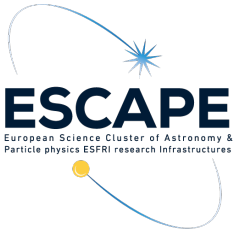

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Discovery of brown dwarfs mining the 2MASS and SDSS database

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Initial development of the tutorial

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updated with the new template for ASTERICS/ESCAPE, new plots and for A*ladin v10 & v11*

Contents

1 Introduction

Brown dwarfs are objects occupying the gap between the least massive stars and the most massive planets. They are intrinsically faint objects so their detection is not straightforward and, in fact, was almost impossible until the advent of global surveys at deep optical and near-infrared bands like SDSS, 2MASS or DENIS among others. We propose here to mine the 2MASS point source catalogue (2MASS-PSC) and SDSS-DR9 databases to identify T-type brown dwarfs through an appropriate combination of colours in the optical and the infrared, an approach that perfectly fits into the Virtual Observatory.

2 Goal of this tutorial

In this use case, we explore different ways to do the same tasks with different VO tools. These tasks include:

- obtaining data from the SDSS and 2MASS catalogues in a given sky region,
- crossmatching the results of these searches,
- filtering the resulting table for brown dwarfs, and
- verifying our sample of brown dwarfs.

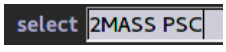
Software packages needed for this tutorial are Aladin, TOPCAT and STILTS.

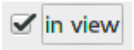
3 Aladin

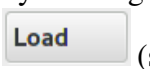
Launch Aladin: Open a terminal and type: `java -jar Aladin.jar &`

Discovery: Search 2MASS-PSC and SDSS-DR9 sources around RA: 08h30m, DEC: 01d30m with a 14 arcmin radius.

- Enter the coordinates `08:30 01:30` in the **Command** line of Aladin 

and press Enter.
- In the main viewing window the DSS colour image centred on the entered coordinates appears. Zoom in and out by scrolling with your mouse or by using the zoom register on the right hand side. Aim for a field of view of approximately 14×14 arcmin. Hint: the cyan/blue numbers in the bottom of both the main viewing window and the overview window in the bottom right corner of Aladin state the current field of view.
- Enter "2MASS PSC" in the **select** line 

below the DATA TREE. This will filter the entries in the DATA TREE to only show those that are affiliated with the 2MASS point source catalogue. Note how some entries are coloured in green and some in orange. This indicates whether a resource has data available in the current field of view (green) or not (orange).
- Choose the only green entry (**Catalog** → **VizieR** → **II-Photometric Data** → **2MASS-PSC...**) by clicking on it. In the pop-up window, make sure to tick **in view** 

and **Load** the data 

(see Figure 1). This will load a catalogue of approximately 1000 sources (Aladin will give you the number of rows of a catalogue when hoovering over the entry of the catalogue in the stack on the right of the main viewing window). You can change the appearance and name

of the data by selecting the plane ”CDS/II/246/out” in the stack and clicking the properties button. Alternatively right-click on the plane and select **Properties...**. Rename the plane to ”2MASS-PSC”.

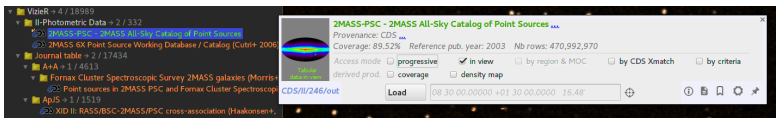


Figure 1: Loading the data available in the current field of view from the 2MASS-PSC in Aladin.

- Now we repeat the same steps for the SDSS-DR9 catalogue:
  - Enter ”SDSS DR9” in the **select** line.
  - Choose the first green entry: **Catalog** → **VizieR** → **V-Combined Data** → **SDSS-DR9...**.
  - **Load** the SDSS-DR9 catalogue data **in view**, which will include of the order of 15,000 sources. Rename the new plane to ”SDSS-DR9”.

Crossmatching: In this next step, we find common sources in the 2MASS-PSC and SDSS-DR9 catalogues.

- Open the **Catalog Cross-match tool** by either clicking the cross-match button or opening the menu **Catalog** → **Cross match objects ...**.
- In the **Catalog Cross-match tool** enter the two catalogues and their coordinate columns, keep the default threshold for source separation ($0 \leq$ threshold ≤ 4) and select **Best matches** (see Figure 2). Make sure that the catalogue with the smaller number of sources is named in the first line. Then hit **Perform cross-match**. A new plane called ”XMatch” will appear in the stack. It contains almost as many sources as the 2MASS-PSC plane.

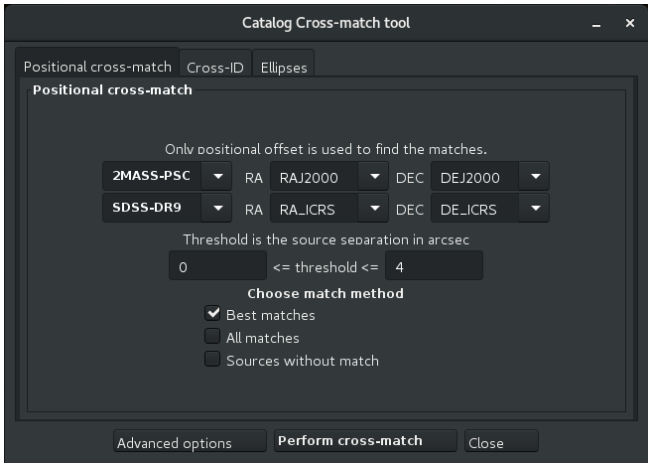


Figure 2: Cross-matching 2MASS-PSC and SDSS DR9 in Aladin.

Filtering: Select those sources from our cross-match catalogue that are SDSS point sources and have characteristics that are expected from brown dwarfs.

- Hide the 2MASS-PSC and SDSS-DR9 planes by clicking on . Note that moving the green controller button in the bottom of this symbol changes the opacity of the plane.

- Select the XMatch plane by clicking on it. Open the **Filter properties** window by either using the **Filter** button  or following the menu through **Catalog** → **Create a filter...**.
- In the opened window **Properties of the filter** move to the **Advanced mode** tab. Click on the Columns ▷ button and chose **Columns in loaded catalogs...**. Select the ”cl_tab2” column from the XMatch catalogue.
- Complete the filter condition. It should be `${cl_tab2}=6 {draw}`. This tells Aladin that only sources from the XMatch table that adhere to the condition cl_tab2=6 should be shown in the main viewing window. The **Actions**, **Maths...**, **Units** and **UCDs** buttons next to the **Columns...** button further help in constructing filter.
- Click on Apply. This will apply the filter to the XMatch plane. Clicking Export will create a new plane ”Filter.src”, which only contains those sources from the XMatch plane that comply with the filter criterion. Approximately 100 sources will be excluded by this filtering action.

Now that we have limited our sample to point sources according to the SDSS data, we move on to select brown dwarf candidates. Brown dwarfs are cool objects so they are not detected in the blue SDSS bands. We therefore select sources with no detection in the u and g SDSS bands `(u > 22.0 && g >22.2`. We furthermore search for sources fulfilling the brown dwarf criteria provided by Burgasser et al. (2000, ApJ, 531, L57): `((J-H)<0.3 && (H-K)<0.3)`.

- Hide the XMatch plane.
- Select the ”Filter.src” plane. If you wish you can again change name colour and plotting symbol by using the  button.
- Repeat the same steps as for the previous filter. The filter condition should now be: `${umag_tab2} > 22.0 && ${gmag_tab2} > 22.2 && ${Jmag_tab1} - ${Hmag_tab1} < 0.3 && ${Hmag_tab1} - ${Kmag_tab1} < 0.3 {draw}`
- Click on Apply. Then click on Export to create a new plane with the filtered sources.
- A new plane ”Filter.src∼1” will be loaded in the Aladin main window. It should contain 1 source. (RA_2MASS:127.703265 deg; DEC_2MASS:1.475320 deg). Note that the corresponding table column will be shown when double-clicking on the source.
- If you have the **Simbad pointer** enabled (see Figure 3), hoover with the mouse over the source until a small grey window appears. This grey window already tells you the name (2MASS J08304878+0128311) and the object type (brownD*) of the source. In order to visit the SIMBAD page for this source, click on the name.

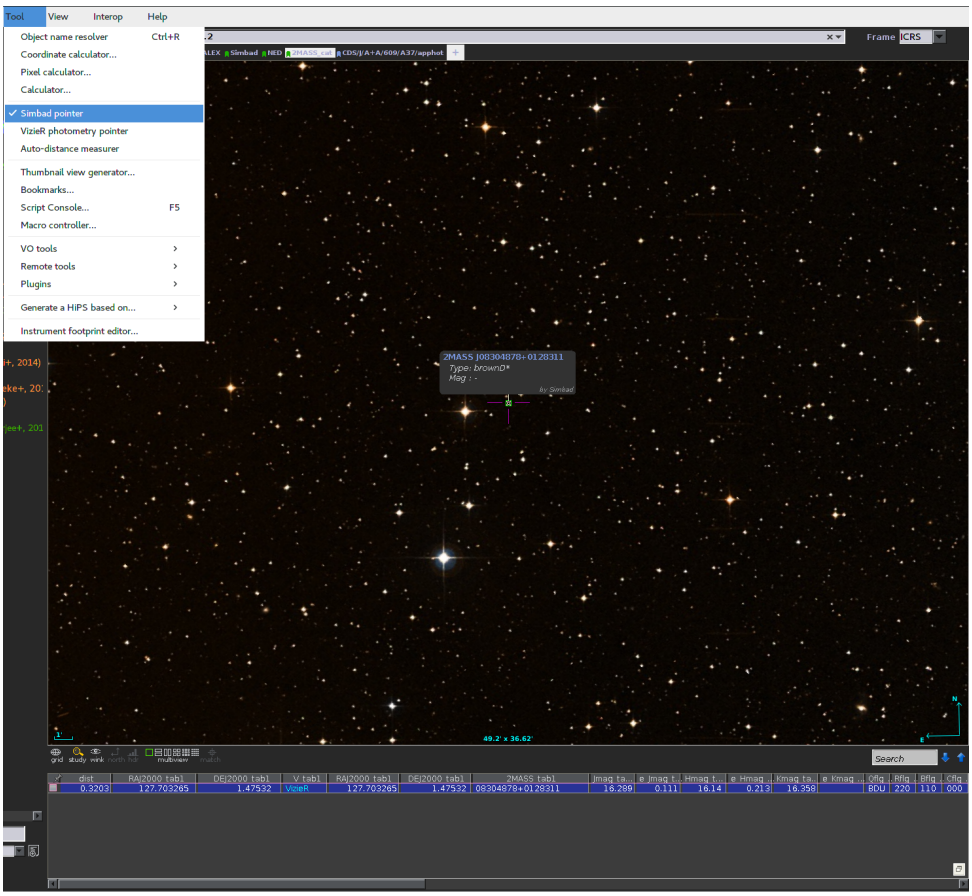


Figure 3: Enabling the Simbad pointer in Aladin and getting basic information on our resulting source. Hurray, it is indeed a brown dwarf!

4 TOPCAT

Launch TOPCAT: Open a terminal and type: `java -jar topcat-full.jar &`

Discovery: Search 2MASS-PSC and SDSS-DR9 sources around RA: 08h30m, DEC: 01d30m with a 14 arcmin radius.

- In the TOPCAT main window follow the menu to **VO** → **VizieR Catalogue Service**. A new window (**VizieR Catalogue Service**) opens.
- In this new window select **Cone Search** 

and enter the coordinates, radius and units:
RA: 08:30:00 hh:mm:ss
Dec: 01:30:00 dd:mm:ss
Radius: 14 arcmin
- In the bottom half of the **VizieR Catalogue Service** window, choose the **Surveys** tab, find and select "2MASS-PSC" and then click OK. This will load the table "II_246_out" with 683 rows (i. e. sources) in the TOPCAT main window.
- Repeat the previous steps for SDSS-DR9. This will load the table "V_139_SDSS9" with 12,404 sources into the TOPCAT main window.

- Alternatively, you could broadcast the 2MASS and SDSS DR9 catalogs from Aladin to TOPCAT using SAMP (Simple Application Messaging Protocol): In Aladin, right-click on the "2MASS-PSC" plane in the stack. Then select **Broadcast selected tables to ...** → **topcat** (see Figure 4). The table should appear in the TOPCAT main window. Use the same approach for the SDSS DR9 sources.

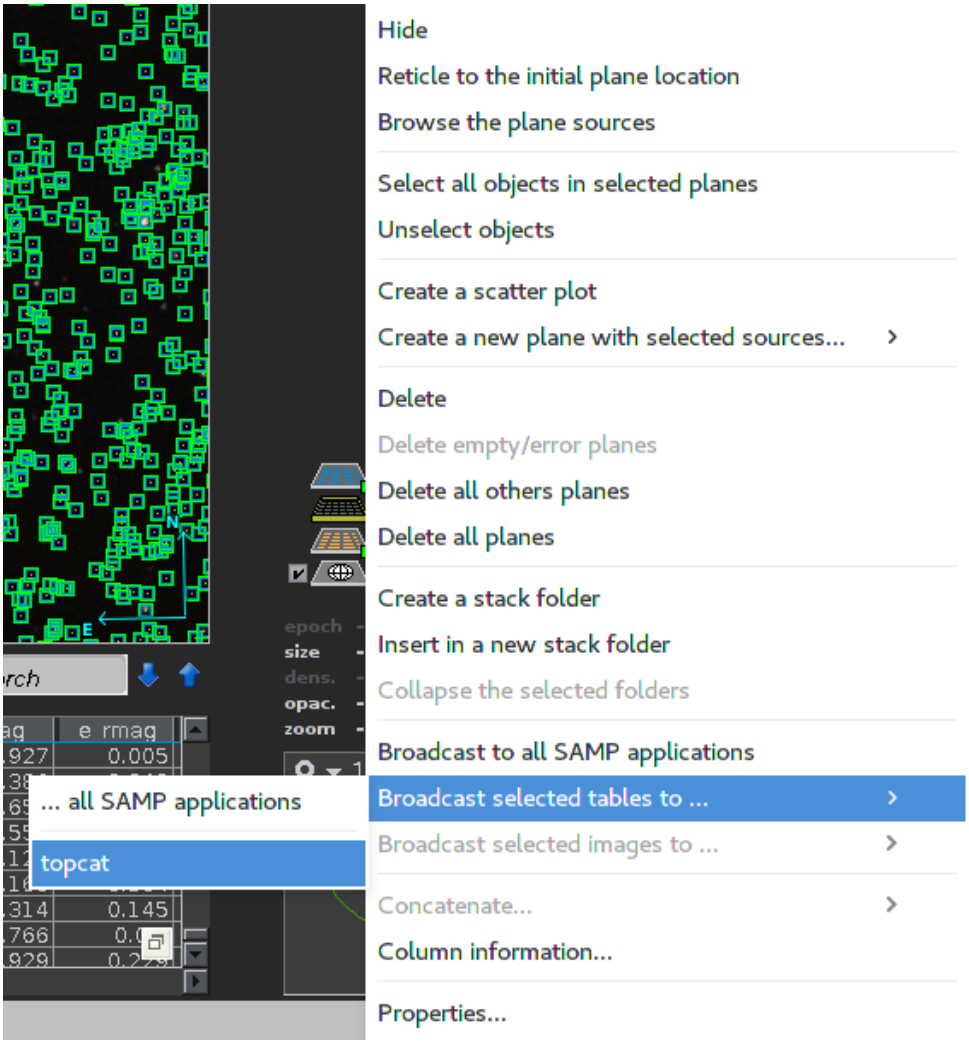


Figure 4: Broadcasting a table from Aladin to TOPCAT via SAMP.

Crossmatching: In this next step, we find common sources in the 2MASS-PSC and SDSS-DR9 catalogues.

- Open the TOPCAT **Match Tables** window by either following the menu in the main window to **Joins** → **Pair Match** or simply using the  button.
- In the **Match Tables** window set the following parameters (see Figure 5):
  - In the Match criteria box:
    Algorithm: Sky
    Max error: 4 arcsec
  - Table1: II_246_out (2MASS-PSC). RA/Dec columns: RAJ2000, DEJ2000.
  - Table2: V_139_sdss9 (SDSS-DR9). RA/Dec columns: RA_ICRS, DE_ICRS.

– Output Rows box:
Match selection: Best match, symmetric
Join Type: 1 and 2

Then click **Go**, get the notification that 679 pairs were found and confirm that a new plane "match(1,2)" with 679 sources is loaded.

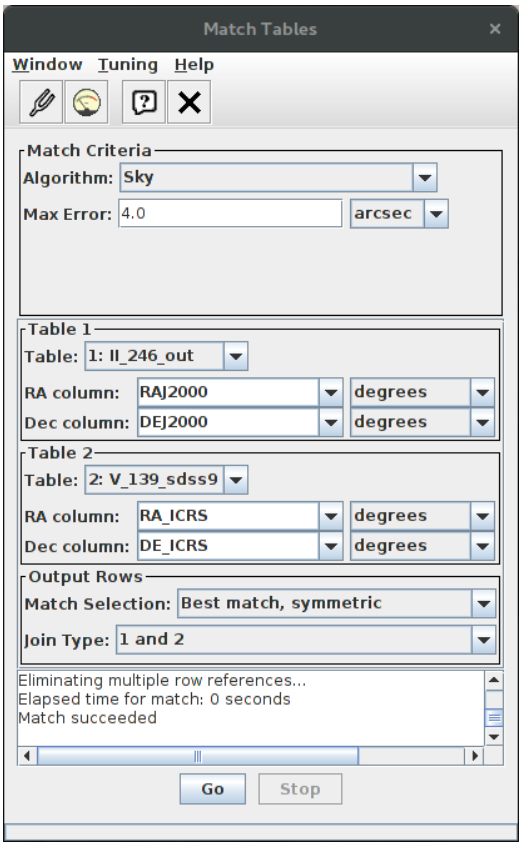


Figure 5: Cross-matching the 2MASS PSC and the SDSS DR9 tables in TOPCAT.

Filtering: Select those sources from our cross-match catalogue that are SDSS point sources and have characteristics that are expected from brown dwarfs.

- Again, we first remove all sources that not SDSS point sources. To do so select the "match(1,2)" table and then open the TOPCAT subset window by either following the menu in the main window to **Views** → **Rows Subsets** or use the  button.
- In the newly opened window **Row Subsets** create a new subset by clicking  .
- In the new **Define Row Subset** window fill in the form with:
Subset Name: filt1
Expression: `c1==6` or `$24==6`. The second option is particularly useful when two columns have the same name except for upper and lower case e. g. one named "cl" and another one "CL", because TOPCAT expression are case insensitive. You can find the number of a column in the table metadata, accessible via  .
- Click **OK**. In the **Current Table Properties** panel in the main window, you can now select in the **Row Subset** dropdown menu between **All** or **filt1**. If you chose **filt1**, 649 sources are included in the table.

- Before we move on, let's have a look at the content of the new table. To do so click  . This will open a new window within which you can scroll through the table.
- In order to implement the brown dwarf selection criteria, we have two options:
  - Go back to the **Row Subset** window of the match(1,2) table (which table the window is working on is mentioned in the line below the buttons). Add a second subset with (see Figure 6):
    Subset Name: filt2
    Expression: `cl==6 && umag>22.0 && gmag> 22.2 && Jmag-Hmag<0.3 && Hmag-Kmag<0.3`
  - Select the match(1,2) table and for **Row Subset filt1**. Then duplicate the table by following the menu to **File** → **Duplicate Table**. This will create a new table called "Copy of 3" that only includes the rows of the filt1 subset. Now we can create a new subset of this table by first selecting it in the main window, then opening the **Row Subsets** window with  and adding a new subset with  . The Expression would be `umag>22.0 && gmag> 22.2 && Jmag-Hmag<0.3 && Hmag-Kmag<0.3`.

  The second option might appear a bit cumbersome but will come in handy for more complex analyses. Either way, after the filtering process only one source remains: RA:127.703265 deg; DEC:1.475320 deg.

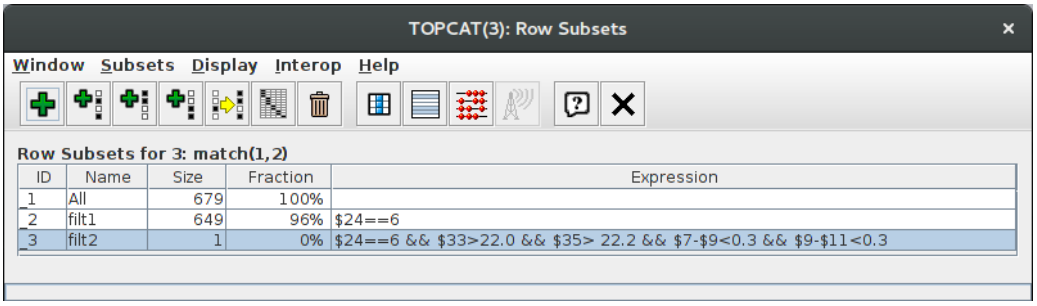


Figure 6: Subset of the cross-matched 2MASS PSC/ SDSS DR9 tables in TOPCAT.

- In order to visualise the source and check whether it is indeed a brown dwarf, you could now broadcast the filtered table to Aladin (if Aladin is running):
  - In the TOPCAT main window select the match(1,2) table and filt2 as the row subset.
  - Now either click the broadcast button  or go through the menu **Interop** → **Send table to...** → **Aladin**.
  - Now a new table should appear in the Aladin stack and you can proceed as before.

5 Advanced Scripting in Aladin

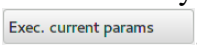
Aladin has a script mode to build a list of commands to be processed. The workflow can be executed automatically for a list of targets. If you closed Aladin launch it again (`java -jar Aladin.jar &`). If Aladin is open, click on any plane, click right mouse button and select "Delete all planes" (to clean up a little bit before we move on).

- Before we get started in Aladin, we create two text files in any text editor and save them. The content of the script file looks as follows:

```
2mass = get VizieR(2MASS-PSC) $1 $2 14'
sync
sdss = get VizieR(SDSS-DR9) $1 $2 14'
sync
2massdss= xmatch 2mass sdss 4 bestmatch
sync
hide 2mass
sync
hide sdss
sync
filter candidates { ${cl_tab2}==6 && ${umag_tab2}>22.0 &&
    ${gmag_tab2}>22.2 && ${Jmag_tab1}-${Hmag_tab1}<0.3 &&
    ${Hmag_tab1}-${Kmag_tab1}<0.3 {draw} }
#(the 3 lines above are 1 single line, remove the tabs and linebreaks)
sync
select 2massdss
sync
cplane candidates
```

  The parameter file looks like this:

```
# RA DEC
08:30:00, 01:30:00
```

- Now go back to the Aladin main window and open an **Macros** window by using the menu **Tool** → **Macro controller...**.
- In the **Macros** window use the menu to load the script file: go to **File** → **Load script** or type CTRL+S. Select and open your script file from where you saved it before.
- Now do the same for the parameter file: go to **File** → **Load params** or type CTRL+P. Select and open your parameter file from where you saved it before.
- Select the coordinate by clicking on their entry in the **Macros** window and push **Exec. current params** 

. Aladin will now go through the script executing the steps we took before by itself. Once Aladin is finished you should see one source highlighted on the screen, which is again the brown dwarf we identified before.

More information on how to build scripts in Aladin can be found in the Aladin menu at: **Help** → **Help on script commands** or by using CTRL+F5.

6 STILTS

STILTS has the same underlying library as TOPCAT but is a command-line tool and can thus be scripted.

- Copy the file "stilts.script" (http://cds.unistra.fr/tutorials/CDS-tutorial/stilts.script) to your local computer. You may also use the version further below. For the version below, be aware that line-breaks had to be inserted to be able to fit the commands on an A4 page. Make sure that you remove all line-breaks, for which the old line does not end with a "\" and the new line has an extra large indent (i. e. all line-breaks that are within a string, an URL, ...). Leave no blank spaces, where you remove these line-breaks.
- Make the script executable by typing `chmod u+x stilts.script` into a command line.
- Execute it by entering `./stilts.script` into a command line. A new file ("candidate.xml") is created. It contains the same single object found in the previous workflows.

The commands included in the STILTS script to find the brown dwarf:

```
java -jar /path/to/stilts/stilts.jar tpipe \
    'in=http://vizier.u-strasbg.fr/viz-bin/conesearch/II/246?
        -out.max=unlimited&verb=3&RA=127.5&DEC=+1.5&SR=0.2333333' \
    out=2mass.xml

java -jar /path/to/stilts/stilts.jar tpipe \
    'in=http://vizier.u-strasbg.fr/viz-bin/conesearch/V/139?
        -out.max=unlimited&verb=3&RA=127.5&DEC=+1.5&SR=0.2333333' \
    out=sdssdr9.xml

java -jar /path/to/stilts/stilts.jar tskymatch2 ifmt1=votable in1=2mass.xml \
    ifmt2=votable in2=sdssdr9.xml ra1=RAJ2000 dec1=DEJ2000 ra2=RA_ICRS \
    dec2=DE_ICRS error=4 find=best join=1and2 ofmt=votable out=cross.xml

java -jar /path/to/stilts/stilts.jar tpipe ifmt=votable in=cross.xml \
    cmd='select "cl==6 && umag>22.0 && gmag>22.2 &&
        Jmag-Hmag<0.3 && Hmag-Kmag<0.3"' \
    ofmt=votable out=candidate.xml
```

7 Python

The tasks in this tutorial can also be accomplished by using Python scripts. Go now to
https://mybinder.org/v2/gh/cds-astro/tutorials/master?filepath=Notebooks
and wait a moment for everything to load. You should then see a list of files. Click on the link to

Discovery_of_Brown_Dwarfs_mining_the_2MASS_and_SDSS_databases.ipynb

and follow the instructions there. You can also download the Jupyter notebook from the github repository to your machine. It was created to run with the packages as listed in the requirements.txt file. Using pip[1] you can install all these packages with the command `pip install [name of the package]`.

[1] https://pip.pypa.io/en/stable/