The Atiyah-Patodi-Singer index and domain-wall fermion Dirac operators

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Introduction

This talk is based on a joint work

arXiv:1910.01987 (to appear in CMP)

of three mathematicians and three physicists:

- Mikio Furuta
- Mayuko Yamashita
- Shinichiroh Matsuo
- Hidenori Fukaya
- Tetsuya Onogi
- Satoshi Yamaguchi

Main theorem

Theorem 1.1 (FFMOYY, arXiv:1910.01987, to appear in CMP)
For $m \gg 0$, we have a formula

$$\mathrm{Ind}_{\mathrm{APS}}(D|_{X_+}) = \frac{\eta(D + m\kappa\gamma) - \eta(D - m\gamma)}{2}.$$

- The Atiyah-Patodi-Singer index is expressed in terms of the η-invariant of domain-wall fermion Dirac operators.
- The original motivation comes from the bulk-edge correspondence of topological insulators in condensed matter physics.
- The proof is based on a Witten localisation argument.

Plan of the talk

1. Reviews of the Atiyah-Singer index and the eta invariant
2. The Atiyah-Patodi-Singer index
3. Domain-wall fermion Dirac operators
4. Main theorem
5. The proof of a toy model
6. The proof of the main theorem: Witten localisation

Index and Eta

Let X be a closed manifold and $S \to X$ a hermitian bundle. Assume $\dim X$ is even. Assume S is $\mathbb{Z}/2$-graded: there exists $\gamma : \Gamma(S) \to \Gamma(S)$ such that $\gamma^2 = \mathrm{id}_S$.

$$\gamma = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

Let $D : \Gamma(S) \to \Gamma(S)$ be a 1st order elliptic differential operator. Assume D is odd and self-adjoint:

$$D = \begin{pmatrix} 0 & D_- \\ D_+ & 0 \end{pmatrix} \text{ and } D_- = (D_+)^*.$$

Definition 2.1 (Atiyah-Singer index)
We define the index $\mathrm{Ind}\, D$ of a self-adjoint, odd, elliptic operator D by

$$\begin{aligned} \mathrm{Ind}\, D &:= \dim \mathrm{Ker}\, D_+ - \dim \mathrm{Ker}\, D_- \\ &= \dim \mathrm{Ker}\, D_+ - \dim \mathrm{Coker}\, D_+. \end{aligned}$$

Fix $m \neq 0$ and consider

$$D + m\gamma = \begin{pmatrix} m & D_- \\ D_+ & -m \end{pmatrix} : \Gamma(S) \to \Gamma(S).$$

This is self-adjoint but no longer odd; thus, its spectrum is real but not symmetric around 0.

For $s \in \mathbb{C}$, let

$$\eta(D + m\gamma)(s) := \sum_{\lambda_j} \frac{\operatorname{sign} \lambda_j}{|\lambda_j|^s},$$

where $\{\lambda_j\} = \operatorname{Spec}(D + m\gamma)$. Note that $\lambda_j \neq 0$ for any j.

- This series converges absolutely when $\operatorname{Re}(s) \gg 0$.
- We can extend $\eta(D + m\gamma)(s)$ meromorphically to the whole complex plane $\mathbb{C}$.
- It is a quite non-trivial result that 0 is not a pole of $\eta(D + m\gamma)(s)$.

Definition 2.2

$$\eta(D + m\gamma) := \eta(D + m\gamma)(0).$$

The eta invariant describes the overall asymmetry of the spectrum of a self-adjoint operator.

Proposition 2.3

For any $m > 0$, we have a formula

$$\mathrm{Ind}(D) = \frac{\eta(D + m\gamma) - \eta(D - m\gamma)}{2}.$$

This formula might be unfamiliar; however, we can prove it easily, for example, by diagonalising D^2 and γ simultaneously. We will explain another proof later.

We will generalise this formula to handle compact manifolds with boundary and the Atiyah-Patodi-Singer index.

Proposition 2.4
For any $m > 0$, we have a formula

$$\mathrm{Ind}(D) = \frac{\eta(D + m\gamma) - \eta(D - m\gamma)}{2}.$$

We will generalise this formula to handle compact manifolds with boundary and the Atiyah-Patodi-Singer index by using domain-wall fermion Dirac operators.

Theorem 2.5 (FFMOYY arXiv:1910.01987)
For $m \gg 0$, we have a formula

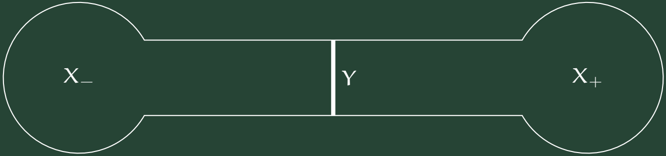
$$\mathrm{Ind}_{\mathrm{APS}}(D|_{X_+}) = \frac{\eta(D + m\kappa\gamma) - \eta(D - m\gamma)}{2}.$$

Next, we review the Atiyah-Patodi-Singer index.

The Atiyah-Patodi-Singer index

Let $Y \subset X$ be a separating submanifold that decomposes X into two compact manifolds X_+ and X_- with common boundary Y. Assume Y has a collar neighbourhood isometric to $(-4, 4) \times Y$.

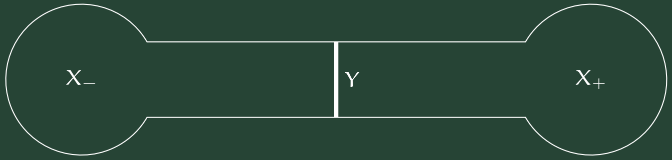
$$(-4, 4) \times Y \subset X = X_- \bigcup_Y X_+$$



Assume $S \to X$ and $D\colon \Gamma(S) \to \Gamma(S)$ are standard on $(-4, 4) \times Y$ in the sense that there exists a hermitian bundle $E \to Y$ and a self-adjoint elliptic operator $A\colon \Gamma(E) \to \Gamma(E)$ such that $S = \mathbb{C}^2 \otimes E$ and

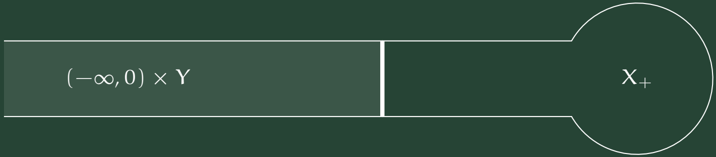
$$D = \begin{pmatrix} 0 & D_+^* \\ D_+ & 0 \end{pmatrix} = \begin{pmatrix} 0 & \partial_u + A \\ -\partial_u + A & 0 \end{pmatrix}$$

on $(-4, 4) \times Y$.



Assume also A has no zero eigenvalues.

Let $\widehat{X_+} := (-\infty, 0] \times Y \cup X_+$.



We assumed D is translation invariant on $(-4, 4) \times Y$:

$$D = \begin{pmatrix} 0 & D_+^* \\ D_+ & 0 \end{pmatrix} = \begin{pmatrix} 0 & \partial_u + A \\ -\partial_u + A & 0 \end{pmatrix}.$$

Thus, $D|_{X_+}$ naturally extends to $\widehat{X_+}$, which is denoted by $\widehat{D}$.

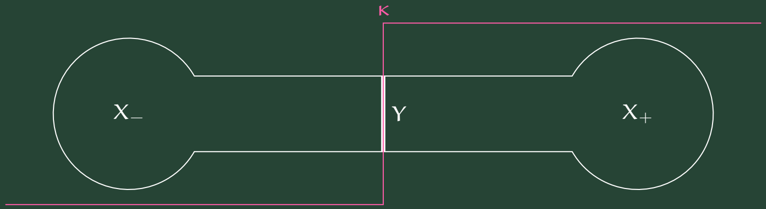
This is Fredholm if A has no zero eigenvalues.

Definition 3.1 (Atiyah-Patodi-Singer index)

$$\mathrm{Ind}_{\mathrm{APS}}(D|_{X_+}) := \mathrm{Ind}(\widehat{D})$$

Domain-wall fermion Dirac operators

Let $\kappa\colon X \to \mathbb{R}$ be a step function such that $\kappa \equiv \pm 1$ on $X_{\pm}$.



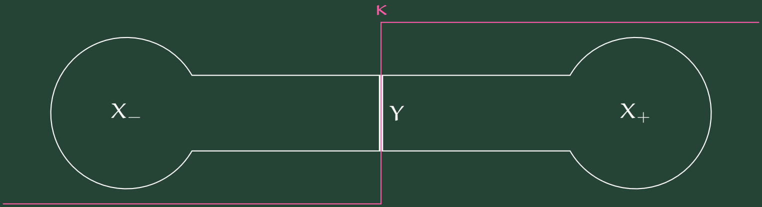
Definition 4.1

For $m > 0$,

$$D + m\kappa\gamma\colon \Gamma(S) \to \Gamma(S)$$

is called a domain-wall fermion Dirac operator.

$D + m\kappa\gamma$ is self-adjoint but not odd.



$$D = \begin{pmatrix} 0 & \partial_u + A \\ -\partial_u + A & 0 \end{pmatrix} \text{ on } (-4, 4) \times Y$$

Proposition 4.2

If $\operatorname{Ker} A = \{0\}$, then $\operatorname{Ker}(D + m\kappa\gamma) = \{0\}$ for $m \gg 0$.

Next we will define $\eta(D + m\kappa\gamma)$.

The eta invariant of domain-wall fermion Dirac operators

Since $\mathrm{Ker}(D + m\kappa\gamma) = \{0\}$, there exists a constant $C_m > 0$ such that $\mathrm{Ker}(D + m\kappa\gamma + f) = \{0\}$ if $\|f\|_2 < C_m$.

Proposition 4.3 (Corollary of the variational formula of the eta invariant)
Assume both $m\kappa\gamma + f_1$ and $m\kappa\gamma + f_2$ are smooth and self-adjoint with $\|f_1\|_2 < C_m$ and $\|f_2\|_2 < C_m$. Then, we have

$$\eta(D + m\kappa\gamma + f_1) = \eta(D + m\kappa\gamma + f_2).$$

Definition 4.4
For any f with $\|f\|_2 < C_m$ and $m\kappa\gamma + f$ smooth and self-adjoint, we set

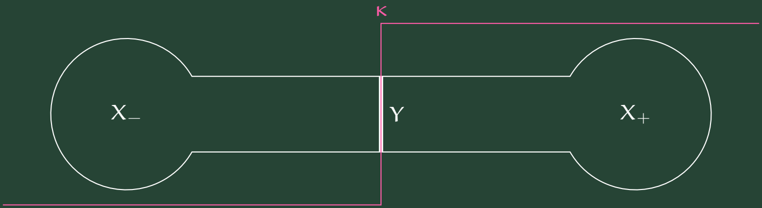
$$\eta(D + m\kappa\gamma) := \eta(D + m\kappa\gamma + f).$$

Main theorem

Main theorem

Theorem 5.1 (FFMOYY arXiv:1910.01987)
For $m \gg 0$, we have a formula

$$\mathrm{Ind}_{\mathrm{APS}}(D|_{X_+}) = \frac{\eta(D + m\kappa\gamma) - \eta(D - m\gamma)}{2}.$$



- The Atiyah-Patodi-Singer index is expressed in terms of the η-invariant of domain-wall fermion Dirac operators.
- The original motivation comes from physics.
- The proof is based on a Witten localisation argument.

The proof of a toy model

Toy model

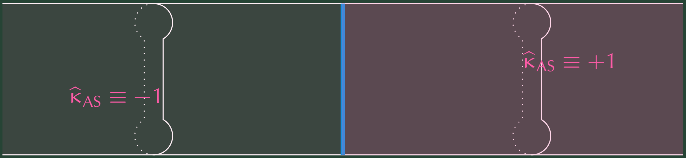
Proposition 6.1

For any $m > 0$, we have a formula

$$\mathrm{Ind}(D) = \frac{\eta(D + m\gamma) - \eta(D - m\gamma)}{2}.$$

As a warm-up, we will prove this formula in the spirit of our proof of the main theorem.

Let $\widehat{\kappa}_{AS} : \mathbb{R} \times X \to \mathbb{R}$ be a step function such that $\widehat{\kappa}_{AS} \equiv 1$ on $(0, \infty) \times X$ and $\widehat{\kappa}_{AS} \equiv -1$ on $(-\infty, 0) \times X$.



We consider $\widehat{D}_m : L^2(\mathbb{R} \times X; S \oplus S) \to L^2(\mathbb{R} \times X; S \oplus S)$ defined by

$$\widehat{D}_m := \begin{pmatrix} 0 & (D + m\widehat{\kappa}_{AS}\gamma) + \partial_t \\ (D + m\widehat{\kappa}_{AS}\gamma) - \partial_t & 0 \end{pmatrix}.$$

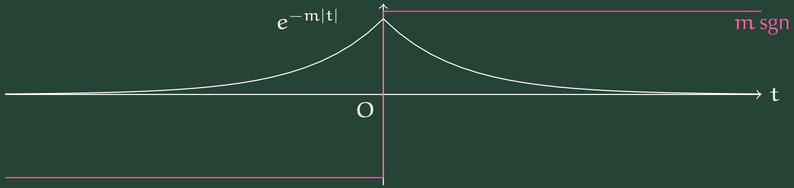
This is a Fredholm operator.

Model case: the Jackiw-Rebbi solution on $\mathbb{R}$

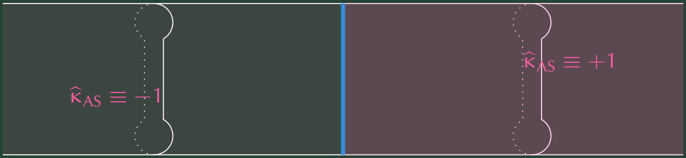
For any $m > 0$, we have

$$\frac{d}{dt} e^{-m|t|} = -m \,\mathrm{sgn}\, e^{-m|t|},$$

where $\mathrm{sgn}(\pm t) = \pm 1$. As $m \to \infty$, the solution concentrates at 0.



$$\begin{pmatrix} 0 & \partial_t + m\,\mathrm{sgn} \\ -\partial_t + m\,\mathrm{sgn} & 0 \end{pmatrix} \begin{pmatrix} 0 \\ e^{-m|t|} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}.$$



$$\widehat{D}_m := \begin{pmatrix} 0 & (D + m\widehat{\kappa}_{AS}\gamma) + \partial_t \\ (D + m\widehat{\kappa}_{AS}\gamma) - \partial_t & 0 \end{pmatrix}$$

$$(e^{-m|t|})' = -m\,\mathrm{sgn}\,e^{-m|t|}$$

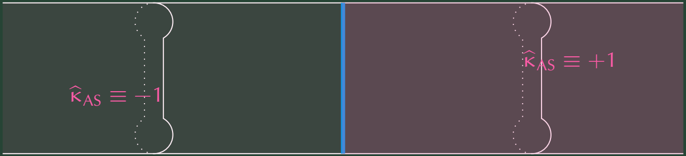
Proposition 6.2 (Product formula)

$$\mathrm{Ind}(D) = \mathrm{Ind}(\widehat{D}_m)$$

(Proof) Assume $D\phi = 0$. Set $\phi_\pm := (\phi \pm \gamma\phi)/2$. Then, we have

$$\begin{pmatrix} 0 & (D + m\widehat{\kappa}_{AS}\gamma) + \partial_t \\ (D + m\widehat{\kappa}_{AS}\gamma) - \partial_t & 0 \end{pmatrix} \begin{pmatrix} e^{-m|t|}\phi_- \\ e^{-m|t|}\phi_+ \end{pmatrix} = 0.$$

□



$$\widehat{D}_m := \begin{pmatrix} 0 & (D + m\widehat{\kappa}_{AS}\gamma) + \partial_t \\ (D + m\widehat{\kappa}_{AS}\gamma) - \partial_t & 0 \end{pmatrix}$$

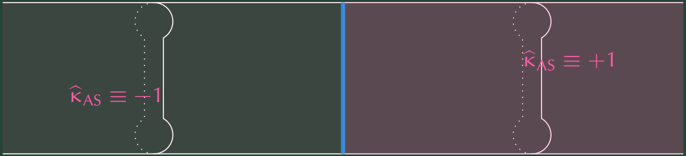
Proposition 6.3 (APS formula)

$$\mathrm{Ind}(\widehat{D}_m) = \frac{\eta(D + m\gamma) - \eta(D - m\gamma)}{2}$$

(Proof)

- Note that $D + m\widehat{\kappa}_{AS}(\pm 1, \cdot)\gamma = D \pm m\gamma$.
- Perturb $\widehat{\kappa}_{AS}$ slightly near $\{0\} \times X$ to get a smooth operator.
- Use the Atiyah-Patodi-Singer index theorem on $\mathbb{R} \times X$.
- Since $\dim \mathbb{R} \times X$ is odd, the constant term in the asymptotic expansion of the heat kernel vanishes.

□



$$\widehat{D}_m := \begin{pmatrix} 0 & (D + m\widehat{\kappa}_{AS}\gamma) + \partial_t \\ (D + m\widehat{\kappa}_{AS}\gamma) - \partial_t & 0 \end{pmatrix}$$

Proposition 6.4

$$\mathrm{Ind}(D) = \frac{\eta(D + m\gamma) - \eta(D - m\gamma)}{2}.$$

(Proof) By the product formula, we have

$$\mathrm{Ind}(D) = \mathrm{Ind}(\widehat{D}_m).$$

By the APS formula, we have

$$\mathrm{Ind}(\widehat{D}_m) = \frac{\eta(D + m\gamma) - \eta(D - m\gamma)}{2}.$$

□

The proof of the main theorem

Outline of the proof

Theorem 7.1 (FFMOYY arXiv:1910.01987)
For $m \gg 0$, we have a formula

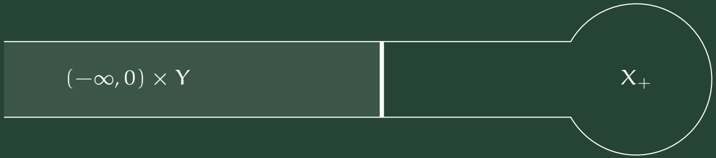
$$\mathrm{Ind}_{\mathrm{APS}}(D|_{X_+}) = \frac{\eta(D + m\kappa\gamma) - \eta(D - m\gamma)}{2}.$$

The proof is modelled on the original embedding proof of the Atiyah-Singer index theorem.

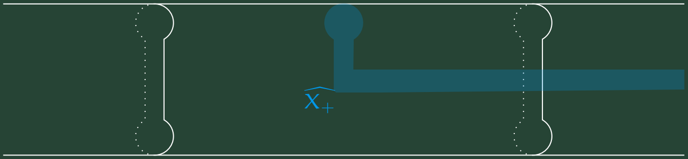
1. Embed $\widehat{X_+}$ into $\mathbb{R} \times X$.
2. Extend both $\widehat{D}$ on $\widehat{X_+}$ and $D + m\kappa\gamma$ on $\{10\} \times X$ to $\mathbb{R} \times X$.
3. Use the product formula, the APS formula, and a Witten localisation argument.

Embedding of $\widehat{X_+}$ into $\mathbb{R} \times X$

$\widehat{X_+} := (-\infty, 0] \times Y \cup X_+$.

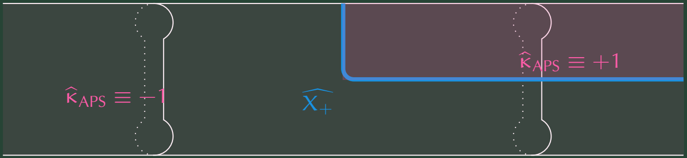


We can embed $\widehat{X_+}$ into $\mathbb{R} \times X$ as follows:



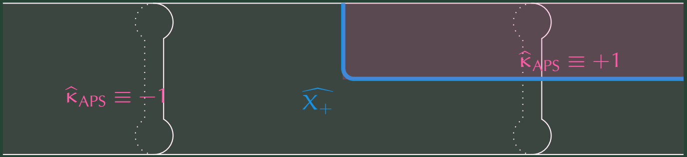
Extension of $\widehat{D}$ and $D + m\kappa\gamma$ to $\mathbb{R} \times X$

$(\mathbb{R} \times X) \setminus \widehat{X_+}$ has two connected components. We denote by $(\mathbb{R} \times X)_-$ the one containing $\{-10\} \times X_+$ and by $(\mathbb{R} \times X)_+$ the other half. Let $\widehat{\kappa}_{APS} \colon \mathbb{R} \times X \to [-1, 1]$ be a step function such that $\widehat{\kappa}_{APS} \equiv \pm 1$ on $(\mathbb{R} \times X)_\pm$.



We consider

$$\widehat{\mathcal{D}}_m := \begin{pmatrix} 0 & (D + m\widehat{\kappa}_{APS}\gamma) + \partial_t \\ (D + m\widehat{\kappa}_{APS}\gamma) - \partial_t & 0 \end{pmatrix}.$$

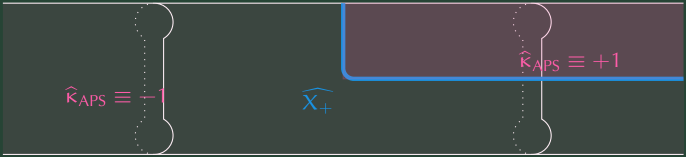


$$\widehat{\mathcal{D}}_m := \begin{pmatrix} 0 & (D + m\widehat{\kappa}_{APS}\gamma) + \partial_t \\ (D + m\widehat{\kappa}_{APS}\gamma) - \partial_t & 0 \end{pmatrix}$$

$$\widehat{\kappa}_{APS} \equiv \kappa \text{ on } \{10\} \times X.$$

Proposition 7.2 (APS formula)

$$\mathrm{Ind}(\widehat{\mathcal{D}}_m) = \frac{\eta(D + m\kappa\gamma) - \eta(D - m\gamma)}{2}$$



$$\widehat{\mathcal{D}}_m := \begin{pmatrix} 0 & (D + m\widehat{\kappa}_{APS}\gamma) + \partial_t \\ (D + m\widehat{\kappa}_{APS}\gamma) - \partial_t & 0 \end{pmatrix}.$$

The restriction of $\widehat{\mathcal{D}}_m$ to a tubular neighbourhood of $\widehat{X_+}$ is isomorphic to

$$\begin{pmatrix} 0 & (\widehat{D} + m\,\mathrm{sgn}\,\gamma) + \partial_t \\ (\widehat{D} + m\,\mathrm{sgn}\,\gamma) - \partial_t & 0 \end{pmatrix}$$

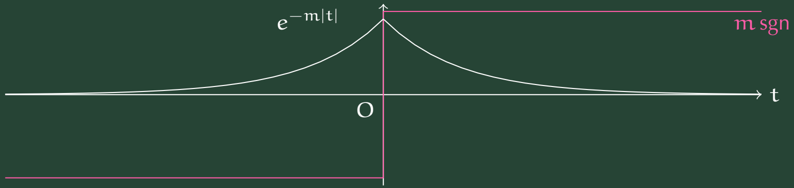
on $\mathbb{R} \times \widehat{X_+}$ near $\{0\} \times \widehat{X_+}$, where $\widehat{D}$ is the extension of $D|_{X_+}$ to $\widehat{X_+}$.

Witten localisation

Theorem 7.3 (Witten localisation)
For $m \gg 0$, we have

$$\operatorname{Ind}(\widehat{\mathcal{D}}_m) = \operatorname{Ind}\begin{pmatrix} 0 & (\widehat{D} + m\operatorname{sgn}\gamma) + \partial_t \\ (\widehat{D} + m\operatorname{sgn}\gamma) - \partial_t & 0 \end{pmatrix}.$$

The proof is too technical to state here, but the idea is simple.



$$\begin{pmatrix} 0 & \partial_t + m\operatorname{sgn} \\ -\partial_t + m\operatorname{sgn} & 0 \end{pmatrix}\begin{pmatrix} 0 \\ e^{-m|t|} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}.$$

Proposition 7.4 (Product formula)

$$\operatorname{Ind}\begin{pmatrix} 0 & (\widehat{D} + m \operatorname{sgn}\gamma) + \partial_t \\ (\widehat{D} + m \operatorname{sgn}\gamma) - \partial_t & 0 \end{pmatrix} = \operatorname{Ind}(\widehat{D})$$

Theorem 7.5 (FFMOYY arXiv:1910.01987)
For $m \gg 0$, we have a formula

$$\mathrm{Ind}_{\mathrm{APS}}(D|_{X_+}) = \frac{\eta(D + m\kappa\gamma) - \eta(D - m\gamma)}{2}.$$

(Proof) By definition, we have $\mathrm{Ind}_{\mathrm{APS}}(D|_{X_+}) = \mathrm{Ind}(\widehat{D})$.
By the product formula, we have

$$\mathrm{Ind}(\widehat{D}) = \mathrm{Ind}\begin{pmatrix} 0 & (\widehat{D} + m\,\mathrm{sgn}\,\gamma) + \partial_t \\ (\widehat{D} + m\,\mathrm{sgn}\,\gamma) - \partial_t & 0 \end{pmatrix}.$$

By the Witten localisation argument, for $m \gg 0$, we have

$$\mathrm{Ind}\begin{pmatrix} 0 & (\widehat{D} + m\,\mathrm{sgn}\,\gamma) + \partial_t \\ (\widehat{D} + m\,\mathrm{sgn}\,\gamma) - \partial_t & 0 \end{pmatrix} = \mathrm{Ind}(\widehat{\mathcal{D}}_m).$$

By the APS formula, we have

$$\mathrm{Ind}(\widehat{\mathcal{D}}_m) = \frac{\eta(D + m\kappa\gamma) - \eta(D - m\gamma)}{2}.$$

Thus, we have proved the formula. □