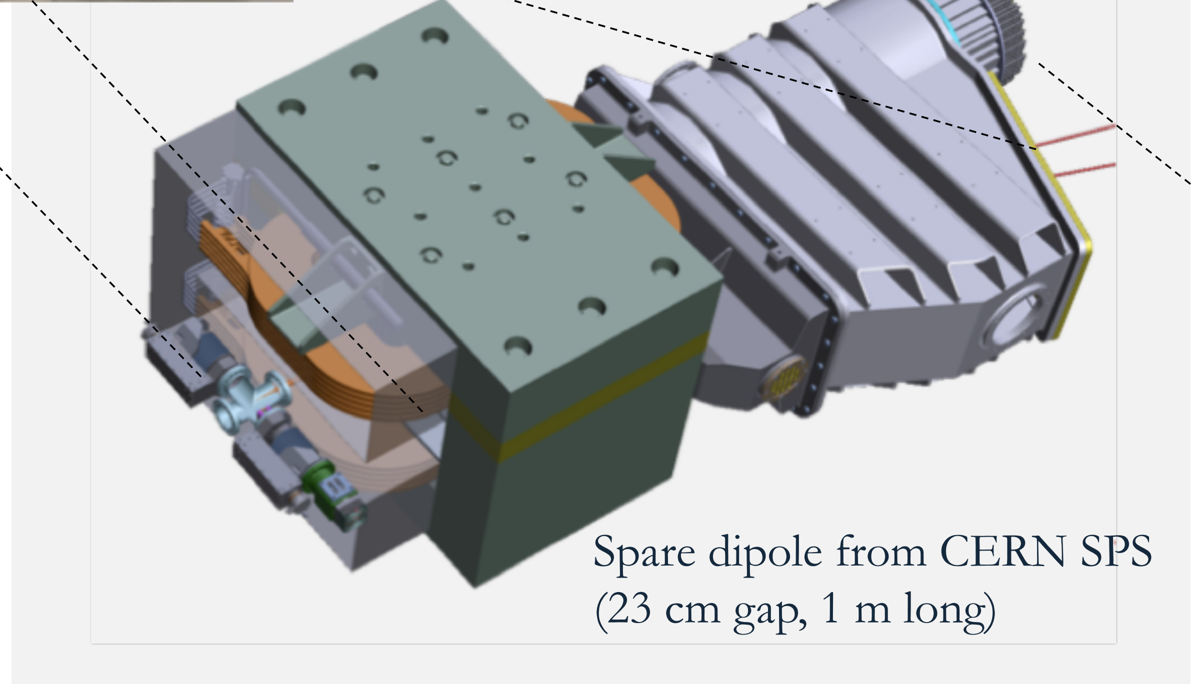


Diamond with grafite strips: All-Carbon active **target**, beam position & size and luminosity monitor; custom electronics

- **2.5 GS/s** waveform digitizers for all the **~1000 channels** (sampling can be changed to 1, 0.75 or 5 GS/s)
- Data through-put **~10 MB/s** (i.e. **~0.9 TB/day**)



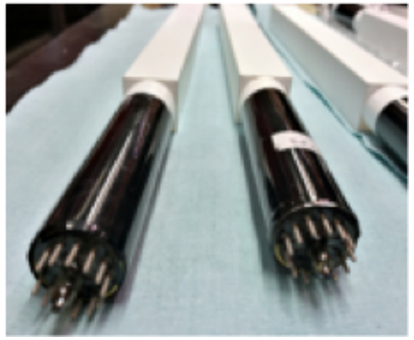
Scintillating bars with **SiPM** readout for rejecting Bremsstrahlung events (tagging positrons); inside vacuum vessel



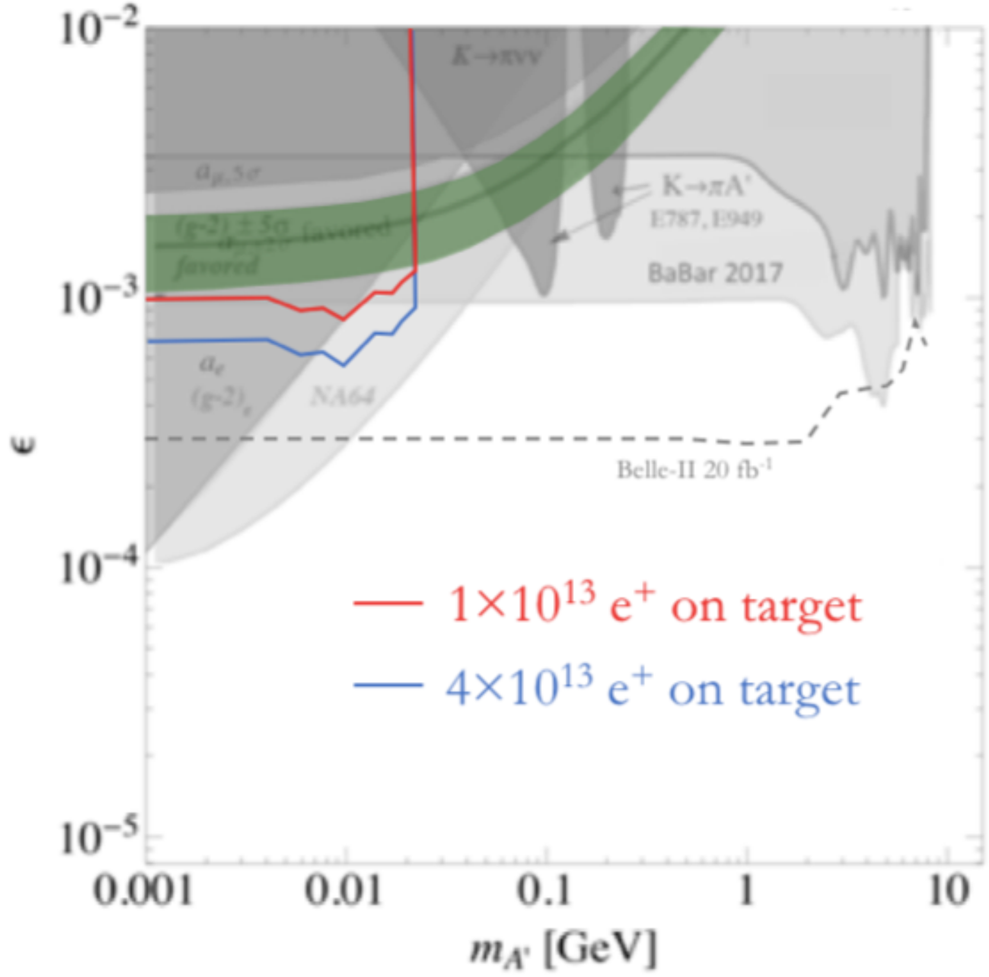
Spare dipole from CERN SPS (23 cm gap, 1 m long)

Very fast **PbF_2 Cherenkov** calorimeter for rejecting 2 and 3 γ backgrounds and withstand Bremsstrahlung, **fast PMT** readout

BGO calorimeter, 19 mm PMT readout



PADME sensitivity (dark photon invisible decays)



PADME Run 1

- 6 months of data taking in 2018, starting in April

PADME Run 2 at BTF?

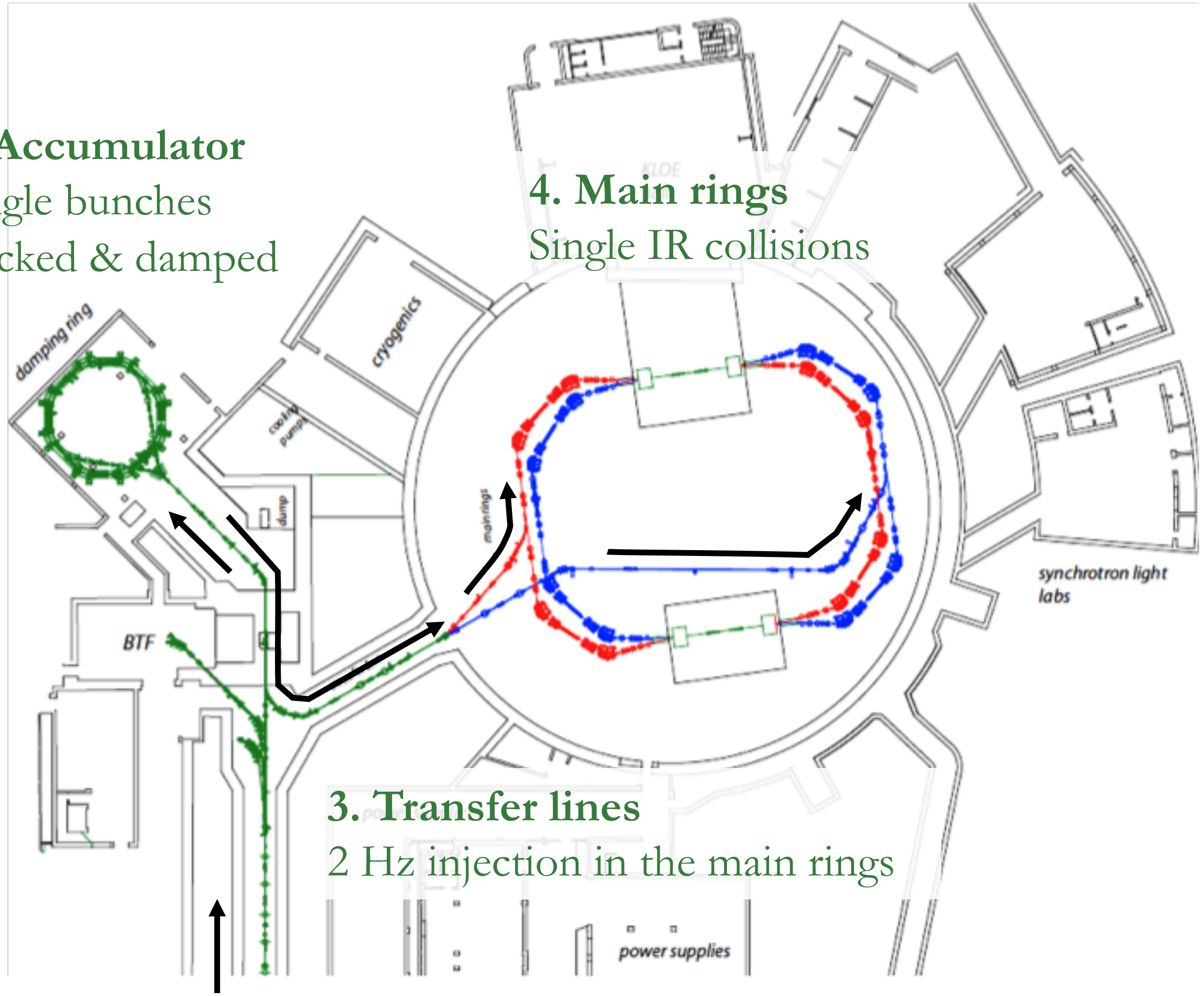
- Possible run after Siddharta data taking in late 2019?

Nota bene:

PADME requires long (≫10 ns) LINAC pulses at E>510 MeV, which is not compatible with continuous injections for DAΦNE topping-up

DAΦNE collider in a nutshell

Parameter	Value
LINAC RF	2857 MHz
LINAC typical charge	1 nC (e^-) 0.5 nC (e^+)
Energy per beam	510 MeV
Machine length	97 m = 324 ns
N. of colliding bunches	100-111
Betatron tune	3.12 (hor.) 1.14 (vert.)
Emittance	1.0 (hor.) 0.01 (vert.) mm mrad
Max. beam current (KLOE run)	2.5 A(e^-) 1.4 A (e^+)
RF frequency	368.67 MHz (main rings) 74 MHz (damping ring)
RF voltage	100-250 kV
Harmonic number	120
Bunch spacing	2.7 ns
Max. Luminosity SIDDHARTA run KLOE run	 4.5 10^{32} cm^{-2}s^{-1} 2.1 10^{32} cm^{-2}s^{-1}



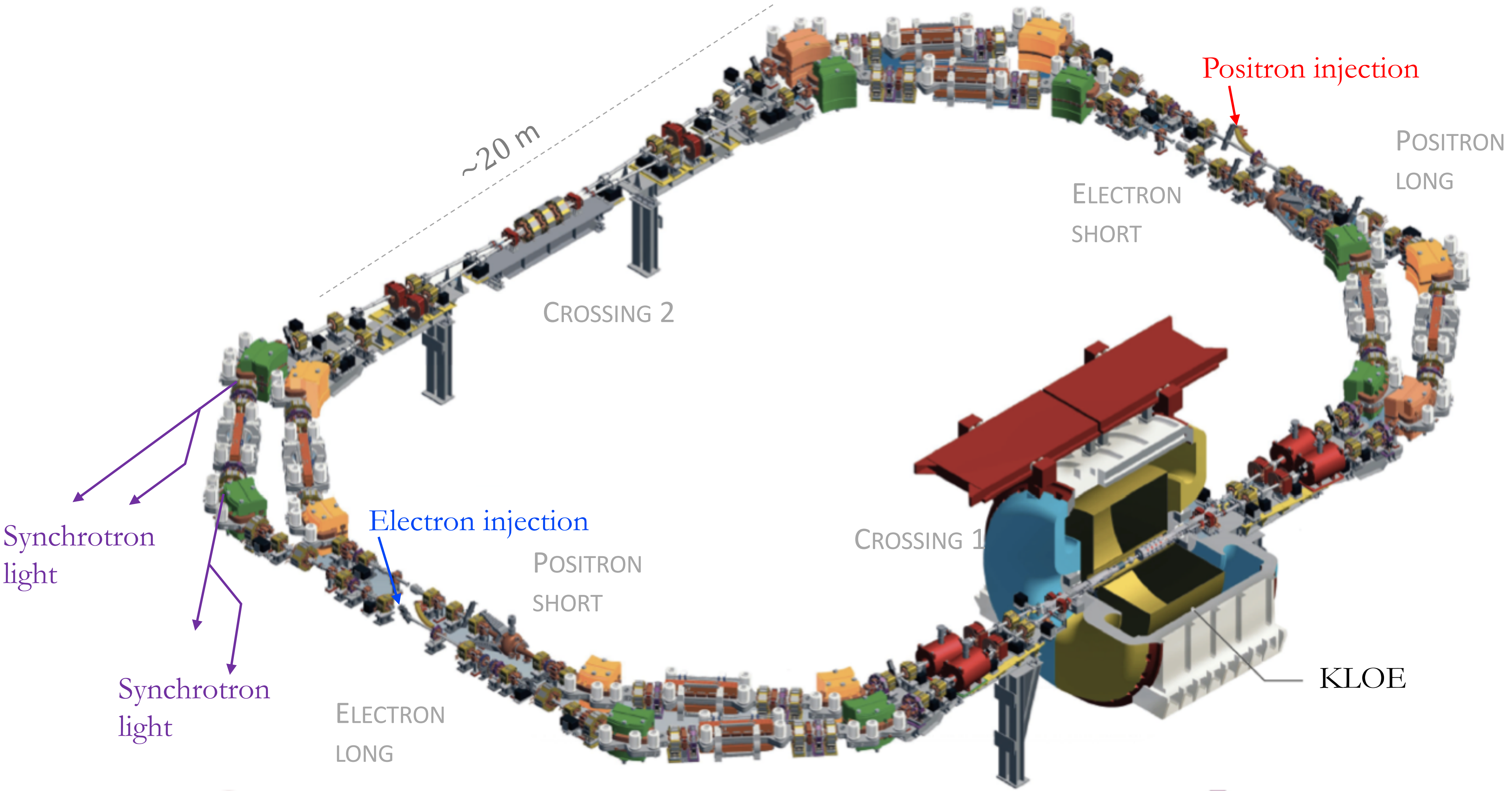
2. Accumulator
Single bunches
stacked & damped

4. Main rings
Single IR collisions

3. Transfer lines
2 Hz injection in the main rings

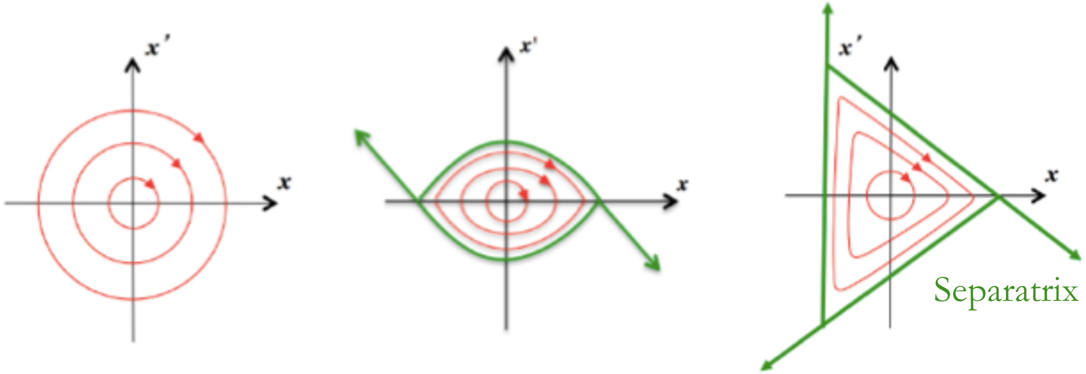
1. High-current LINAC
50 Hz, 10 ns macro-bunches

DAΦNE main rings



Slow extraction

1. Create an **instability** with one (or more) stable region in the phase space

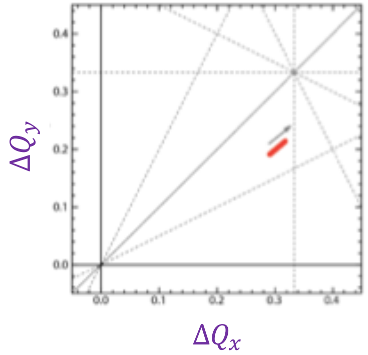


$n + 1/2$ resonance

$n + 1/3$ resonance

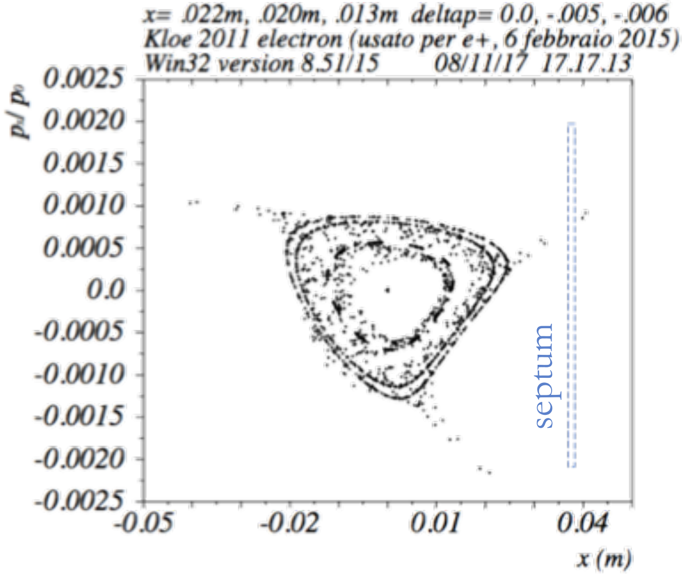
2. Push (at least part of) the beam **out of the stable region**:
   - Shrink the stable region
   - Drive the beam towards a separatrix
3. Extraction septum in a dispersion-free region kicking the beam out (generally in the horizontal plane)

For **electrons** we can use the energy lost by synchrotron radiation to change the tune, slowly approaching the resonance, if the chromaticity is ≠0 ($\Delta Q = C\Delta E$).



Also called "**monochromatic**" extraction, since the energy at extraction is practically constant. When the energy loss is equal to the spread, all particles are extracted.

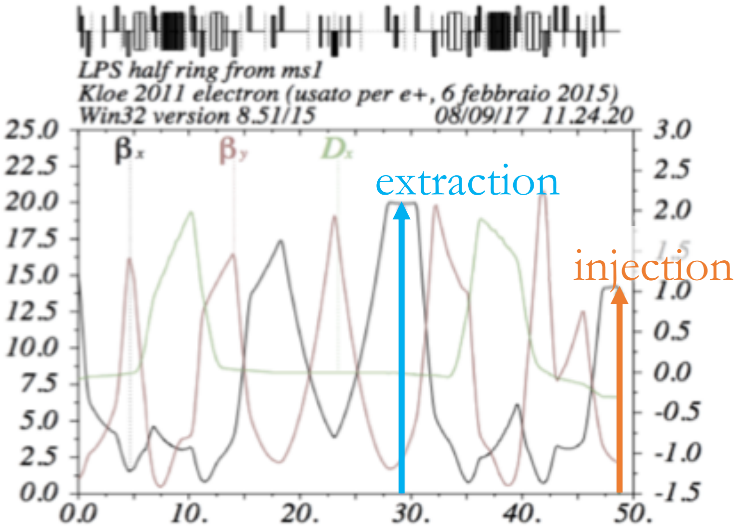
Beam injected off-orbit (horizontally), fills an hollow circle in phase space, defined by minimum and maximum emittance.



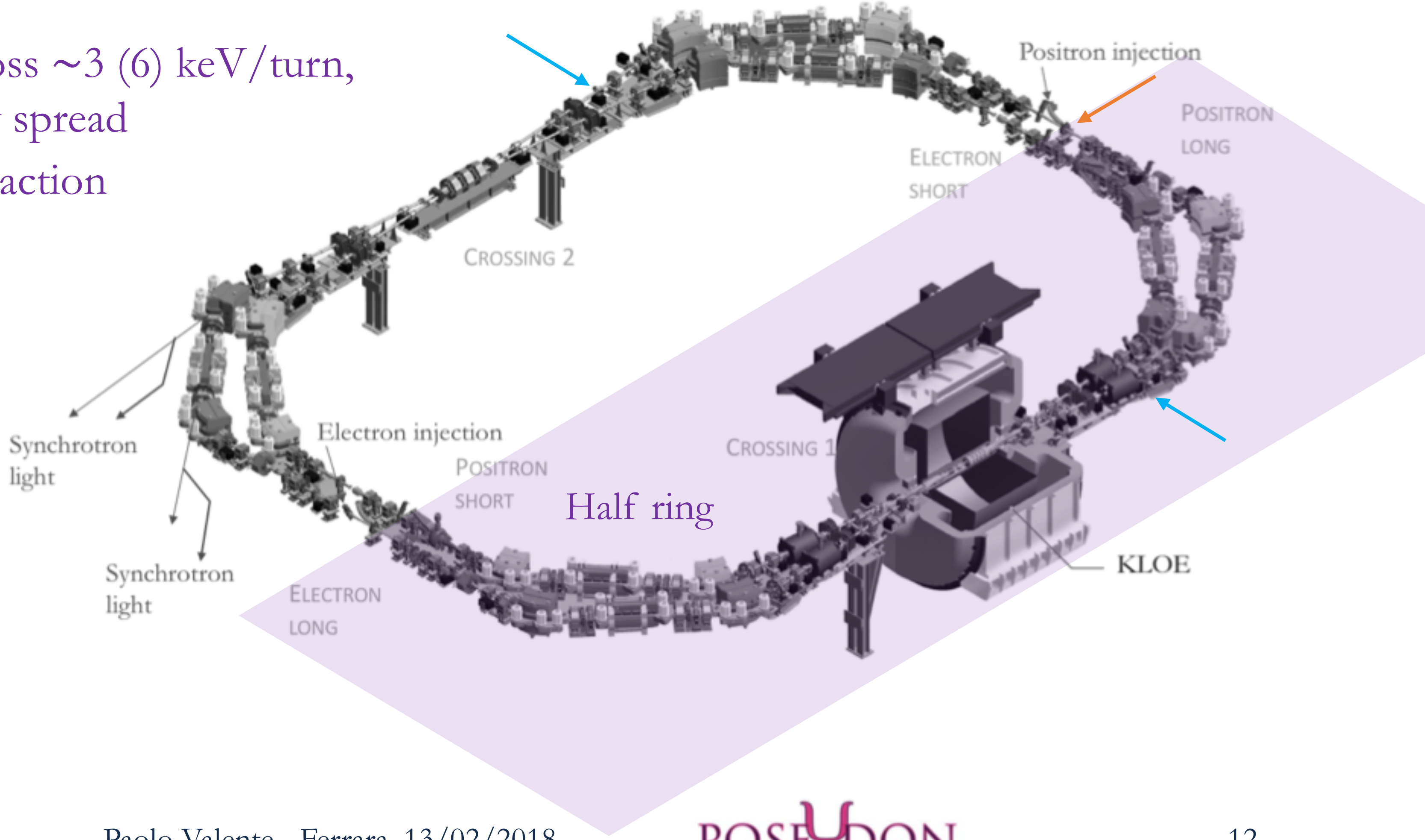
S. Guiducci

DAΦNE optics

- Inject long beam (up to ~324 ns filling the ring)
- Keep ring RF off
  - Or **RF knock-out** (used for protons at CNAO, to be studied for DAΦNE)
- With wigglers off (on), synchrotron loss ~3 (6) keV/turn, spill length 0.4 (0.2) ms for 1% energy spread
- D ~0 and α ~0, β ~maximum at extraction



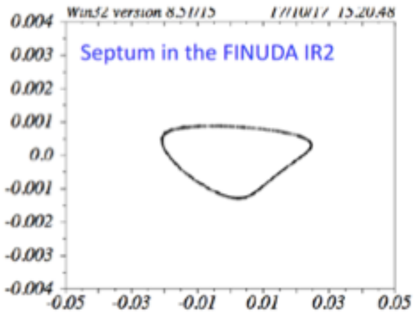
S. Guiducci

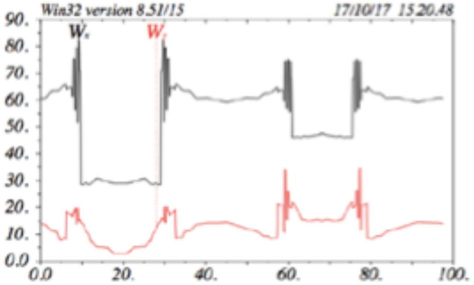


DAΦNE optics

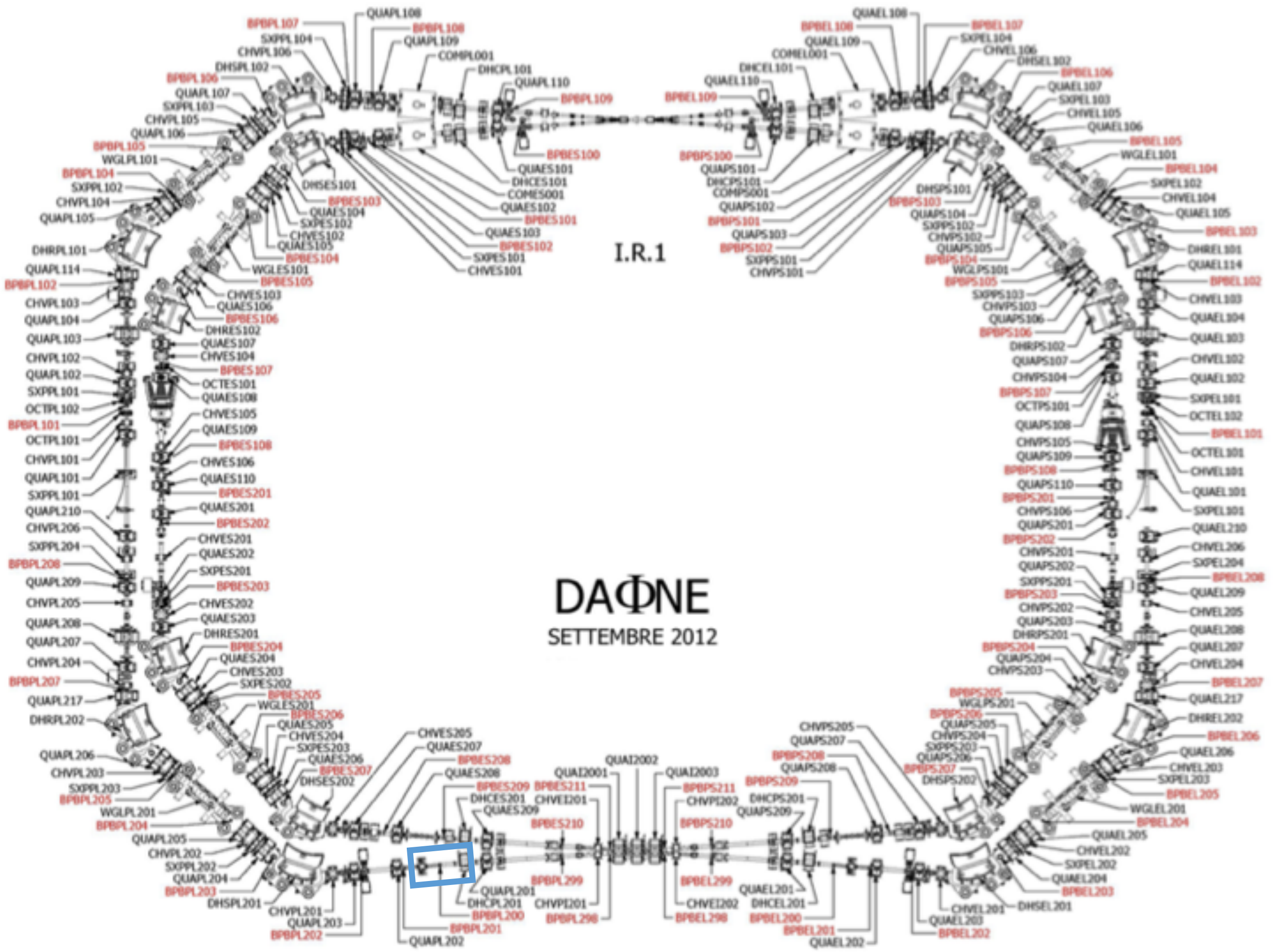
- Chromaticity has to be chosen to get the correct orientation of the stability triangle ($x' > 0$); Strength of the sextupoles.
- Size of injected beam impacts final emittance.
- Adjust the distance of the tune from the resonance: **negative** (positive) chromaticity, approach resonance from **below** (above).

$$Q_x = 4.366, Q_y = 4.27$$
$$C_x = +3.42, C_y = -0.58$$



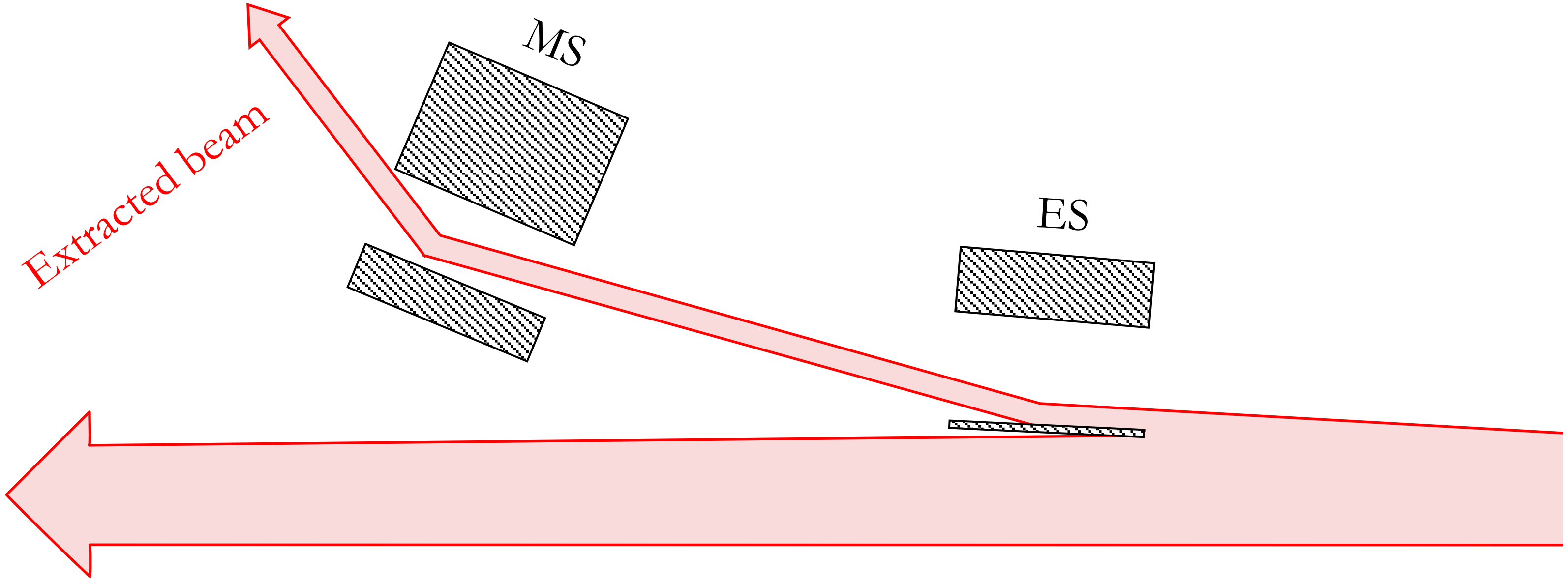


S. Guiducci

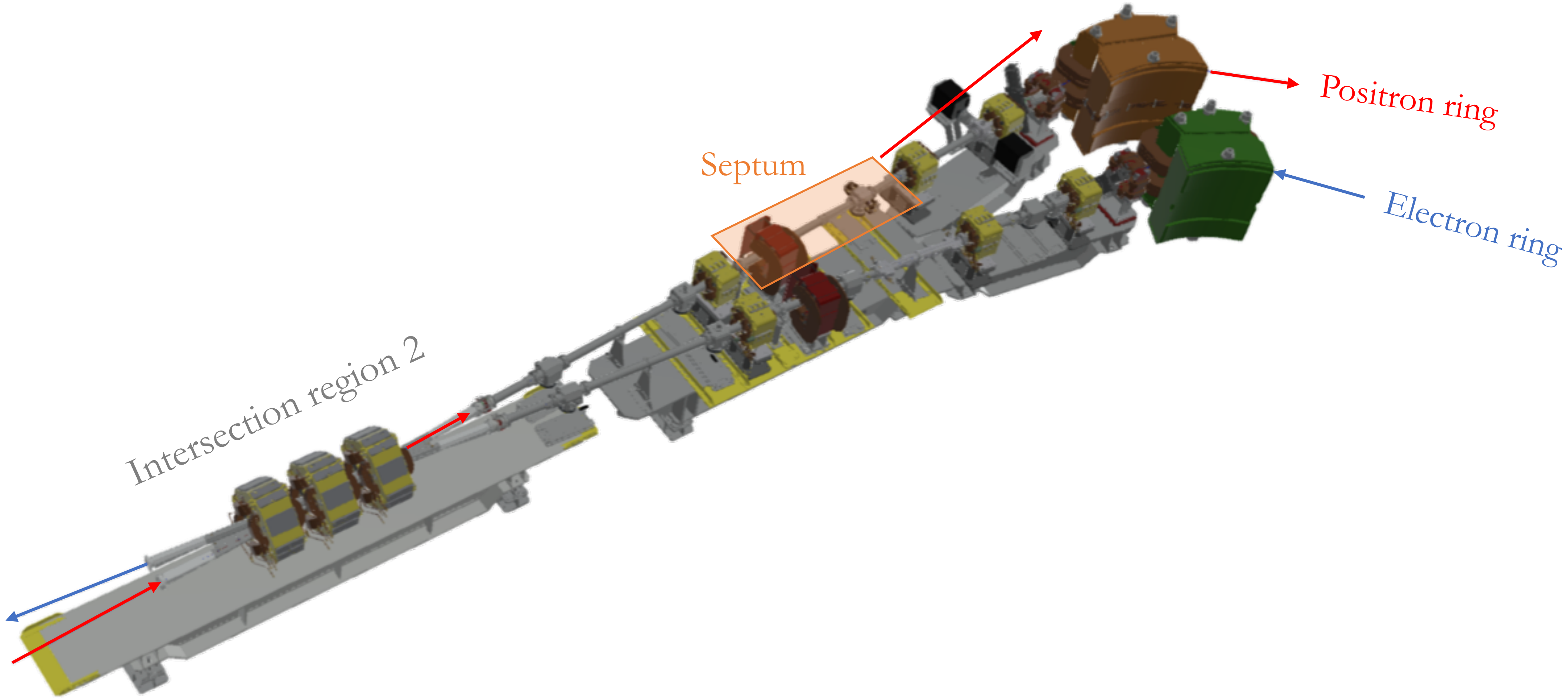


Septa

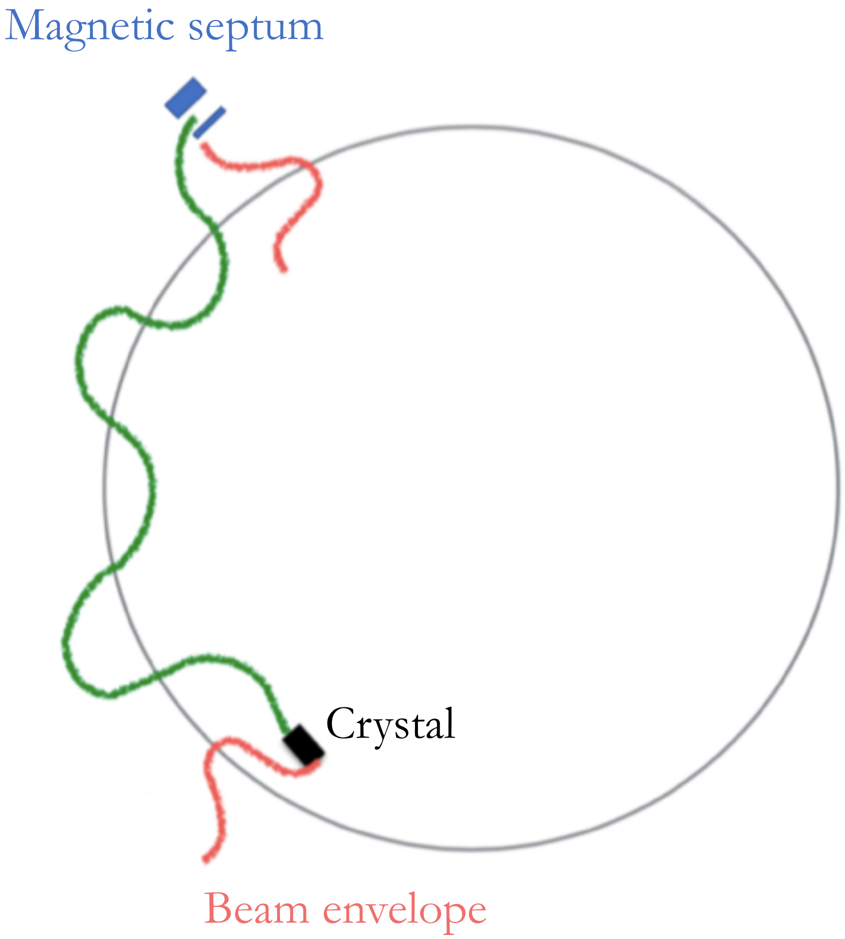
- In the typical configuration an **electrostatic septum** is followed by a **magnetic septum**



Possible septum location



Why crystals?



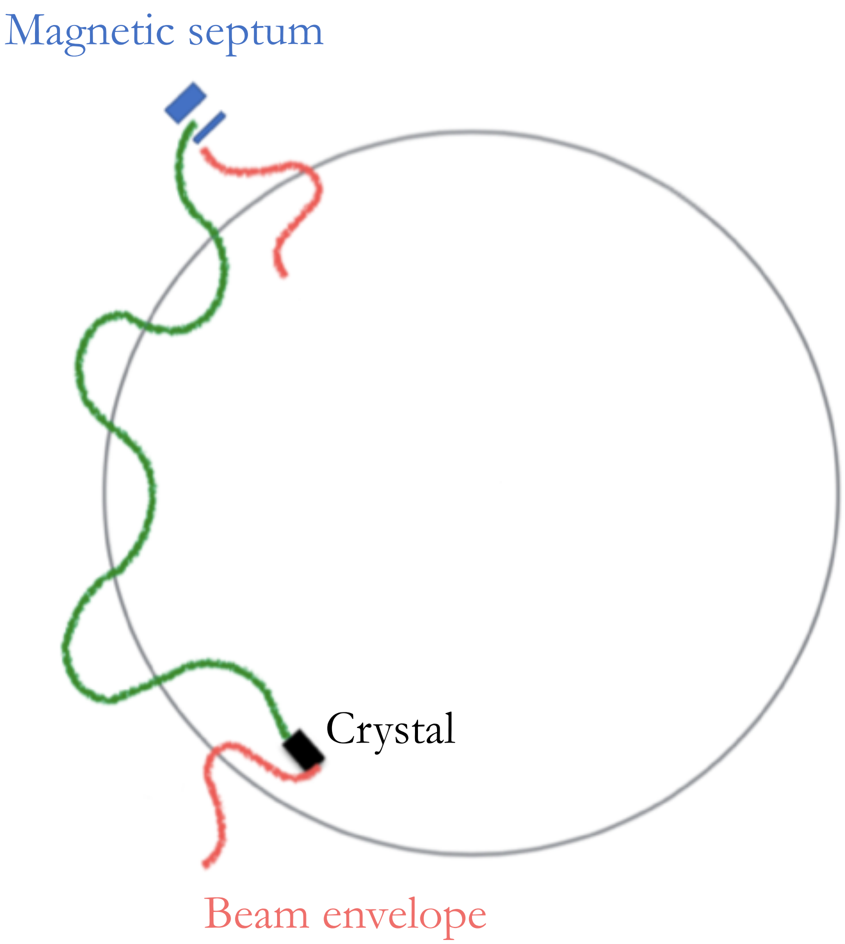
- Monochromatic extraction does not allow controlling the **extraction time** (driven by the synchrotron emission)
- RF knock-out can in principle control the process of spilling positrons out of the RF bucket
- An alternative approach: use **crystal channeling**

The PADME experiment requirements are basically:

1. Dilute positrons in the **longest possible beam pulse**
2. Maximum particle density determined by the **pile-up** probability in the calorimeter: **$\sim 10^2$ particles/ns**
    - PADME@BTF: $2 \cdot 10^4$ positrons/200 ns (10^6/s)
    - PADME@Poseydon: $4 \cdot 10^7$ positrons/0.4 ms ($2 \cdot 10^9$/s)

In both cases, limited by **50 Hz repetition rate**

Why crystals?

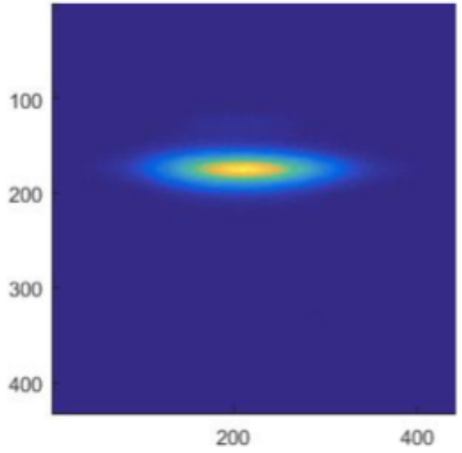


DAΦNE circulating positrons: 1 A current in 120 bunches
$N_+ \sim 2 \cdot 10^{12}$

Assuming an average of 1 extracted particle/turn → 1 e^+/324 ns $\cong 3 \cdot 10^8$ positrons/s:

- 300× with respect to PADME@BTF
- 1/20 with respect to PADME@Poseydon

… but with a continuous time structure of the beam, i.e. "single particle" mode on the target, virtually **no background** in the detector



Transverse size:	at SLM: 1 mm × 200 μm at IP: 260 μm × 3 μm
Emittance:	$\epsilon_x = 0.26$ mm mrad $\epsilon_y = 0.03$ mm mrad
Coupling:	0.5%
Energy spread:	$0.4 \cdot 10^{-3}$

A few numbers

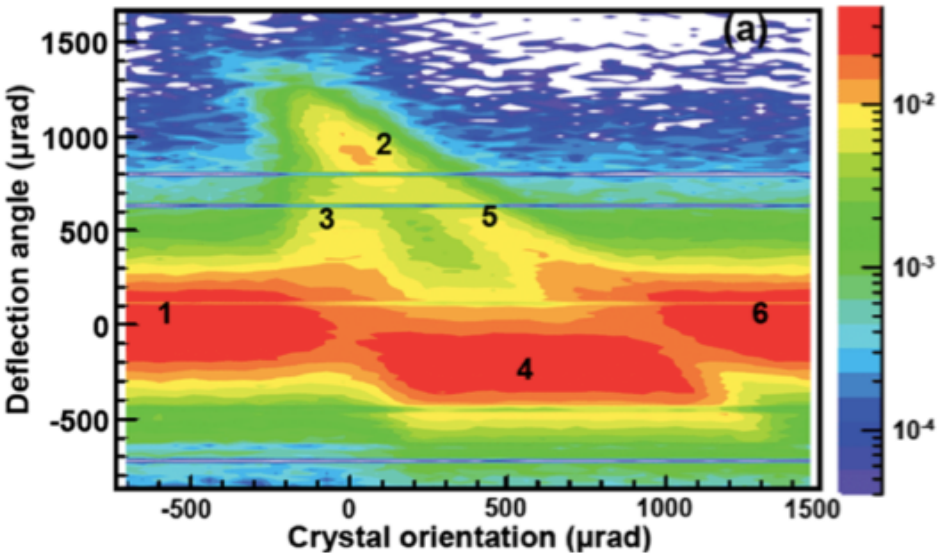
Critical angle for planar channeling, Si(110) at 510 MeV: $\theta_c \sim 210\ \mu\text{rad}$

Multiple scattering angle:

510 MeV, $30\ \mu$m of Si → $480\ \mu$rad

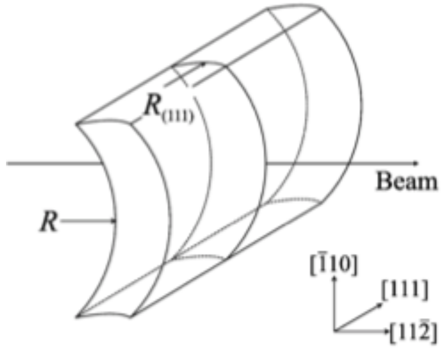
855 MeV, $30\ \mu$m of Si → $280\ \mu$rad

De-channeling length for positrons at 510 MeV $\sim 400\ \mu m$



MAMI experiment
$910\ \mu$rad **bending** along Si(111) planes,
$L = 30.5\ \mu$m, $R = 33.5$ mm
855 MeV electrons

Si(111) at 855 MeV $R_c \sim 0.4$ mm



A few numbers

Problem:
Use thin crystals to reduce **multiple scattering** implies getting close to breaking limit for bending radius for having a sufficient deflection angle $\vartheta = L/R$
$\sim 1 \div 2$ mrad deflection angle: $2 \div 4$ cm from beam at **20 m distance**

Material	x_0 (mm)
Si	93.7
Ge	23
W	3.5

Critical radius of W(110) is $\sim 1/7$ of Si(110), but $x_0 \sim 1/27$
Unless multiple scattering is NOT an issue…

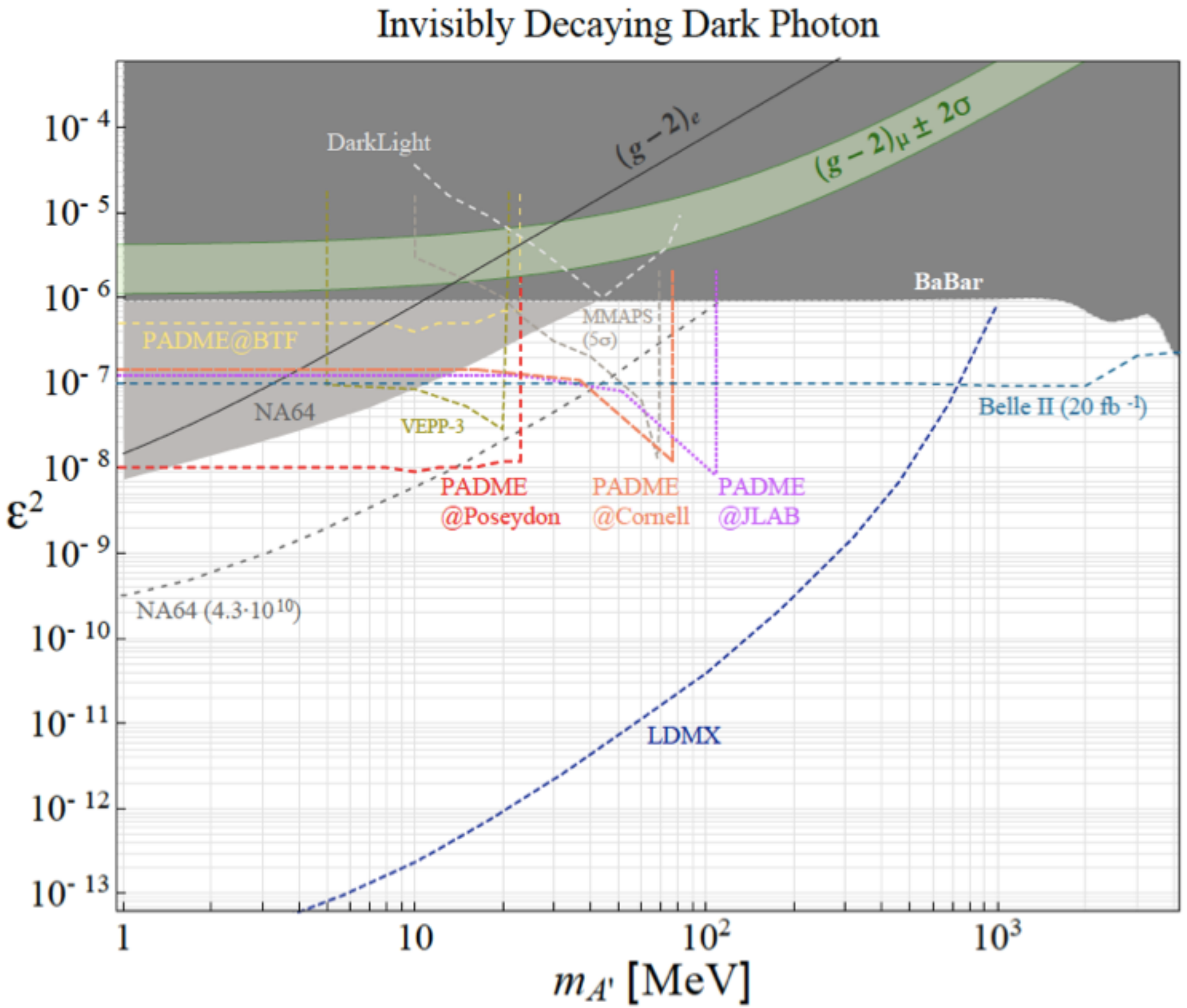
Cut (σ)	Fraction
3.1	$1 \cdot 10^{-3}$
3.7	$1 \cdot 10^{-4}$
4.3	$1 \cdot 10^{-5}$
4.75	$1 \cdot 10^{-6}$
5.2	$1 \cdot 10^{-7}$
5.6	$1 \cdot 10^{-8}$
6.0	$1 \cdot 10^{-9}$
7.0	$1.3 \cdot 10^{-12}$

$\mathbf{2 \cdot 10^4}$ $\boldsymbol{e^+/s}$ **at** $\mathbf{5.6}$ $\boldsymbol{\sigma}$

Assuming **all of them** are lost,
lose entire beam in 10^8 turns, i.e. 0.3 s

Problem:
How to send particles to the halo?

PADME@Poseydon sensitivity



- Increase in sensitivity: 100× with respect to PADME@BTF (1 year of running shown)
- Sensitivity still limited to $m_{A'} \sim \mathbf{24\ MeV/c^2}$

Possible to extend to higher masses increasing the beam energy **but**:

  - (Some of the) DAΦNE dipoles already close to field saturation
  - Currently 550 MeV is the maximum positron energy from the LINAC: the ring should **ramp up**
  - Significant **cost** and **time**
  - Only improves with **square root** of beam energy

Complementary to:

PADME@Cornell

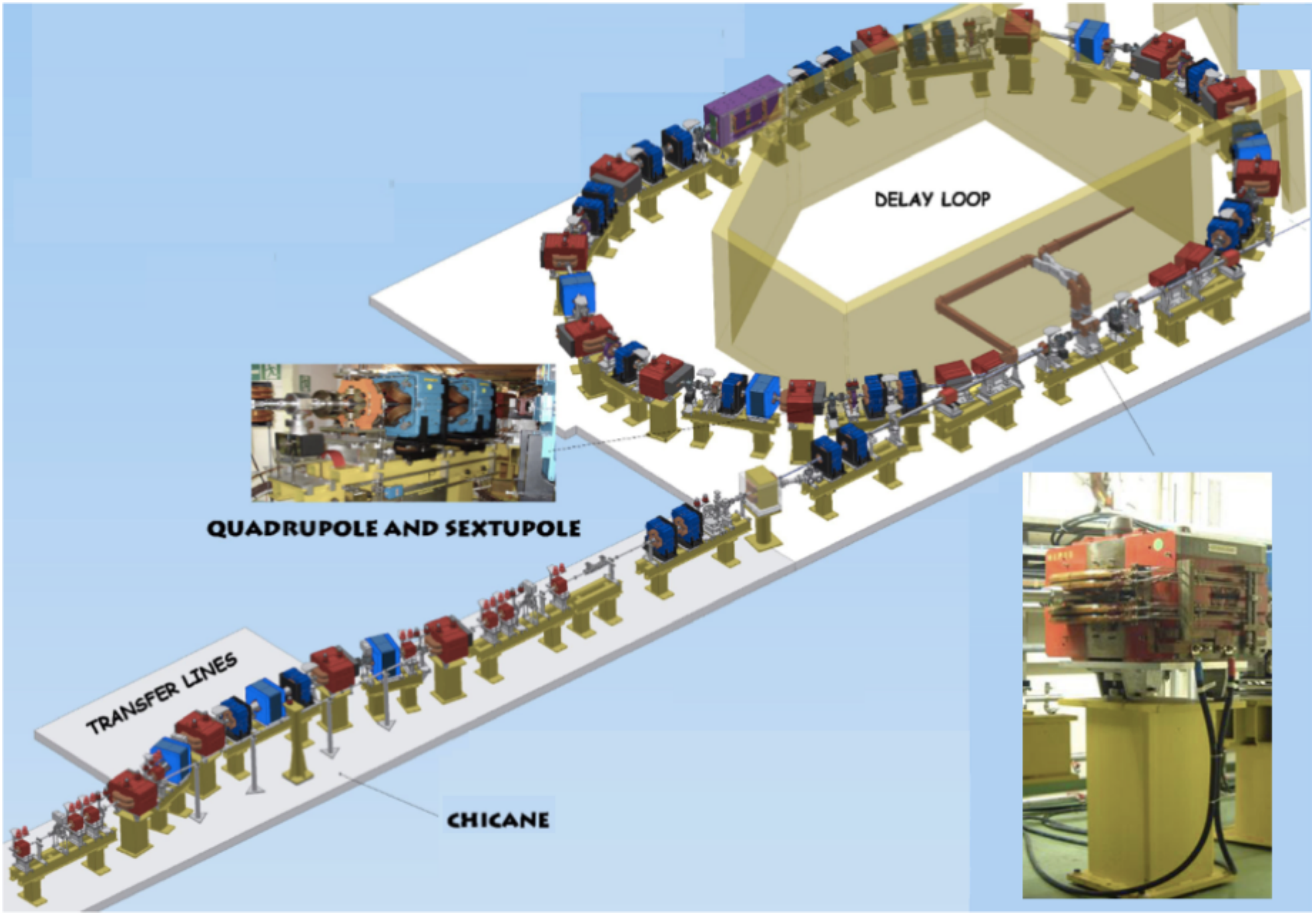
  - If NSF MRI proposal is successful ≥2022

PADME@JLAB

  - No news about positron source at CEBAF

CTF3 magnets

- Official request to CTF3 collaboration for several dipoles, quadrupoles, sextupoles, correctors and diagnostics equipment from machine de-commissioning



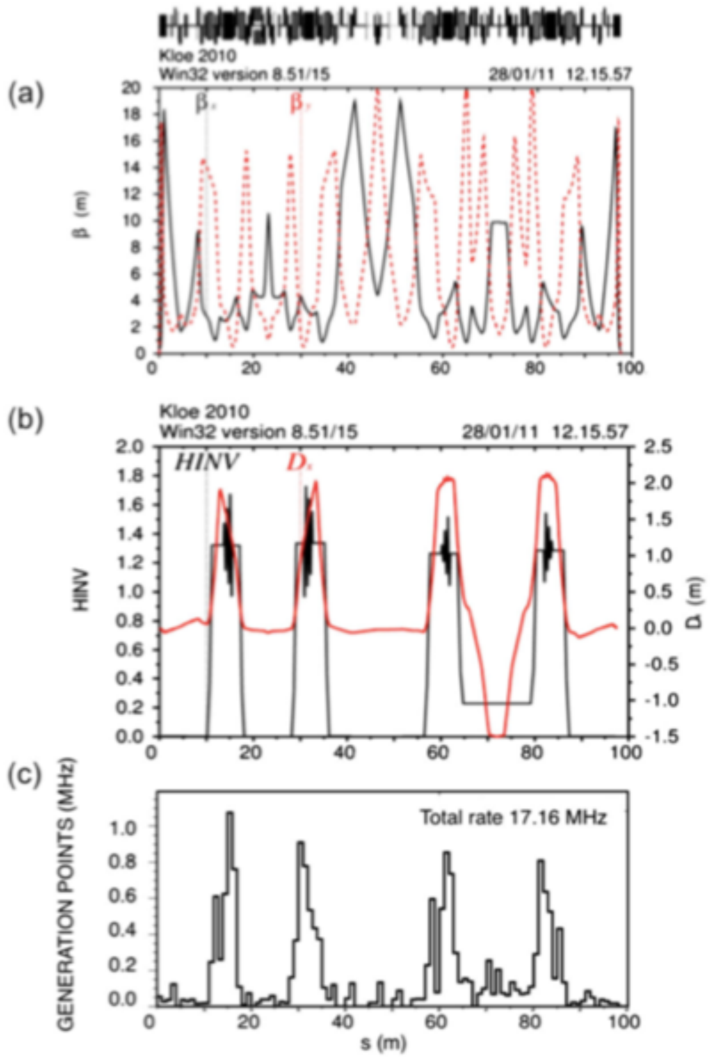
Considerazioni

- Il LINAC di DAΦNE è uno delle pochissime sorgenti di positroni di alta energia (sebbene <0.55 GeV) al mondo
- L'uso di uno dei due anelli di DAΦNE come allungatore dell'impulso del LINAC fornirebbe un fascio di positroni estratto con caratteristiche superiori rispetto a quanto ottenibile alla BTF, e con impulsi lunghi fino a **frazioni di ms/20 ms**
- La **sensitività** di un esperimento di ricerca di mediatori oscuri leggeri come PADME potrebbe essere migliorata di **2 ordini di grandezza** (incremento della statistica di 4 ordini di grandezza)
- L'uso del channeling in luogo dell'estrazione risonante consentirebbe di avere sul setto di estrazione un flusso **praticamente continuo** di positroni, avvicinando le caratteristiche del fascio a quelle ottenibili esclusivamente da un LINAC continuous-wave; un esperimento tipo PADME potrebbe essere condotto in «**single particle**» ovvero praticamente in **assenza di fondo**.
- La disponibilità di un fascio di positroni con queste caratteristiche sarebbe estremamente utile anche per la ricerca nel campo del channeling stesso, per esempio per lo studio della **produzione di radiazione**
- L'uso dell'anello di positroni per questo tipo di attività consentirebbe comunque **l'operazione delle linee di luce di sincrotrone** nell'anello (completamente separato) degli elettroni
- Il costo dell'operazione **senza wigglers**, eventualmente ulteriormente ottimizzato, può essere **<50%** rispetto ad oggi
- **Ad oggi non esiste un piano di medio-lungo termine per il complesso dell'acceleratore DAΦNE**, solo la ragionevole ipotesi che il LINAC e la BTF continueranno ad essere operative anche nel prossimo decennio

P. Valente,"*POSEYDON - Converting the DAFNE Collider into a double Positron Facility: a High Duty-Cycle pulse stretcher and a storage ring*"

arXiv:1711.06877 [physics.acc-ph], Report **INFN-17-15/LNF**

Touschek losses



Dispersion

M. Boscolo